Concept: Gravity Makes Space Come Alive

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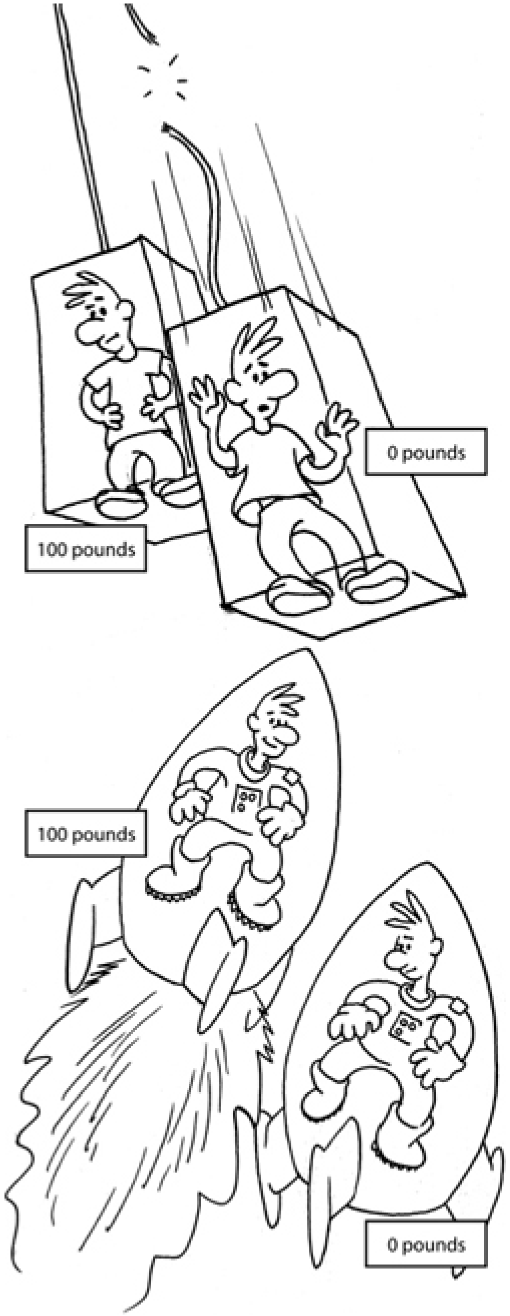

A person’s weight (100 lbs) in a stationary elevator is the same as in an accelerating rocket. A person’s weight (0 lbs) in a free-falling elevator is the same as in a stationary rocket. The person’s mass remains the same in all instances. ©AMNH

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The theories of Special and General Relativity erroneously appear to be about the same topic. Special Relativity is about motion and how measurements are changed if we change the point of view of the observer. General Relativity, on the other hand, is about gravity, or about the interaction of masses with one another. The reason why Einstein called one a generalization of the other, is that while Special Relativity deals with uniform motion, General Relativity is valid for any type of motion, accelerated or not. It is therefore a more general theory.

The Fundamental Incompatibility Between Newton's Gravity and Special Relativity

Despite the predictive success of Newton's Theory of Gravitation, Einstein's Special Relativity highlighted a fundamental flaw in Newton's theory. According to Special Relativity, nothing travels faster than the speed of light. Plenty of things travel slower. For example, a flash of lightning appears almost instantaneously, but the rumble of thunder reaches our ears as much as several seconds after we see the flash. The speed of sound, at 750 miles per hour, is much, much slower that that of light, which travels instead at 670 million miles per hour. When we say nothing travels faster than light, we are actually saying that no information will travel between any two points faster than a beam of light.

And here comes the problem. According to Newton, the force of gravity depends only on the mass of the objects that feel the attraction and their relative distance. Therefore, if the Sun were suddenly to explode, Earth would feel the effect of the changed gravitational attraction instantaneously. If this were the case, information would have to travel at infinite speed. This contradicts a tenet of Special Relativity, which maintains that there is a universal speed limit, the speed of light. It takes light (or information) eight minutes to travel the 93-million-mile distance between the Sun and the Earth. Thus, we would not receive the information about the Sun's explosion in less than that amount of time.

So, despite the fact that Newton's Theory of Gravity had an enormous amount of experimental support, Einstein could not rest with the idea that gravity seemed to propagate instantaneously. So he set out to find a theory of gravity that would be compatible with his Theory of Special Relativity. This search would eventually lead him to the Theory of General Relativity.

Gravitational and Inertial Mass, and the Principle of Equivalence

The initial glimpse into a theory of gravity materialized in Einstein's mind in 1907, while he was still working for the patent office in Bern, Switzerland. Here is how it goes. People and objects stick to Earth because both they and Earth have mass. A large truck will feel a larger gravitational pull, and greater pressure under its tires, than a car. This is because the large truck has a larger mass than the car, and therefore experiences a greater gravitational attraction to Earth. So we conclude that mass is that quantity which allows gravity to act on a body.

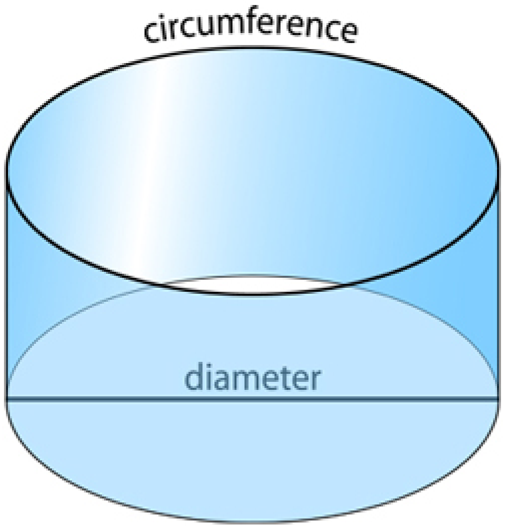

Figure 1

The tornado ride with circumference (*c*) and diameter (*d*). ©AMNH

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Now, if we set both the truck and the car in motion so that they are cruising at 30 miles per hour, it will take much more energy and better brakes to stop the truck than it will to stop the car. Why? After all, they were traveling at the same speed. It is because the car has a lot less inertia than a more massive truck. The less massive the object, the easier it is to bring it to rest. But what confers inertia to a body? Why does the car have less inertia? Inertia is a property of matter that is intimately interwoven with its mass and its motion (a very massive, fast-moving body has a lot of inertia). It has nothing to do with gravity. Inertia, however, just like gravity, exists because of mass. Einstein was extremely puzzled by the fact that gravitational mass, which results in bodies being attracted to each other, and inertial mass, which confers to a body the properties of motion, should be the same. This coincidence of gravitational and inertial mass is called the principle of equivalence.

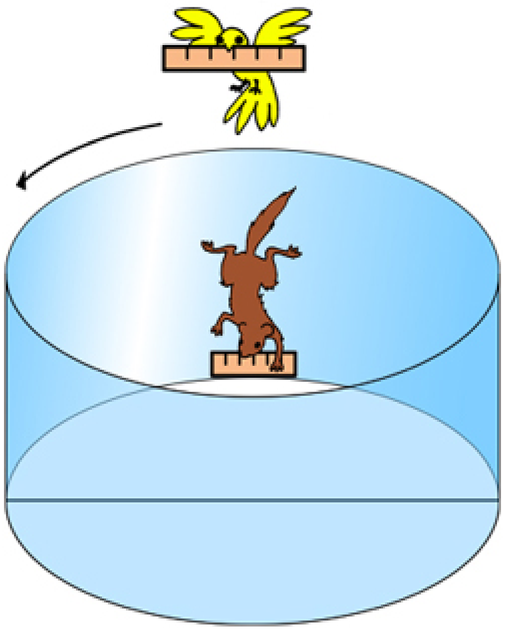

Figure 2

Smart Weasel measures the circumference from inside the tornado ride, while Clever Bird measures it from above. ©AMNH

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Acceleration and Gravity Are Actually the Same

But Einstein, as usual, went further. He considered that if a person is standing in an elevator that is stationary on Earth (and hence within the Earth's gravitational field), he will feel the pressure of Earth's gravitational pull under his feet. If the elevator were in space, the person would feel weightless. But if the elevator in space were accelerating at exactly 10 meters/second^2 (identical to Earth's acceleration due to gravity), the person would feel "attracted" to the floor of the elevator—just as if he were still on Earth. In the absence of a way of looking outside, the person in the elevator would not be able to conduct any experiment that would distinguish whether he was at rest on Earth, or accelerating in space.

But this is the principle of equivalence again. The reason why the person in the elevator cannot tell the difference between being attracted by the gravity of Earth, or being accelerated by the elevator's rocket boosters (this is a pretty fancy elevator), is because his mass is affected by gravity in the same way as it is affected by motion. Now, the principle of equivalence does not of itself explain gravity, but it equates the elusive concept of gravity to the much more straightforward concept of accelerated motion. Stating that a gravitational field is equivalent to accelerated motion opened a doorway into a deeper understanding of gravity.

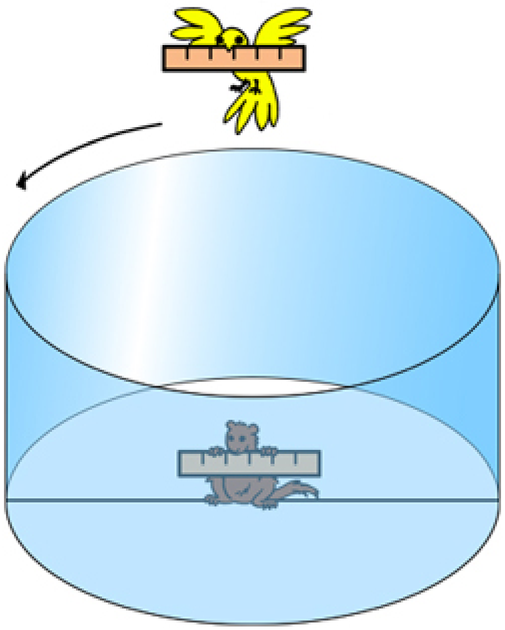

Figure 3

Smart Weasel and Clever Bird measure the ride’s diameter from two different standpoints and determine the same value. ©AMNH

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Acceleration, the Lorentz Contraction, and Non-Euclidian Geometries

The first true leap towards understanding gravity involves the concept of warped space. It is important at this stage to take a deep breath, close one’s eyes, and remember that our senses and experiences limit our view of the true, vast ocean of physical space. It is only with a relaxed mind that we can try to understand the implications of general relativity.

To explain this I will use the tornado ride analogy, used in the excellent book by Brian Green, The Elegant Universe. Tornado rides are large spinning drums. When people stand inside the drum, their backs are pinned to the inner wall by the centrifugal force. Since acceleration is defined either by a change in a body’s velocity or by a change in a body’s direction, a person in a tornado ride is by definition being accelerated, since their direction of motion is constantly changed from rectilinear by the spinning wall [**Figure 1**].

Clever Bird flying above the tornado ride can measure the circumference and diameter of the drum and find that their ratio is equal to p, as dictated by the familiar Euclidian geometry.

If, however, we ask Smart Weasel, who is inside the ride, to carry out the same measurements (first crawling along the diameter of the drum to measure it, and then inching around its wall to get a measurement of the circumference), he will find that the ratio of their measured quantities is not equal to *p* [**Figure 2**]. Why should the result of Weasel inside the ride be different from those obtained by Bird hovering above?

When Smart Weasel is measuring the circumference of the drum, he is moving forward with the tornado ride walls as the tornado ride is spinning. Hence the meter ruler he is using is shortened because of the Lorentz contraction (recall the lessons we learned last week). Hence, with a shorter meter, he will measure a longer circumference than the measurement carried by Clever Bird, who is stationary above the ride. On the other hand, when Smart Weasel was measuring the diameter of the drum by crawling along its length, his meter stick always remained perpendicular to the direction of motion [**Figure 3**], so that it was not affected by the Lorentz contraction. Hence, his measurement of the diameter is identical to that carried out by Clever Bird. As a result, the ratio of circumference and diameter, as measured inside the tornado ride, is larger than p (since the circumference is larger).

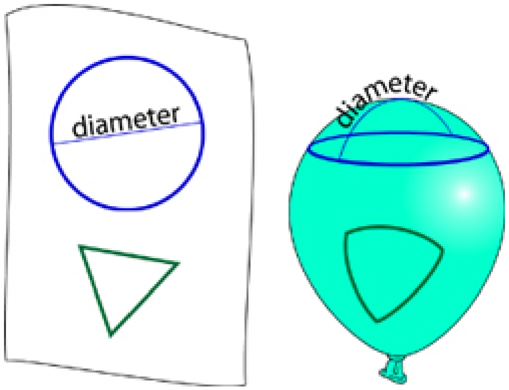

Figure 4

On a flat sheet of paper a circle's circumference measures p times its diameter and triangles have corners that add up to 180°. Not so for circles and triangles drawn on the curved surface of a balloon. ©AMNH

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Acceleration Warps Space, and So Does Gravity

So far we have explained that the reason why the ratio of circumference to radius is not *p*, is because of the Lorentz contraction encountered in Special Relativity. But is there a more fundamental and profound reason? Einstein pointed out that if we draw a circle on the surface of a spherical balloon, the ratio of its circumference and diameter is not equal to *p*. (Just as a triangle drawn on the surface of the same balloon does not have corners which add up to 180 degrees) [**Figure 4**]. Another way of saying this is that the surface of a sphere is not described by Euclidian geometry. In an analogous way, we could say that the acceleration experienced by Smart Weasel as he is measuring the circumference of the tornado ride has warped flat space into space that resembles the surface of a sphere, and which can no longer be described by Euclidian geometry. Flat space, which we can think of as the circular floor of the tornado ride, has been curved, or warped into a spherical section by its very accelerated motion.

And now we need to draw our conclusion. We have established earlier that, by the principle of equivalence, accelerated motion and gravity are one and the same. Hence, if acceleration can warp space, as we have seen in the case of the tornado ride, then this is equivalent to saying that gravity warps space. A mass in space alters its fabric. The often-used analogy is that of a heavy bowling ball resting on a rubber membrane, stretching under its weight [**Figure 5**]. A marble passing near it will be drawn in by the sloping membrane. In an analogous way, we can imagine the Sun in space. Every object in its neighborhood, such as a meteor, a comet or a planet, experiences space differently than it would in the absence of the Sun, because it feels the pull of the Sun's gravity. This feeling is due to the fact that space in the Sun's proximity is altered so that the objects within that space perceive a difference. This is very different from the Newtonian concept of the Sun acting on a planet with some invisible force that instantly grabs the planet across huge distances.

This formulation of gravity also resolved the problem that Newton's gravity acts instantaneously, contrary to the results of Special Relativity, by which information cannot travel faster than the speed of light. In General Relativity, the sudden presence or disappearance of an object would create a disturbance in the fabric of space, just as a pebble thrown in a pond causes a disturbance in the water. As in the analogy of the pond, this disturbance travels out at a finite speed, the speed of light. Thus, if the Sun disappeared, the sudden lack of gravitational attraction would only be felt on Earth after roughly eight minutes, the time it takes space to re-adjust to the new distribution of matter, and exactly the amount of time it takes light to travel from the Sun to Earth.

General Relativity is a tremendous intellectual achievement. It does not simply add a new formula to the set of existing physical laws in order to explain some new phenomenon. General Relativity alters our understanding of physics from the roots. General Relativity has all the qualities of a good theory. It extends the number of explained phenomena while at the same time generalizing and simplifying concepts: gravity, an obscure force that acts across vast spaces, is nothing but the very expression of space. General Relativity tells us that gravity is what space does.

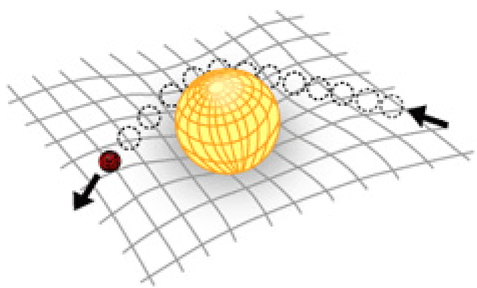

Figure 5

The mass of the large ball (center) curves the space around it. The satellite object that goes around the large ball is deflected by the warping of space. ©AMNH

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Related Links

PBS: Einstein Thought Experiments

These animations illustrate the equivalence of gravitation and acceleration using an elevator and rocket ship as examples, and the warping of the fabric of space-time.