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When I was little I used to like Swiss cheese. The reason for my fondness was that I enjoyed watching my very patient father try to separate the "holes" from the cheese in response to my request that I would only eat the holes. With a surgeon's steady hand, he would take a slice of cheese with a hole and then carve around the hole, presenting me with a ring that I would put in my mouth reluctantly, as it appeared to me that some cheese had gotten into my mouth, mixed up with the hole. A hole in Swiss cheese is the absence of cheese, yet despite being defined as the absence of something, i.e. being defined in the negative, it has a positive entity, rooted in our minds as something that is. A hole is, even if it is the lack of cheese.

How Can We Define Space?

Space, too, is the absence of matter. So space's most immediate definition is not as a thing that is, but as the absence of that something. We see, therefore, that defining space, like defining a hole, presents some difficulties. "[S]pace is that in which a body is or can be, and in the case of eternal things we must treat that which potentially is, as being... " as Archytas of Tarentum— a mathematician, philosopher, and statesman—poetically put it in the fourth century BC. Using another analogy, a cardboard box is not defined by its material cardboard walls, since those walls arranged differently would not constitute a box. A box is, because of its potential to contain something, because of the space within it. A box exists even when it is empty.

The Greeks were sure that space, whether empty or occupied by matter, necessarily *exists*, and they developed the concept of the *pneuma peiron*, the absolute void. Democritus (460BC-370BC), who in the fifth century BC was the first to postulate that matter was composed of small indivisible entities he called atoms (from the Greek *a-tomos*, meaning 'without parts'), needed space to create a substratum in which his atoms could be defined and move about. From here on, space became not only the logical theater in which all matter exists, but also an abstract concept that people acknowledged as an entity.

Besides wondering whether empty space *exists*, people also wondered whether space is infinite or finite. Archytas of Tarentum (420 BC-350BC), whom I mentioned above, wondered what would happen if one traveled to the end of the world and then stretched out a hand. Would one meet the boundary of space? He declared this an absurdity, since that outstretched hand would meet either space or matter, and hence would extend the boundary further. This reaching could then be repeated ad infinitum, making the idea of a boundary for space absurd.

Aristotle, on the other hand, declared that space must be finite. He stated that outside this finite universe, nothing exists, not even space. Aristotle thought that the Earth was at the center of the universe, and that all things revolve around it. So if space were infinite, objects located at infinity would necessarily revolve around Earth at an infinite speed. This was certainly absurd! For Aristotle, it was more absurd to think of objects moving at infinite velocity than to have a finite space suspended in nothingness.

During medieval times, the idea of space became intertwined with religion, just like everything else. Since space appeared to be the substratum of matter, not even God would be able to change it. This idea surely was in open contrast to the covenant that God is omnipotent, and led to the declaration that the concept of space was a heresy.

Later, the French philosopher René Descartes (1596-1650) pondered the concept of space and whether it exists even when it is empty. Descartes did not like the idea of empty space. For him, space would not exist without objects in it. He connected the concept of space with the idea of extension. In this view, space brings bodies into contact, so that without bodies there is no space. As we will see this week, Einstein's own General Theory of Relativity bears some similarity to the Cartesian dislike of empty space.

Newton

Newton's space ontology was not dissimilar to, or more advanced than, what the ancient Greeks had conceived. He did, however, formalize space as a *reference frame*, making it more useful for the description of physical phenomena. He realized that in order to describe the position of an object, one needs to think about space as if an invisible grid permeated it. Space thus becomes divided into parts along the three familiar directions of depth, breadth, and height.

Let's take, for instance, Newton's first law: a body either remains at rest or in continuous uniform motion, unless an outside force causes that state to change. We might ask: at rest with respect to what? Motion away or towards where? Newton's new invisible reference frame allows us to answer these questions with precision; it provides the perfect laboratory in which motion and rest can be measured. Newton stated, "Absolute space in its own nature, without relation to anything external, remains always similar and immovable."

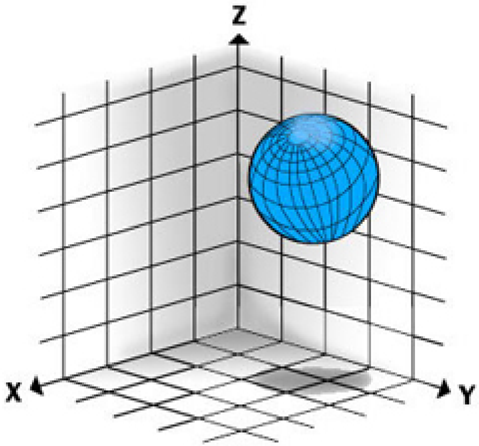
Newton added the concept of time to space, which allows one to describe an object as it changes its position in space. For Newton, time was absolute, ticking relentlessly, always unchanged. Last week we discussed how Einstein discovered that the way time passes, the way that a clock ticks depends on the speed of the person that carries out the measurement. Time, for Newton, flowed unimpeded, always the same, unaffected by the speed of the observer who measures it. Newton simply thought of time as a tool that provides a frame for the measurement of phenomena.

Newton was the first to see space and time as necessary physical measuring devices. Yet he did not provide an explanation of what space actually is. Newton's space and time are not affected by the events that happen within them, nor are those events affected by space and time. Newtonian space and time are non-participating, powerless observers of Nature's workings.

Einstein and the Grand Finale: Space-Time

Einstein revolutionized the concept of space just like he revolutionized the concept of time. As we learned last week, according to Einstein, two different clocks tick at different rates when moving with respect to one another. Since an observer's measure of space motion influences time, time is an integral component of space. This view is very different from Newton's universal time. Time thus becomes a fourth coordinate, meaning that it is not independent of the three dimensions of space. We call this union *space-time*.

Einstein's space is similar to Descartes'. That is, space does not exist independently of mass; it exists *because* of the mass in it. In other words, empty space does not exist. We can also say that mass makes a dent in the texture of space by its mere existence. Space is warped by the presence of mass. A body's mass influences the space that surrounds it, just like a bowling ball deposited on a rubber sheet creates a stretching and depression of the rubber fabric.



A simple Cartesian coordinate system, illustrating width (x), length (y), and height (z). You can define the location of the ball based upon its relation to each axis. ©AMNH

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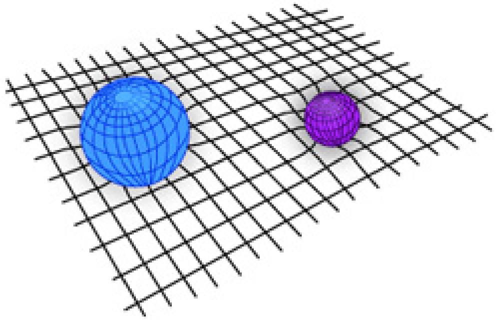
Space-Time and a New View of Gravity

By coupling space and matter, Einstein achieved another incredible feat: he explained gravity. Let's see how. Newton's most astonishing contribution to the physical understanding of the universe is that the same law that makes an apple fall from a tree also keeps the Moon in orbit around the Earth and the Earth in orbit around the Sun. His law of universal gravitation states that two bodies are mutually attracted by a force that is proportional to their masses and inversely proportional to the square of their distance. His formula makes respectable only approximate predictions for the orbits of planets, as well as for the trajectories of projectiles. Yet Newton admitted that the fact that two objects could act on each other at a distance, without the help of a physical agent, was sheer absurdity. Hence, he acknowledged that although his gravitation equations could make adequate predictions, he himself was not sure what gravity actually was.

Einstein revisited the question of gravity. When a meteorite passes by Earth, it is influenced by Earth's gravity. But what is gravity? Earth's mass curves the space around it, Einstein argued, and when the meteorite passes in its vicinity, it will follow a curved path. So gravity exists because mass changes space itself. Space is no longer the backdrop in which bodies move and events take place. Space is no longer there simply to separate mass from mass. On the contrary, space is like mass, an agent of physics, a tangible quantity. So mass and space live in a symbiotic relationship. To quote the contemporary physicist John Archibald Wheeler, "while mass tells space how to bend, space tells mass how to move."

Note: Aristarchus of Tarentum is quoted in Thomas Little Heath's translation of Simplicius' *Physics*.



Given two equally massive (equally heavy) balls, the larger one, with a lower surface gravity, warps space less than the smaller one, which has a higher surface gravity. ©AMNH

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