From:	Lost in Space-Time from New Scientist <lostinspacetime@e.newscientist.com>
Sent:	Tuesday, December 5, 2023 7:01 AM
To:	timothy.revell@newscientist.com
Subject:	How to imagine space-time

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Lost in Space-time

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Hello and welcome back to Lost in Space-Time, a monthly missive about the biggest ideas in the cosmos. Today, our writer is Manil Suri. He's a mathematician and writer with a new book out called *The Big Bang of Numbers,* in which he explores the fundamental mathematical concepts that underpin our universe. For us today, he's focussing on space-time, the very thing that makes up reality. It's a difficult thing to imagine but as Manil explains, he has a trick to make it easier...

But first... this month's top physics stories

1. A mysterious, incredibly energetic cosmic ray has smashed into Earth
2. Physicists worked out the quietest way to pour water from a teapot

3. Check out a majestic photo showing China's Tiangong space station
4. Meet the tiny star found harbouring a huge planet that shouldn’t exist
5. Key molecule for life may have formed on clumps of ice in deep space

A mathematical trick

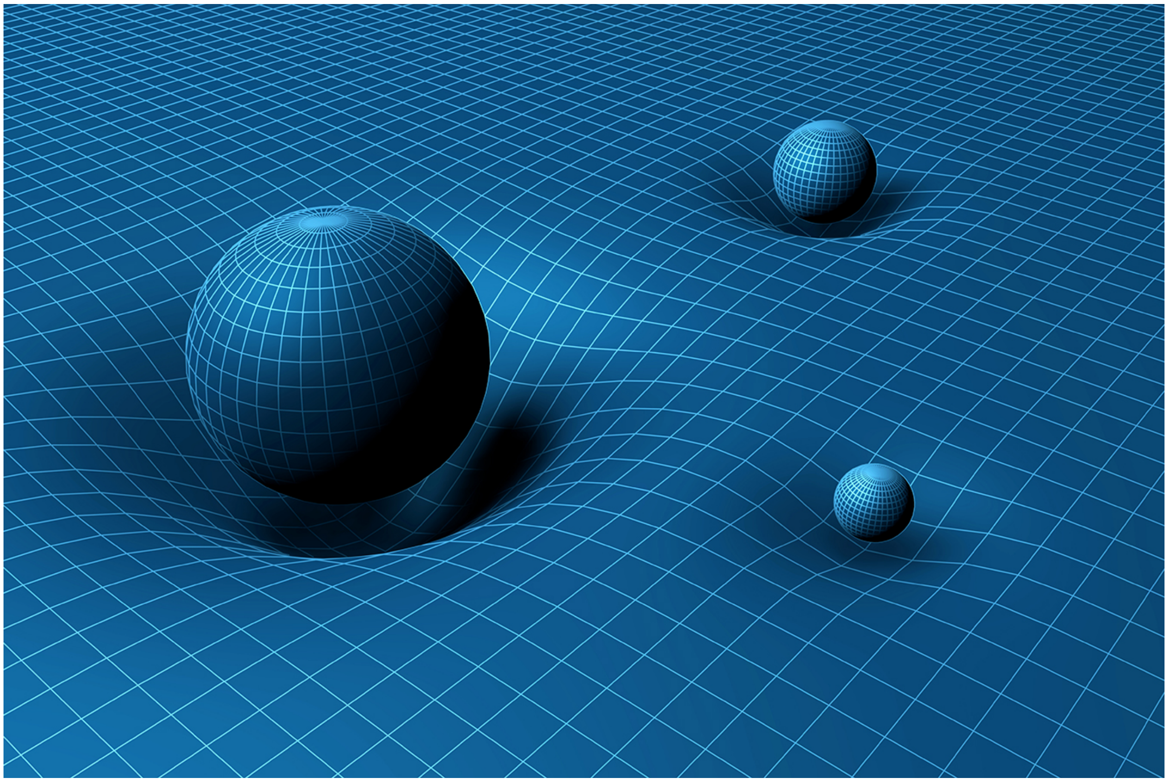
Space-time is a curious thing. Look around and it’s easy enough to visualise what the space component is in the abstract. It’s three dimensions: left-right, forwards-backwards and up-down. It’s a graph with an *x*, *y* and *z* axis. Time, too, is easy enough. We’re always moving forwards in time so we might visualise it as a straight line or one big arrow. Every second is a little nudge forwards.

But space-time, well that’s a little different. Albert Einstein fused space and time together in his theories of relativity. The outcome was a new fabric of reality, a thing called space-time that permeates the universe. How gravity works popped out of the explorations of this new way of thinking. Rather than gravity being a force that somehow operates remotely through space, Einstein proposed that bodies curve space-time, and it is this curvature that causes them to be gravitationally drawn to each other. Our very best descriptions of the cosmos begin with space-time.

Yet, visualising it is next to impossible. The three dimensions of space and one of time give four dimensions in total. But space-time itself is curved, as Einstein proposed. That means to really imagine it, you need a fifth dimension to curve into.

Luckily, all is not lost. There is a mathematical trick to visualising space-time that I’ve come up with. It’s a simplified way of thinking that not only illustrates how space-time can be curved, but also how such curvature can draw bodies towards each other. It can give you new insight into how gravity works in our cosmos.

First, let's start with a typical way to draw space-time. Pictures like the one below are meant to illustrate Einstein's idea that gravity arises in the universe from massive objects distorting space-time. Placing a small object, say a marble, near one of these dimples would result in it rolling towards one of the larger objects, in much the same way that gravity pulls objects together.



Julia Kopacheva/Shutterstock

However, the diagram is missing a lot. While the objects depicted are three dimensional, the space they're curving is only two dimensional. Moreover, time seems to have been entirely omitted, so it's pure space – not space-time – that's curving.

Here's my trick to get around this: simplify things by letting space be only one dimensional. This makes the total number of space-time dimensions a more manageable two.

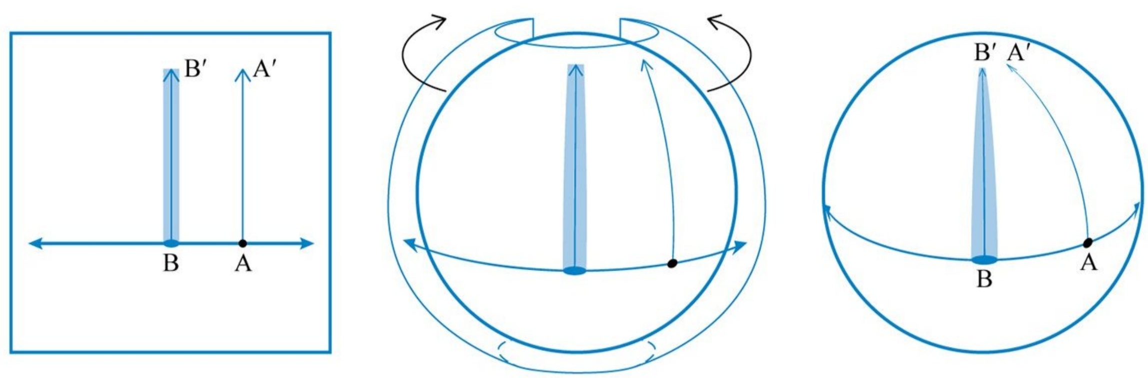
Now we can represent our 1-D space by the double-arrowed horizontal line in the left panel of the diagram below. Let time be represented by the perpendicular direction, giving a two-dimensional space-time plane.

This plane is then successive snapshots, stacked one on top of the other, of where objects are located in the single space dimension at each instant.

Suppose now there are objects – say particles – at points A and B in our universe. Then if these particles remained at rest, their trajectories through space-time would just be the two parallel paths AA' and BB' as shown. This simply represents the fact that for every time instant, the particles remain exactly where they are in 1-D space. Such behaviour is what we'd expect in the absence of gravity or any other forces.

However, if gravity came into play, we would expect the two particles to draw closer to each other as time went on. In other words, A' would be much closer to B' than A was to B.

Now what if gravity, as Einstein proposed, wasn't a force in the usual sense? What if it couldn't act directly on A and B to bring them closer, but rather, could only cause such an effect by deforming the 2-D space-time plane? Would there be a suitable such deformation that would still result in A' getting closer to B'?



Manil Suri

The answer is yes. Were the plane drawn on a rubber sheet, you could stretch it in various ways to easily verify that many such deformations exist. The one we'll pick (why exactly, we'll see below) is to wrap the plane around a sphere, as shown in the middle panel. This can be mathematically accomplished by the same method used to project a rectangular map of the world onto a globe. The formula this involves (called the "equirectangular projection") has been known for almost two millennia: vertical lines on the rectangle correspond to lines of longitude on the sphere and horizontal ones to lines of latitude. You can see from the right panel that A' has indeed gotten closer to B', just as we might expect under gravity.

On the plane, the particles follow the shortest paths between A and A', and B and B', respectively. These are just straight lines. On the sphere, the trajectories AA' and BB' still represent shortest distance paths. This is because the shortest distance between two points on a spherical surface is always along one of the circles of maximal radius (these include, e.g., lines of longitude and the equator). Such curves that produce the shortest distance are called geodesics. So the geodesics AA' and BB' on the plane get transformed to corresponding geodesics on the sphere. (This wouldn't necessarily happen for an arbitrary deformation, which is why we chose our wrapping around the sphere.)

Einstein postulated that particles not subject to external forces will *always* move through space-time along such "shortest path" geodesics. In the absence of gravity, these geodesics are just straight lines. Gravity, when introduced, isn't counted as an external force. Rather, its effect is to curve space-time, hence changing the geodesics. The particles now follow these new geodesics, causing them to draw closer.
This is the key visualisation afforded by our simplified description of space-time. We can begin to understand how gravity, rather than being a force that acts mysteriously at a distance, could really be a result of geometry. How it can act to pull objects together via curvature built into space-time.

The above insight was fundamental to Einstein's incorporation of gravity into his general theory of relativity. The actual theory is much more complicated, since space-time only curves in the local vicinity of bodies, not globally, as in our model. Moreover, the geometry involved must also respect the fact that nothing can travel faster than the speed of light. This effectively means that the concept of "shortest distance" has to also be modified, with the time dimension having to be treated very differently from the space dimensions.

Nevertheless, Einstein's explanation posits, for instance, that the sun's mass curves space-time in our solar system. That is why planets revolve

around the sun rather than flying off in straight lines – they are just following the curved geodesics in this deformed space-time.
This has been confirmed by measuring how light from distant astronomical sources gets distorted by massive galaxies. Space-time truly is curved in our universe, it's not just a mathematical convenience.

There's a classical Buddhist parable about a group of blind men relying only on touch to figure out an animal unfamiliar to them – an elephant. Space-time is *our* elephant here – we can never hope to see it in its full 4-D form, or watch it curve to cause gravity. But the simplified visualisation presented here can help us better understand it.

Manil Suri is at the University of Maryland, Baltimore County. His book, *The Big Bang of Numbers: How to Build the Universe Using Only Math*, is out now.