Einstein's Bottomless Beanbag: Gravity and Black Holes

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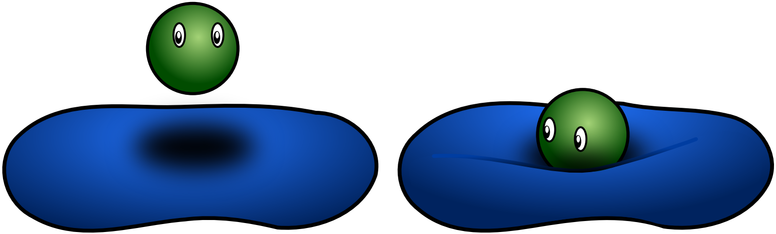
Science 101

Einstein's Beanbag

Bags which sag

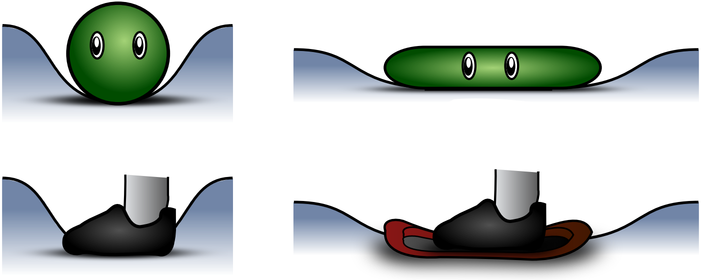
- For hundreds of years, we used Newton's theory of gravity.
- In 1915, Albert Einstein invented a new theory of gravity called general relativity. It says the universe is like a beanbag!



- The beanbag is space itself. It is flat when nothing sits on it. But if we place mass on it, the beanbag will sag.
- John Wheeler: "Matter tells space how to curve." Or: lumps tell the bag how to sag!

Spreading out

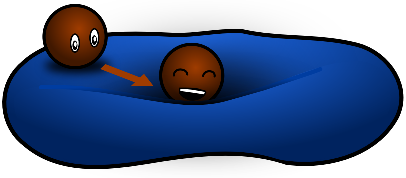
- The depth of a sag depends on how spread out the mass is.
- Ball and pancake have the same mass, but the pancake creates a shallow dip by spreading out its weight. Like snowshoeing!

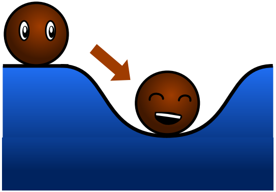


- If an object gets denser without losing mass, it will create a deeper sag. This will be important later!

Lumps which flump

- A small mass comes along looking for somewhere to sit. The beanbag has dips and sags, but we ignore how they get there.
- The most comfortable seat is the lowest!

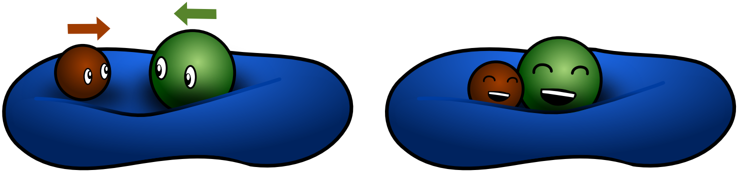




- The mass will roll until it reaches a nearby dip.
- Wheeler: "Space tells matter how to move."
  Or: the bag shows a lump where to flump!

Mutual attraction

- Newton's theory of gravity says that masses are attracted.
- We see something similar on the beanbag:
  1. Two nearby masses will create their own dips.
  2. Masses will roll into nearby dips.
  3. Therefore, nearby masses roll into each other's dips!

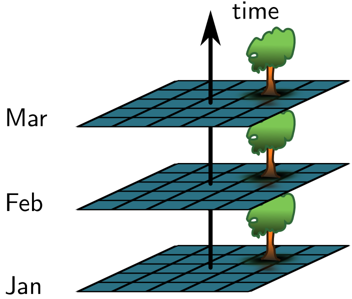


- This looks a lot like the mutual attraction Newton proposed.

Snapshots

An album of snapshots

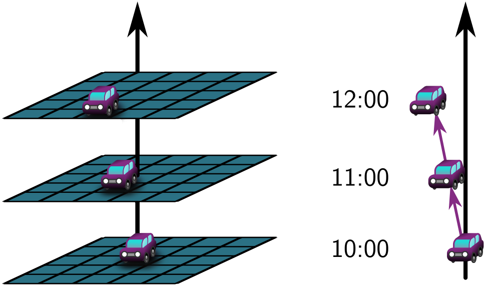
- Let's talk about time. We'll come back to the beanbag later.
- Imagine taking snapshots of space each month, and arranging them in a photo album. We stack the photos vertically.



- Photos are taken from the same perspective.
- Different pages in the album correspond to different times. Going up takes you forward in time, and down goes backwards.

Moving around

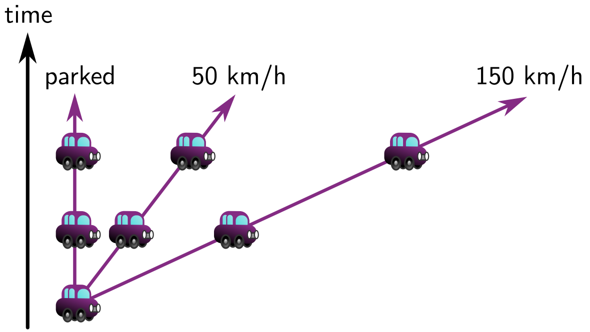
- Suppose we want to understand how a particular object moves with time. We can look at the photos from month to month.
- But photos will contain a lot of unnecessary details. It's easier to ignore everything but the object itself!



- We use arrows to show how the object travels from month to month. These arrows describe movement in space and time.

Need for speed

- The tilt of an arrow depends on the object's speed.
- A parked car stays in the same place, so its arrow is vertical. At 50 km/h it tilts down, and at 150 km/h it tilts even more.

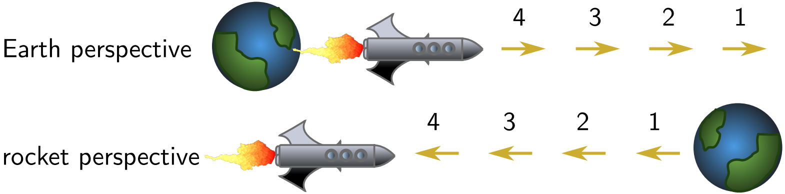


- The faster the object, the more it tilts away from the vertical.

Traffic cones

Racing light

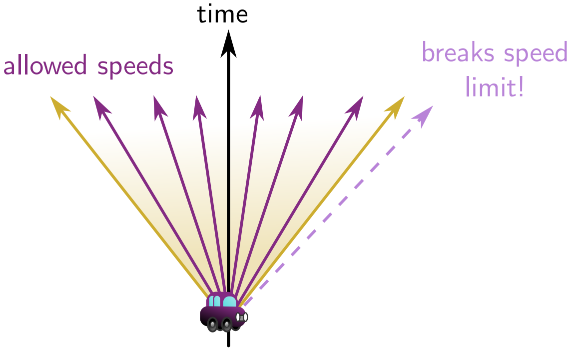
- Is there a speed limit? Or can we go as fast as we like?
- Suppose a spaceship can go faster than the speed of light. It will catch up to light rays which previously left Earth.



- Like a runner overtaking competitors, the rocket encounters light rays in the opposite order to which they left earth.
- From the rocket's perspective, light rays arrive from in front.

Universal speed limit

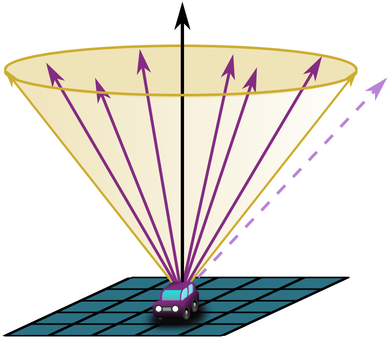
- Overall effect: earth appears in front and backwards in time.
- This is pretty weird! No one has ever seen it. So the speed of light is probably a universal speed limit.



- To obey the speed limit, objects must stay between the yellow lines. These lines are light rays moving in different directions.

The traffic cone

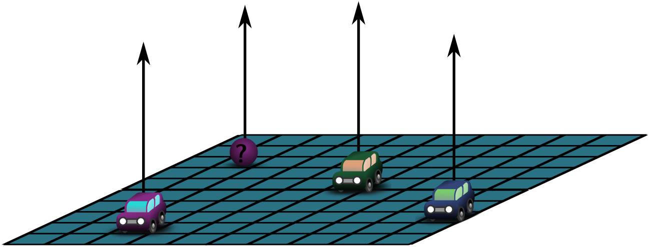
- If light can move in two-dimensional space, then all the light rays leaving a point trace out a cone in our photo album.



- This is called the light cone. The car must stay within the cone to obey the speed limit.
- It's hard to visualise 3 dimensions + time, so we stick to two!

Parking lots

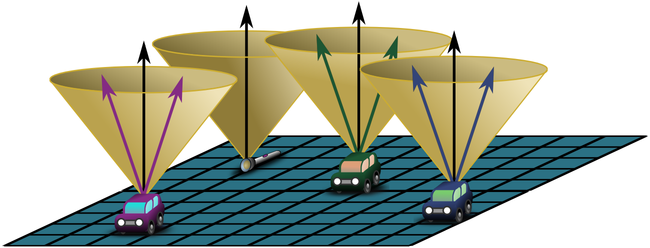
- We have been talking about a single point in space.
- But suppose we have make snapshots of a whole parking lot. Every car has an arrow going vertically up!



- Even where there is no car, we can draw a vertical arrow to indicate what a parked car would do.

Light cones everywhere

- To leave the parking lot, a car needs to move.
- But remember the universal speed limit: each car must move within its light cone!

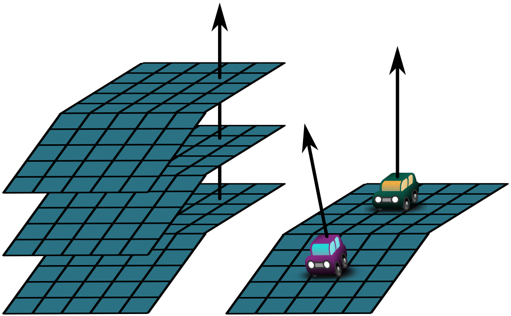


- We don't need cars to have light cones! A light cone is made by rays of light leaving a point, e.g. from a flashlight.

Tilted traffic

Beanbag snapshots

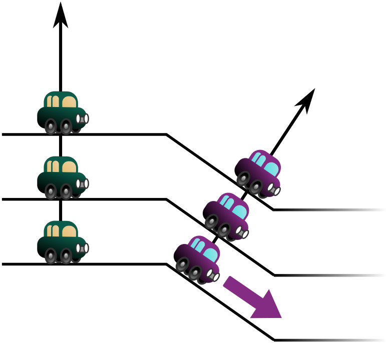
- Until now, we've considered traffic laws for flat surfaces. But on Einstein's beanbag, the surface will sag due to mass.
- To make photo albums, we still stack photos vertically. (We draw kinks rather than sags for simplicity.)



- But if the surface tilts, the arrows tilt with it. Imagine it is firmly attached to the top of the car, or the surface itself.

Parking on a hill

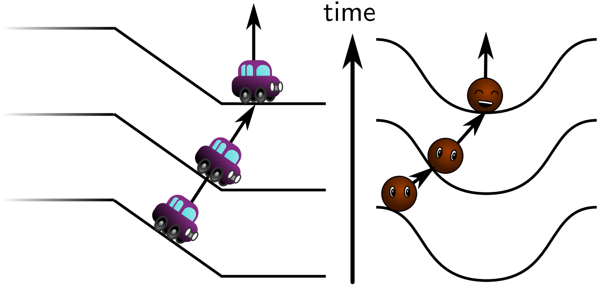
- When we stack photos, we extend tilted arrows to see how "parked" cars move. With a hill, they undergo relative motion!
- The green car's arrow points up, so it stays exactly where it is.



- But the purple car has a tilted arrow, so it seems to roll down. It's like parking on a real hill with the handbrake off!

Flumping revisited

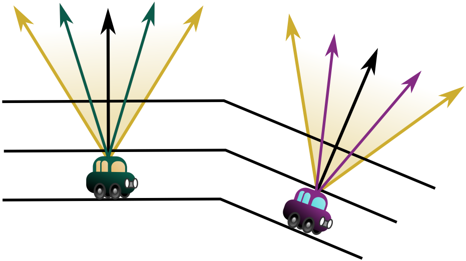
- Suppose the purple car keeps rolling to the bottom of the hill.
- At the bottom, the arrow now points directly up. The car wants to remain in the same place!



- But this is the flumping we discussed earlier! When a lump hits the bottom of a dip, it wants to stay. Now we see why!

Tilting cones

- Not only stationary arrows tip. The whole light cone is attached to the surface and tips over with it.
- This means traffic laws change depending on the slope.

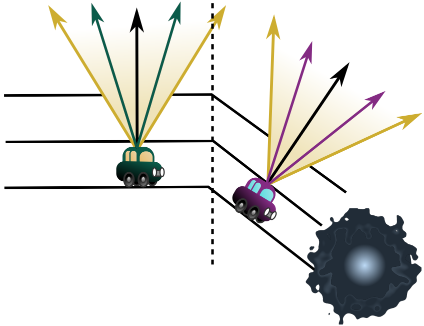


- From green's perspective, purple's maximum speed up the hill is slower. But purple can still get up the hill if it really tries!

Black holes

Trapping light

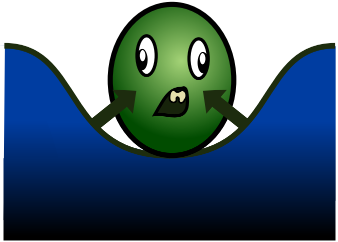
- That is, until purple can't travel up the hill at all.
- This happens when purple's cone tips over so far that light cannot travel to the left. Even the light is trapped!



- Whenever light is trapped in a region, we call it a black hole. The dotted line is the event horizon or point of no return.

Making a black hole

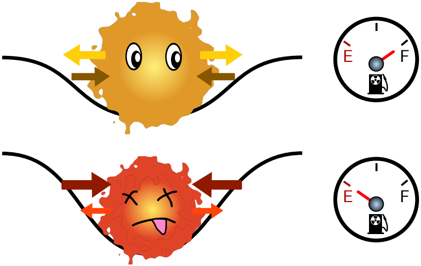
- How are black holes actually formed?
- The main mechanism is self-gravity. Heavy objects are not only attracted to other objects, but also to themselves!



- The sides of the object get pushed towards the centre where the sag is deepest and mass is concentrated.
- Why don't I collapse to form a black hole? The forces holding me together are much stronger than gravity!

Dying stars

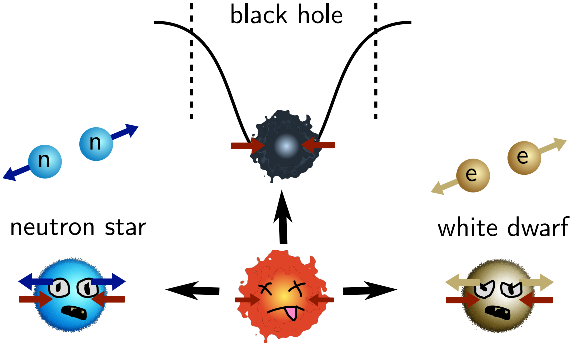
- A star is much heavier and self-gravity much stronger. But a healthy star counters this with pressure from nuclear fusion.



- But when it runs out of nuclear fuel, gravity begins to win!
- It will start to contract under its own weight. As it gets denser, the sag it makes in the beanbag gets deeper.

Stellar collapse

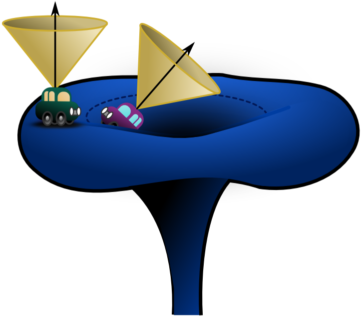
- Not every star forms a black hole. What stops them collapsing once they run out of fuel?
- They are converted into repulsive forms of matter!



- Smaller stars (like our sun) will become white dwarfs made of electrons, while larger stars get turned into neutrons.

The bottomless beanbag

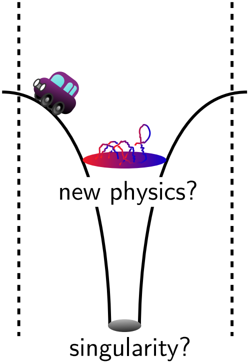
- Once it forms a black hole, the star keeps collapsing until it becomes infinitely dense with a bottomless sag.
- This is the singularity. Anything approaching is ripped apart!



- This is the endpoint of a black hole: a violent singularity surrounded by a light-trapping region.

Avoiding the singularity

- Singularities seem unavoidable, but we're not sure they exist.
- New physical ideas (such as string theory) predict the singularity is smoothed out or capped off.



- The only way to check is to jump in! But you could never come back out to tell anyone.

Seeing is believing

- Although singularities are theoretical, black holes are very real. Below is a photo of the black hole at centre of M87.

- The black hole is the shadow in the middle. The orange ring is a ball of gas the black hole is eating.
- Theory and experiment agree beautifully. Nature is amazing!

Thanks for listening!