6.4: Packard's Acceleration Ramp

The curvature of spacetime and Einstein's concept of gravity may seem like quite a stretch for a non-college classroom; allow me to assure you that it is not! Newton's theory of gravity is no less complex and subtle, yet we feel comfortable with it through long association. Einstein's gravitational model is also powerful and mathematically subtle, but like Newton's ideas of gravity, we can demonstrate it simply with a classroom model that students can grasp cognitively without troubling them (or you!) with the higher mathematics of the subject.

Though you may not realize it, Newton's theory has a huge hole in it. Newton tells us that orbits work because of the force of gravity – a force that pulls all things together. So far so good, but Newton completely sidesteps the issue of ***how gravity works***, he simply insists that it does work, and gives us convincing mathematical models that show us what will happen when any object is in orbit around another. Einstein stepped in and filled in that gap in Newton's theory some 350 years after Newton first published his ideas on gravitation.

Einstein's idea was a simple one, although it may seem a bit odd to you at first. Einstein said that space and time were not separate, but in fact one thing which he called ***spacetime.*** Einstein said that spacetime was a fabric which could be bent and stretched by massive objects. Things like stars and planets caused spacetime to curve, and it was this curvature which we call gravity. If this all seems strange, do not worry – you (and your students!) will see how it works as you build and work with this new model of Einsteinian spacetime-gravity.

Academic Standards

Science and Engineering Practices

- Developing and using models.
- Planning and carrying out investigations.
- Analyzing and interpreting data.
- Using mathematics.
- Argument from evidence.

Crosscutting Concepts

- Cause and effect.
- Systems and system models.

Next Generation Science Standards

- Forces and interactions (K-5, 6-8, 9-12).
- Engineering and design (K-5, 6-8, 9-12).
- Gravitation and orbits (6-8, 9-12).

For the Educator

Facts you need to know

1. Einstein was a visual thinker. The models we are making reflect Einstein's creative, visual, conceptual thinking.
2. Einstein saw space and time not as separate things, but as one united thing he called ***spacetime***.
3. The fabric of spacetime can bend, stretch, and curve. Einstein saw gravity as the ***curvature of spacetime.***

Teaching and Pedagogy

This model is a wonderful toy; students and adults alike seem to find playing with it irresistible. Like all the best models, this simple device shows us quickly, and intuitively how the universe around us works. Draw your attention back to Galileo and Aristotle. Galileo challenged Aristotle's ideas by doing experiments that highlighted the weaknesses in Aristotle's theories. Scientists of the 17th century were forced to abandon Aristotle's theories in favor of those of Copernicus and the sun-centered solar system. Einstein did much the same thing in the early 20th century by challenging Newton's theory of gravitation.

Much like Galileo, Einstein found that challenging an old established figure and a cherished scientific theory did not make him popular. However, when a critical experiment in 1919 proved that stars do bend spacetime – and the light that shines past them – Einstein became famous almost overnight.

Perhaps more than any other model we discuss in this book, Einstein's model of gravitation needs to be ***played with.*** Rolling BB's or small ball bearings across the empty fabric, then adding a massive marble or weight and trying it again. Actually ***seeing gravity in action***, not as a mysterious force, but as the common sense action of a visual model is uniquely powerful for all students.

Student Outcomes

What will the student discover?

1. Gravity is not a mysterious attracting force. Rather it is the simple and logical reaction to a mass moving over a curved surface.
2. It is relatively simple to understand ***how gravity works*** – much easier than learning how to do the math involved!
3. Masses (like planets and stars) tell spacetime how to curve.
4. The curvature of spacetime tells mass how to move.

What will your students learn about science?

1. Powerful new ideas are often visual or physical in nature – the mathematics often comes later, sometimes many years later!
2. Our understanding of complex ideas often first comes to us visually, often viscerally, long before we can describe or explain what we know.
3. To bridge the gap between our first understanding of an idea, and our ability to explain or discuss what we know, a great deal of play and experimentation is often essential.

Conducting the Activity

Materials

1. A 30-inch plastic hula-hoop (or similar)
2. Eight, 15-inch pieces of 1-inch PVC pipe
3. Eight, 1-inch PVC T-connectors
4. Small can of PVC cement or super glue
5. 1 yard of black spandex fabric or similar (must be stretchy in ***both*** directions!)
6. Two billiard balls
7. Several glass marbles of various sizes, BB's or small ball bearings may also be used

Building Einstein's Gravity Model

1. Your local home improvement store almost certainly does not have 15-inch sections of PVC piping, you will have to buy a longer piece and cut these yourself. You can easily cut PVC piping with a hacksaw, or with a PVC pipe cutter. Once you have these pieces cut, glue them securely into the T-connectors so that they each form a rigid T-shape.
2. Once the glue is completely dry, measure exactly 12-inches down from the T-connector and cut the PVC pipe off there – this will insure that all the pieces are the same length. These will be the legs for your model to stand on and they must be the same length for everything to be level and work correctly.
3. The T-connectors now need to be cut down as shown below so that they will snap around the hula-hoop. This can be done with a hacksaw, but I find a belt sander to be easier and faster. Check with your custodial department for help with this!
4. Cut a circle of spandex fabric so that it is about 6-inches larger than your hula hoop. Stretch the fabric over the hoop and snap one of the T-connector legs over the fabric to hold it in place. Work on opposite sides of the hoop, stretching the fabric and snapping in the connectors until the fabric is stretched tightly over the entire hoop. You should now have a 30-inch 'trampoline' of spandex fabric on short legs of PVC piping. Your model is now ready to use.

Exploring Einstein's Gravity Model

1. Explain to your students that the black fabric represents the ***fabric of spacetime***. Roll one of your small glass marbles across the fabric and observe what happens – it will roll straight across the circle.
2. Now place a billiard ball by itself in the center of the fabric – what happens? The fabric is stretched! ***Mass tells spacetime how to curve!*** Try different size marbles and weights, let the students see that ***greater mass causes greater curvature*** of the spacetime fabric.
3. With the billiard ball resting in the center of the fabric, try rolling a small marble straight past the billiard ball. It will not roll straight – it ***curves*** toward the larger ball. ***The curvature of spacetimetells mass how to move!***

Ask your students why the marble curved this time when it rolled straight before? They will quickly realize that the larger ball has stretched and curved the black fabric – it is the curved shape of the fabric that causes the marble's path to bend toward the larger ball.

This is ***how gravity works!*** This is Einstein's explanation for gravity. A large mass causes the spacetime fabric to curve – and the curved shape of spacetime controls how the masses have to move.

4. Try placing two billiard balls several inches apart from each other on the fabric and observe what happens. The curvature of the fabric causes them to roll toward each other – just as gravity causes all things to be pulled together.

5. Can your students get some of the smaller marbles to orbit around one of the billiard balls? Can they get two billiard balls to orbit around each other? Have fun and play with this model for a while – it is fascinating to everyone who sees it and students will easily see how Einstein's ***spacetime fabric*** creates the effect we call gravity.

Discussion Questions

1. How does Einstein's gravity work?
   - **Answer** "Mass tells spacetime how to curve. The curvature of spacetime tells mass how to move." – John Wheeler. This elegant quote from one of Einstein's greatest students explains things perfectly!
2. How is Einstein's model of gravity better than Newton's model?
   - **Answer** This is likely to generate a lot of comment and discussion, but essentially Einstein's model explains ***how gravity works***, Newton's model simply tells us ***what gravity does***, but fails to explain how it works.
3. Robert Hooke's pendulum model showed how planets orbit a star, can you make a model of an orbiting planet or moon with this model?
   - **Answer** Yes! The large billiard ball acts nicely as a star while the small marble acts as a planet in orbit. Like Hooke's model, you will find it almost impossible to create a circular orbit with Einstein's model – and for the same reason. Creating the perfect balance between gravity and momentum is hard and friction will cause any circular orbit to quickly decay into an ellipse in any case.

Supplemental Materials

Going Deeper

Sadly, when we add mathematics to a science lesson, we often end up teaching math instead of science. Let's do something different and use the science concepts to help ***understand what the math means.***

One of the first lessons students learn in physics is sometimes called the ***free fall equation***; this simple equation multiplies two numbers to find out how far something falls in a given amount of time. The equation looks like this:

$$\mathbf{h = g * t}$$

In this equation, ***h*** stands for height (the distance an object falls); ***g*** stands for the acceleration of gravity; and ***t*** stands for the falling time in seconds. In other words, if you know the value of g (9.81 m/s^2) and the number of seconds an object is falling, you can calculate ***how far it falls.***

Unfortunately, we tend to fall back on something like: "Multiply the two numbers and get the answer for how far the rock falls." Let's see if we can help even our youngest students understand what the math means.

t for time is pretty simple, this is how long anything spends falling. It doesn't matter if it is a rock falling off a cliff or a swimmer falling off a diving board. So what does g mean? ***gis the curvature of spacetime!*** Place a billiard ball in the center of our model to represent the Earth and note how much the fabric curves. Allow a BB to roll toward the billiard ball – see how fast it rolls?

Replace the billiard ball with a large marble – the fabric curves much less now! Let this marble represent our Moon, now allow a BB to roll toward the marble – see how much more slowly it rolls? The gravity on the Moon is less (we fall more slowly) because the curvature of spacetime is less. The gravity on the Earth is more (we fall faster than on the Moon) because the curvature of spacetime is greater here.

And that little g in our equation? g represents ***the curvature of spacetime***. Now we understand the math much more completely. Multiply the falling time by the curvature of spacetime, and you find out how far an object falls. The simple equation is no longer just a multiplication problem, we now understand what each number means, and ***how gravity works!***

Being an Astronomer

Let's look at our gravity model again. Place a billiard ball in the center of the model and look closely at the fabric. Do you notice how the fabric has the greatest curvature right under the billiard ball, but the fabric becomes more flat (less curved) as you move away from the billiard ball.

If gravity works because of the curvature of the fabric of spacetime, then our model seems to suggest that ***gravity gets weaker as you move away from a planet or star.*** What does this mean for things in orbit like spacecraft or moons circling a planet?

Start with a marble and see if you can get it to orbit around our billiard ball planet. Do you notice how the marble moon eventually spirals into the billiard ball planet? What do you notice about the marble's speed as it spirals in? That's right! The marble moon moves faster as it gets closer to the planet it orbits. Let's see if we can confirm this prediction made by our marble with our own observations. Do things that are farther away from the Earth move more slowly across the sky?

Find a clear night and begin observing about 30 minutes after sunset. In a dark sky, you will be able to spot satellites moving across the sky. These satellites look like small stars that drift noticeably across the fixed stars in the constellations. You will find that these satellites move fast enough for you to easily detect their motion. If you could time them all the way across the entire sky, they would complete their journey in a matter of minutes.

Now consider the Moon. As we have seen in previous activities, you can track the motion of the Moon across the sky from east to west, but this takes about 14 days. The Moon is also much farther away than any man-made satellite. Our Moon orbits at a distance of about 385,000 km while artificial satellites that we can see orbit at a distance of 100-250 km from the Earth.

Our observations back up what our model tells us about gravity. The force of gravity is stronger near the Earth than it is far out in space; and satellites that orbit closer to the Earth travel faster – just as the marbles do when they orbit around a billiard ball in our gravitational model!

Being a Scientist

One hundred years after Einstein finished his work on ***relativity theory***, scientists are still working to design and build experiments to confirm the predictions of Einstein's theories today. One of these experiments is called LIGO, and it is used to detect gravitational waves.

Einstein predicted that if spacetime was indeed a unified fabric, that there should be waves in spacetime just as there are waves in a pond when you throw a stone into the water. Investigate LIGO on the internet – what would anyone do with a 'telescope' that detects gravitational waves?

Following Up

Einstein is famous for being the first man in 250 years to correct or adjust Newton's theory of gravitation. The idea of becoming famous for correcting someone else's work is common in the history of science. What other scientists and astronomers can you find that have become well known for making corrections or improvements in someone's earlier work?

On the other hand, what astronomers or scientists can you find that are famous for doing their own original work? I'll give you a hint… there are some from each group in this book!