Date:

W2: Scientific Revolution: General Relativity

Scientific models must make predictions that match our observations, or they must be revised or replaced. New scientific models can be revolutionary. In this activity you are going to examine two models of gravity: Newton's classical force model, and Einstein's revolutionary curved spacetime model.

Part A: Modeling Gravity

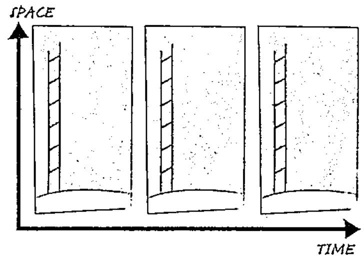
Complete this table after watching >> **Alice & Bob in Wonderland:** ***What Keeps Us Stuck to the Earth?***

<table>
<tr><th></th><th>Force Model</th><th>Acceleration Model</th></tr>
<tr><td>Gravity: How does it work?</td><td></td><td></td></tr>
<tr><td>What's hard to accept?</td><td></td><td></td></tr>
<tr><td>Alice steps off the top of a tall ladder

Bob stands at the bottom of the ladder</td><td colspan="2">In the boxes, sketch snapshots of Alice as she falls to the ground and Bob as he stands at the bottom of the ladder, showing their progression in time. [Hint: Alice moves faster and faster as she falls.]

Connect-the-dots of Alice's position in SPACE (height above the ground) as TIME goes on. Is her path through spacetime straight or curved?

Connect-the-dots of Bob's position in SPACE (height above the ground) as TIME goes on. Is Bob's path through spacetime straight or curved?


</td></tr>
<tr><td>According to Newton...</td><td colspan="2">Alice's path through spacetime is ______________ (straight/curved) because she is accelerating. She is accelerating because gravity is a force pulling on her. Bob's path through spacetime is ______________ (straight/curved) because he is not accelerating—the force of gravity is balanced by the ground pushing up.</td></tr>
<tr><td>According to Einstein...</td><td colspan="2">There is no "force of gravity" pulling down on Alice so she __________ (is/is not) accelerating. Her path through spacetime should be ______________ (straight/curved). The ground pushes up on Bob and since there is no opposing "force of gravity" to balance this force, he should accelerate up and follow a ______________ (straight/curved) path through spacetime.</td></tr>
</table>

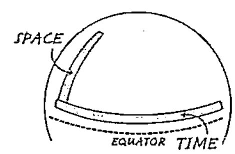
Discussion:

1. Alice has a video camera in her hands as she falls. If she takes a video of herself as she falls, could she tell that she was accelerating by viewing the video? (Ignore the background.)
2. Alice takes a video of Bob as she falls. Could she tell who was accelerating by viewing the video? (Ignore the background.)
3. Alice closes her eyes as she falls. What does she *feel?* Can she tell that she is accelerating?
4. Bob closes his eyes. What does he *feel?* Can he interpret this feeling as accelerating up?

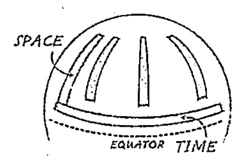
Einstein knew that Newton's model of gravity is wrong. For one thing, it fails to correctly predict the orbit of Mercury; for another, it fails to obey the speed limit of the universe—the speed of light. In his search for a better model, the simple fact that acceleration up mimics force down was too strong of a coincidence to ignore. Einstein needed to find a way to make sense of the ground accelerating up without moving up. How can the ground be accelerating up when the Earth is not expanding? He found the answer in the geometry of spacetime.

Part E: Bending Spacetime

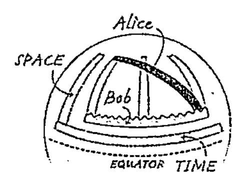
In Part A, we used the fact that accelerating objects trace out curved paths in spacetime and non-accelerating objects trace out straight paths. We also saw that Newton and Einstein would disagree on who is accelerating and who is not. In this part of the activity you will use tape to transfer the spacetime diagram from Part A onto the surface of a large ball to reveal how curving spacetime resolves the problem of who is accelerating.



1. Use a strip of tape to connect two points on your desk with a straight line. Use another strip of tape to make a curved line. Compare the two pieces of tape. Which strip of tape lies flat on the desk and which is crinkled?
2. Build your spacetime diagram on the surface of a large ball. Start with the space and time axes.
   - The space axis is a strip of tape that runs vertically along a line of longitude.
   - The time axis runs horizontally along a circle of latitude (about 15° above the equator).



3. Add three identical strips of tape to represent the ladder in three consecutive snapshots. The ladders must follow lines of longitude on the surface, starting about 2 cm above the time axis and ending about 10 cm from the top.



4. Alice's path is a strip of tape that connects the top of the first ladder with the bottom of the last ladder. Can you make it a straight line? Why would you want to?
5. Bob's path runs parallel to the time axis along a circle of latitude. It will connect the bottoms of the three ladders. Does the tape lie flat or is it crinkled? What does this indicate?

Curved Spacetime:	When we transfer the spacetime diagram to the ball we find that the tape for Alice's path can be ________ (flat/crinkled), which means the line is ________ (straight/curved) so Alice is ________ (accelerating/not accelerating) through curved spacetime. The tape describing Bob's path is ________ (flat/crinkled), which means the line is ________ (straight/curved) so Bob is ________ (accelerating/not accelerating) through curved spacetime. Drawing the spacetime diagram on a curved surface reverses who is accelerating and who is not—just what Einstein needed to make the acceleration model make sense. The ground can be forever accelerating up without moving up! Gravity is not a force—it is curved spacetime.

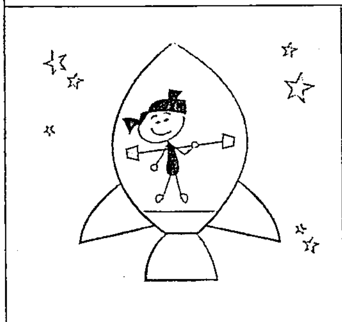
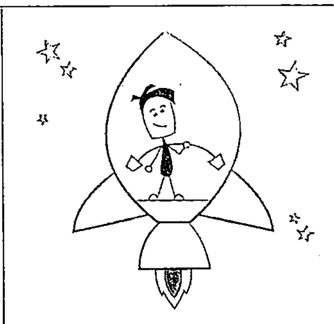
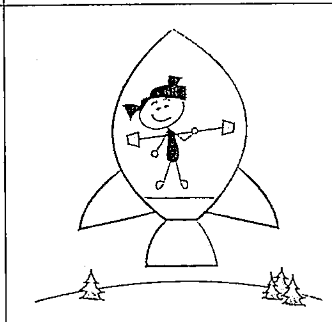
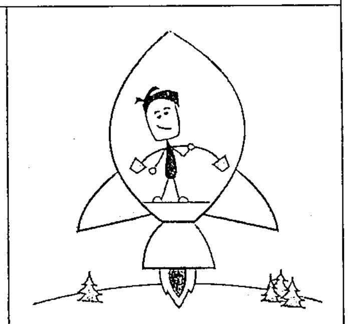
6. The time elapsed for Bob at the bottom of the ladder is the length of his path (i.e. distance in the time direction). If Alice stayed at the top of the ladder, would her elapsed time be the same? Einstein's model predicts time dilation: time passes at different rates depending on height about the ground, which has been verified by atomic clocks. Newton's model makes no such claim. Models cannot be proven right—but they can be proven wrong and time dilation proves that Newton's model of gravity is wrong!

Evaluating Models:	Newton's model fails to predict the orbit of Mercury accurately. Einstein's model does and it also accurately predicts time dilation and the bending of light. We must conclude that the best model of gravity is ________ (Newton's/Einstein's) ________ (force/curved spacetime) model.

By curving spacetime, Alice's path changes from curved to straight—she experiences no "force of gravity" and no acceleration. By curving spacetime, Bob's path changes from straight to curved—he experiences the ground pushing up on him, continually accelerating him up, but without him moving up. Einstein was able to show that gravity is not a mysterious, invisible force—it is the curvature of spacetime. This curved spacetime model asserts that you feel heavy because the surface of the Earth is forever accelerating up without actually moving up.

Part C: Accelerating Up without Moving Up

Consider the type of motion (accelerating or not) in each of the following scenarios:

In Deep Space		Near the Ground	
			
Rocket 1: Floating in deep space, engines off	Rocket 2: Accelerating "up" in deep space, engines on	Rocket 3: In freefall near the ground, engines off	Rocket 4: Hovering near the ground, engines on

1. In Rocket 1, the astronaut knows she is not accelerating; the rod is straight and she is floating. In which other rocket does she make these observations?

2. In Rocket 2, the astronaut knows he is accelerating; the rod is bent and he feels the force of the floor pushing up on him. In which other rocket does he make these observations?

3. The astronaut in Rocket 3 uncovers the window and looks out. She can see the ground and Rocket 4.
   (a) What was her type of motion before looking out the window? (Accelerating or not accelerating)
   (b) How would she describe her motion when she looks out the window?
   (c) Combine your answers from (a) and (b) into a statement.

4. The astronaut in Rocket 4 uncovers the window and looks out. He can see the ground and Rocket 3.
   (a) What was his type of motion before looking out the window? (Accelerating or not accelerating)
   (b) How would he describe his motion when he looks out the window?
   (c) Combine your answers from (a) and (b) into a statement.

We have discovered that astronauts in very different scenarios can experience the same type of motion. This insight is called Einstein's Equivalence Principle: Freefalling in a uniform gravitational field (Rocket 3) is physically identical to floating in deep space (Rocket 1). Hovering in a uniform gravitational field (Rocket 4) is physically identical to constant acceleration in deep space (Rocket 2). The mass of the Earth curves spacetime so that objects in freefall appear to accelerate down, but there is no force causing this "acceleration". It is the same kind of "acceleration" you feel when a car accelerates towards you. You are not accelerating—the car is!