Module 7: Black Holes

Objectives/Key Points

1. Describe gravity as the curvature of spacetime using a stretchy membrane and mass. Note that this is different from our standard conception of gravity as a force and it is one of the ideas that made Einstein famous.
2. Define a black hole as an object of such high density that its gravity prevents light from escaping by the curvature of spacetime.
3. Address misconceptions about when and how black holes suck things in by analyzing the balance of forces in the solar system and in a black hole system with an accretion disk.
4. Enrichment: Discuss what would happen if a person fell into a black hole.

Unit Home

After Waves and Newton's Laws.

Prerequisites

Students should have completed modules 1, 3, 4, 5, and 6 or equivalent material.

Time: 120 min. [Lesson can be split after first or second page of worksheet.]

Materials

a stretchy membrane (note: an average size flat bed sheet can work)
a series of different masses (e.g. hook masses)
a marble
a ball on a string demo is not essential but could be handy

Sticking Points

1. Students can get confused between size, mass, and density of objects.
2. It may be useful to arrange the desks in a circle or U-shape ahead of time, to leave room for the stretchy sheet spacetime demo (and people!) in the center.
3. If at any point students slip up and refer to the observed object motion as being affected by "forces," the teacher should remind them that in Einstein's picture we are not aware of forces but just of the curvature of spacetime. Also the teacher should clarify that the demo shows 2D rather than 3D spacetime, so the student must try to imagine how a 2D creature living in this 2D spacetime would perceive the motion and its cause. In particular, the 2D creature would see 2D circular motion around the central object but would not be aware of the gravitational force (which we perceive in the 3rd dimension). However, the 2D creature could be aware of the curvature of spacetime because of effects like the bending of light (see diagram, bottom of page 2 of the worksheet). The key insight of Einstein was to rethink gravity as curvature rather than forces.

4. Black holes can spark a LOT of questions – to manage the number, it may help for the teacher to assign homework that solicits questions, then choose a few to address in class.

Warm-Up (5 min.)

Optional: Students answer the following questions upon entering the classroom: “Recall the universal law of gravitation. What does each term represent? Could light be affected by a gravitational pull? Why or why not?” Alternatively, have students review the concept of density (example question: “What does it mean to say one liter of air is less dense than one liter of water?”).

Presentation and Concept Checks (80 min.)

1. After warm-up, teacher explains to students that there is another model of gravity Einstein created called “general relativity,” and it treats gravity not as forces but instead as the way we experience the curvature of spacetime.

2. Teacher presents demos with a stretchy membrane and a series of different size masses which will play the role of celestial objects (make clear these are not black holes). Four students come up to the front of the room and grab the edges of the sheet. The stretched-out sheet represents a 2D spacetime.

Demo 1:  Teacher shows what happens when you add larger and larger masses to the sheet.

The following questions should be asked to the class to guide their thinking:

- What do you notice about the shape of spacetime (the sheet) when it is not occupied by any mass?
- What happens to the curvature of spacetime when we add a massive object to it?
- What happens to the curvature of spacetime as we add more massive objects?

Demo 2:  Teacher rolls a marble across the stretchy membrane in the same path next to different massive objects. The steepness of the curvature of gravity will be increased by increasing the mass or density of the central object. Students will note the differences in the path of the marble. Let students try rolling the marble too.

Teacher should now push the students to make a connection between the steepness of the curvature in spacetime and the amount of acceleration an object will feel. Remind students that acceleration can mean change in speed and/or direction.

The following questions can be asked to the class to guide their thinking:

- What do you notice about the amount of deflection in the path of our marble when we increase the size of the massive object in the sheet? (Answer: It is larger. reflecting larger acceleration.)

- For a certain mass, how do I make sure that the marble does not get pulled into the mass? (Answer: Give the marble a higher velocity – have students actually do this.)

3. *Concept Check:* Students perform the ranking task in problem 1 of the appended worksheet, connecting the mass of an object to its effect on the curvature of spacetime. Students then summarize this relationship. Discuss with each other and as a class.

4. Discuss (a) how Einstein's model of gravity is different and (b) what predictions could allow it to be distinguished from Newton's model of gravity.

For (a), ask students to work in pairs to answer "How does Einstein's model of gravity differ from the usual model involving gravitational forces?" Students should be able to articulate that "An alternative way of thinking about the greater force of gravity is by thinking about a greater curvature of spacetime."

For (b), discuss a key prediction of general relativity: bending of light around massive objects (note the historical significance: starlight bending around the Sun was some of the first evidence that Einstein's model was correct). Check understanding by recording concepts in the spaces at the top of the worksheet.

5. Teacher should now remind students of the distinction between high density and high mass – spacetime can be strongly curved by a small mass if the mass is compressed into a tiny volume.

Concept Check: Students should complete part I of the in-class worksheet and compare with a partner, then teacher should review the answers with the class:

1. *ABC*
2. *CBA*
3. *ABC*
4. *ABC*

Summary: The gravitational acceleration is greatest where the curvature is steepest. Two objects with the same mass can cause different curvatures if they have different densities.

Now students should complete part II of the in-class worksheet and compare with a partner, then teacher should review the answers with the class:

1. The density of the black hole must be greater than the density of the Sun because the spacetime curvature around the black hole is stronger.

2. In the diagram of the Sun's spacetime, some of the grid lines curve towards the Sun but curve back outward continuing on their path. In the diagram of the black hole's spacetime, many of the grid lines enter the black hole and do not exit.

3. Light traveling towards the black hole may not exit since the grid lines do not exit the black hole.

4. [No answer required: Discuss the definition of a black hole as an object that is so dense that it creates a curvature in spacetime that is infinitely deep and therefore not even light can escape.]

6. Now the class can address misconceptions associated with black holes sucking matter in. Teacher should lead students through the reasoning exercise in section III of the in-class worksheet to determine what would happen if the Sun turned into a black hole. The teacher can sketch the first diagram, of a ball on a string moving in circular motion, to model for the students what is expected in the next activity. The teacher should then ask the students to draw a diagram of the Earth orbiting the Sun. Once they have finished their diagrams, one student should come up to the board to draw his/her diagram and explain it. Finally, the teacher should instruct the students to draw the same diagram, except this time, replace the Sun with a black hole with the same mass as our Sun. Now discuss these two points as a class:

- What has changed now that you have replaced the Sun with a black hole? Has the acceleration of the Earth changed? Has the velocity of the Earth changed? Has the orbital path of the Earth changed? Does the Sun as a black hole suck in the Earth? *[Answer: In a Newtonian gravitational force picture nothing has changed at all. In Einstein's picture spacetime is more sharply curved close to the Sun, but still the Earth is far away and is in a stable orbit. So in either picture Earth is unaffected and not sucked in.]*

- Teacher should now point out that the idea that black holes suck things in does have some truth, because many black holes have swirling disks of debris surrounding them, called "accretion disks," and in this case, the black hole does suck in the disk material. Discuss why this material is affected differently than the Sun. *[Answer: The matter around the black hole experiences friction so it does not maintain a stable circular orbit and begins to spiral into the black hole.]* Teacher should explain that this friction creates extreme heat and causes black holes to shine brightly, especially in the X-ray part of the spectrum.

Concept Check: Students should complete the rest of part III of the in-class worksheet and compare with a partner, then teacher should review the answers with the class.

Summarizer (5 min.)

Ask students to confer with a partner and answer on a sheet of paper they turn in:

"What key new feature did you learn about spacetime today? What misconception about black holes did we dispel?"

Enrichment (10 min.)

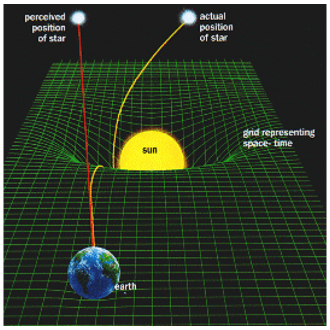
Watch the Neil DeGrasse Tyson video and discuss what would happen if a person fell into a black hole.

http://www.youtube.com/watch?v=h1iJXOUMJpg

Post-Lesson

Have students write down their questions about black holes at home and submit them to the teacher at the beginning of the next class. Then the teacher can choose a few to answer as time permits – and there's no shame in saying "No one knows!"

Black Holes: In-Class Worksheet



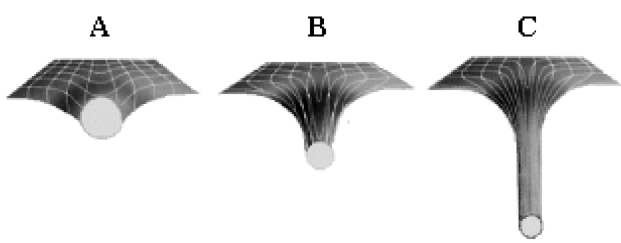
Big Picture: Einstein's alternative model for gravitational acceleration is one in which forces are replaced with ________________________.

How does the picture at left illustrate one different prediction of Einstein's general relativity model for gravity as opposed to Newton's model?

I. Density and the Curvature of Spacetime

Changes in density can affect spacetime curvature as well – if mass is tightly packed into a tiny volume, it will curve spacetime more than if it is loosely packed in a larger volume.

Answer each of the following questions with the diagrams below.



1. Rank the objects from least to greatest curvature of spacetime: ___, ___, ___

2. Rank the objects from least to greatest possible gravitational acceleration: ___, ___, ___

3. If each of the above objects has the same mass, rank them from least to greatest density: ___, ___, ___

4. If each of the above objects has the same volume (no, they don't look like it, but just imagine it's true!), rank them from least to greatest mass: ___, ___, ___

5. Summarize: In one sentence, describe the relationship between the magnitude of the gravitational acceleration and the steepness of the curvature of space-time.

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6. How can two objects with the *same* mass cause *different* curvatures in spacetime?

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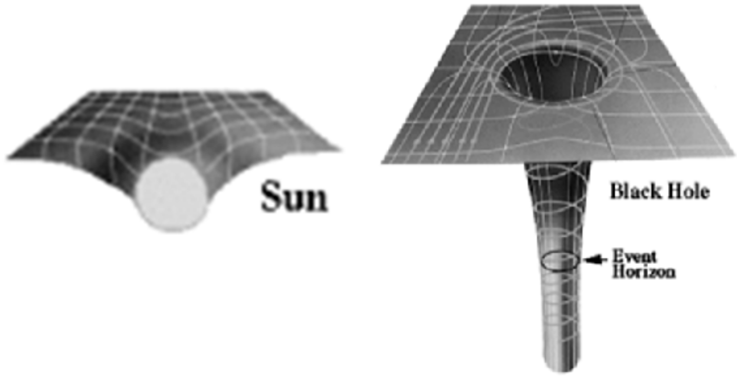
II. Black Holes and Spacetime



The diagrams above show the curvature of spacetime for our Sun and a black hole. Gridlines show the straightest path light can travel. Answer the questions below to learn about what makes a black hole different than most objects in our universe.

1. Imagine that our Sun and the black hole above have the same mass. What must be true about these two objects to create such a difference in the curvatures in spacetime they create?

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2. What is different about the grids in the diagrams above that represent spacetime as you move closer to the central object?

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3. If you were a particle of light (a photon) traveling along these grid lines, how might your path be different if you were traveling towards a black hole versus an object like our Sun?

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4. We will define a black hole as an object that is so dense that it creates a curvature in spacetime that is infinitely deep and therefore not even light can escape. Do your answers to the above three questions confirm this definition? Make adjustments where there is disagreement.

III. Do black holes suck things in?

First let's consider what would happen if the Sun ever turned into a black hole. Could the Sun suck in the Earth?

Sketch	Description
	Draw a force diagram of a ball on a string being swung in a circle. On your diagram, include a vector showing the direction of the force from the string, a vector showing the ball's linear speed at that moment, and the path of the ball.
	Draw a force diagram of the Earth orbiting the Sun as seen from above the plane of the solar system. On your diagram, include a vector showing the direction of the force on the Earth, a vector showing the Earth's linear speed at that moment, and the path of the Earth.
	Draw a force diagram of the Earth orbiting a black hole with the same mass as our Sun as seen from above the plane of the solar system. On your diagram, include a vector showing the direction of the force on the Earth, a vector showing the Earth's linear speed at that moment, and the path of the Earth.

Based on these sketches, would the Sun as a black hole suck in the Earth? Why or why not?

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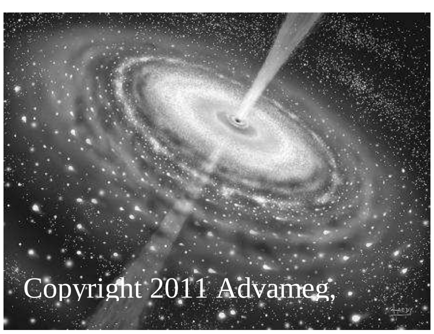

Some black holes have accretion disks surrounding them like the one pictured to the left. In this case, the black hole does suck in the material in the disk. Why is this situation different from the above?

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Why does this mean black holes can be detected even though no light can escape the interior?

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