**Spacetime and Gravity**

S3.1 Multiple-Choice Questions

1) What do we mean by the straightest possible path between two points on Earth's surface?

A) a path that actually is a perfectly straight line

B) a path that follows a circle of latitude

C) a path that follows a circle of longitude

D) a path that crosses the equator

E) the shortest path between the two points

Answer: E

2) Which of the following statements is *not* a prediction of the general theory of relativity?

A) Time runs slightly slower on the surface of the Sun than on the surface of Earth.

B) The Universe has no boundaries and no center.

C) The curvature of spacetime can distort the appearance of distant objects.

D) Different observers can disagree about the fundamental structure of spacetime.

E) A binary star system with two stars orbiting each other rapidly emits gravitational waves.

Answer: D

3) What does the equivalence principle say?

A) Gravity is the same thing as curvature of spacetime.

B) The effects of gravity are exactly equivalent to the effects of acceleration.

C) You cannot distinguish between motion at constant velocity and weight in a gravitational field.

D) The effects of relativity are exactly equivalent to those predicted by Newton's laws of motion.

E) All observers must always measure the same (equivalent) weights for moving objects.

Answer: B

4) Suppose Einstein had never lived and did not publish the special theory of relativity in 1905. According to most historians of science, when would someone else have discovered the theory?

A) within a year

B) in about 10 to 20 years

C) in about 50 years

D) We still wouldn't know about it today.

E) If Einstein hadn't lived, space and time would be very different, and the theory would have been discovered by the ancient Greeks.

Answer: A

Al is floating freely in her spacecraft, and you are accelerating away from her with an acceleration of 1*g.*

5) How will you feel in your spacecraft?

A) You will be floating weightlessly.

B) You will feel weight, but less than on Earth.

C) You will feel weight, but more than on Earth.

D) You will feel the same weight as you do on Earth.

E) You will feel yourself pressed against the back of your spaceship with great force, making it difficult to move.

Answer: D

6) Suppose you claim that you are feeling the effects of a gravitational field. How can you explain the fact that Al is weightless?

A) She is weightless because she is moving at constant velocity.

B) She is weightless because she is in a free-float frame.

C) She is weightless because she is in free-fall.

D) If you are in a gravitational field, then she cannot be weightless.

Answer: C

7) Imagine that you are sitting in a closed room (no windows, no doors) when, magically, it is lifted from Earth and sent accelerating through space with an acceleration of 1*g* (9.8 m/s2). According to Einstein's equivalence principle, which of the following is true?

A) You won't feel any change and will have no way to know that you've left Earth.

B) You'll feel a force that will cause your head to repeatedly bang into the ceiling.

C) You'll know that you left Earth because when you drop a ball it will fall sideways.

D) You'll know that you left Earth because you'll be floating weightlessly in your room.

Answer: A

8) What do we mean by *dimension* in the context of relativity?

A) the size of an object

B) the number of independent directions in which movement is possible

C) the letter used to represent length mathematically

D) the number of sides that we can see when we look at an object

E) the height of an object

Answer: B

9) If you draw a spacetime diagram, the worldline of an object that is stationary in your reference frame is

A) vertical.

B) horizontal.

C) slanted.

D) curved.

E) a circle.

Answer: A

10) If you draw a spacetime diagram, the worldline of an object that is traveling by you at constant speed is

A) vertical.

B) horizontal.

C) slanted.

D) curved.

E) a circle.

Answer: C

11) If you draw a spacetime diagram, the worldline of an object that is accelerating away from you is

A) vertical.

B) horizontal.

C) slanted.

D) curved.

E) a circle.

Answer: D

12) Which of the following correctly describes what we mean by a *great circle* on the surface of Earth?

A) any circle on the surface whose center is at the center of Earth

B) any circle of latitude

C) any circle on the surface that intersects the equator

D) any circle larger than 10,000 km in diameter

E) any circle found on an English farm that happens to have been created by aliens

Answer: A

13) Which of the following correctly describes the conditions under which you will feel weightless, according to general relativity?

A) any time you are traveling through space at constant speed

B) any time your worldline is perfectly straight

C) any time your worldline is following the straightest possible path through spacetime

D) any time you are very far from any planet

E) You can never be truly weightless.

Answer: C

14) Suppose two lines appear to be parallel but eventually meet. What type of geometry are you dealing with?

A) flat geometry

B) spherical geometry

C) saddle-shaped geometry

D) Euclidean geometry

E) This situation can never occur.

Answer: B

15) According to general relativity, why does Earth orbit the Sun?

A) Earth is following the straightest path possible, but spacetime is curved in such a way that this path goes around the Sun.

B) The mysterious force that we call gravity holds Earth in orbit.

C) Earth and the Sun are connected by a "ropelike" set of invisible, subatomic particles.

Answer: A

16) According to general relativity, a black hole is

A) an object that cannot be seen.

B) a hole in the observable universe.

C) a place where light travels slower than the normal speed of light.

D) a place where light travels faster than the normal speed of light.

E) a place where there is no gravity.

Answer: B

17) According to general relativity, how is time affected by gravity?

A) Time is not affected by gravity.

B) Time is affected by gravity, but not in a predictable way.

C) Time is stopped by any gravitational field.

D) Time runs faster in stronger gravitational fields.

E) Time runs slower in stronger gravitational fields.

Answer: E

18) Why do we see a *gravitational redshift* in the spectrum of the Sun?

A) Gravity makes light heavy, causing it to appear redder.

B) Because of gravity, the Sun is always moving away from us, so we see a redshift.

C) Time runs slower on the Sun than on Earth, making lines in the solar spectrum have lower frequency and hence longer wavelength than normal.

D) Spacetime curvature allows red photons of light to escape the Sun more easily than blue photons, leading to an apparent redshift.

Answer: C

19) What evidence supports the predicted existence of gravitational waves?

A) Gravitational waves are frequently and easily detected by large telescopes.

B) Gravitational waves have been detected by observing their effect on large masses suspended on Earth.

C) The orbit of a star system consisting of two neutron stars is slowly decaying, suggesting that energy is being carried away by gravitational waves.

D) The energy generated by gravitational waves from the Sun can be seen as it is absorbed by Jupiter.

E) Photographs of spacetime show the gravitational waves as ripples that are clearly visible.

Answer: C

20) Each of the following is a prediction of the theory of relativity. Which one is crucial to understanding how the Sun provides light and heat to Earth?

A) If you observe someone moving by you, you'll see their time running slowly.

B) Gravity is curvature of spacetime.

C) *E = mc*2

D) Time runs slower on the surface of the Sun than on Earth.

E) Space is different for different observers. Time is different for different observers. Spacetime is the same for everyone.

Answer: C

21) In the text is a photograph that appears to show four identical galaxies arranged as a cross. What are we really seeing?

A) four galaxies that are nearly identical because they were born at about the same time

B) four images of a single background galaxy, created by the gravitational lens of a massive foreground galaxy or cluster

C) a large galaxy with four central masses that glow brightly

D) a picture taken with a poorly made telescope, so that a single large object appears as four fuzzy dots

Answer: B

22) Which of the following is *false*?

A) The speed of light in a vacuum is constant.

B) Nothing can move faster than the speed of light.

C) Observers in different reference frames measure the same speed of light.

D) The absoluteness of the speed of light is an experimentally verified fact.

E) The speed of light slows down near a black hole.

Answer: E

23) Which of the following is *false*?

A) The order of events can be different for observers in different reference frames.

B) From your point of view, time runs slower in the reference frame of anyone moving relative to you.

C) If one observer measures two events to be simultaneous, all observers must agree on their simultaneity.

D) Time dilation is an observationally verified fact.

E) Time runs slower near a black hole.

Answer: C

S3.2 True/False Questions

1) As predicted by general relativity, time runs slightly slower at the peak of Mount Everest than it does at sea level.

Answer: FALSE

2) Gravitational time dilation can be observed in the spectra of atoms on the surface of the Sun.

Answer: TRUE

3) Space is different for different observers. Time is different for different observers. Spacetime is the same for everyone.

Answer: TRUE

4) Mercury's perihelion slowly precesses around the Sun by a bit less than 2° per century. This precession can be fully accounted for by Newton's theory of gravity, although general relativity also gives the same answer.

Answer: FALSE

5) When we look at pictures of distant objects in the universe, the images of the objects often are distorted by gravitational lensing.

Answer: TRUE

6) The theory of general relativity proves that wormholes like those used in science fiction cannot exist.

Answer: FALSE

7) Although many scientists believe general relativity to be correct, there is no experimental evidence supporting the predictions this theory makes about time.

Answer: FALSE

8) *Process of Science:* The equivalence principle is a fundamental assumption of general relativity and cannot be experimentally tested.

Answer: FALSE

S3.3 Short Answer Questions

1) Suppose you stay home on Earth and watch a spaceship that leaves on a long trip at a constant acceleration of 1*g*.

a. At an acceleration of 1*g*, approximately how long will it take before you see the ship traveling away from Earth at *half* the speed of light? Explain. (Use *g* = 9.8 m/s2.)

b. Describe how you will see its speed change as it continues to accelerate. Will it keep gaining speed at a rate of 9.8 m/s each second? Why or why not?

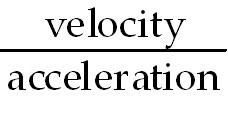
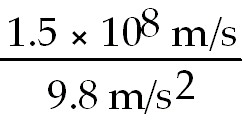
c. Suppose the ship travels to a star that is 500 light-years away. According to you back on Earth, *approximately* how long will this trip take? Explain.

Answer:

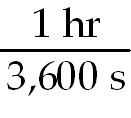
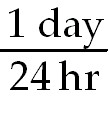
a. As long as time dilation is not a major factor, we can determine the velocity after some time with a given acceleration from the following formula:

velocity = acceleration × time

Although time dilation is noticeable at half the speed of light (1.5 × 108 m/s), it is still a relatively small factor until much higher speeds. Thus, we can get a reasonable approximation of how long it would take the ship to reach half the speed of light at a constant acceleration of 1*g* by neglecting time dilation. We therefore just solve the above formula for time:

time =  =  ≈ 1.5 × 107 s

Converting to days, this time is:

1.5 × 107s ×  ×  ≈ 174 days

At a constant acceleration of 1*g*, the ship will reach a speed of about half the speed of light in about 174 days, or about 6 months.

b. As the ship continues to accelerate away from Earth at 1*g*, you (on Earth) will not continue to see its speed increase by 9.8 m/s with each passing second. From your point of view on Earth, time dilation will begin to noticeably affect the rate at which time is passing on the accelerating ship. Thus, each second on the ship will become much longer than a second on Earth, which means the ship's speed will increase by much less than 9.8 m/s during an Earth second. This effect will become more and more pronounced as the ship's speed approaches the speed of light away from Earth.

c. Since the ship will reach half the speed of light in just a few months, we can conclude that on a long journey it will be traveling *very* close to the speed of light for most of its journey. Thus, the ship will take only slightly longer to make a long trip than it would take a light beam from the point of view of observers on Earth. Thus, from your point of view on Earth, it will take the ship only a little more than 500 years to reach a star 500 light-years away.

2) In your own words, explain what we mean by *spacetime*.

Answer: It is the combination of space and time that all observers will agree upon, even while they may disagree about space and time independently.

3) Briefly explain how the universe can be finite yet have no center and no edges.

Answer: By analogy to Earth's surface, the universe might have a spherical geometry. Just as there is no center to the Earth's surface (e.g., New York is no more central than any other place), the universe would have no center. Just as there is no edge where ships fall off, the universe would have no edge.

4) Describe two observational tests that support general relativity.

Answer: Many possible answers, including: experiments in gravitational time dilation, observations of gravitational redshift, observations of gravitational lenses, evidence from binary pulsars for gravitational waves.

5) What is *gravitational lensing*? According to general relativity, why does it occur?

Answer: It is the distortion of the appearance of distant objects due to gravity and occurs because their light passes through regions of space that are curved.

6) What are gravitational waves? Have they ever been detected?

Answer: Gravitational waves are ripples of spacetime caused by the motion of massive objects (the more massive the object, the greater the ripples). They travel at the speed of light but are so weak that they have not yet been detected. New "telescopes" are being built, however, to search for them. The effect of gravitational waves has been seen in the orbital decay of a very close binary neutron star system: the gravitational waves carry energy away from the binary and the two neutron stars move closer and closer together, speeding up their orbits measurably.

7) *Process of Science*: Describe a piece of observational evidence supporting general relativity.

Answer: Study of Mercury's precession reveals that it precesses more slowly than Newtonian gravity would predict. It takes a general relativity-based approach, accounting for the curvature of spacetime, to correctly predict the precession rate. General Relativistic corrections to time have also been tested by synchronizing clocks that then are flown on airplanes and satellites.

8) *Process of Science:* What would you say to a friend who thinks that the general theory of relativity is a beautiful example of abstract thinking by humankind that explains extreme phenomena in astrophysics but has no application to everyday life?

Answer: The map application in your smartphone would not work nearly as accurately as it does if general relativity was not used to calculate the orbits of the GPS satellites around the Earth.

S3.4 Mastering Astronomy Reading Quiz

1) Einstein's general theory of relativity suggests that gravity is

A) a force of attraction that acts at a distance between two masses.

B) caused by curvature of spacetime.

C) = G × *M*1 × *M*2/*d2.*

D) one of four fundamental forces in nature.

Answer: B

2) Which of the following is *not* a major idea of Einstein's general theory of relativity?

A) Time runs slower near strong gravitational fields.

B) It is possible to travel through wormholes.

C) Our universe can have no center or boundaries, yet be finite.

D) Black holes can exist in spacetime, and falling into a black hole means leaving the observable universe.

Answer: B

3) Einstein's equivalence principle says that

A) everyone measures the speed of light to be equivalent.

B) the effects of gravity are exactly equivalent to the effects of acceleration.

C) someone traveling at 0.9*c* will age at the same rate as someone at 0.99*c.*

D) all people see themselves at an equivalent distance to the center of the universe.

Answer: B

4) What do we mean by *dimension* in the context of relativity?

A) the number of independent directions in which movement is possible

B) the size of an object

C) the number of sides that we can see when we look at an object

D) the letter used to represent length mathematically

Answer: A

5) What do we mean by *hyperspace*?

A) It is another word for spacetime.

B) It is a space through which it is possible to travel very fast.

C) It is a space with a hyperbolic geometry.

D) Any space with more than three dimensions.

Answer: D

6) What is *spacetime*?

A) Time that we measure when traveling in space.

B) It's a graph with four axes.

C) It is a way of viewing books at different angles.

D) The inseparable combination of space and time.

Answer: D

7) If two straight lines start out parallel but eventually cross, then they must be in a

A) flat geometry.

B) saddle-shaped geometry.

C) spherical geometry.

D) spacetime geometry.

Answer: C

8) Which of the following correctly describes what we mean by a *great circle* on the surface of Earth?

A) any circle of latitude

B) any circle whose center is at the center of Earth

C) any circle larger than 10,000 km in diameter

D) a circle of longitude

Answer: B

9) What do we mean by the *event horizon* of a black hole?

A) It is the center of the black hole.

B) It is the "bottomless pit" of the black hole.

C) It is the place where time begins to slow down as you approach a black hole.

D) It is the boundary within which events in the black hole cannot influence events in the outside universe.

Answer: D

10) What do we mean by *gravitational time dilation*?

A) It is the idea that time runs slower in places where gravity is stronger.

B) It is the idea that clocks run slow for people moving at high speed past you.

C) It is the idea that everyone measures time differently, depending on his/her reference frame.

D) It is the idea that clocks run faster in stronger gravitational fields.

Answer: A

11) In what way do observations of Mercury support Einstein's general theory of relativity?

A) Mercury's orbit slowly precesses in a way that matches the prediction of general relativity but disagrees with the prediction based on Newton's universal law of gravitation.

B) Einstein discovered that time runs slower on Mercury than on Earth, as his theory predicted.

C) Einstein was able to explain the fact that Mercury orbits the Sun exactly twice for every three rotations, and Newton's theory of gravity cannot account for this.

D) We can see that Mercury lies deeper in the spacetime bowl that surrounds the Sun than does Earth.

Answer: A

12) Why do we see a *gravitational redshift* in the spectrum of the Sun?

A) Time runs slower on the Sun than on Earth, making lines in the solar spectrum have lower frequency and hence longer wavelength than normal.

B) Gravity makes light heavy, causing it to appear redder.

C) Because of gravity, the Sun is always moving away from us so we see a redshift.

D) Spacetime curvature allows red photons of light to escape the Sun more easily than blue photons, leading to an apparent redshift.

Answer: A

13) Which of the following best describes what we mean by a *worm* hole?

A) A proven way of traveling through space faster than the speed of light.

B) A possible method of traveling through space faster than the speed of light.

C) A discarded idea about time travel that physicists now know to be impossible.

D) A hypothesized but unproven type of "tunnel" through hyperspace that connects distant points in the real universe.

Answer: D

14) Which of the following correctly describes the relationship between Newton's theory of gravity and general relativity?

A) Newton's theory of gravity is now known to be false, and we were previously misled to think it was true by measurement errors.

B) Newton's theory of gravity and general relativity give the same answers, but the former tells us to think of gravity as a force and the latter tells us to think of gravity as curvature of spacetime.

C) Newton's theory of gravity is an approximation to general relativity that works when gravity is relatively weak, but breaks down when gravity is strong.

D) General relativity applies at the sub-atomic level, but Newton's theory of gravity does not.

Answer: C

S3.5 Mastering Astronomy Concept Quiz

1) If you launch two probes in opposite directions from the Space Station, they will meet as they orbit Earth. According to general relativity, why does this happen?

A) They are following the straightest possible paths through space time, but those paths happen to meet.

B) They are following the allowed orbits according to Newton's universal law of gravitation.

C) The force of gravity tugs on the probes and forces them to orbit Earth.

D) Objects launched in space always follow circular paths, no matter where they are.

Answer: A

2) Suppose the room in which you are sitting was magically transported off Earth, and sent accelerating through the universe at 9.8 m/s2 Assuming your doors and windows are sealed and closed, how could you tell that you'd left Earth?

A) You would weigh more than you do on Earth.

B) You couldn't—the equivalence principle tells us that you won't be able to tell the difference.

C) Your time would run slower than it does on Earth.

D) You'd hear a loud whooshing sound as you careened through space.

Answer: B

3) Suppose you are in a spaceship accelerating away from Earth at 9.8 m/ s2 (1 g), so that you can walk on the floor of your spaceship as though experiencing normal gravity on Earth. Is it possible for you to consider yourself to be at rest? Why or why not?

A) No, because you feel a force so you must truly be accelerating.

B) No, because you are accelerating away from Earth, and it's not legitimate to claim that Earth is accelerating away from you.

C) Yes, by assuming you are feeling effects of gravity and that Earth is accelerating away from you because it is in freefall.

D) Yes, but only if believe that you are the center of the universe.

Answer: C

4) In special relativity, we learned that people in different reference frames will measure time differently. According to general relativity, why does this happen?

A) People in different reference frames experience different realities.

B) It is an illusion, and time really is the same for everyone.

C) They have different worldlines.

D) They are experiencing the same spacetime reality, but from different perspectives.

Answer: D

5) Assuming you are sitting still as you take this quiz, how would you draw your own worldline on a spacetime diagram?

A) You would not have a worldline since you are not moving.

B) as a straight, vertical line

C) as a straight, horizontal line

D) as a diagonal line

Answer: B

6) Planes traveling between Seattle and Tokyo often go near Alaska because

A) there is less air traffic to contend with.

B) planes travel faster in cooler air.

C) the distance is shorter.

D) the plane can stay over the safety of land for longer.

Answer: C

7) If your worldline is following the straightest possible path through spacetime, then

A) you will be weightless.

B) you will feel heavier than your normal weight.

C) you must be accelerating.

D) you must be traveling at constant velocity.

Answer: A

8) According to general relativity, why does Earth orbit the Sun?

A) Earth orbits the Sun because the mysterious force that we call gravity holds Earth in orbit.

B) Earth is following the straightest path possible through spacetime, but this path happens to go around and around the Sun.

C) Earth orbits the Sun because Earth and Sun are connected by a "rope-like" set of invisible, subatomic particles.

D) Earth orbits the Sun because a spacetime diagram shows the Sun to be a bowl-shaped dip in a rubber sheet.

Answer: B

9) According to general relativity, what is a black hole?

A) an object that cannot be seen

B) a place where light travels slower than the normal speed of light

C) a place where the strength of gravity is infinite

D) a hole in the observable universe

Answer: D

10) According to general relativity, how is time affected by gravity?

A) Time runs faster in places where gravity is stronger.

B) Time is stopped in places where gravity is strong.

C) Time is not affected by gravity.

D) Time runs slower in places where gravity is stronger.

Answer: D

11) Suppose you and a friend have very precise clocks. You are on the ground floor of a tall building and your friend is on the roof. Which of the following statements is true?

A) You will see your friend's clock ticking faster than yours, and she will see your clock ticking faster than hers.

B) You will see your friend's clock ticking slower than yours, and she will see your clock ticking slower than hers.

C) You will see your friend's clock ticking faster than yours, and she will see your clock ticking slower than hers.

D) You will see your friend's clock ticking slower than yours, and she will see your clock ticking faster than hers.

Answer: C

12) What evidence supports the predicted existence of gravitational waves?

A) The orbit of a star system consisting of two neutron stars is slowly decaying, suggesting that energy is being carried away by gravitational waves.

B) The energy generated by gravitational waves from the Sun can be seen as it is absorbed by Jupiter.

C) Gravitational waves are frequently and easily detected by large telescopes.

D) Photographs of spacetime show the gravitational waves as ripples that are clearly visible.

Answer: A

13) Each of the following is a prediction of the theory of relativity (special or general). Which one is crucial to understanding how the Sun provides light and heat to Earth?

A) Gravity is curvature of spacetime.

B) *E = mc*2

C) If you observe someone moving by you, you'll see his/her time running slow.

D) Space is different for different observers. Time is different for different observers. Spacetime is the same for everyone.

Answer: B

14) Suppose that a ship is accelerating through space in such a way that the passengers are experiencing a *constant* force (due to the thrust of the ship) equivalent to the total weight of the ship and passengers on Earth. From the point of view of observers on Earth, how does the ship accelerate?

A) It has a constant acceleration of 9.8 m/s2, therefore increasing its speed by 9.8 m/s with each passing second.

B) At first, it has a nearly constant acceleration of 9.8 m/ s2. But as it approaches the speed of light, its acceleration gradually slows in such a way that it never stops accelerating, but never reaches the speed of light either.

C) At first, it has a very large acceleration—much larger than 9.8 m/s2. But when it reaches the speed of light it stops accelerating.

D) It has a constant acceleration of 9.8 m/s2 until it reaches a speed of half the speed of light. Then its acceleration suddenly slows so that it can't go much faster.

Answer: B

15) Which of the following best describes the current scientific view of possibilities of travel to distant parts of our galaxy (or universe) with such things as hyperspace, wormholes, or warp drive?

A) We do not know if travel in any of these ways is really possible, but they do not contradict any known laws of physics.

B) There is no doubt that such travel is possible, though it remains well beyond our current technology.

C) They sound like fun, but they are not possible because they allow faster-than-light travel.

D) They seemed to be allowed by special relativity, but general relativity does not allow for them.

Answer: A