I) History of Gravity—Outline

Note—The following represents a summary of the key gravity-related points from the History of Gravity (http://www.adlerplanetarium.org/education/ac/gravity/curriculum/cb1-1.htm) resource. During your discussion, you may wish to refer to the original document for more detailed information.

A) Early Ideas:

- Ideas about gravity originated from everyday experience like: (a) objects fall unless they are supported; (b) "down" is different from "across"; and (c) climbing is harder work then walking level.
- We still use these very basic ideas and properties of objects every day without further thought.
- We tend to equate gravity with "down" (even though gravity is "together" not down).

B) Ancient Greeks: Aristotle:

- The Ancient Greeks—particularly Aristotle—began to unify observations about gravity into one idea.
- Aristotle felt the cause of falling was heaviness—the heavier an object, the faster it falls.
- Aristotle viewed all matter as being made of four elements: Earth, Water, Air and Fire.
- As a result, he concluded that the "natural place" for heavy objects (made principally of earth) was back in the center (or on the ground). If one removed a heavy object from its natural place (i.e., by lifting it) it would naturally return to its "proper" place.

C) Middle Ages:

- During this period, the teachings of Aristotle, which were approved by the Church, were regarded as true and were basically unquestioned.
- Aristotle's ideas about objects and gravity were basically true, since they were based on experience and common sense.
- Problems existed. For example, in the area of cannonball trajectories, the people teaching the theories and the people dealing with the real-world objects were different.
- Experimentation was discouraged in the name of unquestioned faith during this period

D) Renaissance: Galileo:

- Galileo's work represents the beginnings of a modern understanding of gravity.
- His critical contribution was by disavowing any interest in "causes" by trying to answer the question, "How do objects fall?" instead of "Why do objects fall?"
- He began his exploration comparing the rates at which objects fall and how fast they fall.
- His basic conclusions were that: (a) objects of different weight fall at the same speed; (b) falling starting from a complete stop, objects move more and more quickly the longer they fall; and (c) the distance an object falls is proportional to the square of the elapsed time.
- Galileo's contributions to the understanding of gravity were: (a) he changed the question being asked; (b) he based his answers on careful experimentation and measurement; and (c) he gave a mathematical *quantitative description* of his results and gave the limits within which he had verified this description.

E) Enlightenment: Newton:

- Newton developed the modern concept of gravity by positing a *force* of gravity that was responsible for a variety of effects.
- He applied Galileo's law of falling objects to the moon and concluded that the moon is not immune to gravity but is continuously falling towards the earth (and keeps missing it). In other words, the moon is in orbit.
- Newton concluded that gravity also exists in space (and the solar system), a revolutionary idea which clashed with Aristotle's view that laws governing the heavens were different from those on earth.
- Newton found that he could explain the entire motion of the solar system from the planets to the moons to the comets with a single Law of Gravity: *"All bodies attract all other bodies, and the strength of the attraction is*

proportional to the masses of the two bodies and inversely proportional to the square of the distance between the bodies."

- The law is universal because it applies to all bodies in the universe regardless of their nature.
- Gravity is not just about falling, it is about attraction—all objects pull on all other objects!
- Newton and his critics were unhappy with the lack of a mechanism by which gravity worked. Until then, all forces were believed to be "contact forces."
- The Newtonian concept of "action-at-a-distance" was profoundly disturbing to his opponents, who attacked his theory as "occult" and explaining nothing.

F) Post Enlightenment — 1700s, 1800s:

- The theory of gravitation stayed essentially unchanged during this period.
- More sophisticated mathematical tools for understanding the interplay of the planets were developed, but the underlying theory remained stable.
- As with the Aristotelian view, gravitation was viewed as intricately connected with the structure of the universe. The universe was orderly and controlled by gravity and the laws of motion.
- The excitement during this period mainly came from the systematic application of the theory of gravity to the heavens. This included new insights on (a) the paths of comets, (b) the discovery of Neptune, (c) the gravity and mass of stars, and (d) the illumination and rings (particles) of Saturn.
- It was determined that the problems surrounding Uranus's orbit were due to an eighth planet, which upheld Newton's law of gravity.
- Cavendish demonstrated the gravitational force between two objects in the laboratory. Indirectly, this was equivalent to the first measurement of the mass of the earth.

G) Twentieth Century: Einstein:

- He resolved the era's puzzles of the perihelion advance of Mercury and the involvement of mass in Newton's varying laws of gravity and motion by proposing his "thought experiment," which revealed that there is no observable difference between acceleration and gravity and that both masses are identical because acceleration and gravity are really, on some deep level, the same thing.
- Einstein proposed the Special Theory of Relativity, which sets the maximum speed as that of light and gives the famous relationship between energy and matter ($E=mc^2$).
- Einstein's great achievement was to show how to connect, to patch together, the inertial frames in different locations and showing that space itself is bent by the presence of matter. Moreover, objects don't feel a force of gravity, they simply move in straight lines—but the space they move through is bent and so it appears that they move in arcs.
- Einstein's work shed further light on the workings of black holes, indicating that it would require infinite force to move out [escape] from a black hole!

Cosmology:

- Singularities are regions of space (within black holes) where the density of matter becomes infinite, and the very concepts of matter, space, and time lose their meaning. In their vicinity, time travel becomes possible, and the laws of physics break down completely. Luckily for us, black holes' event horizons shield us from the hidden singularities.

H) Future Directions:

- General Relativity is one of the crowning glories of modern physics.
- Quantum Mechanics deals with the interactions of very small objects, such as electrons and protons and is very accurate and is perhaps the most successful theory in all of physics.
- Scientists are looking for a theory that combines both General Relativity (GR) and Quantum Mechanics (QM), creating a Theory of Everything (TOE).
- The highly complicated String Theory is considered a promising candidate for TOE.

II) Modern Concepts—Outline

Note—The following is a summary of the key points from the Modern Concepts (http://www.adlerplanetarium.org/education/ac/gravity/curriculum/cb1-2.htm) resource. During your discussion, you may wish to refer to the original document for more detailed information.

A) Mass versus weight:
- To understand gravity, we must first understand the difference between mass and weight.
- Mass is the amount of material in an object, and measures how hard it is to start an object moving or to slow it down again.
- Weight is the force of attraction between an object and whatever astronomical body it is on.
- Mass is a property of the object itself, but the weight is a property of the object and its location.

B) Newtonian Gravity is still correct:
- We still use Newtonian Gravity (NG) all the time because it is a superb approximation for almost all uses in the solar system.
- NG has few errors and works unless the speeds involved are close to that of light, the masses are tremendous, or both.

C) Gravity pulls things together:
- Gravity is a "together" force, not a "down" force.
- On the earth, the force of gravity is everywhere towards the center of the earth.

D) All objects have gravity:
- Mass is an intrinsic property of matter. Every object exerts a gravitational attraction on every other object in the universe.

E) The more massive an object, the stronger its pull on other objects and the more strongly other objects pull on it:

- Objects with greater mass attract others more strongly. Massive objects are attracted with more force.

F) The closer two objects are to each other, the stronger their gravitational pull on each other:

- The closer the objects the stronger the pull of gravity.

G) Gravity is proportional to mass, not any other property:
- Only the mass is important to gravity. It doesn't matter what else is true about an object.

H) Orbits, center-of-mass, and escape velocity:
- Almost everything in the universe orbits around something else. Moons orbit around planets, planets around stars, stars around galaxies, galaxies in clusters.
- The important thing is that the object in orbit has a bit of motion, so it doesn't just smack into the other object but misses it instead.
- A circular orbit occurs when sideways motion is balanced with the gravitational force. When the motion is too fast, the object will not only miss the central object but it will fly off into space. The speed an object needs to go to fly away forever is called *escape velocity.*
- Gravitational force is reciprocal, so both objects move each other, with the larger of the two moving less.
- Planets and their stars orbit the "center of mass" of the stellar system.

I) Weightlessness is experienced in free fall—not just in space:

- Weightlessness is not the absence of gravity. It occurs anytime one is falling!
- Gravity does not end outside of the earth's atmosphere.

J) Very massive objects (stars, planets, etc.) are round because of gravity's inward pull:

- Gravity pulls things together.
- When there is enough mass, the rigidity of the object is insufficient to hold its shape against the force of gravity. All the matter wants to be as close to the center as possible. The sphere allows this.
- The different sizes and masses of the worlds of the solar system control their shape. The top three worlds have high mass and hence are spherical. Worlds with low mass are not strong enough to make them spherical.

K) All objects at the earth's surface fall towards the earth with the same acceleration:

- Galileo's theory that all objects fall at the same rate regardless of the mass can be mathematically proven using Newton's laws of gravity and motion.
- The acceleration of an object depends only on the mass of the earth, the distance to the earth's center, and Newton's constant G.
- The gravitational force of an object is proportional to the mass but the acceleration is inversely proportional to the mass so the mass cancels out.
- Einstein's theory of General Relativity further supports this "strange" occurrence.

L) Acceleration is equivalent to gravity:

- This is a restatement of the equivalence principle that led Einstein to General Relativity.

M) Tides and Roche's limit:

- When two objects orbit each other, the gravitational force is stronger on the sides facing each other than on the far sides. But the gravitational force is cancelled out by the orbital motion (i.e., the motion of the objects revolving around each other) only precisely at the center of the objects.
- The Roche limit is the critical distance that exists between two massive objects where this tide-raising force is sufficient to tear the smaller object apart.

N) Gravity is the weakest of the four fundamental forces:

- The four fundamental forces in the universe are: the electromagnetic force, the "weak" force, the "strong" force, and gravity.
- The electromagnetic force is perhaps the most common force. It is what holds atoms together, drives chemical reactions, and keeps objects from floating through each other.
- The "weak" and "strong" forces are both only important in the atomic nucleus.
- The strong force is the strongest of the forces, next comes the electromagnetic, weak, then gravity.

O) Gravity is nevertheless the main mover and shaper in the universe:

- In short, the range, distances, and electric charges of the forces prove gravity, the weakest of the forces, to be the main mover in the universe because it is always attractive and never cancels itself out.

P) Gravity determines the fate of the universe:

- The universe began about 12-16 billion years ago. Since then, the universe has been expanding. Gravity controls this expanding process and determines whether the universe will freeze through expansion or re-collapse if it ceases to expand.

Q) Gravity permits the detection of invisible stuff (stars, planets, galaxies, structure in the universe, black holes etc.):

- One of the most important aspects of gravity is that it gives us a tool to determine the mass of objects forever beyond our reach.
- The existence of planets can be inferred even if the planets themselves cannot be seen and gravity allows us to probe the contents of galaxies.

R) What is a black hole?:

- A black hole is an object so massive and so dense that not even light can escape.
- A black hole has two important regions: the singularity and the event horizon.

S) Gravitational waves:

- Gravitational waves are the change in the force of gravity from some distant object.