5. Universal Laws of Motion

"If I have seen farther than others, it is because I have stood on the shoulders of giants."

Sir Isaac Newton (1642 – 1727)
Physicist

Agenda

- **Exercise 6—lab for this week (Due next….week from Tuesday)**
- **Homework—Tutorial "Motion and Gravity" (Due week from Tuesday)**
- Many missing online quiz/tutorial grades…everyone signed up with class?
- Due Tuesday—Project Ideas (a paragraph or so)
  - Who is involved in the project
  - What is the topic/question of the project
  - How will the topic be addressed
- Hand back tests

- Discuss feedback from Thursday
- Chapter 5—Physics light
- Lab and lab reports…a guide

What's this?

Feedback

- Pacing
  - Good or a bit too fast
  - Wasn't sure what you'd say to this
- Ordering/Topics
  - Overall good
  - A few comments disparaging astronomical history--surprising
- Astronomyplace.com
  - Mostly good
- Labs
  - Suggested we go over lab when finished
  - Better explanation of expectations
  - Hard to figure out by yourselves
- Depth/Breadth
  - Nothing too strong either way
  - Need a balance
- Other
  - Tuesday's review notes not posted—sorry—email me!
  - Better understanding of performance/grade
  - Uneven amount of homework

5.1 Describing Motion: Examples from Daily Life
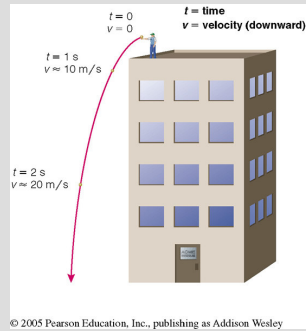
Our goals for learning:

- Distinguish between speed, velocity, and acceleration.
- What is the acceleration of gravity?
- How does the acceleration of gravity depend on the mass of a falling object?
- How do you know when a net force is acting on an object?
- Have you ever been weightless? Have you ever been massless?

Objects in Motion

- **speed** – rate at which an object moves, i.e. the distance traveled per unit time [m/s; mi/hr]
- **velocity** – an object's speed in a certain direction, e.g. "10 m/s moving east"
- **acceleration** – a change in an object's velocity, i.e. a change in either speed or direction is an acceleration [m/s^2]

The Acceleration of Gravity

- As objects fall, they accelerate.
- The acceleration due to Earth's gravity is 10 m/s each second, or $g = 10 \text{ m/s}^2$.
- The higher you drop the ball, the greater its velocity will be at impact.

$t = \text{time}$
$v = \text{velocity (downward)}$

$t = 0$
$v = 0$

$t = 1 \text{ s}$
$v \approx 10 \text{ m/s}$

$t = 2 \text{ s}$
$v \approx 20 \text{ m/s}$

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The Acceleration of Gravity (g)

- Galileo demonstrated that g is the same for all objects, regardless of their mass!
- This was confirmed by the Apollo astronauts on the Moon, where there is no air resistance.
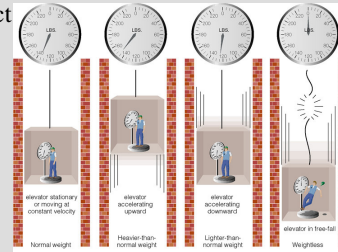
Forces

- Forces change the motion of objects.
- **momentum** – the (mass x velocity) of an object
- **force** – anything that can cause a change in an object's momentum
- As long as the object's mass does not change, the force causes a change in velocity, or an…

acceleration

Is Mass the Same Thing as Weight?

- **mass** – the amount of matter in an object
- **weight** – a measurement of the *force* which acts upon an object

When in "free-fall," you are weightless!!

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Depending on its initial velocity, the cannonball will either fall to Earth, continually free-fall (orbit), or escape the force of Earth's gravity.

Speed 1 km/s 0 — 15 Fire !

Next

5.2 Newton's Laws of Motion

Our goals for learning:

- What are Newton's three laws of motion?
- Why does a spinning skater spin faster as she pulls in her arms?

Sir Isaac Newton (1642-1727)

- Perhaps the greatest genius of all time
- Invented the reflecting telescope
- Invented calculus
- Connected gravity and planetary forces
  Philosophiae naturalis principia mathematica

Newton's Laws of Motion

1 A body at rest or in motion at a constant speed along a straight line remains in that state of rest or motion unless acted upon by an outside force.

This can go against one's "common sense"

Newton's Laws of Motion

2 The change in a body's velocity due to an applied force is in the same direction as the force and proportional to it, but is inversely proportional to the body's mass.

$$F = m\,a$$

Newton's Laws of Motion

3 For every applied force, a force of equal size but opposite direction arises.

These forces act on different objects!

Newton's Laws of Motion

A spaceship needs no fuel to keep moving in space.

A baseball accelerates as the pitcher applies a force by moving his arm. (Once released, this force and acceleration cease, so the ball's path changes only due to gravity and effects of air resistance.)

A rocket is propelled upward by a force equal and opposite to the force with which gas is expelled out its back.
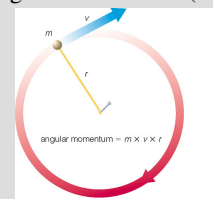
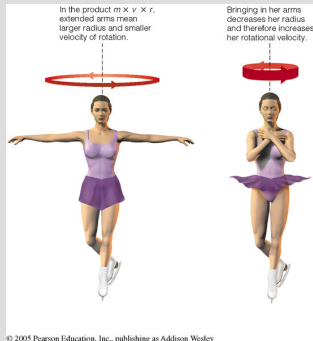© 2005 Pearson Education, Inc., publishing as Addison Wesley

Angular Momentum

- **angular momentum** – the momentum involved in spinning /circling = mass x velocity x radius
- **torque** – anything that can cause a change in an object's angular momentum (*twisting force*)

angular momentum = *m* × *v* × *r*

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Conservation of Angular Momentum

- In the absence of a net torque, the total angular momentum of a system remains constant.

In the product $m \times v \times r$, extended arms mean larger radius and smaller velocity of rotation.

Bringing in her arms decreases her radius and therefore increases her rotational velocity.

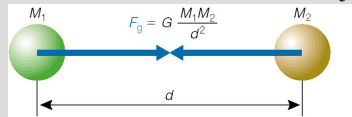© 2005 Pearson Education, Inc., publishing as Addison Wesley

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5.3 The Force of Gravity

Our goals for learning:

- What is the universal law of gravitation?
- What types of orbits are possible according to the law of gravitation?
- How can we determine the mass of distant objects?

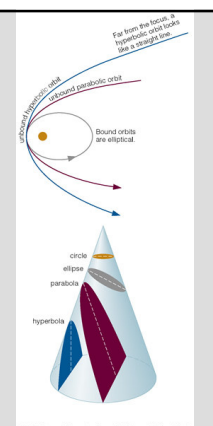
Universal Law of Gravitation

Between every two objects there is an attractive force, the magnitude of which is directly proportional to the mass of each object and inversely proportional to the square of the distance between the centers of the objects.

M_1 $F_g = G \dfrac{M_1 M_2}{d^2}$ M_2

d

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Orbital Paths

- Extending Kepler's Law #1, Newton found that ellipses were not the only orbital paths.
- possible orbital paths
  - ellipse (bound)
  - parabola (unbound)
  - hyperbola (unbound)

Far from the focus, a hyperbolic orbit looks like a straight line

unbound parabolic orbit

Bound orbits are elliptical.

circle
ellipse
parabola
hyperbola

Newton's Version of Kepler's Third Law

Using the calculus, Newton was able to derive Kepler's Third Law from his own Law of Gravity.

In its most general form:

$$P^2 = 4\pi^2\, a^3 / G\,(m_1 + m_2)$$

If you can measure the orbital period of two objects (P) and the distance between them (a), then you can calculate the sum of the masses of both objects ($m_1 + m_2$).

5.4 Tides

Our goals for learning:

- Why are there two high tides on Earth each day?
- Why are tides on Earth caused primarily by the Moon rather than by the Sun?
- Why is Earth's rotation gradually slowing down?
- Why does the Moon always show the same face to Earth?

Tides

tidal bulge opposite Moon   tidal bulge toward Moon

Not to scale! The real tidal bulge raises the oceans by only about 2 meters.

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- Since gravitational force decreases with (distance)^2, the Moon's pull on Earth is strongest on the side facing the Moon, and weakest on the opposite side.
- The Earth gets stretched along the Earth-Moon line.
- The oceans rise relative to land at these points.

Tides

- Every place on Earth passes through these points, called **high tides**, twice per day as the Earth rotates.
- High tides occur every 12 hours 25minutes
  - remember, the Moon moves!
- The Sun's tidal effect on Earth is not as strong.
  - the ratio Earth's diameter : distance to Sun is much less than ratio Earth's diameter : distance to Moon
- When the Sun & Moon pull in the same direction (new & full phases)
  - high tide is higher than usual (**spring**)
- When the Sun & Moon pull at right angles (first & last quarter phases)
  - high tide is lower than usual (**neap**)

neap tides   third-quarter moon   to Sun   first-quarter moon

spring tides   new moon   to Sun   full moon

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Tidal Friction

- This fight between Moon's pull & Earth's rotation causes friction.
- Earth's rotation slows down (1 sec every 50,000 yrs.)
- Conservation of angular momentum causes the Moon to move farther away from Earth.

net result: bulges slightly ahead of Earth-Moon line

Earth's rotation tries to pull bulges along.

Moon

tidal bulges if Earth didn't rotate

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Synchronous Rotation

- …is when the rotation period of a moon, planet, or star equals its orbital period about another object.
- Tidal friction on the Moon (caused by Earth) has slowed its rotation down to a period of one month.
- The Moon now rotates synchronously.
  - We always see the same side of the Moon.
- Tidal friction on the Moon has ceased since its tidal bulges are always aligned with Earth.

5.5 Orbital Energy and Escape Velocity

Our goals for learning:

- What is orbital energy?
- Will a spacecraft passing by a planet be "sucked in"?
- How can an object achieve escape velocity?

Changing Orbits

orbital energy = kinetic energy + gravitational potential energy

conservation of energy implies:

orbits can't change spontaneously

An object can't crash into a planet unless its orbit takes it there.

An orbit can only change if it gains/loses energy from another object, such as a gravitational encounter:

new orbit after Jupiter encounter

Jupiter

comet orbit before Jupiter encounter

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If an object gains enough energy so that its new orbit is unbound, we say that it has reached **escape velocity**.

What have we learned?

- Distinguish between speed, velocity, and acceleration.
  - Speed is the rate at which an object is moving. Velocity is speed in a certain direction. Acceleration is a change in velocity, meaning a change in either speed or direction.
- What is the acceleration of gravity?
  - The acceleration of an object falling to the ground because of gravity. On Earth's surface, it is 9.8 m/s^2.
- How does the acceleration of gravity depend on the mass of a falling object?
  - It does not. All falling objects fall with the same acceleration (on a particular planet).

What have we learned?

- How do you know when a net force is acting on an object?
  - A net force must be acting whenever the object's momentum is changing.
- Have you ever been weightless? Have you ever been massless?
  - You are weightless every time you jump, because you are in free-fall while in the air. You have never been massless, because mass is a basic property of the matter in your body.

What have we learned?

- What are Newton's three laws of motion?
  - (1) In the absence of a net force acting upon it, an object moves with constant velocity. (2) Force = rate of change in momentum (or F = ma). (3)For any force, there is always an equal and opposite reaction force.
- Why does a spinning skater spin faster as she pulls in her arms?
  - On ice, there is little friction and therefore little torque, so the skater's angular momentum is conserved as she spins. Pulling in her arms makes her "radius" smaller, so she must spin faster to keep the same angular momentum.

What have we learned?

- What is the universal law of gravitation?
  - The force of gravity is directly proportional to the product of the objects' masses and declines with the square of the distance between their centers.
- What types of orbits are possible according to the law of gravitation?
  - Objects may follow bound orbits in the shape of ellipses (or circles) and unbound orbits in the shape of parabolas or hyperbolas.
- How can we determine the mass of distant objects?
  - Newton's version of Kepler's third law allows us to calculate the mass of a distant object if it is orbited by another object, and we can measure the orbital distance and period.

What have we learned?

- Why are there two high tides on Earth each day?
  - The Moon's gravity stretches Earth along the Earth-Moon line, so that it bulges both toward and away from the Moon.
- Why are tides on Earth caused primarily by the Moon rather than by the Sun?
  - Earth's gravitational attraction to the sun is stronger than its gravitational attraction to the Moon, but tides are caused by the *difference* between the strength of the gravitational attraction across Earth's diameter. This difference is greater for the gravitational force due to the Moon, because the Moon is so much closer than the Sun.

What have we learned?

- Why is Earth's rotation gradually slowing down?
  - ✓Tidal friction, caused by the way the tidal bulges exert drag on Earth, causes a gradual slowing of Earth's rotation.
- Why does the Moon always show the same face to Earth?
  - ✓The Moon's synchronous rotation is a result of tidal forces. The Moon may once have rotated much faster, but tidal friction slowed its rotation until it became synchronous with its orbit, at which point tidal friction could not slow the orbit any further.

What have we learned?

- What is orbital energy?
  - It is the combined kinetic and gravitational potential energy of an orbiting object.
- Will a spacecraft passing by a planet be "sucked in"?
  - No. Energy must be conserved, so an object's orbital energy cannot change unless it gains or loses energy to something else.
- How can an object achieve escape velocity?
  - It must be given an orbit that is unbound so it will not return. It must be given enough energy to change a bound orbit to an unbound one.

Unique experiments can be carried out in the Space Station because of the lack of gravity.

1. Yes, and the Space Station was built in order to escape gravity.
2. This is not quite right - the Space Station still feels the effect of the Earth's gravity but it is greatly diminished and the experiments are therefore referred to as being performed in "micro-gravity."
3. No, the uniqueness of the experiments is not due to the lack of gravity but to weightlessness.
4. No, similar experiments can be performed on the surface of the Earth.
5. No, similar experiments can be performed on the highest mountaintops on Earth.

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How does the gravitational force between two objects change if the distance between them triples?

1. The force increases by a factor of three.
2. The force increases by a factor of nine.
3. The force remains the same.
4. The force decreases by a factor of three.
5. The force decreases by a factor of nine.

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3. The force remains the same.
4. The force decreases by a factor of three.
5. **The force decreases by a factor of nine.**

If you could go shopping on the Moon to buy a pound of chocolate, you'd get a lot more chocolate than if you bought a pound on Earth.

1. Yes, because of the lower gravity on the Moon, it would take more chocolate to weigh a pound than on Earth.
2. Yes, chocolate would have a lower density on the Moon and therefore more is needed to reach a pound in weight.
3. No, a pound on the Moon is the same as a pound on Earth.
4. No, chocolate weighs the same on the Moon as on Earth.
5. No, mass (and energy) are always conserved.

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I throw a baseball straight up into the air. At the highest point of its arc, the ball changes from going up to going down and is described by

1. Zero velocity for an instant with zero acceleration.
2. Zero velocity for an instant with 10m/s^2 acceleration.
3. Zero acceleration with a velocity of 10m/s.
4. A velocity which depends on how fast you threw it.
5. ?.

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2. **Zero velocity for an instant with 10m/s^2 acceleration.**
3. Zero acceleration with a velocity of 10m/s.
4. A velocity which depends on how fast you threw it.
5. ?.

My calculator rests on this table.

1. Yes, the calculator is weightless and stays on the table.
2. No, the calculator is floating and doesn't actually touch the table.
3. Yes, the calculator's weight exerts a force on the table, but Newton's third law is violated with no equal but opposite force.
4. Yes, but the calculator exerts no force on the table because the Earth attracts the table as well as the calculator.
5. Yes, the calculator exerts a force on the table, and the table does in fact exert an equal and opposite force on the calculator.

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The Sun's gravity binds the Earth to it in its elliptical orbit. If the Sun suddenly collapsed into a black hole, then

1. The Earth would get sucked into the hole.
2. The Earth would fly off out of its orbit and we would all die without the Sun's heat.
3. The Earth would continue in its current orbit, and we would all die without the Sun's heat.
4. Earth's orbit would change into a hyperbole.

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Lab and Labwork

A guide

Lab Work: Repeatability

- Labwork should be repeatable
- Hence, need to show every measurement (as opposed to every calculation)
- Measurements are sacred
- Measurements **must** have:
  - Units
  - Uncertainty

Lab Work: Comparison

- Comparison enters lab frequently and in different guises
  - determination of some constant…compare with accepted value
  - Multiple measurements of the same thing..compare with each other
- Compute percent difference or percent error

Lab Work: Judgment

- Unlike most of lecture, lab is about judgment
- We measure, observe, study, determine, investigate, but after any/all of that just left with those measurements
- What do the measurements mean? Need complete sentences to argue for something
  - Scientific argument—no deception, no sales, no bias
  - Your job to connect the measurements to a conclusion

Example: Height of Pell Hall

- Measured Angle: $\alpha = 58 \pm 3°$
- Measured Distance: $D = 5.00 \pm 0.01m$

- Computed Height:
$$H = (5.00m)(\tan 58°) = 8.0 \pm 0.4m$$
- Estimated Height:
$$H_{est} = (2\, floors)(10'/floor)(1m/3.28\, ft) = 6.1m$$
- Percent Difference of Heights:
$$\frac{8.0m - 6.1m}{\frac{1}{2}(8.0m + 6.1m)} 100\% = 27\%$$

Example: Height of Pell Hall

- What would you conclude?

Example: Height of Pell Hall

- What would you conclude?
- How about:
  - Testing the sextant by measuring the height of Pell Hall resulted in a 27% difference compared to an estimate of its height using 10' per floor. That the ground is not flat would necessarily skew our measurement of the distance D. However, this would not be sufficient to cause a 27% difference. Likewise, our measurement of the angle with the sextant is rather crude. Again however, this would likely be a small effect. Instead, what seems most likely is that our estimate of the height using 10' per floor is simply too crude to expect anything better than 27% difference. We should be able to expect accuracy better than that level for measurements with our sextant.

Example: Angular Size of the Moon

- Altitude of Top of Moon: $top = 58 \pm 1°$
- Altitude of Bottom of Moon: $bottom = 57 \pm 1°$

- Computed angular size:

$$ang.size = top - bottom = \left(58 \pm 1°\right) - \left(57 \pm 1°\right) = 1 \pm 2°$$

- % Error:

$$\frac{1° - 0.5°}{0.5°} 100\% = 100\%$$

Example: Angular Size of the Moon

- Judgment/Conclusion:
  - Our measurement of the angular size of the moon yielded a value (1 degree) quite different than the accepted value (0.5degree), with a 100% difference. This result is by no means evidence that the accepted value is wrong. Instead, it demonstrates that sextant lack the angular resolution to measurement such a small angular size.