Skating

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Observations about Skating

- When you’re at rest on a level surface,
  - without a push, you remain stationary
  - with a push, you start moving that direction
- When you’re moving on a level surface,
  - without a push, you coast steady & straight
  - with a push, you change direction or speed

4 Questions about Skating

1. Why does a stationary skater remain stationary?
2. Why does a moving skater continue moving?
3. Why does a skater need ice or wheels to skate?
4. How does a skater start or stop moving?

Question 1

Q: Why does a stationary skater remain stationary?
A: A body at rest tends to remain at rest

This observed behavior is known as inertia

Question 2

Q: Why does a moving skater continue moving?
A: A body in motion tends to remain in motion

This behavior is the second half of inertia

Newton’s First Law (Version 1)

An object that is free of external influences moves in a straight line and covers equal distances in equal times.

Note that a motionless object obeys this law!
**Question 3**

Q: Why does a skater need ice or wheels to skate?  
A: Real-world complications usually mask inertia  
Solution: minimize or overwhelm complications  
- To observe inertia, therefore,  
  - work on level ground (minimize gravity's effects)  
  - use wheels, ice, or air support (minimize friction)  
  - work fast (overwhelm friction and air resistance)

**Physical Quantities**

1. **Position** – an object’s location  
2. **Velocity** – its change in position with time  
   - Both are vector quantities:  
     - Position is distance and direction from a reference  
     - Velocity is speed and direction of motion

**Newton’s First Law (Version 2)**

An object that is free of external influences moves at a constant velocity.  
Note that a motionless object is “moving” at a constant velocity of zero!

**Physical Quantities**

3. **Force** – a push or a pull  
   - Force is another vector quantity:  
     - the amount and direction of the push or pull  
     - Net force is the vector sum of all forces on an object

**Newton’s First Law**

An object that is not subject to any outside forces moves at a constant velocity.

**Question 4**

Q: How does a skater start or stop moving?  
A: A net force causes the skater to accelerate!  
4. **Acceleration** – change in velocity with time  
5. **Mass** – measure of object’s inertia  
   - Acceleration is yet another vector quantity:  
     - the rate and direction of the change in velocity
**Newton’s Second Law**

An object’s acceleration is equal to the net force exert on it divided by its mass. That acceleration is in the same direction as the net force.

$$\text{acceleration} = \frac{\text{net force}}{\text{mass}}$$

Traditional form: \( \text{net force} = \text{mass} \cdot \text{acceleration} \)

\( F = ma \)

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**About Units**

- **SI or “metric” units:**
  - Position \( \rightarrow \) m \( (\text{meters}) \)
  - Velocity \( \rightarrow \) m/s \( (\text{meters-per-second}) \)
  - Acceleration \( \rightarrow \) m/s² \( (\text{meters-per-second}^2) \)
  - Force \( \rightarrow \) N \( (\text{newtons}) \)
  - Mass \( \rightarrow \) kg \( (\text{kilograms}) \)

- Newton’s second law relates the units:

\[ 1 \text{ m/s}^2 (\text{acceleration}) = \frac{1 \text{ N} (\text{net force})}{1 \text{ kg} (\text{mass})} \]

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**Summary about Skating**

- Skates can free you from external forces
- When you experience no external forces,
  - You coast – you move at constant velocity
  - If you’re at rest, you remain at rest
  - If you’re moving, you move steadily and straight
- When you experience external forces
  - You accelerate – you move at a changing velocity
  - Acceleration depends on force and mass

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**Observations about Falling Balls**

- When you drop a ball, it
  - begins at rest, but acquires downward speed
  - covers more and more distance each second
- When you tossed a ball straight up, it
  - rises to a certain height
  - comes momentarily to a stop
  - and then descends, much like a dropped ball
- A thrown ball travels in an arc

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**Falling Balls**

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**5 Questions about Falling Balls**

1. Why does a dropped ball fall downward?
2. Do different balls fall at different rates?
3. Would a ball fall differently on the moon?
4. Can a ball move upward and still be falling?
5. Does a ball's horizontal motion affect its fall?
Question 1

Q: Why does a dropped ball fall downward?
A: Earth’s gravity exerts a force on the ball

- That force is the ball’s weight
- That weight points toward earth’s center
- Its weight causes the falling ball to accelerate downward—toward earth’s center

Question 2

Q: Do different balls fall at different rates?
A: No, they all fall together!

A ball’s weight is proportional to its mass:

\[
\text{weight of ball} = 9.8 \text{ newtons} \times \frac{\text{mass of ball}}{\text{kilogram}}
\]

Their ratio is called “the acceleration due to gravity”

Question 3

Q: Would a ball fall differently on the moon?
A: Yes!

Moon’s acceleration due to gravity is 1.6 \text{ meters/second}^2

Question 4

Q: Can a ball move upward and still be falling?
A: Yes!

A falling ball experiences only its weight

- Its acceleration is constant and downward
- Its velocity increases in the downward direction

Ball’s initial velocity can be anything, even upward!

Acceleration Due to Gravity

- Why this strange name?

\[
\text{weight of ball} \times \frac{\text{mass of ball}}{\text{mass}} \rightarrow \text{force} \rightarrow \text{acceleration}
\]

- Acceleration due to gravity is an acceleration!

\[
9.8 \text{ newtons} \times \frac{\text{kilogram}}{\text{meter/second}^2} = 9.8 \text{ meter/second}^2
\]

- On earth’s surface, all falling balls accelerate downward at 9.8 meter/second^2

Falling Downward

- When dropped from rest,
  - ball’s velocity starts at zero and increases downward
  - ball’s altitude decreases at an ever faster rate

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</table>
**Falling Upward First**

- When thrown upward, ball’s velocity starts upward but increases downward.
- Ball’s altitude increases at an ever slower rate until...
- Velocity is momentarily zero then ball falls downward.

**Question 5**

Q: Does a ball’s horizontal motion affect its fall?

A: No. Ball falls vertically, but coasts horizontally.

- Ball’s acceleration is purely vertical (downward).
- It falls vertically.
- It coasts horizontally.
- Its path is a parabolic arc.

**Summary About Falling Balls**

- Without gravity, an isolated ball would coast.
- With gravity, an isolated ball experiences its weight, accelerates downward, and its velocity becomes increasingly downward.
- Whether going up or down, it’s still falling.
- It can coast horizontally while falling vertically.

**Ramps**

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**Observations About Ramps**

- It’s difficult to lift a heavy cart straight up.
- It’s easier to push a heavy cart up a ramp.
- That ease depends on the ramp’s steepness.
- Shallow ramps need gentler but longer pushes.

**4 Questions about Ramps**

1. Why doesn’t a cart fall through a sidewalk?
2. How does the sidewalk know how hard to push?
3. Why is it easy to push the cart up the ramp?
4. What physical quantity is the same for any ramp?
Question 1
Q: Why doesn’t a cart fall through a sidewalk?
A: The sidewalk pushes up on it and supports it

Sidewalk and cart cannot occupy the same space
Sidewalk exerts a support force on cart that
- prevents cart from penetrating sidewalk’s surface
- acts perpendicular to sidewalk’s surface \( \rightarrow \) upward
- balances cart’s downward weight

Question 2
Q: How does the sidewalk know how hard to push?
A: The sidewalk and cart negotiate

The cart and sidewalk dent one another slightly
- the more they dent, the harder they push apart
- cart accelerates up or down in response to net force
- cart bounces up and down during this negotiation
Cart comes to rest at equilibrium—zero net force

Newton’s Third Law
For every force that one object exerts on a second object, there is an equal but oppositely directed force that the second object exerts on the first object.

Misconception Alert
The forces two objects exert on one another must be equal and opposite, but each force of that Newton’s third law pair is exerted on a different object, so those forces do not cancel one another.

The Cart and Sidewalk Negotiate
If the cart and sidewalk dent one another too much,
- each one pushes the other away strongly
- they accelerate away from one another
If the cart and sidewalk dent one another too little,
- each one pushes the other away weakly (or not at all)
- they accelerate toward one another
If the cart and sidewalk dent one another just right,
- cart is in equilibrium (zero net force)

Question 3
Q: Why is it easy to push the cart up the ramp?
A: The ramp supports most of the cart’s weight

Net force on cart is the ramp force, which is small
Pushing the Cart up the Ramp

To start the cart moving uphill
- push cart uphill more than the downhill ramp force
- net force is uphill, so cart accelerates uphill

To keep the cart moving uphill
- push cart uphill just enough to balance ramp force
- cart continues uphill at constant velocity

To stop the cart moving uphill,
- push cart uphill less than the downhill ramp force
- net force is downhill, so cart accelerates downhill

Question 4

Q: What physical quantity is the same for any ramp?
A: The work you do lifting the cart a certain height

\[ \text{work} = \text{force} \cdot \text{distance} \]

(where force and distance are in same direction)

For a steep ramp: \( \text{work} = \text{Force} \cdot \text{Distance} \)
For a shallow ramp: \( \text{work} = \text{Force} \cdot \text{Distance} \)

Energy and Work

- **Energy** – a conserved quantity
  - it can’t be created or destroyed
  - it can be transformed or transferred between objects
  - is the capacity to do work
- **Work** – mechanical means of transferring energy
  \[ \text{work} = \text{force} \cdot \text{distance} \]
  (where force and distance are in same direction)

Transfers of Energy

- Energy has two principal forms
  - **Kinetic energy** – energy of motion
  - **Potential energy** – energy stored in forces
- Your work transfers energy from you to the cart
  - Your chemical potential energy decreases
  - Cart’s gravitational potential energy increases

Mechanical Advantage

- Mechanical advantage is doing the same work, using a different balance of force and distance
- A ramp provides mechanical advantage
  - You lift cart with less force but more distance
  - Your work is independent of the ramp’s steepness

Summary about Ramps

- Ramp supports most of the cart’s weight
- You do work pushing the cart up the ramp
- The ramp provides mechanical advantage
  - It allows you to push less hard
  - but you must push for a longer distance
  - Your work is independent of ramp’s steepness
Seesaws

Observations about Seesaws

- A balanced seesaw rocks back and forth easily
- Equal-weight children balance a seesaw
- Unequal-weight children don’t normally balance
- Moving heavier child inward restores balance
- Sitting closer to the pivot speeds up the motion

5 Questions about Seesaws

1. How does a balanced seesaw move?
2. Why does a seesaw need a pivot?
3. Why does a lone rider plummet to the ground?
4. Why do the riders’ weights and positions matter?
5. Why does distance from the pivot affect speed?
6. How do the riders twist each other?

Question 1

Q: How does a balanced seesaw move?
A: It moves at constant angular velocity
    …because the seesaw has rotational inertia!
    Newton’s first law of rotational motion
    A rigid object that’s not wobbling and that is free of outside torques rotates at constant angular velocity.

Physical Quantities

1. Angular Position – an object’s orientation
2. Angular Velocity – change in angular position with time
3. Torque – a twist or spin

- All three are vector quantities
  - Ang. Pos. is angle and rotation axis from reference
  - Ang. Vel. is angular speed and rotation axis
  - Torque is amount and rotation axis of twist or spin

Question 2

Q: Why does a seesaw need a pivot?
A: To prevent translational motion (i.e., falling)

- Pivot is placed at natural pivot—center of mass
- Pivot allows rotation, but not translation
**Question 3**

Q: Why does a lone rider plummet to the ground?
A: Torque on seesaw causes angular acceleration

- The weight of a lone rider produces a torque
  \[ \text{torque} = \text{lever arm} \times \text{force}_{\text{perp}} \]
  (where the lever arm is a vector from pivot to location of force)
- That torque would cause angular acceleration
- Seesaw’s angular velocity would change with time

**Physical Quantities**

4. Angular Acceleration – change in angular velocity with time
5. Rotational Mass – measure of rotational inertia

- Angular acceleration is another vector quantity:
  - The rate and rotation axis of change in ang. velocity

**Newton’s Second Law of Rotational Motion**

An object’s angular acceleration is equal to the net torque exerted on it divided by its rotational mass. The angular acceleration is in the same direction as the torque.

\[ \text{angular acceleration} = \frac{\text{net torque}}{\text{rotational mass}} \]

**Question 4**

Q: Why do the riders’ weights and positions matter?
A: Must balance seesaw—zero net torque

- Adding a second rider adds a second torque
  - The two torques act in opposite directions
  - If net torque due to gravity is zero, seesaw is balanced
- A rider’s torque is their weight times lever arm
  - A heavier rider should sit closer to the pivot
  - A lighter rider should sit farther from the pivot

**Question 5**

Q: Why does distance from the pivot affect speed?
A: Moving toward the pivot reduces rotational mass

- Lever arm is a vector from pivot to rider
- Gravitation torque is proportional to lever arm
- Rotational mass is proportional to lever arm²
- Angular acceleration is proportional to 1/lever arm
- Move toward pivot → faster angular accelerations

**Question 6**

Q: What twists does each rider experience?
A: A gravitational torque and one from other rider

- Each seesaw rider experiences torques about pivot
  - A gravitational torque produced by rider’s weight
  - A torque exert by the other rider
- When seesaw balances, those torques sum to zero
- Riders exert equal but opposite torques on one another
Newton’s Third Law of Rotational Motion
For every torque that one object exerts on a second, there is an equal but oppositely directed torque that the second object exerts on the first.

Summary about Seesaws
- Balanced seesaw: zero gravitational torque
- Balanced seesaw has constant angular velocity
- Net torque causes angular acceleration of seesaw
- Heavier riders need smaller lever arms
- Lighter riders need larger lever arms

Wheels
Turn off all electronic devices

Observations about Wheels
- Friction makes wheel-less objects skid to a stop
- Friction can waste energy and cause wear
- Wheels mitigate the effects of friction
- Wheels can also propel vehicles

5 Questions about Wheels
1. Why does a wagon need wheels?
2. Why is sliding a box hardest at the beginning?
3. What happens to energy as a box skids to rest?
4. How do wheels help a wagon coast?
5. What energy does a wheel have?

Question 1
Q: Why does a wagon need wheels?
A: Friction opposes a wheel-less wagon’s motion

Frictional forces
- oppose relative sliding motion of two surfaces
- act along the surfaces to bring them to one velocity
- come in Newton’s third law pairs
Question 2

Q: Why is sliding a box hardest at the beginning?
A: Static friction is stronger than sliding friction.

Static friction opposes the start of sliding
- varies in amount from zero to a maximum value
Sliding friction opposes ongoing sliding
- has a constant value proportional to support force
Static friction’s maximum exceeds sliding friction

Question 3

Q: What happens to energy as a box skids to rest?
A: That energy becomes thermal energy.

Only sliding friction wastes energy
- The two surfaces travel different distances
- The missing work becomes thermal energy
- The surfaces also experience wear

The Many Forms of Energy

- Kinetic: energy of motion
- Potential: stored in forces between objects
  - Gravitational
  - Magnetic
  - Electrochemical
  - Nuclear
- Thermal energy: disorder into tiny fragments
  - Reassembling thermal energy is statistical impossible

Question 4

Q: How do wheels help a wagon coast?
A: Wheels can eliminate sliding friction.

Wheels & roller bearings eliminate sliding friction
- rollers eliminate sliding friction, but don’t recycle
- simple wheels have sliding friction at their hub/axle
- combining roller bearings with wheels is ideal

Practical Wheels

- Free wheels are turned by the vehicle’s motion
- Powered wheels propel the vehicle as they turn.
**Question 5**

Q: What energy does a wheel have?
A: Kinetic energy, both translation and rotational.

For a translating wheel:
\[ \text{kinetic energy} = \frac{1}{2} \cdot \text{mass} \cdot \text{speed}^2 \]

For a rotating wheel:
\[ \text{kinetic energy} = \frac{1}{2} \cdot \text{rotational mass} \cdot \text{angular speed}^2 \]

The wheel of a moving vehicle has both!

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**Summary about Wheels**

- Sliding friction wastes energy
- Wheels eliminate sliding friction
- A vehicle with wheels coasts well
- Free wheels are turned by static friction
- Powered wheels use static friction to propel car

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**Observations about Bumper Cars**

- Moving cars tend to stay moving
- Changing a car’s motion takes time
- Impacts alter velocities and angular velocities
- Cars often appear to exchange their motions
- The fullest cars are the hardest to redirect
- The least-full cars get slammed during collisions

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**Bumper Cars**

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**3 Questions about Bumper Cars**

1. Does a moving bumper car carry a force?
2. Does a spinning bumper car carry a torque?
3. How does a car accelerate on an uneven floor?

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**Question 1**

Q: Does a moving bumper car carry a force?
A: No, the bumper car carries momentum.

Momentum is a conserved vector quantity
- can’t be created or destroyed, but can be transferred
- combines bumper car’s inertia and velocity
\[ \text{momentum} = \text{mass} \cdot \text{velocity} \]
### Exchanging Momentum

- Bumper cars exchange momentum via impulses
  \[ \text{impulse} = \text{force} \cdot \text{time} \]
- When car_1\ gives an impulse to car_2, car_2\ gives an equal but oppositely directed impulse to car_1.
  - The total momentum doesn’t change
  - Car with least mass changes velocity most,
  - so the littlest riders get creamed

### Question 2

Q: Does a spinning bumper car carry a torque?
A: No, the bumper car carries angular momentum

Angular momentum is a conserved vector quantity
- can’t be created or destroyed, but can be transferred
- combines bumper car’s rotational inertia and velocity
  \[ \text{angular momentum} = \text{rotational mass} \cdot \text{angular velocity} \]

### Exchanging Angular Momentum

- Bumper cars exchange angular momentum via angular impulses
  \[ \text{angular impulse} = \text{torque} \cdot \text{time} \]
- When car_1\ gives an angular impulse to car_2, car_2\ gives an equal but oppositely directed angular impulse to car_1.
  - The total angular momentum doesn’t change
  - Car with least rot. mass changes ang. velocity most.
  - so the littlest riders get spun wildly

### Rotational Mass can Change

- Mass can’t change, so the only way an object’s velocity can change is if its momentum changes
- Rotational mass can change, so an object that changes shape can change its angular velocity without changing its angular momentum

### Question 3

Q: How does a car accelerate on an uneven floor?
A: It reduces potential energy as quickly as possible

- Forces and potential energies are related!
  - A bumper car accelerates in the direction that reduces its total potential energy as quickly as possible
  - On an uneven floor, that is down the steepest slope

### Summary about Bumper Cars

- During collisions, bumper cars exchange
  - momentum via impulses
  - angular momentum via angular impulses
- Collisions have less effect on
  - cars with large masses
  - cars with large rotational masses
Observations about Spring Scales

- They move downward during weighing
- They take a little time to settle
- They're only accurate when everything is at rest

4 Questions about Spring Scales

1. What exactly is a spring scale measuring?
2. How does a spring scale measure weight?
3. What is the scale’s dial or meter actually reporting?
4. Why must you stand still on a spring scale?

Question 1

Q: What exactly is a spring scale measuring?
A: The weight of the object being weighed

- The object has both a mass and a weight
- On the earth’s surface, they are proportional
  - Object’s mass is the same everywhere
  - Object’s weight changes with changes in gravity

Mass as a Measure

- An object’s mass doesn’t depend on location
- Measuring an object’s mass can be done directly:
  - Exert a known force on the object
  - Measure the object’s acceleration
  - Divide the force by the acceleration to find the mass
- Measuring acceleration accurately is difficult

Weight as a Measure

- An object’s weight depends on location (gravity)
- Measuring an object’s weight is done indirectly:
  - The object’s weight is a force that acts on the object
  - There is no direct way to measure that weight
- Fortunately, measuring weight indirectly is easy
- Spring scales measure weight, not mass
Question 2
Q: How does a spring scale measure weight?
A: Measures upward force needed for equilibrium
- Spring scale measures weight using equilibrium
  - Exert an upward force on the object
  - Adjust that force until the object is in equilibrium
  - Measure the amount of that upward force
  - Report that amount as the object’s weight

Using a Spring to Measure Weight
- Springs provide adjustable, measurable forces
- Recall that when an object is at equilibrium, individual forces sum to zero—they cancel perfectly.
  - object is inertial—it remains motionless or it coasts.
- A spring scale
  - uses a spring to support the object
  - allows the spring and object to reach equilibrium
  - reports the spring’s force as the object’s weight

Question 3
Q: What is scale’s dial or meter actually reporting?
A: It’s reporting how far the spring has distorted
- A free spring adopts its equilibrium length
- When distorted, its ends experience forces that
  - act to restore the spring to its equilibrium length
  - make the equilibrium length a stable equilibrium
  - are proportional to the distortion

Hooke’s Law
The restoring force on the end of a spring is equal to a spring constant times the distance the spring is distorted. That force is directed opposite the distortion.
restoring force = – spring constant · distortion

A Spring Scale
- To weigh an object with a spring scale,
  - support the object with a spring,
  - let the object become motionless at equilibrium,
  - and measure the distortion of the spring.
- The spring constant relates distortion to force
- Once the spring constant is calibrated, reporting the spring’s distortion is equivalent to reporting the restoring force that is supporting the object

Question 4
Q: Why must you stand still on a spring scale?
A: Scale is only accurate if you are in equilibrium
- If you are not in equilibrium,
  - the spring force is unrelated to your weight
- Since an accelerating object is not at equilibrium,
  - you mustn’t bounce on a scale!
  - you must wait for the scale to settle before reading!
Oscillation
- When you first load a scale, it bounces
  - It accelerates toward a new equilibrium
  - It then coast through that equilibrium
  - It then accelerates back toward the new equilibrium
  - It returns and overshoots many times
- It oscillates around its stable equilibrium
  - To settle at equilibrium, it must get rid of energy
  - Friction and air resistance help it settle

Summary about Spring Scales
- The spring stretches during weighing
- This stretch is proportional to object's weight
- The scale measures the spring's stretch
- The scale reports that stretch as object's weight

Ball Sports: Bouncing
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Observations about Bouncing Balls
- Some balls bounce better than others
- Dropped balls don’t rebound to their full height
- Balls bounce differently from different surfaces
- Ball bounce differently from moving objects

4 Questions about Bouncing Balls
1. Why doesn’t a ball rebound to its original height?
2. Why does the floor’s surface affect the bounce?
3. How does a moving bat drive a ball forward?
4. What happens to the bat when a ball hits it?

Question 1
Q: Why doesn’t a ball rebound to its original height?
A: It wastes some of its energy during the bounce
  - While slowing as it hits a rigid floor, a ball’s
    - kinetic energy decreases by the collision energy
    - elastic potential energy increases as it dents
  - While rebounding from the floor, the ball’s
    - elastic potential energy decreases as it undents
    - kinetic energy increases by the rebound energy
  - Not all collision energy becomes rebound energy
Measuring a Ball’s Liveliness

- Two common measures of a ball’s liveliness:
  - rebound speed
  - coefficient of restitution
  - energy ratio

- Since kinetic energy is proportional to speed²,
  - energy ratio = coefficient to frestitution²

Question 2

Q: Why does the floor’s surface affect the bounce?
A: If the floor dents, it also receives collision energy

- The denting floor stores and returns energy
- Floor also has an energy ratio that affects the bounce
- Impact forces on ball & floor: equal but opposite,
  - so work done on each is proportional to its dent
  - fraction of collision energy is proportional to its dent
- A soft, lively floor can help the ball bounce!

Question 3

Q: How does a moving bat drive a ball forward?
A: Ball bounces off bat, in bat’s frame of reference

- When bat and ball are moving toward one another
  - Collision speed is their speed of approach
  - Rebound speed is their speed of separation
- In the bat’s inertial frame of reference,
  - perspective in which bat's center of mass is motionless,
  - the ball simply bounces off the bat

Ball and Bat (Part 1)

- Ball heads toward home plate at 100 km/h
- Bat heads toward pitcher at 100 km/h
- Collision speed is 200 km/h

Ball and Bat (Part 2)

- Collision speed is 200 km/h
- Baseball’s coefficient of restitution: 0.55
- Rebound speed is 110 km/h

Ball and Bat (Part 3)

- Rebound speed is 110 km/h
- Bat heads toward pitcher at 100 km/h
- Ball heads toward pitcher at 210 km/h
Question 4

Q: What happens to the bat when a ball hits it?
A: It accelerates, angular accelerates, and vibrates
- The ball's impact force on the bat
  - transfers momentum and angular mom to the bat
  - can deform the bat, causing it to vibrate
  - increases with the stiffnesses of the bat and ball
  - lasts longer when the bat and ball are livelier

Summary about Bouncing Balls
- Each ball has a coefficient of restitution
- Energy lost in a bounce becomes thermal
- The bouncing surface can affect a ball's bounce
- Surfaces bounce, too

Carousels and Roller Coasters

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Observations about Carousels and Roller Coasters
- You can feel your motion with your eyes closed
- You feel pulled in unusual directions
- You sometimes feel weightless
- You can become inverted without feeling it

5 Questions about Carousels and Roller Coasters
1. What aspects of motion do you feel?
2. Why do you feel flung outward on a carousel?
3. Why do you feel light as a roller coaster dives?
4. Why do you feel heavy as a roller coaster turns?
5. How do you stay seated on a loop-the-loop?

Question 1

Q: What aspects of motion do you feel?
A: You feel acceleration, but not velocity
- This feeling of acceleration is not a real force
  - It's just a sensation caused by your body's inertia
  - It's directed opposite your acceleration
  - It's proportional to that acceleration
- You feel an overall apparent weight:
  - feeling of real weight plus feeling of acceleration
The Feeling of Weight

- When you are at equilibrium, a support force balances your weight and that support force acts on your lower surface, while your weight is spread throughout your body.
- You feel internal supporting stresses.
- You identify these stresses as weight.

The Feeling of Acceleration

- When you are accelerating, a support force causes your acceleration and that support force acts on your surface, while your mass is spread throughout your body.
- You feel internal supporting stresses.
- You misidentify these stresses as weight.

Question 2

Q: Why do you feel flung outward on a carousel?
A: You are accelerating inward on the carousel.
- Riders undergo uniform circular motion.
  - They follow a circular path at constant speed.
  - They are accelerating toward the circle’s center.
  - This acceleration depends on speed and circle size.

\[
\text{acceleration} = \frac{\text{velocity}^2}{\text{radius}}
\]

Carousels (Part 2)

- The acceleration of uniform circular motion is a center-directed or centripetal acceleration.
- Caused by a center-directed or centripetal force.
- A centripetal acceleration gives rise to a feeling of acceleration that points away from the center of motion and is a sensation due to inertia, not a real force.
- This feeling is often called “centrifugal force.”

Question 3

Q: Why do you feel light as a roller coaster dives?
A: Your feeling of acceleration is upward.
- As you dive down a hill, your acceleration is downhill.
- Your feeling of acceleration is uphill.
- Your apparent weight is weak and points down & back.

Question 4

Q: Why do you feel heavy as a roller coaster turns?
A: Your feeling of acceleration is outward.
- As you turn at high speed, your acceleration is inward.
- Your feeling of acceleration is outward.
- Your apparent weight is strong and points out & down.
Question 5
Q: How do you stay seated on a loop-the-loop?
A: You are accelerating downward very rapidly
- At you arc through the top of the loop-the-loop,
  - your acceleration is strongly downward
  - your feeling of acceleration is strongly upward
  - your apparent weight points upward!

Choosing a Seat
- As you go over cliff-shaped hills,
  - acceleration is downward
  - feeling of acceleration is upward
- The faster you dive over the first hill,
  - the greater the downward acceleration
  - the stronger the upward feeling of acceleration
- First car dives slowly – weak weightlessness
- Last car dives quickly – strong weightlessness!

Summary about Carousels and Roller Coasters
- You are often accelerating on these rides
- You experience feelings of acceleration
- Those feelings point opposite your acceleration
- Your apparent weight can
  - become larger or smaller than your real weight
  - point at any angle
  - can even point upward!

Bicycles
Turn off all electronic devices

Observations about Bicycles
- They are hard to keep upright while stationary
- They stay upright easily while moving forward
- They require leaning during turns
- They can usually be ridden without hands

5 Questions about Bicycles
1. Why is a stationary tricycle so stable?
2. Why is stationary bicycle so unstable?
3. Why does a moving tricycle flip during turns?
4. Why must you lean a bicycle during turns?
5. Why can you ride a bicycle without hands?
**Question 1**

Q: Why is a stationary tricycle so stable?
A: The tricycle is in a stable equilibrium
- **Stable equilibrium** has restoring influences
  - that tend to return tricycle to equilibrium
- If center of gravity is above base of support,
  - its gravitational potential energy increases as it tips,
  - it accelerates in the direction opposite that tip,
  - and it tends to return to the stable equilibrium.

**Question 2**

Q: Why is stationary bicycle so unstable?
A: The bicycle is in an unstable equilibrium
- **Unstable equilibrium** has destabilizing influences
  - that tend to tip bicycle away from equilibrium
- If center of gravity is above line of support,
  - its gravitational potential energy decreases as it tips,
  - it accelerates in the direction of that tip,
  - and it tends to tip away from the unstable equilibrium.

**Question 3**

Q: Why does a moving tricycle flip during turns?
A: Inertial effects overwhelm its static stability
- During a turn, wheels accelerate to the inside
  - but upright rider is almost inertial (coasts forward),
  - so tricycle and rider begin to tip.
  - Restoring influences arise but they’re too weak,
  - so tricycle and rider tip over.
  - Tricycle drives out from under center of gravity
  - Tricycle is dynamically unstable

**Question 4**

Q: Why must you lean a bicycle during turns?
A: To balance inertial effects with static instability
- During a turn, the wheels accelerate to the inside
  - and leaning rider accelerates to the inside
  - so the rider and bicycle turn together safely.
  - Bicycle drives under rider’s center of gravity
  - Bicycle is dynamically stable

**Question 5**

Q: Why can you ride a bicycle without hands?
A: It automatically steers under center of gravity
- When bicycle begins to lean, it steers because
  - the fork pivots to reduce total potential energy
  - ground’s torque on front wheel causes precession
- A forward-moving bicycle that begins to tip
  - automatically returns to its unstable equilibrium,
  - and thus exhibits wonderful dynamic stability

**Summary about Bicycles**

- **Tricycles**
  - have static stability
  - but inertial effects can flip tricycles during turns
- **Bicycles**
  - are statically unstable
  - can lean during turns to avoid flipping
  - automatically steer back to unstable equilibrium
  - have remarkable dynamic stability
Rockets

Turn off all electronic devices

Observations about Rockets

- Rockets seem to ride torch-like flames
- Rockets can accelerate straight up
- Rockets can go very fast
- The flame only touches the ground initially
- Rockets can apparently operate in empty space
- Rockets usually fly nose-first

6 Questions about Rockets

1. What pushes a rocket forward?
2. How does the rocket use gas to obtain thrust?
3. What keeps a rocket pointing forward?
4. What limits a spaceship's speed, if anything?
5. Once in space, does a spaceship have a weight?
6. What makes a spaceship orbit the earth?

Question 1

Q: What pushes a rocket forward?
A: It's gaseous exhaust pushes it forward
- A rocket's momentum is initially zero
- That momentum is redistributed during thrust
  - Ship pushes on fuel; fuel pushes on ship
  - Fuel (now exhaust) acquires backward momentum
  - Ship acquires forward momentum
  - Rocket's total momentum remains zero

\[
\text{momentum}_{\text{ship}} + \text{momentum}_{\text{fuel}} = 0
\]

Question 2

Q: How does the rocket use gas to obtain thrust?
A: Redirects gas's thermal motion into a directed jet
- Combustion produces hot, high-pressure gas
- This gas speeds up in a de Laval nozzle
- Gas reaches sonic speed in the nozzle's throat
- Beyond the throat, supersonic gas expands to speed up further

Rocket Propulsion

- The ship and fuel have opposite momentums
- The ship’s final momentum is
  \[
  \text{momentum}_{\text{ship}} = -\text{momentum}_{\text{fuel}} = -\text{mass}_{\text{fuel}} \cdot \text{velocity}_{\text{fuel}}
  \]
- The greater the fuel mass and backward velocity, the greater the ship’s forward momentum
Question 3
Q: What keeps a rocket pointing forward?
A: That depends on where the rocket is located
- On the ground, a rocket needs static stability
- In the air, a rocket needs aerodynamic stability
- Center of aerodynamic forces behind center of mass
- In space, a spaceship is a freely rotating object
- Orientation governed by angular momentum
- Small rockets are used to exert torques on spaceship
- Spaceship’s orientation doesn’t affect its travel

Question 4
Q: What limits a spaceship’s speed, if anything?
A: The rocket’s fuel to spaceship ratio
- Spaceship’s ultimate speed increases as the ratio of fuel mass to ship mass increases
- the fuel exhaust speed increases
- If fuel were released with the rocket at rest,

\[ v_{\text{ship}} = -\frac{\text{mass}_{\text{fuel}}}{\text{mass}_{\text{ship}}} \cdot v_{\text{fuel}} \]

Ship’s Ultimate Speed
- But because rocket accelerates during thrust,

\[ v_{\text{ship}} = -\log\left(\frac{\text{mass}_{\text{ship}} + \text{mass}_{\text{fuel}}}{\text{mass}_{\text{ship}}}\right) \cdot v_{\text{fuel}} \]

Question 5
Q: Once in space, does a spaceship have a weight?
A: Yes, but less than at ground level
- Earth’s acceleration due to gravity
  - constant for small changes in height at ground level
  - decreases at large altitudes
- Actual weight of a spaceship at any altitude is
  \[ \text{weight} = \frac{\text{gravitational constant} \cdot \text{mass}_{\text{ship}} \cdot \text{mass}_{\text{earth}}}{(\text{distance between centers of ship and earth})^2} \]

Law of University Gravitation
Two masses attract one another with gravitational forces equal in amount to the gravitational constant times the product of their masses, divided by the square of their separation.

\[ \text{force} = \frac{\text{gravitational constant} \cdot \text{mass}_1 \cdot \text{mass}_2}{(\text{distance between masses})^2} \]

Question 6
Q: What makes a spaceship orbit the earth?
A: An orbiting spaceship falls, but misses the earth
Orbits

- An object that starts with a sideways velocity
  - can miss the earth as it falls
  - follows a trajectory called an orbit
- Orbits can be
  - closed loops: circles and ellipses
  - open arcs: parabolas and hyperbolas
- Minimum speed for low-earth orbit
  - is about 28,000 km/h (17,400 mph)
  - requires far more thrust than merely reaching space

Summary About Rockets

- A rocket’s fuel (as exhaust) pushes it forward
- Total rocket impulse is basically the product of exhaust speed times exhaust mass
- Rockets can be stabilized aerodynamically
- Rockets can be stabilized by thrust alone
- After engine burn-out, spaceships can orbit

Observations about Balloons

- Balloons are held taut by the gases inside
- Some balloon float in air while others don’t
- Hot-air balloons don’t have to be sealed
- Helium balloons leak even when sealed

5 Questions about Balloons

1. How does air inflate a rubber balloon?
2. Why doesn’t the atmosphere fall or collapse?
3. Why does the atmosphere push up on a balloon?
4. Why does a hot air balloon float in cold air?
5. Why does a helium balloon float in air?

Question 1

Q: How does air inflate a rubber balloon?
A: Its pressure pushes the balloon’s skin outward

- Air is a gas: individual atoms and molecules
- Air has pressure: it exerts a force on a surface
- Pressure inside a balloon is greater than outside
  - Total pressure forces on balloon skin are outward
  - Balloon is held taut by those outward pressure forces
**Air and Pressure**

- Air consists of individual atoms and molecules
- Thermal energy keeps them separate and in motion
- Air particles bounce around in free fall, like tiny balls
- Air particles transfer momentum as they bounce
  - Each momentum transfer involves tiny forces
  - A surface exposed to air experiences a force
  - The force on a surface is proportional to its area
  - The force per area is the air’s **pressure**

**Pressure Imbalances**

- Balanced pressures exert no overall force
  - Pressure forces on two sides of a surface are balanced
  - Overall pressure force on that surface is zero
- Unbalanced pressures exert an overall force
  - Pressure forces on two sides of a surface don’t balance
  - Overall pressure force on that surface is non-zero
  - Imbalance pushes surface toward the lower pressure
  - Unbalanced pressures affect the air itself
  - The air is pushed toward lower pressure

**Question 2**

Q: Why doesn’t the atmosphere fall or collapse?
A: A gradient in its pressure supports its weight
  - Air has a **density**: it has mass per volume
  - Air’s pressure is proportional to its density
  - Air’s density gives it a weight per volume
  - The atmosphere is in equilibrium
    - Its density and pressure decrease with altitude
    - The resulting pressure imbalances support its weight

**Air and Density**

- Squeezing air particles more closely together
  - Increases the air’s density: its mass per volume
  - Increases the air’s pressure: its force per area
  - Increases the air’s weight per volume

**The Atmosphere**

- Supporting its weight structures the atmosphere
  - A pressure imbalance supports each layer’s weight
  - Air pressure decreases with altitude, a **pressure gradient**
  - Each layer supports all of the air above it
  - Net force on each layer is zero
  - The atmosphere is in stable equilibrium

**Question 3**

Q: Why does the atmosphere push up on a balloon?
A: Its pressure gradient pushes the balloon upward
  - Because of atmospheric structure, air pressure is
    - Stronger near the bottom of a balloon,
    - Weaker near the top of the balloon,
    - So the air pushes up harder than it pushes down,
    - And this imbalance yields an upward buoyant force
  - The atmosphere pushes upward on the balloon!
**Archimedes’ Principle**

A balloon immersed in a fluid experience an upward buoyant force equal to the weight of the fluid it displaces.

---

**Question 4**

Q: Why does a hot air balloon float in cold air?
A: It weighs less than the air it displaces.
- As the temperature of air increases, its particles move faster, bounce harder, and bounce more often.
- Contribute more to air’s pressure.
- A balloon filled with hot air at ordinary pressure contains fewer particles than the air it displaces.
- Weighs less than the air it displaces.
- Experiences a buoyant force that exceeds its weight.

---

**An Aside About Temperature**

- Air’s temperature on a conventional scale is related to average thermal kinetic energy per particle.
- Air’s temperature on an absolute scale is proportional to average thermal kinetic energy per part.
- SI unit of absolute temperature: kelvins or K.
  - 0 K is absolute zero: no thermal energy available.
  - Step size: 1 K step same as 1 °C step.
  - Room temperature is approximately 300 K.

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**Question 5**

Q: Why does a helium balloon float in air?
A: It weighs less than the air it displaces.
- Compared with air, the particles in helium gas are lighter, but move faster and bounce more often.
- Contribute just as much to pressure.
- A balloon filled with helium at ordinary pressure contains as many particles as the air it displaces.
- Weighs less than the air it displaces.
- Experiences a buoyant force that exceeds its weight.

---

**Pressure and Particle Density**

- Particle density: particles per volume.
- Particles in a gas contribute equally to pressure.
  - Lower-mass particles move faster and bounce more, so all the effects of particle mass cancel out.
- Gases with equal particle densities and equal temperatures have equal pressures.

---

**The Ideal Gas Law**

Is a summary relationship for gases:

\[
\text{pressure} = \text{Boltzmann constant} \cdot \text{particle density} \cdot \text{absolute temperature}
\]

- It assumes perfectly independent particles.
- While real gas particles aren’t perfectly independent, this law is a good approximation for real gases.
Summary about Balloons

- A balloon will float if its average density is less than that of the surrounding air
- A hot-air balloon has a lower particle density and a lower density than the surrounding air
- A helium balloon has the same particle density but a lower density than the surrounding air

Water Distribution

- Turn off all electronic devices

Observations about Water Distribution

- Water is pressurized in the pipes
- Higher pressure water can spray harder
- Higher pressure water can spray higher
- Water is often stored in tall water towers

4 Questions about Water Distr.

1. Why does water move through level pipes?
2. How can you produce pressurized water?
3. Where does the work you do pumping water go?
4. As water flows, what happens to its energy?

Question 1

Q: Why does water move through level pipes?
A: It accelerates toward lower pressure

- Water, like all fluids, obeys Newton’s laws
- When water experiences zero net force, it coasts
- When water experiences a net force, it accelerates
- Pressure imbalances exert net forces on water
- Water accelerates toward lower pressure

Question 2

Q: How can you produce pressurized water?
A: Push inward on the water, using a surface

- To pressurize water, confine it and squeeze
- As you push inward on the water,
- it pushes outward on you (Newton’s third law).
- Water’s outward push is produced by its pressure,
- so the water’s pressure rises as you squeeze it harder.
- Water (a liquid) is incompressible
- Its volume remains constant as its pressure increases
Pumping Water (no gravity)

- To deliver pressurized water to a pipe,
- squeeze water to increase its pressure
- until that pressure exceeds the pressure in the pipe.
- The water will then accelerate toward the pipe
- and pressurized water will flow into the pipe!

Gravity Causes Pressure Gradients

- Like air in the atmosphere, water in a pipe
- has a density and a weight per volume
- has a pressure gradient when it is at equilibrium
- Its pressure decreases with altitude
- That pressure gradient supports its weight
- Water has gravitational potential energy (GPE)
- Its GPE increases with altitude

Pumping Requires Work

- You do work as you pump water into the pipe
- You squeeze the water inward – the force,
- and the water moves inward – the distance.
- The work you do pumping water is:
  \[ \text{work} = \text{pressure} \cdot \text{volume} \]
- The pressurized water carries your work with it
- We'll call this work pressure potential energy

Question 3

Q: Where does the work you do pumping water go?
A: To the water at the delivery-end of the pipe
- Pressure potential energy is unusual because
  - it's not really stored in the pressurized water,
  - it's promised by the water's pressure source.
- In steady state flow (SSF),
  - which is steady flow in motionless surroundings,
  - promised energy is as good as stored energy,
  - so pressure potential energy (PPE) is meaningful.

Question 4

Q: As water flows, what happens to its energy?
A: That energy is converted between several forms
- In SSF, water flows along streamlines
- Water flowing along a single streamline in SSF
  - has both PPE and kinetic energy (KE),
  - must have a constant total energy per volume,
  - and obeys Bernoulli’s equation (no gravity):
    \[ \frac{\text{PPE}}{\text{Volume}} + \frac{\text{KE}}{\text{Volume}} = \text{Constant} \]
- Energy and Bernoulli (with gravity)
  - Water flowing along a single streamline in SSF
    - has PPE, KE, and GPE,
    - must have a constant total energy per volume,
    - and obeys Bernoulli’s equation (with gravity)
      \[ \frac{\text{PPE}}{\text{Volume}} + \frac{\text{KE}}{\text{Volume}} + \frac{\text{GPE}}{\text{Volume}} = \text{Constant} \]
Energy Transformations (part 1)

- As water flows upward in a uniform pipe,
  - its speed can’t change (a jam or a gap would form),
  - so its gravitational potential energy increases
  - and its pressure potential energy decreases.
- As water flows downward in a uniform pipe,
  - its speed can’t change,
  - so its gravitational potential energy decreases
  - and its pressure potential energy increases.

Energy Transformations (part 2)

- As water rises upward from a fountain nozzle,
  - its pressure stays constant (atmospheric),
  - so its gravitational potential energy increases
  - and its kinetic energy decreases.
- As water falls downward from a spout,
  - its pressure stays constant (atmospheric),
  - so its gravitational potential energy decreases
  - and its kinetic energy increases.

Energy Transformations (part 3)

- As water sprays horizontally from a nozzle,
  - its height is constant,
  - so its kinetic energy increases
  - and its pressure potential energy decreases.
- As a horizontal stream of water hits a wall,
  - its height is constant,
  - so its kinetic energy decreases
  - and its pressure potential energy increases.

Summary about Water Distribution

- Water’s energy remains constant during SSF
- Water’s energy changes form as it
  - flows upward or downward inside pipes,
  - rises or falls in open sprays,
  - and shoots out of nozzles or collides with objects.
- Water distribution can driven by
  - pressurized water (PPE)
  - elevated water (GPE)
  - fast-moving water (KE)

Observations about Garden Watering

- Faucets let you to control water flow
- Faucets can make noise when open
- Longer, thinner hoses deliver less water
- Water sprays at high speed from a nozzle
- Water only sprays so high
- A jet of water can push things over

Garden Watering

Turn off all electronic devices
6 Questions about Garden Watering

1. How does a faucet control flow?
2. How much does the diameter of a hose matter?
3. Why does water pour gently from an open hose?
4. Why does water spray fast from a nozzle?
5. What causes hissing in a faucet, hose, or nozzle?
6. Why do pipes rattle when you close the faucet?

Question 1

Q: How does a faucet control flow?
A: Water’s energy and viscosity limit the flow
- Water traverses a narrow passage in the faucet
- Total energy limits flow speed through passage
  - The water turns its total energy into kinetic energy,
  - but its peak speed is limited by its initial pressure
- Motion near surfaces slows water in the passage
  - Because water at the passage walls is stationary,
  - viscous forces within the water slow all of it

Viscous Forces and Viscosity

- Viscous forces
  - oppose relative motion within a fluid
  - and are similar to sliding friction: they waste energy
- Fluids are characterized by their viscosities
  - the measure of the strength of the viscous forces
  - and caused by chemical interactions within the fluids

Question 2

Q: How much does the diameter of a hose matter?
A: It matters a surprisingly large amount
- Water flow through a hose is proportional to
  - pressure difference between hose ends
  - 1/viscosity
  - 1/hose length
  - (hose diameter)^4
flow rate = \( \frac{\pi \cdot \text{pressure difference} \cdot \text{hose diameter}^4}{128 \cdot \text{hose length} \cdot \text{viscosity}} \)

Question 3

Q: Why does water pour gently from an open hose?
A: The free-flowing water wastes most of its energy
- Viscous effects in the hose
  - waste water’s total energy as thermal energy
  - and become stronger with increased flow speed
- Increasing the speed of the flow in the hose
  - increases the energy wasted by each portion of water
  - makes the loss of pressure more rapid

Question 4

Q: Why does water spray fast from a nozzle?
A: The nozzle causes water to turn PPE into KE
- As water flow necks down in a nozzle, it must
  - speed up to avoid a “traffic jam”
  - have a pressure imbalance pushing it forward
  - be flowing from higher pressure to lower pressure
Making Water Accelerate

- Even in steady-state, water can accelerate
- but forward acceleration would leave gaps
- and backward acceleration would cause jams,
- so the acceleration must involve turning.
- Acceleration toward the side (turning)
  - requires obstacles,
  - and involves pressure imbalances
  - and changes in speed.

Bending the Flow in a Hose

- Bending the flow requires a pressure imbalance
- The water accelerates toward lower pressure
- Flow in bent hose develops a pressure gradient
  - higher pressure & lower speed on the outside of the bend
  - lower pressure & higher speed on the inside of the bend
  - and water accelerates from high pressure to lower pressure

Speeding the Flow in a Nozzle

- Speeding the flow requires a pressure imbalance
  - The water accelerates toward lower pressure
  - Flow in nozzle develops a pressure gradient
    - higher pressure & lower speed at start of nozzle
    - lower pressure & higher speed as the nozzle narrows
    - and water accelerates from high pressure to lower pressure

Question 5

Q: What causes hissing in a faucet, hose, or nozzle?
A: Water can become turbulent and produce noise.

- We’ve been examining laminar flow
  - in which viscosity dominates the flow’s behavior
  - and nearby regions of water remain nearby
  - Now we’ll also consider turbulent flow
    - in which inertia dominates the flow’s behavior
    - and nearby regions of water become separated
    - Turbulent flow produces thermal energy

Reynolds Number

- The flow type depends on the Reynolds number
  
  \[
  \text{Reynolds number} = \frac{\text{inertial influences}}{\text{viscous influences}} = \frac{\text{density} \cdot \text{obstacle length} \cdot \text{speed}}{\text{viscosity}}
  \]

- Below \(~2300\) viscosity wins, so flow is laminar
- Above \(~2300\) inertia wins, so flow is turbulent

Question 6

Q: Why do pipes rattle when you close the faucet?
A: Moving water carries momentum.

- Water transfers its momentum via impulses:
  \[\text{impulse} = \text{pressure} \cdot \text{surface area} \cdot \text{time}\]
- Large momentum transfers require
  - large pressures, large surface areas, or long times.
  - Moving water can be surprisingly hard to stop
  - Sudden stops can result in enormous pressures
**Summary about Garden Watering**

- Total energy limits speed, height, and pressure
- Bending water flows develop pressure gradients
- Nozzles exchange pressure for speed
- Viscosity wastes flowing water’s total energy
- Turbulence wastes flowing water’s total energy
- Wasted total energy because thermal energy
- Moving water has momentum, too

**Balls and Air**

- Turn off all electronic devices

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**Observations about Balls and Air**

- Air resistance slows a ball down
- The faster a ball moves, the quicker it slows
- Some balls have textured surfaces to affect the air
- Spinning balls curve in flight

**4 Questions about Balls and Air**

1. Why do balls experience air resistance?
2. How do air flow around a ball?
3. Why do some balls have dimples?
4. Why do spinning balls curve in flight?

---

**Question 1**

Q: Why do balls experience air resistance?

A: Balls interact with and transfer momentum to air

- When a ball moves through air, drag forces arise
  - Air pushes ball downstream, ball pushes air upstream
  - Air transfers downstream momentum to ball
- When a ball deflects passing air, lift forces arise
  - Air pushes ball to one side, ball pushes air to other side
  - Air transfers sideways momentum to ball

---

**Types of Aerodynamic Forces**

- Surface friction causes viscous drag
- Turbulence causes pressure drag
- Deflected flow causes lift
- Deflected flow also leads to induced drag
**Question 2**

Q: How does air flow around a ball?
A: That depends on Reynolds number
- At low Reynolds number, the flow is laminar
  - Only viscous forces transfer momentum to the ball
  - The ball experiences only viscous drag
- At high Reynolds number, the flow is turbulent
  - Pressure forces also transfer momentum to the ball
  - The ball also experiences pressure drag

**Laminar Flow around a Ball**
- Air bends away from ball’s front
  - At front: high pressure, slow flow
- Air bends toward ball’s sides
  - At side: low pressure, fast flow
- Air bends away from ball’s back
  - At back: high pressure, slow flow
- Pressures on opposite sides balance perfectly
- Ball experiences only viscous drag

**The Onset of Turbulence**
- Air flowing into the rising pressure behind ball
  - accelerates backward (decelerates)
  - and converts kinetic energy into pressure potential.
- Air flowing nearest the ball’s surface
  - also experiences viscous drag forces
  - and converts kinetic energy into thermal energy.
  - If it runs out of total energy, it stops or “stalls”
  - If air nearest the ball stalls, turbulence ensues

**Turbulent Flow around Slow Ball**
- Air flowing near ball’s surface
  - stalls beyond ball’s sides
  - and peels main air flow off of ball.
- Big wake forms behind ball
  - Since wake pressure is ambient,
  - ball experiences unbalanced pressures.
- Ball experiences a large pressure drag force

**Question 3**

Q: Why do some balls have dimples?
A: To produce a turbulent boundary layer
- Air affected by ball’s surface is the boundary layer
- Reynolds # <100,000: laminar boundary layer
  - Nearest sublayer is slowed relentlessly by viscous drag
- Reynolds # >100,000: turbulent boundary layer
  - Sublayers tumble and interchange; they help each other
  - Boundary layer penetrates deeper into rising pressure

**Turbulent Flow Around Fast Ball**
- Air flowing near ball’s surface
  - stalls beyond ball’s sides
  - and peels main air flow off of ball.
- Boundary layer is turbulent
  - and retains total energy farther,
  - so it resists peeling better.
- Small wake forms behind ball
- Ball experiences a small pressure drag force
**Tripping the Boundary Layer**

- To reduce pressure drag, some balls have dimples
- Dimples “trips” the boundary layer
- Cause boundary layer to become turbulent.
- Turbulent boundary layer resists peeling better
- Ball's main airflow forms smaller turbulent wake.
- Example: Golf balls

**Question 4**

Q: Why do spinning balls curve in flight?
A: They experience two aerodynamic lift forces

- Laminar effect: Magnus force
  - Turning surface pushes/pulls on the air flow
  - Air on one side makes longer bend toward the ball
- Turbulent effect: Wake deflection force
  - Turning surface alters point of flow separation
  - Flow separation and wake are asymmetric

**Spinning Balls, Magnus Force**

- Turning surface pushes/pulls on the air flow
  - Air on one side makes long bend toward ball
  - Air on other side makes shorter bend away from ball
  - Pressures are unbalanced
- The overall air flow is deflected
  - Ball pushes air to one side
  - Air pushes ball to other side
  - Ball feels Magnus force

**Spinning Balls, Wake Force**

- Turning surface alters point of flow separation
  - Flow separation is delayed on one side
  - and hastened on the other side,
    - so wake is asymmetric
- The overall air flow is deflected
  - Ball pushes air to one side
  - Air pushes ball to other side
  - Ball feels wake deflection force

**Summary about Balls and Air**

- Balls in air experience aerodynamic forces
- Downstream forces are drag forces
- Sideways pressure forces are lift forces
- Moving particles experience viscous drag forces
- Moving balls experience pressure drag forces
- Spinning balls experience Magnus and wake deflection lift forces

**Airplanes**

Turn off all electronic devices
Observations about Airplanes

- Airplanes use the air to support themselves
- Airplanes need airspeed to stay aloft
- Airplanes seem to follow their nose, up or down
- Airplanes can rise only so quickly
- Airplane wings often change shape in flight
- Airplanes have various propulsion systems

6 Questions about Airplanes

1. How does an airplane support itself in the air?
2. How does the airplane “lift off” the runway?
3. Why does plane tilt up to rise; down to descend?
4. Why are there different wing shapes?
5. How does a plane turn?
6. How does a plane propel itself through the air?

Question 1

Q: How does an airplane support itself in the air?
A: It deflects air downward; air pushes it upward
- Air bends away from wing bottom
- Air pressure rises, speed drops
- Air bends toward wing top
- Air pressure drops, speed rises
- There is an upward pressure force on the wing
- Wing transfers downward momentum to the air

Question 2

Q: How does the airplane “lift off” the runway?
A: The airplane sheds a vortex and is lifted upward
- As wing starts moving in air
- the airflow is symmetric
- and the wing experiences no lift
- Trailing edge kink is unstable
- and the wing sheds a vortex
- After the vortex leaves, the wing experiences lift

Question 3

Q: Why does plane tilt up to rise; down to descend?
A: The wing’s angle of attack affects its lift
- A wing’s lift depends on
  - the shape of its airfoil
  - its angle of attack—its tilt relative to approaching air
- Tilting an airplane’s wings affects lift
  - Can make the airplane accelerate up or down
  - Usually requires tilting the airplane’s fuselage
  - Plane’s tilt controls lift, not direction of travel

Limits to Lift: Stalling

- At too great an angle of attack,
  - the upper boundary layer stalls,
  - the airstream detaches from wing,
  - the lift decreases dramatically,
  - and severe pressure drag appears
  - Plane plummets abruptly
### Question 4

Q: Why are there different wing shapes?
A: Airspeed and performance influence wing design
- Asymmetric airfoils produce large lift
  - Are well suited to low-speed flight
- Symmetric airfoils produce small lift
  - Are well suited to high-speed flight
  - Allow plane to fly inverted easily
- Some planes change wing shape in flight

### Question 5

Q: How does a plane turn?
A: It uses lift to accelerate in the direction of turn
- Airplane has three orientation controls:
  - Its angle of attack is controlled by elevators
  - Its left-right tilt is controlled by ailerons
  - Its left-right rotation is controlled by rudder
- Steering involves ailerons and rudder
- Elevation involves elevators and engine

### Question 6

Q: How does a plane propel itself through the air?
A: It pushes air backward with its props or engines
- Propellers are spinning wings
  - They deflect air backward,
  - do work on air (add energy),
  - and pump air toward rear of plane
- Jet engines are ducted air pumps
  - Confine the air and pump it toward rear of plane

### Turbofan Engines

- Turbojet obtains forward momentum by
  - moving relatively little air
  - and giving that air too much energy
- Turbofan obtains forward momentum by
  - moving much more air
  - giving that air less energy

### Summary about Airplanes

- Airplanes use lift to support themselves
- Propulsion overcomes induced drag
- Speed and angle of attack affect altitude
- Extreme angle of attack causes stalling
- Propellers do work on passing airstream
- Jet engines do work on slowed airstream
Woodstoves

Turn off all electronic devices

Observations about Woodstoves

- They burn wood in enclosed fireboxes
- They often have long chimney pipes
- Their surfaces are usually darkly coated
- They’ll burn you if you touch them
- Heat rises off their surfaces
- They warm you when you stand near them

5 Questions about Woodstoves

1. What are thermal energy and heat?
2. How does a woodstove produce thermal energy?
3. Why does heat flow from the stove to the room?
4. Why is a woodstove better than an open fire?
5. How does a woodstove heat the room?

Question 1

Q: What are thermal energy and heat?
A: Disordered energy and its transfer mechanism
- **Thermal energy** is
  - disordered energy within an object’s particles
  - the kinetic and potential energies of those particles
  - responsible for temperature
- **Heat** is energy flowing between objects
  - due to a difference in their temperatures

Question 2

Q: How does a woodstove produce thermal energy?
A: It converts chemical energy into thermal energy
- Fire releases chemical potential energy
  - Wood and air consist of molecules
  - Molecules are bound by chemical bonds
  - When bonds rearrange, they can release energy
  - Burning rearranges bonds and releases energy!

Chemical Forces and Bonds

- Atoms interact via electromagnetic forces
- The chemical forces between two atoms are
  - attractive at long distances
  - repulsive at short distances
  - zero at a specific equilibrium separation
- Atoms at their equilibrium separation
  - are in a stable equilibrium
  - are bound together by an energy deficit
  - Their energy deficit is a chemical bond
A Few Names

- **Molecule**: atoms joined by chemical bonds
- **Chemical bond**: a chemical-force linkage
- **Bond strength**: the work needed to break bond
- **Reactants**: starting molecules
- **Products**: ending molecules

Chemical Reactions

- Breaking old bonds takes work
- Forming new bonds does work
- If new bonds are stronger than the old bonds, chemical potential energy → thermal energy
- However, breaking old bonds requires energy
  - reaction requires **activation energy** to start

When Wood Burns…

- When you ignite wood,
  - the reactants are carbohydrates and oxygen
  - the products are water and carbon dioxide
  - the activation energy comes from a burning match
  - This reaction releases energy as thermal energy

Question 3

**Q**: Why does heat flow from the stove to the room?
**A**: Because the stove is hotter than the room

- Heat naturally flows from hotter to colder
  - Microscopically, thermal energy moves both ways
  - Statistically, the net flow is from hotter to colder
  - At thermal equilibrium, temperatures are equal
  - no heat flows between those objects
  - **Temperature** measures the average thermal kinetic energy per particle (slightly oversimplified)

Question 4

**Q**: Why is a woodstove better than an open fire?
**A**: It releases heat, but not smoke, into the room

- An open fire is energy efficient, but has problems
  - Smoke is released into the room
  - Fire uses up the room’s oxygen
  - Can set fire to the room
  - A fireplace is cleaner, safer, but less efficient
  - A woodstove can be clean, safe, and efficient

Heat Exchangers

- A woodstove is a heat exchanger
  - It separates air used by the fire from room air
  - It transfers heat without transferring smoke
**Question 5**

Q: How does a woodstove heat the room?
A: It uses all three heat transfer mechanisms

- **Conduction:** heat flows through materials
- **Convection:** heat flows via moving fluids
- **Radiation:** heat flows via electromagnetic waves

All three transfer heat from hot to cold.

**Conduction and Woodstoves**

- In conduction, heat flows but atoms stay put
- In an insulator, adjacent atoms jiggle one another
- On average, heat flows from hot to cold atoms
- In a conductor, mobile electrons carry heat long distances
- Conduction moves heat through stove’s walls

**Convection and Woodstoves**

- In convection, heat flows with a fluid’s atoms
- Fluid warms up near a hot object
- Flowing fluid carries thermal energy with it
- Fluid cools down near a cold object
- Overall, heat flows from hot to cold
- Buoyancy drives natural convection
- Warmed fluid rises away from hot object
- Cooled fluid descends away from cold object
- Convection circulates hot air around the room

**Radiation and Woodstoves**

- In radiation, heat flows via electromagnetic waves (radio waves, microwaves, light, …)
- Range of waves depends on temperature
  - Cold: radio wave, microwaves, infrared light
  - Hot: infrared, visible, and ultraviolet light
- Higher temperature → more radiated heat
- Blacker surface → more radiated heat
- Black emits and absorbs radiation perfectly

**Stefan-Boltzmann Law**

- Emissivity is a surface’s emission-absorption efficiency
  - 0 → perfect inefficiency: white, shiny, or clear
  - 1 → perfect efficiency: black
- The amount of heat a surface radiates is
  \[ \text{power} = \text{emissivity} \cdot \text{Stefan-Boltzmann constant} \cdot \text{temperature}^4 \cdot \text{surface area} \]
  where temperature is measured on an absolute scale

**What About Campfires?**

- No conduction, unless you touch hot coals
- No convection, unless you are above fire
- Lots of radiation:
  - Your face feels hot because radiation reaches it
  - Your back feels cold because no radiation reaches it
Summary about Wood Stoves
- Use all three heat transfer mechanisms
- Have tall chimneys for heat exchange
- Are dark-coated to encourage radiation
- Are sealed to keep smoke out of room air

Water, Steam, and Ice

Observations about Water, Steam, and Ice
- Water has three forms or phases
- Ice is common below 32 °F (0 °C)
- Water is common above 32 °F (0 °C)
- Steam is common at high temps
- The three phases sometimes coexist

4 Questions about Water, Steam, Ice
1. How can water and ice coexist in a glass?
2. Can steam exist below 212 °F (100 °C)?
3. Where do ice cubes go in a frostless freezer?
4. Is salt the only chemical that helps melt ice?

Question 1
Q: How can water and ice coexist in a glass?
A: At 32 °F (0 °C), both phases are stable
- Water has three phases: solid, liquid, and gas
- Ice has a melting temperature of 32 °F (0 °C)
  - below which solid ice is the stable phase,
  - above which liquid water is the stable phase,
  - at which ice and water can coexist

Phases of Matter
- Ice is solid: fixed volume and fixed shape
- Water is liquid: fixed volume but variable shape
- Steam is gas: variable volume and variable shape
**Phase Equilibrium**
- When two (or more) phases are present
  - molecules continually shift between the phases
  - one phase may grow at the expense of another phase
  - that growth often takes or releases thermal energy
- At phase equilibrium,
  - two (or more) phases can coexist indefinitely
  - neither phase grows at the expense of the other

**Ice and Water**
- To melt ice at 32 °F (0 °C),
  - destabilize ice relative to water by
    - adding heat
    - increasing pressure (ice is very atypical!)
- To freeze water at 32 °F (0 °C),
  - stabilize ice relative to water by
    - removing heat
    - decreasing pressure (water is very atypical!)
  - Melting ice takes latent heat of melting

**Question 2**
Q: Can steam exist below 212 °F (100 °C)?
A: Yes, but its pressure is less than atmospheric
- Liquid water and gaseous steam
  - can coexist over a broad range of temperatures
  - but equilibrium steam density rises with temperature

**Water and Steam**
- To evaporate water,
  - destabilize water relative to steam by
    - adding heat
    - reducing the density of the steam
- To condense steam,
  - stabilize water relative to steam by
    - removing heat
    - increasing the density of the steam
  - Evaporating water takes latent heat of evaporation

**Boiling (Part 1)**
- Steam bubbles can form inside water
  - Pressure in steam bubble depends on steam density
- If steam pressure exceeds ambient pressure,
  - steam bubbles can survive and grow via evaporation
- Boiling occurs when bubbles
  - *nucleate*—when seed bubbles form
  - grow via evaporation
  - Need for latent heat stabilizes temperature

**Boiling (Part 2)**
- Boiling temperature depends on ambient pressure
- Elevated pressure
  - raises water's boiling temperature
  - Some foods cook faster at sea level or below
- Diminished pressure
  - lowers water's boiling temperature
  - Some foods cook slower at high altitudes
Question 3
Q: Where do ice cubes go in a frostless freezer?
A: The ice sublimes directly into steam
- Solid ice and gaseous steam
  - can coexist over a broad range of temperatures
  - but equilibrium steam density rises with temperature

Ice and Steam
- To sublime ice, destabilize ice relative to steam by
  - adding heat
  - reducing the density of the steam
- To deposit steam, stabilize ice relative to steam by
  - removing heat
  - increasing the density of the steam
- Subliming ice takes latent heats of melting and evaporation

Relative Humidity
- At 100% relative humidity,
  - steam is in phase equilibrium with water and/or ice
- Below 100% relative humidity,
  - water evaporates and/or ice sublimes
- Above 100% relative humidity,
  - steam condenses as liquid water and/or deposits as ice
- Below 0 °C, ice and steam are active phases
- Above 0 °C, water and steam are active phases
- At 0 °C, water, steam, and ice are all active phases

Question 4
Q: Is salt the only chemical that helps melt ice?
A: No, any chemical that dissolves in water works
- Dissolved impurities stabilize liquid water
  - reduce ice's melting temperature
  - increase water's boiling temperature
- Shifts are proportional to solute particle density
- Any soluble material can help ice to melt

Summary about Water, Steam, and Ice
- Phase transitions reflect relative phase stabilities
- Phases in equilibrium are stable and constant
- Temperature and pressure affect phase stabilities
- Phase transitions usually take or release heat

Clothing, Insulation, and Climate

Turn off all electronic devices
Observations about Clothing, Insulation, and Climate

- Clothing keeps you warm in cold places
- Clothing can keep you cool in very hot places
- Insulation controls heat flow in various objects
- Insulation can be obvious, as in foam cups
- Insulation can be subtle, as in special windows
- Greenhouse gases trap heat and warm the earth

4 Questions about Clothing, Insulation, and Climate

1. How does clothing control thermal conduction?
2. How does clothing control thermal convection?
3. How does insulation control thermal radiation?
4. Why do greenhouse gases warm the earth?

Question 1

- How does clothing control thermal conduction?

Thermal Conductivity

- Heat naturally flows from hot to cold
- If one end of a material is hotter than the other
  - it will conduct heat from its hot end to its cold end
  - at a rate equal to the material’s area
  - times the temperature difference
  - times the material’s thermal conductivity
  - divided by the material’s thickness.

\[
\text{heat flow} = \frac{\text{conductivity} \times \text{temperature diff} \times \text{area}}{\text{thickness}}
\]

Question 2

- How does clothing control thermal convection?

Limiting Thermal Conduction

- Clothing is often intended to reduce heat flow
  - so it should use low-thermal conductivity materials
  - electrical insulators, not metals
  - materials that trap air—air is a very poor thermal conductor
  - and it should use relatively thick materials
  - wool sweaters, down coats, heavy blankets

- Reducing exposed area is helpful when possible
- Reducing the temperature difference always helps
Natural Convection
- Heat naturally flows from hot to cold
- If one region of a fluid is hotter than the other
  - those regions will also have different densities
  - and buoyancy may cause the fluid to circulate.
- The rate of heat flow depends on
  - the heat capacity and mobility of the fluid
  - how quickly heat flows into or out of the fluid
  - how well buoyancy circulates fluid from hot to cold

Forced Convection
- Buoyancy isn’t always effective at moving fluids
  - It fails when the hotter fluid is above the colder fluid
  - It fails when fluids experience large drag forces
  - It fails in certain awkward geometries
- Stirring the fluid enhances heat flow
  - Wind leads to faster heat transfer (wind chill)
  - Moving through air or water speeds heat transfer

Limiting Thermal Convection
- Clothing can reduce convective heat flow by
  - preventing fluids from circulating
  - reducing temperature differences in the fluid
- The most effective clothing is thick and fluffy
  - The fluffiness traps air so that it can’t convect
  - The thickness allows the surface temperature to drop to that of your surroundings so that there is no external convection
- A wind breaker minimizes forced convection

Question 3
- How does insulation control thermal radiation?

Thermal Radiation
- Materials all emit thermal radiation because
  - they contain electric charges
  - and thermal energy causes those charges accelerate.
  - Accelerating charges emit electromagnetic waves
- Hotter temperatures yield shorter wavelengths

Black Body Spectrum (Part 1)
- A surface’s efficiency at absorbing and emitting thermal radiation is measured by its emissivity
  - 1 for a perfect emitter-absorber (black)
  - 0 for a nonemitter-nonabsorber (white, clear, shiny)
- The spectrum and intensity of a black surface’s thermal radiation depend only on its temperature
Black Body Spectrum (Part 2)
- The black body spectrum of the sun is white light
- Objects hotter than about 500 °C glow visibly
- But even your skin emits invisible thermal radiation

Radiative Heat Transfer
- Your skin radiates heat at a rate given by the Stefan-Boltzmann law:
  \[ \text{power} = \text{emissivity} \times \text{Stefan-Boltzmann constant} \times \text{temperature}^4 \times \text{surface area} \]
  where temperature is an absolute temperature.
- Because of the 4th power, thermal radiation is extremely sensitive to temperature.
- Black or gray objects with different temperatures can exchange heat via thermal radiation

Limiting Thermal Radiation (Part 1)
- Insulation can reduce radiative heat flow by
  - having surfaces with low emissivities
  - reducing temperature differences between surfaces
- Emissivity depends on temperature
  - You can see high-temperature emissivity
    - black surfaces have high-temperature emissivities near 1
    - white, clear, shiny surfaces values near 0
  - You can’t see low-temperature emissivity
    - most materials have low-temperature emissivities near 1
    - conducting (metallic) surfaces can have values near 0

Limiting Thermal Radiation (Part 2)
- To reduce radiative heat flow
  - use conducting, low-emissivity surfaces
  - allow exterior surfaces to reach ambient temperature

Question 4
Q: Why do greenhouse gases warm the earth?
A: By increasing altitude of earth’s radiating surface
- Earth receives thermal radiation from the sun
- Earth emits thermal radiation into space
  - The atmosphere contributes to that thermal radiation
  - Effective radiating surface is 5 km above sea level
- Balance requires Earth’s radiating surface is -18 °C
- Greenhouse gases increase altitude of that surface

Effects of the Atmosphere
- Atmosphere has a temperature gradient
  - air expands and cools as its altitude increases
  - air temperature decreases 6.6 °C per km of altitude
- Atmosphere’s average temperature
  - at 5 km is -18 °C
  - at sea level is 15 °C
**Effects of Greenhouse Gases**

- Greenhouse gases “darken” the atmosphere
- Low-temperature emissivity of atmosphere increases
- Effective radiating surface moves to higher altitude
- Average temperature at sea level increases
- Increasing greenhouse gases cause global warming
- Greenhouse gases include water, carbon dioxide, nitrogen oxides, and methane
- but not nitrogen or oxygen; they’re transparent to IR
- Limiting greenhouse gases is critical to our future

**Summary about Clothing, Insulation, and Climate**

- Clothing and insulation limit heat transfer
- They use materials with low thermal conductivities
- They introduce drag to impede convection
- They use low emissivities to reduce radiation
- Greenhouse gases affect Earth’s thermal radiation
- Those gases raise Earth’s surface temperature

**Air Conditioners**

- Turn off all electronic devices

**Observations about Air Conditioners**

- They cool the air in a room
- They emit hot air from their outside vents
- They consume lots of electric power
- They are less efficient on hotter days
- Some can be reversed so that they heat room air

**5 Questions about Air Conditioners**

1. Why doesn’t heat flow naturally from cold to hot?
2. Why does an air conditioner need electricity?
3. How does an air conditioner cool room air?
4. What role does the electricity play?
5. How does an air conditioner heat outdoor air?

**Question 1**

Q: Why doesn’t heat flow naturally from cold to hot?  
A: Such heat flow would violate the law of entropy
- There are 4 laws of thermodynamics that
  - govern the flow of thermal energy
  - relate disordered (thermal) energy and ordered energy
  - relate heat and work
- We will consider 3 of those laws
Law of Thermal Equilibrium
This law observes that there is a consistency about situations in which heat does not flow:

“If two objects are in thermal equilibrium with a third object, then they are in thermal equilibrium with each other.”

Law of Conservation of Energy
This law recognizes that heat is a form of energy:

“The change in the internal energy equals the heat in minus the work out”

where:
- The internal energy is thermal + stored energies
- The heat in is the heat transferred into object
- The work out is the external work done by object

Order versus Disorder
- Converting ordered energy into thermal energy
  - involves events that are likely to occur
  - is easy to accomplish and often happens
- Converting thermal energy into ordered energy
  - involves events that are unlikely to occur
  - is hard to accomplish and effectively never happens
- Statistically, disordered never becomes ordered

Entropy
- Entropy
  - is the measure of a system’s disorder
  - includes every type of disorder: energy and structure
- Entropy
  - never decreases in a system that is thermally isolated
  - can be rearranged within a system
  - can be transferred between systems
  - is NOT a conserved quantity!

Law of Entropy
This law observes that entropy guides the time evolution of isolated systems:

“The entropy of a thermally isolated system never decreases”

More on the Law of Entropy
- According to the Law of Entropy:
  - Entropy of thermally isolated system can’t decrease
  - but entropy can be rearranged within that system
  - so part of the system can become colder as another part becomes hotter!
  - Entropy is “exported” from cold part to hot part
- Exporting entropy is like throwing out trash!
Natural Heat Flow

- One unit of thermal energy is more disordering to a cold object than to a hot object.
- When heat flows from hot object to cold object,
  - hot object's entropy: ↓
  - cold object's entropy: ↑↑
  - so their total entropy: ↑
- Law of Entropy is satisfied

Hypothetical Energy and Entropy

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<th>Entropy</th>
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<td>9</td>
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<td>4</td>
<td>10</td>
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</tbody>
</table>

Unnatural Heat Flow

- When heat flows from cold object to hot object,
  - cold object's entropy: ↓↓
  - hot object's entropy: ↑
  - so their total entropy: ↓
- Law of Entropy would be violated,
  - unless we create of additional entropy!
  - unless something ordered becomes disordered!

Question 2

Q: Why does an air conditioner need electricity?
A: Electricity provides the necessary order

- An air conditioner
  - moves heat from cold (room air) to hot (outside air)
  - would cause total entropy of world to decrease
  - were it not for the electric power it consumes!
  - It turns electric power into thermal power
  - so the total entropy of world does not decrease

Heat Machines

- Air conditioners are heat pumps
- use work to transfer heat from cold to hot
- Automobiles are heat engines
- use flow of heat from hot to cold to do work
- Heat machines are governed by law of entropy

Air Conditioner

- An air conditioner uses a working fluid to
  - absorb heat from cold (room air)
  - release heat to hot (outside air)
- The evaporator (indoors)
  - transfers heat from cold (room air) to working fluid
- The condenser (outdoors)
  - transfers heat from working fluid to hot (outside air)
- The compressor (outdoors)
  - does work on working fluid and produces entropy.
Question 3
Q: How does an air conditioner cool room air?
A: Its evaporator absorbs heat from the room air
- Evaporator is wide indoor pipe
- Working fluid
  - enters evaporator as cool low-pressure liquid
  - absorbs heat from room air and evaporates
  - leaves evaporator as a cool low-pressure gas
- Heat has been removed from the room!

Question 4
Q: What role does the electricity play?
A: It powers the compressor and creates entropy
- Compressor increases gas’s pressure and density
- Working fluid
  - enters compressor as a cool low-density gas
  - has work done on it by the compressor
  - leaves compressor as hot high-density gas
- Entropy has been created!

Question 5
Q: How does an air conditioner heat outdoor air?
A: Its condenser releases heat to the outdoor air
- Condenser is narrow outdoor pipe at high pressure
- Working fluid
  - enters condenser as hot high-pressure gas
  - releases heat to outdoor air and condenses
  - leaves condenser as a cool high-pressure liquid
- Heat has been delivered to the outdoors!

Air Conditioner Overview
- Fluid evaporates in evaporator
  - absorbing heat from room air
- Compressor raises pressure
  - evaporation → condensation
- Fluid condenses in condenser
  - releasing heat to outdoor air
- Constriction lowers pressure
  - condensation → evaporation
  - and the cycle repeats endlessly…

Summary about Air Conditioners
- They pump heat from cold to hot
- They don’t violate thermodynamics
- They convert ordered energy to thermal energy

Automobiles
Turn off all electronic devices
Observations about Automobiles

- They burn gas to obtain their power
- They are rated in horsepower and by volume
- Their engines contain “cylinders”
- They have electrical systems
- They are propelled by their wheels

6 Questions about Automobiles

1. How can an automobile run on thermal energy?
2. How efficient can an automobile engine be?
3. How is an automobile engine a heat engine?
4. Why do cars sometime “knock?”
5. How is a diesel engine different?
6. Why does the engine have a catalytic converter?

Question 1

Q: How can an automobile run on thermal energy?
A: An automobile engine is a heat engine

- An automobile
  - allows heat to flow from hot (flame) to cold (air)
  - would cause total entropy of world to increase greatly
  - were it not for the mechanical power it produces!
- It turns some thermal power to mechanical power
  - so the total entropy of world increases only modestly

Question 2

Q: How efficient can an automobile engine be?
A: Its efficiency is limited by the law of entropy

- A heat engine
  - cannot decrease the world's overall entropy
  - efficiency depends on the temperature difference
  - As that temperature difference increases,
    - heat flowing from hot to cold creates more entropy
    - so more heat can be converted to work

About Heat Pumps

- A heat pump
  - cannot decrease the world’s overall entropy
  - efficiency depends on the temperature difference
  - As that temperature difference increases,
    - heat pumped from cold to hot destroys more entropy
    - so more work must be converted to heat

Question 3

Q: How is an automobile engine a heat engine?
A: Heat flows from hot (flame) to cold (outside air)

- An internal combustion engine
  - burns a fuel-air mixture in an enclosed space
  - to produce hot (burned gases).
  - As heat flows from hot to cold (outside air)
    - engine converts some heat into useful work
    - automobile uses that work to propel itself.
**Four Stroke Engine**

- Induction Stroke: fill cylinder with fuel & air
- Compression Stroke: squeeze mixture
- Power Stroke: burn and extract work
- Exhaust Stroke: empty cylinder of exhaust

**Induction Stroke**

- Intake valve opens
- Engine pulls piston out of cylinder
  - Engine does work on piston
  - Low pressure produced inside cylinder
- Fuel-air mixture flows into cylinder
- Intake valve closes

**Compression Stroke**

- Engine pushes piston into cylinder
  - Engine does work on piston
- Mixture is compressed
  - Mixture pressure increases
  - Mixture temperature increases
- Work becomes heat

**Power Stroke**

- Spark plug ignites the fuel-air mixture
- Hot gas pushes piston out of cylinder
  - Piston does work on engine
- Burned gas expands
  - Gas pressure decreases
  - Gas temperature decreases
- Heat becomes work

**Exhaust Stroke**

- Exhaust valve opens
- Engine pushes piston into cylinder
  - Engine does work on piston
  - High pressure produced inside cylinder
- Burned gas flows out of cylinder
- Exhaust valve closes

**Efficiency Limits**

- Overall, an internal combustion engine produces more work than it consumes
- Converts some heat into work
- Law of entropy limits heat becoming work
  - Some heat must be released into outside air
  - Efficiency increases with the temperature difference
  - Real engines never reach ideal efficiency
Question 4
Q: Why do cars sometime “knock?”
A: Compressing a flammable gas can ignite it
- During the compression stroke, fuel-air mixture becomes extremely hot
- Can ignite spontaneously (knocking or preignition)
- To avoid knocking, car can reduce its compression ratio to lower peak temperature
- Use fuel that is more resistant to ignition
- Higher octane fuels are simply harder to ignite

Question 5
Q: How is a diesel engine different?
A: It uses compression heating to ignite fuel
- Diesel engine compresses air to very high pressure & temperature
- Injects fuel between compression and power strokes
- Lets fuel ignite upon entry into the superheated air
- Diesel engine has higher compression ratio, so its fuel burns to a higher final temperature
- It has a higher potential efficiency

Question 6
Q: Why does the engine have a catalytic converter?
A: To remove unwanted components from exhaust
- Imperfect fuel-air mixtures produce pollutants
  - Too rich: carbon monoxide and fuel in exhaust
  - Too lean: nitrogen oxides in exhaust
  - Imperfect diesel: carbonized particulates in exhaust
- Catalytic converter destroys unwanted molecules
- Filter removes and burns unwanted particulates

Catalytic Converters
- Catalytic converter reduces pollutant molecules
  - Platinum helps oxidize carbon monoxide and fuel
  - Rhodium helps remove nitrogen oxides
- Using tiny, high-surface-area catalyst particles increases the fraction of atoms available for reactions
- Decreases the amount of precious metals required

Summary about Automobiles
- Heat flows from hot (burned gas) to cold (air)
- Some of that heat is converted to work
- Energy efficiency is limited by thermodynamics
- Higher temperatures increase efficiency

Clocks
Turn off all electronic devices
Observations About Clocks

- They divide time into uniform intervals
- The measure time by counting those intervals
- Some clocks use motion to mark their intervals
- Others clocks don’t appear to involve motion
- They require energy to operate
- They have good but not perfect accuracy

5 Questions about Clocks

1. Why don’t any modern clocks use hourglasses?
2. Are all repetitive motions equally accurate?
3. Why is a harmonic oscillator a good timekeeper?
4. Why are some clocks particularly accurate?
5. How are harmonic oscillators used in clocks?

Question 1

Q: Why don’t any modern clocks use hourglasses?
A: Hourglasses are best as timers, not clocks
- Hourglasses measure an interval fairly accurately
- They are poorly suited to subdividing the day
- They require frequent operator intervention
- That operator requirement limits their accuracy

Repetitive Motions: Clocks

- Devices that tick off time intervals repetitively,
  - pendulums
  - torsion balances
  - tuning forks
- Began appearing in clocks about 500 years ago.
- They are well suited to subdividing the day
- They require no operator intervention
- Their ticks can be counted automatically

About Repetitive Motions

- Any device with a stable equilibrium
  - can move repetitively about that equilibrium
  - will move repetitively as long as it has excess energy
- The repetitive motion sets a clock’s accuracy
- It mustn’t depend on externals such as
  - temperature, air pressure, or time of day
  - the clock’s store of energy
  - the mechanism that observes the motion

Question 2

Q: Are all repetitive motions equally accurate?
A: Insensitivity to the amplitude of motion helps
- A little terminology…
  - Period: interval between two repetitive motion cycles
  - Frequency: cycles completed per unit of time
  - Amplitude: peak distance away from motion’s center
  - Timekeeper: a clock’s repetitive motion device
- In a good clock, the period of its timekeeper shouldn’t depend on amplitude.
Question 3
Q: Why is a harmonic oscillator a good timekeeper?
A: Its period is independent of its amplitude
- A harmonic oscillator is a system with
  - a stable equilibrium
  - a restoring influence that’s proportional to displacement
- Its period is independent of its amplitude!

Harmonic Oscillators
- A harmonic oscillator always has
  - an inertial aspect (e.g., a mass)
  - a spring-like restoring aspect (e.g., a spring).
- A harmonic oscillator's period decreases as
  - its inertial aspect becomes smaller
  - its spring-like restoring aspect becomes stiffer
- Common harmonic oscillators include
  - mass on a spring, pendulum, flagpole, tuning fork

Question 4
Q: Why are some clocks particularly accurate?
A: They take good care of their harmonic oscillators
- Clocks have practical limits to accuracy
  - Sustaining motion can influence the period
  - Measuring the period can influence the period
  - Temperature, pressure, wind… can influence the period
- Clocks also have fundamental limits to accuracy
  - Oscillation decay limits preciseness of period

Question 5
Q: How are harmonic oscillators used in clocks?
A: Their motions are gently encouraged and counted
- A clock
  - supplies energy to keep its harmonic oscillator going
  - counts cycles of that oscillator and reports the time
- Common harmonic oscillators used in clocks are
  - pendulums
  - balance rings
  - quartz crystals

Pendulums (Part 1)
- A pendulum is (almost) a harmonic oscillator
- For small displacements
  - Its restoring force is proportional to displacement
  - Its period is independent of amplitude
  - Its period is proportional to \((\text{length/}\text{gravity})^{1/2}\)

Pendulums (Part 2)
- A pendulum’s spring-like restoring force
  - is caused by gravity
  - is proportional to the pendulum’s weight
  - is therefore proportional to the pendulum’s mass
- Increasing a pendulum’s mass
  - increases its inertial aspect
  - increases the stiffness of its restoring force aspect
  - therefore has no effect on its period!
Pendulum Clocks
- Pendulum is the clock’s timekeeper
- For accuracy, pendulum’s length is temperature stabilized
- For accuracy, pendulum’s length is adjusted for local gravity
- Friction & air resistance are small
- Motion is sustained gently
- The clock mustn’t move or tilt

Balance Ring Clocks
- Coil spring and balance ring form harmonic osc.
- Balance ring twists back and forth rhythmically
- Gravity exerts no torque about the ring’s pivot
- For accuracy, balance ring’s friction & air resistance are small
- Motion is sustained gently

Quartz Oscillators
- A quartz crystal is a harmonic oscillator
- Crystal’s mass provides the inertial aspect
- Crystal’s body provides the spring-like restoring aspect
- As a harmonic oscillator, a quartz crystal’s oscillation decay is extremely slow
- Fundamental accuracy is extremely high
- Quartz is piezoelectric
  - Its mechanical and electrical changes are coupled
  - Its motion can be induced and measured electrically

Quartz Clocks
- The quartz tuning fork in a quartz clock is kept vibrating by giving it energy electronically
- Observed and its vibrations counted electronically
- Inertive to gravity, temperature, pressure, and acceleration
- Quartz’s slow oscillation decay gives it a very precise period
- The crystal’s tuning-fork shape yields a slow, efficient vibration.

Summary about Clocks
- Most clocks involve harmonic oscillators
- Amplitude independence aids accuracy
- Clock sustains and counts oscillations
- Oscillators that lose little energy work best

Musical Instruments
- Turn off all electronic devices
Observations about Musical Instruments

- They can produce different notes
- They must be tuned to produce the right notes
- They sound different, even on the same note
- They require energy to create sound

Questions about Musical Instruments

1. Why does a taut string have a specific pitch?
2. Why does a vibrating string sound like a string?
3. How does bowing cause a string to vibrate?
4. Why do stringed instruments need surfaces?
5. What is vibrating in a wind instrument?
6. Why does a drum sound particularly different?
7. How does sound travel through air?

Question 1

Q: Why does a taut string have a specific pitch?
A: A taut string is a harmonic oscillator
- A taut string
  - stable equilibrium shape: a straight line
  - mass provides an inertial aspect
  - tension and length provide spring-like restoring aspect
- A taut string is a harmonic oscillator
  - vibrates about its equilibrium shape
  - pitch is independent of its amplitude/volume!

Fundamental Vibration

- A string has a fundamental vibrational mode
- string vibrates up and down as a single arc
- 1 displacement antinode at string’s center
- 2 displacement nodes, 1 node at each end of string
- Its fundamental pitch (frequency of vibration) is
  - proportional to tension\(^{1/2}\)
  - proportional to \(1/\text{length}\)
  - proportional to \(1/\text{mass}^{1/2}\)

A String’s Harmonics

- First overtone involves 2 halfstrings
  - \(2 \times \) the fundamental pitch: 2\(^{nd}\) harmonic
  - One octave above the fundamental frequency
- Second overtone involves 3 third-strings
  - \(3 \times \) the fundamental pitch: 3\(^{rd}\) harmonic
  - An octave and a fifth above the fundamental
- Bowing or plucking a string excites a mixture of fundamental and harmonic vibrations, giving the string its characteristic sound
**Question 3**

Q: How does bowing cause a string to vibrate?
A: Bowing adds a little energy to string each cycle
- Plucking a string transfers energy all at once
- Bowing a string transfers energy gradually
  - bow does a little work on the string every cycle
  - energy accumulates via resonant energy transfer
- A string will exhibit sympathetic vibration when
  - another object vibrates at string’s resonant frequency
  - resonant energy transfer goes from object to string

**Question 4**

Q: Why do stringed instruments need surfaces?
A: Surfaces project sound much better
- In air, sound consists of density fluctuations
  - Air has a stable equilibrium: uniform density
  - Disturbances from uniform density make air vibrate
  - Vibrating strings don’t project sound well
  - air flows easily around narrow vibrating strings
  - Surfaces project sound much better
  - air can’t flow easily around vibrating surfaces
  - air is substantially compressed or rarefied: sound

**Question 5**

Q: What is vibrating in a wind instrument?
A: Air in a tube is a harmonic oscillator
- Air in a tube has
  - a stable equilibrium arrangement: uniform density
  - mass provides an inertial aspect
  - pressure and length provide spring-like restoring aspect
- Air in a tube is a harmonic oscillator
  - vibrates about its equilibrium arrangement
  - pitch is independent of its amplitude/volume!

**Fundamental Vibration**

**Open-Open Column**
- Air column has a fundamental vibrational mode
  - air column vibrates up and down as a single object
  - 1 pressure antinode at air column’s center
  - 2 pressure nodes, 1 node at each open end of column
- Its fundamental pitch is
  - proportional to pressure\(^{1/2}\),
  - proportional to \(1/length\),
  - and proportional to \(1/density^{1/2}\).

**Open-Closed Column**
- Air column has a fundamental vibrational mode
  - air column vibrates up and down as a single object
  - 1 pressure antinode at air column’s closed end
  - 1 pressure node at air column’s open end
- The air column in a open-closed pipe vibrates
  - like half the air column in an open-open pipe
  - at half the frequency of an open-open pipe

**Air Column Harmonics**
- In an open-open pipe, the overtones are at
  - \(2 \times\) the fundamental (2 pressure antinodes)
  - \(3 \times\) the fundamental (3 pressure antinodes)
  - and all integer harmonics
- In an open-closed pipe, the overtones are at
  - \(3 \times\) the fundamental (2 antinodes)
  - \(5 \times\) the fundamental (3 antinodes)
  - and all odd-integer harmonics
Question 6
Q: Why does a drum sound particularly different?
A: Its overtones are not harmonics
   - Most 1-dimensional instruments
     - can vibrate at half, third, quarter length, etc.
     - have harmonic overtones
   - Most 2- or 3-dimensional instruments
     - have complicated higher-order vibrations
     - have non-harmonic overtones.
   - Examples: drums, cymbals, bells

Question 7
Q: How does sound travel through air?
A: Air exhibits longitudinal traveling waves
   - Basic modes of finite objects are standing waves
     - Standing wave: nodes and antinodes don’t move
   - Basic modes of infinite objects are traveling waves
     - Traveling wave: nodes and antinodes travel
   - Open air is infinite, so it exhibits traveling waves

Summary of Musical Instrument
- They use strings, air, etc. as harmonic oscillators
- Pitches are independent of amplitude/volume
- Tuned by tension/pressure, length, density
- Often have harmonic overtones
- Project vibrations into the air as sound

Transverse and Longitudinal Waves
- Some objects vibrate side-to-side: **transverse waves**
  - Finite strings: transverse standing
  - Open string: transverse traveling
- Some objects vibrate along their lengths: **longitudinal waves**
  - Air column: longitudinal standing
  - Open air: longitudinal traveling

The Sea

Turn off all electronic devices
Observations about the Sea

- The sea is rarely calm; it is covered with waves
- The broadest waves travel fastest
- Waves seem to get steeper near shore
- Waves break or crumble near shore
- Waves bend gradually toward the shore

5 Questions about the Sea

1. Why are there tides?
2. How do giant tides develop?
3. How does water in a wave move?
4. How is a tsunami different from normal waves?
5. Why do waves bend and break near shore?

Question 1

Q: Why are there tides?
A: The moon’s gravity causes the oceans to bulge
- Moon’s gravity acts nonuniformly on the earth
- Tidal distortion of the oceans produces two bulges
- Locations of tidal bulges change as the earth rotates
- High and low tides occur almost twice a day

The Sun’s Influence on Tides

- Sun’s gravity also acts nonuniformly on the earth
- Tidal distortion produces bulges
- Sun’s tidal bulges are about 1/3 the size of moon’s tidal bulges
- Moon and Sun bulges compete
- Strongest tides are when moon and sun are aligned
- Weakest tides are when moon and sun are at right angles

Question 2

Q: How do giant tides develop?
A: Sympathetic vibration in channels
- Water in a confined channel can slosh
- It has a stable equilibrium: level
- It has springlike restoring forces
- It’s a harmonic oscillator
- Its period is set by inertia and stiffness
- If its sloshing period matches the tidal period, sympathetic vibration occurs

Standing and Traveling Waves

- Sloshing in a channel involves standing waves
- Water in a finite channel has standing wave modes
- Nodes and antinodes don’t move
- Waves on open water are traveling waves
- Water in an infinite sea has traveling wave modes
- Crests and troughs move
**Question 3**

Q: How does water in a wave move?
A: It circles, but remains approximately in place
- Sloshing involves deep water waves
  - All of the water moves back and forth during a cycle
  - Waves on the open sea are surface water waves
  - Only the surface water moves during a cycle

**The Water's Circling Motion**

- Only the wave structure travels across the water
- Surface water itself circles as the wave passes
- The wave's crests are formed from local water

**Depth of Surface Wave**

- The circling is strongest at the surface
  - Becomes weak about 1/2 wavelength deep

**Question 4**

Q: How is a tsunami different from normal waves?
A: They have much longer wavelengths
- The longer the wavelength of surface wave,
  - the faster it travels
  - the deeper it extends into the water
  - the more power it conveys for its amplitude
- Tsunamis are
  - very long wavelength, deep, and powerful waves
  - not strictly surface waves

**Question 5**

Q: Why do waves bend and break near shore?
A: Shallow water alters the motion of surface waves
- A surface wave slows as water gets shallower
  - its circling motion is distorted by the rising seabed
  - its wavelength decreases
  - its crests grow taller and more tightly bunched
- Wave breaks when the water can’t form a crest
  - If the seabed slopes gradually, there is rolling surf
  - If the seabed slopes sharply, plunging breakers occur

**Changing Wave Speeds**

- Waves experience reflection
  - Changes in wave speed cause partial reflection
  - The bigger the speed change, the more reflection
- Waves experience refraction
  - Changes in wave speed can redirect the wave
  - Waves bend toward shore as they slow in shallowing water
Summary of the Sea

- The moon’s gravity causes the tides
- The tides can cause resonant motion in channels
- Tidal resonances are standing waves
- The open sea exhibits traveling waves
- Water moves in circles in those waves
- Waves break when the water gets too shallow