Physics 105
How Things Work
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Lecture Notes

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Skating

Question:

A rotary lawn mower spins its sharp blade rapidly over the lawn and cuts the tops of the grasses off. Would the blade still cut the grasses if they weren't attached to the ground?

Observations About Skating

- When you're at rest on a level surface:
  - If not pushed, you stay stationary
  - If pushed, you start moving in that direction
- When you're moving on a level surface:
  - If not pushed, you coast steadily and straight
  - If pushed, you change direction or speed

Physics Concept

- Inertia
  - A body at rest tends to remain at rest
  - A body in motion tends to remain in motion

Newton's First Law, First Version

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

Physical Quantities

- Position – an object's location
- Velocity – its change in position with time

Newton's First Law, Second Version

An object that is free of external influences moves at a constant velocity.

Physical Quantities

- Position – an object's location
- Velocity – its change in position with time
- Force – a push or a pull

Newton's First Law

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

Question:

A rotary lawn mower spins its blade rapidly over the lawn and cuts the tops of the grasses off. Would the blade still cut the grasses if they weren't attached to the ground?

Physical Quantities

- Position – an object's location
- Velocity – change in position with time
- Force – a push or a pull
- Acceleration – change in velocity with time
- Mass – measure of object's inertia

Newton's Second Law

The force exerted on an object is equal to the product of that object's mass times its acceleration. The acceleration is in the same direction as the force.

force = mass · acceleration

Summary
About Skating

- Skates can free you from external forces
  - You normally coast – constant velocity
  - If at rest, you stay at rest
  - If moving, you move steadily and straight
- When you experience external forces
  - You accelerate – changing velocity
  - Acceleration depends on force and mass

Falling Balls

Question:

Suppose that I throw a ball upward into the air. After the ball leaves my hand, is there any force pushing the ball upward?

Observations About Falling Balls

- A dropped ball:
  - Begins at rest, but acquires downward speed
  - Covers more and more distance each second
- A tossed ball:
  - Rises to a certain height
  - Comes briefly to a stop
  - Begins to descend, much like dropped ball

Type of Force

- Weight – earth's gravitational force on object

Weight and Mass

- An object's weight is proportional to its mass
  - weight $\propto$ mass
  - weight = constant · mass
- On the Earth's surface, that constant is
  - 9.8 newtons/kilogram
  - called *acceleration due to gravity*

Acceleration Due to Gravity

- Why this strange name?
  - force = mass· acceleration (Newton's 2nd law)
  - 1 newton $\equiv$ 1 kilogram-meter/second^2 (definition)
  - 9.8 newtons/kilogram = 9.8 meter/second^2
  - 9.8 meter/second^2 is an acceleration!
  - *Acceleration due to gravity* actually is an acceleration!
- On Earth's surface, all falling objects accelerate downward at *the acceleration due to gravity*!

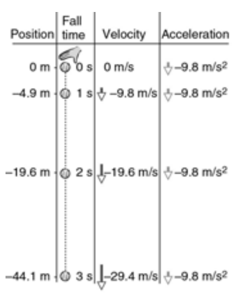
Why Things Fall Together

- Increasing an object's mass
  - increases the downward force on it
  - makes it need more force to accelerate
- These effects balance out perfectly

A Falling Ball

- Falling ball accelerates steadily downward
  - Acceleration is constant and downward
  - Velocity increases in the downward direction
- Falling from rest (stationary):
  - Velocity starts at zero and increases downward
  - Altitude decreases at an ever faster rate

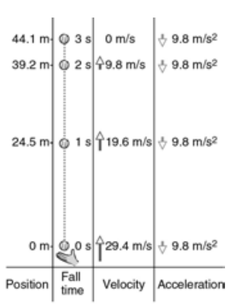
Falling Downward



A Falling Ball, Part 2

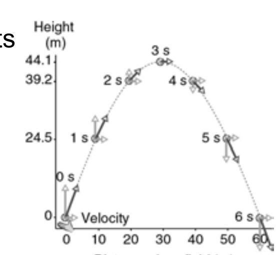
- A falling ball can start by heading upward!
  - Velocity starts in the upward direction
  - Velocity becomes less and less upward
  - Altitude increases at an ever slower rate
  - At some point, velocity is momentarily zero
  - Velocity becomes more and more downward
  - Altitude decreases at ever faster rate

Falling Upward First



Throws and Arcs

- Gravity only affects vertical motion
- A ball can coast horizontally while falling vertically



Question:

Suppose that I throw a ball upward into the air. After the ball leaves my hand, is there any force pushing the ball upward?

Summary About Falling Balls

- A free ball experiences only gravity
  - Its inertia tends to make it go straight
  - But its weight makes it accelerate downward
  - Its velocity becomes increasingly downward
- Whether going up or down, it's still falling
- Horizontal motion is independent of falling

Ramps

Question:

Can a ball ever push downward on a table with a force greater than the ball's weight?

Observations About Ramps

- Lifting an object straight up is often difficult
- Pushing the object up a ramp is usually easier
- The ease depends on the ramp's steepness
- Shallow ramps require only gentle pushes
- You seem to get something for nothing
- How does distance figure in to the picture?

Type of Force

- Support force
  - Prevents something from penetrating surface
  - Points directly away from that surface

Physics Concept

- Net Force
  - The sum of all forces on an object.
  - Determines object's acceleration.

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.

Experiment:

If you push on a friend who is moving away from you, how will the force you exert on your friend compare to the force your friend exerts on you?

1. You push harder
2. Your friend pushes harder
3. The forces are equal in magnitude

Forces Present Part 1:

1. On ball due to gravity (its weight)
2. On ball due to support from table
3. On table due to support from ball

All three forces have the same magnitude for the stationary ball

Forces Present Part 2:

1. On ball due to gravity (its weight)
2. On ball due to support from table
3. On table due to support from ball

Pair

Forces Present Part 3:

1. On earth due to gravity from the ball
2. On ball due to gravity from the earth
3. On ball due to support from table
4. On table due to support from ball

Pair

Pair

- Since the ball doesn't accelerate, 2 and 3 must cancel perfectly

Question:

Can a ball ever push downward on a table with a force greater than the ball's weight?

Two Crucial Notes:

- While the forces two objects exert on one another must be equal and opposite, the net force on each object can be anything.
- Each force within an equal-but-opposite pair is exerted on a different object, so they don't cancel directly.

Physical Quantities

- Energy
  - A conserved quantity
  - The capacity to do work
- Work
  - The mechanical means of transferring energy
  - work = force · distance

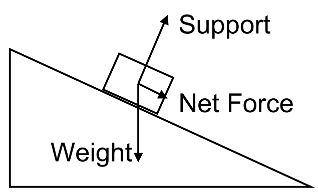
    (where force and distance are in same direction)

Work Lifting a Ball, Part 1

- Going straight up:
  - Force is large
  - Distance is small

work = **force** · distance

Forces on a Ramp



Work Lifting a Ball, Part 2

- Going up ramp:
  - Force is small
  - Distance is large

work = force · **distance**

Work Lifting a Ball, Part 3

- Going straight up:

  work = **force** · distance
- Going up ramp:

  work = force · **distance**
- The work is the same, either way!

Physics Concept

- Mechanical Advantage
  - Doing the same amount of work
  - Redistributing force and distance

Summary about Ramps

- Ramp partially supports object’s weight
- Ramp exchanges force for distance
- Overall work done is unchanged

Seesaws

Question:

- You and a child half your height lean out over the edge of a pool at the same angle. If you both let go simultaneously, who will tip over faster and hit the water first?

Observations About Seesaws

- A balanced seesaw can
  - remain horizontal
  - rock back and forth easily
- Equal-weight children balance a seesaw
- Unequal-weight children don't balance
- But moving the heavy child inward helps

Physics Concept

- Rotational Inertia
  - A body at rest tends to remain at rest.
  - A body that's rotating tends to continue rotating.

Physical Quantities

- Angular Position – an object's orientation
- Angular Velocity – its change in angular position with time
- Torque – a twist or spin

Newton's First Law of Rotational Motion

- A rigid object that's not wobbling and that is free of outside torques rotates at a constant angular velocity.

Center of Mass

- Point about which object's mass balances
- A free object rotates about its center of mass while its center of mass follows the path of a falling object

Physical Quantities

- Angular Position – an object's orientation
- Angular Velocity – its change in angular position with time
- Torque – a twist or spin
- Angular Acceleration – its change in angular velocity with time
- Moment of Inertia – its rotational inertia

Newton's Second Law of Rotational Motion

- The torque exerted on an object is equal to the product of that object's moment of inertia times its angular acceleration. The angular acceleration is in the same direction as the torque.

Torque = Moment of Inertia · Angular Acceleration

Physics Concept

- A force can produce a torque
- A torque can produce a force

Torque = Lever Arm · Force

(where the lever arm is perpendicular to the force)

Physics Concept

- Net Torque
  - The sum of all torques on an object.
  - Determines that object's angular acceleration.

Question:

- You and a child half your height lean out over the edge of a pool at the same angle. If you both let go simultaneously, who will tip over faster and hit the water first?

Summary about Seesaws

- A balanced seesaw
  - experiences zero net torque
  - moves at constant angular velocity
  - requires all the individual torques to cancel
- Force and lever arm contribute to torque
- Heavier children produce more torque
- Sitting close to the pivot reduces torque

Wheels

Question:

- You are in a tremendous hurry and you want your car to accelerate as quickly as possible when the light turns green. Tire damage is not an issue. Will you accelerate faster if you “burn rubber” (skid your wheels) or if you just barely avoid skidding your wheels?

Observations About Wheels

- Without wheels, objects slide to a stop
- Friction is responsible for stopping effect
- Friction seems to make energy disappear
- Wheels eliminate friction, or so it seems
- Wheels can also propel vehicles, but how?

Friction

- Opposes relative motion of two surfaces
- Acts to bring two surfaces to one velocity
- Consists of a matched pair of forces:
  - Object 1 pushes on object 2
  - Object 2 pushes on object 1
  - Equal magnitudes, opposite directions
- Comes in two types: static and sliding

Types of Friction

- Static Friction
  - Acts to prevent objects from starting to slide
  - Forces can vary from zero to an upper limit
- Sliding Friction
  - Acts to stop objects that are already sliding
  - Forces have fixed magnitudes

Frictional Forces

- Increase when you:
  - push the surfaces more tightly together
  - roughen the surfaces
- Peak static force greater than sliding force
  - Surface features can interpenetrate better
  - Friction force drops when sliding begins

Question:

- You are in a tremendous hurry and you want your car to accelerate as quickly as possible when the light turns green. Tire damage is not an issue. Will you accelerate faster if you “burn rubber” (skid your wheels) or if you just barely avoid skidding your wheels?

Friction and Wear

- Static friction
  - No work is done (no distance)
  - No wear occurs
- Sliding friction
  - Work is done (distance in direction of force)
  - Wear occurs
  - Work is turned into thermal energy

Conserved Quantity

- Energy
  - A directionless (scalar) quantity
  - Can’t be created or destroyed
  - Transferable between objects via work
  - Can be converted from one form to another

Forms of Energy

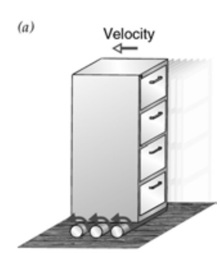
- Kinetic: energy of motion
- Potential: stored in forces between objects
  - Gravitational
  - Elastic
  - Magnetic
  - Electric
  - Electrochemical
  - Chemical
  - Nuclear

Types of Energy

- Ordered Energy
  - Organized in chunks (e.g. work)
- Disordered Energy
  - Fragmented (e.g. thermal energy)
- Sliding friction disorders energy
  - Converts work into thermal energy

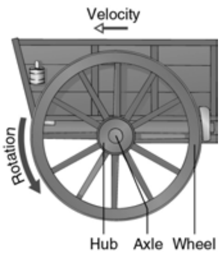
Rollers

- Eliminate sliding friction at roadway
- Are inconvenient because they keep popping out from under the object



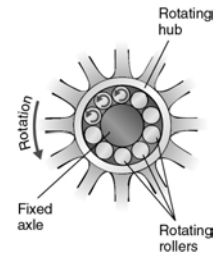
Wheels

- Eliminate sliding friction at roadway
- Are convenient because they don't pop out
- Wheel hubs still have sliding friction



Bearings

- Eliminate sliding friction in wheel hub
- Behave like automatically recycling rollers



Summary about Wheels

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

Bumper Cars

Question:

- You are riding on the edge of a spinning playground merry-go-round. If you pull yourself to the center of the merry-go-round, what will happen to its rotation?
- It will spin faster.
- It will spin slower.
- It will spin at the same rate.

Observations About Bumper Cars

- Moving cars tend to stay moving
- It takes time to change a car's motion
- Impacts alter velocities & ang. velocities
- Cars seem to exchange their motions
- Heavily loaded cars are hardest to redirect
- Heavily loaded cars pack the most wallop

Momentum

- Translating bumper car carries momentum
- Momentum
  - A conserved quantity (can't create or destroy)
  - A directed (vector) quantity
  - Measures difficulty reaching velocity

Momentum = Mass · Velocity

Exchanging Momentum

- Impulse
  - The only way to transfer momentum
  - Impulse is a directed (vector) quantity

Impulse = Force · Time

- Because of Newton's third law, if object 1 gives an impulse to object 2, then object 2 gives an equal but oppositely directed impulse to object 1.

Head-On Collisions

- Cars exchange momentum via impulse
- Total momentum remains unchanged
- The least-massive car experiences largest change in velocity

Angular Momentum

- A spinning car carries angular momentum
- Angular momentum
  - A conserved quantity (can't create or destroy)
  - A directed (vector) quantity
  - Measures difficulty reaching angular velocity

  Angular momentum =
  Moment of inertia · Angular velocity

Newton's Third Law of Rotational Motion

- For every torque that one object exerts on a second object, there is an equal but oppositely directed torque that the second object exerts on the first object.

Exchanging Angular Momentum

- Angular Impulse
  - The only way to transfer angular momentum
  - Angular impulse is a directed (vector) quantity

  Angular impulse = Torque · Time
- Because of Newton's third law, if object 1 gives an angular impulse to object 2, then object 2 gives an equal but oppositely directed angular impulse to object 1.

Glancing Collisions

- Cars exchange angular momentum via angular impulse
- Total angular momentum about a chosen point in space remains unchanged
- The car with smallest moment of inertia about that chosen point experiences largest change in angular velocity

Changing Moment of Inertia

- Mass can't change, so the only way an object's velocity can change is if its momentum changes
- Moment of inertia can change, so an object that changes shape can change its angular velocity without changing its angular momentum

Question:

- You are riding on the edge of a spinning playground merry-go-round. If you pull yourself to the center of the merry-go-round, what will happen to its rotation?
- It will spin faster.
- It will spin slower.
- It will spin at the same rate.

Kinetic Energy

- A moving bumper car has kinetic energy:

  Kinetic energy = ½ · Mass · Speed^2
- A spinning bumper car has kinetic energy:

  Kinetic energy = ½ · Moment of inertia · Angular speed^2
- A typical bumper car has both
- High impact collisions release lots of energy!

Physics Concept

- Acceleration always occurs toward the direction that reduces an object's potential energy as rapidly as possible.

Summary about Bumper Cars

- During collisions, they exchange
  - momentum via impulses
  - angular momentum via angular impulses
- Collisions have less effect on
  - cars with large masses
  - cars with large moments of inertia

Spring Scales

Question:

- A diver stands motionless at the end of a spring board, which bends downward. If her identical twin joins her, how far downward will the board then bend?

- The same amount.
- Twice as far.
- Four times as far.

Observations About Spring Scales

- They move when you weigh things
- They take a moment to settle down
- They weigh best when all is still
- The “zero” often drifts
- They must be positioned carefully
- They grow inaccurate with age

How Much Is There?

- How can you measure quantity?
  – Number
  – Length
  – Volume
  – Weight
  – Mass

Mass as a Measure

- Pros:
  – Independent of measuring location
  – Measured directly by acceleration
- Cons:
  – Acceleration measurements are difficult

Weight as a Measure

- Pros:
  – Proportional to mass (at one location)
  – Easier to measure than mass
- Cons:
  – Dependent on measuring location
  – Can’t be measured directly
- Measured via an equilibrium technique

Equilibrium

- An object in equilibrium
  - experiences zero net force
  - is not accelerating
- At equilibrium,
  - individual forces balance perfectly
  - an object at rest remains at rest
  - an object in motion coasts

Weighing Via Equilibrium

- Use an upward support force to balance an object's downward weight
- Attain equilibrium
- Measure the support force
- The object's weight is equal in magnitude to the measured support force.

A Free Spring

- A free spring adopts a certain length
- Its ends experience zero net force
- Its ends are in equilibrium
- The spring is at its equilibrium length

A Distorted Spring

- Forces act on ends of a distorted spring
- These forces
  - act to restore the spring to equilibrium length
  - are called "restoring forces"
  - make the equilibrium length "stable"
  - 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
  - Allow spring to distort to an equilibrium
  - Measure distortion of spring
  - Spring constant relates distortion to force
  - Report the force

Question:

- A diver stands motionless at the end of a spring board, which bends downward. If her identical twin joins her, how far downward will the board then bend?

- The same amount.
- Twice as far.
- Four times as far.

Spring Scales and Acceleration

- Weight measurement requires equilibrium
- Without equilibrium,
  - spring force doesn't balance weight
  - "measurement" is meaningless
- An accelerating object is not at equilibrium
  - You must not bounce on a scale!
  - Wait for the scale to settle before reading!

Summary about Spring Scales

- The spring stretches during weighing
- This stretch is proportional to the weight
- The scale measures the spring's stretch
- The scale reports weight based on stretch

Bouncing Balls

Question:

- If you place a tennis ball on a basketball and drop this stack on the ground, how high will the tennis ball bounce?

- To approximately its original height.
- Much higher than its original height.
- Much less than its original height.

Observations About Bouncing Balls

- Some balls bounce better than others
- Underinflated balls bounce poorly
- Balls don't bounce higher than they started
- Ball can bounce from moving objects

Bouncing from Rigid, Motionless Surfaces

- Approaching ball has "collision" KE.
- During impact, ball has elastic PE.
- Rebounding ball has "rebound" KE.
- Some collision energy becomes thermal.
  - "Lively" balls lose little energy.
  - "Dead" balls lose much energy.
- In general: rebound KE < collision KE

Coefficient of Restitution

- Measure of a ball's liveliness.
- Ratio of outgoing to incoming speeds.

Coefficient of restitution =
Outgoing speed / Incoming speed

Bouncing from Elastic, Motionless Surfaces

- Both ball and surface dent during bounce.
- Work is proportional to dent distance.
- Denting surface stores & returns energy.
  - "Lively" surface loses little energy.
  - "Dead" surface loses much energy.
- Surface has a coefficient of restitution, too.

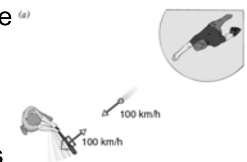
Bouncing from Moving Surfaces

- Incoming speed → Approaching speed.
- Outgoing speed → Separating speed.
- Coefficient of Restitution becomes:

Coefficient of restitution =
Separating speed / Approaching speed

Ball and Bat Part 1

- Ball approaches home plate at 100 km/h.
- Bat approaches pitcher at 100 km/h.
- Approaching speed is 200 km/h.

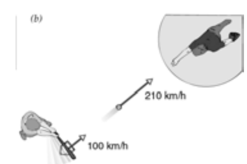


Ball and Bat Part 2

- Approaching speed is 200 km/h.
- Baseball's Coefficient of Restitution: 0.55.
- Separating speed is 110 km/h.

Ball and Bat Part 3

- Separating speed is 110 km/h.
- Bat approaches pitcher at 100 km/h.
- Ball approaches pitcher at 210 km/h.



Question:

- If you place a tennis ball on a basketball and drop this stack on the ground, how high will the tennis ball bounce?

- To approximately its original height.
- Much higher than its original height.
- Much less than its original height.

Bouncing's Effects on Objects

- Bouncing involves momentum transfer
  - Momentum transferred while stopping
  - Momentum transferred while rebounding
  - A better bounce transfers more momentum
- Bouncing can involve energy transfer
- Together, these transfers govern bouncing
  - Identical elastic balls transfer motion perfectly

Impact Forces

- Harder surfaces bounce faster
  - Momentum is transferred faster
  - Time is shorter, so force is larger
- No one likes bouncing off hard surfaces

Ball's Effects on a Bat

- Ball pushes bat back and twists it, too
- When ball hits bat's center of percussion,
  - backward and rotational motions balance.
  - handle doesn't jerk.
- When ball hits vibrational node
  - bat doesn't vibrate.
  - more energy goes into ball.

Summary About Bouncing Balls

- Each ball has a coefficient of restitution
- Energy lost in a bounce becomes thermal
- The surface can affect a ball's bounce
- Surfaces bounce, too.

Carousels and Roller Coasters

Question:

- When the wine glass was directly above my head, was there a force pushing up on the wine glass that kept the glass against the tray?

Observations About Carousels & Roller Coasters

- You can feel motion with your eyes closed
- You feel pulled in unusual directions
- You sometimes feel weightless
- You often can't tell when you're inverted

The Experience of Weight

- When you are at equilibrium,
  - a support force balances your weight
  - support force acts on your lower surfaces
  - weight force acts throughout your body
- You feel internal supporting stresses
- You identify these stresses as weight

The Experience of Acceleration

- When you are accelerating,
  - a support force usually causes acceleration
  - support force acts on your surfaces
  - inertia resists acceleration throughout your body
- You feel internal supporting stresses
- You misidentify these stresses as weight

Acceleration and Weight

- Fictitious "force"—felt while accelerating
  - Feeling caused by your body's inertia
  - Directed opposite your acceleration
  - Proportional to the acceleration
- "Apparent weight"—felt due to the combined effects of gravitational and fictitious "forces"

Carousels, Part 1

- Riders undergo “uniform circular motion”
  - Riders follow a circular path
  - Riders move at constant speed
- UCM involves centripetal acceleration
  - Acceleration points toward the circle’s center
  - Depends on speed and circle size

Acceleration = velocity^2 / radius

Carousels, Part 2

- Centripetal acceleration requires
  - force directed toward circle’s center
  - This centripetal force is a true force
- Centripetal acceleration yields
  - a fictitious “force” called “centrifugal force”
  - “Force” is directed away from circle’s center
  - An experience of inertia, not a real force

Question:

- When the wine glass was directly above my head, was there a real force pushing up on the wine glass that kept the glass against the tray?

Roller Coasters Part 1 – Hills

- During hill descent,
  - acceleration is downhill
  - fictitious “force” is uphill
  - apparent weight is weak and into the track
- At bottom of hill,
  - acceleration is approximately upward
  - fictitious “force” is approximately downward
  - apparent weight is very strong and downward

Roller Coasters Part 2 – Loops

- At top of loop-the-loop,
  - acceleration is strongly downward
  - fictitious “force” is strongly upward
  - apparent weight is weak but upward!

Choosing a Seat

- As you go over cliff-shaped hills,
  - acceleration is downward
  - fictitious “force” is upward
  - higher speed $\rightarrow$ more acceleration and “force”
- First car goes over cliff slowly
- Last car goes over cliff quickly
- Last car has best weightless feeling!

Summary About Carousels & Roller Coasters

- You are often accelerating on these rides
- Feel fictitious “force” opposite acceleration
- Your apparent weight isn’t always down
- Your apparent weight can become small
- Your apparent weight can even point up

Bicycles 1

Bicycles

Bicycles 2

Question:

- How would raising the height of a small pickup truck affect its turning stability?

1. Make it less likely to tip over.
2. Make it more likely to tip over.
3. Have no overall effect on its stability.

Bicycles 3

Observations About Bicycles

- Impossible to keep upright while stationary
- Easy to keep upright while moving forward
- Require leaning during turns
- Can be ridden without hands
- Are easier to ride when they have gears

Bicycles 4

Vehicle's Static Stability, Part 1

- Static stability is determined by
  - base of support: polygon formed by ground contact points
  - center of gravity: effective point at which gravity acts
- Static stability occurs when
  - center of gravity is above base of support

Bicycles 5

Vehicle's Static Stability, Part 2

- Center of gravity above base of support,
  - gravitational potential rises when tipped
  - accelerates away from direction of tip
  - vehicle always returns to equilibrium
  - vehicle in stable equilibrium (statically stable)

Bicycles 6

Vehicle's Static Stability, Part 3

- Center of gravity not above base of support,
  - gravitational potential drops when tipped
  - accelerates in direction of tip
  - vehicle never returns to equilibrium
  - vehicle tips over (statically unstable)

Bicycles 7

Vehicle's Static Stability, Part 4

- Center of gravity is above edge of base,
  - vehicle in unstable equilibrium
  - accelerates in direction of any tip
  - vehicle never returns to this equilibrium

Bicycles 8

Stationary Vehicles

- Base of support requires ≥3 contact points
- Tricycles
  - have 3 contact points
  - are statically stable and hard to tip over
- Bicycles
  - have only 2 contact points
  - are statically unstable and tip over easily

Bicycles 9

Vehicle's Dynamic Stability, Part 1

- Dynamic stability is determined by
  - statics: base of support, center of gravity
  - dynamics: inertia, accelerations, horiz. forces

Bicycles 10

Vehicle's Dynamic Stability, Part 2

- Dynamic effects can fix a vehicle's stability
  - place base of support under center of gravity
  - dynamically stabilize an equilibrium
  - make vehicle dynamically stable

Bicycles 11

Vehicle's Dynamic Stability, Part 3

- Dynamic effects can ruin a vehicle's stability
  - displace base of support from center of gravity
  - dynamically destabilize an equilibrium
  - make vehicle dynamically unstable

Bicycles 12

Moving Vehicles

- Tricycles
  - can't lean during turns
  - dynamically unstable and easy to flip
- Bicycles
  - can lean during turns to maintain stability
  - naturally steer center of gravity under base
  - dynamically stable and hard to flip

Bicycles 13

Bicycle's Automatic Steering

- A bicycle steers automatically
  - places base of support under center of gravity
  - due to gyroscopic precession of front wheel (ground's torque on spinning wheel steers it)
  - due to design of its rotating front fork (fork steers to reduce gravitational potential)

Bicycles 14

Torques and Tipping Over

- Torques act about bicycle's center of mass
  - Support force acts at wheels, causes torque
  - Friction acts at wheels, causes torque
  - Weight acts at center of mass, no torque
- If torques don't cancel
  - net torque on bicycle
  - bicycle undergoes angular acceleration
  - bicycle tips over

Bicycles 15

Leaning During Turns, Part 1

- When not turning and not leaning,
  - zero support torque (force points toward pivot)
  - zero frictional torque (no frictional force)
  - bicycle remains upright

Bicycles 16

Leaning During Turns, Part 2

- When turning and not leaning,
  - zero support torque (force points toward pivot)
  - nonzero frictional torque (frictional force)
  - bicycle flips over

Bicycles 17

Leaning During Turns, Part 3

- When turning and leaning correctly,
  - nonzero support torque (force not at pivot)
  - nonzero frictional torque (frictional force)
  - two torques cancel (if you're leaning properly)
  - bicycle remains at steady angle
- Bicycles can lean and thus avoid flipping
- Tricycles can't lean so flip during turns

Bicycles 18

Question:

- How would raising the height of a small pickup truck affect its turning stability?

1. Make it less likely to tip over.
2. Make it more likely to tip over.
3. Have no overall effect on its stability.

Bicycles 19

Gear Selection

- From rider's perspective, ground is moving
- With each crank, ground moves a distance
  - Ground distance covered increases with gear
  - Work done per crank increases with gear
  - Pedal forces must increase with gear
- High gear yields high speed (level road)
- Low gear yields easy pedaling (steep hills)

Bicycles 20

Mechanical Advantage

- Gears allow you to exchange force for distance or distance for force.
- On hills, low gear lets your feet move large distances to exert large force on wheel.
- On descents, high gear lets your feet push hard to move rear wheel long distances.

Bicycles 21

Rolling and Energy

- Wheel rim moves *and* spins.
- A kilogram in the wheel rim has twice the kinetic energy of a kilogram in the frame.
- To start the bicycle moving, you must provide its energy.
- Massive bicycles, particularly with massive wheels, are hard to start or stop.

Bicycles 22

Rolling Resistance

- As a wheel rolls, its surface dents inward
- Denting a surface requires work
- An underinflated tire
  - has a low coefficient of restitution
  - doesn't return work done on it well
  - wastes energy as it rolls

Bicycles 23

Braking

- Sliding friction wastes bicycle's and rider's kinetic energies as thermal energy.
- Braking power is proportional to:
  - sliding frictional force between pads and rim
  - support force on brake pads
  - tension of brake cable
  - force on brake levers

Bicycles 24

Braking problems

- Brake too hard,
  - wheels stop rotating and start skidding
  - energy is wasted and steering fails
- Slowing force exerts a torque on bicycle
  - Rider and bicycle can flip head first
  - Rear wheel loses traction and may "fishtail"
  - Front wheel has improved traction

Summary
About Bicycles

- Are statically unstable
- Are dynamically stable
- Naturally steer under your center of gravity
- Use gears for mechanical advantage
- Use work from you to get started
- Convert work into thermal energy to stop

Balloons

Question:

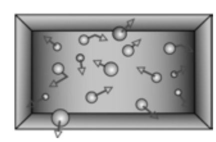
- A helium balloon has mass, yet it doesn't fall to the floor. Is there a real force pushing up on the helium balloon?

Observations About Balloons

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

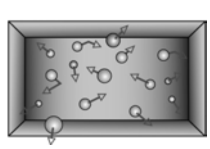
Air's Characteristics

- Air is a gas
  – Consists of individual atoms and molecules
  – Particles kept separate by thermal energy
  – Particles bounce around in free fall



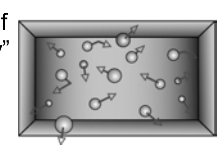
Air and Pressure

- Air has pressure
  – Air particles exerts forces on container walls
  – Average force is proportional to surface area
  – Average force per unit of area is called "pressure"



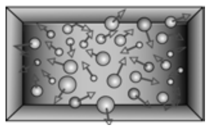
Air and Density

- Air has density
  – Air particles have mass
  – Each volume of air has a mass
  – Average mass per unit of volume is called "density"



Air Pressure and Density

- Air pressure is proportional to density
  - Denser particles hit surface more often
  - Denser air → more pressure



Pressure Imbalances

- Balanced pressure exerts no overall force
  - Forces on balloon's sides cancel
- Unbalanced pressure exerts overall force
  - Forces on balloon's sides don't cancel
  - Forces push balloon toward lower pressure
- Air pressure also pushes on the air itself
  - Air itself is pushed toward lower pressure

The Atmosphere

- Air near the ground supports air overhead
  - Air pressure is highest near the ground
  - Air density is highest near the ground
- Key observations:
  - Air pressure decreases with altitude
  - A balloon feels more force at bottom than top
  - Imbalance yields an upward buoyant force

Archimedes' Principle

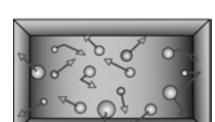
- A balloon immersed in a fluid experience an upward buoyant force equal to the weight of the fluid it displaces

Cold-Air Balloon in Air

- A rubber, cold-air-filled balloon
  - weighs more than the cold air it displaces
  - experiences a downward net force in cold air
  - sinks in cold air
- Its average density is greater than that of cold air

Air and Temperature

- Air pressure is proportional to temperature
  - Faster particles hit surface more and harder
  - Hotter air → more pressure



An Aside About Temperature

- Air has temperature
  - Air particles have thermal kinetic energy
  - Average thermal kinetic energy is proportional to absolute temperature
- SI absolute temperature: kelvins or K
  - 0 K is absolute zero — no thermal energy left
  - Step size: 1 K step same as 1 °C step

Hot-Air Balloon in Air

- A rubber, hot-air-filled balloon
  - contains fewer air particles than if it were cold
  - weighs less than the cold air it displaces
  - experiences an upward net force in cold air
  - floats in cold air
- Its average density is less than that of cold air

Helium vs. Air

- Replacing air particles with helium atoms
  - reduces the gas's density
    - helium atoms have less mass than air particles
  - leaves the gas's pressure unchanged
    - less massive helium atoms travel faster & hit more

Helium Balloon in Air

- A rubber, helium-filled balloon
  - has same particle density as air
  - weighs less than the air it displaces
  - experiences an upward net force in air
  - floats in air
- Its average density is less than that of air

Question:

- A helium balloon has mass, yet it doesn't fall to the floor. Is there a real force pushing up on the helium balloon?

Ideal Gas Law

Pressure = Boltzmann constant · Particle density · Absolute temperature

- Only applies perfectly to independent particles
- Real particles are not completely independent

Summary About Balloons

- Balloons float when their average densities are less than that of air
- Helium balloons float because helium atoms are lighter than air particles
- Hot-air balloons float because hot air is less dense than cold air

Water Distribution

Question:

- Water enters your home plumbing at ground level. Where will you get the strongest spray from a shower?

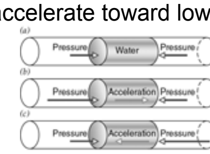
- In the ground floor shower
- In the basement shower
- In the second floor shower

Observations About Water Distribution

- Water is pressurized in the pipes
- Higher pressure water sprays harder
- Higher pressure water sprays higher
- Water is often stored up high

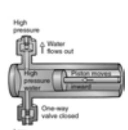
Fluid Motion (no gravity)

- Fluids obey Newton's laws
  - Net forces cause accelerations
  - Net forces are due to pressure imbalances
  - Fluids accelerate toward lowest pressures



Pressurizing Water

- To pressurize water,
  - use of Newton's third law
  - push inward on the water
  - water pushes outward on you
  - water's outward push is due to its pressure
  - water pressure rises as you squeeze it



Pumping Water (no gravity)

- Squeeze water to raise its pressure
- Water accelerates toward lowest pressure
- Water begins flowing
- You do work on the water
  - You keep squeezing as water flows
  - Water moves in direction of your force
  - In this case: Work = Pressure · Volume

Pressure Potential Energy

- Pumping water requires work
- Pumped water carries energy with it
- Energy isn't really stored, it's promised
  – but energy resembles a potential energy
  – so it's called pressure potential energy (PPE)
- PPE requires steady-state flow (SSF)

Energy Conservation (no gravity)

- In SSF through fixed obstacles, fluid's energy and energy/volume are constants
- Energy is PPE + KE (Kinetic Energy)
- Bernoulli's equation (no gravity):

PPE + KE = Constant

PPE/Vol + KE/Vol = Constant/Vol

(along a streamline)

Fluid Motion (with gravity)

- Fluids obey Newton's laws
  – Weight contributes to net force
  – Weight creates pressure gradients
    - Pressure decreases with altitude.
    - Pressure increases with depth.
  – Fluids have gravitational potential energy (GPE)

Energy Conservation (with gravity)

- Energy is PPE + KE + GPE
- Bernoulli's equation:

PPE + KE + GPE = Constant

PPE/Vol + KE/Vol + GPE/Vol = Constant/Vol

(*along a streamline*)

Question:

- Water enters your home plumbing at ground level. Where will you get the most intense shower spray?

- In the ground floor shower
- In the basement shower
- In the second floor shower

Summary About Water Distribution

- Water's energy is conserved during SSF
- Water's energy changes form in pipes
- Pressure drops as water's height or speed rise
- Storing water up high gives it higher energy

Garden Watering

Question:

- Water pours weakly from an open hose but sprays hard when you cover most of the end with your thumb. When is more water coming out of the hose?

- When the hose end is uncovered
- When your thumb covers most of the end

Observations About Garden Watering

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

Faucets: Limiting Flow

- Water's total energy limited by its pressure
  - Maximum kinetic energy limited by total energy
  - Maximum speed limited by kinetic energy
- Water has viscosity (friction within the fluid)
  - Water at the walls is stationary
  - Remaining water slows due to viscous forces

Viscous Forces

- Oppose relative motion within a fluid
- Similar to sliding friction – waste energy
- Fluids are characterized by their viscosities

Hoses: Limiting Flow

- Water flow through a hose:
  - Increases as 1/viscosity
  - Increases as 1/hose length
  - Increases as pressure difference
  - Increases as (pipe diameter)^4
- Poiseuille's law:

Water Flow in a Hose

- Flowing water loses energy to viscous drag
- Viscous drag increases with flow speed
  - Faster flow leads to more viscous energy loss
  - Faster flow causes quicker drop in pressure

Question:

- Water pours weakly from an open hose but sprays hard when you cover most of the end with your thumb. When is more water coming out of the hose?

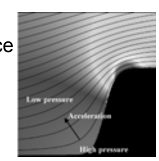
- When the hose end is uncovered
- When your thumb covers most of the end

Accelerating Flows

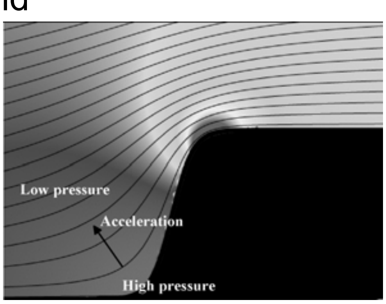
- Water in steady-state flow can accelerate
- Acceleration must be partly to the side
  - Forward acceleration would expand water
  - Backward acceleration would compress water
- Sideways acceleration
  - requires obstacles
  - causes pressure imbalances
  - causes speed changes

Outward Bend

- Deflecting water away from a surface
  - involves acceleration away from the surface
  - is caused by an outward pressure gradient
    - higher pressure near surface
    - lower pressure away from surface
  - causes water to travel slower near the surface

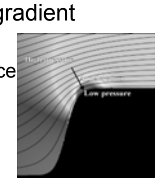


Outward Bend

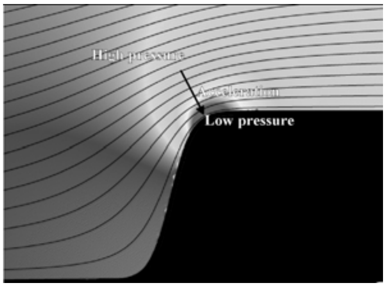


Inward Bend

- Deflecting water toward a surface
  - involves acceleration toward surface
  - is caused by inward pressure gradient
    - lower pressure near surface
    - higher pressure away from surface
  - causes water to travel faster near the surface

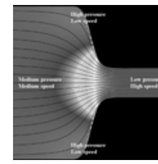


Inward Bend

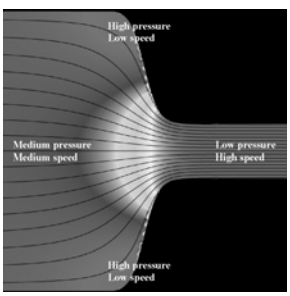


Nozzles: Speeding Water Up

- Water passing through a narrowing
  - speeds up
  - experiences pressure drop
- Water passing through a widening
  - slows down
  - experiences a rise in pressure



Nozzles



Types of Flow

- Laminar Flow
  - Nearby regions of water remain nearby
  - Viscosity dominates flow
- Turbulent Flow
  - Nearby regions of water become separated
  - Inertia dominates flow

Reynolds Number

- Reynolds number controls type of flow
- Below about 2300 : Laminar flow
  - Viscosity dominates
- Above about 2300 : Turbulent flow
  - Inertia dominates

Water and Momentum

- Water carries momentum
- Momentum is transferred by impulses: impulse =
  pressure imbalance · surface area · time
- Large transfers: long times, large surface areas, or large pressure imbalances
- Moving water can be hard to stop

Summary About Garden Watering

- Total energy limits speed, height, pressure
- Nozzles exchange pressure for speed
- Viscosity wastes energy of water
- Turbulence wastes energy of water
- Moving water has momentum, too

Balls and Frisbees

Question:

- A smooth, gentle river is flowing past a cylindrical post. At the sides of the post, is the water level higher, lower, or equal to its level in the open river?

Observations About Balls and Frisbees

- Balls slow down in flight
- The faster a ball goes, the quicker it slows
- Spinning balls curve in flight
- Frisbees use air to support themselves

Aerodynamic Forces

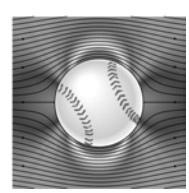
- Drag Forces
  - push the object directly downstream
  - result from slowing the fluid flow
  - transfer downstream momentum to the object
- Lift Forces
  - push the object at right angles to the flow
  - result from deflecting the fluid flow
  - transfer sideways momentum to the object

Drag & Lift

- Surface friction causes viscous drag
- Turbulence causes pressure drag
- Deflected flow causes lift
- Deflected flow causes induced drag

Perfect Flow Around a Ball

- Outward bend in front
  - high pressure, slow flow
- Inward bend on sides
  - low pressure, fast flow
- Outward bend in back
  - high pressure, slow flow
- Pressures balance, so only viscous drag



Question:

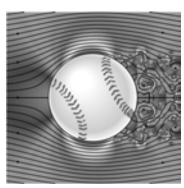
- A smooth, gentle river is flowing past a cylindrical post. At the sides of the post, is the water level higher, lower, or equal to its level in the open river?

Onset of Turbulence

- Rising pressure slows fluid
  - Fluid accelerates backward as pressure rises
  - Fluid loses speed but its pressure rises
- Viscous drag slows flow near surface
  - Surface layer of fluid loses total energy
  - Fluid loses both speed and pressure
- If surface flow stops, turbulence ensues

Imperfect Flow, Low Speeds

- Pressure rises in front
- Pressure drops on side
- Big wake forms behind
- Wake pressure is approximately ambient
- Ball experiences large pressure drag

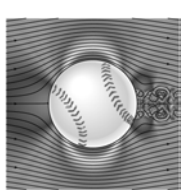


Boundary Layer

- Flow near surface forms “boundary layer”
- At low Reynolds number (<100,000)
  - boundary layer is laminar
  - slowed by viscous drag
- At high Reynolds number (>100,000)
  - boundary layer is turbulent
  - not slowed much

Imperfect Flow, High Speeds

- Pressure rises in front
- Pressure drops on side
- Small wake forms behind
- Wake pressure is approximately ambient
- Ball experiences small pressure drag

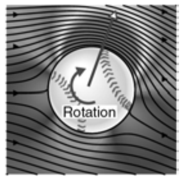


Tripping the Boundary Layer

- To reduce pressure drag
  - initiate turbulence in the boundary layer (trip)
  - delay flow separation on back of ball
  - shrink the turbulent wake
- Examples: Tennis balls and Golf balls

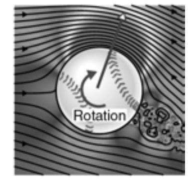
Spinning Balls, Magnus Force

- Surface pulls flow with it
- One side experiences longer inward bend
- That side has lower pressure and faster flow
- Overall flow is deflected
- Magnus lift force



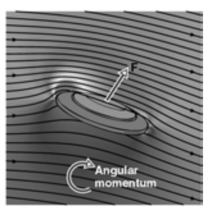
Spinning Balls, Wake Force

- Surface pulls flow with it
- Wake is asymmetric
- Overall flow is deflected
- Wake deflection lift force



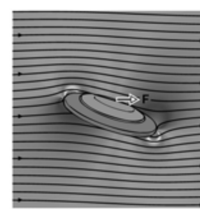
Frisbees

- Above Frisbee
  - airflow bends inward
  - low pressure, high speed
- Below Frisbee
  - airflow bends outward
  - high pressure, low speed
- Pressure imbalance lifts the Frisbee



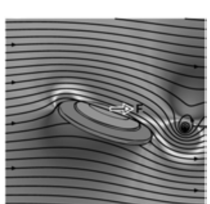
Starting Flight

- Airflow starts symmetric
- No net deflection of air
- No lift



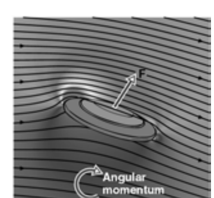
Vortex Shedding

- Trailing airflow unstable
- Vortex peals away with ccw angular momentum
- Remaining airflow has cw angular momentum



Stable lift

- After vortex is shed, Frisbee has lift
- Air is deflected downward overall
- Frisbee is pushed upward by air
- Airflow around Frisbee has angular momentum



Summary About Balls and Frisbees

- The air pressures around these objects are not uniform and result in drag and lift
- Balls experience mostly pressure drag
- Spinning balls experience Magnus and Wake Deflection lift forces
- A Frisbee’s airfoil shape allows it to deflect the air to obtain lift

Airplanes

Question:

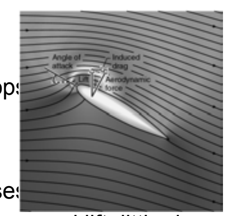
- As you ride in a jet airplane, the clouds are passing you at 600 mph. The air just in front of one of the huge jet engine intake ducts is traveling
- much faster than 600 mph.
- much slower than 600 mph.
- about 600 mph.

Observations About Airplanes

- They support themselves in the air
- They seem to follow their tilt, up or down
- They need airspeed to fly
- They can only rise so quickly
- Their wings often change shape in flight
- They have various propulsion systems

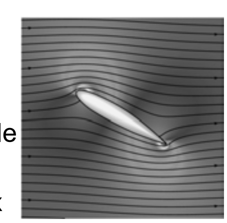
Lifting Wing

- Under the wing,
  - air follows outward bend
  - pressure rises, speed drops
- Over the wing,
  - air follows inward bend
  - pressure drops, speed rises
  - Wing experiences strong upward lift, little drag



At Take-Off

- Wing starts with symmetric airflow
- Wing starts with no lift
- Airflow becomes unstable at the trailing edge bend
- The wing sheds a vortex
- After the vortex leaves, the wing has lift

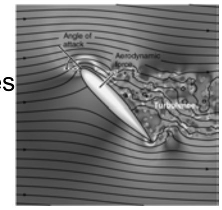


Angle of Attack

- A wing's lift depends on
  - shape of the airfoil
  - angle of attack
- Since wing is attached to plane body, the whole plane tilts to change angle of attack
- Too large an angle of attack causes the wing to "stall" – airflow separation

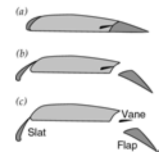
Stalled Wing

- Upper boundary layer stops heading forward
- Upper airstream detaches from wing's top surface
- Lift is reduced
- Pressure drag appears
- Wing can't support plane



Wing Shape

- Asymmetric airfoils produce large lifts
  - well suited to low-speed flight
- Symmetric airfoils produce small lifts
  - well suited to high-speed flight
  - can fly inverted easily
- High-speed planes often change wing shape in flight

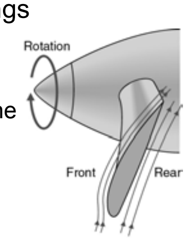


Orientation Control

- Three orientation controls:
  - Angle of attack controlled by elevators
  - Left-right tilt controlled by ailerons
  - Left-right rotation controlled by rudder
- Steering involves ailerons and rudder
- Elevation involves elevators and engine

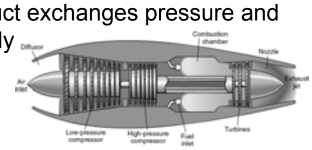
Propellers

- Propellers are spinning wings
  - They deflect air backward
  - Do work on air (add energy)
  - Pump air toward rear of plane
- Action-Reaction
  - They push the air backward
  - Air pushes them forward



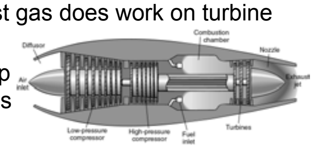
Jet Engines Part 1

- Jet engines pump air toward rear of plane
  - Engine consists of an oval ball with a complicated duct or passageway through it
  - Air inside the duct exchanges pressure and speed repeatedly
  - Engine adds energy to air inside the duct



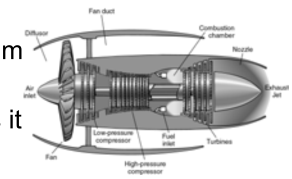
Jet Engines Part 2

- Air entering diffuser slows and pressure rises
- Compressor does work on air
- Fuel is added to air and that mixture is burned
- Expanding exhaust gas does work on turbine
- As exhaust leaves nozzle it speeds up and pressure drops



Jet Engines
Part 3

- Turbojet moves too little air and changes that air's speed too much
- Too much energy
- Too little momentum
- Turbofan moves more air and gives it less energy



Question:

As you ride in a jet airplane, the clouds are passing you at 600 mph. The air just in front of one of the huge jet engine intake ducts is traveling

1. much faster than 600 mph.
2. much slower than 600 mph.
3. about 600 mph.

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

Rockets

Question:

- If there were no launch pad beneath the space shuttle at lift-off, the upward thrust of its engines would be
- approximately unchanged.
- approximately half as much.
- approximately zero.

Observations About Rockets

- Plumes of flame emerge from rockets
- Rockets can accelerate straight up
- Rockets can go very fast
- The flame only touches the ground initially
- Rockets operate fine in empty space
- Rockets usually fly nose-first

Momentum Conservation

- A rocket's momentum is initially zero
- The momentum redistributes during thrust
  - Ship pushes on fuel; fuel pushes on ship
  - Fuel acquires backward momentum
  - Ship acquires forward momentum
- Rocket's total momentum remains zero

Rocket Propulsion

- Neglecting gravity, then
  - rocket's total momentum is always zero

$$\text{momentum}_{\text{fuel}} + \text{momentum}_{\text{ship}} = 0$$

- The momentum of the ship depends on
  - the momentum of the ejected fuel, or
  - the speed of that fuel and
  - the mass of that fuel

Question:

- If there were no launch pad beneath the space shuttle at lift-off, the upward thrust of its engines would be
- approximately unchanged.
- approximately half as much.
- approximately zero.

Rocket Engines

- Chemical reactions produce hot, high-pressure gas
- Gas speeds up in nozzle
- Gas reaches sonic speed in throat of de Laval nozzle
- Beyond throat, supersonic gas expands to speed up further

Stability and Orientation

- On ground, rocket needs static stability
- In air, rocket needs aerodynamic stability
  - Center of dynamic pressure behind c.o.m.
- In space, rocket is a freely rotating object
  - Orientation governed by angular momentum
  - Rocket can travel in any orientation

Ship's Ultimate Speed

- Increases as
  - ratio of fuel mass to ship mass increases
  - fuel exhaust speed increases
- If fuel were released with rocket at rest,

$$\text{speed}_{\text{ultimate}} = \frac{\text{mass}_{\text{fuel}}}{\text{mass}_{\text{ship}}} \cdot \text{speed}_{\text{exhaust}}$$

- Because rocket accelerates during thrust, ultimate speed is less than given above

Gravity Part 1

- The earth's acceleration due to gravity is only constant for small changes in height
- When the distance between two objects changes substantially, the relationship is:

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

Gravity Part 2

- An object's weight is only constant for small changes in height
- When its height changes significantly, the relationship is:

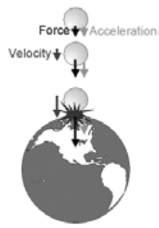
$$\text{weight} = \frac{\text{gravitational constant} \cdot \text{object} \cdot \text{earth}}{(\text{distance between centers of object and earth})^2}$$

Gravity Part 3

- An object high above the earth still weighs
- Astronauts and satellites have weights
  - weights are somewhat less than normal
  - weights depend on altitude
- Astronauts and satellites are in free fall

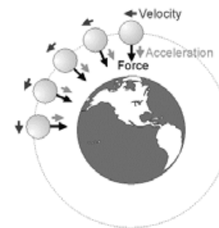
Orbits
Part 1

- An object that begins to fall from rest falls directly toward the earth
- Acceleration and velocity are in the same direction



Orbits
Part 2

- An object that has a sideways velocity follows a trajectory called an orbit
- Orbits can be closed or open, and are ellipses, parabolas, and hyperbolas



Summary
About Rockets

- Rockets are pushed forward by their fuel
- Total rocket impulse is the product of exhaust speed times exhaust mass
- Rockets can be stabilized aerodynamical
- Rockets can be stabilized by thrust alone
- After engine burn-out, rockets can orbit

Woodstoves

Question

- Which is more effective at heating a room:

- a black woodstove
- a white woodstove

Observations About Wood Stoves

- They burn wood inside closed fireboxes
- They often have long chimney pipes
- They are usually black
- You get burned if you touch them
- Heat rises off their surfaces
- It feels hot to stand near them

Thermal Energy

- is disordered energy
- is kinetic and potential energies of atoms
- gives rise to temperature
- does not include order energies:
  - kinetic energy of an object moving or rotating
  - potential energy of outside interactions

Heat

- is energy that flows between objects because of their difference in temperature
- is thermal energy on the move
- Technically, objects don't contain "heat"

Burning Wood

- Fire releases chemical potential energy
  - Wood and air consist of molecules
  - Molecules are bound by chemical bonds
  - When bonds rearrange, they release energy
  - Burning involves bond rearrangement

Chemical Forces
Part 1

- Atoms interact via electromagnetic forces
- Large separations: atoms attract
  – Attraction is weak at great distances
  – Attraction gets stronger as atoms get closer
  – Attraction reaches a maximum strength
  – Attraction weakens as they approach further

Chemical Forces
Part 2

- Medium separations: equilibrium
  – Attraction vanishes altogether at equilibrium
- Small separations: atoms repel
  – Repulsion gets stronger as atoms get closer

Chemical Bonds
Part 1

- When atoms are brought together, they
  – do work
  – release chemical potential energy
- By the time they reach equilibrium, they
  – have released a specific amount of energy
  – have become bound together chemically

Chemical Bonds
Part 2

- To separate the atoms,
  – you must do work on them
  – return the specific amount of energy to them

Chemical
Concepts

- Molecule: atoms joined by chemical bonds
- Chemical bond: chemical-force linkages
- Bond strength: work needed to break bond
- Reactants: starting molecules
- Reaction products: ending molecules

Chemical
Reactions

- Breaking old bonds takes work
- Forming new bonds does work
- If new bonds are stronger than old,
  – chemical potential energy $\rightarrow$ thermal energy
- Breaking old bonds requires energy
  – reaction requires activation energy to start

Burning Wood

- Reactants: carbohydrates and oxygen
- Products: water and carbon dioxide
- Activation energy: a burning match

Thermal Energy and Bonds

- Thermal energy causes atoms to vibrate
- Atoms vibrate about equilibrium
  - Experience restoring forces about equilibrium
  - Energy goes: potential$\rightarrow$kinetic$\rightarrow$potential…
  - Total energy is constant unless transferred
- Temperature set by thermal kinetic energy

Heat and Temperature

- Objects exchange thermal energy
  - Microscopic energy flows both ways
  - Average energy flows from hotter to colder
- Temperature predicts energy flow direction
  - No flow $\rightarrow$ thermal equilibrium $\rightarrow$ same temp
- Temperature is:
  - Average thermal kinetic energy per particle

Open Fire

- Burns wood to release thermal energy
- Good features:
  - Heat flows from hot fire to cold room
- Bad features:
  - Smoke enters room
  - Fire uses up room’s oxygen
  - Can set fire to room

Fireplace

- Burns wood to release thermal energy
- Good features:
  - Heat flows from hot fire to cold room
  - Smoke goes mostly up chimney
  - New oxygen enters room through cracks
  - Less likely to set fire on room
- Bad features:
  - Inefficient at transferring heat to room

Woodstove

- Burns wood to release thermal energy
- Good features:
  - Heat flows from hot fire to cold room
  - All the smoke goes up chimney pipe
  - New oxygen enters room through cracks
  - Relatively little fire hazard
  - Transfers heat efficiently to room

Heat Exchanger

- Woodstove is a heat exchanger
  - Separates air used by the fire from room air
  - Transfers heat without transferring smoke

Heat Transfer Mechanisms

- Conduction: heat flow through materials
- Convection: heat flow via moving fluids
- Radiation: heat flow via light waves
- All three transfer heat from hot to cold

Conduction

- Heat flows but atoms don’t
- In an insulator,
  - adjacent atoms jiggle one another
  - atoms do work and exchange energies
  - on average, heat flows from hot to cold atoms
- In a conductor,
  - mobile electrons carry heat long distances
  - heat flows quickly from hot to cold spots

Woodstoves

- Conduction
  - moves heat through the stove’s metal walls

Convection

- Fluid transports heat stored in its 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
- Natural buoyancy drives convection
  - Warmed fluid rises away from hot object
  - Cooled fluid descends away from cold object

Woodstoves

- Conduction
  - moves heat through the stove’s metal walls
- Convection
  - circulates hot air around the room

Radiation

- Heat flows by electromagnetic waves (radio waves, microwaves, light, …)
- Wave types depend on temperature
  - cold: radio wave, microwaves, infrared light
  - hot: infrared, visible, and ultraviolet light
- Higher temperature $\rightarrow$ more radiated heat
- Black emits and absorbs light best

Stefan-Boltzmann Law

- 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 emissivity is emission efficiency
- Emissivity
  - 0 is worst efficiency: white, shiny, or clear
  - 1 is best efficiency: black

Woodstoves

- Conduction
  - moves heat through the stove's metal walls
- Convection
  - circulates hot air around the room
- Radiation
  - transfers heat directly to your skin as light

Campfires

- No conduction, unless you touch hot coals
- No convection, unless you are above fire
- Lots of radiation:
  - your face feels hot
  - your back feels cold

Question

- Which is more effective at heating a room:

- a black woodstove
- a white woodstove

Summary About Wood Stoves

- Use all three heat transfer mechanisms
- Have tall chimneys for heat exchange
- Are black to encourage radiation
- Are sealed to keep smoke out of room air

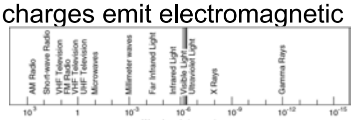
Incandescent Light Bulbs

Question:

- An incandescent light bulb contains some gas with the filament. How would removing the gas affect the bulb's energy efficiency?
- Make it more efficient
- Make it less efficient
- No change

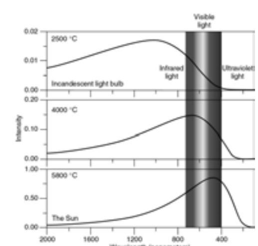
Thermal Radiation

- All materials contain electric charges
- Thermal energy makes charges accelerate
- Accelerating charges emit electromagnetic waves
- All materials emit electro-magnetic waves (thermal radiation)



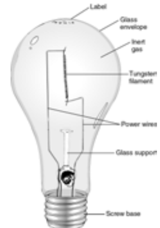
Black Body Spectrum

- The spectrum and intensity of electromagnetic waves from a black body depend only on its temperature



Incandescent Bulbs

- Features:
  - Tungsten filament yields light
  - Electric wires deliver power
  - Glass bulb protects filament
  - Inert gas fill prolongs life



Operation Issues Part 1

- Filament temperature
  - Determines color temperature and efficiency
  - Higher temperature yields higher efficiency
  - Higher temperature shortens filament life
- Filament heating
  - Heats due to power lost by an electric current
  - Requires thinner filament at higher voltages

Operation Issues Part 2

- Filament reactivity
  - Tungsten is reactive
  - Tungsten needs protection from oxygen in air
- Filament sublimation
  - At high temperatures, tungsten atoms sublime
- Non-reactive gas limits sublimation
  - Gas bounces tungsten atoms back to filament
  - Gas leads to convective heat loss

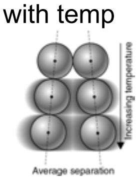
Question:

- An incandescent light bulb contains some gas with the filament. How would removing the gas affect the bulb's energy efficiency?

- Make it more efficient
- Make it less efficient
- No change

Sealing Issues

- Atoms vibrate with thermal energy
- Average separation increases with temp
- Solids expand when heated
- Some materials expand more than others when heated
- To avoid stress and fracture, glass and wires must expand equally

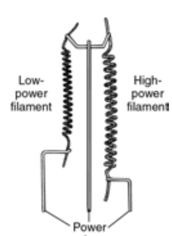


Halogen Bulbs

- Features:
  - Bromine/Iodine/Oxygen gas added to bulb
  - Bulb has small, high temperature envelope
- Produces a filament recycling process

Three-Way Bulbs

- Two separate filaments
  - One low-power filament
  - One high-power filament
- Three light levels
  - Low-power filament only
  - High-power filament only
  - Both filaments together



Specialized Bulbs

- Clear vs. Soft white bulbs
- Long life (high voltage) bulbs
- Rough service bulbs
- Energy-saver bulbs
- Krypton bulbs
- Heat bulbs
- Photoflood bulbs

Air Conditioners

Question

If you operate a window air conditioner on a table in the middle of a room, the average temperature in the room will

1. become colder
2. become hotter
3. stay the same

Observations About Air Conditioners

- They cool room air on hot days
- They emit hot air from their outside vents
- They consume lots of electric power
- They are less efficient on hotter days
- They can sometimes heat houses, too

Heat Machines

- Air conditioners
  - use work to transfer heat from cold to hot
  - are considered to be heat pumps
- Automobiles
  - use flow of heat from hot to cold to do work
  - are considered to be heat engines

Thermodynamics

- Rules governing thermal energy flow
- Relationships between
  - thermal energy and mechanical work
  - disordered energy and ordered energy
- Codified in four laws of thermodynamics

0^{th} Law

Law about Thermal Equilibrium

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

1st Law

Law about Conservation of Energy

"Change in internal energy equals heat in minus work out"

where:

Internal energy: thermal + stored energies

Heat in: heat transferred into object

Work out: external work done by object

Order versus Disorder

- It is easy to convert ordered energy into thermal (disordered) energy
- It is hard to converting thermal energy into ordered energy
- Statistically, order to disorder is one-way

Entropy

- Entropy is measure of object's disorder
  - Includes both thermal and structural disorders
- Isolated system's disorder never decreases
- Entropy can move or be transferred

2nd Law

Law about Disorder (Entropy)

"Entropy of a thermally isolated system never decreases"

3rd Law

Law about Entropy and Temperature

"An object's entropy approaches zero as its temperature approaches absolute zero"

More on the 2nd Law

- According to the 2nd Law:
  - Entropy of a thermally isolated system can't decrease
  - But entropy can be redistributed within the system
  - Part of the system can become hotter while another part becomes colder!

Natural Heat Flow

- Heat naturally flows from hot to cold
  - Removing heat from a hot object, ↓ entropy
  - Adding heat to a cold object, ↑ entropy
- Entropy of combined system increases
- 1 J of thermal energy is more disordering to a cold object than to a hot object

Unnatural Heat Flow

- Heat can’t naturally flow from cold to hot
  - Removing heat from cold object, ↓ entropy
  - Adding heat to hot object, ↑ entropy
  - More entropy removed than added
  - Energy is conserved, but ↓ total entropy
- To save 2nd law, we need more entropy
- Ordered energy must become disordered

Air conditioners Part 1

- Moves heat against its natural flow
  - Flows from cold room air to hot outside air
  - Converts ordered into disordered energy
  - Doesn’t decrease the world’s total entropy!
  - Uses fluid to transfer heat – working fluid
    - Fluid absorbs heat from cool room air
    - Fluid releases heat to warm outside air

Air conditioners Part 2

- Evaporator – located in room air
  - transfers heat from room air to fluid
- Condenser – located in outside air
  - transfers heat from fluid to outside air
- Compressor – located in outside air
  - does work on fluid and creates entropy

Evaporator Part 1

- Heat exchanger made from long metal pipe
- Fluid approaches evaporator
  - as a high pressure liquid near room temperature
- A constriction reduces the fluid’s pressure
- Fluid enters evaporator
  - as a low pressure liquid near room temperature

Evaporator Part 2

- Working fluid evaporates in the evaporator
  - Breaking bonds uses thermal energy
  - Fluid becomes colder gas
  - Heat flows from room air into fluid
- Fluid leaves evaporator
  - as a low pressure gas near room temperature
- Heat has left the room!

Compressor

- Working fluid enters compressor
  - as a low pressure gas near room temperature
- Compressor does work on fluid
  - Pushes gas inward as the gas moves inward
  - Gas temperature rises (first law)
  - Ordered energy becomes disordered energy
- Fluid leaves compressor
  - as hot, high pressure gas

Condenser Part 1

- Heat exchanger made from metal pipe
- Fluid enters condenser
  - as a hot, high pressure gas
  - heat flows from fluid to outside air

Condenser Part 2

- Working Fluid condenses in condenser
  - forming bonds releases thermal energy
  - Fluid becomes hotter liquid
  - More heat flows from fluid into outside air
- Fluid leaves condenser
  - as high-pressure room-temperature liquid
- Heat has reached the outside air!

Air conditioner Overview

- Evaporator – located in room air
  - transfers heat from room air to fluid
- Compressor – located in outside air
  - does work on fluid, so fluid gets hotter
- Condenser – located in outside air
  - transfers heat from fluid to outside air,
    - including thermal energy extracted from inside air
    - and thermal energy added by compressor

Question

If you operate a window air conditioner on a table in the middle of a room, the average temperature in the room will

1. become colder
2. become hotter
3. stay the same

Summary About Air Conditioners

- They pump heat from cold to hot
- They don’t violate thermodynamics
- They consume ordered energy
- They are most efficient for small temperature differences

Automobiles

Question:

- A car burns gasoline to obtain energy but allows some heat to escape into the air. Could a mechanically perfect car avoid releasing heat altogether?

Observations About Automobiles

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

Heat Engines

- A heat engine diverts some heat as it flows naturally from hot to cold and converts that heat into useful work
  - Natural heat flow increases entropy
  - Converting heat to work decreases entropy
- Entropy doesn’t decrease
- Some heat becomes work

Heat Pumps

- A heat pump transfers some heat from cold to hot, against the natural flow, as it converts useful work into heat
  - Reverse heat flow decreases entropy
  - Converting work to heat increases entropy
- Entropy doesn’t decrease
- Some heat flows from cold to hot

Question:

A car burns gasoline to obtain energy but allows some heat to escape into the air. Could a mechanically perfect car avoid releasing heat altogether?

Efficiency

- As the temperature difference between hot and cold increases
  - Heat's change in entropy increases
  - A heat pump becomes less efficient
  - A heat engine becomes more efficient

Internal Combustion Engine

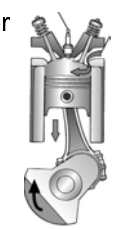
- Burns fuel and air in enclosed space
- Produces hot burned gases
- Allows heat to flow to cold outside air
- Converts some heat into useful work

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

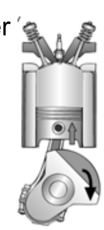
- Engine pulls piston out of cylinder
- Low pressure inside cylinder
- Atmospheric pressure pushes fuel and air mixture into cylinder
- Engine does work on the gases during this stroke



Induction

Compression Stroke

- Engine pushes piston into cylinder
- Mixture is compressed to high pressure and temperature
- Engine does work on the gases during this stroke



Compression

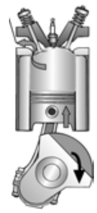
Power Stroke

- Mixture burns to form hot gases
- Gases push piston out of cylinder
- Gases expand to lower pressure and temperature
- Gases do work on engine during this stroke

Power

Exhaust Stroke

- Engine pushes piston into cylinder
- High pressure inside cylinder
- Pressure pushes burned gases out of cylinder
- Engine does work on the gases during this stroke



Exhaust

Ignition System

- Car stores energy in an electromagnet
- Energy is released as a high voltage pulse
- Electric spark ignites fuel and air mixture
- Two basic types of ignition
  - Classic: points and spark coil
  - Electronic: transistors and pulse transformer

Efficiency Limits

- Even ideal engine isn’t perfect
  - Not all the thermal energy can become work
  - Some heat must be ejected into atmosphere
- However, ideal efficiency improves as
  - the burned gases become hotter
  - the outside air becomes colder
- Real engines never reach ideal efficiency

Engine Step 1

- Fuel and air mixture after induction stroke
- Pressure = Atmospheric
- Temperature = Ambient

Engine Step 2

- Fuel/air mixture after compression stroke
- Pressure = High
- Temperature = Hot

Engine Step 3

- Burned gases after ignition
- Pressure = Very high
- Temperature = Very hot

Automobiles 19

Engine Step 4

- Burned gases after power stroke
- Pressure = Moderate
- Temperature = High

Automobiles 20

Engine Step 4a

- Burned gases after extra expansion
- Pressure = Atmospheric
- Temperature = Moderate

Automobiles 21

Engine Step 4b

- Burned gases after even more expansion
- Pressure = Below atmospheric
- Temperature = Ambient

Automobiles 22

Diesel Engine

- Uses compression heating to ignite fuel
  - Squeezes pure air to high pressure/temperature
  - Injects fuel into air between compression and power strokes
  - Fuel burns upon entry into superheated air
- Power stroke extracts work from burned gases
- High compression allows for high efficiency

Automobiles 23

Vehicle Pollution

- Incomplete burning leaves carbon monoxide and hydrocarbons in exhaust
- Accidental oxidization of nitrogen produces nitrogen oxides in exhaust
- Diesel exhaust includes many carbonized particulates

Automobiles 24

Catalytic Converter

- Platinum assists oxidization of carbon monoxide and hydrocarbons to carbon dioxide and water
- Rhodium assists reduction of nitrogen oxides to nitrogen and oxygen.
- Catalysts supported on high specific surface structure in exhaust duct: catalytic converter

Transmissions

- Changes force/distance (actually torque/rotation rate) relationships between the engine and the wheels
- Two basic types
  - Manual: clutch and gears
  - Automatic: fluid coupling and gears

Manual Transmission

- Clutch uses friction to convey torque from engine to drive shaft
  - Opening clutch decouples engine and shaft
  - Closing clutch allows engine to twist shaft
- Gears control mechanical advantage

Automatic Transmission

- Fluid coupling uses moving fluid to convey torque to drive shaft
  - Engine turns impeller (fan) that pushes fluid
  - Moving fluid spins turbine (fan) and drive shaft
  - Decoupling isn't required
- Gears control mechanical advantage

Brakes

- Use sliding friction to reduce car's energy
- Two basic types
  - Drum: cylindrical drum and curved pads
  - Disk: disk-shaped rotor and flat pads
- Brakes are operated hydraulically
  - Pedal squeezes fluid out of master cylinder
  - Fluid entering slave cylinder activates brake

Summary About Automobiles

- Cylinders expand hot gas to do work
- Uses the flow of heat from hot burned gases to cold atmosphere to produce work
- Energy efficiency is limited by thermodyn.
- Higher temperatures increase efficiency

Water, Steam, and Ice

Question:

- A glass of ice water contains both ice and water. After a few minutes of settling, how do the temperatures of the ice and the water compare?
- The ice is colder than the water
- The water is colder than the ice
- They're at the same temperature

Observations About Water, Steam, and Ice

- Water has three forms or phases
- Ice is typically present below 32 °F or 0 °C
- Water is typically present above that
- Steam is typically present at high temps
- The three phases sometimes coexist

Phases of Matter

- Solid: fixed volume and fixed shape
  - Ice: a transparent, low-density solid
- Liquid: fixed volume but variable shape
  - Water: a transparent, mid-density liquid
- Gas: variable volume and variable shape
  - Steam: an invisible gas

Ice and Water

- Melting temperature:
  - Below it, solid (ice) is the stable phase
  - Above it, liquid (water) is the stable phase
  - At it, the liquid and solid phases can coexist
- Coexistence is a form of equilibrium
- Dynamic equilibrium – molecules swap
- Turning ice to water takes (latent) heat

Melting/Freezing Part 1

- Any change that causes more water molecules to leave the solid than return to it causes the ice to melt
- Any change that causes more water molecules to return to the solid than leave it causes the water to freeze

Melting/Freezing Part 2

- To melt ice,
  - add heat
  - or increase pressure (unique to water & ice!)
- To freeze water,
  - remove heat
  - or reduce pressure (unique to water & ice!)

Question:

- A glass of ice water contains both ice and water. After a few minutes of settling, how do the temperatures of the ice and the water compare?
- The ice is colder than the water
- The water is colder than the ice
- They're at the same temperature

Water and Steam

- Liquid and gas can coexist over a broad range of temperatures. But at equilibrium,
  - liquid density remains nearly constant
  - gas density increases with temperature
- Equilibrium gas pressure: Vapor Pressure
- Dynamic equilibrium - molecules swap
- Turning water to steam takes (latent) heat

Evaporation/Condensation Part 1

- Any change that causes more water molecules to leave the liquid than return to it causes the water to evaporate
- Any change that causes more water molecules to return to the liquid than leave it causes the steam to condense

Evaporation/Condensation Part 2

- To make water evaporate,
  - add heat
  - or expand the steam
  - or lower the relative humidity
- To make steam condense,
  - remove heat
  - or compress the steam
  - or raise the relative humidity

Boiling Part 1

- Evaporation bubbles can form inside water
  - Bubble pressure is the vapor pressure
  - When vapor pressure exceeds ambient pressure, the bubble survives and grows
- Boiling occurs when
  - bubbles can nucleate (seed bubbles form)
  - bubbles can grow
- Need for latent heat stabilizes temperature

Boiling
Part 2

- Ambient pressure affects boiling temp
  - Elevated pressure raises boiling temp
  - Diminished pressure lowers boiling temp
- Cooking uses boiling to set temperature
  - Foods cook fast at high pressures (sea level)
  - Foods cook slow at low pressures (↑ height)

Sublimation/Frost

- Solid and gas phases can coexist over a broad range of temperatures
- When ice becomes steam: sublimation
- When steam becomes ice: frost

Impurities

- Dissolved impurities stabilize liquid phase
  - Melting temperature drops
  - Boiling temperature rises
- Proportional to density of dissolved items:
  - Salt ions
  - Sugar molecules

Summary About
Water, Steam, and Ice

- Stable phases determined by equilibria
- Temperature & pressure affect phases
- Shifting between phases involves heat

Clocks

Question:

- You’re bouncing gently up and down at the end of a springboard, without leaving the board’s surface. If you bounce harder, the time it takes for each bounce will
- become shorter
- become longer
- remain the same

Observations About Clocks

- They divide time into uniform intervals
- They count the passage of those intervals
- Some involve obvious mechanical motions
- Some seem to involve no motion at all
- They require an energy source
- They have limited accuracy

Non-Repetitive Clocks

- Measures a single interval of time
  – Sandglasses
  – Water clocks
  – Candles
- Common in antiquity
- Poorly suited to subdividing the day
  – Requires frequent operator intervention
  – Operator requirement limits accuracy

Repetitive Motions

- An object with a stable equilibrium tends to oscillate about that equilibrium
- This oscillation entails at least two types of energy – kinetic and a potential energy
- Once the motion has been started, it repeats spontaneously many times

Repetitive-Motion Clocks

- Developed about 500 years ago
- Require no operator intervention
- Accuracy limited only by repetitive motion
- Motion shouldn’t depend on externals:
  – temperature, air pressure, time of day
  – clock’s store of energy
  – mechanism that observes the motion

Some Specifics

- Terminology
  - Period: time of full repetitive motion cycle
  - Frequency: cycles completed per unit of time
  - Amplitude: peak extent of repetitive motion
- Application
  - In an ideal clock, the repetitive motion’s period shouldn’t depend on its amplitude

A Harmonic Oscillator

- A system with a stable equilibrium and a restoring force that’s proportional to its distortion away from that equilibrium
- A period that’s independent of amplitude
- Examples:
  - Pendulum
  - Mass on a spring

Question:

- You’re bouncing gently up and down at the end of a springboard, without leaving the board’s surface. If you bounce harder, the time it takes for each bounce will
- become shorter
- become longer
- remain the same

Limits to the Accuracy

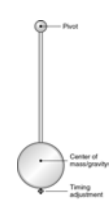
- Fundamental limits:
  - Oscillation decay limits preciseness of period
- Practical Limits:
  - Sustaining motion can influence the period
  - Observing the period can influence the period
  - Sensitivity to temperature, pressure, wind, …

Pendulums

- Pendulum (almost) a harmonic oscillator
- Period proportional to $(\text{length}/\text{gravity})^{1/2}$
- Period (almost) independent of amplitude

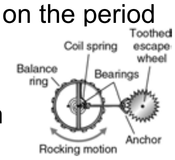
Pendulum Clocks

- Pendulum is clock’s timekeeper
- For accuracy, the pendulum
  - pivot–center-of-gravity distance is
    - temperature stabilized
    - adjustable for local gravity effects
  - streamlined to minimize air drag
  - motion sustained, measured gently
- Limitation: clock mustn't move



Balance Ring Clocks

- A torsional spring causes a balance-ring harmonic oscillator to twist back and forth
- Gravity exerts no torque about the ring's pivot and has no influence on the period
- Twisting is sustained and measured with minimal effects on the ring's motion



Quartz Oscillators Part 1

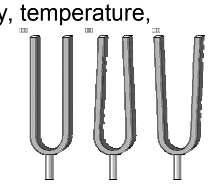
- Crystalline quartz is a harmonic oscillator
  - Crystal provides the inertial mass
  - Stiffness provides restoring force
- Oscillation decay is extremely slow
- Fundamental accuracy is very high

Quartz Oscillators Part 2

- Quartz is piezoelectric
  - mechanical and electrical changes coupled
  - motion is induced and measured electrically

Quartz Clocks

- Electronic system starts crystal vibrating
- Vibrating crystal triggers electronic counter
- Nearly insensitive to gravity, temperature, pressure, and acceleration
- Slow vibration decay leads to precise period
- Tuning-fork shape yields slow, efficient vibration



Atomic Clocks Part 1

- Electrons orbit the nucleus of an atom
- Only certain orbits are possible due to quantum mechanical nature of universe
- Associated with each these orbitals is a specific amount of total energy
- Quantum leap from one orbital to another involves a specific amount of energy

Atomic Clocks Part 2

- Associated with a specific amount of energy is a specific frequency
- Light of a specific frequency carries a certain amount of energy per packet.
- Atoms can only emit or absorb light of specific frequencies: the ones that carry just the right energy to shift electrons between orbitals

Atomic Clocks
Part 3

- Atomic clocks study the interactions of atoms with light
- The atoms act as frequency references for the light: only the right frequency light affects the atoms
- Atomic clocks keep time by with the help of this frequency stabilized light

Summary
About Clocks

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

Violins and Pipe Organs

Question:

Sound can break glass. Which is easiest to break:

- A glass pane exposed to a loud, short sound
- A glass pane exposed to a certain loud tone
- A crystal glass exposed to a loud, short sound
- A crystal glass exposed to a certain loud tone

Observations About Violins and Pipe Organs

- They can produce different pitches
- They must be tuned
- They sound different, even on same pitch
- Sound character is adjustable
- Both require power to create sound
- Can produce blended or dissonant sounds

Strings as Harmonic Oscillators

- A string is a harmonic oscillator
  - Its mass gives it inertia
  - Its tension gives it a restoring force
  - It has a stable equilibrium
  - Restoring forces proportional to displacement
- Pitch independent of amplitude (volume)!

String’s Inertia and Restoring Forces

- String’s restoring force stiffness set by
  - string’s tension
  - string’s curvature (or, equivalently, length)
- String’s inertial characteristics set by
  - string’s mass per length

Fundamental Vibration

- String vibrates as single arc, up and down
  - velocity antinode occurs at center of string
  - velocity nodes occur at ends of string
- This is the fundamental vibrational mode
- Pitch (frequency of vibration) is
  - proportional to tension
  - inversely proportional to string length
  - inversely proportional to mass per length

Overtone Vibrations

- String can also vibrate as
  - two half-strings (one extra antinode)
  - three third-strings (two extra antinodes)
  - etc.
- These are higher-order vibrational modes
- They have higher pitches
- They are called “overtones”

String Harmonics Part 1

- In a string, the overtone pitches are at
  - twice the fundamental frequency
    - One octave above the fundamental frequency
    - Produced by two half-string vibrational mode
  - three times the fundamental frequency
    - An octave and a fifth above the fundamental
    - Produced by three half-string vibrational mode
  - etc.

String Harmonics Part 2

- Integer overtones are called “harmonics”
- Bowing or plucking a string tends to excite a mixture of fundamental and harmonic vibrations, giving character to the sound

Producing Sound

- Thin objects don’t project sound well
  - Air flows around objects
  - Compression and rarefaction is minimal
- Surfaces project sound much better
  - Air can’t flow around surfaces easily
  - Compression and rarefaction is substantial
- Many instruments use surfaces for sound

Plucking and Bowing

- Plucking a string transfers energy instantly
- Bowing a string transfers energy gradually
  - Rhythmic excitation at the right frequency causes sympathetic vibration
  - Bowing always excites string at the right frequency
  - The longer the string’s resonance lasts, the more effective the gradual energy transfer

Question:

Sound can break glass. Which is easiest to break:

- A glass pane exposed to a loud, short sound
- A glass pane exposed to a certain loud tone
- A crystal glass exposed to a loud, short sound
- A crystal glass exposed to a certain loud tone

Air as a Harmonic Oscillator

- A column of air is a harmonic oscillator
  - Its mass gives it inertia
  - Pressure gives it a restoring force
  - It has a stable equilibrium
  - Restoring forces proportional to displacement
- Pitch independent of amplitude (volume)!

Air's Inertia and Restoring Forces

- Air's restoring force stiffness set by
  - pressure
  - pressure gradient (or, equivalently, length)
- Air's inertial characteristics set by
  - air's mass per length (essentially density)

Fundamental Vibration Open-Open Column

- Air column vibrates as a single object
  - Pressure antinode occurs at column center
  - Pressure nodes occur at column ends
- Pitch (frequency of vibration) is
  - proportional to air pressure
  - inversely proportional to column length
  - inversely proportional to air density

Fundamental Vibration Open-Closed Column

- Air column vibrates as a single object
  - Pressure antinode occurs at closed end
  - Pressure node occurs at open end
- Air column in open-closed pipe vibrates
  - as half the column in an open-open pipe
  - at half the frequency of an open-open pipe

Air Harmonics Part 1

- In open-open pipe, the overtones are at
  - twice fundamental (two pressure antinodes)
  - three times fundamental (three antinodes)
  - etc. (all integer multiples or "harmonics")
- In open-closed pipe, the overtones are at
  - three times fundamental (two antinodes)
  - five times fundamental (three antinodes)
  - etc. (all odd integer multiples or "harmonics")

Air Harmonics Part 2

- Blowing across column tends to excite a mixture of fundamental and harmonic vibrations

Other Instruments

- Most 1-dimensional instruments
  - can vibrate at half, third, quarter length, etc.
  - harmonic oscillators with harmonic overtones
- Most 2- or 3- dimensional instruments
  - have complicated higher-order vibrations
  - harmonic osc. with non-harmonic overtones
- Examples: drums, cymbals, glass balls

Summary of Violins and Pipe Organs

- use strings and air as harmonic oscillators
- pitches independent of amplitude/volume
- tuned by tension/pressure, length, density
- have harmonic overtones
- project vibrations into the air as sound

The Sea and Surfing

Question:

You float motionless in an inner tube, just far enough from the shore that the waves aren't breaking on top of you. You will

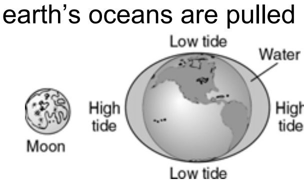
- drift shoreward at the speed of the waves
- drift gradually but steadily shoreward
- move in a circle as each wave passes, but make little or no progress toward shore

Observations About The Sea and Surfing

- The sea is rarely calm—it has ripples on it
- The broadest ripples (waves) travel fastest
- Waves seem to get steeper near shore
- Waves break or crumble near shore
- Waves bend after passing over sandbars
- You can sometimes ride waves

The Tides Part 1

- The moon's gravity acts on the earth
- The moon's gravity isn't uniform
- The earth's oceans are pulled out of round

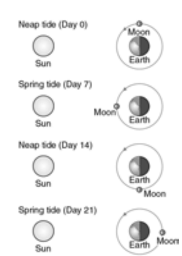


The Tides Part 2

- There are two tidal bulges in the oceans
- As the earth rotates, these bulges moves
- Almost 2 high and 2 low tides per day
- Strongest tides are near equator
- Weakest tides are near poles

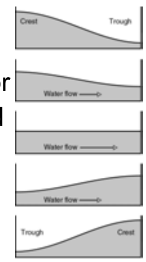
The Sun's Influence

- Sun's gravity affects tides
- Strongest tides are when moon and sun are aligned
- Weakest tides are when moon and sun are at right angles



Tidal Resonance

- Water in a confined channel can slosh back and forth
- It's another harmonic oscillator
- Period depends on inertia and stiffness of the restoring force
- If the sloshing time matches the tidal period, resonance occurs

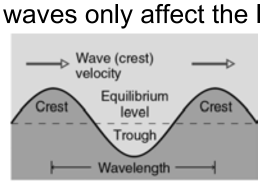


Standing and Traveling Waves

- Sloshing involves standing waves
  - Water exhibits fixed nodes and antinodes
- Open water surf involves traveling waves
  - Wave crests and troughs shift continuously

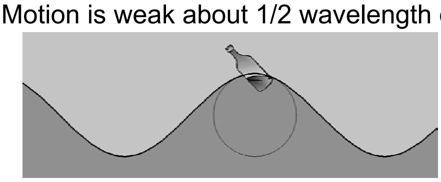
Water Waves

- Sloshing involves deep water waves: the whole liquid moves back and forth
- Surface waves only affect the liquid's top



Water's Motion

- Surface water circles as the wave passes
- Circling is strongest at surface
- Motion is weak about 1/2 wavelength deep



Question:

You float motionless in an inner tube, just far enough from the shore that the waves aren't breaking on top of you. You will

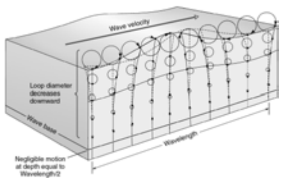
- drift shoreward at the speed of the waves
- drift gradually but steadily shoreward
- move in a circle as each wave passes, but make little or no progress toward shore

Wavelength

- Longer the wavelength of surface wave,
  - faster it travels
  - deeper water moves as it passes
  - more energy it contains for a given amplitude
- Tsunamis are very long wavelength, very deep, very high energy waves (and not strictly surface waves, either)

Water in a Wave

- Only the wave travels, the water circles
- Crests are formed from local water



Breaking Waves

- Surface waves slow down in shallow water
- Waves bunch as the water gets shallower
- Waves get taller as water gets shallower
- Waves break when water can’t form crest
  - Gradually sloping bottom: rolling surf
  - Steeply sloping bottom: plunging breakers

Surfing

- Waves act as moving ramps
- Forces on a surfer:
  - Ramp force (Downhill) formed by sum of
    - buoyant force
    - weight
    - lift
  - Drag force (Uphill)
- Net force is zero during steady surfing

Changing Wave Speeds

- Reflection
  - Wave speed change causes partial reflection
  - The bigger the change, the more reflection
- Refraction
  - Wave speed change can redirect wave
  - Waves bend toward shore as they slow

Summary of The Sea and Surfing

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