Falling Balls 1

Skating

Turn off all electronic devices

Falling Balls 2

Observations about Skating

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

Falling Balls 3

4 Questions about Skating

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

Falling Balls 4

Question 1

Q: Why does a stationary skater remain stationary?

A: A body at rest tends to remain at rest

This observed behavior is known as inertia

Falling Balls 5

Question 2

Q: Why does a moving skater continue moving?

A: A body in motion tends to remain in motion

This behavior is the second half of inertia

Falling Balls 6

Newton's First Law (Version 1)

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

Note that a motionless object obeys this law!

Falling Balls 7

Question 3

Q: Why does a skater need ice or wheels to skate?

A: Real-world complications usually mask inertia

Solution: minimize or overwhelm complications

- To observe inertia, therefore,
  - work on level ground (minimize gravity's effects)
  - use wheels, ice, or air support (minimize friction)
  - work fast (overwhelm friction and air resistance)

Falling Balls 8

Physical Quantities

1. Position – an object's location
2. Velocity – its change in position with time

- Both are vector quantities:
  - Position is distance and direction from reference
  - Velocity is speed and direction of motion

Falling Balls 9

Newton's First Law (Version 2)

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

Note that a motionless object is moving at a constant velocity of zero!

Falling Balls 10

Physical Quantities

3. Force – a push or a pull

- Force is another vector quantity:
  - the amount and direction of the push or pull

Falling Balls 11

Newton's First Law

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

Falling Balls 12

Question 4

Q: How does a skater start or stop moving?

A: A net force causes the skater to accelerate!

4. Acceleration – change in velocity with time
5. Mass – measure of object's inertia

- Acceleration is yet another vector quantity:
  - the rate and direction of the change in velocity

Falling Balls 13

Newton's Second Law

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

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

Traditional form: net force = mass · acceleration

$$F = ma$$

Falling Balls 14

About Units

- SI or "metric" units:
  - Position → m (meters)
  - Velocity → m/s (meters-per-second)
  - Acceleration → m/s^2 (meters-per-second^2)
  - Force → N (newtons)
  - Mass → kg (kilograms)
- Newton's second law relates the units:

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

Falling Balls 15

Summary about Skating

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

Falling Balls 16

Falling Balls

Turn off all electronic devices

Falling Balls 17

Observations about Falling Balls

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

Falling Balls 18

5 Questions about Falling Balls

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

Falling Balls 19

Question 1

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

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

Falling Balls 20

Question 2

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

A ball's weight is proportional to its mass:

$$\frac{\text{weight of ball}}{\text{mass of ball}} = 9.8\ \frac{\text{newtons}}{\text{kilogram}}$$

Their ratio is called "the acceleration due to gravity"

Falling Balls 21

Acceleration Due to Gravity

- Why this strange name?

$$\frac{\text{weight of ball}}{\text{mass of ball}} \rightarrow \frac{\text{force}}{\text{mass}} \rightarrow \text{acceleration}$$

- Acceleration due to gravity is an acceleration!

$$9.8\ \frac{\text{newtons}}{\text{kilogram}} = 9.8\ \frac{\text{meters}}{\text{second}^2}$$

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

Falling Balls 22

Question 3

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

Moon's acceleration due to gravity is $1.6\ \frac{\text{meters}}{\text{second}^2}$

Falling Balls 23

Question 4

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

A falling ball experiences only its weight

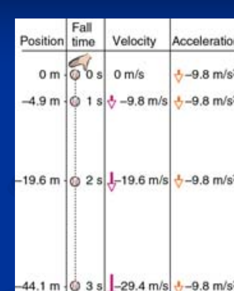
- Its acceleration is constant and downward
- Its velocity increases in the downward direction

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

Falling Balls 24

Falling Downward

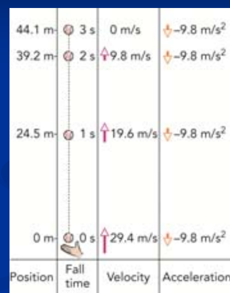
- When dropped from rest,
  - ball's velocity starts at zero and increases downward
  - ball's altitude decreases at an ever faster rate



Falling Balls 25

Falling Upward First

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



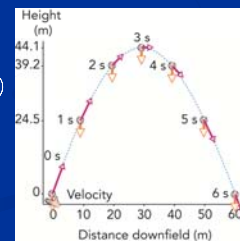
Falling Balls 26

Question 5

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

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

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



Falling Balls 27

Summary About Falling Balls

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

Falling Balls 28

Ramps

Turn off all electronic devices

Falling Balls 29

Observations About Ramps

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

Falling Balls 30

4 Questions about Ramps

1. Why doesn't a cart fall through a sidewalk?
2. How does the sidewalk know how hard to push?
3. Why is it easy to push the cart up the ramp?
4. What physical quantity is the same for any ramp?

Falling Balls 31

Question 1

Q: Why doesn't a cart fall through a sidewalk?

A: The sidewalk pushes up on it and supports it

Sidewalk and cart cannot occupy the same space

Sidewalk exerts a support force on cart that

- prevents cart from penetrating sidewalk's surface
- acts perpendicular to sidewalk's surface → upward
- balances cart's downward weight

Falling Balls 32

Question 2

Q: How does the sidewalk know how hard to push?

A: The sidewalk and cart negotiate

The cart and sidewalk dent one another slightly

- the more they dent, the harder they push apart
- cart accelerates up or down in response to net force
- cart bounces up and down during this negotiation

Cart comes to rest at equilibrium—zero net force

Falling Balls 33

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.

Falling Balls 34

Misconception Alert

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

Falling Balls 35

The Cart and Sidewalk Negotiate

If the cart and sidewalk dent one another too much,

- each one pushes the other away strongly
- they accelerate away from one another

If the cart and sidewalk dent one another too little,

- each one pushes the other away weakly (or not at all)
- they accelerate toward one another

If the cart and sidewalk dent one another just right,

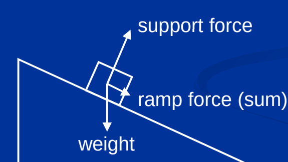
- cart is in equilibrium (zero net force)

Falling Balls 36

Question 3

Q: Why is it easy to push the cart up the ramp?

A: The ramp supports most of the cart's weight



Net force on cart is the ramp force, which is small

Pushing the Cart up the Ramp

To start the cart moving uphill

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

To keep the cart moving uphill

- push cart uphill just enough to balance ramp force
- cart continues uphill at constant velocity

To stop the cart moving uphill,

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

Question 4

Q: What physical quantity is the same for any ramp?

A: The work you do lifting the cart a certain height

work = force · distance

(where force and distance are in same direction)

For a steep ramp: work = **Force** · Distance

For a shallow ramp: work = Force · **Distance**

Energy and Work

- Energy – a conserved quantity
  - it can't be created or destroyed
  - it can be transformed or transferred between objects
  - is the capacity to do work
- Work – mechanical means of transferring energy

work = force · distance

(where force and distance are in same direction)

Transfers of Energy

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

Mechanical Advantage

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

Summary about Ramps

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

Falling Balls 43

Wind Turbines

Turn off all electronic devices

Falling Balls 44

Observations about Wind Turbines

- Wind turbines rotate steadily
- Wind turbines are symmetric and balanced
- Most wind turbines have three blades
- Wind turbines start or stop spinning gradually
- They convert wind energy to electrical energy

Falling Balls 45

5 Questions about Wind Turbines

1. How does a balanced wind turbine move?
2. Why does a wind turbine need a pivot?
3. Why do wind turbines have several blades?
4. How does energy go from wind to generator?
5. Why does a working wind turbine spin steadily?

Falling Balls 46

Question 1

Q: How does a balanced wind turbine move?
A: It moves at constant angular velocity

…because the wind turbine has rotational inertia!

Newton's first law of rotational motion

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

Falling Balls 47

Physical Quantities

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

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

Falling Balls 48

Question 2

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

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

Falling Balls 49

Question 3

Q: Why do wind turbines have several blades?
A: To balance them—zero torque due to gravity

- The weight of a single-blade produces a torque

torque = lever arm · force

(where the lever arm is perpendicular to the force)

- That torque would cause angular acceleration
- Wind-turbine's angular velocity would fluctuate

Falling Balls 50

Physical Quantities

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

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

Falling Balls 51

Newton's Second Law of Rotational Motion

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

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

Falling Balls 52

Balancing the Turbine

- Installing a second blade adds a second torque
  - The two torques act in opposite directions
  - Net torque due to gravity is zero → turbine is balanced
- A three-blade turbine is also balanced

Falling Balls 53

Turbine Size and Responsiveness

- Wind torque is proportional to blade-length^2
  - wind force is proportional to blade-length
  - lever arm is proportional to blade-length
- Rotational mass is proportional to blade-length^3
  - blade mass is proportional to blade-length
  - effect of that mass is proportional to blade-length^2
- Longer blades have slower angular accelerations
- Giant turbines take time to start or stop

Falling Balls 54

Question 4

Q: How does energy go from wind to generator?
A: Wind does rotational work on a generator

work = torque · angle

(where torque and angle in same direction)

- Wind does work on a turbine blade
- Turbine does work on a generator

Falling Balls 55

Question 5

Q: Why does a working wind turbine spin steadily?
A: Generator and wind torques on turbine cancel

Newton's Third Law of Rotational Motion

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

Generator twists turbine, canceling wind torque

Falling Balls 56

Summary about Wind Turbines

- Without wind or generator, balanced turbine
  - experiences zero gravitational torque
  - rotates at constant angular velocity
- Wind forces produce torques on turbine's blades
- Generator exerts opposing torque on turbine
- Wind turbine turns at constant angular velocity
- Energy goes from wind to turbine to generator

Falling Balls 57

Wheels

Turn off all electronic devices

Falling Balls 58

Observations about Wheels

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

Falling Balls 59

5 Questions about Wheels

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

Falling Balls 60

Question 1

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

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

Falling Balls 61

Question 2

Q: Why is sliding a box hardest at the beginning?

A: Static friction is stronger than sliding friction.

Static friction opposes the start of sliding
- varies in amount from zero to a maximum value

Sliding friction opposes ongoing sliding
- has a constant value proportional to support force

Static friction's maximum exceeds sliding friction

Falling Balls 62

Question 3

Q: What happens to energy as a box skids to rest?

A: That energy becomes thermal energy.

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

Falling Balls 63

The Many Forms of Energy

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

Falling Balls 64

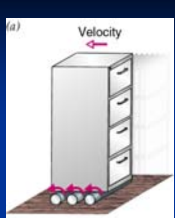
Question 4

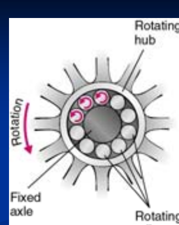
Q: How do wheels help a wagon coast?

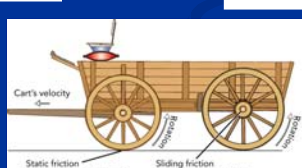
A: Wheels can eliminate sliding friction.

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

Falling Balls 65



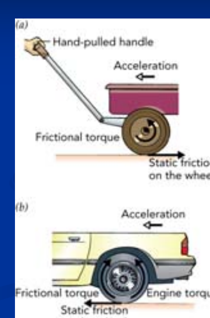




Falling Balls 66

Practical Wheels

- Free wheels are turned by the vehicle's motion
- Powered wheels propel the vehicle as they turn.



Question 5

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

For a translating wheel:

$$\text{kinetic energy} = \frac{1}{2} \cdot \text{mass} \cdot \text{speed}^2$$

For a rotating wheel:

$$\text{kinetic energy} = \frac{1}{2} \cdot \text{rotational mass} \cdot \text{angular speed}^2$$

The wheel of a moving vehicle has both!

Summary about Wheels

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

Bumper Cars

Turn off all electronic devices

Observations about Bumper Cars

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

3 Questions about Bumper Cars

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

Question 1

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

Momentum is a conserved vector quantity
- can't be created or destroyed, but can be transferred
- combines bumper car's inertia and velocity

$$\text{momentum} = \text{mass} \cdot \text{velocity}$$

Falling Balls 73

Exchanging Momentum

- Bumper cars exchange momentum via impulses

  impulse = force · time

- When car_1 gives an impulse to car_2, car_2 gives an equal but oppositely directed impulse to car_1.
  - The total momentum doesn't change
  - Car with least mass changes velocity most,
  - so the littlest riders get creamed

Falling Balls 74

Question 2

Q: Does a spinning bumper car carry a torque?

A: No, the bumper car carries angular momentum

Angular momentum is a conserved vector quantity

- can't be created or destroyed, but can be transferred
- combines bumper car's rotational inertia and velocity

angular momentum = rotational mass· angular velocity

Falling Balls 75

Exchanging Angular Momentum

- Bumper cars exchange angular momentum via angular impulses

  angular impulse = torque · time

- When car_1 gives an angular impulse to car_2, car_2 gives an equal but oppositely directed angular impulse to car_1.
  - The total angular momentum doesn't change
  - Car with least rot. mass changes ang. velocity most.
  - so the littlest riders get spun wildly

Falling Balls 76

Rotational Mass can Change

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

Falling Balls 77

Question 3

Q: How does a car accelerate on an uneven floor?

A: It reduces potential energy as quickly as possible

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

Falling Balls 78

Summary about Bumper Cars

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

Falling Balls 79

Spring Scales

Turn off all electronic devices

Falling Balls 80

Observations about Spring Scales

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

Falling Balls 81

4 Questions about Spring Scales

- What exactly is a spring scale measuring?
- How does a spring scale measure weight?
- What is the scale's dial or meter reporting?
- Why must you stand still on a spring scale?

Falling Balls 82

Question 1

- What exactly is a spring scale measuring?

Falling Balls 83

Mass as a Measure

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

Falling Balls 84

Weight as a Measure

- An object's weight is proportional to its mass
- The proportionality depends on location (gravity)
- Measuring an object's weight is done indirectly:
  - The object's weight is a force that acts on the object
  - There is no direct way to measure that weight
- Fortunately, measuring weight indirectly is easy
- Spring scales measure weight, not mass

Falling Balls 85

Question 2

- How does a spring scale measure weight?

Falling Balls 86

Measuring Weight Indirectly

- Recall that when an object is at equilibrium,
  - individual forces sum to zero—they cancel perfectly.
  - object is inertial—it remains motionless or it coasts.
- Spring scale measures weight using equilibrium
  - Exert an adjustable upward force on the object
  - Adjust that force until the object is in equilibrium
  - Measure the amount of that upward force
  - Report the amount as the object's weight

Falling Balls 87

Spring Scales and Equilibrium

- Springs provide adjustable, measurable forces
- A spring scale
  - supports object with upward force from a spring
  - allows the spring and object to reach equilibrium
  - reports the spring's force as the object's weight

Falling Balls 88

Question 3

- What is the scale's dial or meter reporting?

Falling Balls 89

Springs

- When free, a spring adopts its equilibrium length
  - Its ends experience zero net force
  - Its ends are in equilibrium
- When distorted, its ends experience forces that
  - act to restore the spring to its equilibrium length
  - make the equilibrium length stable
  - are proportional to the distortion
  - are called restoring forces

Falling Balls 90

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 the object to settle at equilibrium,
  - and measure the distortion of the spring.
- The spring constant relates distortion to force
- With proper calibration, reporting the spring's distortion is equivalent to reporting the restoring force that is supporting the object

Question 4

- Why must you stand still on a spring scale?

Spring Scales and Acceleration

- Weight measurements require equilibrium
- Without equilibrium,
  - the spring force doesn't balance the weight
  - the "measurement" is meaningless
- Since an accelerating object is not at equilibrium,
  - you mustn't bounce on a scale!
  - you must wait for the scale to settle before reading!

Oscillation

- When you first load a scale, it bounces
  - It accelerates toward a new equilibrium
  - It then coasts through that equilibrium
  - It then accelerates back toward the new equilibrium
  - It returns and overshoots many times
- It oscillates around its stable equilibrium
  - To settle at equilibrium, it must get rid of energy
  - Friction and air resistance help it settle

Summary about Spring Scales

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

Ball Sports: Bouncing

Turn off all electronic devices

Observations about Bouncing Balls

- Some balls bounce better than others
- Dropped balls don't rebound to their full height
- Balls bounce differently from different surfaces
- Ball bounce differently from moving objects

4 Questions about Bouncing Balls

- Why can't a ball that's dropped on a hard floor rebound to its starting height?
- Why does the floor's surface affect the bounce?
- How does a ball bounce when it hits a bat?
- What happens to the bat when a ball hits it?

Question 1

- Why can't a ball that's dropped on a hard floor rebound to its starting height?

Bouncing from a Rigid Floor

- As it strikes a rigid floor, a ball's
  - kinetic energy decreases by the "collision" energy
  - elastic potential energy increases as it dents
- As it rebounds from that surface, the ball's
  - elastic potential energy decreases as it undents
  - kinetic energy increases by the "rebound" energy
- Rebound energy < collision energy
  - A "lively" ball wastes little energy as thermal energy
  - A "dead" ball wastes most of its energy

Measuring a Ball's Liveliness

- Coefficient of Restitution
  - is a conventional measure of a ball's liveliness
  - is the ratio of outgoing to incoming speeds:

$$\text{coefficient of restitution} = \frac{\text{outgoing speed}}{\text{incoming speed}}$$

Question 2

- Why does the floor's surface affect the bounce?

Falling Balls 103

Bouncing from an Elastic Floor

- Both ball and floor dent during a bounce
- Work is proportional to dent distance
- The denting floor stores and returns energy
  - A "lively" floor wastes little energy
  - A "dead" floor wastes most of its energy
- A floor has a coefficient of restitution, too
- A soft, lively floor can help the ball bounce!

Falling Balls 104

Question 3

- How does a ball bounce when it hits a bat?

Falling Balls 105

Bouncing from Moving Surfaces

- Incoming speed → approaching speed
- Outgoing speed → separating speed
- Coefficient of Restitution becomes:

$$\text{coefficient of restitution} = \frac{\text{separating speed}}{\text{approaching speed}}$$

Falling Balls 106

Ball and Bat (Part 1)

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

Falling Balls 107

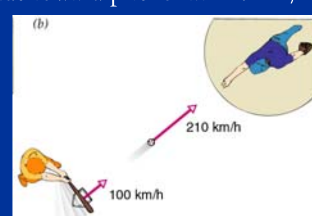
Ball and Bat (Part 2)

- Approaching speed is 200 km/h
- Baseball's coefficient of restitution: 0.55
- Separating speed is 110 km/h

Falling Balls 108

Ball and Bat (Part 3)

- Separating speed is 110 km/h
- Bat heads toward pitcher at 100 km/h
- Ball heads toward pitcher at 210 km/h



Falling Balls 109

Question 4

- What happens to the bat when a ball hits it?

Falling Balls 110

Bouncing's Effects on Objects

- A bouncing ball transfers momentum
  - while stopping
  - while rebounding
  - so a livelier ball transfers more momentum
- A bouncing ball can also transfer energy
- These two transfers together govern bouncing

Falling Balls 111

Impact Forces

- While a ball is bouncing from an object, the two surfaces exert impact forces on one another.
- Harder surfaces bounce faster
  - Momentum is transferred more quickly
  - Time is shorter, so impact forces are larger
- No one likes bouncing off hard surfaces

Falling Balls 112

The Ball's Effects on a Bat

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

Falling Balls 113

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

Falling Balls 114

Carousels and Roller Coasters

Turn off all electronic devices

Falling Balls 115

Observations about Carousels and Roller Coasters

- You can feel your motion with your eyes closed
- You feel pulled in unusual directions
- You sometimes feel weightless
- You can become inverted without feeling it

Falling Balls 116

5 Questions about Carousels and Roller Coasters

- What aspects of motion do you feel?
- Why do you feel flung outward on a carousel?
- Why do you feel light on a roller coaster's dives?
- Why do you feel heavy on a roller coaster's dips?
- How do you stay seated on a loop-the-loop?

Falling Balls 117

Question 1

- What aspects of motion do you feel?

Falling Balls 118

The Feeling of Weight

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

Falling Balls 119

The Feeling of Acceleration

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

Falling Balls 120

Acceleration and Weight

- This "feeling of acceleration" is
  - not a real force
  - just a feeling caused by your body's inertia
  - directed opposite your acceleration
  - proportional to that acceleration
- You feel an overall "apparent weight"
  - feeling of real weight plus "feeling of acceleration"

Question 2

- Why do you feel flung outward on a carousel?

Carousels (Part 1)

- Riders undergo "uniform circular motion"
  - They follow a circular path at constant speed
  - They are accelerating toward the circle's center
  - This acceleration depends on speed and circle size

$$\text{acceleration} = \frac{\text{velocity}^2}{\text{radius}}$$

- The acceleration of uniform circular motion is
  - a center-directed or centripetal acceleration
  - caused by a center-directed or centripetal force

Carousels (Part 2)

- A centripetal acceleration
  - gives rise to a "feeling of acceleration"
  - that points away from the center of motion
  - and is an experience of inertia, not a real force
- This feeling is often called "centrifugal force"

Questions 3 and 4

- Why do you feel light on a roller coaster's dives?
- Why do you feel heavy on a roller coaster's dips?

Roller Coasters (Part 1 – Hills)

- During the dive down a hill,
  - acceleration is downhill
  - feeling of acceleration is uphill
  - apparent weight is weak and into the track
- During the dip at the bottom of a hill,
  - acceleration is approximately upward
  - feeling of acceleration is approximately downward
  - apparent weight is very strong and downward

Question 5

- How do you stay seated on a loop-the-loop?

Falling Balls 127

Roller Coasters (Part 2 – Loops)

- At top of loop-the-loop,
  - acceleration is strongly downward
  - feeling of acceleration is strongly upward
  - apparent weight can point upward!

Falling Balls 128

Choosing a Seat

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

Falling Balls 129

Summary about Carousels and Roller Coasters

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

Falling Balls 130

Bicycles

Turn off all electronic devices

Falling Balls 131

Observations about Bicycles

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

Falling Balls 132

5 Questions about Bicycles

- Why is a stationary tricycle so stable?
- Why is stationary bicycle so unstable?
- Why does a moving tricycle flip during turns?
- Why must you lean a bicycle during turns?
- Why can you ride a bicycle without hands?

Falling Balls 133

Question 1

- Why is a stationary tricycle so stable?

Falling Balls 134

Tricycles: Static Stability (Part 1)

- An upright tricycle has a "base of support"– the polygon formed by its ground contact points
- A tricycle has a center of gravity – the effective point at which its weight is located
- When center of gravity is above base of support, the tricycle is in a stable equilibrium:
  - Its gravitational potential starts to increase if it tips,
  - so it accelerates in the direction opposite the tip
  - and returns to the stable equilibrium.

Falling Balls 135

Tricycles: Static Stability (Part 2)

- When its center of gravity isn't above the base, the tricycle is not in equilibrium:
  - Its gravitational potential drops as it tips one way,
  - so it spontaneously accelerates in that direction
  - and it falls over.

Falling Balls 136

Tricycles: Static Stability (Part 3)

- When its center of gravity is above edge of base, the tricycle is in an unstable equilibrium:
  - Its gravitational potential starts decreasing if it tips,
  - so it accelerates in the direction of that tip
  - and doesn't return to the unstable equilibrium.

Falling Balls 137

Question 2

- Why is stationary bicycle so unstable?

Falling Balls 138

Bicycles: Static Instability

- A base of support requires 3 contact points
- An upright bicycle has only 2 contact points
  - An upright bicycle is in an unstable equilibrium
  - A stationary bicycle tips over easily

Question 3

- Why does a moving tricycle flip during turns?

Tricycles: Dynamic Instability

- When a tricycle is moving, inertia can take it in the direction opposite its acceleration and flip it,
  - so a stable equilibrium doesn't ensure stability.
- During a turn, the wheels accelerate to the inside
  - but the rider tends to coast straight ahead,
  - so the tricycle begins to tip.
  - The stabilizing acceleration appears but it's too slow
  - and the tricycle tips over anyway.
- Tricycle drives out from under center of gravity.

Question 4

- Why must you lean a bicycle during turns?

Bicycles: Dynamic Stability

- During a turn, the wheels accelerate to the inside
  - but a bicycle rider can lean to the inside of the turn
  - and therefore accelerate to the inside of the turn,
  - so the rider and bicycle turn together safely.
- The bicycle drives under center of gravity to return to the unstable equilibrium
- Motion can make a bicycle stable!

Question 5

- Why can you ride a bicycle without hands?

A Bicycle's Automatic Steering

- It naturally steers under its center of gravity
  - due to the design of its rotating front fork (the fork steers to reduce total potential energy)
  - due to gyroscopic precession of the front wheel (the ground's torque on spinning wheel steers it)
- A forward-moving bicycle that begins to tip
  - automatically returns to its unstable equilibrium,
  - and thus exhibits wonderful dynamic stability

Falling Balls 145

Summary about Bicycles

- Tricycles
  - have static stability
  - can flip during turns
- Bicycles
  - are statically unstable
  - can lean during turns to avoid flipping
  - automatically steer back to unstable equilibrium
  - have remarkable dynamic stability

Falling Balls 146

Rockets

Turn off all electronic devices

Falling Balls 147

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 can apparently operate in empty space
- Rockets usually fly nose-first

Falling Balls 148

6 Questions about Rockets

- What pushes a rocket forward?
- How does the rocket use its gas to obtain thrust?
- What keeps a rocket pointing forward?
- What limits a rocket's speed, if anything?
- Once in space, does a spaceship have a weight?
- What makes a spaceship orbit the earth?

Falling Balls 149

Question 1

- What pushes a rocket forward?

Falling Balls 150

Momentum Conservation

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

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

Falling Balls 151

Rocket Propulsion

- The momenta of ship and fuel are opposite
- The ship's final momentum is

$$\text{momentum}_{\text{ship}} = -\text{momentum}_{\text{fuel}}$$
$$= -\text{mass}_{\text{fuel}} \cdot \text{velocity}_{\text{fuel}}$$

- The greater the fuel mass and backward velocity, the greater the ship's forward momentum

Falling Balls 152

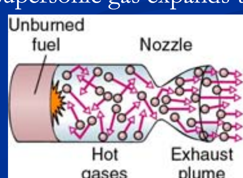
Question 2

- How does the rocket use its gas to obtain thrust?

Falling Balls 153

Rocket Engines

- Combustion produces hot, high-pressure gas
- The gas speeds up in a de Laval nozzle
- Gas reaches sonic speed in the nozzle's throat
- Beyond the throat, supersonic gas expands to speed up further



Falling Balls 154

Question 3

- What keeps a rocket pointing forward?

Falling Balls 155

Stability and Orientation

- On the ground, a rocket needs static stability
- In the air, a rocket needs aerodynamic stability
  - Center of aerodynamic forces behind center of mass
- In space, a spaceship is a freely rotating object
  - Orientation governed by angular momentum
  - Small rockets are used to exert torques on spaceship
  - Spaceship's orientation doesn't affect its travel

Falling Balls 156

Question 4

- What limits a rocket's speed, if anything?

Falling Balls 157

Ship's Ultimate Speed

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

$$\text{velocity}_{\text{ship}} = -\frac{\text{mass}_{\text{fuel}}}{\text{mass}_{\text{ship}}} \cdot \text{velocity}_{\text{fuel}}$$

- But because rocket accelerates during thrust,

$$\text{velocity}_{\text{ship}} = -\log_e\left(\frac{\text{mass}_{\text{ship}} + \text{mass}_{\text{fuel}}}{\text{mass}_{\text{ship}}}\right) \cdot \text{velocity}_{\text{fuel}}$$

Falling Balls 158

Question 5

- Once in space, does a spaceship have a weight?

Falling Balls 159

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:

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

Falling Balls 160

Gravity (Part 2)

- The ship's weight is only constant for small changes in height
- When the ship's height changes significantly:

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

Falling Balls 161

Gravity (Part 3)

- Even far above earth, an object has weight
- Astronauts and spaceships have weights
  - weights are somewhat less than normal
  - weights depend on altitude
- Astronauts and spaceships are in free fall
  - Astronauts feel weightless because they are falling

Falling Balls 162

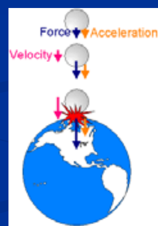
Question 6

- What makes a spaceship orbit the earth?

Falling Balls 163

Orbits (Part 1)

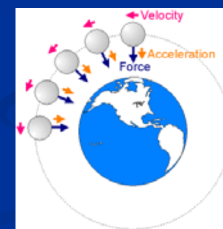
- An object that begins to fall from rest falls directly toward the earth
- Acceleration and velocity are in the same direction



Falling Balls 164

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



Falling Balls 165

Current Rocket Technology

- X-Prize Rockets
- Single Stage to Orbit Rockets
- Improbable Dreams
  - Rockets that rarely require refueling
  - Rockets that can land and leave large planets
  - Rockets that can turn on a dime in space

Falling Balls 166

Summary About Rockets

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

Falling Balls 167

Woodstoves

Turn off all electronic devices

Falling Balls 168

Observations about Woodstoves

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

Falling Balls 169

5 Questions about Woodstoves

- What are thermal energy and heat?
- How does a woodstove produce thermal energy?
- Why does heat flow from the stove to the room?
- Why is a woodstove better than an open fire?
- How does a woodstove heat the room?

Falling Balls 170

Question 1

- What are thermal energy and heat?

Falling Balls 171

Having Thermal Energy

- Thermal energy is
  - disordered energy within an object,
  - the kinetic and potential energies of its atoms,
  - and is responsible for temperature
- Thermal energy doesn't include order energies:
  - kinetic energy of an object moving or rotating
  - potential energy of outside interactions

Falling Balls 172

Transferring Heat

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

Falling Balls 173

Question 2

- How does a woodstove produce thermal energy?

Falling Balls 174

Burning Wood

- Fire releases chemical potential energy
  - Wood and air consist of molecules
  - Molecules are bound by chemical bonds
  - When bonds rearrange, they can release energy
  - Burning rearranges bonds and releases energy!

Falling Balls 175

Chemical Forces and Bonds

- Atoms interact via electromagnetic forces
- The chemical forces between two atoms are
  - attractive at long distances,
  - repulsive at short distances,
  - and zero at a specific equilibrium separation
- Atoms at the equilibrium separation
  - are in a stable equilibrium
  - and are bound together by an energy deficit

Falling Balls 176

A Few Names

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

Falling Balls 177

Chemical Reactions

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

Falling Balls 178

When Wood Burns…

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

Falling Balls 179

Question 3

- Why does heat flow from the stove to the room?

Falling Balls 180

Heat and Temperature

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

Question 4

- Why is a woodstove better than an open fire?

An Open Fire

- An open fire has good features:
  - Heat flows from hot fire to cold room
- and it has bad features:
  - Smoke enters room
  - Fire uses up room's oxygen
  - Can set fire to room

A Fireplace

- A fireplace has 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
- and it has bad features:
  - Inefficient at transferring heat to room

A Woodstove

- A woodstove has good features:
  - Heat flows from hot fire to cold room
  - All the smoke goes up chimney pipe
  - New oxygen enters room through cracks or vents
  - Relatively little fire hazard
  - Transfers heat efficiently to room

Heat Exchangers

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

Question 5

- How does a woodstove heat the room?

Falling Balls 187

Heat Transfer Mechanisms

- There are three heat transfer mechanisms:
  - Conduction: heat flows through materials
  - Convection: heat flows via moving fluids
  - Radiation: heat flows via electromagnetic waves
- All three transfer heat from hot to cold

Falling Balls 188

Conduction and Woodstoves

- In conduction, heat flows but atoms stay put
- 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
- Conduction moves heat through stove's walls

Falling Balls 189

Convection and Woodstoves

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

Falling Balls 190

Radiation and Woodstoves

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

Falling Balls 191

Stefan-Boltzmann Law

- Emissivity is a surface's emission-absorption efficiency
  - 0 → perfect inefficiency: white, shiny, or clear
  - 1 → perfect efficiency: black
- The amount of heat a surface radiates is

$$\text{power} = \text{emissivity} \cdot \text{Stefan-Boltzmann constant} \cdot \text{temperature}^4 \cdot \text{surface area}$$

where temperature is measured on an absolute scale

Falling Balls 192

What About Campfires?

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

Falling Balls 193

Summary about Wood Stoves

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

Falling Balls 194

Water, Steam, and Ice

Turn off all electronic devices

Falling Balls 195

Observations about Water, Steam, and Ice

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

Falling Balls 196

4 Questions about Water, Steam, Ice

- How can water and ice coexist in a glass?
- Can steam exist below 212 °F (100 °C)?
- Where do ice cubes go in a frostless freezer?
- Is salt the only chemical that helps melt ice?

Falling Balls 197

Question 1

- How can water and ice coexist in a glass?

Falling Balls 198

Phases of Matter

- Ice is solid: fixed volume and fixed shape
- Water is liquid: fixed volume but variable shape
- Steam is gas: variable volume and variable shape

Falling Balls 199

Phase Equilibrium

- When two (or more) phases are present
  - molecules continually shift between the phases
  - one phase may grow at the expense of another phase
  - that growth often requires or releases thermal energy
- At phase equilibrium,
  - two (or more) phases can coexist indefinitely
  - neither phase grows at the expense of the other

Falling Balls 200

Ice and Water

- Ice has a melting temperature 32 °F (0 °C)
  - below which solid ice is the stable phase,
  - above which liquid water is the stable phase,
  - and at which ice and water can coexist
- To melt ice at 32 °F (0 °C),
  - destabilize ice relative to water
  - either by adding heat
  - or by increasing pressure (ice is very atypical!)

Falling Balls 201

Ice and Water (con't)

- To freeze water at 32 °F (0 °C),
  - destabilize water relative to ice
  - either by removing heat
  - or by decreasing pressure (water is very atypical!)
- Melting ice requires the latent heat of melting

Falling Balls 202

Question 2

- Can steam exist below 212 °F (100 °C)?

Falling Balls 203

Water and Steam

- Liquid water and gaseous steam
  - can coexist over a broad range of temperatures
  - but equilibrium steam density rises with temperature
- To evaporate water,
  - destabilize water relative to steam
  - either by adding heat
  - or by reducing the density of the steam

Falling Balls 204

Water and Steam (con't)

- To condense steam,
  - destabilize steam relative to water
  - either by removing heat
  - or by increasing the density of the steam
- Evaporating water requires latent heat of evaporation

Falling Balls 205

Boiling (Part 1)

- Evaporation bubbles can form inside water
  - Pressure in steam bubble depends on steam density
  - When steam pressure exceeds ambient pressure, steam bubble can survive and grows
- Boiling occurs when
  - bubbles can nucleate (when seed bubbles form)
  - bubbles can grow via evaporation
- Need for latent heat stabilizes temperature

Falling Balls 206

Boiling (Part 2)

- Boiling temperature depends on ambient pressure
  - Elevated pressure raises boiling temperature
  - Diminished pressure lowers boiling temperature
- Cooking uses boiling to set a stable temperature
  - Foods cook fast at high pressures (sea level)
  - Foods cook slow at low pressures (high altitudes)

Falling Balls 207

Question 3

- Where do ice cubes go in a frostless freezer?

Falling Balls 208

Ice and Steam

- Solid ice and gaseous steam
  - can coexist over a broad range of temperatures
  - but equilibrium steam density rises with temperature
- To sublime ice,
  - destabilize ice relative to steam
  - either by adding heat
  - or by reducing the density of the steam

Falling Balls 209

Ice and Steam (con't)

- To deposit steam,
  - destabilize steam relative to ice
  - either by removing heat
  - or by increasing the density of the steam
- Subliming ice requires latent heats of melting *and* evaporation

Falling Balls 210

Relative Humidity

- At 100% relative humidity,
  - (< 0 °C) ice is in phase equilibrium with steam
  - (> 0 °C) water is in phase equilibrium with steam
- Below 100% relative humidity,
  - (< 0 °C) ice sublimes (goodbye ice cubes!)
  - (> 0 °C) water evaporates
- Above 100% relative humidity,
  - (< 0 °C) frost forms
  - (> 0 °C) steam condenses

Falling Balls 211

Question 4

- Is salt the only chemical that helps melt ice?

Falling Balls 212

Effects of Impurities

- Dissolved impurities stabilize liquid water,
  - so its melting temperature drops
  - and its boiling temperature rises
- These shifts are proportional to solute density,
  - such as the density of salt ions in the water
  - or the density of sugar molecules
- Any soluble material can help ice to melt
- Insoluble materials don't cause ice to melt

Falling Balls 213

Summary about Water, Steam, and Ice

- Phase transitions reflect relative phase stabilities
- Phases in equilibrium are equally stable
- Temperature and pressure affect phase stabilities
- Phase transitions usually require or release heat

Falling Balls 214

Clothing, Insulation, and Climate

Turn off all electronic devices

Falling Balls 215

Observations about Clothing, Insulation, and Climate

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

Falling Balls 216

4 Questions about Clothing, Insulation, and Climate

- How does clothing control thermal conduction?
- How does clothing control thermal convection?
- How does insulation control thermal radiation?
- Why do greenhouse gases warm the earth?

Falling Balls 217

Question 1

- How does clothing control thermal conduction?

Falling Balls 218

Thermal Conductivity

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

$$\text{heat flow} = \frac{\text{conductivity} \cdot \text{temperature diff} \cdot \text{area}}{\text{thickness}}$$

Falling Balls 219

Limiting Thermal Conduction

- Clothing is often intended to reduce heat flow
  - so it should use low-thermal conductivity materials
    - electrical insulators, not metals
    - materials that trap air—air is a very poor thermal conductor
  - and it should use relatively thick materials
    - wool sweaters, down coats, heavy blankets
- Reducing exposed area is helpful when possible
- Reducing the temperature difference always helps

Falling Balls 220

Question 2

- How does clothing control thermal convection?

Falling Balls 221

Natural Convection

- Heat naturally flows from hot to cold
- If one region of a fluid is hotter than the other
  - those regions will also have different densities
  - and buoyancy may cause the fluid to circulate.
- The rate of heat flow depends on
  - the heat capacity and mobility of the fluid
  - how quickly heat flows into or out of the fluid
  - how well buoyancy circulates fluid from hot to cold

Falling Balls 222

Forced Convection

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

Limiting Thermal Convection

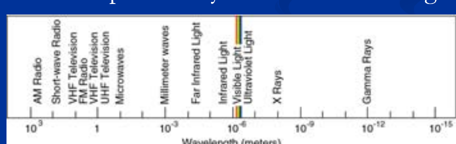
- Clothing can reduce convective heat flow by
  - preventing fluids from circulating
  - reducing temperature differences in the fluid
- The most effective clothing is thick and fluffy
  - The fluffiness traps air so that it can't convect
  - The thickness allows the surface temperature to drop to that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

Question 3

- How does insulation control thermal radiation?

Thermal Radiation

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

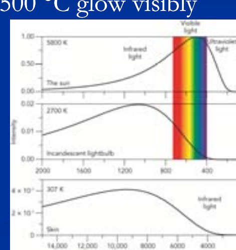


Black Body Spectrum (Part 1)

- A surface's efficiency at absorbing and emitting thermal radiation is measured by its emissivity
  - 1 for a perfect emitter-absorber (black)
  - 0 for a nonemitter-nonabsorber (white, clear, shiny)
- The spectrum and intensity of a black surface's thermal radiation depend only on its temperature

Black Body Spectrum (Part 2)

- The black body spectrum of the sun is white light
- Objects hotter than about 500 °C glow visibly
- But even your skin emits invisible thermal radiation



Radiative Heat Transfer

- Your skin radiates heat at a rate given by the Stefan-Boltzmann law:

$$\text{power} = \text{emissivity} \cdot \text{Stefan-Boltzmann constant} \cdot \text{temperature}^4 \cdot \text{surface area}$$

where temperature is an absolute temperature.

- Because of the 4^{th} power, thermal radiation is extremely sensitive to temperature.
- Black or gray objects with different temperatures can exchange heat via thermal radiation

Falling Balls 229

Limiting Thermal Radiation (Part 1)

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

Falling Balls 230

Limiting Thermal Radiation (Part 2)

- To reduce radiative heat flow
  - use conducting, low-emissivity surfaces
  - allow exterior surfaces to reach ambient temperature

Falling Balls 231

Question 4

- Why do greenhouse gases warm the earth?

Falling Balls 232

Earth Equilibrium Temperature

- Earth receives thermal radiation from the sun
- Earth emits thermal radiation into space
- Earth's temperature set by balance condition:
  - Earth must emit heat at same rate as it absorbs heat
  - Earth's net radiative heat flow must be zero
  - Balance requires Earth's radiating surface is -18 °C.
- Atmosphere contributes to thermal radiation!
- Radiating surface is 5 km above ground level!

Falling Balls 233

Effects of the Atmosphere

- Atmosphere has a temperature gradient
  - air expands and cools is its altitude increases
  - air temperature decreases 6.6 °C per km of altitude
- Atmosphere's average temperature
  - at 5 km is -18 °C
  - at ground level is 15 °C

Falling Balls 234

Effects of Greenhouse Gases

- Greenhouse gases "darken" the atmosphere
  - Low-temperature emissivity of atmosphere increases
  - Effective radiating surface moves to higher altitude
  - Average temperature at ground level increases
- Increasing greenhouse gases cause global warming
- Greenhouse gases
  - include H_2O, CO_2, nitrogen oxides, and methane
  - don't include N_2 or O_2, which are transparent to IR
- Limiting greenhouse gases is critical to our future

Falling Balls 235

Summary about Clothing, Insulation, and Climate

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

Falling Balls 236

Automobiles

Turn off all electronic devices

Falling Balls 237

Observations about Automobiles

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

Falling Balls 238

6 Questions about Automobiles

- How can an automobile run on thermal energy?
- How efficient can an automobile engine be?
- How is an automobile engine a heat engine?
- Why do cars sometime "knock?"
- How is a diesel engine different?
- What about the rest of the automobile?

Falling Balls 239

Question 1

- How can an automobile run on thermal energy?
- Related questions:
  - Doesn't the Law of Entropy forbid this conversion?
  - Doesn't burning destroy gasoline's order completely?

Falling Balls 240

Heat Engines

- An automobile engine is a "heat engine"
- A heat engine
  - allows heat to flow naturally from hot to cold
  - but diverts some and converts it into useful work
- Converting heat to work decreases entropy
  - but natural heat flow increases entropy, so
  - some can be converted without decreasing entropy.

Heat Pumps

- An air conditioner is a "heat pump"
- A heat pump
  - transfers some heat unnaturally from cold to hot
  - while converting useful work into heat
- Unnatural heat flow decreases entropy
  - but converting work to heat increases entropy, so
  - some heat can flow without decreasing entropy.

Question 2

- How efficient can an automobile engine be?
- Related question:
  - What fraction of thermal energy can become work?

Efficiency

- Heat engines and heat pumps are both limited by the Law of Entropy
  - They cannot decrease the world's overall entropy
  - Their efficiencies depend on temperature differences
- As the temperature difference increases,
  - it becomes harder to move heat from cold to hot
  - so a heat pump becomes less efficient,
  - and it becomes easier to move heat from hot to cold
  - so a heat engine becomes more efficient.

Question 3

- How is an automobile engine a heat engine?

Internal Combustion Engine

- An internal combustion engine
  - burns fuel and air in an enclosed space
  - to produces hot burned gases.
- As it allows heat to flow to cold outside air
  - it converts some heat into useful work
  - and uses that work to propel a vehicle.

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

Falling Balls 247

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

Falling Balls 248

Compression Stroke

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

Falling Balls 249

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

Falling Balls 250

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

Falling Balls 251

Ignition System

- Electric spark ignites fuel and air mixture
- Two basic types of ignition
  - Classic: points and spark coil
  - Electronic: transistors and pulse transformer

Falling Balls 252

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
  - and the outside air becomes colder.
- Real engines never reach ideal efficiency

Falling Balls 253

Question 4

- Why do cars sometime "knock?"

Falling Balls 254

Knocking and Gasolines

- Compressing a gas increases its temperature
- During the compression stroke,
  - the fuel and air mixture becomes extremely hot
  - and that mixture can ignite spontaneously
  - in a process called "knocking" or "preignition"
- To avoid knocking,
  - the car can reduce its compression ratio
  - or increase the ignition resistance of its fuel
- Higher "octane" fuels are simply harder to ignite

Falling Balls 255

Question 5

- How is a diesel engine different?

Falling Balls 256

Diesel Engine

- It uses compression heating to ignite fuel
  - It squeeze pure air to high pressure/temperature,
  - injects fuel between compression and power strokes,
  - and fuel burns upon entry into the superheated air
- Power stroke extracts work from burned gases
- Because of its higher compression ratio,
  - its fuel burns to a higher final temperature
  - and the diesel engine has a higher potential efficiency

Falling Balls 257

Question 6

- What about the rest of the automobile?

Falling Balls 258

Vehicle Pollution

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

Falling Balls 259

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

Falling Balls 260

Transmissions

- Provide mechanical advantage and coupling control between the engine and the wheels
- Two basic types
  - Manual: clutch and gears
  - Automatic: fluid coupling and gears

Falling Balls 261

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

Falling Balls 262

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

Falling Balls 263

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

Falling Balls 264

Summary about Automobiles

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

Falling Balls 265

Air Conditioners

Turn off all electronic devices

Falling Balls 266

Observations about Air Conditioners

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

Falling Balls 267

5 Questions about Air Conditioners

- Why doesn't heat flow from cold to hot?
- Why does an air conditioner need electricity?
- How does an air conditioner cool room air?
- What role does the electricity play?
- How does an air conditioner heat outdoor air?

Falling Balls 268

Question 1

- Why doesn't heat flow from cold to hot?

Falling Balls 269

Laws Governing Heat Flow

- The laws of thermodynamics
  - govern the flow of thermal energy
  - establish relationships between
    - disordered (thermal) energy and ordered energy
    - heat and work

Falling Balls 270

Law of Thermal Equilibrium

This law observes that there is a consistency about situations in which heat does not flow:

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

Falling Balls 271

Law of Conservation of Energy

This law recognizes that heat is a form of energy:

"The change in the internal energy equals the heat in minus the work out"

where:

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

Falling Balls 272

Order versus Disorder

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

Falling Balls 273

Entropy

- Entropy is the measure of an object's disorder
  - Includes both thermal and structural disorders
- An isolated system's entropy never decreases,
- but entropy can move or be transferred
- Entropy is NOT a conserved quantity!

Falling Balls 274

Law of Entropy

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

"The entropy of a thermally isolated system never decreases"

Falling Balls 275

More on the Law of Entropy

- According to the Law of Entropy:
  - Entropy of thermally isolated system can't decrease,
  - but entropy can be redistributed within the system
  - so part of the system can become hotter while another part becomes colder!
- Exporting entropy is like throwing out trash!

Falling Balls 276

Natural Heat Flow

- One unit of thermal energy is more disordering to a cold object than to a hot object
- When heat flows from hot object to cold object,
  - the hot object's entropy decreases
  - and the cold object's entropy increases,
  - so the overall entropy of the system increases
  - and the total energy is conserved
- Laws of motion and thermodynamics satisfied

Falling Balls 277

Unnatural Heat Flow

- When heat flows from cold object to hot object,
  - the cold object's entropy decreases,
  - and the hot object's entropy increases
  - so the overall entropy of the system decreases
  - although the total energy is conserved
- The Law of Entropy is violated
  - To save that law, we need more entropy!
  - Something ordered must become disordered!

Falling Balls 278

Question 2

- Why does an air conditioner need electricity?

Falling Balls 279

Air Conditioners and Entropy

- Air conditioners
  - move heat from cold room air to hot outdside air
  - and would cause entropy to decrease
  - were it not for the electric power they consume!
- Electric energy is ordered,
  - so turning it into thermal energy increases entropy.
- Air conditioner satisfies the Law of Entropy by
  - consuming electric energy (or some other order).

Falling Balls 280

Heat Machines

- Air conditioners
  - use work to transfer heat from cold to hot
  - are a type of "heat pump"
- Automobiles
  - use flow of heat from hot to cold to do work
  - are a type of "heat engine"
- Heat pumps and heat engines obey the Law of Entropy!

Falling Balls 281

Air conditioners (Part 1)

- An air conditioner
  - moves heat from cold room air to hot outside air,
  - against its natural flow, therefore
  - it must convert order energy into disordered energy
  - so as not to decrease the world's total entropy!
- An air conditioner uses a "working fluid" to
  - absorb heat from the cool room air
  - and release heat to the warm outside air

Falling Balls 282

Air conditioners (Part 2)

- The air conditioner's indoor evaporator
  - transfers heat from room air to working fluid,
- its outdoor condenser
  - transfers heat from working fluid to outside air
- and its outdoor compressor
  - does work on working fluid and produces entropy.

Falling Balls 283

Question 3

- How does an air conditioner cool room air?

Falling Balls 284

The Evaporator (Part 1)

- The evaporator is a long, wide metal pipe,
  - a heat exchanger between air and working fluid.
- The working fluid
  - arrives as a high pressure, room temperature liquid
  - but loses pressure passing through a constriction
  - and enters the evaporator as a low pressure liquid.
- Loss of pressure destabilizes the liquid phase
- The liquid working fluid begins to evaporate!

Falling Balls 285

The Evaporator (Part 2)

- Working fluid evaporates in the evaporator
  - It needs thermal energy to evaporate,
  - so it absorbs heat from the room air.
- Working fluid leaves the evaporator
  - as a low density gas near room temperature
  - and carries away some of the room's thermal energy
- Heat has left the room!

Falling Balls 286

Question 4

- What role does the electricity play?

Falling Balls 287

The Compressor

- The compressor increases the gas's density
- Working fluid
  - arrives as a low density gas near room temperature,
  - has work done on it by the compressor,
  - and experiences a rise in temperature as a result.
- Working fluid leaves the compressor
  - as a hot, high density gas
  - and carries away electric energy as thermal energy.
- Ordered energy has become disordered energy!

Falling Balls 288

Question 5

- How does an air conditioner heat outdoor air?

Falling Balls 289

The Condenser (Part 1)

- The condenser is a long, narrow metal pipe
  - pipe is heat exchanger between air and working fluid
- The working fluid
  - arrives as a hot, high density gas
  - but begins to lose heat to the cooler outdoor air
- Loss of heat destabilizes the gaseous phase,
  - so the gaseous working fluid begins to condense!

Falling Balls 290

The Condenser (Part 2)

- Working fluid condenses in the condenser
  - It must get rid of thermal energy to condense,
  - so it releases heat into the outside air.
- Working fluid leaves the condenser
  - as high-pressure room-temperature liquid
  - having released some of the room's thermal energy
- Heat has reached the outside air!

Falling Balls 291

Air Conditioner Overview

- Indoor evaporator
  - transfers heat from room air to working fluid
- Outdoor compressor
  - does work on fluid, raising density and temperature
- Outdoor condenser
  - transfers heat from working fluid to outside air,
    - including thermal energy extracted from inside air
    - and thermal energy added by compressor.

Falling Balls 292

Summary about Air Conditioners

- They pump heat from cold to hot
- They don't violate thermodynamics
- They convert ordered energy to thermal energy

Falling Balls 293

Clocks

Turn off all electronic devices

Falling Balls 294

Observations About Clocks

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

Falling Balls 295

4 Questions about Clocks

- Why don't any modern clocks use hourglasses?
- Are all repetitive motions equally accurate?
- Why are some watches more accurate?
- How do clocks use harmonic oscillators?

Falling Balls 296

Question 1

- Why don't any modern clocks use hourglasses?

Falling Balls 297

Non-Repetitive Motions: Timers

- Devices that measure a single interval of time,
  - sandglasses,
  - water clocks,
  - and candles,

  are fine as timers and were common in antiquity.
- They are poorly suited to subdividing the day
  - because they require frequent operator intervention
  - and that operator requirement limits their accuracy.

Falling Balls 298

Repetitive Motions: Clocks

- Devices that tick off time intervals repetitively,
  - pendulums,
  - torsion balances,
  - and tuning forks,

  began appearing in clocks about 500 years ago.
- They are well suited to subdividing the day
  - because they require no operator intervention
  - and their ticks can be counted mechanically.

Falling Balls 299

About Repetitive Motions

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

Falling Balls 300

Question 2

- Are all repetitive motions equally accurate?

Falling Balls 301

Some Specifics

- A little terminology…
  - Period: time of full repetitive motion cycle
  - Frequency: cycles completed per unit of time
  - Amplitude: peak distance away from motion's center
- In an ideal clock, the repetitive motion's period shouldn't depend on its amplitude

Falling Balls 302

Harmonic Oscillators (Part 1)

- A harmonic oscillator
  - has a stable equilibrium
  - and a restoring force that's proportional to displacement from that equilibrium.
- Its period is independent of its amplitude!
- At a conceptual level, it always has
  - an inertial aspect (e.g., a mass)
  - and a spring-like restoring force aspect (e.g., a spring).

Falling Balls 303

Harmonic Oscillators (Part 2)

- The period of a harmonic oscillator decreases as
  - the mass aspect becomes smaller
  - and as the spring-like aspect becomes stiffer
- Common harmonic oscillators include
  - a mass on a spring (the prototypical form)
  - a pendulum
  - a flagpole
  - a tuning fork

Falling Balls 304

Question 3

- Why are some watches more accurate?

Falling Balls 305

The Limits to the Accuracy

- Clocks exhibit practical limits:
  - Sustaining motion can influence the period
  - Observing the period can influence the period
  - Sensitivity to temperature, pressure, wind, …
- Clocks also exhibit fundamental limits:
  - Oscillation decay limits preciseness of period

Falling Balls 306

Question 4

- How do clocks use harmonic oscillators?

Falling Balls 307

Pendulums (Part 1)

- A pendulum is (almost) a harmonic oscillator
  - Its period is proportional to $(\text{length}/\text{gravity})^{1/2}$
  - and its period is (almost) independent of amplitude.

Falling Balls 308

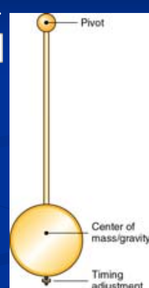
Pendulums (Part 2)

- A pendulum's spring-like restoring force
  - is caused by gravity
  - and is proportional to the pendulum's weight,
  - which is proportional to the pendulum's mass.
- Increasing a pendulum's mass
  - increases its inertial aspect,
  - increases the stiffness of its restoring force aspect,
  - and therefore has no effect on its period!

Falling Balls 309

Pendulum Clocks

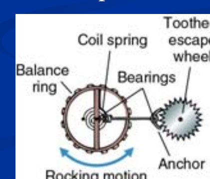
- Pendulum is the clock's timekeeper
- For accuracy, the pendulum's
  - pivot–to-center-of-gravity distance is
    - temperature stabilized
    - and adjustable for variations in gravity.
  - It is streamlined to minimize air drag.
  - Its motion is sustained gently
  - and measured gently.
- The clock mustn't move or tilt.



Falling Balls 310

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 therefore has no influence on the period.
- Twisting is sustained and measured with minimal effects on the ring's motion.



Falling Balls 311

Quartz Oscillators

- Crystalline quartz is a harmonic oscillator
  - The crystal's mass provides the inertial aspect
  - and its body provides the spring-like aspect.
- Quartz's oscillation decay is extremely slow
  - so its fundamental accuracy is very high.
- Quartz is piezoelectric
  - Its mechanical and electrical changes are coupled, so
  - its motion can be induced and measured electrically.

Falling Balls 312

Quartz Clocks

- The quartz tuning fork is excited electronically.
- The clock counts the vibrations electronically.
- The period of those vibrations is insensitive to gravity, temperature, pressure, and acceleration.
- Quartz's slow vibration decay gives it a very precise period.
- The crystal's tuning-fork shape yields a slow, efficient vibration.

Falling Balls 313

Summary about Clocks

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

Falling Balls 314

Musical Instruments

Turn off all electronic devices

Falling Balls 315

Observations about Musical Instruments

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

Falling Balls 316

6 Questions about Musical Instruments

- Why do strings produce specific notes?
- Why does a vibrating string sound like a string?
- How does bowing cause a string to vibrate?
- Why do stringed instruments need surfaces?
- What is vibrating in a wind instrument?
- Why does a drum sound particularly different?

Falling Balls 317

Question 1

- Why do strings produce specific notes?

Falling Balls 318

Oscillations of a Taut String

- A taut string has
  - a mass that provides its inertial aspect,
  - a tension that provides its spring-like aspect,
  - a stable equilibrium shape (straight line),
  - and restoring forces proportional to displacement.
- A taut string is a harmonic oscillator
  - that oscillates about its equilibrium shape
  - with a pitch independent of amplitude (i.e., volume)!

A Taut String's Pitch

- A string's spring-like aspect stiffness is set by
  - its tension and
  - its length (which affects its curvature).
- The string's inertial aspect is set by its mass.

Fundamental Vibration

- A string has a fundamental vibrational mode
  - in which it vibrates as a single arc, up and down,
  - with a displacement antinode at its center
  - and a displacement node at each of its two ends.
- Its fundamental pitch (frequency of vibration) is
  - proportional to tension$^{1/2}$,
  - proportional to 1/length,
  - and proportional to 1/mass$^{1/2}$.

Question 2

- Why does a vibrating string sound like a string?

A String's Harmonics (Part 1)

- A string can also vibrate as
  - two half-strings (one extra antinode),
  - three third-strings (two extra antinodes), and so on.
- These higher-order vibrational modes
  - have pitches higher than the fundamental mode
  - and are called "overtones."
- Overtones with pitches that are integer multiples of the fundamental pitch are called "harmonics."
- A string's overtones are all harmonics!

A String's Harmonics (Part 2)

- First overtone involves two half-strings
  - Twice the fundamental pitch: 2nd harmonic
  - One octave above the fundamental frequency
- Second overtone involves three third-strings
  - Three times the fundamental pitch: 3rd harmonic
  - An octave and a fifth above the fundamental
- Bowing or plucking a string excites a mixture of fundamental and harmonic vibrations, giving the string its characteristic sound

Question 3

- How does bowing cause a string to vibrate?

Plucking and Bowing

- Plucking a string transfers energy instantly
- Bowing a string transfers energy gradually
  - by doing a little work on the string every cycle
  - so that excess energy builds up gradually.
  - This gradual buildup is resonant energy transfer.
- The string will vibrate sympathetically when
  - another object vibrates at its resonant frequency
  - and it gradually extracts energy from that object.

Question 4

- Why do stringed instruments need surfaces?

Projecting Sound

- In air, sound consists of density fluctuations
  - Air has a stable equilibrium: uniform density
  - Disturbances from uniform density make air vibrate
- Vibrating strings barely project sound
  - because air flows around thin vibrating objects
  - and is only slightly compressed or rarefied.
- Surfaces project sound much better
  - because air can't flow around surfaces easily
  - and is substantially compressed or rarefied.

Question 5

- What is vibrating in a wind instrument?

Oscillations of Air in a Tube

- Air in a tube has
  - mass that provides its inertial aspect,
  - pressures that provide its spring-like aspect,
  - a stable equilibrium structure (uniform density),
  - and restoring forces proportional to displacement.
- Air in a tube is a harmonic oscillator
  - that oscillates about its equilibrium shape
  - with a pitch independent of amplitude (i.e., volume)!

Air in a Tube's Pitch

- Air column's springlike aspect stiffness is set by
  - its pressure
  - and its length (which affects its pressure gradient).
- Air column's inertial aspect is set by its mass.

Falling Balls 331

Fundamental Vibration Open-Open Column

- The air column vibrates as a single object
  - with a pressure antinode at the middle of the column
  - and a pressure node at each of the two open ends.
- Its fundamental pitch (frequency of vibration) is
  - proportional to pressure$^{1/2}$,
  - proportional to 1/length,
  - and proportional to 1/density$^{1/2}$.

Falling Balls 332

Fundamental Vibration Open-Closed Column

- The air column vibrates as a single object
  - with a pressure antinode at the closed end
  - and a pressure node at the open end.
- The air column in a open-closed pipe vibrates
  - like half the air column in an open-open pipe
  - and at half the frequency of an open-open pipe.

Falling Balls 333

Air Harmonics (Part 1)

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

Falling Balls 334

Air Harmonics (Part 2)

- Blowing across the column tends to excite a mixture of fundamental and harmonic vibrations
- Examples
  - Organ pipes
  - Recorders
  - Flutes
  - Whistles
- Reeds and horns also use a vibrating air column

Falling Balls 335

Question 6

- Why does a drum sound particularly different?

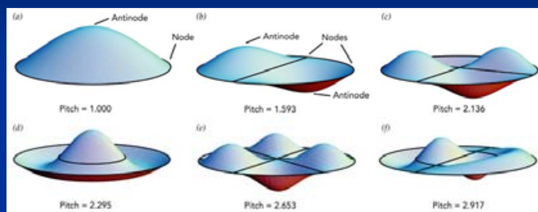
Falling Balls 336

Surface Instruments

- Most 1-dimensional instruments
  - are harmonic oscillators
  - that can vibrate at half, third, quarter length, etc.
  - and have harmonic overtones.
- Most 2- or 3- dimensional instruments
  - are harmonic oscillators
  - that have complicated higher-order vibrations
  - and have non-harmonic overtones.
- Examples: drums, cymbals, bells

Falling Balls 337

Drumhead Vibrations



Falling Balls 338

Summary of Musical Instrument

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

Falling Balls 339

The Sea

Turn off all electronic devices

Falling Balls 340

Observations about the Sea

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

Falling Balls 341

5 Questions about the Sea

- Why are there tides?
- How do giant tides develop?
- How does water in a wave move?
- How is a tsunami different from normal waves?
- Why do waves bend and break near shore?

Falling Balls 342

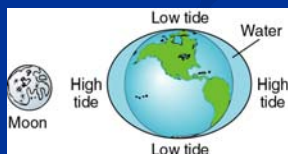
Question 1

- Why are there tides?

Falling Balls 343

The Tides (Part 1)

- The moon's gravity acts on the earth,
- but the moon's gravity is nonuniform
- so the earth's oceans are pulled out of round
- and two tidal bulges form on opposite sides.



Falling Balls 344

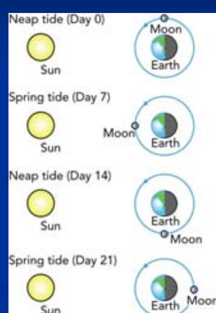
The Tides (Part 2)

- These bulges move as the earth rotates, so
  - each shore experiences almost two high tides per day
  - and almost two low tides per day.
- The heights of these tides vary with latitude.
  - They are strongest near equator
  - and weakest near poles.

Falling Balls 345

The Sun's Influence

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



Falling Balls 346

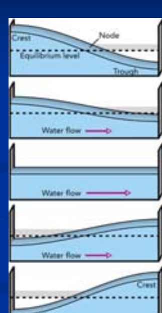
Question 2

- How do giant tides develop?

Falling Balls 347

Tidal Resonance

- Water in a confined channel can slosh back and forth
  - It has a stable equilibrium (level)
  - and it experiences springlike forces.
- It's another harmonic oscillator
- Its period depends on its inertia and its stiffness
- If the sloshing time matches the tidal period, resonance occurs



Falling Balls 348

Standing and Traveling Waves

- Sloshing involves standing waves
  - Water in a finite container has standing wave modes,
  - with nodes and antinodes that remain stationary.
- Open water surf involves traveling waves
  - Water in an infinite sea has traveling wave modes,
  - with crests and troughs that move continuously.

Falling Balls 349

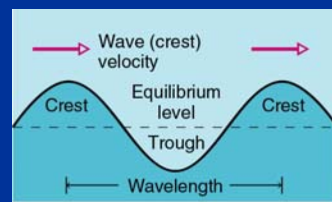
Question 3

- How does water in a wave move?

Falling Balls 350

Water Waves

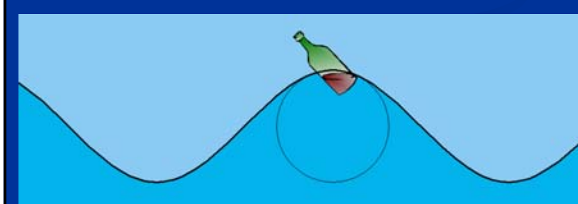
- Sloshing involves deep water waves: all of the water moves back and forth
- Surface waves affect only water near the surface



Falling Balls 351

Water’s Motion (Part 1)

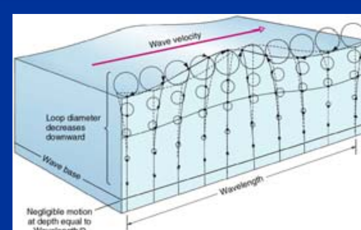
- Only the wave structure travels across the water.
- Surface water itself circles as the wave passes.
- The wave’s crests are formed from local water.



Falling Balls 352

Water’s Motion (Part 2)

- The circling is strongest at the surface,
- and becomes weak about 1/2 wavelength deep.



Falling Balls 353

Question 4

- How is a tsunami different from normal waves?

Falling Balls 354

Waves and Wavelength

- The longer the wavelength of surface wave,
  - the faster it travels,
  - the deeper it extends into the water,
  - and the more power it conveys for its amplitude.
- Tsunamis are
  - very long wavelength, deep, and powerful waves.
  - They are also not strictly surface waves.

Falling Balls 355

Question 5

- Why do waves bend and break near shore?

Falling Balls 356

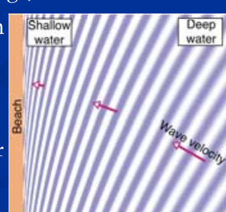
Breaking Waves

- Shallow water distorts a wave's circling motion.
- As the water grows shallower, a surface wave
  - slows down and its wavelength decreases.
  - Its crests grow taller and more tightly bunched.
- Waves break when the water can't form a crest
- The slope of the seabed affects breaking
  - If the seabed slopes gradually, there is rolling surf
  - If the seabed slopes sharply, plunging breakers occur

Falling Balls 357

Changing Wave Speeds

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



Falling Balls 358

Summary of the Sea

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