Skating 1

Skating

Turn off all electronic devices

Skating 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

Skating 3

4 Questions about Skating

- Why does a stationary skater remain stationary?
- Why does a moving skater continue moving?
- Why does a skater need ice or wheels to skate?
- How does a skater start or stop moving?

Skating 4

Question 1

- Why does a stationary skater remain stationary?
- Related Questions:
  - What keeps the dishes in place on a table?
  - If I pull the tablecloth, what will happen?
  - Does the speed at which I pull matter?

Skating 5

Physics Concept

- Inertia (just the first part)
  - A body at rest tends to remain at rest

Skating 6

Question 2

- Why does a moving skater continue moving?
- Related questions:
  - What keeps a moving banana moving?
  - Can I slice a moving banana in midair?

Skating 7

Physics Concept

- Inertia (the whole thing)
  - A body at rest tends to remain at rest
  - A body in motion tends to remain in motion

Skating 8

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.

Skating 9

Question 3

- Why does a skater need ice or wheels to skate?
- Related question:
  - Why does a hovercraft need an air cushion?

Skating 10

Keeping It Simple

- Real-world complications mask simple physics
- Solution: minimize or overwhelm complications
- To demonstrate inertia:
  - work on level ground (goodbye gravity)
  - use wheels, ice, or air support (goodbye friction)
  - work fast (overwhelm friction and air resistance)

Skating 11

Physical Quantities

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

Skating 12

Newton's First Law (Version 2)

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

Skating 13

Physical Quantities

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

Skating 14

Newton's First Law

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

Important Note: That constant velocity may be zero!

Skating 15

Question 4

- How does a skater start or stop moving?
- Related questions
  - What does a push do?
  - What does a skater respond to a push?
  - Do all skaters respond equally to equal pushes?

Skating 16

Physical Quantities

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

Skating 17

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.

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

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

Skating 18

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:

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

Skating 19

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

Skating 20

Falling Balls

Turn off all electronic devices

Skating 21

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

Skating 22

5 Questions about Falling Balls

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

Skating 23

Question 1

- Why does a dropped ball fall downward?
- Related question:
  - What is gravity doing to the ball?

Skating 24

Gravity and Weight

- Earth's gravity exerts a force on the ball
- That force is called the ball's weight
- Ball's weight points toward earth's center
- A dropped ball's weight causes it to accelerate toward earth's center (i.e., downward)

Skating 25

Question 2

- Do different balls fall at different rates?
- Related question:
  - Different balls have different weights and different masses, so are their accelerations related as they fall?

Skating 26

Weight and Mass

- A ball's weight is proportional to its mass

$$\frac{\text{weight of ball}}{\text{mass of ball}} = \text{constant}$$

- That constant
  - is same for all balls (and other objects)!
  - is

$$9.8\ \frac{\text{newtons}}{\text{kilogram}} = 9.8\ \text{N/kg}$$

    at earth's surface
  - is called "acceleration due to gravity"

Skating 27

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!

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

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

Skating 28

Question 3

- Would a ball fall differently on the moon?
- Answer: Yes!
- Moon's acceleration due to gravity is different!

Skating 29

Question 4

- Can a ball move upward and still be falling?
- Related questions:
  - How does falling affect a ball's acceleration?
  - … its velocity?
  - … its position?

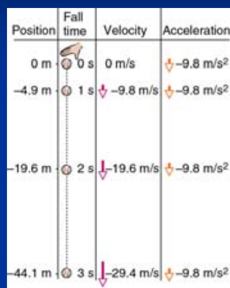
Skating 30

A Falling Ball (Part 1)

- A falling ball accelerates downward steadily
  - Its acceleration is constant and downward
  - Its velocity increases in the downward direction
- When falling from rest (stationary), its
  - velocity starts at zero and increases downward
  - altitude decreases at an ever faster rate

Skating 31

Falling Downward



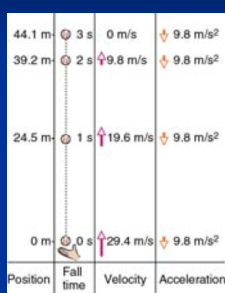
Skating 32

A Falling Ball (Part 2)

- A falling ball can start by heading upward!
  - Its velocity starts in the upward direction
    - Its velocity becomes less and less upward
    - Its altitude increases at an ever slower rate
  - Its velocity is momentarily zero
  - Its velocity continues in the downward direction
    - Its velocity becomes more and more downward
    - Its altitude decreases at ever faster rate

Skating 33

Falling Upward First



Skating 34

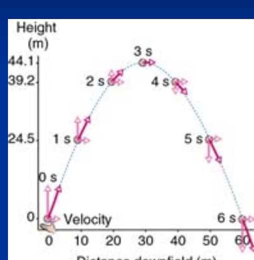
Question 5

- Does a ball's horizontal motion affect its fall?
- Related question:
  - Why does a thrown ball travel in an arc?

Skating 35

Throws and Arcs

- Gravity only affects only the ball's vertical motion
- A ball coasts horizontally while falling vertically
- The ball's overall path is a parabolic arc



Skating 36

Summary About Falling Balls

- Without gravity, a free ball would coast
- With gravity, an otherwise free ball
  - experiences its weight,
  - accelerates downward,
  - and its velocity becomes increasingly downward
- Whether going up or down, it's still falling
- Its horizontal coasting motion is independent of its vertical falling motion

Skating 37

Ramps

Turn off all electronic devices

Skating 38

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

Skating 39

Reading Question 1.3a

When a piano is resting motionless on the sidewalk, the net force on the piano is

A. equal to the upward support force on the piano.
B. equal to the piano's downward weight.
C. equal to half the piano's downward weight.
D. zero.

Skating 40

Reading Question 1.3b

When you push on a cart, you do work on that cart

A. only if it is stationary.
B. only if it is moving in the direction of your push.
C. only if it is moving perpendicular to your push.
D. only if it is moving opposite your push.
E. regardless of its motion.

Skating 41

5 Questions about Ramps

- Why doesn't a cart fall through a sidewalk?
- How does the sidewalk know how hard to push?
- Why doesn't a cart fall through a ramp?
- Why is it easy to push the cart up the ramp?
- Is there a physical quantity that's the same for any trip up the ramp, regardless of its steepness?

Skating 42

Question 1

- Why doesn't a cart fall through a sidewalk?

Skating 43

Support Forces

- On the sidewalk, the cart experiences two forces:
  - 1. Its downward weight (from the earth)
  - 2. An upward support force (from the sidewalk)
- That support force
  - is exerted by sidewalk on cart
  - acts perpendicular to sidewalk's surface (i.e., upward)
  - opposes cart's downward weight
  - prevents cart from penetrating the sidewalk's surface

Skating 44

Adding up the Forces

- Since the cart isn't accelerating,
  - the sum of forces (the net force) on the cart is zero
  - so sidewalk's support force balances cart's weight!
- This balance only affects vertical motion
  - The vertical component of net force on cart is zero
  - The horizontal component of net force can vary
- The cart can still move or accelerate horizontally

Skating 45

Question 2

- How does the sidewalk know how hard to push?

Skating 46

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.

Skating 47

The Cart and Sidewalk Negotiate

- When the cart and sidewalk touch,
  - the sidewalk pushes upward on the cart
  - the cart pushes downward on the sidewalk
- The two objects dent one another slightly
- The more they're dented, the harder they push
- Cart moves up and down until it comes to rest
- Cart is then in equilibrium (zero net force)

Skating 48

The Cart and Sidewalk Negotiate

- If cart is not accelerating, it's in equilibrium
  - sidewalk's support force on cart balances cart's weight
  - cart's support force on sidewalk equals cart's weight
- If cart is accelerating, it's not in equilibrium
  - the two forces on the cart don't balance
  - cart's support force on sidewalk is not cart's weight

Skating 49

Misconception Alert

- While the forces two objects exert on one another must be equal and opposite, the net force on each individual object can be anything.
- Each force within an equal-but-opposite pair is exerted on a different object, so they never cancel directly.

Skating 50

Question 3

- Why doesn't a cart fall through a ramp?

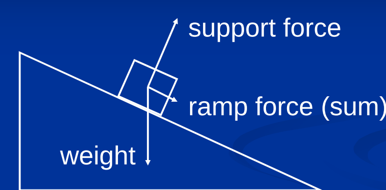
Skating 51

Forces on a Cart on a Ramp (Part 1)

- When the cart rests on the ramp's surface,
  - the ramp's support force prevents the cart from accelerating toward the ramp's surface.
  - cart's weight prevents cart from accelerating away from the ramp's surface.
  - so cart can only accelerate along ramp's surface
- Support force is perpendicular to ramp's surface
- and therefore doesn't point directly upward,
- so cart experiences a net force: a ramp force

Skating 52

Forces on a Cart on a Ramp (Part 2)



- Ramp force causes cart to accelerate downhill

Skating 53

Question 4

- Why is it easy to push the cart up the ramp?
- Related questions:
  - Why does the ramp's steepness matter?
  - Why does the cart tend to roll downhill?

Skating 54

Balanced Cart on Ramp

- If you balance the ramp force,
  - the net force on the cart will be zero,
  - so the cart won't accelerate,
  - and it will coast uphill or downhill or remain at rest
- The more gradual the ramp,
  - the more nearly its weight and the support balance,
  - the smaller the ramp force on the cart,
  - and the easier it is to balance the ramp force!

Skating 55

Question 5

- Is there a physical quantity that's the same for any trip up the ramp, regardless of its steepness?

Skating 56

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 in same direction)

Skating 57

Work Lifting a Cart

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

work = Force · Distance

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

work = Force · Distance

- The work is the same, either way!

Skating 58

Mechanical Advantage

- Mechanical advantage:
  - Doing the same amount of work, but altering the balance between force and distance
- A ramp provides mechanical advantage
  - You can raise a heavy cart with a modest force,
  - but you must push that cart a long distance.
  - Your work is independent of the ramp's steepness

Skating 59

The Transfer 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
  - You do work on the cart
  - Your chemical potential energy decreases
  - The cart's gravitational potential energy increases

Skating 60

Summary about Ramps

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

Skating 61

Wind Turbines

Turn off all electronic devices

Skating 62

Observations about Wind Turbines

- Wind turbines are symmetrical and balanced
- A balanced wind turbine rotates smoothly
- An unbalanced turbine settles heavy-side down
- Most wind turbines have three blades
- Wind turbines start or stop spinning gradually
- Wind turbines extract energy from the wind and convert it into electrical energy

Skating 63

Reading Question 2.1a

When you spin a smooth stone on a slippery table, the stone naturally pivots about its

A. center of mass.
B. center of gravity.
C. rotational mass.
D. torque.

Skating 64

Reading Question 2.1b

When a wind turbine is completely free of external torques, it

A. is horizontal and motionless.
B. can be horizontal or tilted, but it is motionless.
C. has a constant angular velocity, possibly zero.
D. has a constant angular acceleration.

Skating 65

5 Questions about Wind Turbines

- How does a balanced wind turbine move?
- Why does the wind turbine need a pivot?
- Why do wind turbines have two or three blades?
- Why do giant turbines start and stop so slowly?
- How does energy go from wind to generator?

Skating 66

Question 1

- How does a balanced wind turbine move?

Skating 67

Physics Concept

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

Skating 68

Physical Quantities

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

Skating 69

Newton's First Law of Rotational Motion

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

Skating 70

Rotation and Direction

- Angular position/velocity and torque are vectors
  - Each quantity has an amount and a direction
  - Quantity's direction points along a rotational axis,
  - toward the end specified by the right-hand rule.

Skating 71

Balanced Wind Turbine

- A balanced wind turbine in calm air
  - experiences zero net torque
  - has a constant angular velocity (which may be zero)
- Examples of constant angular velocity:
  - motionless and horizontal
  - motionless and tilted
  - turning steadily in a specific direction

Skating 72

Question 2

- Why does the wind turbine need a pivot?

Skating 73

Center of Mass

- A turbine's center of mass is its natural pivot
- An unsupported turbine
  - pivots about its center of mass
  - while its center of mass falls
- A turbine supported at its center of mass
  - can spin freely (rotational motion is permitted)
  - but doesn't fall (translational motion is forbidden)

Skating 74

Question 3

- Why do wind turbines have two or three blades?

Skating 75

A One-Blade Turbine (Part 1)

- A one-blade turbine's angular velocity fluctuates
  - It doesn't obey Newton's first law.
  - Since it is rigid and doesn't wobble,
  - it must be experiencing outside torques.
- Those torques change turbine's angular velocity

Skating 76

Physical Quantities

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

Skating 77

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.

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

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

Skating 78

A One-Blade Turbine (Part 2)

- Blade's weight produces a torque on the blade
- Weight is a force, not a torque
- Blade's weight effectively acts at center of gravity
  - a lever arm separates center of gravity from pivot,
  - so blade's weight produces a torque about the pivot.
- That torque is largest when
  - the blade's weight acts farthest from pivot
  - and it acts perpendicular to the lever arm.

Skating 79

Forces and Torques

- Forces and torques are related:
  - A force can produce a torque
  - A torque can produce a force

torque = lever arm · force

(where the lever arm is perpendicular to the force)

Skating 80

Balancing the Turbine

- Installing a second blade adds a second torque
- Net torque is the sum of all torques on turbine
- The two torques point in opposite directions
  - Left blade torque is ccw (points toward you)
  - Right blade torque is cw (points away from you)
- Turbine is balanced when
  - those torques sum to zero or, equivalently, when
  - turbine's center of gravity is located at the pivot
- Three-blade turbine's center of gravity is at pivot

Skating 81

Question 4

- Why do giant turbines start and stop so slowly?

Skating 82

A Blade's Wind Torque

- Wind torque on a blade is proportional to
  - the wind's force on the blade
  - the blade's effective lever arm
- Doubling the length of the blade
  - increases its wind force by a factor of 2
  - increases its effective lever arm by a factor of 2
  - increases its wind torque by a factor of 4

Skating 83

A Blade's Rotational Mass

- Rotational mass of blade is proportional to
  - the blade's mass
  - the square of blade's effective lever arm
- Doubling the length of a blade
  - increases its mass by a factor of 2
  - increases its lever arm by a factor of 2
  - increases its rotational mass by a factor of 8!

Skating 84

Turbine Size and Responsiveness

- A wind turbine blade's
  - wind torque increases in proportion to its length^2
  - rotational mass increases in proportion to its length^3
- The larger the wind turbine,
  - the slower its angular accelerations
  - the longer it takes to start or stop turning

Skating 85

Question 5

- How does energy go from wind to generator?

Skating 86

Rotational Work

- Work – mechanical means of transferring energy

work = torque · angle

(where torque and angle in same direction)

Skating 87

Rotational Work

- Wind does translational work on a turbine blade:
  - wind exerts a force on the blade
  - blade moves a distance in direction of that force
  - so energy moves from wind to turbine
- Turbine does rotational work on a generator
  - turbine exerts a torque on generator
  - generator turns an angle in direction of that torque
  - so energy moves from wind turbine to generator

Skating 88

Summary about Wind Turbines

- Without air or generator, balanced wind 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

Skating 89

Wheels

Turn off all electronic devices

Skating 90

Observations about Wheels

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

Skating 91

Reading Question 2.2a

I am pushing a file cabinet to your right along a level floor. In which direction does the floor's frictional force on the file cabinet act?

A. Toward your left.
B. Upward and toward your left (at an angle).
C. Toward your right.
D. Upward and toward your right (at an angle).

Skating 92

Reading Question 2.2b

Which types of friction waste ordered energy (work) as disordered energy (thermal energy)?

A. Static friction but not sliding friction
B. Sliding friction but not static friction
C. Both static friction and sliding friction
D. Neither static friction nor sliding friction

Skating 93

5 Questions about Wheels

- Why does a wagon need wheels?
- Why do boxes seem to "break free" and then slide easily when you shove them hard enough?
- What happens to energy as a box skids to rest?
- How do wheels help a wagon coast?
- What energy does a wheel have?

Skating 94

Question 1

- Why does a wagon need wheels?

Skating 95

Frictional Forces

- A frictional force
  - opposes relative sliding motion of two surfaces
  - points along the surfaces
  - acts to bring the two surfaces to one velocity
- Frictional forces always come in 3^{rd} law pairs:
  - Pavement's frictional force pushes cart backward
  - Cart's frictional force pushes pavement forward

Skating 96

The Two Types of Friction

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

Skating 97

Question 2

- Why do boxes seem to "break free" and then slide easily when you shove them hard enough?

Skating 98

Frictional Forces

- Frictional forces increase when you:
  - push the surfaces more tightly together
  - roughen the surfaces
- Peak static force may be greater than sliding force
  - Surface features can interpenetrate better
  - Friction force may drop when sliding begins

Skating 99

Boxes and Friction

- A stationary box
  - experiences static friction
  - won't start moving until you pull very hard
- A moving box
  - experiences sliding friction
  - needs to be pulled or it will slow down and stop
  - experiences wear as it skids along the pavement

Skating 100

Question 3

- What happens to energy as a box skids to rest?

Skating 101

Friction, Energy, and Wear

- Static friction
  - Both surfaces travel the same distance (often zero)
  - No work "disappears" and there is no wear
- Sliding friction
  - The two surfaces travel different distances
  - Some work "disappears" and becomes thermal energy
  - The surfaces experience wear
- A sliding box turns energy into thermal energy

Skating 102

The Many Forms of Energy

- Kinetic: energy of motion
- Potential: stored in forces between objects
  - Gravitational
  - Magnetic
  - Electrochemical
  - Nuclear
  - Elastic
  - Electric
  - Chemical
- Thermal energy: the same forms of energy, but divided up into countless tiny fragments

Skating 103

Energy and Order

- A portion of energy can be
  - Organized – ordered energy (e.g. work)
  - Fragmented – disordered energy (e.g. thermal energy)
- Turning ordered energy into disordered energy
  - is easy to do
  - is statistically likely
- Turning disordered energy into ordered energy
  - is hard to do
  - is statistically so unlikely it never happens

Skating 104

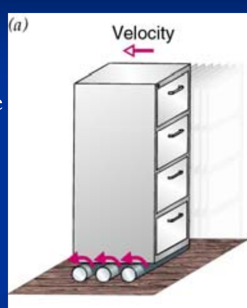
Question 4

- How do wheels help a wagon coast?

Skating 105

Rollers

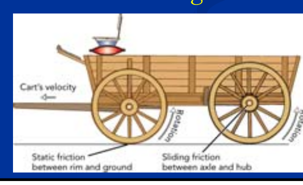
- Eliminate sliding friction at roadway
- Are inconvenient because they keep popping out from under the object



Skating 106

Wheels

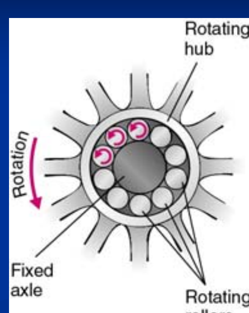
- Eliminate sliding friction at roadway
- Convenient because they don't pop out
- Allow static friction to exert torques on wheels and forces on vehicle
- Wheel hubs still have sliding friction



Skating 107

Bearings

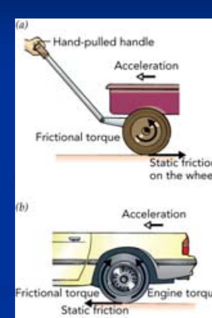
- Eliminate sliding friction in wheel hub
- Behave like automatically recycling rollers



Skating 108

Practical Wheels

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



Question 5

- What energy does a wheel have?

Wheels and Kinetic Energy

- A moving wheel has kinetic energy:

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

- A spinning wheel has kinetic energy:

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

- A moving and spinning wheel has both forms

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

Reading Question 2.3a

Your momentum is equal to

A. your weight times your velocity.
B. your weight times your speed.
C. your mass times your velocity.
D. your mass times your speed.

Skating 115

Reading Question 2.3b

Can you transfer momentum to a rigid, immovable wall?

A. Yes
B. No

Skating 116

3 Questions about Bumper Cars

- Does a moving bumper car carry a "force"?
- Does a spinning bumper car carry a "torque"?
- On an uneven floor, which way does a bumper car accelerate?

Skating 117

Question 1

- Does a moving bumper car carry a "force"?

Skating 118

Momentum

- A translating bumper car carries momentum
- Momentum
  - is a conserved quantity (can't create or destroy)
  - is a directed (vector) quantity
  - measures the translational investment the object needed to reach its present velocity

momentum = mass · velocity

Skating 119

Exchanging Momentum

- Bumper cars exchange momentum via impulses
- An impulse is
  - the only way to transfer momentum
  - a directed (vector) quantity

impulse = force · time

- When car_1 gives an impulse to car_2, car_2 gives an equal but oppositely directed impulse to car_1.

Skating 120

Head-On Collisions

- Bumper cars exchange momentum via impulses
- The total momentum never changes
- Car with the least mass changes velocity most
- The littlest riders get creamed

Skating 121

Question 2

- Does a spinning bumper car carry a "torque"?

Skating 122

Angular Momentum

- A spinning car carries angular momentum
- Angular momentum
  - is a conserved quantity (can't create or destroy)
  - is a directed (vector) quantity
  - measures the rotational investment the object needed to reach its present angular velocity

angular momentum = rotational mass· angular velocity

Skating 123

Newton's Third Law of Rotational Motion

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

Skating 124

Exchanging Angular Momentum

- Bumper cars exchange angular momentum via angular impulses
- An angular impulse is
  - the only way to transfer angular momentum
  - a directed (vector) quantity

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.

Skating 125

Glancing Collisions

- Bumper cars exchange angular momentum via angular impulses
- Total angular momentum about a specific inertial point in space remains unchanged
- Bumper car with the smallest rotational mass about that point changes angular velocity most
- The littlest riders tend to get spun wildly

Skating 126

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

Skating 127

Question 3

- On an uneven floor, which way does a bumper car accelerate?

Skating 128

Potential Energy, Acceleration, and Force

- An object accelerates in the direction that reduces its total potential energy as rapidly as possible
- Forces and potential energies are related!
- A car on an uneven floor accelerates in whatever direction reduces its total potential energy as rapidly as possible

Skating 129

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

Skating 130

Spring Scales

Turn off all electronic devices

Skating 131

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

Skating 132

Reading Question 3.1a

An object that is in equilibrium is

A. accelerating opposite its velocity.
B. accelerating at a constant rate.
C. motionless.
D. motionless or moving at constant velocity.

Skating 133

Reading Question 3.1b

The force a spring exerts on one of its ends is proportional to

A. its weight.
B. its mass.
C. its distortion away from equilibrium.
D. its length.

Skating 134

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?

Skating 135

Question 1

- What exactly is a spring scale measuring?
- Related question:
  - Are all measures of quantity equivalent?

Skating 136

Mass as a Measure

- Pros:
  - Independent of measuring location
  - Can be measured directly:
    - Exert a known force
    - Measure the resulting acceleration
- Cons:
  - Measuring acceleration accurately is difficult

Skating 137

Weight as a Measure

- Pros:
  - Proportional to mass
  - Measuring weight is easy
- Cons:
  - Dependent on measuring location
  - Can't be measured directly
- Spring scales measure weight, not mass

Skating 138

Question 2

- How does a spring scale measure weight?

Skating 139

Equilibrium

- Spring scales measure weight using equilibrium
- An object in equilibrium
  - experiences zero net force
  - is not accelerating
- At equilibrium,
  - individual forces sum to zero (they cancel perfectly).
  - an object at rest remains at rest
  - an object in motion coasts

Skating 140

Weighing via Equilibrium

- Balance the object's weight with a support force
- Attain equilibrium

  weight + support force = 0

- Measure the support force

Skating 141

Question 3

- What is the scale's dial or meter reporting?
- Related question:
  - How do you measure a support force?

Skating 142

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"

Skating 143

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

Skating 144

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

Skating 145

Question 4

- Why must you stand still on a spring scale?
- Related question:
  - Why does the reading bounce briefly?

Skating 146

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!

Skating 147

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

Skating 148

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

Skating 149

Ball Sports: Bouncing

Turn off all electronic devices

Skating 150

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

Skating 151

Reading Question 3.2a

A "bouncy" or "lively" ball bounces higher from a rigid, immovable surface than a "dead" ball does because the "bouncy" ball

A. pushes harder on the surface.
B. transfers less energy to the surface.
C. returns more collision energy as rebound energy.
D. obtains more rebound energy from the surface.

Skating 152

Reading Question 3.2b

When a baseball bounces from a moving bat, the final speed of the baseball

A. is between the initial speeds of bat and baseball.
B. is equal to the initial speed of the baseball.
C. can exceed the initial speed of either object.
D. is less than the initial speed of either object.

Skating 153

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?

Skating 154

Question 1

- Why can't a ball that's dropped on a hard floor rebound to its starting height?
- Related question:
  - What happens to ball's energy as it bounces?

Skating 155

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

Skating 156

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:

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

Skating 157

Question 2

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

Skating 158

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!

Skating 159

Question 3

- How does a ball bounce when it hits a bat?
- Related question:
  - Do both the ball and bat bounce?

Skating 160

Bouncing from Moving Surfaces

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

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

Skating 161

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

Skating 162

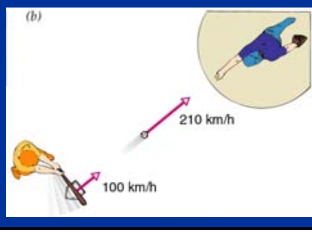
Ball and Bat (Part 2)

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

Skating 163

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



Skating 164

Question 4

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

Skating 165

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

Skating 166

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

Skating 167

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

Skating 168

Summary about Bouncing Balls

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

Carousels and Roller Coasters

Turn off all electronic devices

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

Reading Question 3.3a

When you are riding a carousel that is turning at a steady rate, your acceleration is

A. forward (in the direction of your velocity).
B. toward the center of the carousel.
C. away from the center of the carousel.
D. zero.

Reading Question 3.3b

When you are in free fall, your apparent weight is

A. downward and equal to your weight.
B. upward and equal in amount to your weight.
C. zero.

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?

Question 1

- What aspects of motion do you feel?
- Related questions:
  - Can you feel position?
  - Can you feel velocity?
  - Can you feel acceleration?

The Feeling of Weight

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

The Feeling of Acceleration

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

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?
- Related question:
  - How are you accelerating 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"

Skating 181

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?

Skating 182

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

Skating 183

Question 5

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

Skating 184

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!

Skating 185

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!

Skating 186

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!

Skating 187

Bicycles

Turn off all electronic devices

Skating 188

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

Skating 189

Reading Question 4.1a

A upright tricycle is in a stable equilibrium because tipping it

A. decreases its potential energy.
B. increases its potential energy.
C. decreases its total energy.
D. increases its total energy.

Skating 190

Reading Question 4.1b

One can ride a bicycle without hands because it

A. automatically leans in the direction that it is steering.
B. automatically steers under your center of gravity.
C. has static stability.
D. has no static stability.

Skating 191

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?

Skating 192

Question 1

- Why is a stationary tricycle so stable?

Skating 193

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.

Skating 194

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.

Skating 195

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.

Skating 196

Question 2

- Why is stationary bicycle so unstable?

Skating 197

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

Skating 198

Question 3

- Why does a moving tricycle flip during turns?


Skating 199
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.
Skating 200
Question 4
Why must you lean a bicycle during turns?
Skating 201
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!
Skating 202
Question 5
Why can you ride a bicycle without hands?
Skating 203
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
Skating 204
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

Skating 205

Rockets

Turn off all electronic devices

Skating 206

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

Skating 207

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?

Skating 208

Question 1

- What pushes a rocket forward?

Skating 209

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

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

Skating 210

Rocket Propulsion

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

$$\begin{aligned}\text{momentum}_{\text{ship}} &= -\text{momentum}_{\text{fuel}} \\ &= -\text{mass}_{\text{fuel}} \cdot \text{velocity}_{\text{fuel}}\end{aligned}$$

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

Skating 211

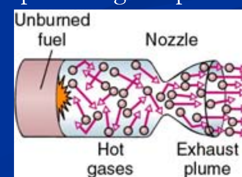
Question 2

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

Skating 212

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



Skating 213

Question 3

- What keeps a rocket pointing forward?

Skating 214

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

Skating 215

Question 4

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

Skating 216

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,

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

Skating 217

Question 5

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

Skating 218

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:

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

Skating 219

Gravity (Part 2)

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

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

Skating 220

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

Skating 221

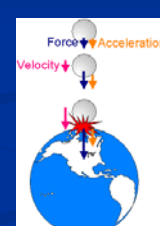
Question 6

- What makes a spaceship orbit the earth?

Skating 222

Orbits (Part 1)

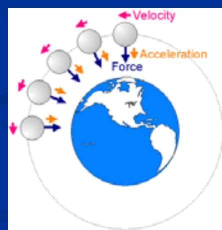
- An object that begins to fall from rest falls directly toward the earth
- Acceleration and velocity are in the same direction



Skating 223

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



Skating 224

Current Rocket Technology

- X-Prize Rockets
- Single State 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

Skating 225

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

Skating 226

Balloons

Turn off all electronic devices

Skating 227

Observations about Balloons

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

Skating 228

Reading Question 5.1a

What keeps the air molecules in our atmosphere from piling up on the ground?

A. The atmosphere’s density
B. The atmosphere’s momentum
C. The atmosphere’s weight
D. The atmosphere’s thermal energy

Skating 229

Reading Question 5.1b

Why is atmospheric pressure lower in the mountains than it is at sea-level?

A. Mountain air has more oxygen in it.
B. Mountain air is more dense.
C. Mountain air has less air above it to support.
D. Mountain air is colder.

Skating 230

5 Questions about Balloons

- How does air “inflate” a rubber balloon?
- Why doesn’t the atmosphere fall or collapse?
- Why does the atmosphere push up on a balloon?
- Why does a hot air balloon float in cold air?
- Why does a helium balloon float in air?

Skating 231

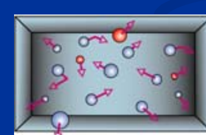
Question 1

- How does air “inflate” a rubber balloon?
- Related questions:
  - How does air occupy space?
  - How does air push on the balloon’s elastic skin?

Skating 232

Air’s Characteristics

- Air is a gas
  - It consists of individual atoms and molecules
  - Its particles are kept separate by thermal energy
  - Its particles bounce around in free fall



Skating 233

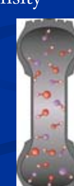
Air and Pressure

- Air has pressure
  - Air particles transfer momentum when they bounce
  - Each momentum transfer/bounce involves forces
  - Bouncing particles exerts forces on container walls
  - Average force is proportional to surface area
  - Average force per unit of area is called “pressure”

Skating 234

Air and Density

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



Skating 235

Air Pressure and Density

- Air’s pressure is proportional to its density
  - In denser air, particles hit the surface more often
  - Denser air → more pressure

Skating 236

Pressure Imbalances

- Balanced pressure exerts no overall force
  - Pressure forces on opposite sides of a balloon cancel
  - Sum of pressure forces on balloon is zero.
- Unbalanced pressure exerts an overall force
  - Forces on opposite sides of a balloon don’t cancel
  - Sum of forces pushes balloon toward lower pressure
- Unbalanced pressure affects the air itself
  - The air is pushed toward lower pressure

Skating 237

Question 2

- Why doesn’t the atmosphere fall or collapse?
- Related questions:
  - Air has weight, so why doesn’t it fall to the ground?
  - How is the atmosphere supported against gravity?
  - Why is the air denser at lower altitudes?

Skating 238

The Atmosphere

- The atmosphere is in stable equilibrium
  - Air pressure decreases with altitude
  - A pressure imbalance pushes each air layer upward
  - This upward force balances the layer’s weight
  - Air near the ground supports the air overhead
- Supporting itself structures the atmosphere
  - Air pressure is highest near the ground
  - Air density is highest near the ground

Skating 239

Question 3

- Why does the atmosphere push up on a balloon?

Skating 240

The Buoyant Force

- Because of atmospheric structure, air pressure is
  - stronger near the bottom of a balloon,
  - weaker near the top of the balloon,
  - so the air pushes up harder than it pushes down,
  - and this imbalance yields an upward buoyant force
- The atmosphere pushes upward on the balloon!

Skating 241

Archimedes' Principle

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

Skating 242

Question 4

- Why does a hot air balloon float in cold air?
- Related questions:
  - Why does a cold air balloon sink in cold air?
  - What is the difference between hot air and cold air?

Skating 243

Room-Air Balloon in Air

- A rubber balloon filled with room air
  - weighs more than the room air it displaces,
  - experiences a downward net force in room air,
  - and sinks in room air
- Balloon's average density > room air's density

Skating 244

Air and Temperature

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

Skating 245

An Aside About Temperature

- Like most things, air has a temperature
  - Air particles have thermal kinetic energy
  - Average thermal kinetic energy per particle is proportional to <u>absolute</u> temperature
- SI unit of absolute temperature: kelvins or K
  - 0 K is absolute zero: no thermal energy left
  - Step size: 1 K step same as 1 °C step
  - Room temperature is approximately 300 K

Skating 246

Hot-Air Balloon in Air

- A rubber balloon filled with hot air
  - contains fewer air particles than if it were cold,
  - weighs less than the room air it displaces,
  - experiences an upward net force in room air,
  - and floats in room air
- Balloon's average density < room air's density

Skating 247

Question 5

- Why does a helium balloon float in air?
- Related questions:
  - How does helium differ from air?
  - Doesn't helium have mass and weight?

Skating 248

Pressure and Particle Density

- A volume of gas has some number of particles
- The average number of gas particles per unit of volume is called the gas's "particle density"
- All gas particles contribute equally to pressure
  - lower-mass particles travel faster and bounce more,
  - so all the effects of particle mass cancel out
- Gases with equal particle densities and equal temperatures have equal pressures

Skating 249

Helium vs. Air

- A helium atom has less mass than an air particle
- At the same temperature, a helium balloon has
  - the same pressure as an air balloon,
  - the same particle density as an air balloon,
  - and therefore less mass than an air balloon

Skating 250

Helium Balloon in Air

- A rubber balloon filled with helium
  - has same particle density as air,
  - weighs less than the air it displaces,
  - experiences an upward net force in air,
  - and floats in air
- Balloon's average density $<$ room air's density

Skating 251

The Ideal Gas Law

- is a summary relationship for gases:

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

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

Skating 252

Summary about Balloons

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

Skating 253

Water Distribution

Turn off all electronic devices

Skating 254

Observations about Water Distribution

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

Skating 255

Reading Question 5.2a

The total energy of a portion of water in steady state flow is constant

A. along a streamline.
B. everywhere in the flow.
C. at the same height in the flow.
D. at the same speed in the flow.

Skating 256

Reading Question 5.2b

Water seeks its level (flows until it is the same height everywhere) because that arrangement

A. maximizes the water's total energy.
B. maximizes the water's total potential energy.
C. minimizes the water's total energy.
D. minimizes the water's total potential energy.

Skating 257

4 Questions about Water Distr.

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

Skating 258

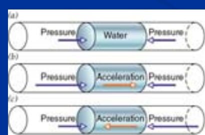
Question 1

- Why does water move through level pipes?
- Related questions:
  - Can water in a level pipe move without a push?
  - How does water in a level pipe respond to a push?
  - How do you push on water in a level pipe?

Skating 259

How Water Moves (no gravity)

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



Skating 260

Question 2

- How can you produce pressurized water?
- Related questions:
  - How can you create pressure?
  - How can you deliver pressurized water to a pipe?
  - Why does pumping water require such effort?

Skating 261

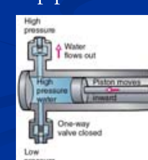
Pressurizing Water

- To pressurize water, confine it and squeeze
  - As you push inward on the water,
  - it pushes outward on you (Newton's third law).
  - Water's outward push is produced by its pressure,
  - so the water's pressure rises as you squeeze it harder.

Skating 262

Pumping Water (no gravity)

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



Skating 263

Pumping Requires Work

- You do work as you pump water into the pipe
  - You squeeze the water inward – the force,
  - and the water moves inward – the distance.
  - In this case, the work you do is:

work = pressure · volume

- The pressurized water carries your work with it
- We'll call this work "pressure potential energy"

Skating 264

Question 3

- Where does the work you do pumping water go?

Skating 265

Pressure Potential Energy

- Pressure potential energy is unusual because
  - it's not really stored in the pressurized water,
  - it's promised by the water's pressure source.
- In steady state flow (SSF),
  - which is steady flow in motionless surroundings,
  - promised energy is as good as stored energy,
  - so pressure potential energy (PPE) is meaningful.

Skating 266

Question 4

- As water flows, what happens to its energy?

Skating 267

Energy and Bernoulli (no gravity)

- In SSF, water flows along streamlines
- Water flowing along a single streamline in SSF
  - has both PPE and kinetic energy (KE),
  - must have a constant total energy per volume,
  - and obeys Bernoulli's equation (no gravity):

$$\frac{\text{PPE}}{\text{Volume}} + \frac{\text{KE}}{\text{Volume}} = \frac{\text{Constant}}{\text{Volume}}$$

Skating 268

How Water Moves (with gravity)

- Weight contributes to the net force on water
- Without a pressure imbalance, water falls
- Water in equilibrium has a pressure gradient
  - Its pressure decreases with altitude
  - Its pressure increases with depth
- Water has gravitational potential energy (GPE)

Skating 269

Energy and Bernoulli (with gravity)

- Water flowing along a single streamline in SSF
  - has PPE, KE, and GPE,
  - must have a constant total energy per volume,
  - and obeys Bernoulli's equation (with gravity)

$$\frac{\text{PPE}}{\text{Volume}} + \frac{\text{KE}}{\text{Volume}} + \frac{\text{GPE}}{\text{Volume}} = \frac{\text{Constant}}{\text{Volume}}$$

Skating 270

Energy Transformations (part 1)

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

Skating 271

Energy Transformations (part 2)

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

Skating 272

Energy Transformations (part 3)

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

Skating 273

Summary about Water Distribution

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

Skating 274

Garden Watering

Turn off all electronic devices

Skating 275

Observations about Garden Watering

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

Skating 276

Reading Question 6.1a

When water flows smoothly in a straight hose, that water's viscosity causes the water to

A. speed up.
B. move with constant momentum.
C. move at constant velocity.
D. waste some of its energy as thermal energy.

Skating 277

Reading Question 6.1b

When water flows smoothly through a bent hose, the water pressure at the bend's inside is

A. more than at the bend's outside.
B. the same as at the bend's outside.
C. less than at the bend's outside.
D. either more or less than at the bend's outside.

Skating 278

6 Questions about Garden Watering

- How does a faucet control flow?
- How much does the diameter of a hose matter?
- Why does water pour gently from an open hose?
- Why does water spray so hard from a nozzle?
- What causes hissing in a faucet, hose, or nozzle?
- Why do pipes rattle when you close the faucet?

Skating 279

Question 1

- How does a faucet control flow?
- Related Question:
  - Why is a small opening different from a large one?

Skating 280

Faucets and Water Flow

- In going through a faucet, water must
  - flow through a narrow passage
  - and pass close to the faucet's stationary surfaces
- Total energy limits flow speed through passage
  - The water turns its total energy into kinetic energy,
  - but its peak speed is limited by its initial pressure
- Motion near the surfaces slows the water
  - Because water at the walls is stationary,
  - viscous forces within the water slow all of it

Skating 281

Viscous Forces and Viscosity

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

Skating 282

Question 2

- How much does the diameter of a hose matter?
- Related Question:
  - Is a 5/8" hose much different from a 3/4" hose?

Skating 283

Hoses and Water Flow (part 1)

- The rate at which water flows through a hose,
  - increases as end-to-end pressure difference increases,
  - decreases as water's viscosity increases,
  - decreases as the hose becomes longer,
  - and increases *dramatically* as the hose becomes wider
- Increasing the hose width
  - enlarges cross-sectional area through which to flow
  - and lets water get farther from the walls of the hose

Skating 284

Hoses and Water Flow (part 2)

- Water flow through a hose is proportional to
  - pressure difference
  - 1/viscosity
  - 1/hose length
  - $(\text{hose diameter})^4$
- Poiseuille's law:

$$\text{flow rate} = \frac{\pi \cdot \text{pressure difference} \cdot \text{hose diameter}^4}{128 \cdot \text{hose length} \cdot \text{viscosity}}$$

Skating 285

Question 3

- Why does water pour gently from an open hose?

Skating 286

Wasting Energy in a Hose

- Viscous effects
  - waste water's total energy as thermal energy
  - and become stronger with increased flow speed
- Increasing the speed of the flow
  - increases the energy wasted by each portion of water
  - makes the loss of pressure more rapid

Skating 287

Question 4

- Why does water spray so hard from a nozzle?

Skating 288

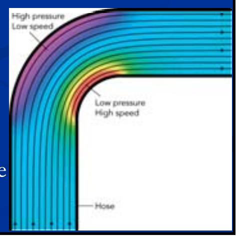
Making Water Accelerate

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

Skating 289

Bending the Flow in a Hose

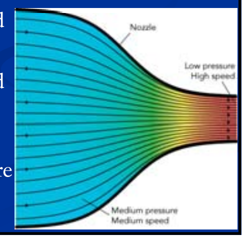
- Bending the flow requires a pressure imbalance
  - The water accelerates toward lower pressure
- Flow in bent hose develops a pressure gradient
  - higher pressure & lower speed on the outside of the bend
  - lower pressure & higher speed on the inside of the bend
  - and water accelerates from high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



Skating 290

Speeding the Flow in a Nozzle

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



Skating 291

Question 5

- What causes hissing in a faucet, hose, or nozzle?

Skating 292

Water Flow Isn't Always Smooth

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

Skating 293

Reynolds Number

- The flow type depends on the Reynolds number

$$\text{Reynolds number} = \frac{\text{inertial influences}}{\text{viscous influences}} = \frac{\text{density} \cdot \text{obstacle length} \cdot \text{speed}}{\text{viscosity}}$$

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

Skating 294

Question 6

- Why do pipes rattle when you close the faucet?

Skating 295

Water and Momentum

- Water carries momentum
- Water transfers its momentum via impulses:

  impulse = pressure · surface area · time

- Large momentum transfers requires
  - large pressures,
  - large surface areas,
  - and/or long times.
- Moving water can be surprisingly hard to stop

Skating 296

Summary about Garden Watering

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

Skating 297

Balls and Air

Turn off all electronic devices

Skating 298

Observations about Balls and Air

- Air resistance slows a ball down
- The faster a ball moves, the quicker it slows
- Some balls have deliberately roughened surfaces
- Spinning balls curve in flight

Skating 299

Reading Question 6.2a

A pitcher throws a baseball toward home plate. Which type(s) of aerodynamic forces push the ball toward the pitcher?

A. Lift forces.
B. Drag forces.
C. Both lift and drag forces.
D. Gravitational forces.

Skating 300

Reading Question 6.2b

You kick a soccer ball toward the goal. The airflow directly behind that ball

A. has a pressure much greater than atmospheric.
B. has a pressure much less than atmospheric.
C. is turbulent.
D. is laminar.

Skating 301

3 Questions about Balls and Air

- Why do balls experience air resistance?
- Why do some balls have dimples?
- Why do spinning balls curve in flight?

Skating 302

Question 1

- Why do balls experience air resistance?
- Related questions:
  - Do viscous forces slow balls?
  - Does air pressure slow balls?

Skating 303

Aerodynamic Forces: Drag

- Air resistance is technically called “drag”
- When a ball moves through air, drag forces arise
  - The air pushes the ball downstream
  - and the ball pushes the air upstream
- Drag forces transfer momentum
  - air transfers downstream momentum to ball
  - ball transfers upstream momentum to air

Skating 304

Aerodynamic Forces: Lift

- When a ball deflects passing air, lift forces arise
  - The air pushes the ball to one side
  - and the ball pushes the air to the other side
- Lift forces transfer momentum
  - air transfers sideways momentum to ball
  - ball transfers sideways momentum to air
- Lift forces don’t always point upward!

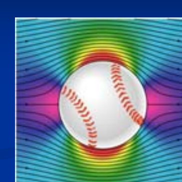
Skating 305

Types of Drag & Lift

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

Skating 306

Perfect Flow Around a Ball



- Air bends away from ball’s front
  - At front: high pressure, slow flow
- Air bends toward ball’s sides
  - At side: low pressure, fast flow
- Air bends away from ball’s back
  - At back: high pressure, slow flow
- Pressures on opposite sides balance perfectly,
- so ball experiences only viscous drag.

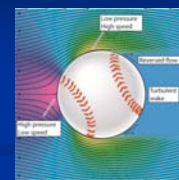
Skating 307

The Onset of Turbulence

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

Skating 308

Imperfect Flow Around Slow Ball



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

Skating 309

Question 2

- Why do some balls have dimples?

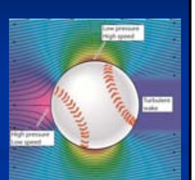
Skating 310

Boundary Layer

- Flow near the surface forms a "boundary layer"
- At low Reynolds number (<100,000)
  - the boundary layer is laminar,
  - so closest layer is slowed relentlessly by viscous drag
- At high Reynolds number (>100,000)
  - the boundary layer itself is turbulent,
  - so tumbling continually renews closest layer's energy
  - boundary layer penetrates deeper into rising pressure

Skating 311

Imperfect Flow Around Fast Ball



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

Skating 312

Tripping the Boundary Layer

- To reduce pressure drag, some balls have dimples
  - Dimples "trips" the boundary layer
  - and causes boundary layer to become turbulent.
  - Since turbulent boundary layer resists peeling better,
  - ball's main airflow forms smaller turbulent wake.
- Example: Golf balls

Skating 313

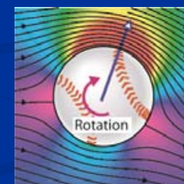
Question 3

- Why do spinning balls curve in flight?

Skating 314

Spinning Balls, Magnus Force

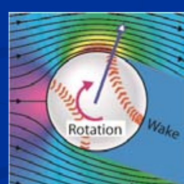
- Turning surface pushes/pulls on the air flow
  - Air on one side makes long bend toward ball
  - Air on other side makes shorter bend away from ball
  - Pressures are unbalanced
- The overall air flow is deflected
  - Ball pushes air to one side
  - Air pushes ball to other side
- Ball feels Magnus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



Skating 315

Spinning Balls, Wake Force

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



Skating 316

Summary about Balls and Air

- The air pressures around these objects are not uniform and result in drag and lift
- Balls experience mostly pressure drag
- Spinning balls experience Magnus and Wake Deflection lift forces

Skating 317

Airplanes

Turn off all electronic devices

Skating 318

Observations about Airplanes

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

Skating 319

6 Questions about Airplanes

- How does an airplane support itself in the air?
- How does the airplane "lift off" the runway?
- Why does plane tilt up to rise; down to descend?
- Why are there different wing shapes?
- How does a plane turn?
- How does a plane propel itself through the air?

Skating 320

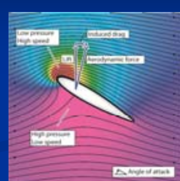
Question 1

- How does an airplane support itself in the air?
- Related questions:
  - What pushes up on airplane to balance its weight?
  - What does it do with the momentum gravity gives it?

Skating 321

Using a Wing to Obtain Lift (part 1)

- As air flows under a wing,
  - air bends away from the wing
  - air's pressure rises, speed drops
- As air flows over the wing,
  - air bends toward the wing
  - air's pressure drops, speed rises
- The wing experiences a pressure imbalance
- There is an upward pressure force on the wing



Skating 322

Using a Wing to Obtain Lift (part 2)

- The wing experiences
  - a strong upward lift force
  - a small downstream drag force
- Wing pushes air down, air pushes wing up!
- Downward momentum is transferred
  - from the earth to the airplane by gravity,
  - from the airplane to the air by lift forces, and
  - from the air to the earth by pressure on the ground

Skating 323

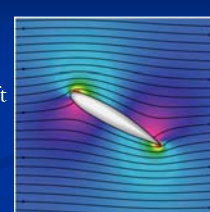
Question 2

- How does the airplane "lift off" the runway?
- Related questions:
  - How does the pilot initiate the rise?
  - How is landing different from takeoff?

Skating 324

At Take-Off

- As a wing starts moving in air
  - the airflow is symmetric
  - and the wing experiences no lift
- However, this airflow is
  - unstable at trailing edge kink
  - and the wing sheds a vortex
- After the vortex leaves, the wing has lift



Skating 325

Question 3

- Why does plane tilt up to rise; down to descend?
- Related questions:
  - Does a plane always go in the direction it's pointed?
  - How can plane land if its nose is higher than its tail?

Skating 326

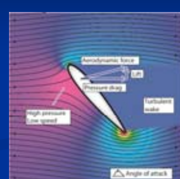
Angle of Attack

- A wing's lift depends on
  - the shape of its airfoil
  - and on its angle of attack–its tilt relative to the wind
- Tilting an airplane's wings
  - changes the net force on the airplane
  - and can make the airplane accelerate up or down
  - but usually requires tilting the airplane's fuselage
- Plane's tilt controls lift, not direction of travel

Skating 327

Limits to Lift: Stalling

- At too great an angle of attack,
  - the upper boundary layer stalls,
  - the airstream detaches from wing,
  - the lift nearly vanishes,
  - and pressure drag appears
- Plane plummets abruptly



Skating 328

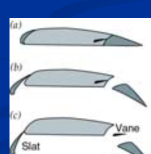
Question 4

- Why are there different wing shapes?

Skating 329

Wing Shape

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



Skating 330

Question 5

- How does a plane turn?

Skating 331

Turning and Orientation

- Airplanes use lift to accelerate to the side
- Three orientation controls:
  - Angle of attack controlled by elevators
  - Left-right tilt controlled by ailerons
  - Left-right rotation controlled by rudder
- Steering involves ailerons and rudder
- Elevation involves elevators and engine

Skating 332

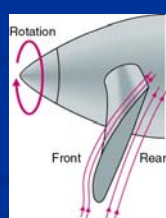
Question 6

- How does a plane propel itself through the air?
- Related question:
  - How does a plane maintain its forward momentum?

Skating 333

Propellers

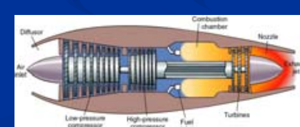
- Propellers are spinning wings
  - They deflect air backward,
  - do work on air (add energy),
  - and pump air toward rear of plane
- Action-Reaction
  - They push the air backward,
  - so air pushes them forward



Skating 334

Jet Engines (Part 1)

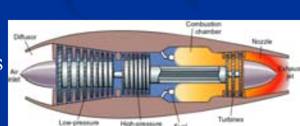
- Jet engines pump air toward rear of plane
  - Engine consists of an oval "ball" with a complicated duct or passageway through it
  - Air passing through the duct exchanges first speed for pressure and then pressure for speed
  - Engine adds energy to air inside the duct



Skating 335

Jet Engines (Part 2)

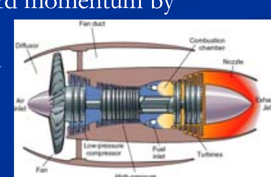
- Air entering diffuser slows and its pressure rises
- Compressor does work on air
- Fuel is added to air and that mixture is burned
- Expanding exhaust gas does work on turbine
- As exhaust leaves nozzle it speeds up and its pressure drops



Skating 336

Jet Engines (Part 3)

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



Skating 337

Summary about Airplanes

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

Skating 338

Woodstoves

Turn off all electronic devices

Skating 339

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

Skating 340

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?

Skating 341

Question 1

- What are thermal energy and heat?
- Related questions:
  - What is the difference between those two quantities?
  - Can those terms be used interchangeably?

Skating 342

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

Skating 343

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"

Skating 344

Question 2

- How does a woodstove produce thermal energy?

Skating 345

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!

Skating 346

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

Skating 347

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

Skating 348

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

Skating 349

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

Skating 350

Question 3

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

Skating 351

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)

Skating 352

Question 4

- Why is a woodstove better than an open fire?

Skating 353

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

Skating 354

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

Skating 355

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

Skating 356

Heat Exchangers

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

Skating 357

Question 5

- How does a woodstove heat the room?

Skating 358

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

Skating 359

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

Skating 360

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

Skating 361

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

Skating 362

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

Skating 363

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

Skating 364

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

Skating 365

Water, Steam, and Ice

Turn off all electronic devices

Skating 366

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

Skating 367

Reading Question 7.2a

At atmospheric pressure, ice can exist in thermal equilibrium

A. only at or below 0 °C (32 °F)
B. only below 0 °C (32 °F)
C. only at 0 °C (32 °F)

Skating 368

Reading Question 7.2b

At 100% relative humidity,

A. water evaporates, but very slowly.
B. steam and liquid water can coexist.
C. steam condenses, but very slowly.
D. steam is an unstable phase of water.

Skating 369

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?

Skating 370

Question 1

- How can water and ice coexist in a glass?

Skating 371

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

Skating 372

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

Skating 373

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!)

Skating 374

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

Skating 375

Question 2

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

Skating 376

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

Skating 377

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

Skating 378

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

Skating 379

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)

Skating 380

Question 3

- Where do ice cubes go in a frostless freezer?

Skating 381

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

Skating 382

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

Skating 383

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

Skating 384

Question 4

- Is salt the only chemical that helps melt ice?

Skating 385

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

Skating 386

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

Skating 387

Clothing, Insulation, and Climate

Turn off all electronic devices

Skating 388

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

Skating 389

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?

Skating 390

Question 1

- How does clothing control thermal conduction?

Skating 391

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.

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

Skating 392

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

Skating 393

Question 2

- How does clothing control thermal convection?

Skating 394

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

Skating 395

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

Skating 396

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

Skating 397

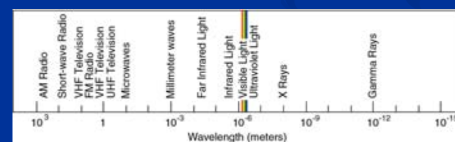
Question 3

- How does insulation control thermal radiation?

Skating 398

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



Skating 399

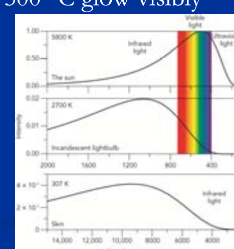
Black Body Spectrum (Part 1)

- 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

Skating 400

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



Skating 401

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

Skating 402

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

Skating 403

Limiting Thermal Radiation (Part 2)

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

Skating 404

Question 4

- Why do greenhouse gases warm the earth?

Skating 405

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!

Skating 406

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

Skating 407

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

Skating 408

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

Skating 409

Automobiles

Turn off all electronic devices

Skating 410

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

Skating 411

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?

Skating 412

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?

Skating 413

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.

Skating 414

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.

Skating 415

Question 2

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

Skating 416

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.

Skating 417

Question 3

- How is an automobile engine a heat engine?

Skating 418

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.

Skating 419

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

Skating 420

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

Skating 421

Compression Stroke

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

Skating 422

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

Skating 423

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

Skating 424

Ignition System

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

Skating 425

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

Skating 426

Question 4

- Why do cars sometime "knock?"

Skating 427

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

Skating 428

Question 5

- How is a diesel engine different?

Skating 429

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

Skating 430

Question 6

- What about the rest of the automobile?

Skating 431

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

Skating 432

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

Skating 433

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

Skating 434

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

Skating 435

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

Skating 436

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

Skating 437

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

Skating 438

Air Conditioners

Turn off all electronic devices

Skating 439

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

Skating 440

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?

Skating 441

Question 1

- Why doesn't heat flow from cold to hot?
- Related questions:
  - Does such heat flow violate the laws of motion?
  - Does such heat flow violate some other laws?

Skating 442

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

Skating 443

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."

Skating 444

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

Skating 445

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

Skating 446

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!

Skating 447

Law of Entropy

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

"The entropy of a thermally isolated system never decreases"

Skating 448

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!

Skating 449

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

Skating 450

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!

Skating 451

Question 2

- Why does an air conditioner need electricity?

Skating 452

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).

Skating 453

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!

Skating 454

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

Skating 455

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.

Skating 456

Question 3

- How does an air conditioner cool room air?

Skating 457

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!

Skating 458

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!

Skating 459

Question 4

- What role does the electricity play?

Skating 460

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!

Skating 461

Question 5

- How does an air conditioner heat outdoor air?

Skating 462

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!

Skating 463

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!

Skating 464

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.

Skating 465

Summary about Air Conditioners

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

Skating 466

Clocks

Turn off all electronic devices

Skating 467

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

Skating 468

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?

Skating 469

Question 1

- Why don't any modern clocks use hourglasses?

Skating 470

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.

Skating 471

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.

Skating 472

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.

Skating 473

Question 2

- Are all repetitive motions equally accurate?

Skating 474

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

Skating 475

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).

Skating 476

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

Skating 477

Question 3

- Why are some watches more accurate?

Skating 478

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

Skating 479

Question 4

- How do clocks use harmonic oscillators?

Skating 480

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.

Skating 481

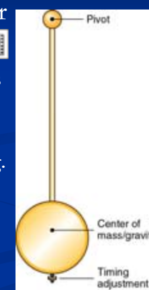
Pendulums (Part 2)

- 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!

Skating 482

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.



Skating 483

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.

Skating 484

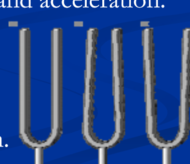
Quartz Oscillators

- 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.

Skating 485

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.



Skating 486

Summary about Clocks

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

Skating 487

Musical Instruments

Turn off all electronic devices

Skating 488

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

Skating 489

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?

Skating 490

Question 1

- Why do strings produce specific notes?

Skating 491

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)!

Skating 492

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.

Skating 493

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 $\text{tension}^{1/2}$,
  - proportional to 1/length,
  - and proportional to $1/\text{mass}^{1/2}$.

Skating 494

Question 2

- Why does a vibrating string sound like a string?

Skating 495

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!

Skating 496

A String's Harmonics (Part 2)

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

Skating 497

Question 3

- How does bowing cause a string to vibrate?

Skating 498

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.

Skating 499

Question 4

- Why do stringed instruments need surfaces?

Skating 500

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.

Skating 501

Question 5

- What is vibrating in a wind instrument?

Skating 502

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)!

Skating 503

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.

Skating 504

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$^{1/2}$.

Skating 505

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.

Skating 506

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").

Skating 507

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

Skating 508

Question 6

- Why does a drum sound particularly different?

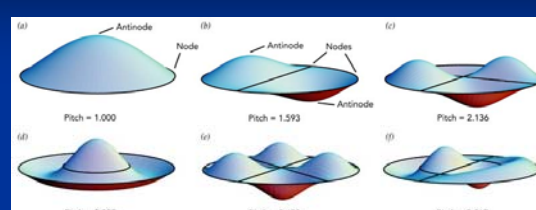
Skating 509

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

Skating 510

Drumhead Vibrations



Skating 511

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

Skating 512

The Sea

Turn off all electronic devices

Skating 513

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

Skating 514

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?

Skating 515

Question 1

- Why are there tides?

Skating 516

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.

Skating 517

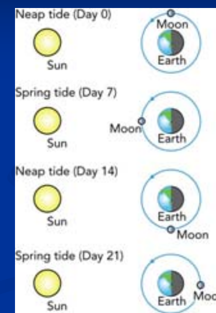
The Tides (Part 2)

- 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.

Skating 518

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



Skating 519

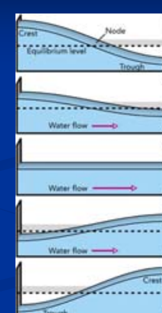
Question 2

- How do giant tides develop?

Skating 520

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



Skating 521

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.

Skating 522

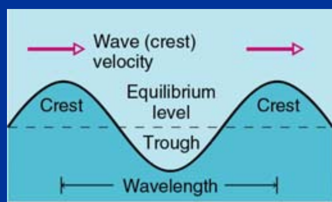
Question 3

- How does water in a wave move?

Skating 523

Water Waves

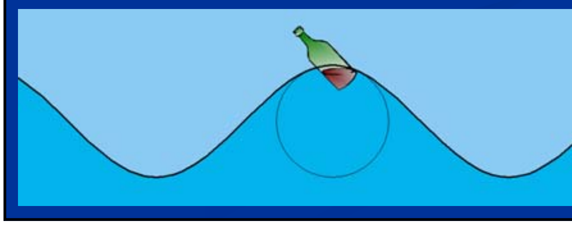
- Sloshing involves deep water waves: all of the water moves back and forth
- Surface waves affect only water near the surface



Skating 524

Water's Motion (Part 1)

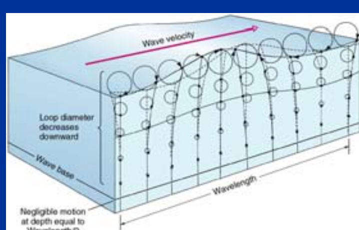
- Only the wave structure travels across the water.
- Surface water itself circles as the wave passes.
- The wave's crests are formed from local water.



Skating 525

Water's Motion (Part 2)

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



Skating 526

Question 4

- How is a tsunami different from normal waves?

Skating 527

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.

Skating 528

Question 5

- Why do waves bend and break near shore?

Skating 529

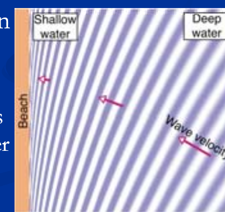
Breaking Waves

- 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

Skating 530

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



Skating 531

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