Balloons

Turn off all electronic devices

Observations about Balloons

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

5 Questions about Balloons

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

Question 1

Q: How does air inflate a rubber balloon?

A: Its pressure pushes the balloon's skin outward

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

Air and Pressure

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

Pressure Imbalances

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

Balloons 7

Question 2

Q: Why doesn't the atmosphere fall or collapse?

A: A gradient in its pressure supports its weight

- Air has a density: it has mass per volume
- Air's pressure is proportional to its density
- Air's density gives it a weight per volume
- The atmosphere is in equilibrium
  - Its density and pressure decrease with altitude
  - The resulting pressure imbalances support its weight

Balloons 8

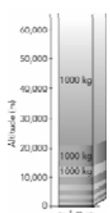
Air and Density

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

Balloons 9

The Atmosphere

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



Balloons 10

Question 3

Q: Why does the atmosphere push up on a balloon?

A: Its pressure gradient pushes the balloon upward

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

Balloons 11

Archimedes' Principle

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

Balloons 12

Question 4

Q: Why does a hot air balloon float in cold air?

A: It weighs less than the air it displaces

- As the temperature of air increases, its particles
  - move faster, bounce harder, and bounce more often
  - contribute more to air's pressure
- A balloon filled with hot air at ordinary pressure
  - contains fewer particles than the air it displaces
  - weighs less than the air it displaces
  - experiences a buoyant force that exceeds its weight

Balloons 13

An Aside About Temperature

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

Balloons 14

Air and Temperature

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

Balloons 15

Question 5

Q: Why does a helium balloon float in air?

A: It weighs less than the air it displaces

Balloons 16

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

Balloons 17

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

Balloons 18

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

Balloons 19

The Ideal Gas Law

- is a summary relationship for gases:

  pressure = Boltzmann constant · particle density · absolute temperature
- It assumes perfectly independent particles
- While real gas particles aren't perfectly independent, this law is a good approximation for real gases.

Balloons 20

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

Balloons 21

Water Distribution

Turn off all electronic devices

Balloons 22

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

Balloons 23

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?

Balloons 24

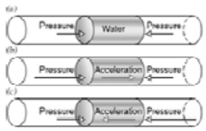
Question 1

- Why does water move through level pipes?

Balloons 25

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



Balloons 26

Question 2

- How can you produce pressurized water?

Balloons 27

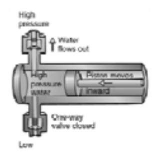
Pressurizing Water

- 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.

Balloons 28

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!



Balloons 29

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:

$$\text{work} = \text{pressure} \cdot \text{volume}$$

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

Balloons 30

Question 3

- Where does the work you do pumping water go?

Balloons 31

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.

Balloons 32

Question 4

- As water flows, what happens to its energy?

Balloons 33

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):

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

Balloons 34

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)

Balloons 35

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)

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

Balloons 36

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.

Balloons 37

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.

Balloons 38

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.

Balloons 39

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)

Balloons 40

Garden Watering

Turn off all electronic devices

Balloons 41

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

Balloons 42

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?

Question 1

- How does a faucet control flow?

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

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

Question 2

- How much does the diameter of a hose matter?

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

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:

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

Balloons 49

Question 3

- Why does water pour gently from an open hose?

Balloons 50

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

Balloons 51

Question 4

- Why does water spray so hard from a nozzle?

Balloons 52

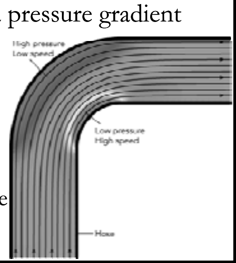
Making Water Accelerate

- 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.

Balloons 53

Bending the Flow in a Hose

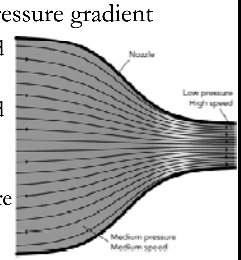
- Bending the flow requires a pressure imbalance
  - The water accelerates toward lower pressure
- Flow in bent hose develops a pressure gradient
  - higher pressure & lower speed on the outside of the bend
  - lower pressure & higher speed on the inside of the bend
  - and water accelerates from high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



Balloons 54

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



Balloons 55

Question 5

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

Balloons 56

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

Balloons 57

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

Balloons 58

Question 6

- Why do pipes rattle when you close the faucet?

Balloons 59

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

Balloons 60

Summary about Garden Watering

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

Balls and Air

Turn off all electronic devices

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

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?

Question 1

- Why do balls experience air resistance?

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

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!

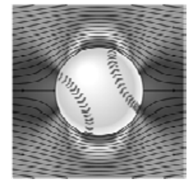
Balloons 67

Types of Drag & Lift

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

Balloons 68

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.

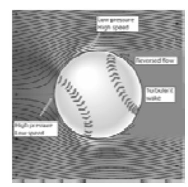
Balloons 69

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

Balloons 70

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

Balloons 71

Question 2

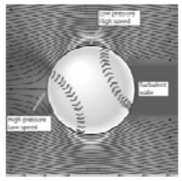
- Why do some balls have dimples?

Balloons 72

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

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

Tripping the Boundary Layer

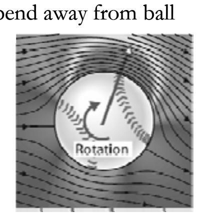
- To reduce pressure drag, some balls have dimples
  - Dimples "trips" the boundary layer
  - and causes boundary layer to become turbulent.
  - Since turbulent boundary layer resists peeling better,
  - ball's main airflow forms smaller turbulent wake.
- Example: Golf balls

Question 3

- Why do spinning balls curve in flight?

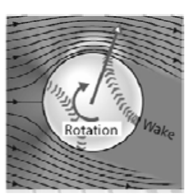
Spinning Balls, Magnus Force

- 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



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



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

Balloons 79

Airplanes

Turn off all electronic devices

Balloons 80

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

Balloons 81

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?

Balloons 82

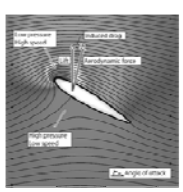
Question 1

- How does an airplane support itself in the air?

Balloons 83

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



Balloons 84

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

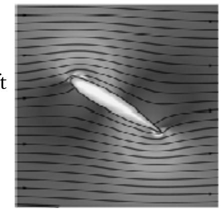
Balloons 85

Question 2

- How does the airplane "lift off" the runway?

Balloons 86

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

Balloons 87

Question 3

- Why does plane tilt up to rise; down to descend?

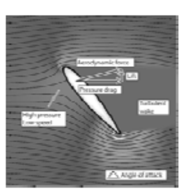
Balloons 88

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

Balloons 89

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

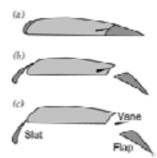
Balloons 90

Question 4

- Why are there different wing shapes?

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



Question 5

- How does a plane turn?

Turning and Orientation

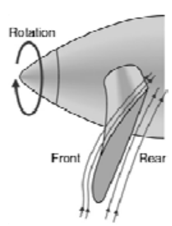
- Airplanes use lift to accelerate to the side
- Three orientation controls:
  - Angle of attack controlled by elevators
  - Left-right tilt controlled by ailerons
  - Left-right rotation controlled by rudder
- Steering involves ailerons and rudder
- Elevation involves elevators and engine

Question 6

- How does a plane propel itself through the air?

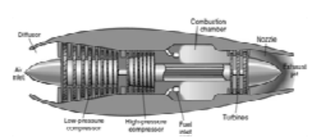
Propellers

- 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



Jet Engines **(Part 1)**

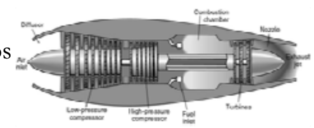
- Jet engines pump air toward rear of plane
  - Engine consists of an oval "ball" with a complicated duct or passageway through it
  - Air passing through the duct exchanges first speed for pressure and then pressure for speed
  - Engine adds energy to air inside the duct



Balloons 97

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



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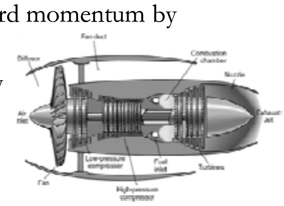
Jet Engines (Part 3)

- 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



Balloons 99

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