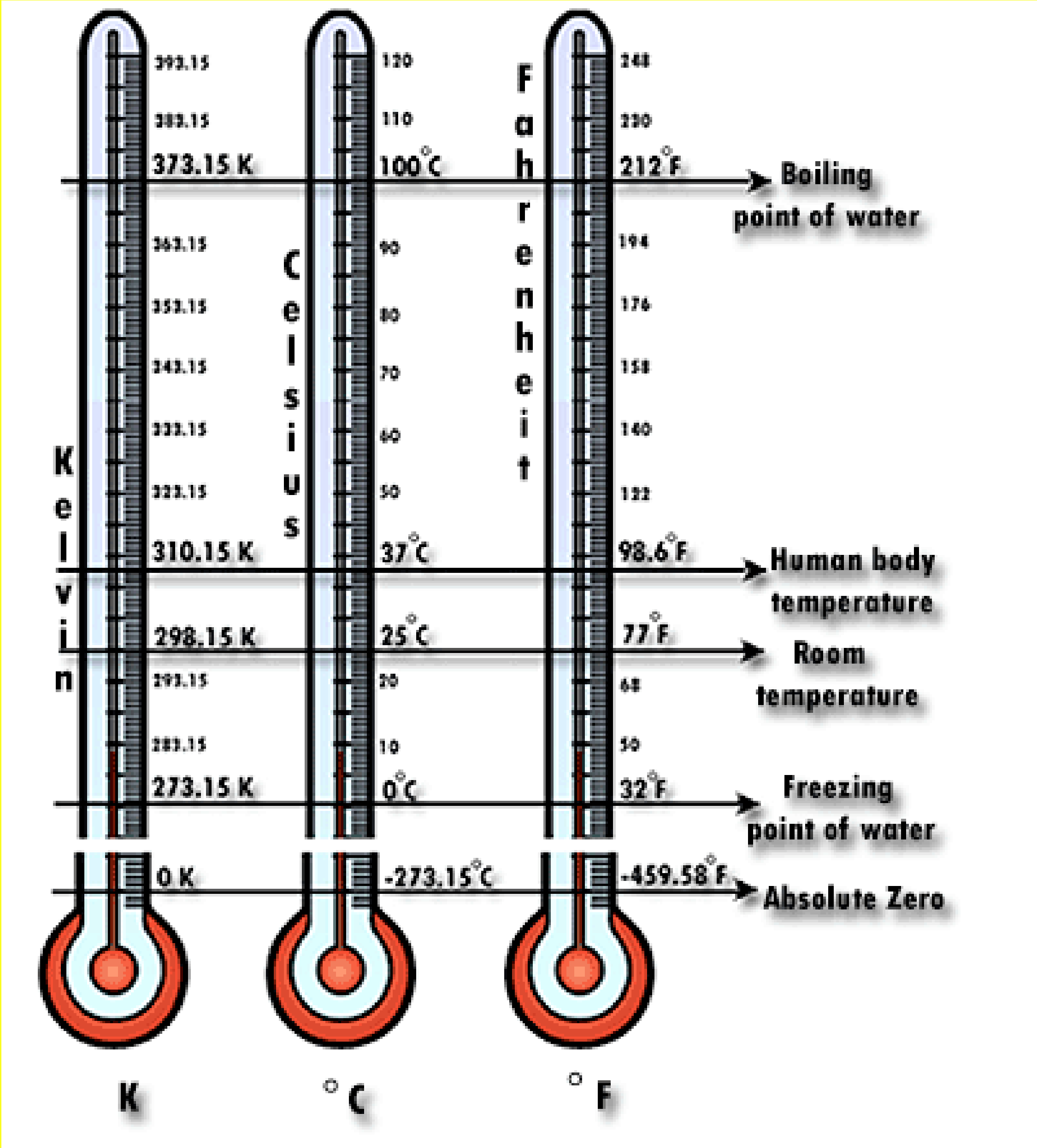
Lecture 13 Chapter 18
Temperature, Heat, and the First Law of Thermodynamics



Lecture 13 Chapter 18
Temperature, Heat, and the First Law of Thermodynamics

- **Temperature and Thermal Equilibrium**
- **Linear Expansion**
- **Heat and Energy Transfer and Specific Heat**
- **Thermal Conductivity**
- **Work and the First Law of Thermodynamics**
  - $\Delta E_{int} = Q - W$
- **Conduction, Convection and Radiation**

Pressure reduction due to cooling inside coke can crushing the coke can as it is placed in water.

Thermal expansion cracking the nut.

Thermal expansion Ring and ball

Thermal effects using liquid nitrogen

Thermal Conductivity

Light The Match

Leslie Cube

Jug O' Air

Boiling by Cooling

Boiling by Reducing Pressure

Radiometer

Dipping Duck Toy

Temperature and Thermal Equilibrium

The zeroth law of thermodynamics:

If two thermal systems are in thermal equilibrium with one another, then *they have the same temperature*.

If two systems are each in thermal equilibrium with a third, then they are in thermal equilibrium with one another.

- If the third body is a thermometer, we can measure the temperature of each body and then say they are in thermal equilibrium without actually doing it.

- What is temperature? A measure of the motion of the atoms in a body.
  - http://www.colorado.edu/physics/2000/bec/

- How do we measure it? For example, by measuring the volume expansion of mercury in a glass tube, which is sensitive to temperature.

Temperature and Thermal Equilibrium

The zeroth law of thermodynamics (cont):

Thermal reservoir: system so large that its temperature doesn’t change when interacting with other systems

Thermal contact can occur through conduction, convection, and radiation

Temperature and Thermal Equilibrium

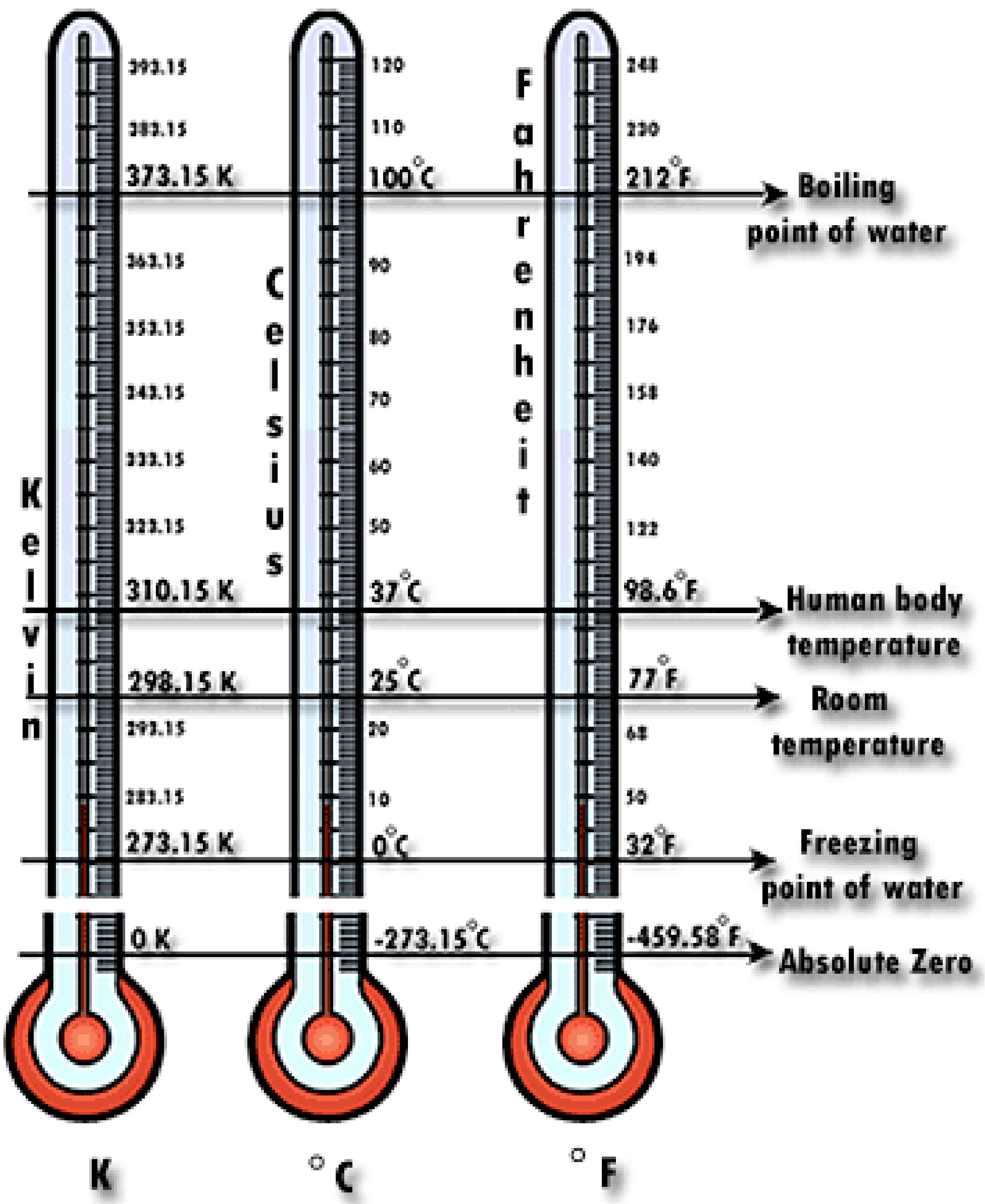
Some Thermometers

TABLE 17–1 • Some Thermometers

Thermometer	Physical Property Measured	Comments
Ideal gas	Pressure and volume of dilute gas	See Section 17–2
Mercury bulb	Expansion or contraction of fluid	Good where fluid does not change phase
Bimetallic strip	Difference in expansion of two metals	
Resistance	Electrical resistance	See Chapter 26
Thermocouple	Electrical voltage across different metals	Most widely used thermometer in industry
Paramagnetic	Magnetic properties of matter	Useful at ultracold temperatures; see Section 31–5
Optical pyrometer	Color of emitted light	Useful at high temperatures; see Section 17–5

How do you calibrate your thermometer?

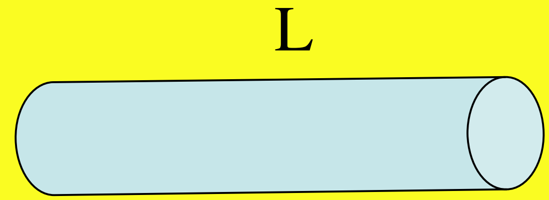
- By international agreement the triple point of water has been assigned the value of 273.16 K. This is called the Kelvin scale or absolute scale.
- Celsius scale $T_C = T - 273.15K = 0.01^\circ C$
- Fahrenheit scale $T_F = \frac{9}{5}T_C + 32 = 32.02^\circ F$



Kelvin
Celsius
Fahrenheit
393.15
383.15
373.15 K
363.15
353.15
343.15
333.15
323.15
310.15 K
298.15 K
293.15
283.15
273.15 K
0 K
120
110
100°C
90
80
70
60
50
37°C
25°C
20
10
0°C
-273.15°C
248
230
212°F
194
176
158
140
122
98.6°F
77°F
68
50
32°F
-459.58°F
Boiling point of water
Human body temperature
Room temperature
Freezing point of water
Absolute Zero
K
°C
°F

Coefficient of Linear expansion

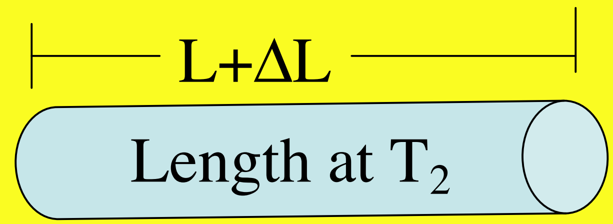
Substance	α (10^{-6}/C)
Ice at 0 deg C	51
Aluminum	23
Brass	19
Copper	17
Steel	11
Glass (pyrex)	3. 2

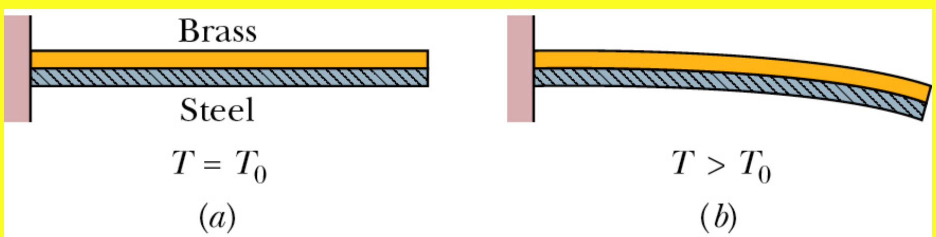


Heat up rod from

T_1 to T_2. $\Delta T = T_1 - T_2$

$$\Delta L = L\alpha\Delta T$$





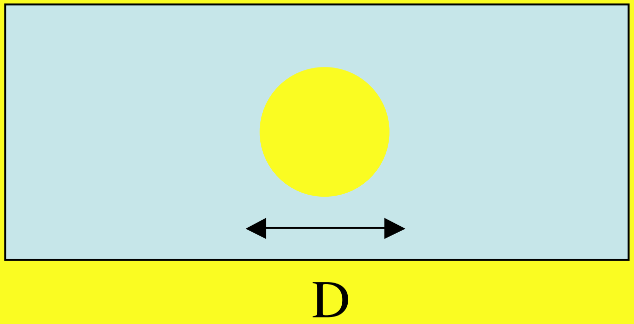
Bimetalic metal strip :Use to measure temperature.

All dimensions increase by the fraction below:

$$\frac{\Delta L}{L} = \alpha\Delta T$$

$$\frac{\Delta V}{V} = 3\alpha\Delta T$$

9) A circular hole in an aluminum plate is 2.725 cm in diameter (D) at 10.0°C. What is the change in its diameter when the temperature of the plate is raised to 110.0°C?



Linear Expansion demos

Thermal expansion Ring and ball
Thermal expansion cracking the nut.
Thermal effects using liquid nitrogen

What is heat?

- What is heat? Heat is energy transferred from one object to another due to a temperature difference. This thermal energy is internal energy consisting of kinetic and potential energy of the atoms and molecules that make up the object. The symbol for heat is Q. It is positive when it is transferred to the system of interest. Heat is energy that is transferred between systems
- A system or object does not contain heat. You can not say an object has 100 Joules of heat or 100 Joules of work. Heat is not a property of the system like temperature, pressure or volume.

The property that measures a substance ability to transfer heat is called specific heat c.

$$c = \frac{Q}{m\Delta T}$$

- The specific heat determined for a solid or liquid depends slightly on the temperature, and usually assumes it is measured at constant pressure (usually atmospheric), and constant volume. It turns out the specific heat for solids and liquids does not very much. Only a few per cent. For gases, however, it can vary a lot with pressure and volume as you will see.

- The units of specific heat are Joules per kg per K

Specific Heat = c

Specific Heats c at Room Temperature	
Substance	Joules/kg/K
lead	128
copper	386
aluminum	900
glass	840
water	4190

- Heat up paper cup of water.

Example: What is the amount of heat Q absorbed to raise the temperature of 100 grams of water from 20 C to 100 C (and not evaporate it)?

Q = 4190 J/kg/K x (80 K)x 0.1 kg = 33520 J = 33.520 KJ

When a solid or liquid absorbs energy as heat, a phase change may occur such as a solid to liquid (melting)or liquid to vapor (boiling)or vice versa. The required heat is called Heat of Fusion and Heat of Vaporization, respectively.

Heat of Fusion $L_F = 333 kJ / kg$

- Ice to water at the same T and vice versa.

  System absorbs/releases energy.

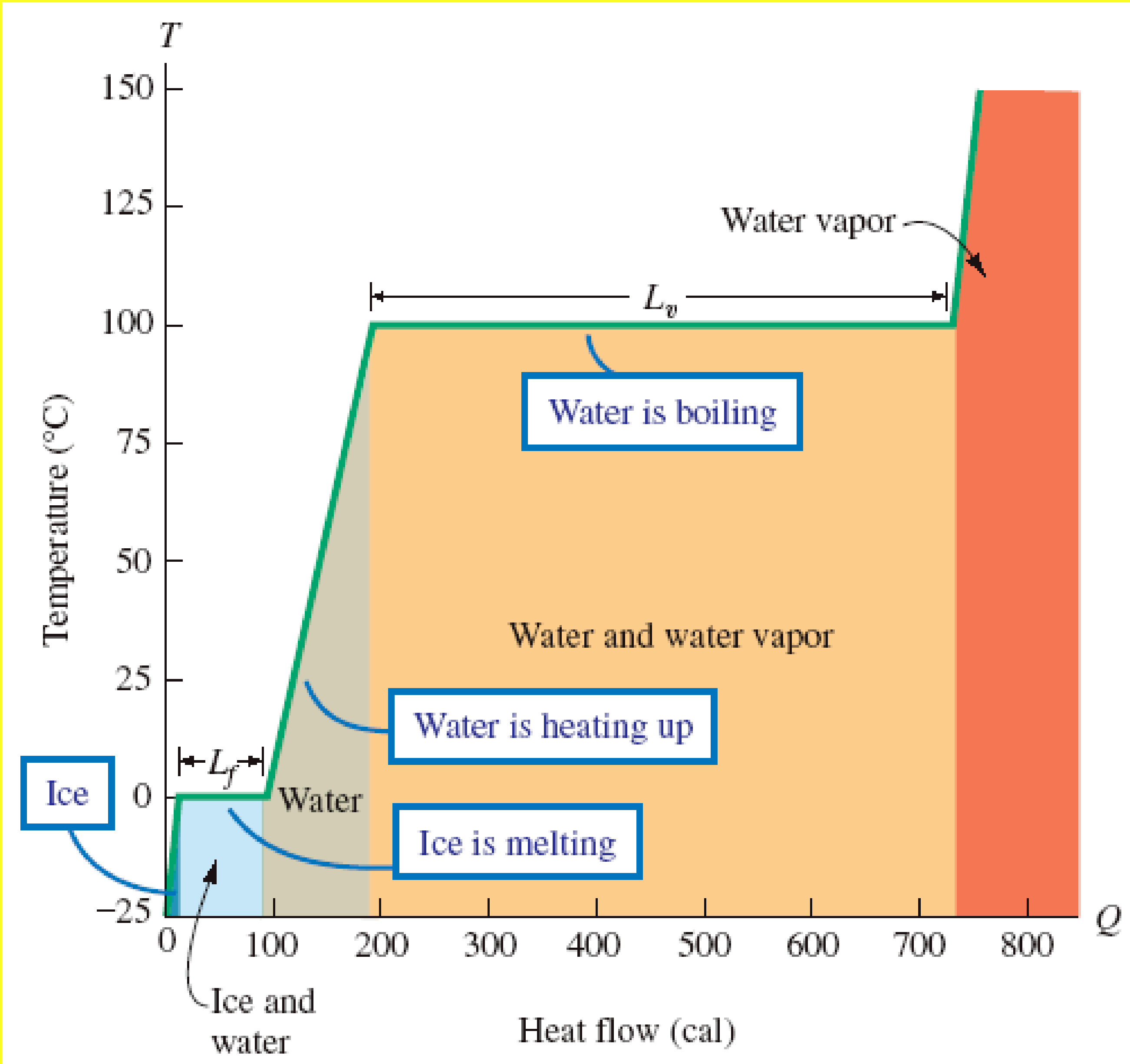
Heat of Vaporization $L_V = 2256 kJ / kg$

- Liquid water to water vapor at same T and vice versa.

  System absorbs/releases energy.

To evaporate 100 grams of water at 100 C would require
$Q = mL_v = 0.100 \text{ kg} \times 2256 \text{ kJ/kg} = 225.6 \text{ kJ}$

Specific heat for water =1 cal/g .C

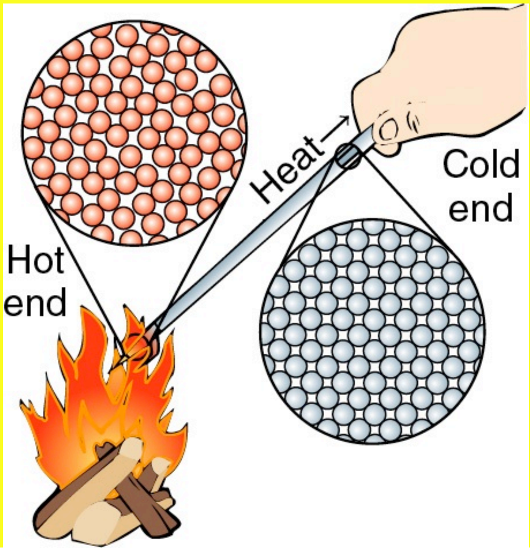


Heat Transfer Mechanism: Conduction, Convection, and Radiation

- Conduction
  - Through solid slabs (poker to handle)
  - Carried by conduction electrons
  - $P_{cond} = Q / t$ (energy/time)

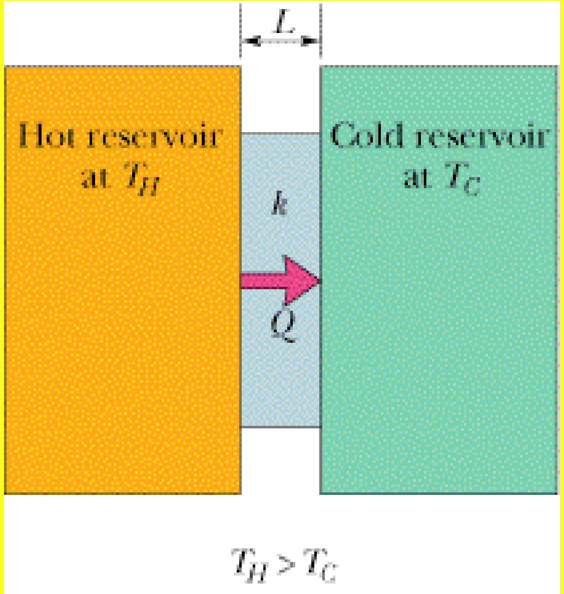
k is called the thermal conductivity

Substance	k (W/m . K)
Stainless steel	14
aluminum	235
copper	401
Polyurethane foam	0.024
air	0.026



Demo: heat up rods. What order will the wads of putty fall off?

Conduction thru one slab in a steady state



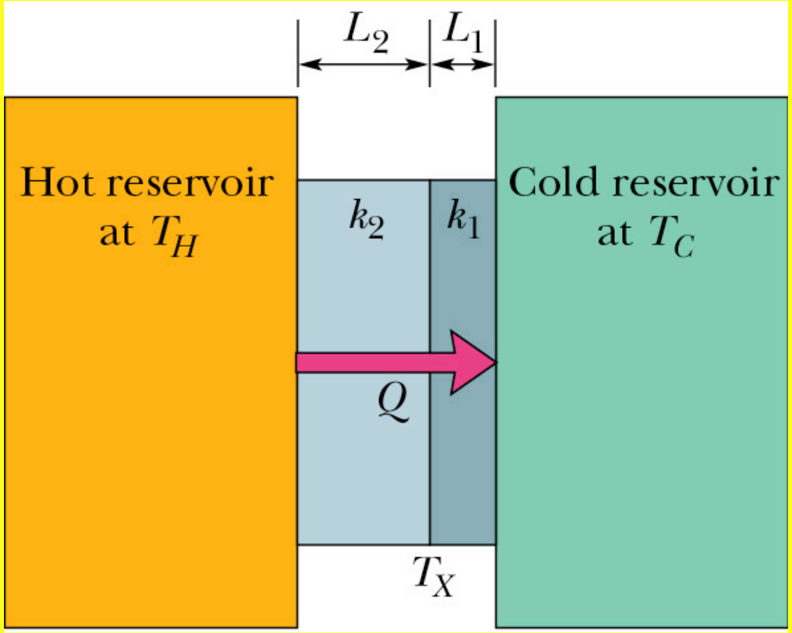
$$\frac{Q}{t} = \frac{kA(T_H - T_C)}{L}$$

- 51) Consider the slab shown above. Suppose that L = 26.0 cm, A = 91.0 cm2, and the material is copper. If T_H = 104°C, T_C = 12.0°C, and a steady state is reached, find the conduction rate through the slab.

Conduction thru two slabs in a steady state

We want to know the conduction rate from T_H to T_C during steady state

Rate through each slab are equal in steady state.



$$P_{cond} = \frac{k_1 A(T_x - T_C)}{L_1} = \frac{k_2 A(T_H - T_x)}{L_2}$$

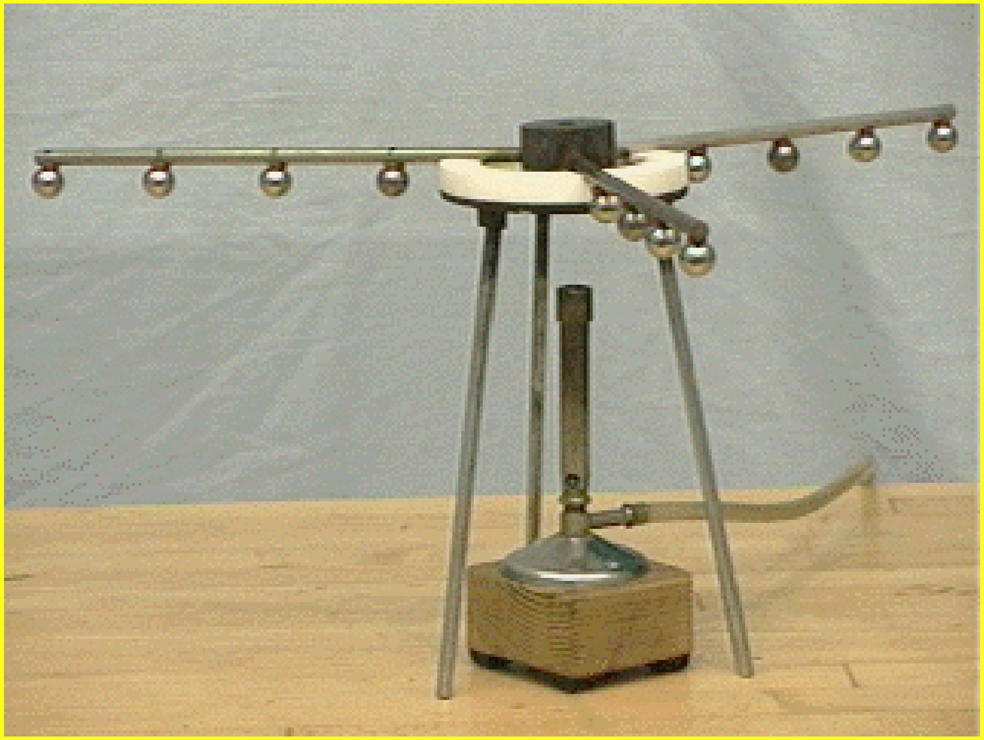
$$P_{cond} = \frac{A(T_H - T_C)}{\frac{L_1}{k_1} + \frac{L_2}{k_2}}$$

Two slabs

$$P_{cond} = \frac{A(T_H - T_C)}{\frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{L_3}{k_3}}$$

Three slabs

Heat Conduction



Copper rod	k = 401 W/m . K
Aluminum rod	k = 235 W/m . K
Steel rod	k = 14 W/m . K

Convection

- Convection and Buoyancy
  - Works because when a fluid such as air or water is heated its density decreases. The unheated fluid below it pushes it up through a buoyant force because the lower colder air, for example is more dense. The heated air from a candle flame or hot stove rises because of this.
  - Requires a medium

Blackbody Radiation

Objects that become sufficiently hot will glow visibly; as they get hotter they go from red, to yellow, to a bluish white.

This is electromagnetic radiation; objects at any temperature will emit it at various frequencies, from radio waves all the way to gamma rays.

Blackbody Radiation

This radiation from a body in thermal equilibrium is called blackbody radiation, as it is purely thermal and doesn’t depend on any properties of the body other than its temperature and area.

Radiation

- No medium is needed for E/M waves. Called thermal radiation or blackbody radiation

$$P_{rad} = \sigma \; \varepsilon \; A \; T_4$$

σ is the Stefan Boltzman constant = 5.603 x 10^{-8} W/m^2 . K^4

e is the emissivity between 0 and 1, e=1 means perfect emitter

Units are Watts

A good emitter is a good absorber

Blackbody Radiation

Deriving the energy density as a function of frequency and temperature required introducing some new concepts:

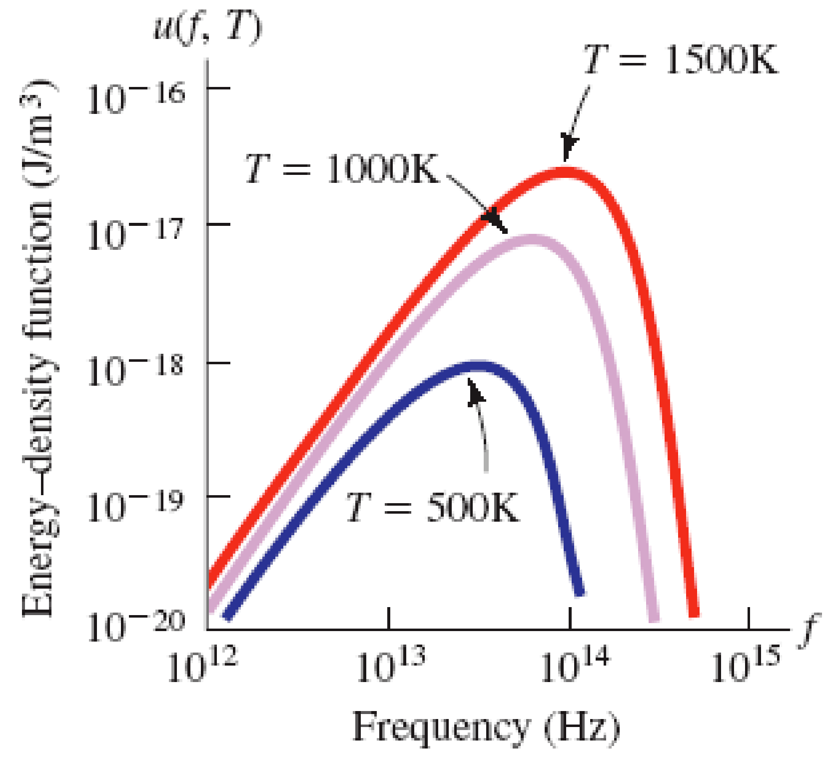
$$u(f, T) = \frac{8\pi h}{c^3} \frac{f^3}{e^{hf/kT} - 1}$$

Here, c is the speed of light:

$$c = 3 \times 10^8 \text{ m/s}$$

And h is Planck's constant:

$$h = 6.625 \times 10^{-34} \text{ J} \cdot \text{s}$$



Blackbody Radiation

The Discovery and Measurement of the Background Radiation of the Universe

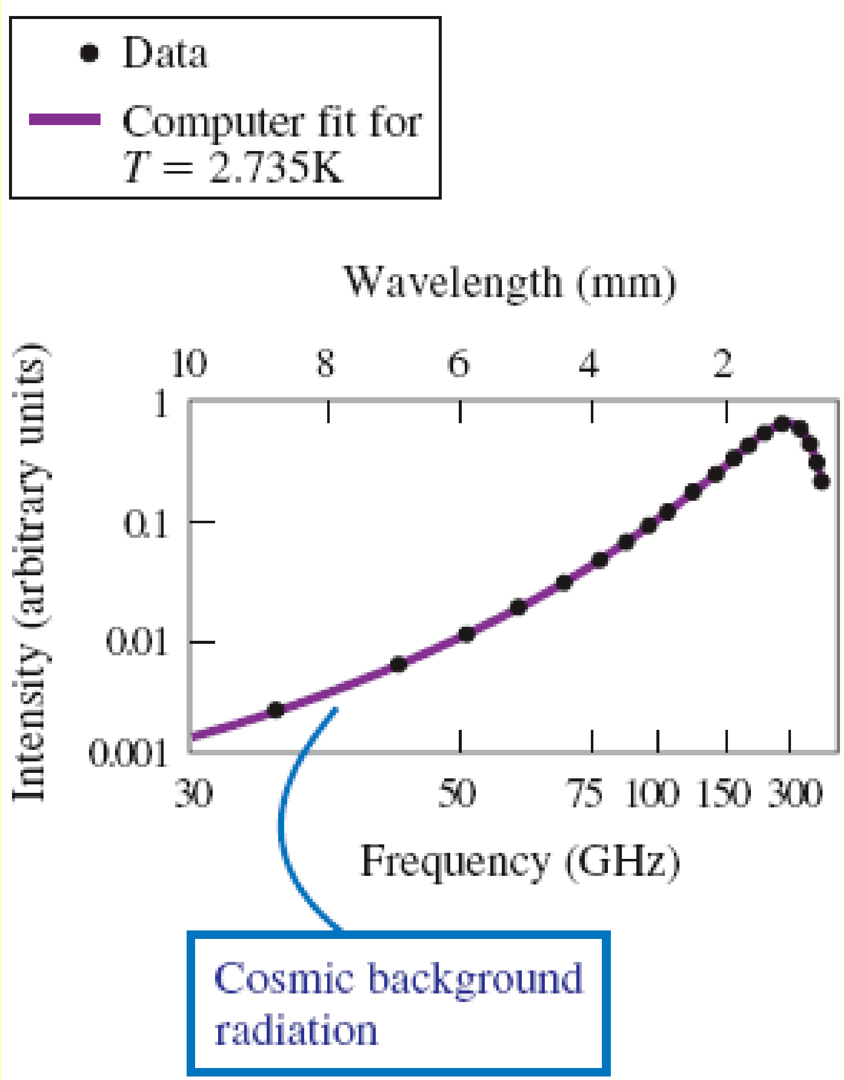
In 1964, background radiation was discovered, coming from no particular source but having a blackbody frequency distribution corresponding to a temperature of about 3K.

This radiation is left over from the early days of the universe.

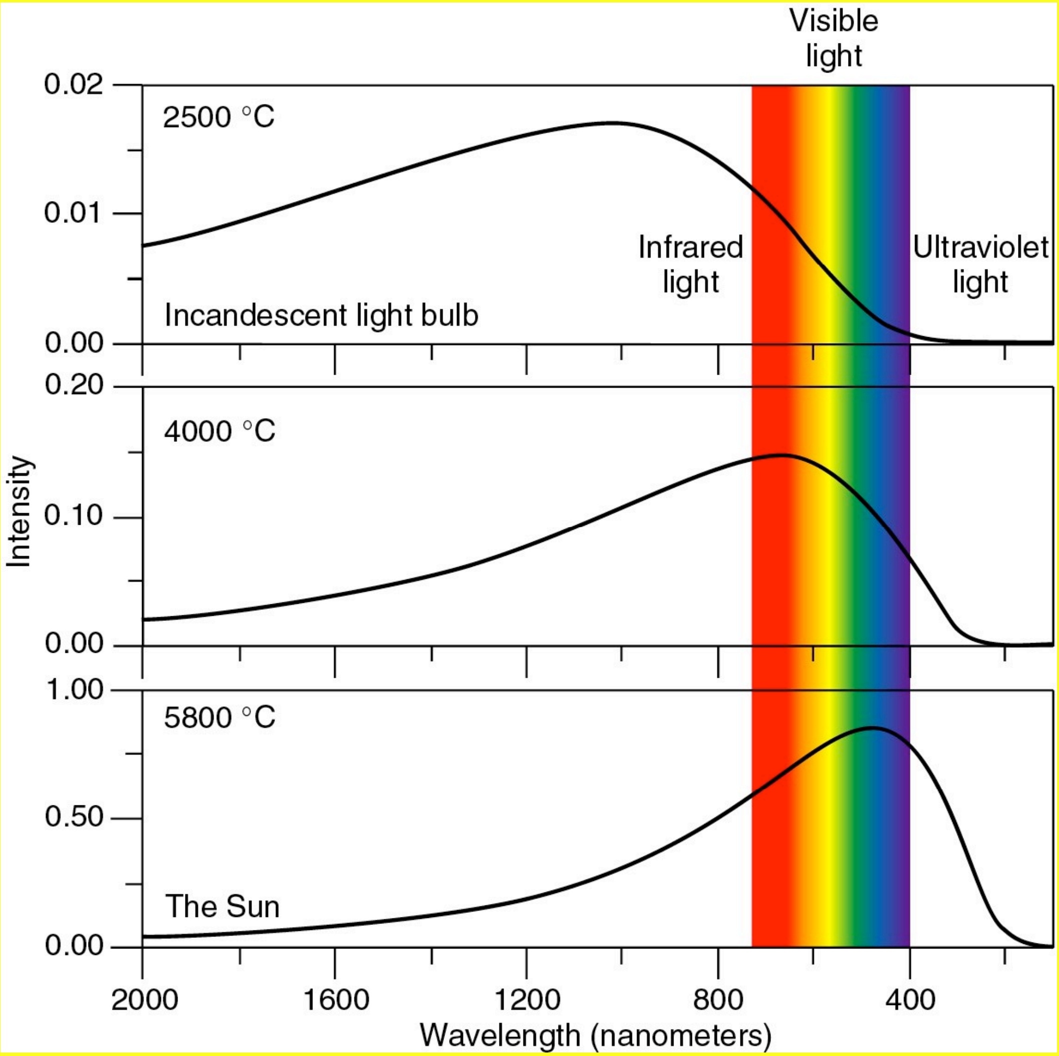
At first, matter and radiation were in thermal equilibrium; as the universe cooled this was no longer true.
The blackbody radiation is the remnant of the frozen-out radiation, cooled to near absolute zero by the expansion of the universe.

Blackbody Radiation

This is the observed blackbody radiation data as well as the distribution for T = 2.735K. The error bars on the data points are smaller than the points themselves.



Electromagnetic spectrum of a black body



Note curve peaks
at Infrared at 2500 C

Radiation related demos

- Light The Match
  - light from a filament focused on a match
- Leslie Cubes
  - compare IR radiation emitted for black surface, white, gray, shiny
- Radiometer
  - Works in reverse. Really demonstrates that hot gas consist of fast moving molecules transferring energy to the vanes

First Law of Thermodynamics
Conservation of energy

$$\Delta E_{\text{int}} = Q - W$$

- E_{int} is the internal energy of the system
  - Q is the heat flow
  - W is the work

- Significance is that that Q - W is path independent. That is it only depends on the initial and final states. Similar to conservation of energy. Found experimentally.

- Q and W are path dependent. Also Q+W and Q-2W.

- The first law extends the conservation of energy to systems that include heat and work done by the system.

18-1 Changes in Thermal Systems

Change where system is always in thermal equilibrium: reversible process

Change where system is not always in thermal equilibrium: irreversible process

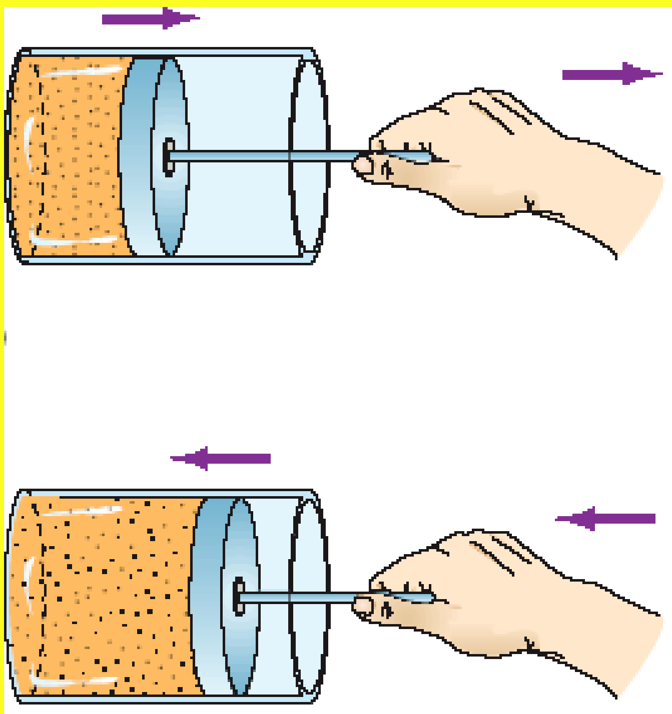
Examples of irreversible processes:

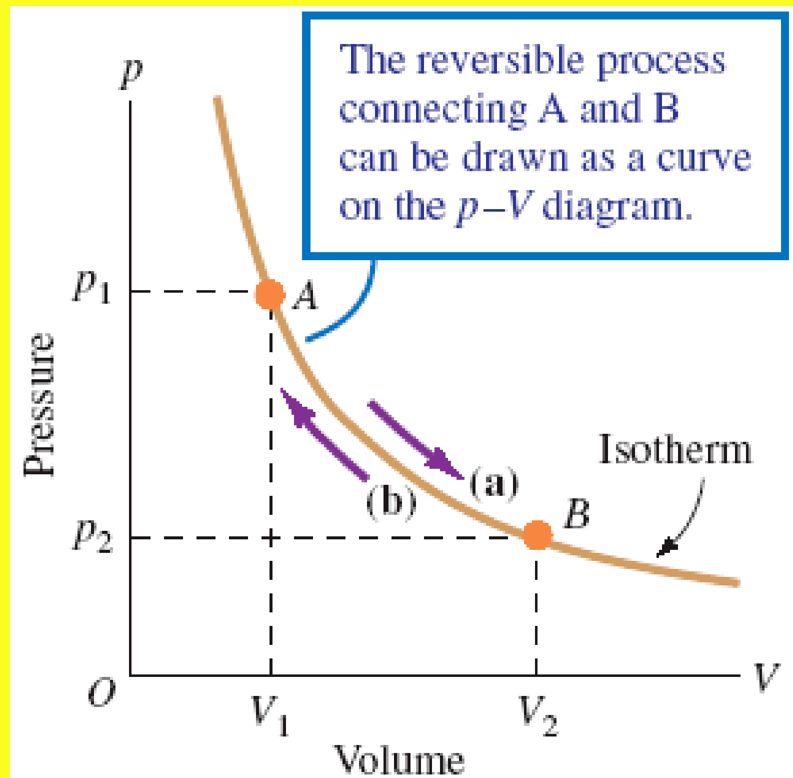
- **Free expansion**
- **melting of ice in warmer liquid**
- **frictional heating**

18-1 Changes in Thermal Systems

Example of a Reversible Process:

Cylinder must be pulled or pushed slowly enough that the system remains in thermal equilibrium

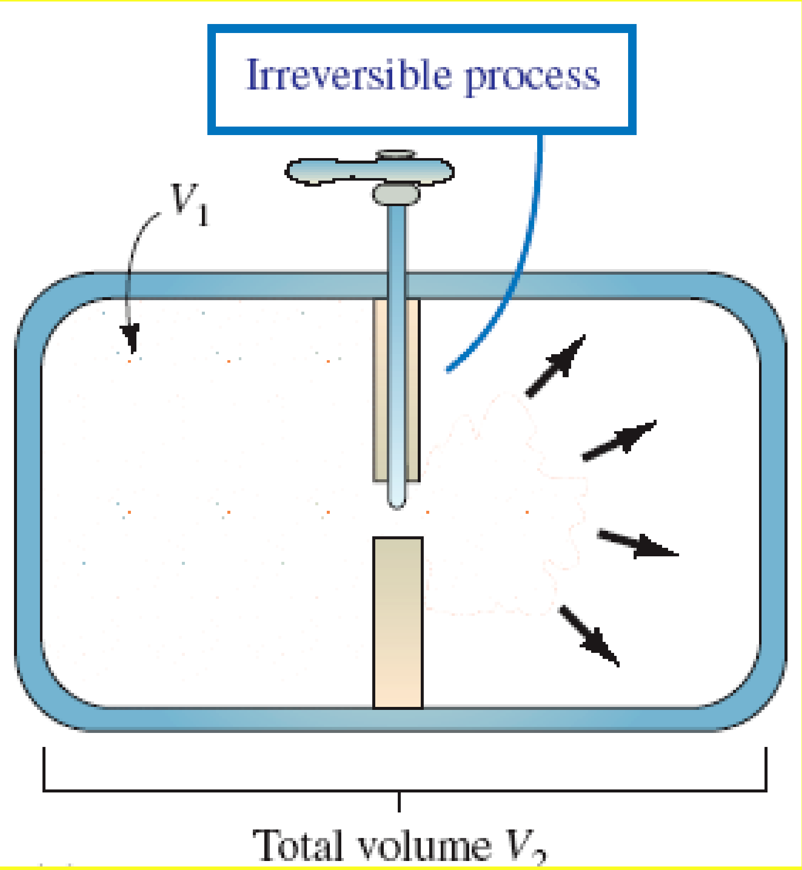


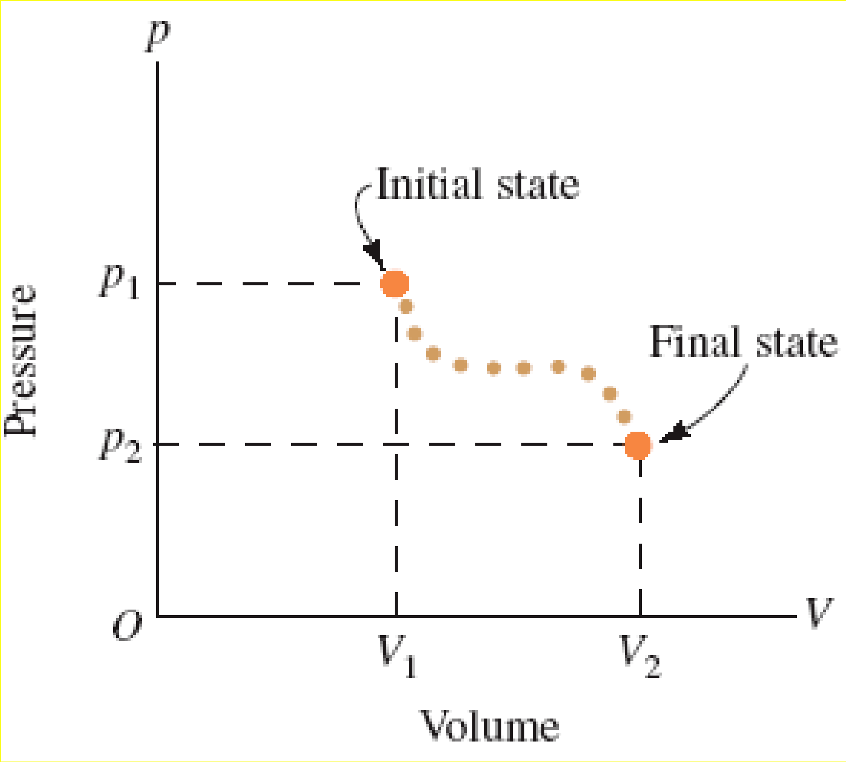


18-1 Changes in Thermal Systems

Example of an Irreversible Process:

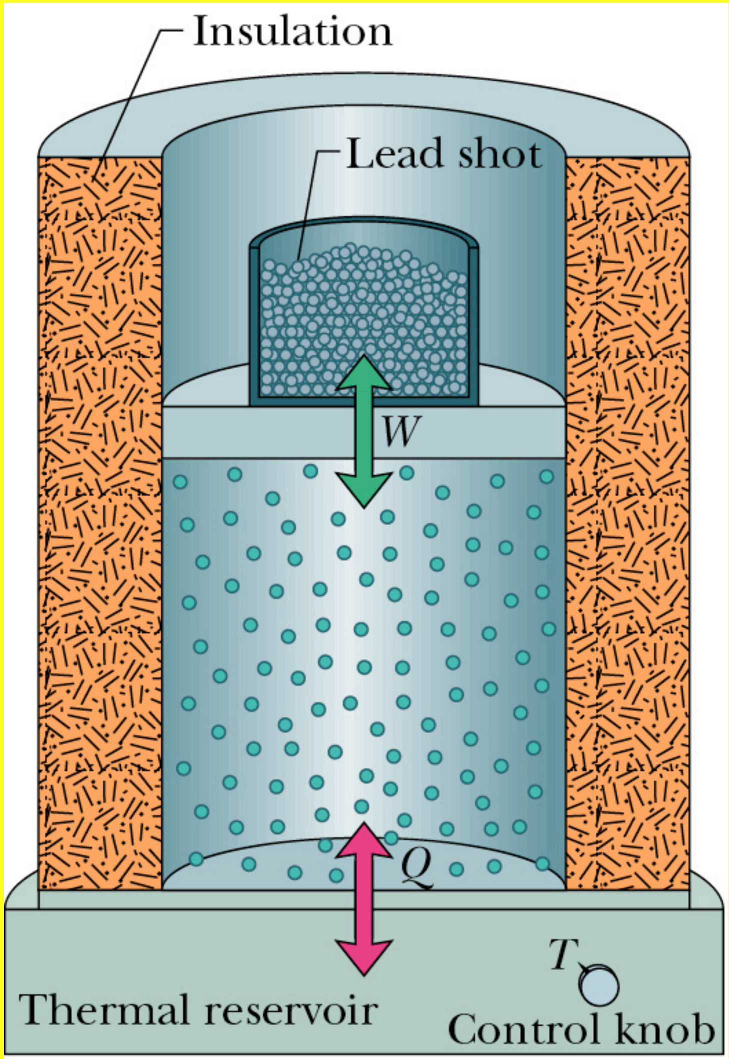
The gas expands freely when the valve is opened.





Work and Heat

$$dW = F.ds = pA.ds = pdV$$



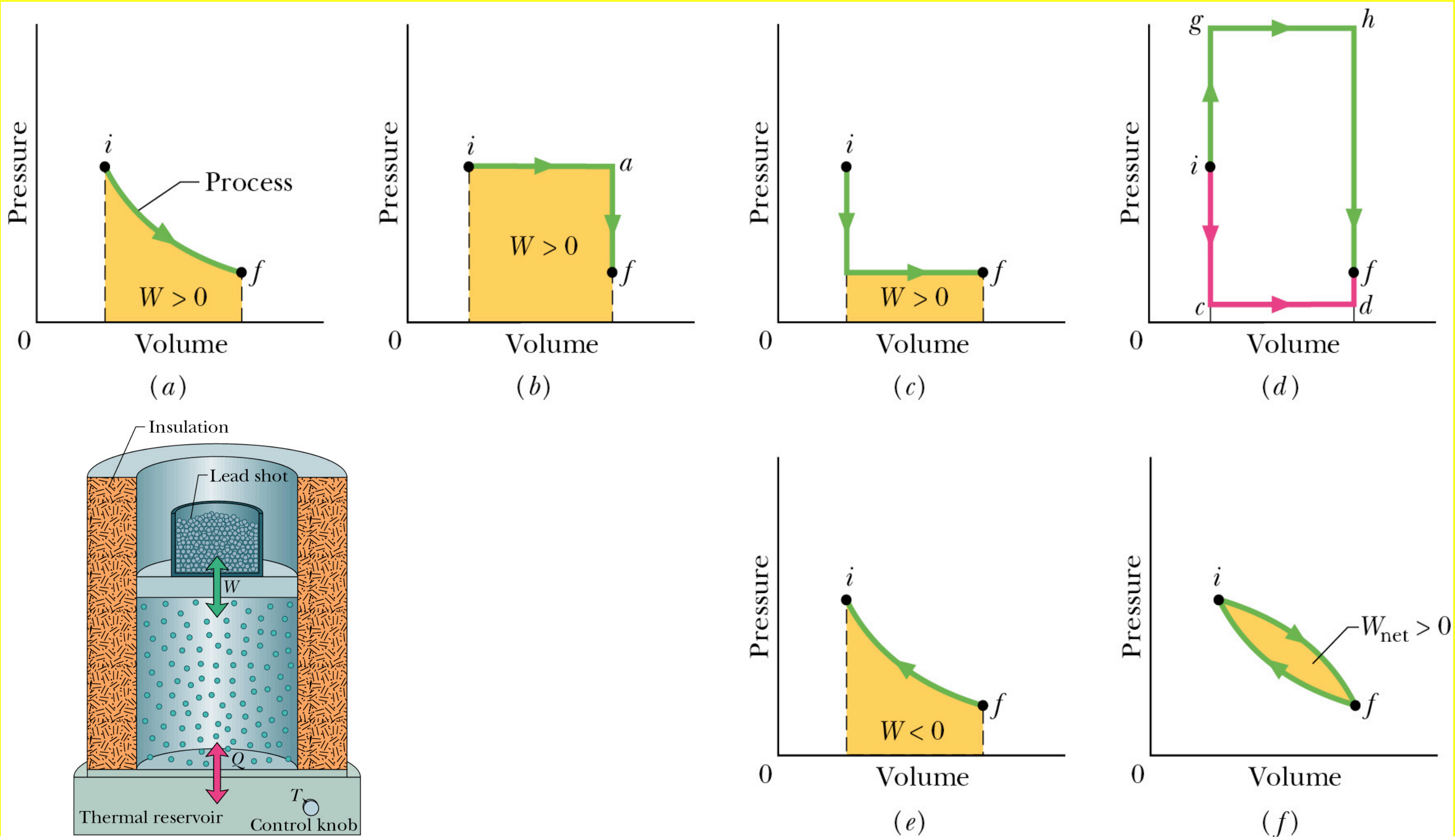
- Consider a system consisting of a gas and a piston in the figure.
- Lead shot rest on the piston and is part of the environment.
- The bottom of the cylinder rest on a thermal reservoir that we can use to control the temperature with a knob.
- The system is insulated from everything else.

Shaded area is the work done by the system

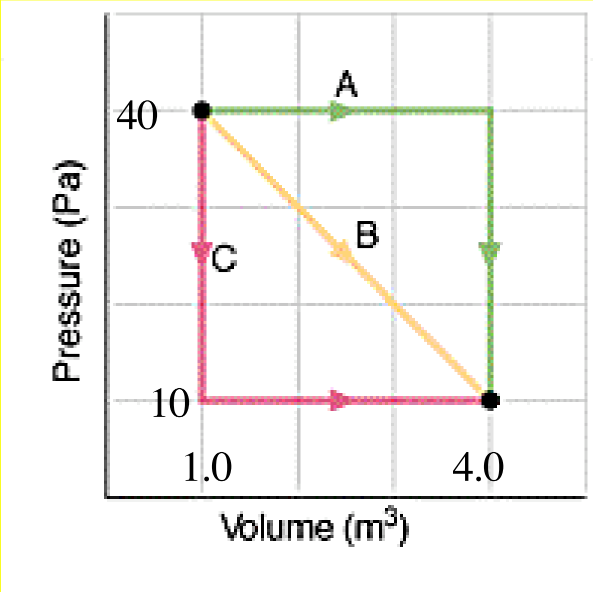
$$W = \int_{V_i}^{V_f} p\,dV$$

p depends on V in general

Below are many ways to take the system from i to f.
The work W done and Q depends on the path.

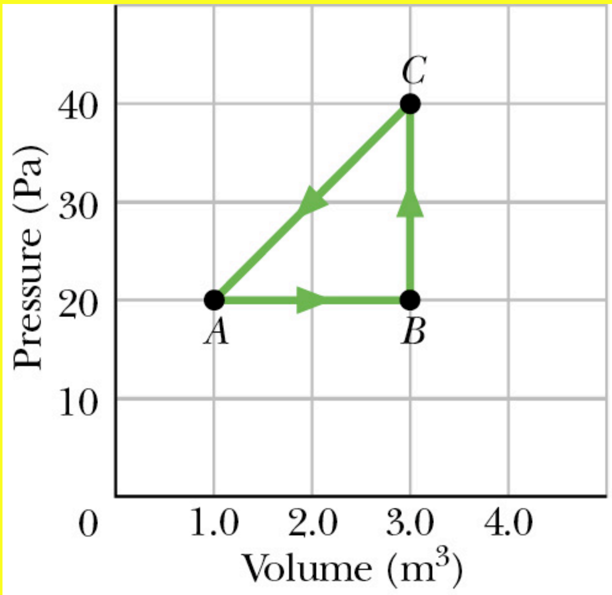


43) A sample of gas expands from 1.0 m^3 to 4.0 m^3 while its pressure decreases from 40 Pa to 10 Pa. How much work is done by the gas if its pressure changes with volume via each of the three paths shown in the Figure below?



Path A: W = +120 J
Path B: W =+75 J
Path C: W =+30 J

Problem 42)



(a)

	Q	W	ΔE_{int}
$A \longrightarrow B$			+
$B \longrightarrow C$	+		
$C \longrightarrow A$			

(b)

Fill in the table +, _, or 0 for Q,W and ΔE_{int} for each path.

Heating Effects Demo

Cooling coke can cause pressure reduction inside. Atmosphere crushes the can as it is placed upside down in water.

Special Cases of the First Law

- Adiabatic process $Q = 0$

  $$\Delta E = -W$$

- Constant - volume process $W = 0$

  $$\Delta E = Q$$

- Cyclical process $\Delta E = 0$

  $$Q = W$$

- Free expansion $Q = W = 0$

  $$\Delta E = 0$$

  – (gas is not in equilibrium during expansion)

ConcepTest 17.1 Degrees

Which is the largest unit: one Celsius degree, one Kelvin degree, or one Fahrenheit degree?

1) one Celsius degree
2) one Kelvin degree
3) one Fahrenheit degree
4) both one Celsius degree and one Kelvin degree
5) both one Fahrenheit degree and one Celsius degree

ConcepTest 17.1 Degrees

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4) both one Celsius degree and one Kelvin degree
5) both one Fahrenheit degree and one Celsius degree

The Celsius degree and the Kelvin degree are the same size. The scales only differ by an offset, not by the size of the degree unit. For Fahrenheit, there are 180 degrees between boiling and freezing (212°F–32°F). For Celsius, there are 100 degrees between the same points, so the Celsius (and Kelvin) degrees must be larger.

ConcepTest 17.3 Thermometers

You may notice that if a mercury-in-glass thermometer is inserted into a hot liquid, the mercury column first drops, and then later starts to rise (as you expect). How do you explain this drop?

1) the mercury contracts before the glass contracts
2) the glass contracts before the mercury contracts
3) the mercury contracts before the glass expands
4) the glass expands before the mercury expands
5) the mercury expands before the glass contracts

ConcepTest 17.3 Thermometers

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2) the glass contracts before the mercury contracts
3) the mercury contracts before the glass expands
4) the glass expands before the mercury expands
5) the mercury expands before the glass contracts

The hot liquid touches the glass first, so initially the glass expands slightly. This increases the volume inside the glass, and so the mercury level drops slightly. Once the mercury heats up, it begins to expand and then the characteristic rise in the mercury column follows, indicating the increase in temperature that you expected to measure.

Follow-up: Is it possible to have the mercury first rise and later drop?

ConcepTest 17.5a Steel Expansion I

A steel tape measure is marked such that it gives accurate length measurements at room temperature. If the tape measure is used outside on a very hot day, how will its length measurements be affected?

1) **measured lengths will be too small**
2) **measured lengths will still be accurate**
3) **measured lengths will be too big**

ConcepTest 17.5a Steel Expansion I

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1) **measured lengths will be too small**
2) **measured lengths will still be accurate**
3) **measured lengths will be too big**

The tape measure will expand, so its markings will spread out farther than the correct amount. When it is laid down next to an object of fixed length, you will read too few markings for that given length, so the measured length will be too small.

ConcepTest 17.9b Ideal Gas Law II

Two identical cylinders at the same pressure contain the same gas. If A contains three times as much gas as B, which cylinder has the higher temperature?

1) cylinder A
2) cylinder B
3) both the same
4) it depends on the pressure P

ConcepTest 17.9a Ideal Gas Law I

Two identical cylinders at the same temperature contain the same gas. If A contains three times as much gas as B, which cylinder has the higher pressure?

1) cylinder A
2) cylinder B
3) both the same
4) it depends on temp. *T*

Ideal gas law: $PV = nRT$

Solve for pressure: $P = nRT / V$

For constant *V* and *T*, the one with more gas (the larger value of *n*) has the higher pressure *P*.

ConcepTest 17.10 Soda Bottle

A plastic soda bottle is empty and sits out in the sun, heating the air inside. Now you put the cap on tightly and put the bottle in the fridge. What happens to the bottle as it cools?

1) it expands and may burst

2) it does not change

3) it contracts and the sides collapse inward

4) it is too dark in the fridge to tell

ConcepTest 17.10 Soda Bottle

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4) it is too dark in the fridge to tell

The air inside the bottle is warm, due to heating by the sun. When the bottle is in the fridge, the air cools. As the temperature drops, the pressure in the bottle also drops. Eventually, the pressure inside is sufficiently lower than the pressure outside (atmosphere) to begin to collapse the bottle.

ConcepTest 17.11 Balloon in Freezer

What happens to the volume of a balloon if you put it in the freezer?

1) it increases

2) it does not change

3) it decreases

ConcepTest 17.11 Balloon in Freezer

What happens to the volume of a balloon if you put it in the freezer?

1) it increases
2) it does not change
3) it decreases

According to the Ideal Gas Law, when the temperature is reduced at constant pressure, the volume is reduced as well. The volume of the balloon therefore decreases.

$$\boxed{PV = nRT}$$

Follow-up: What happens to the volume when the balloon rises in the air?