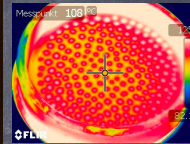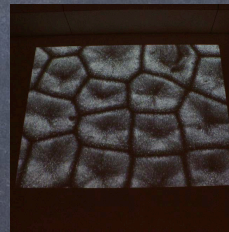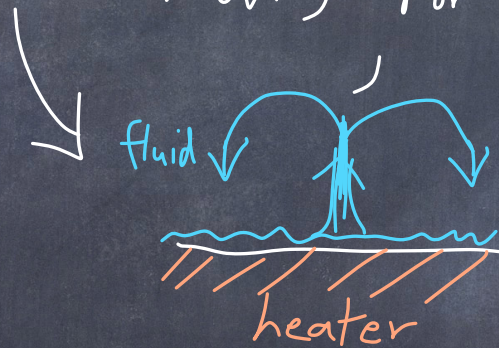# PHY117 HS2023

## Week 7, Lecture 1
## Oct. 29th, 2024
## Prof. Ben Kilminster

Note: $1 \text{ cal} = 4.184 \text{ J}$

$1 \text{ Cal} = 1 \text{ kcal} = 4.184 \text{ kJ}$

Transfer of thermal energy is done by
3 main processes: 1) convection
2) radiation
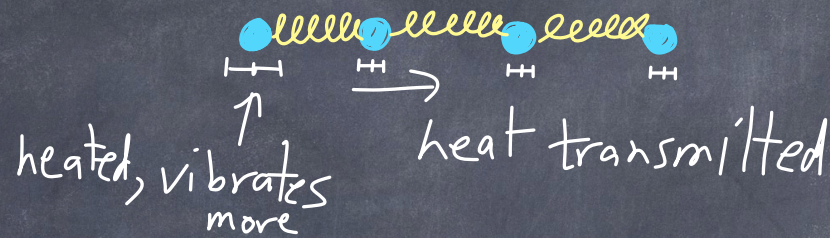3) conduction

1) convection: heat transported by a mass of material
moving. For instance, hot air is less dense
and it rises.

fluid

heater



2) radiation: energy absorbed + emitted in
electromagnetic radiation (visible light,
infrared light,
x-rays)
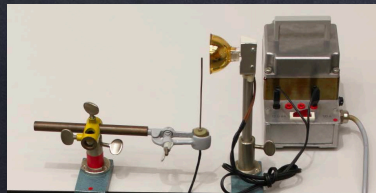
3) Conduction: thermal energy transferred by
interaction between atoms, molecules.



heated, vibrates
more

heat transmitted

Consider a solid bar connecting a
bath of boiling water to a bath of
ice water (we use dry ice $CO_2$ + $C_2H_6$ (ethane)
-78.5°C)



| boiling bath | conducting bar | ice bath |

Source
(constant T)

Q →

sink
(constant T)
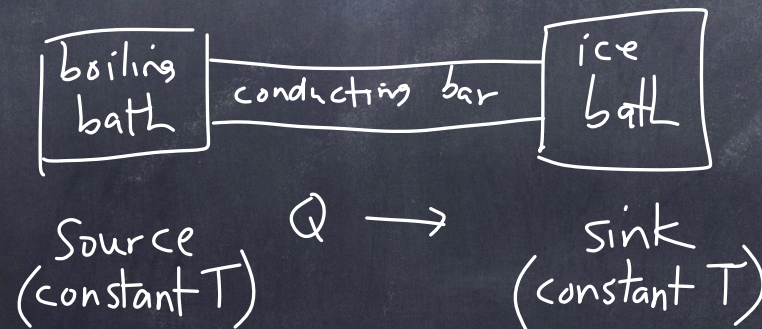
Heat will flow
uniformly across
the bar and
the temperature
of the bar will
vary.

thermal current

$$I = \frac{\Delta Q}{\Delta t} = \kappa A \frac{\Delta T}{\Delta x}$$

heat → $\Delta Q$

material property? coefficient of thermal conductivity → $\kappa$

← temp.

time → $\Delta t$

area → $A$

position → $\Delta x$



hot    Cold

area A    $\Delta x$
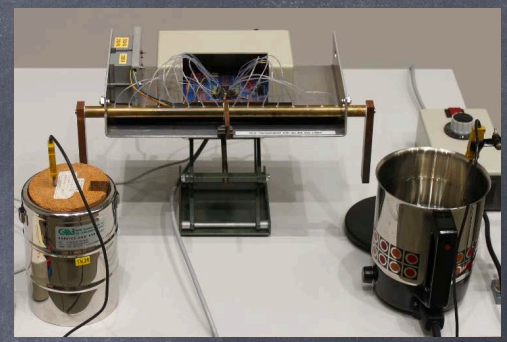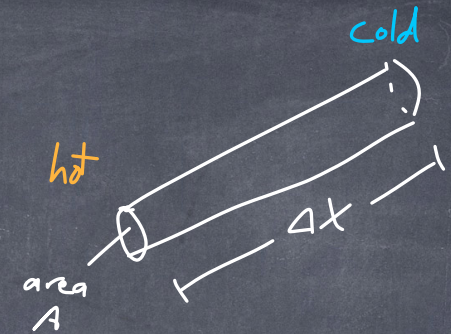
$$I \text{ has units of } \left[\frac{J}{s}\right] = [W]$$
(power)



$$\boxed{\Delta T = I R}$$

where $\boxed{R = \dfrac{\Delta x}{\kappa A} \text{ is thermal resistance}}$

small increments: $\quad I = \dfrac{dQ}{dt} = \kappa A \dfrac{dT}{dx}$

coefficient of thermal conductivity, $k$

| materials | $k$ | units $\left[\dfrac{W}{m \cdot K}\right]$ |
|-----------|-----|--------|
| air | 0.026 | |
| ice | 0.592 | |
| copper | 401 | |
| wood | 0.11 – 0.15 | |
| glass | ~0.8 | |
| aluminum | ≲37 | |
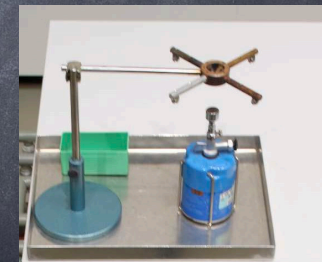
what is R for a cylinder of copper?

$R = 1\,cm$     $\Delta x = 30\,cm$

$$R = \frac{\Delta x}{k A} = \frac{0.3\,m}{\left(400\,\frac{W}{m \cdot K}\right) \pi (0.01\,m)^2} = 2.4\,\frac{K}{W}$$

materials in series



hot | 1 2 3 | cold
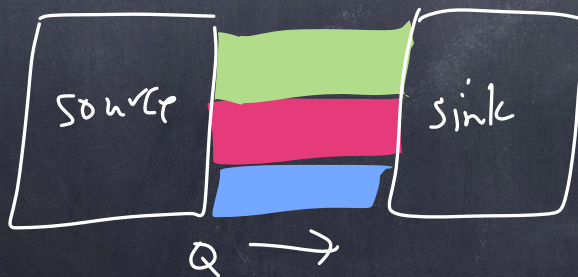
heat source       $\Delta T$       heat sink

$Q \rightarrow$
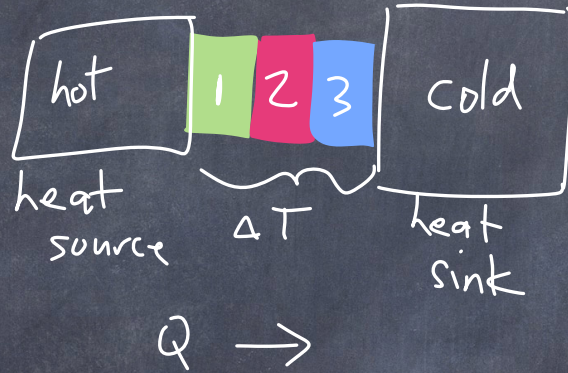
$$R_{eq} = R_1 + R_2 + R_3 + \dots$$

$$\Delta T = R_{eq} \cdot I$$

$R_{eq}$ increases, $I$ decreases

materials in parallel



source            sink

$Q \rightarrow$

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$\Delta T = R_{eq} \cdot I$$

$R_{eq}$ decreases, $I$ increases

6

# Thermal expansion of solids

$T_0$

$L_0$ (length)

$T_0 + \Delta T$

$\Delta L$

$T_0$: initial temp.
$L_0$: initial length
$\Delta T$: change in temperature

$$\Delta L = \alpha L_0 \Delta T \implies dL = \alpha L_0 dT$$
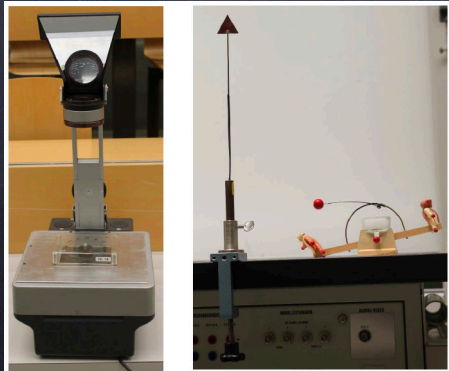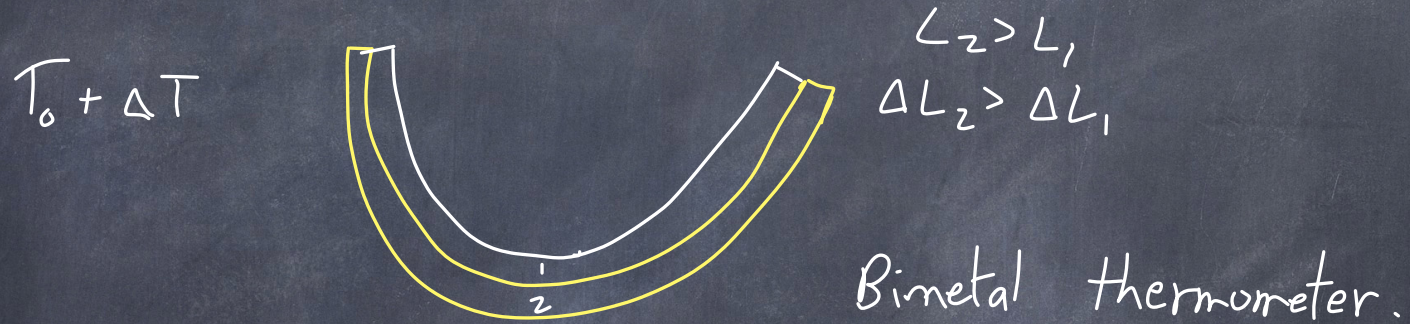
$\alpha$: coefficient of linear expansion

units $\left[\dfrac{1}{K}\right]$ or $\left[\dfrac{1}{^\circ C}\right]$

7

| Material | $\alpha \left[ \dfrac{1}{K} \right]$ |
|---|---|
| Aluminium | 24 E-6 |
| steel | 11 E-6 |
| copper | 17 E-6 |
| brass | 19 E-6 |
| ice | 51 E-6 |
| water (20°C) | 0.207 E-3 |
| alcohol | 1.1 E-3 |

we can turn this into a thermometer.

$T_0$

$\leftarrow \alpha_1$

length,
$L_1 = L_2$

$\leftarrow \alpha_2$

$\alpha_2 > \alpha_1$

$T_0 + \Delta T$

$L_2 > L_1$
$\Delta L_2 > \Delta L_1$

Bimetal thermometer.
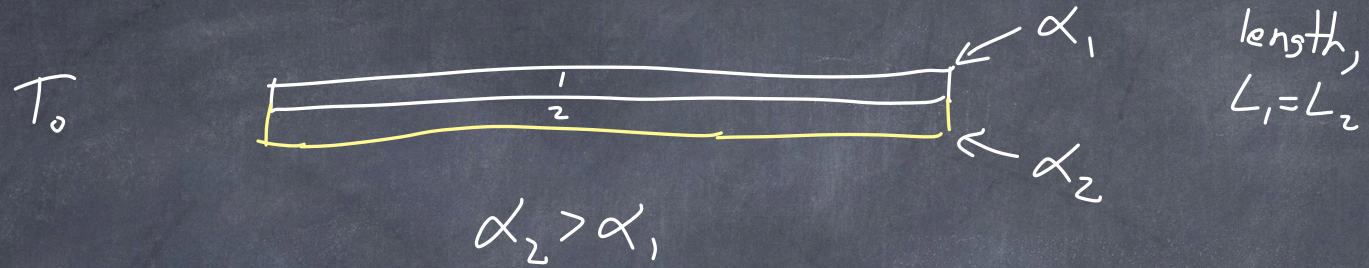
Take this opportunity to point out that a
 change in length, $\frac{\Delta L}{L}$, called a "strain", exerts a force
per area, $\frac{F}{A}$, called a "stress" on a material. The
reverse is also true.



stress
$= F/A$

proportional
limit

elastic limit

A

B    C    Fracture
point
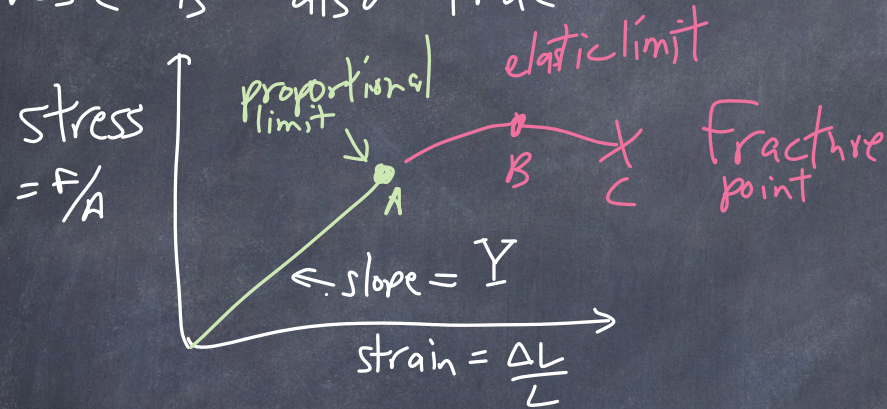
←slope $= Y$

strain $= \frac{\Delta L}{L}$

$$\frac{stress}{strain} = \text{Young's modulus} = Y = \frac{\frac{F}{A}}{\frac{\Delta L}{L}}$$

Up to point A,
the curve is linear and
has a slope of $Y$    → but then deformation
and fractures happen
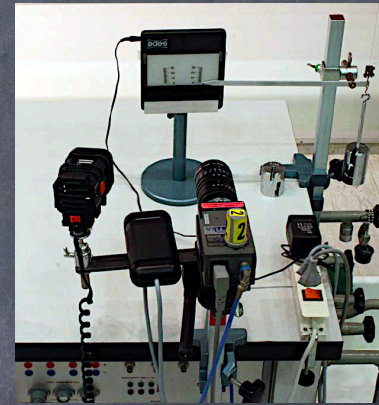
| material | $Y \left[\dfrac{GN}{m^2}\right]$ |
| --- | --- |
| steel | 200 |
| lead | 16 |
| gold | 8 |

We can create a strain, for instance, with a thermal expansion, and this will generate a stress according to $Y$.
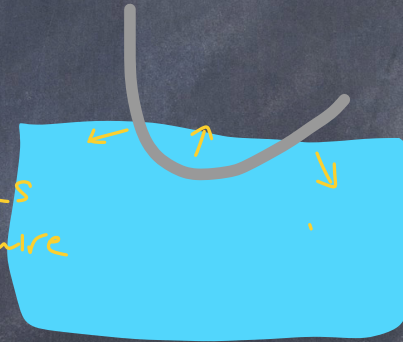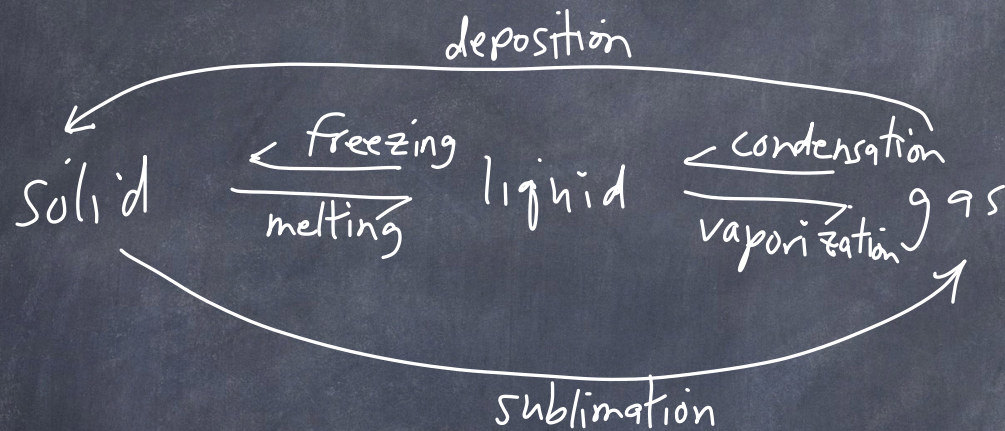
work done by heat



shape memory alloys
remember their original molecular
configuration at high temperatures.

asymmetric forces
tend to straighten wire
when heated

most materials <u>don't</u> do this

Sometimes when heat is absorbed or emitted, the material undergoes a phase change

deposition

solid $\xleftarrow{\text{freezing}}$ liquid $\xleftarrow{\text{condensation}}$ gas
$\xrightarrow{\text{melting}}$ $\xrightarrow{\text{vaporization}}$

sublimation

freezing or melting

$$Q = m L_F$$

heat required to change phase (+) or (−)

mass of material

latent heat of fusion of material

condensation or vaporization

$$Q = m L_V$$

latent heat of vaporization

| | Melting point [K] | latent heat of Fusion $L_f$ $\left[\frac{kJ}{kg}\right]$ | Boiling point [K] | latent heat of vaporization $L_v$ $\left[\frac{kJ}{kg}\right]$ | specific heat $C$ $\left[\frac{kJ}{kg \cdot K}\right]$ |
|---|---|---|---|---|---|
| Gold | 1336 | 62.8 | 3081 | 1701 | 0.126 |
| water | — | 333.5 | 373.15 | 2257 | 4.18 |
| lead | 600 | 24.7 | 2023 | 858 | 0.128 |
| alcohol | 159 | 109 | 351 | 879 | 2.4 |
| ice | 273.15 | 333.5 | — | — | 2.05 |

water good for storing heat & not changing phase

lead good for bullets

14

During evaporation, a liquid loses heat and decreases in temperature.

Experiment.
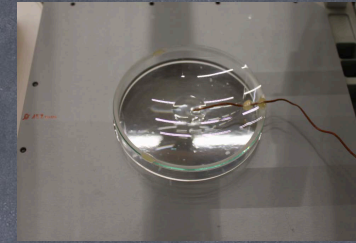


Macroscopic: we put liquid alcohol in a dish, and measure the liquid temperature as the alcohol evaporates. The temperature decreases...
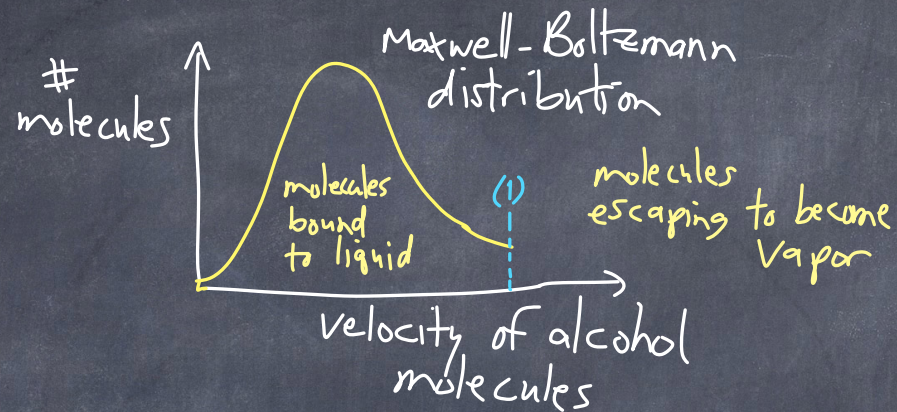
$$\Delta Q_{liquid} = -\Delta m L_v$$

↑ heat loss depends on how much mass $\Delta m$ evaporates.

This changes the temperature of the liquid according to $\Delta Q_{liquid} = m_r c \Delta T$

↑ remaining mass of liquid, $m_r$

Microscopic scale:

# molecules

Maxwell-Boltzmann distribution

molecules bound to liquid

(1)

molecules escaping to become vapor

velocity of alcohol molecules

The alcohol liquid is composed of alcohol molecules, with a velocity distribution like the one above. Molecules are bound to the liquid by a potential energy barrier.

Above a certain velocity[1], molecules have enough velocity to overcome the potential energy holding them.

Since the fastest molecules are the hottest ones, when they escape, the remaining liquid gets cooler.

This is why sweating cools your body.

Phase diagram for a material.:
Shown for P vs. T
One can determine the state of a material.
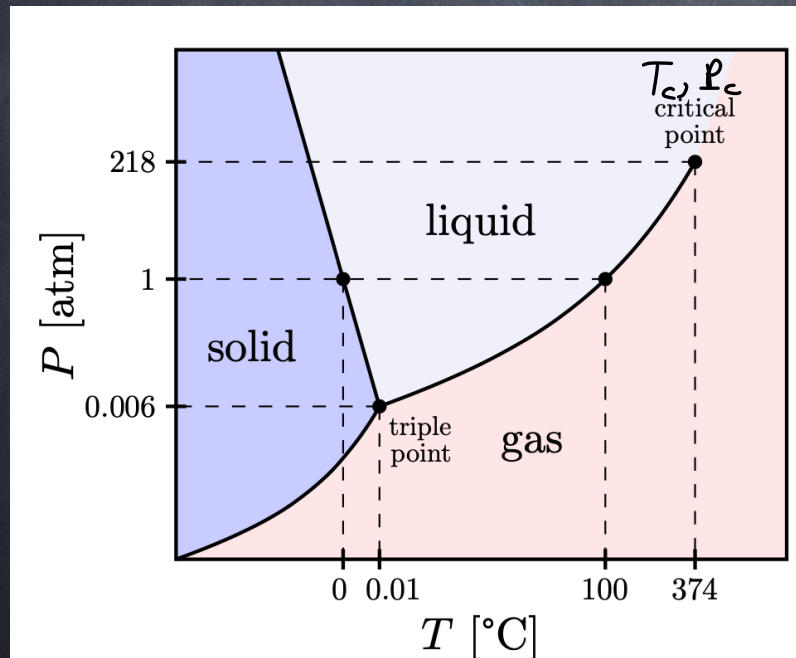


1) Along $\underset{\text{solid black}}{\text{lines}}$ 2 phases can exist
Away from lines, 1 phase exists.

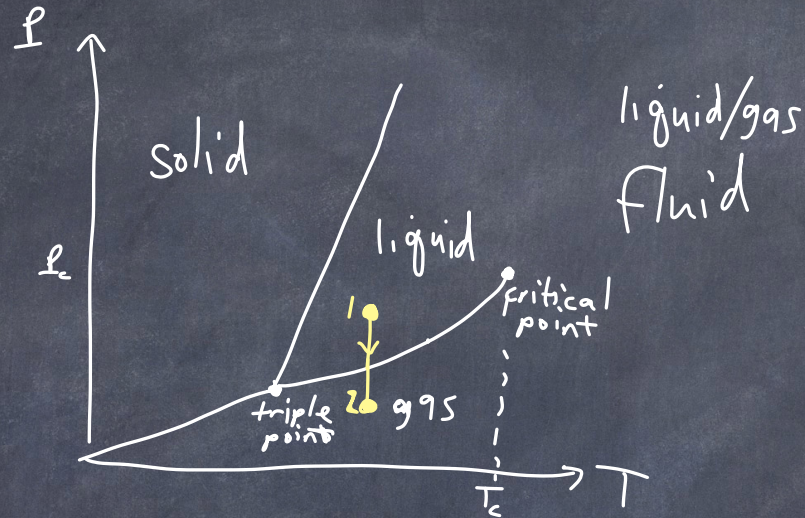2) At triple point, all 3 phases can exist.

3) At $T_c, P_c$, density of liquid + gas phases are the same.
For $T > T_c$ and $P > P_c$, there is no distinction between liquid and gas.

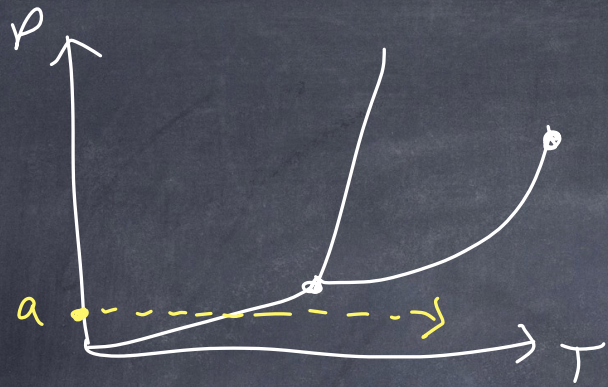$P_c$ : critical pressure
$T_c$ : critical temperature

Expt:    Boiling by vacuum.

phase
diagram
for
water.



P

P_c

solid

liquid

liquid/gas
fluid

critical
point

1

2   gas

triple
point

T_c

T
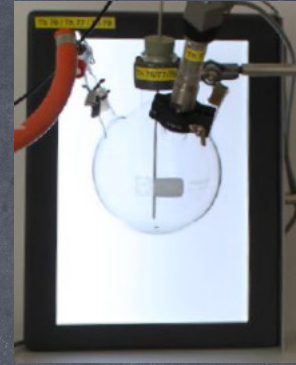
In this experiment, we move along the phase
diagram for water from point 1 ($22°C$, $1000\,hPa$)
to point 2 ($22°C$, $30\,hPa$). We ~~will~~ should see the water
boil.

If we move along line (a), we heat at constant pressure. We are below the triple point pressure, so we go from solid to gas.

$CO_2$ sublimates solid to gas at 1 atm because triple point is at 5.1 atm $(a = P_{atm} = 1\ atm)$

Back to ideal gas. We can add heat while keeping pressure constant or volume constant. The heat will change the internal energy differently.

$C_V$: heat capacity $\left[ \frac{J}{mol \cdot K} \right]$ at constant volume

$C_p$: heat capacity at constant pressure.

There is a relationship between the two.

At constant volume, we add heat to a gas.

$$Q = \Delta U + W^{0} \qquad \text{(No work is done, since V is constant)}$$

$$\Delta U = Q = C_V \Delta T$$

$$\text{As } \Delta T \rightarrow 0, \quad dU = C_V dT \qquad \boxed{C_V = \frac{dU}{dT}} \quad \text{①}$$

Note: $c = \frac{C}{m} \leftarrow$ heat capacity $\left[ \frac{J}{mol \cdot K} \right]$

$\uparrow$
specific $\left[ \frac{J}{kg \cdot K} \right]$ $\cdot m = mass \ kg$
heat

At constant pressure, we add heat to a gas. The gas will expand.

$$Q = \Delta U + W$$

$$C_p \Delta T = \Delta U + P \Delta V$$

for small changes, $\quad C_p dT = dU + P dV \quad$ ②

rewrite $P dV$:

$$PV = nRT \quad \rightarrow \quad P dV = nR \, dT \quad$$ ③

put ① & ③ into ②:

$$C_p \cancel{dT} = C_v \cancel{dT} + nR \cancel{dT}$$

$$\boxed{C_p = C_v + nR}$$

for an ideal gas

$$C_p > C_v \text{ by } nR$$

The ratio of the heat capacities $\frac{C_p}{C_v} = \gamma$ is dimensionless.

For an ideal monatomic gas, $C_v = \frac{3}{2}nR$ $C_p = \frac{5}{2}nR$ so $\gamma = \frac{5}{3}$. For an ideal diatomic gas, $C_v = \frac{5}{2}nR$, $C_p = \frac{7}{2}nR \Rightarrow \gamma = \frac{7}{5}$
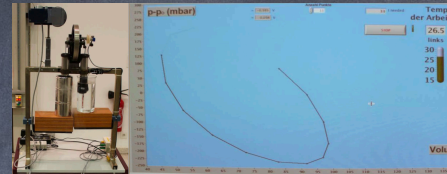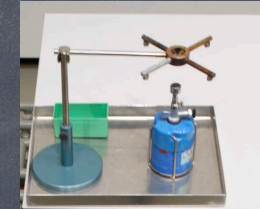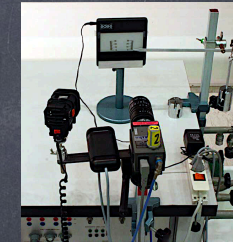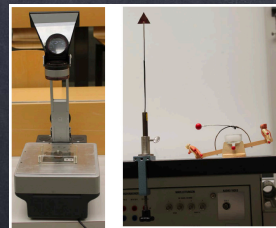
Th81

Th34
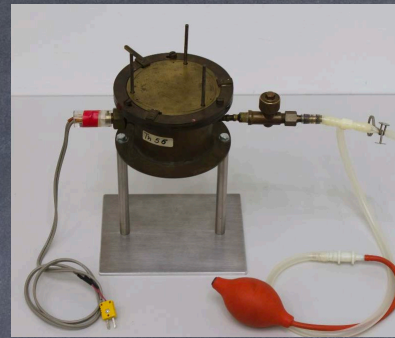
Th55
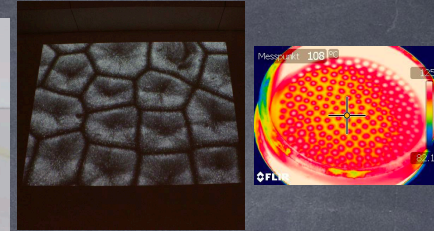
Th35
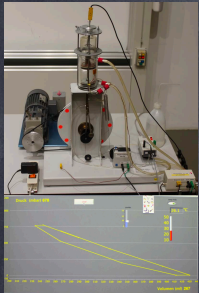
Th70
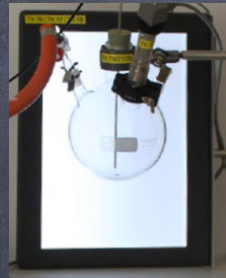
Th20

Th77

Th68

E12

Th19

Th14

Th2

Th22

Th48