Lecture 33

Temperature. Thermometers.
Thermal expansion.

Matter is very complex

A simple cup of coffee contains ~ 10^{23} atoms

Numerically impossible to follow trajectory of each atom, use Newton's laws for force, acceleration etc..

Two options

1. Statistical: probability distribution of molecule velocities
2. Macroscopic: a few variables (temperature, pressure, volume…) characterize the bulk properties of matter

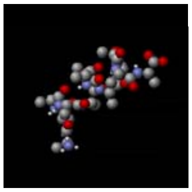
These variables are called state variables.

Temperature and thermal equilbrium

Temperature ~ average kinetic energy of atoms

Two pieces of matter in thermal contact exchange energy until their temperatures (T) are the same (0th law of thermodynamics)

Example:
Molecules in coffee transfer energy to the air molecules.
Eventually all coffee molecules have the same average kinetic energy as the molecules of air in this room

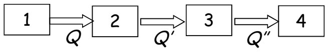


Reaching equilibrium (same T) requires transfer of energy

This energy in transit is called heat Q.

ACT: Temperature

When a series of blocks are connected thermally, heat *starts* to flow between the blocks as shown. What does this tell us about relative temperatures of the blocks?



A. $T_1 = T_2 = T_3 = T_4$

$\boxed{\text{B. } T_1 > T_2 > T_3 > T_4}$

C. $T_1 < T_2 < T_3 < T_4$

This is how the sequence is established empirically.

Also: You just applied the 2nd law of thermodynamics....

Temperature scales: Celsius, Fahrenheit

Celsius

Based on the boiling and freezing points of water.
0°C = freezing point of water
100°C = boiling point of water

Fahrenheit

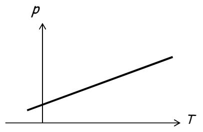
Based on the boiling and freezing points of alcohol.

Connection to Celsius: 0°C = 32°F
100°C = 212°F

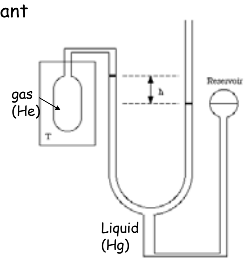
$$\boxed{T_F = \frac{9}{5}T_C + 32}$$

Constant volume gas thermometers

For gases, p is proportional to T for constant volume (Charles' law).



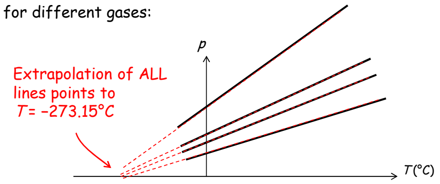
$$\frac{p}{T} = \text{constant}$$



DEMO:
He and N_2
balloons

Temperature scales: Kelvin

$p(T)$ for different gases:



Kelvin scale

0 K = –273.15°C (lowest energy state, quantum motion only)
2nd fixed point: 273.16 K (=0.01°C) is the triple-point for H_2O (ice, water, steam coexist)
With this choice, 1°C = 1K (equal increments)

$$\boxed{T_K = T_C + 273.15}$$

Thermal expansion of a bar

A bar of length L_0 expands ΔL when temperature is increased by ΔT. Experimentally,

$$\boxed{\Delta L = \alpha L_0 \Delta T}$$

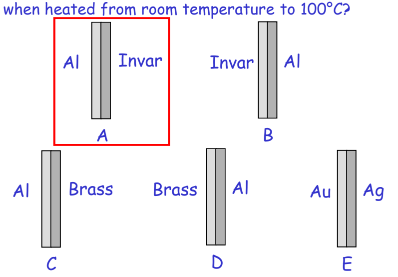
$\alpha =$ coefficient of linear expansion (depends on material)

Basis for many thermometers
e.g. liquid mercury

Critically important in many engineering projects (expansion joints)

In-class example: Bimetallic strips

Which of the following bimetallic strips will bend the furthest to the right when heated from room temperature to 100°C?



	α (1/mK)
Al	24
Invar	1.3
Brass	21
Au	14
Ag	19

DEMO:
Bimetallic
strips

Al/Invar have the largest difference in α. Aluminum expands more than invar, so A will bend to the right.

A couple of applications

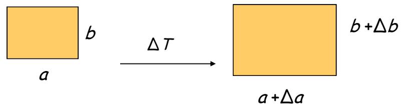
Bimetallic strips can be used as thermostat switches.

About invar: Fe-Ni alloy with very small α

Train tracks have expansion joints (gaps) to prevent buckling in hot weather.
(origin of the "clickety-clac, clickety-clac")

High speed trains cannot afford the vibrations produced by these gaps. Alloys with small α to build tracks are a key development.

Area Thermal Expansion



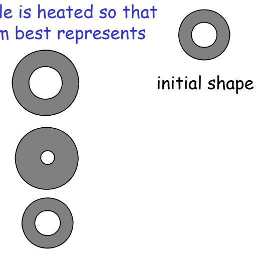
$$
\begin{aligned}
A_{\text{final}} &= (a+\Delta a)(b+\Delta b) \\
&= ab + a\Delta b + b\Delta a + \text{very small terms} \\
&\approx ab + a(b\alpha\Delta T) + b(a\alpha\Delta T) \\
&= ab + \underbrace{2ab\alpha\Delta T}_{\Delta A}
\end{aligned}
$$

$$\boxed{\Delta A = 2\alpha A_0 \Delta T}$$

ACT: Washer

DEMO:
Balls and rings

A circular piece of metal with a round hole is heated so that its temperature increases. Which diagram best represents the final shape of the metal?

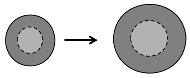


A. Both inner, outer radii larger

B. Inner radius smaller, outer radius larger

C. Same size

Think about how the piece that was cut off the center would grow.



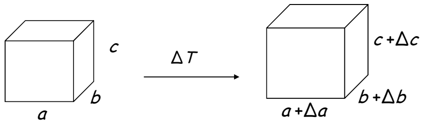
Opening tight jar lids

$\alpha_{\text{glass}} = 0.4\text{-}0.9 \times 10^{-5}\ \text{K}^{-1}$

$\alpha_{\text{brass}} = 2.0 \times 10^{-5}\ \text{K}^{-1}$

If you place the jar top under the hot water faucet, the brass expands more than the glass.

Volume Thermal Expansion



$$V_{\text{final}} = (a+\Delta a)(b+\Delta b)(c+\Delta c)$$
$$= abc + ab\Delta c + ac\Delta b + bc\Delta a + \text{smaller terms}$$
$$\approx abc + 3abc(\alpha\Delta T)$$
$$\approx V_0 + \underbrace{3V_0\alpha\Delta T}_{\Delta V}$$

$$\boxed{\Delta V = \beta V_0 \Delta T}$$

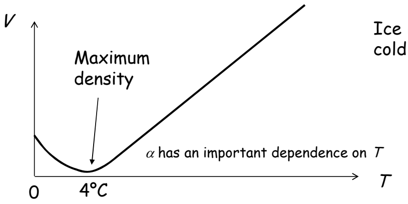
$$\boxed{\beta \approx 3\alpha}$$

Coefficient of volume expansion

The special case of water

Most materials expand when temperature increases.

Water between 0 and 4°C is the exception.



Ice is less dense than cold (< 4°C) water.

↓

Ice floats

This prevents lakes from freezing from the bottom up, which would kill all forms of life.

Thermal stress

A rod of length L_0 and cross-sectional area A fits perfectly between two walls. We want its length to remain constant when we increase the temperature.

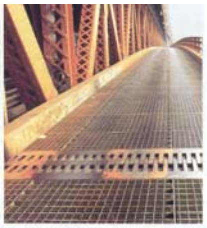
Constant length = zero net strain

$$\Delta L_{\text{all}} = \Delta L_{\text{thermal}} + \Delta L_{\text{applied stress}} = 0$$

$$L_0\alpha\Delta T + \frac{FL_0}{YA} = 0$$

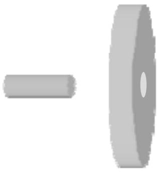
$$\frac{F}{A} = -\alpha Y \Delta T$$

Thermal stress (stress walls need to provide to keep length constant)



Application of thermal stress

For very tight fitting of pieces (like wheels):



Wheel is heated and then axle inserted.

Wheel cools down and shrinks around axle, very tight.