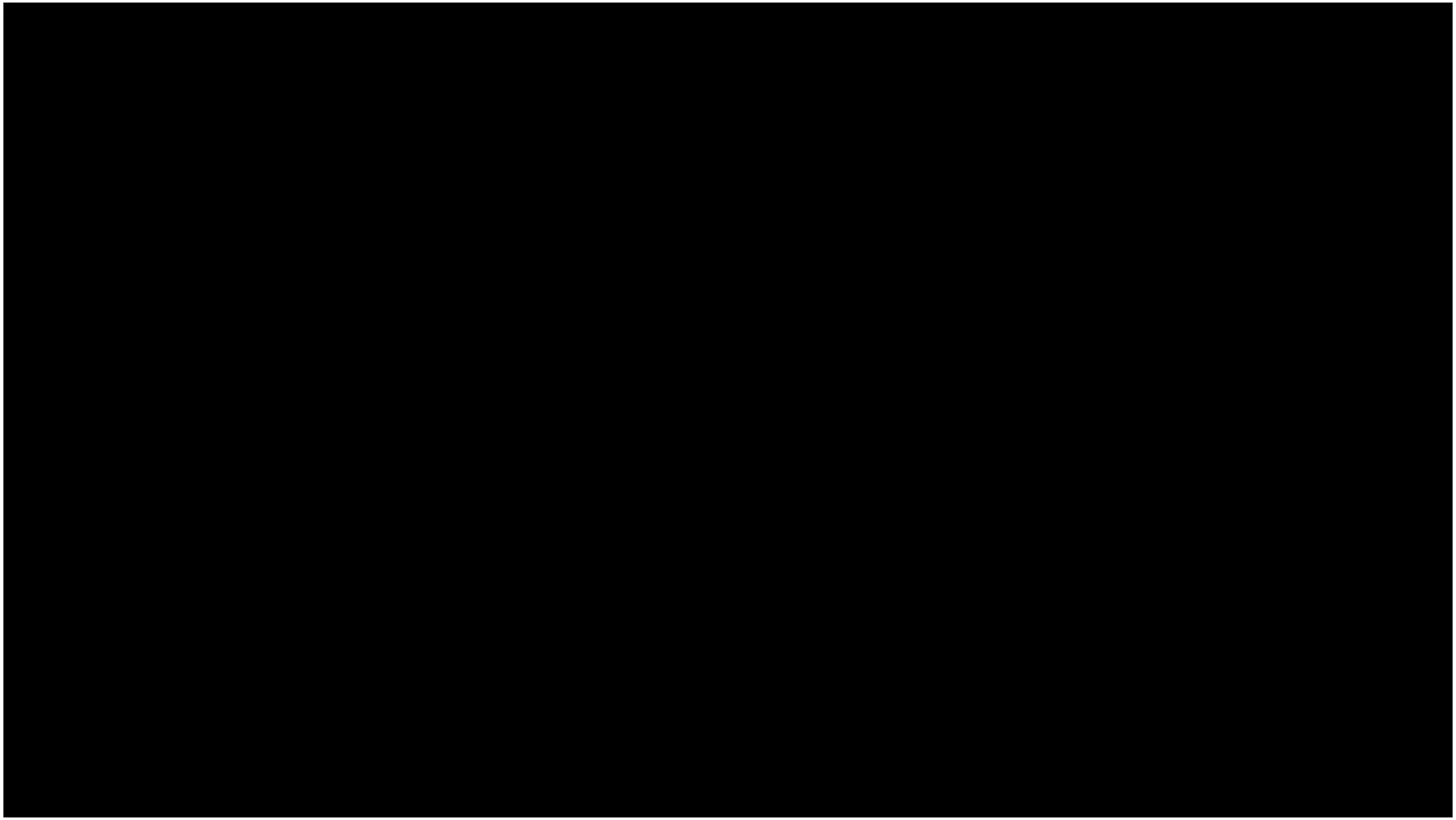
Thermal Physics

Prof. Alex Hamilton

Lecture 1 – Temperature



Thermal Physics

Lecture 1 – Temperature

Textbook reference: 18.1-18.3
See also Liz Angstmann's webstream lectures

https://goo.gl/forms/WywZDSQ0pOBCUOSW2

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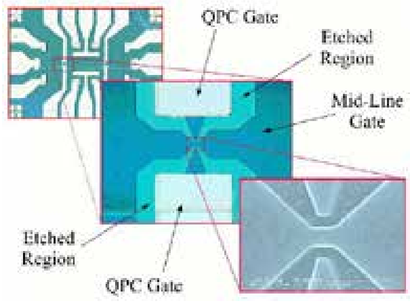
http://www.physics.unsw.edu.au/QED

SpaceX:

https://youtu.be/A0FZIwabctw
https://youtu.be/bvim4rsNHkQ



	Mon	Tues	Wed	Thu	Fri
09:00	Lecture prep		Lecture prep	Lecture prep	PHYS1131B
10:00	PHYS1131B		PHYS1131A	Lecture prep	
11:00				PHYS1131B	
12:00	Lecture prep				1131 Tute
13:00	Lunch	Lunch	Lunch	Lunch	Lunch
14:00	Upper Yr Lab	Lecture prep			
15:00	Upper Yr Lab			Lecture prep	
16:00	Upper Yr Lab			Lecture prep	
17:00	PHYS1131A			PHYS1131A	
18:00	**Office hour**				

In addition to the usual help sessions, I am often in my office in the empty times above. Otherwise fiddling with a helium fridge in Old Main LG48/48A, or playing with vector magnets and quantum dots in Newton G14.

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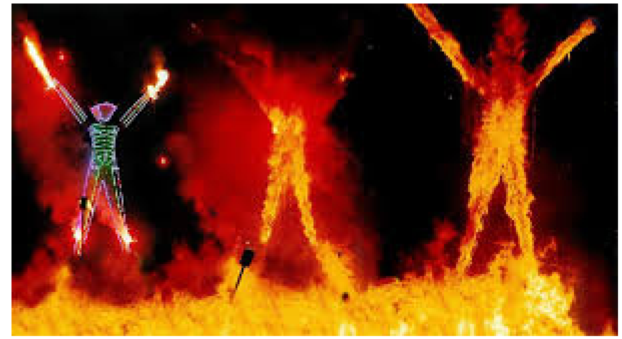
Why bother with thermal physics?



Scientific curiosity:

- What happens when things burn?
- Why do things change when we heat them?
- What is heat made of?

Applications:

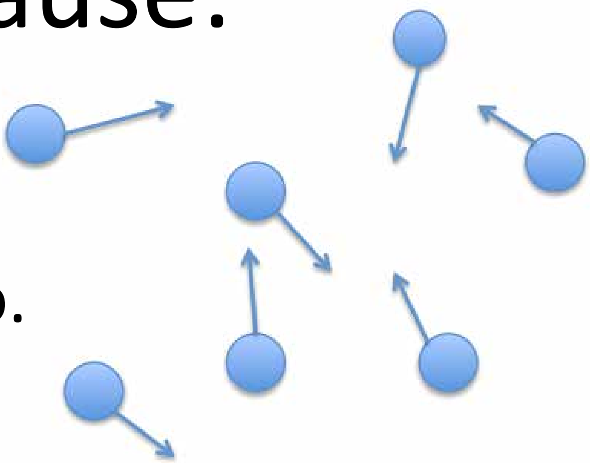
- What is the best material to make a stove from?
- What about a rocket?
- Can we use waste heat to power machines?
- 2nd Year: What is the most efficient engine we can make?

Challenges & opportunities:

- What limits efficiency of a solar cell?
- How can we make faster computers?
- How to solve climate issues –
  unique challenges and opportunities for *your generation* of scientists and engineers.
  Yes you!

Thermal Physics is challenging because:

- Less intuitive than mechanics
- New concepts
- Experiments harder to conduct? No.
  - 1st Year lab – specific & latent heat
  - 1st Year lab – Ideal Gas Law

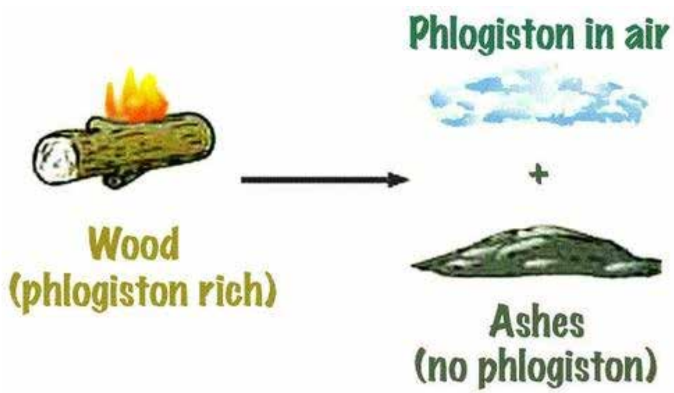


Objective: We will use as much fire and liquid nitrogen as possible to help make this topic clear!

What happens when things burn?

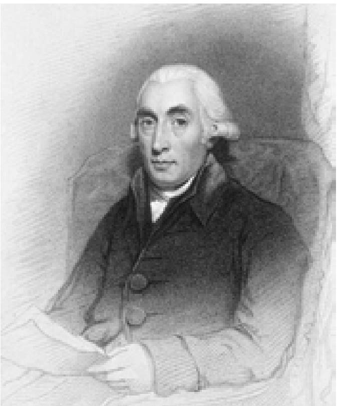
J.J. Becher (1667) & G.E. Stahl (1703):
theory of phlogiston (Ancient Greek, from φλόξ phlóx=flame)

- Some substances burn in air, others don't.
  Wood, paper, coal, oil, wax, fats, etc. are flammable
  Þ contain a substance called phlogiston.
- They get lighter when burnt in air: wood ® ash,
  Þ burning releases heat, light and their phlogiston.



- Theory even explains why candles go out in a jar – air can't absorb too much phlogiston.
- But why do metals get *heavier* when burnt?

What is heat made of?



- Phlogiston theory.
- Joseph Black (1728-1799):
  - – Latent heat of melting – adding heat to bucket of ice water doesn't make it warmer, you just have less ice! Þ heat ≠ temperature
  - – Heat *always* flows from hot things to cold things.

- Caloric theory (Antoine Lavoisier, 1770s):
  - Ø Heat is an invisible fluid, caloric.
    (Like electrical fluid that carries electrical currents)
  - Ø Amount of caloric is conserved.
  - Ø You cannot create or destroy caloric – it just moves from hot things to cold ones.
  - Ø But: How does friction generate heat?
    1798: Count Rumford notices that boring canons makes a *lot* of heat – where is the caloric coming from? (Demo).

- Modern kinetic theory: Heat is vibrations - a form of energy…

Some reading for those suffering from insomnia:

- http://hsm.stackexchange.com/questions/3470/what-are-the-major-flaws-of-the-caloric-theory-of-heat
- http://galileoandeinstein.physics.virginia.edu/more_stuff/TeachingHeat.htm
- Benjamin Count of Rumford, *An inquiry concerning the source of heat which is excited by friction*, Philosophical Transactions of the Royal Society of London, **88**: 80–102 (1798). https://dx.doi.org/10.1098%2Frstl.1798.0006

Modern theory: Some definitions

Q: What allows heat to flow?

A: Thermal Contact: Two objects are in thermal contact with each other if energy can be exchanged between them in the form of heat or electromagnetic radiation.

Energy is exchanged due to a temperature difference.

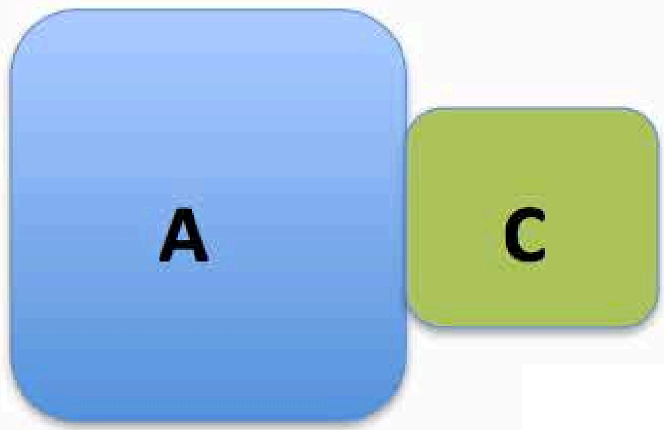
Thermal contact does not necessarily mean physical contact.

Q: When does heat flow stop?

A: Thermal Equilibrium: Thermal equilibrium occurs when two objects would not exchange any net energy if they were placed in thermal contact.

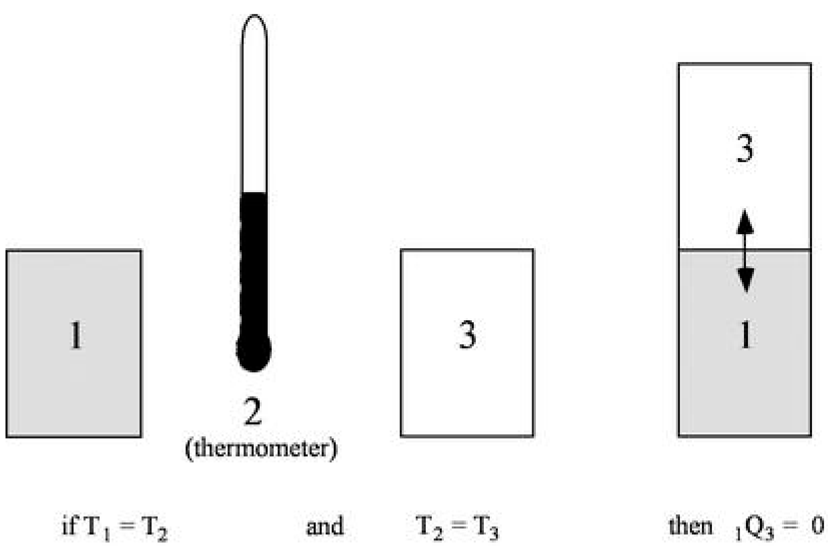
Zeroth Law of Thermodynamics

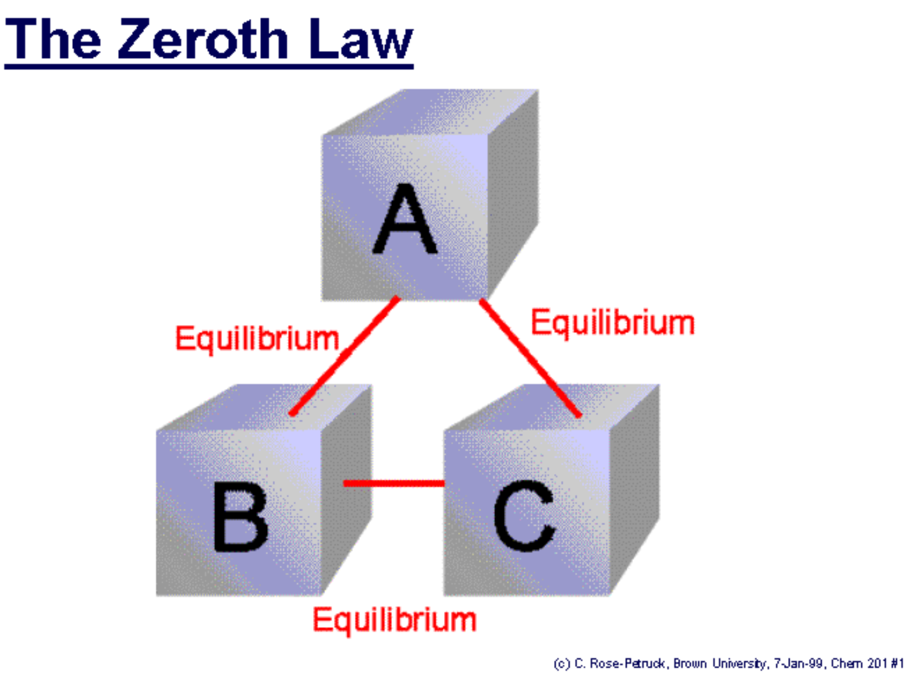
If objects A and C are in thermal equilibrium,
and B and C are in thermal equilibrium,
then A and B are in thermal equilibrium with each other.



Zeroth Law of Thermodynamics

If objects A and B are separately in thermal contact with a third object C, then A and B are in equilibrium with each other.





Temperature...

- **Caution!**
  - Two objects in thermal equilibrium may **feel like** they are at different temperatures when you touch them, because our body's sense of temperature is based on energy flow.

- Example:
  - A stool is left standing in a room at 20°C.
  - The metal part feels cooler when you touch it because energy flows more readily from the metal to your body (at 37°C) than does the cushion.
  - We'll cover heat conductivity later.

Quick Quiz: Two objects, with different sizes, masses, and temperatures, are placed in thermal contact. In which direction does the energy travel?

https://goo.gl/forms/WywZDSQ0pOBCUOSW2

1. Energy travels from the larger object to the smaller object.
2. Energy travels from the object with more mass to the one with less mass.
3. Energy travels from the object at higher temperature to the object at lower temperature.

Temperature measurement...

- In general, the physical properties of a substance change with temperature.

  - Volume of a liquid
  - Volume of a solid
  - Volume of a gas at constant pressure
  - Pressure of a gas at constant volume

Microscopically,
this is due increased
kinetic energy of the
atoms/molecules that
make up the
substance.

  - Colour change

Usually due to changes in the chemical properties
of the substance

Temperature measurement

Physical properties that change with temperature

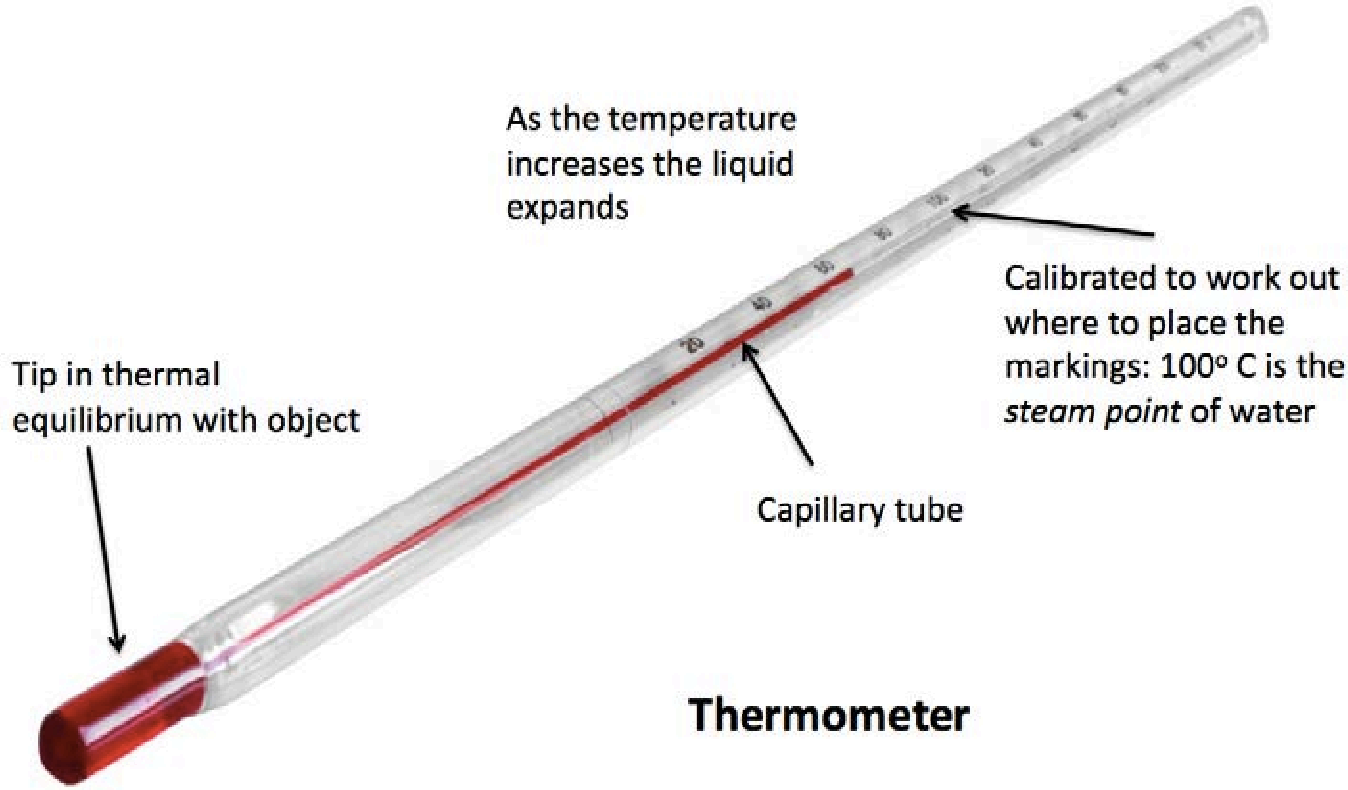
As temperature increases the volume of a liquid will usually increase. Microscopically this is because the particles that make up the liquid start moving about more quickly.

Solids will generally expand when heated.

The pressure of a gas will also increase with temperature. YouTube "exploding aerosol can" for examples….

Temperature measurement...

- In fact that's how medical thermometers work.



An absolute temperature scale...

- Two commonly used temperature scales:
  - Fahrenheit (the United States)
  - Celsius (the rest of the world)

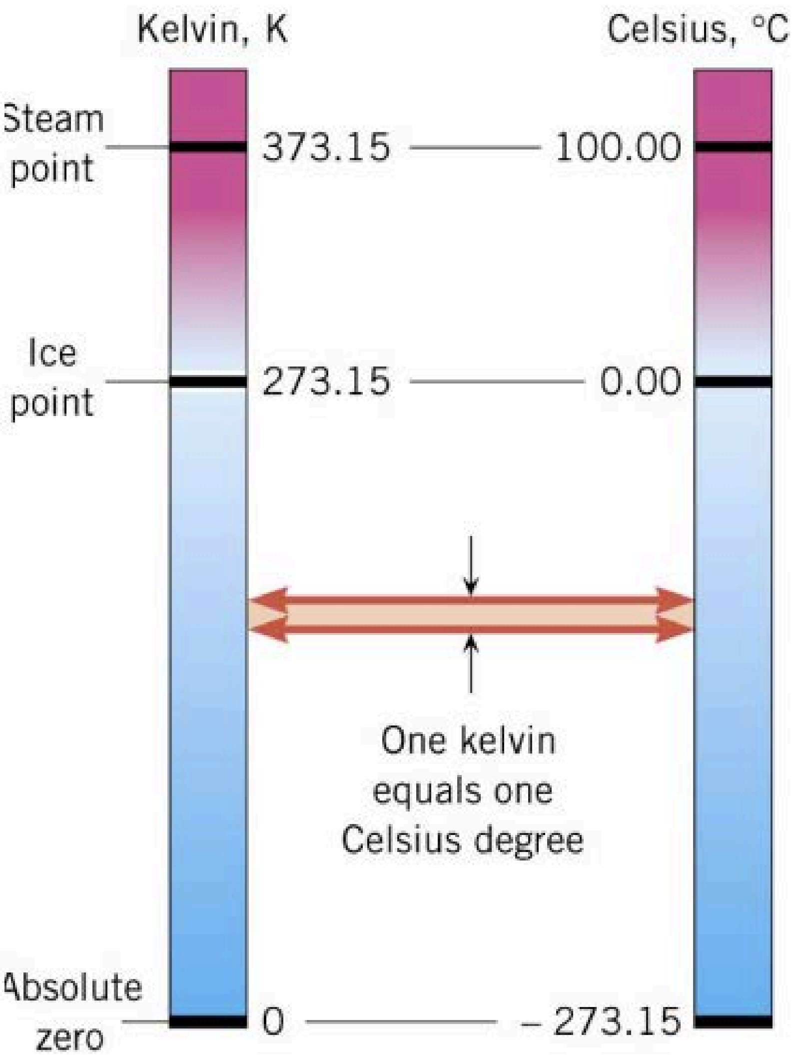
- Neither is an SI unit!

(We use SI units in physics!)

Measuring Temperature

An absolute temperature scale would be useful…

Measuring Temperature



Kelvin temperature

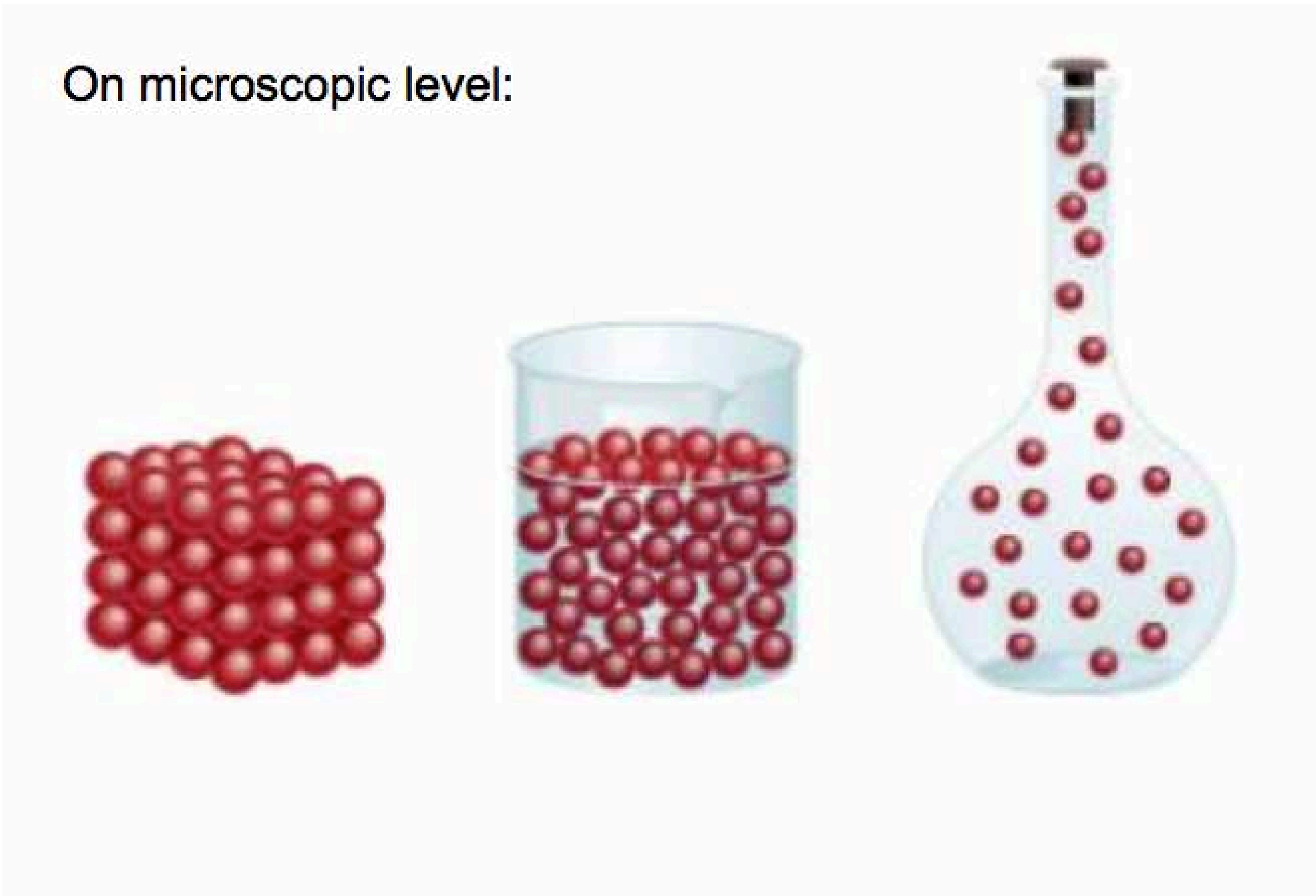
$$T = T_c + 273.15$$

New Kelvin Scale

In 1954 the ice point was replaced by triple point of water:
water, ice and vapor coexist at 0.01°C
And 4.58 mm of mercury.

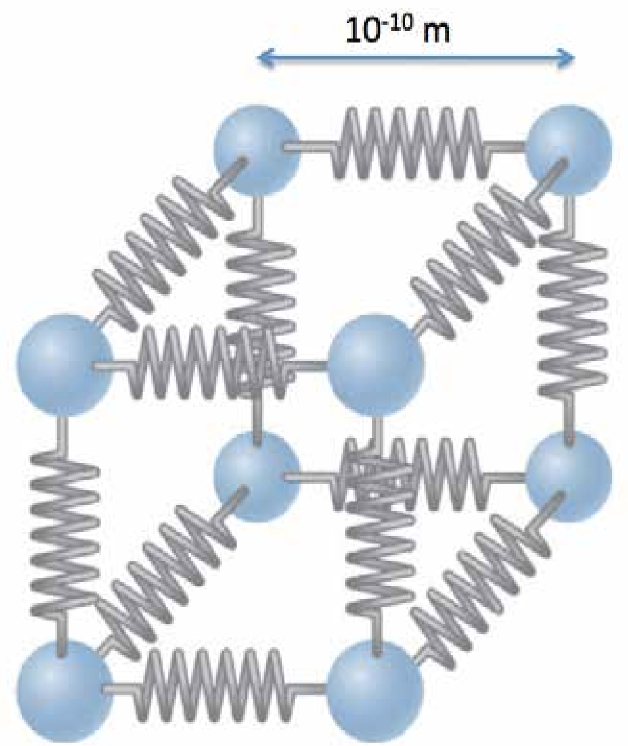
273.16 K

Temperature and physical changes



Temperature and physical changes...

- Even in a solid, where the atoms are bound in a rigid lattice, atoms vibrate about their lattice points.
  - At room temperature:



(cf 10^{-7}m for wavelength of visible light)

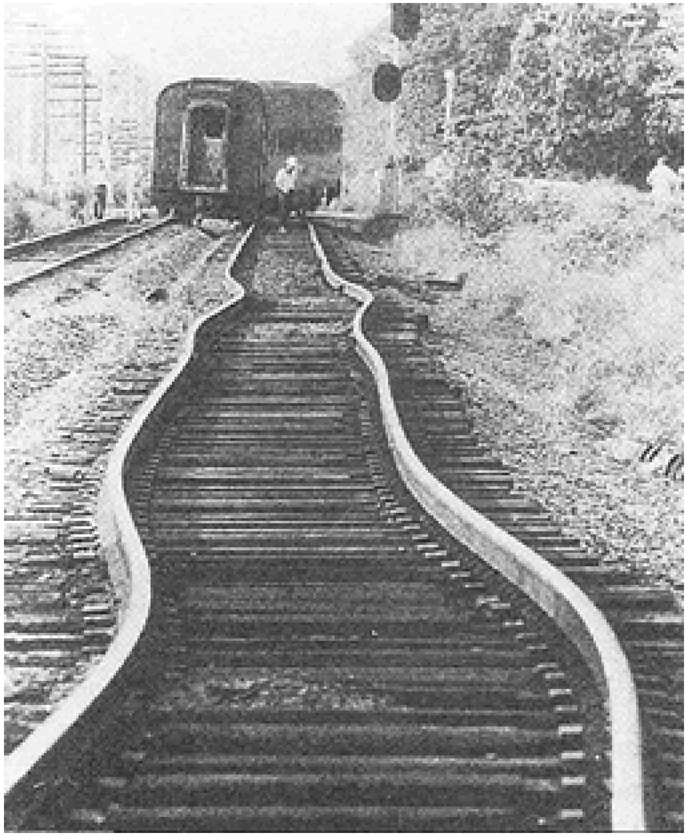
  - Raising the temperature increases the vibration amplitude.

Thermal Expansion: It works

Hot water on jar lid à expands the metal, makes it easier to open.

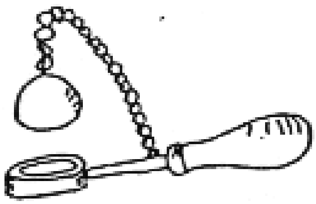
Expansion joint on bridge, so it will not buckle on very hot days.

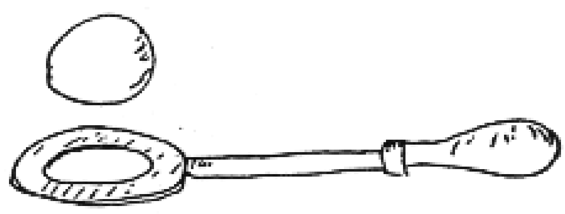

IF YOU DON'T ACCOUNT FOR THERMAL EXPANSION
YOU'RE GONNA HAVE A BAD TIME



Demo Unit Hb1 & Hb2: Thermal Expansion of a Ball and Ring

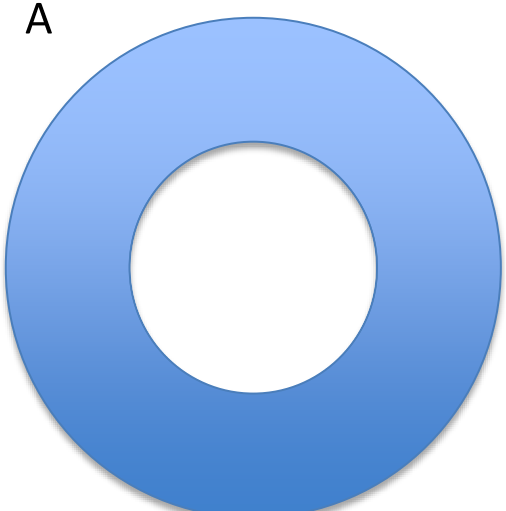
- A ball will pass through a ring at room temperature but what happens if the ball is heated, or if the ring is cooled?





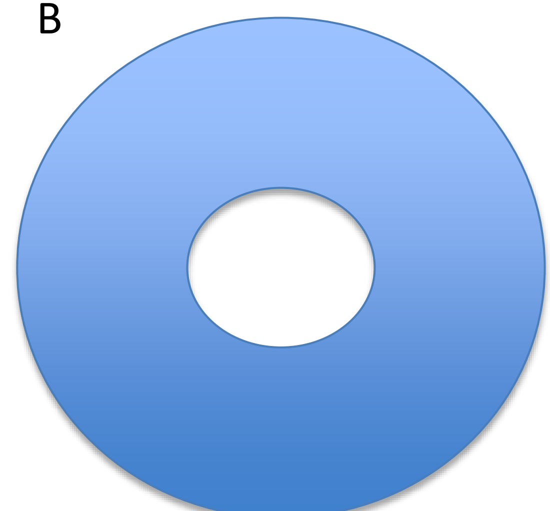
What will happen to a disk when it is heated?

A



Outside expands and so does inside hole

B



Metal expands outside but also to fill the hole

https://goo.gl/forms/WywZDSQ0pOBCUOSW2

Thermal expansion: solids...

- How does the length of a solid object change with temperature?

Average **linear** expansion expansion coefficient; a property of the substance under consideration

Change in length

$$\Delta L = \alpha\, L_{ini}\, \Delta T$$

Change in temperature

Initial length

- **Watch out!**
  - ΔL and L_{ini} must have the same units!
  - Units of ΔT is either ºC or K; units of α is either $ºC^{-1}$ or K^{-1}.

Expansion rate depends on material

Table 19.1

Average Expansion Coefficients for Some Materials Near Room Temperature

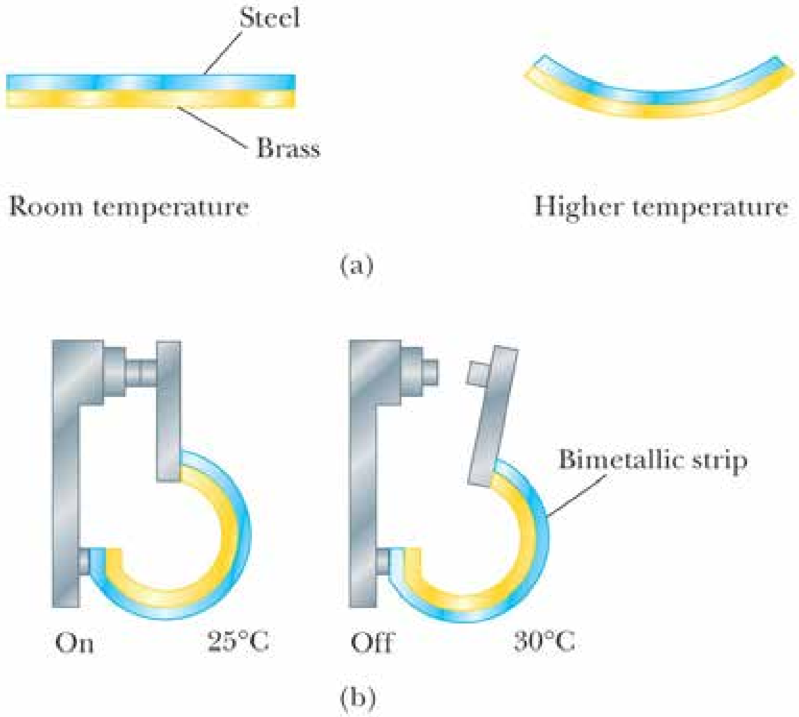
Material	Average Linear Expansion Coefficient $(\alpha)(°C)^{-1}$	Material	Average Volume Expansion Coefficient $(\beta)(°C)^{-1}$
Aluminum	24×10^{-6}	Alcohol, ethyl	1.12×10^{-4}
Brass and bronze	19×10^{-6}	Benzene	1.24×10^{-4}
Copper	17×10^{-6}	Acetone	1.5×10^{-4}
Glass (ordinary)	9×10^{-6}	Glycerin	4.85×10^{-4}
Glass (Pyrex)	3.2×10^{-6}	Mercury	1.82×10^{-4}
Lead	29×10^{-6}	Turpentine	9.0×10^{-4}
Steel	11×10^{-6}	Gasoline	9.6×10^{-4}
Invar (Ni–Fe alloy)	0.9×10^{-6}	Air[a] at 0°C	3.67×10^{-3}
Concrete	12×10^{-6}	Helium[a]	3.665×10^{-3}

[a] Gases do not have a specific value for the volume expansion coefficient because the amount of expansion depends on the type of process through which the gas is taken. The values given here assume that the gas undergoes an expansion at constant pressure.

Bimetallic Strip

$$\alpha_{\text{brass}} = 19 \times 10^{-6} \, / \deg C$$

$$\alpha_{\text{steel}} = 12 \times 10^{-6} \, / \deg C$$



- Each substance has its own characteristic average coefficient of expansion
- In bimetallic strip the brass expands more than the steel for the same temperature rise
  - Strip bends
- An application is the thermostat

Thermal expansion: solids:volume...

- The expression $\Delta L = \alpha L_{ini} \Delta T$

gives the change in the **length** of a solid object.

- To calculate the change in the **volume** of the object, we use

Change in volume

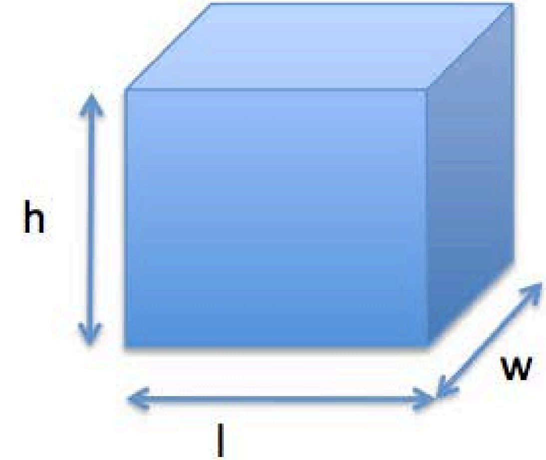
$$\Delta V = 3\alpha V_{ini} \Delta T = \beta V_{ini} \Delta T$$

Same linear expansion coefficient α as above

Initial volume

Average **volume** expansion coefficient

Volume



$$V_i + \Delta V = (l + \Delta l)\,(w + \Delta w)\,(h + \Delta h)$$

$$= (l + \alpha l \Delta T)\,(w + \alpha w \Delta T)\,(h + \alpha h \Delta T)$$

$$= lwh\,(1 + \alpha \Delta T)^3$$

$$= lwh\,(1 + 3\alpha \Delta T + 3(\alpha \Delta T)^2 + (\alpha \Delta T)^3)$$

V_i

$(\alpha \Delta T) < 1$

$$= V_i\,(1 + 3\alpha \Delta T)$$

1

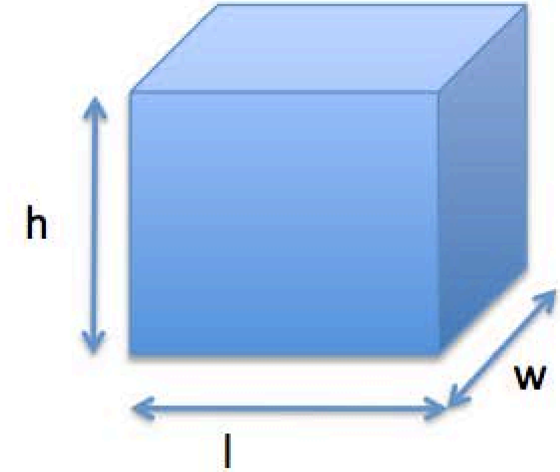
1 1

1 2 1

1 3 3 1

Pascal's Triangle

Volume



$$V_i + \Delta V = V_i\,(1 + 3\alpha\Delta T)$$

$$\Delta V = V_i\,(1 + 3\alpha\Delta T) - V_i$$

$$\Delta V = V_i\,3\alpha\,\Delta T \;=\; \beta\,V_i\,\Delta T$$

$$3\alpha = \beta$$

Task: Show that for a rectangular plate:

$$\Delta A = 2\,\alpha\,A_i\,\Delta T$$

Thermal expansion>liquids...

- Average volume expansion coefficients for some liquids near room temperature. Much larger coefficients for liquids/gases than for solids!

Table 19.1
Average expansion coefficients for some materials near room temperature

Material (Solids)	Average linear expansion coefficient (α) ($°C)^{-1}$	Material (Liquids and gases)	Average volume expansion coefficient (β) ($°C)^{-1}$
Aluminium	24×10^{-6}	Acetone	1.5×10^{-4}
Brass and bronze	19×10^{-6}	Alcohol, ethyl	1.12×10^{-4}
Concrete	12×10^{-6}	Benzene	1.24×10^{-4}
Copper	17×10^{-6}	Petrol	9.6×10^{-4}
Glass (ordinary)	9×10^{-6}	Glycerine	4.85×10^{-4}
Glass (Pyrex)	3.2×10^{-6}	Mercury	1.82×10^{-4}
Invar (Ni–Fe alloy)	0.9×10^{-6}	Turpentine	9.0×10^{-4}
Lead	29×10^{-6}	Air[a] at 0°C	3.67×10^{-3}
Steel	11×10^{-6}	Helium[a]	3.665×10^{-3}

[a]Gases do not have a specific value for the volume expansion coefficient because the amount of expansion depends on the type of process through which the gas is taken. The values given here assume the gas undergoes an expansion at constant pressure.

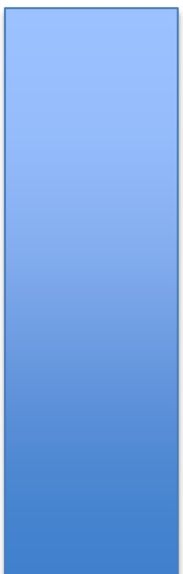
Liquid

A warm day
> 4 ^{o}C
Warm liquid remains on surface as it is less dense

$$\Delta V = \beta\, V_i\, \Delta T$$

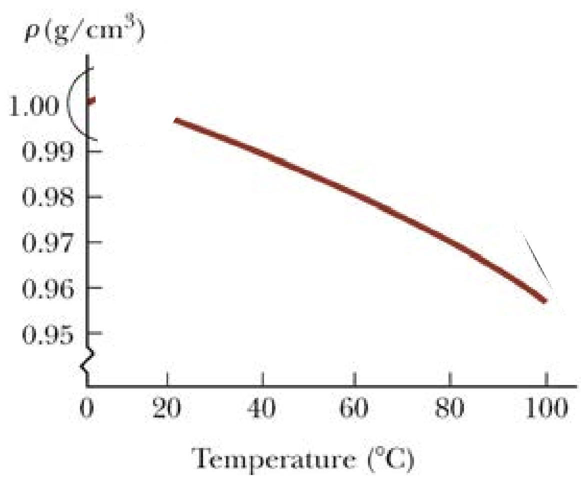
As liquid cools, it freezes from the bottom upwards…

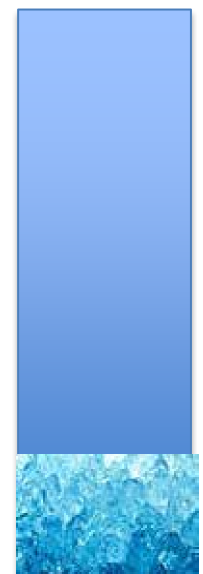
Plankton, amoeba etc trapped in ice & die.



warm

cooler





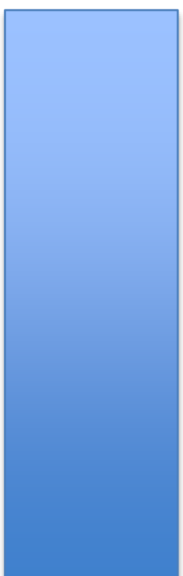
liquid

solid

H_2O is special

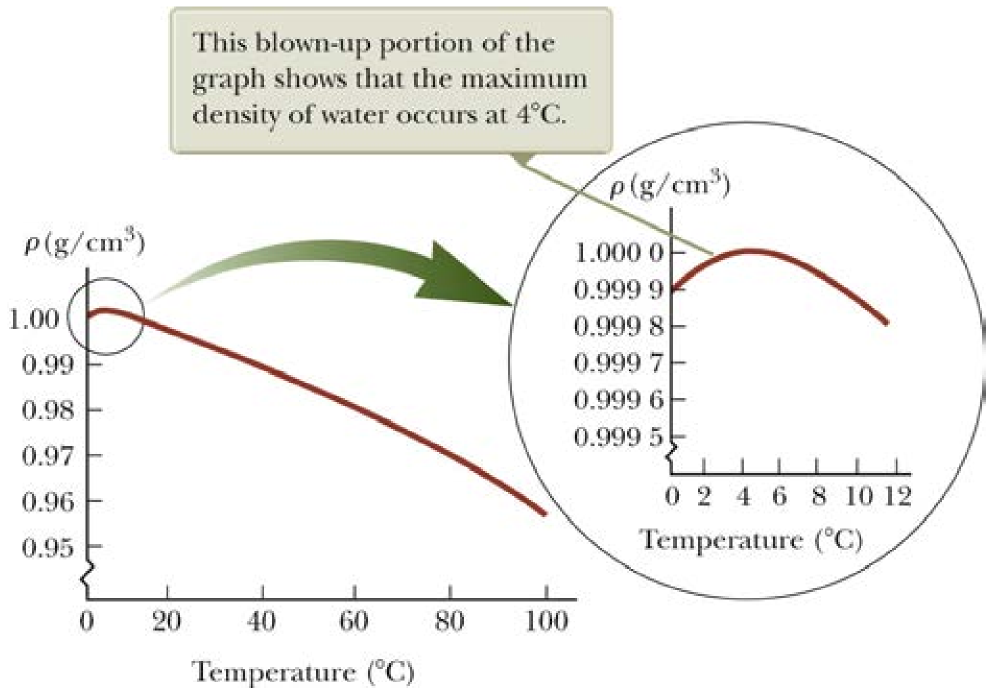
$$\Delta V = \beta \, V_i \, \Delta T$$

A warm day
> 4 °C
Warm water remains on surface as it is less dense



warm

cooler



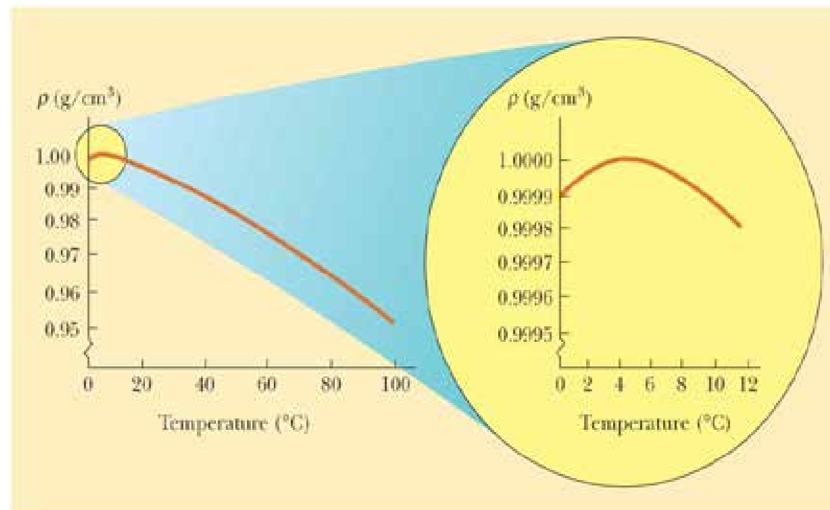
A cool day
< 4 °C
Water sinks when it reaches 4°C:
When it is all 4°C cooler water floats

< 4°C

= 4°C

Water's Unusual Behavior: Why ice floats

- Above 4°C, water expands with increasing temperature
  - Its density decreases
- As the temperature decreases from 4°C to 0°C, water *expands!*
  - Its density decreases
  - Coldest water floats up
- The maximum density of water (1.000 g/cm³) occurs at 4°C
  - Critical for the existence of marine life!

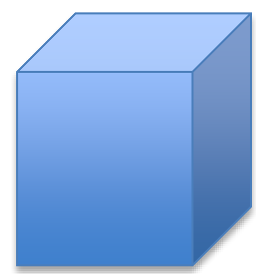


Problem

When the temperature of a copper coin is raised by 100^{o}C, its diameter increases by 0.18%. To two significant figures give the percentage increase in (a) the area of the face, (b) the thickness (c) the volume, and (d) the mass of the coin. (e) Calculate the coefficient of linear expansion of the coin.

Example

An aluminum cup of 100 mL capacity is completely filled with glycerin at 22^{o}C. How much glycerin, if any, will spill out of the cup if the temperature of both cup and the glycerin is increased to 28^{o}C?



Glycerin: $\beta = 4.85 \times 10^{-4}\ (^{o}C)^{-1}$

Aluminum: $\alpha = 24 \times 10^{-6}\ (^{o}C)^{-1}$