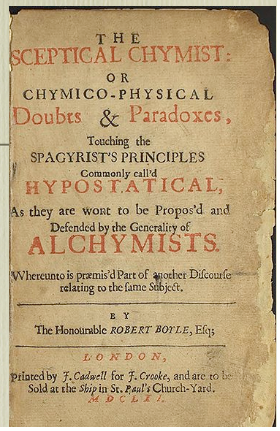
The Last Alchemist

Atoms, Fields and Waves

Peter Watson

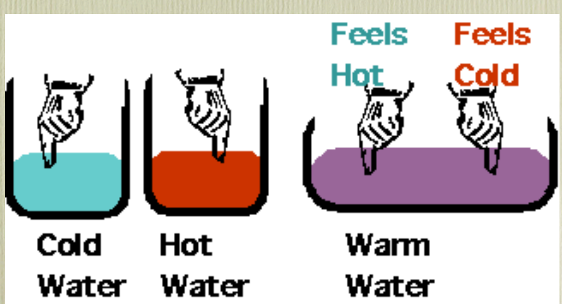

THE
SCEPTICAL CHYMIST:
OR
CHYMICO-PHYSICAL
Doubts & Paradoxes,
Touching the
SPAGYRIST'S PRINCIPLES
Commonly call'd
HYPOSTATICAL,
As they are wont to be Propos'd and
Defended by the Generality of
ALCHYMISTS.
Whereunto is præmis'd Part of another Discourse
relating to the same Subject.
BY
The Honourable ROBERT BOYLE, Esq;
LONDON,
Printed by J. Cadwell for J. Crooke, and are to be
Sold at the Ship in St. Paul's Church-Yard.
MDCLXI.

Atoms, Fields and Waves

- Starting with Robert Boyle, we take atoms seriously
- But we also need fields in space
- and waves (water, sound, light….)

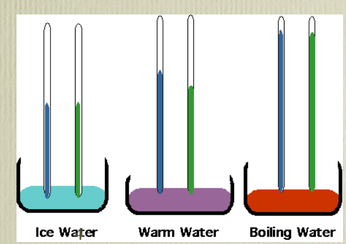
Then we'll understand everything!

Temperature can be felt qualitatively, but physiological estimates are notoriously bad.



What is heat?

- So the starting question is: what is temperature?
- 0°C is water with ice floating in it
- 100°C is boiling water
- Even using thermometers, there is no guarantee that two thermometers will measure the same value:



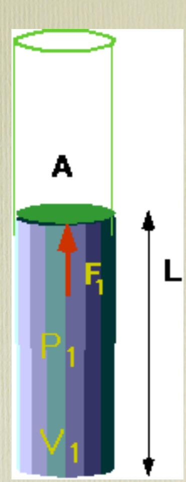
Two Views of Heat

"Macroscopic": i.e. what can we measure in a lab.

"Microscopic": i.e. what happens on the level of atoms.

So where is the energy in heat?

Critical experiments were done with gases:

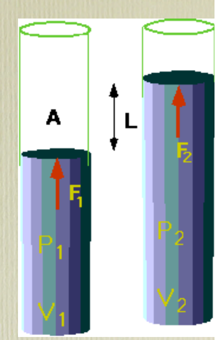


- What happens if you pump on a bicycle pump slowly?
- Vary pressure, keep temp constant.

PV=const

Pressure ×Volume is constant

Boyle's Law



What happens if you heat up a balloon?

Change temperature at constant pressure:

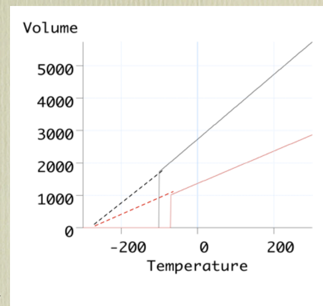
$V=const(T-T_0)$

True for all gases:

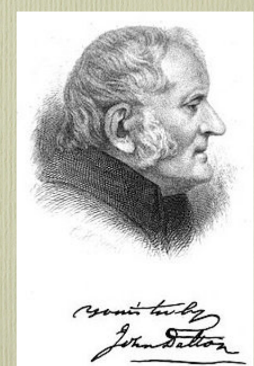
$T_0=-273$ C

Real gas will liquefy (e.g. N2 at ~-200°C)

or solidify (e.g. CO2 at -40°C), and the relation no longer works.



- Defines absolute temp. scale (Kelvin scale)
- 0K =-273.16 °C : the "absolute zero"
- Then $V=const \times T$
- We can combine Charles' law and Boyle's Law to give "Ideal Gas Law"
- Pressure ×Volume ~ Temperature
- $PV=const \times T$
- The constant depends on "amount" of gas (actually number of molecules)



John Dalton
The father of chemistry

Atoms = a-tomos - no slice!

Dalton's Principles

1. Elements are made of extremely small particles: atoms
2. Atoms cannot be subdivided, created, or destroyed
3. Atoms of a given element have same properties (e.g size, mass)
4. Atoms of different elements have different properties.
5. Chemical compounds are created when atoms of different elements combine in simple whole-number ratios.
6. Atoms always combine in the simplest way
7. In chemical reactions, atoms are combined, separated, or rearranged.

Dalton's Principles

Elements are made of extremely small particles called atoms

10/10!

Dalton's Principles

Atoms cannot be subdivided, created, or destroyed

Can fuse or fission nuclei

Can "divide" atoms" e.g. $H \Leftrightarrow H^+ + e^-$

Basis of chemical reaction theory!

6/10

Dalton’s Principles

Atoms of a given element have same properties(e.g size, mass)

Now know that isotopes can have same chemical properties but different mass

E.g: deuterium had twice mass of hydrogen

8/10

Dalton’s Principles

Atoms of different elements have different properties.

10/10

Dalton’s Principles

Chemical compounds are created when atoms of different elements combine in simple whole-number ratios.

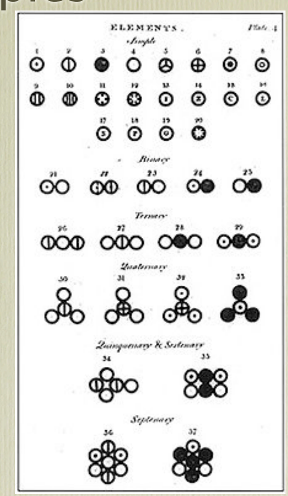
Yes but.....

Dalton’s Principles

Atoms always combine in the simplest way

No! He had water as OH, ammonia as NH

2/10!



Lavoisier/Gay Lussac

- Used our understanding of gases to explain reactions
- E.g.; two volumes of hydrogen combine with one of oxygen to make one of steam
- $2H + O \rightarrow H_2O$
- Actually a bit more complicated
- $2H_2 + O_2 \rightarrow 2H_2O$

Dalton’s Principles

In chemical reactions, atoms are combined, separated, or rearranged.

Yes!!!

10/10

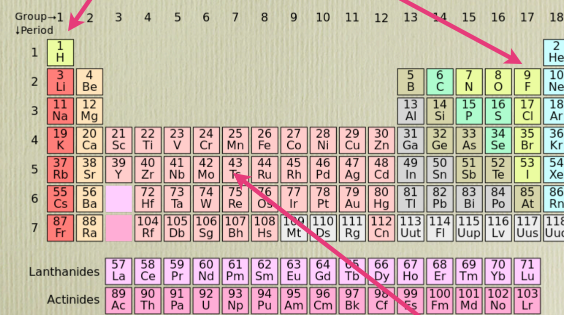
Sixty years later and we understand Dalton and the rest of 19th c chemistry with Mendeleev’s Periodic table: all of the elements combined in simple pattern

Periodic Table and Mendeleev [1869]

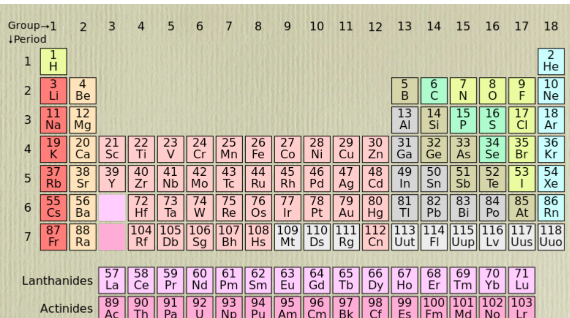
(Needs quantum mechanics to understand it [1925])

Alkali metals (like sodium) Noble gases (like helium)

Halogens (like chlorine)

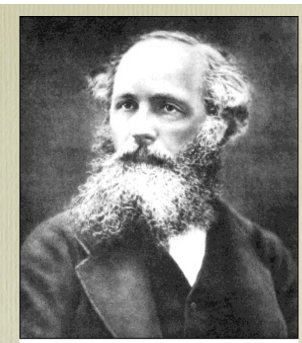


Technetium does not occur in nature



Tom Leher has provided us with a useful mnemonic

What else are atoms good for?



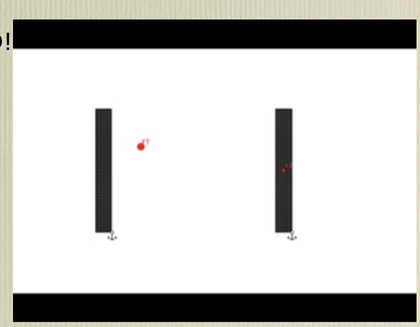
James Clerk Maxwell

Kinetic Theory

A gas consists of atoms interact only as hard spheres with a rigid wall

Collisions with the wall will produce a force on the wall, which is the pressure of the gas.

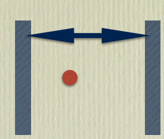
Start with one atom in 1-D!



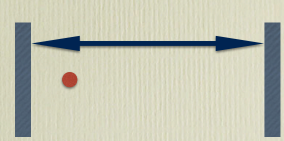
Note…

- Even in this dumb model, we get Boyle's law

Volume ~ distance between walls
Pressure ~ average force

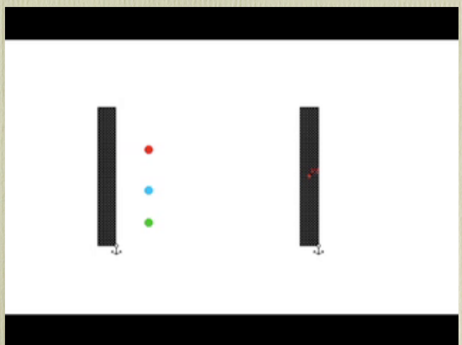


Double distance between walls
Volume ➠ 2×volume
Pressure ➠ 1/2×pressure

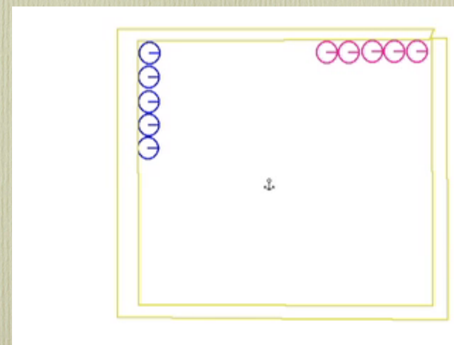


Or 3 atoms: one is moving faster

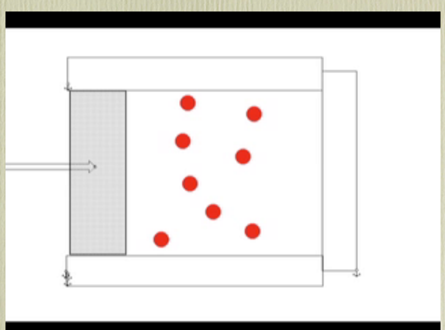
- So force (and hence pressure) is bigger



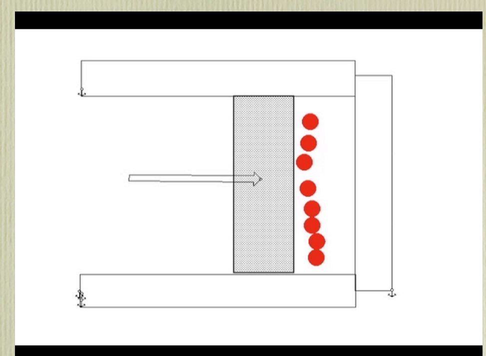
- Collisions redistribute the energy: heavy molecules move slower on average



- We can understand a number of things from the kinetic theory: e.g. how compressing a gas makes it heat up (think of a bicycle pump!)



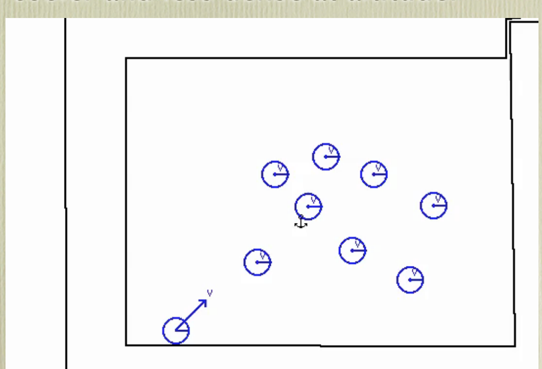
- and how an expanding gas can do work, and the gas cools down (like an auto engine



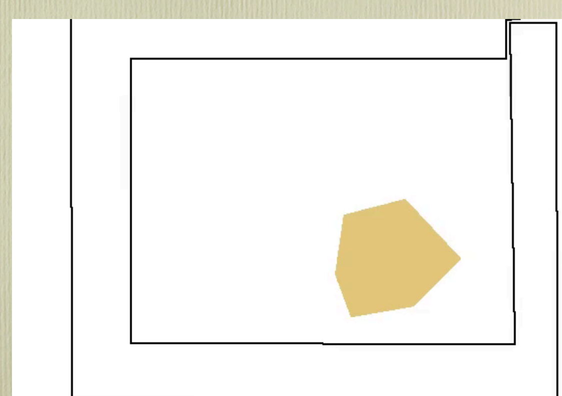
- and this leads to .....

What Else?

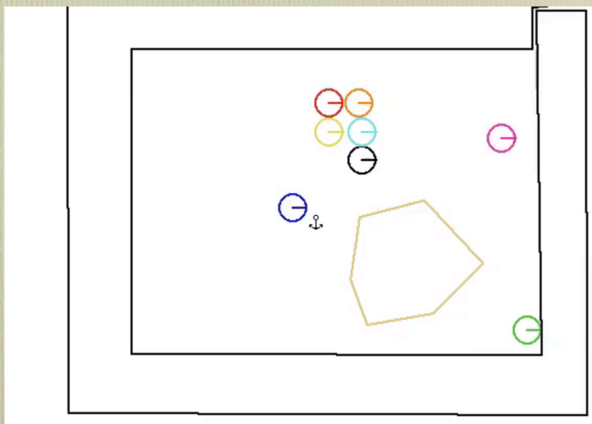
- Why does the Earth's atmosphere get cooler and less dense at altitude?



Brownian Motion

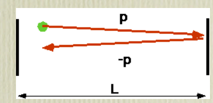


This is what is happening!

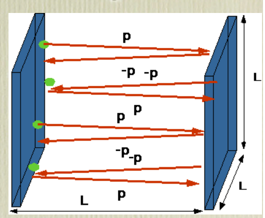


We can turn this into a theory of gases

Energy does not change



- Higher velocity ⇔ **more** energy
- Higher velocity ⇔ **more** collisions ⇔ higher pressure
- Higher velocity ⇔ **harder** collisions ⇔ higher pressure



Temperature is energy!

This tells us ...

- Joule was right: energy and heat are the same thing!
- Energy is required to heat anything up
- Zero of temperature is when things stop moving
- Heavier atoms move slowly than lighter atoms
- Molecule of oxygen at room temp has
- v ~ 1/2 km/s

Kinetic Theory of Gases lets us understand:

- Temperature (how fast the molecules are moving)
- pressure (how many hit a given surface in a given time)
- viscosity of a gas
- specific heat
- speed of sound
- speed of shock waves
- efficiency of engines
- Theory due to James Clerk Maxwell, who developed it around 1860.
- Except that....

A digression: how science is done

- All papers go through a refereeing process
- Note that referees are vital to the process, but sometimes they can totally destroy a good idea.

John Herapath (in 1836) : calculated the speed of sound of a gas, and the effects of air resistance on trains. (Totally ignored by the engineers : how could something as insubstantial as air possibly have any effect on something as massive as a railway engine?)

"the idea that trains could operate at 60 m.p.h. or more (as suggested by Stephenson) is absurd; (remember, he was writing in 1836, a 20 years after the invention of the steam engine) second, every effort should be made to minimize air resistance."

PW

John Waterston: In 1845, submitted paper to the Royal Society, which developed the kinetic theory in great detail: absolutely correct in every important way. The referee's report reads:

To the Secretary of the Physics Committee, R.S.

Dear Sir,
I have received a paper, from the clouds for ought I know, but conjecture that it may have been sent to me by Mr. Weld for a report. In my opinion the paper is nothing but nonsense, unfit even for reading
before the Society.
I am, dear sir
Yours very sincerely
Lubbock

PW

Lubbock was an eminent mathematician.

Waterston's nephew wrote that

"We could never understand the way in which he talked of the learned societies, but any mention of them brought out considerable abuse without any definite reason being assigned."

The RS lost his paper: finally found 40 years later by Kelvin

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(Simple) States of Matter e.g. H_2O

Ice

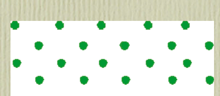
Water

Steam
Actually, a cheat
Steam is transparent

Raising temperature takes energy

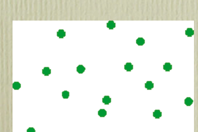
- Heating water:
- to raise 1 kg by 1°C takes 4200 J
- to boil 1 kg water takes 2.3 MJ
- to melt 1kg ice takes 334 kJ

(Simple) States of Matter



Solids: Long range "order"
Forces win over random energy
Atoms fixed (maybe crystal)

Liquids: Short range "order"
Forces ~ random energy,
atoms can move



Gases: No "order"
Random energy wins over Forces
Atoms move freely

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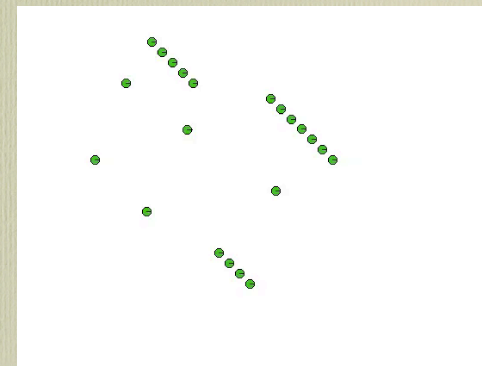
Can we understand this?

- A “gas” of 19 atoms,
- Energy is sucked out of the system



- Gas ➠Liquid➠(crystalline) solid

Note…

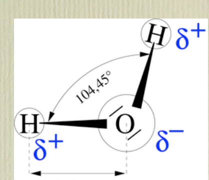
- We didn’t tell the atoms (or birds) to make a gas, solid or liquid
- It is an “emergent phenomenon” from simple rules to complexity

An unusual liquid…. Starlings

An unusual crystal…. Brent geese

- We didn’t tell the atoms (or birds) to make a gas, solid or liquid
- “emergent phenomena” seem to be common
- **Maybe that is what consciousness is….**

We can’t assume all molecules are nice hard spheres



- Water is complicated!
- Like most crystals, the shape depends on how it is formed

Icicles

frost flowers

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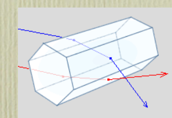
Haloes are caused by
hexagonal crystals forming
in the atmosphere



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- But what are these?

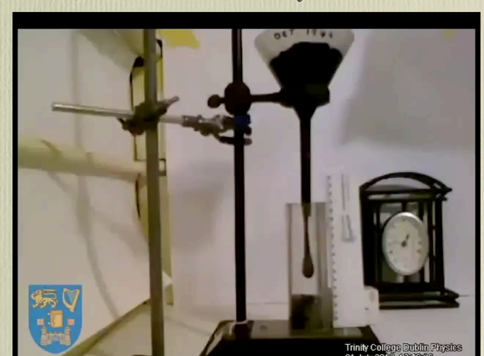
Not all liquids are simple

- Difficulty that atoms move in liquid ➠ viscosity
- Most liquids (e.g. water) have low viscosity until freezing

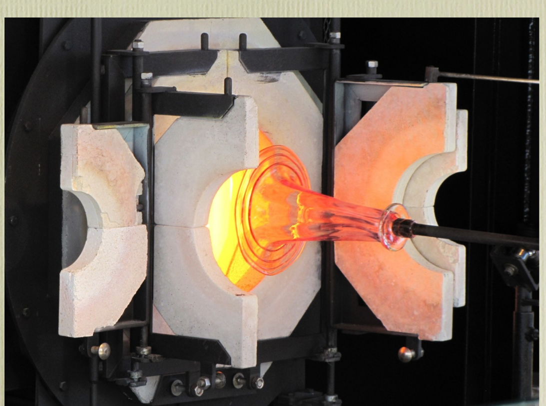
Pitch has very high viscosity

Experiment at Trinity, Dublin started in 1944

Seventh drop just fell



How about Glass?



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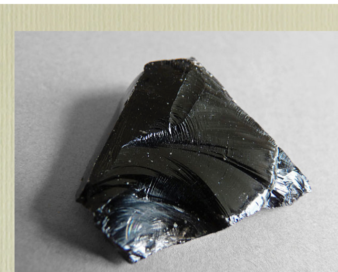
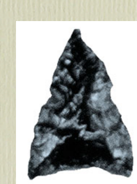
Obsidian

Natural glass, produced in volcanoes.
Note opaque, very hard



- obsidian projectile point



Wikimedia

- Mostly Silicon dioxide (quartz in crystalline form)
- High melting point (1200°C)
- Add Sodium carbonate (washing soda) lowers this to around 700°C

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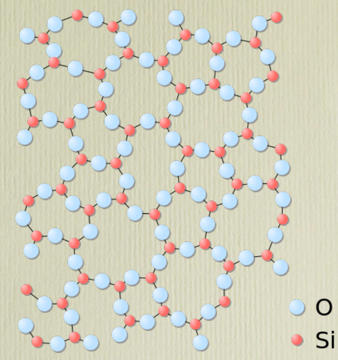
If a liquid is VERY viscous, it can solidify before becoming ordered: this is the "glass transition"

E.g. Amorphous silica:

~ 570°C for soda-glass

Crystallization occurs at ~ 270°C



Wikipedia

- Is glass a solid or a liquid
- The old fallacy:
- Window glass in cathedrals is thicker at the bottom because it "flows"

Seems likely that it is just the safest way to put it in!

Purely semantics: best "it is an amorphous solid"

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- Typically
- hard material ⇔ amorphous solid (but bonds are random and can be weak, so fragile)
- strong material ⇔ crystalline solid (but atoms can move, so more ductile)

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Can work a material to make it more ordered

E.g annealing: hitting a piece of hot material allows atoms to slip into place

WIkipedia

- Crystals are 3-D rigid structures
- This is amethyst quartz

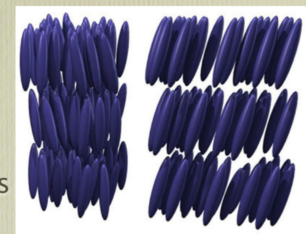
Wikimedia

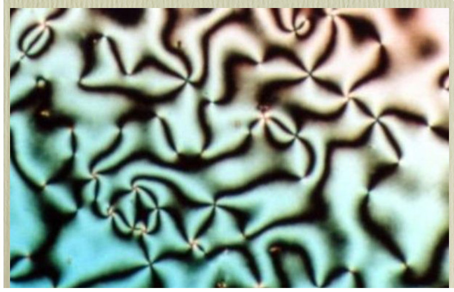
- Liquids are deformable

Wikimedia

Mixing things up..

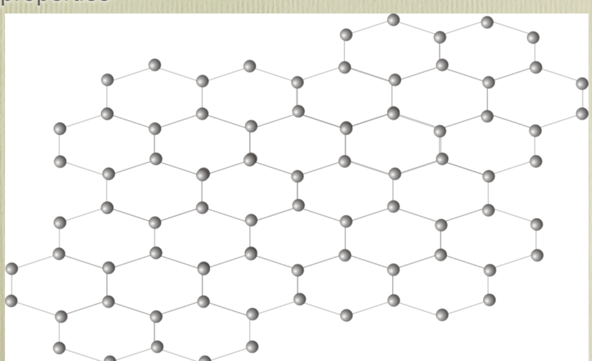
- Liquid Crystals (LCD's)
- Crystals in 1-Dimension
- liquids in other 2-dimensions





2010 Nobel Prize

- Andre Geim and Konstantin Novoselov used a block of carbon and some Scotch tape to create graphene, a new material with extraordinary properties

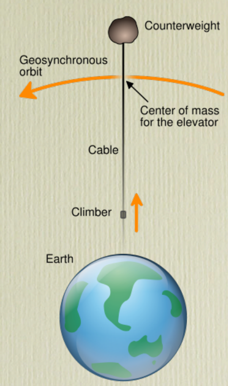


So what?

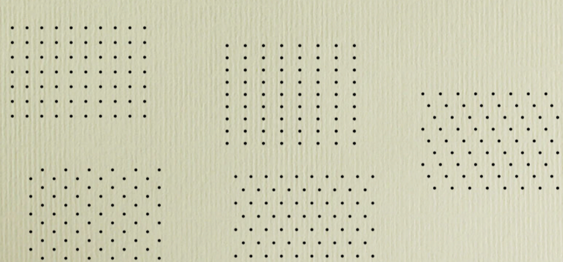
- biomedical and gas sensors, transparent conducting materials,

"............ graphene is incredibly strong – around 200 times stronger than structural steel – but it may also form a stronger interaction when embedded in a polymer."

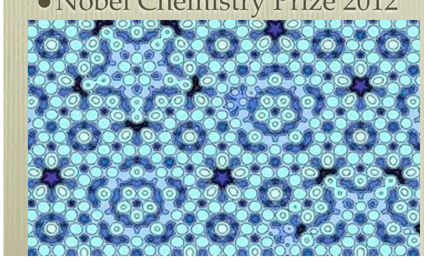
Maybe we could build a space elevator!



- Grapheme has hexagonal symmetry:
- allows atoms to pack efficiently
- How else could we do it?



- But obviously these are the only options
- Except ....
- Daniel Shechtman found quasi-crystals with 5-fold symmetry
- Nobel Chemistry Prize 2012



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