Slide 1

Intermolecular Forces

Love & Hate in the Molecular Realm

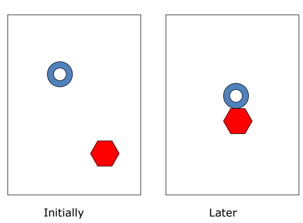
Slide 2

If I put 2 molecules into a sealed flask, what could happen?

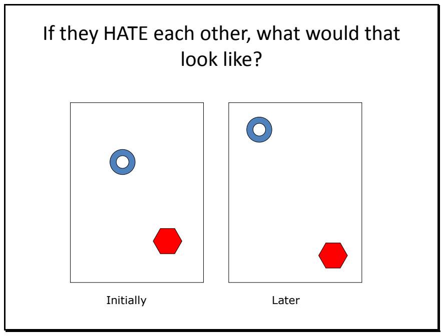
1. They ignore each other.
2. They LOVE each other – they're attracted to each other
3. They HATE each other – they repel each other

Slide 3

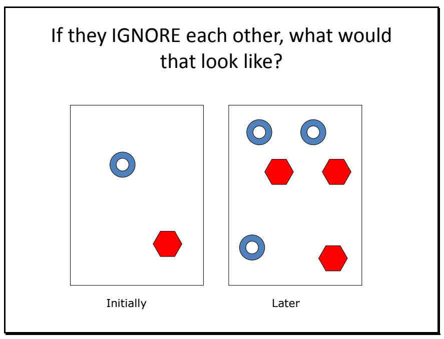
If they LOVE each other, what would that look like?



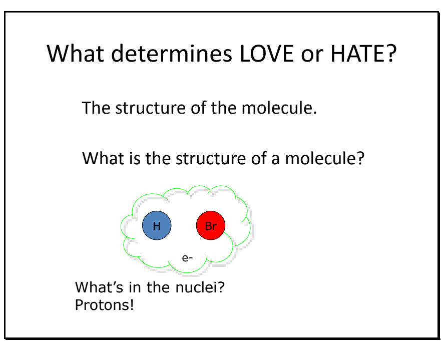
Slide 4



Slide 5



Slide 6



Slide 7

Molecular structure is all about…

POSITIVE & NEGATIVE CHARGES!

So Love & Hate is all about…

Opposites attract, like repel!

Slide 8

Types of Intermolecular Forces

1. London Dispersion forces, aka Van der Waal's forces, aka Instantaneous dipole-induced dipole forces.
2. Dipole-Dipole interactions: either permanent or temporary
3. Hydrogen bonding – particularly strong case of dipole-dipole interaction

Slide 9

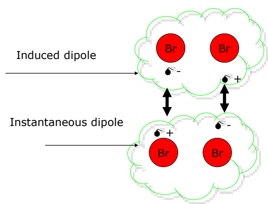
London Dispersion forces, aka Van der Waal's forces, aka Instantaneous dipole-induced dipole forces.

This is NOT the strongest, but it is the primary intermolecular force.

All atoms or molecules with electrons have Van der Waal's forces – so ALL atoms or molecules have Van der Waal's forces

Slide 10

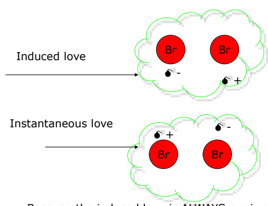
Instantaneous dipole-induced dipole forces



The electron cloud is mobile.
Charge density is constantly moving around

Slide 11

How Great is THAT!?!?!?



Because the induced love is ALWAYS a mirror image of the instantaneous love, dispersion forces are ALWAYS attractive

Slide 12

Dispersion Forces are ALWAYS ATTRACTIVE

All molecules like each other, at least a little bit. So all molecules stick together, at least a little bit.

If they didn't…

…the universe would be a much more chaotic place!

Universal repulsion would have things flying apart all over the place!

Slide 13

Van der Waal's forces

Van der Waal's forces get stronger as the temporary dipole gets stronger.

The temporary dipole is caused by electron mobility, so the more electrons the stronger the Van der Waal's forces.

electrons increases as # protons, so the heavier the molecule the stronger the Van der Waal's forces.

Slide 14

Alkanes

Methane – CH_4
Ethane – CH_3CH_3
Propane – $CH_3CH_2CH_3$
Butane - $CH_3CH_2CH_2CH_3$
Pentane - $CH_3CH_2CH_2CH_2CH_3$
Hexane - $CH_3CH_2CH_2CH_2CH_2CH_3$
Heptane - $CH_3CH_2CH_2CH_2CH_2CH_2CH_3$
Octane - $CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_3$

Slide 15

What do you know about these molecules?

Methane – CH_4
Ethane – CH_3CH_3
Propane – $CH_3CH_2CH_3$
Butane - $CH_3CH_2CH_2CH_3$
Pentane - $CH_3CH_2CH_2CH_2CH_3$
Hexane - $CH_3CH_2CH_2CH_2CH_2CH_3$
Heptane - $CH_3CH_2CH_2CH_2CH_2CH_2CH_3$
Octane - $CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_3$

Slide 16

Which has a higher BP..

A. Bromopropane
B. Propane
C. They are the same
D. I don't know without more structure information.

Propane – $CH_3CH_2CH_3$
1-bromopropane – $CH_3CH_2CH_2Br$

Slide 17

What do you know about these molecules?

- Methane – gas at standard T & P
- Ethane – gas at standard T & P
- Propane – gas at standard T & P – Liquid under slight pressure
- Butane - gas at standard T & P – Liquid under slight pressure
- Pentane - Liquid
- Hexane - Liquid
- Heptane - Liquid
- Octane - Liquid

Slide 18

Solids, Liquids, and Gases

What is the difference between a solid, a liquid, and a gas microscopically?

How tightly stuck together the molecules are!!!

Solids are stuck together more than liquids that are stuck together more than gases

Slide 19

Solids, Liquids, and Gases & Heat

What happens when you heat up a solid?

Eventually it melts – why?

Adding heat adds energy to the molecules, when they have enough energy they can escape their attraction to their neighbors!

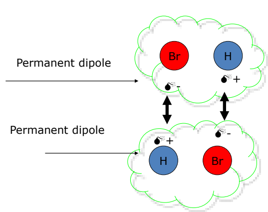
Slide 20

Van der Waal's Forces are…

…the first consideration – but not the last!

Slide 21

Dipole – Dipole Interactions



Slide 22

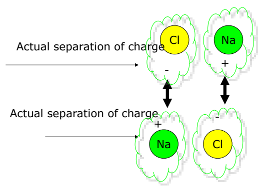
Dipole – Dipole interactions

A molecule with a permanent dipole is called a "polar molecule".

All polar molecules have Dipole-Dipole interactions in ADDITION TO Van der Waal's forces.

Slide 23

Ion – Ion Interactions



Slide 24

Ion-Ion interactions

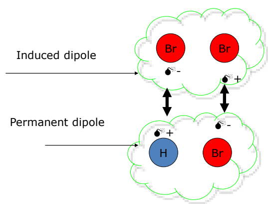
The strongest possible interaction.

The complete charge separation makes it a HUGE dipole-dipole type interaction.

This is why most ionic compounds are solids at room temperature.

Slide 25

Permanent dipole-induced dipole forces



Slide 26

Dipole – Induced Dipole interactions

This is a special case of a Dipole – Dipole interaction where there are 2 different molecules involved and only 1 of them is polar.

Generally weaker than a permanent Dipole-Dipole interaction, it is still IN ADDITION TO Van der Waal's forces.

Slide 27

How do you know if there is a dipole?

Slide 28

NaF vs. F_2

What do you know about these 2 molecules?

NaF is an ionic solid

F_2 is a gas at room temp

NaF has a molar mass of 42 g/mol, F_2 has a molar mass of 38 g/mol.

Slide 29

Ion-ion interactions are the strongest

Based on Van der Waal's forces, you'd expect NaF and F_2 to be similar.

The powerful ionic forces of NaF make it a solid – trumping the Van der Waal's interactoin.

Slide 30

HBr vs. Cl_2

What do you know about these 2 molecules?

HBr is a gas at room temp

Cl_2 is a gas at room temp

HBr has a molar mass of 81 g/mol
Cl_2 has a molar mass of 71 g/mol

HBr is polar, Cl_2 is non-polar

Slide 31

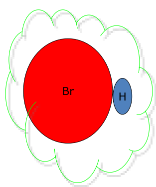
HBr boils at 207 K, Cl_2 boils at 239 K

Based on Van der Waal's forces, you'd expect HBR and Cl_2 to be similar, but HBr should have the higher boiling point since it has the higher molecular weight.

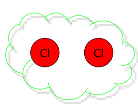
This is why it is dangerous to compare dissimilar molecules. Dipole interactions are a tie-breaker if everything else is the same.

Slide 32

Geometry



Slide 33



Slide 34

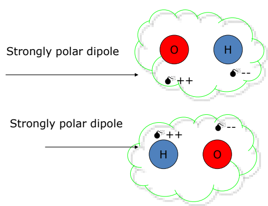
Hydrogen Bonding – just a special case of dipole-dipole interactions

Hydrogen bonding is a dipole-dipole interaction that occurs when hydrogen is bonded to something very electronegative like F, O, or N.

It is just a very strong dipole-dipole interaction because of the very polar nature of the H-F, H-O, or H-N bond.

Slide 35

Hydrogen Bonding – just a special case of dipole-dipole interactions



Slide 36

Compare H_2O to H_2S

Which would you expect to have the higher boiling point?

H_2O has a molar mass of 18 g/mol
H_2S has a molar mass of 34 g/mol

Based on Van der Waal's forces alone, H_2S should have the higher boiling point.

Slide 37

Compare H_2O to H_2S

The boiling point of water is 373 K.

The boiling point of H_2S is 213 K.

H_2S is a gas at room temperature while water is a liquid!

No FON, no Hydrogen bonding

Slide 38

Clicker Question

List the following compounds in order of INCREASING boiling point: NH_3, CH_4, CH_3OH

A. NH_3, CH_4, CH_3OH
B. CH_4, CH_3OH, NH_3
C. NH_3, CH_3OH , CH_4
D. CH_4, NH_3, CH_3OH
E. Just mark me present, okay?

Slide 39

In order of importance

1. Ionic forces (biggest by a lot)
2. Hydrogen bonding (special case of…)
3. Dipole-Dipole
4. Van der Waal's

But 3 and 4 are much weaker than 1 and 2.

3 only matters if the molecules are similar sizes.

Slide 40

Here's some…

Physical properties that show "intermolecular forces":

1. Boiling point
2. Melting point
3. Surface tension
4. Viscosity
5. Capillary action
6. Evaporation

Slide 41

Phase changes

Intermolecular Forces are attractions between molecules.

Temperature is a measure of kinetic energy.

Boiling Point (or Freezing Point) are measures of the strength of intermolecular forces: the higher the temperature, the more kinetic energy required to separate the molecules.

Slide 42

Not just temperature…

We mentioned TWO things that affected molecules and their interactions:

1. Energy
2. Space

Another way of looking at "space" is pressure.

Slide 43

What is "pressure"?

Pressure = Force / Area

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

Pressure is squeezing the molecules together!

Slide 44

Phase Changes

You can create a phase change, by changing the temperature.

Consider a flask full of steam at 200°C.

If I start cooling it down, what happens?

It condenses into liquid water. When?

NOT (necessarily) 100°C.

Slide 45

Normal Boiling Point

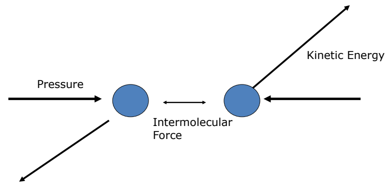
100°C is the "normal boiling point" of water. What's the "normal" for?

Normal means at standard pressure, 1 atm.

One way to condense steam is to decrease the temperature, another way is to increase the pressure.

Slide 46

It's all about forces!



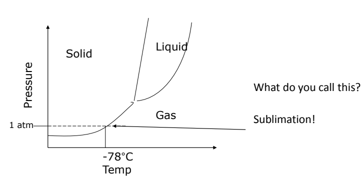
Slide 47

Phase Diagrams

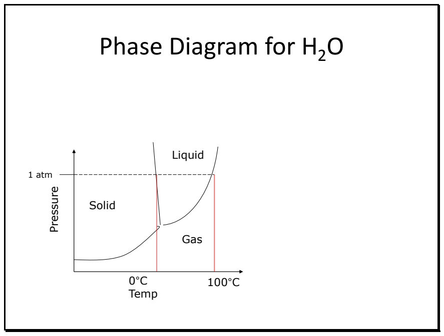
A "phase diagram" collects all the P, T and phase information and displays it in one simple graph.

Slide 48

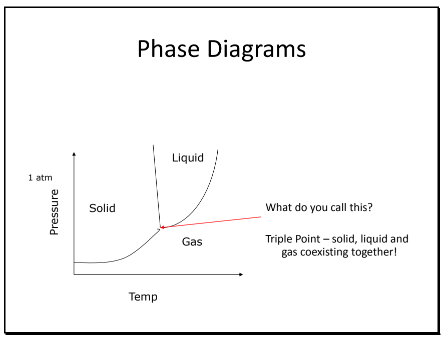
Phase Diagram for CO_2



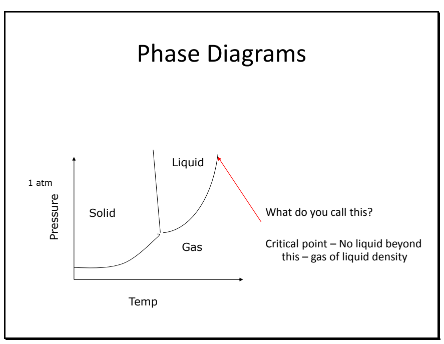
Slide 49



Slide 50



Slide 51



Slide 52

Energy of Phase Changes

How do you define "boiling"?

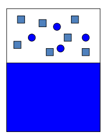
Vapor pressure = atmospheric pressure

What's vapor pressure?

It's the pressure exerted by the vapor above a liquid.

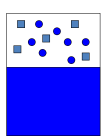
Slide 53

As you raise T, you raise P_{vap} until $P_{vap} = P_{atm}$



Slide 54

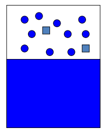
As you raise T, you raise P_{vap} until $P_{vap} = P_{atm}$



Slide 55

Remember $P_{tot} = P_1 + P_2 +$

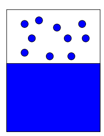
The vapor crowds out the air above the solution since P_{tot} must always be P_{atm}



Slide 56

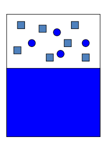
Remember $P_{tot} = P_1 + P_2 +$

P_{tot} must always be $P_{atm.}$ When $P_{vap} = P_{atm}$, it's all water vapor and WE ARE BOILING!



Slide 57

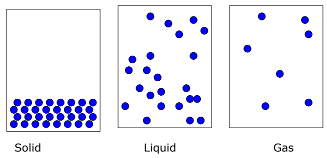
What do you have to do to become "vapor"?
You have to go from a liquid to a gas!
What do you need to do to go from a liquid to a gas?
GAIN ENERGY!



Slide 58

Remember, all molecules like each other.

So the difference between a solid, a liquid and a gas…



Slide 59

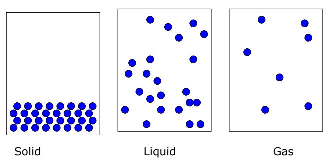
Does liquid water like another liquid water molecule more or less than an ice molecule likes another molecule?

A. More
B. Less
C. None of the above
D. Both A and B
E. Your mother.

Slide 60

…is all relative to the Energy

There are two different energies (or forces). The attraction between molecules, the individual energy of the molecules.



Slide 61

clicker

Suppose I tie myself to one of you using a noodle. Could you escape?

A. Yes
B. No

Slide 62

Of course you could.

You just start walking away and the noodle breaks.

Suppose I tie myself to you using a piece of thread?

You may have to walk faster or pull harder but you can still break away.

Slide 63

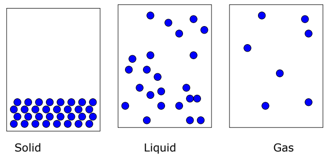
Suppose I tie myself to you using a piece of copper wire?

You may have to run or tug or get your friends to also tug, but you can break the wire.

Slide 64

Same for phases of matter.

They like each other, you want to separate them you need to overcome the "like". Easiest way: heat 'em up so they are moving faster!



Slide 65

Making a phase change…

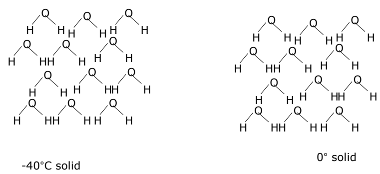
Suppose I start with 100 g of ice at -40°C (1 atm) and start heating it up, what happens?

The ice gets warmer and warmer until…melting point!

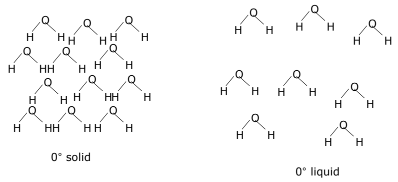
Suppose I am ice at 0°C, do I just spontaneously melt?

Not exactly. I am warm enough, but I'm still a solid and my molecules are still "associated" with each other. I need to get ripped away from my brothers.

Slide 66



Slide 67



Slide 68

At the phase transition temperature…

…you still need energy to make the transition.

Going from solid to liquid, this is called the “heat of fusion” ($\Delta H_{fus}°$)

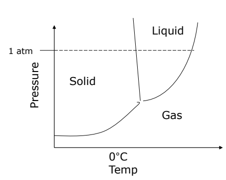
Going from liquid to gas, this is called “heat of vaporization” ($\Delta H_{vap}°$)

Going from solid to gas, this is called the “heat of sublimation” ($\Delta H_{sub}°$)

Slide 69

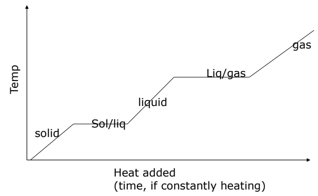
Phase Diagram for H_2O

The “°” in the ΔH° means standard conditions.



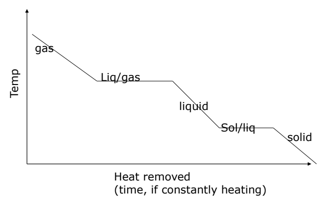
Slide 70

Heating/cooling curves



Slide 71

Heating/cooling curves

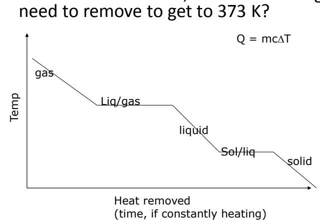


Slide 72

Could we quantify the energy?

If I have steam at 500 K, how much energy do I need to remove to get to 373 K?

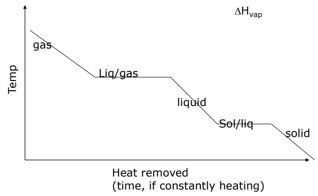
$Q = mc\Delta T$



Slide 73

Could we quantify the energy?

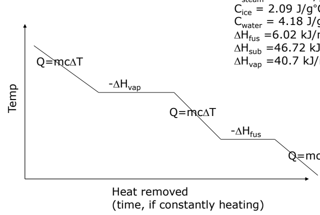
Once my steam is down to 373 K, how much energy do I need to remove to turn it into a liquid?



Slide 74

Just follow the curve.

For water:
C_{steam} = 1.84 J/g°c
C_{ice} = 2.09 J/g°C
C_{water} = 4.18 J/g°C
ΔH_{fus} =6.02 kJ/mol
ΔH_{sub} =46.72 kJ/mol
ΔH_{vap} =40.7 kJ/mol

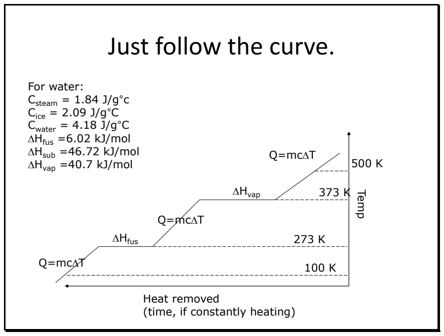


Slide 75

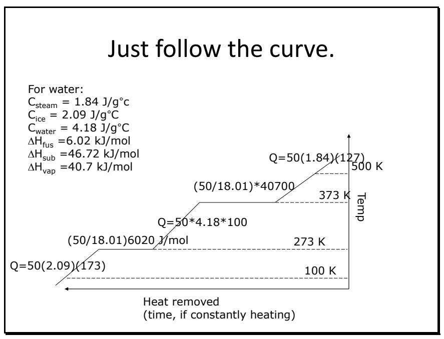
A little problem

I have 50 g of ice at 100 K. How much energy would I need to add to get steam at 500 K?

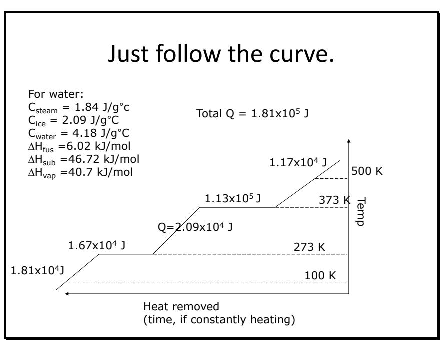
Slide 76



Slide 77



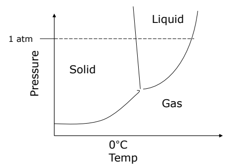
Slide 78



Slide 79

Phase Diagram for H_2O

For most phase transitions, temperature is more helpful than pressure…except when a gas is involved.



Slide 80

Hence "vapor pressure"…

…only really applies to sublimation or boiling.

And unsurprisingly, it depends on Temperature (how fast the molecules are moving) and ΔH_{vap} (how much energy it takes to separate the molecules and make them into gases).

Slide 81

Vapor Pressure

Vapor pressure depends on temperature. Vapor pressure also depends on ΔH_{vap}

Clausius-Clapeyron equation:

$$\ln P_{vap} = -\frac{\Delta H_{vap}}{R}\frac{1}{T} + C$$

Where C is a constant, R is the ideal gas constant.

Slide 82

Not completely useful in this form

Clausius-Clapeyron equation:

$$\ln P_{vap} = -\frac{\Delta H_{vap}}{R}\frac{1}{T} + C$$

If I want to calculate P_{vap}, I need to know ΔH_{vap}, C, and T. Except for T, the other two parameters are specific to each compound measured. But algebra (as ALWAYS!) can Save The Day!!

Slide 83

Common trick

Compare two values

$$\ln P_{vap,1} = -\frac{\Delta H_{vap}}{R}\frac{1}{T_1} + C$$

$$\ln P_{vap,2} = -\frac{\Delta H_{vap}}{R}\frac{1}{T_2} + C$$

The C and the ΔH_{vap} depend a little bit on temperature but not much, so they should be the same in both equations. So, what do I do? Simply "compare" the two values by subtracting them!

Slide 84

Common trick

Compare two values

$$\ln P_{vap,1} - \ln P_{vap,2} = -\frac{\Delta H_{vap}}{R}\frac{1}{T_1} + C - \left[-\frac{\Delta H_{vap}}{R}\frac{1}{T_2} + C\right]$$

Doing a little algebra…

Slide 85

Vapor Pressure

More helpful form – find the P_{vap} at 2 different temperatures:

$$\ln \frac{P_{vap1}}{P_{vap2}} = \frac{-\Delta H_{vap}}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

This is more helpful for a couple reasons. First of all…I lost "C"!!! That's one less material specific variable to worry about!

Slide 86

Vapor Pressure

And then there's "normal":

$$\ln \frac{P_{vap1}}{P_{vap2}} = \frac{-\Delta H_{vap}}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

I usually know the "normal boiling point" of a material…which is?

The boiling point at P_{atm} = 1 atm. Since boiling occurs when $P_{vap} = P_{atm}$, I know one set of P_{vap} and T!

Slide 87

Sample problem:

What is the vapor pressure of water at 50°C?

I say vapor pressure, you think…

Clausius-Clapeyron!

Slide 88

Vapor Pressure

$$\ln \frac{P_{vap1}}{P_{vap2}} = -\frac{\Delta H_{vap}}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

What do I know?

P_{vap1} = ?

P_{vap2} = ?

$\Delta H_{vap,\ water}$ = ?

T_2 = ?

T_1 = ?

R = ?

Slide 89

Vapor Pressure

$$\ln \frac{P_{vap1}}{P_{vap2}} = -\frac{\Delta H_{vap}}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

What do I know?

P_{vap1} = 1 atm

P_{vap2} = ?

$\Delta H_{vap,\ water}$ = 40.7 kJ/mol at boiling point (pg 472, Tro)
= 44.0 kJ/mol at 25 °C

T_2 = 50°C = 323.15 K

T_1 = 100 °C = 373.15 K

R = 8.314 J/(mol K)

Slide 90

Plugging and chugging time…

$$\ln \frac{P_{vap1}}{P_{vap2}} = -\frac{\Delta H_{vap}}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

What do I know?

P_{vap1} = 1 atm

P_{vap2} = ?

$\Delta H_{vap,\ water}$ = 44.0 kJ/mol at 25 °C

T_2 = 50°C = 323.15 K

T_1 = 100 °C = 373.15 K

R = 8.314 J/(mol K)

Slide 91

Plugging and chugging time…

$\ln \frac{1\text{ atm}}{P_{vap2}} = \frac{-44.0\text{x}10^3\text{ J/mol}}{8.314\text{ J/(mol K)}} \left[\frac{1}{373.15} - \frac{1}{323.15}\right]$

Whatever you do, DON'T ROUND!

$\ln \frac{1\text{ atm}}{P_{vap2}} = \frac{-44.0\text{x}10^3\text{ J/mol}}{8.314\text{ J/(mol K)}}$ [0.0026798- 0.00309453]

$\ln \frac{1\text{ atm}}{P_{vap2}} = 2.194446789$

How do I isolate P_{vap2}?

That's right e^x!

Slide 92

Plugging and chugging time…

$\ln \frac{1\text{ atm}}{P_{vap2}} = 2.194446789$

$\frac{1\text{ atm}}{P_{vap2}} = e^{2.194446789} = 8.97880$

$P_{vap2} = 1\text{ atm}/8.97880 = 0.111373\text{ atm}$`

Does this make sense?

It is less than 1 atm and I'm below the boiling point!

Slide 93

Another little problem

What is the boiling point of water at the top of Mt. Everest where the average atmospheric pressure is 0.64 atm?

Slide 94

Vapor Pressure

$\ln \frac{P_{vap1}}{P_{vap2}} = -\frac{\Delta H_{vap}}{R}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]$

What do I know?

P_{vap1} = ?
P_{vap2} = ?
$\Delta H_{vap,\ water}$ = ?
T_2 = ?
T_1 = ?
R = ?

Slide 95

Vapor Pressure

$\ln \frac{P_{vap1}}{P_{vap2}} = -\frac{\Delta H_{vap}}{R}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]$

What do I know?

P_{vap1} = 1 atm
P_{vap2} = 0.64 atm
$\Delta H_{vap,\ water}$ = 44.0 kJ/mol at 25 °C
T_2 = ?
T_1 = 100 °C = 373.15 K
R = 8.314 J/(mol K)

Slide 96

Plugging and chugging time…

$\ln \frac{1\ \text{atm}}{0.64\ \text{atm}} = -\frac{44.0\times10^3\ \text{J/mol}}{8.314\ \text{J/(mol K)}}\left[\frac{1}{373.15} - \frac{1}{T_2}\right]$

Whatever you do, DON'T ROUND!

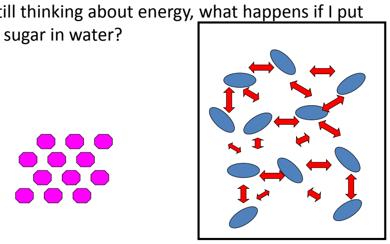
ln 1.5625= -5292.278 [0.0026798 – $1/T_2$]

0.446287 = -5292.278 [0.0026798 – $1/T_2$]
-0.00008432797 = 0.0026798 – $1/T_2$
$1/T_2$ = 0.0027642
T_2 = 361.77 K = 88.6 °C
Does this make sense?
Lower atmospheric pressure, lower boiling point!

Slide 97

What about solutions?

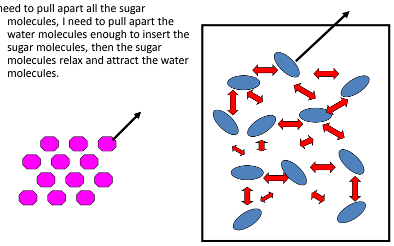
Still thinking about energy, what happens if I put sugar in water?



Slide 98

What about solutions?

I need to pull apart all the sugar molecules, I need to pull apart the water molecules enough to insert the sugar molecules, then the sugar molecules relax and attract the water molecules.



Slide 99

What about solutions?

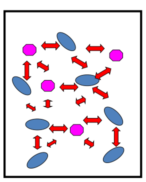
The energy change is, as always, simply the sum of the processes:

$\Delta H_{soln} = \Delta H_{solute} + \Delta H_{solvent} + \Delta H_{mix}$

ΔH_{solute} = endothermic (pull apart solute)

$\Delta H_{solvent}$ = endothermic (pull apart solvent)

ΔH_{mix} = exothermic (solvent/solute attract each other)



Slide 100

Sometimes its endo, sometimes its exo

$\Delta H_{soln} = \Delta H_{solute} + \Delta H_{solvent} + \Delta H_{mix}$

ΔH_{solute} = endothermic (pull apart solute)

$\Delta H_{solvent}$ = endothermic (pull apart solvent)

ΔH_{mix} = exothermic (solvent/solute attract each other)

So $\Delta H_{soln} = (\Delta H_{solute} + \Delta H_{solvent}) + \Delta H_{mix}$

= (+ pull Joules) + (-mix Joules)

Hot pack/Cold pack!

Slide 101