NEW JERSEY CENTER
FOR TEACHING & LEARNING

Intermolecular Forces, Liquids, and Solids

Table of Contents

Click on the topic to go to that section

- States of Matter
- Intermolecular Forces
- Types of Intermolecular Forces
- Intermolecular Forces and Physical Properties
- Vapor Pressure
- Phase Changes and Phase Diagrams
- Types of Solids

States of Matter

Return to Table of Contents

Matter We See

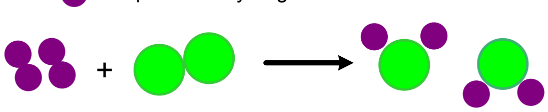
Atoms are the basic units of matter. At the atomic level, we know atoms bond together to create compounds due to electronegativity and Coulombic or electrostatic attraction.

Chemical compounds react with each other, breaking and re-forming bonds, to make new chemicals.

What molecules are formed in the reaction below? Write the chemical equation.

Represents Oxygen atom

Represents Hydrogen atom



Matter We See

We also know that atoms and molecules are very small. We can't actually see a substance unless it is made up of many particles.

1 mL of water at 4 Celsius = 1 gram of water
1 gram of water = 0.056 moles of water
0.056 moles of water = 3.34×10^{22} molecules of water

What makes all of the water molecules stick together to make a large enough amount we can actually see?

Slide 7 / 136

So far this year....

We first explained atoms, elements and how to build up the periodic table from quantum numbers.

Then we explained how atoms combine to form molecules - the most common way we find most atoms in nature - and learned about how atoms from molecules rearrange in chemical reactions to form new chemical compounds.

Now, we're going to use intermolecular forces between molecules to create the common states of matter.

Slide 8 / 136

Intermolecular Forces

Intermolecular forces are the piece we need to add to the puzzle to explain the world around us.

Without intermolecular forces, we wouldn't have tables, lakes, wall...or even our bodies.

Intermolecular forces shape our world.

Slide 9 / 136

States of Matter

While there are many states of matter, the three common states that dominate our world are gases, liquids and solids.

We won't be discussing more exotic states such as plasma, nuclear matter, etc.

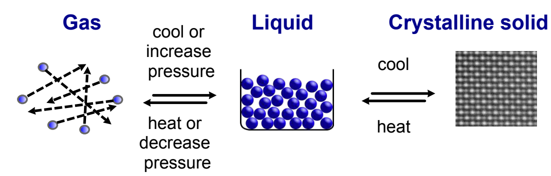
The 2 fundamental differences between states of matter are:

the distance between particles

the particles' freedom to move

Slide 10 / 136

States of Matter



Gas	Liquid	Crystalline solid
Particles are far apart, total freedom, much of empty space, total disorder	disorder, freedom, free to move relative to each other, close together	ordered arrangement, particles are in fixed positions, close together

Slide 11 / 136

Solid **Liquid** **Gas**

Enjoy this musical interlude by They Might Be Giants!

Slide 12 / 136

Characteristics of the States of Matter

	Gas
SHAPE	Assumes the shape of its container
VOLUME	Expands to the volume of its container
COMPRESSION	Is compressible
FLOW	Flows easily
DIFFUSION	Very Rapid

Slide 13 / 136

Characteristics of the States of Matter

Liquid	
SHAPE	Assumes the shape of the part of a container it occupies
VOLUME	Does not expand to the volume of the container
COMPRESSION	Is virtually incompressible
FLOW	Flows easily
DIFFUSION	Within a liquid, slow

Slide 14 / 136

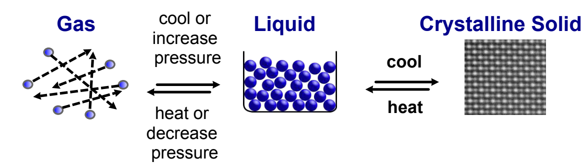
Characteristics of the States of Matter

Solid	
SHAPE	Retains its own shape regardless of container
VOLUME	Does not expand to the volume of its container
COMPRESSION	Is virtually incompressible
FLOW	Does not flow
DIFFUSION	Within a solid, very very slow

Slide 15 / 136

Condensed Phases

In the solid and liquid states particles are closer together, we refer to those states as condensed phases.



Particles are far apart, total freedom, much of empty space, total disorder

disorder, freedom, free to move relative to each other, close together

ordered arrangement, particles are in fixed positions, close together

Slide 16 / 136

1 Which of the following is a characteristic of a gas?

- A Fills only a portion of its container
- B Molecules are in relatively rigid positions
- C Takes on the shape of its entire container
- D Is not compressible
- E Diffuses very slowly

Slide 17 / 136

2 Which of the following is a characteristic of a liquid?

- A Fills only a portion of its container
- B Molecules are in relatively rigid positions
- C Takes on the shape of its entire container
- D Is compressible
- E Diffusion is very rapid within it

Slide 18 / 136

3 Which of the following is a characteristic of a solid?

- A Fills all of its container
- B Molecules are in relatively rigid positions
- C Takes on the shape of its entire container
- D Is compressible
- E Diffusion is very rapid within it

Slide 19 / 136

Intermolecular Forces

Return to Table of Contents

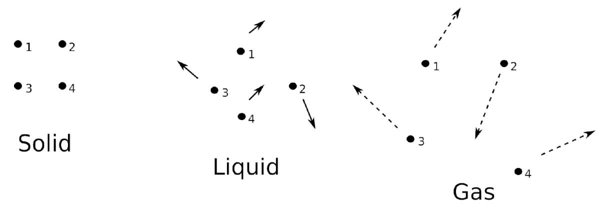
Slide 20 / 136

States of Matter & Intermolecular Forces

The state of a substance at a particular temperature and pressure depends on two major factors:

The **strength of the intermolecular forces** that hold molecules together

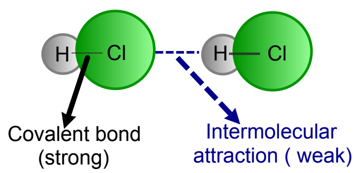
The **kinetic energy of the molecules**



Molecules have the highest kinetic energy in which state?

Slide 21 / 136

Intermolecular Forces



Intermolecular forces are electrostatic forces of attraction or repulsion that exists between molecules.

The attractions between molecules, **inter**molecular forces, are not nearly as strong as the **intra**molecular attractions that hold compounds together.

Slide 22 / 136

4 A chemical bond is

- A an electrostatic force of repulsion
- B an electrostatic force of attraction
- C a physical connection between objects that are touching
- D none of the above

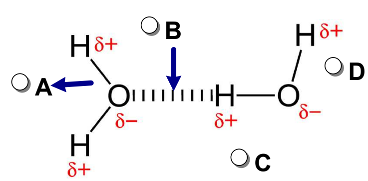
Slide 23 / 136

5 Which of the following correctly ranks electrostatic forces from weakest to strongest?

- A covalent bond, ionic bond, intermolecular forces
- B ionic bond, covalent bond, intermolecular forces
- C intermolecular forces, covalent bond, ionic bond
- D intermolecular forces, ionic bond, covalent bond

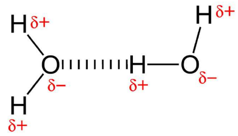
Slide 24 / 136

6 Which of the following is pointing to an intermolecular bond?



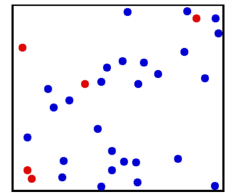
7 The arrow below is pointing to a(n)

- A Intramolecular bond
- B Ionic bond
- C Intermolecular bond
- D Both A and B
- E Both B and C



States of Matter & Intermolecular Forces

Without intermolecular forces (IMF's), all substances would behave like ideal gases...there would be no liquids or solids.



Kinetic Energy and Temperature

Temperature is directly proportional to the average kinetic energy of the molecules that make up a substance.

Sorry, this element requires Flash, which is not currently supported in PDFs.

Please refer to the original Notebook file.

clip: Indiana University

The more kinetic energy molecules have, the higher the temperature.

Intermolecular Forces & Boiling Points

Boiling represents a transition from a liquid to a gas.

To make that transition, molecules in the liquid must break free of the intermolecular forces that bind them.

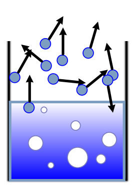
Intermolecular Forces & Boiling Points

The kinetic energy of the molecules is proportional to the temperature: as kinetic energy rises, so does temperature.

The boiling point refers to the temperature at which the molecules' energy overcomes the intermolecular forces binding them together.

The higher the boiling point of a substance, the stronger the intermolecular forces.

Water molecules overcome their intermolecular forces at 100 C.



8 Intermolecular forces are strongest in

- A solids
- B liquids
- C gases

9 A substance boils when the kinetic energy of its molecules

- A overcomes the intermolecular forces bonding them together
- B overcomes the intramolecular forces bonding them together
- C reaches 100 Celsius
- D none of the above

Types of Intermolecular Forces

Return to Table of Contents

Intermolecular Forces

There are three types of Intermolecular Forces (also known as van der Waals Forces) that bond molecules together:

Dipole-dipole interactions

London dispersion forces (LDF's)

Hydrogen bonding

Dipole-Dipole Interactions

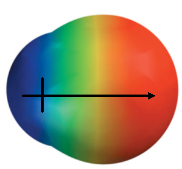
A dipole is a polar molecule.

Remember what makes a molecule polar?

Bond Type	Electronegativity Difference
Non-Polar Covalent	very small or zero
Polar Covalent	about 0.2 to 1.6
Ionic	above 1.7 (between metal & non-metal)

Dipoles

HF is an example of a polar molecule or dipole. The fluorine end of the molecule has higher electron density than the hydrogen end.



We use the ⟶ symbol to designate a dipole (2 poles). The "+" end is on the more positive end of the molecule and the arrow points towards the more negative end.

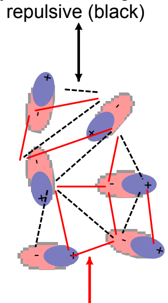
Dipole-Dipole Interactions

Molecules that have permanent dipoles are attracted to each other.

The positive end of one is attracted to the negative end of the other and vice-versa.

These forces are only important when the molecules are close to each other.

Only polar molecules will have this type of Intermolecular Force.



Dipole-Dipole Interactions

The polarity of a molecule is measured by its dipole moment, m. The more polar the molecule, the greater its dipole moment.

The more polar the molecule, the stronger the attraction between molecules, the higher the boiling point.

Substance	Molecular Weight (amu)	Dipole Moment u(D)	Boiling Point (k)
Acetonitrile, CH_3CN	41	3.9	355
Acetaldehyde, CH_3CHO	44	2.7	294
Methyl chloride, CH_3Cl	50	1.9	249
Dimethyl ether, CH_3OCH_3	46	1.3	248
Propane, $CH_3CH_2CH_3$	44	0.1	231

10 Which of the molecules below will have the highest boiling point?

- A $CH_3CH_2CH_3$
- B CH_3OCH_3
- C CH_3Cl
- D CH_3CHO
- E CH_3CN

Substance	Molecular Wt.	Dipole Moment
$CH_3CH_2CH_3$	44	0.1
CH_3OCH_3	46	1.3
CH_3Cl	50	1.9
CH_3CHO	44	2.7
CH_3CN	41	3.9

Answer

11 Which of the following will have the lowest boiling point?

- A $CH_3CH_2CH_3$
- B CH_3OCH_3
- C CH_3Cl
- D CH_3CHO
- E CH_3CN

Substance	Molecular Wt.	Dipole Moment
$CH_3CH_2CH_3$	44	0.1
CH_3OCH_3	46	1.3
CH_3Cl	50	1.9
CH_3CHO	44	2.7
CH_3CN	41	3.9

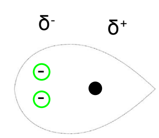
Answer

London Dispersion Forces

London Dispersion Forces occur between all molecules.

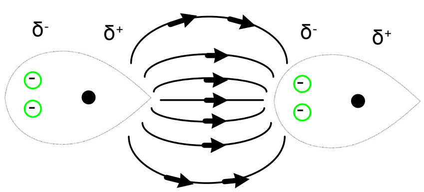
They result from the fact that electrons are in constant motion and sometimes are the same side of the molecule.

When they are on one side, the molecule is polarized: one side is negative and the other is positive; the molecule acts like a dipole.



London Dispersion Forces

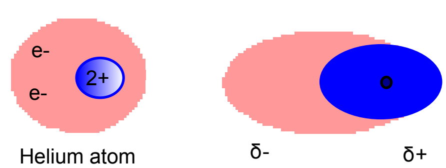
That polarization creates an electric field that oppositely polarizes nearby molecules...leading to an attraction.



London Dispersion Forces

While the electrons in helium atoms repel each other, they occasionally wind up on the same side of an atom.

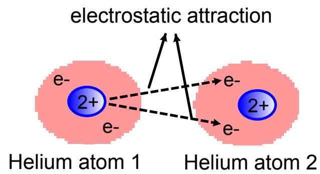
At that instant, the helium atom is polar, with an excess of electrons on one side and a shortage on the other.



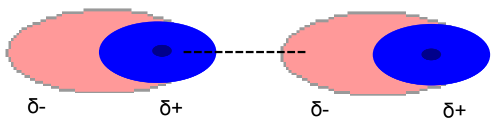
Slide 43 / 136

London Dispersion Forces

Another helium atom nearby becomes polarized as the electrons on the left side of the first atom repel the electrons in the second atom.



London dispersion forces, or dispersion forces, are attractions between an instantaneous dipole and an induced dipole.



Slide 44 / 136

Polarizability

These forces are present in *all* molecules, whether they are polar or nonpolar.

The tendency of an electron cloud to distort in this way is called **polarizability**.

Because larger molecules have more electrons, they are more polarizable. Molecules with more electrons experience stronger London dispersion forces.

Slide 45 / 136

London Dispersion Forces

Examine the trends among the Halogens and the Noble Gases:

Halogen	Number of electrons	Boiling Point (K)	Noble gas	Number of electrons	Boiling point (K)
F_2	18	85.1	He	2	4.6
Cl_2	34	238.6	Ne	10	27.3
Br_2	70	332.0	Ar	18	87.5
I_2	106	457.6	Kr	36	120.9
			Xe	54	166.1

the greater the number of electrons,
the more polarizable the particles are,
resulting in stronger London dispersion forces.

Slide 46 / 136

12 Only polar molecules are bonded together by London dispersion forces.

- True
- False

Slide 47 / 136

13 Molecules with more electrons experience stronger London dispersion forces.

- True
- False

Slide 48 / 136

14 Which of the following molecules will have the highest boiling point?

- A F_2
- B Cl_2
- C Br_2
- D I_2

Slide 49 / 136

15 Which of the following molecules will have the lowest boiling point?

A F_2

B Cl_2

C Br_2

D I_2

Slide 50 / 136

16 Which of the following gases will have the highest boiling point?

A He

B Ne

C Ar

D Kr

E Xe

Slide 51 / 136

17 Which of the following gases will have the lowest boiling point?

A He

B Ne

C Ar

D Kr

E Xe

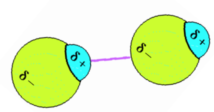
Slide 52 / 136

Which Have a Greater Effect?

Dipole-Dipole Interactions or Lond Dispersion Forces

Dipole-Dipole

If two **polar molecules are of comparable size**, dipole-dipole interactions are the dominating force.



London Dispersion Forces

If **one molecule is much larger than another**, dispersion forces will likely determine its physical properties.

If **molecules are nonpolar**, dispersion forces will dominate, since all molecules experience dispersion forces.

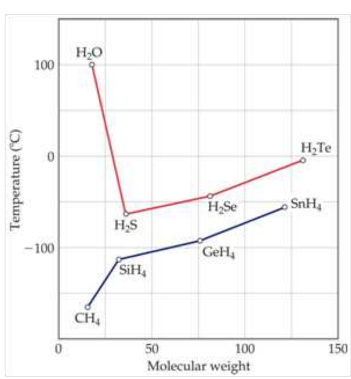
Slide 53 / 136

Hydrogen Bonding

The graph showsthe boiling points for four polar and four non-polar compounds.

For the non-polar series (CH_4 to SnH_4) boiling points increase with higher number of electrons.

There are stronger dispersion forces due to greater polarizability.

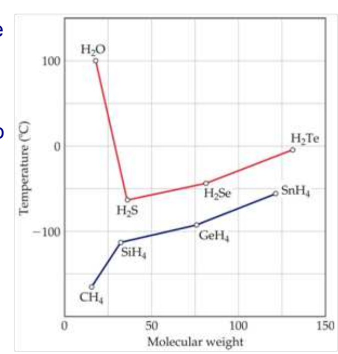


Slide 54 / 136

Hydrogen Bonding

Examine the boiling points for the four polar compounds (4,2,2 = bent) called Group 16 hydrides.

First look at the trend from H_2S to H_2Te. The boiling points are higher than the non-polar series, and the boiling points increase with greater molecular weight/ greater numbers of electrons as expected.

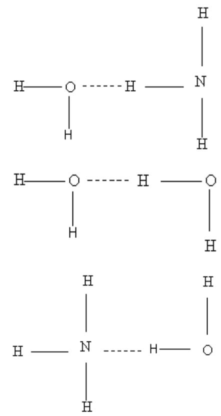


What is going on with water?
Based on molecular weight/electron number, it should have the lowest boiling point among the polar compounds, but instead its boiling point is extremely high.

Hydrogen Bonding

The dipole-dipole interactions experienced when H is bonded to N, O, or F are unusually strong.

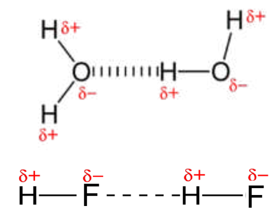
We call these interactions **hydrogen bonds**.

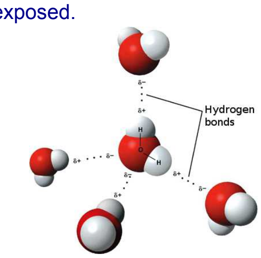


Hydrogen Bonding

Hydrogen bonding arises in part from the high electronegativity and small radius of nitrogen, oxygen, and fluorine.

When hydrogen is bonded to one of those very electronegative elements, the hydrogen nucleus is exposed.





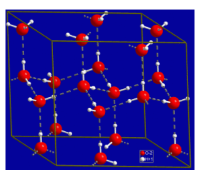
Click here to watch an animation about Hydrogen Bonding

Hydrogen Bonding

Water is the only substance that is less dense in the solid state than in the liquid state; therefore, solid water, or ice, floats on liquid water.

If it didn't, life on Earth would be very different. For instance, lakes would freeze from the bottom and fish couldn't survive winters.

Hydrogen bonding creates the space in ice that explains its low density.



Click here to watch an animation of the Water - Ice transition

18 Which of the following molecules has hydrogen bonding as one of its intermolecular forces?

- A HF
- B HCl
- C HBr
- D HI
- E All of the above

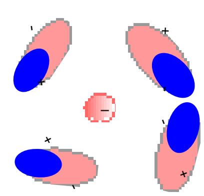
19 Which of the following molecules has hydrogen bonding as one of its IMF's?

- A CH_3F
- B CH_3Cl
- C HBr
- D NO_2
- E None of the above

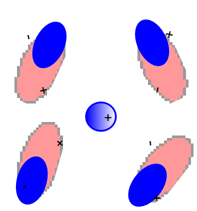
Ion-Dipole Interactions

There is a fourth intermolecular force between ions and molecules that will be important as we explore solutions later this year. Ion-dipole interactions are not considered a van der Waals force.

The ion-dipole forces cause ionic substances to dissolve in polar solvents.

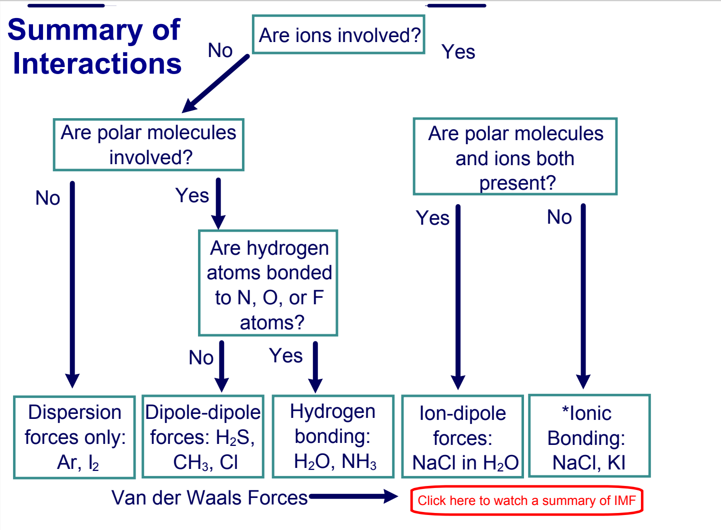


Anion-dipole attractions



Cation-dipole attractions

Slide 61 / 136



Slide 62 / 136

IMF Summary

	London Dispersion Forces	Dipole-Dipole	Hydrogen-Bonding
Strength	Weakest IMF	Stronger IMF	Strongest IMF
Types of molecules	All nonpolar molecules; All molecules	Only polar molecules	Only polar molecules with H bonded to N, O, or F
When in doubt...	Look at number of electrons	Look at given Dipole moment	Look for H-N, H-O, or H-F bonds

Slide 63 / 136

20 Which of the following has London dispersion forces as its only IMF?

- A PH_3
- B H_2S
- C HCl
- D SiH_4
- E None of the above

Slide 64 / 136

21 How many of these substances would have dipole-dipole interactions?

H_2O CO_2 CH_4 NH_3

- A 0
- B 1
- C 3
- D 3
- E 4

Slide 65 / 136

22 Which of the following molecules will have the highest boiling point?

- A H_2O
- B CO_2
- C CH_4
- D NH_3

Slide 66 / 136

23 Which of the following diatomic molecules has the highest boiling point?

- A N_2
- B Br_2
- C H_2
- D Cl_2
- E O_2

24 Of the following diatomic molecules, which as the lowest boiling point?

- A N_2
- B Br_2
- C H_2
- D Cl_2
- E O_2

25 Which one of the following derivatives of methane (CH_4) has the lowest boiling point?

- A CBr_4
- B CF_4
- C CCl_4
- D CI_4

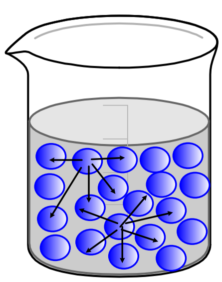
26 Which one of the following derivatives of methane (CH_4) has the highest boiling point?

- A CBr_4
- B CF_4
- C CCl_4
- D CI_4

IMF's and Physical Properties

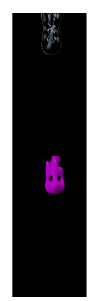
Return to Table of Contents

Intermolecular Forces Affect Many Physical Properties



The strength of the attractions between particles can greatly affect the properties of a substance or solution.

Properties of Liquids: Viscosity



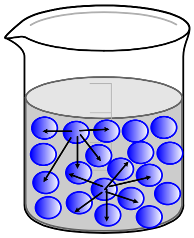
Resistance of a liquid to flow is called **viscosity**.

It is related to the ease with which molecules can move past each other. Viscosity increases with stronger intermolecular forces and decreases with higher temperature.

Which liquid to the right is more viscous?

Substance	Formula	Viscosity (kg/m-s)
Hexane	$CH_3CH_2CH_2CH_2CH_2CH_3$	3.26×10^{-4}
Heptane	$CH_3CH_2CH_2CH_2CH_2CH_2CH_3$	4.09×10^{-4}
Octane	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_3$	5.42×10^{-4}
Nonane	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3$	7.11×10^{-4}
Decane	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3$	1.42×10^{-3}

Properties of Liquids: Surface Tension



Surface tension results from the net inward force experienced by the molecules on the surface of a liquid.

Properties of Liquids: Surface Tension

The surface tension of a liquid is directly related to the attractive forces between its molecules. The stronger the attractive forces the more surface tension is needed to increase the surface area of the liquid.

Water has a relatively high surface tension 7.29×10^{-2} J/m^2 at 20℃.

However, mercury has an even higher surface tension: 4.6×10^{-1} J/m^2.

What do you think could cause mercury to have such a high surface tension relative to water?

27 A substance's viscosity is directly proportional to the strength of its intermolecular forces?

- True
- False

28 Which of the following substances would have the greatest viscosity?

- A $CH_3CH_2CH_2CH_2CH_2CH_3$
- B $CH_3CH_2CH_2CH_3$
- C $CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_3$
- D $CH_3CH_2CH_2CH_3$

29 The unbalanced attraction of molecules at the surface of a liquid tends to pull the bulk of the molecules ____________ leaving a minimal number on the surface.

- A outward
- B inward
- C in all directions

Vapor Pressure

Return to Table of Contents

Slide 79 / 136

Vaporization

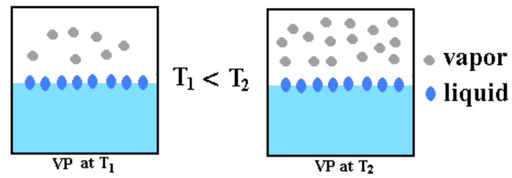
Boiling and evaporation are two ways in which a liquid can vaporize into a gas. However, there are important distinctions between these processes.

Boiling	Evaporation
Occurs at a specific temperature, the boiling point (B.P.)	Occurs below the boiling point
Occurs throughout the entire liquid	Occurs only at the surface of a liquid
Achieved when atmospheric pressure equals vapor pressure ($P_{atm} = P_{vap}$)	

Slide 80 / 136

Vapor Pressure

Vapor pressure is the pressure exerted by gas molecules above the surface of an enclosed liquid.



Sample (A) at a lower temperature shows some vapor above the surface of the liquid.

Sample (B) at a higher temperature shows a greater number of vapor particles, thus resulting in higher vapor pressure.

Slide 81 / 136

Properties of Liquids: Volatility

Volatility is another characteristic of a liquid that is based upon the strength of its intermolecular forces.

The more volatile a liquid:

- the more quickly it evaporates
- the higher its vapor pressure at a given temperature
- the weaker its intermolecular forces

Acetone is used to quickly dry glassware in a chemistry lab? Why?

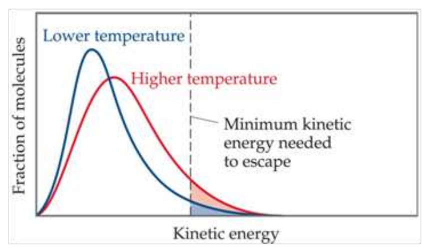
Click here to see a short video on volatility

Slide 82 / 136

Vapor Pressure

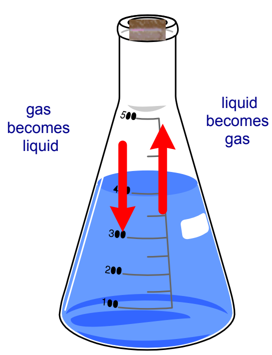
At any temperature some molecules in a liquid have enough energy to escape.

As the temperature rises, the fraction of molecules that have enough energy to escape increases.



Slide 83 / 136

Liquid - Vapor Equilibrium



As more molecules escape the liquid, the pressure they exert increases.

$$\uparrow P = \frac{\uparrow F}{A}$$

Eventually, the liquid and vapor reach a state of dynamic equilibrium: liquid molecules evaporate and vapor molecules condense *at the same rate.*

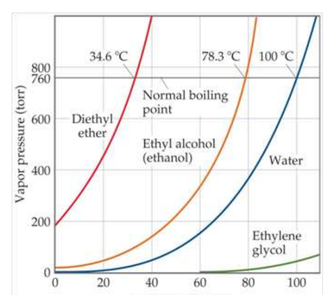
Slide 84 / 136

Vapor Pressure Curve

Like any line, the curve is made up of an infinite number of points.
Each point along the curve shows the temperature at which atmospheric pressure equals vapor pressure

$P_{atm} = P_{vap}$

In other words, each point along the curve indicates a boiling point.

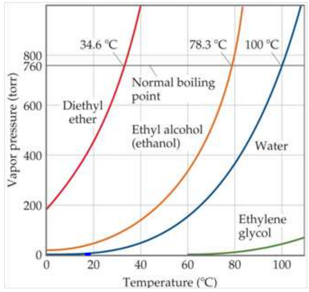


The type of graph shown here is called a vapor pressure curve.

Vapor Pressure Curve

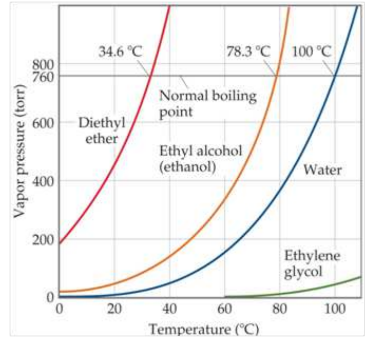
The boiling point of a liquid is the temperature at which its vapor pressure equals atmospheric pressure.

The normal boiling point is the temperature at which its vapor pressure is 760 torr. (AKA 760 mm Hg = 1 atm)



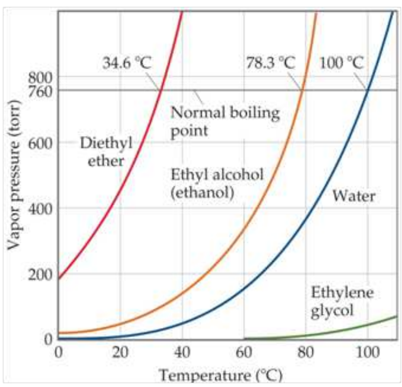
30 What is the normal boiling point of ethanol?

- A 34.6
- B 40.0
- C 60.0
- D 78.3
- E 100.0



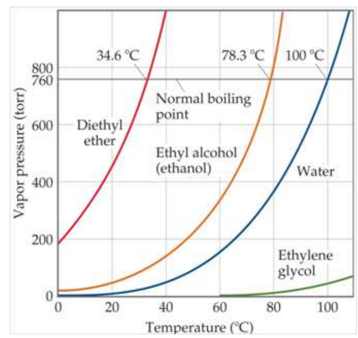
31 What is the boiling point (in °C) of diethyl ether at 200 torr?

- A -10
- B 0
- C 760
- D 35



32 What is the boiling point of water at 300 torr?

- A 50
- B 75
- C 90
- D 100
- E 200



Pressure Cooking

A liquid will boil when its vapor pressure equals atmospheric pressure.

A pressure cooker works by increasing the"atmospheric" pressure inside it, so water

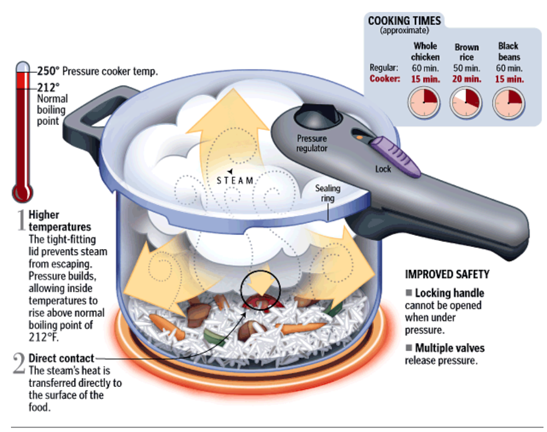
will not boil at 100℃;

instead, it may be heated
Raising the cooking temperature cuts cooking time drastically.

up to 120℃ before turning

to steam.

Pressure Cooking



Slide 91 / 136

Boiling Point and Pressure

Recall that boiling occurs when $P_{vap} = P_{atm}$

Since atmospheric pressure is so low at high altitudes, (e.g. top of Mount Everest) water will boil at a much lower temperature than in New Jersey.

Click here for a video of water boiling at room temperature

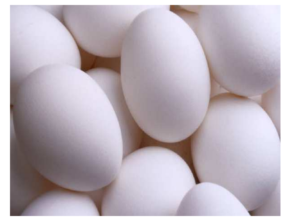
P_{atm} = 33 kPa on Mt. Everest

P_{atm} = 101.3 kPa at sea level

Slide 92 / 136

33 It will take longer to hard-boil an egg (cooking time only)

- A At the summit of Mt. Everest
- B At sea level
- C Cooking times are equal at both elevations



Slide 93 / 136

Phase Diagrams

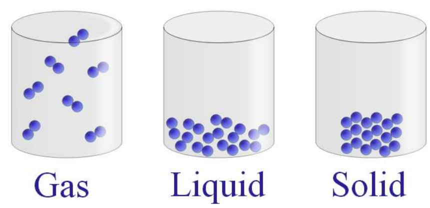
Return to Table of Contents

Slide 94 / 136

Phase Changes

A phase change is a physical rearrangement of molecules.

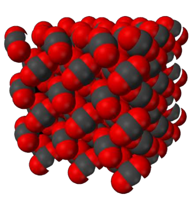
Substances can change states or phases as a result of change in external conditions like pressure and temperature.



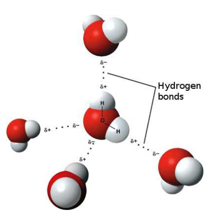
Slide 95 / 136

Phase Changes

The temperature and pressure at which a substance will change phases depends on the intermolecular forces holding the substance together.



At STP, CO_2 sublimates at -78.5 Celsius



At STP, H_2O boils at 100 Celsius

Slide 96 / 136

Energy Changes Associated with Changes of State

Chemical and physical changes are usually accompanied by changes in energy.

When energy is released in the form of heat, the process is **exothermic**.

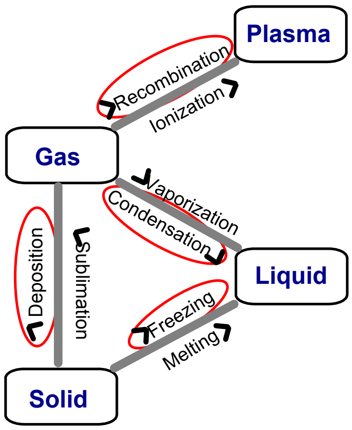
Examples: making ice cubes, formation of snow in clouds, condensation of rain water, a candle flame

When energy is absorbed by the system, the process is **endothermic**.

Examples: melting ice cubes, conversion of frost to water vapor, evaporation of water, baking bread, cooking an egg, melting solid salts.

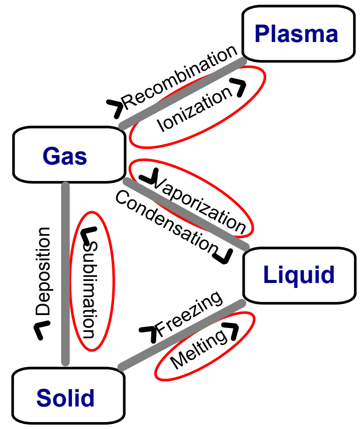
Slide 97 / 136

Exothermic Processes



Slide 98 / 136

Endothermic Processes



Slide 99 / 136

*34 What is the VSEPR number of the only substance we commonly see in all 3 states of matter?

- A 220
- B 422
- C 431
- D I don't remember how to do this

Slide 100 / 136

35 Which of the following is not a phase change?

- A Vaporization
- B Effusion
- C Melting
- D Sublimation

Slide 101 / 136

36 The change of a substance from a solid to a gas is called?

- A Vaporization
- B Effusion
- C Melting
- D Sublimation

Slide 102 / 136

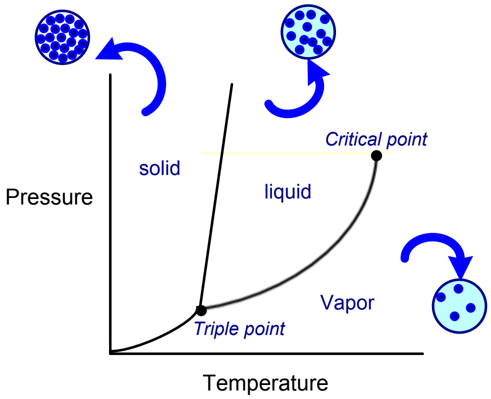
37 Which of the following is an endothermic process?

- A Condensation
- B Deposition
- C Melting
- D Freezing

Slide 103 / 136

Phase Diagrams

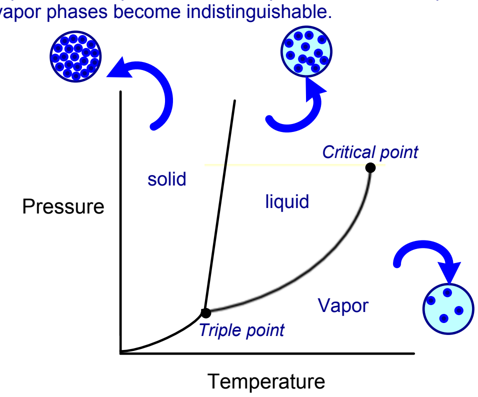
A phase diagram indicates what state a substance is in at a given temperature and pressure.



Slide 104 / 136

Phase Diagrams

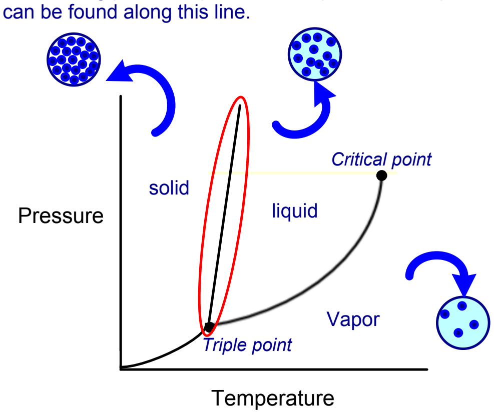
The **triple point** represents the pressure and temperature at which all three states are in equilibrium. The **critical point** represents the pressure and temperature at which liquid and vapor phases become indistinguishable.



Slide 105 / 136

Phase Diagrams

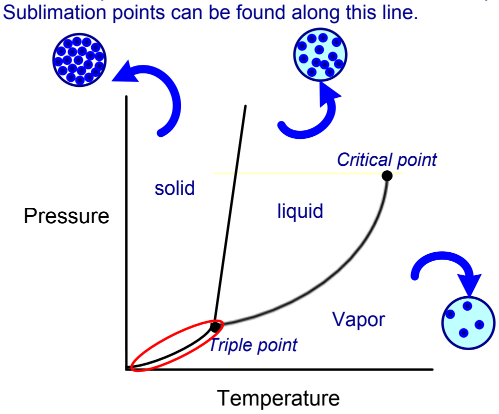
This line represents the interface between solid and liquid. The melting point at a particular temperature and pressure can be found along this line.



Slide 106 / 136

Phase Diagrams

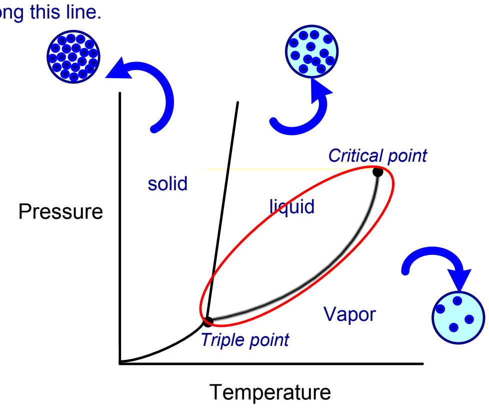
Below the triple point, a substance cannot exist in liquid state. This line represents the interface between solid and vapor. Sublimation points can be found along this line.



Slide 107 / 136

Phase Diagrams

The line between the triple point and the critical point represents the interface between liquid and vapor. Evaporation points can be found along this line.

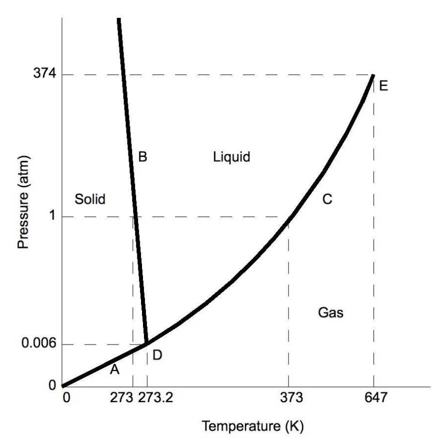


Slide 108 / 136

Phase Diagram of Water

Note the high critical temperature and critical pressure.

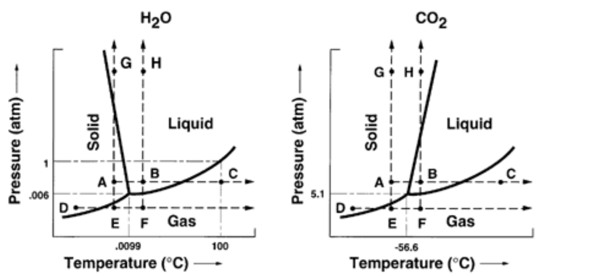
These are due to the strong van der Waals forces between water molecules.



Slide 109 / 136

Comparison of Two Phase Diagrams

The Phase Diagrams of H_2O and CO_2

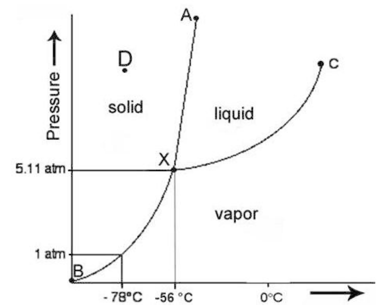


For water, the slope of the solid-liquid line is negative. This means that an increase in pressure can cause this substance to melt. Water is the only substance that does this.

For carbon dioxide, the slope of the solid-liquid line is positive, as it is for most other substances. Thismeans that an increase in pressure can cause substances to freeze.

Slide 110 / 136

Phase Diagram of Carbon Dioxide



Carbon dioxide cannot exist in the liquid state at pressures below 5.11 atm;
CO_2 sublimes at normal pressures.

Click here to see video of "dry ice"

Slide 111 / 136

38 For a given substance, the temperature and pressure at which liquid and gas phases are indistinguishable is called

- A The vapor point
- B The triple point
- C The critical point
- D The danger zone

Slide 112 / 136

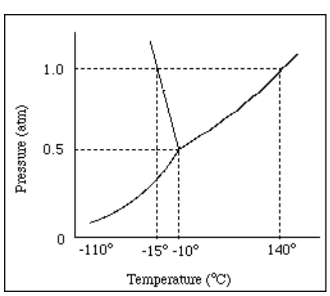
39 The temperature and pressure at which a substance can simultaneously melt, evaporate, and sublime is called

- A The vapor point
- B The triple point
- C The critical point
- D The danger zone

Slide 113 / 136

40 At which temperature and pressure can the substance below simultaneously melt, sublime, and evaporate?

- A -10 C, 1 atm
- B 140 C, 1 atm
- C 10 C, 0.5 atm
- D -110 C, 0.4 atm

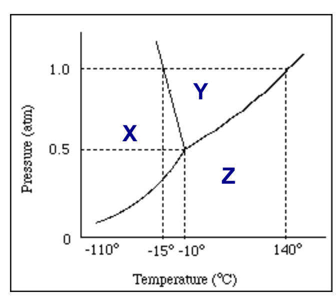


Phase Diagram for Imaginary Substance

Slide 114 / 136

41 For the substance below, X represents which phase?

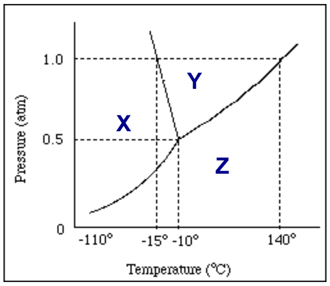
- A solid
- B liquid
- C vapor
- D plasma



Phase Diagram for Imaginary Substance

42 For the substance below, Y represents which phase?

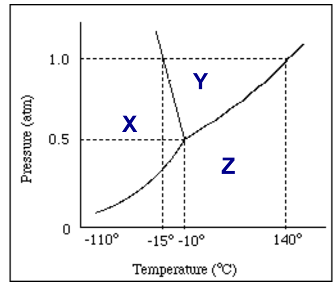
- A solid
- B liquid
- C vapor
- D plasma



Phase Diagram for Imaginary Substance

43 At standard atmospheric pressure (1 atm), at what temperature will the substance below melt?

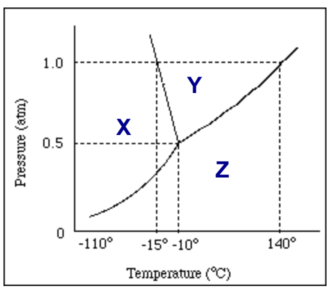
- A -20 C
- B -15 C
- C -10 C
- D 0 C



Phase Diagram for Imaginary Substance

44 For the substance below, Z represents which phase?

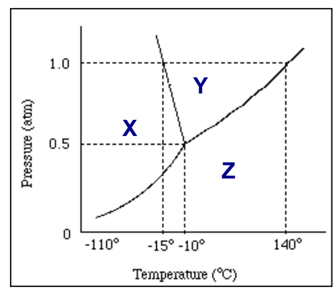
- A solid
- B liquid
- C vapor
- D plasma



Phase Diagram for Imaginary Substance

45 At 0.5 atm and -15 C the substance will

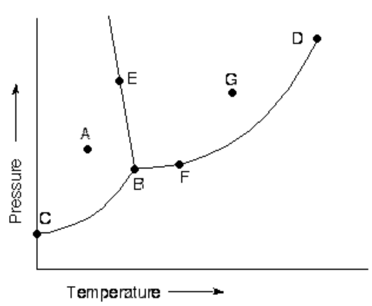
- A remain solid
- B melt
- C sublime
- D super cool



Phase Diagram for Imaginary Substance

46 Which line segment indicates this is definitely a phase diagram for water? Why?

- A A
- B B-F
- C C-B
- D D-F
- E E-B



Types of Solids

Return to Table of Contents

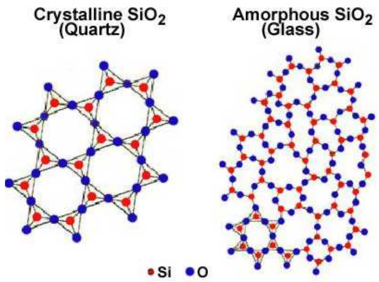
Slide 121 / 136

Solids

We can think of solids as falling into two groups.

Crystalline, in which particles are in highly ordered arrangement.

Amorphous, in which there is no particular order in the arrangement of particles.



NDT Education Resource Center

Slide 122 / 136

Amorphous Solids

Some examples of amorphous solids are: rubber, glass, paraffin wax and cotton candy.

Crystalline solids include ionic compounds, metals and another group called covalent-network solids. Crystalline solids are categorized by bonding type as shown on the next slide.

Slide 123 / 136

Types of Bonding in Crystalline Solids

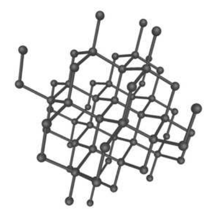
Type of Solid	Form of Unit Particles	Forces Between Particles	Properties	Examples
Molecular	Atoms or molecules	London dispersion, dipole-dipole hydrogen bonds	Hard and brittle, low melting point, poor thermal and electrical conduction	Ar, CH_4, CO_2, $C_6H_{12}O_6$
Covalent-network	Atoms	Covalent bonds	Fairly soft, low to moderately high melting point, poor thermal and electrical conduction	Diamond (C), Quartz (SiO_2)
Ionic	Positive and negative ions	Coulombic attractions	Very hard, very high melting point, variable thermal and electrical conduction	Typical salts
Metallic	Atoms	Metallic bonds	Soft to very hard, low to very high melting point, excellent thermal and electrical conduction, malleable and ductile	All Metallic Elements: Cu, Fe, Al, etc.

Slide 124 / 136

Covalent-Network Solids: Diamond

Diamonds are an example of a covalent-network solid, in which carbon atoms are covalently bonded to four other carbon atoms.

They tend to be hard and have high melting points.

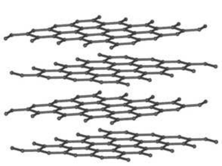


Slide 125 / 136

Covalent-Network Solids: Graphite

Graphite is another example of a covalent-network solid. Each carbon atom is covalently bonded to 3 others in layers of interconnected hexagonal rings.

The layers are held together by weak dispersion forces. The layers slide easily across one another, so graphite is used as a lubricant as well as the "lead" in pencils.

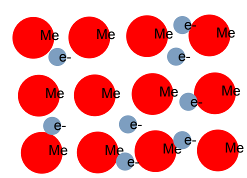


Slide 126 / 136

Metallic Solids

Metals are not covalently bonded, but the attractions between atoms are too strong to be van der Waals forces.

In metals, valence electrons are delocalized throughout the solid. This means that the "sea" of electrons moves freely around all the nuclei.



click here for an animation about metallic bonding

Slide 127 / 136

Properties of Metallic Solids

The delocalized nature of the electrons in metals accounts for many physical properties.

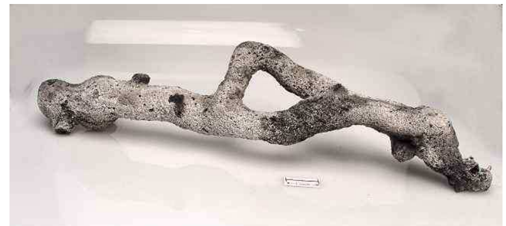
For example, metals are generally:
good conductors of heat and electricity malleable and ductile, (i.e. may be drawn into wires)

Slide 128 / 136

Glass Making

Glass is made by melting a mixture of sand and other minerals in a furnace at 1800 C.

Lightning can also fuse sand into silica glass at 1800 C.



Fulgurite via the Mineralogical Research Company

Click here to see a video of how glass is made from sand

Slide 129 / 136

47 What type of solid is depicted in image below?

- A crystalline solid
- B amorphous solid
- C metallic solid
- D covalent-network solid
- E Impossible to determine

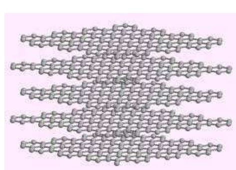
Slide 130 / 136

48 What type of solid is depicted in image below?

- A ionic solid
- B amorphous solid
- C metallic solid
- D covalent-network solid
- E Impossible to determine

Slide 131 / 136

49 What type of solid is depicted in image below?



- A ionic solid
- B amorphous solid
- C metallic solid
- D covalent-network solid
- E Impossible to determine

Slide 132 / 136

50 Metallic solids are best classified as ______.

- A particles arranged in regularly repeating patterns.
- B a sea of de-localized electrons making them good conductors of electricity.
- C held together by weak intermolecular forces that result in them being soft with low melting points
- D held together by large networks of covalent bonds.
- E cations and anions held together by electrostatic attractions.

51 Ionic solids tend to have higher melting points than molecular solids because ionic bonds are stronger than the intermolecular forces that hold molecular solids together.

- True
- False

52 Covalent-network solids are harder than molecular solids because covalent-network solids are held together by intermolecular forces and molecular solids are held together by large networks of covalent bonds.

- True
- False

53 Which of the following solids would have the highest melting point?

- A sodium metal
- B table salt
- C cotton candy
- D graphite