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
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.

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, walls...or even our bodies.

Intermolecular forces shape our world.

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

**States of Matter**

**Solid**
- Dispersity of the particles is fixed
- Orderly arrangement of the particles
- Cannot flow

**Liquid**
- Dispersity of the particles is not fixed
- Orderly arrangement of the particles
- Can flow

**Gas**
- Dispersity of the particles is not fixed
- No orderly arrangement of the particles
- Can flow

**Characteristics of the States of Matter**

<table>
<thead>
<tr>
<th>State</th>
<th>Gas</th>
<th>Liquid</th>
<th>Crystalline solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHAPE</td>
<td>Assumes the shape of its container</td>
<td>Expands to the volume of its container</td>
<td>ordered arrangement, particles are in fixed positions, close together</td>
</tr>
<tr>
<td>VOLUME</td>
<td>Expands to the volume of its container</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMPRESSION</td>
<td>Is compressible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLOW</td>
<td>Flows easily</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIFFUSION</td>
<td>Very Rapid</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Enjoy this musical interlude by They Might Be Giants!
### Characteristics of the States of Matter

<table>
<thead>
<tr>
<th></th>
<th>Liquid</th>
<th>Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SHAPE</strong></td>
<td>Assumes the shape of the part of a container it occupies</td>
<td>Retains its own shape regardless of container</td>
</tr>
<tr>
<td><strong>VOLUME</strong></td>
<td>Does not expand to the volume of the container</td>
<td>Does not expand to the volume of its container</td>
</tr>
<tr>
<td><strong>COMPRESSION</strong></td>
<td>Is virtually incompressible</td>
<td>Is virtually incompressible</td>
</tr>
<tr>
<td><strong>FLOW</strong></td>
<td>Flows easily</td>
<td>Does not flow</td>
</tr>
<tr>
<td><strong>DIFFUSION</strong></td>
<td>Within a liquid, slow</td>
<td>Within a solid, very very slow</td>
</tr>
</tbody>
</table>

### Condensed Phases

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

- **Gas**: Particles are far apart, total freedom, much of empty space, total disorder.
- **Liquid**: Disorder, freedom, free to move relative to each other, close together.
- **Crystalline Solid**: Ordered arrangement, particles are in fixed positions, close together.

### Questions

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

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

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
Intermolecular Forces

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?

Intermolecular Forces

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

The attractions between molecules, intermolecular forces, are not nearly as strong as the intramolecular attractions that hold compounds together.

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

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

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

- A
- B
- C
- D
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.

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.

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

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?

<table>
<thead>
<tr>
<th>Bond Type</th>
<th>Electronegativity Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Polar Covalent</td>
<td>very small or zero</td>
</tr>
<tr>
<td>Polar Covalent</td>
<td>about 0.2 to 1.6</td>
</tr>
<tr>
<td>Ionic</td>
<td>above 1.7 (between metal &amp; non-metal)</td>
</tr>
</tbody>
</table>

---

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.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Molecular Weight (amu)</th>
<th>Dipole Moment ( u(D) )</th>
<th>Boiling Point (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetonitrile, CH₃CN</td>
<td>41</td>
<td>3.9</td>
<td>355</td>
</tr>
<tr>
<td>Acetaldehyde, CH₃CHO</td>
<td>44</td>
<td>2.7</td>
<td>294</td>
</tr>
<tr>
<td>Methyl chloride, CH₃Cl</td>
<td>50</td>
<td>1.9</td>
<td>249</td>
</tr>
<tr>
<td>Dimethyl ether, CH₃OCH₃</td>
<td>46</td>
<td>1.3</td>
<td>248</td>
</tr>
<tr>
<td>Propane, CH₃CH₃CH₃</td>
<td>44</td>
<td>0.1</td>
<td>231</td>
</tr>
</tbody>
</table>

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

- A CH₃CH₂CH₃
- B CH₃OCH₃
- C CH₃Cl
- D CH₃CHO
- E CH₃CN

**Answer**

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

- A CH₃CH₂CH₃
- B CH₃OCH₃
- C CH₃Cl
- D CH₃CHO
- E CH₃CN

**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.
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.

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.

Examine the trends among the Halogens and the Noble Gases:

<table>
<thead>
<tr>
<th>Halogen</th>
<th>Number of electrons</th>
<th>Boiling Point (K)</th>
<th>Noble gas</th>
<th>Number of electrons</th>
<th>Boiling point (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F₂</td>
<td>18</td>
<td>85.1</td>
<td>He</td>
<td>2</td>
<td>4.6</td>
</tr>
<tr>
<td>Cl₂</td>
<td>34</td>
<td>238.6</td>
<td>Ne</td>
<td>10</td>
<td>27.3</td>
</tr>
<tr>
<td>Br₂</td>
<td>70</td>
<td>332.0</td>
<td>Ar</td>
<td>18</td>
<td>87.5</td>
</tr>
<tr>
<td>I₂</td>
<td>106</td>
<td>457.6</td>
<td>Kr</td>
<td>36</td>
<td>120.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Xe</td>
<td>54</td>
<td>166.1</td>
</tr>
</tbody>
</table>

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

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

13 Molecules with more electrons experience stronger London dispersion forces.
- True
- False

14 Which of the following molecules will have the highest boiling point?
- A F₂
- B Cl₂
- C Br₂
- D I₂
15 Which of the following molecules will have the lowest boiling point?

- A $\text{F}_2$
- B $\text{Cl}_2$
- C $\text{Br}_2$
- D $\text{I}_2$

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

- A He
- B Ne
- C Ar
- D Kr
- E Xe

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

- A He
- B Ne
- C Ar
- D Kr
- E Xe

**Which Have a Greater Effect?**

**Dipole-Dipole Interactions or London 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.

**Hydrogen Bonding**

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

For the non-polar series (CH to SnH$_4$), boiling points increase with higher number of electrons. There are stronger dispersion forces due to greater polarizability.

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

First look at the trend from H$_2$S to H$_2$Te. 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.
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 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.

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.

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 CH₃F
- B CH₃Cl
- C HBr
- D NO₂
- 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.
Summary of Interactions

- Are ions involved? No
- Are polar molecules involved? No
- Are hydrogen atoms bonded to N, O, or F atoms? No
- Are polar molecules and ions both present? Yes

IMF Summary

<table>
<thead>
<tr>
<th>Strength</th>
<th>London Dispersion Forces</th>
<th>Dipole-Dipole</th>
<th>Hydrogen-Bonding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types of molecules</td>
<td>All nonpolar molecules; All molecules</td>
<td>Only polar molecules</td>
<td>Only polar molecules with H bonded to N, O, or F</td>
</tr>
<tr>
<td>When in doubt...</td>
<td>Look at number of electrons</td>
<td>Look at given Dipole moment</td>
<td>Look for H-N, H-O, or H-F bonds</td>
</tr>
</tbody>
</table>

20 Which of the following has London dispersion forces as its only IMF?
- A PH₃
- B H₂S
- C HCl
- D SiH₄
- E None of the above

21 How many of these substances would have dipole-dipole interactions?
- A H₂O
- B CO₂
- C CH₄
- D NH₃

22 Which of the following molecules will have the highest boiling point?
- A H₂O
- B CO₂
- C CH₄
- D NH₃

23 Which of the following diatomic molecules has the highest boiling point?
- A N₂
- B Br₂
- C H₂
- D Cl₂
- E O₂
24 Of the following diatomic molecules, which has the lowest boiling point?

- A N₂
- B Br₂
- C H₂
- D Cl₂
- E O₂

25 Which one of the following derivatives of methane (CH₄) has the lowest boiling point?

- A CBr₄
- B CF₄
- C CCl₄
- D Cl₄

26 Which one of the following derivatives of methane (CH₄) has the highest boiling point?

- A CBr₄
- B CF₄
- C CCl₄
- D Cl₄

**IMF’s and Physical Properties**

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?

<table>
<thead>
<tr>
<th>Substance</th>
<th>Formula</th>
<th>Viscosity (kg/m·s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexane</td>
<td>CH₃·CH₂·CH₃·CH₄</td>
<td>3.88 x 10⁻⁴</td>
</tr>
<tr>
<td>Heptane</td>
<td>CH₃·CH₂·CH₂·CH₃·CH₄</td>
<td>4.09 x 10⁻⁴</td>
</tr>
<tr>
<td>Octane</td>
<td>CH₃·CH₂·CH₂·CH₂·CH₃·CH₄</td>
<td>5.42 x 10⁻⁴</td>
</tr>
<tr>
<td>Nonane</td>
<td>CH₃·CH₂·CH₂·CH₂·CH₂·CH₃·CH₄</td>
<td>7.11 x 10⁻⁴</td>
</tr>
<tr>
<td>Decane</td>
<td>CH₃·CH₂·CH₂·CH₂·CH₂·CH₂·CH₃·CH₄</td>
<td>1.42 x 10⁻³</td>
</tr>
</tbody>
</table>

The strength of the attractions between particles can greatly affect the properties of a substance or solution.
**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: $7.29 \times 10^{-2}$ J/m$^2$ at 20°C.

However, mercury has an even higher surface tension: $4.6 \times 10^{-1}$ 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$_3$CH$_2$CH$_2$CH$_2$CH$_3$
- B. CH$_3$CH$_2$CH$_3$
- C. CH$_3$CH$_2$CH$_2$CH$_2$CH$_2$CH$_3$
- D. CH$_3$CH$_2$CH$_2$CH$_3$

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
Vaporization

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

<table>
<thead>
<tr>
<th>Boiling</th>
<th>Evaporation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occurs at a specific temperature, the boiling point (B.P.)</td>
<td>Occurs below the boiling point</td>
</tr>
<tr>
<td>Occurs throughout the entire liquid</td>
<td>Occurs only at the surface of a liquid</td>
</tr>
<tr>
<td>Achieved when atmospheric pressure equals vapor pressure ($P_{\text{atm}} = P_{\text{vap}}$)</td>
<td></td>
</tr>
</tbody>
</table>

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.

Properties of Liquids: Volatility

Volutility 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.

Liquid - Vapor Equilibrium

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

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

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:

$$P_{\text{atm}} = P_{\text{vap}}$$

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

instead, it may be heated up to 120°C before turning to steam.
Boiling Point and Pressure

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

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.

$P_{\text{atm}} = 33 \, \text{kPa}$ on Mt. Everest

$P_{\text{atm}} = 101.3 \, \text{kPa}$ at sea level

Click here for a video of water boiling at room temperature

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

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.

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.
**Exothermic Processes**

- Plasma
- Recombination
- Ionization
- Vaporization
- Condensation
- Melting
- Deposition
- Sublimation

**Endothermic Processes**

- Plasma
- Recombination
- Ionization
- Vaporization
- Condensation
- Melting
- Deposition
- Sublimation

---

**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

**35.** Which of the following is not a phase change?
- A Vaporization
- B Effusion
- C Melting
- D Sublimation

**36.** The change of a substance from a solid to a gas is called?
- A Vaporization
- B Effusion
- C Melting
- D Sublimation

**37.** Which of the following is an endothermic process?
- A Condensation
- B Deposition
- C Melting
- D Freezing
Phase Diagrams
A phase diagram indicates what state a substance is in at a given temperature and pressure.

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.

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.

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.

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.

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.

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.
Comparison of Two Phase Diagrams

The Phase Diagrams of H₂O and CO₂

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. This means that an increase in pressure can cause substances to freeze.

Phase Diagram of Carbon Dioxide

Carbon dioxide cannot exist in the liquid state at pressures below 5.11 atm; CO₂ sublimes at normal pressures.

Click here to see video of “dry ice”

---

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

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

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

41. For the substance below, X represents which phase?
   A. solid
   B. liquid
   C. vapor
   D. plasma
42 For the substance below, Y represents which phase?

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

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

44 For the substance below, Z represents which phase?

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

45 At 0.5 atm and -15 °C the substance will

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

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
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.

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.

Types of Bonding in Crystalline Solids

<table>
<thead>
<tr>
<th>Type of Solid</th>
<th>Form of Unit Particles</th>
<th>Forces Between Particles</th>
<th>Properties</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular</td>
<td>Atoms or molecules</td>
<td>London dispersion, dipole-dipole hydrogen bonds</td>
<td>Hard and brittle, low melting point, poor thermal and electrical conduction</td>
<td>Ar, CH₄, CO₂, C₆H₁₂O₆</td>
</tr>
<tr>
<td>Covalent-network</td>
<td>Atoms</td>
<td>Covalent bonds</td>
<td>Fairly soft, low to moderately high melting point, poor thermal and electrical conduction</td>
<td>Diamond (C), Quartz (SiO₂)</td>
</tr>
<tr>
<td>Ionic</td>
<td>Positive and negative ions</td>
<td>Coulombic attractions</td>
<td>Very hard, very high melting point, variable thermal and electrical conduction</td>
<td>Typical salts</td>
</tr>
<tr>
<td>Metallic</td>
<td>Atoms</td>
<td>Metallic bonds</td>
<td>Soft to very hard, low to very high melting point, excellent thermal and electrical conduction, malleable and ductile</td>
<td>All Metallic Elements: Cu, Fe, Al, etc.</td>
</tr>
</tbody>
</table>

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.

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.

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.
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)

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.

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

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

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

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