

EXTENSION ACTIVITY
GENERAL CHEMISTRY

LATENT HEAT - KEY



Activity
Directions

This activity will serve as practice for the topics covered in the Latent Heat game. This activity is best used in conjunction with not only the tutorial levels, but also supplementary learning resources such as course lectures, textbook reading, etc. Questions labeled “Lock It In” are simply opportunities for you to solidify what you have accomplished in each task and help ensure you meet each objective.

1. Log into Collisions and navigate to the Latent Heat Game.
2. Play the Tutorial levels, if you haven't done so already.
3. Exit the levels and enter the Latent Heat sandbox.
4. Follow all instructions as written below. Be sure to reference your course's textbook, lecture notes, etc. as needed.



KEY TERMS & CONCEPTS

Before you begin completing this extension activity, please be sure to have an understanding of the terms summarized below. The extension activity will assume a solid understanding of each term based on what you saw in the Latent Heat and Intermolecular Forces games. In the case that you realize you need more than the summary, please reference your textbook or lecture notes.

Latent Heat - This term describes processes where heat is either absorbed or released by a system without any change in temperature to the system. You encountered such a phenomena while exploring the levels of the Latent Heat game—think about the lack of temperature change when you broke or re-formed the intermolecular forces in a substance. The term is most commonly encountered when describing the **Latent Heat of Vaporization** or **Latent Heat of Fusion**, both of which you will see in this activity.

London Dispersion Forces - These are generally weak interactions that form between molecules due to the formation of instantaneous dipoles. The magnitude of the forces increases for molecules that have more electrons. As a result, molar mass is often used as a proxy.

Dipole-Dipole Interactions - These interactions occur when molecules have net dipoles as the result of unbalanced polar bonds. Some molecules have more significant dipoles than others depending on their composition and geometry. These dipoles can allow molecules to interact with one another based on their partial charges.

Hydrogen Bonding - These interactions occur when molecules contain bonds between hydrogen atoms and either nitrogen, oxygen, or fluorine. Due to the large electronegativity difference between hydrogen and each of the listed atoms, particularly strong dipole interactions can form between the lone pairs of the more electronegative atom and partially positive hydrogen atoms.

Temperature - It is very important when discussing the topics covered by the Latent Heat Game to realize that temperature and heat are two distinct concepts. Temperature measures the **average** kinetic energy of the particles in a substance. For example, when we measure the air temperature, it is important to realize that molecules in the air are of different masses and moving at a wide variety of speeds. As such, they have a wide variety of kinetic energies. The air temperature simply tells us the *average* kinetic energy of the particles in the air. Heating of the air would increase the speed of the particles and thus increase the average kinetic energies. This increase in kinetic energy would be reflected by an increase in temperature.



OBJECTIVE 1

Demonstrate an understanding of the relationships between intermolecular forces, the heat of vaporization and the processes of boiling, evaporation, and condensation.

Understanding intermolecular forces is key to understanding phase changes. Substances with greater intermolecular forces will require more energy to change their phase of matter. Some very interesting examples arise when we consider substances showing each of the different intermolecular forces that you have seen so far.

London Dispersion Forces: The molecules propane (C_3H_8), octane (C_8H_{18}), and *n*-icosane ($C_{20}H_{42}$) all contain the same nonpolar carbon—hydrogen and carbon—carbon bonds. However, at 20°C and one atmosphere of pressure, propane is a gas, octane is a liquid, and *n*-icosane is a solid. The large number of electrons in *n*-icosane ($C_{20}H_{42}$) compared to octane and propane give it greater London dispersion forces. The same is true of octane compared to propane. As a result, the melting and boiling points of *n*-icosane are higher than those of octane, which are higher than those of propane.

Dipole-Dipole Interactions: The molecules butane (C_4H_{10}) and acetone (C_3H_6O) have very similar molar masses but very different boiling points. At room temperature and one atmosphere of pressure, butane with a boiling point of -1°C is a gas. But acetone with a boiling point of 56°C would be a liquid. An acetone molecule's dipole resulting from its bond between carbon and oxygen increases its interactions with other acetone molecules. The interactions between nonpolar butane molecules, however, are much less. Dipole-dipole interactions have increased the amount of energy necessary for a phase change.

Hydrogen-Bonding: The molecules ethanol (C_2H_6O), acetaldehyde (C_2H_4O), and propane (C_3H_8) also have very similar molar masses with very different boiling points. At room

temperature and one atmosphere of pressure, they have boiling points of 78.32°C, 20.2°C, and -42°C respectively. Acetaldehyde has a significant dipole due to its polar bond between carbon and oxygen. As a result, it has a much higher boiling point than propane. Ethanol, however, has an oxygen arranged so that it is bonded directly to a hydrogen atom. Such an arrangement allows for ethanol molecules to form hydrogen bonds, significantly increasing the boiling point to higher than that of acetaldehyde.

An important related concept is known as the **Enthalpy or Heat of Vaporization (ΔH_{vap})**, which is also known as the **Latent Heat of Vaporization**. The Heat of Vaporization of a substance is the amount of energy needed to convert a certain quantity from a liquid to gas (vaporization). ΔH_{vap} is given as a positive value because it is an endothermic process—energy must be absorbed for it to happen. The opposite process of condensation (gas to liquid) is exothermic and the $\Delta H_{\text{condensation}}$ is thus negative.

The amount of energy needed for vaporization is the direct result of the intermolecular forces in the substance. It takes more energy to overcome stronger intermolecular forces, and thus one can typically infer relative heats of vaporization by looking at the composition and structure of a substance. You saw this while completing the levels of the Latent Heat Game. The amount of intermolecular forces you had to “break” by clicking them varied from substance to substance. Please be sure to revisit your textbook or lecture notes for more detail about boiling and the heat of vaporization. Be sure you can distinguish boiling from evaporation and explain why ΔH_{vap} and boiling points are not the same concept.



OBJECTIVE 1

Demonstrate an understanding of the relationships between intermolecular forces, the heat of vaporization and the processes of boiling, evaporation, and condensation.

TASK 1: Rank the substances available to you in the sandbox and listed in the table below by their heat of vaporization at their boiling points using only what you know about their composition and geometry. Use a periodic table, electronegativity table, and the structure of the molecules in the sandbox to help you. Simply rank the substances with the numbers 1-5, where “1” has the largest heat of vaporization and “5” has the smallest. Provide your justification for each ranking in the last column of the table by discussing the intermolecular forces present.

Substance	Ranking	Justification
Methane (CH ₄)	5	Methane is both a small molecule (has few electrons) and neither has a dipole nor hydrogen bonding capabilities. As a result, it has the smallest intermolecular forces and lowest heat of vaporization.
Sodium Chloride (NaCl)	1	The stronger the interactions between individual units of a compound, the higher the heat of vaporization. Since sodium chloride is an ionic compound, it has very strong ionic bonding. As a result, it will take a lot of energy to convert it to the gaseous state thus giving it a high heat of vaporization.
Xenon (Xe)	4	The only intermolecular force between xenon atoms will be dispersion forces, unlike the other molecules in the table that have stronger interactions. However, since it has many more electrons than methane, it is more polarizable and thus has greater dispersion forces and a higher heat of vaporization.
Water (H ₂ O)	2	Water, although small, displays very strong hydrogen bonding. While hydrogen bonding is not nearly as strong as the ionic bonds of sodium chloride, it is stronger than the intermolecular forces of the other substances in this table.
Fluoromethane (CH ₃ F)	3	Although fluoromethane does not have the hydrogen bonding present in water, it does have dipole-dipole interactions due to the polar bond between carbon and fluorine. As a result, it has a higher heat of vaporization than Xenon (despite its smaller number of electrons) and methane.

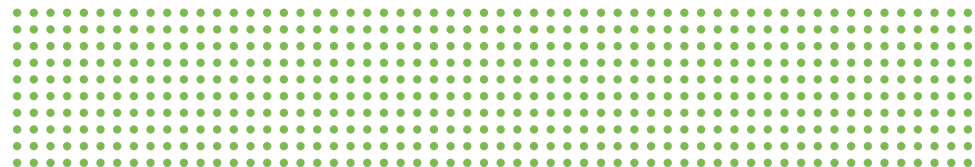


OBJECTIVE 1

Demonstrate an understanding of the relationships between intermolecular forces, the heat of vaporization and the processes of boiling, evaporation, and condensation.

LOCK IT IN:

Would you expect to see the same ranking if these substances were ranked by their normal boiling points instead of the heat of vaporization? Why or why not?



You would expect to see the same ranking of these substances by boiling point as by heat of vaporization. Although the boiling point is distinct from the heat of vaporization, they are very much related. Both are the result of the amount of energy that is required to move particles of a substance from the liquid to the gas state. A higher heat of vaporization tells us that there are greater intermolecular forces keeping the particles together. This suggests that a higher temperature would also be required to make those substances boil (go from liquid to gas). As such, the substances in the table would have an identical ranking by normal boiling points as they had by heat of vaporization.

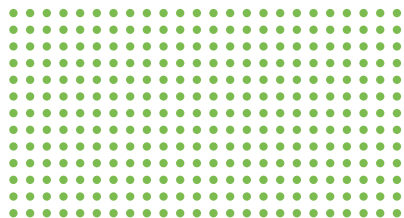
TASK 2: Take the following substances and convert them to gases: ammonia (NH_3), nitrogen trifluoride (NF_3), argon (Ar), and magnesium oxide (MgO). These substances represent either hydrogen bonding, dipole-dipole interactions, London dispersion forces, or ionic bonding respectively. Pay careful attention to how much energy is used in breaking the intermolecular forces in order to convert each substance from liquid to gas. This is the heat of vaporization! Record the total number of clicks it takes to remove the intermolecular forces that are holding the liquid together just before it becomes a gas. For one of them you might have to infer how many clicks would be necessary. Explain in the space beneath the table how what you saw helps demonstrate the role of intermolecular forces in vaporization.

As these substances increase in the strength of their intermolecular forces, the total number of clicks required to convert them from liquid to gas increases. Argon represents London dispersion forces that in small molecules require the least energy to overcome. Nitrogen trifluoride represents dipole-dipole interactions that generally require more energy (and more clicks) to overcome. Ammonia represents hydrogen bonding which is considered an even stronger intermolecular force and requires even more clicks to overcome. And finally, magnesium oxide is an ionic compound whose coulombic forces require very large amounts of energy (and clicks) to overcome. This directly reflects the increased heat of vaporization that occurs as intermolecular forces become stronger. Please note that the number of clicks have been simplified in the game for the sake of clarity. The relationship in heat of vaporization for these substances is not actually so straightforward.



OBJECTIVE 1

Demonstrate an understanding of the relationships between intermolecular forces, the heat of vaporization and the processes of boiling, evaporation, and condensation.



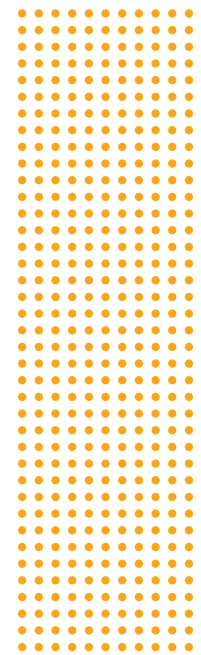
Substance	Number of Clicks (IMF Strength)
Argon (Ar)	6
Nitrogen Trifluoride (NF ₃)	9
Ammonia (NH ₃)	12
Magnesium Oxide (MgO)	15 (inferred)

LOCK IT IN:

Does the temperature of the substance change as you break the intermolecular forces? How does this demonstrate that the Enthalpy/Heat of Vaporization is an example of a latent heat?



The temperature of the substance in the game does not increase as you break the intermolecular forces. By definition, latent heat is heat transfer that occurs without a temperature change. This definition perfectly describes what happens in the game. The heat of vaporization is represented by the total number of clicks necessary to convert the substance from liquid to gas. The fact that the temperature does not increase during this process demonstrates that the heat of vaporization is a latent heat. Accordingly, it is sometimes referred to as the latent heat of vaporization.





OBJECTIVE 1

Demonstrate an understanding of the relationships between intermolecular forces, the heat of vaporization and the processes of boiling, evaporation, and condensation.

The heat of vaporization of a substance can be used in many useful ways. One simple calculation that helps to reinforce your understanding of the concept is the use of the heat of vaporization to determine the amount of energy that would be needed to vaporize a certain quantity of a substance. Take a look at the steps below to see how ΔH_{vap} is used to determine the amount of energy needed to vaporize 4 grams of ethanol ($\text{C}_2\text{H}_6\text{O}$) at its normal boiling point of 78.3°C .

Conversion Sequence: Mass of Substance \rightarrow Moles of Substance \rightarrow Energy Required to Vaporize

$$4.00 \text{ g C}_2\text{H}_6\text{O} \times \frac{1 \text{ mol C}_2\text{H}_6\text{O}}{46.1 \text{ g C}_2\text{H}_6\text{O}} \times \frac{40.7 \text{ kJ}}{1 \text{ mol C}_2\text{H}_6\text{O}} = 3.53 \text{ kJ}$$

TASK 3: Use the heat of vaporization to calculate the amount of energy needed to vaporize 10.0 grams of each of the substances from the sandbox below at their boiling points. The ΔH_{vap} at the normal boiling point of each substance has been provided for you. Use a periodic table to help you determine any molar masses.

Substance	ΔH_{vap} at Normal Boiling Point (kJ/mol)	Calculations	Energy Needed to Vaporize 10 grams at Normal Boiling Point (kJ)
Hydrogen Iodide (HI)	19.76	$10.0 \text{ g HI} \times \frac{1 \text{ mol HI}}{127.9 \text{ g HI}} \times \frac{19.76 \text{ kJ}}{1 \text{ mol HI}}$	1.54
Ammonia (NH_3)	23.37	$10.0 \text{ g NH}_3 \times \frac{1 \text{ mol NH}_3}{17.0 \text{ g NH}_3} \times \frac{23.37 \text{ kJ}}{1 \text{ mol NH}_3}$	13.7



OBJECTIVE 1

Demonstrate an understanding of the relationships between intermolecular forces, the heat of vaporization and the processes of boiling, evaporation, and condensation.

Magnesium Oxide (MgO)	330.7	$10.0 \text{ g MgO} \times \frac{1 \text{ mol MgO}}{40.3 \text{ g MgO}} \times \frac{330.7 \text{ kJ}}{1 \text{ mol MgO}}$	82.1
Dinitrogen (N ₂)	2.79	$10.0 \text{ g N}_2 \times \frac{1 \text{ mol N}_2}{28.0 \text{ g N}_2} \times \frac{2.79 \text{ kJ}}{1 \text{ mol N}_2}$	0.996

LOCK IT IN:

Explain why the amount of energy required to vaporize 10.0 grams of ammonia is so much greater than that required for dinitrogen.



LOCK IT IN:

Make sure to convert any new substances in the table from liquid to gas in the sandbox. Did the substance for which you calculated the highest amount of energy needed to vaporize 10 grams require more clicks than the one for which you calculated the least?

The amount of energy needed to vaporize these substances at their boiling points increases with the increase in strength of the intermolecular forces. Ammonia is capable of hydrogen bonding while dinitrogen is not. In fact, dinitrogen does not even have a dipole. As a result, much less energy is required to vaporize dinitrogen than ammonia.

Yes, dinitrogen only required six clicks compared to magnesium oxide for which there was not enough energy available to vaporize it in the sandbox.

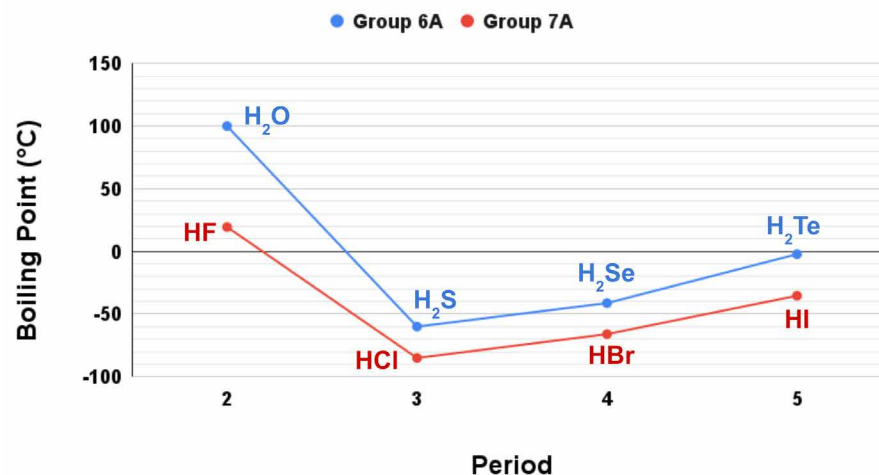


OBJECTIVE 1

Demonstrate an understanding of the relationships between intermolecular forces, the heat of vaporization and the processes of boiling, evaporation, and condensation.

TASK 4: Study the graph below. Explain why the normal boiling points of the hydrides of oxygen (H_2O) and fluorine (HF) are anomalously high when compared to their analogs in periods 3, 4, and 5. Would you expect the same with the hydride of nitrogen (NH_3) compared to the rest of its group? What about the hydride of carbon (CH_4) compared to the rest of its group? Explain your answers.

Boiling Points of the Hydrogen Chalcogenides and Hydrogen Halides



The hydrides of oxygen (water) and fluorine (hydrogen fluoride) are anomalously high due to their ability to form hydrogen bonds. Because oxygen and fluorine are small, electronegative atoms compared to the other members of their groups, they are able to create strongly polar bonds with hydrogen atoms that can then interact with the lone pairs on other water or hydrogen fluoride molecules. This relatively strong interaction gives them much higher boiling points than would be predicted based on group and molar mass alone. A similar pattern would be expected for the hydride of nitrogen (ammonia) due to nitrogen's high electronegativity, but not the hydride of carbon (methane). The bond between carbon and hydrogen is not nearly polar enough to allow for hydrogen bonding. As a result, it does not have the elevated boiling point seen in the other three substances.

LOCK IT IN:

Would you expect the same pattern to exist in the heat of vaporization of these substances at their boiling points? Why or why not?



The same pattern would be expected to hold for the heats of vaporization for these substances. The hydrogen bonding capabilities of water, hydrogen fluoride, and ammonia increases the amount of energy required to vaporize them, thus giving each an anomalously high heat of vaporization. For example, both oxygen and sulfur are in the same group with sulfur having more electrons than oxygen (and is thus more polarizable). However, the heat of vaporization of water at its boiling point is just under 41 kJ/mol, while it is less than 20 kJ/mol for hydrogen sulfide.

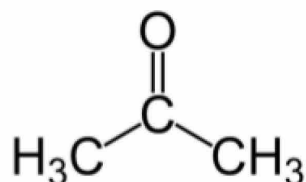


OBJECTIVE 1

Demonstrate an understanding of the relationships between intermolecular forces, the heat of vaporization and the processes of boiling, evaporation, and condensation.

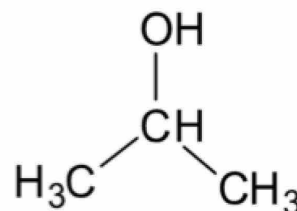
TASK 5: The same volume of each of the substances shown below are spread on a surface such that they have an equivalent surface area exposed to the air. Which substance will evaporate the fastest? Justify your answer. Make sure to include the term **heat of vaporization** in your explanation.

Acetone



Molar Mass - 58.1 g/mol

Isopropyl Alcohol



Molar Mass - 60.1 g/mol

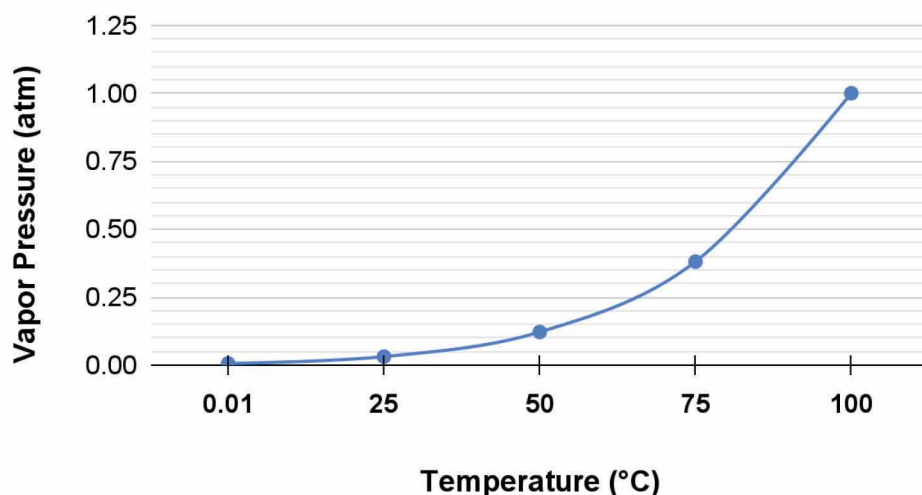
Acetone will evaporate faster than isopropyl alcohol due to its lower heat of vaporization. Although both substances are of similar size and structure, isopropyl alcohol is capable of hydrogen bonding while acetone is not. In both molecules there is an oxygen atom bonded to the central carbon atom. In acetone, this oxygen forms a double bond with carbon. However, in isopropyl alcohol, the oxygen atom forms a single bond with carbon AND a single bond with a hydrogen atom. The presence of this hydrogen atom bonded to oxygen allows for hydrogen bonding in isopropyl alcohol stronger than the dipole-dipole interaction between acetone molecules. As a result, isopropyl alcohol has a higher heat of vaporization and thus a higher energy requirement for evaporation.



OBJECTIVE 2

Demonstrate an understanding of how the Clausius-Clapeyron Equation can be used to determine the heat of vaporization and predict vapor pressure.

Vapor Pressure of Water as a function of Temperature



The **boiling point** of a substance is simply the temperature at which its **vapor pressure** is equivalent to the surrounding pressure (please reference your textbook for more information on vapor pressure). This definition helps explain why the boiling point of water in Denver, Colorado at a higher elevation, and thus lower atmospheric pressure, is lower than in New York City which is near sea level.

Note the graph of the vapor pressure of water by temperature. As the temperature of the water increases, so does its vapor pressure. However, the relationship between temperature and vapor pressure is not linear. Instead, vapor pressure increases exponentially and for water does not equal the mean atmospheric pressure at sea level until it reaches 100°C in temperature.

The relationship between vapor pressure and temperature can be given using the **Clausius-Clapeyron equation** (see your textbook for more information). A modified version of the equation allows us to predict the vapor pressure of a substance at a given temperature where P is pressure, R is the ideal gas constant, ΔH_{vap} is the heat of vaporization, and T is temperature:

$$\ln \frac{P_2}{P_1} = -\frac{\Delta H_{\text{vap}}}{R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right)$$



OBJECTIVE 2

Demonstrate an understanding of how the Clausius-Clapeyron Equation can be used to determine the heat of vaporization and predict vapor pressure.

Let's use a simple example to practice using the Clausius-Clapeyron equation to estimate vapor pressure. Note that this will be an estimate and not an exact calculation due to the fact that the heat of vaporization varies with temperature.

The boiling point of water at 1 atm of pressure is 100°C and the ΔH_{vap} is 40.7 kJ/mol. Predict the vapor pressure of water at 61°C.

Convert the temperatures from degrees Celsius to Kelvin.	$T_1 = 100^\circ\text{C} + 273.15 = 373.15 \text{ K}$ $T_2 = 61^\circ\text{C} + 273.15 = 334.15 \text{ K}$
Convert the ΔH_{vap} from kJ/mol to J/mol.	$\frac{40.7 \text{ kJ}}{1 \text{ mol}} \times \frac{1000 \text{ J}}{1 \text{ kJ}} = 40,700 \text{ J}$
Enter the following into the Clausius-Clapeyron equation: <ul style="list-style-type: none">• 1 atm for P_1• 40,700 J/mol for ΔH_{vap}• 8.134 J/mol K for R• 334.15 K for T_2• 373.15 K for T_1	$\ln \frac{P_2}{1 \text{ atm}} = \frac{-40,700 \frac{\text{J}}{\text{mol}}}{8.134 \frac{\text{J}}{\text{mol K}}} \left(\frac{1}{334.15 \text{ K}} - \frac{1}{373.15 \text{ K}} \right)$
Solve for P_2 (vapor pressure at temperature of interest) algebraically.	$e^{\left(\ln \frac{P_2}{1 \text{ atm}} \right)} = \frac{-40,700 \frac{\text{J}}{\text{mol}}}{8.134 \frac{\text{J}}{\text{mol K}}} \left(\frac{1}{334.15 \text{ K}} - \frac{1}{373.15 \text{ K}} \right)$ $e^{-1.53}$ $P_2 = e^{-1.53}$ $P_2 = 0.216 \text{ atm}$



OBJECTIVE 2

Demonstrate an understanding of how the Clausius-Clapeyron Equation can be used to determine the heat of vaporization and predict vapor pressure.

TASK 6: Use the Clausius-Clapeyron equation to determine the vapor pressures at 200 Kelvin for three substances found in the sandbox.

Substance	Boiling Point at 1 atm of pressure (K)	ΔH_{vap} (kJ/mol)	Calculation	Vapor Pressure at 200 K (atm)
Fluoromethane (CH ₃ F)	194.75	17.1	$P_2 = e^{\frac{-17,100 \frac{\text{J}}{\text{mol}}}{8.134 \frac{\text{J}}{\text{mol K}}} \left(\frac{1}{200 \text{ K}} - \frac{1}{194.75} \right)}$	1.33
Methane (CH ₄)	111.55	8.17	$P_2 = e^{\frac{-8,170 \frac{\text{J}}{\text{mol}}}{8.134 \frac{\text{J}}{\text{mol K}}} \left(\frac{1}{200 \text{ K}} - \frac{1}{111.55} \right)}$	53.6
Ammonia (NH ₃)	239.85	23.4	$P_2 = e^{\frac{-23,400 \frac{\text{J}}{\text{mol}}}{8.134 \frac{\text{J}}{\text{mol K}}} \left(\frac{1}{200 \text{ K}} - \frac{1}{239.85} \right)}$	0.787

LOCK IT IN:

Explain why these substances had different vapor pressures using each of the following terms: heat of vaporization, London dispersion forces, dipole-dipole interactions, and hydrogen bonding.



The heat of vaporization tells us the amount of energy that is required to break the intermolecular forces in a liquid so that a substance becomes a gas. The stronger the intermolecular forces, the higher the heat of vaporization, and the lower the vapor pressure of the substance at a given temperature. All of the substances have dispersion forces, but substances like ammonia are capable of hydrogen bonding. The relative strength of hydrogen bonding helps keep ammonia's vapor pressure the lowest of the three. Notice how 200 K is below the normal boiling point of ammonia, so its vapor pressure is not yet equal to 1 atmosphere. Fluoromethane is not capable of hydrogen bonding, but does have dipole-dipole interactions. This gives it the second lowest vapor pressure. Methane has both weaker dispersion forces than fluoromethane and lacks hydrogen bonding or dipole-dipole interactions. As a result, it vaporizes the easiest and results in the highest vapor pressure.



OBJECTIVE 2

Demonstrate an understanding of how the Clausius-Clapeyron Equation can be used to determine the heat of vaporization and predict vapor pressure.

Let's use another example to practice using the Clausius-Clapeyron equation to estimate the heat of vaporization instead:

At 100.00°C, the vapor pressure of water is 1.000 atm. The vapor pressure of water at 45.00°C is 0.0943 atm.

Convert the temperatures from degrees Celsius to Kelvin.	$T_1 = 100.00^\circ\text{C} + 273.15 = 373.15 \text{ K}$ $T_2 = 45.00^\circ\text{C} + 273.15 = 318.15 \text{ K}$
Enter the following into the Clausius-Clapeyron equation: <ul style="list-style-type: none"> • 1 atm for P_1 • 0.0943 atm for P_2 • 8.134 J/mol K for R • 318.15 K for T_2 • 373.15 K for T_1 	$\ln \frac{0.0943 \text{ atm}}{1.00 \text{ atm}} = \frac{-\Delta H_{\text{vap}}}{8.134 \frac{\text{J}}{\text{mol} \cdot \text{K}}} \left(\frac{1}{318.15 \text{ K}} - \frac{1}{373.15 \text{ K}} \right)$
Solve algebraically for ΔH_{vap}	$\ln \frac{0.0943 \text{ atm}}{1.00 \text{ atm}} = \frac{-\Delta H_{\text{vap}}}{8.134 \frac{\text{J}}{\text{mol} \cdot \text{K}}} \left(\frac{1}{318.15 \text{ K}} - \frac{1}{373.15 \text{ K}} \right)$ $-2.3613 = \frac{-\Delta H_{\text{vap}}}{8.134 \frac{\text{J}}{\text{mol} \cdot \text{K}}} \left(0.00046328 \text{ K}^{-1} \right)$ $\Delta H_{\text{vap}} = 41,500 \frac{\text{J}}{\text{mol}}$
Convert the ΔH_{vap} from J/mol to kJ/mol when necessary.	$\frac{41,500 \text{ J}}{1 \text{ mol}} \times \frac{1 \text{ kJ}}{1000 \text{ J}} = 41.5 \frac{\text{kJ}}{\text{mol}}$ <p>*Note that your answer is only an estimate of ΔH_{vap}</p>



OBJECTIVE 2

Demonstrate an understanding of how the Clausius-Clapeyron Equation can be used to determine the heat of vaporization and predict vapor pressure.

TASK 7: Calculate ΔH_{vap} at the normal boiling point for three sandbox substances using the Clausius-Clapeyron equation.

Substance	Boiling Point at 1.00 atm (K)	Vapor Pressure at 200.0 K (atm)	Calculation	Estimated ΔH_{vap} (kJ/mol)
Xenon (Xe)	165.05	4.998	$\ln \frac{4.998 \text{ atm}}{1.00 \text{ atm}} = \frac{-\Delta H_{\text{vap}}}{8.134 \frac{\text{J}}{\text{mol} \cdot \text{K}}} \left(\frac{1}{200.0 \text{ K}} - \frac{1}{165.05 \text{ K}} \right)$	12.4
Nitrogen Trifluoride (NF ₃)	144.05	14.88	$\ln \frac{14.88 \text{ atm}}{1.00 \text{ atm}} = \frac{-\Delta H_{\text{vap}}}{8.134 \frac{\text{J}}{\text{mol} \cdot \text{K}}} \left(\frac{1}{200.0 \text{ K}} - \frac{1}{144.05 \text{ K}} \right)$	11.3
Formaldehyde (CH ₂ O)	254.05	0.04465	$\ln \frac{0.04465 \text{ atm}}{1.00 \text{ atm}} = \frac{-\Delta H_{\text{vap}}}{8.134 \frac{\text{J}}{\text{mol} \cdot \text{K}}} \left(\frac{1}{200.0 \text{ K}} - \frac{1}{254.05 \text{ K}} \right)$	23.8



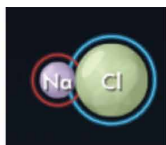
OBJECTIVE 3

Demonstrate an understanding of the role of the heat of fusion in the processes of melting and freezing.

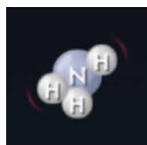
Melting and freezing are probably the two most well-known phase changes. They, too, involve a latent heat like we saw when discussing vaporization. However, this latent heat is known as the heat/enthalpy of fusion (ΔH_{fus}). When a mole of ice melts, it has absorbed 6.02 kJ of heat. This means that the heat of fusion of water is + 6.02 kJ/mol. Since melting is an endothermic process, the heat of fusion is positive. The opposite is true for freezing, which is an exothermic process. Accordingly, the heat/enthalpy of solidification is equal and opposite the heat of fusion. For water, this means the heat of solidification is - 6.02 kJ/mol.

As with the heat of vaporization and heat of condensation, the heat of fusion and heat of solidification are directly related to the strength of the intermolecular forces in a substance. It requires more energy to overcome stronger intermolecular forces and enact a phase change.

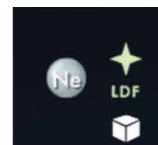
TASK 8: Below are four substances available to you in the sandbox. Rank them by their heat of fusion and justify your logic.



Sodium Chloride (NaCl)



Ammonia (NH₃)



Neon (Ne)



Dinitrogen (N₂)

	Substance	Justification
Highest Heat of Fusion	Sodium Chloride (NaCl)	The strength of the interaction between oppositely charged ions causes sodium chloride to have a much higher heat of fusion than the other substances here.
	Ammonia (NH ₃)	Although not nearly as strong as the interactions between ions in a crystal, hydrogen bonding in ammonia gives it a higher heat of fusion than neon and dinitrogen.
	Dinitrogen (N ₂)	Both neon and dinitrogen have only dispersion forces between particles, however dinitrogen has more electrons and is thus more polarizable. The result is slightly greater dispersion forces and a slightly larger heat of fusion.
Lowest Heat of Fusion	Neon (Ne)	Neon, as a small noble gas, has relatively weak dispersion forces and thus the lowest heat of fusion of these substances.

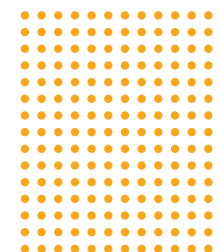


OBJECTIVE 3

Demonstrate an understanding of the role of the heat of fusion in the processes of melting and freezing.

TASK 9: Take the following substances and convert them to liquids in the sandbox: **ammonia (NH₃), nitrogen trifluoride (NF₃), argon (Ar), and magnesium oxide (MgO)**. Each substance has been chosen to represent hydrogen bonding, dipole-dipole interactions, London dispersion forces, and ionic bonding respectively. Pay careful attention to how much energy is used in breaking the intermolecular forces in order to convert each substance from solid to liquid. This is the heat of fusion! Record the **total number of clicks** it takes to remove the intermolecular forces that are holding the solid together just before it becomes a liquid. **Then return to Task 2 and copy into the table below the total number of clicks that represent the heat of vaporization.**

Substance	Number of Clicks (Heat of Fusion)	Number of Clicks (Heat of Vaporization)
Argon (Ar)	2	6
Nitrogen Trifluoride (NF ₃)	3	9
Ammonia (NH ₃)	4	12
Magnesium Oxide (MgO)	5	15 (inferred)



LOCK IT IN:

Compare the amount of energy needed to melt a substance (heat of fusion) with the amount of energy needed to vaporize a substance (heat of vaporization). Explain why such a difference exists.



The energy needed to melt a substance (heat of fusion) is much less than the energy needed to vaporize a substance (heat of vaporization). We know that energy is required to overcome the intermolecular forces that keep the particles of a solid together and thus melt a substance. This is the heat of fusion. Although the attraction that particles in a liquid have towards one another is less than the attraction in a solid, the distinction is much greater between liquids and gases. Particles in the gaseous state have overcome intermolecular forces enough to move independently and spread out. The amount of energy to enact such a change (the heat of vaporization) is much greater than for the change from solid to liquid.



OBJECTIVE 4

Demonstrate an understanding of the concepts of sublimation and deposition.

If you have ever spent a long time in a cold, snowy region during the winter, you have probably noticed that even when the temperature remains below freezing for a long time after a snowstorm, the snowpack still gradually diminishes. The answer as to how this snow “disappears” is that the process of sublimation is occurring. During sublimation, water molecules in the solid state enter directly into the gaseous state without ever entering the liquid state. The amount of energy required to convert a solid directly into a gas is known as the **heat of sublimation (ΔH_{sub})** and is given a positive value due to being an endothermic process. The opposite of the heat of sublimation is the **heat of deposition (ΔH_{dep})**, which describes the energy released as a substance goes from the gaseous state directly to the solid state.

The heat of sublimation is essentially the sum of a substance’s heat of fusion and heat of vaporization since those two enthalpies overall represent the energy required to disrupt the intermolecular forces enough to produce a gas from a solid. Likewise, the heat of deposition is essentially the sum of the heat of condensation and heat of solidification.

Argon atoms and carbon dioxide molecules are both small particles in which London dispersion forces are the only intermolecular force. Convert each substance from a solid to a gas using the sandbox. Notice that solid argon goes through a liquid phase before becoming a gas, while carbon dioxide does not. At one atmosphere of pressure, argon goes through both melting and boiling. At the same pressure, carbon dioxide only goes through sublimation. The best way to think about why this distinction occurs is by considering the **triple point** of each substance. The triple point is the temperature and pressure at which a substance exists stably in the gas, liquid, and solid phases (covered in Task 10). Sublimation typically occurs at temperatures and pressures below the triple point of a substance. The triple point of argon is at about 84 K and 0.68 atmospheres. Since the game uses a pressure of 1 atmosphere—above the triple point pressure of argon—melting and boiling occur. Carbon dioxide’s triple point, however, is just under 216 K and 5.11 atmospheres. The triple point pressure of carbon dioxide is well above the conditions of the game, and thus we can see sublimation occur instead.

LOCK IT IN:

Explain why the game uses the same number of clicks to convert argon from a solid to a gas as it does for carbon dioxide even though carbon dioxide only goes through one phase change compared to argon’s two.



The game uses the same number of clicks to emphasize that even though the process of sublimation essentially skips the liquid state, the amount of energy required to convert a substance from a solid to a gas cannot be skipped. This is because the energy required to free particles from the intermolecular forces of a solid and into a gas is the same whether or not a liquid state is included.

***Note:** The heat energy to convert argon from a solid to a gas is not actually equal due to them being different substances. However, they are both used to represent small molecules with only dispersion forces between particles.



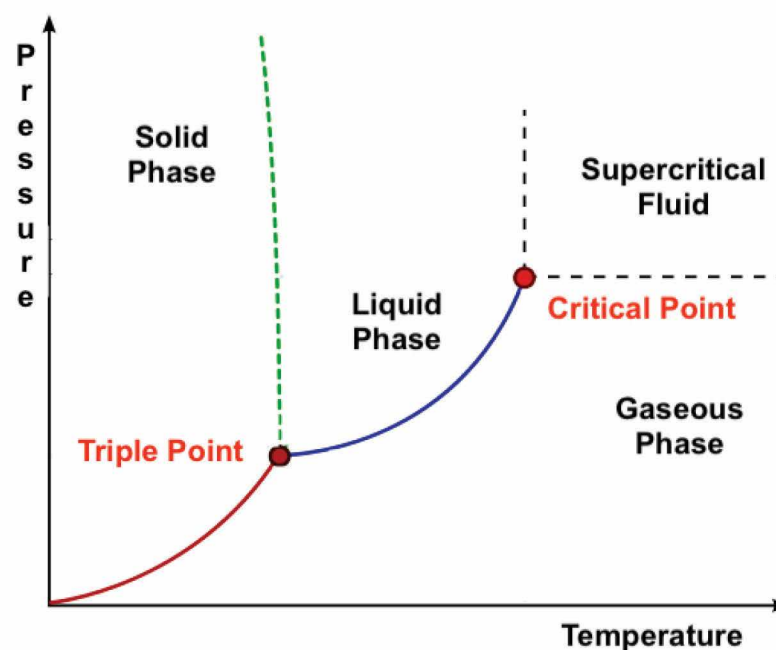
OBJECTIVE 5

Demonstrate an understanding of how to interpret heating curves and phase diagrams.

It is important to remember that the phase of matter of a substance is not only determined by temperature, but also pressure. **Phase diagrams** are a graphical means of depicting the phase of matter in which a substance will be at a given temperature and pressure. There are several key components of a phase diagram, each of which gives us important information.

1. The lines on the diagram represent temperatures and pressures at which the substance is in equilibrium between two phases. One line is the sublimation curve (solid to gas), another the vaporization curve (liquid to gas), and the third is the fusion curve (solid to liquid).
2. The regions between the lines represent a range of temperatures and pressures where substances are in the same phase of matter.
3. The point where the three lines meet is called the **triple point**. At this temperature and pressure, the substance is stable in the solid, liquid, and gas phases.
4. The point where the vaporization curve ends is known as the **critical point** and marks the temperature and pressure above which the substance will be a **supercritical fluid**.

For more detailed information on phase diagrams, please reference your textbook or lecture notes.



Phase diagram by Matthieu Marechal, [CC-BY SA 3.0](https://creativecommons.org/licenses/by-sa/3.0/)



OBJECTIVE 5

Demonstrate an understanding of how to interpret heating curves and phase diagrams.

TASK 10: Use the phase diagram below to answer each of the questions.

1. In what phase of matter is this substance at a temperature of 275 K and a pressure of 100 bar?

The substance is a liquid at a temperature of 275 K and a pressure of 100 bar.

2. What phase transition occurs when this substance is heated from 200 K to 250 K at a pressure of 5 bar?

At 5 bar, the transition described would be sublimation.

3. What phase transition occurs when this substance is cooled from 290 K to 200 K at a pressure of 100 bar?

At 100 bar, the transition described would be freezing.

4. What phase transition occurs when this substance is maintained at a constant temperature of 250 K but the pressure is increased from 1 bar to 70 bar?

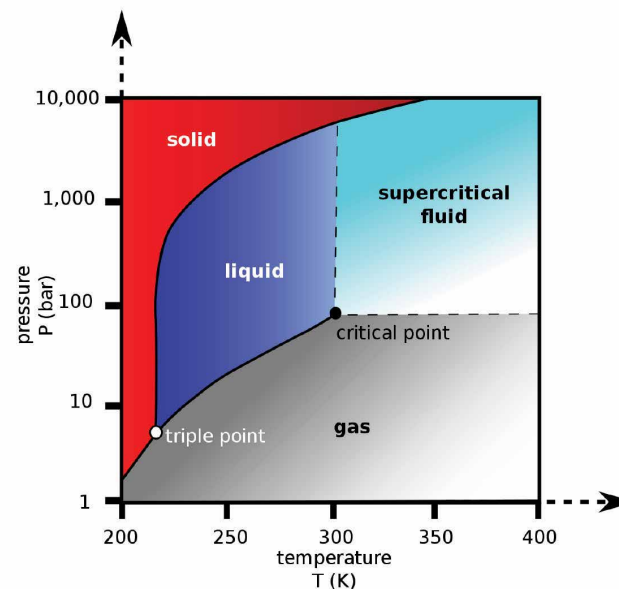
At 250 K, the transition described would be condensation.

5. Identify a pressure at which this substance would change from solid to liquid to gas if heated from 200 to 250 K.

This would be true at any pressure between the triple and critical point pressures (~5.2 bar to ~73.8 bar).

6. The phase changes in the sandbox are performed at one atmosphere of pressure (about 1.013 bar). Use the sandbox to determine if the phase diagram is that of hydrogen iodide (HI), ammonia (NH₃), or carbon dioxide (CO₂). Justify your answer.

This phase diagram is for carbon dioxide. At just above 1 bar of pressure for the substance in the diagram is sublimation. Of the three options provided, only carbon dioxide undergoes sublimation in the sandbox.



Phase Diagram by Mark Jacobs, [CCO](#)



OBJECTIVE 5

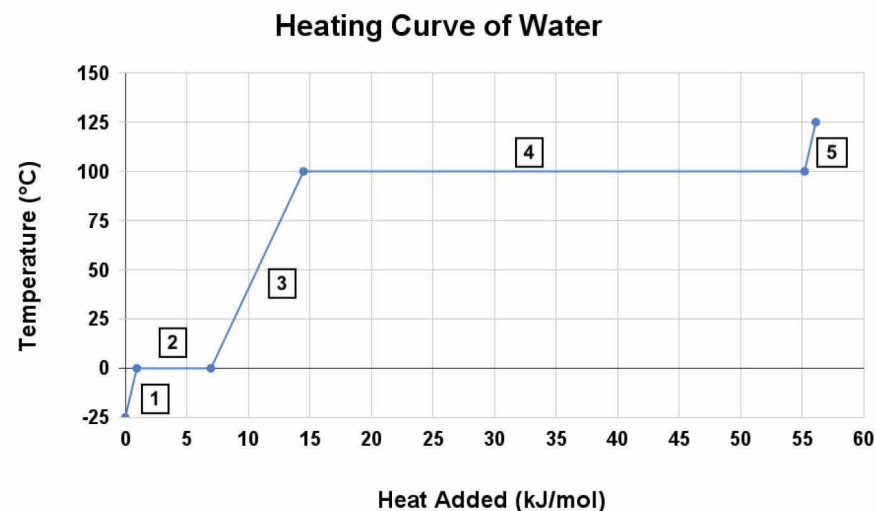
Demonstrate an understanding of how to interpret heating curves and phase diagrams.

Heating curves are graphs that show the temperature of a substance as heat is added to it at a constant pressure. They are essentially a graphical representation of all of the concepts you have seen as part of this extension activity.



Take a close look at the heating curve above for the heating of water at one atmosphere of pressure. Key aspects of the curve can be outlined in five main parts that match the numbered sections of the graph.

1. Starting with ice and adding heat, the temperature increases until it reaches water's melting point of 0°C .
2. As you saw in the Latent Heat Game, additional heat at the melting point goes into breaking intermolecular forces as the solid ice melts into liquid water. The temperature does not change here and this added heat reflects the heat of fusion.
3. Additional heat causes the temperature of the now liquid water to increase further, but at a slower rate as indicated by the smaller slope of the curve. This difference in heating rate is the result of ice having a much lower heat capacity than liquid water. The heat capacity of a substance describes the amount of heat required to change the temperature of the substance by a certain amount.
4. The temperature of the water continues increasing until it reaches its boiling point at 100°C . At this point, additional heat once again goes into breaking intermolecular forces and the temperature does not increase. Notice that the amount of heat added during this stage is much larger than in stage two. This is because the heat of vaporization is typically much greater than the heat of fusion.
5. After all of the liquid water has been converted to vapor, added heat continues to increase the temperature of the water. However, the rate of increase changes yet again and becomes quicker than when the water was a liquid. This difference in the rate of heating is the result of a difference in heat capacity between water vapor and liquid water.

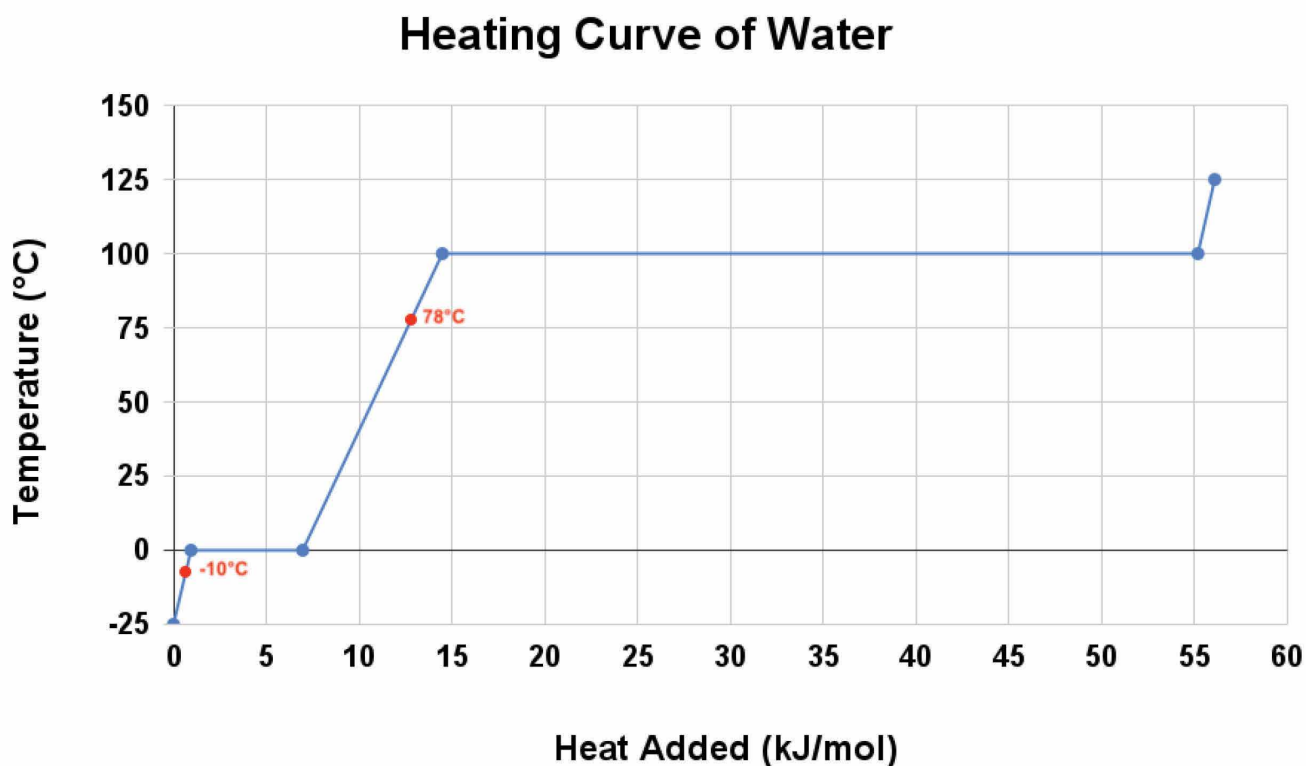




OBJECTIVE 5

Demonstrate an understanding of how to interpret heating curves and phase diagrams.

Heating curves can be helpful in calculating the amount of heat needed to raise the temperature of a substance by a certain amount. Take a look at the steps below on how to determine the amount of heat that would need to be added to **10.0 grams of ice at -10.0°C to convert it to liquid water at 78.0°C** . Use the example to help you complete Task 11.





OBJECTIVE 5

Demonstrate an understanding of how to interpret heating curves and phase diagrams.

Step Description	Process
Use the heating curve to help you determine the regions of heating to calculate.	<ol style="list-style-type: none"> From - 10°C to 0°C (warming of the ice) From 0°C ice to 0°C liquid water (heat of fusion) From 0°C to 78°C (warming of the liquid water)
<p>Use the following formula to calculate the heat necessary for each region of heating:</p> $q = mc \Delta T$ <p> q = heat transferred m = mass C = specific heat capacity (not present for latent heat) ΔT = change in temperature (or latent heat) </p>	<ol style="list-style-type: none"> From - 10°C to 0°C Specific Heat Capacity of Ice: 2.093 J/g $q = (10.0 \text{ g}) (2.093 \frac{\text{J}}{\text{g}^\circ\text{C}}) (10.0^\circ\text{C})$ $q = 209.3 \text{ J}$ Heat of Fusion Heat of Fusion of Water: 334 J/g $q = (10.0 \text{ g}) (334 \frac{\text{J}}{\text{g}})$ $q = 3340 \text{ J}$ From 0°C to 78°C Specific Heat Capacity of Liquid Water: 4.184 J/g $q = (10.0 \text{ g}) (4.184 \frac{\text{J}}{\text{g}^\circ\text{C}}) (78.0^\circ\text{C})$ $q = 3,263.52 \text{ J}$
Sum the heats calculated for each region of the heating curve. Convert to kilojoules (kJ) by dividing by 1000 if needed.	$q = 209.3 \text{ J} + 3,263.52 \text{ J} + 3340 \text{ J}$ $q = 6,812 \text{ J}$ $q = 6.812 \text{ kJ}$





OBJECTIVE 5

Demonstrate an understanding of how to interpret heating curves and phase diagrams.

TASK 11: Determine the amount of heat needed to take 22.0 grams of water from ice at -2.00°C to steam at 110.0°C . Show your work in the space below and write your final answer in kilojoules (kJ). The heat of vaporization of water at its normal boiling point is 2257 J/g and the specific heat capacity of water vapor is $2.03 \text{ J/g } ^{\circ}\text{C}$. Obtain the remaining values from the example problem.

$$q_{\text{ice}} = (22.0 \text{ g}) (2.093 \frac{\text{J}}{\text{g}^{\circ}\text{C}}) (2.00^{\circ}\text{C})$$
$$q_{\text{ice}} = 92.092 \text{ J}$$

$$q_{\text{fus}} = (22.0 \text{ g}) (334 \frac{\text{J}}{\text{g}})$$
$$q_{\text{fus}} = 7,348 \text{ J}$$

$$q_{\text{water}} = (22.0 \text{ g}) (4.184 \frac{\text{J}}{\text{g}^{\circ}\text{C}}) (100.0^{\circ}\text{C})$$
$$q_{\text{water}} = 9,204.8 \text{ J}$$

$$q_{\text{vap}} = (22.0 \text{ g}) (2257 \frac{\text{J}}{\text{g}})$$
$$q_{\text{vap}} = 49,654 \text{ J}$$

$$q_{\text{steam}} = (22.0 \text{ g}) (2.03 \frac{\text{J}}{\text{g}^{\circ}\text{C}}) (10.0^{\circ}\text{C})$$
$$q_{\text{steam}} = 446.6 \text{ J}$$

$$q_{\text{total}} = q_{\text{ice}} + q_{\text{fus}} + q_{\text{water}} + q_{\text{vap}} + q_{\text{steam}}$$

$$q_{\text{total}} = 92.092 \text{ J} + 7,348 \text{ J} + 9,204.8 \text{ J} + 49,654 \text{ J} + 446.6 \text{ J}$$

$$q_{\text{total}} = 66,745 \text{ J}$$

$$q_{\text{total}} = 66.745 \text{ kJ}$$



OBJECTIVE 6

Demonstrate an understanding of the fundamental types of crystalline solids and their phase changes.

As you might have noticed while playing the Latent Heat game, the particles in the solid phase of each sandbox substance are arranged into an ordered pattern held together by intermolecular forces. All of these substances are examples of crystalline solids, of which there are three broad categories—**molecular solids**, **ionic solids**, and **atomic solids**.

- In molecular solids, each individual particle in the crystal is a molecule. Dry ice (solid carbon dioxide) would be an example of a molecular solid. Molecular solids are held together either by dispersion forces, dipole-dipole interactions, and/or hydrogen bonding.
- In ionic solids, each individual particle is an ion. A calcium chloride crystal would be an example of an ionic solid. Ionic solids are held together by coulombic forces.
- In atomic solids, each individual particle is an atom. Solid radon, a piece of iron, and a diamond are all examples of atomic solids. Each represents a different category of atomic solid. Solid radon is held together only by dispersion forces and is thus considered a **nonbonding solid**. A piece of iron, however, is held together by metallic bonds (see your textbook for details) and is thus considered a **metallic solid**. Diamond is composed of carbon atoms covalently bonded together to form an extensive network. Diamond is thus considered a **network covalent solid**.



OBJECTIVE 6

Demonstrate an understanding of the fundamental types of crystalline solids and their phase changes.

TASK 12: Sort all of the substances available in the sandbox into the type of solid they form by completing the table below.

Crystalline Solid Type	Examples
Molecular Solid	HI, OF ₂ , H ₂ O, SO ₂ , CO ₂ , N ₂ , NF ₃ , NH ₃ , HCN, CH ₂ O, CH ₄ , and CH ₃ F
Ionic Solid	MgO and NaCl
Atomic Solid (nonbonding)	Ne, Ar, and Xe

LOCK IT IN:

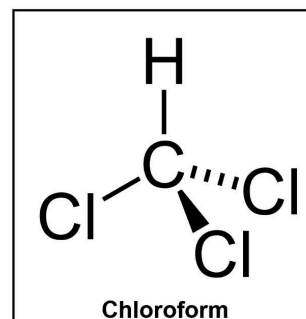
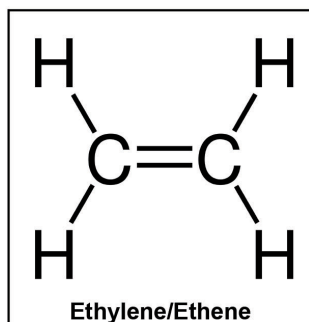
Use the sandbox to determine the melting points at one atmosphere of pressure of two solids of each type. Which type of crystalline solid as a group has the highest melting point—molecular, ionic, or nonbonding atomic solids? Explain why this is the case.

Of these groups, the ionic solids have the highest melting points. This is the result of the stronger intermolecular forces in an ionic crystal compared to molecular solids and nonbonding atomic solids.



CLOSURE

CLOSURE: Below are two molecules that are not found in the sandbox. For each property, determine which value belongs to each molecule using your knowledge of intermolecular forces and the concepts in the latent heat game. Simply write the correct option in the column underneath the picture of the molecule. Justify your choices in the column to the far right of the table.



Property		Options		Justification
Intermolecular Forces Present	London Dispersion Forces	Choose as many as needed: Hydrogen Bonding London Dispersion Forces Dipole-Dipole Interactions	Dipole-Dipole Interactions London Dispersion Forces	Ethylene is composed solely of carbon and hydrogen and thus has no polar bonds. As a result, only dispersion forces are present. Chloroform, however, has a dipole and thus dipole-dipole interactions in addition to dispersion forces.
Melting Point (°C)	-169.2	-169.2 or -63.5	-63.5	Chloroform's larger number of electrons give it greater dispersion forces than ethylene. It also has dipole-dipole interactions. As a result, it should have a higher melting point.



CLOSURE

Boiling Point (°C)	-103.7	-103.7 or 61.2	61.2	Chloroform's larger number of electrons give it greater dispersion forces than ethylene. It also has dipole-dipole interactions. As a result, it should have a higher boiling point.
Heat of Fusion (kJ/mol)	3.35	8.8 or 3.35	8.8	Stronger intermolecular forces increase the amount of energy required to melt a substance. As such, chloroform should have the greater heat of fusion.
Heat of Vaporization (kJ/mol)	13.5	31.4 or 13.5	31.4	Stronger intermolecular forces increase the amount of energy required to vaporize a substance. As such, chloroform should have the greater heat of vaporization.

