The American Chemical Society General Chemistry Performance Expectations Project: From Task Force to Distributed Process for Implementing Multidimensional Learning

Samuel Pazicni[1*], Donald J. Wink[2], Ashley Donovan[3], John A. Conrad[4], Joshua P. Darr[4], Rachel A. Morgan Theall[5], Dana L. Richter-Egger[4], Adrian Villalta-Cerdas[6], and Deborah Rush Walker[7]

[1]Department of Chemistry, University of Wisconsin, Madison, WI 53706, United States

[2]Department of Chemistry, University of Illinois Chicago, Chicago, IL 60607, United States

[3]Education Division, American Chemical Society, Washington, DC 20036, United States

[4]Department of Chemistry, University of Nebraska Omaha, Omaha, NE 68182, United States

[5]Department of Chemistry and Physics, Southeast Missouri State University, Cape Girardeau, MO 63701, United States

[6]Department of Chemistry, Sam Houston State University, Huntsville, TX 77340, United States

[7]Department of Chemistry, University of Texas Austin, Austin, TX 78712, United States

SUPPORTING INFORMATION

UNIVERISTY OF NEBRASKA OMAHA LEARNING ACTIVITY

Topic: Intermolecular forces

DCI: Structures of chemical compounds influence their physical behavior

CCC: Structure and function

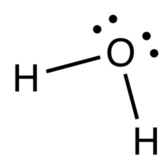
SEP: Developing and using models

Learning Performance: Develop and use a model to explain why a stream of water is attracted to an electrically charged balloon (property) based on bond polarity, molecular geometry, molecular polarity (structure), and the force associated with the attraction between opposite charges.

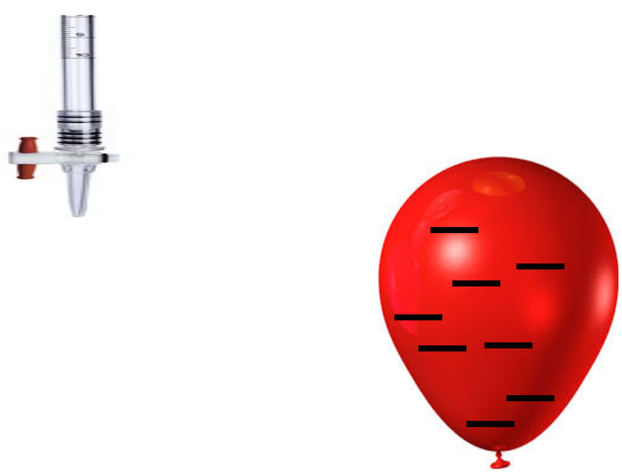
Evidence of Learning Specification: Students use molecular polarity and Coulomb's Law to explain why water is strongly attracted to a negatively charged balloon and oil is not.

TASK

1. Use arrows to indicate bond and molecular polarity of water. Label all regions of partially positive and negative charge. EN(H) = 2.1, EN(O) = 3.5.

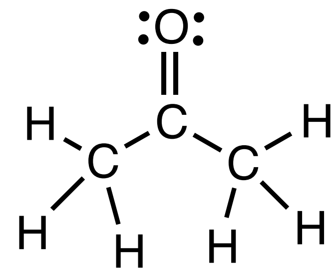


2. Draw a molecular level view of the interaction between the electrically charged balloon and the stream of water. In your drawing include three water molecules at different points along the stream interacting with the electrically charged balloon. Include an arrow to indicate the overall trajectory/flow of the stream.

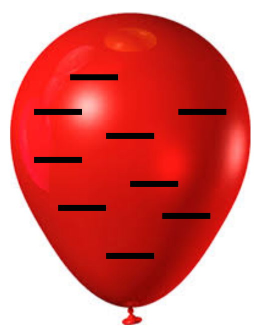


3. Briefly, summarize the interaction between water and the electrically charged balloon.

4. Use arrows to indicate bond and molecular polarity of acetone. Label all regions of partially positive and negative charge. EN(C) = 2.5, EN(H) = 2.1, EN(O) = 3.5.



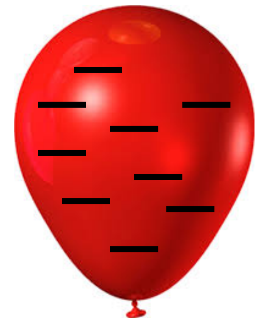
5. Predict and then draw a molecular level view of the possible interaction between the electrically charged balloon and acetone. In your drawing include one acetone molecule interacting with the electrically charged balloon. Include an arrow to indicate the overall trajectory/flow of the stream.



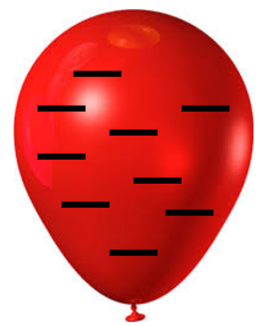
6. Briefly, summarize the interaction between acetone and the electrically charged balloon observed in the demo.

7. After watching the demo of a stream of oil and the electrically charged balloon, what can you conclude about the polarity of the oil?

8. How would a stream of CF_4 interact with this same electrically charged balloon? If an interaction would occur, draw the interaction between one CF_4 molecule and the electrically charge balloon.



9. How would a stream of CH_2F_2 interact with this same electrically charged balloon? If an interaction would occur then draw the interaction between one CH_2F_2 molecule and the electrically charged balloon.



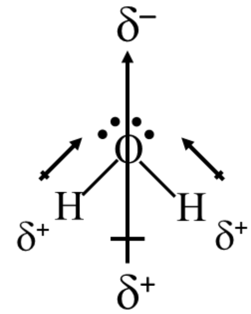
10. What equation have we seen before that describes the attractive nature between charged substances?

11. Using the water and the electrically charge balloon demo as an example, indicate which variables in the equation correspond to the water and the electrically charged balloon?

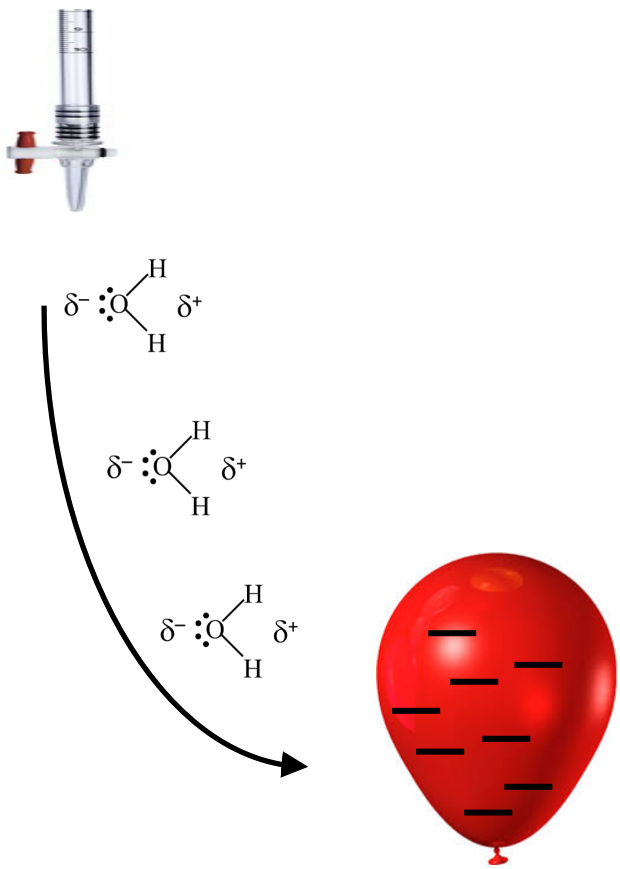
12. Structure-function relationships are very important throughout science and engineering. What is necessary in a molecular structure in order to observe this electrostatic force at the macroscopic level?

IDEAL STUDENT RESPONSES

1. Use arrows to indicate bond and molecular polarity of water. Label all regions of partially positive and negative charge. EN(H) = 2.1, EN(O) = 3.5.



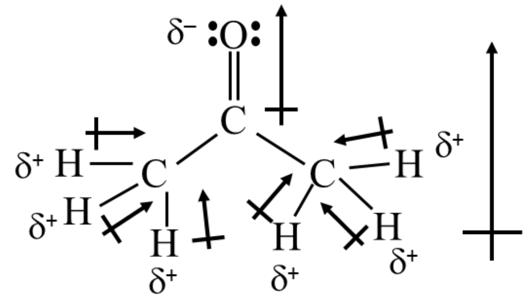
2. Draw a molecular level view of the interaction between the electrically charged balloon and the stream of water. In your drawing include three water molecules at different points along the stream interacting with the electrically charged balloon. Include an arrow to indicate the overall trajectory/flow of the stream.



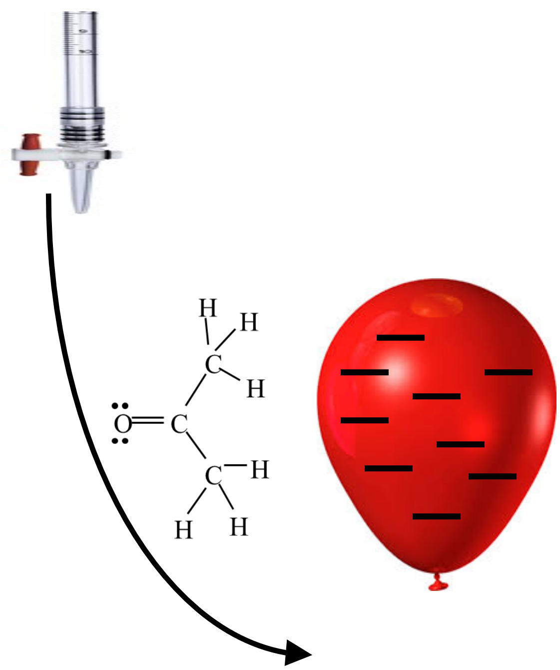
3. Briefly, summarize the interaction between water and the electrically charged balloon.

The water molecules orient themselves so that the partial positive hydrogens are closest to the negatively charged balloon. The attraction between the partially positive hydrogens and negative balloon moves the water towards the balloon.

4. Use arrows to indicate bond and molecular polarity of acetone. Label all regions of partially positive and negative charge. EN(C) = 2.5, EN(H) = 2.1, EN(O) = 3.5.



5. Predict and then draw a molecular level view of the possible interaction between the electrically charged balloon and acetone. In your drawing include one acetone molecule interacting with the electrically charged balloon. Include an arrow to indicate the overall trajectory/flow of the stream.



6. Briefly, summarize the interaction between acetone and the electrically charged balloon observed in the demo.

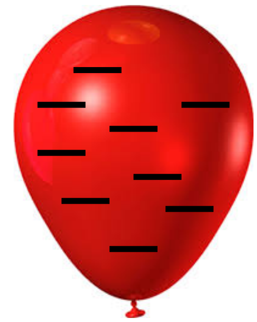
   The acetone molecules orient themselves so that the partially positive region with the hydrogens is closest to the negative balloon. The positive/negative attraction moves the acetone molecules towards the balloon.

7. After watching the demo of a stream of oil and the electrically charged balloon, what can you conclude about the polarity of the oil?

   Oil is nonpolar.

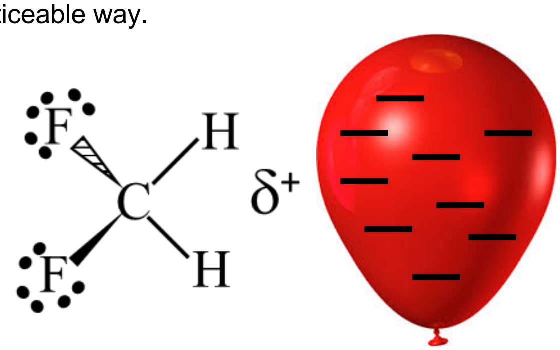
8. How would a stream of CF_4 interact with this same electrically charged balloon? If an interaction would occur, draw the interaction between one CF_4 molecule and the electrically charge balloon.

CF$_4$ would not move towards the balloon in any significant way.



9. How would a stream of CH_2F_2 interact with this same electrically charged balloon? If an interaction would occur then draw the interaction between one CH_2F_2 molecule and the electrically charged balloon.

CH_2F_2 would move towards the balloon in a noticeable way.



10. What equation have we seen before that describes the attractive nature between charged substances?

$$E = \frac{kQ_1Q_2}{d}$$

11. Using the water and the electrically charge balloon demo as an example, indicate which variables in the equation correspond to the water and the electrically charged balloon?

Q_1 = partial positive from water
Q_2 = negatively charged balloon (the one and two subscripts are arbitrary, so the answers could be reversed)

12. Structure-function relationships are very important throughout science and engineering. What is necessary in a molecular structure in order to observe this electrostatic force at the macroscopic level?

Polarity

EXPLANATORY MATERIAL

- This activity is done in conjunction with a demonstration that is projected onto a screen to enhance the students' ability to observe it.
- The static electricity is applied using the instructor's hair. Alternatively, a sweater or anything else that can generate a good static charge can be used.
- The water and acetone are dispensed through a burette; the oil used (vegetable oil) is too viscous to flow through the burette, so a separatory funnel is used.
- Before conducting the demonstration with the oil, we typically give the students a representative Lewis structure of a long hydrocarbon and ask them to use their clicker or polling app to predict what will happen.
- After concluding the demonstrations, the instructors have the students complete the task in small groups while the instructor goes around answering questions that arise.
- In an effort to remind the student of the Coulomb's law in question 10, the instructors usually refer the students to their previous class when they learned about trends in lattice energy.
- The last question is designed to make students think more broadly about the structure-function cross-cutting concept.

SAM HOUSTON STATE UNIVERSITY LEARNING ACTIVITY

Topic: Chemical kinetics

DCI: Kinetics: chemical changes have a timescale over which they occur

CCC: Cause and effect: Mechanism and explanation.

SEP: Developing and using models

Learning Performance: Given kinetic data from a series of reactions in which one specified parameter was systematically varied, use models of molecular motion to explain how variation in the parameter causes the observed kinetic data.

Evidence of Learning Specification: Students use collision theory, Brownian motion, and molecular diffusion to explain why a reaction is faster when a less viscous solvent (i.e., hexane) is used in comparison to a more viscous solvent (i.e., dodecane.)

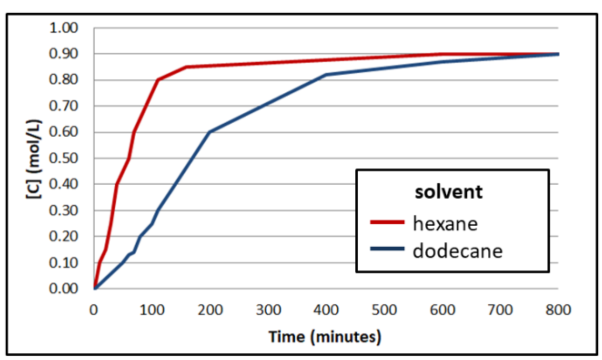
<u>TASK</u>

Short answer: This is an open-ended question.

The reaction below is run in a sealed metal container with a fixed volume of 2.50 liter. The reaction is run in the presence of a catalyst, and the temperature is kept constant for the duration of the whole process.

$$A + 2\,B \longrightarrow 2\,C + D \qquad \Delta H > 0$$

A chemist wants to determine if changing the solvent affects the rate of production of compound "C." Therefore she plans her experiment by running the reaction under the same experimental conditions (i.e., temperature, pressure, and volume) but uses different solvents. The solvents under investigation are dodecane and hexane. These solvents have similar chemical structures but dodecane has a higher viscosity—diffusion is slower in this solvent.



IDEAL STUDENT RESPONSES

Exemplar Student Response #1

"Using hexane as the solvent for the given reaction increases the production of compound C. Dodecane has a higher viscosity, meaning it is "thicker" in its liquid state. The higher viscosity means molecules are moving slower, and fewer molecules interact with the amount of energy required to produce the product C. Since hexane has a lower viscosity, molecules are able to move more freely, interacting more often than in the dodecane, increasing the rate at which product C is formed. Since diffusion is lower in the presence of dodecane, the A and B molecules do not come into contact as quickly as they do in hexane. The more frequent the collisions of reactants, the more likely a reaction is to occur. Therefore, by changing the solvent from dodecane to hexane, the reaction proceeds at a faster rate."

Exemplar Student Response #2

"According to the graph given, when hexane is used as the solvent, the reaction occurs much faster. Changing the solvent to dodecane, which is a thicker substance, therefore having slower moving particles, slows the reaction because the rate of collisions will decrease. The faster the particles move, the more likely they are to collide with the correct amount of energy to react according to the kinetic molecular theory.

Exemplar Student Response #3

"Changing the solvent does affect the production of compound "C". Both solvents start at 0 and end at 0.90; however, hexane completes the process faster because it is less viscous and is able to process faster when kept at constant presence of catalyst, temp., pressure and volume. The balanced equation will yield the same end products with both solvents, the only difference will be the time taken to complete the process. Where hexane completes the process in approx. 150 min and dodecane in approx. 790, but yield the same amount of product. Quicker diffusion allows the process of collisions to go quicker."

SCORING RUBRIC

Grading student responses was done at three numerical levels:

100%: student makes a clear connection between the chemical problem (i.e., the correct interpretation of graphical information, and chemical participants are clearly identified as reactants, products, and solvents) and chemical theories (e.g., molecular motion, diffusion, collision theory.)

50%: student makes incorrect inferences regarding the chemical process (i.e., solvent molecules role is confused by reactants in the chemical process), but students correctly identify that limitations in molecular movement (due to lower diffusion, higher viscosity) affect the rate of the reaction.

0%: student makes incorrect inferences regarding the chemical process and fails to interpret the graphical information correctly.

EXPLANATORY MATERIAL

- The task is completed after the in-class discussion of fundamental concepts of chemical kinetics. Central to the discussion are examples of reaction mechanisms aided by molecular animations contrasting how the collisions, energies, and molecular orientation are fundamental points to consider when determining the rate of reactions.
- Factors affecting rates of reaction are described early during class discussions, being careful not to incorporate the potential effect the solvent has on liquid-phase reactions. This is done, to avoid exposing students to the content of the designed task to evaluate the *evidence of learning specification.*
- Once all factors affecting rates of reaction are discussed, the class activities move to the graphical interpretation of chemical concentrations changing over different time scales and how to determine instantaneous rates of reaction from such graphs. Clicker questions and think-pair-share activities were used to promote discussion amongst students regarding graphical data and interpretation.

- After concluding all in-class discussions and during a different class session, the task was given to students as an individual-work, in-class quiz evaluation, with a duration of 15 min.

UNIVERSITY OF TEXAS LEARNING ACTIVITY

Topic: Key Characteristics of Boiling Point Temperatures: Intermolecular Forces

DCI: Intermolecular forces

CCC: Structure and function

SEP: Developing and using models

Learning Performance: Develop and use a model to rank substances in order of boiling point temperatures using chemical structure and intermolecular forces (IMFs) as the key focus.

Evidence of Learning Specification: Students successfully rank boiling point temperatures by intermolecular forces, not by molecular weight or other factors.

TASKS

Tasks are embedded in the following engaged lesson on intermolecular forces and boiling points. Paul McCord, Ph.D., created the graphical figures in this activity. Used with permission

Presented herein is a sequence of steps and sets of molecules that have shown to be successful in helping students form a reliable mental model for ranking intermolecular forces and boiling point temperatures. Prior knowledge students need before this activity is shown in Figure 4A of the main manuscript and includes the ability to draw Lewis structures, identify bond type including polar bonds, identify polar molecules, and consider systems before and after a change (ability to compare systems and ability to consider liquids vs. gas samples).

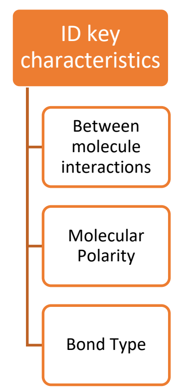
This activity was designed to be used across a variety of teachers and classroom conditions. It focuses on the newly integrated 3-D Learning Performances aspects of the instruction. As such, it is not a standalone activity and is not a daily lesson plan.

This activity is intended to be used at the very beginning of an intermolecular forces unit, but can be adapted for use at other times throughout the curriculum. Before this activity, students will have practiced and ideally mastered the prior knowledge shown in Figure 4A:

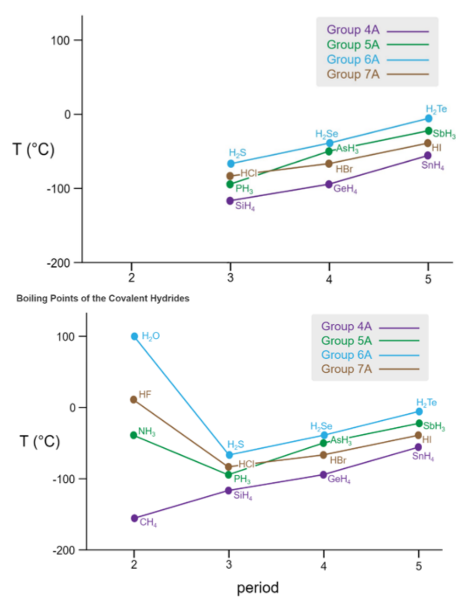
Lewis dot, polarity, bond types, and changes. Students will have practiced placing substances along the bond continuum and will have familiarity with alkanes.

Students first group molecules by bond type, then by intermolecular force (IMF), and finally use that information to predict boiling point temperature. Hydrogen bonding is presented separately, after initial grouping by IMF, but sequence can be adapted as each instructor deems necessary.

The goal is for students to be able to rank molecules in order of increasing boiling point temperature. The information students need to solve this type of question is extensive. The mental steps a novice may use to work this problem may include those shown in Figure 4B.



We notice that students master many of the early steps with practice; however, the step shown at right continues to elude many students and forms a barrier to success for the latter steps. This activity proactively engages the students in tasks of identifying bond type, then identifying polar molecules, then looking at between-molecule interactions. It consists of two parts designed to cross two class sessions. The first part is about 50-minutes in length. The second part uses 10-15 minutes. A break overnight allows students to process and practice the information. However, this activity can be adapted to as needed for each instructor.

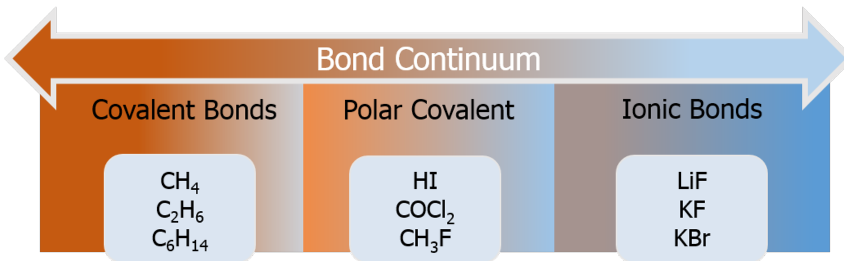


Students understandably tend to rank boiling point temperature by molecular weight or periodicity (right, above). However, the figure at right (below) reveals that the trend with molecular weight does not always hold true - there must be more to the story. The next task is to discover what must determine boiling point temperatures besides molecular weight.

The selection of molecules at right have similarities within their groups and key differences between groups.

Group 1	Group 2	Group 3
CH_4 C_2H_6 C_6H_{14}	HI $COCl_2$ CH_3F	LiF KF KBr

These groupings correspond with bond type, which is a critical component for identifying IMFs.



When reviewing molecular polarity, consider including the following molecules: CO_2, HCN, BF_3, CH_4, CH_2F_2, H_2O, CH_3OH, H_2CO, CH_3OCH_3.

When practicing hydrogen bonding with the students, consider that some of them have seen hydrogen bonding in their biology class or prior chemistry coursework. There may be misconceptions to address, but there may also be a wealth of prior knowledge to revive. Consider using these molecules for practice identifying whether a pure substance can exhibit hydrogen bonding: CH_3OH, HCl, H_2S, and CH_3NH_2.

Classify the following molecules according to H-bond potential: CH_3OH, HCl, H_2S, and CH_3NH_2. Each is a pure liquid.

Categories: **Can form H-bonds** **Does not form H-bonds**

Alternative wording: Identify which of the following pairs of molecules can form H-bonds between them:

1. CH_3OH and CH_3OH
2. HCl and HCl
3. H_2S and H_2S
4. CH_3NH_2 and CH_3NH_2

IDEAL STUDENT RESPONSES

Can form hydrogen bonds with another molecule of itself	Cannot form hydrogen bonds with another molecule of itself
CH_3OH and CH_3OH	HCl and HCl
CH_3NH_2 and CH_3NH_2	H_2S and H_2S

Option: Create a clicker or polling question

The liquids of which of these molecules will exhibit hydrogen bonding?
1. **CH_3NH_2**
2. HCl
3. H_2S
4. All of the other answers are correct.

At this point, students tend to create the mistaken model that any molecule having H and F, O, or N will be able to form hydrogen bonds. To challenge and refine their mental model, consider assigning the following molecules**: CH_3CH_2CHO (propanal), CH_2F_2, CH_3COOH, and CH_3NF_2.** These structures are more challenging for students, so they may need extra time to draw the structures. Our experience suggests that we get better use of class time if we:

1. Offer brief time (1 min) for students' first guess (because they try to just look at it and answer),
2. Take a quick poll of responses and announce approximate percentage of students who missed it (without revealing the answers)
3. Offer students 3-5 minutes to work in groups (time to draw the Lewis structures and to analyze interactions)
4. Re-do poll of responses using method of choice

Additional benefit comes from drawing at least three molecules and the hydrogen bonding that can occur between them. Students, especially biology students, tend to identify the covalent bonds involving hydrogen as being hydrogen bonds. It is important to make it obvious (and reinforce several times) that IMFs are **between two (or more) molecules**.

It is also helpful to call attention to the fact that the "mostly nonpolar" C-H bond does not have a hydrogen that is sufficiently partial-positive as to form hydrogen bonds. This explains the suggested inclusion of propanal, CH_2F_2, and CH_3NF_2 for the activity.

Alternative wording:

Is it enough to have H and F, O, or N on the molecule? Let's see… Which of the following will exhibit hydrogen bonding in its pure liquid form?

a. CH_3CH_2CHO
b. CH_2F_2
c. CH_3COOH
d. CH_3NF_2
e. All of these

IDEAL STUDENT RESPONSES

Can form hydrogen bonds with another molecule of itself	Cannot form hydrogen bonds with another molecule of itself
CH_3COO**H**	CH_3CH_2CHO The H attached to C is not sufficiently partial positive
	CH_2F_2
	CH_3NF_2

It is important that students recognize that hydrogen bonding occurs between a partially positive H (not just any H) and a lone pair of electrons on a partially negative F, O, or N atom within a nearby molecule. The strength of the hydrogen bond increases with the partial positive of the H involved, as well as the proximity to the lone pair on the F, O, or N atom.

At this point, one may explain the "mysterious outliers" from the trend in Figure 1.5. Molecular weight is not the primary factor. IMFs are the main factor to consider. Invite students to check with their neighbor, to be certain they can explain it.

Optionally, ask students to prepare a full explanation of the "mysterious outliers". Some ideas:

- Have each student choose one of the molecules they have seen in this lesson, then model its behavior in the liquid state and its behavior in the gas state. Pay special attention to the IMFs in each state.
- Write a paragraph, using complete sentences, of what happens when a liquid boils

- Draw 2-3 molecules in the particulate view, showing the IMFs that may occur in the liquid state (Asking students to do this can reveal misconceptions.)
- Describe the intermolecular forces for each outlier and compare against those substances that followed the molecular weight trend.

After students have had a chance for IMFs to “soak in” through time and a bit of practice (ex. homework), present students with additional in-class practice.

Task:

- Use your knowledge of IMFs to match molecule to boiling points below.

CH_3COONa CH_3CH_2OH H_2O CH_2Cl_2 C_2H_6

Boiling Point	Molecule	Justification
881.4°C		
78.3 °C		
-89.0 °C		
100.0 °C		
39.6 °C		

Ideal Student Responses:

- Use your knowledge of IMFs to match molecule to boiling points below.

CH_3COONa CH_3CH_2OH H_2O CH_2Cl_2 C_2H_6

Boiling Point	Molecule	Justification
881.4°C	CH_3COONa	Ion-ion
78.3 °C	CH_3CH_2OH	H-bonding
-89.0 °C	C_2H_6	Dispersion
100.0 °C	H_2O	H-bonding *x 2*
39.6 °C	CH_2Cl_2	Dipole-dipole

Optional extension activity:

After refining understanding of IMFs and after becoming fairly comfortable with identifying IMFs in pure liquids or pure solids, move on to aqueous solutions. Identify the IMFs of various substances in water. Begin with ionic compounds, to make (and define) ion-dipole IMFs. Save hydrogen-bonding for last, as it is a refining step. Relate all to solubility and the general (albeit overused) phrase “like dissolves like” as “similar IMFs are more likely to dissolve”.

Possible Assessment Tasks

Select the option that correctly lists the substances in order of INCREASING boiling points.

1. O_2, C_2H_6, C_3H_8, NH_3, H_2O, NaCl, CaO CORRECT
2. O_2, C_3H_8, C_2H_6, NH_3, H_2O, NaCl, CaO
3. O_2, NH_3, C_3H_8, C_2H_6, NaCl, CaO, H_2O
4. O_2, NH_3, C_2H_6, C_3H_8, H_2O, CaO, NaCl
5. None of these places the substances in correct order of increasing boiling points.

Which of the following can form hydrogen bonds with another molecule of itself?

I. ammonia

II. ethanol

III. CH_3OCH_3

IV. H_2CO

1. I, II only CORRECT

2. I, II, III, IV

3. I, III, IV only

4. I only

SOUTHEAST MISSOURI STATE UNIVERSITY LEARNING ACTIVITY

Topic: Thermodynamics

DCI: Entropy is dispersion of particles and energy

CCC: Patterns

SEP: Analyzing and interpreting data

Learning Performance: Analyze and interpret data of processes to show that ΔS_{sys} values follow a pattern; dispersion of energy or particles results in a positive change in entropy.

Evidence of Learning Specification: Indicate whether the entropy change is positive, negative, or ~0.

Tasks:

During lecture time, students worked over three class periods in groups to build their understanding of the concept of entropy. The structure of the class was short lectures on entropy followed by a group activity that was done on a handout and then class discussion of the results. The activity was handed in at the end of class. Dr. Philip Crawford was the lecturer and provided the assessment questions. The in-class activities were designed to meet the LP by a committee of faculty at the university. Students were sometimes provided data in lecture or asked to create a model that they would interpret.

In-class Group Activity 1:

1.(a) How many ways can 4 different coins be arranged as either heads or tails? Draw them.

(b) How many “ordered” states are there and what are these? Which states are most probable?

2. Consider a gas cylinder that contains just three gas molecules (A, B, C). If the cylinder is divided into only two chambers, how many ways can the molecules be distributed between them? Draw them.

3. (a) Consider a gas cylinder that contains just three gas molecules (A, B, C). If the cylinder is divided into only three chambers, how many ways can the molecules be distributed between them? (b) Which system has more entropy associated with it, that in problem 2 or problem 3?

Ideal Student Responses for Activity 1:

1. There are 16 ways for the coins to be arranged in head or tails. The ways that the students draw this will vary. There are 3 ordered states, 1 heads/3 tails, 3 heads/1 tails, and 2 heads, 2 tails. The most probably state is 2 heads, 2 tails - there are 6 ways for this arrangement to occur.

In-class Group Activity 2:

1. Consider the different states of matter. How does the entropy of a substance in the solid, liquid, and gas phase vary? Why?

2. Explain the differences in the standard entropies for each of the following:

   a. $CH_4(g)$ vs. $C_3H_8(g)$

   b. Na(s) vs. Cs(s)

   c. $I_2(s)$ vs. $I_2(g)$

   d. NaCl(s) vs. $Na_2CO_3(s)$

Ideal Student Responses for Activity 2:

1. Students should explain the states of matter in terms of dispersion of energy and particles and conclude that the gaseous state has the highest entropy because it has the greatest dispersion of energy and particles.
2. Building on their explanations from the first question, we've now added in mass and complexity of the molecule. The greater the mass or the more complex the molecule, the greater the entropy.

In-Class Group Activity 3:

1. Predict whether the entropy increases or decreases for each of the following reactions:

$4PCl_3(g) \rightarrow P_4(g) + 6Cl_2(g)$

$2NO(g) + O_2(g) \rightarrow 2NO_2(g)$

$CaO(s) + CO_2(g) \rightarrow CaCO_3(s)$

$2KClO_3(s) \rightarrow 2KCl(s) + 3O_2(g)$

$AgCl(s) \rightarrow Ag^+(aq) + Cl^-(aq)$

2. How can the entropy for a chemical reaction be calculated? Consider:

$$2SO_2(g) + O_2(g) \rightarrow 2SO_3(g)$$

$$CaCO_3(s) \dashrightarrow CaO(s) + CO_2(g)$$

Calculate the entropy for each reaction and explain the differences between them.

Ideal Student Responses for Activity 3:

1. These responses are all just predictions, so the answers may vary. Some are particularly difficult to determine just by looking at the equation. So, the answer may depend on the justification.

$4PCl_3(g) \rightarrow P_4(g) + 6Cl_2(g)$ Increase, more particles of products (dispersion of mass)

$2NO(g) + O_2(g) \rightarrow 2NO_2(g)$ Decrease, fewer particles of products

$CaO(s) + CO_2(g) \rightarrow CaCO_3(s)$ Increase - more complex molecule produced or Decrease - less particles in products

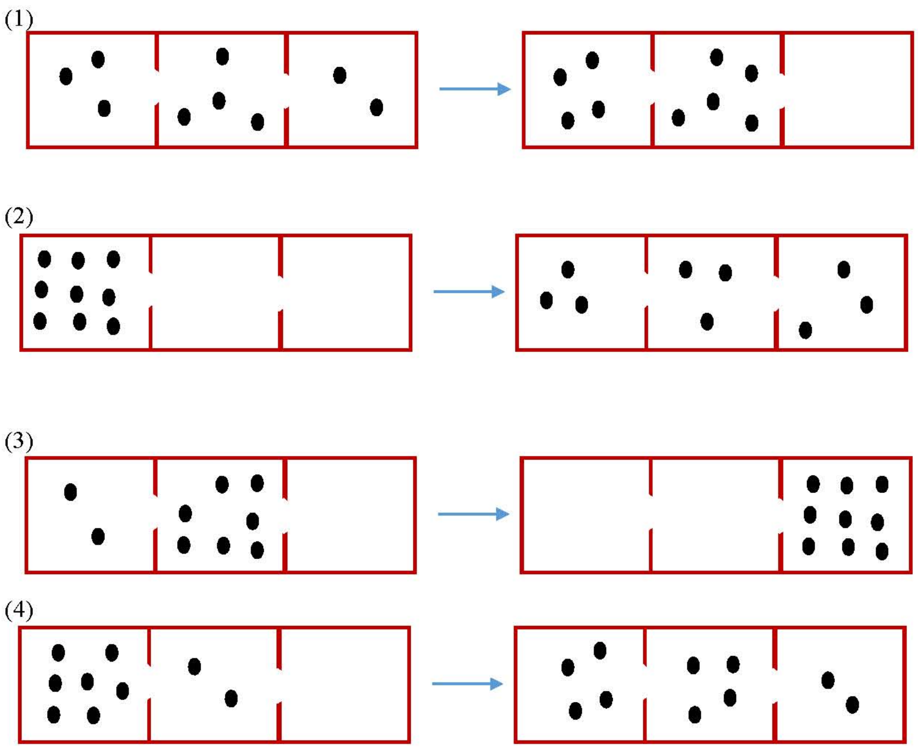
$2KClO_3(s) \rightarrow 2KCl(s) + 3O_2(g)$ Increase - more particles in products

$AgCl(s) \rightarrow Ag^+(aq) + Cl^-(aq)$ Increase - solid to aqueous results in more dispersal of particles

Assessment Task:

Questions were designed for the exam based on these activities. Students were observed drawing similar responses on the exams as they had drawn during the in-class tasks. Possible questions:

1. Consider the following changes in the distribution of 9 gas particles into a container that has three interconnected boxes. In each case, indicate whether the entropy change is positive or negative, or is close to zero.



nw

2a. For the following reaction, calculate $\Delta S°_{rxn}$ and $\Delta S°_{univ}$ using the appropriate data (25°C) provided below.

$$2NO(g) + O_2(g) \rightarrow 2NO_2(g)$$

2b. For the following reaction, calculate $\Delta S°_{rxn}$ and $\Delta S°_{univ}$ using the appropriate data (25°C) provided below.

$$NH_4NO_3(g) \rightarrow N_2O(g) + 2H_2O(g)$$

Data for 2a and 2b

Compound	S°, J K^{-1} mol^{-1}	$\Delta H°_f$ (kJ/mol)	$\Delta G°_f$ (kJ/mol)
NO(g)	210.6	90.4	86.7
N_2O	219.99	81.56	103.6
NH_4NO_3(g)	151.0	-365.6	-184.0
NO_2(g)	240.46	33.84	51.8
H_2O(g)	188.83	-241.82	-228.57
H_2O(l)	69.91	-285.83	-237.13
O_2(g)	205.0	0	0

3. Short response. (Six were chosen for each version of the exam.) For each of the following processes, predict whether the entropy change is positive ($\Delta S > 0$), negative ($\Delta S > 0$), or approximately equal to zero ($\Delta S \approx 0$).

a. molten aluminum solidifies ________________

b. $NaClO_3(s) \rightarrow Na^+(aq) + ClO_3^-(aq)$ ________________

c. $H_2O(g) + Cl_2O(g) \rightarrow 2HClO(g)$ ________________

d. air in a syringe is compressed ________________

e. $2NH_4NO_3(s) \rightarrow 2N_2(g) + 4H_2O(g) + O_2(g)$ ________________

f. dissolved sugar precipitates out of solution ________________

g. $H_2(g) + F_2(g) \rightarrow 2HF(g)$ ________________

h. molten iron solidifies ________________

i. $2SO_2(g) + O_2(g) \rightarrow 2SO_3(g)$ ________________

j. gaseous CO_2 bubbles out of a carbonated beverage when the can is opened ________________

k. $2Cu_2O(s) \rightarrow 2Cu(s) + O_2(g)$ ________________

Ideal Student Responses for Assessment:

1. 1. Negative 2. Positive 3. Negative 4. Positive

2a. $\Delta S°_{rxn}$ = -145.28 J/Kmol $\Delta S°_{univ} = \Delta S°_{rxn} - \Delta H°_{rxn}/T$ = -145.66 J/Kmol

2b. $\Delta S°_{rxn}$ = -70.83 J/Kmol $\Delta S°_{univ} = \Delta S°_{rxn} - \Delta H°_{rxn}/T$ = -70.41 J/Kmol

3. a. molten aluminum solidifies negative

b. $NaClO_3(s) \rightarrow Na^+(aq) + ClO_3^-(aq)$ positive

c. $H_2O(g) + Cl_2O(g) \rightarrow 2HClO(g)$ ~0

d. air in a syringe is compressed negative

e. $2NH_4NO_3(s) \rightarrow 2N_2(g) + 4H_2O(g) + O_2(g)$ positive

f. dissolved sugar precipitates out of solution negative

g. $H_2(g) + F_2(g) \rightarrow 2HF(g)$ ~0

h. molten iron solidifies negative

i. $2SO_2(g) + O_2(g) \rightarrow 2SO_3(g)$ negative

j. gaseous CO_2 bubbles out of a carbonated
beverage when the can is opened positive

k. $2Cu_2O(s) \rightarrow 2Cu(s) + O_2(g)$ positive