How Long Can You Go?

Submitted by: Anne Lavelle, Chemistry
St. Edward High School, North Olmsted, OH

Target Grade: 10th-11th Grade Chemistry

Time Required: 3 Days, 45 minute lessons

Standards

Next Generation Science Standards (NGSS):

- HS-PS1-3: Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles.
- PS1.A: The structure and interactions of matter at the bulk scale are determined by electrical forces between material objects.

Lesson Objectives

Students will:

- Use Kinetic Molecular Theory to explain the relative energy changes associated with each phase change (ΔH_{vap} and ΔH_{fus}).
- Use intermolecular forces found in a water bottle to explain the crystallization of water at its freezing point.
- Use heat capacities and heat of fusion and vaporization to calculate the heat absorbed or evolved when a substance is heated or cooled and undergoes phase changes.

Central Focus

This lesson focuses on the phenomenon of a cooled water bottle instantly freezing once shaken. Students will engage in an online simulation and an interactive lab to observe water molecules at different temperatures. By the end of the lesson, students should be able to relate the phenomenon to a complete heating/cooling curve of water molecules.

Key terms: hydrogen bonding, kinetic molecular theory, enthalpy, chemistry, groups, heat capacity, energy, phase change, intermolecular forces, crystallization, fusion, vaporization

Background Information

Students should be aware of intermolecular forces of polar molecules and hydrogen bonding in water. Water molecules are held together by hydrogen bonds, which are one of the strongest intermolecular force found in substances.

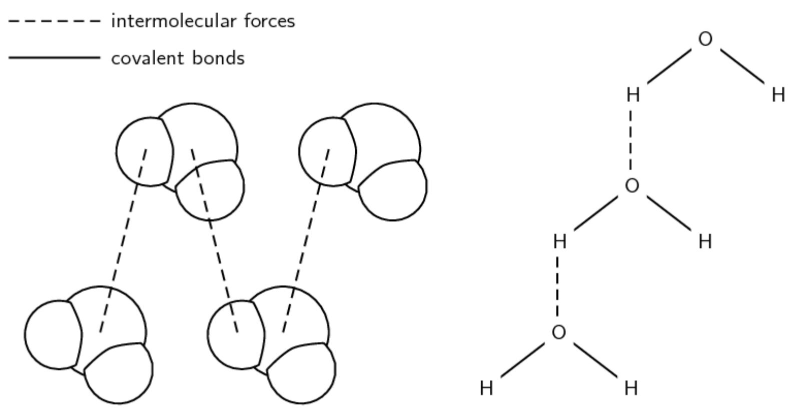


Image taken from the helpful source: https://www.siyavula.com/read/science/grade-11/intermolecular-forces/04-intermolecular-forces-02#:~:text=Water%20molecules%20are%20held%20together,(interatomic%20forces)%20in%20water.

Students should be familiar with the following phase change vocabulary:

- **Melting point/ freezing point**: Freezing point is the temperature at which a liquid becomes a solid at normal atmospheric pressure. Alternatively, a melting point is the temperature at which a solid becomes a liquid at normal atmospheric pressure
- **Heat of fusion**: The change in its enthalpy resulting from providing energy, typically heat, to a specific quantity of the substance to change its state from a solid to a liquid, at constant pressure.
- **Heat of vaporization**: The amount of energy that must be added to a liquid substance to transform a quantity of that substance into a gas. The enthalpy of vaporization is a function of the pressure at which that transformation takes place.
- **Normal boiling point**: The temperature at which a liquid boils at 1 atmosphere of pressure. The normal boiling point is a more useful value when comparing different liquids, since boiling is affected by altitude and pressure.

Students will need a basic understanding of the kinetic molecular theory. The kinetic molecular theory is what explains the behaviour of gasses through experimental observation. The kinetic molecular theory is based on the following assumptions:

- Gases are composed of a large number of particles that behave like hard, spherical objects in a state of constant, random motion.
- These particles move in a straight line until they collide with another particle or the walls of the container.

- These particles are much smaller than the distance between particles. This shows that most of the volume of a gas is empty space.
- There is no force of attraction between gas particles or between the particles and the walls of the container.
- Collisions between gas particles or collisions with the walls of the container are perfectly elastic. None of the energy of a gas particle is lost when it collides with another particle or with the walls of the container.
- The average kinetic energy of a collection of gas particles depends on the temperature of the gas and nothing else.

Helpful source: http://chemed.chem.purdue.edu/genchem/topicreview/bp/ch4/kinetic4.html

Materials

- 3 Unopened water bottles
- Freezer

For each lab group:

- 20 ml test tubes
- 50 ml graduated cylinder
- 400 ml beaker
- Ring stand
- Stirring rod
- Rock salts
- Test tube clamps
- Plastic spoons
- Ice
- Digital thermometer

Instructions

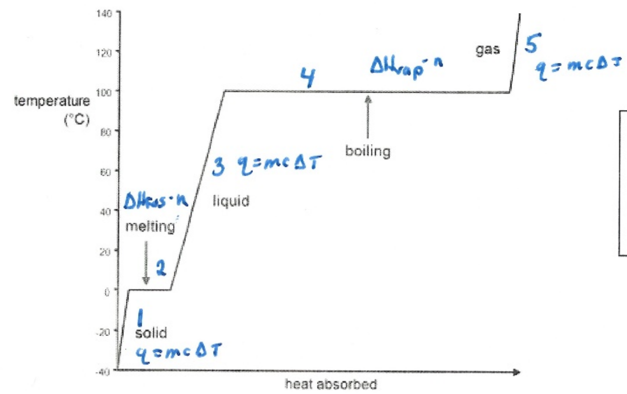
Day 1

Before class prep: Place three unopened water bottles in a freezer for 2-3 hours.

- Begin the class by showing the students the frozen water bottle demonstration.
    - Take out one of the cold water bottles for the students to see.
    - Tap, pound, or squeeze the bottle to activate the crystallization.

- The teacher can repeat the demonstration if needed with the remaining two bottles.
- Ask students to break into small groups to discuss the following questions:
  - How cold do you think the water in this bottle is?
  - What is happening while it is freezing on the particle level?
  - What is happening to the energy of the system?
- After the students have had a few minutes to discuss the question, conduct a class wide discussion of the questions and what each group talked about.
- Place students into groups to begin the PHet state of matter simulation.
  - Have students open the simulation on their laptops.
    - https://phet.colorado.edu/sims/html/states-of-matter-basics/latest/states-of-matter-basics_en.html
  - Click on Phase Changes.
  - Select neon while noting phase change temps.
  - Select oxygen while noting phase change temps.
  - Select the Water Molecule.
  - Play with heating and cooling to show particle motion.
- Ask the class the following questions. After asking each question, allow student to discuss in groups before discussing with the class.
  - Discuss the major difference between the water molecule and oxygen molecule.
  - On a whiteboard, draw the three phases of the water molecules.
  - Discuss the freezing point of the water and what could affect it.
  - Discuss the melting point of water in comparison to the freezing point.
  - Discuss what was different about the super-cooled water. Why it would be colder than the freezing point?
  - Discuss what is happing to the energy as heat is added (how it is being used).
  - Discuss what happens when water is super cooled.
- While discussing the answers to these topics, correct any misconceptions the students may have.
- In groups, have the students draw water molecules in crystal form while noting the intermolecular forces.
  - The drawing should show the hexagonal nature of water.
- Follow this with a discussion of what is happening to the energy of the particles during a phase change.
- Demonstrate a cooling graph sample problem.

Sample problem:



Specific heat of water 4.18 J/g°C
Specific heat of ice = 2.03 J/g°C
Specific heat of steam = 2.00 J/g°C
Heat of Vaporization of water: 40.8 kJ/mol
Heat of Fusion of Water: 6.02 kJ/mol

https://courses.lumenlearning.com/introchem/chapter/heating-curve-for-water/

Calculate the enthalpy change needed to melt ice (10.0g) at -40.0°C to water vapor at 140.0°C

* change to kJ will make easier at end

1. -40.0° C to 0.0 °C $q = mc\Delta T$
   - $m = 10.0g$
   - $c_{ice} = 2.03\ J/g\cdot°C$
   - $\Delta T = 0.0-(-40.0°C)$
   - $q = 10.0g\,(2.03\ \frac{J}{g\cdot°C})(40°C)$
   - $q = 812\ J$ = $0.812\ kJ$
2. At 0.0° C
   1. g → moles $10.0g \times \frac{1\ mol}{18.02g} = 0.555\ mol$
   2. $q = \Delta H_{fus}(mol)$ $(6.02\ kJ/mol)(0.555\ mol) = 3.34\ kJ$
3. 0.0°C to 100.0 °C
   - $m = 10.0g$
   - $c_{water} = 4.18\ J/g\cdot°C$
   - $\Delta T = 100°C$
   - $q = mc\Delta T$
   - $q = (10.0g)(4.18\ J/g\cdot°C)(100°C) = 4180\ J = 4.18\ kJ$
4. At 100.0°C
   1. g → mol (0.555 mol)
   2. $q = \Delta H_{vap}\cdot mol$ $q = (40.8\ kJ \cdot 0.555\ mol) = 22.7\ kJ$
5. From 100.0°C to 140.0 °C
   - $m = 10.0g$
   - $c_{steam} = 4.18\ J\cdot g\cdot°C$
   - $\Delta T = 40°C$
   - $q = mc\Delta T$
   - $= (10.0)(2.00\ J/g\cdot°C)(40°)$
   - $= 800\ J = 0.800\ kJ$

+ because endothermic

Total Energy :

1 + 2 + 3 + 4 + 5 = q_{total}

0.812 kJ + 3.34 kJ + 4.18 kJ + 22.7 kJ + 0.800 kJ = 31.8 kJ

- Tell the students that their challenge for the next day in lab will be two-fold: can you super-cool water? What is the lowest temperature they can get before their water freezes?
- For homework, give students the *Putting it all together: Heating/Cooling curves* to practice a phase change problem.

Day 2

- Display the phase change problem that was assigned for homework allowing the students to correct mistakes and ask questions as they enter the classroom.
- After discussing the homework, share the https://physicsworld.com/a/water-supercooled-to-record-breaking-low-temperature/ article on the board or class site discussing how super cooled water can reach very low temperatures.
- Have students read the article and hold a class discussion of the main take away from the article.
- In groups, have students complete the lab How Long Can You Go?
- Lab instructions:
    - Fill the 400ml beaker halfway with ice and then add 150 ml of water.
    - Add three to four tablespoons of rock salt. Mix well.

    - With the graduated cylinder, measure approximately 20 – 25 ml of distilled water – measure and record the exact amount in data table. Pour into test tube.
    - Clamp test tube to ring stand as shown in diagram.
    - Gently place digital temperature probe in the test tube water making sure that you can gently move the probe up and down without removing the probe. Begin continuous data collection monitoring the graph of temperature.
    - Gently stir the water inside of the test tube with the probe for the first five minutes.
    - After the first five minutes, stop moving the probe.
    - Add rock salt and ice as needed to continue to lower the temperature of the outer bath.
    - Stop data collection 4-5 minutes after the water turns to a solid.
    - Save graphs to print later.
    - Repeat with another 25.0 ml of water. Salt and ice mixture may be reused.

- Student will fill out the following table for each observation:

	Trial 1	Trial 2
Volume of water (ml)		
Starting Temperature °C		
Freezing Point °C		
Lowest Temperature Reached °C		
Qualitative Observations		

- Once the students have completed the lab, their packet will instruct them to analyze their results and answer post lab questions.
- The students will answer the following:
    - Analyze the graphs:
        - Label each with "supercooled" dip (if achieved).
        - Label freezing point
    - For each trial:
        - Calculate the amount of heat lost as the temperature decreased. Show a fully labeled calculation for one of the trials.
        - Calculate the amount of heat lost as the water was undergoing the phase change. Show a fully labeled calculation for one of the trials.
        - Calculate the amount of heat lost as the water was undergoing the phase change. Show a fully labeled calculation for one of the trials.
    - Did your values agree? What were the possible errors involved in this lab? Would the errors lead your value to be higher or to be lower than expected?
    - Explain the areas of your curve in terms of kinetic and potential energy of the water molecule (diagonal line vs horizontal line).
    - Can this experiment be redesigned to test a solid substance? What additional steps would that require?

Day 3

- Allow time for students to finish parts of the lab if necessary.
- Discuss the following from the lab:
    - The energy numbers per mole
        - Review calculations if necessary.
    - The kinetic energy and potential energy at different graph areas (diagonal line vs horizontal line)
    - An experiment to calculate melting point
- Have students complete the Heating/Cooling Curves quiz.

Differentiation

- For students who benefit from visual aids, the teacher can set up a model lab to refer to as the instructions are discussed.
- Google translate and speech to text is available online and may be utilized for students with special needs or ELL.
- For students who need more practice with heating curves the following will add additional explanations and practice problems:
    - https://youtu.be/STURzRg7LDQ
    - https://www.youtube.com/watch?v=ys2RHRiRc88
    - https://www.youtube.com/watch?v=AhKRUA4_viY

Assessment

Formative assessment:

- Throughout the lesson, the teacher will engage in multiple classroom discussions. This will allow the teacher to gauge the students understanding of the concept and correct any misconceptions students may have.
- The student's homework can be used to check for understanding.
- Student's lab sheet will allow the teacher to check for pacing when completing the lab, as well as engagement and misconceptions.

Summative assessment:

- The Heating/Cooling Curves quiz will allow both teacher and students to gauge their understanding of the lesson.

How Low Can You Go?

Objectives:

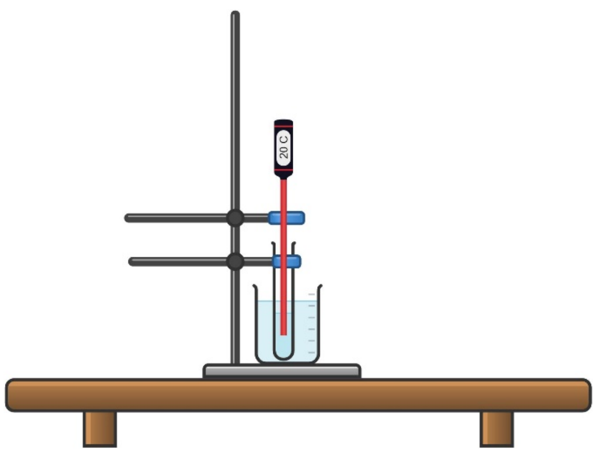
Determine the freezing point/melting point of water by graphing temperature.
Calculate the energy changes in the phase change of water

Challenge:

Can you get your water sample to remain a liquid below the standard freezing point of water?

Materials:

- Test tubes (25 x 150 mm)
- 50 ml Graduated cylinder
- 400 ml beaker
- Ring stand
- Stirring rod
- Test tube clamps
- Rock salt
- Ice
- Digital thermometer and interface for real time data



Procedure:

1. Fill the 400ml beaker halfway with ice and then add 150 ml of water.
2. Add three to four tablespoons of rock salt. Mix well.
3. Measure approximately 20 – 25 ml of distilled water – measure and record the exact amount in data table. Pour into test tube.
4. Clamp test tube to ring stand as shown in diagram.
5. Gently place digital temperature probe in the test tube water making sure that you can gently move the probe up and down without removing the probe.
6. Begin continuous data collection monitoring the graph of temperature.
7. Gently stir the water inside of the test tube with the probe for the first five minutes.
8. After the first five minutes, stop moving the probe.
9. Add rock salt and ice as needed to continue to lower the temperature of the outer bath.
10. Stop data collection 4-5 minutes after the water turns to a solid.
11. Save graphs to print later
12. Repeat with another 25.0 ml of water. Salt and ice mixture may be reused

Data:

	Trial 1	Trial 2
Volume of water (ml)		
Starting Temperature °C		
Freezing Point °C		
Lowest temperature Reached °C		
Qualitative Observations		

Analysis/ Results:

1. Analyze the graphs:
    a. Label each with “supercooled” dip (if achieved).
    b. Freezing point

2. For each trial
    a. Calculate the amount of heat lost as the temperature decreased. Show a fully labeled calculation for one of the trials:

    b. Calculate the amount of heat lost as the water was undergoing the phase change. Show a fully labeled calculation for one of the trials below

c. Calculate the amount of heat lost as the water was undergoing the phase change. Show a fully labeled calculation for one of the trials.

Trial	Heat lost during temperature decrease	Heat lost during phase change	Total heat lost by sample	Total heat lost per mole of water.
1				
2				

Questions:

1. Did your values agree? What were the possible errors involved in this lab? Would the errors lead your value to be higher or to be lower than expected? – Remember your partner is not an error!

2. Explain the areas of your curve in terms of kinetic and potential energy of the water molecule (diagonal line vs horizontal line).

3. Can this experiment be redesigned to test a solid substance? What additional steps would that require?

Quiz: Heating/Cooling Curves Name ____

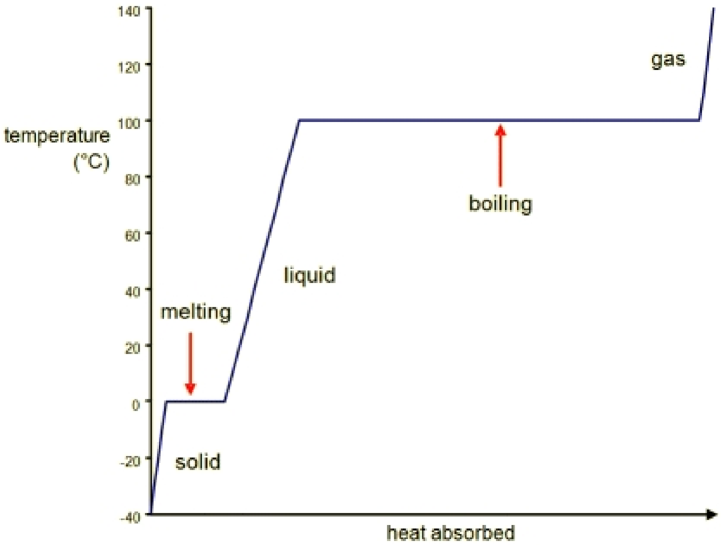
Using the following constants: Sketch the graph and calculate the enthalpy change needed to cool water vapor at ________ to solid ice at ____________Show all work and label areas of the class as demonstrated in class.

Specific heat of water 4.18 J/g°C
Specific heat of ice = 2.03 J/g°C
Specific heat of steam = 2.00 J/g°C
Heat of Vaporization of water: 40.8 kJ/mol
Heat of Fusion of Water: 6.02 kJ/mol

Total energy of phase change = ____

Putting it all together: Heating/Cooling curves Name ___________________________________

Notes/ Sample Problem



https://courses.lumenlearning.com/introchem/chapter/heating-curve-for-water/

Specific heat of water 4.18 J/g°C Specific heat of ice = 2.03 J/g°C Specific heat of steam = 2.00 J/g°C Heat of Vaporization of water: 40.8 kJ/mol Heat of Fusion of Water: 6.02 kJ/mol

Calculate the enthalpy change needed to melt ice at -40.0°C to water vapor at 140.0°C

1. -40.0° C to 0.0 °C

2. At 0.0° C

3. 0.0°C to 100.0 °C

4. At 100.0°C

5. From 100.0°C to 140.0 °C

Total Energy:

Putting it all together: Heating/Cooling curves Name ___________________________________

Homework:

Sketch graph and calculate the enthalpy change needed to cool water at 130.0°C to solid ice at -20.0°C

Specific heat of water 4.18 J/g°C Specific heat of ice = 2.03 J/g°C Specific heat of steam = 2.00 J/g°C Heat of Vaporization of water: 40.8 kJ/mol Heat of Fusion of Water: 6.02 kJ/mol

1.

2.

3.

4.

5.

Total Energy:

Quiz: Heating/Cooling Curves Name ____

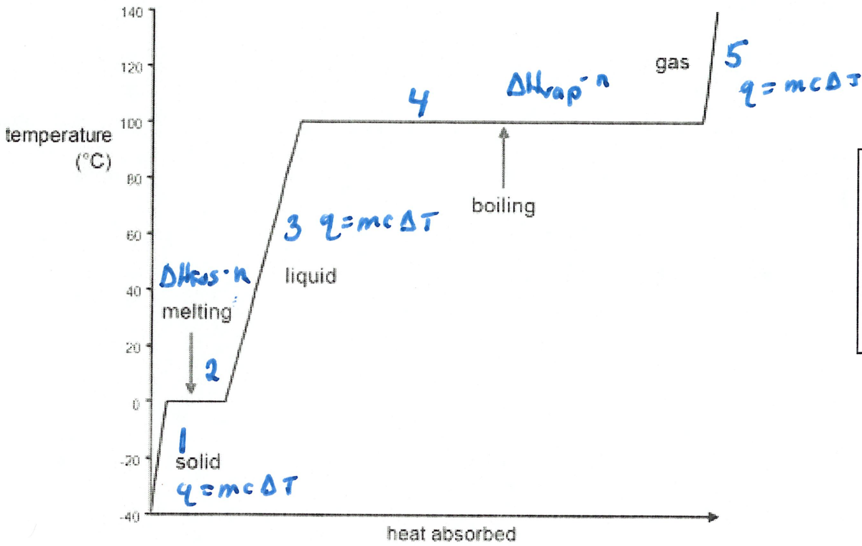
Using the following constants: Sketch the graph and calculate the enthalpy change needed to cool water vapor at ________ to solid ice at ____________Show all work and label areas of the class as demonstrated in class.

Specific heat of water 4.18 J/g°C
Specific heat of ice = 2.03 J/g°C
Specific heat of steam = 2.00 J/g°C
Heat of Vaporization of water: 40.8 kJ/mol
Heat of Fusion of Water: 6.02 kJ/mol

Putting it all together: Heating/Cooling curves

Name KEY

Notes/ Sample Problem



https://courses.lumenlearning.com/introchem/chapter/heating-curve-for-water/

Specific heat of water 4.18 J/g°C
Specific heat of ice = 2.03 J/g°C
Specific heat of steam = 2.00 J/g°C
Heat of Vaporization of water: 40.8 kJ/mol
Heat of Fusion of Water: 6.02 kJ/mol

Calculate the enthalpy change needed to melt (10.0g) ice at -40.0°C to water vapor at 140.0°C

* change to kJ will make easier at end

1. -40.0° C to 0.0 °C $q = mc\Delta T$

   m = 10.0g
   c_{ice} = 2.03 J g°C
   ΔT = 0.0-(-40.0°C)

   $q = 10.0g \left(2.03 \frac{J}{g \cdot °C}\right)(40°C)$
   $q = 812 J$ = **0.812 kJ**

2. At 0.0° C

   1. g → moles $10.0g \times \frac{1 mol}{18.02g} = 0.555 mol$
   2. $q = \Delta H_{fus}(mol)$ $(6.02 kJ/mol)(0.555 mol)$ = **3.34 kJ**

3. 0.0°C to 100.0 °C

   m = 10.0g
   c_{water} = 4.18 J/g·c
   ΔT = 100°C

   $q = mc\Delta T$
   $q = (10.0g)(4.18 J/g \cdot °C)(100°C)$ = **4180 J** = **4.18 kJ**

4. At 100.0°C

   1. g → mol (0.555 mol)
   2. $q = \Delta H_{vap} \cdot mol$ $q = (40.8 kJ \cdot 0.555 mol)$ = **22.7 kJ**

5. From 100.0°C to 140.0 °C

   m = 10.0g
   c_{steam} = 4.18 J·g°C
   ΔT = 40°C

   $q = mc\Delta T$
   $= (10.0)(2.00 J/g°C)(40°)$
   $= 800 J$ = **0.800 kJ**

Total Energy :

1 + 2 + 3 + 4 + 5 = q_{total}

0.812 kJ + 3.34 kJ + 4.18 kJ + 22.7 kJ + 0.800 kJ = **31.8 kJ**

+ because endothermic