SUPERCHARGED SCIENCE

Unit 13: Thermodynamics

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Appropriate for Grades:
K-12 (see notes on each project)
Duration: 5-15 hours, depending on how many activities you do!

Objects whose molecules are moving very quickly are said to have high thermal energy, or a high temperature. The higher the temperature, the faster the molecules are moving. Temperature is just a speedometer for molecules!

In this unit, we are going to learn what heat is and how it moves from place to place. Believe it or not, the concept of heat is really a bit tricky. What we call heat in common language is really not what heat is as far as physics goes. Heat, in a way, doesn't exist as nothing *has* heat. Things can have a temperature. They can have thermal energy but they can't have heat. Heat is really the transfer of thermal energy or, in other words, the movement of thermal energy from one object to another. Are you ready to start?

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Key Vocabulary

Changing from a liquid to a gas is called **boiling**, evaporating, or vaporizing. Boiling point is the temperature at which a material changes from liquid to gas. Objects absorb heat as they evaporate.

Changing from a gas to a liquid is called **condensation**. Condensation point is the temperature at which a material changes from gas to liquid. Objects release heat as they condense.

Conduction is the wiggle and bump method of heat transfer. Faster moving molecules bump into slower moving molecules, speeding them up. Those molecules then bump into other molecules speeding them up and so on, increasing the temperature of the object.

Convection is heat being transferred by currents of moving gas or liquid caused by hot air/liquid rising and cold air/liquid falling.

Changing from a liquid to a solid is called **freezing**. Freezing point is the temperature at which a material changes from liquid to solid. Objects release heat as they freeze.

Energy is the ability to do work. Energy can be transferred. In other words it can be changed from one form to another and from one object to another.

Gases have no bonds between the molecules.

Heat is the movement of thermal energy from one object to another. Heat can only flow from an object of a higher temperature to an object of a lower temperature. Heat can be transferred from one object to another through conduction, convection, and radiation.

Heat capacity is how much heat an object can absorb before its temperature increases. Heat capacity is influenced by the specific heat of the material and/or the amount of the material. A larger amount of something will have a higher heat capacity then a smaller amount of something. (Water has a very high heat capacity.)

Liquids have loose, stringy bonds between molecules that hold molecules together but allow them some flexibility.

Changing from a solid to a liquid is called **melting**. Melting point is the temperature at which a material changes from solid to liquid. Objects absorb heat as they melt.

Plasma is similar to gas but it is a state of matter in which the molecules are very highly energized.

Radiation is the transfer of heat by electromagnetic radiation, specifically infrared radiation.

Solids have strong, stiff bonds between molecules that hold the molecules in place.

Specific heat is how much heat energy a mass of a material must absorb before it increases 1°C. Each material has its own specific heat. The higher a material's specific heat is, the more heat it must absorb before its temperature increases.

There are four **states of matter**: solid, liquid, gas and plasma. (The fifth state, BEC, is found only in a lab, so we'll disregard it for now.)

Materials change from one **state** to another depending on the temperature and these bonds. All materials have given points at which they change from state to state. As objects change state they do not change temperature. The heat that goes into something as it is changing phases is used to change the "bonds" between molecules. Freezing points, melting points, boiling points and condensation points are the "speed limits" of the phases. Once the molecules reach that speed they must change state.

Temperature is basically a speedometer for molecules. The faster they are wiggling and jiggling, the higher the temperature and the higher the thermal energy that object has. Your skin, mouth and tongue are antennas which can sense thermal energy. When an object absorbs heat it does not necessarily change temperature.

There are three different **temperature scales** for measuring temperature: Fahrenheit, Celsius and Kelvin. (The fourth scale, Rankine, the absolute scale for Fahrenheit, is usually reserved for college engineering students and NASA engineers.)

The terms hot, cold, warm, etc. describe what physicists call **thermal energy**. Thermal energy is how much the molecules are moving inside an object. The faster molecules move, the more thermal energy an object has.

Unit Description

If you put an ice cube in a glass of lemonade, the ice cube melts. The thermal energy from your lemonade moves to the ice cube, increasing the temperature of the ice cube and decreasing the temperature of your lemonade. The movement of thermal energy is called heat. The ice cube receives heat from your lemonade. Your lemonade gives heat to the ice cube.

Heat can only move from an object of higher temperature to an object of lower temperature. We're going to learn about temperature, heat energy, atoms, matter, phase changes, and more in our unit on thermodynamics.

Objectives

Lesson 1: Temperature

Objects whose molecules are moving very quickly are said to have high thermal energy, or high temperature. The higher the temperature, the faster the molecules are moving. You may remember that temperature is just a speedometer for molecules.

You may have asked yourself the question, “So, if everything is made of molecules, and these molecules are often speeding up and slowing down, what happens to the stuff these molecules are made of if they change speed a lot? Will my kitchen table start vibrating across the room if the table somehow gets too hot?” No, it’s pretty unlikely that your table will begin jumping around the room, no matter how hot it gets. However, some interesting things do happen when molecules change speeds.

Highlights

- The terms hot, cold, warm, etc. describe what physicists call thermal energy.
- Thermal energy is how much the molecules are moving inside an object.
- The faster molecules move, the more thermal energy an object has.
- There are three different scales for measuring temperature: Fahrenheit, Celsius and Kelvin.
- Temperature is basically a speedometer for molecules. The faster the molecules are wiggling and jiggling, the higher the temperature and the more thermal energy that object has.
- Your skin, mouth and tongue are antennas which can sense thermal energy.
- There are four states of matter: solid, liquid, gas and plasma.
- Solids have strong, stiff bonds between molecules that hold the molecules in place.
- Liquids have loose, stringy bonds between molecules that hold molecules together but allow them some flexibility.
- Gasses have no bonds between the molecules.
- Plasma is similar to gas but it is a state of matter in which the molecules are very highly energized.
- Materials change from one state to another depending

on the temperature and their bonds.

- Changing from a solid to a liquid is called melting.
- Changing from a liquid to a gas is called boiling, evaporating, or vaporizing.
- Changing from a gas to a liquid is called condensation.
- Changing from a liquid to a solid is called freezing.
- All materials have given points at which they change from state to state.
- Melting point is the temperature at which a material changes from solid to liquid.
- Boiling point is the temperature at which a material changes from liquid to gas.
- Condensation point is the temperature at which a material changes from gas to liquid.
- Freezing point is the temperature at which a material changes from liquid to solid.

Objectives

Lesson 2: Heat

Believe it or not, the concept of heat is really a bit tricky. What we call heat in common language, is really not what heat is as far as physics goes. Heat, in a way, doesn't exist as nothing *has* heat. Things can have a temperature and thermal energy but they can't have heat. Heat is really the transfer of thermal energy or, in other words, the movement of thermal energy from one object to another. Confused yet?

Highlights

- Heat is the movement of thermal energy from one object to another.
- Heat can only flow from an object of a higher temperature to an object of a lower temperature.
- Heat can be transferred from one object to another through conduction, convection and radiation.
- Conduction is the wiggle and bump method of heat transfer. Faster moving molecules bump into slower moving molecules, speeding them up. Those molecules then bump into other molecules speeding them up and so on, increasing the temperature of the object.
- Convection is heat being transferred by currents of moving gas or liquid caused by hot air/liquid rising and cold air/liquid falling.
- Radiation is the transfer of heat by electromagnetic radiation, specifically infrared radiation.
- Heat is movement of thermal energy from one object to another.
- When an object absorbs heat it does not necessarily change temperature.
- As objects change state they do not change temperature.
- The heat that goes into something as it is changing phases is used to change the bonds between molecules.
- Objects release heat as they freeze and condense.
- Objects absorb heat as they evaporate and melt.
- Freezing points, melting points, boiling points and condensation points are the "speed limits" of the phases. Once the molecules reach that speed they must change state.
- Heat capacity is how much heat an object can absorb

before its temperature increases.

- Specific heat is how much heat energy a mass of a material must absorb before it increases 1°C.
- Heat capacity is influenced by the specific heat of the material and/or the amount of the material.
- Each material has its own specific heat. The higher a material's specific heat is, the more heat it must absorb before its temperature increases.
- A larger amount of something will have a higher heat capacity then a smaller amount of something.
- Water has a very high heat capacity.

Textbook Reading

"I'm too cold. Get me a sweater!"

"This soup's too hot!"

"Phew, I'm sweating."

"Yowtch, that pan handle burned me!"

If you've ever made any of the above comments, then you were talking about thermal energy. Very clever of you, don't you think?

Thermal energy is basically the energy of the molecules moving inside something. The faster the molecules are moving, the more thermal energy that something has. The slower they are moving, the less thermal energy that something has.

I'm sure at some point you've said, *"Wow, my internal thermal energy is way high! I need a liquid with a low thermal energy."*

What…you've never said that?!? Oh, wait. I bet it sounded like this when you said it, *"Wow, I'm hot! I need a cool drink."* Whenever we talk about the temperature of something, we are talking about its thermal energy.

Temperature

Temperature is a way of talking about, measuring, and comparing the thermal energy of objects. We use three different kinds of scales to measure temperature: Fahrenheit, Celsius, and Kelvin. (The fourth, Rankine, which is the absolute scale for Fahrenheit, is the one you'll learn about in college.)

Way back when, like in the 18th century, Mr. Fahreheit created a scale using a mercury thermometer to measure temperature. He marked 0° as the temperature ice melts in a tub of salt. (Ice melts at lower temperatures when it sits in salt. This is why we salt our driveways to get rid of ice). To standardize the higher point of his scale, he used the body temperature of his wife—96°.

As you can tell, this wasn't the most precise or useful scale for measurement. I can just imagine Mr. Fahrenheit saying, *"Hmmm, something cold...something cold. I got it! Ice in salt. Good, okay there's zero, excellent. Now, for something hot. Ummm, my wife! She always feels warm. Perfect, 96°. "* I hope he never tried to make a thermometer when she had a fever!

Just kidding, I'm sure he was very precise and careful, but it does seem kind of weird. Over time, the scale was made more precise, and today body temperature is usually around 98.6°F.

Later, (still in the 18th century) Mr. Celsius came along and created his scale. He decided that he was going to use water as his standard. He chose the temperature that water freezes as his 0° mark. He chose the temperature that water boils at as his 100° mark. From there, he put in 100 evenly spaced lines and a thermometer was born.

Last but not least, Mr. Kelvin came along and wanted to create another scale. He said, I want my zero to be ZERO! So he chose absolute zero to be the zero on his scale.

Absolute zero is the theoretical temperature where molecules and atoms stop moving. They do not vibrate, jiggle or move in any way at absolute zero. In Celsius, absolute zero is -273 ° C. In Fahrenheit, absolute zero is -459°F (or 0°R). It doesn't get colder than that!

As you can see, creating the temperature scales was really rather arbitrary:

"I think 0° is when water freezes with salt."
"I think it's just when water freezes."
"Oh, yeah, well I think it's when atoms stop!"

Many of our measuring systems started rather arbitrarily and then, due to standardization over time, became the systems we use today.

What is Temperature Measuring?

So that's how temperature is measured, but what is temperature measuring? Temperature is measuring thermal energy, which is how fast the molecules in something are vibrating and moving.

The higher the temperature something has, the faster the molecules are moving. Water at 34°F has molecules moving much more slowly than water at 150°F. Temperature is really a molecular speedometer. This demonstration may make this clearer.

Sensing Temperature

When something feels hot to you, the molecules in that something are moving very fast. When something feels cool to you, the molecules in that object aren't moving quite so fast.

Believe it or not, your body perceives how fast molecules are moving by how hot or cold something feels. Your body has a variety of antennae to detect energy. Your eyes perceive certain frequencies of electromagnetic waves as light. Your ears perceive certain frequencies of longitudinal waves as sound. Your skin, mouth and tongue can perceive thermal energy as hot or cold. What a magnificent energy sensing instrument you are!

Thermal Energy

Objects whose molecules are moving very quickly are said to have high thermal energy or high temperature. The higher the temperature, the faster the molecules are moving. You may remember that temperature is just a speedometer for molecules.

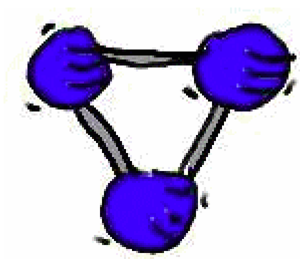
You may have asked yourself the question, *"So, if everything is made of molecules, and these molecules are often speeding up and slowing down…what happens to the stuff these molecules are made of if they change speed a lot? Will my kitchen table start vibrating across the room if the table somehow gets too hot?"*

No, it's pretty unlikely that your table will begin jumping around the room, no matter how hot it gets. However, some interesting things do happen when molecules change speeds.

Changes of State

Matter has a tendency to hang out in fairly stable states under normal temperatures. There are three common states of matter: solid, liquid, and gas.

There is another state of matter called plasma, but it is not common on Earth. Plasma is a highly energized gas. It is used in florescent lights. I'm going to assume you know a bit about solids, liquids, and gasses so I won't go into much detail about them here (see Unit 3 and 8 for more information).



What I do want to talk about is what happens as temperatures change in a substance. Let's take one of the neatest substances on the Earth—water. Water is quite special since it can be in its solid, liquid, and gas states at relatively "normal" temperatures. It's quite special for a variety of other reasons too, but we'll leave it at that for now.

Pretend we have an ice cube on a frying pan (poor ice cube). Right now the water is in a solid state. It's holding its shape. The molecules in the water are held together by strong, stiff bonds. These bonds hold the water molecules in a tight, very specific pattern called a matrix.

This matrix holds the water molecules in a crystalline pattern and the solid water holds its shape. Now, let's turn on the heat. The heat is transferred from the stove to the frying pan to the ice cube. (We'll talk about heat transfer a bit later.)

As the ice cube absorbs the heat, the molecules begin to vibrate faster (the temperature is increasing).

When the molecules vibrate at a certain speed (gain enough thermal energy) they stretch those strong, stiff bonds enough that the bonds become more like rubber bands or springs.

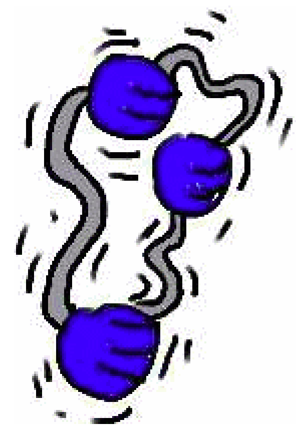
When the bonds loosen up, the water loosens up and becomes liquid. There are still bonds between the molecules, but they are a bit loose, allowing the molecules to move and flow around each other.

The act of changing from a solid to a liquid is called melting. The temperature at which a substance changes from a solid to a liquid is called its melting point. For water, that point is 32° F or 0° C.

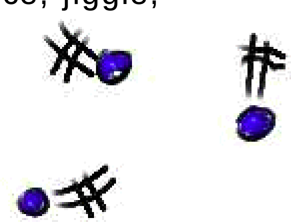
Now we will watch carefully as our ice cube continues to melt (little is more exciting than watching an ice cube melt—golf maybe?). A bit after we see our ice cube go from solid to completely liquid, we notice bubbling.

What's going on now? If we were able to see the molecules of water at this point, we'd be quite amazed at the fantastic scene before us.

At 212°F, or 100°C, water goes from a liquid state to a gaseous state. This means that the loosey-goosey bonds that connected the molecules before have been stretched as far as they go, can't hold on any longer, and "POW!" they snap.



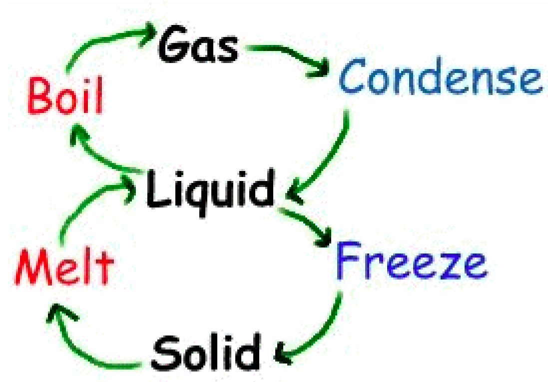
Those water molecules no longer have any bonds and are free to roam aimlessly around the room. Gas molecules move at very quick speeds as they bounce, jiggle, crash and zip around any container they are in. The act of changing from a liquid to a gas is called evaporation, or boiling, and the temperature at which a substance changes from a liquid to a gas is called its boiling point.



I don't know about you, but I think it's getting a bit hot in here. Let's turn the heat down a bit and see what happens. If our gaseous water molecules get close to something cool, they will combine and turn from a gaseous to a liquid state.

This is what happens to your bathroom mirror during a shower or bath. The gaseous water molecules that are having fun bouncing and jiggling around the bathroom get close to the mirror. The mirror is colder than the air. As the gas molecules get close they slow down due to loss of temperature. If they slow enough, they form loosey-goosey bonds with other gas molecules and change from a gaseous to a liquid state.

The act of changing from gas to liquid is called condensation. The temperature at which molecules change from a gas to a liquid is called the condensation point. Clouds are made of hundreds of billions of tiny little droplets of liquid water that have condensed onto particles of some sort of dust.



Now let's turn the heat down a bit more and see what happens. As the temperature drops and the molecules continue to slow, the bonds between the molecules can pull them together tighter and tighter.

Eventually the molecules will fall into a matrix, or pattern, and stick together quite tightly. This would be the solid state. The act of changing from a liquid to a solid is called freezing, and the temperature at which it changes is called (say it with me now) freezing point.

Think about this for a second—is the freezing point and melting point of an object at the same temperature? Does something go from solid to liquid or from liquid to solid at the same temperature?

If you said yes, you're right! The freezing point of water and the melting point of water are both 32°F, or 0° C. The temperature is the same. It just depends on whether it is getting hotter or colder as to whether the water is freezing or melting.

The boiling and condensation point is also the same point. Now I'm going to mess things up a little bit. Substances can change state at temperatures other than their different freezing or boiling points. Many liquids change from liquid to gas and from gas to liquid relatively easily at room temperatures.

And, believe it or not, solids can change to liquids and even gases and vice versa at temperatures other than the usual melting, freezing, or boiling points. So what's the point of the points?

At a substance's boiling, freezing, etc, points, all of the substance must change to the next state. The condition of the bonds cannot remain the same at that temperature. For example, at 100°C, water must change from a liquid to a gas. That is the speed limit of liquid water molecules. At 100°C the liquid bonds can no longer hold on, and all the molecules convert to gas.

Heat Transfer

The heat is on! Now we are going to learn what heat is and how it moves from place to place. You know how they say, *"If you can't stand the heat, get out of the kitchen."*?

Well after this lesson you'll know exactly what it is that you can't stand!

Heat

Believe it or not, the concept of heat is really a bit tricky. What we call heat in common language is really not what heat is as far as physics goes.

Heat, in a way, doesn't exist as nothing *has* heat. Things can have a temperature or thermal energy, but they can't have heat. **Heat is really the transfer of thermal energy** or, in other words, the movement of thermal energy from one object to another.

If you put an ice cube in a glass of lemonade, the ice cube melts. The thermal energy from your lemonade moves to the ice cube, increasing the temperature of the ice cube and decreasing the temperature of your lemonade.

The movement of thermal energy is called heat. The ice cube receives heat from your lemonade. Your lemonade gives heat to the ice cube.

Heat can only move from an object of higher temperature to an object of lower temperature. **Heat goes from hot to cold.** Coffee cools down and ice water heats up. That's one of the laws of thermodynamics.

Do you remember what temperature is? Temperature measures how fast molecules are moving, right?

Well, when heat transfers (moves) from one object to another, the movement of the molecules in the higher temperature object slows down, and the movement of the molecules in the lower temperature object speeds up.

In our example of the ice and the lemonade, it would work like this: the lemonade has a higher temperature than the ice. (The molecules are moving faster than the ice molecules.)

The faster moving molecules of the lemonade would transfer heat to the ice, causing the ice molecules to move faster (increase temperature) and eventually change from solid to liquid.

In turn, since the faster moving molecules of the lemonade move energy (transfers heat) to the ice, the molecules slow down. This causes the temperature of your drink to decrease, and that is what makes your lemonade nice and cold. Heat can be transferred in three different ways: conduction, convection and radiation.

Conduction

Let's start with conduction. Heat is transferred through conduction the same way pool balls are scattered around a table in the opening break. On a pool table, one ball crashes into another ball which crashes into another ball speeding the balls up and moving them around the table.

Heat transferred from one object to another through conduction does the same thing. The molecules near the heat source (candle, stove, etc.) begin moving faster (their temperature increases).

As they move faster they crash into other molecules around them which causes them to move faster. As those molecules move faster they crash into more molecules...etc, etc. Thus the molecules in the object are all moving faster.

In this process, heat has been transferred by conduction and the temperature of the object is higher. The conduction experiment may make this clearer.

Radiation

Heat is transferred by radiation through electromagnetic waves. Remember when we talked about waves and energy in Unit 9? Well, heat can be transferred by electromagnetic waves.

Energy is vibrating particles that can move by waves over distances, right? Well, if those vibrating particles hit something and cause those particles to vibrate (causing them to move faster/increasing their temperature) then heat is being transferred by waves.

These types of electromagnetic waves that transfer heat are infrared (IR) waves. The Sun transfers heat to the Earth through radiation. (There's nothing between the Earth and the Sun to conduct through or convect with.)

Now let's explore how, even though heat can move from one object to another, it doesn't necessarily mean that the temperature of the objects will change. You may ask, *"What? Heat can move from one object to another without temperature changing one little bit?!?!"*

Yeah…confusing huh? In this lesson we're going to take a look at one of the ways heat can move while the thermometer doesn't.

Changing Phases

When things change phases (like changing from a solid to a liquid or a liquid to a gas or…well, you get the picture) the temperature of those objects doesn't change. If you were able to take the temperature of water as it changed from a solid (ice) to a liquid you would notice that the temperature of that piece of ice stays at about 32°F until that piece of ice is completely melted. The temperature would not increase at all.

Even if that ice were in an oven, its temperature would stay the same. Once all the solid ice had disappeared, then you would see the temperature of the puddle of water increase.

(By the way, as the ice is melting, from where is heat being transferred? Heat is being transferred, by conduction, from the air.)

Heat Capacity

Think of a dry sponge. Now imagine putting that sponge under a slowly running faucet. The sponge would continue to fill with water until it reached a certain point and then water would start to drip from it. You could say that the sponge had a water capacity. That is, the sponge would be able to hold only so much water before it wouldn't be able to hold any more. Then the water would start dripping out.

Heat capacity is similar. Heat capacity is how much heat an object can absorb before it increases in temperature. This is also referred to as specific heat. Specific heat is how much heat energy a mass of a material must absorb before its temperature increases 1° C.

Each material has its own specific heat. The higher a material's specific heat, the more heat it must absorb before it increases in temperature.

Water is unique in that it has a very high specific heat. Liquid water's specific heat is over 4, which is very high. In comparison, granite is 0.8, aluminum is 0.9, rubbing alcohol is 2.4 and gold is 0.1.

To get the same amount of rubbing alcohol and liquid water to increase the same amount of temperature, you would need to pump about twice the amount of heat into the water.

To get the same amount of gold and liquid water to increase the same amount of temperature, you would need to pump 40 times the amount of heat into the water!

In other words, it takes more energy to heat water then it does to heat alcohol, gold, or, for that matter, most other things.

