Essential idea: Thermal physics deftly demonstrates the links between the macroscopic measurements essential to many scientific models with the microscopic properties that underlie these models.

Nature of science: Evidence through experimentation: Scientists from the 17th and 18th centuries were working without the knowledge of atomic structure and sometimes developed theories that were later found to be incorrect, such as phlogiston and perpetual motion capabilities. Our current understanding relies on statistical mechanics providing a basis for our use and understanding of energy transfer in science.
**Topic 3: Thermal physics**

3.1 – Thermal concepts

**Understandings:**

- Molecular theory of solids, liquids and gases
- Temperature and absolute temperature
- Internal energy
- Specific heat capacity
- Phase change
- Specific latent heat
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Applications and skills:
• Describing temperature change in terms of internal energy
• Using Kelvin and Celsius temperature scales and converting between them
• Applying the calorimetric techniques of specific heat capacity or specific latent heat experimentally
• Describing phase change in terms of molecular behaviour
• Sketching and interpreting phase change graphs
• Calculating energy changes involving specific heat capacity and specific latent heat of fusion and vaporization
Guidance:

- Internal energy is taken to be the total intermolecular potential energy + the total random kinetic energy of the molecules
- Phase change graphs may have axes of temperature versus time or temperature versus energy
- The effects of cooling should be understood qualitatively but cooling correction calculations are not required

Data booklet reference:
- $Q = mc\Delta T$
- $Q = mL$
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International-mindedness:
• The topic of thermal physics is a good example of the use of international systems of measurement that allow scientists to collaborate effectively

Theory of knowledge:
• Observation through sense perception plays a key role in making measurements. Does sense perception play different roles in different areas of knowledge?
Utilization:

• Pressure gauges, barometers and manometers are a good way to present aspects of this sub-topic.
• Higher level students, especially those studying option B, can be shown links to thermodynamics (see Physics topic 9 and option sub-topic B.4).
• Particulate nature of matter (see Chemistry sub-topic 1.3) and measuring energy changes (see Chemistry sub-topic 5.1).
• Water (see Biology sub-topic 2.2).
Aims:

- **Aim 3**: An understanding of thermal concepts is a fundamental aspect of many areas of science.
- **Aim 6**: Experiments could include (but are not limited to): transfer of energy due to temperature difference; calorimetric investigations; energy involved in phase changes.
Molecular theory of solids, liquids and gases

- The three phases of matter are **solid**, **liquid**, and **gas**.
- In a solid the molecules can only vibrate. They cannot translate.
- In a liquid the molecules can vibrate and move about freely in a fixed volume.
- In going from a **solid** to a **liquid**, some of the intermolecular bonds are broken, giving the molecules more freedom of motion.
- In going from a **liquid** to a **gas**, most of the intermolecular bonds are broken.
Phase change
• The process of going from a solid to a liquid is called melting.
• The process of going from a liquid to a gas is called boiling.
• Each process can be reversed.

<table>
<thead>
<tr>
<th>PHASE CHANGE</th>
<th>PROCESS</th>
<th>EXAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>solid → liquid</td>
<td>melting</td>
<td>ice to water</td>
</tr>
<tr>
<td>liquid → solid</td>
<td>freezing</td>
<td>water to ice</td>
</tr>
<tr>
<td>liquid → gas</td>
<td>boiling</td>
<td>water to steam</td>
</tr>
<tr>
<td>gas → liquid</td>
<td>condensing</td>
<td>steam to droplets</td>
</tr>
<tr>
<td>solid → gas</td>
<td>sublimation</td>
<td>frost evaporation</td>
</tr>
<tr>
<td>gas → solid</td>
<td>deposition</td>
<td>frost</td>
</tr>
</tbody>
</table>
**Internal energy**

- All substances are composed of individual molecules that are in vibration.
- As we heat up a substance its vibrations become more energetic. This is an increase in the kinetic energy of the molecules.
- Simultaneously, as heat energy is being added the molecules are also moving farther apart. This is an increase in the potential energy of the substance.
- The two energies together are called the internal energy of the substance. Thus $E_{\text{INT}} = E_K + E_P$.
- When thermal energy (heat) is added to a substance it is stored as internal energy.
**Internal energy**

\[ E_{\text{INT}} = E_K + E_P. \]

**Total Internal Energy**

<table>
<thead>
<tr>
<th>Potential Energy</th>
<th>Kinetic Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>(due to inter-molecular forces)</td>
<td>(due to vibration and translation)</td>
</tr>
</tbody>
</table>

Think of Hooke’s law \( F = -kx \) and phase change

The thermometer measures internal kinetic energy
Temperature and absolute temperature

- Because absorption of thermal energy (heat) causes materials to expand, the fluid in a thermometer can be used to indirectly measure temperature.
- Since water is a readily-available substance that can be frozen, and boiled within a narrow range of temperatures, many thermometers are calibrated using these temperatures.
- We will be using the Celsius scale in physics because it is a simpler scale.
- Temperature only reveals the internal kinetic energy.
- Expansión reveals internal potential energy.
Temperature and absolute temperature

- When gas is heated in an enclosed space its pressure $p$ increases.
- The following experiment plots pressure $p$ vs. temperature $T$ in Celsius.
- We can extrapolate the graph.
- Now we repeat using different gases.
The lowest pressure $p$ that can exist is zero.

Surprisingly, the temperature at which any gas attains a pressure of zero is the same, regardless of the gas.

The Celsius temperature at which the pressure is zero (for all gases) is -273 °C.
Because the lowest pressure that can exist is zero, this temperature is the lowest temperature that can exist, and it is called **absolute zero**.

A new temperature scale that has absolute zero as its lowest value is called the **Kelvin temperature scale**.

**Temperature and absolute temperature**

-273.15 °C
Converting between Kelvin and Celsius temperatures

- The simple relationship between the Kelvin and Celsius scales is given here:

\[ T(K) = T(°C) + 273 \]

**FYI** - Note that there is no degree symbol on Kelvin temperatures.

**EXAMPLE:** Convert 100°C to Kelvin, and 100 K to °C.

**SOLUTION:**
- \[ T(K) = T(°C) + 273 \]
- \[ T = 100 + 273 = 373 \text{ K} \]
- \[ 100 = T(°C) + 273 \]
- \[ T = -173 °C \]
Specific heat capacity

- Traditionally in the U.S., heat energy is measured in calories or kilocalories.

One kilocalorie is the amount of heat needed to raise the temperature of one kilogram of water by exactly 1 °C.

- 1 calorie is needed to raise the temperature of 1 gram (instead of a kilogram) of water 1 °C.
- In Europe they don’t talk about “low calorie cola.”
- Instead, they talk about “low Joule cola.”
Specific heat capacity

- Obviously there must be a conversion between Joules (J) and kilocalories (kcal).

1 kcal = 4.186 kJ

Mechanical equivalent of heat
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Specific heat capacity

EXAMPLE: How many joules is 450000 calories?
SOLUTION: Use 1 kcal = 4.186 kJ:
450000 cal = (450 kcal)(4.186 kJ / 1 kcal)
= 1900 kJ.

PRACTICE: A Snickers™ bar has 273.0 Cal. For foods, Calories are really kcal. How many joules are in a Snickers™ bar?

• 273.0 Cal = (273.0 kcal)(4.186 kJ / 1 kcal)
  = 1143 kJ = 1,143,000 J!
**Specific heat capacity**

- Different materials absorb heat energy in different ways.
- This means that if we have two different substances having the same mass \( m \), and each absorbs the same amount of heat \( Q \), their increase in temperature \( \Delta T \) may be different.
- We define the specific heat capacity \( c \) of a substance as the amount of heat needed per unit temperature increase per unit mass.

\[
Q = mc\Delta T
\]

- Each material has its own unique value for \( c \).
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Specific heat capacity

- Here are some specific heats for various materials.

<table>
<thead>
<tr>
<th>Substance</th>
<th>J / kg·C°</th>
<th>kcal/kg·C° (or cal/g·C°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air (at 50°C)</td>
<td>1050</td>
<td>0.25</td>
</tr>
<tr>
<td>Water (at 15°C)</td>
<td>4186</td>
<td>1.00</td>
</tr>
<tr>
<td>Steam (at 110°C)</td>
<td>2010</td>
<td>0.48</td>
</tr>
<tr>
<td>Ice (at -5°C)</td>
<td>2100</td>
<td>0.50</td>
</tr>
<tr>
<td>Wood</td>
<td>1680</td>
<td>0.40</td>
</tr>
<tr>
<td>Ethyl Alcohol</td>
<td>2430</td>
<td>0.58</td>
</tr>
<tr>
<td>Steel</td>
<td>460</td>
<td>0.11</td>
</tr>
</tbody>
</table>

FYI
- Note that specific heat units for $c$ are (J kg$^{-1}$ C°$^{-1}$).
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**Calculating energies involving specific heat capacity**

\[ Q = mc\Delta T \]

**EXAMPLE:** Air has a density of about \( \rho = 1.2 \text{ kg m}^{-3} \). How much heat, in joules, is needed to raise the temperature of the air in a 3.0 m by 4.0 m by 5.0 m room by 5°C?

**SOLUTION:**

- From the previous table we see that \( c = 1050 \).
- The change in temperature is given: \( \Delta T = 5 \degree C \).
- We get the mass from \( \rho = m / V \) or \( m = \rho V = (1.2)(3)(4)(5) = 72 \text{ kg} \).
- \( Q = mc\Delta T = (72)(1050)(5) = 378000 \text{ J or 380 kJ} \).
PRACTICE: Suppose we have a 200.-kg steel ingot and a 200.-kg block of wood, both at room temperature (20.0 °C). If we add 1,143,000 J of heat (the energy of a Snickers™ bar) to each object, what will its final temperature be?

SOLUTION:
• For both, \( Q = mc\Delta T = mc(T - T_0) \).
• Steel: \( 1143000 = 200(460)(T - 20) \)
  \[ 12.4 = T - 20 \text{ or } T = 32.4 \degree C. \]
• Wood: \( 1143000 = 200(1680)(T - 20) \)
  \[ 3.40 = T - 20 \text{ or } T = 23.4 \degree C. \]
Suppose a thermometer is frozen in ice, and the ice is further cooled to a temperature of \(-20^\circ C\). We slowly add heat, and plot the temperature vs. the heat \(Q\) added:

Since the thermometer measures kinetic energy, and since the temperature doesn’t change during the phase change, the heat must be getting stored **ONLY** as potential energy during phase change.
Phase change in terms of molecular behavior

- As a model to help explain phase change consider a molecule in an open box which can move left and right but must remain “captured” in the box.
- As more heat is stored as potential energy, the particle in our model gains height.
- Finally, the potential energy is great enough to break the intermolecular bonds and change the phase of the substance.
- The molecule is free!


**Specific latent heat**

- *Latent heat* means *hidden heat*, by which we mean that there is no temperature indication that heat is being lost or gained by a substance.

- The **specific latent heat** $L$ is defined in this formula:

  \[ Q = mL \]

  \[ \text{specific latent heat } L \text{ defined} \]

- Note that since there is no temperature change during a phase change, there is no $\Delta T$ in our formula. The units for $L$ are (J kg$^{-1}$).

**FYI**

- Use $Q = mL$ during phase change (when $\Delta T = 0$).
- Use $Q = mc\Delta T$ otherwise (when $\Delta T \neq 0$).
Specific latent heat

- Since there are two phase changes (two plateaus), each substance has two latent heats.

Latent Heats $L$ of Various Substances at 1 atm.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Melting Point °C</th>
<th>$L_f$</th>
<th>Boiling Point °C</th>
<th>$L_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>J/kg</td>
<td>kcal/kg</td>
<td>J/kg</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>$3.33 \times 10^5$</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Mercury</td>
<td>-39</td>
<td>$0.12 \times 10^5$</td>
<td>2.8</td>
<td>357</td>
</tr>
<tr>
<td>Oxygen</td>
<td>-219</td>
<td>$0.14 \times 10^5$</td>
<td>3.3</td>
<td>-183</td>
</tr>
<tr>
<td>Gold</td>
<td>1063</td>
<td>$0.65 \times 10^5$</td>
<td>15.4</td>
<td>2660</td>
</tr>
</tbody>
</table>

- $L_f$ is the latent heat of fusion.
- $L_v$ is the latent heat of vaporization.
- The temperatures associated with the phase changes are also given.
EXAMPLE: Compare boiling and evaporation.

SOLUTION:

- **Boiling** takes place within the whole liquid at the **same** temperature, called the *boiling point*.
- **Evaporation** occurs only at the surface of a liquid and can occur at **any** temperature.
- Evaporation can be enhanced by increasing the surface area, warming the liquid, or having air movement at the surface.
- **Boiling and evaporation both remove the same amount of heat energy from the liquid.** This is why sweating removes excess body heat so well!
EXAMPLE:
Bob has designed a 525-kg ice chair. How much heat must he remove from water at 0°C to make the ice chair (also at 0°C)?

SOLUTION:
• In a phase change $\Delta T = 0$ so we use $Q = mL$.
• Since the phase change is freezing, we use $L_f$.
• For the water-to-ice phase change $L_f = 3.33 \times 10^5$ J kg$^{-1}$.
• Thus $Q = mL = (525)(3.33 \times 10^5) = 175 \times 10^6$ J.
• Bob can now chill in his new chair.
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*Conduction, convection and thermal radiation*

- Thermal energy can be transferred from a warmer mass to a cooler mass by three means: conduction, convection, and radiation.
- This energy transfer is called **heating** and **cooling**.
- Only **thermal radiation** transfers heat without any physical medium such as solid, liquid or gas.

**EXAMPLE:** The heat from a wood-burning stove can be felt from all the way across the room because photons carrying infrared energy can travel through empty space. When these photons strike you, they are absorbed as heat. This process of thermal energy transfer is called **thermal radiation**. *See Topic 8.2.*
Conduction, convection and thermal radiation

- When two solids of different temperatures touch, thermal energy is transferred from the hotter object to the cooler object through a process called conduction.
- When atoms of one portion of a material are in contact with vibrating atoms of another portion, the vibration is transferred from atom to atom.

Direction of heat flow

- High $T$ portions vibrate more than low $T$ portions, so we can imagine the vibration “impulse” to travel through the material, from high $T$ to low $T$. 
Conduction, convection and thermal radiation

- Consider a material that acts as a conductor of heat from the hot object to the cold object.

At the end of the process the two ends have reached thermal equilibrium at which point there is no more net transfer of heat.
Conduction, convection and thermal radiation

- Another form of heat transfer is called convection.
- Convection requires a fluid as a medium of heat transfer.
- For example, hot air is less dense than cold air, so it rises.
- But as it rises it cools, and so becomes denser and sinks.
- We thus obtain a cycle, which forms a circulation called a convection current.
- Convection currents drive many interesting physical systems as the next slides illustrate.
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*Conduction, convection and thermal radiation*

EXAMPLE: Atmospheric convection - thunderheads.
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Conduction, convection and thermal radiation

EXAMPLE:
Atmospheric convection - nuclear detonation.
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Conduction, convection and thermal radiation

EXAMPLE: Oceanic convection - currents.
Topic 3: Thermal physics
3.1 – Thermal concepts

Conduction, convection and thermal radiation

EXAMPLE: Solar convection – sunspots and flares.
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Conduction, convection and thermal radiation

EXAMPLE: Mantle convection – plate tectonics.
Plate tectonics - convection

- The residual heat from the formation of Earth, and the heat generated by radioactive decay deep within the mantle, combine to produce the perfect conditions for convection currents.

- Even though the mantle acts similar to a solid in many ways, it is really a special kind of fluid that would be liquid like lava if it weren’t for the tremendous pressure it is under due to overlaying layers.
Plate tectonics - convection

- Specific to the NGSS, and related to convection currents, we have **plate tectonics**, which is the study of crustal plate motion over the surface of Earth over time.
- It is these convection currents in the mantle that drive plate tectonics.
  
  Spreading center  Subduction zone

  | Crustal Plate | Crustal Plate | Crustal Plate |

- Spreading centers are where plates separate.
- Subduction zones are where plates collide.
Plate tectonics - convection

- Spreading centers are usually located in the ocean and produce landforms called oceanic ridges.
- Oceanic ridges form because as the oceanic plates separate, magma can well up into the void.

New crust is formed at the spreading centers.
Plate tectonics - convection

- A true subduction zone is where one of two colliding plates is driven underneath the other.
- Mountains created by the buckling crust can form, as well as volcanoes, powered by melting crustal material.
Plate tectonics - convection

• Generally when oceanic plates collide with land plates, the oceanic plate is the one that is driven underneath in the subduction zone.
• Plates can also collide and crumple, forming mountains without subduction.
• These are usually two land plates colliding.
Plate tectonics

- **Pangaea** is the name given to the early landform that was more or less all the present-day continents placed close together.

- Because of continental drift (on the average of two inches per year), Pangaea has split up into the present-day continents, which are still in motion.

- In the following animation, note how the **Indie plate** collides with the **Eurazja plate**. What mountain range do you think this collision created?
Credit: Jean Besse, Institut de Physique du Globe de Paris
PRACTICE: How do you think continental drift might affect the evolution of living species?