Section 9: Special Topics

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9.01
Temperature and Specific Heat

Temperature is a property of an object that is related to the average kinetic energy of the particles comprising the object.

The two primary scales of temperature used in science are ***Celsius***, measured in degrees Celsius (°C), and ***Kelvin***, measured in kelvins (K).

- The Celsius scale is based on properties of water and is designed so that the freezing point of water is $0\ ^\circ\mathrm{C}$ and the boiling point of water is $100\ ^\circ\mathrm{C}$.
- The Kelvin scale ensures that all temperatures are positive values when performing calculations.
- To convert Celsius temperature to Kelvin, use the following equation:

$$T_K = T_C + 273$$

Absolute zero is the lowest theoretical temperature possible. It is defined as $0\ \mathrm{K}$.

There are three primary ways that heat flows between objects:

1) ***Conduction*** – the process by which particles in an object come into contact with one another, resulting in a transfer of thermal energy
   Example: Placing a pot on a stove causes not only the pot but also the attached handle to heat up because of conduction.
2) ***Convection*** – the process by which temperature differences in a fluid cause the fluid to move so that energy is transferred between the different regions of the fluid
   Example: When water boils in a pot, warmer water at the bottom of the pot flows to the top of the pot where the colder water sits. This causes the cold water to be displaced and heat to be transferred.
3) ***Radiation*** – the transfer of energy via electromagnetic waves
   Example: The Sun heats the Earth by radiating energy through electromagnetic waves (sunlight).

The ***specific heat*** of a material is the amount of energy required to raise the temperature of one unit of mass of that material by one temperature unit.

- The symbol for specific heat is C.
- The SI unit for specific heat is $\frac{\mathrm{J}}{\mathrm{kg \cdot K}}$.

To calculate the amount of heat (Q) required to change the temperature of an object with mass m, use the following equation:

$$Q = mC\Delta T$$

The following table shows the specific heats of several common substances:

Material	Specific Heat (J/kg·K)
Aluminum	897
Brass	376
Copper	385
Ice	2,060
Iron	450
Silver	235
Steam	2,020
Water	4,180

1. Suppose the cooling system of a car contains 25 L of water. Find the change in temperature of the water if the engine operates until 800 kJ of heat is added. Assume that 1 L of water has a mass of 1 kg.

2. Taking a shower uses about 65 L of water on average. Juan lives in Dallas, and he likes his shower water to be at a temperature of $40\ ^{\circ}\text{C}$. The water delivered through his plumbing system starts at a temperature of $19\ ^{\circ}\text{C}$. If TXU Energy sells energy to its Dallas customers for $\$0.12/\text{kWh}$, calculate the cost of an average shower for Juan. Recall that $1 \text{ kWh} = 3.6\times10^{6} \text{ J}$.

9.02
Pressure

Pressure is the force on a surface divided by the area of the surface over which the pressure is distributed. It is illustrated by the following equation:

$$P = \frac{F}{A}$$

- The force is always assumed to be acting perpendicularly to the surface.
- Pressure is a scalar quantity.
- Pressure is measured in ***pascals*** (Pa). One pascal is equal to $1\,\frac{\text{N}}{\text{m}^2}$.
  Because the pascal is a relatively small unit, it is more common to see pressure measurements expressed in kilopascals (kPa).
- The concept of pressure appears frequently in the study of fluids (gases and liquids) and the atmosphere.
  - Atmospheric pressure is the pressure that atmospheric gases exert on objects near the surface of a planet.
  - Humans hardly notice the effect of atmospheric pressure because the human body balances out the effect with its own outward forces.

1. Paola is out ice fishing and is sitting on a stool on a frozen lake. Suppose Paola weighs $1{,}000\ \text{N}$ and the stool weighs $50\ \text{N}$. The legs of the stool touch the ground over an area of $22\ \text{cm}^2$. Find the average pressure that Paola and the stool exert on the ice.

9.03
The Laws of Thermodynamics

First law of thermodynamics – The change in the internal energy of a system is equal to the heat (thermal energy) delivered to the system minus the work done by the system on its environment.

- This law is simply another way of stating the law of conservation of energy: Energy in equals energy out.
- Mathematically, $\Delta U = Q - W$.
- Devices that absorb heat and do work as a result are known as ***heat engines***. Like any system, a heat engine must obey the first law of thermodynamics.
- The internal energy of a closed system is a function of its temperature. If temperature increases, then internal energy increases as well.

1. Suppose a heat engine is used to power a 2,000-kg boat, accelerating it to 10 $\frac{\mathrm{m}}{\mathrm{s}}$. According to the first law of thermodynamics, what is the minimum amount of thermal energy that the engine must absorb to perform this task, assuming that the engine maintains a constant temperature during the process?

Second law of thermodynamics – The total entropy of a closed system cannot decrease over time. Systems in nature tend to increase in entropy over time.

- ***Entropy*** is a measurement of disorder or chaos in a system.
- Lower entropy in a system is associated with a greater ability to do work.
- Thermal energy is considered a high-entropy form of energy, whereas other forms of energy, such as gravitational potential energy or electrical energy are considered to be lower in entropy.
- Here's an example: As a block slides down an incline with friction at constant speed, ____________________________ energy is transformed into _____________________ energy. While the total energy of the system remains constant over time, it is impossible for this process to naturally reverse itself.

Third law of thermodynamics – It is impossible to lower a system's temperature to absolute zero.

- A simplified way of understanding the third law is to consider how you would *attempt* to cool an object to absolute zero. To cool something, you'd place it in contact with something cooler than itself, meaning you'd need an object at absolute zero in the first place to cool a second object to absolute zero.
- Note that a temperature of absolute zero would correspond to the lowest possible entropy state of a system.

Optics – the study of how images are formed by light

- In the study of optics, an ***object*** is something an image will be made of.
- An ***image*** is a recreation of the appearance of an object by light.
  - A ***real image*** is any image that can be projected onto a screen. The image formed by a camera on film or a digital sensor is real, for example.
  - A ***virtual image*** is any image that cannot be projected onto a screen. The image formed by a bathroom mirror is virtual, for example.
  - An ***upright image*** appears in the same vertical orientation as the object.
  - An ***inverted image*** appears upside down with respect to the object.

Plane mirror – a flat, reflective surface that forms virtual images by reflection

- When an object is placed a certain distance in front of a plane mirror, an upright, virtual image of the object, of the same size as the object, is created at the same apparent distance behind the mirror.
- The reflection you see of yourself in any plane mirror is a virtual image created by the mirror.
- Draw a diagram of an image formed by a plane mirror:

  For plane mirrors, two key equations apply:
  - The first is $d_i = d_o$, in which d_i is the distance of the image from the mirror, and d_o is the distance of the object from the mirror.
  - The second is $h_i = h_o$, in which h_i represents image height, and h_o represents object height.
- Not all mirrors are plane mirrors. Mirrors can be curved, and such mirrors follow different rules.
  - Here's an example: The small ***convex mirror*** on the side of a semitruck creates shrunken images of the objects reflected in it.
  - Here's an example: Makeup mirrors are ***concave mirrors*** used to create magnified images of facial skin.

Refraction – The bending of light rays as they pass through a different medium, such as when light passes from air into glass

Convex lens – An outwardly curved, transparent piece of material that forms images by refraction

- Every lens has a property called ***focal length*** (f) that depends on the lens's curvature and the type of material it is made of. The focal length of a convex lens is always positive.
- Convex lenses can form both real and virtual images, as well as both upright and inverted images, depending on how the object's distance from the lens compares to the focal length of the lens.

$\boldsymbol{d_o}$	$\boldsymbol{d_i}$	**Enlarged or Reduced?**	**Upright or Inverted?**	**Real or Virtual?**
$d_o > 2f$	$2f > d_i > f$	Reduced	Inverted	Real
$2f > d_o > f$	$d_i > 2f$	Enlarged	Inverted	Real
$f > d_o > 0$	$d_i < 0$ and $\lvert d_i \rvert > f$	Enlarged	Upright	Virtual

- Draw a diagram of a convex lens forming a real, enlarged, inverted image:

- When image distance is positive, the image appears on the opposite side of the lens from the object. When image distance is negative, the image appears on the same side of the lens as the object.
- For convex lenses, two key equations apply:
    - $\frac{1}{f} = \frac{1}{d_i} + \frac{1}{d_o}$
    - $\frac{-d_i}{d_o} = \frac{h_i}{h_o}$

1. A convex lens with a focal length of 15 cm is placed 25 cm from an object. At what distance from the lens will the image of the object be formed? Will it be real or virtual? Upright or inverted? Enlarged or reduced?

9.05
The Photoelectric Effect

Photoelectric effect – The observation that when light shines on a material, electrons can be ejected from that material

- When light shines on a material, energy from that light is imparted to electrons in the material as ________________ energy, so the electrons fly off at high speeds.
- Originally, scientists believed that light was a simple wave. Thus, they expected that shining higher-intensity light on a material would cause electrons to fly off with higher speeds, and shining sufficiently low-intensity light would fail to eject any electrons.
- Upon further research, scientists found that electrons could be ejected by *any* intensity of light, but only light of certain frequencies.
- This discovery provided support for the theory that light behaves in some respects as a particle and in other respects as a wave. This is the ***dual nature of light***.
- It was proposed that each individual particle of light, called a ***photon***, carried a specific amount of energy proportional to its frequency. Thus, whether an electron is ejected from a material depends on how much energy the photon striking it carries, not on the intensity of the light. Even a single photon of sufficient frequency could dislodge an electron.
    - Think of intensity as the number of photons striking the material.
    - Since frequency is proportional to photon energy, think of frequency as how energetic *each* photon is.
- The discovery that light behaves like a particle in some respects was foundational to the field of modern physics called __________________ mechanics.
- The photoelectric effect is used in digital cameras with charge-coupled diode (CCD) image sensors. Photons strike the sensor, which causes electrons to be ejected. These electrons are stored during the period over which the camera's shutter is open, and the total number of electrons ejected is recorded when the image is finally processed.

9.06
Atomic Emission Spectra

Emission spectrum – The particular frequencies of light that are emitted when a particular material's electrons are excited, for example by heating

- Using a device called a ***spectrometer***, which splits light using a prism, one can analyze which specific frequencies of light are emitted when a gas is electrically excited.
- An important and peculiar discovery in the history of physics was of the fact that certain elements' emission spectra are ***discrete***. This means that only very specific, individual wavelengths are emitted, rather than a continuous spectrum of wavelengths.

The emission spectrum of hydrogen (violet on left to red on right):

- Looking at the emission spectrum of hydrogen, we can immediately see that particular colors (wavelengths) stand out sharply.
- Photons are emitted from atoms when electrons "jump" from a higher energy level to a lower one. The fact that emission spectra are discrete is evidence of the fact that electrons can only jump between very specific energy levels, corresponding to photons of very specific wavelengths being emitted. This, in turn, is evidence of the idea that energy is ***quantized***, meaning that energy comes in specific packet sizes and cannot be transferred in arbitrary quantities. Quantization of energy was a foundational realization in the modern field of physics known as __________________ mechanics.

9.07
Nuclear Physics

- Nuclear physics is the study of the nucleus of the atom.
- An atom's nucleus is made of protons and neutrons.
    - The ***atomic number*** (Z) of an atom is the number of protons in the nucleus.
    - The total charge of the nucleus is the number of protons multiplied by the elementary charge (e) as given by the following equation:

$$\text{nuclear charge} = Ze$$

    - The ***mass number*** (A) of the nucleus is the total number of neutrons and protons.
    - The ***atomic mass unit*** (u) is the approximate mass of a proton or a neutron.

$$1\ \mathrm{u} = 1.66\times10^{-27}\ \mathrm{kg}$$

    - The approximate total mass of an atomic nucleus is given by the following equation:

$$\text{nuclear mass} \approx A\mathrm{u}$$

- The nucleus is extremely dense.
    - Nearly all the mass of an atom resides in its nucleus.
    - The diameter of the nucleus is approximately $10^{-14}\ \mathrm{m}$.
    - Proportionally speaking, the nucleus occupies less space in an atom than the Sun does in the entire solar system.
    - If the nucleus had a volume of $1\ \mathrm{cm}^3$, it would have a mass of approximately 1 billion tons.

- An important question to address is “What holds the nucleus together?”
    - Negatively charged electrons that surround the positively charged nucleus are held together by the attractive electromagnetic force.
    - The ***strong nuclear force*** acts between protons and neutrons that are close together (as they are in the nucleus).
    - The strong nuclear force is nearly 100 times stronger than the electromagnetic force.
- Both protons and neutrons are referred to as ***nucleons***.
- The ***binding energy*** of the nucleus is the difference between the work associated with removing a nucleon from the nucleus and the energy associated with a set of protons and neutrons on their own.

- The ***energy equivalent of mass*** is Einstein’s famous equation relating the amounts of mass and energy contained in matter.

$$E = mc^2$$

- This means that the binding energy can be expressed in terms of an equivalent amount of mass.

- ***Nuclear fission*** is the division of a nucleus into two or more fragments.
    - Nuclear fission releases neutrons and energy.
    - A uranium atom undergoes fission when it is bombarded with neutrons.
    - The release of these neutrons causes more fission reactions to occur, creating a ***chain reaction***.
    - In a nuclear reactor, this chain reaction is controlled by placing the uranium in a material that can slow down the neutrons that are released. This material is called a ***moderator***.
- ***Nuclear fusion*** is the process of nuclei with small masses combining to form a nucleus with a larger mass.
    - Since a larger nucleus is more tightly bound, its mass is less than the sum of the masses of the smaller nuclei. This difference in mass is accounted for as a release of energy (using Einstein’s equation).