PGCC: PHYS 2030 - GENERAL PHYSICS

Neeharika Thakur
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Neeharika Thakur

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This text was compiled on 06/12/2026

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Licensing

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CHAPTER OVERVIEW

12: Temperature and Kinetic Theory

Topic hierarchy

12.1: Introduction
12.2: Temperature and Temperature Scales
12.3: Thermal Expansion
12.4: Ideal Gas Law
12.5: Kinetic Theory
12.6: Phase Changes
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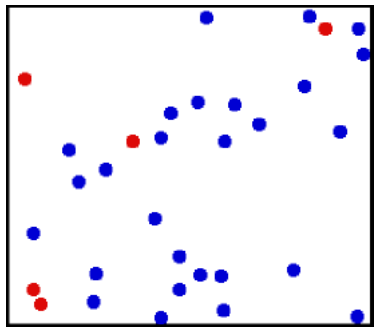
12.1: Introduction

learning objectives

- Describe gas using the kinetic theory of gases

Introduction to Temperature and Kinetic Theory

The kinetic theory of gases describes a gas as a large number of small particles (atoms or molecules), all of which are in constant, random motion. The rapidly moving particles constantly collide with each other, and with the walls of the container. Kinetic theory explains macroscopic properties of gases (such as pressure, temperature, and volume) by considering their molecular composition and motion. Essentially, the theory posits that pressure is due not to static repulsion between molecules (as was Isaac Newton's conjecture) but rather due to collisions between molecules moving at different velocities through Brownian motion. Also, the temperature of an ideal monatomic gas is a measure of the average kinetic energy of its atoms, as illustrated in.



Translational Motion of Helium: Real gases do not always behave according to the ideal model under certain conditions, such as high pressure. Here, the size of helium atoms relative to their spacing is shown to scale under 1950 atmospheres of pressure.

The kinetic theory of gases uses the model of the ideal gas to relate temperature to the average translational kinetic energy of the molecules in a container of gas in thermodynamic equilibrium. Classical mechanics defines the translational kinetic energy of a gas molecule as follows:

$$\mathrm{E_k} = \frac{1}{2}\mathrm{mv}^2, \tag{12.1.1}$$

where m is the particle mass and v its speed (the magnitude of its velocity). The distribution of the speeds (which determine the translational kinetic energies) of the particles in a classical ideal gas is called the Maxwell-Boltzmann distribution. In kinetic theory, the temperature of a classical ideal gas is related to its average kinetic energy per degree of freedom $\mathrm{E_k}$ via the equation:

$$\bar{\mathrm{E}}_\mathrm{k} = \frac{1}{2}\mathrm{kT}, \tag{12.1.2}$$

(k: Boltzmann's constant). We will derive this relationship in the following atoms. We will also derive the ideal gas law:

$$\mathrm{pV} = \mathrm{nRT}, \tag{12.1.3}$$

(R: ideal gas constant, n: number of moles of gas) from a microscopic theory.

Atomic Theory of Matter

Atomic theory is a scientific theory of the nature of matter which states that matter is composed of discrete units called atoms.

learning objectives

- Formulate five postulates of John Dalton's atomic theory

Atomic theory is a scientific theory of the nature of matter which states that matter is composed of discrete units called atoms, as opposed to the obsolete notion that matter could be divided into any arbitrarily small quantity. Although physicists discovered that the so-called "indivisible atom" was actually a conglomerate of various subatomic particles, the concept of atoms is still important because they are building blocks of matter and form the basis of chemistry.

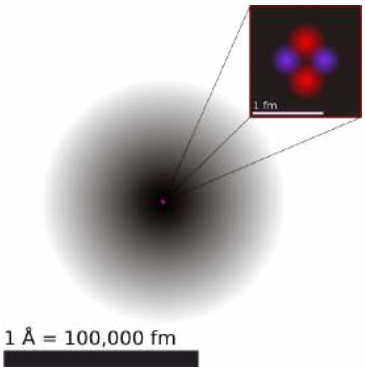


Illustration of the Helium Atom: This is an illustration of the helium atom, depicting the nucleus (pink) and the electron cloud distribution (black). The nucleus (upper right) in helium-4 is in reality spherically symmetric and closely resembles the electron cloud, although for more complicated nuclei this is not always the case. The black bar is one angstrom (10-10 m, or 100 pm).

Dalton's Atomic Hypothesis

Philosophical proposals regarding atoms have been suggested since the years of the ancient Greeks, but John Dalton was the first to propose a scientific theory of atoms. He based his study on two laws about chemical reactions that emerged (without referring to the notion of an atomic theory) in the late 18thcentury. The first was the law of conservation of mass, formulated by Antoine Lavoisier in 1789, which states that the total mass in a chemical reaction remains constant (that is, the reactants have the same mass as the products). The second was the law of definite proportions, first proven by the French chemist Joseph Louis Proust.

Dalton proposed that each chemical element is composed of atoms of a single, unique type, and though they cannot be altered or destroyed by chemical means, they can combine to form more complex structures (chemical compounds). This marked the first truly scientific theory of the atom, since Dalton reached his conclusions by experimentation and examination of the results in an empirical fashion. For this reason, Dalton is considered the originator of modern atomic theory.

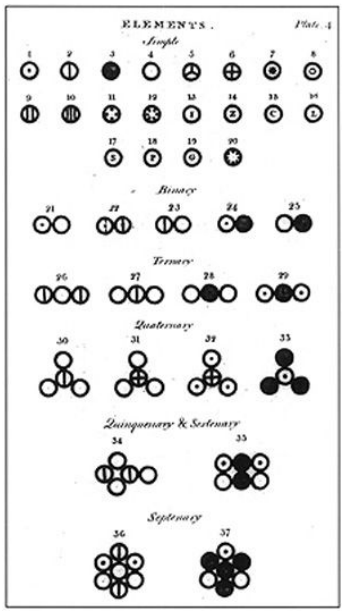
5 Main Points

Dalton's atomic theory had 5 main points:

1. Elements are made of extremely small particles called atoms.
2. Atoms of a given element are identical in size, mass, and other properties; atoms of different elements differ in size, mass, and other properties.
3. Atoms cannot be subdivided, created, or destroyed.
4. Atoms of different elements combine in simple whole-number ratios to form chemical compounds.
5. In chemical reactions, atoms are combined, separated, or rearranged.

Of these five, only three are still considered valid today. 1, 4, and 5 are valid, while 2 and 3 have turned out not to be the case. Atoms can be broken down into smaller pieces, and atoms of a given element can vary in mass and other properties (see isotopes and ions).

Knowing that a gas is composed of small atomic and molecular particles, it is natural to try to explain properties of the gas from a microscopic point of view. This effort led to the development of the kinetic theory of gases, where macroscopic properties of gases, such as pressure, temperature, and volume, are explained by considering their molecular composition and motion.



John Dalton's A New System of Chemical Philosophy: Various atoms and molecules as depicted in John Dalton's A New System of Chemical Philosophy (1808).

Key Points

- The kinetic theory posits that pressure is due to collisions between molecules moving at different velocities through Brownian motion.
- The temperature of an ideal monatomic gas is a measure of the average kinetic energy of its atoms. In kinetic theory, it is related to its average kinetic energy per degree of freedom E_k via the equation: $\bar{E}_k = \frac{1}{2}kT$.
- The kinetic theory of gases uses the model of the ideal gas to relate temperature to the average translational kinetic energy of the molecules in a container of gas in thermodynamic equilibrium.
- John Dalton was the first to propose a scientific theory of atoms. He based his study on two laws: the law of conservation of mass and the law of definite proportions.
- Dalton proposed that each chemical element is composed of atoms of a single, unique type, and though they cannot be altered or destroyed by chemical means, they can combine to form more complex structures.
- Kinetic theory of gases explain macroscopic properties of gases, such as pressure, temperature, and volume, by considering their molecular composition and motion.
- While Dalton's idea of matter being composed of various atoms was correct, he was wrong about some of their properties. Atoms can be broken down into smaller parts. Atoms of the same element can have slightly different masses and behave differently. See isotopes and ions for examples.

Key Terms

- **ideal gas**: A hypothetical gas whose molecules exhibit no interaction and undergo elastic collision with each other and with the walls of the container.
- **degree of freedom**: Any of the coordinates, a minimum number of which are needed to specify the motion of a mechanical system.
- **Brownian motion**: Random motion of particles suspended in a fluid, arising from those particles being struck by individual molecules of the fluid.
- **atom**: The smallest possible amount of matter which still retains its identity as a chemical element, now known to consist of a nucleus surrounded by electrons.
- **kinetic theory of gases**: The kinetic theory of gases describes a gas as a large number of small particles (atoms or molecules), all of which are in constant, random motion.
- **chemical reaction**: A process, involving the breaking or making of interatomic bonds, in which one or more substances are changed into others.

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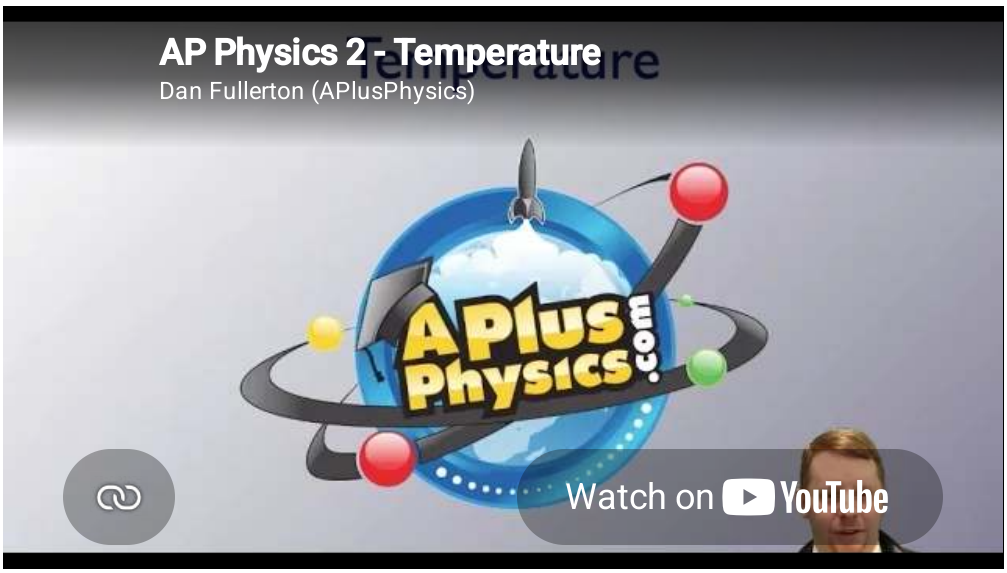
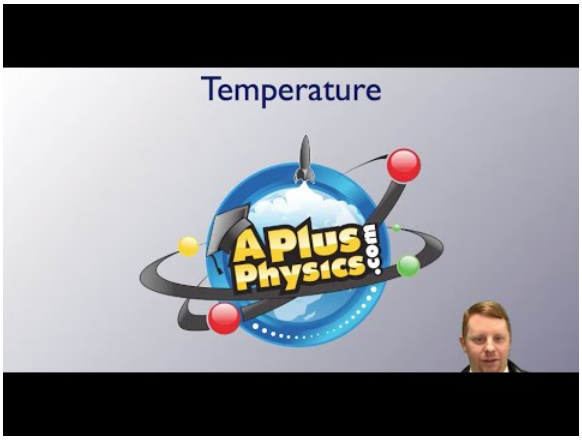
12.2: Temperature and Temperature Scales

learning objectives

- Explain how the Celsius scale is defined

Celsius, also known as centigrade, is a scale to measure temperature. The unit of measurement is the degree Celsius (°C). It is one of the most commonly used temperature units in the world. The unit system is named after the Swedish astronomer Anders Celsius (1701-1744), who developed a similar temperature scale.

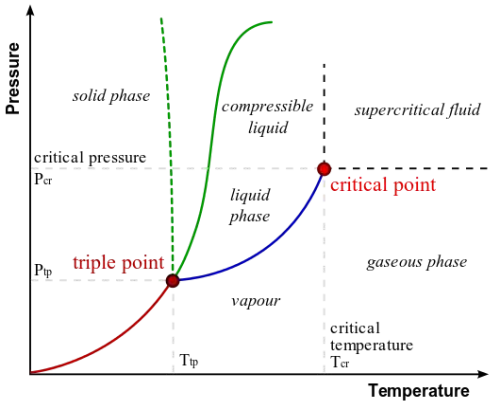




Temperature Scales: A brief introduction to temperature and temperature scales for students studying thermal physics or thermodynamics.

Thermometer: A thermometer calibrated in degrees Celsius

From 1743 until 1954, 0°C was defined as the freezing point of water, and 100°C was defined as the boiling point of water, both at a pressure of one standard atmosphere, with mercury as the working material. Although these defining correlations are commonly taught in schools today, by international agreement the unit "degree Celsius" and the Celsius scale are currently defined by two different temperatures: absolute zero and the triple point of Vienna Standard Mean Ocean Water (VSMOW; specially purified water). This definition also precisely relates the Celsius scale to the Kelvin scale, which defines the SI base unit of thermodynamic temperature and which uses the symbol K. Absolute zero, the lowest temperature possible (the temperature at which matter reaches minimum entropy), is defined as being precisely 0K and -273.15°C. The temperature of the triple point of water is defined as precisely 273.16K and 0.01°C. Based on this, the relationship between degree Celsius and Kelvin is as follows:



Phase Diagram of Water: In this typical phase diagram of water, the green lines mark the freezing point, and the blue line marks the boiling point, showing how they vary with pressure. The dotted line illustrates the anomalous behavior of water. Note that water changes states based on the pressure and temperature.

$$T_{\text{Celsius}} = T_{\text{Kelvin}} - 273.15. \tag{12.2.1}$$

Besides expressing specific temperatures along its scale (e.g., “Gallium melts at 29.7646°C” and “The temperature outside is 23 degrees Celsius”), the degree Celsius is also suitable for expressing temperature intervals — differences between temperatures, or their uncertainties (e.g. “The output of the heat exchanger is hotter by 40 degrees Celsius” and “Our standard uncertainty is ±3°C”). Because of this dual usage, one must not rely upon the unit name or its symbol to denote that a quantity is a temperature interval; it must be clear through context or explicit statement that the quantity is an interval.

Farenheit Scale

In the Fahrenheit scale, the freezing of water is defined at 32 degrees, while the boiling point of water is defined to be 212 degrees.

learning objectives

- Explain how the Fahrenheit scale is defined and convert between it and Celsius

The Fahrenheit scale measures temperature. It is based on a scale proposed in 1724 by physicist Daniel Gabriel Fahrenheit (1686-1736). The unit of this scale is the degree Fahrenheit (°F). On this scale, water’s freezing point is defined to be 32 degrees, while water’s boiling point is defined to be 212 degrees.

Historically, the zero point of the Fahrenheit scale was determined by evaluating a thermometer placed in brine. Fahrenheit himself used a mixture of ice, water, and ammonium chloride (a salt) at a 1:1:1 ratio. This is a frigorific mixture, which stabilizes its temperature automatically; the stable temperature of this mixture was defined as 0 °F (-17.78 °C). The second determining point, 32 degrees, was a mixture of just ice and water at a 1:1 ratio. The third determining point, 96 degrees, was approximately the temperature of the human body, then called “blood-heat. ”

The Fahrenheit system puts the boiling and freezing points of water exactly 180 degrees apart. Therefore, a degree on the Fahrenheit scale is 1/180 of the interval between the freezing point and the boiling point. On the Celsius scale, the freezing and boiling points of water are 100 degrees apart. A temperature interval of 1 °F is equal to an interval of 5/9 degrees Celsius (°C). To convert °F to °C, you can use the following formula:

$$T_{\text{Celsius}} = \frac{5}{9}(T_{\text{Fahrenheit}} - 32) \tag{12.2.2}$$

The Fahrenheit and Celsius scales intersect at -40° (-40 °F and -40 °C represent the same temperature). Absolute zero (-273.15 °C, or 0K) is defined as -459.67 °F.

The Fahrenheit scale was replaced by the Celsius scale in most countries in the mid- to late-20th century, though Canada retains it as a supplementary scale that can be used alongside the Celsius scale. The Fahrenheit scale remains the official scale of the United States, the Cayman Islands, Palau, the Bahamas, and Belize.

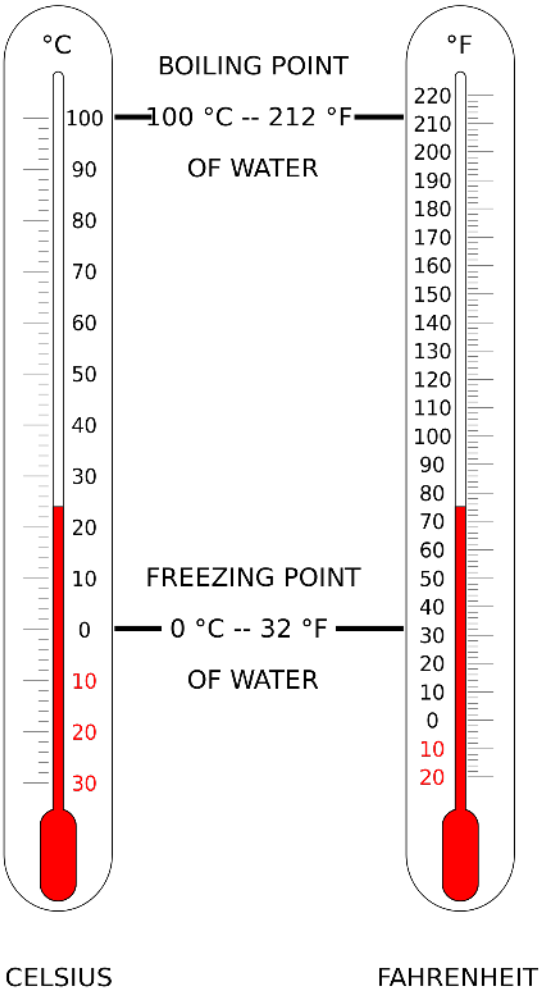
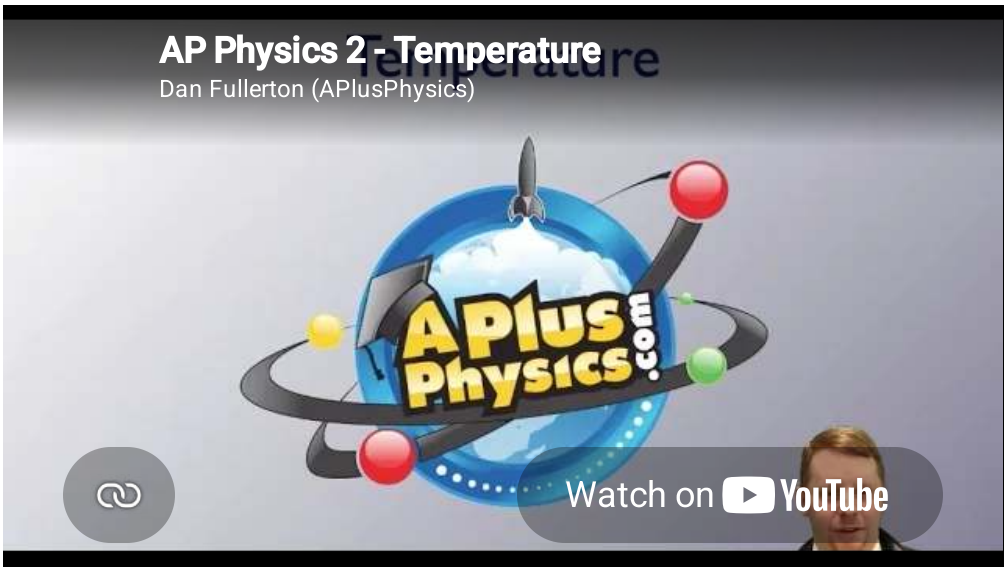
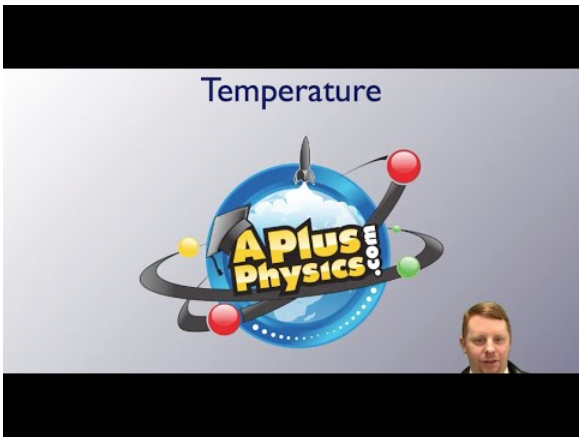


Fig 2: Comparison of Celsius vs Fahrenheit scales.





Temperature Scales: A brief introduction to temperature and temperature scales for students studying thermal physics or thermodynamics.

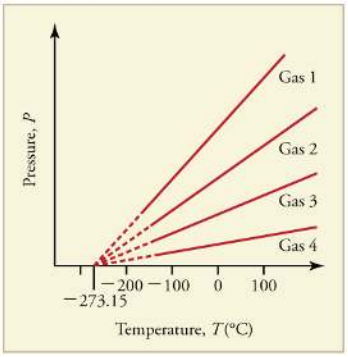
Absolute Zero

Absolute zero is the coldest possible temperature; formally, it is the temperature at which entropy reaches its minimum value.

learning objectives

- Explain why absolute zero is a natural choice as the null point for a temperature unit system

Absolute zerois the coldest possible temperature. Formally, it is the temperature at which entropy reaches its minimum value. More simply put, absolute zero refers to a state in which all the energy of a system is extracted (by definition, the lowest energy state the system can have). Absolute zero is universal in the sense that all matteris in ground state at this temperature. Therefore, it is a natural choice as the null point for a temperature unit system.

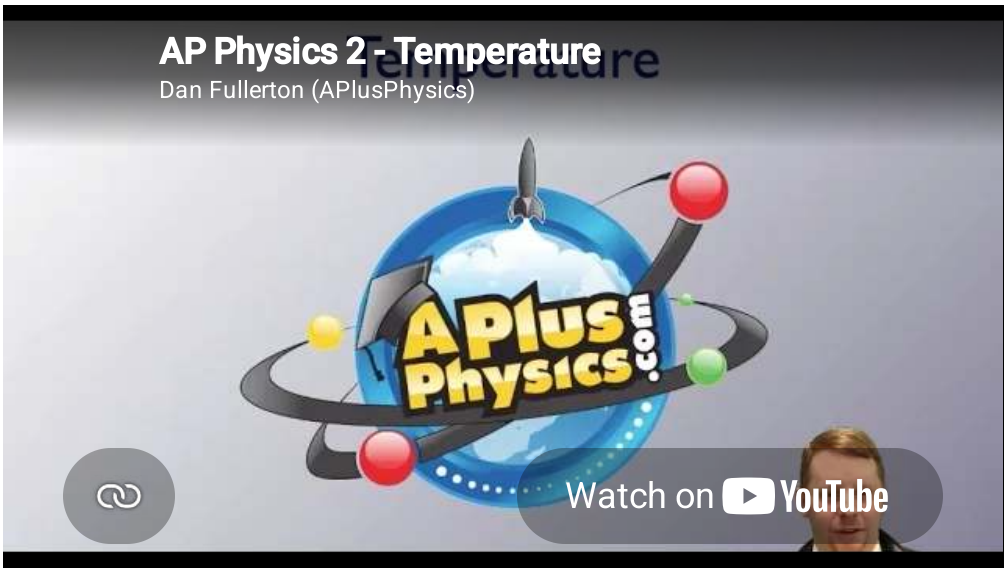


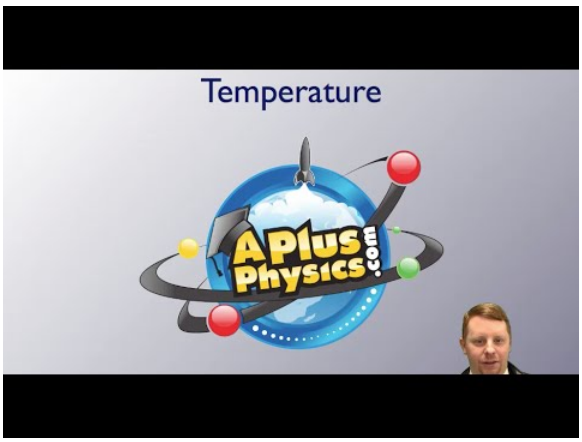
Graph of Pressure Versus Temperature: Graph of pressure versus temperature for various gases kept at a constant volume. Note that all of the graphs extrapolate to zero pressure at the same temperature

To be precise, a system at absolute zero still possesses quantum mechanical zero-point energy, the energy of its ground state. The uncertainty principle states that the position of a particle cannot be determined with absolute precision; therefore a particle is in motion even if it is at absolute zero, and a ground state still carries a minimal amount of kinetic energy. However, in the interpretation of classical thermodynamics, kinetic energy can be zero, and the thermal energy of matter vanishes.

The zero point of a thermodynamic temperature scale, such as the Kelvin scale, is set at absolute zero. By international agreement, absolute zero is defined as 0K on the Kelvin scale and as -273.15° on the Celsius scale (equivalent to -459.67° on the Fahrenheit scale). Scientists have brought systems to temperatures very close to absolute zero, at which point matter exhibits quantum effects such as superconductivity and superfluidity. The lowest temperature that has been achieved in the laboratory is in the 100 pK range, where pK (pico-Kelvin) is equivalent to 10^{-12} K. The lowest natural temperature ever recorded is approximately 1K, observed in the rapid expansion of gases leaving the Boomerang Nebula, shown below.

Boomerang Nebula: The rapid expansion of gases resulting in the Boomerang Nebula causes the lowest observed temperature outside a laboratory.





Temperature Scales: A brief introduction to temperature and temperature scales for students studying thermal physics or thermodynamics.

Kelvin Scale

The kelvin is a unit of measurement for temperature; the null point of the Kelvin scale is absolute zero, the lowest possible temperature.

learning objectives

- Explain how the Kelvin scale is defined

The kelvin is a unit of measurement for temperature. It is one of the seven base units in the International System of Units (SI) and is assigned the unit symbol K. The Kelvin scale is an absolute, thermodynamic temperature scale using absolute zero as its null point. In the classical description of thermodynamics, absolute zero is the temperature at which all thermal motion ceases.

The choice of absolute zero as null point for the Kelvin scale is logical. Different types of matter boil or freeze at different temperatures, but at 0K (absolute zero), *all* thermal motions of *any* matter are maximally suppressed. The Kelvin scale is used extensively in scientific work because a number of physical quantities, such as the volume of an ideal gas, are directly related to absolute temperature.

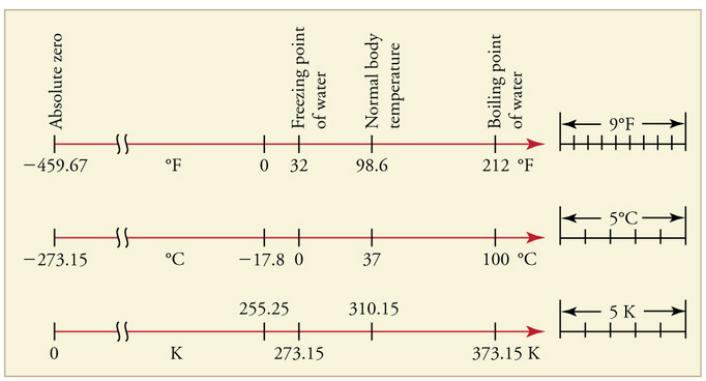
The Kelvin scale is named after Glasgow University engineer and physicist William Thomson, 1st Baron Kelvin (1824-1907), who wrote of the need for an “absolute thermometric scale. ” Unlike the degree Fahrenheit and the degree Celsius, the kelvin is not referred to or typeset as a degree. The kelvin is the primary unit of measurement in the physical sciences, but it is often used in conjunction with the degree Celsius, which has the same magnitude. The kelvin is defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water (exactly 0.01°C, or 32.018°F). To convert kelvin to degrees Celsius, we use the following formula:

$$\mathrm{T}_{\mathrm{Celsius}} = \mathrm{T}_{\mathrm{Kelvin}} - 273.15 \tag{12.2.3}$$

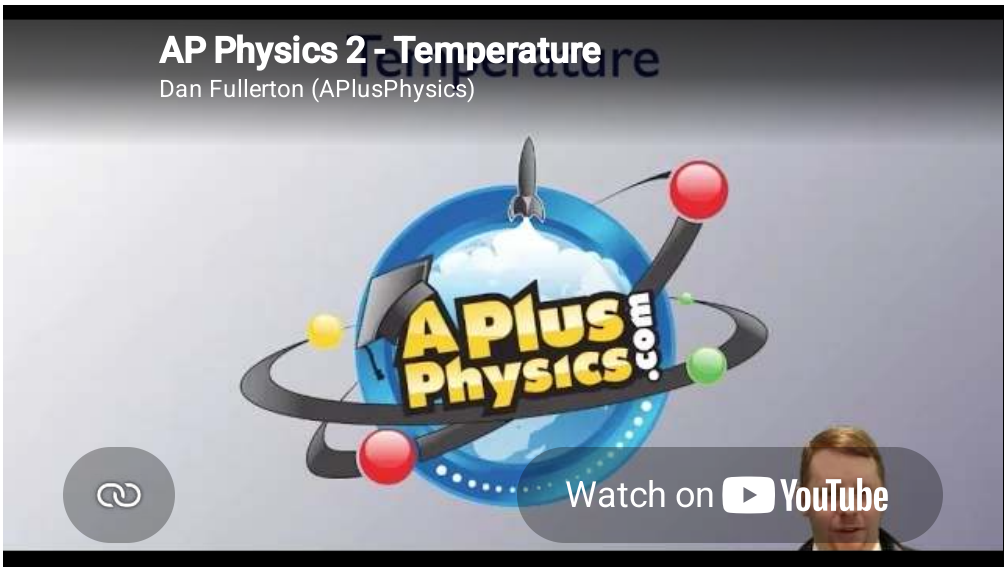
Subtracting 273.16K from the temperature of the triple point of water, 0.01°C, makes absolute zero (0K) equivalent to -273.15°C and -460°F.

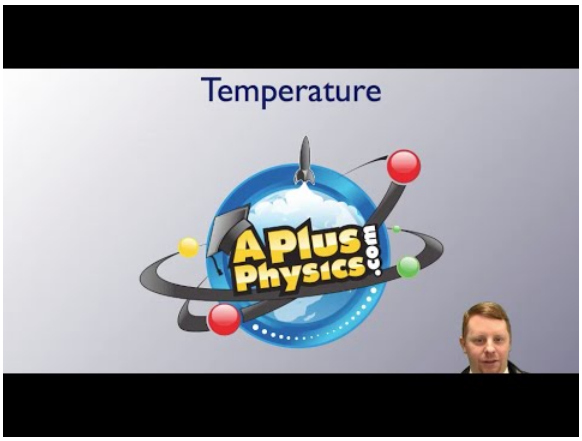
where n_1 = # of scores in group 1
n_2 = # of scores in group 2
R_1 = sum of ranks for group 1
R_2 = sum of ranks for group 2

Calculating U



Relationships Between the Temperature Scales: Relationships between the Fahrenheit, Celsius, and Kelvin temperature scales, rounded to the nearest degree. The relative sizes of the scales are also shown





Temperature Scales: A brief introduction to temperature and temperature scales for students studying thermal physics or thermodynamics.

Key Points

- The degree Celsius (°C) can refer to a specific temperature on the Celsius scale as well as a unit to indicate a temperature interval, a difference between two temperatures or an uncertainty.
- The Celsius scale is currently defined by two different temperatures: absolute zero and the triple point of Vienna Standard Mean Ocean Water (VSMOW; specially purified water).
- Based on this, the relationship between Celsius and Kelvin is as follows: $\mathrm{T_{Celsius}} = \mathrm{T_{Kelvin}} - 273.15$.
- The Fahrenheit system puts the boiling and freezing points of water exactly 180 degrees apart. Therefore, a degree on the Fahrenheit scale is 1⁄180 of the interval between the freezing point and the boiling point.
- To convert °F to °C, you can use the following formula: $\mathrm{T_{Celsius}} = \frac{5}{9}(\mathrm{T_{Fahrenheit}} - 32)$. The Fahrenheit and Celsius scales intersect at −40°.
- The Fahrenheit scale was replaced by the Celsius scale in most countries during the mid to late 20th century. Fahrenheit remains the official scale of the United States, Cayman Islands, Palau, Bahamas and Belize.
- Absolute zero is universal in the sense that all matter is in ground state at this temperature. Therefore, it is a natural choice as the null point for a temperature unit system.
- K system at absolute zero still possesses quantum mechanical zero-point energy, the energy of its ground state. However, in the interpretation of classical thermodynamics, kinetic energy can be zero, and the thermal energy of matter vanishes.
- The lowest temperature that has been achieved in the laboratory is in the 100 pK range, where pK (pico- Kelvin) is equivalent to 10-12 K. The lowest natural temperature ever recorded is approximately 1K, observed in the rapid expansion of gases leaving the Boomerang Nebula.

- 0K (absolute zero) is universal because all thermal motions of all matter are maximally suppressed at this temperature. Absolute zero is therefore the natural choice as the null point of the Kelvin scale.
- The Kelvin scale is used extensively in scientific work because a number of physical quantities, such as the volume of an ideal gas, are directly related to absolute temperature.
- To convert kelvin to degree Celsius, we use the following formula: $\mathrm{T}_{\text{Celsius}} = \mathrm{T}_{\text{Kelvin}} - 273.15$.

Key Terms

- **kelvin**: in the International System of Units, the base unit of thermodynamic temperature; 1/273.16 of the thermodynamic temperature of the triple point of water; symbolized as K
- **absolute zero**: The coldest possible temperature: zero on the Kelvin scale and approximately -273.15°C and -459.67°F. The total absence of heat; the temperature at which motion of all molecules would cease.
- **standard atmosphere**: an international reference pressure defined as 101.325 kPa and formerly used as a unit of pressure
- **brine**: a solution of salt (usually sodium chloride) in water
- **frigorific mixture**: A mixture of two or more chemicals that reaches an equilibrium temperature independent of the temperature of any of its constituent chemicals. The temperature is also relatively independent of the quantities of mixtures as long as a significant amount of each original chemical is present in its pure form
- **entropy**: A measure of how evenly energy (or some analogous property) is distributed in a system.
- **thermodynamics**: a branch of natural science concerned with heat and its relation to energy and work
- **absolute zero**: The coldest possible temperature: zero on the Kelvin scale and approximately -273.15°C and -459.67°F. The total absence of heat; the temperature at which motion of all molecules would cease.
- **Triple point**: The unique temperature and pressure at which the solid, liquid and gas phases of a substance are all in equilibrium.
- **ideal gas**: A hypothetical gas whose molecules exhibit no interaction and undergo elastic collision with each other and with the walls of the container.

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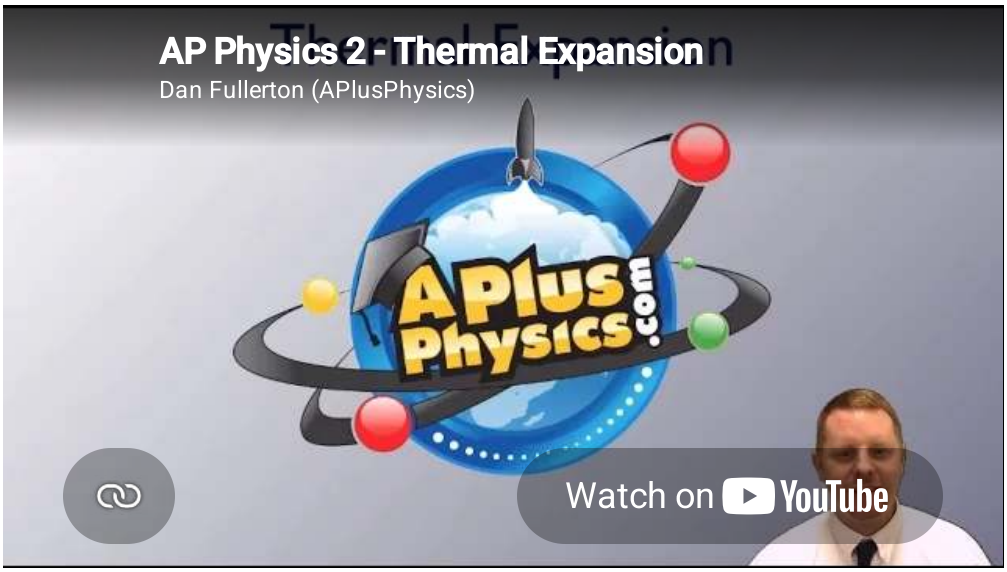
12.3: Thermal Expansion

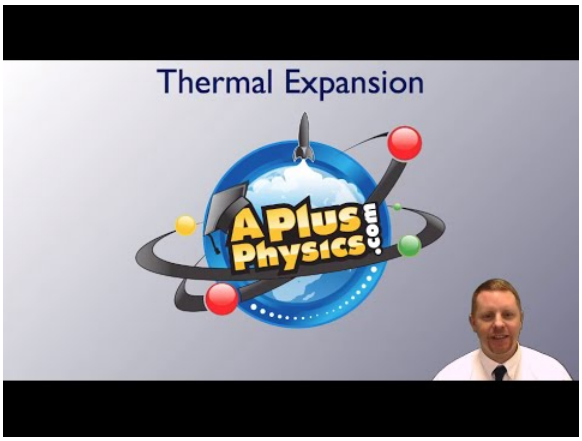
learning objectives

- Describe volume changes that take place in response to a temperature change

Thermal expansion is the tendency of matter to change in volume in response to a change in temperature. (An example of this is the buckling of railroad track, as seen in.) Atoms and molecules in a solid, for instance, constantly oscillate around its equilibrium point. This kind of excitation is called thermal motion. When a substance is heated, its constituent particles begin moving more, thus maintaining a greater average separation with their neighboring particles. The degree of expansion divided by the change in temperature is called the material's coefficient of thermal expansion; it generally varies with temperature.

Fig 1: Thermal expansion of long continuous sections of rail tracks is the driving force for rail buckling. This phenomenon resulted in 190 train derailments during 1998–2002 in the US alone.





Thermal Expansion: A brief introduction to thermal expansion for students.

Expansion, Not Contraction

Why does matter usually expand when heated? The answer can be found in the shape of the typical particle-particle potential in matter. Particles in solids and liquids constantly feel the presence of other neighboring particles. This interaction can be represented mathematically as a potential curve. Fig 2 illustrates how this inter-particle potential usually takes an asymmetric form rather than a symmetric form, as a function of particle-particle distance. Note that the potential curve is steeper for shorter distance. In the diagram, (b) shows that as the substance is heated, the equilibrium (or average) particle-particle distance increases. Materials which contract or maintain their shape with increasing temperature are rare. This effect is limited in size, and only occurs within limited temperature ranges.

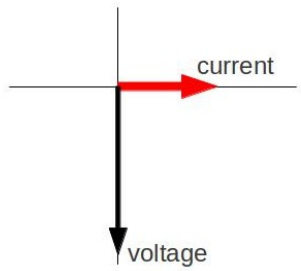


Fig 2: Typical inter-particle potential in condensed matter (such as solid or liquid).

Linear Expansion

To a first approximation, the change in length measurements of an object (*linear*dimension as opposed to, for example, volumetric dimension) due to thermal expansion is related to temperature change by a *linear expansion coefficient*. It is the fractional change in length per degree of temperature change. Assuming negligible effect of pressure, we may write:

$$\alpha_{\mathrm{L}} = \frac{1}{\mathrm{L}} \frac{\mathrm{dL}}{\mathrm{dT}}, \tag{12.3.1}$$

where L is a particular length measurement and $\frac{\mathrm{dL}}{\mathrm{dT}}$ is the rate of change of that linear dimension per unit change in temperature. From the definition of the expansion coefficient, the change in the linear dimension $\Delta\mathrm{L}$ over a temperature range $\Delta\mathrm{T}$ can be estimated to be:

$$\frac{\Delta\mathrm{L}}{\mathrm{L}} = \alpha_{\mathrm{L}} \Delta\mathrm{T}. \tag{12.3.2}$$

This equation works well as long as the linear-expansion coefficient does not change much over the change in temperature. If it does, the equation must be integrated.

Area Expansion

Objects expand in all dimensions. That is, their areas and volumes, as well as their lengths, increase with temperature.

learning objectives

- Express the area thermal expansion coefficient in the form of an equation

We learned about the linear expansion (in one dimension) in the previous Atom. Objects expand in all dimensions, and we can extend the thermal expansion for 1D to two (or three) dimensions. That is, their areas and volumes, as well as their lengths, increase with temperature.

Quiz

Before we look into details, here is an interesting question. Imagine that we have a rectangular sheet of metal with a circular hole in the middle. If the metal is heated, we can guess that the the piece, in general, will get larger due to thermal expansion. Now, what is going to happen with the circular hole in the middle? Is the hole going to be larger or smaller? Answer: Imagine that we have a

similar metal sheet but without a hole. Draw an imaginary circular line representing the circular hole in our quiz. How does this imaginary circle change as the metal is heated? Yes. It will get bigger. Therefore, you can guess that the hole in our quiz will get larger.

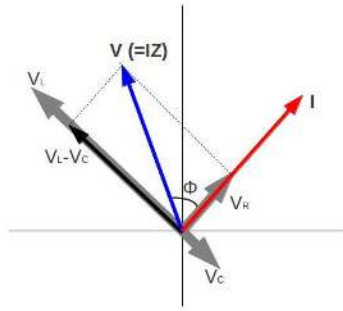


Fig 1: In general, objects expand in all directions as temperature increases. In these drawings, the original boundaries of the objects are shown with solid lines, and the expanded boundaries with dashed lines. (a) Area increases because both length and width increase. The area of a circular plug also increases. (b) If the plug is removed, the hole it leaves becomes larger with increasing temperature, just as if the expanding plug were still in place.

Area thermal expansion coefficient

The area thermal expansion coefficient relates the change in a material's area dimensions to a change in temperature. It is the fractional change in area per degree of temperature change. Ignoring pressure, we may write: $\alpha_{\mathrm{A}}=\frac{1}{\mathrm{A}} \frac{\mathrm{dA}}{\mathrm{dT}}$, where is some area of interest on the object, and $\frac{\mathrm{dA}}{\mathrm{dT}}$ is the rate of change of that area per unit change in temperature. The change in the linear dimension can be estimated as: $\frac{\Delta \mathrm{A}}{\mathrm{A}}=\alpha_{\mathrm{A}} \Delta \mathrm{T}$. This equation works well as long as the linear expansion coefficient does not change much over the change in temperature $\Delta \mathrm{T}$. If it does, the equation must be integrated.

Relationship to linear thermal expansion coefficient

For isotropic materials, and for small expansions, the linear thermal expansion coefficient is one half of the area coefficient. To derive the relationship, let's take a square of steel that has sides of length *L*. The original area will be $\mathrm{A}=\mathrm{L}^2$,and the new area, after a temperature increase, will be

$$\begin{aligned} \mathrm{A}+\Delta \mathrm{A} &= (\mathrm{L}+\Delta \mathrm{L})^2 && (12.3.3) \\ &= \mathrm{L}^2+2 \mathrm{L} \Delta \mathrm{L}+(\Delta \mathrm{L})^2 && (12.3.4) \\ &\approx \mathrm{L}^2+2 \mathrm{L} \Delta \mathrm{L} && (12.3.5) \\ &= \mathrm{A}+2 \mathrm{A} \frac{\Delta \mathrm{L}}{\mathrm{L}} && (12.3.6) \end{aligned}$$

The approximation holds for a sufficiently small $\Delta \mathrm{L}$ campared to L. Since $\frac{\Delta \mathrm{A}}{\mathrm{A}}=2 \frac{\Delta \mathrm{L}}{\mathrm{L}}$ from the equation above (and from the definitions of the thermal coefficients), we get $\alpha_{\mathrm{A}}=2_{\alpha \mathrm{L}}$.

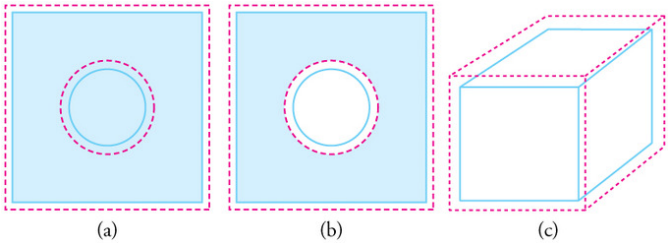
Volume Expansion

Substances expand or contract when their temperature changes, with expansion or contraction occurring in all directions.

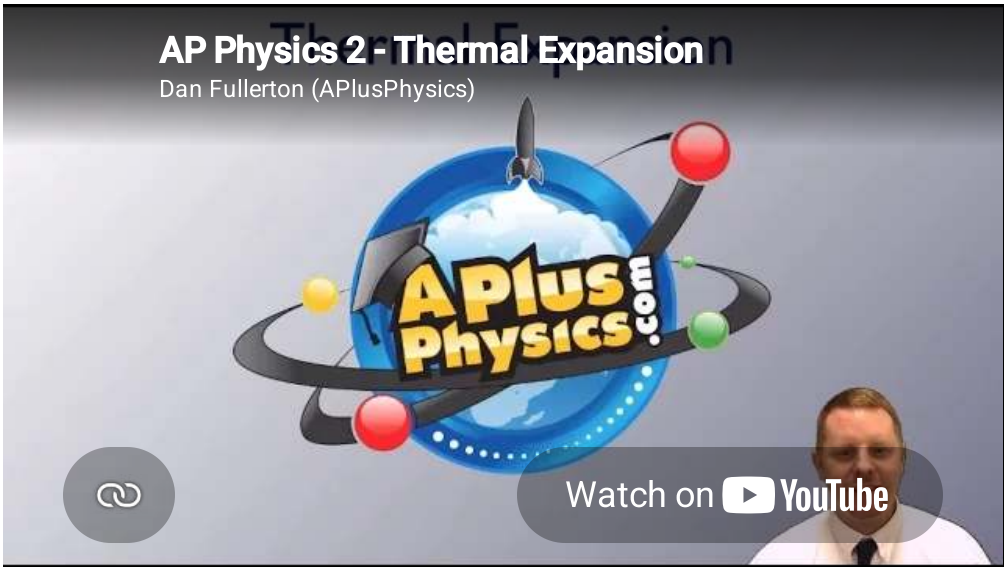
learning objectives

- Compare the effects of the pressure on the expansion of gaseous and solid materials

The volumetric thermal expansion coefficient is the most basic thermal expansion coefficient. illustrates that, in general, substances expand or contract when their temperature changes, with expansion or contraction occurring in all directions. Such substances that expand in all directions are called isotropic. For isotropic materials, the area and linear coefficients may be calculated from the volumetric coefficient (discussed below).



Volumetric Expansion: In general, objects expand in all directions as temperature increases. In these drawings, the original boundaries of the objects are shown with solid lines, and the expanded boundaries with dashed lines. (a) Area increases because both length and width increase. The area of a circular plug also increases. (b) If the plug is removed, the hole it leaves becomes larger with increasing temperature, just as if the expanding plug were still in place. (c) Volume also increases, because all three dimensions increase.



Thermal Expansion – Volume Expansion: A brief introduction to thermal expansion for students.

Mathematical definitions of these coefficients are defined below for solids, liquids, and gasses:

$$\alpha_V = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p. \tag{12.3.7}$$

The subscript *p* indicates that the pressure is held constant during the expansion. In the case of a gas, the fact that the pressure is held constant is important, as the volume of a gas will vary appreciably with pressure as well as with temperature.

For a solid, we can ignore the effects of pressure on the material, thus the volumetric thermal expansion coefficient can be written:

$$\frac{1}{V}\frac{dV}{}$$

$$\alpha_V = \frac{1}{V}\frac{dV}{dT}, \tag{12.3.8}$$

where V is the volume of the material, and is dV/dT the rate of change of that volume with temperature. This means that the volume of a material changes by some fixed fractional amount. For example, a steel block with a volume of 1 cubic meter might expand to 1.002 cubic meters when the temperature is raised by 50 °C. This is an expansion of 0.2%. The volumetric expansion coefficient would be 0.2% for 50 °C, or 0.004% per degree C.

Relationship to Linear Thermal Expansion Coefficient

For isotropic material, and for small expansions, the linear thermal expansion coefficient is one third the volumetric coefficient. To derive the relationship, let's take a cube of steel that has sides of length *L*. The original volume will be $V = L^3$,and the new volume, after a temperature increase, will be:

$$\begin{aligned} V + \Delta V &= (L + \Delta L)^3 && (12.3.9)\\ &= L^3 + 3L^2\Delta L + 3L(\Delta L)^2 + (\Delta L)^3 && (12.3.10)\\ &\approx L^3 + 3L^2\Delta L && (12.3.11)\\ &= V + 3V\frac{\Delta L}{L}. && (12.3.12) \end{aligned}$$

The approximation holds for a sufficiently small ΔL compared to L. Since:

$$\frac{\Delta V}{V} = 3\frac{\Delta L}{L} \tag{12.3.13}$$

(and from the definitions of the thermal coefficients), we arrive at:

$$\alpha_V = 3\alpha_L \tag{12.3.14}$$

Special Properties of Water

Objects will expand with increasing temperature, but water is the most important exception to the general rule.

learning objectives

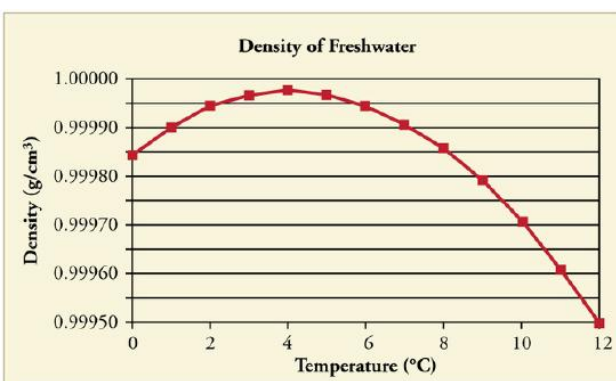
- Describe thermal expansion properties of water

Special Properties of Water

In general, objects will expand with increasing temperature. However, a number of materials contract on heating within certain temperature ranges; this is usually called negative thermal expansion, rather than "thermal contraction. " Water is the most important exception to the general rule. Water has this unique characteristic because of the particular nature of the hydrogen bond in H_2O.

Density of Water as Temperature Changes

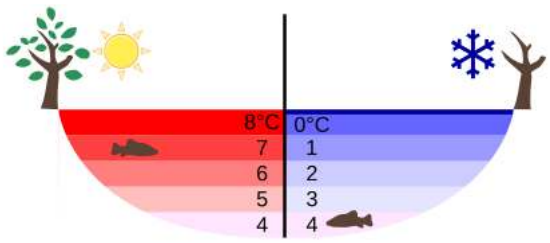
At temperatures greater than 4ºC (40ºF) water expands with increasing temperature (its density decreases). However, it expands with decreasing temperature when it is between +4ºC and 0ºC (40ºF to 32ºF). Water is densest at +4ºC.



Water Density vs. Temperature: The density of water as a function of temperature. Note that the thermal expansion is actually very small. The maximum density at +4ºC is only 0.0075% greater than the density at 2ºC, and 0.012% greater than that at 0ºC.

Perhaps the most striking effect of this phenomenon is the freezing of water in a pond. When water near the surface cools down to 4ºC it is denser than the remaining water and thus will sink to the bottom. This "turnover" results in a layer of warmer water near the surface, which is then cooled. Eventually the pond has a uniform temperature of 4ºC. If the temperature in the surface layer drops below 4ºC, the water is less dense than the water below, and thus stays near the top.

As a result, the pond surface can completely freeze over, while the bottom may remain at 4ºC. The ice on top of liquid water provides an insulating layer from winter's harsh exterior air temperatures. Fish and other aquatic life can survive in 4ºC water beneath ice, due to this unusual characteristic of water. It also produces circulation of water in the pond that is necessary for a healthy ecosystem of the body of water.



Temperature in a Lake: Temperature distribution in a lake on warm and cold days in winter

Ice Versus Water

The solid form of most substances is denser than the liquid phase; thus, a block of most solids will sink in the liquid. However, a block of ice floats in liquid water because ice is less dense. Upon freezing, the density of water decreases by about 9%.

Key Points

- Inter-particle potential usually takes an asymmetric form, rather than a symmetric form as a function of particle-particle distance. This is why matters expands and contracts as temperature changes.
- The change in length measurements of an object due to thermal expansion is related to temperature change by a "linear expansion coefficient", which is given as $\alpha_L = \frac{1}{L}\frac{dL}{dT}$.
- The linear expansion coefficient is as an approximation over a narrow temperature interval only.
- The area thermal expansion coefficient relates the change in a material's area dimensions to a change in temperature. It is defined as $\alpha_A = \frac{1}{A}\frac{dA}{dT}$.
- The relationship between the area and linear thermal expansion coefficient is given as the following: $\alpha_A = 2\alpha_L$.
- Just like the linear expansion coefficient, the area thermal expansion coefficient works as an approximation over a narrow temperature interval only.
- Substances that expand at the same rate in every direction are called isotropic.
- In the case of a gas, expansion depends on how the pressure changed in the process because the volume of a gas will vary appreciably with pressure as well as temperature.
- For a solid, we can ignore the effects of pressure on the material, and the volumetric thermal expansion coefficient can be written as $\alpha_V = \frac{1}{V}\frac{dV}{dT}$. For isotropic materials, $\alpha_V = 3\alpha_L$.
- Water expands with increasing temperature (its density decreases) when it is at temperatures greater than 4ºC (40ºF). However, it expands with decreasing temperature when it is between +4ºC and 0ºC (40ºF to 32ºF). Water is densest at +4ºC.
- Due to the peculiar thermal expansion property of water, a pond surface can completely freeze over, while the bottom may remain at 4ºC. Fish and other aquatic life can survive in 4ºC water beneath ice, due to this unusual characteristic of water.
- The solid form of most substances is denser than the liquid phase; thus, a block of most solids will sink in the liquid. However, a block of ice floats in liquid water because ice is less dense.

Key Terms

- **potential**: A curve describing the situation where the difference in the potential energies of an object in two different positions depends only on those positions.

- **linear thermal expansion coefficient**: The fractional change in length per degree of temperature change.
- **isotropic**: Having properties that are identical in all directions; exhibiting isotropy.
- **hydrogen bond**: A weak bond in which a hydrogen atom in one molecule is attracted to an electronegative atom (usually nitrogen or oxygen) in the same or different molecule.

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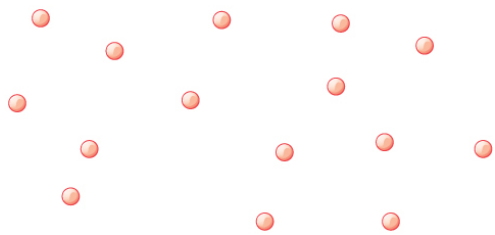
12.4: Ideal Gas Law

learning objectives

- Describe how ideal gas law was derived.

The ideal gas law is the equation of state of a hypothetical ideal gas (an illustration is offered in). In an ideal gas, there is no molecule-molecule interaction, and only elastic collisions are allowed. It is a good approximation to the behavior of many gases under many conditions, although it has several limitations. It was first stated by Émile Clapeyron in 1834 as a combination of Boyle's law and Charles' law.



Atoms and Modules in a Gas: Atoms and molecules in a gas are typically widely separated, as shown. Because the forces between them are quite weak at these distances, they are often described by the ideal gas law.

Empirical Derivation

Boyle's law states that pressure P and volume V of a given mass of confined gas are inversely proportional:

$$\mathrm{P} \propto \frac{1}{\mathrm{V}}, \tag{12.4.1}$$

while Charles' law states that volume of a gas is proportional to the absolute temperature T of the gas at constant pressure

$$\mathrm{V} \propto \mathrm{T}. \tag{12.4.2}$$

By combining the two laws, we get

$$\frac{\mathrm{PV}}{\mathrm{T}} = \mathrm{C}, \tag{12.4.3}$$

where C is a constant which is directly proportional to the amount of gas, n (representing the number of moles).

The proportionality factor is the universal gas constant, R, i.e. $\mathrm{C} = \mathrm{nR}$.

Hence the ideal gas law

$$\mathrm{PV} = \mathrm{nRT} \tag{12.4.4}$$

Equivalently, it can be written as $\mathrm{PV} = \mathrm{NkT}$,

where k is Boltzmann's constant and N is the number of molecules.

(Since N = nN_A, you can see that $\mathrm{R} = \mathrm{N_{Ak}}$, where N_A is Avogadro's number.)

Note that the empirical derivation does not consider microscopic details. However, the equation can be derived from first principles in the classical thermodynamics (which goes beyond the scope of this Atom).

Microscopic version

We have seen in the Atom on "Origin of Pressure" that

$$\mathrm{P} = \frac{\mathrm{Nm}\bar{\mathrm{v}}^2}{3\mathrm{V}}, \tag{12.4.5}$$

where P is the pressure, N is the number of molecules, m is the mass of the molecule, v is the speed of molecules, and V is the volume of the gas. Therefore, we derive a microscopic version of the ideal gas law

$$\mathrm{PV} = \frac{1}{}\mathrm{Nm}\bar{\mathrm{v}}^2 \tag{12.4.6}$$

Isotherms

An isothermal process is a change of a system in which the temperature remains constant: $\Delta T = 0$.

learning objectives

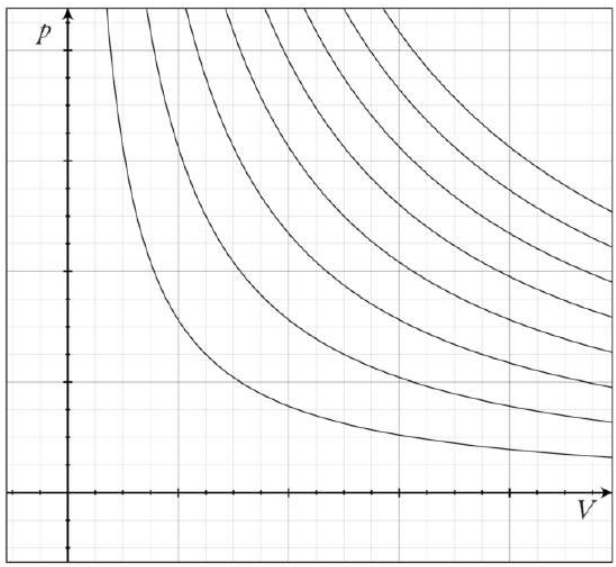
- Identify conditions at which isothermal processes can occur.

An isothermal process is a change of a system in which the temperature remains constant: ΔT = 0. Typically this occurs when a system is in contact with an outside thermal reservoir (heat bath), and the change occurs slowly enough to allow the system to adjust continually to the temperature of the reservoir through heat exchange. In contrast, an adiabatic process occurs when a system exchanges no heat with its surroundings (Q = 0). In other words, in an isothermal process, the value ΔT = 0 but Q ≠ 0, while in an adiabatic process, ΔT ≠ 0 but Q = 0.

For an ideal gas, the product PV (P: pressure, V: volume) is a constant if the gas is kept at isothermal conditions (Boyle's law). According to the ideal gas law, the value of the constant is NkT, where N is the number of molecules of gas and k is Boltzmann's constant.

This means that $p = \frac{NkT}{V} = \frac{\text{Constant}}{V}$ holds.

The family of curves generated by this equation is shown in the graph presented in. Each curve is called an isotherm. Such graphs are termed indicator diagrams—first used by James Watt and others to monitor the efficiency of engines. The temperature corresponding to each curve in the figure increases from the lower left to the upper right.



Isotherms of an Ideal Gas: Several isotherms of an ideal gas on a PV diagram.

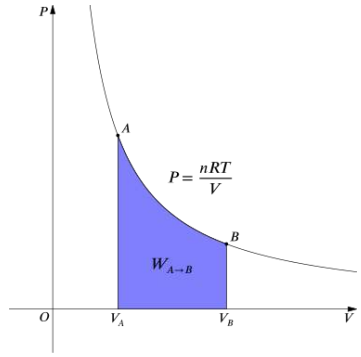
Calculation of Work

In thermodynamics, the work involved when a gas changes from state A to state B is simply:

$$W_{A\to B} = \int_{V_A}^{V_B} PdV. \tag{12.4.7}$$

(This equation is derived in our Atom on "Constant Pressure" under kinetic theory. Note that $P = \frac{F}{A}$. This definition is consistent with our definition of work being force times distance.)

For an isothermal, reversible process, this integral equals the area under the relevant pressure-volume isotherm, and is indicated in blue in for an ideal gas. Again, $P = \frac{nRT}{V}$ applies and with T being constant (as this is an isothermal process), we have:



Work Done by Gas During Expansion: The blue area represents "work" done by the gas during expansion for this isothermal change.

$$W_{A\to B} = \int_{V_A}^{V_B} pdV = \int_{V_A}^{V_B} \frac{NkT}{V} dV \tag{12.4.8}$$

$$= NkT \ln \frac{V_B}{V_A}. \tag{12.4.9}$$

By convention, work is defined as the work the system does on its environment. If, for example, the system expands by a piston moving in the direction of force applied by the internal pressure of a gas, then the work is counted as positive. As this work is done by using internal energy of the system, the result is that the internal energy decreases. Conversely, if the environment does work on the system so that its internal energy increases, the work is counted as negative (for details on internal energy, check our Atom on "Internal Energy of an Ideal Gas").

Constant Pressure

Isobaric processis a thermodynamic process in which the pressure stays constant (at constant pressure, work done by a gas is $P\Delta V$).

learning objectives

- Describe behavior of monatomic gas during isobaric processes.

Under a certain constraint (e.g., pressure), gases can expand or contract; depending on the type of constraint, the final state of the gas may change. For example, an ideal gas that expands while its temperature is kept constant (called isothermal process) will exist in a different state than a gas that expands while pressure stays constant (called isobaric process). This Atom addresses isobaric process and correlated terms. We will discuss isothermal process in a subsequent Atom.

Isobaric Process

An isobaric process is a thermodynamic process in which pressure stays constant: $\Delta P = 0$. For an ideal gas, this means the volume of a gas is proportional to its temperature (historically, this is called Charles' law). Let's consider a case in which a gas does work on a piston at constant pressure P, referring to Fig 1 as illustration. Since the pressure is constant, the force exerted is constant and the work done is given as W=Fd, where F (=PA) is the force on the piston applied by the pressure and d is the displacement of the piston. Therefore, the work done by the gas (W) is:

$$W = PAd \tag{12.4.10}$$

Because the change in volume of a cylinder is its cross-sectional area A times the displacement d, we see that Ad=ΔV, the change in volume. Thus,

$$W = P\Delta V \tag{12.4.11}$$

(as seen in Fig 2—isobaric process). Note: if ΔV is positive, then W is positive, meaning that work is done by the gas on the outside world. Using the ideal gas law $PV = NkT(P = \text{const})$,

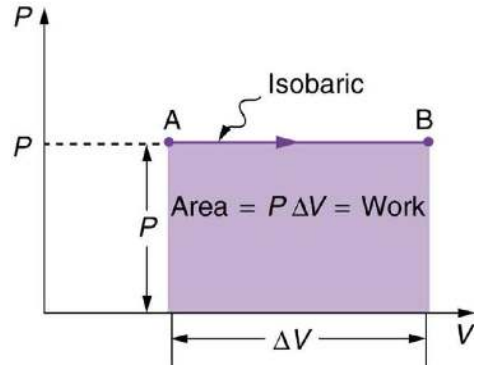


Fig 2: A graph of pressure versus volume for a constant-pressure, or isobaric process. The area under the curve equals the work done by the gas, since W=PΔV.

$$\mathrm{W} = \mathrm{Nk}\Delta\mathrm{T} \tag{12.4.12}$$

(Eq. 1) for an ideal gas undergoing an isobaric process.

Monatomic Gas

According to the first law of thermodynamics,

$$\mathrm{Q} = \Delta\mathrm{U} + \mathrm{W} \tag{12.4.13}$$

(Eq. 2), where W is work done by the system, U is internal energy, and Q is heat. The law says that the heat transferred to the system does work but also changes the internal energy of the system. Since,

$\mathrm{U} = \frac{3}{2}\mathrm{NkT}$ for a monatomic gas, we get $\Delta\mathrm{U} = \frac{3}{2}\mathrm{Nk}\Delta\mathrm{T}$

(Eq. 3; for the details on internal energy, see our Atom on “Internal Energy of an Ideal Gas”). By using the Equations 1 and 3, Eq. 2 can be written as:

$\mathrm{Q} = \frac{5}{2}\mathrm{Nk}\Delta\mathrm{T}$ for monatomic gas in an isobaric process.

Specific Heat

Specific heat at constant pressure is defined by the following equation:

$\mathrm{Q} = \mathrm{ncP}\Delta\mathrm{T}$

Here n is the amount of particles in a gas represented in moles. By noting that $\mathrm{N} = \mathrm{N_{An}}$ and $\mathrm{R} = \mathrm{kN_A}$ (N_A: Avogadro’s number, R: universal gas constant), we derive:

$\mathrm{c_P} = \frac{5}{2}\mathrm{kN_A} = \frac{5}{2}\mathrm{R}$ for a monatomic gas.

Problem Solving

With the ideal gas law we can figure pressure, volume or temperature, and the number of moles of gases under ideal thermodynamic conditions.

learning objectives

- Identify steps used to solve the ideal gas equation.

The Ideal Gas Law is the equation of state of a hypothetical ideal gas. It is a good approximation to the behavior of many gases under many conditions, although it has several limitations. It is most accurate for monatomic gases at high temperatures and low pressures.

The ideal gas law has the form:

$$\mathrm{PV} = \mathrm{nRT}, \tag{12.4.14}$$

where R is the universal gas constant, and with it we can find values of the pressure P, volume V, temperature T, or number of moles n under a certain ideal thermodynamic condition. Typically, you are given enough parameters to calculate the unknown.

Variations of the ideal gas equation may help solving the problem easily. Here are some general tips.

The ideal gas law can also come in the form:

$$PV = NkT, \tag{12.4.15}$$

where N is the number of particles in the gas and k is the Boltzmann constant.

To solve the ideal gas equation:

1. Write down all the information that you know about the gas.
2. If necessary, convert the known values to SI units.
3. Choose a relevant gas law equation that will allow you to calculate the unknown variable.
4. Substitute the known values into the equation. Calculate the unknown variable.

Remember that the general gas equation only applies if the molar quantity of the gas is fixed. For example, if a gas is mixed with another gas, you may have to apply the equation separately for individual gases.

Example

Let's imagine that at the beginning of a journey a truck tire has a volume of 30,000 cm^3 and an internal pressure of 170 kPa. The temperature of the tire is 16°C. By the end of the trip, the volume of the tire has increased to 32,000 cm^3 and the temperature of the air inside the tire is 40°C. What is the tire pressure at the end of the journey?

Tire Pressure: Tire pressure may change significantly during the operation of the vehicle. This is mostly due to the temperature change of the air in tires.

Solution:

Step 1. Write down all the information that you know about the gas: P_1= 170 kPa and P_2 is unknown. V_1 = 30,000 cm^3 and V_2 = 32,000 cm^3. T_1 = 16°C and T_2 = 40°C.

Step 2. Convert the known values to SI units if necessary: Here, temperature must be converted into Kelvin. Therefore, T_1 = 16 + 273 = 289 K, T_2 = 40 + 273 = 313 K

Step 3. Choose a relevant gas law equation that will allow you to calculate the unknown variable: We can use the general gas equation to solve this problem: $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$.

Therefore, $P_2 = \frac{P_1 \times V_1 \times T_2}{T_1 \times V_2}$.

Step 4. Substitute the known values into the equation. Calculate the unknown variable:

$$P_2 = \frac{170 \times 30,000 \times 313}{289 \times 32,000} = 173 \text{ kPa} \tag{12.4.16}$$

The pressure of the tire at the end of the journey is 173 kPa.

Note that in Step 2 we did not bother to convert the volume values to m^3. In Step 4, pressure appears both in the numerator and denominator. In this case the conversion was not necessary.

Avogador's Number

The number of molecules in a mole is called Avogadro's number (N_A)—defined as 6.02x 10^{23} mol^{-1}.

learning objectives

- Explain relationship between Avogadro's number and mole.

When measuring the amount of substance, it is sometimes easier to work with a unit other than the number of molecules. A mole (abbreviated mol) is a base unit in the International System of Units (SI). It is defined as any substance containing as many atoms or molecules as there are in exactly 12 grams (0.012 kg) of carbon-12. The actual number of atoms or molecules in one mole is called *Avogadro's constant (N_A)*, in recognition of Italian scientist Amedeo Avogadro.

Amadeo Avogadro: Amedeo Avogadro (1776–1856). He established the relationship between the masses of the same volume of different gases (at the same temperature and pressure) corresponds to the relationship between their respective molecular weights.

Avogadro's number (N) refers to the number of molecules in one gram-molecule of oxygen. This indicates an amount of substance as opposed to an independent dimension of measurement. In 1811 Amedeo Avogadro first proposed that the volume of a gas (at a given pressure and temperature) is proportional to the number of atoms or molecules, regardless of the nature of the gas (i.e., this number is universal and independent of the type of gas). In 1926, Jean Perrin won the Nobel Prize in Physics, largely for his work in determining the Avogadro constant (by several different methods). The value of Avogadro's constant, N_A , has been found to equal $6.02\times10^{23}mol^{-1}$.

Role in Science

Avogadro's constant is a scaling factor between macroscopic and microscopic (atomic scale) observations of nature. As such, it provides the relation between other physical constants and properties. For example, it establishes a relationship between the gas constant R and the Boltzmann constant k,

$$\mathrm{R} = \mathrm{kN_A} = 8.314472(15)\mathrm{J\ mol^{-1}K^{-1}}; \tag{12.4.17}$$

and the Faraday constant F and the elementary charge e,

$$F = N_{Ae} = 96485.3383(83) C\ mol^{-1}. \tag{12.4.18}$$

Measuring N_A

The determination of N_A is crucial to the calculation of an atom's mass, since the latter is obtained by dividing the mass of a mole of the gas by Avogadro's constant. In his study on Brownian motion in 1905, Albert Einstein proposed that this constant could be determined based on the quantities observable in Brownian motion. Subsequently, Einstein's idea was verified, leading to the first determination of N_A in 1908 through the experimental work of Jean Baptiste Perrin.

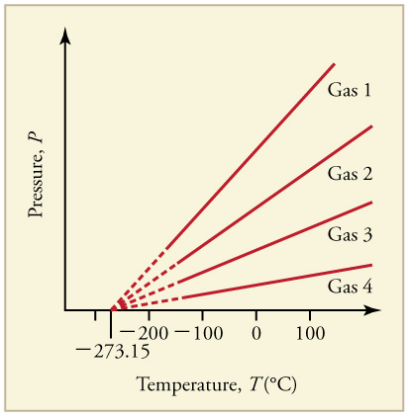
Absolute Temperature

Absolute temperature is the most commoly used thermodyanmic temperature unit and is the standard unit of temperature.

learning objectives

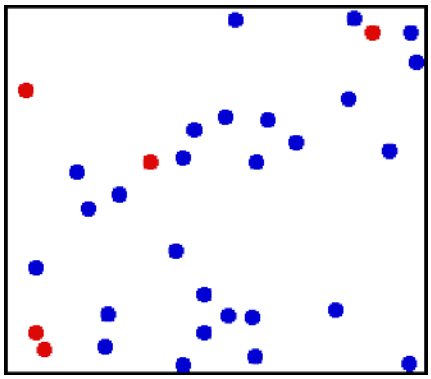
- Describe relationship between absolute temperature and kinetic energy.

Thermodynamic temperature is the absolute measure of temperature. It is one of the principal parameters of thermodynamics and kinetic theory of gases. Thermodynamic temperature is an "absolute" scale because it is the measure of the fundamental property underlying temperature: its null or zero point ("absolute zero") is the temperature at which the particle constituents of matter have minimal motion and cannot become any colder. That is, they have minimal motion, retaining only quantum mechanical motion, as diagramed in.



Graph of Pressure Versus Temperature: Graph of pressure versus temperature for various gases kept at a constant volume. Note that all of the graphs extrapolate to zero pressure at the same temperature

At its simplest, "temperature" arises from the kinetic energy of the random motions of matter's particle constituents such as molecules or atoms, as seen in. Therefore, it is reasonable to choose absolute zero, where all classical motion ceases, as the reference point (T=0) of our temperature system. By using the absolute temperature scale (Kelvin system), which is the most commonly used thermodynamic temperature, we have shown that the average translational kinetic energy (KE) of a particle in a gas has a simple relationship to the temperature:



Translational Motion of Helium: Real gases do not always behave according to the ideal model under certain conditions, such as high pressure. Here, the size of helium atoms relative to their spacing is shown to scale under 1950 atmospheres of pressure.

$$\bar{KE} = \frac{3}{2}kT. \tag{12.4.19}$$

Note that this equation would not look this elegant if the Fahrenheit scale were used instead.

The Kelvin scale

The kelvin (or "absolute temperature") is the standard thermodyanmic temperature unit. It is one of the seven base units in the International System of Units (SI) and is assigned the unit symbol K. By international agreement, the unit kelvin and its scale are defined by two points: absolute zero and the triple point of Vienna Standard Mean Ocean Water (water with a specified blend of hydrogen and oxygen isotopes). Absolute zero, the lowest possible temperature, is defined precisely as 0 K and −273.15 °C. The triple point of water is defined precisely as 273.16 K and 0.01 °C.

Key Points

- Ideal gas law was derived empirically by combining Boyle's law and Charles' law.
- Although the empirical derivation of the equation does not consider microscopic details, the ideal gas law can be derived from first principles in the classical thermodynamics.
- Pressure and volume of a gas can be related to the average velocity of molecues: $PV = \frac{1}{3}Nm\bar{v}^2$.
- Isothermal processes typically occur when a system is in contact with an outside thermal reservoir (heat bath), and the change occurs slowly enough to allow the system to adjust continually to the temperature of the reservoir through heat exchange.
- For an ideal gas, from the ideal gas law $PV = NkT, PV$ remains constant through an isothermal process. A curve in a P-V diagram generated by the equation $PV = const$ is called an isotherm.
- For an isothermal, reversible process, the work done by the gas is equal to the area under the relevant pressure -volume isotherm. It is given as $W_A \rightarrow B = NkT \ln \frac{V_B}{V_A}$.
- Gases can expand or contract under a certain constraint. Depending on the constraint, the final state of the gas may change.
- The heat transferred to the system does work but also changes the internal energy of the system. In an isobaric process for a monatomic gas, heat and the temperature change satisfy the following equation: $Q = \frac{5}{2}Nk\Delta T$.
- For a monatomic ideal gas, specific heat at constant pressure is $\frac{5}{2}R$.
- Write down all the information that you know about the gas and convert the known values to SI units if necessary.
- Choose a relevant gas law equation that will allow you to calculate the unknown variable, and substitute the known values into the equation. Then calculate the unknown variable.
- The general gas equation only applies if the molar quantity of the gas is fixed.
- Avogadro hypothesized that equal volumes of gas, at the same pressure and temperature, contain equal numbers of molecules, regardless of the type of gas.
- Avogadro's constant is a scaling factor between macroscopic and microscopic (atomic scale) observations of nature. It provides the relation between other physical constants and properties.
- Albert Einstein proposed that Avogadro's number could be determined based on the quantities observable in Brownian motion. NA was measured for the first time by Jean Baptiste Perrin in 1908.
- Temperature arises from the kinetic energy of the random motions of matter 's particle constituents such as molecules or atoms. Therefore, it is reasonable to choose absolute zero, where all classical motion ceases, as the reference point.
- By international agreement, the unit kelvin and its scale are defined by two points: absolute zero and the triple point of the standardized water.
- At absolute zero, the particle constituents of matter have minimal motion and cannot become any colder. They retain minimal, quantum mechanical motion.

Key Terms

- **mole**: In the International System of Units, the base unit of amount of substance; the amount of substance of a system which contains as many elementary entities as there are atoms in 12 g of carbon-12. Symbol: mol.
- **ideal gas**: A hypothetical gas whose molecules exhibit no interaction and undergo elastic collision with each other and with the walls of the container.
- **Avogadro's number**: the number of constituent particles (usually atoms or molecules) in one mole of a given substance. It has dimensions of reciprocal mol and its value is equal to 6.02214129·1023 mol-1

- **adiabatic**: Occurring without gain or loss of heat.
- **internal energy**: The sum of all energy present in the system, including kinetic and potential energy; equivalently, the energy needed to create a system, excluding the energy necessary to displace its surroundings.
- **the first law of thermodynamics**: A version of the law of energy conservation: the change in the internal energy of a closed system is equal to the amount of heat supplied to the system, minus the amount of work done by the system on its surroundings.
- **specific heat**: The ratio of the amount of heat needed to raise the temperature of a unit mass of substance by a unit degree to the amount of heat needed to raise that of the same mass of water by the same amount.
- **SI units**: International System of Units (abbreviated SI from French: Le Système international d'unités). It is the modern form of the metric system.
- **gas constant**: A universal constant, R, that appears in the ideal gas law, (PV = nRT), derived from two fundamental constants, the Boltzman constant and Avogadro's number, (R = NAk).
- **Faraday constant**: The magnitude of electric charge per mole of electrons.
- **Brownian motion**: Random motion of particles suspended in a fluid, arising from those particles being struck by individual molecules of the fluid.
- **absolute zero**: The coldest possible temperature: zero on the Kelvin scale and approximately -273.15°C and -459.67°F. The total absence of heat; the temperature at which motion of all molecules would cease.
- **International System of Units**: (SI): The standard set of basic units of measurement used in scientific literature worldwide.
- **Vienna Standard Mean Ocean Water**: A standard defining a standardized isotopic composition of water.

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12.5: Kinetic Theory

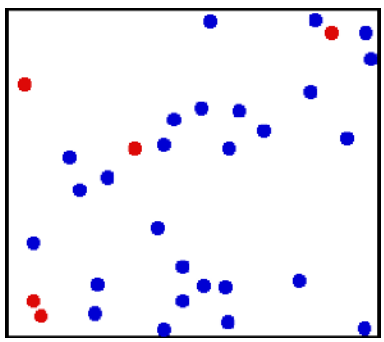
learning objectives

- Express the relationship between the pressure and the average kinetic energy of gas molecules in the form of equation

In Newtonian mechanics, if pressure is the force divided by the area on which the force is exerted, then what is the origin of pressure in a gas? What forces create the pressure? We can gain a better understanding of pressure (and temperature as well) from the kinetic theory of gases, which assumes that atoms and molecules are in continuous random motion.

Microscopic Origin of Pressure

Pressure is explained by kinetic theory as arising from the force exerted by molecules or atoms impacting on the walls of a container, as illustrated in the figure below. Consider a gas of N molecules, each of mass m, enclosed in a cubical container of volume $V=L^3$. When a gas molecule collides with the wall of the container perpendicular to the x coordinate axis and bounces off in the opposite direction with the same speed (an elastic collision), then the momentum lost by the particle and gained by the wall (Δp) is:



Translational Motion of Helium: Real gases do not always behave according to the ideal model under certain conditions, such as high pressure. Here, the size of helium atoms relative to their spacing is shown to scale under 1950 atmospheres of pressure.

$$\Delta p = p_{i,x} - p_{f,x} = p_{i,x} - (-p_{i,x}) \tag{12.5.1}$$
$$= 2p_{i,x} = 2mv_x \tag{12.5.2}$$

where v_x is the x-component of the initial velocity of the particle.

The particle impacts one specific side wall once every $\Delta t = \frac{2L}{v_x}$,

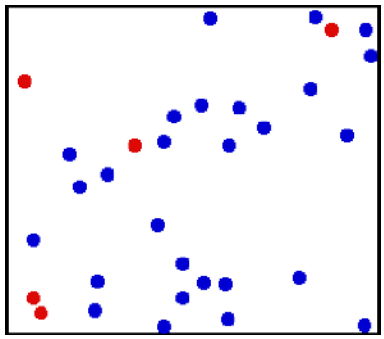
(where L is the distance between opposite walls). The force due to this particle is:

$$F = \frac{\Delta p}{\Delta t} = \frac{mv_x^2}{L}. \tag{12.5.3}$$

The total force on the wall, therefore, is:

$$F = \frac{Nm\bar{v}_x^2}{L} \tag{12.5.4}$$

where the bar denotes an average over the *N* particles. Since the assumption is that the particles move in random directions, if we divide the velocity vectors of all particles in three mutually perpendicular directions, the average value of the squared velocity along each direction must be same. (This does not mean that each particle always travel in 45 degrees to the coordinate axes.)



Pressure: Pressure arises from the force exerted by molecules or atoms impacting on the walls of a container.

This gives $\bar{v_x^2} = \frac{\bar{v^2}}{3}$. We can rewrite the force as $F = \frac{Nm\bar{v^2}}{3L}$.

This force is exerted on an area L^2. Therefore the pressure of the gas is:

$$P = \frac{F}{L^2} = \frac{Nm\bar{v^2}}{3V} = \frac{nm\bar{v^2}}{3}, \tag{12.5.5}$$

where $V=L^3$ is the volume of the box. The fraction $n=N/V$ is the number density of the gas. This is a first non-trivial result of the kinetic theory because it relates pressure (a macroscopic property) to the average (translational) kinetic energy per molecule which is a microscopic property.

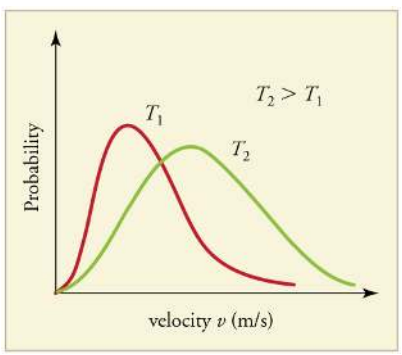
Speed Distribution of Molecules

A gas of many molecules has a predictable distribution of molecular speeds, known as the Maxwell-Boltzmann distribution.

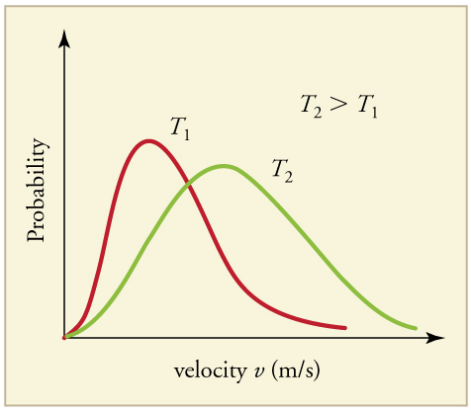
learning objectives

- Describe the shape and temperature dependence of the Maxwell-Boltzmann distribution curve

The motion of molecules in a gas is random in magnitude and direction for individual molecules, but a gas of many molecules has a predictable distribution of molecular speeds, known as the Maxwell-Boltzmann distribution (illustrated in). The distribution has a long tail because some molecules may go several times the rms speed. The most probable speed v_p (at the peak of the curve) is less than the rms speed v_{rms}. As shown in, the curve is shifted to higher speeds at higher temperatures, with a broader range of speeds.



Maxwell-Boltzmann Distribution at Higher Temperatures: The Maxwell-Boltzmann distribution is shifted to higher speeds and is broadened at higher temperatures.



Maxwell-Boltzmann Distribution: The Maxwell-Boltzmann distribution of molecular speeds in an ideal gas. The most likely speed v_p is less than the rms speed v_rms. Although very high speeds are possible, only a tiny fraction of the molecules have speeds that are an order of magnitude greater than v_rms.

Maxwell-Boltzmann Distribution

Maxwell-Boltzmann distribution is a probability distribution. It applies to ideal gases close to thermodynamic equilibrium, and is given as the following equation:

$$\mathrm{f_v(v_x, v_y, v_z) = (\frac{m}{2\pi kT})^{3/2} exp[-\frac{m(v_x^2 + v_y^2 + v_z^2)}{2kT}]}, \tag{12.5.6}$$

where fv is the velocity probability density function. (Derivation of the formula goes beyond the scope of introductory physics.) The formula calculates the probability of finding a particle with velocity in the infinitesimal element [dv_x, dv_y, dv_z] about velocity v = [v_x, v_y, v_z] is:

Double subscripts: use braces to clarify

It can also be shown that the Maxwell–Boltzmann velocity distribution for the vector velocity [v_x, v_y, v_z] is the product of the distributions for each of the three directions:

$$\mathrm{f_v(v_x, v_y, v_z) = f_v(v_x) f_v(v_y) f_v(v_z)} \tag{12.5.7}$$

where the distribution for a single direction is,

$$\mathrm{f_v(v_i) = \sqrt{\frac{m}{2\pi kT}}\ exp[\frac{-mv_i^2}{2kT}]}. \tag{12.5.8}$$

This makes sense because particles are moving randomly, meaning that each component of the velocity should be independent.

Distribution for the Speed

Usually, we are more interested in the speeds of molecules rather than their component velocities. The Maxwell–Boltzmann distribution for the speed follows immediately from the distribution of the velocity vector, above. Note that the speed is:

$$\mathrm{v = \sqrt{v_x^2 + v_y^2 + v_z^2}} \tag{12.5.9}$$

and the increment of volume is:

$$\mathrm{dv_x\ dv_y\ dv_z = v^2 \sin\phi\ dv\ d\theta\ d\phi}, \tag{12.5.10}$$

where θ and ϕ are the "course" (azimuth of the velocity vector) and "path angle" (elevation angle of the velocity vector). Integration of the normal probability density function of the velocity, above, over the course (from 0 to 2π) and path angle (from 0 to π), with substitution of the speed for the sum of the squares of the vector components, yields the following probability density function (known simply as the Maxwell distribution):

$\mathrm{f(v) = \sqrt{(\frac{m}{2\pi kT})^3 4\pi v^2\ exp(\frac{-mv^2}{2kT})}}$ for speed v.

Temperature

Temperature is directly proportional to the average translational kinetic energy of molecules in an ideal gas.

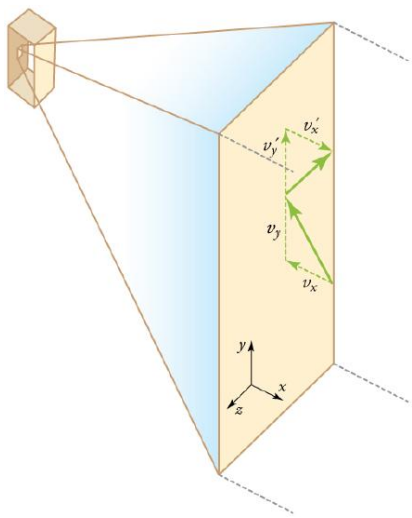
learning objectives

- Describe relationship between temperature and energy of molecules in an ideal gas

Intuitively, hotter air suggests faster movement of air molecules. In this atom, we will derive an equation relating the temperature of a gas (a macroscopic quantity) to the average kinetic energy of individual molecules (a microscopic quantity). This is a basic and extremely important relationship in the kinetic theory of gases.

Microscopic View

We assume that a molecule is small compared with the separation of molecules in the gas (confined in a three dimensional container), and that its interaction with other molecules can be ignored. Also, we assume elastic collisions when molecules hit the wall of the container, as illustrated in.



Elastic Collisions When Molecules Hit the Wall of the Container: Gas in a box exerts an outward pressure on its walls. A molecule colliding with a rigid wall has the direction of its velocity and momentum in the x-direction reversed. This direction is perpendicular to the wall. The components of its velocity momentum in the y- and z-directions are not changed, which means there is no force parallel to the wall.

We have seen in the Atom on “Origin of Pressure ” that, for an ideal gas under our assumptions:

$$\mathrm{P} = \frac{\mathrm{Nm}\bar{\mathrm{v}}^2}{3\mathrm{V}}, \tag{12.5.11}$$

where P is the pressure, N is the number of molecules, m is the mass of the molecule, v is the speed of molecules, and V is the volume of the gas. From the equation, we get:

$$\mathrm{PV} = \frac{1}{3}\mathrm{Nm}\bar{\mathrm{v}}^2 \text{ (Eq.1)}. \tag{12.5.12}$$

What can we learn from this atomic and molecular version of the ideal gas law ? We can derive a relationship between temperature and the average translational kinetic energy of molecules in a gas. Recall the macroscopic expression of the ideal gas law:

$$\mathrm{PV} = \mathrm{NkT} \text{ (Eq.2)}, \tag{12.5.13}$$

where N is the number of molecules, T is the temperature of the gas, and k is the Boltzmann constant.

Equating the right hand sides of the macroscopic and microscopic versions of the ideal gas law (Eq. 1 & 2) gives:

$$\frac{1}{3}\mathrm{m}\bar{\mathrm{v}}^2 = \mathrm{kT}. \tag{12.5.14}$$

Thermal Energy

Note that the average kinetic energy (KE) of a molecule in the gas is:

$$\frac{1}{2}m\bar{v^2}. \tag{12.5.15}$$

Therefore, we derive the relation between average KE and temperature as follows:

$$\bar{KE} = \frac{1}{2}m\bar{v^2} = \frac{3}{2}kT, \text{ (Eq.3)}. \tag{12.5.16}$$

The average translational kinetic energy of a molecule is called thermal energy.

RMS Speed

Eq. 3 is a molecular interpretation of temperature. It has been found to be valid for gases and reasonably accurate in liquids and solids. It is another definition of temperature based on an expression of the molecular energy. It is sometimes useful to know the average speed of molecules in a gas in terms of temperature:

$$\bar{v^2} = v_{rms} = \sqrt{\frac{3kT}{m}}, \tag{12.5.17}$$

where v_{rms} stands for root-mean-square (rms) speed.

Internal Energy of an Ideal Gas

Internal energy is the total energy contained by a thermodynamic system, and has two major components: kinetic energy and potential energy.

learning objectives

- Determine the number of degrees of freedom and calculate the internal energy for an ideal gas molecule

In thermodynamics, internal energy is the total energy contained by a thermodynamic system. Internal energy has two major components: kinetic energy and potential energy. The kinetic energy is due to the motion of the system's particles (e.g., translations, rotations, vibrations). In ideal gases, there is no inter-particle interaction. Therefore, we will disregard potential energy and only focus on the kinetic energy contribution to the internal energy.

Monatomic Gases

A monatomic gas is one in which atoms are not bound to each other. Noble gases (He, Ne, etc.) are typical examples. A helium balloon is shown in the following figure. In this case, the kinetic energy consists only of the translational energy of the individual atoms. Monoatomic particles do not vibrate, and their rotational energy can be neglected because atomic moment of inertia is so small. Also, they are not electronically excited to higher energies except at very high temperatures. Therefore, practical internal energy changes in an ideal gas may be described solely by changes in its translational kinetic energy.

Helium Blimp: Helium, like other noble gases, is a monatomic gas, which often can be described by the ideal gas law. It is the gas of choice to fill airships such as the Goodyear blimp.

The average kinetic energy (KE) of a particle in an ideal gas is given as:

$$\bar{KE} = \frac{1}{2}m\bar{v^2} = \frac{3}{2}kT, \tag{12.5.18}$$

where k is the Boltzmann's constant. (See the Atom on "Temperature" in kinetic theory.) With N atoms in the gas, its total internal energy U is given as:

$$U = \frac{3}{2}NkT \tag{12.5.19}$$

where N is the number of atoms in the gas. Note that there are three degrees of freedom in monatomic gases: translation in x, y and z directions.

Since atomic motion is random (and therefore isotropic), each degrees of freedom contribute $\frac{1}{2}kT$ per atom to the internal energy.

Diatomic gases

A diatomic molecule (H_2, O_2, N_2, etc.) has 5 degrees of freedom (3 for translation in x, y and z directions, and 2 for rotation). Therefore, the internal energy for diatomic gases is $U = \frac{5}{2}NkT$.

Key Points

- We can gain a better understanding of pressure (and temperature as well) from the kinetic theory of gases, which assumes that atoms and molecules are in continuous random motion.
- Pressure, a macroscopic property, can be related to the average (translational) kinetic energy per molecule which is a microscopic property by $P = \frac{nm\bar{v^2}}{3}$.
- Since the assumption is that the particles move in random directions, the average value of velocity squared along each direction must be same. This gives: $\bar{v_x^2} = \bar{v_y^2} = \bar{v_z^2} = \bar{v^2}/3$.
- The Maxwell-Boltzmann distribution has a long tail, and the most probable speed v_p is less than the rms speed v_{rms}. The distribution curve is shifted to higher speeds at higher temperatures, with a broader range of speeds.
- Maxwell-Boltzmann distribution is given as follows: $f_v(v_x, v_y, v_z) = (\frac{m}{2\pi kT})^{3/2} \exp[-\frac{m(v_x^2+v_y^2+v_z^2)}{2kT}]$. It is a product of three independent 1D Maxwell-Boltzmann distributions.
- Molecular speed distribution is given as $f(v) = \sqrt{(\frac{m}{2\pi kT})^3} 4\pi v^2 \exp(\frac{-mv^2}{2kT})$. This is simply called Maxwell distribution.
- The average translational kinetic energy of a molecule is equivalent to $\frac{3}{2}kT$ and is called thermal energy.
- In kinematic theory of gases, macroscopic quantities (such as press and temperature) are explained by considering microscopic (random) motion of molecules.
- The rms speed of molecules in a gas is given as $\sqrt{\frac{3kT}{m}}$.
- In ideal gases, there is no inter-particle interaction. Therefore, only the kinetic energy contribute to the internal energy.
- Each degrees of freedom contribute $\frac{1}{2}kT$ per atom to the internal energy.
- For monatomic ideal gases with N atoms, its total internal energy U is given as $U = \frac{3}{2}NkT$. For diatomic gases, $U = \frac{5}{2}NkT$.

Key Terms

- **kinetic theory of gases**: The kinetic theory of gases describes a gas as a large number of small particles (atoms or molecules), all of which are in constant, random motion.
- **Newtonian mechanics**: Early classical mechanics as propounded by Isaac Newton, especially that based on his laws of motion and theory of gravity.
- **rms**: Root mean square: a statistical measure of the magnitude of a varying quantity.
- **ideal gas**: A hypothetical gas whose molecules exhibit no interaction and undergo elastic collision with each other and with the walls of the container.
- **Boltzmann's constant**: The physical constant relating energy at the particle level with temperature observed at the bulk level. It is the gas constant R divided by Avogadro's number, NA.
- **moment of inertia**: A measure of a body's resistance to a change in its angular rotation velocity
- **noble gas**: Any of the elements of group 18 of the periodic table, being monatomic and (with very limited exceptions) inert.

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12.6: Phase Changes

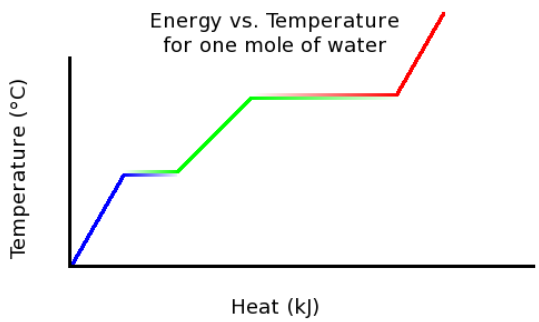
learning objectives

- Describe behavior of the medium during a phase transition

A phase of a thermodynamic system and the states of matter have uniform physical properties. During a phase transition of a given medium certain properties of the medium change, often discontinuously, as a result of some external condition, such as temperature or pressure. For example, a liquid may become gas upon heating to the boiling point, resulting in an abrupt change in volume. The measurement of the external conditions at which the transformation occurs is termed the phase transition. The term is most commonly used to describe transitions between solid, liquid and gaseous states of matter and, in rare cases, plasma.

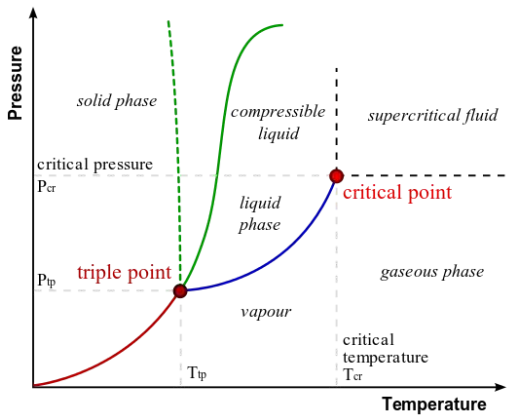
As an example, if you boil water, it never goes above 100 degrees Celsius. Only after it has completely evaporated will it get any hotter. This is because once water reaches the boiling point, extra energy is used to change the state of matter and increase the potential energy instead of the kinetic energy. The opposite happens when water freezes. To boil or melt one mole of a substance, a certain amount of energy is required. These amounts of energy are the molar heat of vaporization and molar heat of fusion. If that amount of energy is added to a mole of that substance at boiling or freezing point, all of it will melt or boil, but the temperature won't change.

Temperature increases linearly with heat, until the melting point. But the heat added does not change the temperature; that heat energy is instead used to break intermolecular bonds and convert ice into water. At this point, there is a mixture of both ice and water. Once all ice has been melted, the temperature again rises linearly with heat added. At the boiling point, temperature no longer rises with heat added because the energy is once again being used to break intermolecular bonds. Once all water has been boiled to steam, the temperature will continue to rise linearly as heat is added.



Temperature vs. Heat: This graph shows the temperature of ice as heat is added.

The plots of pressure versus temperatures provide considerable insight into thermal properties of substances. There are well-defined regions on these graphs that correspond to various phases of matter, so PT graphs are called phase diagrams. Using the graph, if you know the pressure and temperature you can determine the phase of water. The solid lines—boundaries between phases—indicate temperatures and pressures at which the phases coexist (that is, they exist together in ratios, depending on pressure and temperature). For example, the boiling point of water is 100º C at 1.00 atm. As the pressure increases, the boiling temperature rises steadily to 374º C at a pressure of 218 atm. A pressure cooker (or even a covered pot) will cook food faster because the water can exist as a liquid at temperatures greater than 100º C without all boiling away. The curve ends at a point called the critical point, because at higher temperatures the liquid phase does not exist at any pressure. The critical temperature for oxygen is -118ºC, so oxygen cannot be liquefied above this temperature.



Phase Diagram of Water: In this typical phase diagram of water, the green lines mark the freezing point, and the blue line marks the boiling point, showing how they vary with pressure. The dotted line illustrates the anomalous behavior of water. Note that water changes states based on the pressure and temperature.

Humidity, Evaporation, and Boiling

The amount of water vapor in air is a result of evaporation or boiling, until an equilibrium is reached.

learning objectives

- Explain why water boils at 100 °C

Overview

The term relative humidity refers to how much water vapor is in the air compared with the maximum possible. At its maximum, denoted as saturation, the relative humidity is 100%, and evaporation is inhibited. The amount of water vapor the air can hold depends on its temperature. For example, relative humidity rises in the evening, as air temperature declines, sometimes reaching the dew point. At the dew point temperature, relative humidity is 100%, and fog may result from the condensation of water droplets if they are small enough to stay in suspension. Conversely, if one wished to dry something, it is more effective to blow hot air over it rather than cold air, because, among other things, hot air can hold more water vapor.

Evaporation

The capacity of air to hold water vapor is based on vapor pressure of water. The liquid and solid phases are continuously giving off vapor because some of the molecules have high enough speeds to enter the gas phase, a process called evaporation; see (a). For the molecules to evaporate, they must be located near the surface, be moving in the proper direction, and have sufficient kinetic energy to overcome liquid-phase intermolecular forces. When only a small proportion of the molecules meet these criteria, the rate of evaporation is low. Since the kinetic energy of a molecule is proportional to its temperature, evaporation proceeds more quickly at higher temperatures.

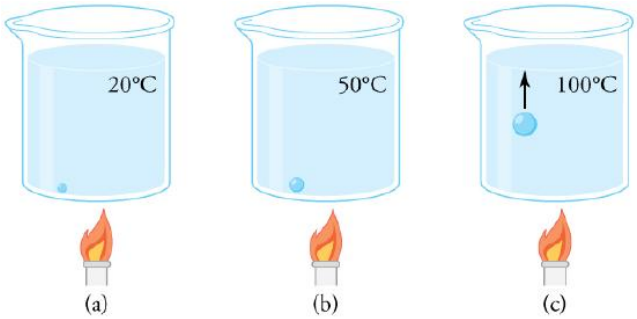
If a lid is placed over the container, as in (b), evaporation continues, increasing the pressure, until sufficient vapor has built up for condensation to balance evaporation. Then equilibrium has been achieved, and the vapor pressure is equal to the partial pressure of water in the container. Vapor pressure increases with temperature because molecular speeds are higher as temperature increases.

As the faster-moving molecules escape, the remaining molecules have lower average kinetic energy, and the temperature of the liquid decreases. This phenomenon is also called evaporative cooling. This is why evaporating sweat cools the human body. Evaporation also tends to proceed more quickly with higher flow rates between the gaseous and liquid phase and in liquids with higher vapor pressure. For example, laundry on a clothes line will dry (by evaporation) more rapidly on a windy day than on a still day.

Application for Boiling Water

Why does water boil at 100ºC? The vapor pressure of water at 100ºC is 1.01×10^5 Pa, or 1.00 atm. Thus, it can evaporate without limit at this temperature and pressure. But why does it form bubbles when it boils? This is because water ordinarily contains significant amounts of dissolved air and other impurities, which are observed as small bubbles of air in a glass of water. If a bubble

starts out at the bottom of the container at 20ºC, it contains water vapor (about 2.30%). The pressure inside the bubble is fixed at 1.00 atm (we ignore the slight pressure exerted by the water around it). As the temperature rises, the amount of air in the bubble stays the same, but the water vapor increases; the bubble expands to keep the pressure at 1.00 atm. At 100ºC, water vapor enters the bubble continuously since the partial pressure of water is equal to 1.00 atm in equilibrium. It cannot reach this pressure, however, since the bubble also contains air and total pressure is 1.00 atm. The bubble grows in size and thereby increases the buoyant force. The bubble breaks away and rises rapidly to the surface, resulting in boiling. (See.)



Close-up of the Boiling Process: (a) An air bubble in water starts out saturated with water vapor at 20ºC. (b) As the temperature rises, water vapor enters the bubble because its vapor pressure increases. The bubble expands to keep its pressure at 1.00 atm. (c) At 100ºC, water vapor enters the bubble continuously because water's vapor pressure exceeds its partial pressure in the bubble, which must be less than 1.00 atm. The bubble grows and rises to the surface.

Key Points

- The term is most commonly used to describe transitions between solid, liquid and gaseous states of matter and, in rare cases, plasma.
- Once water reaches the boiling point, extra energy is used to change the state of matter and increase the potential energy instead of the kinetic energy.
- Plots of pressure versus temperatures, an example of a phase diagram, provide considerable insight into thermal properties of substances.
- Relative humidity is the fraction of water vapor in a gas compared to the saturation value.
- Since the kinetic energy of a molecule is proportional to its temperature, evaporation proceeds more quickly at higher temperatures.
- Vapor pressure increases with temperature because molecular speeds are higher as temperature increases.
- Water boils at 100 °C because the vapor pressure exceeds atmospheric pressure at this temperature.

Key Terms

- **intermolecular**: from one molecule to another; between molecules
- **plasma**: a state of matter consisting of partially ionized gas
- **thermodynamic**: Relating to the conversion of heat into other forms of energy.
- **equilibrium**: The state of a body at rest or in uniform motion, the resultant of all forces on which is zero.
- **vapor pressure**: The pressure that a vapor exerts, or the partial pressure if it is mixed with other gases.
- **humidity**: The amount of water vapor in the air.

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12.7: The Zeroth Law of Thermodynamics

learning objectives

- Identify major implications of the Zeroth Law of Thermodynamics

The Zeroth Law of Thermodynamics

There are a few ways to state the Zeroth Law of Thermodynamics, but the simplest is as follows: systems that are in thermal equilibrium exist at the same temperature.

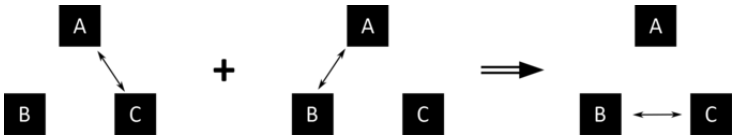
Systems are in thermal equilibrium if they do not transfer heat, even though they are in a position to do so, based on other factors. For example, food that's been in the refrigerator overnight is in thermal equilibrium with the air in the refrigerator: heat no longer flows from one source (the food) to the other source (the air) or back.

What the Zeroth Law of Thermodynamics means is that temperature is something worth measuring, because it indicates whether heat will move between objects. This will be true regardless of how the objects interact. Even if two objects don't touch, heat may still flow between them, such as by radiation (as from a heat lamp). However, according to the Zeroth Law of Thermodynamics, if the systems are in thermal equilibrium, no heat flow will take place.

There are more formal ways to state the Zeroth Law of Thermodynamics, which is commonly stated in the following manner:

Let A, B, and C be three systems. If A and C are in thermal equilibrium, and A and B are in thermal equilibrium, then B and C are in thermal equilibrium.

This statement is represented symbolically in. Temperature is not mentioned explicitly, but it's implied that temperature exists. Temperature is the quantity that is always the same for all systems in thermal equilibrium with one another.



Zeroth Law of Thermodynamics: The double arrow represents thermal equilibrium between systems. If systems A and C are in equilibrium, and systems A and B are in equilibrium, then systems B and C are in equilibrium. The systems A, B, and C are at the same temperature.

Key Points

- Assuming A, B, and C are three systems, if A and C are in thermal equilibrium, and A and B are in thermal equilibrium, then B and C are in thermal equilibrium.
- Two systems are in thermal equilibrium if they could transfer heat between each other, but do not.
- The Zeroth Law of Thermodynamics implies that temperature is a quantity worth measuring.

Key Terms

- **thermal equilibrium**: Two systems are in thermal equilibrium if they could transfer heat between each other, but don't.
- **zeroth law of thermodynamics**: Let A, B and C be three systems. If A and C are in thermal equilibrium, and A and B are in thermal equilibrium, then B and C are in thermal equilibrium.

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12.8: Thermal Stresses

learning objectives

- Formulate relationship between thermal stress and thermal expansion

Thermal Expansion

Thermal expansion is the change in size or volume of a given mass with temperature. The expansion of alcohol in a thermometer is one of many commonly encountered examples of this. Hot air rises because its volume increases, which causes the hot air's density to be smaller than the density of surrounding air, causing a buoyant (upward) force on the hot air. The same happens in all liquids and gases, driving natural heat transfer upward in homes, oceans, and weather systems. Solids also undergo thermal expansion. Railroad tracks and bridges, for example, have expansion joints to allow them to freely expand and contract with temperature changes.

Thermal Expansion Joints: Thermal expansion joints like these in the Auckland Harbour Bridge in New Zealand allow bridges to change length without buckling. (credit: Ingolfson, Wikimedia Commons)

What are the basic properties of thermal expansion? First, thermal expansion is clearly related to temperature change. The greater the temperature change, the more a bimetallic strip will bend. Second, it depends on the material. In a thermometer, for example, the expansion of alcohol is much greater than the expansion of the glass containing it.

What is the underlying cause of thermal expansion? An increase in temperature implies an increase in the kinetic energy of the individual atoms. In a solid, unlike in a gas, the atoms or molecules are closely packed together, but their kinetic energy (in the form of small, rapid vibrations) pushes neighboring atoms or molecules apart from each other. This neighbor-to-neighbor pushing results in a slightly greater distance, on average, between neighbors, and adds up to a larger size for the whole body. For most substances under ordinary conditions, there is no preferred direction, and an increase in temperature will increase the solid's size by a certain fraction in each dimension.

To be more quantitative, the change in length ΔL is proportional to length L. The dependence of thermal expansion on temperature, substance, and length is summarized in the equation

$$\Delta L = \alpha L \Delta T \tag{12.8.1}$$

where ΔL is the change in length L, ΔT is the change in temperature, and α is the coefficient of linear expansion, which varies slightly with temperature.

Thermal Stress

Thermal stress is created by thermal expansion or contraction. Thermal stress can be destructive, such as when expanding gasoline ruptures a tank. It can also be useful, for example, when two parts are joined together by heating one in manufacturing, then slipping it over the other and allowing the combination to cool. Thermal stress can explain many phenomena, such as the weathering of rocks and pavement by the expansion of ice when it freezes.

Forces and pressures created by thermal stress can be quite large. Railroad tracks and roadways can buckle on hot days if they lack sufficient expansion joints. Power lines sag more in the summer than in the winter, and will snap in cold weather if there is insufficient slack. Cracks open and close in plaster walls as a house warms and cools. Glass cooking pans will crack if cooled rapidly or unevenly, because of differential contraction and the stresses it creates. (Pyrex® is less susceptible because of its small coefficient of thermal expansion.) Nuclear reactor pressure vessels are threatened by overly rapid cooling, and although none have failed, several have been cooled faster than considered desirable. Biological cells are ruptured when foods are frozen, detracting from their taste. Repeated thawing and freezing accentuates the damage. Even the oceans can be affected. A significant portion of the rise in sea level that is resulting from global warming is due to the thermal expansion of sea water.

Metal is regularly used in the human body for hip and knee implants. Most implants need to be replaced over time because, among other things, metal does not bond with bone. Researchers are trying to find better metal coatings that would allow metal-to-bone bonding. One challenge is to find a coating that has an expansion coefficient similar to that of metal. If the expansion coefficients are too different, the thermal stresses during the manufacturing process lead to cracks at the coating-metal interface.

Another example of thermal stress is found in the mouth. Dental fillings can expand differently from tooth enamel. It can give pain when eating ice cream or having a hot drink. Cracks might occur in the filling. Metal fillings (gold, silver, etc.) are being replaced by composite fillings (porcelain), which have smaller coefficients of expansion, and are closer to those of teeth.

Key Points

- Thermal expansion is the change in size or volume of a given mass with changing temperature.
- An increase in temperature implies an increase in the kinetic energy of the individual atoms, which will increase a solid's size by a certain fraction in each dimension.
- Thermal stress is created when thermal expansion is constrained.

Key Terms

- **stress**: The internal distribution of force per unit area (pressure) within a body reacting to applied forces which causes strain or deformation and is typically symbolized by σ.
- **differential**: A qualitative or quantitative difference between similar or comparable things.

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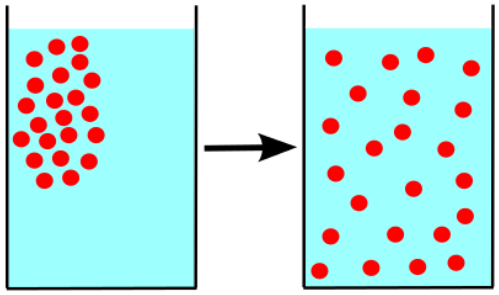
12.9: Diffusion

learning objectives

- Discuss the process and results of diffusion, identifying factors that affect its rate

Diffusion is the movement of particles move from an area of high concentration to an area of low concentration until equilibrium is reached. A distinguishing feature of diffusion is that it results in mixing or mass transport without requiring bulk motion. Thus, diffusion should not be confused with convection or advection, which are other transport mechanisms that use bulk motion to move particles from one place to another.



Diffusion: Particles moving from areas of high concentration to areas of low concentration.

Molecular diffusion, often called simply diffusion, is the thermal motion of all (liquid or gas) particles at temperatures above absolute zero. The rate of this movement is a function of temperature, viscosity of the fluid and the size (mass) of the particles. Diffusion explains the net flux of molecules from a region of higher concentration to one of lower concentration. However, diffusion can still occur in the absence of a concentration gradient.

The result of diffusion is a gradual mixing of material. In a phase with uniform temperature, absent external net forces acting on the particles, the diffusion process will eventually result in complete mixing.

Key Points

- Molecular diffusion, often called simply diffusion, is the thermal motion of all (liquid or gas) particles at temperatures above absolute zero.
- The result of diffusion is a gradual mixing of material. In a phase with uniform temperature, absent external net forces acting on the particles, the diffusion process will eventually result in complete mixing.
- Diffusion can also occur in the absence of a concentration gradient — equilibrium particles are still moving around their container.

Key Terms

- **equilibrium**: The state of a body at rest or in uniform motion, the resultant of all forces on which is zero.
- **diffusion**: Diffusion is the movement of particles from regions of high concentration toward regions of lower concentration.
- **concentration**: The proportion of a substance in a mixture.

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CHAPTER OVERVIEW

13: Heat and Heat Transfer

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CHAPTER OVERVIEW

14: Thermodynamics

Topic hierarchy

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CHAPTER OVERVIEW

17: Electric Charge and Field

Topic hierarchy

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CHAPTER OVERVIEW

18: Electric Potential and Electric Field

Topic hierarchy

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CHAPTER OVERVIEW

19: Electric Current and Resistance

Topic hierarchy

19.1: Overview
19.2: Electric Current
19.3: Resistance and Resistors
19.4: Electric Power and Energy
19.5: Alternating Currents
19.6: Electricity in the World

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19.1: Overview

learning objectives

- Explain difference between conductor and resistor

Introduction to Electric Current and Resistance

From ceiling lights to circuit chips, from power steering to Internet browsing, electricity provides the basis for our technology and civilization. The firing of neurons in your brain is also an example of electric current – that is, the movement of electric charge through a conductive medium. In electric circuits, this charge is often carried by moving electrons in a wire. It can also be carried by ions in an electrolyte, or by both ions and electrons such as in a plasma.

Electric Current

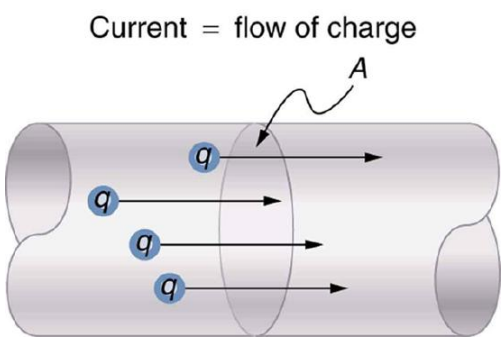
When we speak of electric current, often we are referring to a specific quantity – the *rate* at which charge flows. A large current, such as that used to start a truck engine, moves a large amount of charge in a small time, whereas a small current, such as that used to operate a hand-held calculator, moves a small amount of charge over a long period of time. In equation form, electric current I is defined to be

$$\mathrm{I} = \frac{\Delta \mathrm{Q}}{\Delta \mathrm{T}} \tag{19.1.1}$$

where Q is the amount of charge passing through a given area in time t. The SI unit for current is the ampere (A), named for the French physicist André-Marie Ampère (1775–1836). Since I=ΔQ/Δt, we see that an ampere is one coulomb per second:

$$1\mathrm{A} = 1\mathrm{C/s} \tag{19.1.2}$$

The flow of electricity requires a medium in which charge can flow. We call an object or medium that allows charge to flow a *conductor*, while the empirical measure of a material's ability to conduct charge is called the electrical *conductance*. The SI unit for conductance is the siemens (S).



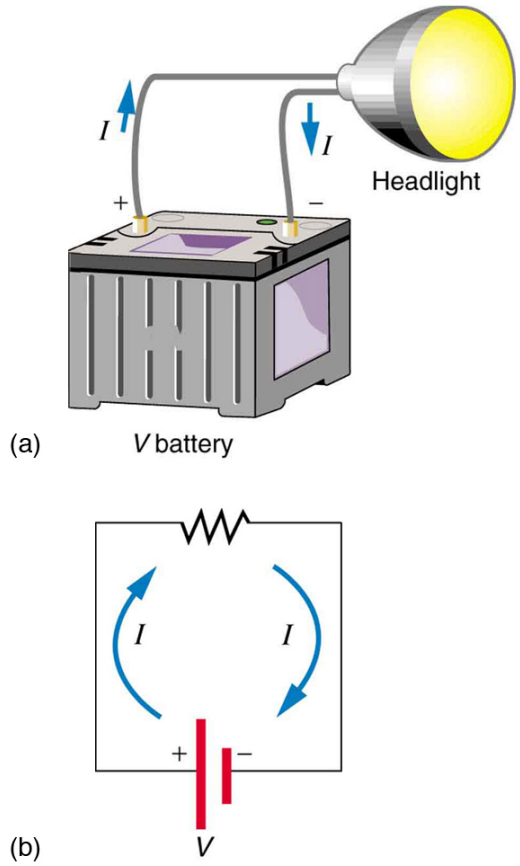
Electric Current: The rate of flow of charge is current. An ampere is the flow of one coulomb through an area in one second.

Resistance

The opposite of conductance is resistance – a quantity that describes how strongly a material opposes the flow of electric current. An object or medium that has high electrical resistance is called a *resistor.* We will see that the resistance of an object depends on its shape and the material of which it is composed. The SI unit for resistance is the *ohm* (symbol:).

Electric Circuits

A useful and practical way to learn about electric current and resistance is to study circuits. The figure above shows a simple circuit and the standard schematic representation of a battery, conducting path, and load (a resistor). Schematics are very useful in visualizing the main features of a circuit. A single schematic can represent a wide variety of situations. The schematic in (b), for example, can represent anything from a truck battery connected to a headlight lighting the street in front of the truck to a small battery connected to a penlight lighting a keyhole in a door. Such schematics are useful because the analysis is the same for a wide variety of situations. We need to understand a few schematics to apply the concepts and analysis to many more situations.



Simple Electric Circuit: (a) A simple electric circuit. A closed path for current to flow through is supplied by conducting wires connecting a load to the terminals of a battery. (b) In this schematic, the battery is represented by the two parallel red lines, conducting wires are shown as straight lines, and the zigzag represents the load. The schematic represents a wide variety of similar circuits.

Note that the direction of current flow in the figure is from positive to negative. The direction of conventional current is the direction that positive charge would flow. Depending on the situation, positive charges, negative charges, or both may move. In metal wires, for example, current is carried by electrons—that is, negative charges move. In ionic solutions, such as salt water, both positive and negative charges move.

It is important to realize that there is an electric field in conductors responsible for producing the current. Unlike static electricity, where a conductor in equilibrium cannot have an electric field in it, conductors carrying a current have an electric field and are not in static equilibrium. An electric field is needed to supply energy to move the charges.

Armed with these basics, we'll begin to tackle the harder details of this topic in the next section.

Key Points

- Electric current is the movement of electric charge through a conductive medium.
- We also use the term "current" as a quantity to describe the rate at which charge flows through a medium. The SI unit for current is the ampere (A), which is equal to a coulomb per second (C/s).
- Conductance is a quantity describing how easily charge can flow through a material, while resistance is the inverse, a measure of how strongly a material opposes electric flow.
- An object that allows charge to flow easily is called a conductor, while an object that resists the flow of charge is called a resistor.

Key Terms

- **conductive medium**: A material that can transmit electricity.

- **electrical resistance**: The opposition offered by an electrical conductor to the flow of a current through itself, resulting in a conversion of electrical energy into heat and radiation. The SI derived unit of resistance is the ohm. Symbol: R.
- **electric charge**: A quantum number that determines the electromagnetic interactions of some subatomic particles; by convention, the electron has an electric charge of -1 and the proton +1, and quarks have fractional charge.

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19.2: Electric Current

learning objectives

- Describe the functions and identify the major components of a battery

A battery is a device that converts chemical energy directly to electrical energy. It consists of a number of voltaic cells connected in series by a conductive electrolyte containing anions and cations. One half-cell includes electrolyte and the anode, or negative electrode; the other half-cell includes electrolyte and the cathode, or positive electrode. In the redox (reduction-oxidation) reaction that powers the battery, cations are reduced (electrons are added) at the cathode, while anions are oxidized (electrons are removed) at the anode. The electrodes do not touch each other but are electrically connected by the electrolyte. Some cells use two half-cells with different electrolytes. A separator between half-cells allows ions to flow, but prevents mixing of the electrolytes.

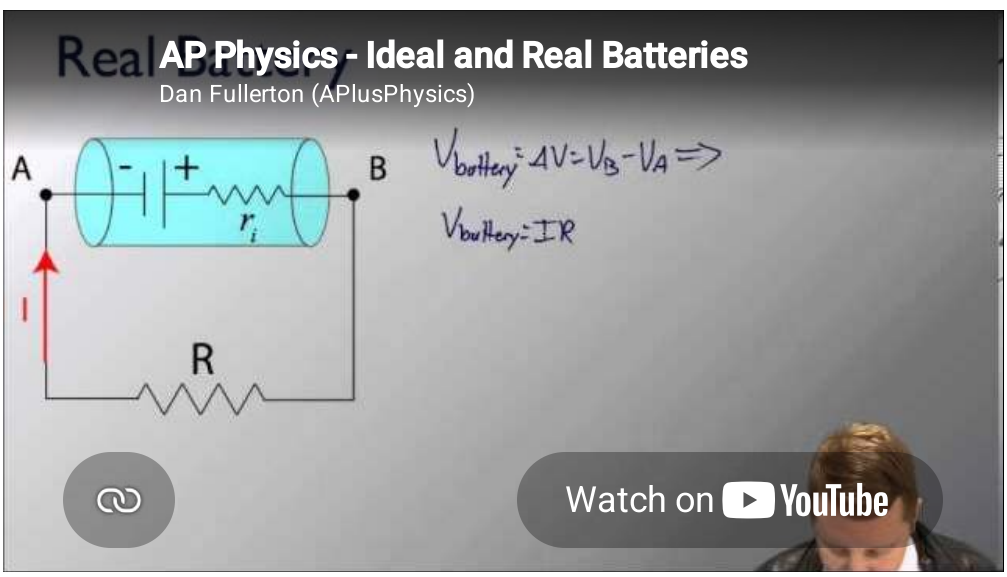
Each half-cell has an electromotive force (or emf), determined by its ability to drive electric current from the interior to the exterior of the cell. The net emf of the cell is the difference between the emfs of its half-cells, or the difference between the reduction potentials of the half-reactions.

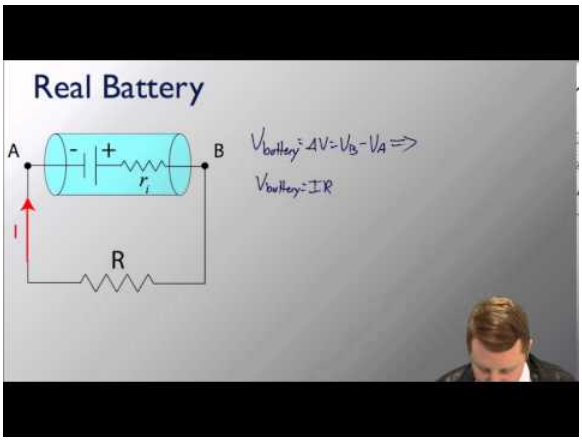
The electrical driving force across the terminals of a cell is known as the terminal voltage (difference) and is measured in volts. When a battery is connected to a circuit, the electrons from the anode travel through the circuit toward the cathode in a direct circuit. The voltage of a battery is synonymous with its electromotive force, or emf. This force is responsible for the flow of charge through the circuit, known as the electric current.

A battery stores electrical potential from the chemical reaction. When it is connected to a circuit, that electric potential is converted to kinetic energy as the electrons travel through the circuit. Electric potential is defined as the potential energy per unit charge (q). The voltage, or potential difference, between two points is defined to be the change in potential energy of a charge q moved from point 1 to point 2, divided by the charge. Rearranged, this mathematical relationship can be described as:

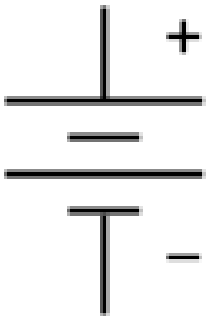
$$\Delta \mathrm{PE} = \mathrm{q}\Delta \mathrm{V} \tag{19.2.1}$$

Voltage is not the same as energy. Voltage is the energy per unit charge. Thus a motorcycle battery and a car battery can both have the same voltage (more precisely, the same potential difference between battery terminals), yet one stores much more energy than the other. The car battery can move more charge than the motorcycle battery, although both are 12V batteries.





Ideal and Real Batteries: A brief introduction to ideal and real batteries for students studying circuits.



Symbol of a Battery in a Circuit Diagram: This is the symbol for a battery in a circuit diagram. It originated as a schematic drawing of the earliest type of battery, a voltaic pile. Notice the positive cathode and negative anode. This orientation is important when drawing circuit diagrams to depict the correct flow of electrons.

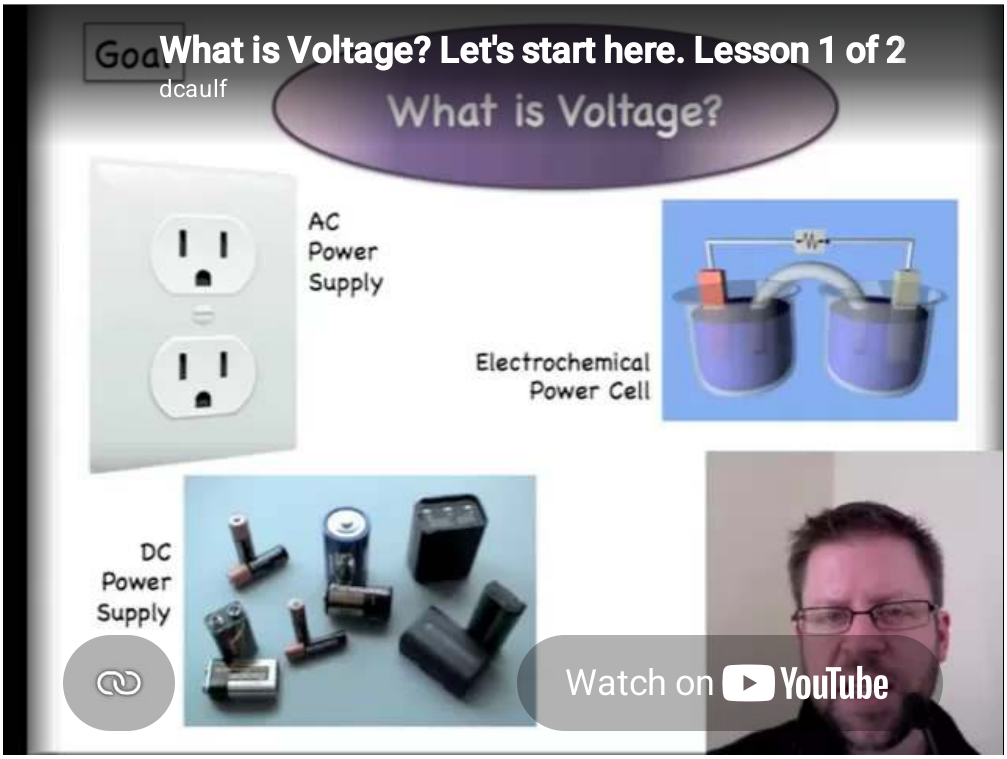
Current and Voltage Measurements in Circuits

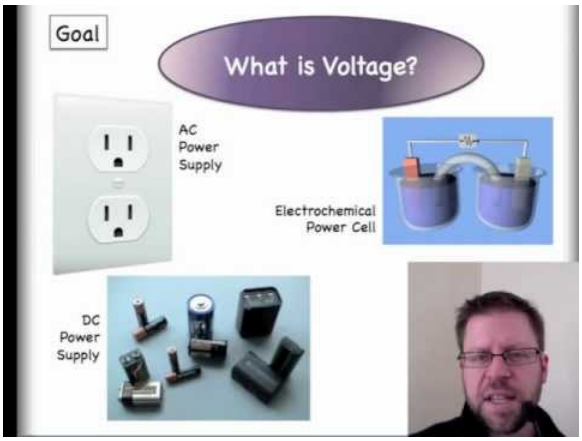
The electrical current is directly proportional to the voltage applied and inversely related to the resistance in a circuit.

learning objectives

- Describe the relationship between the electrical current, voltage, and resistance in a circuit

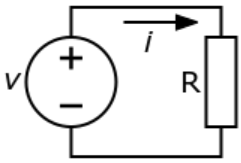
To understand how to measure current and voltage in a circuit, you must also have a general understanding of how a circuit works and how its electrical measurements are related.





What is Voltage?: This video helps with a conceptual understanding of voltage.

An electrical circuit is a type of network that has a closed loop, which provides a return path for the current. A simple circuit consists of a voltage source and a resistor and can be schematically represented as in.



A Simple Circuit: A simple electric circuit made up of a voltage source and a resistor

According to Ohm's law, The electrical current *I*, or movement of charge, that flows through most substances is directly proportional to the voltage *V* applied to it. The electric property that impedes current (crudely similar to friction and air resistance) is called resistance *R*. Collisions of moving charges with atoms and molecules in a substance transfer energy to the substance and limit current. Resistance is inversely proportional to current. Ohm's law can therefore be written as follows:

$$I = \frac{V}{R} \tag{19.2.2}$$

where *I* is the current through the conductor in amperes, *V* is the potential difference measured across the conductor in volts, and *R* is the resistance of the conductor in ohms (Ω). More specifically, Ohm's law states that *R* in this relation is constant, independent of the current. Using this equation, we can calculate the current, voltage, or resistance in a given circuit.

For example, if we had a 1.5V battery that was connected in a closed circuit to a lightbulb with a resistance of 5Ω, what is the current flowing through the circuit? To solve this problem, we would just substitute the given values into Ohm's law: *I* = 1.5V/5Ω; I = 0.3 amperes. If we know the current and the resistance, we can rearrange the Ohm's law equation and solve for voltage *V*:

$$V = IR \tag{19.2.3}$$

A Microscopic View: Drift Speed

The drift velocity is the average velocity that a particle achieves due to an electric field.

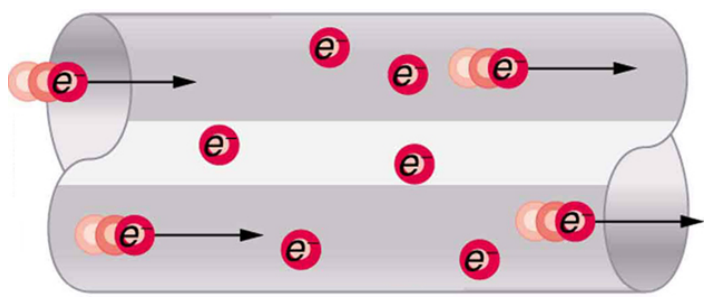
learning objectives

- Relate the drift velocity with the velocity of free charges in conductors

Drift Speed

Electrical signals are known to move very rapidly. Telephone conversations carried by currents in wires cover large distances without noticeable delays. Lights come on as soon as a switch is flicked. Most electrical signals carried by currents travel at speeds on the order of 10^8m/s, a significant fraction of the speed of light. Interestingly, the individual charges that make up the current move much more slowly on average, typically drifting at speeds on the order of 10^{-4}m/s.

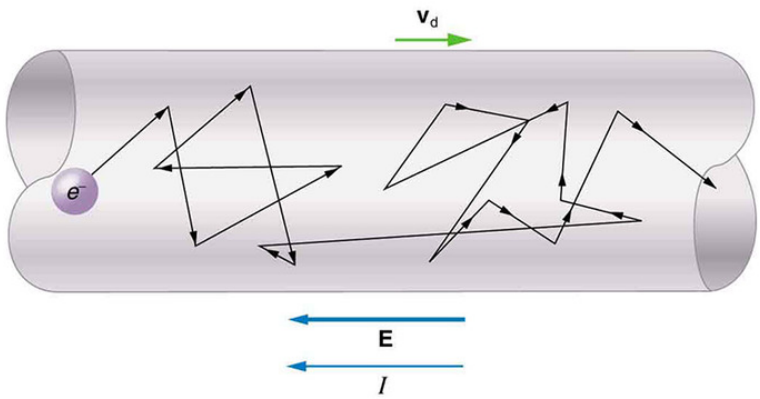
The high speed of electrical signals results from the fact that the force between charges acts rapidly at a distance. Thus, when a free charge is forced into a wire, the incoming charge pushes other charges ahead of it, which in turn push on charges farther down the line. The resulting electrical shock wave moves through the system at nearly the speed of light. To be precise, this rapidly moving signal or shock wave is a rapidly propagating change in the electric field.



Electrons Moving Through a Conductor: When charged particles are forced into this volume of a conductor, an equal number are quickly forced to leave. The repulsion between like charges makes it difficult to increase the number of charges in a volume. Thus, as one charge enters, another leaves almost immediately, carrying the signal rapidly forward.

Drift Velocity

Good conductors have large numbers of free charges in them. In metals, the free charges are free electrons. The distance that an individual electron can move between collisions with atoms or other electrons is quite small. The electron paths thus appear nearly random, like the motion of atoms in a gas. However, there is an electric field in the conductor that causes the electrons to drift in the direction shown (opposite to the field, since they are negative). The drift velocity $v_d$is the average velocity of the free charges after applying the field. The drift velocity is quite small, since there are so many free charges. Given an estimate of the density of free electrons in a conductor (the number of electrons per unit volume), it is possible to calculate the drift velocity for a given current. The larger the density, the lower the velocity required for a given current.



Drift Speed: Free electrons moving in a conductor make many collisions with other electrons and atoms. The path of one electron is shown. The average velocity of the free charges is called the drift velocity and is in the direction opposite to the electric field for electrons. The collisions normally transfer energy to the conductor, requiring a constant supply of energy to maintain a steady current.

It is possible to obtain an expression for the relationship between the current and drift velocity by considering the number of free charges in a segment of wire. *The number of free charges per unit volume* is given the symbol *n* and depends on the material. *Ax* is the volume of a segment, so that the number of free charges in it is *nAx*. The charge *ΔQ* in this segment is thus *qnAx*, where *q* is the amount of charge on each carrier. (Recall that for electrons, *q* is 1.60×10−19C.) The current is the charge moved per unit time. Thus, if all the original charges move out of this segment in time t, the current is:

$$\mathrm{I} = \frac{\Delta \mathrm{Q}}{\Delta \mathrm{t}} = \mathrm{qnA}\frac{\mathrm{x}}{\Delta \mathrm{t}} \tag{19.2.4}$$

Notably, x/Δt is the magnitude of the drift velocity v_d, since the charges move an average distance *x* in a time t. Rearranging terms gives: $I = qnAv_d$, where *I* is the current through a wire of cross-sectional area *A* made of a material with a free charge density *n*. The carriers of the current each have charges *q* and move with a drift velocity of magnitude v_d.

Current density is the electric current per unit area of cross-section. It has units of Amperes per square meter.

Key Points

- A battery stores electrical potential from the chemical reaction. When it is connected to a circuit, that electric potential is converted to kinetic energy as the electrons travel through the circuit.
- The voltage or potential difference between two points is defined to be the change in potential energy of a charge q moved from point 1 to point 2, divided by the charge.
- The voltage of a battery is synonymous with its electromotive force, or emf. This force is responsible for the flow of charge through the circuit, known as the electric current.
- A simple circuit consists of a voltage source and a resistor.
- Ohm ‘s law gives the relationship between current *I*, voltage *V*, and resistance *R* in a simple circuit: $I = V/R$.
- The SI unit for measuring the rate of flow of electric charge is the ampere, which is equal to a charge flowing through some surface at the rate of one coulomb per second.
- There is an electric field in conductors that causes electrons to drift in the direction opposite to the field. The drift velocity is the average velocity of these free charges.
- The expression for the relationship between the current and drift velocity can be obtained by considering the number of free charges in a segment of wire.
- $I = qnAv$ relates the drift velocity to the current, where *I* is the current through a wire of cross-sectional area *A* made of a material with a free charge density *n*. The carriers of the current each have a charge *q* and move with a drift velocity of magnitude *v*.

Key Terms

- **battery**: A device that produces electricity by a chemical reaction between two substances.
- **current**: The time rate of flow of electric charge.
- **voltage**: The amount of electrostatic potential between two points in space.

- **electrical current**: the movement of charge through a circuit
- **ohm**: in the International System of Units, the derived unit of electrical resistance; the electrical resistance of a device across which a potential difference of one volt causes a current of one ampere; symbol: Ω
- **ampere**: A unit of electrical current; the standard base unit in the International System of Units. Abbreviation: amp. Symbol: A.
- **drift velocity**: The average velocity of the free charges in a conductor.

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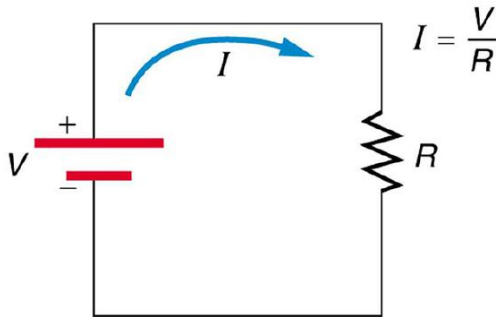
19.3: Resistance and Resistors

- Contrast shape of current-voltage plots for ohmic and non-ohmic circuits

Ohm's Law

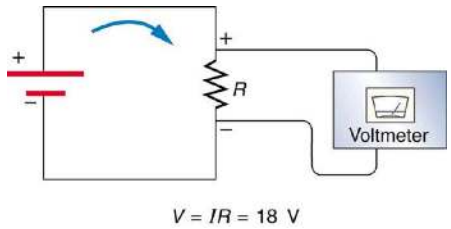
What drives current? We can think of various devices—such as batteries, generators, wall outlets, and so on—which are necessary to maintain a current. All such devices create a potential difference and are loosely referred to as voltage sources. When a voltage source is connected to a conductor, it applies a potential difference V that creates an electric field. The electric field, in turn, exerts force on charges, causing current. The current that flows through most substances is directly proportional to the voltage V applied to it. The German physicist Georg Simon Ohm (1787-1854) was the first to experimentally demonstrate that the current in a metal wire is directly proportional to the voltage applied:\ $mathrmI \propto \mathrm{V}$.

This important relationship is known as Ohm's law. It can be viewed as a cause-and-effect relationship, with voltage the cause and current the effect. This is an empirical law like that for friction—an experimentally observed phenomenon. Such a linear relationship doesn't always occur. Recall that while voltage drives current, resistance impedes it. Collisions of moving charges with atoms and molecules in a substance transfer energy to the substance and limit current. The current is therefore inversely proportional to the resistance: $\mathrm{I} \propto \frac{1}{\mathrm{R}}$.



Simple Circuit: A simple electric circuit in which a closed path for current to flow is supplied by conductors (usually metal wires) connecting a load to the terminals of a battery, represented by the red parallel lines. The zigzag symbol represents the single resistor and includes any resistance in the connections to the voltage source.

The unit for resistance is the ohm where 1Ω = 1 V/A. We can combine the two relations above to obtain I = V/R. This relationship is also called Ohm's law. In this form Ohm's law really defines resistance for certain materials. Ohm's law (like Hooke's law) is not universally valid. The many substances for which Ohm's law holds are called ohmic. These include good conductors like copper and aluminum, and some poor conductors under certain circumstances. Ohmic materials have a resistance R that is independent of voltage V and current I. An object that has simple resistance is called a resistor, even if its resistance is small.

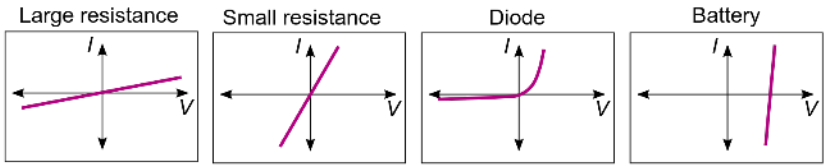


Voltage Drop: The voltage drop across a resistor in a simple circuit equals the voltage output of the battery.

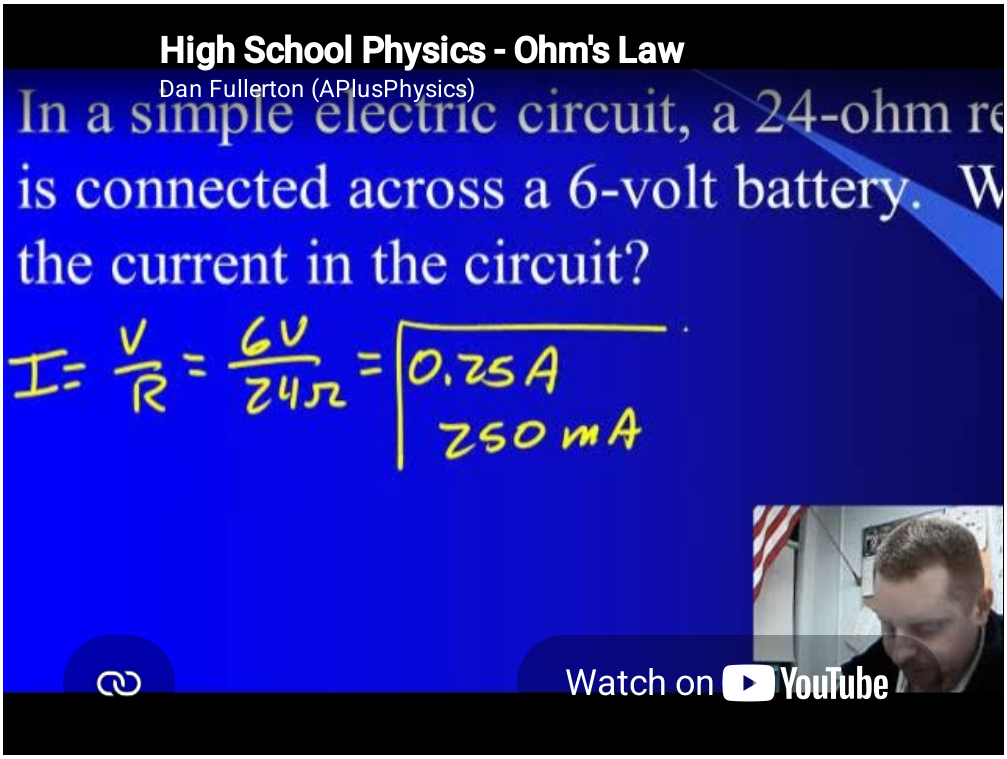
Additional insight is gained by solving I=V/R for V, yielding V=IR. This expression for V can be interpreted as the voltage drop across a resistor produced by the flow of current I. The phrase IR drop is often used for this voltage. If voltage is measured at various points in a circuit, it will be seen to increase at the voltage source and decrease at the resistor. Voltage is similar to fluid pressure. The voltage source is like a pump, creating a pressure difference, causing current—the flow of charge. The resistor is like a pipe that reduces pressure and limits flow because of its resistance. Conservation of energy has important consequences here. The voltage source supplies energy (causing an electric field and a current), and the resistor converts it to another form (such as thermal energy). In a simple circuit (one with a single simple resistor), the voltage supplied by the source equals the voltage drop across the

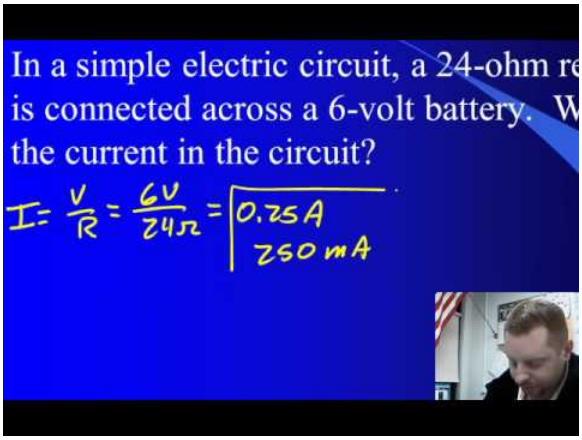
resistor, since E=qΔV, and the same q flows through each. Thus, the energy supplied by the voltage source and the energy converted by the resistor are equal.

In a true ohmic device, the same value of resistance will be calculated from R = V/I regardless of the value of the applied voltage V. That is, the ratio of V/I is constant, and when current is plotted as a function of voltage the curve is linear (a straight line). If voltage is forced to some value V, then that voltage V divided by measured current I will equal R. Or if the current is forced to some value I, then the measured voltage V divided by that current I is also R. We visualize the plot of I versus V as a straight line. There are, however, components of electrical circuits which do not obey Ohm's law; that is, their relationship between current and voltage (their I–V curve) is nonlinear (or non-ohmic). An example is the p-n junction diode.



Current-Voltage Curves: The I–V curves of four devices: two resistors, a diode, and a battery. The two resistors follow Ohm's law: The plot is a straight line through the origin. The other two devices do not follow Ohm's law.





Ohm's Law: A brief overview of Ohm's Law.

Temperature and Superconductivity

Superconductivity is a phenomenon of zero electrical resistance and expulsion of magnetic fields in certain materials below a critical temp.

learning objectives

- Describe behaviors of a superconductor below a critical temperature and in a weak external magnetic field

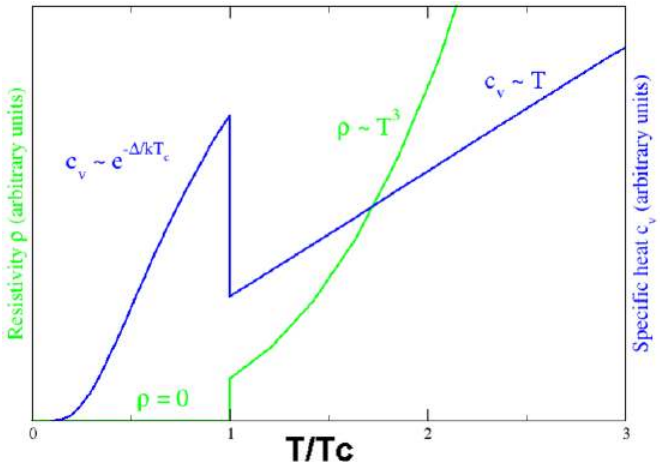
Superconductivity is a phenomenon of exactly zero electrical resistance and expulsion of magnetic fields occurring in certain materials when cooled below a characteristic critical temperature. It was discovered by Heike Kamerlingh Onnes (shown in) on April 8, 1911 in Leiden.

Heike Kamerlingh Onnes: Heike Kamerlingh Onnes (1853-1926).

Most of the physical properties of superconductors vary from material to material, such as the heat capacity and the critical temperature, critical field, and critical current density at which superconductivity is destroyed. On the other hand, there is a class of properties independent of the underlying material. For instance, all superconductors have exactly zero resistivity to low applied currents when there is no magnetic field present or if the applied field does not exceed a critical value. The existence of these "universal" properties implies that superconductivity is a thermodynamic phase, and thus possesses certain distinguishing properties that are largely independent of microscopic details.

In superconducting materials, the characteristics of superconductivity appear when the temperature T is lowered below a critical temperature T_c. The onset of superconductivity is accompanied by abrupt changes in various physical properties—the hallmark of a phase transition. For example, the electronic heat capacity is proportional to the temperature in the normal (non-superconducting) regime. At the superconducting transition, it suffers a discontinuous jump and thereafter ceases to be linear, as illustrated in.

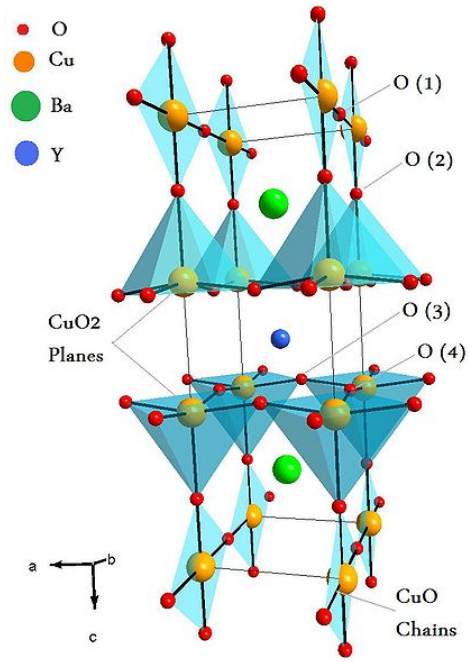
When a superconductor is placed in a weak external magnetic field H, and cooled below its transition temperature, the magnetic field is ejected. The Meissner effect does not cause the field to be completely ejected. Rather, the field penetrates the superconductor to a very small distance (characterized by a parameter λ), called the London penetration depth. It decays exponentially to zero within the bulk of the material. The Meissner effect is a defining characteristic of superconductivity. For most superconductors, the London penetration depth is on the order of 100 nm.



Superconducting phase transition: Behavior of heat capacity (cv, blue) and resistivity (ρ, green) at the superconducting phase transition.

Superconductors are also able to maintain a current with no applied voltage whatsoever—a property exploited in superconducting electromagnets such as those found in MRI machines. Experiments have demonstrated that currents in superconducting coils can persist for years without any measurable degradation. Experimental evidence points to a current lifetime of at least 100,000 years. Theoretical estimates for the lifetime of a persistent current can exceed the estimated lifetime of the universe, depending on the wire geometry and the temperature.

The value of this critical temperature varies from material to material. Usually, conventional superconductors have critical temperatures ranging from around 20 K to less than 1 K. Solid mercury, for example, has a critical temperature of 4.2 K. As of 2009, the highest critical temperature found for a conventional superconductor is 39 K for magnesium diboride (MgB_2), although this material's exotic properties cause some doubt about accurately classifying it as a "conventional" superconductor. High-temperature superconductors can have much higher critical temperatures. For example, $YBa_2Cu_3O_7$, one of the first cuprate superconductors to be discovered, has a critical temperature of 92 K; mercury-based cuprates have been found with critical temperatures in excess of 130 K. It is of note that the chemical composition and crystal structure of superconducting materials can be quite complex, as seen in.



Unit Cell of YBaCuO superconductor: Unit Cell of YBaCuO superconductor. Atoms are indicated with different colors.

Resistance and Resistivity

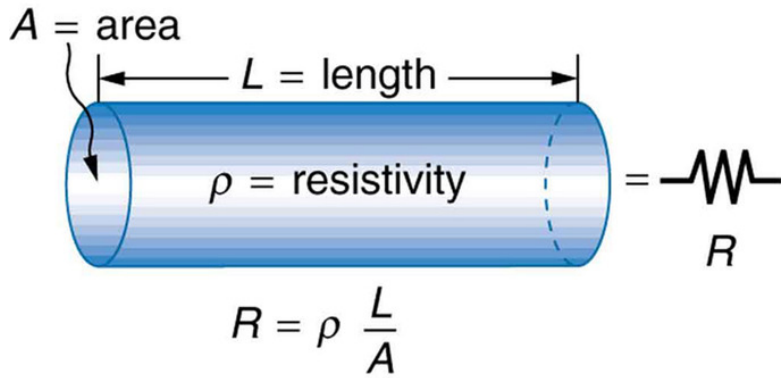
Resistance and resistivity describe the extent to which an object or material impedes the flow of electric current.

learning objectives

- Identify properties of the material that are described by the resistance and resistivity

Resistance and Resistivity

Resistance is the electric property that impedes a current. A current flowing through a wire (or resistor) is like water flowing through a pipe, and the voltage drop across the wire is like the pressure drop which pushes water through the pipe. Resistance is proportional to how much pressure is required to achieve a given flow, while conductance is proportional to how much flow occurs for a given pressure. Conductance and resistance are reciprocals. The resistance of an object depends on its shape and the material of which it is composed. The cylindrical resistor is easy to analyze, and by so doing we can gain insight into the resistance of more complicated shapes. As you might expect, the cylinder's electric resistance R is directly proportional to its length L, similar to the resistance of a pipe to fluid flow. The longer the cylinder, the more collisions charges will make with its atoms. The greater the diameter of the cylinder, the more current it can carry (again, similar to the flow of fluid through a pipe). In fact, R is inversely proportional to the cylinder's cross-sectional area A.



Cylindrical Resistor: A uniform cylinder of length L and cross-sectional area A. Its resistance to the flow of current is similar to the resistance posed by a pipe to fluid flow. The longer the cylinder, the greater its resistance. The larger its cross-sectional area A, the smaller its resistance.

As mentioned, for a given shape, the resistance depends on the material of which the object is composed. Different materials offer different resistance to the flow of charge. We define the resistivity ρ of a substance so that theresistanceR of an object is directly proportional to ρ. Resistivity ρ is an *intrinsic* property of a material, independent of its shape or size. In contrast, the resistance R is an extrinsic property that does depend on the size an shape of the resistor. (A similar intrinsic/extrinsic relation exists between heat capacity C and the specific heat c). Recall that an object whose resistance is proportional to the voltage and current is known as a resistor.

Typical Resistor: A typical axial-lead resistor.

What determines resistivity? The resistivity of different materials varies by an enormous amount. For example, the conductivity of teflon is about 1030 times lower than the conductivity of copper. Why is there such a difference? Loosely speaking, a metal has large numbers of "delocalized" electrons that are not stuck in any one place, but free to move across large distances, whereas in an insulator (like teflon), each electron is tightly bound to a single atom, and a great force is required to pull it away. Likewise, resistors range over many orders of magnitude. Some ceramic insulators, such as those used to support power lines, have resistances of $10^{12}\,\Omega$ or more. A dry person may have a hand-to-foot resistance of $10^{5}\,\Omega$, whereas the resistance of the human heart is about $10^{3}\,\Omega$. A meter-long piece of large-diameter copper wire may have a resistance of $10^{-5}\,\Omega$, and superconductors have no resistance at all (they are non-ohmic). The potential difference (voltage) seen across the network is the sum of those voltages, thus the total resistance (the series equivalent resistance) can be found as the sum of those resistances:

$$\mathrm{R_{eq}} = \mathrm{R_1} + \mathrm{R_2} + \cdots + \mathrm{R_N} \tag{19.3.1}$$

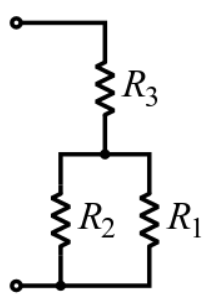
As a special case, the resistance of N resistors connected in series, each of the same resistance R, is given by NR.Resistors in a parallel configuration are each subject to the same potential difference (voltage), however the currents through them add. Thus the equivalent resistance (Req) of the network can be computed:

$$\frac{1}{\mathrm{Req}} = \frac{1}{\mathrm{R_1}} + \frac{1}{\mathrm{R_2}} + \cdots + \frac{1}{\mathrm{RN}} \tag{19.3.2}$$

The parallel equivalent resistance can be represented in equations by two vertical lines "‖" (as in geometry) as a simplified notation. Occasionally two slashes "//" are used instead of "‖", in case the keyboard or font lacks the vertical line symbol. For the case of two resistors in parallel, this can be calculated using:

$$\mathrm{R_{eq}} = \mathrm{R_1} \| \mathrm{R_2} = \frac{\mathrm{R_1 R_2}}{\mathrm{R_1} + \mathrm{R_2}} \tag{19.3.3}$$

As a special case, the resistance of N resistors connected in parallel, each of the same resistance R, is given by R/N. A resistor network that is a combination of parallel and series connections can be broken up into smaller parts that are either one or the other, such as is shown in.



Resistor Network: In this combination circuit, the circuit can be broken up into a series component and a parallel component.

However, some complex networks of resistors cannot be resolved in this manner. These require a more sophisticated circuit analysis. One practical application of these relationships is that a non-standard value of resistance can generally be synthesized by connecting a number of standard values in series or parallel. This can also be used to obtain a resistance with a higher power rating than that of the individual resistors used. In the special case of N identical resistors all connected in series or all connected in parallel, the power rating of the individual resistors is thereby multiplied by N.

Resistance, Resistors, and Resistivity: A brief overview of resistance, resistors, and resistivity.

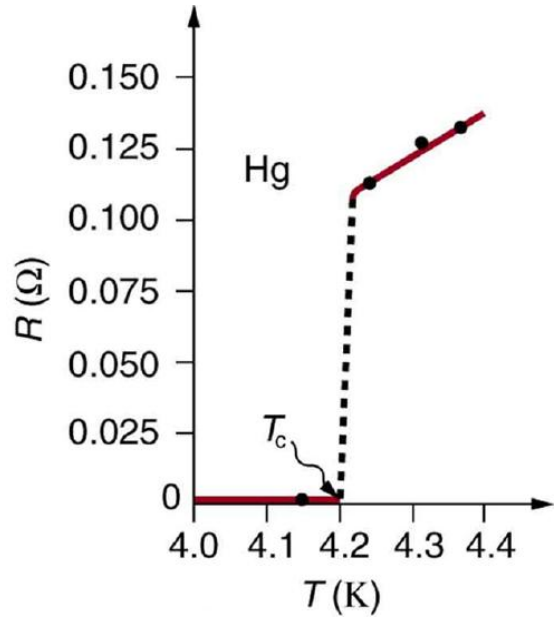
Dependence of Resistance on Temperature

Resistivity and resistance depend on temperature with the dependence being linear for small temperature changes and nonlinear for large.

learning objectives

- Compare temperature dependence of resistivity and resistance for large and small temperature changes

The resistivity of all materials depends on temperature. Some materials can become superconductors (zero resistivity) at very low temperatures (see). Conversely, the resistivity of conductors increases with increasing temperature. Since the atoms vibrate more rapidly and over larger distances at higher temperatures, the electrons moving through a metal, for example, create more collisions, effectively making the resistivity higher. Over relatively small temperature changes (about 100ºC or less), resistivity ρ varies with temperature change ΔT as expressed in the following equation:



Resistance of a sample of mercury: The resistance of a sample of mercury is zero at very low temperatures—it is a superconductor up to about 4.2 K. Above that critical temperature, its resistance makes a sudden jump and then increases nearly linearly with temperature.

$$\mathrm{p} = \mathrm{p}_0(1 + \alpha\Delta\mathrm{T}) \tag{19.3.4}$$

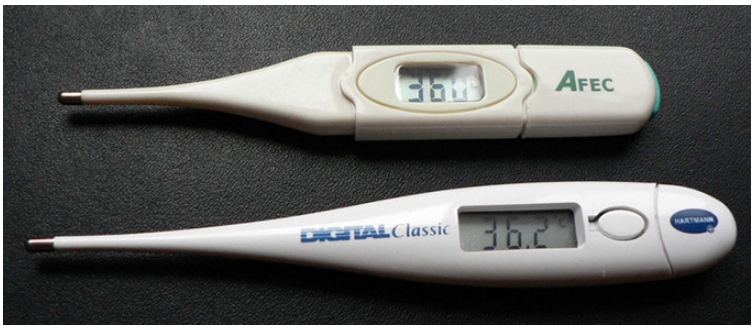
where ρ_0 is the original resistivity and α is the temperature coefficient of resistivity. For larger temperature changes, α may vary, or a nonlinear equation may be needed to find ρ. For this reason it is usual to specify a suffix for the temperature at which the substance was measured (such as α_{15}) and the relationship only holds in a range of temperatures around the reference. Note that α is positive for metals, meaning their resistivity increases with temperature. The temperature coefficient is typically $+3\times10^{-3}\ \mathrm{K}^{-1}$ to $+6\times10^{-3}\ \mathrm{K}^{-1}$ for metals near room temperature. Some alloys have been developed specifically to have a small temperature dependence. Manganin (made of copper, manganese and nickel), for example, has α close to zero, so its resistivity varies only slightly with temperature. This is useful for making a temperature-independent resistance standard, for example.

Note also that α is negative for semiconductors, meaning that their resistivity decreases with increasing temperature. They become better conductors at higher temperature because increased thermal agitation increases the number of free charges available to carry current. This property of decreasing ρ with temperature is also related to the type and amount of impurities present in the semiconductors.

The resistance of an object also depends on temperature, since R_0 is directly proportional to ρ. For a cylinder we know R=ρL/A, so if L and A do not change greatly with temperature, R will have the same temperature dependence as ρ. (Examination of the coefficients of linear expansion shows them to be about two orders of magnitude less than typical temperature coefficients of resistivity, and so the effect of temperature on L and A is about two orders of magnitude less than on ρ.) Thus,

$$\mathrm{R} = \mathrm{R}_0(1 + \alpha\Delta\mathrm{T}) \tag{19.3.5}$$

is the temperature dependence of the resistance of an object, where R_0 is the original resistance and R is the resistance after a temperature change T. Numerous thermometers are based on the effect of temperature on resistance (see). One of the most common is the thermistor, a semiconductor crystal with a strong temperature dependence, the resistance of which is measured to obtain its temperature. The device is small so it quickly comes into thermal equilibrium with the part of a person it touches.



Thermometers: These familiar thermometers are based on the automated measurement of a thermistor's temperature-dependent resistance.

Key Points

- Voltage drives current while resistance impedes it.
- Ohm 's Law refers to the proportion relation between voltage and current. It also applies to the specific equation V=IR, which is valid when considering circuits that contain simple resistors (whose resistance is independent of voltage and current).
- Circuits or components that obey the relation V=IR are known as ohmic and have current-voltage plots that are linear and pass through the origin.
- There are components and circuits that are non-ohmic; their I-V plots are not linear and/or don't pass through the origin.
- Superconductivity is a Superconductivity is a thermodynamic phase and possesses certain distinguishing properties which are largely independent of microscopic details.
- In superconducting materials, the characteristics of superconductivity appear when the temperature is lowered below a critical temperature. The onset of superconductivity is accompanied by abrupt changes in various physical properties.
- When a superconductor is placed in a weak external magnetic field H, and cooled below its transition temperature, the magnetic field is ejected.
- Superconductors are able to maintain a current with no applied voltage.
- The resistance of an object (i.e., a resistor) depends on its shape and the material of which it is composed.
- Resistivity ρ is an intrinsic property of a material and directly proportional to the total resistance R, an extrinsic quantity that depends on the length and cross-sectional area of a resistor.
- The resistivity of different materials varies by an enormous amount. Likewise, resistors range over many orders of magnitude.
- Resistors are arranged in series or parallel configurations. The equivalent resistance of a network of resistors in series is the sum of all the resistance. The inverse of the equivalent resistance of a network of resistors in parallel is the sum of the inverse of the resistance of each resistor.
- Over temperature changes of 100ºC or less, resistivity (ρ) varies with temperature change ΔT as: p=p0(1+αΔT)p=p0(1+αΔT) where ρ_0 is the original resistivity and α is the temperature coefficient of resistivity.
- For large temperature changes, nonlinear variation of resistivity with temperature is observed.
- The resistance of an object demonstrates similar temperature dependence as resistivity since resistance is directly proportional to resistivity.

Key Terms

- **simple circuit**: A circuit with a single voltage source and a single resistor.
- **ohmic**: That which obeys Ohm's law.
- **high-temperature superconductors**: Materials that behave as superconductors at unusually high temperatures (above about 30 K).
- **critical temperature**: In superconducting materials, the characteristics of superconductivity appears at (and continues below) this temperature.
- **superconductivity**: The property of a material whereby it has no resistance to the flow of an electric current.
- **series equivalent resistance**: The resistance of a network of resistors arranged such that the voltage across the network is the sum of the voltage across each resistor. In this case, the equivalent resistance is the sum of the resistance of all the resistors in the network.

- **parallel equivalent resistance**: the resistance of a network such that each resistor is subject to the same potential difference (voltage), so that the currents through them add. In this case the inverse of the equivalent resistance is equal to the sum of the inverse resistance of all the resistors in the network.
- **resistivity**: In general, the resistance to electric current of a material; in particular, the degree to which a material resists the flow of electricity.
- **temperature coefficient of resistivity**: An empirical quantity, denoted by α, which describes the change in resistance or resistivity of a material with temperature.
- **semiconductor**: A substance with electrical properties intermediate between a good conductor and a good insulator.

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19.4: Electric Power and Energy

learning objectives

- Formulate the relationship between the energy usage and the electric power

In many cases it is necessary to calculate the energy usage by an electric device or a collection of devices, such as in a home. For example, we (or the electric power utility) may want to calculate the amount of money owed for electricity consumed. In another case, we might need to determine the energy necessary to power a component or apparatus for a given period of time. The last distinction is crucial – the energy used by a circuit or component is *the time integral of the electric power*.

Power

Recall that power is the rate at which work is done – or the rate at which energy is consumed or produced – and is measured in watts (W). The electric power in watts produced by an electric current I consisting of a charge of Q coulombs every t seconds passing through an electric potential (voltage) difference of V is $\mathrm{P} = \frac{\mathrm{QV}}{\mathrm{t}} = \mathrm{IV}$, where Q is electric charge in coulombs, t is time in seconds, I is electric current in amperes, and V is electric potential or voltage in volts.

In resistive circuits where Ohm 's Law applies, the power can be expressed as $\mathrm{P} = \mathrm{I}^2\mathrm{R} = \frac{\mathrm{V}^2}{\mathrm{R}}$, where R is the electrical resistance. Power isn't necessarily constant; it may vary over time. The general expression for electric power is then

$$\mathrm{P(t)} = \mathrm{I(t)V(t)} \tag{19.4.1}$$

where the current I and voltage V may be time variable.

Energy

In any given time interval, the energy consumed (or provided, depending on your perspective) is given by $\mathrm{PE} = \mathrm{qV}$, where E is the electric energy, V is the voltage, and q is the amount of charge moved in the time interval under consideration. We can relate the total energy consumed to the power by integrating over time:. Positive energy corresponds to consumed energy and negative energy corresponds to energy production. Note that a circuit element having a power profile that is both positive and negative over some time interval could consume or produce energy according to the sign of the integral of power. If the power is constant over the time interval then the energy can be expressed simply as:

$$\mathrm{E} = \mathrm{Pt} \tag{19.4.2}$$

Units of Energy Usage

We are of course very familiar with the SI unit of energy, the joule. However, typically, residential energy bills state household energy consumption in kilowatt-hours (kWh). Additionally, this unit is often seen elsewhere when the energy usage of power consuming devices, structures, or jurisdictions is under consideration. We can parse out the conversion from kilowatt-hours to joules in this way: 1 W = 1 J/s and a kilowatt is 1000 W while one hour is 3,600 seconds, so 1 kWh is (1000 J/s)(3600 s)=3,600,000 joules. This is the scale of American home energy usage, which is on the order of hundreds of kilowatt-hours per month.

Reducing Energy Usage

The electrical energy (E) used can be reduced either by reducing the time of use or by reducing the power consumption of that appliance or fixture. This will not only reduce the cost, but it will also result in a reduced impact on the environment. Improvements to lighting are some of the fastest ways to reduce the electrical energy used in a home or business. About 20% of a home's use of energy goes to lighting, while the number for commercial establishments is closer to 40%. Fluorescent lights are about four times more efficient than incandescent lights—this is true for both the long tubes and the compact fluorescent lights (CFL). Thus, a 60-W incandescent bulb can be replaced by a 15-W CFL, which has the same brightness and color. CFLs have a bent tube inside a globe or a spiral-shaped tube, all connected to a standard screw-in base that fits standard incandescent light sockets. (Original problems with color, flicker, shape, and high initial investment for CFLs have been addressed in recent years.) The heat transfer from these CFLs is less, and they last up to 10 times longer.

Compact Fluorescent Light (CFL): CFLs are much more efficient than incandescent bulbs and so consume much less energy for the intensity light produces.

Key Points

- Recall that power is the rate work is done, or the rate at which energy is consumed or produced. In terms of current and voltage it is P=IV.
- The energy used is the amount of charge q moved through voltage V in a time interval t. It is equal to the integral of power over time.
- A common unit used to describe energy usage is the kilowatt-hour, the energy of 1000 W acting over one hour.

Key Terms

- **kilowatt-hour**: a unit of electrical energy equal to that done by one kilowatt acting for one hour; equal to 3.6 mega-joules. Symbol: kWh.

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19.5: Alternating Currents

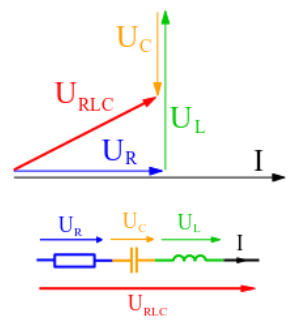
learning objectives

- Discuss applications of a phase vector

Phasors

Complex numbers play an important role in physics. Usually, complex numbers are written in terms of their real part plus the imaginary part. For example, $\mathrm{a}+\mathrm{bi}$ where a and b are real numbers, and ii signals the imaginary part. However, it is often practical to write complex numbers in the form of an exponential called a phasor.

In physics, a phase vector, or phasor, is a representation of a sinusoidal function whose amplitude (A), frequency (ω), and phase (θ) are time-invariant, as diagramed in. Phasors separate the dependencies on A, ω, and θ into three independent factors. This can be particularly useful because the frequency factor (which includes the time-dependence of the sinusoid) is often common to all the components of a linear combination of sinusoids. In those situations, phasors allow this common feature to be factored out, leaving just the A and θ features. The result is that trigonometry reduces to algebra, and linear differential equations become algebraic ones. The term phasor therefore often refers to just those two factors.



***Phasor Diagram**: An example of series RLC circuit and respective phasor diagram for a specific ω. Electrical engineers, electronics engineers, electronic engineering technicians and aircraft engineers all use phasor diagrams to visualize complex constants and variables (phasors). Like vectors, arrows drawn on graph paper or computer displays represent phasors.*

Phasors are often used in electrical systems when considering voltages and currents that vary sinusoidally in time, such as in RLC circuits.

Definition

Sinusoids can be represented mathematically as the sum of two complex-valued functions:

$$\mathrm{A} \cdot \cos(\omega t+\theta)=\mathrm{A} \cdot \frac{\mathrm{e}^{\mathrm{i}(\omega t+\theta)}+\mathrm{e}^{-\mathrm{i}(\omega t+\theta)}}{2} \tag{19.5.1}$$

or as the real part of one of the functions:

$$\mathrm{A} \cdot \cos(\omega t+\theta)=\operatorname{Re}\left\{\mathrm{A} \cdot \mathrm{e}^{\mathrm{i}(\omega t+\theta)}\right\}=\operatorname{Re}\left\{\mathrm{A} \mathrm{e}^{\mathrm{i} \theta} \cdot \mathrm{e}^{\mathrm{i} \omega t}\right\} \tag{19.5.2}$$

As indicated above, phasor can refer to either Aeiθ·eiωtAeiθ·eiωt or just the complex constant, AeiθAeiθ. In the latter case, it is understood to be a shorthand notation, encoding the amplitude and phase of an underlying sinusoid.

Phasor Representation of Signals

There are two key ideas behind the phasor representation of a signal:

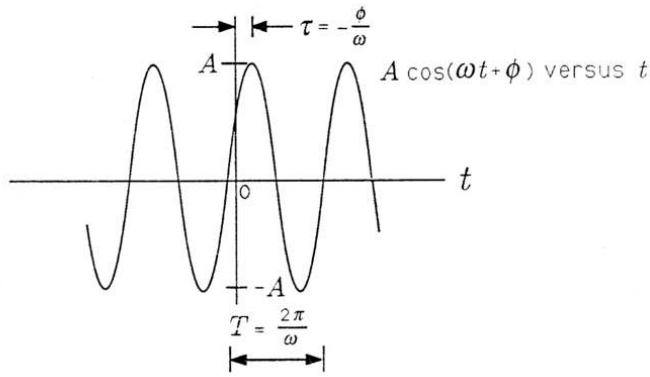
1. a real, time-varying signal may be represented by a complex, time-varying signal; and
2. a complex, time-varying signal may be represented as the product of a complex number that is independent of time and a complex signal that is dependent on time.

The signal:

$$\mathrm{x}(\mathrm{t})=\mathrm{A} \cos(\omega \mathrm{t}+\theta) \tag{19.5.3}$$

illustrated in the figure below is a cosinusoidal signal with amplitude *A*, frequency, and phase θ. The amplitude *A* characterizes the peak-to-peak swing of *2A*, the angular frequency ω characterizes the period $T=2\pi/\omega$ between negative- to-positive zero crossings (or positive peaks or negative peaks), and the phase θ characterizes the time $\tau=-\theta/\omega$ when the signal reaches its first peak. With so defined, the signal *x(t)* may also be written as

$$\mathrm{x(t)} = \mathrm{Acos(t-}\tau) \tag{19.5.4}$$



Cosinusoidal Signal: A Cosinusoidal Signal.

When τ is positive, then τ is a "time delay" that describes the time (greater than zero) when the first peak is achieved. When τ is negative, then τ is a "time advance" that describes the time (less than zero) when the last peak was achieved. With the substitution $=2\pi/T$ we obtain a third way of writing x(t):

$$\mathrm{x(t)} = \mathrm{Acos}\,\frac{2\pi}{\mathrm{T}}(\mathrm{t}-\boldsymbol{\tau}) \tag{19.5.5}$$

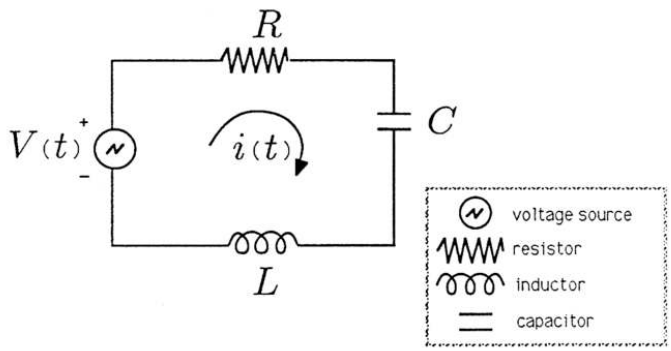
In this form the signal is easy to plot. Simply draw a cosinusoidal wave with amplitude *A* and period *T*; then strike the origin (t=0) so that the signal reaches its peak at τ. In summary, the parameters that determine a cosinusoidal signal have the following units:

- *A*, arbitrary (e.g., volts or meters/sec, depending upon the application)
- ω, in radians /sec (rad/sec)
- *T*, in seconds (sec)
- θ, in radians (rad)
- τ, in seconds (sec)

Sinusoidal Steady State and the Series RLC CircuitPhasors may be used to analyze the behavior of electrical and mechanical systems that have reached a kind of equilibrium called sinusoidal steady state.

In the sinusoidal steady state, every voltage and current (or force and velocity) in a system is sinusoidal with angular frequency ω. However, the amplitudes and phases of these sinusoidal voltages and currents are all different.

For example, the voltage across a resistor might lead the voltage across a capacitor by 90° and lag the voltage across an inductor by 90°. In order to make our application of phasors to electrical systems concrete, we consider the series *RLC* circuit illustrated in. The arrow labeled *i(t)* denotes a current that flows in response to the voltage applied.



Series RLC Circuit: Series RLC Circuit.

We will assume that the voltage source is an audio oscillator that produces the voltage:

$$\mathrm{V(t)} = \mathrm{A}\cos(\omega \mathrm{t} + \theta) \tag{19.5.6}$$

We represent this voltage as the complex signal:

$$\mathrm{V(t)} \leftrightarrow \mathrm{Ae}^{\mathrm{i}\theta} \cdot \mathrm{e}^{\mathrm{i}\omega \mathrm{t}} \tag{19.5.7}$$

and give it the phasor representation,

$$\mathrm{V(t)} \leftrightarrow \mathrm{V}; \mathrm{V} = \mathrm{Ae}^{\mathrm{i}\theta} \tag{19.5.8}$$

We then describe the voltage source by the phasor *V* and remember that we can always compute the actual voltage by multiplying by $e^{i\omega t}$and taking the real part.

Root Mean Square Values

The root mean square (RMS) voltage or current is the time-averaged voltage or current in an AC system.

learning objectives

- Relate the root mean square voltage and current in an alternating circut with the peak voltage and current and the average power

Root Mean Square Values and Alternating Current

Recall that in the case of alternating current (AC) the flow of electric charge periodically reverses direction. Unlike direct current (DC), where the currents and voltages are constant, AC currents and voltages vary over time. Recall that most residential and commercial power sources use AC. It is often the case that we wish to know the *time averaged*current, or voltage. Given the current or voltage as a function of time, we can take the root mean square over time to report the average quantities.

Definition

The root mean square (abbreviated RMS or rms), also known as the quadratic mean, is a statistical measure of the magnitude of a varying quantity. It is especially useful when the function alternates between positive and negative values, e.g., sinusoids.The RMS value of a set of values (or a continuous-time function such as a sinusoid) is the square root of the arithmetic mean of the squares of the original values (or the square of the function). In the case of a set of *n* values $\{x_1,x_2,\ldots,x_n\}$, the RMS value is given by this formula:

$$\mathrm{x_{rms}} = \sqrt{\frac{1}{\mathrm{n}}\left(\mathrm{x_1^2} + \mathrm{x_2^2} + \cdots + \mathrm{x_n^2}\right)} \tag{19.5.9}$$

The corresponding formula for a continuous function *f(t)*defined over the interval $T_1 \le t \le T_2$ is as follows:

$$\mathrm{f_{rms}} = \sqrt{\frac{1}{\mathrm{T_2} - \mathrm{T_1}} \int_{\mathrm{T_1}}^{\mathrm{T_2}} [\mathrm{t(t)}]^2 \mathrm{dt}} \tag{19.5.10}$$

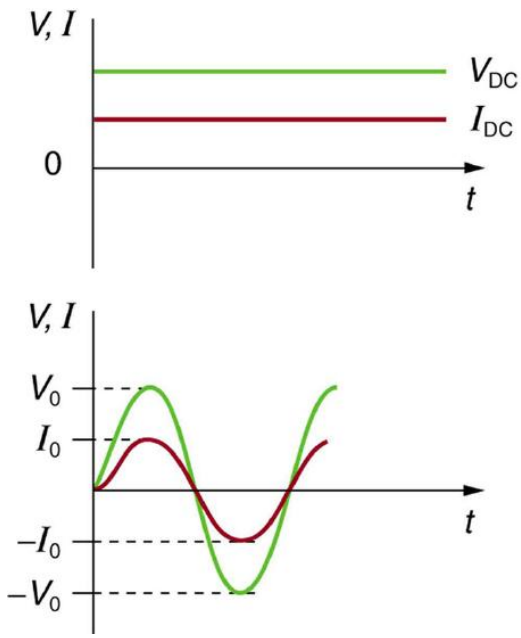
The RMS for a function over all time is below.

$$f_{rms} = \lim_{T\to\infty} \sqrt{\frac{1}{T}\int_0^T [t(t)]^2 dt} \tag{19.5.11}$$

The RMS over all time of a periodic function is equal to the RMS of one period of the function. The RMS value of a continuous function or signal can be approximated by taking the RMS of a series of equally spaced samples.

Application to Voltage and Current

Consider the case of sinusoidally varying voltage:



Sinusoidal Voltage and Current: (a) DC voltage and current are constant in time, once the current is established. (b) A graph of voltage and current versus time for 60-Hz AC power. The voltage and current are sinusoidal and are in phase for a simple resistance circuit. The frequencies and peak voltages of AC sources differ greatly.

$$V = V_0 \sin(2\pi ft) \tag{19.5.12}$$

V is the voltage at time t, V_0 is the peak voltage, and f is the frequency in hertz. For this simple resistance circuit, I=V/R, and so the AC current is as follows:

$$\mathbf{I} = \mathbf{I}_0 \sin(2\pi ft) \tag{19.5.13}$$

Here, I is the current at time t, and I_0=V_0/R is the peak current. Now using the definition above, let's calculate the rms voltage and rms current. First, we have

$$V_{rms} = \sqrt{\frac{1}{T_2 - T_1}} \int_{T_1}^{T_2} [V_0 \sin(\omega t)]^2 \, dt \tag{19.5.14}$$

Here, we have replaced 2πf with ω. Since V_0 is a constant, we can factor it out of the square root, and use a trig identity to replace the squared sine function.

$$V_{rms} = V_0 \sqrt{\frac{1}{T_2 - T_1}} \int_{T_1}^{T_2} \frac{1 - \cos(2\omega t)}{2} dt \tag{19.5.15}$$

Integrating the above, we have:

$$V_{rms} = V_0 \sqrt{\frac{1}{T_2 - T_1} \left[\frac{t}{2} - \frac{\sin(2\omega t)}{4\omega}\right]_{T_1}^{T_2}} \tag{19.5.16}$$

Since the interval is a whole number of complete cycles (per definition of RMS), the terms will cancel out, leaving:

$$\mathrm{V_{rm}} = \mathrm{V_0}\sqrt{\frac{1}{\mathrm{T_2}-\mathrm{T_1}}\left[\frac{\mathrm{t}}{2}\right]\mathrm{T_1}} = \mathrm{V_0}\sqrt{\frac{1}{\mathrm{T_2}-\mathrm{T_1}}\frac{\mathrm{T_2}-\mathrm{T_1}}{2}} \tag{19.5.17}$$

$$= \frac{V_0}{\sqrt{2}} \tag{19.5.18}$$

Similarly, you can find that the RMS current can be expressed fairly simply:

$$\mathrm{I_{rms}} = \mathrm{I_0}/\sqrt{2} \tag{19.5.19}$$

Updated Circuit Equations for AC

Many of the equations we derived for DC current apply equally to AC. If we are concerned with the time averaged result and the relevant variables are expressed as their rms values. For example, Ohm ‘s Law for AC is written as follows:

$$\mathrm{I_{rms}} = \frac{\mathrm{V_{rms}}}{\mathrm{R}} \tag{19.5.20}$$

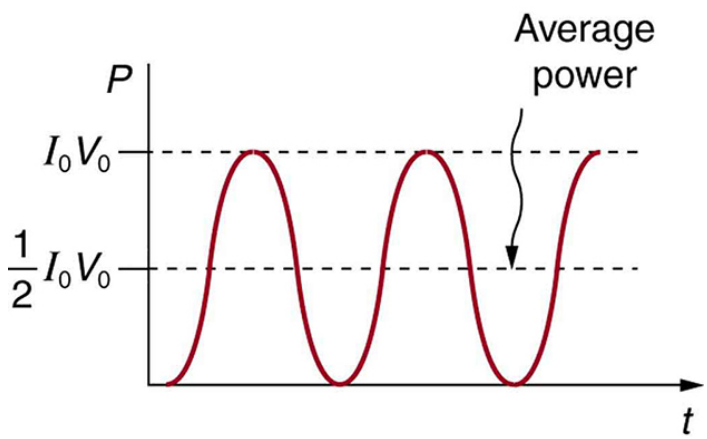
The various expressions for AC power are below:

$$\mathrm{P_{ave}} = \mathrm{I_{rms}V_{rms}} \tag{19.5.21}$$

$$\mathrm{P_{ave}} = \frac{\mathrm{V_{ms}^2}}{\mathrm{R}} \tag{19.5.22}$$

$$\mathrm{P_{ave}} = \mathrm{I_{rms}^2R} \tag{19.5.23}$$

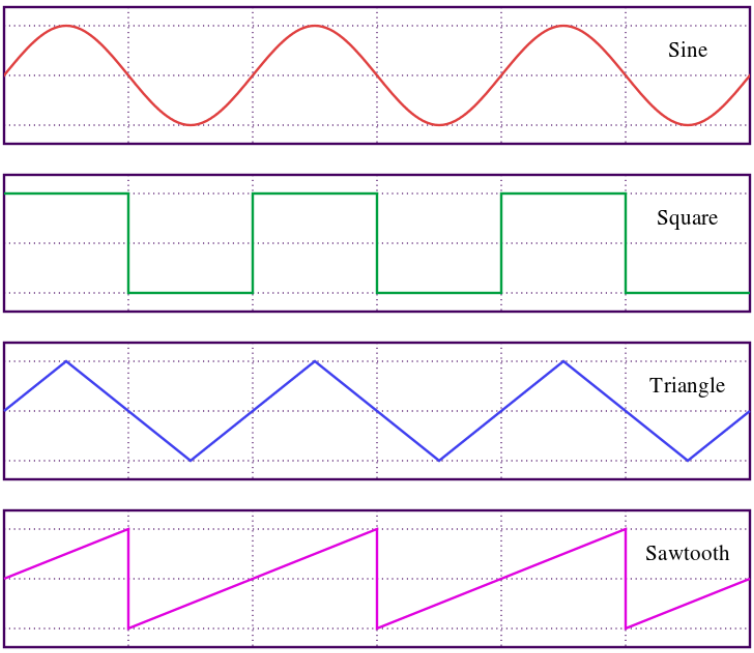
We can see from the above equations that we can express the average power as a function of the peak voltage and current (in the case of sinusoidally varying current and voltage):



Average Power: AC power as a function of time. Since the voltage and current are in phase here, their product is non-negative and fluctuates between zero and I0V0. Average power is (1/2)I0V0.

$$\mathrm{P_{ave}} = \mathrm{I_{rms}}V_{\mathrm{rms}} = \frac{\mathrm{I_0}}{\sqrt{2}}\frac{\mathrm{V_0}}{\sqrt{2}} = \frac{1}{2}\mathrm{V_0I_0} \tag{19.5.24}$$

The RMS values are also useful if the voltage varies by some waveform other than sinusoids, such as with a square, triangular or sawtooth waves.



Waveforms: Sine, square, triangle, and sawtooth waveforms

Safety Precautions in the Household

Electrical safety systems and devices are designed and widely used to reduce the risks of thermal and shock hazards.

learning objectives

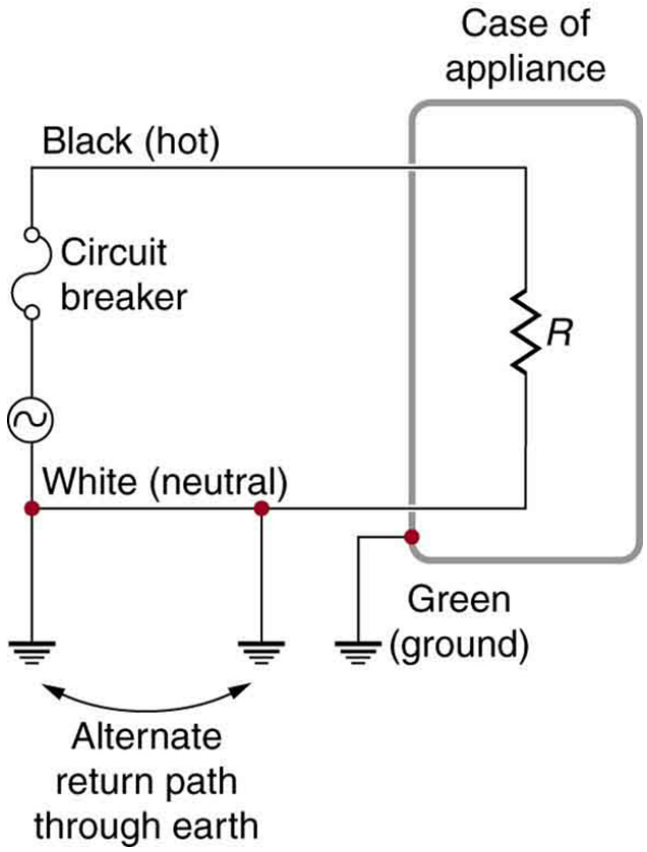
- Identify major risks associated with the electrical circuits and strategies to mitigate those risks

Electrical Safety and Household Appliances

Electricity has two hazards. A thermal hazard occurs in cases of electrical overheating. A shock hazard occurs when an electric current passes through a person. There are many systems and devices that prevent electrical hazards.

AC Circuit Lacking Safety Features: A schematic of a simple AC circuit with a voltage source and a single appliance represented by the resistance R. It lacks safety features.

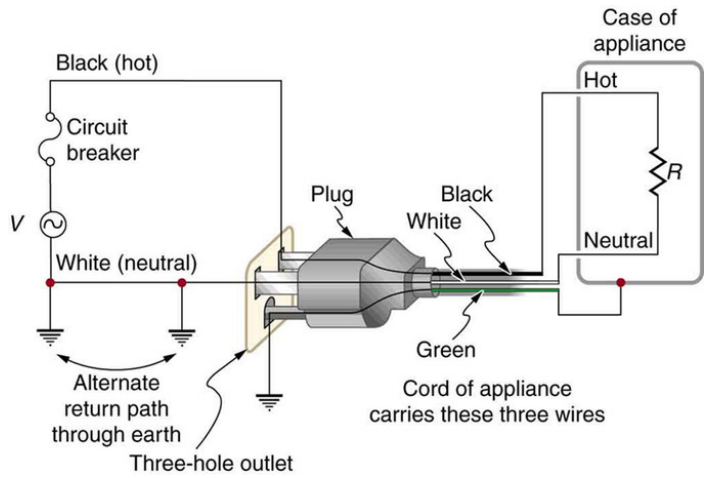
In practice, a simple AC circuit with no safety features is not how power is distributed. Modern household and industrial wiring requires the three-wire system, which has several safety features. The first safety feature is the familiar circuit breaker (or fuse) that prevents thermal overload. Secondly, there is a protective case around the appliance, as with a toaster or refrigerator. The case prevents people from touching exposed wires and coming into electrical contact with the circuit, helping prevent shocks.



Three-Wire System: The three-wire system connects the neutral wire to the earth at the voltage source and the user location. It exists at zero volts and supplies an alternative return path for the current through the earth. The case of the appliance is also grounded to zero volts. A circuit breaker or fuse prevents thermal overload and exists in series on the active (live/hot) wire. Wire insulation colors vary by region. It is essential to check locally to determine which color codes are in use, even if they were followed in one particular installation.

There are three connections to the earth or ground (earth/ground,). An earth/ground connection is a low-resistance path directly to the earth. The two earth/ground connections on the neutral wire force it to exist at zero volts relative to the earth, giving the wire its name. This wire is therefore safe to touch even if its insulation is missing. The neutral wire is the return path for the current to follow in order to complete the circuit.

The two earth/ground connections supply an alternative path through the earth to complete the circuit, since the earth is a good conductor. The earth/ground connection closest to the power source could be at the generating plant, while the other is situated at the user's location. The third earth/ground connection involves the case of the appliance, through the green earth/ground wire, forcing the case to be at zero volts. The live or hot wire (live/hot) supplies the voltage and current to operate the appliance. The three-wire system is connected to an appliance through a three-prong plug.



Three-Prong Plug: The standard three-prong plug can only be inserted one way to ensure the proper function of the three-wire system.

The Three-Prong Plug

The three-wire system replaced the older two-wire system, which lacks an earth/ground wire. Under ordinary circumstances, insulation on the live/hot and neutral wires prevents the case from being situated directly within the circuit, so that the earth/ground wire may seem like double protection. Grounding the case solves more than one problem, however. The simplest problem is worn insulation on the live/hot wire that allows it to contact the case. When lacking an earth/ground connection (some people cut the third prong off the plug because they only have outdated two-hole receptacles), a severe shock is possible. This is particularly dangerous in the kitchen, where a good earth/ground connection is available through water on the floor or a water faucet.

With the earth/ground connection intact, the circuit breaker will trip, thus requiring appliance repair. Some appliances are still sold with two-prong plugs. These appliances, including power tools with impact resistant plastic cases, have nonconducting cases and are called ‘doubly insulated. ‘ Modern two-prong plugs can be inserted into the asymmetric standard outlet in only one way, ensuring the proper connection of live/hot and neutral wires.

Color-Coding

Insulating plastic is color-coded to identify live/hot, neutral, and ground wires, but these codes vary throughout the world. Live/hot wires may be brown, red, black, blue, or grey. Neutral wires may be blue, black, or white. Since the same color may be used for live/hot or neutral wires in different parts of the world, it is essential to confirm the color code for any given local region. The only exception is the earth/ground wire, which is often green but may be yellow or ‘bare wire. ‘ Striped coatings are sometimes used for the benefit of those who are colorblind.

Induction and Leakage Current

Electromagnetic induction causes a subtler problem solved by grounding the case. The alternating current in appliances can induce an EMF on the case. If grounded, the case voltage is kept near zero, but if the case is not grounded, a shock can occur. Current that is driven by the induced case EMF is called a leakage current, although current does not necessarily pass from the resistor to the case.

Key Points

- A phasor is a representation of a sinusoidal function whose amplitude (A), frequency (ω), and phase (θ) are time-invariant. If ω is shared by all components of the system, it can be factored out, leaving just A and ω. The term phasor usually refers to the last two factors.
- Phasors greatly reduce the complexity of expressing sinusoidally varying signals.
- Phasors may be used to analyze the behavior of electrical systems, such as RLC circuits, that have reached a kind of equilibrium called sinusoidal steady state. In the sinusoidal steady state, every voltage and current in a system is sinusoidal with angular frequency ω.
- Phasors allow us to apply techniques used to solve DC circuits to solve RC circuits.

- Recall that unlike DC current and voltage, which are constant, AC current and voltage vary over time. This is called alternating current because the direction alternates.
- The root mean square (abbreviated RMS or rms) is a statistical measure of the magnitude of a varying quantity. We use the root mean square to express the average current or voltage in an AC system.
- The RMS current and voltage (for sinusoidal systems) are the peak current and voltage over the square root of two.
- The average power in an AC circuit is the product of the RMS current and RMS voltage.
- Electrical circuits carry the risks of overheating and potential electrical shocks.
- Fuses and circuit breakers are used to stop currents that exceed a set safety limit, thus preventing overheating.
- The three-wire system protects against thermal and shock hazards by using live, neutral, and ground wires, and grounding the neutral wire and the conducting cases of appliances.
- Before altering any circuitry, it is important to establish the correct color-coding scheme for your region (the color of live/hot, neutral, and ground wires).
- Alternating current has the potential to induce an EMF on the case of an appliance, which poses a shock hazard, so it is important to ground the case.

Key Terms

- **sinusoidal steady state**: Indicates every voltage and current in a system is sinusoidal with the same angular frequency ω.
- **complex numbers**: Numbers that have an imaginary part. Usually represented as i.
- **phasor**: A representation of a complex number in terms of a complex exponential.
- **root mean square**: The square root of the arithmetic mean of the squares.
- **rms current**: the root mean square of the current, $\mathrm{I_{rms}} = \frac{\mathrm{I_0}}{\sqrt{2}}$, where I0 is the peak current, in an AC system
- **rms voltage**: the root mean square of the voltage, $\mathrm{V_{rms}} = \frac{\mathrm{V_0}}{\sqrt{2}}$, where V0 is the peak voltage, in an AC system
- **thermal hazard**: an electrical hazard caused by overheating (e.g., in a resistive element)
- **shock hazard**: an electrical hazard that poses the risk of passing current through the body
- **three-wire system**: a modern wiring system with safety precautions; contains live, neutral, and ground wires

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19.6: Electricity in the World

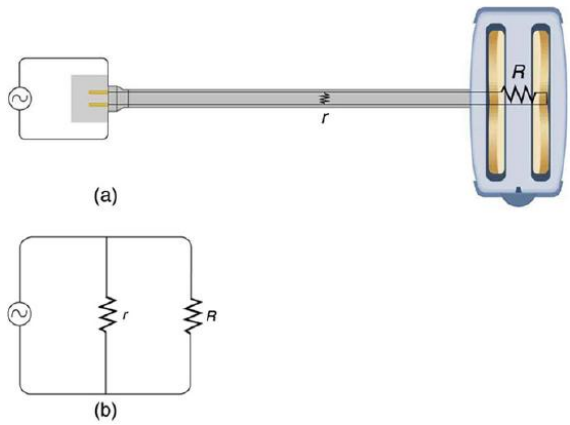
learning objectives

- Identify factors that determine the lethality of an electric shock

There are two known categories of electrical hazards: thermal hazards and shock hazards. A thermal hazard is when excessive electric power causes undesired thermal effects, such as starting a fire in the wall of a house. A shock hazard occurs when electric current passes through a person. Shocks range in severity from painful but otherwise harmless to heart-stoppingly lethal.

Thermal Hazards

Electric power causes undesired heating effects whenever electric energy is converted to thermal energy at a rate faster than it can be safely dissipated. A classic example of this is the short circuit, shown in. A short circuit is a low- resistance path between terminals of a voltage source. Insulation on the appliance's wires has worn through, allowing the two wires to come into contact. Such an undesired contact with a high voltage is called a short. Since the resistance of the short, r, is very small, the power dissipated in the short, $P = V^2/r$, is very large. For example, if V is 120 V and r is 0.100 Ω, then the power is 144 kW, much greater than that used by a typical household appliance. Thermal energy delivered at this rate will very quickly raise the temperature of surrounding materials, melting or perhaps igniting them.



Short Circuit: A short circuit is an undesired low-resistance path across a voltage source. (a) Worn insulation on the wires of a toaster allows them to come into contact with a low resistance r. Since P = V2/r, thermal power is created so rapidly that the cord melts or burns. (b) A schematic of the short circuit.

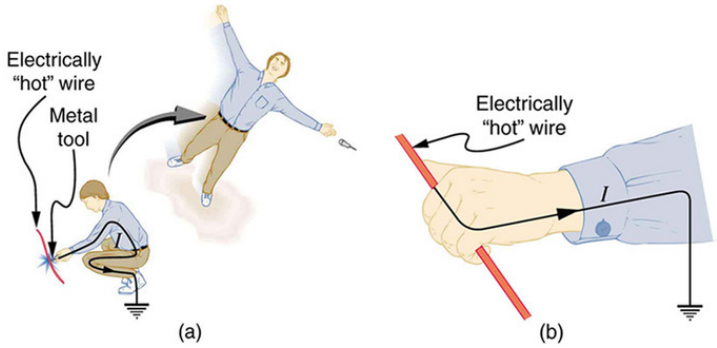
A thermal hazard can be created even when a short circuit is not present if the wires in a circuit are overloaded with too much current. The power dissipated in the supply wires is $P = I^2R_w$, where R_w is the resistance of the wires and I the current flowing through them. If either I or R_w is too large, the wires overheat. Thermal hazards can cause moderate to severe burns to those who come in contact with the affected appliance or circuit.

Shock Hazards

Electric shock occurs upon contact of a body part with any source of electricity that causes a sufficient current through the skin, muscles, or hair. Typically, the expression is used to describe an injurious exposure to electricity.The minimum current a human can feel depends on the current type (AC or DC) and frequency. A person can feel at least 1 mA (rms) of AC current at 60 Hz and at least 5 mA of DC current. The current may, if it is high enough, cause tissue damage or fibrillation, which leads to cardiac arrest. 60 mA of AC (rms, 60 Hz) or 300-500 mA of DC can cause fibrillation.The potential severity of the shock depends on paths through the body that the currents take. If an electrical circuit is established by electrodes introduced in the body, bypassing the skin, then the potential for lethality is much higher if a circuit through the heart is established. This is known as a microshock. Currents of only 10 µA can be sufficient to cause fibrillation in this case.

A very dangerous possibility is the "can't let go" effect illustrated in. The muscles that close the fingers are stronger than those that open them, so the hand involuntarily closes around the wire shocking it. This can prolong the shock indefinitely. It can also be a

danger to a person trying to rescue the victim, because the rescuer's hand may close about the victim's wrist. Usually the best way to help the victim is to give the fist a hard blow with an insulator or to throw an insulator at the fist.

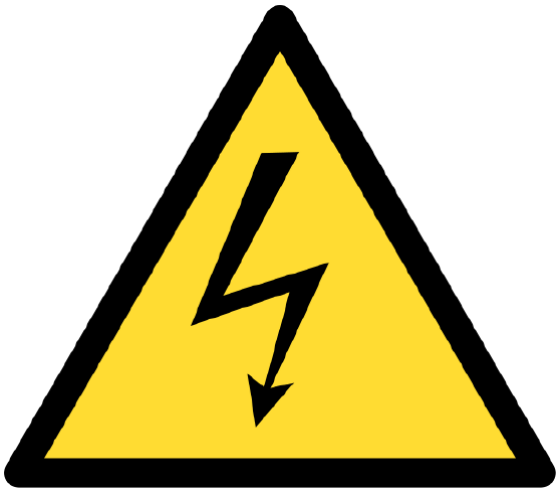


Electric Shock and Muscular Contractions: An electric current can cause muscular contractions with varying effects. (a) The victim is "thrown" backward by involuntary muscle contractions that extend the legs and torso. (b) The victim can't let go of the wire that is stimulating all the muscles in the hand. Those that close the fingers are stronger than those that open them.

Factors in the Lethality of Electric Shock

The lethality of an electric shock is dependent on several variables:

- Current: The higher the current, the more likely it is lethal. Since current is proportional to voltage when resistance is fixed (Ohm 's law), high voltage is an indirect risk for producing higher currents.
- Duration: The longer the duration, the more likely it is lethal — safety switches may limit the time of current flow.
- Pathway: If current flows through the heart muscle, it is more likely to be lethal.
- Very high voltage (over about 600 volts): This poses an additional risk beyond the simple ability of high voltage to cause high current at a fixed resistance. Very high voltage, enough to cause burns, will cause dielectric breakdown at the skin, actually lowering total body resistance and, ultimately, causing even higher current than when the voltage was first applied. Contact with voltages over 600 volts can cause enough skin burning to decrease the total resistance of a path though the body to 500 ohms or less.
- Frequency: Very high-frequency electric current causes tissue burning but does not penetrate the body far enough to cause cardiac arrest.



High Voltage Warning: International safety symbol "Caution, risk of electric shock" (ISO 3864), also known as the high-voltage symbol

Nerve Conduction and Electrocardiograms

Voltage pulses along a cell membrane, called action potentials, allow us to sense the world, control parts of our body, and think.

learning objectives

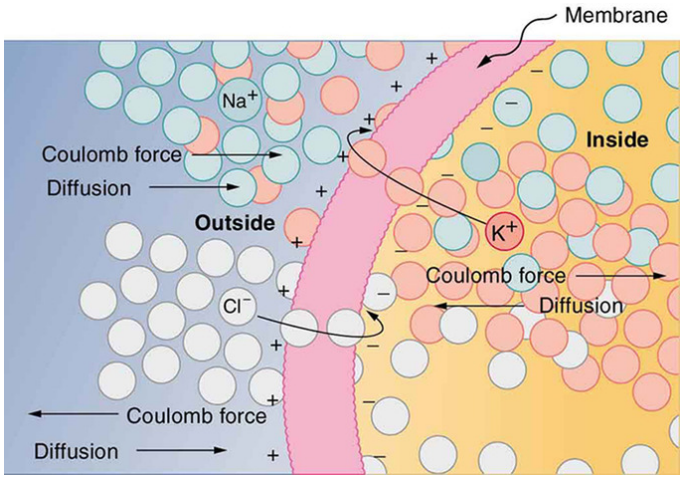
- Explain purpose of the electrocardiogram and identify functions performed by electric currents in the nerve system

Nerve Conduction and Electrocardiograms

Nerve Conduction

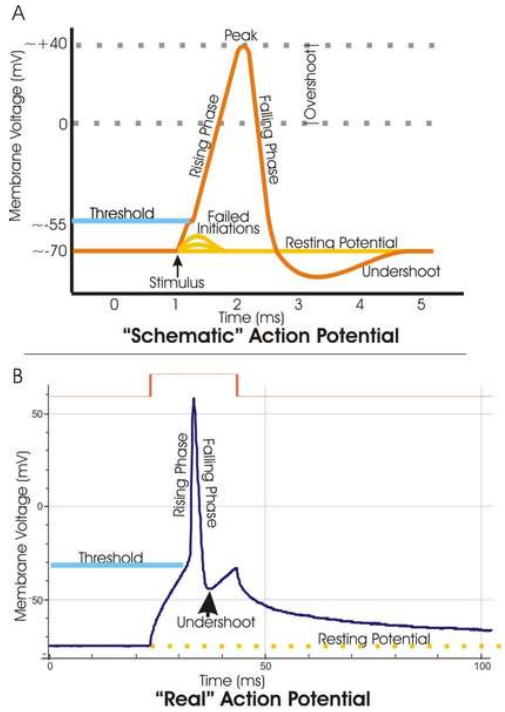
Electric currents in the complex system of nerves in our body allow us to sense the world, control parts of our body, and think. There are three major functions of nerves. First, nerves carry messages from our sensory organs to the central nervous system, consisting of the brain and spinal cord. Second, nerves carry messages from the central nervous system to muscles and other organs. Third, nerves transmit and process signals within the central nervous system.

Nerve conduction is a general term for electrical signals carried by nerve cells. A voltage is created across the cell membrane of a neuron in its resting state. This membrane separates electrically neutral fluids having differing concentrations of ions, the most important varieties being Na^+, K^+, and Cl^- (these are sodium, potassium, and chlorine ions). Free ions will diffuse from a region of high concentration to one of low concentration. The cell membrane is *semipermeable*, meaning that some ions may cross it while others cannot. In its resting state, the cell membrane is permeable to K^+ and Cl^-, and impermeable to Na^+. Diffusion of K^+ and Cl^- thus creates the layers of positive and negative charge on the outside and inside of the membrane, and the Coulomb force prevents the ions from diffusing across in their entirety.



Creating a Voltage Across a Cell Membrane: The semipermeable membrane of a cell has different concentrations of ions inside and out. Diffusion moves the K+ and Cl− ions in the direction shown, until the Coulomb force halts further transfer. This results in a layer of positive charge on the outside, a layer of negative charge on the inside, and thus a voltage across the cell membrane. The membrane is normally impermeable to Na+.

Once the charge layer has built up, the repulsion of like charges prevents more from moving across, and the attraction of unlike charges prevents more from leaving either side. The result is two layers of charge right on the membrane, with diffusion being balanced by the Coulomb force. A tiny fraction of the charges move across and the fluids remain neutral, while a separation of charge and a voltage have been created across the membrane. Electric currents along the cell membrane are created by any stimulus that changes the membrane's permeability. The membrane thus temporarily becomes permeable to Na^+, which then rushes in, driven both by diffusion and the Coulomb force. This inrush of Na+ first neutralizes the inside membrane (called depolarization), and then makes it slightly positive. The depolarization causes the membrane to again become impermeable to Na^+, and the movement of K^+ quickly returns the cell to its resting potential, referred to as repolarization. This sequence of events results in a voltage pulse, called the action potential and is shown in.



Voltage channels are critical in the generation of an action potential: Top: view of an idealized action potential shows its various phases as the action potential passes a point on a cell membrane. Bottom: Recordings of action potentials are often distorted compared to the schematic view because of variations in electrophysiological techniques used to make the recording.

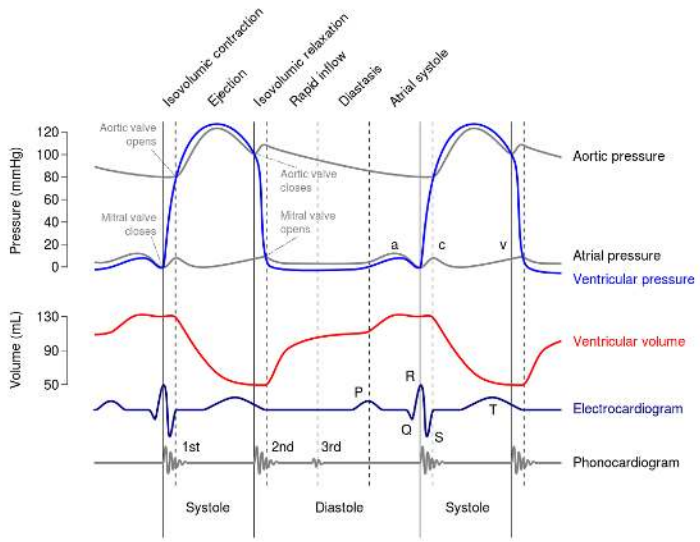
Only small fractions of the ions move, so that the cell can fire many hundreds of times without depleting the excess concentrations of Na+ and K+. This is an example of active transport, wherein cell energy is used to move ions across membranes against diffusion gradients and the Coulomb force. The action potential is a voltage pulse at one location on a cell membrane.

How does it get transmitted along the cell membrane as a nerve impulse ? The changing voltage and electric fields affect the permeability of the adjacent cell membrane, so that the same process takes place there. The adjacent membrane depolarizes, affecting the membrane farther down, and so on. Thus the action potential stimulated at one location triggers a nerve impulse that moves slowly (about 1 m/s) along the cell membrane.

Electrocardiograms

Just as nerve impulses are transmitted by depolarization and repolarization of an adjacent membrane, the depolarization that causes muscle contraction can also stimulate adjacent muscle cells to depolarize (fire) and contract. Thus, a depolarization wave can be sent across the heart, coordinating its rhythmic contractions and enabling it to perform its vital function of propelling blood through the circulatory system. An electrocardiogram (ECG) is a record of the voltages created by the wave of depolarization (and subsequent repolarization) in the heart. Historically, ECGs were performed by placing electrodes on the left and right arms and the left leg. The voltage between the right arm and the left leg is called the lead II potential and is an indicator of heart-muscle function.

shows an ECG of the lead II potential and a graph of other major events during the cardiac cycle. The major features are labeled P, Q, R, S, and T. The *P wave* is generated by the depolarization and contraction of the atria as they pump blood into the ventricles. The *QRS complex* has a characteristic shape and time span, and is created by the depolarization of the ventricles as they pump blood to the body. The lead II QRS signal also masks the repolarization of the atria. Finally, the *T wave*is generated by the repolarization of the ventricles and is followed by the P wave in the next heartbeat. Arterial blood pressure varies with each part of the heartbeat, with systolic (maximum) pressure occurring closely after the QRS complex, signaling the contraction of the ventricles.



ECG Curve: A normal ECG curve synchronized with other major events during the cardiac cycle.

Electric Activity in the Heart

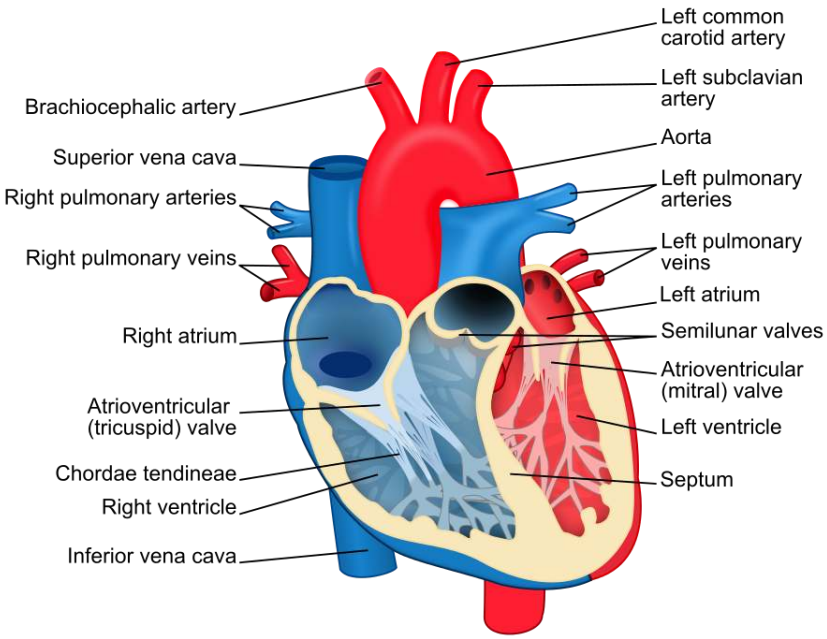
Electric energy stimulating the heart occurs in the sinoatrial node, the heart's pacemaker, and is transmitted partially by Perkinje fibers.

learning objectives

- Identify part of the heart that acts as a pacemaker

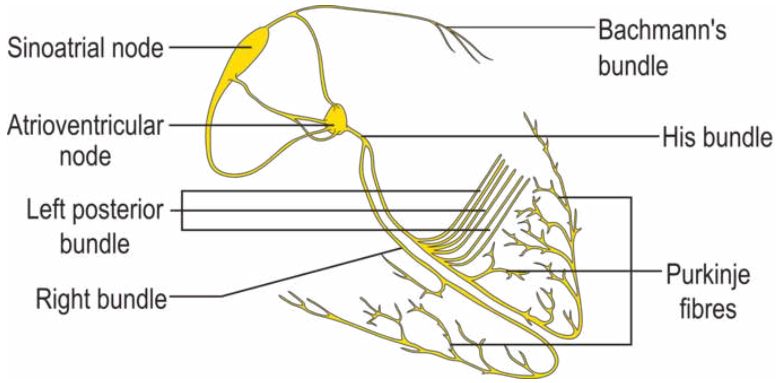
Electric Activity in the Heart

The human heart provides continuous blood circulation through the cardiac cycle and is unsurprisingly one of the most vital organs in the human body. The heart is divided into four main chambers: the two upper chambers are called the left and right atria (singular atrium) and two lower chambers are called the right and left ventricles. As can be seen in, there is a thick wall of muscle separating the right side and the left side of the heart called the septum. Normally with each beat the right ventricle pumps the same amount of blood into the lungs that the left ventricle pumps out into the body. Physicians commonly refer to the right atrium and right ventricle together as the right heart and to the left atrium and left ventricle as the left heart.



Structure of the heart: Structure diagram of a coronal section of the human heart from an anterior view. The two larger chambers are the ventricles.

The electric energy that stimulates the heart occurs in the sinoatrial node, which produces a definite potential and then discharges, sending an impulse across the atria. In the atria the electrical signal moves from cell to cell (see section on nerve conduction and the electrocardiogram) while in the ventricles the signal is carried by specialized tissue called the Purkinje fibers which then transmit the electric charge to the myocardium. shows the isolated heart conduction system.

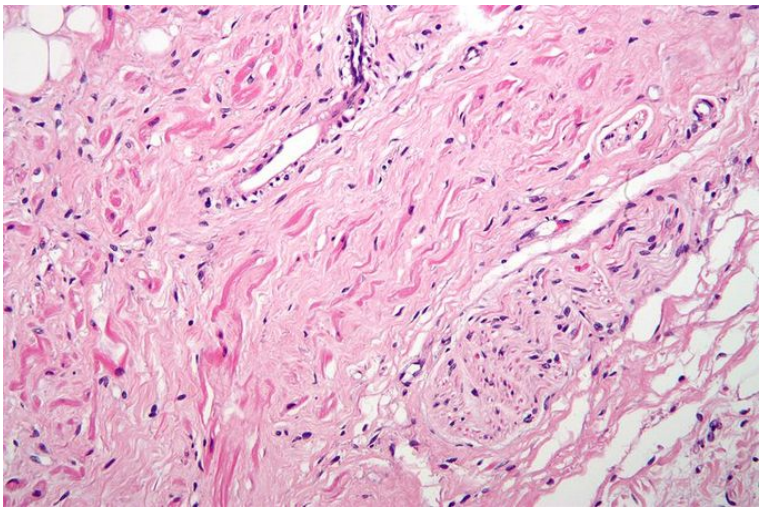


Conduction System of the Heart: Isolated heart conduction system, showing the sinoatrial and Purkinje fibers.

The Sinotrial Node's Role as a Pacemaker

The sinoatrial node (also commonly spelled sinuatrial node) is the impulse-generating (pacemaker) tissue located in the right atrium of the heart: i.e., generator of normal sinus rhythm. It is a group of cells positioned on the wall of the right atrium. These cells are specialized cardiomycetes (cardiac muscle cells).

The sinoatrial node (also commonly spelled sinuatrial node, abbreviated SA node) is the impulse-generating (pacemaker) tissue located in the right atrium of the heart, and thus the generator of normal sinus rhythm. It is a group of cells positioned on the wall of the right atrium. Although all of the heart's cells have the ability to generate the electrical impulses (or action potentials) that trigger cardiac contraction, the sinoatrial node normally initiates it, simply because it generates impulses slightly faster than the other areas with pacemaker potential.



Sinoatrial Node Tissue: High magnification micrograph of sinoatrial node tissue and an adjacent nerve fiber.

Cells in the SA node, located in the upper right corner of the heart, will typically discharge (create action potentials) at about 60-100 beats/minute. Because the sinoatrial node is responsible for the rest of the heart's electrical activity, it is sometimes called the primary pacemaker. If the SA node does not function, or the impulse generated in the SA node is blocked before it travels down the electrical conduction system, a group of cells further down the heart will become the heart's pacemaker. These cells form the atrioventricular node (AV node), which is an area between the atria and ventricles, within the atrial septum. If the AV node also fails, Purkinje fibers are capable of acting as the pacemaker. The reason Purkinje cells do not normally control the heart rate is that they generate action potentials at a lower frequency than the AV or SA nodes.

Purkinje Fibers

The Purkinje fibers are located in the inner ventricular walls of the heart. These fibers consist of specialized cardiomyocytes that are able to conduct cardiac action potentials more quickly and efficiently than any other cells in the heart. Purkinje fibers allow the heart's conduction system to create synchronized contractions of its ventricles, and are therefore essential for maintaining a consistent heart rhythm.

During the ventricular contraction portion of the cardiac cycle, the Purkinje fibers carry the contraction impulse from both the left and right bundle branch to the myocardium of the ventricles. This causes the muscle tissue of the ventricles to contract, thus enabling a force to eject blood out of the heart. Atrial and ventricular discharge through the Purkinje trees is assigned on a standard Electrocardiogram as the P Wave and QRS complex, respectively.

Purkinje fibers also have the ability of automatically firing at a rate of 15-40 beats per minute if left to their own devices. In contrast, the SA node outside of parasympathetic control can fire a rate of almost 100 beats per minute. In short, they generate action potentials, but at a slower rate than sinoatrial node and other atrial ectopic pacemakers. Thus they serve as the last resort when other pacemakers fail.

Key Points

- Electric power causes undesired heating effects whenever electric energy is converted to thermal energy at a rate faster than it can be safely dissipated, such as in the case of a short circuit. This is referred to as a thermal hazard.
- A shock hazard occurs when electric current passes through a person. If the current is high enough it can cause tissue damage or fibrillation, which can lead to cardiac arrest.
- The lethality of an electric shock is dependent on many variables, including current, duration, pathway, and the presence or absence of very high voltage.
- Nerves carry messages from our sensory organs to the central nervous system, from the central nervous system to muscles, and within the central nervous system itself.
- The effects of diffusion and the Coulomb force act together to allow ions like Na+, K+, and Cl- to create a voltage across cell membranes.
- An action potential is an event which alters the permeability of a cell membrane due to electric currents.

- The depolarization that causes muscle contraction can also stimulate contraction in adjacent muscle cells. A depolarization wave across the heart is responsible for rhythmic contractions. An electrocardiogram (ECG) is a record of the voltages in the heart.
- The human heart provides continuous blood circulation through the cardiac cycle and is unsurprisingly one of the most vital organs in the human body.
- The heart is divided into four main chambers: the two upper chambers are called the left and right atria (singular atrium) and two lower chambers are called the right and left ventricles. See for an illustration. There is a conduction system that transports impulses through the heart.
- The electric energy that stimulates the heart occurs in the sinoatrial node, which produces a definite potential and then discharges, sending an impulse across the atria. It is thus the generator of normal sinus rhythm and functions as the heart's pacemaker.
- In the atria the electrical signal moves from cell to cell while in the ventricles the signal is carried by specialized tissue called the Purkinje fibers.
- Purkinje fibers allow the heart's conduction system to create synchronized contractions of its ventricles, and are therefore essential for maintaining a consistent heart rhythm.

Key Terms

- **shock hazard**: an electrical hazard that poses the risk of passing current through the body
- **thermal hazard**: an electrical hazard caused by overheating (e.g., in a resistive element)
- **fibrillation**: the rapid, irregular, and unsynchronized contraction of the muscle fibers of the heart
- **diffusion**: the intermingling of the molecules of a fluid due to random thermal agitation
- **electrocardiogram**: The visual output that an electrocardiograph produces
- **action potential**: A short term change in the electrical potential that travels along a cell such as a nerve or muscle fiber.
- **sinoatrial node**: a group of specialized cardiac muscle cells (tissue) located in the right atrium of the heart, which generates the impulses that establish the normal sinus rhythm.
- **Purkinje fibers**: specialized cardiac muscle cells that are able to conduct cardiac muscle potentials quickly and efficiently; essential for maintaining consistent heart rhythm.
- **myocardium**: The middle of the three layers forming the wall of the heart.

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CHAPTER OVERVIEW

20: Circuits and Direct Currents

Topic hierarchy

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CHAPTER OVERVIEW

21: Magnetism

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SECTION OVERVIEW

7: Electric Circuits

01. Concepts and Principles

02. Analysis Tools

03. Analysis Tools 2

04. Activities

Paul D'Alessandris (Monroe Community College)

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01. Concepts and Principles

1. Electric Circuits as Applied Physics
2. The Resistor
3. The Capacitor
4. The Inductor

Electric Circuits as Applied Physics

Electric circuits are one of the most practical applications of our understanding of electric and magnetic fields. In general, an electric circuit is any device that consists of a closed path for charges to move (a current), a source of energy to "drive" the motion of the charges (a potential difference, or voltage, often in the form of a battery), and various circuit elements that can either convert (resistors) or store (capacitors and inductors) the energy supplied by the energy source.

The study of circuits is incredibly broad, since there are limitless ways to combine these elements into an electric circuit. We will restrict ourselves to studying circuits with only a limited number of elements, and with a source that supplies a constant voltage[1].

The Resistor

In general, a *resistor* is any device that converts electrical energy into another form of energy, often heat. For example, a fluorescent light bulb converts electrical energy into light (with about a 20% efficiency, the remaining energy is converted into heat) and an incandescent light bulb converts electrical energy very efficiently into heat (with only about 5% of the incident energy converted to light). Since a conversion of electrical energy takes place in these devices, they are resistors.

In all resistors, the electric potential energy of the charges entering the device is larger than the electric potential energy of the charges exiting the device, because some of the potential energy has been converted to other forms. This decrease in potential energy is due to a decrease in electric potential between the two ends of the device and is directly proportional to the *resistance* of the device.

The definition of resistance for a device is:

pic 1

where

- DV is the potential difference between the two ends of the device, often termed the *voltage drop* across the device,
- and i is the current that flows through the device.

The unit of resistance, pic 2, is defined as the ohm (W).

The previous expression relates the resistance of a resistor to properties of the circuit it is part of. However, it is also sometimes useful to directly relate the resistance to the actual physical parameters of the device itself. For simple, passive resistors (basically blocks of material connected to a voltage source), resistance is defined as:

pic 3

where

- is the *resistivity* of the material from which the resistor is constructed,
- L is the length of the resistor in the direction of current flow,
- and A is the cross-sectional area of the resistor.

Resistivity can range from 0 for a perfect conductor to for a perfect insulator.

One final note on the properties of resistors concerns their rate of energy conversion. Since electric potential is the electric potential per unit of charge, and current is the charge flowing through the devicde per second, the product of change in electric potential and current is the change in electric potential energy per second. Thus, the rate of energy conversion, or *power*, in a resistor is given by:

pic 4

The Capacitor

A *capacitor* is a device that stores energy in the electric field between two closely spaced conducting surfaces. When connected to a voltage source, electric charge accumulates on the two surfaces but, since the conducting surfaces are separated by an insulator, the charges cannot travel from one surface to the other. The charges create an electric field in the space between the surfaces, and the two surfaces have a difference in electrical potential.

pic 5

Once "charged", if the capacitor is removed from the original circuit and connected to a second circuit it can act as a voltage source and "drive" its collected charge through the second circuit. When used in this way, the capacitor clearly acts as a temporary storehouse of energy.

To determine the energy stored in a capacitor, we first need to define the *capacitance* of the capacitor. The capacitance of a capacitor is defined as:

pic 6

where

- Q is the magnitude of the electric charge stored on either conducting surface,
- and DV is the potential difference between the surfaces.

The unit of capacitance,pic 7, is defined as the *farad* (F).

The amount of energy that can be stored on a capacitor is a function of both its capacitance and the potential difference between its surfaces. The relationship between stored energy and these parameters is:

pic 8

The Inductor

An *inductor* is a device that stores energy in the magnetic field created when current passes through a coil of wire. When connected to a voltage source, current will flow through the inductor, establishing a magnetic field.

pic 9

If the voltage source is suddenly removed, current will continue to flow in the coil because of electromagnetic induction. This induced current will act to replace the disappearing source current. The energy needed to drive this current comes from the energy stored in the magnetic field, so in this case the inductor acts as a temporary storehouse of energy.

To determine the energy stored in an inductor, we first need to define the *inductance* of the inductor. The inductance of the inductor is defined as:

pic 10

where

- F is the magnetic flux within the inductor,
- and i is the current flowing through the inductor.

The unit of capacitance, pic 11, is defined as the *henry* (H).

The amount of energy that can be stored in an inductor is a function of both its inductance and the current flowing through it. The relationship between stored energy and these parameters is:

pic 12

---

[1]Circuits with constant voltage sources are referred to as DC, or direct current, circuits.

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02. Analysis Tools

1. Resistors in Circuits
2. Capacitor Properties
3. Capacitors in Circuits

Resistors in Circuits

The circuit at right represents a 12 V car battery and two mismatched headlights, R_1 = 1.9 W and R_2 = 2.1 W.

a. Determine the magnitude of the potential difference across and the current through each circuit component.

b. If the battery has a total stored energy of 800 W hr, and produce a constant potential difference until discharged, how long will the bulbs stay lit?

pic 1

The potential difference across the car battery is given as 12 V. This means that the electric potential in the wire coming out of the "top" of the battery is 12 V larger than the potential in the wire coming from the "bottom". Since each of the resistors are attached to these same two wires, the top of each resistor is 12 V higher in potential than the bottom. Therefore the potential difference across each resistor is 12 V. When circuit elements are connected such that the elements all have the same potential difference, the elements are said to be in *parallel*.

Since the potential difference across each resistor is known, we can use the definition of resistance to calculate the current through each branch of the circuit. Analyzing branch #1 yields

pic 2

and branch #2

pic 3

The current that flows through R_1 and the current that flows through R_2 must also flow through both the top and bottom wires connected to the battery. To complete the mental image of a closed circuit of current, we will say the current flows "through" the battery as well, although this is not technically true. Therefore, the current that flows through the battery (the total current flowing in the circuit) is:

pic 4

We can summarize this information in a simple table:

	V_{across} (V)	$i_{through}$ (A)
battery	12	12.0
R_1	12	6.32
R_2	12	5.71

To determine how long the headlights will stay lit, we must calculate the total power of the circuit (the total amount of electrical energy converted per second). We can do this separately for each headlight and then add the results:

pic 5

and

pic 6

so the total power of the circuit is:

pic 7

Therefore, the battery will last for

pic 8

Capacitor Properties

Imagine a pair of long, hollow nested cylinders of inner radius a and outer radius b. Calculate the capacitance, per meter, for these nested cylinders.

pic 9

Since capacitance is defined by the relation

pic 10

we need to determine the potential difference that would develop between these cylinders if charges Q (and -Q) where placed on the two surfaces.'To do this, imagine that a charge +Q (per meter) was placed on the inner cylinder. Using Gauss' Law, this leads to an electric field between the cylinders of:

pic 11

This field is directed radially away from the central axis of the cylinders.

Once the electric field between the cylinders is known, the magnitude of the potential difference between the cylinders can be calculated by:

pic 12

Substituting this result into definition of capacitance yields:

pic 13

Thus, the capacitance permeter of a set of nested cylinders depends on the natural logarithm of the ratio of the cylinder radii. Notice that is the cylinders are very close together (b is not much larger than a), the capacitance is very large. The capacitance of a capacitor is always enhanced by having the two charged surfaces very close together. However, as the surfaces get closer together, the possibility of electrical breakdown (charges "jumping" across the gap) becomes larger. For this reason, and several others, the space between the surfaces in a capacitor is typically filled with a type of material, called a *dielectric*, which both enhances the capacitance of the capacitor and inhibits electrical breakdown.

Capacitors in Circuits

The device at right represents a simplified camera flash circuit. With V = 3 V and R = 100 , find C such that the flash reaches 80% of its final voltage in 1.0 s.

pic 14

The circuit above, termed an *RC circuit*, can best be analyzed by considering the changes in electric potential experienced by a hypothetical charge "journeying" around the circuit:

- as it "passes through" the battery the potential increases by V,
- as it passes through the resistor the potential decreases by

pic 15

- and as it "passes through" the capacitor the potential decreases by

pic 16

Putting these changes in potential together results in:

pic 17

Note that the total change in potential (and potential energy) must be zero since the energy given to the charge by the battery is partially converted by the resistor and partially stored by the capacitor.

If we take a time derivative of the above equation (noting that V, R, and C are constants, but that Q, the charge on the capacitor, is changing) we are left with a differential equation for the current in the circuit:

pic 18

This equation says that the time derivative of the cureent is equal to the product of the current and the numerical factor pic 19. The only mathematical function that has the property that its derivative is proportional to itself is the exponential function. Therefore,

the current must be given by the function:

pic 20

where i_0 is the current at t = 0 s.

If we assume that the capacitor is uncharged when the switch is first closed, then

pic 21

so the final expression for the current in the circuit as a function of time is:

pic 22

Using this expression we can determine the time-dependence of any other circuit parameter.

For example, the question asks about the voltage across the capacitor. Since the voltage across the resistor can be expressed as:

pic 23

the voltage across the capacitor is the amount of the source voltage that "remains":

pic 24

This function shows that after a long time ($t \to \infty$), the voltage across the capacitor will equal the voltage of the source.

Therefore,

pic 25

Thus, a 6.21 mF capacitor will reach 80% of its final voltage in 1.0 s.

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03. Analysis Tools 2

1. Inductor Properties
2. Inductors in Circuits

Inductor Properties

Imagine a pair of long, hollow nested wires of inner radius a and outer radius b, designed to carry current into and out of the page. Calculate the inductance, per meter, for these nested wires.

pic 1

Since inductance is defined by the relation

pic 2

we need to determine the flux that would develop between these wires if current i (and -i) flowed along the two wires:

To do this, imagine that current i flowed out of the page along the inner wire. Using Ampere's Law, this leads to a magnetic field between the cylinders of:

pic 3

To help calculated the flux between the wires, the diagram at right is a top view of the nested wires. The dashed area is the area over which we will calculate the flux. (The current along the inner wire flows toward the top of the page, resulting in magnetic field pointing directly out of the page in the area of interest.)

The shaded sliver is the differential element, located a distance r from the center of the wires, with thickness dr and length l. The magnetic flux is then:

pic 4

Substituting this result into the definition of inductance yields:

pic 5

The inductance per meter is then:

pic 6

Thus, the inductance per meter of a set of nested wires depends on the natural lograithm of the ratio of the wire radii. Notice that if the wires are very far apart, the inductance is larger. However, as the wires get farther apart, the size of the device gets larger and may become impractical. For this reason, and several others, the space containing the magnetic flux in an inductor is typically filled with a material with a high magnetic permeability, like iron, in order to "concentrate" the magnetic flux into a smaller region of space.

Inductors in Circuits

The device below represents a simplified electromagnet. With V = 100 V and R = 15 W, find L such that the current reaches 5.0 A in 0.5 s.

pic 7

The circuit above, termed an *RL circuit*, can best be analyzed by considering the changes in electric potential experienced by a hypothetical charge "journeying" around the circuit:

- as it "passes through" the battery the potential increases by V,
- as it passes through the resistor the potential decreases by

pic 8

- and as it "passes through" the inductor's potential changes by

pic 9

Since by Faraday's Law of Induction,

pic 10

The emf induced by the inductor is the potential drop across it, so

pic 11

Putting these changes in potential together results in:

pic 12

Again, note that the total change in potential (and potential energy) must be zero since the energy given to the charge by the battery is partially converted by the resistor and partially stored by the inductor.

If we take a time derivative of the above equation (noting that V, R, and L are constant) we are left with a differential equation for the current in the circuit:

pic 13

This equation says that the time derivative of the *derivative* of the current is equal to the product of the *derivative* of the current and a numerical factor. This means that the derivative of the current must be exponential function. Therefore, the derivative of the current must be given by the function:

pic 14

where A is an arbitrary constant. Integrating this result leads to a current of the form:

pic 15

where B and D are arbitrary constants.

To determine these constants, consider the current in the circuit after a very long time ($t \rightarrow \infty$). After this amount of time the circuit will have reached an equilibrium value, so the change in the current will be zero. Thus,

pic 16

Therefore,

pic 17

Now consider the current in the circuit the instant you first close the switch ($t \rightarrow 0$). At this instant, no current can be flowing in the circuit. This is because if there was current flowing instantaneously after the switch was closed, this would be discontinuous change in current and the inductor would create an infinite emf to oppose this "infinite" increase in current. Therefore,

pic 18

Now that we know the values of the two constants, the final expression for the current in the circuit as a function of time is:

pic 19

Using this expression we can determine the time-dependence of any other circuit parameter.

Since the question asks about the current directly,

pic 20

Therefore, if the electromagnet has an inductance of 5.4 H, it will take 0.5 s for the current to rise to 5.0 A.

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04. Activities

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