I. KINEMATICS

i. *Displacement, Velocity and Acceleration* 1-7

$$\bar{v} = \frac{x - x_0}{\Delta t}$$

Velocity is the rate of change of position.

$$\bar{a} = \frac{v - v_0}{\Delta t}$$

Acceleration is the rate of change of velocity.

ii. *The Kinematics of Constant Acceleration* 8-15

The four equations of kinematics for one dimensional motion of uniform acceleration.

$$v = v_0 + at$$

$$x - x_0 = \tfrac{1}{2}(v + v_0)t$$

$$x - x_0 = v_0 t + \tfrac{1}{2}at^2$$

$$v^2 = v_0^2 + 2a(x - x_0)$$

iii. *Motion in Two Dimensions* 16-23

$$a_r = \frac{v^2}{r}$$

Centripetal acceleration

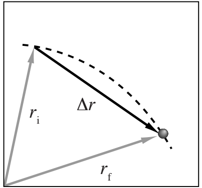
$$v_x = v_{x_0} = \text{constant}$$

The horizontal component of projectile velocity is constant.

$$v_y = v_{y_0} - gt$$

The vertical component is under the influence of the acceleration due to gravity.

- The purpose of kinematics is describing motion.
- The fundamental kinematical quantities are *displacement*, *velocity*, and *acceleration*.
- *Displacement* is the vector difference between an object's final position and its initial position. How far did it go? In which direction?
- *Velocity* is the vector rate of change of the displacement. It combines both the speed and direction of motion. How many *meters per second* is the object travelling in that direction?
- *Acceleration* is the rate of change of velocity. How many meters per second does the velocity change per second (meters per second per second) = (m/s^2).



The motion of a particle in time interval Δt for a net displacement of Δr.

Average velocity: $\bar{v} = \frac{\Delta r}{\Delta t}$

MANY STUDENTS SEE FORMULAS JUST AS PLUG-AND-CHUG MACHINES FOR PROBLEMS. PHYSICAL FORMULAS, THOUGH, EXPRESS RELATIONSHIPS OF PHYSICAL QUANTITIES. PART OF UNDERSTANDING PHYSICS IS LEARNING TO READ FORMULAS AS A CONCEPTUAL LANGUAGE.

II. DYNAMICS

$$\text{If } \Sigma \boldsymbol{F} = 0 \text{ then } \boldsymbol{a} = 0$$

1st Law - the Law of Inertia

$$\boldsymbol{F} = m\boldsymbol{a}$$

2nd Law - Net force causes acceleration

$$\boldsymbol{F}_{12} = -\boldsymbol{F}_{21}$$

3rd Law - action and reaction

$$\tau = F\,d$$

Torque equals force times moment arm.

$$F_s \leq \mu_s N$$

Force of static friction

$$F_k = \mu_k N$$

Force of kinetic friction

$$F = G\frac{m_1 m_2}{r^2}$$

Gravitational force

$$F = k\frac{q_1 q_2}{r^2}$$

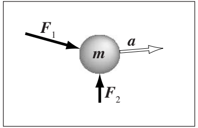
Electrostatic force

$$F = qB\,v\sin\theta$$

Magnetic force

This is a brief introduction. These forces are treated in greater depth in later chapters.

- Newton's First Law - If the net force on an object is zero, its acceleration is zero. Velocity is constant.



- Newton's Second Law - Acceleration is proportional to net force and inversely proproportional to the object's mass.
- Newton's Third Law - The force from object 1 onto object 2 is accompanied by an equal and opposite force from object 2 onto object 1.
- There are four known fundamental forces. In classical physics we work mainly with two of these, the gravitational force and the electromagnetic force (Electromagnetic force has two flip sides, electrostatic force and magnetic force).
- Careful construction of a free body diagram helps you recognize all the forces acting within a system.
- Static friction force prevents sliding motion. Kinetic friction force occurs while the object is moving and resists sliding motion.

KINEMATICS DESCRIBES *HOW* MOTION OCCURS. DYNAMICS DESCRIBES *WHY* MOTION OCCURS. FORCE IS THE PHYSICAL QUANTITY REPRESENTING THE INTERACTION BETWEEN AN OBJECT AND ITS SURROUNDINGS THAT AFFECTS THE OBJECT'S STATE OF MOTION.

III. WORK, ENERGY, AND POWER

$W = (F \cos \theta)s$

Work is the product of force and the component of the displacement in the direction of the force (‘work equals force times distance’).

$K = \frac{1}{2}mv^2$

Kinetic energy increases with mass and the speed squared. Work increases an object’s kinetic energy by speeding it up or decreases kinetic energy by slowing the object down.

Potential energy, the energy of position...

$U = mgh$ — when an object is raised against Earth’s gravity

$U_{spr} = \frac{1}{2}kx^2$ — in a stretched spring

$U_g = -G\frac{m_1 m_2}{r}$ — between two masses attracted by gravity

$U_e = k\frac{q_1 q_2}{r}$ — between two charges interacting by electric force

$K_i + U_i = K_f + U_f$

With only conservative forces at play, system energy doesn’t dissipate into the environment but interchanges between kinetic energy and potential energy.

$\bar{P} = \frac{\Delta W}{\Delta t}$

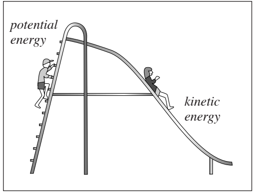
Power is the rate of energy expenditure or work done.

$P = Fv$

A force in the direction of motion expends energy in proportion to speed.

- Energy measures the capacity of a body or system to perform work. Work equals the product of the force and the parallel component of the displacement. ‘Work equals force times distance’ if both the force and the motion are in the same direction.

- A body possesses kinetic energy because of motion. Kinetic energy equals the work the body would do in coming to rest.



- Potential energy is stored in a system when a change in position requires working against a conservative force. Lifting an object against gravity stores gravitational potential energy equal to the force required (the weight) times the height.

- Power is the rate of doing work. A system operating at high power expends a lot of energy in little time.

THE BASIC CONCEPTS OF WORK AND ENERGY ARE FUNDAMENTAL TO THE SCIENTIFIC INTERPRETATION OF THE PHYSICAL AND NATURAL WORLDS. WITH EACH NEW SET OF PHENOMENA TO INTERPRET, A GOOD APPROACH IS TO LOOK AT THE SITUATION IN TERMS OF WORK AND ENERGY.

IV. HARMONIC MOTION

i. ***Simple Harmonic Motion*** *....................93-97*

$$x = A\cos(\omega t + \delta)$$

$$f = \frac{1}{T} = \frac{\omega}{2\pi} \qquad T = \frac{2\pi}{\omega}$$

Angular frequency, ω, describes the rate the motion repeats (rad/s). Amplitude, A, sets the maximum displacement from equilibrium.

The frequency and the period describe a repetition as a cycle. To convert from angular frequency, remember: 2π radians per cycle.

ii. ***Hooke's Law and the Mass-Spring*** *....................98-105*

$$F = -kx$$

The restoring force in a mass-spring is proportional to the change in length. A high spring constant, k, means the spring is strong.

$$\omega = \sqrt{\frac{k}{m}}$$

The angular frequency of a mass spring increases with the square root of the spring constant and decreases with the square root of the mass.

$$U = \tfrac{1}{2}kx^2$$

The mass-spring stores elastic potential energy equal to the work required to displace the spring from equilibrium.

iii. ***The Pendulum*** *....................106-109*

$$\omega = \sqrt{\frac{g}{L}}$$

The angular frequency of a pendulum increases with the square root of the acceleration due to gravity and decreases with the square root of pendulum length. When the pendulum bob is displaced from equilibrium the system stores gravitational potential energy, mgh.

- Because harmonic motion repeats itself, it can be modeled using the cosine (or sine) function. As time passes in the harmonic motion equation, the value returned by cosine oscillates between -1 and 1, so the value of the displacement oscillates between -A and A, the amplitude. The angular frequency, ω, determines the rate of repetition in time. A phase angle, δ, is sometimes included in the expression to account for initial conditions.

- Two model systems are most important for harmonic motion: the mass-spring and the pendulum.

- The frequency of a mass spring increases with the square root of the spring constant and decreases with the square root of the mass. The frequency of a pendulum increases with the square root of the acceleration due to gravity and decreases with the square root of pendulum length.

FOR BOTH THE MASS-SPRING AND THE PENDULUM, SIMPLE HARMONIC MOTION OCCURS BECAUSE A RESTORING FORCE IN BOTH SYSTEMS PULLS THE MASS BACK TOWARD EQUILIBRIUM IN RESPONSE TO DISPLACEMENT.

V. ELASTICITY

$$\text{elastic modulus} = \frac{\text{stress}}{\text{strain}}$$

Stress describes the forces causing a deformation. Strain measures the deformation. The elastic modulus governs the relationship between stress and strain.

$$\text{Young's modulus} = \frac{F/A}{\Delta L/L_o}$$

Young's modulus describes this relationship for tensile deformation, the *tensile strain* a given material experiences under *tensile stress*.

$$\text{shear modulus} = \frac{F/A}{\Delta x/h}$$

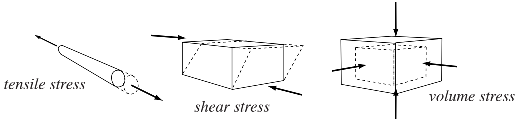
Shear modulus describes the degree of *shear strain* an object experiences under a *shearing stress* (when an object is subjected to a force along one of tis faces while the other is held in a fixed position).

$$\text{bulk modulus} = -\frac{F/A}{\Delta V/V}$$

Bulk modulus predicts the degree of *volume strain* a material exhibits under a *volume stress* (when an object is subjected to a uniform pressure on all of its faces).

- Elasticity describes how a material responds to mechanical stress. A particular stress is an *array* of forces causing a deformation. Strain measures the degree of deformation. The elastic modulus governs the relationship between stress and strain below a certain tolerance where stress and strain are directly proportional, below the elastic limit. The elastic limit is also called the yield point after which the deformation is no longer completely reversible (the object no longer resumes its original shape when the stress is removed).

- Three types of elastic modulus describe the three major kinds of deformation, Young's modulus (tensile stress and strain), shear modulus (shear stress and strain), and bulk modulus (volume stress and strain).



MATERIAL PROPERTIES IS A CRUCIAL TOPIC FOR ENGINEERS. ADDITIONALLY, ELASTICITY IS FUNDAMENTAL TO UNDERSTANDING VIBRATIONS (THE SPRING CONSTANT, k, IS A KIND OF ELASTIC MODULUS) AND THE PROPAGATION OF SOUND WAVES.

VI. FLUID MECHANICS

i. *Density and Pressure*......120-127

$\rho = \dfrac{m}{V}$ Density is the mass per unit volume.

$P = \dfrac{F}{A}$ Pressure is the force exerted by a fluid per unit area of surface in contact.

$P = P_a + \rho g h$ The surface pressure of a fluid is the atmospheric pressure and increases with depth in direct proportion to its density.

ii. *Pascal's Law and the Hydraulic Press*......128

$\dfrac{F_a}{A_a} = \dfrac{F_b}{A_b}$ In a hydraulic press a small force on a small piston results in a pressure increase throughout an enclosed fluid, resulting in a large force on a large piston.

iii. *Archimedes Principle*......129-133

$B = W_{\text{fluid displaced}}$ The buoyant force on submerged object equals the weight of the water displaced.

iv. *The Flow of an Ideal Fluid*......134-139

$A_1 v_1 = A_2 v_2 = \text{constant}$

The volume flux is constant, so the flow will be fast where cross-sectional area is small.

$P + \frac{1}{2}\rho v^2 + \rho g y = \text{constant}$

Bernoulli's Law is a consequence of energy conservation within an ideal fluid.

v. *The Flow of a Real Fluid*......140-147

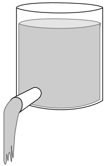
$RN = \dfrac{\rho v d}{\eta}$ The Reynolds number predicts whether flow will be turbulent.

$Q = \dfrac{\Delta P \pi r^4}{8 \eta l}$ Poiseuille's Law describes the flow of a viscous fluid through a pipe or tube.

- In a stationary fluid, the pressure increases with the depth and is independent of the shape and size of the container.
- According to Pascal's Law, an increase in pressure in one part of an enclosed incompressible fluid is transmitted undiminished throughout the fluid.
- For a submerged object, the buoyant force equals the weight of fluid displaced.
- The continuity equation describes how the flow speed of an ideal fluid through a vessel is inversely proportional to cross-sectional area.
- Bernoulli's equation represents energy in fluid flow as interchanging between pressure, kinetic energy and potential energy related terms.
- Unlike an ideal fluid, a real fluid can flow with turbulence. An important attribute for a real fluid is viscosity, η, resistance to flow.

$P + \frac{1}{2}\rho v^2 + \rho g y = \text{constant}$

Bernoulli's equation



WHEN THE PRINCIPLES FROM FLUID MECHANICS, I.E. THE CHANGE OF PRESSURE WITH DEPTH, BUOYANT FORCE, THE CONTINUITY EQUATION, BERNOULLI'S LAW, APPEAR ON COMPREHENSIVE EXAMS, IT'S OFTEN IN THE FORM OF CONCEPTUAL QUESTIONS.

VII. WAVES

$v = \sqrt{\dfrac{F}{\mu}}$ Speed of a wave on a stretched string

$v = \lambda f$ For a harmonic wave, which repeats itself, the speed equals wavelength times frequency

$v = \sqrt{\dfrac{B}{\rho}}$ Speed of sound

$\beta = 10 \log \left(\dfrac{I}{I_0}\right)$ Loudness in decibels

$I = \text{constant}$ $\quad I \propto \dfrac{1}{r}$ $\quad I \propto \dfrac{1}{r^2}$

Intensity vs. distance with planar, cylindrical or spherical sound waves.

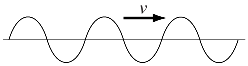
$f' = f\left(\dfrac{v \pm v_0}{v \mp v_s}\right)$ With motion between the source and observer, observed frequency is different than source frequency.

$$\lambda_n = 2L, L, \frac{2L}{3}, \ldots \frac{2L}{n} \qquad (n = 1,2,3,\ldots) \qquad f = \frac{v}{\lambda_n} = \frac{n}{2L}v$$

With standing waves, such as a string that is fixed at both ends, the boundary conditions determine where the nodes and antinodes must be located.

$f_b = f_1 - f_2$ Beat frequency equals the frequency difference of the waves.

- A mechanical wave is a disturbance traveling through a medium by virtue or the elastic properties of the medium. As a wave passes, the displacements of mass points within the medium are relatively small, returning to zero after the wave has passed. If the displacements are parallel to the direction of wave propagation, the wave is longitudinal. If the displacements are perpendicular to wave propagation, the wave is transverse.



- A wave form that repeats itself is a harmonic wave.

- Sound waves are longitudinal mechanical compression waves in matter. The speed of sound is faster the more incompressible the media (with the square root of bulk modulus) and is slower the more dense the media is.

- Resulting when two or more waves occupy the same space, interference is either constructive or destructive depending on whether the the waves are in phase or out of phase. Standing waves result from the interference of incident bounded waves combining with their own reflections.

WAVE FUNDAMENTALS WILL BE EXCEEDINGLY IMPORTANT LATER IN THE TOPICS OF ELECTROMAGNETIC RADIATION AND MODERN PHYSICS.

VIII.GRAVITATION

$$F = G\frac{m_1 m_2}{r^2}$$

The gravitational force between two masses is directly proportional to the masses and inversely proportional to the square of the distance between their centers of mass.

$$g = G\frac{m}{r^2}$$

The gravitational field of a mass permeates the space surrounding the object, representing the force that would be exerted per hypothetical mass at a location.

First Law - The Orbital Rule

Each planet moves in an elliptical orbit about the sun with the sun at one of the focal points of the ellipse.

Second Law - The Area Rule

The radius vector from the sun to the planet sweeps out equal areas in equal times.

Third Law - The Period Rule

The square of the orbital period and the cube of the ellipse's semimajor axis have the same ratio for all the planets in the solar system.

$$T^2 = \left(\frac{4\pi^2}{GM_{sun}}\right) a^3$$

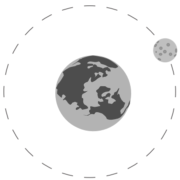
$$U_g = -G\frac{m_1 m_2}{r}$$

A system of two masses can store gravitational potential energy. As they are moved apart, work is done against gravitiy, work becoming stored potential energy.

- Gravitational force is a fundamental force, a mutual attraction of all bodies. Every mass attracts every other mass. Gravitational force is given by Newton's Law of Universal Gravitation:

  $$F = G\frac{m_1 m_2}{r^2}$$

  Gravitational force is directly proportional to the masses and inversely proportional to the square of the distance betwen them.



- Just as we can discuss a specific force between two masses, we can also single out the *gravitational field* of a single mass, permeating space around it, representing its capacity to exert gravitational force on other masses.

- Two masses form a system that can store energy. The work that must be done to completely separate them is the binding energy of the system.

YOU SHOULD BE ABLE TO ANALYZE GRAVITATIONAL SYSTEMS IN TERMS OF FORCE, FIELD, AND POTENTIAL ENERGY.

IX. HEAT AND TEMPERATURE

Zeroth Law: If two bodies are each in thermal equilibrium with a third body, then all three bodies are in thermal equilibrium with each other.

$$T_c = \frac{5}{9}(T_f - 32)$$
$$T_f = \frac{9}{5}T_c + 32$$

Conversion between the Celsius and Fahrenheit temperature scales

$$T = T_c + 273.15$$

The Kelvin temperature is the true thermodynamic temperature.

$$\Delta l = \alpha\, l_0\, \Delta T$$

Linear expansion

$$\Delta A = 2\alpha\, A_0\, \Delta T$$

Area expansion

$$\Delta V = \beta\, V_0\, \Delta T$$
$$\Delta V = 3\alpha\, V_0\, \Delta T$$

Volume expansion

$$Q = m\, c\, \Delta T$$

Specific heat, c, tells how many joules per gram to raise the temperature one degree kelvin

$$Q = n\, C\, \Delta T$$

Molar heat capacity, C, tells us how many joules per mole to raise the temperature one degree kelvin

$$\frac{Q}{t} = K\, A\, \frac{\Delta T}{\Delta x}$$

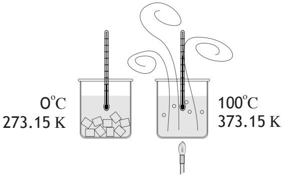
Rate of heat flow by conduction

$$\frac{Q}{t} = A\varepsilon\sigma T^4$$

Rate of heat flow by radiation

- Temperature is the property of a body that determines the direction of heat flow when it is brought into thermal contact with another body.

- Both the Celsius and Kelvin temperature scales are 'centigrade': 100 degrees separate the freezing and boiling points of water. However, the Kelvin scale is a true thermodynamic temperature scale. Zero on the Kelvin scale is absolute zero.



- *Heat capacity* is heat flow required to change a body's temperature one degree. *Specific heat* is heat capacity per gram. *Molar heat capacity* is per mole.

- Heat flow can occur by *conduction*, *convection*, or *radiation*. The rate of conduction depends on the surface area, the conductivity of the material, the thickness and the temperature gradient. The rate of emission of radiation depends on the area of the emitter, its emissivitiy, and the temperature.

THE ZEROTH LAW IS THE BASIS TO DEFINE TEMPERATURE IN TERMS OF THE DIRECTION OF HEAT FLOW. IN THE TOPIC OF KINETIC THEORY, LATER WE WILL DISCUSS HOW THE KELVIN TEMPERATURE RELATES TO THE TRANSLATIONAL KINETIC ENERGY OF THE MOLECULES.

X. THE IDEAL GAS AND KINETIC THEORY

i. *The Gas Laws* 220-229

$$P_1V_1 = P_2V_2$$

Boyle's Law - At constant temperature the pressure of an ideal gas is inversely proportional to its volume, i.e. PV = constant.

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Charles's Law - At constant pressure the volume of an ideal gas is inversely proportional to its temperature, i.e. V/T = constant.

$$PV = nRT$$

The Ideal Gas Law - The ideal gas law completely defines the macrostate of an ideal gas in terms of the thermodynamic state funcitons, pressure, volume, and temperature.

ii. *Kinetic Theory* 230-238

$$\tfrac{1}{2}m\overline{v^2} = \tfrac{3}{2}kT$$

The average kinetic translational kinetic energy per molecule is directly proportional to the temperature.

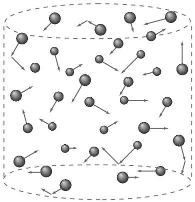
$$U = \tfrac{3}{2}nRT \qquad U = \tfrac{3}{2}NkT$$

An ideal gas only contains internal energy in the form of the translational kinetic energy of the moledcules. Therefore, the internal energy of an ideal gas is directly proportional to the temperature.

$$\frac{\overline{v}_A}{\overline{v}_B} = \frac{\sqrt{m_B}}{\sqrt{m_A}}$$

For two ideal gas samples at the same temperature, average molecular speed (root mean square speed) is inversely proportional to the square root of particle mass.

- An ideal gas is a theoretical construct created by conceptualizing a gas that perfectly obeys the gas laws at all temperatures and pressures. For an ideal gas, the particles themselves are point masses of negligible volume with negligible force existing between particles. All collisions within the gas are perfectly elastic. Real gases behave most like an ideal gas at high temperature and low pressure.



- The *macrostate* of an ideal gas is described with the gas laws. The relationship of pressure, volume, and temperature in an ideal gas is described by the Ideal Gas Equation (and the related Boyle's Law and Charles's Law). The *microstate* of an ideal gas, the description at the particle level, is the subject of kinetic theory. One of the principles of kinetic theory is that internal energy in an ideal gas only exists in the form of the translational kinetic energy of the particles.

USE YOUR CONCEPTUAL IMAGINATION TO PICTURE THE IDEAL GAS. MOVE BETWEEN THE MACROSTATE AND MICROSTATE PERSPECTIVES. WORK TO GET A CLEAR, CONCRETE SENSE OF THE MEANING OF THE PRESSURE, VOLUME AND TEMPERATURE.

XI. FIRST LAW OF THERMODYNAMICS

i. *Energy Conservation in Thermodynamic Systems* 239-245

$$\Delta U = Q - W$$
$$= Q - P^{*}\Delta V$$

The First Law of Thermodynamics - The internal energy change of a thermodynamic system exactly equals the net energy exchange of the system with its surroundings through heat flow and work.

*Work is performed by the system exerting pressure through a change in volume. If the pressure is constant, the work is the simple product of the pressure and the change in volume.

ii. *Model Thermodynamic Transformations* 246-255

$$Q = 0$$
$$\Delta U = -W$$

In an *adiabatic process* no heat flow occurs. The internal energy change equals the work per-

$$\Delta U = 0$$
$$Q = -W$$

In an *isothermal process* the temperature is constant. For an ideal gas, this means constant internal energy. Any heat flow is compensated by work.

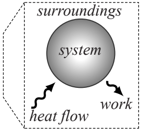
$$W = 0$$
$$\Delta U = Q$$

In an *isovolumetric process* no work occurs. The internal energy change equals the heat flow.

$$W = P\,\Delta V$$
$$\Delta U = Q - P\,\Delta V$$

An *isobaric process* has constant pressure. (This makes the work term easy to compute.)

- The First Law of Thermodynamics states that the change in the internal energy of a thermodynamic system is the sum of the energy gained or lost through these two modes of energy exchange, heat flow and work.



The first law interprets the situation at left. Heat flow into the system exceeds the work performed. Therefore, the system gains internal energy.

- In an *adiabatic* process, no heat flow occurs. Internal energy change corresponds to the work.
- In an *isothermal* process, the temperature is constant. For an ideal gas, this means that the internal energy is constant. If heat flows in, the system must be losing an equal amount of energy through work. Likewise, if work is being performed on the system in an isothermal process, heat must be flowing out.
- In an *isovolumetric* process, no work is performed $(W = P\,\Delta V)$. The system gains or loses energy only through heat flow.
- An *isobaric* process occurs with constant pressure.

MANY STUDENTS MAKE A MISTAKE IN THINKING THAT THE KEY TO LEARNING THIS MATERIAL IS TO MEMORIZE ALL THESE FORMULAS. CONCENTRATE ON UNDERSTANDING THE FUNDAMENTAL CONCEPTS FIRST AND THE FORMULAS WILL SEEM LIKE COMMON SENSE.

XII. HEAT ENGINES & THE 2ND LAW OF THERMODYNAMICS

i. ***Thermodynamic Cycles and Efficiency*** *255-259*

$$\varepsilon = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{Q_c}{Q_h}$$

$$\varepsilon = \frac{T_h - T_c}{T_h} = 1 - \frac{T_c}{T_h}$$

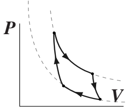
The thermal efficiency of a heat engine is the ratio of net work to heat input through one cycle. If heat input and output occur at constant temperature, thermal efficiency can be expressed in terms of the temperatures of the hot and cold reservoirs. The hotter the hot sink and the colder the cold sink, the more efficient the engine.

$$\mathrm{COP} = \frac{Q_h}{W} = \frac{T_h}{T_h - T_c}$$

A heat pump is a heat engine operating in reverse, using work to move heat from a cold sink to a hot sink. The Coefficient of Performance measures the ratio of work input to heat expelled.

ii. ***The Carnot Cycle***...*260-263*

The Carnot Cycle represents the most efficient possible heat engine. The system expands isothermally at T_h taking in Q_h. Then it expands adiabatically, the temperature decreasing from T_h to T_c. The system then compresses isothermally at T_c expelling Q_c. Then it compresses adiabatically with the temperature increasing from T_c to T_h.



iii. ***Entropy and the Second Law of Thermodynamics*** *264-270*

Entropy represents the state of microscopic disorder in a thermodynamic system. For a reversible pathway, the entropy change can be determined from the heat flow and the temperature. Total entropy in the universe always increases.

$$\Delta S = \frac{\Delta Q_r}{T}$$

- A heat engine operates through a cycle, converting some of the heat it takes in to macroscopic work and discarding the rest in a cold reservoir.
- The efficiency of a heat engine is the ratio of net work to input through one cycle. Either making the hot sink hotter or the cold sink colder would increase the efficiency of a heat engine.
- A heat pump employs work to move heat from a cold sink to a hot sink. The smaller the temperature difference, the greater the heat pumps coefficient of performance (the less work is required to deliver a given amount of heat to the hot sink).
- The Carnot cycle is the most efficient possible heat engine. It consists of four stages: isothermal expansion, adiabatic expansion, isothermal compression, adiabatic compression.
- According to the 2nd Law of Thermodynamics, the entropy, or disorder in the universe, is always increasing.

AS A TOPIC, HEAT ENGINES & THE 2ND LAW OF THERMODYNAMICS IS BOTH DIFFICULT (FOR MOST STUDENTS) AND IMPORTANT. GO STEP BY STEP. MAKE SURE YOU UNDERSTAND EACH STAGE BEFORE YOU TRY TO TACKLE THE NEXT ONE.

XIII. ELECTRICITY

i. ***Electrostatic Force*** *271-279*

$$F = k\frac{q_1 q_2}{r^2}$$

Coulomb's Law for the electrostatic force between two point charges: Force is proportional to each charge and inversely proportional to the square of the distance between them.

ii. ***Electric Fields*** *280-286*

$$E = \frac{F}{q_t}$$

The electric field predicts the force that would exert on a test charge.

$$E = k\frac{q}{r^2}$$

Electric field around a point charge.

$$\Phi_g = \frac{q}{\varepsilon_0}$$

Gauss's Law

iii. ***Electric Potential Energy*** *287-292*

$$U_e = k\frac{q_1 q_2}{r}$$

The electrostatic potential energy between two point charges is zero at $r = \infty$. U increases as like charges are brought together and decreases below zero as unlike charges are brought together.

iv. ***Electric Potential - Voltage*** *293-298*

$$V_B - V_A = \frac{\Delta U}{q_t}$$

Voltage tells us the work a field can do on a test charge.

$$V_B - V_A = k\,q\left[\frac{1}{r_B} - \frac{1}{r_A}\right]$$

The potential difference of two points in space near a point charge.

$$V_B - V_A = E\,d$$

Potential difference between parallel charged plates.

$$C = \frac{Q}{V}$$

Capacitance reflects the relationship between charge density, geometry and voltage.

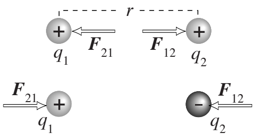
$$C = 4\pi\varepsilon_0 R$$

Capacitance of a spherical shell.

$$C = k_d\frac{\varepsilon_0 A}{d}$$

Capacitance of parallel charged plates.

- Like charges repel each other and unlike charges attract. The electrostatic force between point charges is directly proportional to the product of the two charges and inversely proportional to the square of the distance between the particles.



- While *force* describes a specific interaction between charged particles, the *electric field* describes the ability of a charge or charge distribution to exert force. This ability, the field, permeates the space around the charge.
- An electrostatic system of two or more charges can store energy. Unlike charges store energy equal to the work required to pull them apart. Like charges store energy equal to the work required to push them together.
- While *potential energy* describes the state of a specific system, *electric potential or voltage* describes the ability of an electric field to perform work between two points in space.

THE S.I. UNITS IN ELECTRICITY ARE AN ESPECIALLY USEFUL CONCEPTUAL SHORTHAND. THE ELECTRIC FIELD IS MEASURED IN NEWTONS OF FORCE PER COULOMB OF (TEST) CHARGE. VOLTAGE IS MEASURED IN JOULES PER COULOMB (VOLTS).

XIV. DC CURRENT

$V = IR \quad I = \frac{V}{R}$ Ohm's Law: The current is directly proportional to the voltage and inversely proportional to the resistance.

$R = \frac{L}{\sigma A} = \rho \frac{L}{A}$ A uniform conductor's resistance increases with length and decreases with cross-sectional area and conductivity, an intrinsic property, the reciprocal of resistivity.

$P = IV = I^2R = \frac{V^2}{R}$ Power is the rate of energy consumption. Each different way of expressing power in terms of the current parameters highlights a separate, important concept.

$R_{ser} = R_1 + R_2 + R_3 + \cdots$

Resistance of resistors in series.

$\frac{1}{R_{par}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$

Resistance of resistors in parallel.

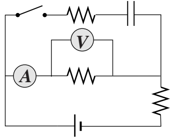
$\frac{1}{C_{ser}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots$

Capacitance of capacitors in series.

$C_{par} = C_1 + C_2 + C_3 + \cdots$

Capacitance of capacitors in parallel.

- Ohm's Law describes the relationship between the voltage across a conducting element, its resistance, and the current through it. Current is directly proportional to voltage and inversely proportional to resistance.
- Kirchhoff's Rules are simple, but very powerful, analytical tools for interpreting circuits:
  1) The sum of the currents into a junction equals the sum of currents out of the junction.
  2) The sum of the changes in potential around any closed path is zero.



- Power (joules per second) is the product of the voltage (joules per coulomb) and the current (coulombs per second). With constant voltage, if the resistance is decreased, the power increases because of the higher current.
- Placing resistors in series *increases* resistance, while placing resistors in parallel *decreases* resistance.
- Placing capacitors in series *decreases* capacitance, while placing capacitors in parallel *increases* capacitance.

HELPFUL TIPS WITH DC CIRCUITS: 1) REMEMBER HOW THE UNITS ARE BUILT UP (A VOLT IS A JOULE PER COULOMB; AN AMPERE IS A COULOMB PER SECOND . . .) 2) BE PATIENT WITH COMPLICATED CIRCUITS. OHM'S LAW AND KIRCHHOFF'S RULES CAN UNPACK IT FOR YOU.

XV. MAGNETISM

$F = qB\, v \sin\theta$ The magnetic force on a particle with velocity perpendicular to a magnetic field.

$r = \dfrac{mv}{qB}$ A particle moving perpendicular to a magnetic field experiences a centripetal magnetic force leading to uniform circular motion.

$F = L B I \sin\theta$ Magnetic force on a segment of current carrying conductor.

$\tau = IAB \cos\phi$ Torque on a current loop within a uniform magnetic field.

$B = \dfrac{\mu_0 I}{2\pi d}$ The magnetic field of a straight wire.

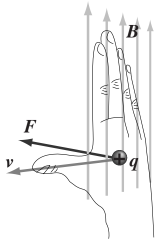
$B = \dfrac{\mu_0 I}{2r}$ At the center of a current loop.

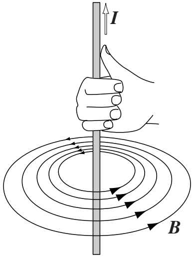
Within a solenoid. $B = n\mu_0 I$

Ampere's Law - Describes the relationship between a current and the magnetic field it produces. For any closed loop path, the sum of the products of the length elements and the magnetic field in the direction of the length elements is proportional to the electric current enclosed in the loop.

Magnetism in Matter - Weakly attracted by magnetic fields, **paramagnetic** substances contain unpaired electrons within atomic or molecular orbitals. Substances in which all electrons are paired are **diamagnetic**. Diamagnetic substances are very, very weakly repelled by magnetic fields. With electron spins that can align cooperatively in domains, **ferromagnetic** substances can be permanently magnetized. Ferromagnetism is much stronger than paramagnetism.

Right Hand Rules





- **Magnetic Force -** The magnetic force is perpendicular to both the magnetic field and the particle's velocity (or the component of the velocity perpendicular to the field).

- **Magnetic Field -** The lines of a magnetic field form a closed loop around a current element.

THE ODD GEOMETRIES CAUSE MAGNETISM TO BE INTUITIVELY STRANGE. THIS STRANGENESS IS EASIER TO ACCEPT AFTER LEARNING THAT MAGNETISM IS THE RELATIVISTIC FLIP-SIDE OF ELECTRICITY. MAGNETIC FIELDS HAVE TO DO WITH HOW ELECTRIC FIELDS LOOK TO PARTICLES MOVING AT RELATIVISTIC SPEEDS.

XVI. ELECTROMAGNETIC WAVES

$$c = \frac{E}{B}$$

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

Light waves are transverse waves that consist of electric and magnetic field oscillations perpendicular to each other and to the direction of propagation. The speed of light equals the ratio of instantaneous electric field strength to magnetic field strength within the waves, a ratio determined by the electric permittivity and magnetic permeability of the medium. When the medium is empty space, the speed of light is c.

$$c = f\lambda$$

In the case of light travelling through a vacuum, $c = 3 \times 10^8$ m/s. (Wave speed is the product of frequency and wavelength.)

$$\theta_i = \theta_i'$$

With regular reflection , the angle of reflection equals the angle of incidence.

$$n_1 \sin\theta_i = n_2 \sin\theta_r$$

Refraction is the bending of light transversing the boundary between media. Angle of incidence and angle of refraction are related by Snell's Law.

$$n = \frac{c}{v}$$

The index of refraction for a medium is determined by the speed of light within that medium. Slower media are more refractive.

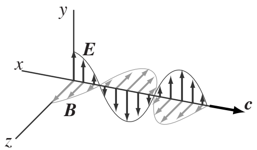
$$\frac{v_2}{v_1} = \frac{n_1}{n_2} \qquad \frac{\lambda_2}{\lambda_1} = \frac{v_2}{v_1} \qquad \frac{\lambda_2}{\lambda_1} = \frac{n_1}{n_2}$$

The speed of light through a medium is inversely proportional to its index of refraction. Frequency stays the same, so wavelength changes between media.

$$\sin\theta_c = \frac{n_2}{n_1}$$

At the interface between a slow and fast medium, internal reflection occurs if the angle of incidence exceeds the critical angle.

- Electromagnetic radiation consists of electric and magnetic field oscillations propagating through space.



- The speed of light within a medium depends on the electric permittivity and magnetic permeability of the medium (ε and μ). To make a conceptual start, think of these quantities as the inherent capacitive and inductive 'responsiveness' of the medium.
- Light impinging on the interface between two media may be either reflected or refracted. In refraction, the light ray changes direction as it enters the new substance. If the light is moving from a fast to a slow medium, refraction bends the light towards the normal. If light is moving from a slow to a fast medium, refraction is away from the normal. In the latter case, if the angle of incidence is greater than the *critical angle*, internal reflection occurs.

A SOPHISTICATED GRASP OF THE PROPAGATION OF LIGHT IS HONESTLY A FEW STEPS BEYOND 1ST YEAR COLLEGE PHYSICS. AT THIS LEVEL, A DISTURBING SENSE THAT YOU AREN'T REALLY 'GETTING IT' CAN'T BE HELPED, DON'T LET YOURSELF BE INTIMIDATED.

XVII. GEOMETRIC OPTICS

A virtual image is created when rays of light appear to originate from an image point. With a real image, rays of light actually intersect at the image point.

$$\frac{1}{F} = \frac{1}{I} + \frac{1}{O}$$

The focal length of the optical device determines the relationship between image distance and object distance.

$$M = \frac{-I}{O}$$

The magnitude of lateral magnification equals the ratio of image to object distance (if negative, the image is inverted). A single convex mirror or diverging lens has negative focal length and always form images that are DEV, diminished, erect, virtual.

$$\frac{1}{F} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

The focal length of a lens is governed by the index of refraction and the radii of curvature of the two lens surfaces.

$$m = \frac{\theta}{\theta_0}$$

Angular magnification

$$m_{max} = 1 + \frac{25\text{ cm}}{F}$$

Simple Magnifier

$$m = -\frac{L}{F_0}\left(\frac{25\text{ cm}}{F_E}\right)$$

Compound Microscope

$$m = \frac{\theta}{\theta_0} = \frac{F_O}{F_E}$$

Astronomical Telescope

- Optical devices create images by reflecting or refracting light. With a *virtual image*, the rays of light do not intersect at the image point but appear to originate from the image point. With a *real image*, the rays of light actually intersect at the image point. A real image can be cast on a screen.

- With concave mirrors or converging lenses, if the object distance is greater than the focal length, the image produced is real. If the object distance is less than the focal length, the image is virtual.

- Convex mirrors and diverging lenses normally produce images that are DEV (diminished, erect, virtual).

- To solve problems with optical devices consisting of multiple lenses or mirrors, take the image of the first lens as the object of the next.

ON COMPREHENSIVE EXAMS LIKE THE AP PHYSICS EXAM OR THE MCAT, QUANTITATIVE PROBLEMS FROM GEOMETRIC OPTICS ARE MUCH LESS FREQUENT THAN CONCEPTUAL QUESTIONS. OFTEN THE QUESTION IS TO PREDICT THE KIND OF IMAGE PRODUCED BY AN OPTICAL DEVICE.

XVIII. WAVE OPTICS

$d \sin\theta = m\lambda$ $(m = 0, \pm 1, \pm 2, \ldots)$ In double slit interference, constructive interference occurs where path difference is an integral number of wavelengths

$y_{br} = \dfrac{\lambda D}{d} m$ $(m = 0, \pm 1, \pm 2, \ldots)$ Vertical position of bright fringes depends on λ, screen distance, and slit separation. Note: closer slits widen the pattern.

$2t = (m + \frac{1}{2})\lambda_n$ $(m = 0, 1, 2, \ldots)$ With thin films, bright fringes occur where twice film thickness is an integral number of wavelengths (offset 1/2 λ for a phase change at one interface here).

$\Delta x = \dfrac{n\lambda}{2}$ Michelson Interferometer fringe shifts.

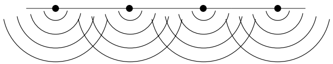
$\sin\theta = \dfrac{n\lambda}{w}$ $(n = 0, \pm 1, \pm 2, \ldots)$ The angular positions of *dark* fringes in single slit diffraction, produced by interference from different portions of the same aperture.

$d \sin\theta = m\lambda$ $(m = 0, 1, 2, 3, \ldots)$ A diffraction grating is similar to double slit interference, but resolution is much greater.

With plane polarized light, the electric field vibrates in a single plane perpendicular to wave propagation.

$\tan\theta_B = \dfrac{n_2}{n_1}$ (if $n_1 \sim 1$) $\tan\theta_B = n_2$ Reflection is one way to produce polarized light. Light reflected at Brewster's angle is completely polarized.

- *Huygen's principle* is fundamental to wave optics, every point on a wave front acts as a source of spherical wavelets. Wave front propagation is seen as the wavelets combining and recombining to create the wave front within the progression of time. Huygen's principle is helpful to explaining diffraction, which is the ability of waves to bend around corners, and refraction.



- While each has its own complexities, for the most part the model systems for studying interference, Young's double slit, thin films, the Michelson interferometer, and diffraction gratings, all involve light arriving at a certain point by different pathways, where constructive or destructive interference occurs depending on the path difference. (Single slit diffraction is a bit more complicated because interference occurs with light from different portions of the same aperture.)
- Polarization is a separate topic of wave optics. With plane polarized light, the electric field vibrates in a single plane perpendicular to wave propagation.

OF ALL TOPICS IN PHYSICS, WAVE OPTICS IS PROBABLY THE ONE WITH THE BIGGEST DIFFERENCE BETWEEN HOW DIFFICULT STUDENTS THINK IT IS TO UNDERSTAND AND HOW EASY IT REALLY IS. TAKE YOUR TIME. THIS IS NOT A HARD TOPIC.

XIX. MODERN PHYSICS

i. *Quantum Theory of Light* 384-390

$E = hf$ Photon energy is directly proportional to frequency.

$K_m = hf - \phi$ Photoelectric effect - the maximum kinetic energy of an emitted electron.

$\Delta\lambda = \frac{h}{mc}(1 - \cos\theta)$ Compton effect - the shift in scattered X-ray wavelength.

ii. *Wave Mechanics and Atomic Theory* 391-404

$E = -\frac{2\pi^2 m Z^2 e^4}{n^2 h^2} = -\frac{13.6\text{ eV}}{n^2}$ Bohr theory - quantized energy of electron orbitals in hydrogen.

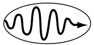
$\lambda = \frac{h}{p} = \frac{h}{mv}$ De Broglie wavelength decreases with greater particle momentum.

$\Delta x\,\Delta p \geq \hbar$ Heisenberg uncertainty principle.

Quantum numbers $n = 1, 2, 3, \ldots$ $l = 0, 1, 2, \ldots, n-1$

$m_l = -l\ldots -2, -1, 0, 1, 2, \ldots l$ $m_s = \frac{1}{2}$ or $-\frac{1}{2}$

- At the beginning of the 20th century two new theories, the theory of relativity and quantum mechanics, revolutionized physics.
- Special relativity overthrew the concepts of absolute space and time. The theory derives from two postulates. (1) Physical laws are the same for all observers in uniform relative motion. (2) The speed of light in a vacuum is the same for all observers. The coordinates of space and time used by different observers are related by the concepts of *time dilation* and *length contraction*.
- Quantum mechanics introduced the principle that certain physical quantities only assume discrete values. Quantum mechanics was introduced by Planck who postulated that a radiation source (black-body) only lost energy in discrete packages. Early advancements included Einstein's description of the *photoelectric effect* and the description of the *Compton effect* was also seminal.
- Beginning with Bohr's theory of the hydrogen atom, quantum mechanics have been successful in descibing the electronic structure of the atom. The wave mechanics of De Broglie, Heisenberg, and Schrödinger introduced to concept of particle-wave duality.



RELATIVITY THEORY AND QUANTUM MECHANICS BOTH HAVE COUNTER-INTUITIVE ELEMENTS. IT IS ONLY NATURAL FOR YOUR MIND TO REQUIRE TIME AND CONDITIONING BEFORE IT CAN ANTICIPATE THE RESULTS OF THESE THEORIES.

XX. NUCLEAR PHYSICS

A nucleus consists of protons and neutrons held together by the strong nuclear force. A nucleus is characterized by chemical symbol, X, atomic number, Z, mass number, A, and neutron number, N.

If a given nucleus possesses either an odd mass number or an odd atomic number, it will have a quantized spin momentum and a quantized spin magnetic moment.

Alpha Decay

$^{226}_{88}\mathbf{Ra} \longrightarrow {}^{222}_{86}\mathbf{Rn} + {}^{4}_{2}\mathbf{He}$

Beta Decay

$^{14}_{6}\mathbf{C} \longrightarrow {}^{14}_{7}\mathbf{N} + {}^{0}_{-1}\beta^{-} + \bar{v}$

$^{13}_{7}\mathbf{N} \longrightarrow {}^{13}_{6}\mathbf{C} + {}^{0}_{1}\beta^{+} + v$

Electron Capture

$^{7}_{4}\mathbf{Be} + {}^{0}_{-1}\mathbf{e} \longrightarrow {}^{7}_{3}\mathbf{Li} + v$

Gamma Decay

$^{125}_{53}\mathbf{I}^{U} \longrightarrow {}^{125}_{53}\mathbf{I} + \gamma$

Activity

$$A = \frac{\Delta N}{\Delta t} = -\lambda N$$

Exponential Decay

$$N = N_0 e^{-\lambda t}$$

Half Life

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

$$Q = \Delta m c^2$$

Energy change directly corresponds to a mass change via Einstein's mass-energy equivalence.

$$E_b = [Zm_p + Nm_n - M_{Nu}] \times c^2$$

Binding energy compares the mass energy of a nucleus to the mass energy of free nucleons.

Nuclear fusion occurs when two light nuclei combine to form a heavier nucleus. Nuclear fission occurs when a heavier nucleus splits into two smaller nuclei.

- The nucleus contains *nucleons*, positively charged *protons* and neutrally charged *neutrons*, bound together in the nucleus by the *strong nuclear force*.
- A nucleus may possess a net quantized spin magnetic moment. Nuclear spin is the basis of the technology of nuclear magnetic resonance (NMR) spectroscopy.
- Radioactive substances emit three kinds of radiation: alpha (α) decay is the emission of an α particle, consisting of two protons and two neutrons; beta (β) decay is the emission of β particles (β^-,electrons, or β^+,positrons); gamma (γ) decay is the emission of extremely high energy photons (gamma rays). Half-life is an important concept for tracking the progress of radioactive decay in time.
- All nuclear reactions involve a change in rest-mass, which corresonds to energy change via Einstein's mass energy equivalence.
- Nuclear fusion occurs when two light nuclei combine to form a heavier nucleus. Nuclear fission occurs when a heavier nucleus splits into two smaller nuclei. Because fission of $^{235}_{92}\mathbf{U}$ is initiated with the capture of a neutron and two or three neutrons are typically produced, the fission of a $^{235}_{92}\mathbf{U}$ nucleus can lead to a chain reaction.

UNDERSTAND WHAT LEADS A NUCLEUS TO BE UNSTABLE AND LEARN THE KINDS OF DECAY. MOST OF THE REST OF THE MATERIAL WILL FOLLOW AS A LOGICAL PROGRESSION.