Phil's Orderly Physics Curriculum Important Concepts List (POPCICL) 1B

[Warning : This list is not intended to be comprehensive, but rather to highlight a few key concepts]

Charge & Electric Force

There are only two types of charges : positive charge and negative charges.

Opposite charges attract each other. Like charges repel each other.

With the exception of neutrons, all neutral objects are made of equal numbers of positive and negative charges.

A special characteristic of charge is that it is conserved (similar to energy and momentum).

Charge is quantized. The smallest possible isolated charge is the charge of an electron (or a proton).

The unit of charge is the Coulomb. An electron has a charge of -1.6×10^{-19} C

A conductor is a material in which many of the charges are free to move throughout the material.

An insulator is a material in which the charges are not free to move throughout the material.

The electric force between two charged particle is described by Couloumb's Law : $F_e = k_e q_1 q_2 / r^2$.

The electric force between two particles acts along the line that connects the centers of both charges.

The strength of the electric force falls off quadratically with distance.

The electric force obeys the superposition principle. The net electric force on a charged particle due to a collection of charges is the vector sum of the electric forces between the charged particle and every other charge, taken one pair at a time.

Electric Field

Electric force can be viewed as a two-step process: A source charge produces an electric field that permeates space, and a test charge some distance away experiences a force due to that electric field.

The electric field at some distance, r, from a charge Q is given by $E = k_e Q / r^2$.

The electric field is a map of the force that would be experienced by a +1C test charge placed at any location.

The elctric field is a vector quantity with the units of newtons per coulomb (N/C).

The electric field points away from positive charges and towards negative charges.

The electric field is the electric force on a test divided by the magnitude of that test charge. : $E = F_e/q_0$

The electric field obeys the superposition principle. The net electric field due a collection of charges is the vector sum of the electric fields due to the individual charges considered one-at-a-time.

Electric fields are visualized by electric field lines that originate on positive charges (or at ∞, for a single isolated positive charge) and terminate on negative charges (or at ∞, for a single isolated negative charge)

The number of electric field lines that originate/terminate on a particle is proportional to its charge.

The density of electric field lines is proportional to the local magnitude of the electric field

The tangent to the electric field lines represents the local orientation of the electric field.

Electric field lines can never cross. The direction of the electric force is unique at each point.

The electric field above a uniform, infinite plane of charge points straight towards or away from the plane.

The electric field due to a uniform, infinite filament of charge points radially inward or outward from the filament.

The electric field due to a uniform sphere or uniform spherical shell of charge points spherically inward or outward from the center of the sphere.

If a charged particle of mass, m, and charge, q_0, is place in an electric field, E, it will experience an acceleration given by Newton's second law : $a = F_e / m = q_0 E / m$

Electric Flux

Electric flux is a measure of the perpendicular component of the electric field passing through a surface area.

Electric flux is proportional to the number of electric field lines that cross a surface.

Electric flux depends on the magnitude of the electric field, and the area and orientation of the surface.

$$\Phi_E = \int \vec{E} \cdot d\vec{A}.$$

The area vector of a surface has a magnitude equal to the surface's area and a direction that is perpendicular to the surface. The area vector points outward for closed surfaces.

Gauss's Law states that the electric flux through any closed surface is equal to the net enclosed charge (divided by the constant, ε_0). $\Phi_E = q_{enc}/\varepsilon_0$

For charge distribution with sufficient symmetry (infinite plane or filament, sphere, or spherical shell), you can equate combine Gauss's Law with the definition of flux to determine the electric field at a particular location relative to the charge distribution. $\Phi_E = \int \vec{E} \cdot d\vec{A} = q_{enc}/\varepsilon_0$

Electrostatic Equilibrium

In steady state, the electric field is zero everywhere inside of a solid or hollow conductor

In steady state, any excess charge (positive or negative) on a conductor will reside entirely on its outer surface.

In steady state, the electric field immediately outside a conductor is pependicular to the local surface.

In steady state, excess charge density on the surface of an irregularly-shaped conductor will be greatest at edges, sharp points, or tightly curved corners. The electric field outside the conductor will be more concentrated around these sharp regions of high charge density.

Electric Potential Energy & Electric Potential

A pair of charges has an electric potential energy that is inversely proportional to the separation between them.

Potential energy can be thought of as the potential to gain kinetic (or some other) energy by converting it from the energy stored in a particular configuration.

Two unlike charges have the greatest potential energy when they are very far apart.

Two like charges have the greatest potential energy when they are very close together.

Electric potential (voltage) can be thought of as a map of the electric potential energy that would be experienced by a standard +1C test charge if it were placed at any location relative to other charges.

Electric potential (voltage) is a scalar quantity. The voltage due to multiple charges is the algebraic sum of the electric potential (voltage) due to each charge individually.

When a test charge moves from a position at one electric potential (voltage) to another, its change in electric potential energy is given by : $\Delta U_e = q_0 \Delta V$

The electric potential energy is analogous to gravitational potential energy in the analogy to gravity.

The electric potential (voltage) is analogous to height in the analogy to gravity.

The electric field is analagous to the slope of an incline in the analogy to gravity : $E_x = dV / dx$

Equipotential lines indicate regions that are at the same value of electric potential (voltage) - they are analogous to contours of constant altitude on a geographic contour map.

The electric potential nearby a positive point charge is a large positive value and it decreases towards zero as you move infinitely far away from the positive point charge.

The electric potential nearby a negative point charge is a large negative value and increases (becomes less negative) towards zero as you move infinitely far away from the negative point charge.

Capacitors

A capacitor is a device that stores energy in the form of an electric field between two separated conductors.

Capacitance is a measure of charge per voltage. That is, the capacitance of a capacitor is the amount of charge that can be stored when a particular voltage is applied across its two conductors (plates).

Capacitance is measured in units of Farads, or more typically microFarads, nanoFarads, or picoFarads.

A vacuum-filled parallel plate capacitor is the simplest example of a capacitor consisting of two plates of area A separated by a gap of width d. Its capacitnce is given by $C = \varepsilon_0 A / d$.

There are three ways to increase the capacitance of a parallel plate capacitor : (1) increase the plate area, (2) decrease the plate separation, (3) insert a dielectric inisde the gap with high dielectric constant, $\kappa>1$.

Capacitors in parallel must have the same voltage difference across them.

Capacitors in parallel can be replaced by a parallel equivalent capacitor whose value is given by : $C_{eq} = C_1 + C_2 +...$

The charge on the parallel equivalent capacitor equals the sum of the charges on the capacitors that it replaces.

Capacitors in series must have the same charge on each capacitor.

Capacitors in series can be replaced by an series equivalent capacitor whose value is given by : $1/C_{eq} = 1/C_1 + 1/C_2 +...$

The voltage difference across the parallel equivalent equals the sum of those across the capacitors that it replaces.

The dielectric constant is a property of an insulator that describe how much it increases the capacitance of a capacitor when inserted between the plates.

The dieelctric strength is a property of an insulator that describes how strong of an electric field it can withstand before the material “breaks down” and becomes conducting. (a lightning strike occurs across it).

Electrical Current & Resistance

An electric current in a conductor is equal to the amount of charge that passes through a cross-sectional area of the conductor in a given period of time.

The SI unit for current is the Ampere. 1Ampere is equal to 1 Coulomb per second.

Microscopically, the average velocity of an electron in the direction of the current is called the drift velocity. The drift velocity is typically very slow compared the speed of an electrical signal in a circuit.

Electrical resistance, R, is a measure of how much a circuit element reduces the current through the circuit. Resistance on an element depends on both material (resistivity, ρ) and geometric (length, area) effects.

Electrical resistivity is a material property that depends only on the material used and its temperature.

Electrical resistivity generally increases with temperature. The temperature coefficient of resistivity, α, is a material-dependent property that describes the rate of change in resistivity with increasing temperature.

Electrical conducitivity, σ, is the inverse of electrical resistivity ($\sigma= 1/\rho$) .

A resistor is a circuit element that provides electrical resistance in a circuit.

If two or more resistors are connected in a single line with only simple wires (with no junctions) between them, then they are said to be connected in series.

Two or more resistors in series have an equivalent resistance given by : $R_{eq} = R_1 + R_2 + R_3 + \ldots$, and will be larger than any of the individual resistances.

If two or more resistors are connected so that the front (top) end of each resistor is connected to each other only by wires (through wire junctions) and the back (bottom) end of each resistor is connected to each other only by wires (through wire junctions), then they are said to be connected in parallel.

Two or more resistors in parallel havean equivalent resistance given by $(1/R_{eq}) = (1/R_1) + (1/R_2) + (1/R_3) +....$, and will be smaller than any of the individual resistances.

Batteries and Electric Circuits

Ohm's Law describes the a linear relationship between the voltage, current, and resistance in a circuit: $\Delta V = IR$. An ohmic material is one that obey's Ohm's Law.

An electrical circuit can be driven by an voltage source that provides the "push" on electrical charges so that they flow as current through the circuit.

An ideal voltage source is described by an EMF, $\mathcal{E}$, that serves as an "enforcer of voltage". An ideal EMF will provide whatever current is necessary to maintain its rated voltage difference across it.

A real battery can be visualized an ideal EMF in series with an "internal" resistance. The terminal voltage of a battery is taken across its external terminals an includes the effect of the internal resistance.

Because of its non-zero internal resistance, the terminal voltage of a real battery will be less than or equal to the ideal EMF, depending on the "load" (the effective resistance of the circuit to which it is attached).

The power associated with a circuit element may be calculated by the relationship : $P = I\Delta V$.

Power has the units of energy per time. The SI unit of Power is Watts. 1 Watt = 1 Joule / sec.

Circuits involving multiple voltage sources can be solved using Kirchhoff's Rules.

Kirchhoff's Current (Junction) Rule states that at any wire junction, the sum of the currents must equal zero. That is, the total current into the junction must equal to the total current out of the junction.

Kirchhoff's Voltage (Loop) Rule states that around any closed loop, the sum of the voltage differences must equal zero. To apply this rule, you must first (arbitrarily) choose a proposed direction for the current through each element and (arbitrarily) choose a direction (CW or CCW) for each loop.

Kirchhoff's Voltage (Loop) Rule, when the loop runs in the same direction as the current, then a battery or EMF provides an increase in voltage while a resistor provides a decrease in voltage. When the loop runs in the opposite direction of the current, then the reverse is true.

An RC circuit combines a resistor and a capacitor in a single circuit and introduces a characteristic time to the circuit. The characteristic time of an RC circuit is given by $\tau = RC$ and has the units of seconds.

When an EMF is connected to a series RC circuit, the current through the resistor is initially large but the charge on the capacitor is initially small (zero at the very first instant). As time progresses, the charge on the capacitor grows, as does the voltage across the capacitor; and as a result, the current through the resistor goes down. Eventually, the capacitor reaches a maximum charge of $Q = \mathcal{E} C$, the voltage across the capacitor becomes equal to that of the EMF source, $\mathcal{E}$, and the current through the resistor falls to zero.

When a previously-charged capacitor is connected in a closed loop to a resistor, then capacitor will discharge through the resistor. Initially, the current through the resistor is large, but as time progresses, both the charge on the capacitor and the current through the resistor gradually fall to zero.

The time-dependent behavior of RC circuits is characterized mathematically by exponential charging and discharging : $e^{-t/\tau}$, where $\tau = RC$.

Magnetic Forces & Fields

A magnetic field can be produced by moving charges, such as the current in a wire.

The magnetic field lines that describe the magnetic field around a straight current-carrying wire form circles centered on the wire and that circulate around the wire in a direction given by the current right-hand-rule.

The current right-hand-rule states that if your point your outstretched thumb along the wire in the direction of the conventional current, your fingers will curl in the circulation direction of the magnetic field lines.

The direction of the magnetic field at any point is tangent to the direction of the magnetic field line at that point.

Magnetic Forces & Fields (continued)

In the presence of a magnetic field, a moving charge will experience a magnetic force that is directed perpendicular to both the magnetic field and the instantaneous velocity vector of the particle. There are two possible directions for this perpendicular magnetic force (e.g., up/down, left/right, in/out, east/west, north/south). The appropriate choice between these two possible directions is given by the force right-hand-rule

The force right-hand-rule dictates that you fully open your right hand and align your fingers with the direction of the velocity vector (v) of the charged particle. You then roll your hand so that magnetic field vector (B) appears to point straight out of your palm. You should now be able to use your fingertips to “push (rotate)” the velocity vector into the direction of the magnetic field vector by curling your fingers into a closed fist. In this orientation, your outstretched thumb will point in the direction of the magnetic force on a moving POSITIVE charge. If the actual charge of the particle is negative, simply reverse the direction.]

The magnitude of the magnetic force on a moving charged particle is proportional to four quantities: (i) the charge of the particle, (ii) the charge's velocity, (iii) the magnitude of the magnetic field, and (iv) the sine of the angle between the magnetic field vector and the velocity vector.

A charged particle moving parallel or anti-parallel to a magnetic field will experience no magnetic force. A charged particle moving perpendicular to a magnetic field will be deflected with the maximal force.

In a uniform magnetic field, B, a charged particle or mass, m, moving with velocity, v, perpendicular to the magnetic field will undergo uniform circular motion with a radius, r, found by equating the magnitude of the magnetic force to the centripetal force required for that particular circular motion.

The sum of the magnetic force and electric force on a moving charged particle is called the Lorentz force. The electric force is independent of the charged particle's velocity, but the magnetic force is dependent on the charged particle's velocity.

A region that contain both a magnetic field and an electric field oriented perpendicular to each other, can act as a velocity selector for particles injected perpendicular to both fields.

A mass spectrometer utilizes a velocity selector followed by the circular motion of a particle in a magnetic field to separate charged molecules and atoms based on the charge-to-mass ratio.

A current-carrying wire in a magnetic field will experience a force on the wire whose magnitude is proportional to four quantities: (i) the current, I, (ii) the length, l, of the wire exposed to the field, (iii) the magnitude of the magnetic field, and (iv) the sine of the angle between the directions of the magnetic field and the current.

For a loop of current, the magnetic field inside the loop due the current will all be directed in the same general direction (upwards vs downward), but is non-uniform and divergent (angles away from the center)

We can associate a “magnetic moment” vector, (mu vector) with a current loop which has a magnitude proportional to the current and the area of the loop, and whose direction is given by the right-hand-rule. (curl your right fingers in the sense of the current loop; your outstretched thumb aligns with the mu-vector)

An (infinitely) long, tightly wound spiral of current is called an (ideal) solenoid. The solenoid has a uniform magnetic field inside of it that is all directed parallel to the axis of the solenoid.

A loop of current in an external magnetic field can experience a torque that will cause it to rotate to align with the magnetic field in such a way that maximizes the loop area through which magnetic field lines pass. (i.e., so that its magnetic moment vector aligns with the magnetic field)

Biot-Savart Law and Ampere's Law

The magnitude of the magnetic field due to a current can be found by two different methods : Biot-Savart law or Ampere's Law.

The Biot-Savart law gives us the infinitesimel magnetic field contribution at a point, P, some distance, r, from an infinitesimal segment (ds) of a wire carrying a current, I.

We can find the total magnetic field due to any wire by integrating the contributions given by Biot-Savart's law along the entire length of the wire.

Ampere's law allows us to easily calculate the magnetic field due to current-carrying wires if the wire configuration has sufficient symmetry, such as a single long straight wire, a solenoid, or a toroid.

To apply Ampere's law, draw an imaginary amperian loop that encircles some cross-section(s) of the current carrying wire in a way that the magnetic field is known (by symmetry) to be constant or zero over different segments of the loop.