Introduction: DC Circuits

Unit: DC Circuits

Topics covered in this chapter:

This chapter discusses DC Circuits, particularly those containing batteries, resistors and/or capacitors., how they behave, and how they relate to each other.

- *Electric Current & Ohm's Law* describes equations and calculations involving the flow of charged particles (electric current).
- *Electrical Components* shows pictures of and circuit diagram symbols for common electrical components.
- *EMF & Internal Resistance of a Battery* explains the difference between the voltage supplied by the chemical cells in a battery and the voltage that the battery is actually able to supply in a circuit.
- *Circuits*, *Series Circuits*, *Parallel Circuits*, and *Mixed Series & Parallel Circuits* describe arrangements of circuits that contain batteries and resistors (or other components that have resistance) and the equations that relate to them.
- *Measuring Voltage, Current & Resistance* describes how to correctly measure those quantities for components in a circuit.
- *Capacitance* and *Capacitors in Series & Parallel Circuits* describes capacitors and how they behave in circuits.

- *DC Resistor-Capacitor (RC) Circuits* describes calculations for time-varying circuits that contain a resistor and a capacitor.

One of the new challenges encountered in this chapter is interpreting and simplifying circuit diagrams, in which different equations may apply to different parts of the circuit.

Standards addressed in this chapter:

NGSS Standards/MA Curriculum Frameworks (2016):

HS-PS2-4. Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.

HS-PS3-1. Use algebraic expressions and the principle of energy conservation to calculate the change in energy of one component of a system when the change in energy of the other component(s) of the system, as well as the total energy of the system including any energy entering or leaving the system, is known. Identify any transformations from one form of energy to another, including thermal, kinetic, gravitational, magnetic, or electrical energy, in the system.

HS-PS3-2. Develop and use a model to illustrate that energy at the macroscopic scale can be accounted for as either motions of particles and objects or energy stored in fields.

HS-PS3-5. Develop and use a model of magnetic or electric fields to illustrate the forces and changes in energy between two magnetically or electrically charged objects changing relative position in a magnetic or electric field, respectively.

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AP® Physics 2 Learning Objectives/Essential Knowledge (2024):

10.6.A: Describe the physical properties of a parallel-plate capacitor.

10.6.A.1: A parallel-plate capacitor consists of two separated parallel conducting surfaces that can hold equal amounts of charge with opposite signs.

10.6.A.2: Capacitance relates the magnitude of the charge stored on each plate to the electric potential difference created by the separation of those charges.

10.6.A.2.i: The capacitance of a capacitor depends only on the physical properties of the capacitor, such as the capacitor's shape and the material used to separate the plates.

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10.6.A.2.ii: The capacitance of a parallel-plate capacitor is proportional to the area of one of its plates and inversely proportional to the distance between its plates. The constant of proportionality is the product of the dielectric constant, κ (ε_r), of the material between the plates and the electric permittivity of free space, ε_o.

10.6.A.3: The electric field between two charged parallel plates with uniformly distributed electric charge, such as in a parallel-plate capacitor, is constant in both magnitude and direction, except near the edges of the plates.

10.6.A.3.i: The magnitude of the electric field between two charged parallel plates, where the plate separation is much smaller than the dimensions of the plates, can be described with the equation $E_c = \frac{Q}{\kappa \varepsilon_o A}$.

10.6.A.3.ii: A charged particle between two oppositely charged parallel plates undergoes constant acceleration and therefore its motion shares characteristics with the projectile motion of an object with mass in the gravitational field near Earth's surface.

10.6.A.4: The electric potential energy stored in a capacitor is equal to the work done by an external force to separate that amount of charge on the capacitor.

10.6.A.5: The electric potential energy stored in a capacitor is described by the equation $U_c = \frac{1}{2} Q \Delta V$

10.6.A.6: Adding a dielectric between two plates of a capacitor changes the capacitance of the capacitor and induces an electric field in the dielectric in the opposite direction to the field between the plates.

11.1.A: Describe the movement of electric charges through a medium.

11.1.A.1: Current is the rate at which charge passes through a cross-sectional area of a wire.

11.1.A.1.i: Electric charge moves in a circuit in response to an electric potential difference, sometimes referred to as electromotive force, or emf (ε).

11.1.A.1.ii: If the current is zero in a section of wire, the net motion of charge carriers in the wire is also zero, although individual charge carriers will not have zero speed.

11.1.A.2: Although current is not a vector quantity, it does have a direction. The direction of current is associated with what the motion of positive charge would be but not with any coordinate system in space.

11.1.A.2.i: The direction of conventional current is chosen to be the direction in which positive charge would move.

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11.1.A.2.ii: In common circuits, current is actually due to the movement of electrons (negative charge carriers).

11.2.A: Describe the behavior of a circuit.

11.2.A.1: A circuit is composed of electrical loops, which may include circuit elements such as wires, batteries, resistors, lightbulbs, capacitors, switches, ammeters, and voltmeters.

11.2.A.2: A closed electrical loop is a closed path through which charges may flow.

11.2.A.2.i: A closed circuit is one in which charges would be able to flow.

11.2.A.2.ii: An open circuit is one in which charges would not be able to flow.

11.2.A.2.iii: A short circuit is one in which charges would be able to flow with no change in potential difference.

11.2.A.3: A single circuit element may be part of multiple electrical loops.

11.2.A.4: Circuit schematics are representations used to describe and analyze electric circuits.

11.2.A.4.i: The properties of an electric circuit are dependent on the physical arrangement of its constituent elements.

11.2.A.4.ii: Circuit elements have common symbols that are used to create schematic diagrams. Variable elements are indicate by a diagonal strikethrough arrow across the standard symbol for that element.

11.3.A: Describe the resistance of an object using physical properties of that object.

11.3.A.1: Resistance is a measure of the degree to which an object opposes the movement of electric charge.

11.3.A.2: The resistance of a resistor with uniform geometry is proportional to its resistivity and length and is inversely proportional to its cross-sectional area.

11.3.A.2.i: Resistivity is a fundamental property of a material that depends on its atomic and molecular structure and quantifies how strongly the material opposes the motion of electric charge.

11.3.A.2.ii: The resistivity of a conductor typically increases with temperature.

11.3.B: Describe the electrical characteristics of elements of a circuit.

11.3.B.1: Ohm's law relates current, resistance, and potential difference across a conductive element of a circuit.

11.3.B.1.i: Materials that obey Ohm's law have constant resistance for all currents and are called ohmic materials.

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11.3.B.1.ii: The resistivity of an ohmic material is constant regardless of temperature.

11.3.B.1.iii: Resistors can also convert electrical energy to thermal energy, which may change the temperature of both the resistor and the resistor's environment.

11.3.B.1.iv: The resistance of an ohmic circuit element can be determined from the slope of a graph of the current in the element as a function of the potential difference across the element.

11.4.A: Describe the transfer of energy into, out of, or within an electric circuit, in terms of power.

11.4.A.1: The rate at which energy is transferred, converted, or dissipated by a circuit element depends on the current in the element and the electric potential difference across it.

11.4.A.2: The brightness of a bulb increases with power, so power can be used to qualitatively predict the brightness of bulbs in a circuit.

11.5.A: Describe the equivalent resistance of multiple resistors connected in a circuit.

11.5.A.1: Circuit elements may be connected in series and/or in parallel.

11.5.A.1.i: A series connection is one in which any charge passing through one circuit element must proceed through all elements in that connection and has no other path available. The current in each element in series must be the same.

11.5.A.1.ii: A parallel connection is one in which charges may flow through one of two or more paths. Across each path, the potential difference is the same.

11.5.A.2: A collection of resistors in a circuit may be analyzed as though it were a single resistor with an equivalent resistance R_{eq}.

11.5.A.2.i: The equivalent resistance of a set of resistors in series is the sum of the individual resistances.

11.5.A.2.ii: The inverse of the equivalent resistance of a set of resistors connected in parallel is equal to the sum of the inverses of the individual resistances.

11.5.A.2.iii: When resistors are connected in parallel, the number of paths available to charges increases, and the equivalent resistance of the group of resistors decreases.

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11.5.B: Describe a circuit with resistive wires and a battery with internal resistance.

11.5.B.1: Ideal batteries have negligible internal resistance. Ideal wires have negligible resistance.

11.5.B.1.i: The resistance of wires that are good conductors may normally be neglected, because their resistance is much smaller than that of other elements of a circuit.

11.5.B.1.ii: The resistance of wires may only be neglected if the circuit contains other elements that do have resistance.

11.5.B.1.iii: The potential difference a battery would supply if it were ideal is the potential difference measured across the terminals when there is no current in the battery and is sometimes referred to as its emf (ε).

11.5.B.2: The internal resistance of a nonideal battery may be treated as the resistance of a resistor in series with an ideal battery and the remainder of the circuit.

11.5.B.3: When there is current in a nonideal battery with internal resistance r, the potential difference across the terminals of the battery is reduced relative to the potential difference when there is no current in the battery.

11.5.C: Describe the measurement of current and potential difference in a circuit.

11.5.C.1: Ammeters are used to measure current at a specific point in a circuit.

11.5.C.1.i: Ammeters must be connected in series with the element in which current is being measured.

11.5.C.1.ii: Ideal ammeters have zero resistance so that they do not affect the current in the element that they are in series with.

11.5.C.2: Voltmeters are used to measure electric potential difference between two points in a circuit.

11.5.C.2.i: Voltmeters must be connected in parallel with the element across which potential difference is being measured.

11.5.C.2.ii: Ideal voltmeters have an infinite resistance so that no charge flows through them.

11.5.C.3: Nonideal ammeters and voltmeters will change the properties of the circuit being measured.

11.6.A: Describe a circuit or elements of a circuit by applying Kirchhoff's loop rule.

11.6.A.1: Energy changes in simple electrical circuits may be represented in terms of charges moving through electric potential differences within circuit elements.

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11.6.A.2: Kirchhoff's loop rule is a consequence of the conservation of energy.

11.6.A.3: Kirchhoff's loop rule states that the sum of potential differences across all circuit elements in a single closed loop must equal zero.

11.6.A.4: The values of electric potential at points in a circuit can be represented by a graph of electric potential as a function of position within a loop.

11.7.A: Describe a circuit or elements of a circuit by applying Kirchhoff's junction rule.

11.7.A.1: Kirchhoff's junction rule is a consequence of the conservation of electric charge.

11.7.A.2: Kirchhoff's junction rule states that the total amount of charge entering a junction per unit time must equal the total amount of charge exiting that junction per unit time.

11.8.A: Describe the equivalent capacitance of multiple capacitors.

11.8.A.1: A collection of capacitors in a circuit may be analyzed as though it were a single capacitor with an equivalent capacitance C_{eq}.

11.8.A.1.i: The inverse of the equivalent capacitance of a set of capacitors connected in series is equal to the sum of the inverses of the individual capacitances.

11.8.A.1.ii: The equivalent capacitance of a set of capacitors in series is less than the capacitance of the smallest capacitor.

11.8.A.1.iii: The equivalent capacitance of a set of capacitors in parallel is the sum of the individual capacitances.

11.8.A.2: As a result of conservation of charge, each of the capacitors in series must have the same magnitude of charge on each plate.

11.8.B: Describe the behavior of a circuit containing combinations of resistors and capacitors.

11.8.B.1: The time constant is a significant feature of an RC circuit.

11.8.B.1.i: The time constant of an RC circuit is a measure of how quickly the capacitor will charge or discharge and is defined as $\tau = R_{eq}C_{eq}$.

11.8.B.1.ii: For a charging capacitor, the time constant represents the time required for the capacitor's charge to increase from zero to approximately 63 percent of its final asymptotic value.

11.8.B.1.iii: For a discharging capacitor, the time constant represents the time required for the capacitor's charge to decrease from fully charged to approximately 37 percent of its initial value.

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11.8.B.2: The potential difference across a capacitor and the current in the branch of the circuit containing the capacitor each change over time as the capacitor charges and discharges, but both will reach a steady state after a long time interval.

11.8.B.2.i: Immediately after being placed in a circuit, an uncharged capacitor acts like a wire, and charge can easily flow to or from the plates of the capacitor.

11.8.B.2.ii: As a capacitor charges, changes to the potential difference across the capacitor affect the charge on the plates of the capacitor, the current circuit branch in which the capacitor is located, and the electric potential energy stored in the capacitor.

11.8.B.2.iii: The potential difference across a capacitor, the current in the circuit branch in which the capacitor is located, and the electric potential energy stored in the capacitor all change with respect to time and asymptotically approach steady state conditions.

11.8.B.2.iv: After a long time, a charging capacitor approaches a state of being fully charged, reaching a maximum potential difference at which there is zero current in the circuit branch in which the capacitor is located.

11.8.B.2.v: Immediately after a charged capacitor begins discharging, the amount of charge on the capacitor plates and the energy stored in the capacitor begin to decrease.

11.8.B.2.vi: As a capacitor discharges, the amount of charge on the capacitor, the potential difference across the capacitor, and the current in the circuit branch in which the capacitor is located all decrease until a steady state is reached.

11.8.B.2.vii: After either charging or discharging for times much greater than the time constant, the capacitor and the relevant circuit branch may be modeled using steady-state conditions.

Skills learned & applied in this chapter:

- Working with material-specific constants from a table.
- Identifying electric circuit components.
- Simplifying circuit diagrams.