PLANNED INSTRUCTION

A PLANNED COURSE FOR:

AP PHYSICS C: MECHANICS
and
AP PHYSICS C: ELECTRICITY & MAGNETISM

Curriculum writing committee:
Steve Rhule

Grade Level: **12th Grade**

Date of Board Approval: _____2024_______________

Course Weighting: AP Physics C: Mechanics

Major Assessments	**45%**
Skills Application	**30%**
Skills Practice	**20%**
Participation	**5%**
Total	**100%**

Course Weighting: AP Physics C: Electricity & Magnetism

Major Assessments	**45%**
Skills Application	**30%**
Skills Practice	**20%**
Participation	**5%**
Total	**100%**

Curriculum Map

Marking Period One – Overview with time range in days:
MECHANICS UNIT ONE: Kinematics

- Day 1 – 2: Slope & Derivatives
- Day 2 – 3: Area & Integration
- Day 4: Vector Addition
- Day 5: Vector Multiplication
- Day 6 – 10: Kinematics: Motion in One Dimension
- Day 11 – 15: Kinematics: Motion in Two Dimensions

MECHANICS UNIT TWO: Newton's Laws of Motion

- Day 1: Newton's First Law
- Day 2: Newton's Second Law
- Day 3 - Day 4: Applications of Newton's Second Law
- Day 5: Newton's Third Law
- Day 6: Friction and Air Resistance

- Day 7: Uniform Circular Motion
- Day 8 - Day 10: More Applications of Newton's Second Law

MECHANICS UNIT THREE: Work, Energy, and Power
- Day 1: Energy
- Day 2 - Day 3: Work and Kinetic Energy
- Day 4: Work Done by Gravity
- Day 5: Work Done by a Variable Force
- Day 6: Power
- Day 7: Work and Potential Energy
- Day 8 - Mechanical Energy
- Day 9 - Day 10: Law of Conservation of Energy

MECHANICS UNIT FOUR: Systems of Particles and Linear Momentum
- Day 1 - Day 2: Center of Mass
- Day 3 - Linear Momentum
- Day 4: Impulse
- Day 5: Law of Conservation of Momentum
- Day 6: Inelastic Collisions
- Day 7 - Day 8: One Dimensional Elastic Collisions
- Day 9: Two Dimensional Collisions
- Day 10: Variable Mass Systems

Marking Period Two – Overview with time range in days:
MECHANICS UNIT FIVE: Rotation
- Day 1: Angular Variables
- Day 2: Constant Angular Acceleration Motion
- Day 3 - Day 4: Rotational Kinetic Energy and Rotational Inertia
- Day 5: Newton's Second Law for Rotation
- Day 6: Rotation and Translation
- Day 7: Work and Energy of Rolling
- Day 8: Torque
- Day 9: Angular Momentum
- Day 10: Law of Conservation of Angular Momentum
- Day 11 - 12.5: Static Equilibrium

MECHANICS UNIT SIX: Oscillations
- Day 1: Linear Restoring Force and Periodic Motion
- Day 2 - Day 3: Simple Harmonic Motion
- Day 4: Applications of Simple Harmonic Motion
- Day 5: Simple Pendulum
- Day 6: Simple Harmonic Motion and Uniform Circular Motion

- Day 7: Damped and Driven Harmonic Motion
- Day 7.5: Resonance

MECHANICS UNIT SEVEN: Gravitation
- Day 1 - Day 3: Newton's Law of Gravitation
- Day 4: Gravity Near Earth
- Day 5: Gravitational Potential Energy
- Day 6 - Day 7: Kepler's Laws of Planetary Motion
- Day 8 - Day 9: Orbits and Energy
- Day 10: Einstein's General Theory of Relativity

ELECTRICITY & MAGNETISM UNIT ONE: Electrostatics
- Day 1: Electric Charge
- Day 2: Coulomb's Law
- Day 3: Charge Quantization & Charge Conservation
- Day 4: Conductors, Insulators, Semiconductors, & Super Conductors
- Day 5: Electric Field & Electric Field Force
- Day 6: Electric Field Lines
- Day 7: Electric Dipole in an Electric Field
- Day 8: Electric Field Flux
- Day 9: Gauss' Law
- Day 10: Enclosed Charge
- Day 11 - Day 13: Spherical, Cylindrical, & Planar Symmetry
- Day 14: Electric Potential Energy
- Day 15: Electric Potential

Marking Period Three – Overview with time range in days:
ELECTRICITY & MAGNETISM UNIT ONE: Electrostatics (continued)
- Day 15 - Day 17: Electric Field & Electric Potential for Charge Distributions
- Day 18: Calculating Potential from Field
- Day 19: Calculating Field from Potential
- Day 20: Charged Isolated Conductors

ELECTRICITY & MAGNETISM UNIT TWO: Conductors, Capacitors, Dielectrics
- Day 1: Capacitors & Capacitance
- Day 2: Capacitors in Series and Parallel
- Day 3: Equivalent Capacitance
- Day 4: Energy in a Capacitor
- Day 5: Dielectrics

ELECTRICITY & MAGNETISM UNIT THREE: Electric Circuits
- Day 1: Electric Current

- Day 2: Current Density & Drift Speed
- Day 3 Resistance & Resistivity
- Day 4: Ohm’s law
- Day 5: Power in a DC Circuit
- Day 6: Electromotive Force & Internal Resistance
- Day 7: Series and Parallel Circuits
- Day 8: Resistors in Series & Parallel
- Day 9 – Day 10: Circuit Analysis by Equivalent Resistance and Kirchoff’s Rules
- Day 11 - Day 13: Kirchoff Method Circuit Analysis
- Day 14 - Day 15: RC Circuits

ELECTRICITY & MAGNETISM UNIT FOUR: Magnetic Fields

- Day 1: Magnetism & Magnetic Fields
- Day 2: Magnetic Field Lines
- Day 3: Magnetic Field Force on a Moving Charge
- Day 4: Moving Charges in Magnetic Fields
- Day 5: Torque on a Current Loop in a Magnetic Field
- Day 6: Magnetic Dipole Moment
- Day 7: Biot-Savart Law & Ampere’s Law
- Day 8: Magnetic Field Force on Current Carrying Wire
- Day 9 - Day 10: Magnetic Fields of Current Carrying Wire Coils and Solenoids

ELECTRICITY & MAGNETISM UNIT FIVE: Electromagnetism

- Day 1: Magnetic Field Flux
- Day 2: Faraday’s Law & Lenz’s Law
- Day 3: Induced Electric Fields
- Day 4: Inductors & Inductance
- Day 5 - Day 6: RL Circuits
- Day 7: Energy in Magnetic Fields
- Day 8: Mutual Induction & Transformers
- Day 9 - Day 10: Maxwell’s Equations

Marking Period Four – Overview with time range in days:
AP PHYSICS C EXAM REVIEW UNIT THIRTEEN

- Day 1 - Day 15: Mechanics Review
- Day 16 - Day 25: Electricity & Magnetism Review

PHYSICS LABS UNIT FOURTEEN

- Day 26 - Day 45: Physics Labs including – 1D and 2D Kinematics, Newton’s Second Law, Circular Motion, Conservation of Energy, Impulse and Momentum, Harmonic Motion, Rotational Motion, Resistor Circuits, RC Circuits, Magnetism, Electromagnetic Induction

Big Ideas:

- BIG IDEA 1: CHANGE - Interactions produce changes in motion.
- BIG IDEA 2: FORCE INTERACTIONS - Forces characterize interactions between objects or systems.
- BIG IDEA 3: FIELDS - Fields predict and describe interactions.
- BIG IDEA 4: CONSERVATION - Conservation laws constrain interactions.

Big Ideas	Unit 1: Kinematics	Unit 2: Newton's Laws of Motion	Unit 3: Work, Energy, & Power	Unit 4: Systems of Particles & Linear Momentum	Unit 5: Rotation	Unit 6: Oscillations	Unit 7: Gravitation
Change	✓			✓	✓		
Force Interactions		✓	✓	✓	✓	✓	
Fields							✓
Conservation			✓	✓	✓		✓

Table 1: **Spiraling the Big Ideas. The above table shows the MECHANICS units in which each big idea appears (AP Physics C, 2019).**

Big Ideas	Unit 1: Electrostatics	Unit 2: Conductors, Capacitors, Dielectrics	Unit 3: Electric Circuits	Unit 4: Magnetic Fields	Unit 5: Electromagnetism
Change				✓	
Force Interactions	✓	✓			✓
Fields	✓	✓	✓	✓	✓
Conservation	✓	✓	✓	✓	✓

Table 2: **Spiraling the Big Ideas. The above table shows the electricity & magnetism units in which each big idea appears (AP Physics C, 2019).**

Textbook and Supplemental Resources:

- Fundamentals of Physics: Extended, 11th Edition by Halliday, Resnick, and Walker (ISBN for this will be ISBN-13: 978-1119585244)
- Wiley Plus - Student Companion Site for Fundamentals of Physics: Extended, 11th Edition (www.wileyplus.com)
- AP Classroom (myap.collegeboard.org)
- AP Physics C: Mechanics Course and Exam Description
- AP Physics C: Electricity and Magnetism Course and Exam Description

Curriculum Plan

- AP Physics C: Mechanics Course and Exam Description (Attached)
  - https://apcentral.collegeboard.org/media/pdf/ap-physics-c-mechanics-course-framework-effective-fall-2024.pdf

- AP Physics C: Electricity and Magnetism Course and Exam Description (Attached)
  - https://apcentral.collegeboard.org/media/pdf/ap-physics-c-electricity-and-magnetism-course-framework-effective-fall-2024.pdf

Science Practices

Practice 1	Practice 2	Practice 3
Creating Representations **1** Create representations that depict physical phenomena.situations, excluding graphs.	***Mathematical Routines*** **2** Conduct analyses to derive, calculate, estimate, or predict.	***Scientific Questioning and Argumentation*** **3** Describe experimental procedures, analyze data, and support claims.
SKILLS		
1.A Create diagrams, tables, charts, or schematics to represent physical situations. **1.B** Create quantitative graphs with appropriate scales and units, including plotting data. **1.C** Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.	**2.A** Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway. **2.B** Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway. **2.C** Compare physical quantities between two or more scenarios or at different times and locations in a single scenario. **2.D** Predict new values or factors of change of physical quantities using functional dependence between variables.	**3.A** Create experimental procedures that are appropriate for a given scientific question. **3.B** Apply an appropriate law, definition, theoretical relationship, or model to make a claim. **3.C** Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 1.1
Scalars and Vectors

Required Course Content

LEARNING OBJECTIVE

1.1.A

Describe a scalar or vector quantity using magnitude and direction, as appropriate.

ESSENTIAL KNOWLEDGE

1.1.A.1

Scalars are quantities described by magnitude only; vectors are quantities described by both magnitude and direction.

1.1.A.2

Vectors can be visually modeled as arrows with appropriate direction and lengths proportional to their magnitude.

1.1.A.3

Distance and speed are examples of scalar quantities, while position, displacement, velocity, and acceleration are examples of vector quantities.

1.1.A.4

Vectors can be expressed in unit vector notation or as a magnitude and a direction.

i. Unit vector notation can be used to represent vectors as the sum of their constituent components in the *x*-, *y*-, and *z*-directions, denoted by $\hat{i}$, $\hat{j}$, and $\hat{k}$, respectively.

Relevant equation:

$$\vec{r} = \left(A\hat{i} + B\hat{j} + C\hat{k}\right)$$

ii. The position vector of a point is given by $\vec{r}$, and the unit vector in the direction of the position vector is denoted $\hat{r}$.

iii. A resultant vector is the vector sum of the addend vectors' components.

Relevant equation:

$$\vec{C} = \vec{A} + \vec{B}$$

$$\vec{C} = \left(A_x + B_x\right)\hat{i} + \left(A_y + B_y\right)\hat{j}$$

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SUGGESTED SCIENCE PRACTICES

1.A

Create diagrams, tables, charts, or schematics to represent physical situations.

2.A

Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.B

Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
1.1.A Describe a scalar or vector quantity using magnitude and direction, as appropriate.	**1.1.A.5** In a given one-dimensional coordinate system, opposite directions are denoted by opposite signs.

TOPIC 1.2

Displacement, Velocity, and Acceleration

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
1.2.A Describe a change in an object's position.	**1.2.A.1** When using the object model, the size, shape, and internal configuration are ignored. The object may be treated as a single point with extensive properties such as mass and charge. **1.2.A.2** Displacement is the change in an object's position. *Relevant equation:* $\Delta x = x - x_0$
1.2.B Describe the average velocity and acceleration of an object.	**1.2.B.1** Averages of velocity and acceleration are calculated considering the initial and final states of an object over an interval of time. **1.2.B.2** Average velocity is the displacement of an object divided by the interval of time in which that displacement occurs. $\vec{v}_{\text{avg}} = \frac{\Delta\vec{x}}{\Delta t}$ **1.2.B.3** Average acceleration is the change in velocity divided by the interval of time in which that change in velocity occurs. $\vec{a}_{\text{avg}} = \frac{\Delta\vec{v}}{\Delta t}$ **1.2.B.4** An object is accelerating if either the magnitude and/or direction of the object's velocity are changing.

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SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
1.2.B Describe the average velocity and acceleration of an object.	**1.2.B.5** Calculating average velocity or average acceleration over a very small time interval yields a value that is very close to the instantaneous velocity or instantaneous acceleration.
1.2.C Describe the instantaneous position, velocity, and acceleration of an object as a function of time.	**1.2.C.1** As the time interval used to calculate the average value of a quantity approaches zero, the average value of that quantity approaches the value of the quantity at that instant, called the instantaneous value. i. Instantaneous velocity is the rate of change of the object's position, which is equal to the derivative of position with respect to time. *Relevant equations:* $\vec{v} = \frac{d\vec{r}}{dt}$ $v_x = \frac{dx}{dt}$ ii. Instantaneous acceleration is the rate of change of the object's velocity, which is equal to the derivative of velocity with respect to time. *Relevant equations:* $\vec{a} = \frac{d\vec{v}}{dt}$ $a_x = \frac{dv_x}{dt}$ **1.2.C.2** Time-dependent functions and instantaneous values of position, velocity, and acceleration can be determined using differentiation and integration.

TOPIC 1.3
Representing Motion

SUGGESTED SCIENCE PRACTICES

1.C
Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

Required Course Content

LEARNING OBJECTIVE

1.3.A
Describe the position, velocity, and acceleration of an object using representations of that object's motion.

ESSENTIAL KNOWLEDGE

1.3.A.1
Motion can be represented by motion diagrams, figures, graphs, equations, and narrative descriptions.

1.3.A.2
For constant acceleration, three kinematic equations can be used to describe instantaneous linear motion in one dimension:

$$v_x = v_{x0} + a_x t$$

$$x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$$

$$v_x^2 = v_{x0}^2 + 2a_x \left(x - x_0\right)$$

Note: The equations above are written to indicate motion in the x*-direction, but these equations can be used in any single dimension as appropriate.*

1.3.A.3
Near the surface of Earth, the vertical acceleration caused by the force of gravity is downward, constant, and has a measured value approximately equal to

$$a_g = g \approx 10 \text{ m/s}^2.$$

1.3.A.4
Graphs of position, velocity, and acceleration as functions of time can be used to find the relationships between those quantities.

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LEARNING OBJECTIVE

1.3.A

Describe the position, velocity, and acceleration of an object using representations of that object's motion.

ESSENTIAL KNOWLEDGE

i. An object's instantaneous velocity is the rate of change of the object's position, which is equal to the slope of a line tangent to a point on a graph of the object's position as a function of time.

Relevant equation:

$$v_x = \frac{dx}{dt}$$

ii. An object's instantaneous acceleration is the rate of change of the object's velocity, which is equal to the slope of a line tangent to a point on a graph of the object's velocity as a function of time.

Relevant equation:

$$a_x = \frac{dv_x}{dt}$$

iii. The displacement of an object during a time interval is equal to the area under the curve of a graph of the object's velocity as a function of time (i.e., the area bounded by the function and the horizontal axis for the appropriate interval).

Relevant equation:

$$\Delta x = \int_{t_1}^{t_2} v_x(t)\ dt$$

iv. The change in velocity of an object during a time interval is equal to the area under the curve of a graph of the acceleration of the object as a function of time.

Relevant equation:

$$\Delta v_x = \int_{t_1}^{t_2} a_x(t)\ dt$$

BOUNDARY STATEMENT

AP Physics C: Mechanics and AP Physics C: Electricity & Magnetism expects that for all situations in which a numerical quantity is required for g, the value $g \approx 10\ \mathrm{m/s^2}$ *will be used. However, students will not be penalized for correctly using the more precise commonly accepted values of* $g = 9.81\ \mathrm{m/s^2}$ *or* $g = 9.8\ \mathrm{m/s^2}$.

TOPIC 1.4

Reference Frames & Relative Motion

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
1.4.A Describe the reference frame of a given observer.	**1.4.A.1** The choice of reference frame will determine the direction and magnitude of quantities measured by an observer in that reference frame.
1.4.B Describe the motion of objects as measured by observers in different inertial reference frames.	**1.4.B.1** Measurements from a given reference frame may be converted to measurements from another reference frame. **1.4.B.2** The observed velocity of an object results from the combination of the object's velocity and the velocity of the observer's reference frame. i. Combining the motion of an object and the motion of an observer in a given reference frame involves the addition or subtraction of vectors. ii. The acceleration of any object is the same as measured from all inertial reference frames.

BOUNDARY STATEMENT:

Unless otherwise stated, the frame of reference of any problem may be assumed to be inertial.

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data. Create quantitative graphs with appropriate scales and units, including plotting data.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 1.5
Motion in Two or Three Dimensions

Required Course Content

LEARNING OBJECTIVE

1.5.A
Describe the motion of an object moving in two or three dimensions.

ESSENTIAL KNOWLEDGE

1.5.A.1
Motion in two or three dimensions can be analyzed using one-dimensional kinematic relationships if the motion is separated into components.

1.5.A.2
Velocity and acceleration may be different in each dimension and may be nonuniform.

1.5.A.3
Motion in one dimension may be changed without causing a change in a perpendicular dimension.

1.5.A.4
Projectile motion is a special case of two-dimensional motion that has zero acceleration in one dimension and constant, nonzero acceleration in the second dimension.

BOUNDARY STATEMENT
AP Physics C: Mechanics only expects students to quantitatively analyze the motion of an object in two dimensions. AP Physics C: Electricity & Magnetism expects students to also qualitatively describe the motion of a particle in three dimensions.

TOPIC 2.1

Systems and Center of Mass

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
2.1.A Describe the properties and interactions of a system.	**2.1.A.1** System properties are determined by the interactions between objects within the system. **2.1.A.2** If the properties or interactions of the constituent objects within a system are not important in modeling the behavior of the macroscopic system, the system can itself be treated as a single object. **2.1.A.3** Systems may allow interactions between constituent parts of the system and the environment, which may result in the transfer of energy or mass. **2.1.A.4** Individual objects within a chosen system may behave differently from each other as well as from the system as a whole. **2.1.A.5** The internal structure of a system affects the analysis of that system. **2.1.A.6** As variables external to a system are changed, the system's substructure may change.

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SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

LEARNING OBJECTIVE

2.1.B

Describe the location of a system's center of mass with respect to the system's constituent parts.

ESSENTIAL KNOWLEDGE

2.1.B.1

For objects or systems with symmetrical mass distributions, the center of mass is located on lines of symmetry.

2.1.B.2

The location of a system's center of mass along a given axis can be calculated using the equation

$$\vec{x}_{\text{cm}} = \frac{\sum m_i \vec{x}_i}{\sum m_i}.$$

2.1.B.3

For a nonuniform solid that can be considered as a collection of differential masses, dm, the solid's center of mass can be calculated using the equation

$$\vec{r}_{\text{cm}} = \frac{\int \vec{r}\, dm}{\int dm}.$$

i. The linear mass density of a rod or other linear rigid body is the derivative of the rod's mass with respect to the position of the differential mass element on the rigid body.

Relevant equation:

$$\lambda = \frac{d}{d\ell} m(\ell)$$

ii. If a function of mass density is given for a solid, the total mass can be determined by integrating the mass density over the length (one dimension), area (two dimensions), or volume (three dimensions) of the solid. For example:

$$M_{\text{total}} = \int \rho(r)\, dV$$

2.1.B.4

A system can be modeled as a singular object that is located at the system's center of mass.

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TOPIC 2.2

Forces and Free-Body Diagrams

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
2.2.A Describe a force as an interaction between two objects or systems	**2.2.A.1** Forces are vector quantities that describe the interactions between objects or systems. i. A force exerted on an object or system is always due to the interaction of that object or system with another object or system. ii. An object or system cannot exert a net force on itself. **2.2.A.2** Contact forces describe the interaction of an object or system touching another object or system and are macroscopic effects of interatomic electric forces.
2.2.B Describe the forces exerted on an object or system using a free-body diagram.	**2.2.B.1** Free-body diagrams are useful tools for visualizing forces being exerted on a single object or system and for determining the equations that represent a physical situation. **2.2.B.2** The free-body diagram of an object or system shows each of the forces exerted on the object or system by the environment. **2.2.B.3** Forces exerted on an object or system are represented as vectors originating from the representation of the center of mass, such as a dot. A system is treated as though all of its mass is located at the center of mass.

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SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

LEARNING OBJECTIVE

2.2.B

Describe the forces exerted on an object or system using a free-body diagram.

ESSENTIAL KNOWLEDGE

2.2.B.4

A coordinate system with one axis parallel to the direction of acceleration of the object or system simplifies the translation from free-body diagram to algebraic representation. For example, in a free-body diagram of an object on an inclined plane, it is useful to set one axis parallel to the surface of the incline.

BOUNDARY STATEMENT:

AP Physics C: Mechanics and AP Physics C: Electricity & Magnetism only expects students to depict the forces exerted on objects, not the force components on free-body diagrams. On the AP Physics exams, individual forces represented on a free-body diagram must be drawn as individual straight arrows, originating on the dot and pointing in the direction of the force. Individual forces that are in the same direction must be drawn side by side, not overlapping.

TOPIC 2.3

Newton's Third Law

Required Course Content

LEARNING OBJECTIVE

2.3.A

Describe the interaction of two objects or systems using Newton's third law and a representation of paired forces exerted on each object or system.

ESSENTIAL KNOWLEDGE

2.3.A.1

Newton's third law describes the interaction of two objects or systems in terms of the paired forces that each exerts on the other.

2.3.A.2

Interactions between objects within a system (internal forces) do not influence the motion of a system's center of mass.

2.3.A.3

Tension is the macroscopic net result of forces that infinitesimal segments of a string, cable, chain, or similar system exert on each other in response to an external force.

i. An ideal string has negligible mass and does not stretch when under tension.

ii. The tension in an ideal string is the same at all points within the string.

iii. In a string with nonnegligible mass, tension may not be the same at all points within the string.

iv. An ideal pulley is a pulley that has negligible mass and rotates about an axle through its center of mass with negligible friction.

SUGGESTED SCIENCE PRACTICES

1.A Create diagrams, tables, charts, or schematics to represent physical situations.

2.C Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.B Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

3.C Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

SUGGESTED SCIENCE PRACTICES

1.C
Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 2.4
Newton's First Law

Required Course Content

LEARNING OBJECTIVE

2.4.A
Describe the conditions under which a system's velocity remains constant.

ESSENTIAL KNOWLEDGE

2.4.A.1
The net force on a system is the vector sum of all forces exerted on the system.

2.4.A.2
Translational equilibrium is the configuration of forces such that the net force exerted on a system is zero.

Derived equation:

$$\sum \vec{F}_i = 0$$

2.4.A.3
Newton's first law states that if the net force exerted on a system is zero, the velocity of that system will remain constant.

2.4.A.4
Forces may be balanced in one dimension but unbalanced in another. The system's velocity will change only in the direction of the unbalanced force.

2.4.A.5
An inertial reference frame is one from which an observer would verify Newton's first law of motion.

TOPIC 2.5

Newton's Second Law

Required Course Content

LEARNING OBJECTIVE

2.5.A

Describe the conditions under which a system's velocity changes.

ESSENTIAL KNOWLEDGE

2.5.A.1

Unbalanced forces are a configuration of forces such that the net force exerted on a system is not equal to zero.

2.5.A.2

Newton's second law of motion states that the acceleration of a system's center of mass has a magnitude proportional to the magnitude of the net force exerted on the system and is in the same direction as that net force.

Relevant equation:

$$\vec{a}_{\text{sys}} = \frac{\sum \vec{F}}{m_{\text{sys}}} = \frac{\vec{F}_{\text{net}}}{m_{\text{sys}}}$$

2.5.A.3

The velocity of a system's center of mass will only change if a nonzero net external force is exerted on that system.

SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

SUGGESTED SCIENCE PRACTICES

1.C

Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.A

Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D

Predict new values or factors of change of physical quantities using functional dependence between variables.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 2.6
Gravitational Force

Required Course Content

LEARNING OBJECTIVE

2.6.A

Describe the gravitational interaction between two objects or systems with mass.

ESSENTIAL KNOWLEDGE

2.6.A.1

Newton's law of universal gravitation describes the gravitational force between two objects or systems as directly proportional to each of their masses and inversely proportional to the square of the distance between the systems' centers of mass.

Relevant equation:

$$\left|\vec{F}_g\right| = G\frac{m_1 m_2}{r^2}$$

i. The gravitational force is attractive.

ii. The gravitational force is always exerted along the line connecting the center of mass of the two interacting systems.

iii. The gravitational force on a system can be considered to be exerted on the system's center of mass.

2.6.A.2

A field models the effects of a noncontact force exerted on an object at various positions in space.

i. The magnitude of the gravitational field created by a system of mass M at a point in space is equal to the ratio of the gravitational force exerted by the system on a test object of mass m to the mass of the test object.

Derived equation:

$$\left|\vec{g}\right| = \frac{\left|\vec{F}_g\right|}{m} = G\frac{M}{r^2}$$

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LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
2.6.A Describe the gravitational interaction between two objects or systems with mass.	ii. If the gravitational force is the only force exerted on an object, the observed acceleration of the object (in $\mathrm{m/s^2}$) is numerically equal to the magnitude of the gravitational field strength (in $\mathrm{N/kg}$) at that location. **2.6.A.3** The gravitational force exerted by an astronomical body on a relatively small nearby object is called weight. *Derived equation:* $\text{Weight} = F_g = mg$
2.6.B Describe situations in which the gravitational force can be considered constant.	**2.6.B.1** If the gravitational force between two systems' centers of mass has a negligible change as the relative position of the two systems changes, the gravitational force can be considered constant at all points between the initial and final positions of the systems. **2.6.B.2** Near the surface of Earth, the strength of the gravitational field is $g \approx 10\ \mathrm{N/kg}$.
2.6.C Describe the conditions under which the magnitude of a system's apparent weight is different from the magnitude of the gravitational force exerted on that system.	**2.6.C.1** The magnitude of the apparent weight of a system is the magnitude of the normal force exerted on the system. **2.6.C.2** If the system is accelerating, the apparent weight of the system is not equal to the magnitude of the gravitational force exerted on the system. **2.6.C.3** A system appears weightless when there are no forces exerted on the system or when the force of gravity is the only force exerted on the system. **2.6.C.4** The equivalence principle states that an observer in a noninertial reference frame is unable to distinguish between an object's apparent weight and the gravitational force exerted on the object by a gravitational field.

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LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
2.6.D Describe inertial and gravitational mass.	**2.6.D.1** Objects have inertial mass, or inertia, a property that determines how much an object's motion resists changes when interacting with another object. **2.6.D.2** Gravitational mass is related to the force of attraction between two systems with mass. **2.6.D.3** Inertial mass and gravitational mass have been experimentally verified to be equivalent.
2.6.E Describe the gravitational force exerted on an object by a uniform spherical distribution of mass.	**2.6.E.1** The net gravitational force exerted on an object by a uniform spherical distribution of mass is the sum of the individual forces from small differential masses that comprise the distribution. **2.6.E.2** Newton's shell theorem describes the net gravitational force exerted on an object by a uniform spherical shell of mass. i. The net gravitational force exerted on an object inside a thin spherical shell is zero. ii. The net gravitational force exerted on an object outside a thin spherical shell can be determined by treating the shell as a single massive object located at the center of the shell. iii. An object inside a sphere of uniform density experiences a net gravitational force from only a partial mass of the sphere. iv. The partial mass of a sphere that contributes to the net gravitational force exerted on an object within that sphere is the portion of the sphere's mass located a distance less than or equal to the object's distance from the center of the sphere and can be calculated using the density of the sphere. *Derived equation:* $m_{\text{partial}} = \rho \frac{4}{3}\pi \left(r_{\text{partial}}\right)^3$

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LEARNING OBJECTIVE

2.6.E

Describe the gravitational force exerted on an object by a uniform spherical distribution of mass.

ESSENTIAL KNOWLEDGE

2.6.E.3

The gravitational force exerted on an object within a uniform sphere can be shown to be proportional to the object's distance from the sphere's center.

Derived equation:

$F_{g,\text{partial}} = -kr_{\text{partial}}$

BOUNDARY STATEMENT:

AP Physics C: Mechanics does not expect students to mathematically prove or derive Newton's shell theorem.

SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim

TOPIC 2.7
Kinetic and Static Friction

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
2.7.A Describe kinetic friction between two surfaces.	**2.7.A.1** Kinetic friction occurs when two surfaces in contact move relative to each other. i. The kinetic friction force is exerted in a direction opposite the motion of each surface relative to the other surface. ii. The force of friction between two surfaces does not depend on the size of the surface area of contact. **2.7.A.2** The magnitude of the kinetic friction force exerted on an object is the product of the normal force the surface exerts on the object and the coefficient of kinetic friction. *Relevant equation:* $\left\|\vec{F}_{f,k}\right\| = \left\|\mu_k \vec{F}_N\right\|$ i. The coefficient of kinetic friction depends on the material properties of the surfaces that are in contact. ii. Normal force is the perpendicular component of the force exerted on an object by the surface with which it is in contact; it is directed away from the surface.
2.7.B Describe static friction between two surfaces.	**2.7.B.1** Static friction may occur between the contacting surfaces of two objects that are not moving relative to each other.

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LEARNING OBJECTIVE

2.7.B

Describe static friction between two surfaces.

ESSENTIAL KNOWLEDGE

2.7.B.2

Static friction adopts the value and direction required to prevent an object from slipping or sliding on a surface.

Relevant equation:

$$\left|\vec{F}_{f,s}\right| \leq \left|\mu_s \vec{F}_N\right|$$

i. Slipping and sliding refer to situations in which two surfaces are moving relative to each other.

ii. There exists a maximum value for which static friction will prevent an object from slipping on a given surface.

   Derived equation:

   $$F_{f,s,\max} = \mu_s F_N$$

2.7.B.3

The coefficient of static friction is typically greater than the coefficient of kinetic friction for a given pair of surfaces.

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 2.8
Spring Forces

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
2.8.A Describe the force exerted on an object by an ideal spring.	**2.8.A.1** An ideal spring has negligible mass and exerts a force that is proportional to the change in its length as measured from its relaxed length. A nonideal spring either has nonnegligible mass or exerts a force that is not proportional to the change in its length as measured from its relaxed length. **2.8.A.2** The magnitude of the force exerted by an ideal spring on an object is given by Hooke's law: $\vec{F}_s = -k\Delta\vec{x}$ **2.8.A.3** The force exerted on an object by a spring is always directed towards the equilibrium position of the object–spring system.
2.8.B Describe the equivalent spring constant of a combination of springs exerting forces on an object.	**2.8.B.1** A collection of springs that exert forces on an object may behave as though they were a single spring with an equivalent spring constant k_{eq}. i. The inverse of the equivalent spring constant of a set of springs in series is equal to the sum of the inverses of the individual spring constants. *Derived equation:* $\frac{1}{k_{\text{eq, series}}} = \sum_i \frac{1}{k_i} = \frac{1}{k_1} + \frac{1}{k_2} + \ldots$

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LEARNING OBJECTIVE

2.8.B

Describe the equivalent spring constant of a combination of springs exerting forces on an object.

ESSENTIAL KNOWLEDGE

ii. The equivalent spring constant of a set of springs arranged in series is smaller than the smallest constituent spring constant.

iii. The equivalent spring constant of a set of springs arranged in parallel is the sum of the individual spring constants.

Derived equation:

$$k_{\text{eq, parallel}} = \sum_i k_i = k_1 + k_2 + \ldots$$

BOUNDARY STATEMENT:

AP Physics C: Mechanics only expects students to find the effective spring constant of systems of springs that are arranged either in series or in parallel and does not expect students to find the effective spring constant of a system in which springs are arranged in both series and parallel.

SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 2.9
Resistive Forces

Required Course Content

LEARNING OBJECTIVE

2.9.A
Describe the motion of an object subject to a resistive force.

ESSENTIAL KNOWLEDGE

2.9.A.1
A resistive force is defined as a velocity-dependent force in the opposite direction of an object's velocity, for example:

$$\vec{F}_r = -k\vec{v}$$

2.9.A.2
Applying Newton's second law to an object upon which a resistive force is exerted results in a differential equation for velocity.

i. Using the method of separation of variables, the velocity can be determined by integrating over the proper limits of integration.

ii. The acceleration or position of a moving object that is subject to a velocity-dependent force may be determined using initial conditions of the object and methods of calculus, once a function for velocity is determined.

iii. The position, velocity, and acceleration as functions of time of an object under the influence of a resistive force of the form $\vec{F}_r = -k\vec{v}$ are exponential and have asymptotes that are determined by the initial conditions of the object and the forces exerted on the object.

2.9.A.3
Terminal velocity is defined as the maximum speed achieved by an object moving under the influence of a constant force and a resistive force that are exerted on the object in opposite directions. The terminal condition is reached when the net force exerted on the object is zero.

TOPIC 2.10
Circular Motion

Required Course Content

LEARNING OBJECTIVE

2.10.A
Describe the motion of an object traveling in a circular path.

ESSENTIAL KNOWLEDGE

2.10.A.1
Centripetal acceleration is the component of an object's acceleration directed toward the center of the object's circular path.

i. The magnitude of centripetal acceleration for an object moving in a circular path is the ratio of the object's tangential speed squared to the radius of the circular path.

Relevant equation:

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

ii. Centripetal acceleration is directed toward the center of an object's circular path.

2.10.A.2
Centripetal acceleration can result from a single force, more than one force, or components of forces that are exerted on an object in circular motion.

i. At the top of a vertical, circular loop, an object requires a minimum speed to maintain circular motion. At this point, and with this minimum velocity, the gravitational force is the only force that causes the centripetal acceleration.

Derived equation:

$$v = \sqrt{gr}$$

ii. Components of the static friction force and the normal force can contribute to the net force producing centripetal acceleration of an object traveling in a circle on a banked surface.

iii. A component of tension contributes to the net force producing centripetal acceleration experienced by a conical pendulum.

SUGGESTED SCIENCE PRACTICES

1.A
Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

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LEARNING OBJECTIVE

2.10.A

Describe the motion of an object traveling in a circular path.

ESSENTIAL KNOWLEDGE

2.10.A.3

Tangential acceleration is the rate at which an object's speed changes and is directed tangent to the object's circular path.

2.10.A.4

The net acceleration of an object moving in a circle is the vector sum of the centripetal acceleration and tangential acceleration.

2.10.A.5

The revolution of an object traveling in a circular path at a constant speed (uniform circular motion) can be described using period and frequency.

i. The time to complete one full circular path is defined as period, T.

ii. The rate at which an object is completing revolutions is defined as frequency, f.

Relevant equation:

$$T = \frac{1}{f}$$

iii. For an object traveling at a constant speed in a circular path, the period is given by the derived equation $T = \frac{2\pi r}{v}$.

2.10.B

Describe circular orbits using Kepler's third law.

2.10.B.1

For a satellite in circular orbit around a central body, the satellite's centripetal acceleration is caused only by gravitational attraction. The period and radius of the circular orbit are related to the mass of the central body.

Derived equation:

$$T^2 = \frac{4\pi^2}{GM}R^3$$

BOUNDARY STATEMENT:

AP Physics C: Mechanics does not expect students to know Kepler's first or second laws of planetary motion.

TOPIC 3.1
Translational Kinetic Energy

Required Course Content

LEARNING OBJECTIVE

3.1.A

Describe the translational kinetic energy of an object in terms of the object's mass and velocity.

ESSENTIAL KNOWLEDGE

3.1.A.1

An object's translational kinetic energy is given by the equation

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

3.1.A.2

Translational kinetic energy is a scalar quantity.

3.1.A.3

Different observers may measure different values of the translational kinetic energy of an object, depending on the observer's frame of reference.

SUGGESTED SCIENCE PRACTICES

1.C

Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.C

Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

3.C

Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

1.C
Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 3.2
Work

Required Course Content

LEARNING OBJECTIVE

3.2.A
Describe the work done on an object or system by a given force or collection of forces.

ESSENTIAL KNOWLEDGE

3.2.A.1
Work is the amount of energy transferred into or out of a system by a force exerted on that system over a distance.

i. The work done by a conservative force exerted on a system is path-independent and only depends on the initial and final configurations of that system.
ii. The work done by a conservative force on a system—or the change in the potential energy of the system—will be zero if the system returns to its initial configuration.
iii. Potential energies are associated only with conservative forces.
iv. The work done by a nonconservative force is path-dependent.
v. The most common nonconservative forces are friction and air resistance.

3.2.A.2
Work is a scalar quantity that may be positive, negative, or zero.

3.2.A.3
The work done on an object by a variable force is calculated using

$$W = \int_a^b \vec{F}(r) \cdot d\vec{r},$$

where the integral is taken over the path from point *a* to point *b*.

i. The dot product between two vectors, $\vec{A}$ and $\vec{B}$, results in a scalar quantity of magnitude

$$\vec{A} \cdot \vec{B} = AB\cos\theta.$$

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LEARNING OBJECTIVE

3.2.A

Describe the work done on an object or system by a given force or collection of forces.

ESSENTIAL KNOWLEDGE

ii. Only the component of the force exerted on a system that is parallel to the displacement of the point of application of the force will change the system's total energy.

iii. If the component of the force exerted on a system that is parallel to the displacement is constant, the work done on the system by the force is given by the derived equation

$$W = F_{\parallel} d = Fd\cos\theta.$$

iv. The component of the force exerted on a system perpendicular to the direction of the displacement of the system's center of mass can change the direction of the system's motion without changing the system's kinetic energy.

3.2.A.4

The work–energy theorem states that the change in an object's kinetic energy is equal to the sum of the work (net work) being done by all forces exerted on the object.

Relevant equation:

$$\Delta K = \sum W_i = \sum F_{\parallel,i}\, d_i$$

i. An external force may change the configuration of a system. The component of the external force parallel to the displacement times the displacement of the point of application of the force gives the change in kinetic energy of the system.

ii. If the system's center of mass and the point of application of the force move the same distance when a force is exerted on a system, then the system may be modeled as an object, and only the system's kinetic energy can change.

iii. The energy dissipated by friction is typically equated to the force of friction times the length of the path over which the force is exerted.

$$\Delta E_{\text{mech}} = F_f d\cos\theta$$

3.2.A.5

Work is equal to the area under the curve of a graph of $F_{\parallel}$ as a function of displacement.

BOUNDARY STATEMENT:

AP Physics C: Mechanics only expects students to analyze the transfer of mechanical energy, although students should be aware that mechanical energy may be dissipated in the form of thermal energy or sound.

SUGGESTED SCIENCE PRACTICES

1.C
Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 3.3
Potential Energy

Required Course Content

LEARNING OBJECTIVE

3.3.A
Describe the potential energy of a system.

ESSENTIAL KNOWLEDGE

3.3.A.1
A system composed of two or more objects has potential energy if the objects within that system only interact with each other through conservative forces.

3.3.A.2
Potential energy is a scalar quantity associated with the position of objects within a system.

3.3.A.3
The definition of zero potential energy for a given system is a decision made by the observer considering the situation to simplify or otherwise assist in analysis.

3.3.A.4
The relationship between conservative forces exerted on a system and the system's potential energy is

$$\Delta U = -\int_a^b \vec{F}_{cf}(r) \cdot d\vec{r} \cdot$$

3.3.A.5
The conservative forces exerted on a system in a single dimension can be determined using the slope of the system's potential energy with respect to position in that dimension; these forces point in the direction of decreasing potential energy.

Relevant equation:

$$F_x = -\frac{dU(x)}{dx}$$

3.3.A.6
Graphs of a system's potential energy as a function of its position can be useful in determining physical properties of that system.

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LEARNING OBJECTIVE

3.3.A

Describe the potential energy of a system.

ESSENTIAL KNOWLEDGE

i. Stable equilibrium is a location at which a small displacement in an object's position results in a force exerted on the object opposite to the direction of the small displacement, accelerating the object back toward the equilibrium position.

ii. Unstable equilibrium is a location at which a small displacement in an object's position results in a force exerted on the object in the same direction as the small displacement, accelerating the object away from the equilibrium position.

iii. In a given dimension, stable equilibrium positions exist at locations where the potential energy as a function of position in that dimension has a local minimum.

iv. In a given dimension, unstable equilibrium positions occur at locations where the potential energy as a function of position in that dimension has a local maximum.

3.3.A.7

The potential energy of common physical systems can be described using the physical properties of that system.

i. The elastic potential energy of an ideal spring is given by the following equation, where Δx is the distance the spring has been stretched or compressed from its equilibrium length.

Relevant equation:

$$U_s = \frac{1}{2}k(\Delta x)^2$$

ii. The general form for the gravitational potential energy of a system consisting of two approximately spherical distributions of mass (e.g., moons, planets, or stars) is given by the equation

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

iii. Because the gravitational field near the surface of a planet is nearly constant, the change in gravitational potential energy in a system consisting of an object with mass *m* and a planet with gravitational field of magnitude *g* when the object is near the surface of the planet may be approximated by the equation

$$\Delta U_g = mg\Delta y.$$

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LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
3.3.A Describe the potential energy of a system.	**3.3.A.8** The total potential energy of a system containing more than two objects is the sum of the potential energy of each pair of objects within the system.

TOPIC 3.4

Conservation of Energy

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
3.4.A Describe the energies present in a system.	**3.4.A.1** A system composed of only a single object can only have kinetic energy. **3.4.A.2** A system that contains objects that interact via conservative forces or that can change its shape reversibly may have both kinetic and potential energies.
3.4.B Describe the behavior of a system using conservation of mechanical energy principles.	**3.4.B.1** Mechanical energy is the sum of a system's kinetic and potential energies. **3.4.B.2** Any change to a type of energy within a system must be balanced by an equivalent change of other types of energies within the system or by a transfer of energy between the system and its surroundings. **3.4.B.3** A system may be selected so that the total energy of that system is constant. **3.4.B.4** If the total energy of a system changes, that change will be equivalent to the energy transferred into or out of the system.

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SUGGESTED SCIENCE PRACTICES

1.B Create quantitative graphs with appropriate scales and units, including plotting data.

2.A Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.A Create experimental procedures that are appropriate for a given scientific question.

3.B Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

LEARNING OBJECTIVE

3.4.C

Describe how the selection of a system determines whether the energy of that system changes.

ESSENTIAL KNOWLEDGE

3.4.C.1

Energy is conserved in all interactions.

3.4.C.2

If the work done on a selected system is zero and there are no nonconservative interactions within the system, the total mechanical energy of the system is constant.

3.4.C.3

If the work done on a selected system is nonzero, energy is transferred between the system and the environment.

BOUNDARY STATEMENT:

AP Physics C: Mechanics expects students to know that mechanical energy can be dissipated as thermal energy or sound by nonconservative forces.

TOPIC 3.5

Power

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

Required Course Content

LEARNING OBJECTIVE

3.5.A
Describe the transfer of energy into, out of, or within a system in terms of power.

ESSENTIAL KNOWLEDGE

3.5.A.1
Power is the rate at which energy changes with respect to time, either by transfer into or out of a system or by conversion from one type to another within a system.

3.5.A.2
Average power is the amount of energy being transferred or converted, divided by the time it took for that transfer or conversion to occur.

Relevant equation:

$$P_{\text{avg}} = \frac{\Delta E}{\Delta t}$$

3.5.A.3
Because work is the change in energy of an object or system due to a force, average power is the total work done, divided by the time during which that work was done.

Relevant equation:

$$P_{\text{avg}} = \frac{W}{\Delta t}$$

3.5.A.4
The instantaneous power delivered to an object by a force is given by the equation

$$P_{\text{inst}} = \frac{dW}{dt}.$$

3.5.A.5
The instantaneous power delivered to an object by the component of a constant force parallel to the object's velocity can be described with the derived equation

$$P_{\text{inst}} = F_{\parallel} v = Fv\cos\theta.$$

TOPIC 4.1
Linear Momentum

Required Course Content

LEARNING OBJECTIVE

4.1.A
Describe the linear momentum of an object or system.

ESSENTIAL KNOWLEDGE

4.1.A.1
Linear momentum is defined by the equation $\vec{p} = m\vec{v}$.

4.1.A.2
Momentum is a vector quantity and has the same direction as the velocity.

4.1.A.3
Momentum can be used to analyze collisions and explosions.

i. A collision is a model for an interaction where the forces exerted between the involved objects in the system are much larger than the net external force exerted on those objects during the interaction.

ii. As only the initial and final states of a collision are analyzed, the object model may be used to analyze collisions.

iii. An explosion is a model for an interaction in which forces internal to the system move objects within that system apart.

SUGGESTED SCIENCE PRACTICES

1.C
Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

SUGGESTED SCIENCE PRACTICES

1.C

Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.A

Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C

Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.C

Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 4.2

Change in Momentum and Impulse

Required Course Content

LEARNING OBJECTIVE

4.2.A

Describe the impulse delivered to an object or system.

ESSENTIAL KNOWLEDGE

4.2.A.1

The rate of change of a system's momentum is equal to the net external force exerted on that system.

Relevant equation:

$$\vec{F}_{\text{net}} = \frac{d\vec{p}}{dt}$$

4.2.A.2

Impulse is defined as the integral of a force exerted on an object or system over a time interval.

Relevant equation:

$$\vec{J} = \int_{t_1}^{t_2} \vec{F}_{\text{net}}(t)\,dt$$

4.2.A.3

Impulse is a vector quantity and has the same direction as the net force exerted on the system.

4.2.A.4

The impulse delivered to a system by a net external force is equal to the area under the curve of a graph of the net external force exerted on the system as a function of time.

4.2.A.5

The net external force exerted on a system is equal to the slope of a graph of the momentum of the system as a function of time.

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LEARNING OBJECTIVE

4.2.B

Describe the relationship between the impulse exerted on an object or system and the change in momentum of the object or system.

ESSENTIAL KNOWLEDGE

4.2.B.1

Change in momentum is the difference between a system's final momentum and its initial momentum.

Relevant equation:

$$\Delta\vec{p} = \vec{p} - \vec{p}_0$$

4.2.B.2

The impulse–momentum theorem relates the impulse delivered to an object and the object's change in momentum.

i. The impulse exerted on an object is equal to the object's change in momentum.

Relevant equation:

$$\vec{J} = \int_{t_1}^{t_2} \vec{F}_{\text{net}}(t)dt = \Delta\vec{p}$$

ii. Newton's second law of motion is a direct result of the impulse–momentum theorem applied to systems with constant mass.

$$\vec{F}_{\text{net}} = \frac{d\vec{p}}{dt} = m\frac{d\vec{v}}{dt} = m\vec{a}$$

iii. The impulse–momentum theorem also describes the behavior of a system in which the velocity is constant but the mass changes with respect to time.

$$\vec{F}_{\text{net}} = \frac{d\vec{p}}{dt} = \frac{dm}{dt}\vec{v}$$

SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data.

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 4.3
Conservation of Linear Momentum

Required Course Content

LEARNING OBJECTIVE

4.3.A
Describe the behavior of a system using conservation of linear momentum.

ESSENTIAL KNOWLEDGE

4.3.A.1
A collection of objects with individual momenta can be described as one system with one center-of-mass velocity.

i. For a collection of objects, the velocity of a system's center of mass can be calculated using the equation

$$\vec{v}_{\mathrm{cm}} = \frac{\sum \vec{p}_i}{\sum m_i} = \frac{\sum (m_i \vec{v}_i)}{\sum m_i}.$$

ii. The velocity of a system's center of mass is constant in the absence of a net external force.

4.3.A.2
The total momentum of a system is the sum of the momenta of the system's constituent parts.

4.3.A.3
In the absence of net external forces, any change to the momentum of an object within a system must be balanced by an equivalent and opposite change of momentum elsewhere within the system. Any change to the momentum of a system is due to a transfer of momentum between the system and its surroundings.

i. The impulse exerted by one object on a second object is equal and opposite to the impulse exerted by the second object on the first. This is a direct result of Newton's third law.

ii. A system may be selected so that the total momentum of that system is constant.

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LEARNING OBJECTIVE

4.3.A

Describe the behavior of a system using conservation of linear momentum.

ESSENTIAL KNOWLEDGE

iii. If the total momentum of a system changes, that change will be equivalent to the impulse exerted on the system.

Relevant equation:

$$\vec{J} = \Delta\vec{p}$$

4.3.A.4

Correct application of conservation of momentum can be used to determine the velocity of a system immediately before and immediately after collisions or explosions.

BOUNDARY STATEMENT:

AP Physics C: Mechanics only expects students to quantitatively analyze collisions and interactions in one or two dimensions. Three-dimensional collisions may be analyzed qualitatively.

4.3.B

Describe how the selection of a system determines whether the momentum of that system changes.

4.3.B.1

Momentum is conserved in all interactions.

4.3.B.2

If the net external force on the selected system is zero, the total momentum of the system is constant.

4.3.B.3

If the net external force on the selected system is nonzero, momentum is transferred between the system and the environment.

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 4.4
Elastic and Inelastic Collisions

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
4.4.A Describe whether an interaction between objects is elastic or inelastic.	**4.4.A.1** An elastic collision between objects is one in which the initial kinetic energy of the system is equal to the final kinetic energy of the system. **4.4.A.2** In an elastic collision, the final kinetic energies of each of the objects within the system may be different from their initial kinetic energies. **4.4.A.3** An inelastic collision between objects is one in which the total kinetic energy of the system decreases. **4.4.A.4** In an inelastic collision, some of the initial kinetic energy is not restored to kinetic energy but is transformed by nonconservative forces into other forms of energy. **4.4.A.5** In a perfectly inelastic collision, the objects stick together and move with the same velocity after the collision.

TOPIC 5.1

Rotational Kinematics

Required Course Content

LEARNING OBJECTIVE

5.1.A

Describe the rotation of a system with respect to time using angular displacement, angular velocity, and angular acceleration.

ESSENTIAL KNOWLEDGE

5.1.A.1

Angular displacement is the measurement of the angle, in radians, through which a point on a rigid system rotates about a specified axis.

Relevant equation:

$$\Delta\theta = \theta - \theta_0$$

i. A rigid system is one that holds its shape but in which different points on the system move in different directions during rotation. A rigid system cannot be modeled as an object.

ii. One direction of angular displacement about an axis of rotation — clockwise or counterclockwise — is typically indicated as mathematically positive, with the other direction becoming mathematically negative.

iii. If the rotation of a system about an axis may be well described using the motion of the system's center of mass, the system may be treated as a single object. For example, the rotation of Earth about its axis may be considered negligible when considering the revolution of Earth about the center of mass of the Earth-Sun system.

5.1.A.2

Angular velocity is the rate at which angular position changes with respect to time.

Relevant equation:

$$\omega = \frac{d\theta}{dt}$$

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SUGGESTED SCIENCE PRACTICES

1.C

Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.B

Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.D

Predict new values or factors of change of physical quantities using functional dependence between variables.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

LEARNING OBJECTIVE

5.1.A

Describe the rotation of a system with respect to time using angular displacement, angular velocity, and angular acceleration

ESSENTIAL KNOWLEDGE

5.1.A.3

Angular acceleration is the rate at which angular velocity changes with respect to time.

Relevant equation:

$$\alpha = \frac{d\omega}{dt}$$

5.1.A.4

Angular displacement, angular velocity, and angular acceleration around one axis are analogous to linear displacement, velocity, and acceleration in one dimension and demonstrate the same mathematical relationships.

i. For constant angular acceleration, the mathematical relationships between angular displacement, angular velocity, and angular acceleration can be described with the following equations:

$$\omega = \omega_0 + \alpha t$$

$$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$$

$$\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$$

ii. Graphs of angular displacement, angular velocity, and angular acceleration as functions of time can be used to find the relationships between those quantities.

BOUNDARY STATEMENT:

AP Physics C: Mechanics expects students to be able to mathematically manipulate the magnitudes of angular displacement, angular velocity, and angular acceleration using vector conventions. However, the directions of said vectors will not be assessed on the exam.

Descriptions of the directions of rotational kinematics quantities for a point or object are limited to clockwise and counterclockwise with respect to a given axis of rotation.

TOPIC 5.2
Connecting Linear and Rotational Motion

Required Course Content

LEARNING OBJECTIVE

5.2.A
Describe the linear motion of a point on a rotating rigid system that corresponds to the rotational motion of that point, and vice versa.

ESSENTIAL KNOWLEDGE

5.2.A.1
For a point at a distance r from a fixed axis of rotation, the linear distance s traveled by the point as the system rotates through an angle $\Delta\theta$ is given by the equation $\Delta s = r\Delta\theta$.

5.2.A.2
Derived relationships of linear velocity and of the tangential component of acceleration to their respective angular quantities are given by the following equations:

$$s = r\theta$$
$$v = r\omega$$
$$a_T = r\alpha$$

5.2.A.3
For a rigid system, all points within that system have the same angular velocity and angular acceleration.

BOUNDARY STATEMENT:

AP Physics C: Mechanics expects students to be able to mathematically manipulate the magnitudes of angular displacement, angular velocity, and angular acceleration using vector conventions. However, the directions of the vectors will not be assessed on the exam.

Descriptions of the directions of rotational kinematics quantities for a point or rigid body are limited to clockwise and counterclockwise with respect to a given axis of rotation.

SUGGESTED SCIENCE PRACTICES

1.C
Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 5.3
Torque

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
5.3.A Identify the torques exerted on a rigid system.	**5.3.A.1** Torque results only from the force component perpendicular to the position vector from the axis of rotation to the point of application of the force. **5.3.A.2** The lever arm is the perpendicular distance from the axis of rotation to the line of action of the exerted force.
5.3.B Describe the torques exerted on a rigid system.	**5.3.B.1** Torques can be described using force diagrams. i. Force diagrams are similar to free-body diagrams and are used to analyze the torques exerted on a rigid system. ii. Similar to free-body diagrams, force diagrams represent the relative magnitude and direction of the forces exerted on a rigid system. Force diagrams also depict the location at which those forces are exerted relative to the axis of rotation. **5.3.B.2** The torque exerted on a rigid system about a chosen pivot point by a given force is described by $\vec{\tau} = \vec{r} \times \vec{F}$. i. The cross-product between two vectors, $\vec{A}$ and $\vec{B}$, results in a vector quantity of magnitude $\vec{A} \times \vec{B} = AB \sin\theta$.

continued on next page

LEARNING OBJECTIVE

5.3.B

Describe the torques exerted on a rigid system.

ESSENTIAL KNOWLEDGE

ii. The direction of the vector resulting from the cross-product of vectors $\vec{A}$ and $\vec{B}$ is perpendicular to both vectors $\vec{A}$ and $\vec{B}$ and therefore is normal to the plane defined by vectors $\vec{A}$ and $\vec{B}$.

iii. The direction of the vector resulting from the cross-product of vectors $\vec{A}$ and $\vec{B}$ can be qualitatively determined by applying the appropriate right-hand rule.

SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 5.4
Rotational Inertia

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
5.4.A Describe the rotational inertia of a rigid system relative to a given axis of rotation.	**5.4.A.1** Rotational inertia measures a rigid system's resistance to changes in rotation and is related to the mass of the system and the distribution of that mass relative to the axis of rotation. **5.4.A.2** The rotational inertia of an object rotating a perpendicular distance r from an axis is described by the equation $I = mr^2$. **5.4.A.3** The total rotational inertia of a collection of objects about an axis is the sum of the rotational inertias of each object about that axis. $I_{tot} = \sum I_i = \sum m_i r_i^2$ **5.4.A.4** For a solid that can be considered as a collection of differential masses, dm, the solid's rotational inertia can be calculated using the equation $I = \int r^2\, dm$, where r is the perpendicular distance from dm to the axis of rotation.
5.4.B Describe the rotational inertia of a rigid system rotating about an axis that does not pass through the system's center of mass.	**5.4.B.1** A rigid system's rotational inertia in a given plane is at a minimum when the rotational axis passes through the system's center of mass.

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LEARNING OBJECTIVE

5.4.B

Describe the rotational inertia of a rigid system rotating about an axis that does not pass through the system's center of mass.

ESSENTIAL KNOWLEDGE

5.4.B.2

The parallel axis theorem uses the following equation to relate the rotational inertia of a rigid system about any axis that is parallel to an axis through its center of mass:

$$I' = I_{cm} + Md^2$$

BOUNDARY STATEMENT:

AP Physics C: Mechanics only expects students to use calculus in the derivations of the rotational inertia of thin rods of uniform or nonuniform density about an arbitrary axis perpendicular to the rod, as well as derivations of the rotational inertia of a thin cylindrical shell, disk, or rigid bodies that can be considered to be made up of coaxial rings or shells about an axis that passes through their centers (e.g., annular rings).

Students should have a qualitative understanding of the factors that affect rotational inertia; for example, how rotational inertia is greater when mass is farther from the axis of rotation, which is why a hoop has more rotational inertia than a solid puck of the same mass and radius.

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 5.5

Rotational Equilibrium and Newton's First Law in Rotational Form

Required Course Content

LEARNING OBJECTIVE

5.5.A
Describe the conditions under which a system's angular velocity remains constant.

ESSENTIAL KNOWLEDGE

5.5.A.1
A system may exhibit rotational equilibrium (constant angular velocity) without being in translational equilibrium, and vice versa.

i. Free-body and force diagrams describe the nature of the forces and torques exerted on an object or rigid system.

ii. Rotational equilibrium is a configuration of torques such that the net torque exerted on the system is zero.

Relevant equation:

$$\sum \tau_i = 0$$

iii. The rotational analog of Newton's first law is that a system will have a constant angular velocity only if the net torque exerted on the system is zero.

5.5.A.2
A rotational corollary to Newton's second law states that if the torques exerted on a rigid system are not balanced, the system's angular velocity must be changing.

BOUNDARY STATEMENT:
AP Physics C: Mechanics does not expect students to simultaneously analyze rotation in multiple planes.

TOPIC 5.6

Newton's Second Law in Rotational Form

SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

Required Course Content

LEARNING OBJECTIVE

5.6.A
Describe the conditions under which a system's angular velocity changes.

ESSENTIAL KNOWLEDGE

5.6.A.1
Angular velocity changes when the net torque exerted on the object or system is not equal to zero.

5.6.A.2
The rate at which the angular velocity of a rigid system changes is directly proportional to the net torque exerted on the rigid system and is in the same direction. The angular acceleration of the rigid system is inversely proportional to the rotational inertia of the rigid system.

Relevant equation:

$$\alpha_{\text{sys}} = \frac{\Sigma\tau}{I_{\text{sys}}} = \frac{\tau_{\text{net}}}{I_{\text{sys}}}$$

5.6.A.3
To fully describe a rotating rigid system, linear and rotational analyses may need to be performed independently.

TOPIC 6.1

Rotational Kinetic Energy

Required Course Content

LEARNING OBJECTIVE

6.1.A

Describe the rotational kinetic energy of a rigid system in terms of the rotational inertia and angular velocity of that rigid system.

ESSENTIAL KNOWLEDGE

6.1.A.1

The rotational kinetic energy of an object or rigid system is related to the rotational inertia and angular velocity of the rigid system and is given by the equation

$$K_{\text{rot}} = \frac{1}{2} I\omega^2.$$

i. The rotational inertia of an object about a fixed axis can be used to show that the rotational kinetic energy of that object is equivalent to its translational kinetic energy, which is its total kinetic energy.

ii. The total kinetic energy of a rigid system is the sum of its rotational kinetic energy due to its rotation about its center of mass and the translational kinetic energy due to the linear motion of its center of mass.

6.1.A.2

A rigid system can have rotational kinetic energy while its center of mass is at rest due to the individual points within the rigid system having linear speed and, therefore, kinetic energy.

6.1.A.3

Rotational kinetic energy is a scalar quantity.

SUGGESTED SCIENCE PRACTICES

1.C

Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.C

Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

3.C

Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 6.2

Torque and Work

Required Course Content

LEARNING OBJECTIVE

6.2.A
Describe the work done on a rigid system by a given torque or collection of torques.

ESSENTIAL KNOWLEDGE

6.2.A.1
A torque can transfer energy into or out of an object or rigid system if the torque is exerted over an angular displacement.

6.2.A.2
The amount of work done on a rigid system by a torque is related to the magnitude of that torque and the angular displacement through which the rigid system rotates during the interval in which that torque is exerted.

Relevant equation:

$$W = \int_{\theta_1}^{\theta_2} \tau \, d\theta$$

6.2.A.3
Work done on a rigid system by a given torque can be found from the area under the curve of a graph of the torque as a function of angular position.

TOPIC 6.3
Angular Momentum and Angular Impulse

SUGGESTED SCIENCE PRACTICES

1.C
Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

Required Course Content

LEARNING OBJECTIVE

6.3.A
Describe the angular momentum of an object or rigid system.

ESSENTIAL KNOWLEDGE

6.3.A.1
The magnitude of the angular momentum of a rigid system about a specific axis can be described with the equation

$L = I\omega.$

6.3.A.2
The angular momentum of an object about a given point is

$\vec{L} = \vec{r} \times \vec{p}.$

i. The selection of the axis about which an object is considered to rotate influences the determination of the angular momentum of that object.
ii. The measured angular momentum of an object traveling in a straight line depends on the distance between the reference point and the object, the mass of the object, the speed of the object, and the angle between the radial distance and the velocity of the object.

LEARNING OBJECTIVE

6.3.B
Describe the angular impulse delivered to an object or rigid system by a torque.

ESSENTIAL KNOWLEDGE

6.3.B.1
Angular impulse is defined as the product of the torque exerted on an object or rigid system and the time interval during which the torque is exerted.

Relevant equation:

$$\text{angular impluse} = \int \tau \, dt$$

6.3.B.2
Angular impulse has the same direction as the torque imparting it.

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LEARNING OBJECTIVE

6.3.B

Describe the angular impulse delivered to an object or rigid system by a torque.

6.3.C

Relate the change in angular momentum of an object or rigid system to the angular impulse given to that object or rigid system.

ESSENTIAL KNOWLEDGE

6.3.B.3

The angular impulse delivered to an object or rigid system by a torque can be found from the area under the curve of a graph of the torque as a function of time.

6.3.C.1

The magnitude of the change in angular momentum can be described by comparing the magnitudes of the final and initial momenta of the object or rigid system.

$\Delta L = L - L_0$

6.3.C.2

A rotational form of the impulse–momentum theorem relates the angular impulse delivered to an object or rigid system and the change in angular momentum of that object or rigid system.

i. The angular impulse exerted on an object or rigid system is equal to the change in angular momentum of that object or rigid system.

   Relevant equation:

$$\Delta L = \int_{t_1}^{t_2} \tau \, dt$$

ii. The rotational form of the impulse–momentum theorem is a direct result of Newton's second law of motion for cases in which rotational inertia is constant.

$$\tau_{\text{net}} = \frac{dL}{dt} = I\frac{d\omega}{dt} = I\alpha$$

6.3.C.3

The net torque exerted on an object or rigid system is equal to the slope of the graph of the angular momentum of an object as a function of time.

6.3.C.4

The angular impulse delivered to an object or rigid system is equal to the area under the curve of a graph of the net external torque exerted on an object as a function of time.

TOPIC 6.4

Conservation of Angular Momentum

Required Course Content

LEARNING OBJECTIVE

6.4.A

Describe the behavior of a system using conservation of angular momentum.

ESSENTIAL KNOWLEDGE

6.4.A.1

The total angular momentum of a system about a rotational axis is the sum of the angular momenta of the system's constituent parts about that rotational axis.

6.4.A.2

Any change to a system's angular momentum must be due to an interaction between the system and its surroundings.

i. The angular impulse exerted by one object or system on a second object or system is equal and opposite to the angular impulse exerted by the second object or system on the first. This is a direct result of Newton's third law.

ii. A system may be selected so that the total angular momentum of that system is constant.

iii. The angular speed of a nonrigid, system may change without the angular momentum of the system changing if the system changes shape by moving mass closer to or farther from the rotational axis.

iv. If the total angular momentum of a system changes, that change will be equivalent to the angular impulse exerted on the system.

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SUGGESTED SCIENCE PRACTICES

1.C

Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.B

Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

3.C

Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
6.4.B Describe how the selection of a system determines whether the angular momentum of that system changes.	**6.4.B.1** Angular momentum is conserved in all interactions. **6.4.B.2** If the net external torque exerted on a selected object or rigid system is zero, the total angular momentum of that system is constant. **6.4.B.3** If the net external torque exerted on a selected object or rigid system is nonzero, angular momentum is transferred between the system and the environment.

TOPIC 6.5
Rolling

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
6.5.A Describe the kinetic energy of a system that has translational and rotational motion.	**6.5.A.1** The total kinetic energy of a system is the sum of the system's translational and rotational kinetic energies. *Relevant equation:* $K_{\text{tot}} = K_{\text{trans}} + K_{\text{rot}}$
6.5.B Describe the motion of a system that is rolling without slipping.	**6.5.B.1** While rolling without slipping, the translational motion of a system's center of mass is related to the rotational motion of the system itself with the following equations: $\Delta x_{\text{cm}} = r\Delta\theta$ $v_{\text{cm}} = r\omega$ $a_{\text{cm}} = r\alpha$ **6.5.B.2** For ideal cases, rolling without slipping implies that the frictional force does not dissipate any energy from the rolling system.
6.5.C Describe the motion of a system that is rolling while slipping.	**6.5.C.1** When slipping, the motion of a system's center of mass and the system's rotational motion cannot be directly related. **6.5.C.2** When a rotating system is slipping relative to another surface, the point of application of the force of kinetic friction exerted on the system moves with respect to the surface, so the force of kinetic friction will dissipate energy from the system.

BOUNDARY STATEMENT:

Rolling friction is beyond the scope of AP Physics C: Mechanics.

SUGGESTED SCIENCE PRACTICES

1.B Create quantitative graphs with appropriate scales and units, including plotting data.

2.A Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D Predict new values or factors of change of physical quantities using functional dependence between variables.

3.A Create experimental procedures that are appropriate for a given scientific question.

3.B Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

SUGGESTED SCIENCE PRACTICES

1.C
Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 6.6

Motion of Orbiting Satellites

Required Course Content

LEARNING OBJECTIVE

6.6.A
Describe the motions of a system consisting of two objects or systems interacting only via gravitational forces.

ESSENTIAL KNOWLEDGE

6.6.A.1
In a system consisting only of a massive central object and an orbiting satellite with mass that is negligible in comparison to the central object's mass, the motion of the central object itself is negligible.

6.6.A.2
The motion of satellites in orbits is constrained by conservation laws.

i. In circular orbits, the system's total mechanical energy, the system's gravitational potential energy, and the satellite's angular momentum and kinetic energy are constant.
ii. In elliptical orbits, the system's total mechanical energy and the satellite's angular momentum are constant, but the system's gravitational potential energy and the satellite's kinetic energy can each change.
iii. The gravitational potential energy of a system consisting of a satellite and a massive central object is defined to be zero when the satellite is an infinite distance from the central object.

Relevant equation:

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

continued on next page

LEARNING OBJECTIVE

6.6.A

Describe the motions of a system consisting of two objects interacting only via gravitational forces.

ESSENTIAL KNOWLEDGE

6.6.A.3

The total energy of a system consisting of a satellite orbiting a central object in a circular path can be written in terms of the gravitational potential energy of that system or the kinetic energy of the satellite.

Derived equations:

$$K = -\frac{1}{2}U$$

$$E_{total} = \frac{1}{2}U = -\frac{GMm}{2r}$$

6.6.A.4

The escape velocity of a satellite is the satellite's velocity such that the mechanical energy of the satellite–central-object system is equal to zero.

i. When the only force exerted on a satellite is gravity from a central object, a satellite that reaches escape velocity will move away from the central body until its speed reaches zero at an infinite distance from the central body.

ii. The escape velocity of a satellite from a central body of mass M can be derived using conservation of energy laws.

Derived equation:

$$v_{esc} = \sqrt{\frac{2GM}{r}}$$

TOPIC 7.1

Defining Simple Harmonic Motion (SHM)

Required Course Content

LEARNING OBJECTIVE

7.1.A

Describe simple harmonic motion.

ESSENTIAL KNOWLEDGE

7.1.A.1

Simple harmonic motion is a special case of periodic motion.

7.1.A.2

SHM results when the magnitude of the restoring force exerted on an object is proportional to that object's displacement from its equilibrium position.

Derived equation:

$ma_x = -k\Delta x$

i. A restoring force is a force that is exerted in a direction opposite to the object's displacement from an equilibrium position.

ii. An equilibrium position is a location at which the net force exerted on an object or system is zero.

SUGGESTED SCIENCE PRACTICES

1.A

Create diagrams, tables, charts, or schematics to represent physical situations.

2.C

Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

3.C

Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

SUGGESTED SCIENCE PRACTICES

1.C
Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 7.2

Frequency and Period of SHM

Required Course Content

LEARNING OBJECTIVE

7.2.A
Describe the frequency and period of an object exhibiting SHM.

ESSENTIAL KNOWLEDGE

7.2.A.1
The period of SHM is related to the angular frequency, ω, of the object's motion by the following equation:

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

i. The period of an object– ideal spring oscillator is given by the equation

$$T_s = 2\pi\sqrt{\frac{m}{k}}.$$

ii. The period of a simple pendulum displaced by a small angle is given by the equation

$$T_p = 2\pi\sqrt{\frac{l}{g}}.$$

TOPIC 7.3

Representing and Analyzing SHM

Required Course Content

LEARNING OBJECTIVE

7.3.A

Describe the displacement, velocity, and acceleration of an object exhibiting SHM.

ESSENTIAL KNOWLEDGE

7.3.A.1

For an object exhibiting SHM, the displacement of that object measured from its equilibrium position can be represented by the equations

$x = A\cos(2\pi ft)$ or $x = A\sin(2\pi ft)$.

i. Minima, maxima, and zeros of displacement, velocity, and acceleration are features of harmonic motion.

ii. Recognizing the positions or times at which the displacement, velocity, and acceleration for SHM have extrema or zeros can help in qualitatively describing the behavior of the motion.

7.3.A.2

The position as a function of time for an object exhibiting SHM is a solution of the second-order differential equation derived from the application of Newton's second law.

Derived equation:

$$\frac{d^2x}{dt^2} = -\omega^2 x$$

7.3.A.3

Characteristics of SHM, such as velocity and acceleration, can be determined by or derived from the equation

$x = A\cos(\omega t + \phi)$.

i. The acceleration of an object exhibiting SHM is related to the object's angular frequency and position.

Derived equation:

$a = -\omega^2 x$

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SUGGESTED SCIENCE PRACTICES

1.C

Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.A

Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C

Compare physical quantities between two or more scenarios or at different times and/or locations within a single scenario.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

LEARNING OBJECTIVE

7.3.A

Describe the displacement, velocity, and acceleration of an object exhibiting SHM.

ESSENTIAL KNOWLEDGE

ii. It can be shown that the maximum velocity and acceleration of an object exhibiting SHM are related to the angular frequency of the object's motion.

Derived equations:

$$v_{max} = A\omega$$

$$a_{max} = A\omega^2$$

7.3.A.4

In the presence of a sinusoidal external force, a system may exhibit resonance.

i. Resonance occurs when an external force is exerted at the natural frequency of an oscillating system.

ii. Resonance increases the amplitude of oscillating motion.

iii. The natural frequency of a system is the frequency at which the system will oscillate when it is displaced from its equilibrium position.

7.3.A.5

Changing the amplitude of a system exhibiting SHM will not change its period.

7.3.A.6

Properties of SHM can be determined and analyzed using graphical representations.

BOUNDARY STATEMENT:

AP Physics C: Mechanics only expects students to know the solution to the second-order differential equation that describes SHM, as well as be able to identify SHM. AP Physics C: Mechanics does not expect students to mathematically prove that the solution is correct.

TOPIC 7.4

Energy of Simple Harmonic Oscillators

Required Course Content

LEARNING OBJECTIVE

7.4.A

Describe the mechanical energy of a system exhibiting SHM.

ESSENTIAL KNOWLEDGE

7.4.A.1

The total energy of a system exhibiting SHM is the sum of the system's kinetic and potential energies.

Relevant equation:

$$E_{\text{total}} = U + K$$

7.4.A.2

Conservation of energy indicates that the total energy of a system exhibiting SHM is constant.

7.4.A.3

The kinetic energy of a system exhibiting SHM is at a maximum when the system's potential energy is at a minimum.

7.4.A.4

The potential energy of a system exhibiting SHM is at a maximum when the system's kinetic energy is at a minimum.

i. The minimum kinetic energy of a system exhibiting SHM is zero.

ii. Changing the amplitude of a system exhibiting SHM will change the maximum potential energy of the system and, therefore, the total energy of the system.

Relevant equation for a spring–object system:

$$E_{\text{total}} = \frac{1}{2}kA^2$$

SUGGESTED SCIENCE PRACTICES

1.C
Create qualitative sketches of graphs that represent features of a model or the behavior of the physical system.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 7.5

Simple and Physical Pendulums

Required Course Content

LEARNING OBJECTIVE

7.5.A
Describe the properties of a physical pendulum.

ESSENTIAL KNOWLEDGE

7.5.A.1
A physical pendulum is a rigid body that undergoes oscillation about a fixed axis.

7.5.A.2
For small amplitudes of motion, the period of a physical pendulum is derived from the application of Newton's second law in rotational form.

Relevant equation:

$$T_{\text{phys}} = 2\pi\sqrt{\frac{I}{mgd}}$$

i. When displaced from equilibrium, the gravitational force exerted on a physical pendulum's center of mass provides a restoring torque.

Derived equation:

$$\tau = -mgd\sin\theta$$

ii. For small amplitudes of motion, the small-angle approximation can be applied to the restoring torque.

Derived equation:

$$\sin\theta \approx \theta$$
$$\tau = -mgd\theta = I\alpha$$

iii. The small-angle approximation and Newton's second law in rotational form yield a second-order differential equation that describes SHM:

$$\frac{d^2\theta}{dt^2} = -\omega^2\theta$$

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LEARNING OBJECTIVE

7.5.A

Describe the properties of a physical pendulum.

ESSENTIAL KNOWLEDGE

7.5.A.3

A simple pendulum is a special case of physical pendulums in which the hanging object can be modeled as a point mass at a distance, *l*, from the pivot point.

Relevant equation:

$$T_p = 2\pi\sqrt{\frac{\ell}{g}}$$

7.5.A.4

A torsion pendulum is a case of SHM where the restoring torque is proportional to the angular displacement of a rotating system. For example, a horizontal disk that is suspended from a wire attached to its center of mass may undergo rotational oscillations about the wire in the horizontal plane.

Derived equation:

$$I\alpha = -k\Delta\theta$$

TOPIC 8.1

Electric Charge and Electric Force

Required Course Content

LEARNING OBJECTIVE

8.1.A

Describe the electric force that results from the interactions between charged objects or systems.

ESSENTIAL KNOWLEDGE

8.1.A.1

Charge is a fundamental property of all matter.

i. Charge is a scalar quantity and is described as positive or negative.

ii. The magnitude of the charge of a single electron or proton, the elementary charge e, can be considered to be the smallest divisible amount of charge.

iii. The charge of an electron is $-e$ and the charge of a proton is $+e$.

iv. A point charge is a model in which the physical size of a charged object or system is negligible in the context of the situation being analyzed.

8.1.A.2

Coulomb's law describes the electrostatic force between two charged objects as directly proportional to the magnitude of each of the charges and inversely proportional to the square of the distance between the objects.

Relevant equation:

$$\left|\vec{F}_E\right| = \frac{1}{4\pi\varepsilon_0}\frac{\left|q_1 q_2\right|}{r^2} = k\frac{\left|q_1 q_2\right|}{r^2}$$

8.1.A.3

The direction of the electrostatic force depends on the signs of the charges of the interacting objects and is along the line of separation between the objects.

i. Two objects with charges of the same sign exert repulsive forces on each other.

ii. Two objects with charges of opposite signs exert attractive forces on each other.

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SUGGESTED SCIENCE PRACTICES

1.A

Create diagrams, tables, charts, or schematics to represent physical situations.

2.B

Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.D

Predict new values or factors of change of physical quantities using functional dependence between variables.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

Electric Charges, Fields, and Gauss's Law

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
8.1.A Describe the electric force that results from the interactions between charged objects or systems.	**8.1.A.4** Electric forces are responsible for some of the macroscopic properties of objects in everyday experiences. However, the large number of particle interactions that occur make it more convenient to treat everyday forces in terms of nonfundamental forces called contact forces, such as normal force, friction, and tension.
8.1.B Describe the electric and gravitational forces that result from interactions between charged objects with mass.	**8.1.B.1** Electrostatic forces can be attractive or repulsive, while gravitational forces are always attractive. **8.1.B.2** For any two objects that have mass and electric charge, the magnitude of the gravitational force is usually much smaller than the magnitude of the electrostatic force. **8.1.B.3** Gravitational forces dominate at larger scales even though they are weaker than electrostatic forces, because systems at large scales tend to be electrically neutral.
8.1.C Describe the electric permittivity of a material or medium.	**8.1.C.1** Electric permittivity is a measurement of the degree to which a material or medium is polarized in the presence of an electric field. **8.1.C.2** Electric polarization can be modeled as the induced rearrangement of electrons by an external electric field, resulting in a separation of positive and negative charges within a material or medium. **8.1.C.3** Free space has a constant value of electric permittivity, ε_0, that appears in physical relationships. **8.1.C.4** The permittivity of matter has a value different from that of free space that arises from the matter's composition and arrangement. i. In a given material, electric permittivity is determined by the ease with which electrons can change configurations within the material.

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LEARNING OBJECTIVE

8.1.C

Describe the electric permittivity of a material or medium.

ESSENTIAL KNOWLEDGE

ii. Conductors are made from electrically conducting materials in which charge carriers move easily; insulators are made from electrically nonconducting materials in which charge carriers cannot move easily.

BOUNDARY STATEMENT:

AP Physics C: Electricity & Magnetism only expects students to make calculations of the electric force between four or fewer interacting charged objects or systems. The analysis of the resulting electric force from more charges is allowed in situations of high symmetry. Note that students are expected to calculate the electric fields of charge distributions, as described in Topics 8.6 and 8.7.

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.C
Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 8.2

Conservation of Electric Charge and the Process of Charging

Required Course Content

LEARNING OBJECTIVE

8.2.A
Describe the behavior of a system using conservation of charge.

ESSENTIAL KNOWLEDGE

8.2.A.1
The net charge or charge distribution of a system can change in response to the presence of, or changes in, the net charge or charge distribution of other systems.

i. The net charge of a system can change due to friction or contact between systems.

ii. Induced charge separation occurs when the electrostatic force between two systems alters the distribution of charges within the systems, resulting in the polarization of one or both systems.

iii. Induced charge separation can occur in neutral systems.

8.2.A.2
Any change to a system's net charge is due to a transfer of charge between the system and its surroundings.

i. The charging of a system typically involves the transfer of electrons to and from the system.

ii. The net charge of a system will be constant unless there is a transfer of charge to or from the system.

8.2.A.3
Grounding involves electrically connecting a charged object to a much larger and approximately neutral system (e.g., Earth).

TOPIC 8.3
Electric Fields

Required Course Content

LEARNING OBJECTIVE

8.3.A

Describe the electric field produced by a charged object or configuration of point charges.

ESSENTIAL KNOWLEDGE

8.3.A.1

Electric fields may originate from charged objects.

8.3.A.2

The electric field at a given point is the ratio of the electric force exerted on a test charge at the point to the charge of the test charge.

Relevant equation:

$$\vec{E} = \frac{\vec{F}_E}{q}$$

i. A test charge is a point charge of small enough magnitude such that its presence does not significantly affect an electric field in its vicinity.

ii. An electric field points away from isolated positive charges and toward isolated negative charges.

iii. The electric force exerted on a positive test charge by an electric field is in the same direction as the electric field. The electric force exerted on a negative test charge by an electric field is in the opposite direction of the electric field.

8.3.A.3

The electric field is a vector quantity and can be represented in space using vector field maps.

i. The net electric field at a given location is the vector sum of individual electric fields created by nearby charged objects.

ii. Electric field maps use vectors to depict the magnitude and direction of the electric field at many locations within a given region.

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SUGGESTED SCIENCE PRACTICES

1.B

Create quantitative graphs with appropriate scales and units, including plotting data.

2.A

Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D

Predict new values or factors of change of physical quantities using functional dependence between variables.

3.A

Create experimental procedures that are appropriate for a given scientific question.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
8.3.A Describe the electric field produced by a charged object or configuration of point charges.	iii. Electric field line diagrams are simplified models of electric field maps and can be used to determine the relative magnitude and direction of the electric field at any position in the diagram.
8.3.B Describe the electric field generated by charged conductors or insulators.	8.3.B.1 While in electrostatic equilibrium, the excess charge of a solid conductor is distributed on the surface of the conductor, and the electric field within the conductor is zero. i. At the surface of a charged conductor, the electric field is perpendicular to the surface. ii. The electric field outside an isolated sphere with spherically symmetric charge distribution is the same as the electric field due to a point charge with the same net charge as the sphere located at the center of the sphere. *Relevant equation:* $\left\|\vec{F}_E\right\| = \frac{1}{4\pi\varepsilon_0}\frac{\|q_1 q_2\|}{r^2} = k\frac{\|q_1 q_2\|}{r^2}$ 8.3.B.2 While in electrostatic equilibrium, the excess charge of an insulator is distributed throughout the interior of the insulator as well as at the surface, and the electric field within the insulator may have a nonzero value.

TOPIC 8.4

Electric Fields of Charge Distributions

Required Course Content

LEARNING OBJECTIVE

8.4.A

Describe the electric field resulting from a given charge distribution.

ESSENTIAL KNOWLEDGE

8.4.A.1

Expressions for the electric field of specified charge distributions can be found using integration and the principle of superposition.

Relevant equation:

$$\vec{E} = \frac{1}{4\pi\varepsilon_0}\int \frac{dq}{r^2}\hat{r}$$

8.4.A.2

Symmetry considerations of certain charge distributions can simplify analysis of the electric field resulting from those charge distributions.

BOUNDARY STATEMENT:

AP Physics C: Electricity & Magnetism only expects students to use calculus to find the electric field resulting from the following charge distributions and locations: an infinitely long, uniformly charged wire or cylinder at a distance from its central axis, a thin ring of charge at a location along the axis of the ring, a semicircular arc or part of a semicircular arc at its center, and a finite wire or line charge at a point collinear with the line charge or at a location along its perpendicular bisector.

SUGGESTED SCIENCE PRACTICES

1.C

Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.

2.A

Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C

Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.C

Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 8.5
Electric Flux

Required Course Content

LEARNING OBJECTIVE

8.5.A
Describe the electric flux through an arbitrary area or geometric shape.

ESSENTIAL KNOWLEDGE

8.5.A.1
Flux describes the amount of a given quantity that passes through a given area.

8.5.A.2
For an electric field $\vec{E}$ that is constant across an area $\vec{A}$, the electric flux through the area is defined as

$\Phi_E = \vec{E} \bullet \vec{A}$.

i. The direction of the area vector is defined as perpendicular to the plane of the surface and outward from a closed surface.

ii. The sign of flux is given by the dot product of the electric field vector and the area vector.

8.5.A.3
The total electric flux passing through a surface is defined by the surface integral of the electric field over the surface.

Relevant equation:

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

TOPIC 8.6

Gauss's Law

Required Course Content

LEARNING OBJECTIVE

8.6.A

Describe the properties of a charge distribution by applying Gauss's law.

ESSENTIAL KNOWLEDGE

8.6.A.1

Gauss's law relates electric flux through a Gaussian surface to the charge enclosed by that surface.

Relevant equations:

$$\Phi_E = \frac{q_{\text{enc}}}{\varepsilon_0}$$

$$\oint \vec{E} \cdot d\vec{A} = \frac{q_{\text{enc}}}{\varepsilon_0}$$

8.6.A.2

A Gaussian surface is a three-dimensional, closed surface.

8.6.A.3

The total electric flux through a Gaussian surface is independent of the size of the Gaussian surface if the amount of enclosed charge remains constant.

8.6.A.4

Gaussian surfaces are typically constructed such that the electric field generated by the enclosed charge is either perpendicular or parallel to different regions of the Gaussian surface, resulting in a simplified surface integral.

8.6.A.5

If a function of charge density is given for a charge distribution, the total charge can be determined by integrating the charge density over the length (one dimension), area (two dimensions), or volume (three dimensions) of the charge distribution. For example:

$$Q_{\text{total}} = \int \rho(\vec{r})\,dV$$

SUGGESTED SCIENCE PRACTICES

1.A Create diagrams, tables, charts, or schematics to represent physical situations.

2.A Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.B Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.D Predict new values or factors of change of physical quantities using functional dependence between variables.

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LEARNING OBJECTIVE

8.6.A

Describe the properties of a charge distribution by applying Gauss's law.

ESSENTIAL KNOWLEDGE

8.6.A.6

Maxwell's equations are the collection of equations that fully describe electromagnetism. Gauss's law is Maxwell's first equation.

Relevant equation:

$$\oint \vec{E} \cdot d\vec{A} = \frac{q_{enc}}{\varepsilon_0}$$

BOUNDARY STATEMENT:

AP Physics C: Electricity & Magnetism only expects students to quantitatively apply Gauss's law to point charges and charge distributions that have spherical, cylindrical, or planar symmetry.

TOPIC 9.1

Electric Potential Energy

Required Course Content

LEARNING OBJECTIVE

9.1.A

Describe the electric potential energy of a system.

ESSENTIAL KNOWLEDGE

9.1.A.1

The electric potential energy of a system of two point charges equals the amount of work required for an external force to bring the point charges to their current positions from infinitely far away.

9.1.A.2

The general form for the electric potential energy between two charged objects is given by the equation

$$U_E = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r} = k\frac{q_1 q_2}{r}.$$

9.1.A.3

The total electric potential energy of a system can be determined by finding the sum of the electric potential energies of the individual interactions between each pair of charged objects in the system.

SUGGESTED SCIENCE PRACTICES

1.C

Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.

2.C

Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

3.C

Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

SUGGESTED SCIENCE PRACTICES

1.B

Create quantitative graphs with appropriate scales and units, including plotting data.

2.A

Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.B

Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 9.2
Electric Potential

Required Course Content

LEARNING OBJECTIVE

9.2.A

Describe the electric potential due to a configuration of charged objects.

ESSENTIAL KNOWLEDGE

9.2.A.1

Electric potential describes the electric potential energy per unit charge at a point in space.

9.2.A.2

Expressions for the electric potential of charge distributions can be found using integration and the principle of superposition.

Relevant equation:

$$V = \frac{1}{4\pi\varepsilon_0}\int \frac{dq}{r}$$

i. The electric potential for single point charge is

$$V = \frac{q}{4\pi\varepsilon_0 r}$$

ii. The electric potential due to multiple point charges can be determined by the principle of scalar superposition of the electric potential due to each of the point charges.

Relevant equation:

$$V = \frac{1}{4\pi\varepsilon_0}\sum_i \frac{q_i}{r_i}$$

9.2.A.3

The electric potential difference between two points is the change in electric potential energy per unit charge when a test charge is moved between the two points.

$$\Delta V = \frac{\Delta U_E}{q}$$

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LEARNING OBJECTIVE

9.2.A

Describe the electric potential due to a configuration of charged objects.

ESSENTIAL KNOWLEDGE

9.2.A.4

Electric potential difference may also result from chemical processes that cause positive and negative charges to separate, such as in a battery.

BOUNDARY STATEMENT:

AP Physics C: Electricity & Magnetism only expects students to use calculus to find the electric potential resulting from the following charge distributions and locations: an infinitely long, uniformly charged wire or cylinder at a distance from its central axis, a thin ring of charge at a location along the axis of the ring, a semicircular arc or part of a semicircular arc at its center, and a finite wire or line charge at a point collinear with the line charge or at a location along its perpendicular bisector.

9.2.B

Describe the relationship between electric potential and electric field.

9.2.B.1

The value of an electric field component in any direction at a given location is equal to the opposite of the spatial rate of change in electric potential at that location.

Relevant equation:

$$E_x = -\frac{dV}{dx}$$

9.2.B.2

The change in electric potential between two points can be determined by integrating the dot product of the electric field and the displacement along the path connecting the points.

Relevant equation:

$$\Delta V = V_b - V_a = -\int_a^b \vec{E} \cdot d\vec{r}$$

9.2.B.3

Electric field vector maps and equipotential lines are tools to describe the field produced by a charge or configuration of charges and can be used to predict the motion of charged objects in the field.

i. Equipotential lines represent lines of equal electric potential. These lines are also referred to as isolines of electric potential.

ii. Isolines are perpendicular to electric field vectors. An isoline map of electric potential can be constructed from an electric field vector map, and an electric field map may be constructed from an isoline map.

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LEARNING OBJECTIVE

9.2.B

Describe the relationship between electric potential and electric field.

ESSENTIAL KNOWLEDGE

iii. An electric field vector points in the direction of decreasing potential.

iv. There is no component of an electric field along an isoline.

TOPIC 9.3

Conservation of Electric Energy

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
9.3.A Describe changes in a system due to a difference in electric potential between two locations.	**9.3.A.1** When a charged object moves between two locations with different electric potentials, the resulting change in the electric potential energy of the object-field system is given by the following equation. *Relevant equation:* $\Delta U_E = q\Delta V$ **9.3.A.2** The movement of a charged object between two points with different electric potentials results in a change in kinetic energy of the object consistent with the conservation of energy.

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.C
Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 10.1

Electrostatics with Conductors

Required Course Content

LEARNING OBJECTIVE

10.1.A

Describe the charge distribution within a conductor.

ESSENTIAL KNOWLEDGE

10.1.A.1

An ideal conductor is a material in which electrons are able to move freely.

10.1.A.2

When a conductor is in electrostatic equilibrium, mutual repulsion of excess charge carriers results in those charge carriers residing entirely on the surface of the conductor.

i. In a conductor with a negative net charge, excess electrons reside on the surface of the conductor.

ii. In a conductor with a positive net charge, the surface becomes deficient in electrons, and can be modeled as if positive charge carriers reside on the surface of the conductor.

10.1.A.3

Excess charges will move to the surface of a conductor to create a state of electrostatic equilibrium within the conductor.

i. The time interval over which charges reach electrostatic equilibrium within a conductor is so short as to be negligible.

ii. When a conductor reaches electrostatic equilibrium, all points on the surface of the conductor have the same electric potential, and the conductor becomes an equipotential surface.

iii. The charge density on the surface of a conductor will be greater where there are points or edges compared to planar areas.

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SUGGESTED SCIENCE PRACTICES

1.A

Create diagrams, tables, charts, or schematics to represent physical situations.

2.C

Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

3.C

Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
10.1.A Describe the charge distribution within a conductor.	**10.1.A.4** All excess charges reside on the surface of a conductor, which means there is no net charge in the interior of the conductor, and the electric field is zero within the conductor.
	10.1.A.5 The electric field is perpendicular to the outer surface of a conductor.
	10.1.A.6 A conductor can be polarized in the presence of an external electric field. This is a consequence of the conductor remaining an equipotential surface.
	10.1.A.7 Electrostatic shielding is the process of surrounding an area with a closed, conducting shell to create a region inside the conductor that is free from external electric fields.

TOPIC 10.2

Redistribution of Charge between Conductors

Required Course Content

LEARNING OBJECTIVE

10.2.A

Describe the movement of charge and the resulting interactions when conductors physically contact each other.

ESSENTIAL KNOWLEDGE

10.2.A.1

When conductors are in electrical contact, charges will be redistributed such that the surfaces of each conductor are at the same electric potential.

10.2.A.2

Ground is an idealized reference point that has zero electric potential and can absorb or provide an infinite amount of charge without changing its electric potential.

10.2.A.3

Charge can be induced on a conductor by grounding the conductor in the presence of an external electric field.

SUGGESTED SCIENCE PRACTICES

1.A

Create diagrams, tables, charts, or schematics to represent physical situations.

2.A

Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C

Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

SUGGESTED SCIENCE PRACTICES

1.C
Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 10.3
Capacitors

Required Course Content

LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

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

10.3.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.

Relevant equation:

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

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.

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, of the material between the plates and the electric permittivity of free space, ε_0.

Relevant equation:

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

continued on next page

LEARNING OBJECTIVE

10.3.A

Describe the physical properties of a parallel-plate capacitor.

ESSENTIAL KNOWLEDGE

10.3.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.

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 determined by applying Gauss's law and the principle of superposition.

Derived equation:

$$E = \frac{Q}{\varepsilon_0 A}$$

ii. The electric field is proportional to the surface charge density on either plate of the capacitor.

iii. 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.

10.3.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.

10.3.A.5

The electric potential energy stored in a capacitor is described by the equation

$$U_C = \frac{1}{2} Q \Delta V .$$

BOUNDARY STATEMENT:

While other shapes are also able to separate charges, AP Physics C: Electricity & Magnetism only expects the quantitative analysis and description of parallel-plate capacitors, concentric spherical capacitors, and coaxial cylindrical capacitors.

SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 10.4
Dielectrics

Required Course Content

LEARNING OBJECTIVE

10.4.A
Describe how a dielectric inserted between the plates of a capacitor changes the properties of the capacitor.

ESSENTIAL KNOWLEDGE

10.4.A.1
In a dielectric material, electric charges are not as free to move as they are in a conductor. Instead, the material becomes polarized in the presence of an external electric field.

10.4.A.2
The dielectric constant of a material relates the electric permittivity of that material to the permittivity of free space.

Relevant equation:

$$\kappa = \frac{\varepsilon}{\varepsilon_0}$$

10.4.A.3
The electric field created by a polarized dielectric is opposite in direction to the external field.

10.4.A.4
The electric field between the plates of an isolated parallel-plate capacitor decreases when a dielectric is placed between the plates.

Derived equation:

$$\kappa = \frac{E_0}{E}$$

10.4.A.5
The insertion of a dielectric into a capacitor may change the capacitance of the capacitor.

Derived equation:

$$C = \kappa C_0$$

TOPIC 11.1
Electric Current

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

Required Course Content

LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

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

Relevant equation:

$$I = \frac{dq}{dt}$$

i. Current within a conductor consists of charge carriers traveling through the conductor with an average drift velocity.

Relevant equation:

$$I = nqv_d A$$

ii. Electric charge moves in a circuit in response to an electric potential difference, sometimes referred to as electromotive force, or emf ($\mathcal{E}$).

iii. 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
Current density is the flow of charge per unit area.

Relevant equation:

$$I = \int \vec{J} \cdot d\vec{A}$$

i. Current density is related to the motion of the charge carriers within a conductor.

Relevant equation:

$$\vec{J} = nq\vec{v}_d$$

continued on next page

LEARNING OBJECTIVE

11.1.A

Describe the movement of electric charges through a medium.

ESSENTIAL KNOWLEDGE

ii. Current density is a vector quantity.

iii. A potential difference across a conductor creates an electric field within the conductor that is proportional to the resistivity of the conductor and the current density.

Relevant equation:

$$\vec{E} = \rho\vec{J}$$

11.1.A.3

If a function of current density is given, the total current can be determined by integrating the current density over the area.

Derived equation:

$$I_{\text{tot}} = \int \vec{J}(r) \cdot d\vec{A}$$

11.1.A.4

Although current is a scalar quantity, it does have a direction. Because its direction is relative to the current carrier and not space, current does not obey the laws of vector addition and has no vector components.

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

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

TOPIC 11.2
Simple Circuits

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
11.2.A Describe the behavior of a circuit.	**11.2.A.1** A circuit is composed of electrical loops, which can include wires, batteries, resistors, lightbulbs, capacitors, inductors, switches, ammeters, and voltmeters.
	11.2.A.2 A closed electrical loop is a closed path through which charges may flow. i. A closed circuit is one in which charges would be able to flow. ii. An open circuit is one in which charges would not be able to flow. 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. i. The properties of an electric circuit are dependent on the physical arrangement of its constituent elements.

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SUGGESTED SCIENCE PRACTICES

1.A Create diagrams, tables, charts, or schematics to represent physical situations.

2.C Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.B Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

3.C Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

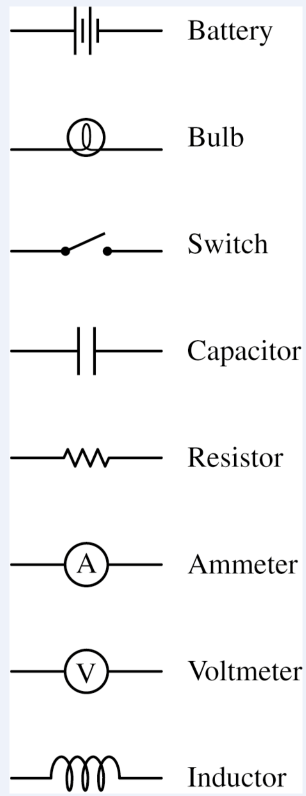
LEARNING OBJECTIVE

11.2.A

Describe the behavior of a circuit.

ESSENTIAL KNOWLEDGE

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



BOUNDARY STATEMENT:

Unless otherwise specified, all circuit schematic diagrams will be drawn using conventional current.

TOPIC 11.3

Resistance, Resistivity, and Ohm's Law

Required Course Content

LEARNING OBJECTIVE

11.3.A

Describe the resistance of an object using physical properties of that object.

ESSENTIAL KNOWLEDGE

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.

Relevant equation:

$$R = \frac{\rho \ell}{A}$$

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.

ii. The resistivity of a conductor typically increases with temperature.

iii. The total resistance of a resistor with uniform geometry, but that is made of a material whose resistivity varies along the length of the resistor, is given by

$$R = \int \frac{\rho(\ell)\, d\ell}{A}$$

LEARNING OBJECTIVE

11.3.B

Describe the electrical characteristics of elements of a circuit.

ESSENTIAL KNOWLEDGE

11.3.B.1

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

Relevant equation:

$$I = \frac{\Delta V}{R}$$

SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

continued on next page

LEARNING OBJECTIVE

11.3.B

Describe the electrical characteristics of elements of a circuit.

ESSENTIAL KNOWLEDGE

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

ii. The resistivity of an ohmic material is constant regardless of temperature.

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

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.

TOPIC 11.4
Electric Power

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

Required Course Content

LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

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

Relevant equation:

$$P = I\Delta V$$

Derived equation:

$$P = I^2 R = \frac{\Delta V^2}{R}$$

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

BOUNDARY STATEMENT:
AP Physics C: Electricity & Magnetism only expects students to analyze the transfer of mechanical and electrical energy, although students should be aware that electrical energy can also be dissipated in the form of thermal energy.

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 11.5
Compound Direct Current Circuits

Required Course Content

LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

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

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.

ii. A parallel connection is one in which charges may pass 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}.

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

Relevant equation:

$$R_{eq,s} = \sum_i R_i$$

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.

Relevant equation:

$$\frac{1}{R_{eq,p}} = \sum_i \frac{1}{R_i}$$

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LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
11.5.A Describe the equivalent resistance of multiple resistors connected in a circuit.	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.
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. 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. ii. The resistance of wires may only be neglected if the circuit contains other elements that do have resistance. 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 $(\mathcal{E})$. **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. *Derived equation:* $\Delta V_{\text{terminal}} = \mathcal{E} - Ir$
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. i. Ammeters must be connected in series with the element in which current is being measured. ii. Ideal ammeters have zero resistance so that they do not affect the current in the element that they are in series with.

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LEARNING OBJECTIVE

11.5.C

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

ESSENTIAL KNOWLEDGE

11.5.C.2

Voltmeters are used to measure electric potential difference between two points in a circuit.

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

ii. Ideal voltmeters have 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.

BOUNDARY STATEMENT:

Unless otherwise stated, all batteries, wires, and meters are assumed to be ideal. Circuits with batteries of different potential differences connected in parallel will not be assessed.

TOPIC 11.6
Kirchhoff's Loop Rule

Required Course Content

LEARNING OBJECTIVE

11.6.A

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

ESSENTIAL KNOWLEDGE

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.

Relevant equation:

$$\Delta U_{\mathrm{E}} = q\Delta V$$

11.6.A.2

Kirchhoff's loop rule is a consequence of the conservation of energy.

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

   Relevant equation:

   $$\sum \Delta V = 0$$

ii. 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.

SUGGESTED SCIENCE PRACTICES

1.C

Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.

2.A

Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C

Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 11.7
Kirchhoff's Junction Rule

Required Course Content

LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

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.

Relevant equation:

$$\sum I_{\text{in}} = \sum I_{\text{out}}$$

TOPIC 11.8

Resistor-Capacitor (RC) Circuits

Required Course Content

LEARNING OBJECTIVE

11.8.A

Describe the equivalent capacitance of multiple capacitors.

ESSENTIAL KNOWLEDGE

11.8.A.1

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

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.

Relevant equation:

$$\frac{1}{C_{\text{eq},s}} = \sum_i \frac{1}{C_i}$$

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

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

Relevant equation:

$$C_{\text{eq},p} = \sum_i C_i$$

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.

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SUGGESTED SCIENCE PRACTICES

1.B Create quantitative graphs with appropriate scales and units, including plotting data.

2.A Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D Predict new values or factors of change of physical quantities using functional dependence between variables.

3.A Create experimental procedures that are appropriate for a given scientific question.

3.C Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

LEARNING OBJECTIVE

11.8.B

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

ESSENTIAL KNOWLEDGE

11.8.B.1

The charge on a capacitor or the current through a resistor in an RC circuit can be described by a fundamental differential equation derived from Kirchhoff's loop rule.

Derived equation:

$$\mathcal{E} = \frac{dq}{dt}R + \frac{q}{C}$$

11.8.B.2

The time constant (τ) is a significant feature of an RC circuit.

i. The time constant of an RC circuit is a measure of how quickly the capacitor will charge or discharge and is defined as

$$\tau = R_{eq}C_{eq}.$$

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.

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.

11.8.B.3

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.

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.

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

continued on next page

LEARNING OBJECTIVE

11.8.B

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

ESSENTIAL KNOWLEDGE

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.

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.

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

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.

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.

TOPIC 12.1

Magnetic Fields

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.C
Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

Required Course Content

LEARNING OBJECTIVE

12.1.A
Describe the properties of a magnetic field.

ESSENTIAL KNOWLEDGE

12.1.A.1
A magnetic field is a vector field that describes the magnetic force exerted on moving electric charges, electric currents, or magnetic materials.

i. Magnetic fields can be produced by magnetic dipoles or combinations of dipoles, but never by monopoles.

ii. Magnetic dipoles have north and south polarity.

12.1.A.2
A magnetic field is a vector quantity and can be represented using vector field maps.

12.1.A.3
Magnetic field lines must form closed loops, as described by Gauss's law for magnetism.

i. Maxwell's equations are the collection of equations that fully describe electromagnetism. Gauss's law for magnetism is Maxwell's second equation.

Relevant equation:

$$\oint \vec{B} \cdot d\vec{A} = 0$$

ii. Magnetic fields in a bar magnet form closed loops, with the external magnetic field pointing away from one end (defined as the north pole) and returning to the other end (defined as the south pole).

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LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
12.1.B Describe the magnetic behavior of a material as a result of the configuration of magnetic dipoles in the material.	**12.1.B.1** Magnetic dipoles result from the circular or rotational motion of electric charges. In magnetic materials, this can be the motion of electrons. i. Permanent magnetism and induced magnetism are system properties that both result from the alignment of magnetic dipoles within a system. ii. No magnetic north pole is ever found in isolation from a south pole. For example, if a bar magnet is broken in half, both halves are magnetic dipoles. iii. Magnetic poles of the same polarity will repel; magnetic poles of opposite polarity will attract. iv. The magnitude of the magnetic field from a magnetic dipole decreases with increasing distance from the dipole. **12.1.B.2** A magnetic dipole, such as a magnetic compass, placed in a magnetic field will tend to align with the magnetic field. **12.1.B.3** A material's composition influences its magnetic behavior in the presence of an external magnetic field. i. Ferromagnetic materials such as iron, nickel, and cobalt can be permanently magnetized by an external field that causes the alignment of magnetic domains or atomic magnetic dipoles. ii. Paramagnetic materials such as aluminum, titanium, and magnesium interact weakly with an external magnetic field, in that the magnetic dipoles of the material do not remain aligned after the external field is removed. iii. All materials have the property of diamagnetism, in that their electronic structure creates a usually weak alignment of the dipole moments of the material opposite the external magnetic field. **12.1.B.4** Earth's magnetic field may be approximated as a magnetic dipole.

continued on next page

LEARNING OBJECTIVE

12.1.C

Describe the magnetic permeability of a material.

ESSENTIAL KNOWLEDGE

12.1.C.1

Magnetic permeability is a measurement of the amount of magnetization in a material in response to an external magnetic field.

12.1.C.2

Free space has a constant value of magnetic permeability, known as the vacuum permeability μ_0, that appears in equations representing physical relationships.

12.1.C.3

The permeability of matter has values different from that of free space and arises from the matter's composition and arrangement. It is not a constant for a material and varies based on many factors, including temperature, orientation, and strength of the external field.

SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 12.2

Magnetism and Moving Charges

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
12.2.A Describe the magnetic field produced by moving charged objects.	**12.2.A.1** A single moving charged object produces a magnetic field. i. The magnetic field at a particular point produced by a moving charged object depends on the object's velocity and the distance between the point and the object. ii. At a point in space, the direction of the magnetic field produced by a moving charged object is perpendicular to both the velocity of the object and the position vector from the object to that point in space and can be determined using the right-hand rule. iii. The magnitude of the magnetic field is a maximum when the velocity vector and the position vector from the object to that point in space are perpendicular.
12.2.B Describe the force exerted on moving charged objects by a magnetic field.	**12.2.B.1** A magnetic field will exert a force on a charged object moving within that field, with magnitude and direction that depend on the cross-product of the charge's velocity and the magnetic field. *Relevant equation:* $\vec{F}_B = q\left(\vec{v} \times \vec{B}\right)$

continued on next page

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
12.2.B Describe the force exerted on moving charged objects by a magnetic field.	**12.2.B.2** In a region containing both a magnetic field and an electric field, a moving charged object will experience independent forces from each field. **12.2.B.3** The Hall effect describes the potential difference created in a conductor by an external magnetic field that has a component perpendicular to the direction of charges moving in the conductor.

SUGGESTED SCIENCE PRACTICES

1.C
Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 12.3

Magnetic Fields of Current-Carrying Wires and the Biot-Savart Law

Required Course Content

LEARNING OBJECTIVE

12.3.A
Describe the magnetic field produced by a current-carrying wire.

ESSENTIAL KNOWLEDGE

12.3.A.1
The Biot-Savart law defines the magnitude and direction of a magnetic field created by an electrical current.

Relevant equation:

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I(d\vec{\ell}\times\hat{r})}{r^2}$$

12.3.A.2
The magnetic field vectors around a small segment of a current-carrying wire are tangent to concentric circles centered on that wire. The field has no component toward, away from, or parallel to the segment of the current-carrying wire.

12.3.A.3
The Biot-Savart law can be used to derive the magnitudes and directions of magnetic fields around segments of current-carrying wires, for example at the center of a circular loop of wire.

Derived equation:

$$B_{\text{center of loop}} = \frac{\mu_0 I}{2R}$$

continued on next page

LEARNING OBJECTIVE

12.3.B

Describe the force exerted on current-carrying wires by a magnetic field.

ESSENTIAL KNOWLEDGE

12.3.B.1

A magnetic field will exert a force on a current-carrying wire.

Relevant equation:

$$\vec{F}_B = \int I\left(d\vec{\ell} \times \vec{B}\right)$$

BOUNDARY STATEMENT:

AP Physics C: Electricity & Magnetism only expects students to perform quantitative analysis of certain cases of current-carrying conductors using the Biot-Savart law, such as at a location along the perpendicular bisector of a straight conductor, at a location along the central axis of a circular loop, or at the center of a segment of a circular loop.

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 12.4
Ampère’s Law

Required Course Content

LEARNING OBJECTIVE

12.4.A
Use Ampère’s law to describe the magnetic field created by a moving charge carrier.

ESSENTIAL KNOWLEDGE

12.4.A.1
Ampère’s law relates the magnitude of the magnetic field to the current enclosed by a closed imaginary path called an Amperian loop.

Relevant equation:

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{enc}}$$

i. Ampère’s law can be used to determine the magnetic field near a long, straight current-carrying wire.
   Derived equation:
   $$B_{\text{wire}} = \frac{\mu_0}{2\pi}\frac{I}{r}$$

ii. Unless otherwise stated, all solenoids are assumed to be very long, with uniform magnetic fields inside the solenoids and negligible magnetic fields outside the solenoids. Solenoid assumptions (long, B field uniform inside, negligible outside)

iii. Ampère’s law can be used to determine the magnetic field inside of a long solenoid.
   Derived equation:
   $$B_{\text{sol}} = \mu_0 n I$$

12.4.A.2
An Amperian loop is a closed path around a current-carrying conductor.

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LEARNING OBJECTIVE

12.4.A

Use Ampère's law to describe the magnetic field created by a moving charge carrier.

ESSENTIAL KNOWLEDGE

12.4.A.3

The principle of superposition can be used to determine the net magnetic field at a point in space created by various combinations of current-carrying conductors, or conducting loops, segments, or cylinders.

12.4.A.4

Maxwell's equations are the collection of equations that fully describe electromagnetism. Maxwell's fourth equation is Ampère's law with Maxwell's addition; it states that magnetic fields can be generated by electric current (Ampère's law) and that a changing electric field creates a magnetic field, similar to the way a moving charge creates a magnetic field (Maxwell's addition).

Relevant equations:

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I + \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$$

BOUNDARY STATEMENT:

AP Physics C: Electricity & Magnetism only expects quantitative application of Ampère's law limited to situations involving symmetrical magnetic fields. Long straight wires, long solenoids carrying currents, as well as conductive slabs or cylindrical conductors carrying a current density, are the types of shapes to which Ampère's law will be applied on the AP Physics C: Electricity & Magnetism Exam.

BOUNDARY STATEMENT:

AP Physics C: Electricity & Magnetism does not expect students to use Maxwell's fourth equation with a changing electric field. However, students should understand that a changing electric field generates a magnetic field.

TOPIC 13.1

Magnetic Flux

Required Course Content

LEARNING OBJECTIVE

13.1.A

Describe the magnetic flux through an arbitrary area or geometric shape.

ESSENTIAL KNOWLEDGE

13.1.A.1

For a magnetic field $\vec{B}$ that is constant across an area $\vec{A}$, the magnetic flux through the area is defined as

$\Phi_B = \vec{B} \cdot \vec{A}$.

i. The area vector is defined as perpendicular to the plane of the surface and outward from a closed surface.

ii. The sign of flux is given by the dot product of the magnetic field vector and the area vector.

13.1.A.2

The total magnetic flux passing through a surface is defined by the surface integral of the magnetic field over the surface area.

Relevant equation:

$$\Phi_B = \int \vec{B} \cdot d\vec{A}$$

SUGGESTED SCIENCE PRACTICES

1.A

Create diagrams, tables, charts, or schematics to represent physical situations.

2.A

Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C

Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

SUGGESTED SCIENCE PRACTICES

1.B
Create quantitative graphs with appropriate scales and units, including plotting data.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.A
Create experimental procedures that are appropriate for a given scientific question.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 13.2
Electromagnetic Induction

Required Course Content

LEARNING OBJECTIVE

13.2.A
Describe the induced electric potential difference resulting from a change in magnetic flux.

ESSENTIAL KNOWLEDGE

13.2.A.1
Faraday's law describes the relationship between changing magnetic flux and the resulting induced emf in a system.

Relevant equation:

$$\mathcal{E} = -\frac{d\Phi_B}{dt} = -\frac{d\left(\vec{B}\cdot\vec{A}\right)}{dt}$$

i. When the area of the surface being considered is constant, the induced emf is equal to the area multiplied by the rate of change in the component of the magnetic field perpendicular to the surface.

ii. When the magnetic field is constant, the induced emf is equal to the magnetic field multiplied by the rate of change in area perpendicular to the magnetic field.

iii. When an emf is induced in a long solenoid, the total induced emf is equal to the induced emf in a single loop multiplied by the number of loops in the solenoid.

Relevant equation:

$$\left|\mathcal{E}_{sol}\right| = N\left|\frac{d\Phi_B}{dt}\right|$$

13.2.A.2
Lenz's law is used to determine the direction of an induced emf resulting from a changing magnetic flux.

i. An induced emf generates a current that creates a magnetic field that opposes the change in magnetic flux.

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LEARNING OBJECTIVE

13.2.A

Describe the induced electric potential difference resulting from a change in magnetic flux.

ESSENTIAL KNOWLEDGE

ii. The right-hand rule is used to determine the relationships between current, emf, and magnetic flux.

13.2.A.3

Maxwell's equations are the collection of equations that fully describe electromagnetism. Maxwell's third equation is Faraday's law of induction, which describes the relationship between a changing magnetic flux and an induced electric field.

Relevant equation:

$$\mathcal{E} = \oint \vec{E} \cdot d\vec{\ell} = -\frac{d\Phi_B}{dt}$$

13.2.A.4

Maxwell's equations can be used to show that electric and magnetic fields obey wave equations and that electromagnetic waves travel at a constant speed in free space.

Derived equation:

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

BOUNDARY STATEMENT:

AP Physics C: Electricity & Magnetism does not expect students to mathematically derive the speed of light in free space from Maxwell's equations. This relationship is included above solely as an indication of the further applications, implications, and connections to physical phenomena that students may study in more advanced physics courses.

SUGGESTED SCIENCE PRACTICES

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.B
Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 13.3
Induced Currents and Magnetic Forces

Required Course Content

LEARNING OBJECTIVE

13.3.A
Describe the force exerted on a conductor due to the interaction between an external magnetic field and an induced current within that conductor.

ESSENTIAL KNOWLEDGE

13.3.A.1
When an induced current is created in a conductive loop, the already-present magnetic field will exert a magnetic force on the moving charge carriers within the loop.

Relevant equation:

$$\vec{F}_B = \int I\left(d\vec{\ell} \times \vec{B}\right)$$

13.3.A.2
When current is induced in a conducting loop, magnetic forces are only exerted on the segments of the loop that are within the external magnetic field. These magnetic forces may cause translational or rotational acceleration.

13.3.A.3
The force on a conducting loop is proportional to the induced current in the loop, which depends on the rate of change of magnetic flux, the resistance of the loop, and the velocity of the loop.

13.3.A.4
Newton's second law can be applied to a conducting loop moving in a magnetic field as it experiences an induced emf.

TOPIC 13.4
Inductance

Required Course Content

LEARNING OBJECTIVE

13.4.A

Describe the physical and electrical properties of an inductor.

ESSENTIAL KNOWLEDGE

13.4.A.1

Inductance is the tendency of a conductor to oppose a change in electrical current.

i. Inductance of a conductor depends on the physical properties of the conductor. Straight wires are typically modeled as having zero inductance.

ii. An inductor, such as a solenoid, is a circuit element that has significant inductance.

iii. The inductance of a solenoid is dependent on the total number of turns, the length of the solenoid, the cross-sectional area of the solenoid, and magnetic permeability of the solenoid's core.

Relevant equation:

$$L = \frac{\mu_{\text{core}} N^2 A}{\ell}$$

13.4.A.2

Inductors store energy in the magnetic field that is generated by current in the inductor.

Relevant equation:

$$U_L = \frac{1}{2} L I^2$$

i. The energy stored in the magnetic field generated by an inductor in which current is flowing can be dissipated through a resistor or used to charge a capacitor.

ii. The transfer of energy generated in an inductor to other forms of energy obeys conservation laws.

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SUGGESTED SCIENCE PRACTICES

1.C

Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.

2.A

Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C

Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

LEARNING OBJECTIVE

13.4.A

Describe the physical and electrical properties of an inductor.

ESSENTIAL KNOWLEDGE

13.4.A.3

By applying Faraday's law to an inductor and using the definition of inductance, induced emf can be related to inductance and the rate of change of current.

Relevant equation:

$$\mathcal{E}_i = -L\frac{dI}{dt}$$

TOPIC 13.5

Circuits with Resistors and Inductors (LR Circuits)

Required Course Content

LEARNING OBJECTIVE

13.5.A

Describe the physical and electrical properties of a circuit containing a combination of resistors and a single inductor.

ESSENTIAL KNOWLEDGE

13.5.A.1

A resistor will dissipate energy that was stored in an inductor as the current changes.

13.5.A.2

Kirchhoff's loop rule can be applied to a series LR circuit, resulting in a differential equation that describes the current in the loop.

Derived equation:

$$\mathcal{E} = IR + L\frac{dI}{dt}$$

13.5.A.3

The time constant is a significant feature of the behavior of an LR circuit.

i. The time constant of a circuit is a measure of how quickly an LR circuit will reach a steady state and is described with the equation

$$\tau = \frac{L}{R_{eq}}.$$

ii. The time constant represents the time an LR circuit would take to reach a steady state if the system continued to change at the initial rate of change.

iii. For an inductor that has zero initial current, the time constant represents the time required for the current in the inductor to reach approximately 63 percent of its final asymptotic value.

iv. For an inductor with an initial current, the time constant represents the time required for the current in the inductor to reach approximately 37 percent of its initial value.

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SUGGESTED SCIENCE PRACTICES

1.C

Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.

2.A

Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C

Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.C

Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

LEARNING OBJECTIVE

13.5.A

Describe the physical and electrical properties of a circuit containing a combination of resistors and a single inductor.

ESSENTIAL KNOWLEDGE

13.5.A.4

The electric properties of inductors change during the time interval in which the current through the inductor changes, but will exhibit steady state behavior after a long time interval.

i. When a switch is initially closed or opened in a circuit containing an inductor, the induced emf will be equal in magnitude and opposite in direction to the applied potential difference across the branch containing the inductor.
ii. The potential difference across an inductor, the current passing through the inductor, and the energy stored in the inductor are exponential with respect to time and have asymptotes that are determined by the initial conditions of the circuit.
iii. After a time much greater than the time constant of the circuit, an inductor will behave as a conducting wire with zero resistance.

TOPIC 13.6

Circuits with Capacitors and Inductors (LC Circuits)

Required Course Content

LEARNING OBJECTIVE

13.6.A

Describe the physical and electrical properties of a circuit containing a combination of capacitors and a single inductor.

ESSENTIAL KNOWLEDGE

13.6.A.1

In circuits containing only a charged capacitor and an inductor, the maximum current through the inductor can be determined using conservation of energy within the circuit.

13.6.A.2

In circuits containing only a charged capacitor and an inductor, the time dependence of the charge stored in the capacitor can be modeled as simple harmonic motion.

Derived equation:

$$\frac{d^2q}{dt^2} = -\frac{1}{LC}q$$

13.6.A.3

The angular frequency of an oscillating LC circuit can be derived from the differential equation that describes an LC circuit.

Derived equation:

$$\omega = \frac{1}{\sqrt{LC}}$$

SUGGESTED SCIENCE PRACTICES

1.B

Create quantitative graphs with appropriate scales and units, including plotting data.

2.B

Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.C

Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.A

Create experimental procedures that are appropriate for a given scientific question.

3.B

Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

Unit 14: Physics Labs

20 Days

Note: Unit Days may be adjusted based on the date of the AP Physics C exam.

Standards: SCIENCE, TECHNOLOGY & ENGINEERING, AND ENVIRONMENTAL LITERACY & SUSTAINABILITY STANDARDS (STEELS):

- 3.5.9-12.Y (ETS) Technology and Engineering: Design Thinking in Technology & Engineering Education
  - Students who demonstrate understanding can design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.
  - Clarifying Statement: Criteria may need to be broken down into simpler ones that can be approached systematically, and decisions about the priority of certain criteria over others (trade-offs) may be needed.
- SCIENCE AND ENGINEERING PRACTICE(S) (SEPS)
  SEP 2: Developing and using models
  SEP 3: Planning and carrying out investigations
  SEP 4: Analyzing and interpreting data
  SEP 5: Using mathematics and computational thinking
  SEP 8: Obtaining, evaluating, and communicating information

Anchors:

N/A

Eligible Content:

All CED Essential Knowledge statements from the following units: Kinematics; Newton's Laws of Motion; Work, Energy & Power; Systems of Particles and Linear Momentum; Rotation; Oscillations; Gravitation; Electrostatics; Conductors, Capacitors & Dielectrics; Electric Circuits; Magnetic Fields; and Electromagnetism

Objectives:

2.A Identify a testable scientific question or problem (DOK 1).
2.B Make a claim or predict the results of an experiment (DOK 2).
2.D Make observations or collect data from representations of laboratory setups or results (DOK 2).
2.E Identify or describe potential sources of experimental error (DOK 3).
2.F Explain modifications to an experimental procedure that will alter results (DOK 3).
3.A Select and plot appropriate data (DOK 2).
3.B Represent features of a model or the behavior of a physical system using appropriate graphing techniques, appropriate scale, and units (DOK 2).

3.C Sketch a graph that shows a functional relationship between two quantities (DOK 2).4.A Identify and describe patterns and trends in data or a graph (DOK 3).
4.C Linearize data and/or determine a best fit line or curve (DOK 2).
4.D Select relevant features of a graph to describe a physical situation or solve problems (DOK 2).

4.E Explain how the data or graph illustrates a physics principle, process, concept or theory (DOK 3).
5.E Derive a symbolic expression from known quantities by selecting and following logical algebraic pathway (DOK 2).
6.D Assess the reasonableness of results or solutions (DOK 4).
7.B Support a claim with evidence from experimental data (DOK 4).
7.D Provide reasoning to justify a claim using physical principles or laws (DOK 4). 7.E Explain the between experimental results and larger physical principles, laws, or theories (DOK 4).
7.F Explain how potential sources of experimental error may affect results and/or conclusions (DOK 2).

Core Activities and Corresponding Instructional Methods:

- Conduct laboratory investigations of physics concepts
- Predict experimental results based on mathematical models describing physical laws
- Measure physical quantities contained in mathematical models describing physical laws
- Analyze experimental results
- Use statistics to test applicability of mathematical models to describe experimental results
- Draw conclusions based on statistical analyses of experimental results
- Communicate experimental results

Assessments:

- **Diagnostic:**
  - N/A
- **Formative:**
  - Teacher observations, questioning techniques, and discussions
- **Summative:**
  - Student presentations of lab results using the model: title slide, hypothesis slide, experiment slide, results slide, conclusion slide