AP® Physics C: Electricity and Magnetism

COURSE FRAMEWORK AND EXAM OVERVIEW

Effective Fall 2024
What AP® Stands For

Thousands of Advanced Placement teachers have contributed to the principles articulated here. These principles are not new; they are, rather, a reminder of how AP already works in classrooms nationwide. The following principles are designed to ensure that teachers’ expertise is respected, required course content is understood, and that students are academically challenged and free to make up their own minds.

1. AP stands for clarity and transparency. Teachers and students deserve clear expectations. The Advanced Placement Program makes public its course frameworks and sample assessments. Confusion about what is permitted in the classroom disrupts teachers and students as they navigate demanding work.

2. AP is an unflinching encounter with evidence. AP courses enable students to develop as independent thinkers and to draw their own conclusions. Evidence and the scientific method are the starting place for conversations in AP courses.

3. AP opposes censorship. AP is animated by a deep respect for the intellectual freedom of teachers and students alike. If a school bans required topics from their AP courses, the AP Program removes the AP designation from that course and its inclusion in the AP Course Ledger provided to colleges and universities. For example, the concepts of evolution are at the heart of college biology, and a course that neglects such concepts does not pass muster as AP Biology.

4. AP opposes indoctrination. AP students are expected to analyze different perspectives from their own, and no points on an AP Exam are awarded for agreement with any specific viewpoint. AP students are not required to feel certain ways about themselves or the course content. AP courses instead develop students’ abilities to assess the credibility of sources, draw conclusions, and make up their own minds.

   As the AP English Literature course description states: “AP students are not expected or asked to subscribe to any one specific set of cultural or political values, but are expected to have the maturity to analyze perspectives different from their own and to question the meaning, purpose, or effect of such content within the literary work as a whole.”

5. AP courses foster an open-minded approach to the histories and cultures of different peoples. The study of different nationalities, cultures, religions, races, and ethnicities is essential within a variety of academic disciplines. AP courses ground such studies in primary sources so that students can evaluate experiences and evidence for themselves.

6. Every AP student who engages with evidence is listened to and respected. Students are encouraged to evaluate arguments but not one another. AP classrooms respect diversity in backgrounds, experiences, and viewpoints. The perspectives and contributions of the full range of AP students are sought and considered. Respectful debate of ideas is cultivated and protected; personal attacks have no place in AP.

7. AP is a choice for parents and students. Parents and students freely choose to enroll in AP courses. Course descriptions are available online for parents and students to inform their choice. Parents do not define which college-level topics are suitable within AP courses; AP course and exam materials are crafted by committees of professors and other expert educators in each field. AP courses and exams are then further validated by the American Council on Education and studies that confirm the use of AP scores for college credits by thousands of colleges and universities nationwide.

The AP Program encourages educators to review these principles with parents and students so they know what to expect in an AP course. Advanced Placement is always a choice, and it should be an informed one. AP teachers should be given the confidence and clarity that once parents have enrolled their child in an AP course, they have agreed to a classroom experience that embodies these principles.
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About AP

The Advanced Placement® Program (AP®) enables willing and academically prepared students to pursue college-level studies—with the opportunity to earn college credit, advanced placement, or both—while still in high school. Through AP courses in 39 subjects, each culminating in a challenging exam, students learn to think critically, construct solid arguments, and see many sides of an issue—skills that prepare them for college and beyond. Taking AP courses demonstrates to college admission officers that students have sought the most challenging curriculum available to them, and research indicates that students who score a 3 or higher on an AP Exam typically experience greater academic success in college and are more likely to earn a college degree than non-AP students. Each AP teacher’s syllabus is evaluated and approved by faculty from some of the nation’s leading colleges and universities, and AP Exams are developed and scored by college faculty and experienced AP teachers. Most four-year colleges and universities in the United States grant credit, advanced placement, or both on the basis of successful AP Exam scores—more than 3,300 institutions worldwide annually receive AP scores.

AP Course Development

In an ongoing effort to maintain alignment with best practices in college-level learning, AP courses and exams emphasize challenging, research-based curricula aligned with higher education expectations. Individual teachers are responsible for designing their own curriculum for AP courses, selecting appropriate college-level readings, assignments, and resources. This course framework and exam overview presents the content and skills that are the focus of the corresponding college course and that appear on the AP Exam. It also organizes the content and skills into a series of units that represent a sequence found in widely adopted college textbooks and that many AP teachers have told us they follow in order to focus their instruction. The intention of this publication is to respect teachers’ time and expertise by providing a roadmap that they can modify and adapt to their local priorities and preferences. Moreover, by organizing the AP course content and skills into units, the AP Program is able to provide teachers and students with free formative assessments—Progress Checks—that teachers can assign throughout the year to measure student progress as they acquire content knowledge and develop skills.

Enrolling Students: Equity and Access

The AP Program strongly encourages educators to make equitable access a guiding principle for their AP programs by giving all willing and academically prepared students the opportunity to participate in AP. We encourage the elimination of barriers that restrict access to AP for students from ethnic, racial, and socioeconomic groups that have been traditionally underserved. The AP Program also believes that all students should have access to academically challenging coursework before they enroll in AP classes, which can prepare them for AP success. It is only through a commitment to equitable preparation and access that true equity and excellence can be achieved.

Offering AP Courses: The AP Course Audit

The AP Program unequivocally supports the principle that each school implements its own curriculum that will enable students to develop the content understandings and skills described in the course framework. While the unit sequence represented in this publication is optional, the AP Program does have a short list of curricular and resource requirements that must be fulfilled before a school can label a course “Advanced Placement” or “AP.” Schools wishing to offer AP courses must participate in the AP Course Audit, a process through which AP teachers’ course materials are reviewed by college faculty. The AP Course Audit was created to provide teachers and administrators with clear guidelines on curricular and resource requirements for AP courses and to help colleges and universities validate courses marked “AP” on students’ transcripts. This process ensures that AP teachers’ courses meet or exceed the curricular and resource expectations that college and secondary school faculty have established for college-level courses.
The AP Course Audit form is submitted by the AP teacher and the school principal (or designated administrator) to confirm awareness and understanding of the curricular and resource requirements. A syllabus or course outline, detailing how course requirements are met, is submitted by the AP teacher for review by college faculty.

Please visit collegeboard.org/apcourseaudit for more information to support the preparation and submission of materials for the AP Course Audit.

**How the AP Program Is Developed**

The scope of content for an AP course and exam is derived from an analysis of hundreds of syllabi and course offerings of colleges and universities. Using this research and data, a committee of college faculty and expert AP teachers work within the scope of the corresponding college course to articulate what students should know and be able to do upon the completion of the AP course. The resulting course framework is the heart of this course framework and exam overview and serves as a blueprint of the content and skills that can appear on an AP Exam.

The AP Test Development Committees are responsible for developing each AP Exam, ensuring the exam questions are aligned to the course framework. The AP Exam development process is a multiyear endeavor; all AP Exams undergo extensive review, revision, piloting, and analysis to ensure that questions are accurate, fair, and valid, and that there is an appropriate spread of difficulty across the questions.

Committee members are selected to represent a variety of perspectives and institutions (public and private, small and large schools and colleges), and a range of gender, racial/ethnic, and regional groups. A list of each subject’s current AP Test Development Committee members is available on apcentral.collegeboard.org.

Throughout AP course and exam development, College Board gathers feedback from various stakeholders in both secondary schools and higher education institutions. This feedback is carefully considered to ensure that AP courses and exams are able to provide students with a college-level learning experience and the opportunity to demonstrate their qualifications for advanced placement or college credit.

**How AP Exams Are Scored**

The exam scoring process, like the course and exam development process, relies on the expertise of both AP teachers and college faculty. While multiple-choice questions are scored by machine, the free-response questions and through-course performance assessments, as applicable, are scored by thousands of college faculty and expert AP teachers. Most are scored at the annual AP Reading, while a small portion is scored online. All AP Readers are thoroughly trained, and their work is monitored throughout the Reading for fairness and consistency. In each subject, a highly respected college faculty member serves as Chief Faculty Consultant and, with the help of AP Readers in leadership positions, maintains the accuracy of the scoring standards. Scores on the free-response questions and performance assessments are weighted and combined with the results of the computer-scored multiple-choice questions, and this raw score is converted into a composite AP score on a 1–5 scale.

AP Exams are **not** norm-referenced or graded on a curve. Instead, they are criterion-referenced, which means that every student who meets the criteria for an AP score of 2, 3, 4, or 5 will receive that score, no matter how many students that is. The criteria for the number of points students must earn on the AP Exam to receive scores of 3, 4, or 5—the scores that research consistently validates for credit and placement purposes—include:

- The number of points successful college students earn when their professors administer AP Exam questions to them.
- The number of points researchers have found to be predictive that an AP student will succeed when placed into a subsequent higher-level college course.
- Achievement-level descriptions formulated by college faculty who review each AP Exam question.

**Using and Interpreting AP Scores**

The extensive work done by college faculty and AP teachers in the development of the course and exam and throughout the scoring process ensures that AP Exam scores accurately represent students’ achievement in the equivalent college course. Frequent and regular research studies establish the validity of AP scores as follows:

<table>
<thead>
<tr>
<th>AP Score</th>
<th>Credit Recommendation</th>
<th>College Grade Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Extremely well qualified</td>
<td>A</td>
</tr>
<tr>
<td>4</td>
<td>Well qualified</td>
<td>A-, B+, B</td>
</tr>
<tr>
<td>3</td>
<td>Qualified</td>
<td>B-, C+, C</td>
</tr>
<tr>
<td>2</td>
<td>Possibly qualified</td>
<td>n/a</td>
</tr>
<tr>
<td>1</td>
<td>No recommendation</td>
<td>n/a</td>
</tr>
</tbody>
</table>
While colleges and universities are responsible for setting their own credit and placement policies, most private colleges and universities award credit and/or advanced placement for AP scores of 3 or higher. Additionally, most states in the U.S. have adopted statewide credit policies that ensure college credit for scores of 3 or higher at public colleges and universities. To confirm a specific college’s AP credit/placement policy, a search engine is available at collegeboard.org/creditandplacement/searchcredit-policies.

**BECOMING AN AP READER**
Each June, thousands of AP teachers and college faculty members from around the world gather for seven days in multiple locations to evaluate and score the free-response sections of the AP Exams. Ninetyeight percent of surveyed educators who took part in the AP Reading say it was a positive experience.

There are many reasons to consider becoming an AP Reader, including opportunities to:

- **Bring positive changes to the classroom:** Surveys show that the vast majority of returning AP Readers—both high school and college educators—make improvements to the way they teach or score because of their experience at the AP Reading.
- **Gain in-depth understanding of AP Exam and AP scoring standards:** AP Readers gain exposure to the quality and depth of the responses from the entire pool of AP Exam takers, and thus are better able to assess their students’ work in the classroom.
- **Receive compensation:** AP Readers are compensated for their work during the Reading. Expenses, lodging, and meals are covered for Readers who travel.
- **Score from home:** AP Readers have online distributed scoring opportunities for certain subjects. Check collegeboard.org/apreading for details.
- **Earn Continuing Education Units (CEUs):** AP Readers earn professional development hours and CEUs that can be applied to PD requirements by states, districts, and schools.

**How to Apply**
Visit collegeboard.org/apreading for eligibility requirements and to start the application process.
About the AP Physics C: Electricity and Magnetism Course

AP Physics C: Electricity and Magnetism is a calculus-based introductory college-level physics course. Students cultivate their understanding of physics by developing models of physical phenomena through inquiry-based investigations.

Students build their understanding of physical models as they explore and solve problems in these topics:

- Electric Charges, Fields, and Gauss's Law
- Electric Potential
- Conductors and Capacitors
- Electric Circuits
- Magnetic Fields and Electromagnetism
- Electromagnetic Induction

College Course Equivalent
AP Physics C: Electricity and Magnetism is equivalent to the second course in an introductory college course sequence in calculus-based physics.

Timing and Pacing
If AP Physics C: Electricity and Magnetism is taught as a full-year course, approximately 45 minutes per day plus an additional 45-minute lab period per week (approximately 270 minutes per week) is necessary to devote sufficient time to study the material at an appropriate depth and to allow time for laboratory investigations. In a school that uses block scheduling, one of the AP Physics C courses, but not both, can be taught in a single semester. Whichever approach is taken, the nature of the AP Physics C: Electricity and Magnetism course requires teachers to spend time on the extra preparation needed for both class and laboratory. AP teachers should have a teaching load that is adjusted accordingly.

In some schools, AP Physics C: Electricity and Magnetism has been taught successfully as the second part of a two-semester physics curriculum in conjunction with Calculus-Based AP Physics C: Mechanics. Because of the intense pace of taking both of these courses in a single academic year, it is strongly recommended that students take a standard high-school physics course prior to taking both of the Calculus-Based AP Physics courses in a subsequent year.

Whichever approach is taken, the nature of the AP Physics C: Electricity and Magnetism course requires teachers to spend time on the extra preparation needed for both class and laboratory. AP teachers should have a teaching load that is adjusted accordingly.

Prerequisites
Students should have taken or be concurrently taking calculus. Students should have taken AP Physics C: Mechanics, AP Physics 1 or other mechanics-based physics course prior to taking AP Physics C: Electricity and Magnetism.
Laboratory Requirement

This course requires that 25 percent of instructional time be spent in hands-on laboratory work, with an emphasis on inquiry-based investigations that provide students with opportunities to demonstrate the foundational physics principles and apply the science practices.

Inquiry-based laboratory experiences support the AP Physics C: Electricity and Magnetism course and AP Course Audit curricular requirements by providing opportunities for students to engage in the science practices as they design plans for experiments, make predictions, collect and analyze data, apply mathematical routines, develop explanations, and communicate about their work.

Colleges may require students to present their laboratory materials from AP science courses before granting college credit for laboratory work, so students should be encouraged to retain their laboratory notebooks, reports, and other materials.
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Introduction

The AP Physics C: Electricity and Magnetism course outlined in this framework reflects a commitment to what physics teachers, professors, and researchers have agreed is the main goal of a college – level physics course: to help students develop a deep understanding of the foundational principles that shape classical mechanics. By confronting complex physical situations or scenarios, the course is designed to enable students to develop the ability to reason about physical phenomena using important science practices, such as creating and analyzing representations of physical scenarios, designing experiments, analyzing data, and using mathematics to model and to solve problems.

To foster this deeper level of learning, the AP Physics C: Electricity and Magnetism course defines concepts, skills, and understandings required by representative colleges and universities for granting college credit and placement. Students will practice reasoning skills used by physicists by discussing and debating, with peers, the physical phenomena investigated in class, as well as by designing and conducting inquiry-based laboratory investigations to solve problems through first-hand observations, data collection, analysis, and interpretation.

This document is not a complete curriculum. Teachers create their own local curriculum by selecting, for each concept, content that enables students to explore the course learning objectives and meets state or local requirements. This results in a course that prepares students for college credit and placement.
Course Framework Components

Overview
This course framework provides a clear and detailed description of the course requirements necessary for student success. The framework specifies what students must know, be able to do, and understand to qualify for college credit or placement.

The course framework includes two essential components:

1. **SCIENCE PRACTICES**
The science practices are central to the study and practice of physics. Students should develop and apply the described practices on a regular basis over the span of the course.

2. **COURSE CONTENT**
The course content is organized into commonly taught units of study that provide a suggested sequence for the course and detail required content and conceptual understandings that colleges and universities typically expect students to master to qualify for college credit and/or placement.
The table that follows presents the science practices that students should develop during the AP Physics C: Electricity and Magnetism course. These practices form the basis of many tasks on the AP Physics C: Electricity and Magnetism Exam.

More detailed information about teaching the science practices will be provided in the Course and Exam Description publication scheduled for release in spring 2024.
# Science Practices

## Practice 1

**Creating Representations**

1. Create diagrams, tables, charts, or schematics to represent physical situations.
2. Create quantitative graphs with appropriate scales and units, including plotting data.
3. Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.

## Practice 2

**Mathematical Routines**

1. Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.
2. Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.
3. Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.
4. Predict new values or factors of change of physical quantities using functional dependence between variables.

## Practice 3

**Scientific Questioning and Argumentation**

1. Create experimental procedures that are appropriate for a given scientific question.
2. Apply an appropriate law, definition, theoretical relationship, or model to make a claim.
3. Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.
AP PHYSICS C: ELECTRICITY AND MAGNETISM

Course Content

The AP Physics C: Electricity and Magnetism course framework is intended to provide a clear and detailed description of the course requirements necessary for student success. The framework specifies what students should be able to do upon completing the course, and it encourages instruction that allows students to make connections through a broader way of thinking about the physical world.

UNITS

The course content is organized into commonly taught units. The units have been arranged in a logical sequence frequently found in many college courses and textbooks.

The six units in AP Physics C: Electricity and Magnetism and their relevant weightings on the multiple-choice section of the AP Exam are listed below.

Pacing recommendations on the Course at a Glance page provide suggestions for how teachers can cover both the required course content and the Progress Checks. The suggested class periods are based on a schedule in which the class meets five days a week for 45 minutes each day. While these recommendations have been made to aid in planning, teachers are free to adjust the pacing based on the needs of their students, alternate schedules (e.g., block scheduling), or their school’s academic calendar.
Learning Objectives and Science Practices

In the AP Physics C: Electricity and Magnetism course and exam, every assessment of student proficiency will be aligned to a Learning Objective and a Skill. The Learning Objectives represent the content domain, while the Skill represents the Science Practice required to successfully complete the assessment. The three categories of science practices are described as discrete practices; but they are in fact interrelated. For example, scientific questions and predictions are associated with the underlying mathematical relationships, and those relationships are used to create diagrams and graphs. The ordering of the science practices is not meant to describe any hierarchy of importance or difficulty.

The three science practices, and their associated skills, will be applied to all learning objectives in the Course Framework. The task verb “describe,” which is used in nearly all learning objectives, encompasses the range of possible graphical, mathematical, or verbal skill applications. Within these multiple representations, students should be able to “describe” a physical concept graphically, mathematically, and in prose.

For example, for a given Learning Objective, teachers are encouraged to ask the following questions about a physical phenomenon:

- How would students create or interpret graphs or other visual representations?
- What quantitative problems could students solve?
- What experiment could a student design, or what data would students analyze?
- How could the concepts be characterized using prose?
- How could the material be used as evidence to justify or support a claim about the behavior of a system, physical phenomena, or outcome of an experiment?

Required Equations

Not all equations in this curriculum framework appear on the equation sheet provided to students while taking the AP Physics C: Electricity and Magnetism Exam. Many of the equations in this document are provided for reference and guidance, or to demonstrate the final results of derivations expected of students on the exam. These equations are denoted as “Derived Equations.” Additionally, variables used within this curriculum framework follow the definitions given on the equation sheet. For a complete list of the equations available to students on the AP Physics C: Electricity and Magnetism Exam, please see the AP Physics C: Electricity and Magnetism reference sheet in the Appendix.
**Course at a Glance**

**Plan**
The Course at a Glance provides a useful visual organization for the AP Physics 2 course components, including:

- Sequence of units, along with approximate weighting and suggested pacing. Please note, pacing is based on 50-minute class periods, meeting five days each week for a full academic year.
- Progression of topics within each unit.
- Spiraling of the science practices across units.

**Teach**
**PRACTICES**
*Science Practices spiral throughout the course*

- Creating Representations
- Mathematical Routines
- Scientific Questioning and Argumentation

**Assess**
Assign the Progress Checks—either as homework or in class—for each unit. Each Personal Progress Check contains formative multiple-choice and free-response questions. The feedback from these checks shows students the areas where they need to focus.

**Progress Check 8**
*Multiple choice questions—18*
*FRQ: 4*
- Math Routines Question
- Qualitative/Quantitative Translation
- Experimental Design
- Translation Between Representation

**Progress Check 9**
*Multiple choice questions—18*
*FRQ: 4*
- Math Routines Question
- Qualitative/Quantitative Translation
- Experimental Design
- Translation Between Representation
Progress Check 13

Multiple choice questions~18
FRQ: 2 questions
- Math Routines Question
- Qualitative/Quantitative Translation
- Experimental Design
- Translation Between Representation
AP PHYSICS C: ELECTRICITY AND MAGNETISM

UNIT 8

Electric Charges, Fields, and Gauss’s Law

18–22% AP EXAM WEIGHTING

~12/~24 CLASS PERIODS
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:

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

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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# Electric Charges, Fields, and Gauss’s Law

## Learning Objective

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

### 8.1.B
Describe the electric and gravitational forces that result from interactions between charged objects with mass.

### 8.1.C
Describe the electric permittivity of a material or medium.

## Essential Knowledge

### 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.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.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, $\varepsilon_0$, 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

i. 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.
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).
# Electric Fields

**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:*

\[
\vec{E} = \frac{\vec{F}}{q}
\]

- 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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**LEARNING OBJECTIVE**

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

8.3.B
Describe the electric field generated by charged conductors or insulators.

**ESSENTIAL KNOWLEDGE**

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.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:*

\[ \vec{E} = \frac{1}{4\pi\varepsilon_0} \frac{|q_1 q_2|}{r^2} \]

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.
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

\[
\Phi_E = \vec{E} \cdot \vec{A}.
\]

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:

\[
\Phi_E = \int \vec{E} \cdot d\vec{A}
\]
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:

\[ \Phi_E = \frac{q_{enc}}{\varepsilon_0} \]

\[ \oint E \cdot dA = \frac{q_{enc}}{\varepsilon_0} \]

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:

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

continued on next page
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:
\[ \oint E \cdot dA = \frac{q_{\text{enc}}}{\epsilon_0} \]

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.
UNIT 9
Electric Potential

14–18% AP EXAM WEIGHTING

~10/~19 CLASS PERIODS
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.
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:

\[ V = \frac{1}{4\pi\varepsilon_0} \sum \frac{q_i}{r_i} \]

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.

\[ \Delta V = \frac{\Delta U_i}{q} \]
Electric Potential

LEARNING OBJECTIVE

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

9.2.B
Describe the relationship between electric potential and electric field.

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.

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.

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.

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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**

9.3.A
Describe changes in a system due to a difference in electric potential between two locations.

**ESSENTIAL KNOWLEDGE**

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.
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AP PHYSICS C: ELECTRICITY AND MAGNETISM

UNIT 10

Conductors and Capacitors

10–14% AP EXAM WEIGHTING

~8/~16 CLASS PERIODS
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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<table>
<thead>
<tr>
<th>LEARNING OBJECTIVE</th>
<th>ESSENTIAL KNOWLEDGE</th>
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<tbody>
<tr>
<td>10.1.A</td>
<td><strong>10.1.A.4</strong></td>
</tr>
<tr>
<td>Describe the charge distribution within a conductor.</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td><strong>10.1.A.5</strong></td>
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<td></td>
<td>The electric field is perpendicular to the outer surface of a conductor.</td>
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<td></td>
<td><strong>10.1.A.6</strong></td>
</tr>
<tr>
<td></td>
<td>A conductor can be polarized in the presence of an external electric field. This is a consequence of the conductor remaining an equipotential surface.</td>
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<td></td>
<td><strong>10.1.A.7</strong></td>
</tr>
<tr>
<td></td>
<td>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.</td>
</tr>
</tbody>
</table>
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.
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, \( \kappa \), of the material between the plates and the electric permittivity of free space, \( \varepsilon_0 \).

Relevant equation:

\[ C = \frac{\kappa \varepsilon_0 A}{d} \]

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**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.
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.

Relevant equation:
\[ \kappa = \frac{E}{E_0} \]

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:
\[ C = \kappa C_0 \]
UNIT 11

Electric Circuits

AP PHYSICS C: ELECTRICITY AND MAGNETISM

18–22% AP EXAM WEIGHTING

~12/~24 CLASS PERIODS
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TOPIC 11.1
Electric Current

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:
\[ I = nqv_d \text{A} \]

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:
\[ \mathbf{I} = \int \mathbf{j} \cdot d\mathbf{A} \]

i. Current density is related to the motion of the charge carriers within a conductor.
Relevant equation:
\[ \mathbf{j} = nqv_d \]

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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:

\[ E = \rho \vec{j} \]

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:

\[ I_{\text{tot}} = \int \vec{j}(r) \cdot dA \]

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).
Electric Circuits

TOPIC 11.2
Simple Circuits

Required Course Content

LEARNING OBJECTIVE
11.2.A
Describe the behavior of a circuit.

ESSENTIAL KNOWLEDGE
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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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.

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

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

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

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

Relevant equation:

\[ I = \frac{\Delta V}{R} \]
# Electric Circuits

## LEARNING OBJECTIVE

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

## ESSENTIAL KNOWLEDGE

- Materials that obey Ohm’s law have constant resistance for all currents and are called ohmic materials.
- The resistivity of an ohmic material is constant regardless of temperature.
- Resistors can also convert electrical energy to thermal energy, which may change the temperature of both the resistor and the resistor’s environment.
- 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.
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.
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

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

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

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

ESSENTIAL KNOWLEDGE

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.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 (\(E\)).

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:

\[ \Delta V_{\text{terminal}} = E - Ir \]

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.
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:

\[ \Delta U_e = q \Delta V \]

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.

3.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

**11.7.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:

\[ \sum I_{in} = \sum I_{out} \]
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:*

$$\frac{1}{C_{eq,s}} = \sum_{i} \frac{1}{C_i}$$

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:*

$$C_{eq,p} = \sum_{i} C_i$$

**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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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:
\[ \epsilon = \frac{dq}{dt} + \frac{q}{RC} \]

11.8.B.2
The time constant (\( \tau \)) 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

\[ \tau = R_C C \]

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.
UNIT 12

Magnetic Fields and Electromagnetism

AP EXAM WEIGHTING

14–18%

CLASS PERIODS

~10/~19
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TOPIC 12.1
Magnetic Fields

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:
\[ \oint B \cdot d\vec{A} = 0 \]

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).

continued on next page
### LEARNING OBJECTIVE

12.1.B
Describe the magnetic behavior of a material as a result of the configuration of magnetic dipoles in the material.

### ESSENTIAL KNOWLEDGE

**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.
**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 \( \mu_0 \), 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.
TOPIC 12.2
Magnetism and Moving Charges

Required Course Content

LEARNING OBJECTIVE

12.2.A
Describe the magnetic field produced by moving charged objects.

ESSENTIAL KNOWLEDGE

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:
\[ F = q(\vec{v} \times \vec{B}) \]

continued on next page
LEARNING OBJECTIVE

12.2.B
Describe the force exerted on moving charged objects by a magnetic field.

ESSENTIAL KNOWLEDGE

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.
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:
\[ dB = \frac{\mu_0 I (d \hat{r} \times \hat{r})}{4\pi r^2} \]

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:

\[ \vec{F}_n = \int (d\vec{l} \times \vec{B}) \]

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.
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:
\[ \oint B \cdot d\ell = \mu_0 I_{\text{enc}} \]

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.

continued on next page
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:

\[ \oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I + \mu_0 \frac{d\Phi_E}{dt} \]

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.
UNIT 13

Electromagnetic Induction

AP EXAM WEIGHTING

14–18%

CLASS PERIODS

~10/~19
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 \( \Phi = \vec{B} \cdot \vec{A} \).
   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:

\[ \Phi = \int \vec{B} \cdot d\vec{A} \]
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:

\[ \varepsilon = -\frac{d\Phi_B}{dt} = -\frac{d(\vec{B} \cdot \vec{A})}{dt} \]

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:

\[ |\varepsilon_{\text{tot}}| = N \left| \frac{d\Phi_B}{dt} \right| \]

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.

continued on next page
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:

\[ E = \oint E \cdot dl = -\frac{d\Phi_B}{dt} \]

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.
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:
\[ \vec{F} = \int I (d\vec{r} \times \vec{B}) \]

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.
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:

\[ L = \frac{\mu_0 N^2 A}{\ell} \]

13.4.A.2
Inductors store energy in the magnetic field that is generated by current in the inductor.

Relevant equation:

\[ U_L = \frac{1}{2} LI^2 \]

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.

continued on next page
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:
\[ \mathcal{E} = -L \frac{dI}{dt} \]
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:
\[ E = IR + L \frac{dI}{dt} \]

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.

continued on next page
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.

Derived equation:
\[
\frac{dq}{dt} = -\frac{1}{LC}q
\]

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.

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:
\[
\omega = \frac{1}{\sqrt{LC}}
\]
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The AP Physics C: Electricity and Magnetism exam assesses student application of the science practices and understanding of the learning objectives outlined in the course framework. The exam is 3 hours long and includes 45–50 multiple-choice questions and 4 free-response questions. A four-function scientific or graphing calculator is allowed on both sections of the exam. The details of the exam, including exam weighting and timing, can be found below:

<table>
<thead>
<tr>
<th>Section</th>
<th>Type of Questions</th>
<th>Weighting</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Multiple-choice questions</td>
<td>50%</td>
<td>90 minutes</td>
</tr>
<tr>
<td>II</td>
<td>Free-response questions</td>
<td>50%</td>
<td>90 minutes</td>
</tr>
</tbody>
</table>

Question 1: Mathematical Routines
Question 2: Translation Between Representations
Question 3: Experimental Design
Question 4: Qualitative/Quantitative Translation

The exam also assesses each of the seven units of instruction with the following exam weightings on the multiple-choice section of the AP exam:
### Exam Weighting for the Multiple-Choice Section of the AP Exam

<table>
<thead>
<tr>
<th>Unit of Instruction</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unit 8:</strong> Electric Charges, Fields, and Gauss’s Law</td>
<td>18–22%</td>
</tr>
<tr>
<td><strong>Unit 9:</strong> Electric Potential</td>
<td>14–18%</td>
</tr>
<tr>
<td><strong>Unit 10:</strong> Conductors and Capacitors</td>
<td>10–14%</td>
</tr>
<tr>
<td><strong>Unit 11:</strong> Electric Circuits</td>
<td>18–22%</td>
</tr>
<tr>
<td><strong>Unit 12:</strong> Magnetic Fields and Electromagnetism</td>
<td>14–18%</td>
</tr>
<tr>
<td><strong>Unit 13:</strong> Electromagnetic Induction</td>
<td>14–18%</td>
</tr>
</tbody>
</table>
How Student Learning Is Assessed on the AP Exam

Exam Weighting by Science Practice

Science Practices 2 and 3 are assessed in the multiple-choice section with the following weighting (Science Practice 1 will not be assessed in the multiple-choice section). Science Practices 1, 2 and 3 are all assessed in the free-response section with the following weighting.

Please note: Required course content (Learning Objectives and Essential Knowledge) can be assessed with any skill.

<table>
<thead>
<tr>
<th>Science Practice</th>
<th>Approximate MCQ Exam Weighting</th>
<th>Approximate FR Exam Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.A</td>
<td>N/A</td>
<td>25–30%</td>
</tr>
<tr>
<td>1.B</td>
<td>Create quantitative graphs with appropriate scales, and units, including plotting data.</td>
<td>N/A</td>
</tr>
<tr>
<td>1.C</td>
<td>Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.</td>
<td>N/A</td>
</tr>
<tr>
<td>2.A</td>
<td>Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.</td>
<td>70–80%</td>
</tr>
<tr>
<td>2.B</td>
<td>Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.</td>
<td>70–80%</td>
</tr>
<tr>
<td>2.C</td>
<td>Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.</td>
<td>70–80%</td>
</tr>
<tr>
<td>2.D</td>
<td>Predict new values or factors of change of physical quantities using functional dependence between variables.</td>
<td>70–80%</td>
</tr>
</tbody>
</table>

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Free-Response Questions
The free-response section of the AP Physics C: Electricity and Magnetism Exam consists of four question types listed below. Each question type appears on the exam.

Mathematical Routines (MRs)
10 points; suggested time: 20–25 minutes

The Mathematical Routines (MRs) question assesses students’ ability to use mathematics to analyze a scenario and make predictions about that scenario. Students will be expected to symbolically derive relationships between variables, as well as calculate numerical values. Students will be expected to create and use representations that describe the scenario, either to help guide the mathematical analysis (such as drawing a free-body diagram) or that are applicable to the scenario (such as sketching velocity as a function of time).

Translating Between Representations (TBRs)
12 points, suggested time: 25–30 minutes

The Translating Between Representations (TBRs) question assesses students’ ability to connect different representations of a scenario. Students will be expected to create a visual representation that describes a given scenario. Students will derive equations that are mathematically relevant to the scenario. Students will draw graphs that relate quantities within the scenario. Finally, students will be asked to do any one of the following:

- Justify why their answers to any two of the previous parts do/do not agree with each other.
- Use their representations, mathematical analysis, or graph to make a prediction about another situation and justify their prediction using that reasoning or analysis.
- Use their representations, mathematical analysis, or graph to make a prediction about how those representations would change if properties of the scenario were altered and justify that claim using consistent reasoning or analysis.
Experimental Design and Analysis (LAB)


12 points; suggested time: 25–30 minutes

The Experimental Design and Analysis (LAB) question assesses students’ ability to create scientific procedures that can be used with appropriate data analysis techniques to determine the answer to given questions. The LAB question can roughly be divided into two sections: Design and Analysis. In the Design portion of the LAB question, students will be asked to develop a method by which a question about a given physical scenario could be answered. The experimental procedure is expected to be scientifically sound: vary a single parameter, and measure how that change affects a single characteristic. Methods must be able to be performed in a typical high school laboratory. Measurements must be made with realistically obtainable equipment or sensors. Students will be expected to describe a method by which the collected data could be analyzed in order to answer the posed question, by either graphical or comparative analyses.

Students will then be given experimental data collected in order to answer a similar, but not identical, question to what was asked in the Design portion of the question. Students will be asked to use the data provided to create and plot a graph that can be analyzed to determine the answer to the given question. For instance, the slope or intercepts of the line may be used to determine a physical quantity or perhaps the nature of the slope would answer the posed question.

Finally, students will be asked an extension or reflection question about the experiment. For instance, identifying possible sources of experimental error and how that source may have affected the results. Students may be asked what the likely outcome would be if the experiment was modified and to use physics concepts to justify their predictions.

Qualitative/Quantitative Translation (QQT)


8 points; suggested time: 15–20 minutes

The Qualitative/Quantitative Translation (QQT) question assesses students’ ability to connect the nature of the scenario, the physical laws that govern the scenario, and mathematical representations of that scenario to each other. Students will be asked to make and justify a claim about a given scenario, as well as derive an equation related to that scenario. Finally, students will be asked to do any one of the following:

- Justify why their answers to any of the previous parts do/do not agree with each other.
- Use their representations or mathematical analysis to make a prediction about another situation and justify their prediction using that reasoning or analysis.
- Use their representations and mathematical analysis to make a prediction about how those representations would change if properties of the scenario were altered and justify that claim using consistent reasoning or analysis.

While students may not be directly assessed on their ability to create diagrams or other representations of the system to answer the QQT, those skills may still help students to answer the QQT. For instance, some students may find that drawing a free-body diagram is useful when determining the acceleration of a system. However, the student will earn points for the explanation and conclusions that diagram indicates (or perhaps the derivation that results from the diagram), rather than for creating the diagram itself.