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 and exam description 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 and exam description 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 freeresponse 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 apstudent.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. Ninety-eight 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 2 Course

AP Physics 2 is an algebra-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:

- Thermodynamics
- Electric Force, Field, and Potential
- Electric Circuits
- Magnetism and Electromagnetism
- Geometric Optics
- Waves, Sound, and Physical Optics
- Modern Physics

College Course Equivalent

AP Physics 2 is equivalent to the second course in an introductory college course sequence in algebra-based physics.

Prerequisites

Students should have completed AP Physics 1 or a comparable introductory physics course and should have taken or be concurrently taking pre-calculus or an equivalent course.

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 2 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 2 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 survey course: to help students develop a deep understanding of the foundational principles that shape classical mechanics and modern physics. 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 explaining relationships, applying and justifying the use of mathematical routines, designing experiments, analyzing data, and making connections across multiple topics within the course.

To foster this deeper level of learning, the AP Physics 2 course defines concepts, science practices, 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. The result is a course that prepares students for college credit and placement.
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.
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Science Practices

The table that follows presents the science practices that students should develop during the AP Physics 2 course. These practices form the basis of many tasks on the AP Physics 2 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.
# AP PHYSICS 2
## Science Practices

<table>
<thead>
<tr>
<th>Practice 1</th>
<th>Practice 2</th>
<th>Practice 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Creating Representations</strong> 1</td>
<td><strong>Mathematical Routines</strong> 2</td>
<td><strong>Scientific Questioning and Argumentation</strong> 3</td>
</tr>
<tr>
<td>Create representations that depict physical phenomena.</td>
<td>Conduct analyses to derive, calculate, estimate, or predict.</td>
<td>Describe experimental procedures, analyze data, and support claims.</td>
</tr>
</tbody>
</table>

### Skills

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

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

| 3.A | Create experimental procedures that are appropriate for a given scientific question. |
| 3.B | Apply an appropriate law, definition, theoretical relationship, or model to make a claim. |
| 3.C | Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws. |
This course framework provides a clear and detailed description of the course requirements for student success. The framework specifies what students must know, be able to do, and understand with a focus on ideas that encompass core principles, theories, and processes of physics. This framework also encourages instruction that prepares students to make connections across domains 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 seven units in AP Physics 2 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.
Exam Weighting for the Multiple-Choice Section of the AP Physics 2 Exam.

<table>
<thead>
<tr>
<th>Units of Instruction</th>
<th>Exam Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unit 9: Thermodynamics</strong></td>
<td>16–18%</td>
</tr>
<tr>
<td><strong>Unit 10: Electric Force, Field, and Potential</strong></td>
<td>16–18%</td>
</tr>
<tr>
<td><strong>Unit 11: Electric Circuits</strong></td>
<td>16–18%</td>
</tr>
<tr>
<td><strong>Unit 12: Magnetism and Electromagnetism</strong></td>
<td>14–16%</td>
</tr>
<tr>
<td><strong>Unit 13: Geometric Optics</strong></td>
<td>10–14%</td>
</tr>
<tr>
<td><strong>Unit 14: Waves, Sound, and Physical Optics</strong></td>
<td>10–14%</td>
</tr>
<tr>
<td><strong>Unit 15: Modern Physics</strong></td>
<td>10–14%</td>
</tr>
</tbody>
</table>

TOPICS

Each unit is divided into teachable segments called topics. Visit the topic pages to see all the required content for each topic.

Learning Objectives and Science Practices

In the AP Physics 2 courses and exams, 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 2 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 2 Exam, please see the AP Physics 2 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

Progress Check 1
Multiple-choice: questions~18
FRQ: 4
- Math Routines Question
- Qualitative/Quantitative Translation
- Experimental Design
- Translation Between Representation

Assess
Assign the Progress Checks—either as homework or in class—for each unit. Each Progress Check contains formative multiple-choice and free-response questions. The feedback from these checks shows students the areas where they need to focus.
UNIT 11 Electric Circuits
~12–20 Class Periods 16–18% AP Exam Weighting

1  11.1 Electric Current
2  11.2 Simple Circuits
3  11.3 Resistance, Resistivity, and Ohm’s Law
4  11.4 Electric Power
5  11.5 Compound Direct Current (DC) Circuits
6  11.6 Kirchhoff’s Loop Rule
7  11.7 Kirchhoff’s Junction Rule
8  11.8 Resistor-Capacitor (RC) Circuits

UNIT 12 Magnetism and Electromagnetism
~10–14 Class Periods 14–16% AP Exam Weighting

1  12.1 Magnetic Fields
2  12.2 Magnetism and Moving Charges
3  12.3 Magnetism and Current-Carrying Wires
4  12.4 Electromagnetic Induction and Faraday’s Law

UNIT 13 Geometric Optics
~8–12 Class Periods 10–14% AP Exam Weighting

1  13.1 Reflection
2  13.2 Images Formed by Mirrors
3  13.3 Refraction
4  13.4 Images Formed by Lenses

Progress Check 3
Multiple-choice: questions~24
FRQ: 4
- Math Routines Question
- Qualitative/Quantitative Translation
- Experimental Design
- Translation Between Representation

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

Progress Check 5
Multiple-choice: questions~18
FRQ: 4
- Math Routines Question
- Qualitative/Quantitative Translation
- Experimental Design
- Translation Between Representation
UNIT 14 Waves, Sound, and Physical Optics

~14–23 Class Periods 10–14% AP Exam Weighting

1 14.1 Properties of Wave Pulses and Waves
2 14.2 Periodic Waves
3 14.3 Boundary Behavior of Waves and Polarization
4 14.4 Electromagnetic Waves
5 14.5 The Doppler Effect
6 14.6 Wave Interference and Standing Waves
7 14.7 Diffraction
8 14.8 Double-Slit Interference and Diffraction Gratings
9 14.9 Thin-Film Interference

UNIT 15 Modern Physics

~14–22 Class Periods 10–14% AP Exam Weighting

1 15.1 Quantum Theory and Wave-Particle Duality
2 15.2 The Bohr Model of Atomic Structure
3 15.3 Emission and Absorption Spectra
4 15.4 Blackbody Radiation
5 15.5 The Photoelectric Effect
6 15.6 Compton Scattering
7 15.7 Fission, Fusion, and Nuclear Decay
8 15.8 Types of Radioactive Decay

Progress Check 6
Multiple-choice: questions~30
FRQ: 2 questions
• Math Routines Question
• Qualitative/Quantitative Translation
• Experimental Design
• Translation Between Representation

Progress Check 7
Multiple-choice: questions~24
FRQ: 4
• Math Routines Question
• Qualitative/Quantitative Translation
• Experimental Design
• Translation Between Representation
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AP PHYSICS 2

UNIT 9

Thermodynamics

16–18% AP EXAM WEIGHTING

~10–16 CLASS PERIODS
TOPIC 9.1

Kinetic Theory of Temperature and Pressure

Required Course Content

LEARNING OBJECTIVE

9.1.A
Describe the pressure a gas exerts on its container in terms of atomic motion within that gas.

ESSENTIAL KNOWLEDGE

9.1.A.1
Atoms in a gas collide with and exert forces on other atoms in the gas and with the container in which the gas is contained.

i. Collisions involving pairs of atoms or an atom and a fixed object, can be described and analyzed using conservation of momentum principles.

ii. The pressure exerted by a gas on a surface is the ratio of the sum of the magnitudes of the perpendicular components of the forces exerted by the gas’s atoms on the surface to the area of the surface.

Relevant equation:

\[ P = \frac{F_{\perp}}{A} \]

iii. Pressure exists throughout the gas itself, not just at the boundary between the gas and the container.

9.1.B
Describe the temperature of a system in terms of the atomic motion within that system.

9.1.B.1
The temperature of a system is characterized by the average kinetic energy of the atoms within that system.

i. The Maxwell-Boltzmann distribution provides a graphical representation of the energies and speeds of atoms at a given temperature.

continued on next page
# Thermodynamics

## LEARNING OBJECTIVE

**9.1.B**

Describe the temperature of a system in terms of the atomic motion within that system.

## ESSENTIAL KNOWLEDGE

**ii.** The root-mean-square speed corresponding to the average kinetic energy for an ideal gas is related to the temperature of the gas by

\[
K_{\text{avg}} = \frac{3}{2} k_B T = \frac{1}{2} m v_{\text{rms}}^2
\]

## BOUNDARY STATEMENT:

*AP Physics 2 only expects students to perform qualitative and quantitative analysis of collisions in one and two dimensions. Students are not expected to know the functional form of the Maxwell-Boltzmann distribution but are expected to be familiar with how features of the distribution are related to the temperature of the gas.*
TOPIC 9.2
The Ideal Gas Law

Required Course Content

LEARNING OBJECTIVE

9.2.A
Describe the properties of an ideal gas.

ESSENTIAL KNOWLEDGE

9.2.A.1
The classical model of an ideal gas assumes that the instantaneous velocities of atoms are random, the volumes of the atoms are negligible compared to the total volume occupied by the gas, the atoms collide elastically, and the only appreciable forces on the atoms are those that occur during collisions.

9.2.A.2
An ideal gas is one in which the relationships between pressure, volume, the number of moles or number of atoms, and temperature of a gas can be modeled using the equation

\[ PV = nRT = Nk_B T. \]

9.2.A.3
Graphs modeling the pressure, temperature, and volume of gases can be used to describe or determine properties of that gas.

9.2.A.4
A temperature at which an ideal gas has zero pressure can be extrapolated from a graph of pressure as a function of temperature.
LEARNING OBJECTIVE

9.3.A
Describe the transfer of energy between two systems in thermal contact due to temperature differences of those two systems.

ESSENTIAL KNOWLEDGE

9.3.A.1
Two systems are in thermal contact if the systems may transfer energy by thermal processes.
   i. Heating is the transfer of energy into a system by thermal processes.
   ii. Cooling is the transfer of energy out of a system by thermal processes.

9.3.A.2
The thermal processes by which energy may be transferred between systems at different temperatures are conduction, convection, and radiation.

9.3.A.3
Energy is transferred through thermal processes spontaneously from a higher-temperature system to a lower-temperature system.
   i. In collisions between atoms from different systems, energy is most likely to be transferred from higher-energy atoms to lower-energy atoms.
   ii. After many collisions of atoms from different systems, the most probable state is one in which both systems have the same temperature.

9.3.A.4
Thermal equilibrium results when no net energy is transferred by thermal processes between two systems in thermal contact with each other.
## TOPIC 9.4
### The First Law of Thermodynamics

#### Required Course Content

<table>
<thead>
<tr>
<th>LEARNING OBJECTIVE</th>
<th>ESSENTIAL KNOWLEDGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>9.4.A</strong></td>
<td>Describe the internal energy of a system.</td>
</tr>
<tr>
<td><strong>9.4.A.1</strong></td>
<td>The internal energy of a system is the sum of the kinetic energy of the objects that make up the system and the potential energy of the configuration of those objects.</td>
</tr>
<tr>
<td></td>
<td>i. The atoms in an ideal gas do not interact with each other via conservative forces, and the internal structure is not considered. Therefore, an ideal gas does not have internal potential energy.</td>
</tr>
<tr>
<td></td>
<td>ii. The internal energy of an ideal monatomic gas is the sum of the kinetic energies of the constituent atoms in the gas.</td>
</tr>
<tr>
<td></td>
<td>Relevant equation:</td>
</tr>
<tr>
<td></td>
<td>[ \Delta U = \frac{3}{2} nR\Delta T = \frac{3}{2} Nk_B\Delta T ]</td>
</tr>
<tr>
<td><strong>9.4.A.2</strong></td>
<td>Changes to a system’s internal energy can result in changes to the internal structure and internal behavior of that system without changing the motion of the system’s center of mass.</td>
</tr>
<tr>
<td><strong>9.4.B</strong></td>
<td>Describe the behavior of a system using thermodynamic processes.</td>
</tr>
<tr>
<td><strong>9.4.B.1</strong></td>
<td>The first law of thermodynamics is a restatement of conservation of energy that accounts for energy transferred into or out of a system by work, heating, or cooling.</td>
</tr>
<tr>
<td></td>
<td>i. For an isolated system, the total energy is constant.</td>
</tr>
</tbody>
</table>

*continued on next page*
LEARNING OBJECTIVE

Describe the behavior of a system using thermodynamic processes.

ESSENTIAL KNOWLEDGE

9.4.B

ii. For a closed system, the change in internal energy is the sum of energy transferred to or from the system by heating, or work done on the system.

\[ \Delta U = Q + W \]

Relevant equation:

iii. The work done on a system by a constant or average external pressure that changes the volume of that system (for example, a piston compressing a gas in a container) is defined as

\[ W = -P \Delta V. \]

9.4.B.2

Pressure-volume graphs (also known as PV diagrams) are representations used to represent thermodynamic processes.

i. Lines of constant temperature on a PV diagram are called isotherms.

ii. The absolute value of the work done on a gas when the gas expands or compresses is equal to the area underneath the curve of a plot of pressure vs. volume for the gas.

9.4.B.3

Special cases of thermal processes depend on the relationship between the configuration of the system, the nature of the work done on the system, and the system’s surroundings. These include constant volume (isovolumetric), constant temperature (isothermal), and constant pressure (isobaric), as well as processes where no energy is transferred to or from the system through thermal processes (adiabatic).
TOPIC 9.5
Specific Heat and Thermal Conductivity

Required Course Content

LEARNING OBJECTIVE

9.5.A
Describe the energy required to change the temperature of an object by a certain amount.

ESSENTIAL KNOWLEDGE

9.5.A.1
The amount of energy required to change the temperature of a material is related to the material’s specific heat.

Relevant equation:
\[ Q = mc\Delta T \]

9.5.A.2
The specific heat of a material is an intrinsic property of that material that depends on the arrangement and interactions of the atoms that make up the material.

9.5.B
Describe the rate at which energy is transferred by conduction through a given material.

9.5.B.1
The rate at which energy is transferred by conduction through a given material is related to the thermal conductivity, the physical dimensions of the material, and the temperature difference across the material.

Relevant equation:
\[ \frac{Q}{\Delta t} = k\frac{A\Delta T}{L} \]

9.5.B.2
The thermal conductivity of a material is an intrinsic property of that material that depends on the arrangement and interactions of the atoms that make up the material.

BOUNDARY STATEMENT:

AP Physics 2 will model specific heat as independent of temperature.
TOPIC 9.6
Entropy and the Second Law of Thermodynamics

Required Course Content

LEARNING OBJECTIVE

9.6.A
Describe the change in entropy for a given system over time.

ESSENTIAL KNOWLEDGE

9.6.A.1
The second law of thermodynamics states that the total entropy of an isolated system can never decrease and is constant only when all processes the system undergoes are reversible.

9.6.A.2
Entropy can be qualitatively described as the tendency of energy to spread or the unavailability of some of the system’s energy to do work.
   i. Localized energy will tend to disperse and spread out.
   ii. Entropy is a state function and therefore only depends on the current state or configuration of a system, not how the system reached that state.
   iii. Maximum entropy occurs when a system is in thermodynamic equilibrium.

9.6.A.3
The change in a system’s entropy is determined by the system’s interactions with its surroundings.
   i. Closed systems spontaneously move toward thermodynamic equilibrium.

continued on next page
LEARNING OBJECTIVE

9.6.A
Describe the change in entropy for a given system over time.

ESSENTIAL KNOWLEDGE

ii. The entropy of a closed system never decreases, but the entropy of an open system can decrease because energy can be transferred into or out of the system.

BOUNDARY STATEMENT:
Only qualitative treatment of the second law of thermodynamics is within the scope of AP Physics 2.
UNIT 10

Electric Force, Field, and Potential

AP EXAM WEIGHTING

16–18%

CLASS PERIODS

~14–21
TOPIC 10.1
Electric Charge and Electric Force

Required Course Content

LEARNING OBJECTIVE
10.1.A
Describe the electric force that results from the interactions between charged objects or systems.

ESSENTIAL KNOWLEDGE
10.1.A.1
Charge is a fundamental property of all matter.
   i. Charge is described as positive or negative.
   ii. The magnitude of the charge of a single electron or proton, the elementary charge, can be considered to be the smallest divisible amount of charge.
   iii. The charge of an electron is $-e$, the charge of a proton is $+e$, and a neutron has no electric charge.
   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.

10.1.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:
\[
\vec{F}_{12} = \frac{1}{4\pi\varepsilon_0} \frac{|q_1 q_2|}{r^2} = k \frac{|q_1 q_2|}{r^2}
\]

10.1.A.3
The direction of the electrostatic force depends on the signs of the charges on the interacting objects and is parallel to the line of separation between the objects.

continued on next page
LEARNING OBJECTIVE

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

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

10.1.C
Describe the electric permittivity of a material or medium.

ESSENTIAL KNOWLEDGE

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.

10.1.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.

10.1.B.1
Electrostatic forces can be attractive or repulsive, while gravitational forces are always attractive.

10.1.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.

10.1.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.

10.1.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.

10.1.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.

10.1.C.3
Free space has a constant value of electric permittivity, \( \varepsilon_0 \), that appears in physical relationships.

continued on next page
LEARNING OBJECTIVE 10.1.C
Describe the electric permittivity of a material or medium.

ESSENTIAL KNOWLEDGE 10.1.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.

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

BOUNDARY STATEMENT:
AP Physics 2 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.
TOPIC 10.2
Conservation of Electric Charge and the Process of Charging

Required Course Content

LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

10.2.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.

10.2.A.2
Any change to a system’s 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.

10.2.A.3
Grounding involves electrically connecting a charged system to a much larger and approximately neutral system (e.g., Earth).
TOPIC 10.3
Electric Fields

Required Course Content

LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

10.3.A.1
Electric fields may originate from charged objects.

10.3.A.2
The electric field at a given point is the ratio of the electric force exerted on a test charge at that 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.

10.3.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.

continued on next page
**10.3.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:*

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

**10.3.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.

**BOUNDARY STATEMENT:**
*AP Physics 2 only expects students to make calculations of the electric field resulting from four or fewer charged objects or systems. Analysis of the electric field resulting from more charges is allowed in situations of high symmetry. Students will only be expected to perform qualitative analysis of electric fields within insulators.*
TOPIC 10.4
Electric Potential Energy

Required Course Content

LEARNING OBJECTIVE
10.4.A
Describe the electric potential energy of a system.

ESSENTIAL KNOWLEDGE
10.4.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.

10.4.A.2
The general form for the electric potential energy of two charged objects is given by the equation

\[ U_e = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r} = k \frac{q_1 q_2}{r} \]

10.4.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.

BOUNDARY STATEMENT:
As the methods to calculate the electric potential energy due to extended charge distributions exceed the scope of the course, AP Physics 2 only requires that students calculate the electric potential energy of configurations of four or fewer point charges.
## TOPIC 10.5
### Electric Potential

#### Required Course Content

<table>
<thead>
<tr>
<th>LEARNING OBJECTIVE</th>
<th>ESSENTIAL KNOWLEDGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>10.5.A</strong>&lt;br&gt;Describe the electric potential due to a configuration of charged objects.</td>
<td><strong>10.5.A.1</strong>&lt;br&gt;Electric potential describes the electric potential energy per unit charge at a point in space.</td>
</tr>
</tbody>
</table>
| **10.5.A.2**<br>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:<br>\[ V = \frac{1}{4\pi\varepsilon_0} \sum_i q_i \frac{1}{r_i} \] | **10.5.A.3**<br>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. Relevant equation:<br>\[ \Delta V = \frac{\Delta U}{q} \]
| **10.5.A.4**<br>When conductors are in electrical contact, electrons will be redistributed such that the surfaces of the conductors are at the same electric potential. |

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

*continued on next page*
**LEARNING OBJECTIVE**

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

**ESSENTIAL KNOWLEDGE**

10.5.B.1
The average electric field between two points in space is equal to the electric potential difference between the two points divided by the distance between the two points.

Relevant equation:

\[ |\vec{E}| = \frac{\Delta V}{\Delta r} \]

10.5.B.2
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 in space. 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.

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

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

**BOUNDARY STATEMENT:**

As the methods to calculate the electric potential due to extended charges exceed the scope of the course, AP Physics 2 only expects that students calculate the electric potential of configurations of four or fewer particles (or more in situations of high symmetry).
TOPIC 10.6
Capacitors

Required Course Content

LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

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

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

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:

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

continued on next page
LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

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

i. The magnitude of the electric field between two charged parallel plates, where the plate separation is much smaller than the dimensions of the plates, can be described with the equation

\[ E_c = \frac{Q}{\kappa \epsilon_0 A} \]

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

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

10.6.A.5
The electric potential energy stored in a capacitor is described by the equation

\[ U_c = \frac{1}{2} Q \Delta V. \]

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

BOUNDARY STATEMENT:
While other shapes are also able to separate charges, only the analysis and descriptions of parallel-plate capacitors are required for AP Physics 2. Edge effects will be ignored unless explicitly stated otherwise.
## TOPIC 10.7
Conservation of Electric Energy

**Required Course Content**

<table>
<thead>
<tr>
<th>LEARNING OBJECTIVE</th>
<th>ESSENTIAL KNOWLEDGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>10.7.A</strong></td>
<td><strong>10.7.A.1</strong></td>
</tr>
<tr>
<td>Describe changes in energy in a system due to a difference in electric potential between two locations.</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td>Relevant equation: $\Delta U_E = q\Delta V$</td>
</tr>
<tr>
<td></td>
<td><strong>10.7.A.2</strong></td>
</tr>
<tr>
<td></td>
<td>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.</td>
</tr>
</tbody>
</table>
UNIT 11

Electric Circuits

16–18% AP EXAM WEIGHTING

~12–20 CLASS PERIODS
### Required Course Content

#### LEARNING OBJECTIVE

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

#### ESSENTIAL KNOWLEDGE

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

\[ I = \frac{\Delta q}{\Delta t} \]

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

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

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

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

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

---

**SUGGESTED SCIENCE PRACTICES**

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

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

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

3. **C**
   Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.
TOPIC 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 may include circuit elements such as wires, batteries, resistors, lightbulbs, capacitors, switches, ammeters, and voltmeters.

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

continued on next page
**LEARNING OBJECTIVE**

11.2.A
Describe the behavior of a circuit.

**ESSENTIAL KNOWLEDGE**

i. 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.

![Diagram of circuit elements: Battery, Bulb, Switch, Capacitor, Resistor, Ammeter, Voltmeter.]

**BOUNDARY STATEMENT:**

Unless otherwise specified, all circuit schematic diagrams will be drawn using conventional current.
TOPIC 11.3
Resistance, Resistivity, and Ohm’s Law

Required Course Content

LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

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

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

Relevant equation:
\[ R = \frac{\rho \ell}{A} \]

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

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

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

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

Relevant equation:
\[ I = \frac{\Delta V}{R} \]
LEARNING OBJECTIVE

11.2.A
Describe the behavior of a circuit.

ESSENTIAL KNOWLEDGE

i. Materials that obey Ohm’s law have constant resistance for all currents and are called ohmic materials.
ii. The resistivity of an ohmic material is constant regardless of temperature.
iii. Resistors can also convert electrical energy to thermal energy, which may change the temperature of both the resistor and the resistor’s environment.
iv. The resistance of an ohmic circuit element can be determined from the slope of a graph of the current in the element as a function of the potential difference across the element.
TOPIC 11.4
Electric Power

Required Course Content

<table>
<thead>
<tr>
<th>LEARNING OBJECTIVE</th>
<th>ESSENTIAL KNOWLEDGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>11.4.A</strong></td>
<td><strong>11.4.A.1</strong></td>
</tr>
<tr>
<td>Describe the transfer of energy into, out of, or within an electric circuit, in terms of power.</td>
<td>The rate at which energy is transferred, converted, or dissipated by a circuit element depends on the current in the element and the electric potential difference across it. Relevant equation: ( P = I\Delta V ) Derived equations: ( P = I^2R = \frac{(\Delta V)^2}{R} )</td>
</tr>
</tbody>
</table>

11.4.A.2
The brightness of a bulb increases with power, so power can be used to qualitatively predict the brightness of bulbs in a circuit.
TOPIC 11.5
Compound Direct Current (DC) Circuits

Required Course Content

LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

11.5.A.1
Circuit elements may be connected in series and/or in parallel.
   i. A series connection is one in which any charge passing through one circuit element must proceed through all elements in that connection and has no other path available. The current in each element in series must be the same.
   ii. A parallel connection is one in which charges may flow through one of two or more paths. Across each path, the potential difference is the same.

11.5.A.2
A collection of resistors in a circuit may be analyzed as though it were a single resistor with an equivalent resistance $R_{eq}$.
   i. The equivalent resistance of a set of resistors in series is the sum of the individual resistances.
      Relevant equation:
      $$R_{eq,s} = \sum R_i$$
   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:
      $$\frac{1}{R_{eq,p}} = \sum \frac{1}{R_i}$$

continued on next page
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 (ε).

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

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

Derived equation:

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

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 an infinite resistance so that no charge flows through them.

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

**BOUNDARY STATEMENT:**

*AP Physics 2 only expects students to qualitatively discuss how a nonideal ammeter or voltmeter will affect the results of measurements. 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.*
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.

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

Relevant equation:
\[ \sum \Delta V = 0 \]

11.6.A.4
The values of electric potential at points in a circuit can be represented by a graph of electric potential as a function of position within a loop.
TOPIC 11.7
Kirchhoff’s Junction Rule

Required Course Content

LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

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

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

Relevant equation:

\[ \sum I_{\text{in}} = \sum I_{\text{out}} \]
TOPIC 11.8
Resistor-Capacitor (RC) Circuits

Required Course Content

LEARNING OBJECTIVE

11.8.A
Describe the equivalent capacitance of multiple capacitors.

ESSENTIAL KNOWLEDGE

11.8.A.1
A collection of capacitors in a circuit may be analyzed as though it were 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.

continued on next page
LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

11.8.B.1
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 $\tau = \frac{RC}{eq}$

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

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

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

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 circuit branch in which the capacitor is located, and the electric potential energy stored in the capacitor.

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.

continued on next page
LEARNING OBJECTIVE
11.8.B
Describe the behavior of a circuit containing combinations of resistors and capacitors.

ESSENTIAL KNOWLEDGE
v. Immediately after a charged capacitor begins discharging, the amount of charge on the capacitor plates and the energy stored in the capacitor begin to decrease.

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.

BOUNDARY STATEMENT:
Descriptions of charging/discharging RC circuits in AP Physics 2 are limited to qualitative descriptions and representations. While students should be able to mathematically describe initial and final states of RC circuits, students are not expected to mathematically model these behaviors with respect to time.
AP PHYSICS 2

UNIT 12

Magnetism and Electromagnetism

AP EXAM WEIGHTING
14–16%

CLASS PERIODS
~10–14
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.
- Magnetic fields can be produced by magnetic dipoles or combinations of dipoles, but never by monopoles.
- 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.
- Magnetic field lines form closed loops.
- 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).

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

12.1.B.1
Magnetic dipoles result from the circular or rotational motion of electric charges. In magnetic materials, this can be the motion of electrons.
- Permanent magnetism and induced magnetism are system properties that both result from the alignment of magnetic dipoles within a system.
- 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.

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.

12.1.C
Describe the magnetic permeability of a material.

ESSENTIAL KNOWLEDGE

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.

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.

continued on next page
LEARNING OBJECTIVE

12.1.C
Describe the magnetic permeability of a material.

ESSENTIAL KNOWLEDGE

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
Magnetic forces describe interactions between moving charged objects.

12.2.B.2
A magnetic field may exert a force on a charged object moving in that field.

continued on next page
LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

i. The magnitude of the force exerted by a magnetic field on a moving charged object is proportional to the magnitude of the charge, the magnitude of the charged object’s velocity, and the magnitude of the magnetic field and also depends on the angle between the velocity and magnetic field vectors.

Relevant equation:

\[ \mathbf{F} = q \mathbf{v} \times \mathbf{B} \sin \theta \]

ii. The direction of the force exerted by a magnetic field on a moving charged object is perpendicular to both the direction of the magnetic field and the velocity of the charge, as defined by the right-hand rule.

12.2.B.3
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.4
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.

BOUNDARY STATEMENT:

Quantitative treatment of the magnitude of the magnetic force exerted by a magnetic field on a moving charge is limited to angles of 0, 90, and 180 degrees between the velocity and the magnetic field. Qualitative analysis of other angles is permitted.
TOPIC 12.3
Magnetism and Current-Carrying Wires

Required Course Content

LEARNING OBJECTIVE

12.3.A
Describe the magnetic field produced by a current-carrying wire.

ESSENTIAL KNOWLEDGE

12.3.A.1
A current-carrying wire produces a magnetic field.

i. The magnetic field vectors around a long, straight, current-carrying wire are tangent to concentric circles centered on that wire. The field has no component toward, away from, or parallel to the long, straight, current-carrying wire.

ii. At a point in space, the magnitude of the magnetic field due to a long, straight, current-carrying wire is proportional to the magnitude of the current in the wire and inversely proportional to the perpendicular distance from the central axis of the wire to the point.

Relevant equation:

\[ B = \frac{\mu_0 I}{2\pi r} \]

iii. The direction of the magnetic field created by a current-carrying wire is determined with the right-hand rule.

iv. The direction of the magnetic field at the center of a current-carrying loop is directed along the axis of the loop and can be found using the right-hand rule.

v. The magnetic field at a location near two or more current-carrying wires can be determined using vector addition principles.

continued on next page
# Magnetism and Electromagnetism

## 12.3.B
Describe the force exerted on a current-carrying wire by a magnetic field.

## Essential Knowledge

### 12.3.B.1
A magnetic field may exert a force on a current-carrying wire.

1. The magnitude of the force exerted by a magnetic field on a current-carrying wire is proportional to the current, the length of the portion of the wire within the magnetic field, and the magnitude of the magnetic field, and also depends on the angle between the direction of the current in the wire and the direction of the magnetic field.

   **Relevant equation:**
   
   \[ F = I \ell B \sin \theta \]

2. The direction of the force exerted by the magnetic field on a current-carrying wire is determined by the right-hand rule.

### Boundary Statement:

Quantitative treatment of the magnitude of the magnetic force exerted by a magnetic field on a moving charge is limited to angles of 0, 90, and 180 degrees between the velocity and the magnetic field. Qualitative analysis of other angles is permitted.
TOPIC 12.4
Electromagnetic Induction and Faraday’s Law

Required Course Content

LEARNING OBJECTIVE
12.4.A
Describe the induced electric potential difference resulting from a change in magnetic flux.

ESSENTIAL KNOWLEDGE
12.4.A.1
Magnetic flux is a description of the amount of the component of a magnetic field that is perpendicular to a cross-sectional area.

Magnetic flux through a surface is proportional to the magnitude of the component of the magnetic field perpendicular to the surface and to the cross-sectional area of the surface.

Relevant equation:
\[ \Phi = BA \cos \theta \]

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

ii. The sign of the magnetic flux indicates whether the magnetic field is parallel to or antiparallel to the area vector.

12.4.A.2
Faraday’s law describes the relationship between changing magnetic flux and the resulting induced emf in a system.

Relevant equation:
\[ \varepsilon = \frac{\Delta \Phi}{\Delta t} \]

12.4.A.3
Lenz’s law is used to determine the direction of an induced emf resulting from a changing magnetic flux.

Relevant equation:
\[ \varepsilon = -\frac{\Delta \Phi}{\Delta t} = -\frac{\Delta (BA \cos \theta)}{\Delta t} \]

continued on next page
LEARNING OBJECTIVE

12.4.A
Describe the induced electric potential difference resulting from a change in magnetic flux.

ESSENTIAL KNOWLEDGE

i. An induced emf generates a current that creates a magnetic field that opposes the change in magnetic flux.

ii. The right-hand rule is used to determine the relationships between current, emf, and magnetic flux.

12.4.A.5
A common example of electromagnetic induction is a conducting rod on conducting rails in a region with a uniform magnetic field.

Derived equation:
\[ \mathcal{E} = B \ell v \]
AP PHYSICS 2

UNIT 13

Geometric Optics

10–14%  
AP EXAM WEIGHTING

~8–12  
CLASS PERIODS
**TOPIC 13.1**

**Reflection**

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**Required Course Content**

<table>
<thead>
<tr>
<th>LEARNING OBJECTIVE</th>
<th>ESSENTIAL KNOWLEDGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>13.1.A</strong> Describe light as a ray.</td>
<td><strong>13.1.A.1</strong> A light ray is a straight line that is perpendicular to the wavefront of a light wave and points in the direction of travel of the wave.</td>
</tr>
<tr>
<td><strong>i.</strong> Light rays can be used to determine the behavior of light in geometric optics, where the wave nature of light can be neglected.</td>
<td></td>
</tr>
<tr>
<td><strong>ii.</strong> Rays are not sufficient to understand the spreading of light. In interference and diffraction, the wave nature of the light is important.</td>
<td></td>
</tr>
<tr>
<td><strong>iii.</strong> A laser is a common source of a single coherent, monochromatic beam of light that can be modeled as a ray. The wave nature of lasers will be considered in Unit 14.</td>
<td></td>
</tr>
<tr>
<td><strong>13.1.A.2</strong> Ray diagrams depict the path of light before and after an interaction with matter.</td>
<td></td>
</tr>
<tr>
<td><strong>13.1.B</strong> Describe the reflection of light from a surface.</td>
<td><strong>13.1.B.1</strong> Light that is incident on a surface can be reflected.</td>
</tr>
<tr>
<td><strong>13.1.B.2</strong> The law of reflection states that the angle between the incident ray and the normal (the line perpendicular to the surface) is equal to the angle between the reflected ray and the normal.</td>
<td></td>
</tr>
</tbody>
</table>

*Relevant equation:*

\[ \theta_i = \theta_r \]
**ESSENTIAL KNOWLEDGE**

| 13.1.B.3 | Diffuse reflection is the reflection of light from a rough surface and results in light reflected in many different directions, because the line normal to the surface varies over the area over which the light is incident. |
| 13.1.B.4 | Specular reflection is the reflection of light from a smooth surface and results in light uniformly reflected from the surface, because the line normal to the surface has an approximately constant direction over the area the light strikes. |

*The wave nature of light will be discussed in greater detail in Unit 14.*
TOPIC 13.2
Images Formed by Mirrors

Required Course Content

LEARNING OBJECTIVE
13.2.A
Describe the image formed by a mirror.

ESSENTIAL KNOWLEDGE
13.2.A.1
Incident light rays parallel to the principal axis of a concave (converging) mirror will be reflected toward a common location, called the focal point.

13.2.A.2
Incident light rays parallel to the principal axis of a convex (diverging) mirror will be reflected such that they appear to have originated from a common location behind the mirror, called the focal point.

13.2.A.3
The focal point of a plane mirror is an infinite distance from the mirror.

13.2.A.4
The focal point of a spherical mirror may be approximated as a point located on the principal axis of the mirror halfway between the surface of the mirror and the center of the mirror’s radius of curvature.

13.2.A.5
A real image is formed by a mirror when light rays emanating from a common point are reflected and then intersect at a common point.

13.2.A.6
A virtual image is formed by a mirror when reflected light rays diverge such that they appear to have originated from a common point.

continued on next page
13.2.A.7
The location of an image depends on the focal length of the mirror and the distance between the object and the surface of the mirror.

Relevant equation:
\[ \frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f} \]

i. The locations of a mirror’s focal point, an object near the mirror, and the image of the object formed by the mirror follow sign conventions that are used to determine those locations relative to the mirror itself.

ii. The distance between the image formed and a plane mirror is equal to the distance between the object and the plane mirror.

13.2.A.8
The magnification of an image formed by a mirror is the ratio of the size of the image produced to the size of the object itself and depends on the locations of the object and image relative to the mirror.

Relevant equation:
\[ |M| = \frac{h_i}{h_o} = \frac{s_i}{s_o} \]

13.2.A.9
Ray diagrams can be used to determine the location, type, size, and orientation of images formed by mirrors.

i. The three principal rays are typically used to find the images formed by mirrors. The principal rays are 1) the ray parallel to the principal axis, 2) the ray that reflects at the center of the mirror where the principal axis intersects the mirror, and 3) the ray that passes through the focal point of the mirror.

ii. Images formed by a mirror can be upright or inverted, virtual or real, and reduced, enlarged, or the same size as the object.
TOPIC 13.3
Refraction

Required Course Content

LEARNING OBJECTIVE
13.3.A
Describe the refraction of light between two media.

ESSENTIAL KNOWLEDGE
13.3.A.1
Refraction is the change in direction of a light ray as the ray passes from one medium into another.

13.3.A.2
Refraction is a result of the speed of light changing when light enters a new medium.

13.3.A.3
The index of refraction of a given medium is inversely proportional to the speed of light in the medium.

Relevant equation:
\[ n = \frac{c}{v} \]

13.3.A.4
Snell’s law relates the angles of incidence and refraction of a light ray passing from one medium into another to the indices of refraction of the two media.

Relevant equation:
\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

i. When a light ray travels from a medium with a higher index of refraction into a medium with a lower index of refraction, the ray refracts away from the normal.

ii. When a light ray travels from a medium with a lower index of refraction into a medium with a higher index of refraction, the ray refracts toward the normal.

continued on next page
iii. When a light ray is incident along the normal to a surface, the transmitted ray is not refracted.

13.3.A.5
Total internal reflection may occur when light passes from one medium into another medium with a lower index of refraction.

i. Total internal reflection of light occurs beyond a critical angle of incidence.

Derived equation:

\[ \sin \theta_{\text{critical}} = \frac{n_2}{n_1} \]

ii. For incident rays at the critical angle, the ray refracts at 90 degrees and travels along the surface of the material.

iii. For incident rays beyond the critical angle, all light is reflected (no light is transmitted into the other medium).
TOPIC 13.4
Images Formed by Lenses

Required Course Content

LEARNING OBJECTIVE

13.4.A
Describe the image formed by a lens.

ESSENTIAL KNOWLEDGE

13.4.A.1
Incident light rays parallel to the principal axis of a thin convex (converging) lens will be refracted and converge toward a common location on the transmitted side of the lens, called the focal point.

13.4.A.2
Incident light rays parallel to the principal axis of a thin concave (diverging) lens will be refracted and diverge as if they originated from a focal point on the incident side of the lens.

13.4.A.3
A real image is formed by a lens when light rays originating from a common point are refracted such that they intersect at another common point.

13.4.A.4
A virtual image is formed by a lens when refracted light rays diverge such that they appear to have originated from a common point.

13.4.A.5
For a thin lens, the location of an image depends on the focal length of the lens and the distance between the object and the midline of the lens, as given by the thin-lens equation:

\[ \frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f} \]

continued on next page
LEARNING OBJECTIVE

13.4.A
Describe the image formed by a lens.

ESSENTIAL KNOWLEDGE

i. The locations of a lens’s focal point, an object, and the image of the object formed by the lens follow sign conventions that are used to determine those locations relative to the lens itself.

ii. Lenses have a focal point on both sides of the lens that depends on the shape of the respective side of the lens.

13.4.A.6
For a thin lens, the magnification of an image is the ratio of the size of the image produced to the size of the object itself and depends on the locations of the object and image relative to the lens.

Relevant equation:

\[ |M| = \left| \frac{h_i}{h_o} \right| = \left| \frac{s_i}{s_o} \right| \]

13.4.A.7
Ray diagrams can be used to determine the location, type, size, and orientation of images formed by lenses.

i. The three principal rays are typically used to find the images formed by lenses. The principal rays are 1) the ray parallel to the principal axis, 2) the ray that passes through the center of the lens where the principal axis intersects the lens, and 3) the ray that passes through the focal point of the lens.

ii. Images formed by a lens can be upright or inverted, virtual or real, and reduced, enlarged, or the same size as the object.
UNIT 14

Waves, Sound, and Physical Optics

10–14% AP EXAM WEIGHTING

~14–23 CLASS PERIODS
TOPIC 14.1
Properties of Wave Pulses and Waves

Required Course Content

LEARNING OBJECTIVE

14.1.A
Describe the physical properties of waves and wave pulses.

ESSENTIAL KNOWLEDGE

14.1.A.1
Waves transfer energy between two locations without transferring matter between those locations.
   i. A wave pulse is a single disturbance that transfers energy without transferring matter between two locations.
   ii. A wave is modeled as a continuous, periodic disturbance with well-defined wavelength and frequency.

14.1.A.2
Mechanical waves or wave pulses require a medium in which to propagate. Electromagnetic waves or wave pulses do not require a medium in which to propagate.

14.1.A.3
The speed at which a wave or wave pulse propagates through a medium depends on the type of wave and the properties of the medium.
   i. The speed of all electromagnetic waves in a vacuum is a universal physical constant, $c = 3.00 \times 10^8$ m/s.
   ii. The speed at which a wave pulse or wave propagates along a string is dependent upon the tension in the string, $F_T$, and the mass per length of the string. Relevant equation:
      
      $v_{\text{string}} = \sqrt{\frac{F_T}{m/\ell}}$

   iii. In a given medium, the speed of sound waves increases with the temperature of the medium.

continued on next page
LEARNING OBJECTIVE

14.1.A
Describe the physical properties of waves and wave pulses.

ESSENTIAL KNOWLEDGE

14.1.A.4
In a transverse wave, the direction of the disturbance is perpendicular to the direction of propagation of the wave.

14.1.A.5
In a longitudinal wave, the direction of the disturbance is parallel to the direction of propagation of the wave.
   i. Sound waves are modeled as mechanical longitudinal waves.
   ii. The regions of high and low pressure in a sound wave are called compressions and rarefactions, respectively.

14.1.A.6
Amplitude is the maximum displacement of a wave from its equilibrium position.
   i. The amplitude of a longitudinal pressure wave may be determined by the maximum increase or decrease in pressure from equilibrium pressure.
   ii. The amplitude of a sound wave is related to the loudness of that sound wave.
   iii. The energy carried by a wave increases with increasing amplitude.
TOPIC 14.2
Periodic Waves

Required Course Content

LEARNING OBJECTIVE

14.2.A
Describe the physical properties of a periodic wave.

ESSENTIAL KNOWLEDGE

14.2.A.1
Periodic waves have regular repetitions that can be described using period and frequency.

i. The period is the time for one complete oscillation of the wave.

ii. The frequency is the rate at which the wave repeats.

Relevant equation:

\[ T = \frac{1}{f} \]

iii. The amplitude of a wave is independent of the period and the frequency of that wave.

iv. The energy of a wave increases with increasing frequency.

v. The frequency of a sound wave is related to its pitch.

vi. Wavelength is the distance between successive corresponding positions (such as peaks or troughs) on a wave.

14.2.A.2
A sinusoidal wave can be described by equations for the displacement from equilibrium at a specific location as a function of time. A wave can also be described by an equation for the displacement from equilibrium at a specific time as a function of position.

Example equations:

\[ x(t) = A \cos(\omega t) = A \cos(2\pi ft) \]

\[ y(x) = A \cos\left(2\pi \frac{x}{\lambda}\right) \]

continued on next page
ESSENTIAL KNOWLEDGE

14.2.A.3
For a periodic wave, the wavelength is proportional to the wave's speed and inversely proportional to the wave's frequency.

Relevant equation:

\[ \lambda = \frac{v}{f} \]
**TOPIC 14.3**

**Boundary Behavior of Waves and Polarization**

**Required Course Content**

**LEARNING OBJECTIVE**

14.3.A

Describe the interaction between a wave and a boundary.

**ESSENTIAL KNOWLEDGE**

14.3.A.1

A wave that travels from one medium to another can be transmitted or reflected, depending on the properties of the boundary separating the two media.

i. A wave traveling from one medium to another (for example, a wave traveling between low-mass and high-mass strings), will result in reflected and transmitted waves.

ii. A reflected wave is inverted if the transmitted wave travels into a medium in which the speed of the wave decreases.

iii. A reflected wave is not inverted if the transmitted wave travels into a medium in which the speed of the wave increases.

iv. The frequency of a wave does not change when it travels from one medium to another.

14.3.A.2

Transverse waves that are reflected from a surface, refracted through a medium, or pass through specific openings may be polarized.

i. Transverse waves can be polarized and oscillate in a single plane.

ii. Longitudinal waves cannot be polarized.

*continued on next page*
LEARNING OBJECTIVE
14.3.A
Describe the interaction between a wave and a boundary.

ESSENTIAL KNOWLEDGE
14.3.A.3
Polarization of a wave may result in a reduction of the wave's intensity.

i. Intensity is a measure of the amount of power transferred per unit area.

ii. The intensity of a wave is the average power per unit area over one period of the wave.
TOPIC 14.4
Electromagnetic Waves

Required Course Content

LEARNING OBJECTIVE

14.4.A Describe the properties of an electromagnetic wave.

ESSENTIAL KNOWLEDGE

14.4.A.1 Electromagnetic waves consist of oscillating electric and magnetic fields that are mutually perpendicular.
   i. Electromagnetic waves are transverse waves because the oscillations of the electric and magnetic fields are perpendicular to the direction of propagation.
   ii. Electromagnetic waves are commonly assumed to be plane waves, which are characterized by planar wave fronts.

14.4.A.2 Electromagnetic waves do not need a medium through which to propagate.

14.4.A.3 Categories of electromagnetic waves are characterized by their wavelengths.
   i. Categories of electromagnetic waves include (in order of decreasing wavelength, spanning a range from kilometers to picometers) radio waves, microwaves, infrared, visible, ultraviolet, x-rays, and gamma rays.
   ii. Visible electromagnetic waves are further broken into categories of color, including (in order of decreasing wavelength) red, orange, yellow, green, blue, and violet.

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LEARNING OBJECTIVE
14.4.A
Describe the properties of an electromagnetic wave.

ESSENTIAL KNOWLEDGE
iii. Visible electromagnetic waves are also called light. Sometimes, electromagnetic waves of all wavelengths are collectively referred to as light or electromagnetic radiation.

BOUNDARY STATEMENT:
AP Physics 2 expects students to know the ordering of the electromagnetic spectrum (including visible light). However, students will not be expected to define exact wavelength ranges within the electromagnetic spectrum.
TOPIC 14.5  
The Doppler Effect

Required Course Content

LEARNING OBJECTIVE  
14.5.A  
Describe the properties of a wave based on the relative motion between the source of the wave and the observer of the wave.

ESSENTIAL KNOWLEDGE  
14.5.A.1  
The Doppler effect describes the relationship between the rest frequency of a wave source, the observed frequency of the source, and the relative velocity of the source and the observer.

14.5.A.2  
A greater relative velocity results in a greater measured difference between the observed and rest frequencies.
   i. For a wave source moving at the same velocity as the observer, the observed frequency is equal to the rest frequency.
   ii. For a wave source moving toward an observer, the observed frequency is greater than the rest frequency.
   iii. For a wave source moving away from an observer, the observed frequency is less than the rest frequency.

BOUNDARY STATEMENT:  
Only qualitative treatments of the Doppler effect are required for AP Physics 2.
LEARNING OBJECTIVE

14.6.A Describe the net disturbance that occurs when two or more wave pulses or waves overlap.

ESSENTIAL KNOWLEDGE

14.6.A.1 Wave interference is the interaction of two or more wave pulses or waves.

14.6.A.2 When two or more wave pulses or waves interact with each other, they travel through each other and overlap rather than bouncing off each other.

14.6.A.3 When two or more wave pulses or waves overlap, the resulting displacement can be determined by adding the individual displacements. This is called superposition.

14.6.A.4 Wave interference may be constructive or destructive.

i. When the displacements of the superposed wave pulses or waves are in the same direction, the interaction is called constructive interference.

ii. When the displacements of the superposed wave pulses or waves are in opposite directions, the interaction is called destructive interference.

iii. Two or more traveling wave pulses or waves can interact in such a way as to produce amplitude variations in the resultant wave pulse or wave.

14.6.A.5 Visual representations of wave pulses or waves are useful in determining the result of two interacting wave pulses or waves.

continued on next page
# ESSENTIAL KNOWLEDGE

### 14.6.A.6
Beats arise from the addition of two waves of slightly different frequency.

1. Waves with different frequencies are sometimes in phase and sometimes out of phase at locations along the waves, causing periodic amplitude changes in the resultant wave.
2. The beat frequency is the difference in the frequencies of the two waves.
   \[ f_{\text{beat}} = | f_1 - f_2 | \]
3. Tuning forks are devices that are commonly used to demonstrate beat frequencies.

### 14.6.B.1
Standing waves can result from interference between two waves that are confined to a region and traveling in opposite directions.

1. Standing waves have nodes and antinodes. A node is a point on the standing wave where the amplitude is always zero. An antinode is a point on the standing wave where the amplitude is always at maximum.
2. The possible wavelengths of a standing wave are determined by the size and boundary conditions of the region to which it is confined.
3. Common regions where standing waves can form include pipes with open or closed ends, as well as strings with fixed or loose ends.

### 14.6.B.2
For a standing wave, the longest possible wavelength is called the fundamental or first harmonic. The second-longest wavelength is called the second harmonic, and so on.

### 14.6.B.3
Visual representations of standing waves are useful in determining the relationships between length of the region, wavelength, frequency, wave speed, and harmonic.
TOPIC 14.7
Diffraction

Required Course Content

LEARNING OBJECTIVE

14.7.A
Describe the behavior of a wave and the diffraction pattern resulting from a wave passing through a single opening.

ESSENTIAL KNOWLEDGE

14.7.A.1
Diffraction is the spreading of a wave around the edges of an obstacle or through an opening.

14.7.A.2
Diffraction is most pronounced when the size of the opening is comparable to the wavelength of the wave.

14.7.A.3
Diffraction of multiple wavefronts through a single opening leads to observable interference patterns.

14.7.A.4
For small angles, the distance $y$ from the middle of the central bright fringe of a diffraction pattern to the $m^{th}$ point of minimum brightness produced at a distance of $D$ from a single opening with aperture size $a$ by a wave of wavelength $\lambda$ passing through the opening can be approximated by

$$y_{\text{min}} = \frac{m\lambda D}{a}.$$

14.7.A.5
The diffraction pattern produced by a wave passing through an opening depends on the shape of the opening.

14.7.A.6
Visual representations of single-slit diffraction patterns are useful in determining the physical properties of the slit and the interacting waves.
TOPIC 14.8
Double-Slit
Interference and
Diffraction Gratings

Required Course Content

LEARNING OBJECTIVE

14.8.A
Describe the behavior of a wave and the diffraction pattern resulting from the wave passing through multiple openings.

ESSENTIAL KNOWLEDGE

14.8.A.1
The pattern resulting from a wave interacting with a double slit is caused by a combination of wave diffraction and wave interference.

i. When only considering wave interference, a double slit creates a pattern of uniformly spaced maxima.

ii. The local maxima of an interference pattern can be calculated with the following equation, where $y$ is the distance between the $m^{th}$ bright line and the central maximum (as viewed on a screen at a distance, $D$, from the slits), and $d$ is the distance between the two slits.

Relevant equation:

$$y_{\text{max}} = \frac{m\lambda D}{d}$$

iii. When considering wave interference and wave diffraction, a double slit creates a diffraction pattern of maxima and minima superimposed within the envelope created by single-slit diffraction.

14.8.A.2
Interference patterns produced by light interacting with a double slit indicate that light has wave properties. The source of this discovery was Young’s double-slit experiment.

14.8.A.3
Visual representations of double-slit diffraction patterns are useful in determining the physical properties of the slits and the interacting waves.

continued on next page
LEARNING OBJECTIVE

14.8.A
Describe the behavior of a wave and the diffraction pattern resulting from the wave passing through multiple openings.

ESSENTIAL KNOWLEDGE

14.8.A.4
A diffraction grating is a collection of evenly spaced parallel slits or openings that produce an interference pattern that is the combination of numerous diffraction patterns superimposed on each other.

14.8.A.5
When white light is incident on a diffraction grating, the center maximum is white and the higher-order maxima disperse white light into a rainbow of colors, with the longest-wavelength light (red) appearing farthest from the central maximum.
TOPIC 14.9
Thin-Film Interference

Required Course Content

**LEARNING OBJECTIVE**

14.9.A
Describe the behavior of light that interacts with a thin film.

**ESSENTIAL KNOWLEDGE**

14.9.A.1
When light travels from one medium to another, some of the light is transmitted, some is reflected, and some is absorbed.

14.9.A.2
The phase change of a reflected ray depends on the relative indices of refraction of the materials with which the ray interacts.
   i. A phase change of 180 degrees occurs when a light ray is reflected from a medium with a greater index of refraction than the medium through which the ray is traveling.
   ii. No phase change occurs when a light ray is reflected from a medium with a lower index of refraction than the medium through which the ray is traveling.

14.9.A.3
The phase of a wave does not change when it is refracted as it passes from one medium into another.

14.9.A.4
Thin-film interference occurs when light interacts with a medium whose thickness is comparable to the light’s wavelength.
   i. The interactions between the initial reflected light and the light exiting the thin film after being reflected from the second interface exhibit wave interference behavior, resulting in a single wave that is the sum of the two interacting waves.

continued on next page
**LEARNING OBJECTIVE**

14.9.A
Describe the behavior of light that interacts with a thin film.

**ESSENTIAL KNOWLEDGE**

ii. The amount of constructive or destructive interference between the two reflected waves depends on the relationship between the thickness of the film, the wavelength of light, any phase shifts, and the angle at which the incident light strikes the film.

14.9.A.5
Practical examples of thin-film interference include the color variations seen in soap bubbles and oil films, as well as antireflection coatings.

i. The spectrum of colors observed in oil films and soap bubbles arises from differences in the thickness of the film.

ii. Antireflection coatings eliminate reflected light by applying the relationships between indices of refraction, phase shift, and wave interference to create destructive interference of the light reflected from the two surfaces of the coating.

iii. The simplest antireflection coating has a thickness equal to one-quarter of the wavelength of the light in the coating, and the index of refraction of the coating is greater than that of air and less than that of the surface upon which the coating is applied. This assumes incident light is normal to the surface.

**BOUNDARY STATEMENT:**

Quantitative analysis of thin-film interference is limited to waves that are normal to the incident surface.
UNIT 15
Modern Physics

10–14% AP EXAM WEIGHTING

~14–22 CLASS PERIODS
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TOPIC 15.1
Quantum Theory and Wave-Particle Duality

Required Course Content

LEARNING OBJECTIVE
15.1.A
Describe the properties and behavior of an object that exhibits both particle-like and wave-like behavior.

ESSENTIAL KNOWLEDGE
15.1.A.1
Quantum theory was developed to explain observations of matter and energy that could not be explained using classical mechanics. These phenomena include, but are not limited to, atomic spectra, blackbody radiation, and the photoelectric effect.
   i. Quantum theory is necessary to describe the properties of matter at atomic and subatomic scales.
   ii. In quantum theory, fundamental particles can exhibit both particle-like and wave-like behavior.

15.1.A.2
Light can be modeled both as a wave and as discrete particles, called photons.
   i. A photon is a massless, electrically neutral particle with energy proportional to the photon’s frequency.
   Relevant equations:
   \[ E = hf \]
   \[ \lambda = \frac{c}{f} \]
   ii. Photons travel in straight lines unless they interact with matter.

15.1.A.3
The speed of a photon depends on the medium through which the photon travels.
   i. The speed of all photons in free space is equal to the classical speed of light, \( c = 3.00 \times 10^8 \) m/s.

continued on next page
15.1.A
Describe the properties and behavior of an object that exhibits both particle-like and wave-like behavior.

ESSENTIAL KNOWLEDGE

15.1.A.4
Particles can demonstrate wave properties, as shown by variations of Young’s double-slit experiment.

i. A wave model of matter is quantified by the de Broglie wavelength, which increases as the momentum of a particle decreases. Relevant equation:

\[ \lambda = \frac{h}{p} \]

ii. Quantum theory is necessary to describe systems where the de Broglie wavelength is comparable to the size of the system.

15.1.A.5
Values of energy and momentum have discrete, or quantized, values for bound systems described by quantum theory.
TOPIC 15.2
The Bohr Model of Atomic Structure

Required Course Content

LEARNING OBJECTIVE

15.2.A
Describe the properties of an atom.

ESSENTIAL KNOWLEDGE

15.2.A.1
Atoms have internal structure.

i. Atoms consist of a small, positively charged nucleus surrounded by one or more negatively-charged electrons.

ii. The nucleus of an atom is made up of protons and neutrons.

iii. The number of neutrons and protons in an atom can be represented using nuclear notation.

iv. An ion is an atom with a nonzero net electric charge.

15.2.A.2
Each atomic element has a unique number of protons.

i. The number and arrangements of electrons affects how atoms interact.

ii. The total number of neutrons and protons identifies the isotope of an element.

iii. The mass of an atom is dominated by the total mass of the protons and neutrons in its nucleus.

15.2.A.3
The Bohr model of the atom is based on classical physics and was the historical representation of the atom that led to the description of the hydrogen atom in terms of discrete energy states.

continued on next page
LEARNING OBJECTIVE

15.2.A
Describe the properties of an atom.

ESSENTIAL KNOWLEDGE

i. In the Bohr model of the atom, electrons are modeled as moving around the nucleus in circular orbits determined by the electron’s charge and mass, as well as the electric force between the electron and the nucleus.

Relevant equations:

\[ F_e = k \frac{q_1 q_2}{r^2} \]
\[ F_{\text{net}} = m \frac{v^2}{r} \]

ii. The standing wave model of electrons accounts for the existence of specific allowed energy states of an electron in an atom, because the electron orbit’s circumference must be an integer multiple of the electron’s de Broglie wavelength.

BOUNDARY STATEMENT:
The analysis and description of electron structure is limited to energy levels and will not include such advanced descriptions as orbitals, orbital shapes, or probability functions.
TOPIC 15.3
Emission and Absorption Spectra

Required Course Content

LEARNING OBJECTIVE

**15.3.A**
Describe the emission or absorption of photons by atoms.

ESSENTIAL KNOWLEDGE

**15.3.A.1**
Energy transfer occurs when photons are absorbed or emitted by atoms.

**15.3.A.2**
Energy can only be absorbed or emitted by an atom if the amount of energy being absorbed or emitted corresponds to the energy difference between two atomic energy states.

i. An atom in a given energy state may absorb a photon of the appropriate energy and transition to a higher energy state.

ii. An atom in an excited energy state may emit a photon of the appropriate energy to spontaneously move to a lower energy state.

**15.3.A.3**
Transitions between two energy states of an atom correspond to the absorption or emission of a photon of a single frequency and, therefore, a single wavelength.

**15.3.A.4**
Atoms of each element have a unique set of allowed energy levels and thereby a unique set of absorption and emission frequencies. The unique set of frequencies determines the element’s spectrum.

i. An emission spectrum can be used to determine the elements in a source of light.

ii. An absorption spectrum can be used to determine the elements composing a substance by observing what light the substance has absorbed.

continued on next page
LEARNING OBJECTIVE

15.3.A
Describe the emission or absorption of photons by atoms.

ESSENTIAL KNOWLEDGE

15.3.A.5
Binding energy is the energy required to remove an electron from an atom, causing the atom to become ionized. An atom in the lowest energy level (ground state) will require the greatest amount of energy to remove the electron from the atom.
LEARNING OBJECTIVE

15.4.A
Describe the electromagnetic radiation emitted by an object due to its temperature.

ESSENTIAL KNOWLEDGE

15.4.A.1
Matter will spontaneously convert some of its internal thermal energy into electromagnetic energy.

15.4.A.2
A blackbody is an idealized model of matter that absorbs all radiation that falls on the body. If the body is in equilibrium at a constant temperature, then it must in turn emit energy.

15.4.A.3
A blackbody will emit a continuous spectrum that only depends on the body’s temperature. The radiation emitted by a blackbody is often modeled by plotting intensity per unit wavelength as a function of wavelength.

i. The distribution of the intensity of a blackbody’s spectrum as a function of temperature cannot be modeled using only classical physics concepts. A blackbody’s spectrum is described by Planck’s law, which assumes that the energy of light is quantized.

ii. The peak wavelength emitted by a blackbody (the wavelength at which the blackbody emits the greatest amount of radiation per unit wavelength) decreases with increasing temperature, as described by Wien’s law.

Relevant equation:

\[ \lambda_{\text{max}} = \frac{b}{T} \]
LEARNING OBJECTIVE
15.4.A
Describe the electromagnetic radiation emitted by an object due to its temperature.

ESSENTIAL KNOWLEDGE

iii. The rate at which energy is emitted (power) by a blackbody is proportional to the surface area of the body and to the temperature of the body raised to the fourth power, as described by the Stefan-Boltzmann law.

Relevant equation:
\[ P = A\sigma T^4 \]
LEARNING OBJECTIVE

15.5.A
Describe an interaction between photons and matter using the photoelectric effect.

ESSENTIAL KNOWLEDGE

15.5.A.1
The photoelectric effect is the emission of electrons when electromagnetic radiation is incident upon a photoactive material.

15.5.A.2
The emission of electrons via the photoelectric effect requires a minimum frequency of incident light, called the threshold frequency.
   i. Light that is incident on a material and is at the threshold frequency or higher will induce electron emission, regardless of the number of photons that strike the material.
   ii. The energy of the emitted electrons is not dependent on the number of photons that are incident upon the material, which provides evidence that light is a collection of discrete, quantized energy packets called photons.

15.5.A.3
The maximum kinetic energy of an emitted electron is related to the frequency of the incident light and the work function of the material, \( \phi \).
   i. The work function of a material is the minimum energy required to emit an electron from atoms in the material.
   ii. The maximum kinetic energy of an emitted electron is given by the equation
   \[
   K_{\text{max}} = hf - \phi.
   \]

continued on next page
Modern Physics

UNIT 15

LEARNING OBJECTIVE

15.5.A
Describe an interaction between photons and matter using the photoelectric effect.

ESSENTIAL KNOWLEDGE

iii. In a typical experimental setup to demonstrate the photoelectric effect and determine the work function of a metal, two metal plates are placed in a vacuum chamber and connected to a variable source of potential difference. One of the plates is illuminated by monochromatic light that causes electrons to be ejected and the potential difference between the plates is adjusted until no current is measured in the circuit.

BOUNDARY STATEMENTS:
Where applicable, work functions for materials will be provided on the exam; students are not expected to know values of work functions or variables of a material that influence the magnitude of its work function.
TOPIC 15.6
Compton Scattering

Required Course Content

LEARNING OBJECTIVE

15.6.A
Describe the interaction between photons and matter using Compton scattering.

ESSENTIAL KNOWLEDGE

15.6.A.1
In Compton scattering, a photon interacts with a free electron. The Compton effect is when a photon that emerges from the interaction has a lower energy and longer wavelength than the incoming photon. The magnitude of the change is related to the direction of the photon after the collision.

15.6.A.2
Compton scattering provides evidence that light is a collection of discrete, quantized energy packets called photons.

i. Compton scattering can be explained by treating a photon as a particle and applying conservation of energy and conservation of momentum to the collision between the photon and electron.

ii. The transfer of a photon's energy to an electron results in the energy, momentum, frequency, and wavelength of the photon changing.

Relevant equations:

\[ E = hf \]

\[ \lambda = \frac{h}{P} \]

continued on next page
LEARNING OBJECTIVE

15.6.A
Describe the interaction between photons and matter using the Compton scattering.

ESSENTIAL KNOWLEDGE

15.6.A.3
The change in wavelength experienced by a photon after colliding with an electron is related to how much the photon's direction changes.

Relevant equation:

$$\Delta \lambda = \frac{h}{m_c} (1 - \cos \theta)$$

BOUNDARY STATEMENT:

AP Physics 2 includes full quantitative and qualitative treatments of conservation of momentum in two dimensions.
LEARNING OBJECTIVE

15.7.A
Describe the physical properties that constrain the behavior of interacting nuclei, subatomic particles, and nucleons.

ESSENTIAL KNOWLEDGE

15.7.A.1
The strong force is exerted at nuclear scales and dominates the interactions of nucleons (protons or neutrons).

15.7.A.2
Possible nuclear reactions are constrained by the law of conservation of nucleon number.

15.7.A.3
The behavior of the constituent particles of a nuclear reaction is constrained by laws of conservation of energy, energy-mass equivalence, and conservation of momentum.

15.7.A.4
For all nuclear reactions, mass and energy may be exchanged due to mass-energy equivalence. Relevant equation: \[ E = mc^2 \]

15.7.A.5
Energy may be released in nuclear processes in the form of kinetic energy of the products or as photons.

15.7.A.6
Nuclear fusion is the process by which two or more smaller nuclei combine to form a larger nucleus, as well as subatomic particles.

15.7.A.7
Nuclear fission is the process by which the nucleus of an atom splits into two or more smaller nuclei, as well as subatomic particles.

15.7.A.8
Nuclear fission may occur spontaneously or may require an energy input, depending on the binding energy of the nucleus.
LEARNING OBJECTIVE

15.7.B Describe the radioactive decay of a given sample of material consisting of a finite number of nuclei.

ESSENTIAL KNOWLEDGE

15.7.B.1 Radioactive decay is the spontaneous fission of an atomic nucleus.
   i. The time at which an individual nucleus undergoes radioactive decay is indeterminable, but decay rates can be described using probability.
   ii. The half-life, $t_{1/2}$, of a radioactive material is the time it takes for half of the initial number of radioactive nuclei to have spontaneously decayed.
   iii. The decay constant $\lambda$ can be related to the half-life of a radioactive material with the equation
   $$\lambda = \frac{\ln 2}{t_{1/2}}$$

15.7.B.2 A material's decay constant may be used to predict the number of nuclei remaining in a sample after a period of time, or the age of a material if the initial amount of material is known.

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

   Derived equation:
   $$\ln \left( \frac{N}{N_0} \right) = -\lambda t$$

15.7.B.3 Different unstable elements and isotopes may have vastly different half-lives, ranging from fractions of a second to billions of years.
TOPIC 15.8
Types of Radioactive Decay

Required Course Content

LEARNING OBJECTIVE

15.8.A
Describe the processes by which individual nuclei decay.

ESSENTIAL KNOWLEDGE

15.8.A.1
Some processes by which nuclei decay emit subatomic particles with unique properties.

i. An alpha particle, or helium nucleus, consists of two neutrons and two protons and is symbolized by \( {\alpha} \) or \( \text{He}^{+}\).

ii. Neutrinos and antineutrinos are subatomic particles that have no electrical charge, have negligible mass, and are symbolized by \( \nu \) and \( \bar{\nu} \), respectively.

iii. Neutrinos and antineutrinos only interact with matter via the weak force and the gravitational force, which results in very little interaction with normal matter.

iv. Positrons, or antielectrons, are subatomic particles that have an electric charge opposite that of an electron, have the same mass as an electron, and are symbolized by \( e^+ \) or \( \beta^+ \).

15.8.A.2
Nuclei can undergo radioactive decay via alpha decay, beta-minus decay (\( \beta^- \)), beta-plus decay (\( \beta^+ \)), and gamma decay (\( \gamma \)).

i. In all nuclear decays, nucleon number (the number of neutrons and protons), lepton number (the number of electrons and neutrinos), and charge are conserved.

ii. Alpha decay occurs when a nucleus ejects an alpha particle.

iii. Beta-minus decay occurs when a neutron changes to a proton by emitting an electron and antineutrino.
**LEARNING OBJECTIVE**

15.8.A
Describe the processes by which individual nuclei decay

**ESSENTIAL KNOWLEDGE**

iv. Beta-plus decay occurs when a proton changes to a neutron by emitting a positron and neutrino.

v. Gamma decay occurs after a nucleus has undergone alpha or beta decay and the excited nucleus decays to a lower energy state by emitting a photon.

15.8.A.3
The type of decay exhibited by a given nucleus is determined by the isotope of the element.

**BOUNDARY STATEMENT:**

AP Physics 2 does not expect students to memorize the processes by which specific isotopes decay or the half-lives of specific isotopes. Neutron emission and electron capture are not included in the AP Physics 2 curriculum framework. Additionally, types of neutrinos, the characteristics that distinguish neutrinos and antineutrinos, and an explanation or application of the weak force are not within the scope of this course.
Exam Information
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The AP Physics 2 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>Exam Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unit 9</strong>: Thermodynamics</td>
<td>16–18%</td>
</tr>
<tr>
<td><strong>Unit 10</strong>: Electric Force, Field, and Potential</td>
<td>16–18%</td>
</tr>
<tr>
<td><strong>Unit 11</strong>: Electric Circuits</td>
<td>16–18%</td>
</tr>
<tr>
<td><strong>Unit 12</strong>: Magnetism and Electromagnetism</td>
<td>14–16%</td>
</tr>
<tr>
<td><strong>Unit 13</strong>: Geometric Optics</td>
<td>10–14%</td>
</tr>
<tr>
<td><strong>Unit 14</strong>: Waves, Sound, and Physical Optics</td>
<td>10–14%</td>
</tr>
<tr>
<td><strong>Unit 15</strong>: Modern Physics</td>
<td>10–14%</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></td>
<td></td>
</tr>
<tr>
<td>Create diagrams, tables, charts, or schematics to represent physical situations.</td>
<td>N/A</td>
<td>25–30%</td>
</tr>
<tr>
<td>1.B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Create quantitative graphs with appropriate scales, and units, including plotting data.</td>
<td>N/A</td>
<td>25–30%</td>
</tr>
<tr>
<td>1.C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.</td>
<td>N/A</td>
<td>25–30%</td>
</tr>
<tr>
<td>2.A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.</td>
<td>50–70%</td>
<td>30–35%</td>
</tr>
<tr>
<td>2.B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.</td>
<td>50–70%</td>
<td>30–35%</td>
</tr>
<tr>
<td>2.C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.</td>
<td>50–70%</td>
<td>30–35%</td>
</tr>
<tr>
<td>2.D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predict new values or factors of change of physical quantities using functional dependence between variables.</td>
<td>50–70%</td>
<td>30–35%</td>
</tr>
</tbody>
</table>

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### Science Practice

<table>
<thead>
<tr>
<th>Science Practice</th>
<th>Approximate MCQ Exam Weighting</th>
<th>Approximate FR Exam Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Create experimental procedures that are appropriate for a given scientific question.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.B</td>
<td>30–50%</td>
<td>35–45%</td>
</tr>
<tr>
<td>Apply an appropriate law, definition, theoretical relationship, or model to make a claim.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Free-Response Questions

The free-response section of the AP Physics 2 Exam consists of four question types listed below. Each question type appears on the exam.

**Mathematical Routines (MR)**


The Mathematical Routines (MR) 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).

For AP Physics 1 and AP Physics 2, the MR question will ask students to make a claim or prediction about the scenario and use appropriate physics concepts and principles to support and justify that claim. The justification is expected to be a logical and sequential application of physics concepts that demonstrates a student’s ability to connect multiple concepts to each other.

**Translating Between Representations (TBR)**


The Translating Between Representations (TBR) 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)

Science Practices: 1B 2B 2D 3A 3B 3C

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)

Science Practices: 1A 2D 3B 3C

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.
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