CollegeBoard AP

PHYSICS

PHYSICS C: MECHANICS
PHYSICS C: ELECTRICITY AND MAGNETISM

Course Description

Effective Fall 2014

AP Course Descriptions are updated regularly. Please visit AP Central® (apcentral.collegeboard.org) to determine whether a more recent Course Description PDF is available.

The College Board

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AP Equity and Access Policy

The College Board 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. Schools should make every effort to ensure their AP classes reflect the diversity of their student population. The College Board also believes that all students should have access to academically challenging course work 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.

AP Course Descriptions

AP course descriptions are updated regularly. Please visit AP Central® (apcentral.collegeboard.org) to determine whether a more recent course description PDF is available.

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About AP®

The College Board's Advanced Placement Program® (AP®) enables students to pursue college-level studies while still in high school. Through more than 30 courses, each culminating in a rigorous exam, AP provides willing and academically prepared students with the opportunity to earn college credit, advanced placement, or both. Taking AP courses also demonstrates to college admission officers that students have sought out the most rigorous course work available to them.

Each AP course is modeled upon a comparable college course, and college and university faculty play a vital role in ensuring that AP courses align with college-level standards. Talented and dedicated AP teachers help AP students in classrooms around the world develop and apply the content knowledge and skills they will need later in college.

Each AP course concludes with a college-level assessment developed and scored by college and university faculty as well as experienced AP teachers. AP Exams are an essential part of the AP experience, enabling students to demonstrate their mastery of college-level course work. Most four-year colleges and universities in the United States and universities in more than 60 countries recognize AP in the admissions process and grant students credit, placement, or both on the basis of successful AP Exam scores. Visit www.collegeboard.org/ap/creditpolicy to view AP credit and placement policies at more than 1,000 colleges and universities.

Performing well on an AP Exam means more than just the successful completion of a course; it is a gateway to success in college. Research consistently shows that students who receive a score of 3 or higher on AP Exams typically experience greater academic success in college and have higher graduation rates than their non-AP peers[1]. Additional AP studies are available at www.collegeboard.org/research.

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[1]See the following research studies for more details:

Linda Hargrove, Donn Godin, and Barbara Dodd, *College Outcomes Comparisons by AP and Non-AP High School Experiences* (New York: The College Board, 2008).

Chrys Dougherty, Lynn Mellor, and Shuling Jian, *The Relationship Between Advanced Placement and College Graduation* (Austin, Texas: National Center for Educational Accountability, 2006).

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Offering AP Courses and Enrolling Students

Each AP course and exam description details the essential information required to understand the objectives and expectations of an AP course. The AP Program unequivocally supports the principle that each school implements its own curriculum that will enable students to develop the content knowledge and skills described here.

Schools wishing to offer AP courses must participate in the AP Course Audit, a process through which AP teachers' syllabi are reviewed by college faculty. The AP Course Audit was created at the request of College Board members who sought a means for the College Board 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' syllabi meet or exceed the curricular and resource expectations that college and secondary school faculty have established for college-level courses. For more information on the AP Course Audit, visit www.collegeboard.org/apcourseaudit.

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How AP Courses and Exams Are Developed

AP courses and exams are designed by committees of college faculty and expert AP teachers who ensure that each AP subject reflects and assesses college-level expectations. To find a list of each subject's current AP Development Committee members, please visit press.collegeboard.org/ap/committees. AP Development Committees define the scope and expectations of the course, articulating through a curriculum framework what students should know and be able to do upon completion of the AP course. Their work is informed by data collected from a range of colleges and universities to ensure that AP coursework reflects current scholarship and advances in the discipline.

The AP Development Committees are also responsible for drawing clear and well-articulated connections between the AP course and AP Exam — work that includes designing and approving exam specifications and exam questions. The AP Exam development process is a multiyear endeavor; all AP Exams undergo extensive review, revision, piloting, and analysis to ensure that questions are high quality and fair and that there is an appropriate spread of difficulty across the questions.

Throughout AP course and exam development, the 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 upon college entrance.

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How AP Exams Are Scored

The exam scoring process, like the course and exam development process, relies on the expertise of both AP teachers and college faculty. While multiple-choice questions are scored by machine, the free-response questions are scored by thousands of college faculty and expert AP teachers at the annual AP Reading. AP Exam 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 fills the role of Chief Reader, who, with the help of AP Readers in leadership positions, maintains the accuracy of the scoring standards. Scores on the free-response questions are weighted and combined with the results of the computer-scored multiple-choice questions, and this raw score is converted into a composite AP Exam score of 5, 4, 3, 2, or 1.

The score-setting process is both precise and labor intensive, involving numerous psychometric analyses of the results of a specific AP Exam in a specific year and of the particular group of students who took that exam. Additionally, to ensure alignment with college-level standards, part of the score-setting process involves comparing the performance of AP students with the performance of students enrolled in comparable courses in colleges throughout the United States. In general, the AP composite score points are set so that the lowest raw score needed to earn an AP Exam score of 5 is equivalent to the average score among college students earning grades of A in the college course. Similarly, AP Exam scores of 4 are equivalent to college grades of A–, B+, and B. AP Exam scores of 3 are equivalent to college grades of B–, C+, and C.

Using and Interpreting AP Scores

The extensive work done by college faculty and AP teachers in the development of the course and the exam and throughout the scoring process ensures that AP Exam scores accurately represent students' achievement in the equivalent college course. While colleges and universities are responsible for setting their own credit and placement policies, AP scores signify how qualified students are to receive college credit or placement:

AP Score	Qualification
5	Extremely well qualified
4	Well qualified
3	Qualified
2	Possibly qualified
1	No recommendation

Additional Resources

Visit apcentral.collegeboard.org for more information about the AP Program.

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AP Physics C

INTRODUCTION

What We Are About: A Message from the Development Committee

The AP Physics C Development Committee recognizes that curriculum, course content and assessment of scholastic achievement play complementary roles in shaping education at all levels. The committee believes that assessment should support and encourage the following broad instructional goals:

1. *Physics knowledge* — Basic knowledge of the discipline of physics, including phenomenology, theories and techniques, concepts and general principles
2. *Problem solving* — Ability to ask physical questions and to obtain solutions to physical questions through the use of qualitative, quantitative reasoning and experimental investigation
3. *Student attributes* — Fostering of important student attributes, including appreciation of the physical world and the discipline of physics, curiosity, creativity and reasoned skepticism
4. *Connections* — Understanding connections of physics to other disciplines and to societal issues

The AP Physics C Exams have always emphasized achievement of the first two goals. Over the years, the definitions of basic knowledge of the discipline and problem solving have evolved. The AP Physics C courses have reflected changes in college courses, consistent with our primary charge. We have increased our emphasis on physical intuition, experimental investigation and creativity. We include more open-ended questions in order to assess students' ability to explain their understanding of physical concepts. We structure questions that stress the use of mathematics to illuminate the physical situation rather than to show manipulative abilities.

The committee is dedicated to developing exams that can be graded fairly and consistently and that are free of ethnic, gender, economic or other bias. We operate under practical constraints of testing methods, allotted time and large numbers of students at widely spread geographical locations. In spite of these constraints, the committee strives to design exams that promote excellent and appropriate instruction in physics.

THE COURSES

The AP Physics C Exams are designed to test student achievement in the AP Physics C courses described in this book. These courses are intended to be representative of courses commonly offered in colleges and universities, but they do not necessarily correspond precisely to courses at any particular institution. The aim of an AP secondary school course in physics should be to develop the students' abilities to do the following:

1. Read, understand, and interpret physical information — verbal, mathematical, and graphical

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2. Describe and explain the sequence of steps in the analysis of a particular physical phenomenon or problem; that is,
   a. describe the idealized model to be used in the analysis, including simplifying assumptions where necessary;
   b. state the concepts or definitions that are applicable;
   c. specify relevant limitations on applications of these principles;
   d. carry out and describe the steps of the analysis, verbally, mathematically, or graphically; and
   e. interpret the results or conclusions, including discussion of particular cases of special interest
3. Use basic mathematical reasoning — arithmetic, algebraic, geometric, trigonometric, or calculus, where appropriate — in a physical situation or problem
4. Perform experiments and interpret the results of observations, including making an assessment of experimental uncertainties

In the AP Physics C Exams, an attempt is made through the use of multiple-choice and free-response questions to determine how well these goals have been achieved by the student either in a conventional course or through independent study. The level of the student's achievement is assigned an AP Exam score of 1 to 5, and many colleges use this score alone as the basis for placement and credit decisions.

Introductory college physics courses typically fall into one of three categories, designated as A, B, and C in the following discussion.

Category A includes courses in which major concepts of physics are covered without as much mathematical rigor as in more formal courses, such as *Category B* and *Category C*, which are described below. The emphasis in *Category A* courses is on developing a qualitative conceptual understanding of general principles and models and on the nature of scientific inquiry. Some courses may also view physics primarily from a cultural or historical perspective. *Category A* courses are generally intended for students not majoring in a science-related field. The level of mathematical sophistication usually includes some algebra and may extend to simple trigonometry, but rarely beyond. These courses vary widely in content and approach, and at present there is no AP course or exam in this category. A high school version of a *Category A* course that concentrates on conceptual development and that provides an enriching laboratory experience may be taken by students in the ninth or tenth grade and should provide the first course in physics that prepares them for a more mathematically rigorous AP Physics 1, 2, or C course.

Category B courses build on the conceptual understanding attained in a first course in physics, such as the *Category A* course described previously. These courses provide a systematic development of the main principles of physics, emphasizing problem solving and helping students develop a deep understanding of physics concepts. It is assumed that students are familiar with algebra and trigonometry, although some theoretical developments may use basic concepts of calculus. In most colleges, this is a one-year terminal course including a laboratory component and is not the usual preparation for more advanced physics and engineering courses. However, *Category B*

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courses often provide a foundation in physics for students in the life sciences, premedicine, and some applied sciences, as well as other fields not directly related to science. AP Physics 1 and 2 are intended to be equivalent to such courses.

Category C courses also build on the conceptual understanding attained in a first course in physics, such as the *Category A* course described above. These courses normally form the college sequence that serves as the foundation in physics for students majoring in the physical sciences or engineering. The sequence is parallel to or preceded by mathematics courses that include calculus. Methods of calculus are used in formulating physical principles and in applying them to physical problems. The sequence is more intensive and analytic than in *Category B* courses. Strong emphasis is placed on solving a variety of challenging problems, some requiring calculus, as well as continuing to develop a deep understanding of physics concepts. A *Category C* sequence may be a very intensive one-year course in college but often will extend over one and one-half to two years, and a laboratory component is also included. AP Physics C is intended to be equivalent to part of a *Category C* sequence and covers two major areas: mechanics, and electricity and magnetism, with equal emphasis on both.

In certain colleges and universities, other types of unusually high-level introductory courses are taken by a few selected students. Selection of students for these courses is often based on results of AP Exams, other college admission information, or a college-administered exam. The AP Exams are not designed to grant credit or exemption for such high-level courses but may facilitate admission to them.

Course Selection

It is important for those teaching and advising AP students to consider the relation of AP courses to a student's college plans. In some circumstances it is advantageous to take the AP Physics 1 and 2 courses. The student may be interested in studying physics as a basis for more advanced work in the life sciences, medicine, geology, and related areas, or as a component in a nonscience college program that has science requirements. Credit or advanced placement for the Physics 1 and 2 courses provides the student with an opportunity either to have an accelerated college program or to meet a basic science requirement; in either case the student's college program may be enriched. Access to an intensive physics sequence for physics or science majors is another opportunity that may be available.

For students planning to specialize in a physical science or in engineering, most colleges require an introductory physics sequence that includes courses equivalent to Physics C. Because a previous or concurrent course in calculus is often required of students taking Physics C, students who expect advanced placement or credit for either Physics C exam should attempt an AP course in calculus as well; otherwise, placement in the next-in-sequence physics course may be delayed or even denied. Either of the AP Calculus courses, Calculus AB or Calculus BC, should provide an acceptable basis for students preparing to major in the physical sciences or engineering, but Calculus BC is recommended. Therefore, if such students must choose between AP Physics C or AP Calculus while in high school, they should probably choose AP Calculus.

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There are four separate AP Physics Exams, Physics 1, Physics 2, Physics C: Mechanics and Physics C: Electricity and Magnetism. Each exam contains multiple-choice and free-response questions. The Physics 1 and 2 Exams are for students who have taken a Physics 1 or 2 course or who have mastered the material of this course through independent study. The Physics 1 Exam covers topics in mechanics, electricity, and waves; a single exam score is reported. The Physics 2 Exam covers topics in electricity and magnetism, fluid mechanics and thermal physics, waves and optics, and atomic and nuclear physics; a single exam score is reported. The two Physics C Exams correspond to the Physics C course sequence. One exam covers mechanics; the other covers electricity and magnetism. Students may take either or both exams, and separate scores are reported.

Further descriptions of the AP Physics C courses and their corresponding exams in terms of topics, level, mathematical rigor and typical textbooks are presented in the pages that follow. Information about organizing and conducting AP Physics courses, of interest to both beginning and experienced AP teachers, may be found on the AP Physics home pages on AP Central (apcentral.collegeboard.org). These pages include practical advice from successful AP teachers. The 2009 *AP Physics B and Physics C Released Exams* book contains the complete exams, with solutions and grading standards for the free-response sections and sample student responses, as well as statistical data on student performance. For information about ordering these publications and others, see page 59.

Instructional Approaches

It is strongly recommended that Physics C be taught as second-year physics courses. A first-year physics course aimed at developing a thorough understanding of important physical principles and that permits students to explore concepts in the laboratory provides a richer experience in the process of science and better prepares them for the more analytical approaches taken in AP courses.

However, secondary school programs for the achievement of AP course goals can take other forms as well, and the imaginative teacher can design approaches that best fit the needs of his or her students. In some schools, AP Physics C has been taught successfully as a very intensive first-year course; but in this case there may not be enough time to cover the material in sufficient depth to reinforce the students' conceptual understanding or to provide adequate laboratory experiences. This approach can work for highly motivated, able students but is not generally recommended. Independent study or other first-year physics courses supplemented with extra work for individual motivated students are also possibilities that have been successfully implemented.

If AP Physics C is taught as a second-year course, it is recommended that the course meet for at least 250 minutes per week (the equivalent of a 50-minute period every day). However, if it is to be taught as a first-year course, approximately 90 minutes per day (450 minutes per week) is recommended in order to devote sufficient time to study the material to an appropriate depth and allow time for labs. In a school that uses block scheduling, each of the Physics C courses, but not both, can be taught in one semester.

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

Laboratory

Importance and Rationale

Laboratory experience must be part of the education of AP Physics C students and should be included in all AP Physics courses, just as it is in introductory college physics courses. In textbooks and problems, most attention is paid to idealized situations: friction is often assumed to be constant or absent; meters read true values; heat insulators are perfect; gases follow the ideal gas equation. It is in the laboratory that the validity of these assumptions can be questioned, because there the student meets nature as it is rather than in idealized form. Consequently, AP students should be able to:

- design experiments;
- observe and measure real phenomena;
- organize, display and critically analyze data;
- analyze sources of error and determine uncertainties in measurement;
- draw inferences from observations and data; and
- communicate results, including suggested ways to improve experiments and proposed questions for further study.

Laboratory experience is also important in helping students understand the topics being considered. Thus it is valuable to ask students to write informally about what they have done, observed and concluded, as well as for them to keep well-organized laboratory notebooks.

Students need to be proficient in problem solving and in the application of fundamental principles to a wide variety of situations. Problem-solving ability can be fostered by investigations that are somewhat nonspecific. Such investigations are often more interesting and valuable than "cookbook" experiments that merely investigate a well-established relationship and can take important time away from the rest of the course.

Some questions or parts of questions on each AP Physics Exam deal with lab-related skills, such as design of experiments, data analysis, and error analysis, and are intended to distinguish between students who have had laboratory experience and those who have not. In addition, understanding gained in the laboratory may improve a student's test performance overall.

Implementation and Recommendations

Laboratory programs in both college courses and AP courses differ widely, and there is no clear evidence that any one approach is necessarily best. This diversity of approaches should be encouraging to the high school teacher of an AP course. The

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success of a given program depends strongly on the interests and enthusiasm of the teacher and on the general ability and motivation of the students involved.

Although programs differ, the AP Physics C Development Committee has made some recommendations in regard to school resources and scheduling. **Because an AP course is a college course, the equipment and time allotted to laboratories should be similar to that in a college course. Therefore, school administrators should realize the implications, in both cost and time, of incorporating serious laboratories into their program. Schools must ensure that students have access to scientific equipment and all materials necessary to conduct hands-on, college-level physics laboratory investigations as outlined in the teacher's course syllabus.**

In addition to equipment commonly included in college labs, students in AP Physics C should have adequate and timely access to computers that are connected to the Internet and its many online resources. Students should also have access to computers with appropriate sensing devices and software for use in gathering, graphing and analyzing laboratory data and writing reports. Although using computers in this way is a useful activity and is encouraged, some initial experience with gathering, graphing, and manipulating data by hand is also important so that students attain a better feel for the physical realities involved in the experiments. And it should be emphasized that simulating an experiment on a computer cannot adequately replace the actual, hands-on experience of doing an experiment.

Flexible or modular scheduling is best in order to meet the time requirements identified in the course outline. Some schools are able to assign daily double periods so that laboratory and quantitative problem-solving skills may be fully developed. A weekly extended or double laboratory period is recommended for labs. It is not advisable to attempt to complete high-quality AP laboratory work entirely within standard 45- to 50-minute periods, although teachers without access to a double period can sometimes extend the laboratory experience over two class days.

If AP Physics C is taught as a second-year physics course, the AP labs should build on and extend the lab experiences of the first-year course. The important criterion is that students completing an AP Physics C course must have had laboratory experiences that are roughly equivalent to those in a comparable introductory college course.

Past surveys of introductory college physics courses, both noncalculus and calculus-based, have revealed that on average about 20 percent of the total course credit awarded can be attributed to lab performance; from two to three hours per week are typically devoted to laboratory activities. Secondary schools may have difficulty scheduling this much weekly time for lab. However, the college academic year typically contains fewer weeks than the secondary school year, so AP teachers may be able to schedule a few more lab periods during the year than can colleges. Also, college faculty have reported that some lab time occasionally may be used for other purposes. Nevertheless, in order for AP students to have sufficient time for lab, at least one double or extended period per week is recommended for all AP Physics courses.

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Laboratory activities in colleges and AP courses can involve different levels of student involvement. They can generally be classified as: (1) prescribed or "cookbook," (2) limited investigations with some direction provided and (3) open investigations with little or no direction provided. While many college professors believe that labs in the latter two categories have more value to students, they report often being limited in their ability to institute them by large class sizes and other factors. In this respect, AP teachers often have an advantage in being able to offer more open-ended labs to their students.

In past surveys, colleges have cited use of the following techniques to assess student lab performance: lab reports, direct observation, written tests designed specifically for lab, lab-related questions on regular lecture tests, lab practical exams, and maintenance of lab notebooks. When the colleges assessed laboratory skills with written test questions, they reported attempting to assess the following skills in order of decreasing frequency: analysis of data, analysis of errors, design of experiments, and evaluation of experiments and suggestions for future investigations.

A more detailed laboratory guide is AP Physics C is available and can be ordered through AP Central. This guide contains descriptions of a number of experiments that typify the type and level of skills that should be developed by AP Physics C students in conducting laboratory investigations. The experiments are not mandatory; they can be modified or similar experiments substituted as long as they assist the student in developing these skills. Additional suggestions for the laboratory can be found on the AP Physics course home pages on AP Central (apcentral.collegeboard.org).

Documenting Laboratory Experience

The laboratory is important for both AP and college students. Students who have had laboratory experience in high school will be in a better position to validate their AP courses as equivalent to the corresponding college courses and to undertake the laboratory work in more advanced courses with greater confidence. Most college placement policies assume that students have had laboratory experience, and students should be prepared to show evidence of their laboratory work in case the college asks for it. Such experience should be documented for the AP course by keeping a lab notebook or a portfolio of lab reports. Students should be encouraged to keep copies of this work and any other work from previous lab experience. Presenting evidence of *adequate college-level* laboratory experience to the colleges they attend, as an adjunct to their AP scores, can be very useful to students if they desire credit for or exemption from an introductory college course that includes a laboratory. Although colleges can expect that most entering AP students have been exposed to many of the same laboratory experiments performed by their own introductory students, individual consultation with students is often used to help determine the nature of their laboratory experience.

Physics C Courses

There are two AP Physics C courses — Physics C: Mechanics and Physics C: Electricity and Magnetism, each corresponding to approximately a semester of college

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work. Mechanics is typically taught first, and some AP teachers may choose to teach this course only. If both courses are taught over the course of a year, approximately equal time should be given to each. Both courses should use guided inquiry and student-centered learning to foster the development of critical thinking skills and should use introductory differential and integral calculus throughout the course.

Physics C: Mechanics should provide instruction in each of the following six content areas: kinematics; Newton's laws of motion; work, energy and power; systems of particles and linear momentum; circular motion and rotation; and oscillations and gravitation.

Physics C: Electricity and Magnetism should provide instruction in each of the following five content areas: electrostatics; conductors, capacitors and dielectrics; electric circuits; magnetic fields; and electromagnetism.

Content outlines for both courses and percentage goals for covering each major topic in the exams are on pages 13–15. A more detailed topic outline is contained in the "Learning Objectives for AP Physics C," which start on page 16.

Most colleges and universities include in similar courses additional topics such as wave motion, kinetic theory and thermodynamics, optics, alternating current circuits or special relativity. Although wave motion, optics and kinetic theory and thermodynamics are usually the most commonly included, there is little uniformity among such offerings, and these topics are not included in the Physics C Exams. The Development Committee recommends that supplementary material be added to Physics C when it is possible to do so. Many teachers have found that a good time to do this is late in the year, after the AP Exams have been given.

Each AP Physics C course should also include a hands-on laboratory component comparable to a semester-long introductory college-level physics laboratory. Students should spend a minimum of 20 percent of instructional time engaged in hands-on laboratory work. Each student should complete a lab notebook or portfolio of lab reports.

The school should ensure that each student has a calculus-based college-level textbook (supplemented when necessary to meet the curricular requirements) for individual use inside and outside of the classroom. A link to lists of examples of acceptable textbooks can be found on the AP Physics C course home pages on the AP Central website.

Topics in Physics C

To serve as an aid for devising AP Physics C courses and to more clearly identify the specifics of the exams, a detailed topical structure has been developed that relies heavily on information obtained in college surveys. The general areas covered by the two AP Physics C courses are subdivided into major categories on pages 13–15, and for each category the percentage goals for each exam are given. These goals should serve only as a guide and should not be construed as reflecting the proportion of course time that should be devoted to each category.

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Also, for each major category, some important subtopics are listed. Questions for the exam will come from these subtopics, but not all of the subtopics will necessarily be included in every exam, just as they are not necessarily included in every AP or college course. It should be noted that although fewer topics are covered in Physics C than in Physics 1 and 2, they are covered in greater depth and with greater analytical and mathematical sophistication, including calculus applications.

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Content Outline for AP Physics C

A more detailed topic outline is contained in the "Learning Objectives for AP Physics C," which follow this outline.

Content Area	*Percentage Goals for Exams*
AP Physics C: Mechanics	100%
A. Kinematics (including vectors, vector algebra, components of vectors, coordinate systems, displacement, velocity, and acceleration) 1. Motion in one dimension 2. Motion in two dimensions, including projectile motion	18%
B. Newton's laws of motion 1. Static equilibrium (first law) 2. Dynamics of a single particle (second law) 3. Systems of two or more objects (third law)	20%
C. Work, energy, power 1. Work and work–energy theorem 2. Forces and potential energy 3. Conservation of energy 4. Power	14%
D. Systems of particles, linear momentum 1. Center of mass 2. Impulse and momentum 3. Conservation of linear momentum, collisions	12%
E. Circular motion and rotation 1. Uniform circular motion 2. Torque and rotational statics 3. Rotational kinematics and dynamics 4. Angular momentum and its conservation	18%
F. Oscillations and gravitation 1. Simple harmonic motion (dynamics and energy relationships) 2. Mass on a spring 3. Pendulum and other oscillations 4. Newton's law of gravity 5. Orbits of planets and satellites a. Circular b. General	18%

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Content Area	*Percentage Goals for Exams*
AP Physics C: Electricity and Magnetism	100%
A. Electrostatics	30%
1. Charge and Coulomb's law	
2. Electric field and electric potential (including point charges)	
3. Gauss's law	
4. Fields and potentials of other charge distributions	
B. Conductors, capacitors, dielectrics	14%
1. Electrostatics with conductors	
2. Capacitors	
a. Capacitance	
b. Parallel plate	
c. Spherical and cylindrical	
3. Dielectrics	
C. Electric circuits	20%
1. Current, resistance, power	
2. Steady-state direct current circuits with batteries and resistors only	
3. Capacitors in circuits	
a. Steady state	
b. Transients in RC circuits	
D. Magnetic Fields	20%
1. Forces on moving charges in magnetic fields	
2. Forces on current-carrying wires in magnetic fields	
3. Fields of long current-carrying wires	
4. Biot–Savart law and Ampere's law	
E. Electromagnetism	16%
1. Electromagnetic induction (including Faraday's law and Lenz's law)	
2. Inductance (including LR and LC circuits)	
3. Maxwell's equations	

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Laboratory and experimental situations: Each exam will include one or more questions or parts of questions posed in a laboratory or experimental setting. These questions are classified according to the content area that provides the setting for the situation, and each content area may include such questions. These questions generally assess some understanding of content as well as experimental skills, as described on the following pages.

Miscellaneous: Each exam may include occasional questions that overlap several major topical areas or questions on miscellaneous topics such as identification of vectors and scalars, vector mathematics, or graphs of functions.

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Learning Objectives for AP Physics C

These course objectives are intended to elaborate on the content outline for Physics C. In addition to the content areas, objectives are included for laboratory skills, which have become an important part of the AP Physics C Exams.

The objectives listed below are generally representative of the cumulative content of recently administered exams, although no single exam can cover them all. It is reasonable to expect that future exams will continue to sample primarily from among these objectives. However, there may be an occasional question that is within the scope of the included topics but is not specifically covered by one of the listed objectives. Questions may also be based on variations or combinations of these objectives, rephrasing them but still assessing the essential concepts.

The objectives listed below are continually revised to keep them as current as possible with the content outline and the coverage of the exams.

Objectives for AP® Physics C

AP PHYSICS C: MECHANICS

A. Kinematics (including vectors, vector algebra, components of vectors, coordinate systems, displacement, velocity and acceleration)

1. Motion in one dimension

a) Students should understand the general relationships among position, velocity and acceleration for the motion of a particle along a straight line, so that:

1) Given a graph of one of the kinematic quantities, position, velocity or acceleration, as a function of time, they can recognize in what time intervals the other two are positive, negative, or zero and can identify or sketch a graph of each as a function of time.

2) Given an expression for one of the kinematic quantities, position, velocity or acceleration, as a function of time, they can determine the other two as a function of time, and find when these quantities are zero or achieve their maximum and minimum values.

b) Students should understand the special case of motion with constant acceleration, so they can:

1) Write down expressions for velocity and position as functions of time, and identify or sketch graphs of these quantities.

2) Use the equations $v_x = v_{x0} + a_x t$, $x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$, and $v_x^2 = {v_{x0}}^2 + 2a_x (x - x_0)$ to solve problems involving one-dimensional motion with constant acceleration.

c) Students should know how to deal with situations in which acceleration is a specified function of velocity and time so they can write an appropriate differential equation and solve it for $v(t)$ by separation of variables, incorporating correctly a given initial value of v.

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2. **Motion in two dimensions, including projectile motion**

   a) Students should be able to add, subtract and resolve displacement and velocity vectors, so they can:

      1) Determine components of a vector along two specified, mutually perpendicular axes.

      2) Determine the net displacement of a particle or the location of a particle relative to another.

      3) Determine the change in velocity of a particle or the velocity of one particle relative to another.

   b) Students should understand the general motion of a particle in two dimensions so that, given functions $x(t)$ and $y(t)$ which describe this motion, they can determine the components, magnitude and direction of the particle's velocity and acceleration as functions of time.

   c) Students should understand the motion of projectiles in a uniform gravitational field, so they can:

      1) Write down expressions for the horizontal and vertical components of velocity and position as functions of time, and sketch or identify graphs of these components.

      2) Use these expressions in analyzing the motion of a projectile that is projected with an arbitrary initial velocity.

B. Newton's laws of motion

1. **Static equilibrium (first law)**

   Students should be able to analyze situations in which a particle remains at rest, or moves with constant velocity, under the influence of several forces.

2. **Dynamics of a single particle (second law)**

   a) Students should understand the relation between the force that acts on an object and the resulting change in the object's velocity, so they can:

      1) Calculate, for an object moving in one dimension, the velocity change that results when a constant force $\vec{F}$ acts over a specified time interval.

      2) Calculate, for an object moving in one dimension, the velocity change that results when a force $\vec{F}(t)$ acts over a specified time interval.

      3) Determine, for an object moving in a plane whose velocity vector undergoes a specified change over a specified time interval, the average force that acted on the object.

   b) Students should understand how Newton's second law, $\sum \vec{F} = \vec{F}_{net} = m\vec{a}$, applies to an object subject to forces such as gravity, the pull of strings, or contact forces, so they can:

      1) Draw a well-labeled, free-body diagram showing all real forces that act on the object.

      2) Write down the vector equation that results from applying Newton's second law to the object, and take components of this equation along appropriate axes.

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c) Students should be able to analyze situations in which an object moves with specified acceleration under the influence of one or more forces so they can determine the magnitude and direction of the net force, or of one of the forces that makes up the net force, such as motion up or down with constant acceleration.

d) Students should understand the significance of the coefficient of friction, so they can:

1) Write down the relationship between the normal and frictional forces on a surface.

2) Analyze situations in which an object moves along a rough inclined plane or horizontal surface.

3) Analyze under what circumstances an object will start to slip, or to calculate the magnitude of the force of static friction.

e) Students should understand the effect of drag forces on the motion of an object, so they can:

1) Find the terminal velocity of an object moving vertically under the influence of a retarding force dependent on velocity.

2) Describe qualitatively, with the aid of graphs, the acceleration, velocity and displacement of such a particle when it is released from rest or is projected vertically with specified initial velocity.

3) Use Newton's second law to write a differential equation for the velocity of the object as a function of time.

4) Use the method of separation of variables to derive the equation for the velocity as a function of time from the differential equation that follows from Newton's second law.

5) Derive an expression for the acceleration as a function of time for an object falling under the influence of drag forces.

3. Systems of two or more objects (third law)

a) Students should understand Newton's third law so that, for a given system, they can identify the force pairs and the objects on which they act, and state the magnitude and direction of each force.

b) Students should be able to apply Newton's third law in analyzing the force of contact between two objects that accelerate together along a horizontal or vertical line, or between two surfaces that slide across one another.

c) Students should know that the tension is constant in a light string that passes over a massless pulley and should be able to use this fact in analyzing the motion of a system of two objects joined by a string.

d) Students should be able to solve problems in which application of Newton's laws leads to two or three simultaneous linear equations involving unknown forces or accelerations.

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C. Work, energy, power

1. Work and the work-energy theorem

a) Students should understand the definition of work, including when it is positive, negative or zero, so they can:

1) Calculate the work done by a specified constant force on an object that undergoes a specified displacement.

2) Relate the work done by a force to the area under a graph of force as a function of position, and calculate this work in the case where the force is a linear function of position.

3) Use integration to calculate the work performed by a force $\vec{F}(x)$ on an object that undergoes a specified displacement in one dimension.

4) Use the scalar product operation to calculate the work performed by a specified constant force $\vec{F}$ on an object that undergoes a displacement in a plane.

b) Students should understand and be able to apply the work-energy theorem, so they can:

1) Calculate the change in kinetic energy or speed that results from performing a specified amount of work on an object.

2) Calculate the work performed by the net force, or by each of the forces that make up the net force, on an object that undergoes a specified change in speed or kinetic energy.

3) Apply the theorem to determine the change in an object's kinetic energy and speed that result from the application of specified forces, or to determine the force that is required in order to bring an object to rest in a specified distance.

2. Forces and potential energy

a) Students should understand the concept of a conservative force, so they can:

1) State alternative definitions of "conservative force" and explain why these definitions are equivalent.

2) Describe examples of conservative forces and non-conservative forces.

b) Students should understand the concept of potential energy, so they can:

1) State the general relation between force and potential energy, and explain why potential energy can be associated only with conservative forces.

2) Calculate a potential energy function associated with a specified one-dimensional force $\vec{F}(x)$.

3) Calculate the magnitude and direction of a one-dimensional force when given the potential energy function $U(x)$ for the force.

4) Write an expression for the force exerted by an ideal spring and for the potential energy of a stretched or compressed spring.

5) Calculate the potential energy of one or more objects in a uniform gravitational field.

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3. Conservation of energy

a) Students should understand the concepts of mechanical energy and of total energy, so they can:

1) State and apply the relation between the work performed on an object by non-conservative forces and the change in an object's mechanical energy.

2) Describe and identify situations in which mechanical energy is converted to other forms of energy.

3) Analyze situations in which an object's mechanical energy is changed by friction or by a specified externally applied force.

b) Students should understand conservation of energy, so they can:

1) Identify situations in which mechanical energy is or is not conserved.

2) Apply conservation of energy in analyzing the motion of systems of connected objects, such as an Atwood's machine.

3) Apply conservation of energy in analyzing the motion of objects that move under the influence of springs.

4) Apply conservation of energy in analyzing the motion of objects that move under the influence of other non-constant one-dimensional forces.

c) Students should be able to recognize and solve problems that call for application both of conservation of energy and Newton's laws.

4. Power

Students should understand the definition of power, so they can:

a) Calculate the power required to maintain the motion of an object with constant acceleration (e.g., to move an object along a level surface, to raise an object at a constant rate, or to overcome friction for an object that is moving at a constant speed).

b) Calculate the work performed by a force that supplies constant power, or the average power supplied by a force that performs a specified amount of work.

D. Systems of particles, linear momentum

1. Center of mass

a) Students should understand the technique for finding center of mass, so they can:

1) Identify by inspection the center of mass of a symmetrical object.

2) Locate the center of mass of a system consisting of two such objects.

3) Use integration to find the center of mass of a thin rod of non-uniform density.

b) Students should be able to understand and apply the relation between center-of-mass velocity and linear momentum, and between center-of-mass acceleration and net external force for a system of particles.

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c) Students should be able to define center of gravity and to use this concept to express the gravitational potential energy of a rigid object in terms of the position of its center of mass.

2. Impulse and momentum

Students should understand impulse and linear momentum, so they can:

a) Relate mass, velocity, and linear momentum for a moving object, and calculate the total linear momentum of a system of objects.

b) Relate impulse to the change in linear momentum and the average force acting on an object.

c) State and apply the relations between linear momentum and center-of-mass motion for a system of particles.

d) Calculate the area under a force versus time graph and relate it to the change in momentum of an object.

e) Calculate the change in momentum of an object given a function $\vec{F}(t)$ for the net force acting on the object.

3. Conservation of linear momentum, collisions

a) Students should understand linear momentum conservation, so they can:

1) Explain how linear momentum conservation follows as a consequence of Newton's third law for an isolated system.

2) Identify situations in which linear momentum, or a component of the linear momentum vector, is conserved.

3) Apply linear momentum conservation to one-dimensional elastic and inelastic collisions and two-dimensional completely inelastic collisions.

4) Apply linear momentum conservation to two-dimensional elastic and inelastic collisions.

5) Analyze situations in which two or more objects are pushed apart by a spring or other agency, and calculate how much energy is released in such a process.

b) Students should understand frames of reference, so they can:

1) Analyze the uniform motion of an object relative to a moving medium such as a flowing stream.

2) Analyze the motion of particles relative to a frame of reference that is accelerating horizontally or vertically at a uniform rate.

E. Circular motion and rotation

1. Uniform circular motion

Students should understand the uniform circular motion of a particle, so they can:

a) Relate the radius of the circle and the speed or rate of revolution of the particle to the magnitude of the centripetal acceleration.

b) Describe the direction of the particle's velocity and acceleration at any instant during the motion.

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c) Determine the components of the velocity and acceleration vectors at any instant, and sketch or identify graphs of these quantities.

d) Analyze situations in which an object moves with specified acceleration under the influence of one or more forces so they can determine the magnitude and direction of the net force, or of one of the forces that makes up the net force, in situations such as the following:

1) Motion in a horizontal circle (e.g., mass on a rotating merry-go-round, or car rounding a banked curve).

2) Motion in a vertical circle (e.g., mass swinging on the end of a string, cart rolling down a curved track, rider on a Ferris wheel).

2. Torque and rotational statics

a) Students should understand the concept of torque, so they can:

1) Calculate the magnitude and direction of the torque associated with a given force.

2) Calculate the torque on a rigid object due to gravity.

b) Students should be able to analyze problems in statics, so they can:

1) State the conditions for translational and rotational equilibrium of a rigid object.

2) Apply these conditions in analyzing the equilibrium of a rigid object under the combined influence of a number of coplanar forces applied at different locations.

c) Students should develop a qualitative understanding of rotational inertia, so they can:

1) Determine by inspection which of a set of symmetrical objects of equal mass has the greatest rotational inertia.

2) Determine by what factor an object's rotational inertia changes if all its dimensions are increased by the same factor.

d) Students should develop skill in computing rotational inertia so they can find the rotational inertia of:

1) A collection of point masses lying in a plane about an axis perpendicular to the plane.

2) A thin rod of uniform density, about an arbitrary axis perpendicular to the rod.

3) A thin cylindrical shell about its axis, or an object that may be viewed as being made up of coaxial shells.

e) Students should be able to state and apply the parallel-axis theorem.

3. Rotational kinematics and dynamics

a) Students should understand the analogy between translational and rotational kinematics so they can write and apply relations among the angular acceleration, angular velocity, and angular displacement of an object that rotates about a fixed axis with constant angular acceleration.

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b) Students should be able to use the right-hand rule to associate an angular velocity vector with a rotating object.

c) Students should understand the dynamics of fixed-axis rotation, so they can:

1) Describe in detail the analogy between fixed-axis rotation and straight-line translation.

2) Determine the angular acceleration with which a rigid object is accelerated about a fixed axis when subjected to a specified external torque or force.

3) Determine the radial and tangential acceleration of a point on a rigid object.

4) Apply conservation of energy to problems of fixed-axis rotation.

5) Analyze problems involving strings and massive pulleys.

d) Students should understand the motion of a rigid object along a surface, so they can:

1) Write down, justify and apply the relation between linear and angular velocity, or between linear and angular acceleration, for an object of circular cross-section that rolls without slipping along a fixed plane, and determine the velocity and acceleration of an arbitrary point on such an object.

2) Apply the equations of translational and rotational motion simultaneously in analyzing rolling with slipping.

3) Calculate the total kinetic energy of an object that is undergoing both translational and rotational motion, and apply energy conservation in analyzing such motion.

4. Angular momentum and its conservation

a) Students should be able to use the vector product and the right-hand rule, so they can:

1) Calculate the torque of a specified force about an arbitrary origin.

2) Calculate the angular momentum vector for a moving particle.

3) Calculate the angular momentum vector for a rotating rigid object in simple cases where this vector lies parallel to the angular velocity vector.

b) Students should understand angular momentum conservation, so they can:

1) Recognize the conditions under which the law of conservation is applicable and relate this law to one- and two-particle systems such as satellite orbits.

2) State the relation between net external torque and angular momentum, and identify situations in which angular momentum is conserved.

3) Analyze problems in which the moment of inertia of an object is changed as it rotates freely about a fixed axis.

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4) Analyze a collision between a moving particle and a rigid object that can rotate about a fixed axis or about its center of mass.

F. Oscillations and Gravitation

1. Simple harmonic motion (dynamics and energy relationships)

Students should understand simple harmonic motion, so they can:

a) Sketch or identify a graph of displacement as a function of time, and determine from such a graph the amplitude, period and frequency of the motion.

b) Write down an appropriate expression for displacement of the form $A\sin(\omega t)$ or $A\cos(\omega t)$ to describe the motion.

c) Find an expression for velocity as a function of time.

d) State the relations between acceleration, velocity and displacement, and identify points in the motion where these quantities are zero or achieve their greatest positive and negative values.

e) State and apply the relation between frequency and period.

f) Recognize that a system that obeys a differential equation of the form $d^2x/dt^2 = -\omega^2 x$ must execute simple harmonic motion, and determine the frequency and period of such motion.

g) State how the total energy of an oscillating system depends on the amplitude of the motion, sketch or identify a graph of kinetic or potential energy as a function of time, and identify points in the motion where this energy is all potential or all kinetic.

h) Calculate the kinetic and potential energies of an oscillating system as functions of time, sketch or identify graphs of these functions, and prove that the sum of kinetic and potential energy is constant.

i) Calculate the maximum displacement or velocity of a particle that moves in simple harmonic motion with specified initial position and velocity.

j) Develop a qualitative understanding of resonance so they can identify situations in which a system will resonate in response to a sinusoidal external force.

2. Mass on a spring

Students should be able to apply their knowledge of simple harmonic motion to the case of a mass on a spring, so they can:

a) Derive the expression for the period of oscillation of a mass on a spring.

b) Apply the expression for the period of oscillation of a mass on a spring.

c) Analyze problems in which a mass hangs from a spring and oscillates vertically.

d) Analyze problems in which a mass attached to a spring oscillates horizontally.

e) Determine the period of oscillation for systems involving series or parallel combinations of identical springs, or springs of differing lengths.

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3. **Pendulum and other oscillations**

Students should be able to apply their knowledge of simple harmonic motion to the case of a pendulum, so they can:

a) Derive the expression for the period of a simple pendulum.

b) Apply the expression for the period of a simple pendulum.

c) State what approximation must be made in deriving the period.

d) Analyze the motion of a torsional pendulum or physical pendulum in order to determine the period of small oscillations.

4. **Newton's law of gravity**

Students should know Newton's law of universal gravitation, so they can:

a) Determine the force that one spherically symmetrical mass exerts on another.

b) Determine the strength of the gravitational field at a specified point outside a spherically symmetrical mass.

c) Describe the gravitational force inside and outside a uniform sphere, and calculate how the field at the surface depends on the radius and density of the sphere.

5. **Orbits of planets and satellites**

Students should understand the motion of an object in orbit under the influence of gravitational forces, so they can:

a) For a circular orbit:

1) Recognize that the motion does not depend on the object's mass; describe qualitatively how the velocity, period of revolution and centripetal acceleration depend upon the radius of the orbit; and derive expressions for the velocity and period of revolution in such an orbit.

2) Derive Kepler's third law for the case of circular orbits.

3) Derive and apply the relations among kinetic energy, potential energy and total energy for such an orbit.

b) For a general orbit:

1) State Kepler's three laws of planetary motion and use them to describe in qualitative terms the motion of an object in an elliptical orbit.

2) Apply conservation of angular momentum to determine the velocity and radial distance at any point in the orbit.

3) Apply angular momentum conservation and energy conservation to relate the speeds of an object at the two extremes of an elliptical orbit.

4) Apply energy conservation in analyzing the motion of an object that is projected straight up from a planet's surface or that is projected directly toward the planet from far above the surface.

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AP PHYSICS C: ELECTRICITY AND MAGNETISM

A. Electrostatics

1. Charge and Coulomb's law

a) Students should understand the concept of electric charge, so they can:
   1) Describe the types of charge and the attraction and repulsion of charges.
   2) Describe polarization and induced charges.

b) Students should understand Coulomb's law and the principle of superposition, so they can:
   1) Calculate the magnitude and direction of the force on a positive or negative charge due to other specified point charges.
   2) Analyze the motion of a particle of specified charge and mass under the influence of an electrostatic force.

2. Electric field and electric potential (including point charges)

a) Students should understand the concept of electric field, so they can:
   1) Define it in terms of the force on a test charge.
   2) Describe and calculate the electric field of a single point charge.
   3) Calculate the magnitude and direction of the electric field produced by two or more point charges.
   4) Calculate the magnitude and direction of the force on a positive or negative charge placed in a specified field.
   5) Interpret an electric field diagram.
   6) Analyze the motion of a particle of specified charge and mass in a uniform electric field.

b) Students should understand the concept of electric potential, so they can:
   1) Determine the electric potential in the vicinity of one or more point charges.
   2) Calculate the electrical work done on a charge or use conservation of energy to determine the speed of a charge that moves through a specified potential difference.
   3) Determine the direction and approximate magnitude of the electric field at various positions given a sketch of equipotentials.
   4) Calculate the potential difference between two points in a uniform electric field, and state which point is at the higher potential.
   5) Calculate how much work is required to move a test charge from one location to another in the field of fixed point charges.
   6) Calculate the electrostatic potential energy of a system of two or more point charges, and calculate how much work is required to establish the charge system.

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7) Use integration to determine electric potential difference between two points on a line, given electric field strength as a function of position along that line.

8) State the general relationship between field and potential, and define and apply the concept of a conservative electric field.

3. Gauss's law

a) Students should understand the relationship between electric field and electric flux, so they can:

1) Calculate the flux of an electric field through an arbitrary surface or of a field uniform in magnitude over a Gaussian surface and perpendicular to it.

2) Calculate the flux of the electric field through a rectangle when the field is perpendicular to the rectangle and a function of one coordinate only.

3) State and apply the relationship between flux and lines of force.

b) Students should understand Gauss's law, so they can:

1) State the law in integral form, and apply it qualitatively to relate flux and electric charge for a specified surface.

2) Apply the law, along with symmetry arguments, to determine the electric field for a planar, spherical or cylindrically symmetric charge distribution.

3) Apply the law to determine the charge density or total charge on a surface in terms of the electric field near the surface.

4. Fields and potentials of other charge distributions

a) Students should be able to use the principle of superposition to calculate by integration:

1) The electric field of a straight, uniformly charged wire.

2) The electric field and potential on the axis of a thin ring of charge, or at the center of a circular arc of charge.

3) The electric potential on the axis of a uniformly charged disk.

b) Students should know the fields of highly symmetric charge distributions, so they can:

1) Identify situations in which the direction of the electric field produced by a charge distribution can be deduced from symmetry considerations.

2) Describe qualitatively the patterns and variation with distance of the electric field of:

a. Oppositely-charged parallel plates.

b. A long, uniformly-charged wire, or thin cylindrical or spherical shell.

3) Use superposition to determine the fields of parallel charged planes, coaxial cylinders or concentric spheres.

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4) Derive expressions for electric potential as a function of position in the above cases.

B. Conductors, capacitors, dielectrics

1. Electrostatics with conductors

a) Students should understand the nature of electric fields in and around conductors, so they can:

1) Explain the mechanics responsible for the absence of electric field inside a conductor, and know that all excess charge must reside on the surface of the conductor.

2) Explain why a conductor must be an equipotential, and apply this principle in analyzing what happens when conductors are connected by wires.

3) Show that all excess charge on a conductor must reside on its surface and that the field outside the conductor must be perpendicular to the surface.

b) Students should be able to describe and sketch a graph of the electric field and potential inside and outside a charged conducting sphere.

c) Students should understand induced charge and electrostatic shielding, so they can:

1) Describe the process of charging by induction.

2) Explain why a neutral conductor is attracted to a charged object.

3) Explain why there can be no electric field in a charge-free region completely surrounded by a single conductor, and recognize consequences of this result.

4) Explain why the electric field outside a closed conducting surface cannot depend on the precise location of charge in the space enclosed by the conductor, and identify consequences of this result.

2. Capacitors

a) Students should understand the definition and function of capacitance, so they can:

1) Relate stored charge and voltage for a capacitor.

2) Relate voltage, charge and stored energy for a capacitor.

3) Recognize situations in which energy stored in a capacitor is converted to other forms.

b) Students should understand the physics of the parallel-plate capacitor, so they can:

1) Describe the electric field inside the capacitor, and relate the strength of this field to the potential difference between the plates and the plate separation.

2) Relate the electric field to the density of the charge on the plates.

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3) Derive an expression for the capacitance of a parallel-plate capacitor.
4) Determine how changes in dimension will affect the value of the capacitance.
5) Derive and apply expressions for the energy stored in a parallel-plate capacitor and for the energy density in the field between the plates.
6) Analyze situations in which capacitor plates are moved apart or moved closer together, or in which a conducting slab is inserted between capacitor plates, either with a battery connected between the plates or with the charge on the plates held fixed.

c) Students should understand cylindrical and spherical capacitors, so they can:
1) Describe the electric field inside each.
2) Derive an expression for the capacitance of each.

3. Dielectrics

Students should understand the behavior of dielectrics, so they can:

a) Describe how the insertion of a dielectric between the plates of a charged parallel-plate capacitor affects its capacitance and the field strength and voltage between the plates.

b) Analyze situations in which a dielectric slab is inserted between the plates of a capacitor.

C. Electric circuits

1. Current, resistance, power

a) Students should understand the definition of electric current, so they can relate the magnitude and direction of the current to the rate of flow of positive and negative charge.

b) Students should understand conductivity, resistivity and resistance, so they can:
1) Relate current and voltage for a resistor.
2) Write the relationship between electric field strength and current density in a conductor, and describe, in terms of the drift velocity of electrons, why such a relationship is plausible.
3) Describe how the resistance of a resistor depends upon its length and cross-sectional area, and apply this result in comparing current flow in resistors of different material or different geometry.
4) Derive an expression for the resistance of a resistor of uniform cross-section in terms of its dimensions and the resistivity of the material from which it is constructed.
5) Derive expressions that relate the current, voltage and resistance to the rate at which heat is produced when current passes through a resistor.
6) Apply the relationships for the rate of heat production in a resistor.

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2. **Steady-state direct current circuits with batteries and resistors only**
   a) Students should understand the behavior of series and parallel combinations of resistors, so they can:
      1) Identify on a circuit diagram whether resistors are in series or in parallel.
      2) Determine the ratio of the voltages across resistors connected in series or the ratio of the currents through resistors connected in parallel.
      3) Calculate the equivalent resistance of a network of resistors that can be broken down into series and parallel combinations.
      4) Calculate the voltage, current and power dissipation for any resistor in such a network of resistors connected to a single power supply.
      5) Design a simple series-parallel circuit that produces a given current through and potential difference across one specified component, and draw a diagram for the circuit using conventional symbols.
   b) Students should understand the properties of ideal and real batteries, so they can:
      1) Calculate the terminal voltage of a battery of specified emf and internal resistance from which a known current is flowing.
      2) Calculate the rate at which a battery is supplying energy to a circuit or is being charged up by a circuit.
   c) Students should be able to apply Ohm's law and Kirchhoff's rules to direct-current circuits, in order to:
      1) Determine a single unknown current, voltage or resistance.
      2) Set up and solve simultaneous equations to determine two unknown currents.
   d) Students should understand the properties of voltmeters and ammeters, so they can:
      1) State whether the resistance of each is high or low.
      2) Identify or show correct methods of connecting meters into circuits in order to measure voltage or current.
      3) Assess qualitatively the effect of finite meter resistance on a circuit into which these meters are connected.
3. **Capacitors in circuits**
   a) Students should understand the $t = 0$ and steady-state behavior of capacitors connected in series or in parallel, so they can:
      1) Calculate the equivalent capacitance of a series or parallel combination.
      2) Describe how stored charge is divided between capacitors connected in parallel.
      3) Determine the ratio of voltages for capacitors connected in series.
      4) Calculate the voltage or stored charge, under steady-state conditions, for a capacitor connected to a circuit consisting of a battery and resistors.

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b) Students should understand the discharging or charging of a capacitor through a resistor, so they can:

1) Calculate and interpret the time constant of the circuit.
2) Sketch or identify graphs of stored charge or voltage for the capacitor, or of current or voltage for the resistor, and indicate on the graph the significance of the time constant.
3) Write expressions to describe the time dependence of the stored charge or voltage for the capacitor, or of the current or voltage for the resistor.
4) Analyze the behavior of circuits containing several capacitors and resistors, including analyzing or sketching graphs that correctly indicate how voltages and currents vary with time.

D. Magnetic Fields

1. Forces on moving charges in magnetic fields

Students should understand the force experienced by a charged particle in a magnetic field, so they can:

a) Calculate the magnitude and direction of the force in terms of q, $\vec{v}$, and $\vec{B}$, and explain why the magnetic force can perform no work.
b) Deduce the direction of a magnetic field from information about the forces experienced by charged particles moving through that field.
c) Describe the paths of charged particles moving in uniform magnetic fields.
d) Derive and apply the formula for the radius of the circular path of a charge that moves perpendicular to a uniform magnetic field.
e) Describe under what conditions particles will move with constant velocity through crossed electric and magnetic fields.

2. Forces on current-carrying wires in magnetic fields

Students should understand the force exerted on a current-carrying wire in a magnetic field, so they can:

a) Calculate the magnitude and direction of the force on a straight segment of current-carrying wire in a uniform magnetic field.
b) Indicate the direction of magnetic forces on a current-carrying loop of wire in a magnetic field, and determine how the loop will tend to rotate as a consequence of these forces.
c) Calculate the magnitude and direction of the torque experienced by a rectangular loop of wire carrying a current in a magnetic field.

3. Fields of long current-carrying wires

Students should understand the magnetic field produced by a long straight current-carrying wire, so they can:

a) Calculate the magnitude and direction of the field at a point in the vicinity of such a wire.
b) Use superposition to determine the magnetic field produced by two long wires.

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c) Calculate the force of attraction or repulsion between two long current-carrying wires.

4. Biot-Savart law and Ampere's law

a) Students should understand the Biot-Savart law, so they can:

1) Deduce the magnitude and direction of the contribution to the magnetic field made by a short straight segment of current-carrying wire.

2) Derive and apply the expression for the magnitude of $\vec{B}$ on the axis of a circular loop of current.

b) Students should understand the statement and application of Ampere's law in integral form, so they can:

1) State the law precisely.

2) Use Ampere's law, plus symmetry arguments and the right-hand rule, to relate magnetic field strength to current for planar or cylindrical symmetries.

c) Students should be able to apply the superposition principle so they can determine the magnetic field produced by combinations of the configurations listed above.

E. Electromagnetism

1. Electromagnetic induction (including Faraday's law and Lenz's law)

a) Students should understand the concept of magnetic flux, so they can:

1) Calculate the flux of a uniform magnetic field through a loop of arbitrary orientation.

2) Use integration to calculate the flux of a non-uniform magnetic field, whose magnitude is a function of one coordinate, through a rectangular loop perpendicular to the field.

b) Students should understand Faraday's law and Lenz's law, so they can:

1) Recognize situations in which changing flux through a loop will cause an induced emf or current in the loop.

2) Calculate the magnitude and direction of the induced emf and current in a loop of wire or a conducting bar under the following conditions:

a. The magnitude of a related quantity such as magnetic field or area of the loop is changing at a constant rate.

b. The magnitude of a related quantity such as magnetic field or area of the loop is a specified non-linear function of time.

c) Students should be able to analyze the forces that act on induced currents so they can determine the mechanical consequences of those forces.

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2. **Inductance (including *LR* and *LC* circuits)**
   a) Students should understand the concept of inductance, so they can:
      1) Calculate the magnitude and sense of the emf in an inductor through which a specified changing current is flowing.
      2) Derive and apply the expression for the self-inductance of a long solenoid.
   b) Students should understand the transient and steady state behavior of DC circuits containing resistors and inductors, so they can:
      1) Apply Kirchhoff's rules to a simple *LR* series circuit to obtain a differential equation for the current as a function of time.
      2) Solve the differential equation obtained in (1) for the current as a function of time through the battery, using separation of variables.
      3) Calculate the initial transient currents and final steady state currents through any part of a simple series and parallel circuit containing an inductor and one or more resistors.
      4) Sketch graphs of the current through or voltage across the resistors or inductor in a simple series and parallel circuit.
      5) Calculate the rate of change of current in the inductor as a function of time.
      6) Calculate the energy stored in an inductor that has a steady current flowing through it.
3. **Maxwell's equations**

   Students should be familiar with Maxwell's equations so they can associate each equation with its implications.

LABORATORY AND EXPERIMENTAL SITUATIONS

These objectives overlay the content objectives, and are assessed in the context of those objectives.

1. **Design experiments**

   Students should understand the process of designing experiments, so they can:
   a) Describe the purpose of an experiment or a problem to be investigated.
   b) Identify equipment needed and describe how it is to be used.
   c) Draw a diagram or provide a description of an experimental setup.
   d) Describe procedures to be used, including controls and measurements to be taken.
2. **Observe and measure real phenomena**

   Students should be able to make relevant observations, and be able to take measurements with a variety of instruments (cannot be assessed via paper-and-pencil examinations).

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3. **Analyze data**

   Students should understand how to analyze data, so they can:

   a) Display data in graphical or tabular form.

   b) Fit lines and curves to data points in graphs.

   c) Perform calculations with data.

   d) Make extrapolations and interpolations from data.

4. **Analyze errors**

   Students should understand measurement and experimental error, so they can:

   a) Identify sources of error and how they propagate.

   b) Estimate magnitude and direction of errors.

   c) Determine significant digits.

   d) Identify ways to reduce error.

5. **Communicate results**

   Students should understand how to summarize and communicate results, so they can:

   a) Draw inferences and conclusions from experimental data.

   b) Suggest ways to improve experiment.

   c) Propose questions for further study.

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THE EXAMS

Each Physics C Exam is 1 hour and 30 minutes long. A student may take either or both exams, and separate scores are reported for each. The time for each exam is divided equally between a 35-question multiple-choice section and a free-response section; the two sections are weighted equally in the determination of each score. The usual format for each free-response section has been 3 questions, each taking about 15 minutes. However, future exams might include a larger number of shorter questions.

The percentages of each exam devoted to each major category are specified in the preceding pages. Departures from these percentages in the free-response section in any given year are compensated for in the multiple-choice section so that the overall topic distribution for the entire exam is achieved as closely as possible, although it may not be reached exactly.

Some questions, particularly in the free-response sections, may involve topics from two or more major categories. For example, a question may use a setting involving principles from electricity and magnetism, but parts of the question may also involve the application of principles of mechanics to this setting, either alone or in combination with the principles from electricity and magnetism. Such a question would not be classified uniquely according to any particular topic but would receive partial classifications by topics in proportion to the principles needed to arrive at the answers.

On both exams the multiple-choice section emphasizes the breadth of the students' knowledge and understanding of the basic principles of physics; the free-response section emphasizes the application of these principles in greater depth in solving more extended problems. In general, questions may ask students to:

- determine directions of vectors or paths of particles;
- draw or interpret diagrams;
- interpret or express physical relationships in graphical form;
- account for observed phenomena;
- interpret experimental data, including their limitations and uncertainties;
- construct and use conceptual models and explain their limitations;
- explain steps taken to arrive at a result or to predict future physical behavior;
- manipulate equations that describe physical relationships;
- obtain reasonable estimates;
- solve problems that require the determination of physical quantities in either numerical or symbolic form and that may require the application of single or multiple physical concepts; or
- derive relationships from fundamental physical concepts.

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Laboratory-related questions may ask students to:

- design experiments, including identifying equipment needed and describing how it is to be used, drawing diagrams or providing descriptions of experimental setups, or describing procedures to be used, including controls and measurements to be taken;
- analyze data, including displaying data in graphical or tabular form, fitting lines and curves to data points in graphs, performing calculations with data or making extrapolations and interpolations from data, manipulating data to fit a certain model, especially a linear one;
- analyze errors, including identifying sources of errors and how they propagate, estimating magnitude and direction of errors, determining significant digits or identifying ways to reduce errors; or
- communicate results, including drawing inferences and conclusions from experimental data, suggesting ways to improve experiments or proposing questions for further study.

The free-response section of each exam is printed in a separate booklet in which each part of a question is followed by a blank space for the student's solution. Near the front of both the multiple-choice and free-response exam booklets, a Table of Information and tables of commonly used equations is provided. The Table of Information includes numerical values of some physical constants and conversion factors and states some conventions used in the exams. The equation tables are described in greater detail in a later section. The International System of Units (SI) is used predominantly in both exams. The use of rulers or straightedges is permitted on the free-response sections to facilitate the sketching of graphs or diagrams that might be required in these sections.

Since the complete exams are intended to provide the maximum information about differences in students' achievement in physics, students may find them more difficult than many classroom exams. The best way for teachers to familiarize their students with the level of difficulty is to give them actual released exams (both multiple-choice and free-response sections) from past administrations. Information about ordering publications is on page 59. Recent free-response sections can also be found on AP Central, along with scoring guidelines and some sample student responses.

The Free-Response Sections — Student Presentation

Students are expected to show their work in the spaces provided for the solution for each part of a free-response question. If they need more space, they should clearly indicate where the work is continued or they may lose credit for it. If students make a mistake, they may cross it out or erase it. Crossed-out work will not be scored, and credit may be lost for incorrect work that is not crossed out.

In scoring the free-response sections, credit for the answers depends on the quality of the solutions and the explanations given; partial solutions may receive partial credit, so students are advised to show all their work. Correct answers without supporting work may lose credit. This is especially true when students are asked specifically to

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justify their answers, in which case the Exam Readers are looking for some verbal or mathematical analysis that shows how the students arrived at their answers. Also, all final numerical answers should include appropriate units.

On the AP Physics C Exams the words "justify," "explain," "calculate," "what is," "determine," "derive," "sketch," and "plot" have precise meanings. Students should pay careful attention to these words in order to obtain maximum credit and should avoid including irrelevant or extraneous material in their answers.

The ability to justify an answer in words shows understanding of the principles underlying physical phenomena in addition to the ability to perform the mathematical manipulations necessary to generate a correct answer. Students will be directed to justify or explain their answers on many of the questions they encounter on the AP Physics C Exams. The words "justify" and "explain" indicate that the student should support the answer with prose, equations, calculations, diagrams or graphs. The prose or equations may in some cases refer to fundamental ideas or relations in physics, such as Newton's laws, conservation of energy, or Gauss's law. In other cases, the justification or explanation may take the form of analyzing the behavior of an equation for large or small values of a variable in the equation.

The words "calculate," "what is," "determine," and "derive" have distinct meanings on the AP Physics C Exams. "Calculate" means that a student is expected to show work leading to a final answer, which may be algebraic but more often is numerical. "What is" and "determine" indicate that work need not necessarily be explicitly shown to obtain full credit. Showing work leading to answers is a good idea, as it may earn a student partial credit in the case of an incorrect answer, but this step may be skipped by the confident or harried student. "Derive" is more specific and indicates that the students need to begin their solutions with one or more fundamental equations, such as those given on the AP Physics C Exam equation sheet. The final answer, usually algebraic, is then obtained through the appropriate use of mathematics.

The words "sketch" and "plot" relate to student-produced graphs. "Sketch" means to draw a graph that illustrates key trends in a particular relationship, such as slope, curvature, intercept(s), or asymptote(s). Numerical scaling or specific data points are not required in a sketch. "Plot" means to draw the data points given in the problem on the grid provided, either using the given scale or indicating the scale and units when none are provided.

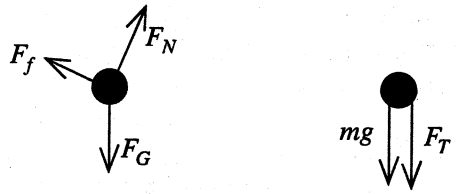
An exam question that requires the drawing of a free-body or force diagram will direct the students as follows:

> "On the dot below, which represents the [object], draw and label the forces (not components) that act on the [object]. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot",

where [object] is replaced by a reference specific to the question, such as "the car when it reaches the top of the hill." Any components that are included in the diagram

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will be scored in the same way as incorrect or extraneous forces. Examples of acceptable free-body diagrams are shown below.



In addition, in any subsequent part asking for a solution that would typically make use of the diagram, the following will be included: "If you need to draw anything other than what you have shown in part [x] to assist in your solution, use the space below. Do NOT add anything to the figure in part [x]." This will give students the opportunity to construct a working diagram showing any components that are appropriate to the solution of the problem. This second diagram will not be scored.

The use of significant figures is an important skill in any introductory college physics course. However, this skill is rarely assessed on numerical problems on the actual AP exam. A general rule for the Physics C tests is to use 2 to 4 significant figures for all numerical answers.

There are exceptions to this general rule. When an AP problem is clearly a laboratory-based question and students are asked to manipulate data or sets of data, then the use of significant figures may be assessed in the actual scoring rubric. Another exception that could appear in the scoring of an AP problem is when students are asked to give numerical answers for known physical constants, and these answers clearly conflict with known information about that physical constant — such as stating that the mass of the electron is $9.1000000 \times 10^{-31}$ kg or that the acceleration due to gravity is $g = 9.9000000$ m/s^2. Students have access to these known quantities (and associated significant figures) in the table of information provided with the exam.

Simplification of algebraic and numerical answers is encouraged, though it should always be balanced with students' efficient use of exam time. Simplifying an answer will often reveal a characteristic of the underlying physics that may be useful in a subsequent part of the exam question. A simplified answer is the clearest way to communicate with the professors and AP teachers who score the exams. Equivalent answers are entitled to full credit, and the Exam Readers always evaluate unsimplified answers for correctness. Yet, however careful the Readers are, there is always the chance for error in their evaluations, and thus simplification may be in the students' best interest.

Additional information about study skills and test-taking strategies can be found at AP Central.

Calculators and Equation Tables

Students will be allowed to use a calculator on the entire AP Physics C: Mechanics and Physics C: Electricity and Magnetism exams — including both the multiple-choice and free-response sections. Scientific or graphing calculators (including the approved graphing calculators listed at www.collegeboard.org/ap/calculators) may be used,

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provided that they do not have any unapproved features or capabilities. Calculator memories do not need to be cleared before or after the exam. Since graphing calculators can be used to store data, including text, proctors should monitor that students are using their calculators appropriately. Communication between calculators is prohibited during the exam administration. Attempts by students to use the calculator to remove exam questions and/or answers from the room may result in the invalidation of AP Exam scores. The policy regarding the use of calculators on the AP Physics C exams was developed to address the rapid expansion of the capabilities of calculators, which include not only programming and graphing functions but also the availability of stored equations and other data. Students should be allowed to use the calculators to which they are accustomed. However, students should be encouraged to develop their skills in estimating answers and orders of magnitude quickly and in recognizing answers that are physically unreasonable or unlikely.

Tables containing equations commonly used in physics will be provided for students to use during the entire AP Physics C: Mechanics and Physics C: Electricity and Magnetism exams. In general, the equations for each year's exam are printed and distributed with the course and exam description at least a year in advance so that students can become accustomed to using them throughout the year. However, because the equation tables will be provided with the exam, students will NOT be allowed to bring their own copies to the exam room. The latest version of the equations and formulas list is included in Appendix B to this course and exam description. One of the purposes of providing the tables of commonly employed equations for use with the exam is to address the issue of equity for those students who do not have access to equations stored in their calculators. The availability of these equations to all students means that in the scoring of the exam, little or no credit will be awarded for simply writing down equations or for answers unsupported by explanations or logical development.

In general, the purpose of allowing calculators and equation sheets to be used in both sections of the exam is to place greater emphasis on the understanding and application of fundamental physical principles and concepts. For solving problems and writing essays, a sophisticated scientific or graphing calculator, or the availability of stored equations, is no substitute for a thorough grasp of the physics involved.

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AP Physics C: Mechanics Sample Multiple-Choice Questions

Most of the following sample questions have appeared in past exams. The answers are on page 44. Additional questions can be found in the 2009 *AP Physics B and Physics C Released Exams* book.

Note: Units associated with numerical quantities are abbreviated, using the abbreviations listed in the table of information included with the exams (see insert in this book). To simplify calculations, you may use $g = 10\ \text{m/s}^2$ in all problems.

Directions: Each of the questions or incomplete statements below is followed by five suggested answers or completions. Select the one that is best in each case.

Questions 1–2

The speed v of an automobile moving on a straight road is given in meters per second as a function of time t in seconds by the following equation:

$$v(t) = 4 + 2t^3$$

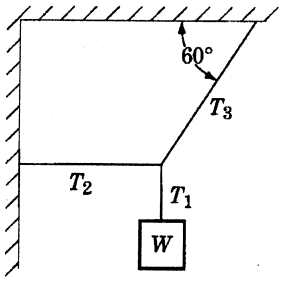
1. What is the acceleration of the automobile at $t = 2$ s?
   (A) $12\ \text{m/s}^2$
   (B) $16\ \text{m/s}^2$
   (C) $20\ \text{m/s}^2$
   (D) $24\ \text{m/s}^2$
   (E) $28\ \text{m/s}^2$

2. How far has the automobile traveled in the interval between $t = 0$ and $t = 2$ s?
   (A) 16 m
   (B) 20 m
   (C) 24 m
   (D) 32 m
   (E) 72 m

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3. If a particle moves in a plane so that its position is described by the functions $x = A \cos \omega t$ and $y = A \sin \omega t$, the particle is

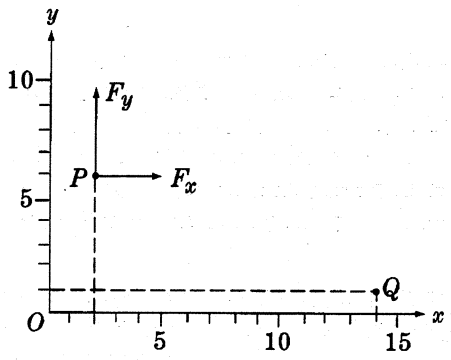
   (A) moving with constant speed along a circle
   (B) moving with varying speed along a circle
   (C) moving with constant acceleration along a straight line
   (D) moving along a parabola
   (E) oscillating back and forth along a straight line



4. A system in equilibrium consists of an object of weight W that hangs from three ropes, as shown above. The tensions in the ropes are T_1, T_2, and T_3. Which of the following are correct values of T_2 and T_3?

	T_2	T_3
(A)	$W \tan 60°$	$\dfrac{W}{\cos 60°}$
(B)	$W \tan 60°$	$\dfrac{W}{\sin 60°}$
(C)	$W \tan 60°$	$W \sin 60°$
(D)	$\dfrac{W}{\tan 60°}$	$\dfrac{W}{\cos 60°}$
(E)	$\dfrac{W}{\tan 60°}$	$\dfrac{W}{\sin 60°}$

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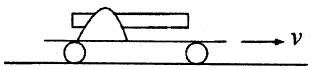
5. The constant force $\vec{F}$ with components $F_x = 3$ N and $F_y = 4$ N, shown above, acts on a body while that body moves from the point P ($x = 2$ m, $y = 6$ m) to the point Q ($x = 14$ m, $y = 1$ m). How much work does the force do on the body during this process?

(A) 16 J
(B) 30 J
(C) 46 J
(D) 56 J
(E) 65 J

6. The sum of all the external forces on a system of particles is zero. Which of the following must be true of the system?

(A) The total mechanical energy is constant.
(B) The total potential energy is constant.
(C) The total kinetic energy is constant.
(D) The total linear momentum is constant.
(E) It is in static equilibrium.

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7. A toy cannon is fixed to a small cart and both move to the right with speed v along a straight track, as shown above. The cannon points in the direction of motion. When the cannon fires a projectile the cart and cannon are brought to rest. If M is the mass of the cart and cannon combined without the projectile, and m is the mass of the projectile, what is the speed of the projectile relative to the ground immediately after it is fired?

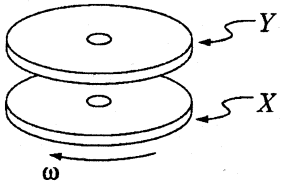
(A) $\frac{Mv}{m}$

(B) $\frac{(M+m)v}{m}$

(C) $\frac{(M-m)v}{m}$

(D) $\frac{mv}{(M)}$

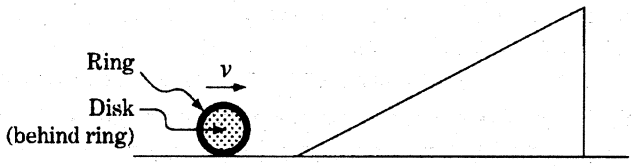
(E) $\frac{mv}{(M-m)}$



8. A disk X rotates freely with angular velocity ω on frictionless bearings, as shown above. A second identical disk Y, initially not rotating, is placed on X so that both disks rotate together without slipping. When the disks are rotating together, which of the following is half what it was before?

(A) Moment of inertia of X
(B) Moment of inertia of Y
(C) Angular velocity of X
(D) Angular velocity of Y
(E) Angular momentum of both disks

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9. The ring and the disk shown above have identical masses, radii, and velocities, and are not attached to each other. If the ring and the disk each roll without slipping up an inclined plane, how will the distances that they move up the plane before coming to rest compare?

   (A) The ring will move farther than will the disk.
   (B) The disk will move farther than will the ring.
   (C) The ring and the disk will move equal distances.
   (D) The relative distances depend on the angle of elevation of the plane.
   (E) The relative distances depend on the length of the plane.

10. Let g be the acceleration due to gravity at the surface of a planet of radius R. Which of the following is a dimensionally correct formula for the minimum kinetic energy K that a projectile of mass m must have at the planet's surface if the projectile is to escape from the planet's gravitational field?

    (A) $K = \sqrt{gR}$

    (B) $K = mgR$

    (C) $K = \frac{mg}{R}$

    (D) $K = m\sqrt{\frac{g}{R}}$

    (E) $K = gR$

Answers to AP Physics C: Mechanics Multiple-Choice Questions				
1 – D	3 – A	5 – A	7 – B	9 – A
2 – A	4 – E	6 – D	8 – C	10 – B

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AP Physics C: Mechanics Sample Free-Response Questions

AP PHYSICS C: MECHANICS
SECTION II
Time—45 minutes
3 Questions

Directions: Answer all three questions. The suggested time is about 15 minutes for answering each of the questions, which are worth 15 points each. The parts within a question may not have equal weight.



Mech. 1.

Students are to conduct an experiment to investigate the relationship between the terminal speed of a stack of falling paper coffee filters and its mass. Their procedure involves stacking a number of coffee filters, like the one shown in the figure above, and dropping the stack from rest. The students change the number of filters in the stack to vary the mass m while keeping the shape of the stack the same. As a stack of coffee filters falls, there is an air resistance (drag) force acting on the filters.

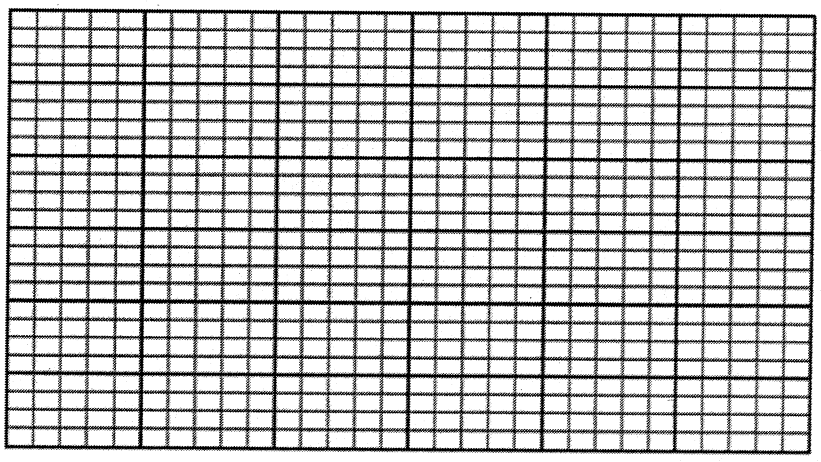
(a) The students suspect that the drag force F_D is proportional to the square of the speed v: $F_D = Cv^2$, where C is a constant. Using this relationship, derive an expression relating the terminal speed v_T to the mass m.

The students conduct the experiment and obtain the following data.

Mass of the stack of filters, m (kg)	1.12×10^{-3}	2.04×10^{-3}	2.96×10^{-3}	4.18×10^{-3}	5.10×10^{-3}
Terminal speed, v_T (m/s)	0.51	0.62	0.82	0.92	1.06

(b)

(i) Assuming the functional relationship for the drag force above,use the grid below to plot a linear graph as a function of m to verify the relationship. Use the empty boxes in the data table, as appropriate, to record any calculated values you are graphing. Label the vertical axis as appropriate, and place numbers on both axes.



m (kg)

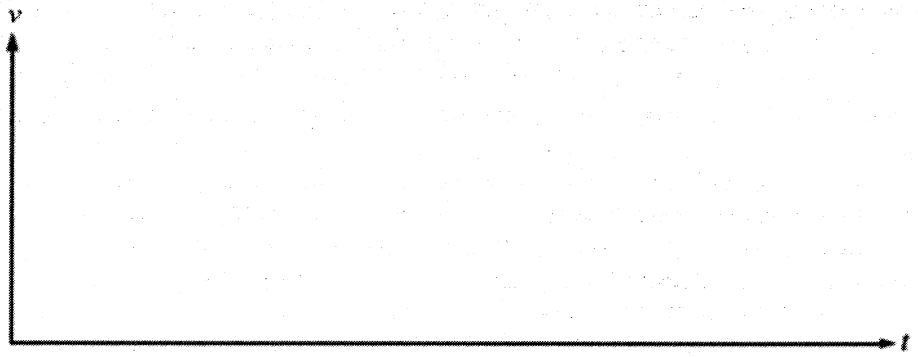
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(ii) Use your graph to calculate C.

A particular stack of filters with mass m is dropped from rest and reaches a speed very close to terminal speed by the time it has fallen a vertical distance Y.

(c)

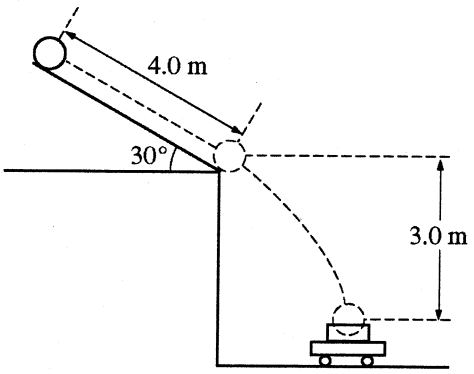
(i) Sketch an approximate graph of speed versus time from the time the filters are released up to the time $t = T$ that the filters have fallen the distance Y. Indicate time $t = T$ and terminal speed $v = v_T$ on the graph.



(ii) Suppose you had a graph like the one sketched in (c)(i) that had a numerical scale on each axis. Describe how you could use the graph to approximate the distance Y.

(d) Determine an expression for the approximate amount of mechanical energy dissipated, ΔE, due to air resistance during the time the stack falls a distance y, where $y > Y$. Express your answer in terms of y, m, v_T, and fundamental constants.

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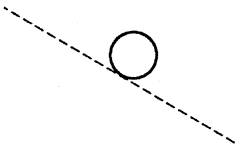


Note: Figure not drawn to scale.

Mech. 2.

A bowling ball of mass 6.0 kg is released from rest from the top of a slanted roof that is 4.0 m long and angled at 30°, as shown above. The ball rolls along the roof without slipping. The rotational inertia of a sphere of mass M and radius R about its center of mass is $\frac{2}{5}MR^2$.

(a) On the figure below, draw and label the forces (not components) acting on the ball at their points of application as it rolls along the roof.

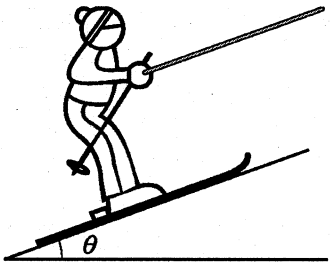


(b) Calculate the force due to friction acting on the ball as it rolls along the roof. If you need to draw anything other than what you have shown in part (a) to assist in your solution, use the space below. Do NOT add anything to the figure in part (a).

(c) Calculate the linear speed of the center of mass of the ball when it reaches the bottom edge of the roof.

(d) A wagon containing a box is at rest on the ground below the roof so that the ball falls a vertical distance of 3.0 m and lands and sticks in the center of the box. The total mass of the wagon and the box is 12 kg. Calculate the horizontal speed of the wagon immediately after the ball lands in it.

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Mech. 3.

A skier of mass m will be pulled up a hill by a rope, as shown above. The magnitude of the acceleration of the skier as a function of time t can be modeled by the equations

$$a = a_{\max} \sin\frac{\pi t}{T} \qquad (0 < t < T)$$
$$= 0 \qquad (t \geq T),$$

where $a_{\max}$ and T are constants. The hill is inclined at an angle θ above the horizontal, and friction between the skis and the snow is negligible. Express your answers in terms of given quantities and fundamental constants.

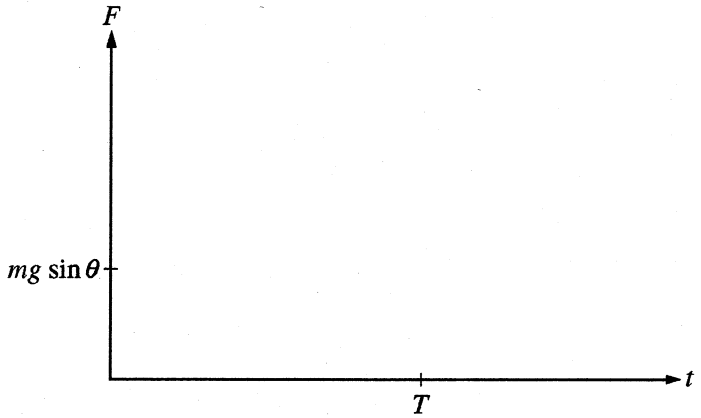
(a) Derive an expression for the velocity of the skier as a function of time during the acceleration. Assume the skier starts from rest.

(b) Derive an expression for the work done by the net force on the skier from rest until terminal speed is reached.

(c) Determine the magnitude of the force exerted by the rope on the skier at terminal speed.

(d) Derive an expression for the total impulse imparted to the skier during the acceleration.

(e) Suppose that the magnitude of the acceleration is instead modeled as $a = a_{\max} e^{-\pi t/2T}$ for all $t > 0$, where $a_{\max}$ and T are the same as in the original model. On the axes below, sketch the graphs of the force exerted by the rope on the skier for the two models, from $t = 0$ to a time $t > T$. Label the original model F_1 and the new model F_2.



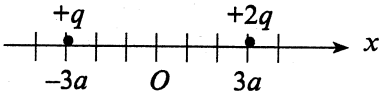
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AP Physics C: Electricity and Magnetism Sample Multiple-Choice Questions

Most of the following sample questions have appeared in past exams. The answers are on page 55. Additional questions can be found in the 2009 *AP Physics B and Physics C Released Exams* book.

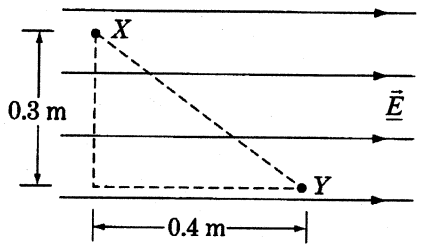
Note: Units associated with numerical quantities are abbreviated, using the abbreviations listed in the table of information included with the exams (see insert in this book.)

Directions: Each of the questions or incomplete statements below is followed by five suggested answers or completions. Select the one that is best in each case.



1. Two charges are located on the x-axis of a coordinate system as shown above. The charge $+2q$ is located at $x = +3a$ and the charge $+q$ is located at $x = -3a$. Where on the x-axis should an additional charge $+4q$ be located to produce an electric field equal to zero at the origin O?

   (A) $x = -6a$
   (B) $x = -2a$
   (C) $x = +a$
   (D) $x = +2a$
   (E) $x = +6a$

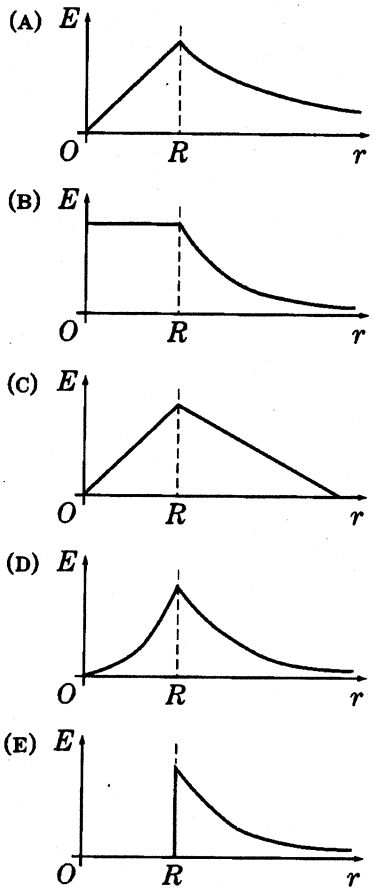


2. A uniform electric field $\vec{E}$ of magnitude 6,000 V/m exists in a region of space as shown above. What is the electric potential difference, $V_X - V_Y$, between points X and Y?

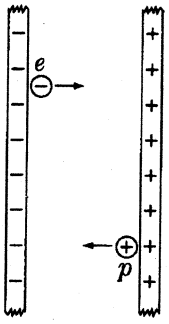
   (A) −12,000 V
   (B) 0 V
   (C) 1,800 V
   (D) 2,400 V
   (E) 3,000 V

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3. Charge is distributed uniformly throughout a long nonconducting cylinder of radius R. Which of the following graphs best represents the magnitude of the resulting electric field E as a function of r, the distance from the axis of the cylinder?

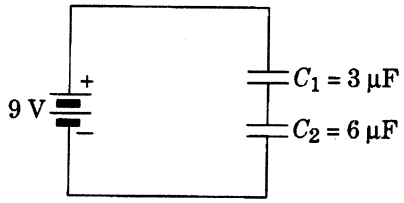


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4. A proton p and an electron e are released simultaneously on opposite sides of an evacuated area between large, charged parallel plates, as shown above. Each particle is accelerated toward the oppositely charged plate. The particles are far enough apart so that they do not affect each other. Which particle has the greater kinetic energy upon reaching the oppositely charged plate?

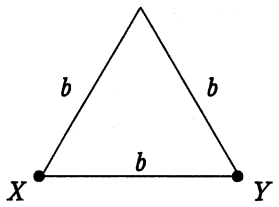
(A) The electron
(B) The proton
(C) Neither particle; both kinetic energies are the same.
(D) It cannot be determined without knowing the value of the potential difference between the plates.
(E) It cannot be determined without knowing the amount of charge on the plates.



5. Two capacitors initially uncharged are connected in series to a battery, as shown above. What is the charge on the top plate of C_1?

(A) −81 μC
(B) −18 μC
(C) 0 μC
(D) +18 μC
(E) +81 μC

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6. Wire of resistivity ρ and cross-sectional area A is formed into an equilateral triangle of side b, as shown above. The resistance between two vertices of the triangle, X and Y, is

(A) $\frac{3}{2}\frac{A}{\rho b}$

(B) $3\frac{A}{\rho b}$

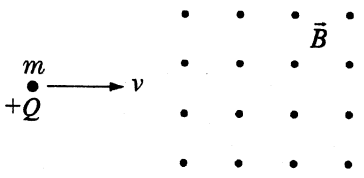
(C) $\frac{2}{3}\frac{\rho b}{A}$

(D) $\frac{3}{2}\frac{\rho b}{A}$

(E) $3\frac{\rho b}{A}$

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Questions 7–8



A particle of electric charge $+Q$ and mass m initially moves along a straight line in the plane of the page with constant speed v, as shown above. The particle enters a uniform magnetic field of magnitude B directed out of the page and moves in a semicircular arc of radius R.

7. Which of the following best indicates the magnitude and the direction of the magnetic force $\vec{F}$ on the charge just after the charge enters the magnetic field?

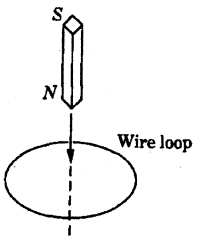
	Magnitude	Direction
(A)	$\frac{kQ^2}{R^2}$	Toward the top of the page
(B)	$\frac{kQ^2}{R^2}$	Toward the bottom of the page
(C)	QvB	Out of the plane of the page
(D)	QvB	Toward the top of the page
(E)	QvB	Toward the bottom of the page

8. If the magnetic field strength is increased, which of the following will be true about the radius R?

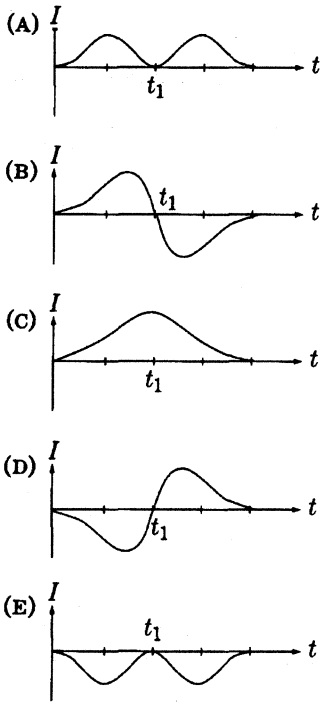
I. R increases if the incident speed is held constant.
II. For R to remain constant, the incident speed must be increased.
III. For R to remain constant, the incident speed must be decreased.

(A) I only
(B) II only
(C) III only
(D) I and II only
(E) I and III only

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9. A bar magnet is lowered at constant speed through a loop of wire as shown in the diagram above. The time at which the midpoint of the bar magnet passes through the loop is t_1. Which of the following graphs best represents the time dependence of the induced current in the loop? (A positive current represents a counterclockwise current in the loop as viewed from above.)



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10. A loop of wire enclosing an area of 1.5 m^2 is placed perpendicular to a magnetic field. The field is given in teslas as a function of time t in seconds by

$$B(t) = \frac{20t}{3} - 5$$

The induced emf in the loop at $t = 3$ s is most nearly

(A) 0 V
(B) 5 V
(C) 10 V
(D) 15 V
(E) 20 V

Answers to AP Physics C: Electricity and Magnetism Multiple-Choice Questions

1 – A	3 – A	5 – D	7 – E	9 – B
2 – D	4 – C	6 – C	8 – B	10 – C

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AP Physics C: Electricity and Magnetism Sample Free-Response Questions

AP PHYSICS C: ELECTRICITY AND MAGNETISM

SECTION II
Time—45 minutes
3 Questions

Directions: Answer all three questions. The suggested time is about 15 minutes for answering each of the questions, which are worth 15 points each. The parts within a question may not have equal weight.

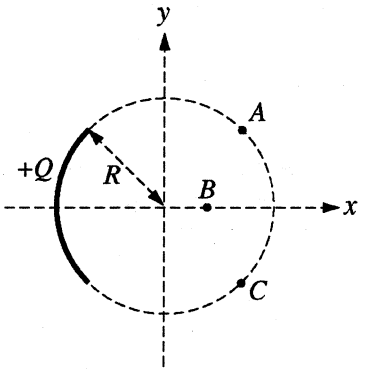


Figure I

E&M. 1.

A charge $+Q$ is uniformly distributed over a quarter circle of radius R, as shown above. Points A, B, and C are located as shown, with A and C located symmetrically relative to the x-axis. Express all algebraic answers in terms of the given quantities and fundamental constants.

(a) Rank the magnitude of the electric potential at points A, B, and C from greatest to least, with number 1 being greatest. If two points have the same potential, give them the same ranking.

____V_A ____V_B ____V_C

Justify your rankings.

Point P is at the origin, as shown below, and is the center of curvature of the charge distribution.

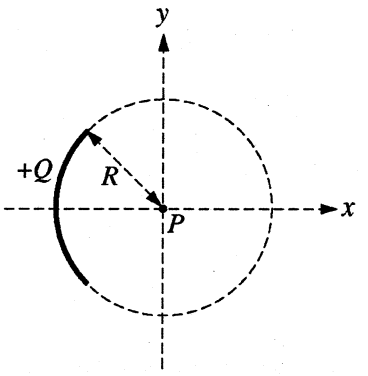


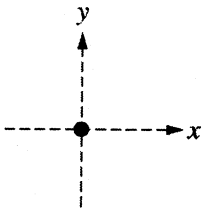
Figure II

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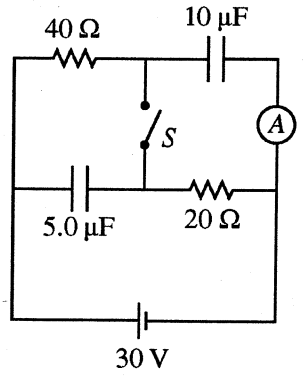
(b) Determine an expression for the electric potential at point P due to the charge Q.

(c) A positive point charge q with mass m is placed at point P and released from rest. Derive an expression for the speed of the point charge when it is very far from the origin.

(d) On the dot representing point P below, indicate the direction of the electric field at point P due to the charge Q.



(e) Derive an expression for the magnitude of the electric field at point P.



E&M. 2.

In the circuit illustrated above, switch S is initially open and the battery has been connected for a long time.

(a) What is the steady-state current through the ammeter?

(b) Calculate the charge on the 10 μF capacitor.

(c) Calculate the energy stored in the 5.0 μF capacitor.

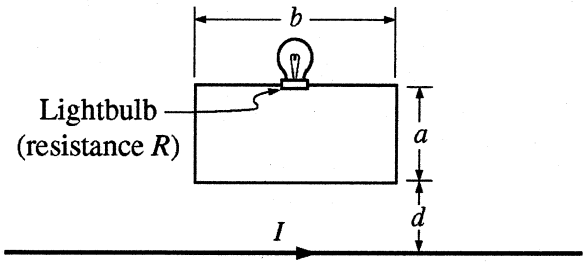
The switch is now closed, and the circuit comes to a new steady state.

(d) Calculate the steady-state current through the battery.

(e) Calculate the final charge on the 5.0 μF capacitor.

(f) Calculate the energy dissipated as heat in the 40 Ω resistor in one minute once the circuit has reached steady state.

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E&M. 3.

The long straight wire illustrated above carries a current I to the right. The current varies with time t according to the equation $I = I_0 - Kt$, where I_0 and K are positive constants and I remains positive throughout the time period of interest. The bottom of a rectangular loop of wire of width b and height a is located a distance d above the long wire, with the long wire in the plane of the loop as shown. A lightbulb with resistance R is connected in the loop. Express all algebraic answers in terms of the given quantities and fundamental constants.

(a) Indicate the direction of the current in the loop.

____Clockwise ____Counterclockwise

Justify your answer.

(b) Indicate whether the lightbulb gets brighter, gets dimmer, or stays the same brightness over the time period of interest.

____Gets brighter ____Gets dimmer ____Remains the same

Justify your answer.

(c) Determine the magnetic field at $t = 0$ due to the current in the long wire at distance r from the long wire.

(d) Derive an expression for the magnetic flux through the loop as a function of time.

(e) Derive an expression for the power dissipated by the lightbulb.

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ADVANCED PLACEMENT PHYSICS C TABLE OF INFORMATION

CONSTANTS AND CONVERSION FACTORS

Proton mass, $m_p = 1.67 \times 10^{-27}$ kg	Electron charge magnitude, $e = 1.60 \times 10^{-19}$ C
Neutron mass, $m_n = 1.67 \times 10^{-27}$ kg	1 electron volt, 1 eV $= 1.60 \times 10^{-19}$ J
Electron mass, $m_e = 9.11 \times 10^{-31}$ kg	Speed of light, $c = 3.00 \times 10^{8}$ m/s
Avogadro's number, $N_0 = 6.02 \times 10^{23}$ mol^{-1}	Universal gravitational constant, $G = 6.67 \times 10^{-11}$ $\left(\text{N}\cdot\text{m}^2\right)/\text{kg}^2$
Universal gas constant, $R = 8.31$ J/(mol·K)	Acceleration due to gravity at Earth's surface, $g = 9.8$ m/s^2
Boltzmann's constant, $k_B = 1.38 \times 10^{-23}$ J/K	

1 unified atomic mass unit,	$1\text{ u} = 1.66 \times 10^{-27}$ kg $= 931$ MeV/c^2
Planck's constant,	$h = 6.63 \times 10^{-34}$ J·s $= 4.14 \times 10^{-15}$ eV·s
	$hc = 1.99 \times 10^{-25}$ J·m $= 1.24 \times 10^{3}$ eV·nm
Vacuum permittivity,	$\varepsilon_0 = 8.85 \times 10^{-12}$ $\text{C}^2/\left(\text{N}\cdot\text{m}^2\right)$
Coulomb's law constant,	$k = 1/(4\pi\varepsilon_0) = 9.0 \times 10^{9}$ $\left(\text{N}\cdot\text{m}^2\right)/\text{C}^2$
Vacuum permeability,	$\mu_0 = 4\pi \times 10^{-7}$ (T·m)/A
Magnetic constant,	$k' = \mu_0/(4\pi) = 1 \times 10^{-7}$ (T·m)/A
1 atmosphere pressure,	$1\text{ atm} = 1.0 \times 10^{5}$ N/m^2 $= 1.0 \times 10^{5}$ Pa

UNIT SYMBOLS								
	meter,	m	mole,	mol	watt,	W	farad,	F
	kilogram,	kg	hertz,	Hz	coulomb,	C	tesla,	T
	second,	s	newton,	N	volt,	V	degree Celsius,	°C
	ampere,	A	pascal,	Pa	ohm,	Ω	electron volt,	eV
	kelvin,	K	joule,	J	henry,	H		

PREFIXES		
Factor	Prefix	Symbol
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

VALUES OF TRIGONOMETRIC FUNCTIONS FOR COMMON ANGLES							
θ	0°	30°	37°	45°	53°	60°	90°
$\sin\theta$	0	1/2	3/5	$\sqrt{2}/2$	4/5	$\sqrt{3}/2$	1
$\cos\theta$	1	$\sqrt{3}/2$	4/5	$\sqrt{2}/2$	3/5	1/2	0
$\tan\theta$	0	$\sqrt{3}/3$	3/4	1	4/3	$\sqrt{3}$	∞

The following assumptions are used in this exam.

I. The frame of reference of any problem is inertial unless otherwise stated.
II. The direction of current is the direction in which positive charges would drift.
III. The electric potential is zero at an infinite distance from an isolated point charge.
IV. All batteries and meters are ideal unless otherwise stated.
V. Edge effects for the electric field of a parallel plate capacitor are negligible unless otherwise stated.

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ADVANCED PLACEMENT PHYSICS C EQUATIONS

MECHANICS

$v_x = v_{x0} + a_x t$

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

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

$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$

$\vec{F} = \frac{d\vec{p}}{dt}$

$\vec{J} = \int \vec{F}\, dt = \Delta\vec{p}$

$\vec{p} = m\vec{v}$

$|\vec{F}_f| \le \mu |\vec{F}_N|$

$\Delta E = W = \int \vec{F} \cdot d\vec{r}$

$K = \frac{1}{2} m v^2$

$P = \frac{dE}{dt}$

$P = \vec{F} \cdot \vec{v}$

$\Delta U_g = mg\Delta h$

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

$\vec{\tau} = \vec{r} \times \vec{F}$

$\vec{\alpha} = \frac{\sum \vec{\tau}}{I} = \frac{\vec{\tau}_{net}}{I}$

$I = \int r^2 dm = \sum m r^2$

$x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$

$v = r\omega$

$\vec{L} = \vec{r} \times \vec{p} = I\vec{\omega}$

$K = \frac{1}{2} I \omega^2$

$\omega = \omega_0 + \alpha t$

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

a = acceleration
E = energy
F = force
f = frequency
h = height
I = rotational inertia
J = impulse
K = kinetic energy
k = spring constant
ℓ = length
L = angular momentum
m = mass
P = power
p = momentum
r = radius or distance
T = period
t = time
U = potential energy
v = velocity or speed
W = work done on a system
x = position
μ = coefficient of friction
θ = angle
τ = torque
ω = angular speed
α = angular acceleration
ϕ = phase angle

$\vec{F}_s = -k\Delta\vec{x}$

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

$x = x_{\max} \cos(\omega t + \phi)$

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

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

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

$|\vec{F}_G| = \frac{G m_1 m_2}{r^2}$

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

ELECTRICITY AND MAGNETISM

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

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

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

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

$\Delta V = -\int \vec{E} \cdot d\vec{r}$

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

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

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

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

$C_p = \sum_i C_i$

$\frac{1}{C_s} = \sum_i \frac{1}{C_i}$

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

$U_C = \frac{1}{2} Q \Delta V = \frac{1}{2} C (\Delta V)^2$

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

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

$I = N e v_d A$

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

$R_s = \sum_i R_i$

$\frac{1}{R_p} = \sum_i \frac{1}{R_i}$

$P = I\Delta V$

A = area
B = magnetic field
C = capacitance
d = distance
E = electric field
$\mathcal{E}$ = emf
F = force
I = current
J = current density
L = inductance
ℓ = length
n = number of loops of wire per unit length
N = number of charge carriers per unit volume
P = power
Q = charge
q = point charge
R = resistance
r = radius or distance
t = time
U = potential or stored energy
V = electric potential
v = velocity or speed
ρ = resistivity
Φ = flux
κ = dielectric constant

$\vec{F}_M = q\vec{v} \times \vec{B}$

$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I$

$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I\, d\vec{\ell} \times \hat{r}}{r^2}$

$\vec{F} = \int I\, d\vec{\ell} \times \vec{B}$

$B_s = \mu_0 n I$

$\Phi_B = \int \vec{B} \cdot d\vec{A}$

$\mathcal{E} = \oint \vec{E} \cdot d\vec{\ell} = -\frac{d\Phi_B}{dt}$

$\mathcal{E} = -L\frac{dI}{dt}$

$U_L = \frac{1}{2} L I^2$

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ADVANCED PLACEMENT PHYSICS C EQUATIONS

GEOMETRY AND TRIGONOMETRY

Rectangle

$A = bh$

Triangle

$A = \frac{1}{2}bh$

Circle

$A = \pi r^2$

$C = 2\pi r$

$s = r\theta$

Rectangular Solid

$V = \ell wh$

Cylinder

$V = \pi r^2 \ell$

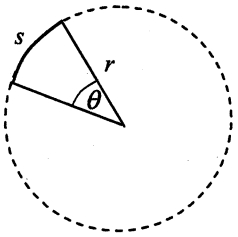
$S = 2\pi r\ell + 2\pi r^2$

Sphere

$V = \frac{4}{3}\pi r^3$

$S = 4\pi r^2$

A = area
C = circumference
V = volume
S = surface area
b = base
h = height
ℓ = length
w = width
r = radius
s = arc length
θ = angle



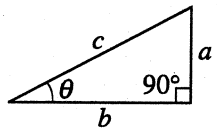
Right Triangle

$a^2 + b^2 = c^2$

$\sin\theta = \frac{a}{c}$

$\cos\theta = \frac{b}{c}$

$\tan\theta = \frac{a}{b}$



CALCULUS

$$\frac{df}{dx} = \frac{df}{du}\frac{du}{dx}$$

$$\frac{d}{dx}(x^n) = nx^{n-1}$$

$$\frac{d}{dx}(e^{ax}) = ae^{ax}$$

$$\frac{d}{dx}(\ln ax) = \frac{1}{x}$$

$$\frac{d}{dx}[\sin(ax)] = a\cos(ax)$$

$$\frac{d}{dx}[\cos(ax)] = -a\sin(ax)$$

$$\int x^n dx = \frac{1}{n+1}x^{n+1},\ n \neq -1$$

$$\int e^{ax} dx = \frac{1}{a}e^{ax}$$

$$\int \frac{dx}{x+a} = \ln|x+a|$$

$$\int \cos(ax)dx = \frac{1}{a}\sin(ax)$$

$$\int \sin(ax)dx = -\frac{1}{a}\cos(ax)$$

VECTOR PRODUCTS

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

$|\vec{A} \times \vec{B}| = AB\sin\theta$

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