CollegeBoard

AP® Physics C: Electricity and Magnetism Practice Exam

From the 2016 Administration

Contents

Note: This publication shows the page numbers that appeared in the ***2015–16 AP Exam Instructions*** book and in the actual exam. This publication was not repaginated to begin with page 1.

Exam Instructions

The following contains instructions taken from the *2015–16 AP Exam Instructions* book.

AP® Physics C: Electricity and Magnetism Exam

Regularly Scheduled Exam Date: Monday afternoon, May 9, 2016

Late-Testing Exam Date: Friday afternoon, May 20, 2016

Section I Total Time: 45 min.   Section II Total Time: 45 min.

Section I **Total Time:** 45 minutes Calculator Allowed **Number of Questions:** 35* **Percent of Total Score:** 50% **Writing Instrument:** Pencil required **The number of questions may vary slightly depending on the form of the exam.*	**Section II** **Total Time:** 45 minutes Calculator Allowed **Number of Questions:** 3 **Percent of Total Score:** 50% **Writing Instrument:** Pen with black or dark blue ink, or pencil

What Proctors Need to Bring to This Exam

- Exam packets
- Answer sheets
- AP Student Packs
- *2015-16 AP Coordinator's Manual*
- This book — *AP Exam Instructions*
- AP Exam Seating Chart template(s)
- School Code and Home-School/Self-Study Codes
- Extra calculators
- Extra rulers or straightedges
- Pencil sharpener
- Container for students' electronic devices (if needed)
- Extra No. 2 pencils with erasers
- Extra pens with black or dark blue ink
- Extra paper
- Stapler
- Watch
- Signs for the door to the testing room
  – "Exam in Progress"
  – "Cell phones are prohibited in the testing room"

Students are permitted to use rulers, straightedges, and four-function, scientific, or graphing calculators for the entire exam (Sections I and II). Before starting the exam administration, make sure each student has an appropriate calculator, and any student with a graphing calculator has a model from the approved list on page 47 of the *2015-16 AP Coordinator's Manual*. See pages 44–47 of the *AP Coordinator's Manual* for more information. If a student does not have an appropriate calculator or has a graphing calculator not on the approved list, you may provide one from your supply. If the student does not want to use the calculator you provide or does not want to use a calculator at all, he or she must hand copy, date, and sign the release statement on page 45 of the *AP Coordinator's Manual*.

During the administration of Section II, students may have no more than two calculators on their desks. Calculators may not be shared. Calculator memories do not need to be cleared before or after the exam. Students with Hewlett-Packard 48–50 Series and Casio FX-9860 graphing calculators may use cards designed for use with these calculators. Proctors should make sure infrared ports (Hewlett-Packard) are not facing each other. **Since graphing calculators can be used to store data, including text, proctors should monitor that students are using their calculators appropriately. Attempts by students to use the calculator to remove exam questions and/or answers from the room may result in the cancellation of AP Exam scores.**

Tables containing equations commonly used in physics are included in each AP Exam booklet, for use during the entire exam. Students are NOT allowed to bring their own copies of the equation tables to the exam room.

Students may take both Physics C exams, Mechanics only, or Electricity and Magnetism only. The Mechanics exam is administered first, after which students taking both exams are given a break. Then the Electricity and Magnetism exam is administered. Prior to testing day, determine which students are taking only Electricity and Magnetism, and tell them to report to the testing room at approximately 2 p.m. (1 p.m. in Alaska). You should instruct them to wait quietly outside the room until told to come in, since students taking Mechanics may not have been dismissed yet. If all students are taking Electricity and Magnetism only, you must not begin the exam before 2 p.m.

SECTION I: Multiple Choice

! Do not begin the exam instructions below until you have completed the appropriate General Instructions for your group.

This exam includes survey questions. The time allowed for the survey questions is in addition to the actual test-taking time.

Make sure that you begin the exam at the designated time. Remember, you must complete a seating chart for this exam. See pages 305–306 for a seating chart template and instructions. See the *2015-16 AP Coordinator's Manual* for exam seating requirements (pages 49–52).

If you are giving the regularly scheduled exam, say:

> **It is Monday afternoon, May 9, and you will be taking the AP Physics C: Electricity and Magnetism Exam.**

If you are giving the alternate exam for late testing, say:

> **It is Friday afternoon, May 20, and you will be taking the AP Physics C: Electricity and Magnetism Exam.**

> **In a moment, you will open the packet that contains your exam materials. By opening this packet, you agree to all of the AP Program's policies and procedures outlined in the *2015-16 Bulletin for AP Students and Parents*. You may now remove the shrinkwrap from your exam packet and take out the Section I booklet, but do not open the booklet or the shrinkwrapped Section II materials. Put the white seals aside. . . .**

> **Carefully remove the AP Exam label found near the top left of your exam booklet cover. Now place it on page 1 of your answer sheet on the light blue box near the top right-hand corner that reads "AP Exam Label."**

If students accidentally place the exam label in the space for the number label or vice versa, advise them to leave the labels in place. They should not try to remove the label; their exam can still be processed correctly.

> **Read the statements on the front cover of Section I and look up when you have finished. . . .**

Sign your name and write today's date. Look up when you have finished. . . .

Now print your full legal name where indicated. Are there any questions? . . .

Turn to the back cover of your exam booklet and read it completely. Look up when you have finished. . . .

Are there any questions? . . .

You will now take the multiple-choice portion of the exam. You should have in front of you the multiple-choice booklet and your answer sheet. Open your answer sheet to page 2. You may never discuss these specific multiple-choice questions at any time in any form with anyone, including your teacher and other students. If you disclose these questions through any means, your AP Exam score will be canceled.

You must complete the answer sheet using a No. 2 pencil only. Mark all of your responses beginning on page 2 of your answer sheet, one response per question. Completely fill in the circles. If you need to erase, do so carefully and completely. No credit will be given for anything written in the exam booklet. Scratch paper is not allowed, but you may use the margins or any blank space in the exam booklet for scratch work. Rulers, straightedges, and calculators may be used for the entire exam. You may place these items on your desk. Are there any questions? . . .

You have 45 minutes for this section. Open your Section I booklet and begin.

Note Start Time here ___________. Note Stop Time here ___________. Check that students are marking their answers in pencil on their answer sheets and that they are not looking at their shrinkwrapped Section II booklets. After 35 minutes, say:

There are 10 minutes remaining.

After 10 minutes, say:

Stop working and turn to the last page of your booklet. . . .

You have 2 minutes to answer Questions 101–106. These are survey questions and will not affect your score. You may not go back to work on any of the exam questions. You may now begin.

To help you and your proctors make sure students are not working on the exam questions, the two pages with the survey questions are identified with a large S on the upper corner of each page. Give students 2 minutes to answer the survey questions. Then say:

Close your booklet and put your answer sheet on your desk, face up. Make sure you have your AP number label and an AP Exam label on page 1 of your answer sheet. Sit quietly while I collect your answer sheets.

Collect an answer sheet from each student. Check that each answer sheet has an AP number label and an AP Exam label. After all answer sheets have been collected, say:

Now you must seal your exam booklet using the white seals you set aside earlier. Remove the white seals from the backing and press one on each area

of your exam booklet cover marked "PLACE SEAL HERE." Fold each seal over the back cover. When you have finished, place the booklet on your desk, face up. I will now collect your Section I booklet. . . .

SECTION II: Free Response

Check that each student has signed the front cover of the sealed Section I booklet. When all Section I materials have been collected and accounted for, say:

May I have everyone's attention? Place your Student Pack on your desk. . . .

You may now remove the shrinkwrap from the Section II packet, but do not open the exam booklet until you are told to do so. . . .

Read the bulleted statements on the front cover of the exam booklet. Look up when you have finished. . . .

Now take an AP number label from your Student Pack and place it on the shaded box. If you don't have any AP number labels, write your AP number in the box. Look up when you have finished. . . .

Read the last statement. . . .

Using a pen with black or dark blue ink, print the first, middle, and last initials of your legal name in the boxes and print today's date where indicated. This constitutes your signature and your agreement to the statements on the front cover. . . .

Turn to the back cover and, using your pen, complete Item 1 under "Important Identification Information." Print the first two letters of your last name and the first letter of your first name in the boxes. Look up when you have finished. . . .

In Item 2, print your date of birth in the boxes. . . .

In Item 3, write the school code you printed on the front of your Student Pack in the boxes. . . .

Read Item 4. . . .

Are there any questions? . . .

I need to collect the Student Pack from anyone who will be taking another AP Exam. You may keep it only if you are not taking any other AP Exams this year. If you have no other AP Exams to take, place your Student Pack under your chair now. . . .

Read the information on the back cover of the exam booklet. Do not open the booklet until you are told to do so. Look up when you have finished. . . .

Collect the Student Packs. Then say:

Are there any questions? . . .

Rulers, straightedges, and calculators may be used for Section II. Be sure these items are on your desk. . . .

You have 45 minutes to complete Section II. You are responsible for pacing yourself and may proceed freely from one question to the next. You must write your answers in the exam booklet using a pen with black or dark blue ink or a No. 2 pencil. If you use a pencil, be sure that your writing is dark enough to be easily read. If you need more paper during the exam, raise your hand. At the top of each extra sheet of paper you use be sure to write only your AP number and the question number you are working on. Do not write your name. Are there any questions? . . .

You may begin.

Note Start Time here __________. Note Stop Time here __________. You should also make sure that Hewlett-Packard calculators' infrared ports are not facing each other and that students are not sharing calculators. After 35 minutes, say:

There are 10 minutes remaining.

After 10 minutes, say:

Stop working and close your exam booklet. Place it on your desk, face up. . . .

If any students used extra paper for a question in the free-response section, have those students staple the extra sheet(s) to the first page corresponding to that question in their exam booklets. Complete an Incident Report. A single Incident Report may be completed for multiple students per exam subject per administration (regular or late testing) as long as all of the required information is provided. Include all exam booklets with extra sheets of paper in an Incident Report return envelope (see page 60 of the *2015-16 AP Coordinator's Manual* for complete details). Then say:

Remain in your seat, without talking, while the exam materials are collected. . . .

Collect a Section II booklet from each student. Check for the following:

- Exam booklet front cover: The student placed an AP number label on the shaded box and printed his or her initials and today's date.
- Exam booklet back cover: The student completed the "Important Identification Information" area.

When all exam materials have been collected and accounted for, return to students any electronic devices you may have collected before the start of the exam.

If you are giving the regularly scheduled exam, say:

You may not discuss or share these specific free-response questions with anyone unless they are released on the College Board website in about two days. Your AP Exam score results will be available online in July.

If you are giving the alternate exam for late testing, say:

None of the questions in this exam may ever be discussed or shared in any way at any time. Your AP Exam score results will be available online in July.

If any students completed the AP number card at the beginning of this exam, say:

> **Please remember to take your AP number card with you. You will need the information on this card to view your scores and order AP score reporting services online.**

Then say:

> **You are now dismissed.**

All exam materials must be placed in secure storage until they are returned to the AP Program after your school's last administration. Before storing materials, check the "School Use Only" section on page 1 of the answer sheet and:

- Fill in the appropriate section number circle in order to access a separate AP Instructional Planning Report (for regularly scheduled exams only) or subject score roster at the class section or teacher level. See "Post-Exam Activities" in the *2015-16 AP Coordinator's Manual*.
- Check your list of students who are eligible for fee reductions and fill in the appropriate circle on their registration answer sheets.

Be sure to give the completed seating chart to the AP Coordinator. Schools must retain seating charts for at least six months (unless the state or district requires that they be retained for a longer period of time). Schools should not return any seating charts in their exam shipments unless they are required as part of an Incident Report.

Student Answer Sheet for the Multiple-Choice Section

Use this section to capture student responses. (Note that the following answer sheet is a sample, and may differ from one used in an actual exam.)

AP Answer Sheet 2016

AP Number Label (from Student Pack)

B123456789T

AP Exam Label (from Section I Booklet)

CollegeBoard

COMPLETE THIS AREA AT EVERY EXAM. USE NO. 2 PENCIL ONLY

To maintain the security of the exam and the validity of my AP score, I will allow no one else to see the multiple-choice questions. I will seal the multiple-choice booklet when asked to do so, and I will not discuss these questions with anyone at any time after completing the section. I am aware of and agree to the AP Program's policies and procedures as outlined in the *2015-16 Bulletin for AP Students and Parents*, including using testing accommodations (e.g., extended time, computer, etc.) only if I have been preapproved by College Board Services for Students with Disabilities.

A. SIGNATURE — Sign your legal name as it will appear on your college applications. Date

B. LEGAL NAME — Omit apostrophes, Jr., II.

Legal Last Name — First 15 Letters | Legal First Name — First 12 Letters | MI

C. YOUR AP NUMBER

D. EXAM DATE — Month | Day

E. EXAM START TIME — AM | PM

F. MULTIPLE-CHOICE BOOKLET SERIAL NUMBER — S

G. ONLINE PROVIDER CODE

H. AP EXAM I AM TAKING USING THIS ANSWER SHEET — Exam Name: | Form: | Form Code:

785208

SCHOOL USE ONLY

Section Number: 1 2 3 4 5 6 7 8 9

Fee Reduction Granted: 1 Option 1 2 Option 2

COMPLETE THIS AREA ONLY ONCE.

I. AREA CODE AND PHONE NUMBER

INTERNATIONAL PHONE

J. SCHOOL YOU ATTEND

SCHOOL CODE — School Name, City, State, Country

K. DATE OF BIRTH

Month | Day | Year

Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec

L. SOCIAL SECURITY NUMBER (Optional)

M. COLLEGE TO RECEIVE YOUR AP SCORE REPORT

COLLEGE CODE — Using the college code listed in the AP Student Pack, indicate the **ONE** college that you want to receive your AP score report.

College Name, City, State, Country

N. CURRENT GRADE LEVEL

- Not yet in 9th grade
- 9th
- 10th
- 11th
- 12th
- No longer in high school

O. STUDENT SEARCH SERVICE®

Colleges and scholarship programs may request your information to inform you of educational opportunities and financial aid.

Would you like us to supply your information?

- Yes
- No

If you don't answer and previously chose to participate in this service, we will continue providing your information.

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COMPLETE THIS AREA AT EACH EXAM (IF APPLICABLE).

P. SURVEY QUESTIONS — Answer the survey questions in the AP Student Pack. Do not put responses to exam questions in this section.

1	A B C D E F G H I	4	A B C D E F G H I	7	A B C D E F G H I
2	A B C D E F G H I	5	A B C D E F G H I	8	A B C D E F G H I
3	A B C D E F G H I	6	A B C D E F G H I	9	A B C D E F G H I

Q. LANGUAGE — Do not complete this section unless instructed to do so.

If this answer sheet is for the French Language and Culture, German Language and Culture, Italian Language and Culture, Spanish Language and Culture, or Spanish Literature and Culture Exam, please answer the following questions. Your responses will not affect your score.

1. Have you lived or studied for one month or more in a country where the language of the exam you are now taking is spoken?

   Yes No

2. Do you regularly speak or hear the language at home?

   Yes No

QUESTIONS 1–75

Indicate your answers to the exam questions in this section (pages 2 and 3). Mark only one response per question for Questions 1 through 120. If a question has only four answer options, do not mark option E. Answers written in the multiple-choice booklet will not be scored.

COMPLETE MARK

EXAMPLES OF INCOMPLETE MARKS

You must use a No. 2 pencil and marks must be complete. Do not use a mechanical pencil. It is very important that you fill in the entire circle darkly and completely. If you change your response, erase as completely as possible. Incomplete marks or erasures may affect your score.

1	A B C D E	26	A B C D E	51	A B C D E
2	A B C D E	27	A B C D E	52	A B C D E
3	A B C D E	28	A B C D E	53	A B C D E
4	A B C D E	29	A B C D E	54	A B C D E
5	A B C D E	30	A B C D E	55	A B C D E
6	A B C D E	31	A B C D E	56	A B C D E
7	A B C D E	32	A B C D E	57	A B C D E
8	A B C D E	33	A B C D E	58	A B C D E
9	A B C D E	34	A B C D E	59	A B C D E
10	A B C D E	35	A B C D E	60	A B C D E
11	A B C D E	36	A B C D E	61	A B C D E
12	A B C D E	37	A B C D E	62	A B C D E
13	A B C D E	38	A B C D E	63	A B C D E
14	A B C D E	39	A B C D E	64	A B C D E
15	A B C D E	40	A B C D E	65	A B C D E
16	A B C D E	41	A B C D E	66	A B C D E
17	A B C D E	42	A B C D E	67	A B C D E
18	A B C D E	43	A B C D E	68	A B C D E
19	A B C D E	44	A B C D E	69	A B C D E
20	A B C D E	45	A B C D E	70	A B C D E
21	A B C D E	46	A B C D E	71	A B C D E
22	A B C D E	47	A B C D E	72	A B C D E
23	A B C D E	48	A B C D E	73	A B C D E
24	A B C D E	49	A B C D E	74	A B C D E
25	A B C D E	50	A B C D E	75	A B C D E

ETS USE ONLY

Exam		0 1 2 3 4 5 6 7 8 9
		0 1 2 3 4 5 6 7 8 9
Exam		0 1 2 3 4 5 6 7 8 9
		0 1 2 3 4 5 6 7 8 9

SELECTED MEDIA EXAMS	R	W	O	OTHER EXAMS	R	W	O
PT02				TOTAL			
PT03				Subscore (if applicable)			
PT04				Subscore (if applicable)			

DO NOT WRITE IN THIS AREA

QUESTIONS 76–120

Be sure each mark is dark and completely fills the circle. If a question has only four answer options, do not mark option E.

76	A B C D E	91	A B C D E	106	A B C D E
77	A B C D E	92	A B C D E	107	A B C D E
78	A B C D E	93	A B C D E	108	A B C D E
79	A B C D E	94	A B C D E	109	A B C D E
80	A B C D E	95	A B C D E	110	A B C D E
81	A B C D E	96	A B C D E	111	A B C D E
82	A B C D E	97	A B C D E	112	A B C D E
83	A B C D E	98	A B C D E	113	A B C D E
84	A B C D E	99	A B C D E	114	A B C D E
85	A B C D E	100	A B C D E	115	A B C D E
86	A B C D E	101	A B C D E	116	A B C D E
87	A B C D E	102	A B C D E	117	A B C D E
88	A B C D E	103	A B C D E	118	A B C D E
89	A B C D E	104	A B C D E	119	A B C D E
90	A B C D E	105	A B C D E	120	A B C D E

QUESTIONS 121–126

For Students Taking AP Biology

Write your answer in the boxes at the top of the griddable area and fill in the corresponding circles. Mark only one circle in any column. You will receive credit only if the circles are filled in correctly.

121

		/	/	/	
–	.	.	.	.	.
		0	0	0	0
	1	1	1	1	1
	2	2	2	2	2
	3	3	3	3	3
	4	4	4	4	4
	5	5	5	5	5
	6	6	6	6	6
	7	7	7	7	7
	8	8	8	8	8
	9	9	9	9	9

122

		/	/	/	
–	.	.	.	.	.
		0	0	0	0
	1	1	1	1	1
	2	2	2	2	2
	3	3	3	3	3
	4	4	4	4	4
	5	5	5	5	5
	6	6	6	6	6
	7	7	7	7	7
	8	8	8	8	8
	9	9	9	9	9

123

		/	/	/	
–	.	.	.	.	.
		0	0	0	0
	1	1	1	1	1
	2	2	2	2	2
	3	3	3	3	3
	4	4	4	4	4
	5	5	5	5	5
	6	6	6	6	6
	7	7	7	7	7
	8	8	8	8	8
	9	9	9	9	9

124

		/	/	/	
–	.	.	.	.	.
		0	0	0	0
	1	1	1	1	1
	2	2	2	2	2
	3	3	3	3	3
	4	4	4	4	4
	5	5	5	5	5
	6	6	6	6	6
	7	7	7	7	7
	8	8	8	8	8
	9	9	9	9	9

125

		/	/	/	
–	.	.	.	.	.
		0	0	0	0
	1	1	1	1	1
	2	2	2	2	2
	3	3	3	3	3
	4	4	4	4	4
	5	5	5	5	5
	6	6	6	6	6
	7	7	7	7	7
	8	8	8	8	8
	9	9	9	9	9

126

		/	/	/	
–	.	.	.	.	.
		0	0	0	0
	1	1	1	1	1
	2	2	2	2	2
	3	3	3	3	3
	4	4	4	4	4
	5	5	5	5	5
	6	6	6	6	6
	7	7	7	7	7
	8	8	8	8	8
	9	9	9	9	9

QUESTIONS 131–142

For Students Taking AP Physics 1 or AP Physics 2

Mark two responses per question. You will receive credit only if both correct responses are selected.

131	A B C D	135	A B C D	139	A B C D
132	A B C D	136	A B C D	140	A B C D
133	A B C D	137	A B C D	141	A B C D
134	A B C D	138	A B C D	142	A B C D

DO NOT WRITE IN THIS AREA

COMPLETE THIS AREA ONLY ONCE.

R. YOUR MAILING ADDRESS

Use the address abbreviations from your AP Student Pack. Fill in only one circle per column. Indicate a space in your address by leaving a blank box; do not grid that column.

STREET ADDRESS (include street number, street name, apartment number, etc.)

CITY

ZIP OR POSTAL CODE

COUNTRY CODE

STATE

AK, AL, AR, AZ, CA, CO, CT, DC, DE, FL, GA, HI, IA, ID, IL, IN, KS, KY, LA, MA, MD, ME, MI, MN, MO, MS, MT, NC, ND, NE, NH, NJ, NM, NV, NY, OH, OK, OR, PA, RI, SC, SD, TN, TX, UT, VA, VT, WA, WI, WV, WY, Puerto Rico, AA, AE, AP, Other

S. FOR STUDENTS OUTSIDE THE UNITED STATES ONLY

If your address does not fit in the spaces provided in Item R, fill in as many circles as you can, then fill in the circle in Item S and print the remainder of your address in the spaces provided.

Address | City | State or Province | Country | ZIP or Postal Code

T. STUDENT IDENTIFIER (Student ID Number)

U. EMAIL ADDRESS

By providing your email address, you are granting the College Board permission to use your email in accordance with the policies in the *2015-16 Bulletin for AP Students and Parents.*

V. SEX

- Female
- Male

W. WHICH LANGUAGE DO YOU KNOW BEST?

- English
- English and another language about the same
- Another language

X. RACIAL/ETHNIC GROUP

Please answer both questions about Hispanic origin and about race. For the following questions about your identity, Hispanic origins are not races.

(You may mark all that apply.)

a. Are you of Hispanic, Latino, or Spanish origin?

- No, not of Hispanic, Latino, or Spanish origin
- Yes, Cuban
- Yes, Mexican
- Yes, Puerto Rican
- Yes, another Hispanic, Latino, or Spanish origin

b. What is your race?

- American Indian or Alaska Native
- Asian (including Indian subcontinent and Philippines origin)
- Black or African American (including Africa and Afro-Caribbean origin)
- Native Hawaiian or other Pacific Islander
- White (including Middle Eastern origin)

Y. PARENTAL EDUCATION LEVEL

In the first column, indicate the highest level of education of one parent/guardian, and indicate whether this is your mother/female guardian or father/male guardian. Then, if applicable, indicate the highest level of education of your other parent/guardian in the second column, and indicate whether this is your mother/female guardian or father/male guardian.

- **Mother or female guardian**
- **Father or male guardian**
- Grade school
- Some high school
- High school diploma or equivalent
- Vocational or trade school
- Some college
- Associate or two-year degree
- Bachelor's or four-year degree
- Some graduate or professional school
- Graduate or professional degree

Section I: Multiple-Choice Questions

This is the multiple-choice section of the 2016 AP exam.
It includes cover material and other administrative instructions
to help familiarize students with the mechanics of the exam.
(Note that future exams may differ in look from the following content.)

AP® Physics C: Electricity and Magnetism Exam

SECTION I: Multiple Choice **2016**

DO NOT OPEN THIS BOOKLET UNTIL YOU ARE TOLD TO DO SO.

At a Glance

Total Time
45 minutes
Number of Questions
35
Percent of Total Score
50%
Writing Instrument
Pencil required
Electronic Device
Calculator allowed

Instructions

Section I of this exam contains 35 multiple-choice questions. For these questions, fill in only the circles for numbers 1 through 35 on your answer sheet. A table of information and lists of equations that may be helpful are in the booklet. Calculators, rulers and straightedges may be used in this section.

Indicate all of your answers to the multiple-choice questions on the answer sheet. No credit will be given for anything written in this exam booklet, but you may use the booklet for notes or scratch work. After you have decided which of the suggested answers is best, completely fill in the corresponding circle on the answer sheet. Give only one answer to each question. If you change an answer, be sure that the previous mark is erased completely. Here is a sample question and answer.

Sample Question	Sample Answer
Chicago is a (A) state (B) city (C) country (D) continent (E) village	Ⓐ ● Ⓒ Ⓓ Ⓔ

Use your time effectively, working as quickly as you can without losing accuracy. Do not spend too much time on any one question. Go on to other questions and come back to the ones you have not answered if you have time. It is not expected that everyone will know the answers to all of the multiple-choice questions.

Your total score on the multiple-choice section is based only on the number of questions answered correctly. Points are not deducted for incorrect answers or unanswered questions.

Form I
Form Code 4MBP4-S
82

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, $1 \text{ eV} = 1.60 \times 10^{-19}$ 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, $N_0 = 6.02 \times 10^{23}\ \text{mol}^{-1}$	Universal gravitational constant, $G = 6.67 \times 10^{-11}\ (\text{N}\cdot\text{m}^2)/\text{kg}^2$
Universal gas constant, $R = 8.31$ J/(mol•K)	Acceleration due to gravity at Earth's surface, $g = 9.8\ \text{m/s}^2$
Boltzmann's constant, $k_B = 1.38 \times 10^{-23}$ J/K	

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

ADVANCED PLACEMENT PHYSICS C EQUATIONS

MECHANICS

$v_x = v_{x0} + a_x t$

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

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

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

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

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

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

$\left|\vec{F}_f\right| \leq \mu \left|\vec{F}_N\right|$

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

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

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

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

$\Delta U_g = mg\Delta h$

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

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

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

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

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

$v = r\omega$

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

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

$\omega = \omega_0 + \alpha t$

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

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

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

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

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

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

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

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

$\left|\vec{F}_G\right| = \frac{Gm_1 m_2}{r^2}$

$U_G = -\frac{Gm_1 m_2}{r}$

ELECTRICITY AND MAGNETISM

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

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

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

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

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

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

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

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

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

$C_p = \sum_i C_i$

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

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

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

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

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

$I = Nev_d A$

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

$R_s = \sum_i R_i$

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

$P = I\Delta V$

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

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

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

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

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

$B_s = \mu_0 nI$

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

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

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

$U_L = \frac{1}{2} LI^2$

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

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

$S = 4\pi r^2$

Right Triangle

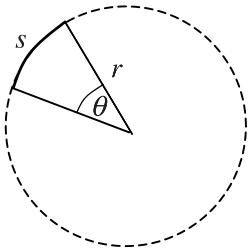
$a^2 + b^2 = c^2$

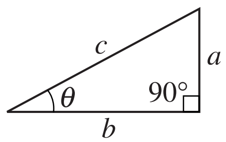
$\sin\theta = \frac{a}{c}$

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

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

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





CALCULUS

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

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

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

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

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

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

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

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

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

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

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

VECTOR PRODUCTS

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

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

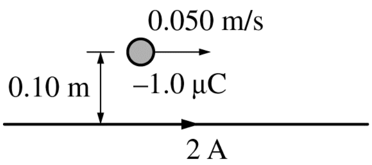
PHYSICS C: ELECTRICITY AND MAGNETISM

SECTION I

Time—45 minutes

35 Questions

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 and then fill in the corresponding circle on the answer sheet.



1. A small object of charge $-1.0\ \mu C$ that is 0.10 m above a long, straight wire moves at a speed of $0.050\ m/s$ parallel to the wire, as shown in the figure above. The current in the wire is 2 A. What is the magnitude and direction of the magnetic force on the object?

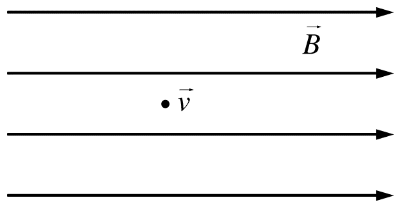
(A) 2×10^{-13} N, toward the wire

(B) 2×10^{-13} N, away from the wire

(C) $4\pi \times 10^{-13}$ N, toward the wire

(D) $4\pi \times 10^{-13}$ N, away from the wire

(E) 0, direction is undefined



2. An electron travels through a uniform magnetic field $\vec{B}$ directed to the right. The electron's velocity $\vec{v}$ is directed out of the page, as shown in the figure above. The direction of the force on the electron due to the magnetic field at the instant shown is

(A) toward the top of the page
(B) toward the bottom of the page
(C) to the left
(D) to the right
(E) into the page

3. Two long parallel wires have currents of I_1 and I_2 and are a distance d apart. The force per unit length exerted by one wire on the other is F/L. The current in each wire is doubled, and the distance between the wires is reduced to $d/2$. The new force per unit length is

(A) $\dfrac{F}{2L}$

(B) $\dfrac{F}{L}$

(C) $\dfrac{2F}{L}$

(D) $\dfrac{4F}{L}$

(E) $\dfrac{8F}{L}$

Questions 4-5

A capacitor is constructed of two large, identical, parallel metal plates separated by a small distance d. A battery fully charges the capacitor and is then disconnected.

4. The plate separation is now increased to a distance $2d$. Which of the following correctly describes the change, if any, of the voltage across the capacitor, the electric field between the plates, and the energy stored in the capacitor?

	Voltage	Electric Field	Energy
(A)	Does not change	Does not change	Does not change
(B)	Does not change	Doubles	Does not change
(C)	Doubles	Doubles	Does not change
(D)	Doubles	Does not change	Doubles
(E)	Doubles	Doubles	Doubles

5. If, instead of separating the plates, the empty space between the plates is filled with a slab of insulating material that has a dielectric constant $K = 2$, which of the following correctly describes the change, if any, of the voltage across the capacitor, the electric field between the plates, and the energy stored in the capacitor?

	Voltage	Electric Field	Energy
(A)	Halves	Halves	Halves
(B)	Halves	Halves	Does not change
(C)	Does not change	Does not change	Halves
(D)	Does not change	Halves	Halves
(E)	Does not change	Does not change	Does not change

---

6. A capacitor stores energy U_1 when it holds charge Q. The same capacitor stores energy U_2 when it holds charge $16Q$. What is the ratio U_2/U_1?

(A) 8
(B) 16
(C) 64
(D) 128
(E) 256

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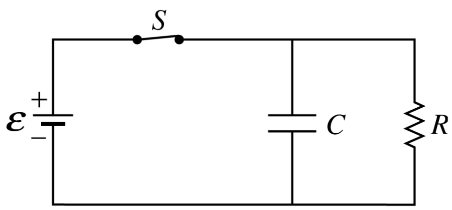
Questions 7-8



Switch S in the circuit shown above has been closed for a long time.

7. Which of the following is the correct expression for the current in the resistor?

   (A) $\dfrac{\mathcal{E}}{R}$

   (B) $\dfrac{C\mathcal{E}}{R}$

   (C) $C\mathcal{E}$

   (D) $\dfrac{\mathcal{E}}{RC}$

   (E) Zero

8. Suppose that the switch is opened at time $t = 0$. Which of the following combinations of a differential equation and an initial condition can be used to solve for the charge $Q(t)$ on the upper plate of the capacitor as a function of time t?

	Differential Equation	Initial Condition
(A)	$\dfrac{Q}{C} - R\dfrac{dQ}{dt} = 0$	$Q(0) = C\mathcal{E}$
(B)	$\dfrac{Q}{C} - R\dfrac{dQ}{dt} = \mathcal{E}$	$Q(0) = 0$
(C)	$\dfrac{Q}{C} + R\dfrac{dQ}{dt} = \mathcal{E}$	$Q(0) = C\mathcal{E}$
(D)	$\dfrac{Q}{C} + R\dfrac{dQ}{dt} = 0$	$Q(0) = 0$
(E)	$\dfrac{Q}{C} + R\dfrac{dQ}{dt} = 0$	$Q(0) = C\mathcal{E}$

9. A nonconducting sphere of radius R has a uniform volume charge density ρ. At the surface of the sphere, the electric field strength is E. If a second sphere of radius $2R$ was created of the same material and with the same charge density, what would be the strength of the electric field at the surface of the second sphere?

   (A) $E/4$

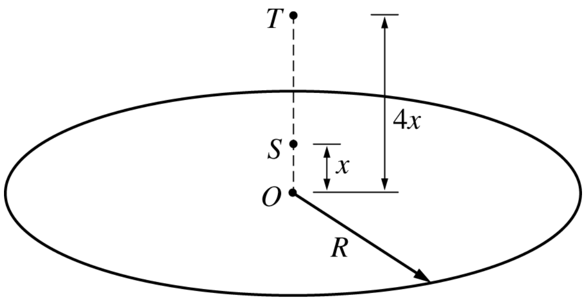
   (B) $E/2$

   (C) E

   (D) $2E$

   (E) $4E$

Questions 10-11



Note: Figure not drawn to scale.

The figure above shows a thin, circular nonconducting sheet of positive charge uniformly distributed over its area. The radius of the sheet is R. Point O is at the center of the sheet. Point S is a distance x from the center of the sheet, and point T is a distance $4x$ from the center of the sheet. Assume $R \gg x$.

10. If the magnitude of the electric field at point T is E_T, which of the following best represents the magnitude of the electric field at point S?

(A) $E_T/16$

(B) $E_T/4$

(C) E_T

(D) $4E_T$

(E) $16E_T$

11. A small sphere of mass m and charge $-q$ is released from rest at point T. If the electric potentials at points S and T are V_S and V_T, respectively, what is the speed of the sphere when it reaches point S? Ignore the effects of gravity.

(A) $\frac{2q}{m}(V_S + V_T)$

(B) $\frac{4q}{m}(V_S + V_T)$

(C) $\sqrt{\frac{q}{2m}(V_S - V_T)}$

(D) $\sqrt{\frac{q}{2m}(V_S + V_T)}$

(E) $\sqrt{\frac{2q}{m}(V_S - V_T)}$

GO ON TO THE NEXT PAGE.

Questions 12-13

Capacitor	K	L	M	N
Plate area	A	A	$2A$	$2A$
Plate separation	d	$2d$	d	$2d$

The chart above shows the plate area and separation for four different air-filled parallel-plate capacitors: K, L, M, and N.

12. Each capacitor is charged such that the same electric field is created between the plates. Which of the following correctly ranks the charge stored on each capacitor?

(A) $(Q_M = Q_N) > (Q_K = Q_L)$
(B) $Q_M > Q_K > Q_N > Q_L$
(C) $(Q_K = Q_M) > (Q_L = Q_N)$
(D) $Q_K = Q_L = Q_M = Q_N$
(E) $Q_M > (Q_K = Q_N) > Q_L$

13. Each capacitor is charged such that the same potential difference exists across the plates. Which of the following correctly ranks the magnitude of electric field between the plates of each capacitor?

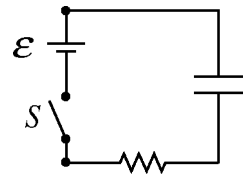
(A) $(E_M = E_N) > (E_K = E_L)$
(B) $E_M > E_K > E_N > E_L$
(C) $(E_K = E_M) > (E_L = E_N)$
(D) $E_K = E_L = E_M = E_N$
(E) $E_L > (E_K = E_N) > E_M$

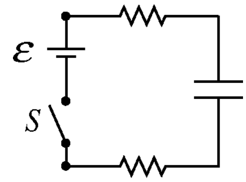
---

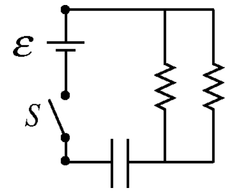
14. A parallel-plate capacitor stores 240 nC when fully charged by the application of a 12 V potential difference across its plates. What is its capacitance?

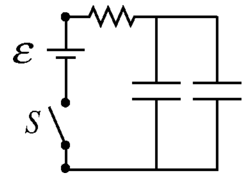
(A) 5.0×10^{-11} F
(B) 1.7×10^{-9} F
(C) 2.0×10^{-8} F
(D) 2.9×10^{-6} F
(E) 4.8×10^{-6} F

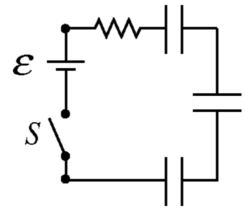
15. Identical resistors and identical uncharged capacitors are connected to identical ideal batteries of emf $\mathcal{E}$ in the circuits shown below. Each circuit has a switch S in the open position. In which circuit will the capacitors reach half their maximum charge in the least amount of time when switch S is closed?

(A)


(B)


(C)


(D)


(E)


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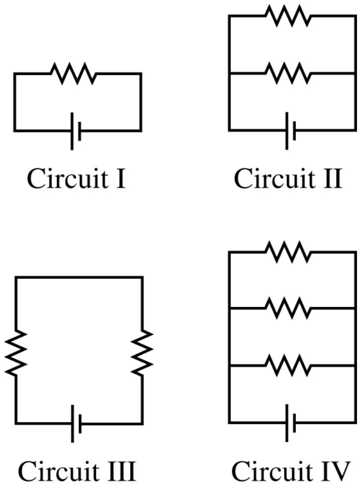
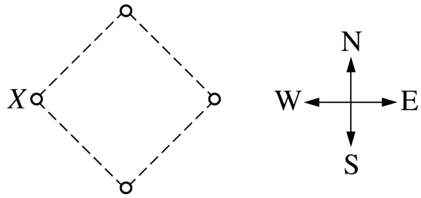


16. All four circuits shown above contain identical ideal batteries and identical resistors. Which circuits draw the most and least power from the battery?

	Most Power	Least Power
(A)	I	II
(B)	I	V
(C)	II	III
(D)	IV	I
(E)	IV	III

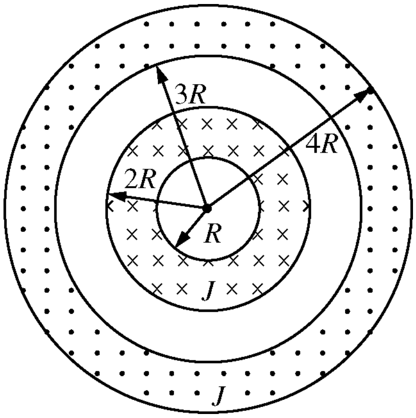
17. The current in a $10\ \Omega$ resistor is given as a function of time t by the equation $I = I_0 e^{-\alpha t}$, where $I_0 = 4\text{ A}$ and $\alpha = 2\text{ s}^{-1}$. What is the total energy dissipated in the resistor from time $t = 0$ until the current becomes zero?

(A) 20 J
(B) 40 J
(C) 80 J
(D) 160 J
(E) 320 J



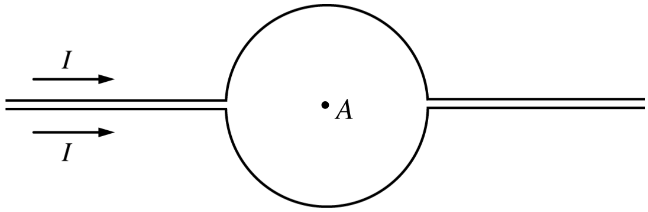
18. Four conducting wires perpendicular to the plane of the page are at the corners of a square, as shown in cross section in the figure above. The wires carry equal currents in the same direction. What is the direction of the total magnetic force on wire X caused by the other three wires?

(A) To the north
(B) To the south
(C) To the east
(D) To the west
(E) In none of the directions above, since the magnitude of the force is zero



19. Two long, hollow, concentric conducting cylinders carry currents in opposite directions into and out of the plane of the page, as shown in the cross section above. The currents are unequal, but the current density J is the same for both cylinders. In which of the following regions can the net magnetic field be zero at some nonzero finite distance r from the central axis?

(A) $r < R$ only
(B) Both $r < R$ and $R < r < 2R$
(C) Both $r < R$ and $2R < r < 3R$
(D) Both $r < R$ and $3R < r < 4R$
(E) $r > 4R$ only



20. The middle sections of two long, straight wires are each bent into semicircular shapes. The two wires are placed close to each other in a plane as shown above. Point A is the center of the circle formed by the two wires. There is a current I in each wire. Which of the following best represents the direction of the magnetic field, if any, at point A due to the currents?

(A) $\downarrow$

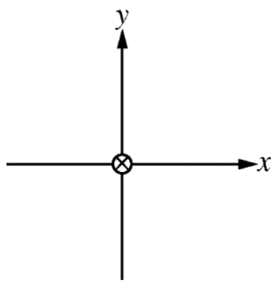
(B) $\uparrow$

(C) $\odot$ (Out of the page)

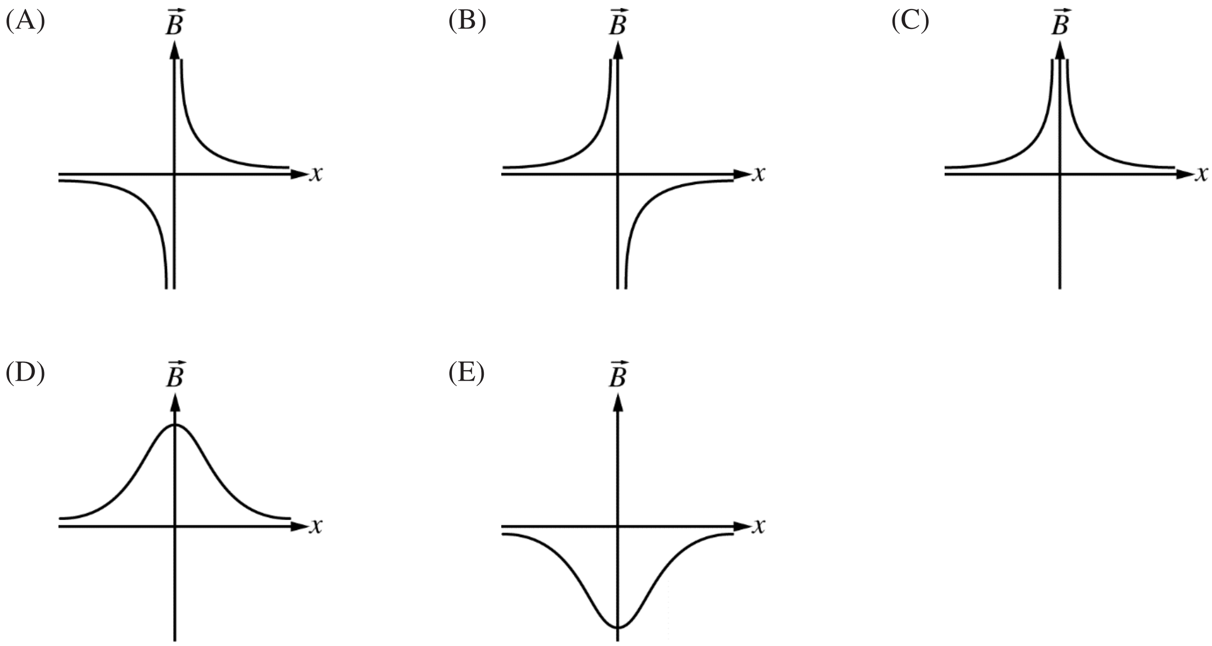
(D) $\otimes$ (Into the page)

(E) There is no direction, because the magnetic field is zero.

GO ON TO THE NEXT PAGE.



21. A long straight wire is located at the origin of an *xy*-coordinate system and is perpendicular to the *xy*-plane. The wire has a current that is directed into the page, as shown in the figure above. Which of the following graphs best represents the magnetic field $\vec{B}$ due to the current as a function of the position x along the *x*-axis? Assume a positive magnetic field to be directed in the +*y* direction.



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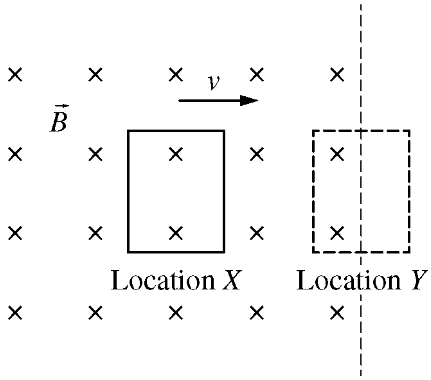


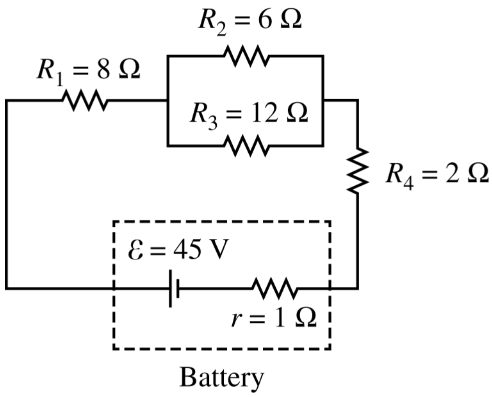
22. A loop of wire at location X is moving toward the right with constant speed v in a region of uniform magnetic field $\vec{B}$, which is perpendicular to the plane of the loop. The magnetic field region ends at the dashed line, as shown in the figure above. Later, the loop is at location Y and exiting the magnetic field with the same constant speed v. The process is then repeated with the loop moving at a speed of $2v$. Which of the following best describes the emf in the loop at the two positions shown when the process is repeated at a speed of $2v$?

	Emf at Location X	Emf at Location Y
(A)	Nonzero and halved	Nonzero and halved
(B)	Nonzero and doubled	Nonzero and doubled
(C)	Nonzero and doubled	Zero at both speeds
(D)	Zero at both speeds	Zero at both speeds
(E)	Zero at both speeds	Nonzero and doubled

GO ON TO THE NEXT PAGE.

23. A long solenoid has 300 loops. The region inside the solenoid has a uniform magnetic field that is directed parallel to the axis of the solenoid. Each loop has an area $2 \times 10^{-4}\ \text{m}^2$. The magnetic field decreases at a constant rate from 0.5 T to zero. What is the time duration for the change in magnetic field if a potential difference of 10 V is induced between the ends of the solenoid while the field is decreasing?

(A) 1×10^{-5} s
(B) 3×10^{-5} s
(C) 3×10^{-3} s
(D) 1×10^{-2} s
(E) 3×10^{-2} s



Questions 24-25

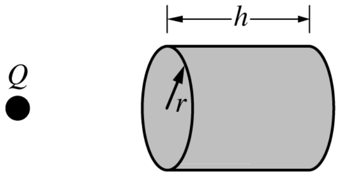
The circuit represented in the figure above contains four resistors and a battery. The 45 V battery has a $1\ \Omega$ internal resistance.

24. Which of the following ranks the absolute values of the potential differences ΔV across the resistors from highest to lowest?

(A) $\Delta V_3 > \Delta V_1 > \Delta V_2 > \Delta V_4$
(B) $\Delta V_4 > \Delta V_2 > \Delta V_1 > \Delta V_3$
(C) $\Delta V_1 > \Delta V_4 > \Delta V_2 > \Delta V_3$
(D) $\Delta V_1 > (\Delta V_2 = \Delta V_3) > \Delta V_4$
(E) $\Delta V_4 > (\Delta V_2 = \Delta V_3) > \Delta V_1$

25. How much energy is dissipated by the battery's internal resistance in 60 s?

(A) 9 J
(B) 180 J
(C) 540 J
(D) 900 J
(E) 8100 J



26. A closed cylindrical shell of volume $\pi r^2 h$ is placed close to an object with a charge of Q, as shown in the figure above. There are no other charged objects nearby. The electric flux through the closed cylindrical shell is

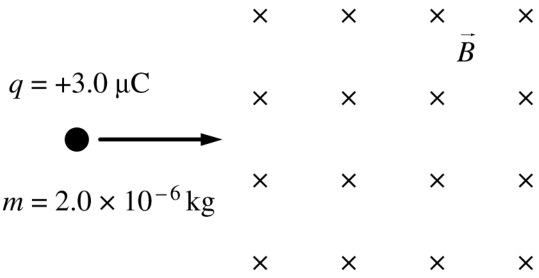
(A) 0
(B) Q/ε_0
(C) $\pi r^2 Q$
(D) $2\pi rhQ$
(E) $2\pi r^2 Q + 2\pi rhQ$

27. The electric field is zero everywhere within a certain region of space. The electric potential everywhere within the region

(A) must be zero
(B) must be uniform
(C) must be positive
(D) must be negative
(E) can be both positive and negative in different parts of the region

28. Two particles with positive charges q_1 and q_2 are both at rest and are very far apart. How much work would be done by external forces to bring the particles to rest at a distance d apart?

(A) Zero
(B) $\dfrac{kq_1q_2}{d}$
(C) $-\dfrac{kq_1q_2}{d}$
(D) $\dfrac{2kq_1q_2}{d}$
(E) $-\dfrac{2kq_1q_2}{d}$

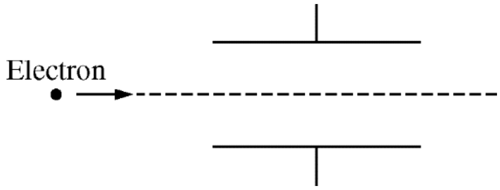


29. A small object with a charge of $q = +3.0\ \mu C$ and a mass $m = 2.0 \times 10^{-6}$ kg enters a magnetic field of magnitude $B = 0.20$ T directed into the page, as shown in the figure above. If the speed of the object is $1000\ m/s$, the object's acceleration at the moment it enters the field is most nearly

(A) zero because the velocity is perpendicular to the magnetic field
(B) $300\ m/s^2$ toward the bottom of the page
(C) $300\ m/s^2$ toward the top of the page
(D) $600\ m/s^2$ toward the bottom of the page
(E) $600\ m/s^2$ toward the top of the page

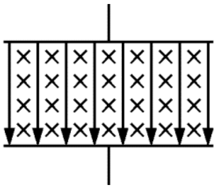
30. A 0.20 m long wire carries a current of 15 A and lies perpendicular to a magnetic field. The magnetic force on the wire is measured to be 0.060 N. What is the magnitude of the magnetic field?

(A) 0.010 T
(B) 0.020 T
(C) 0.040 T
(D) 0.060 T
(E) 0.080 T

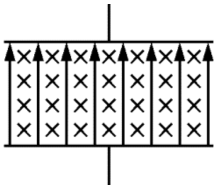


31. Uniform magnetic and electric fields exist between the two oppositely charged parallel plates shown in the figure above. An electron travels horizontally between the plates. Assuming gravitational effects to be negligible, which of the following diagrams shows a combination of electric and magnetic field directions that will allow the electron to travel undeflected?

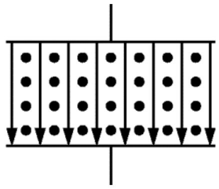
(A)



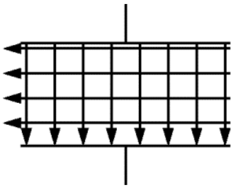
(B)



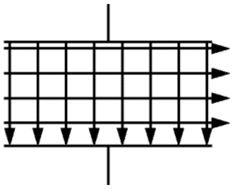
(C)

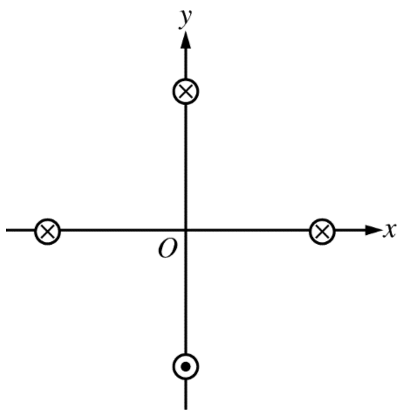


(D)



(E)





32. Four long, straight wires are perpendicular to the *xy*-plane. Each wire is the same distance from the origin *O*, as shown in the figure above. The wires have equal currents that are in the directions shown. Which of the following best represents the direction of the net magnetic field, if any, at the origin due to the four currents?

(A) 

(B)

(C) 

(D)

(E) Undefined because the net field is zero.

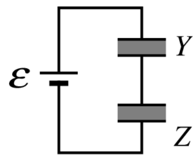


Figure 1

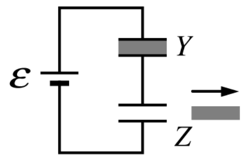
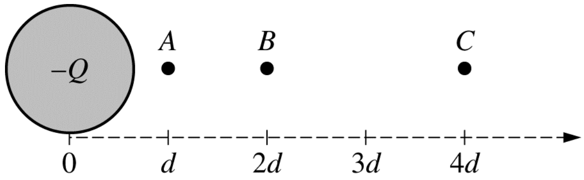


Figure 2

33. Two identical capacitors, Y and Z, are connected in series with an ideal battery, as shown in figure 1 above, and fully charged. Each capacitor has a dielectric slab of dielectric constant $\kappa > 1$ between its plates. If the dielectric slab is removed from capacitor Z, which of the following describes what happens to the voltage across each capacitor?

	Voltage across <u>Capacitor *Y*</u>	Voltage across <u>Capacitor *Z*</u>
(A)	Increases	Decreases
(B)	Increases	Increases
(C)	Remains the same	Remains the same
(D)	Decreases	Decreases
(E)	Decreases	Increases



34. A particle of charge $+q$ is released from rest at position B, which is a distance $2d$ from the center of a fixed nonconducting sphere that has a charge of $-Q$ distributed uniformly throughout its volume, as shown in the figure above. When the particle reaches position A, which is a distance d from the center of the charged sphere, its kinetic energy is K_0. The same particle is now released from rest at position C, which is a distance $4d$ from the center of the nonconducting sphere. The kinetic energy of the particle when it again reaches position A is

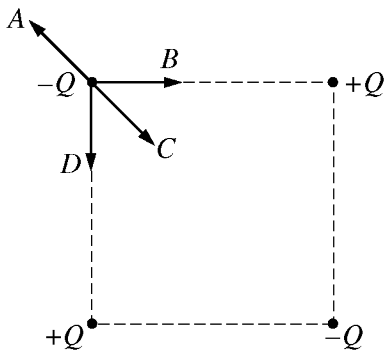
(A) K_0

(B) $3K_0/2$

(C) $2K_0$

(D) $5K_0/2$

(E) $3K_0$



35. Four point charges of equal magnitude but different signs are arranged on the corners of a square as shown above. Which of the vectors shown represents the direction of the net force acting on the charge at the upper left-hand corner of the square due to the other charges?

(A) A
(B) B
(C) C
(D) D
(E) It has no direction because the force is zero.

S T O P

END OF ELECTRICITY AND MAGNETISM SECTION I

IF YOU FINISH BEFORE TIME IS CALLED,
YOU MAY CHECK YOUR WORK ON ELECTRICITY AND MAGNETISM SECTION I ONLY.

DO NOT TURN TO ANY OTHER TEST MATERIALS.

MAKE SURE YOU HAVE DONE THE FOLLOWING.

- **PLACED YOUR AP NUMBER LABEL ON YOUR ANSWER SHEET**
- **WRITTEN AND GRIDDED YOUR AP NUMBER CORRECTLY ON YOUR ANSWER SHEET**
- **TAKEN THE AP EXAM LABEL FROM THE FRONT OF THIS BOOKLET AND PLACED IT ON YOUR ANSWER SHEET**

Section II: Free-Response Questions

This is the free-response section of the 2016 AP exam.
It includes cover material and other administrative instructions
to help familiarize students with the mechanics of the exam.
(Note that future exams may differ in look from the following content.)

AP® Physics C: Electricity and Magnetism Exam

SECTION II: Free Response 2016

DO NOT OPEN THIS BOOKLET UNTIL YOU ARE TOLD TO DO SO.

At a Glance

Total Time
45 minutes
Number of Questions
3
Percent of Total Score
50%
Writing Instrument
Either pencil or pen with black or dark blue ink
Electronic Device
Calculator allowed
Weight
The questions are weighted equally.

IMPORTANT Identification Information

PLEASE PRINT WITH PEN:

1. First two letters of your last name

   First letter of your first name

2. Date of birth

   Month Day Year

3. Six-digit school code

4. Unless I check the box below, I grant the College Board the unlimited right to use, reproduce, and publish my free-response materials, both written and oral, for educational research and instructional purposes. My name and the name of my school will not be used in any way in connection with my free-response materials. I understand that I am free to mark "No" with no effect on my score or its reporting.

   No, I do not grant the College Board these rights.

Instructions

The questions for Section II are printed in this booklet. You may use any blank space in the booklet for scratch work, but you must write your answers in the spaces provided for each answer. A table of information and lists of equations that may be helpful are in the booklet. Calculators, rulers, and straightedges may be used in this section.

All final numerical answers should include appropriate units. Credit for your work depends on demonstrating that you know which physical principles would be appropriate to apply in a particular situation. Therefore, you should show your work for each part in the space provided after that part. If you need more space, be sure to clearly indicate where you continue your work. Credit will be awarded only for work that is clearly designated as the solution to a specific part of a question. Credit also depends on the quality of your solutions and explanations, so you should show your work.

Write clearly and legibly. Cross out any errors you make; erased or crossed-out work will not be scored. You may lose credit for incorrect work that is not crossed out.

Manage your time carefully. You may proceed freely from one question to the next. You may review your responses if you finish before the end of the exam is announced.

Form I
Form Code 4MBP4-S
82

ADVANCED PLACEMENT PHYSICS C TABLE OF INFORMATION

CONSTANTS AND CONVERSION FACTORS

Proton mass,	$m_p = 1.67 \times 10^{-27}$ kg
Neutron mass,	$m_n = 1.67 \times 10^{-27}$ kg
Electron mass,	$m_e = 9.11 \times 10^{-31}$ kg
Avogadro's number,	$N_0 = 6.02 \times 10^{23}\ \text{mol}^{-1}$
Universal gas constant,	$R = 8.31\ \text{J/(mol·K)}$
Boltzmann's constant,	$k_B = 1.38 \times 10^{-23}$ J/K
Electron charge magnitude,	$e = 1.60 \times 10^{-19}$ C
1 electron volt,	$1\ \text{eV} = 1.60 \times 10^{-19}$ J
Speed of light,	$c = 3.00 \times 10^{8}$ m/s
Universal gravitational constant,	$G = 6.67 \times 10^{-11}\ (\text{N·m}^2)/\text{kg}^2$
Acceleration due to gravity at Earth's surface,	$g = 9.8\ \text{m/s}^2$
1 unified atomic mass unit,	$1\ \text{u} = 1.66 \times 10^{-27}\ \text{kg} = 931\ \text{MeV}/c^2$
Planck's constant,	$h = 6.63 \times 10^{-34}\ \text{J·s} = 4.14 \times 10^{-15}\ \text{eV·s}$
	$hc = 1.99 \times 10^{-25}\ \text{J·m} = 1.24 \times 10^{3}\ \text{eV·nm}$
Vacuum permittivity,	$\varepsilon_0 = 8.85 \times 10^{-12}\ \text{C}^2/(\text{N·m}^2)$
Coulomb's law constant,	$k = 1/(4\pi\varepsilon_0) = 9.0 \times 10^{9}\ (\text{N·m}^2)/\text{C}^2$
Vacuum permeability,	$\mu_0 = 4\pi \times 10^{-7}\ (\text{T·m})/\text{A}$
Magnetic constant,	$k' = \mu_0/(4\pi) = 1 \times 10^{-7}\ (\text{T·m})/\text{A}$
1 atmosphere pressure,	$1\ \text{atm} = 1.0 \times 10^{5}\ \text{N/m}^2 = 1.0 \times 10^{5}$ 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.

ADVANCED PLACEMENT PHYSICS C EQUATIONS

MECHANICS

$v_x = v_{x0} + a_x t$

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

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

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

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

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

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

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

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

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

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

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

$\Delta U_g = mg\Delta h$

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

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

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

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

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

$v = r\omega$

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

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

$\omega = \omega_0 + \alpha t$

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

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

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

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

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

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

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

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

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

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

ELECTRICITY AND MAGNETISM

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

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

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

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

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

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

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

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

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

$C_p = \sum_i C_i$

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

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

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

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

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

$I = N e v_d A$

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

$R_s = \sum_i R_i$

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

$P = I \Delta V$

A = area
B = magnetic field
C = capacitance
d = distance
E = electric field
ε = 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

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

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

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

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

$B_s = \mu_0 n I$

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

$\varepsilon = \oint \vec{E} \bullet d\vec{\ell} = -\frac{d\Phi_B}{dt}$

$\varepsilon = -L \frac{dI}{dt}$

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

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

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

$S = 4\pi r^2$

Right Triangle

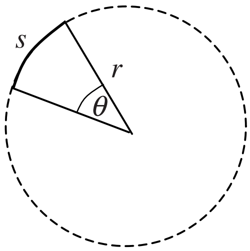
$a^2 + b^2 = c^2$

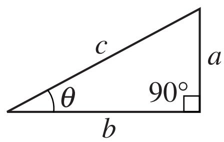
$\sin\theta = \frac{a}{c}$

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

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

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





CALCULUS

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

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

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

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

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

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

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

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

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

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

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

VECTOR PRODUCTS

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

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

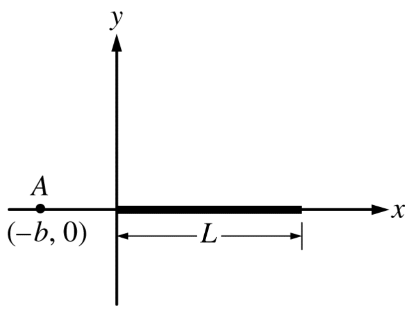
PHYSICS C: ELECTRICITY AND MAGNETISM

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. Show all your work in this booklet in the spaces provided after each part.



E&M.1.

A rod of length L lies along the x-axis with its left end at the origin, as shown in the figure above. The rod has a nonuniform linear charge density $\lambda = \alpha x$, where α is a positive constant.

(a) Determine the units of the constant α.

(b) Derive an expression for the total charge on the rod. Express your answer in terms of α, L, and physical constants, as appropriate.

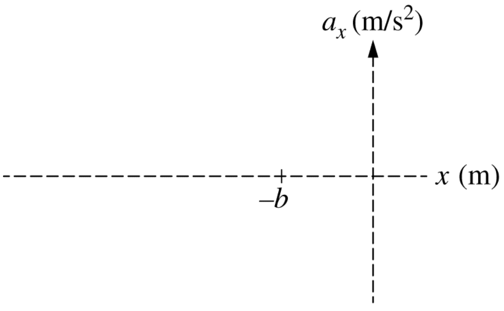
GO ON TO THE NEXT PAGE.

The rod is replaced with one of the same length but with a uniform positive linear charge density λ_0.

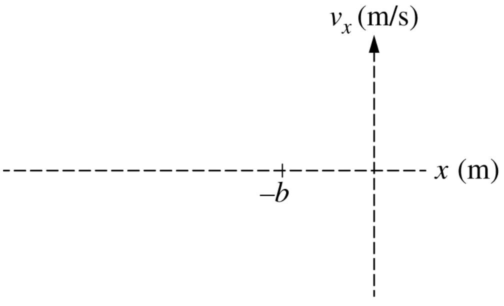
(c) Show that the electric field at point *A*, which is a distance *b* to the left of the rod, has a magnitude of $E = \dfrac{\lambda_0 L}{4\pi\varepsilon_0 b(b+L)}$.

(d) A proton is placed at point *A*, at position (–*b*, 0), near the positively charged rod and released from rest.

i. Sketch a graph of the horizontal component of the acceleration of the proton a_x as a function of its position *x* for the region in which the proton travels after it is released. Sketch any asymptote, but do not indicate its value.



ii. Sketch a graph of the horizontal component of the velocity of the proton v_x as a function of its position *x* for the region in which the proton travels after it is released. Sketch any asymptote but do not indicate its value.



Question 1 continues on next page.

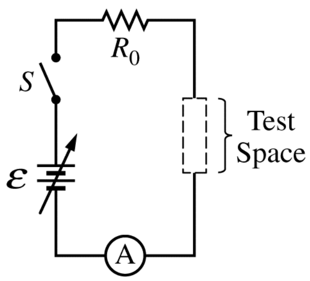
GO ON TO THE NEXT PAGE.

iii. Instead of a proton, an alpha particle (a particle with twice the charge and four times the mass of a proton) is now placed at point A. Is the magnitude of the initial acceleration of the alpha particle greater than, less than, or equal to the magnitude of the initial acceleration of the proton from part (d)i?

____ Greater than ____ Less than ____ Equal to

(e) Using the equation from part (c), show that the magnitude of the electric field at a point on the x-axis very far away from the rod is approximately equal to the electric field due to a point charge of magnitude $Q = \lambda_0 L$ located at the origin.

THIS PAGE MAY BE USED FOR SCRATCH WORK.



E&M.2.

The circuit above consists of a variable DC power supply, an ammeter A, a switch S, and a resistor of unknown resistance R_0 connected in series with a test space into which different circuit elements can be placed. In order to determine R_0, a wire of negligible resistance is placed in the test space. The power supply is set at various potential differences, and the current in the circuit is measured. The data are shown below.

$\mathcal{E}$ (V)	2.00	4.00	6.00	8.00
Current (mA)	0.146	0.310	0.433	0.577

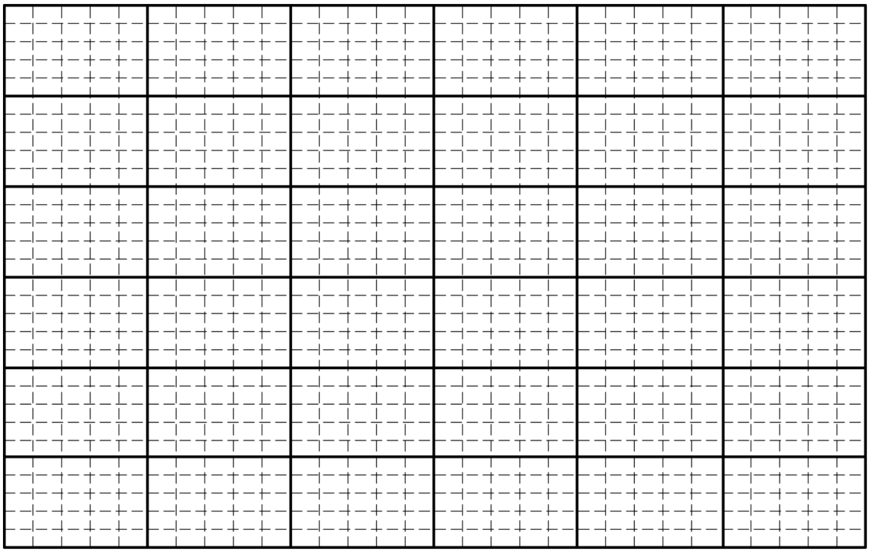
(a) Indicate below which quantities should be graphed to yield a straight line that has a slope that could be used to calculate a numerical value for the resistance R_0.

Horizontal axis: ____________________

Vertical axis: ____________________

Use the remaining rows in the table above, as needed, to record any quantities that you indicated that are not given.

(b) Plot the straight line data points on the graph below. Clearly scale and label all axes, including units, if appropriate. Draw a straight line that best represents the data.



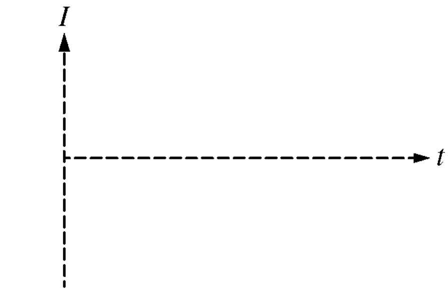
(c) Using your straight line, calculate an experimental value for R_0 .

Question 2 continues on next page.

GO ON TO THE NEXT PAGE.

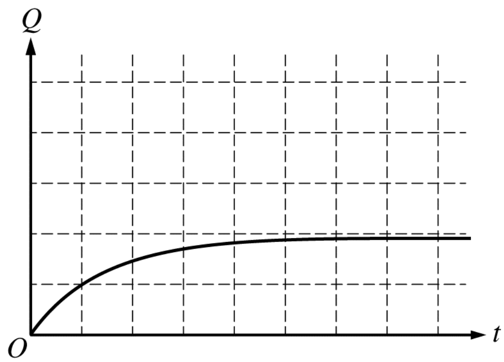
(d) The power supply is set to 4.00 V and an uncharged, air-filled capacitor is placed in the test space. The switch is closed at time $t = 0$, and the capacitor is allowed to fully charge.

i. On the axes shown, sketch the current I through the ammeter as a function of time t. Explicitly label any intercepts, asymptotes, maxima, or minima with numerical values or algebraic expressions, as appropriate.



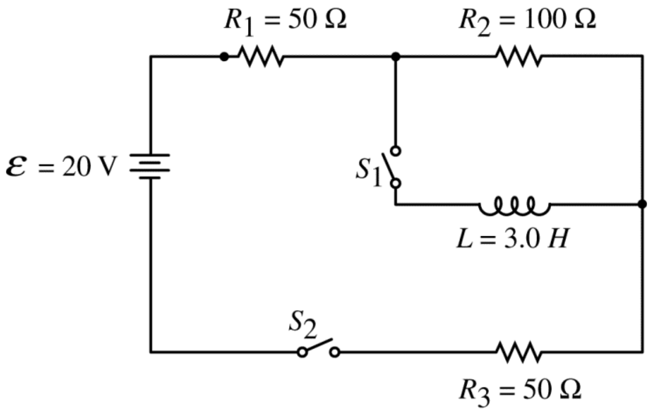
ii. It is determined that the time constant is 0.045 s. The capacitor is charged to 4 V. Calculate the energy stored in the capacitor.

iii. The graph below shows the charge Q on the capacitor as a function of time t. The capacitor is discharged, and a dielectric with dielectric constant $\kappa = 2$ is inserted between the plates. The same charging procedure is repeated. On the graph below, sketch the curve showing the charge Q on the dielectric-filled capacitor as a function of time t.



THIS PAGE MAY BE USED FOR SCRATCH WORK.

GO ON TO THE NEXT PAGE.



E&M.3.

An ideal battery is connected to three resistors, an ideal inductor, and two switches, as shown in the circuit above. Both switches are initially open. Switch S_2 is then closed.

(a) Calculate the voltage across resistor R_2.

Switch S_1 is then closed.

(b) Calculate the magnitude of the rate of change of the current through the inductor immediately after switch S_1 is closed.

(c) At time t after switch S_1 is closed, the instantaneous current through resistor R_2 is measured to be 0.020 A.

i. Calculate the current through resistor R_3 at time t.

ii. Calculate the energy stored in the inductor at time t.

After a long time, the currents reach a steady value. Switch S_2 is then opened.

(d) Calculate the current through the inductor immediately after switch S_2 is opened.

(e) Write, but do NOT solve, a differential equation that can be used to determine the current through resistor R_2 at time t after switch S_2 is opened.

(f) Using the differential equation from part (e), derive an expression for the current through resistor R_2 as a function of time t after switch S_2 is opened.

THIS PAGE MAY BE USED FOR SCRATCH WORK.

STOP

END OF EXAM

THE FOLLOWING INSTRUCTIONS APPLY TO THE COVERS OF THE SECTION II BOOKLET.

- **MAKE SURE YOU HAVE COMPLETED THE IDENTIFICATION INFORMATION AS REQUESTED ON THE FRONT AND BACK COVERS OF THE SECTION II BOOKLET.**
- **CHECK TO SEE THAT YOUR AP NUMBER LABEL APPEARS IN THE BOX ON THE COVER.**
- **MAKE SURE YOU HAVE USED THE SAME SET OF AP NUMBER LABELS ON ALL AP EXAMS YOU HAVE TAKEN THIS YEAR.**

Multiple-Choice Answer Key

The following contains the answers to
the multiple-choice questions in this exam.

Answer Key for AP Physics C: Electricity and Magnetism Practice Exam, Section I

Question 1: B
Question 2: B
Question 3: E
Question 4: D
Question 5: A
Question 6: E
Question 7: A
Question 8: E
Question 9: D
Question 10: C
Question 11: E
Question 12: A
Question 13: C
Question 14: C
Question 15: E
Question 16: E
Question 17: B
Question 18: C
Question 19: D
Question 20: E
Question 21: B
Question 22: E
Question 23: C
Question 24: D
Question 25: C
Question 26: A
Question 27: B
Question 28: B
Question 29: C
Question 30: B
Question 31: A
Question 32: D
Question 33: E
Question 34: B
Question 35: C

Free-Response Scoring Guidelines

The following contains the scoring guidelines
for the free-response questions in this exam.

Question 1

15 points total | **Distribution of points**

(a) 2 points

For correctly solving the given equation for α — 1 point

$\lambda = \alpha x$

$\alpha = \dfrac{\lambda}{x} = \dfrac{Q/L}{x}$

Substituting units into the above equation:

$\alpha = \dfrac{\text{C/m}}{\text{m}}$

For a correct answer — 1 point

$\alpha = \text{C/m}^2$

(b) 2 points

For integrating with the correct limits or constant of integration — 1 point

$$Q = \int \lambda dx = \int_{x=0}^{x=L} \alpha x dx = \left[\frac{1}{2}\alpha x^2\right]_{x=0}^{x=L} = \frac{1}{2}\alpha\left(L^2 - 0\right)$$

For a correct answer — 1 point

$$Q = \frac{1}{2}\alpha L^2$$

(c) 3 points

Using a correct integral expression for Coulomb's law

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

For correctly expressing the charge element in terms of the linear charge density — 1 point

$\lambda_0 = Q/L$ so $dq = \lambda_0 dr$

For correctly substituting into the first equation — 1 point

$$E = \int \frac{1}{4\pi\varepsilon_0}\frac{\lambda_0}{r^2}\, dr$$

For integrating with the correct limits or constant of integration — 1 point

$$E = \frac{\lambda_0}{4\pi\varepsilon_0}\int_{r=b}^{r=b+L}\frac{1}{r^2}\, dr = \frac{\lambda_0}{4\pi\varepsilon_0}\left[-\frac{1}{r}\right]_{r=b}^{r=b+L} = \frac{\lambda_0}{4\pi\varepsilon_0}\left(-\frac{1}{b+L} - \left(-\frac{1}{b}\right)\right)$$

$$E = \frac{\lambda_0}{4\pi\varepsilon_0}\left(\frac{-b+b+L}{b(b+L)}\right)$$

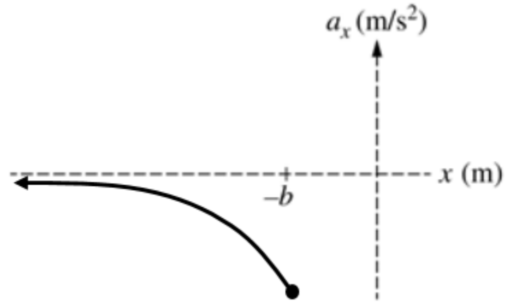
$$E = \frac{1}{4\pi\varepsilon_0}\frac{\lambda_0 L}{b(b+L)}$$

Question 1 (continued)

Distribution of points

(d)

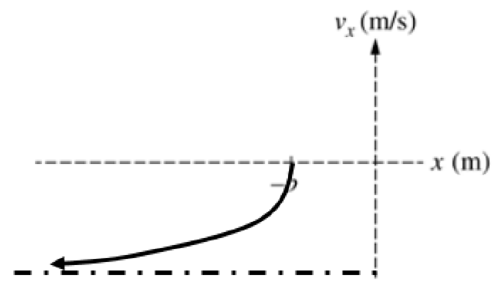
i. 2 points



For a curve starting at negative b, extending in the negative x direction, and approaching zero — 1 point

For a curve starting at a finite value that is below the horizontal axis and has the horizontal axis as an asymptote — 1 point

ii. 3 points



For a curve starting at negative b and extending in the negative x direction — 1 point

For a concave up curve that is below the horizontal axis — 1 point

For a curve that has a horizontal non-zero asymptote — 1 point

iii. 1 point

For correctly selecting "Less than" — 1 point

Question 1 (continued)

Distribution of points

(e) 2 points

For correctly using the assumption that the distance is much greater than the length of the rod — 1 point

$$E = \frac{1}{4\pi\varepsilon_0}\frac{\lambda_0 L}{b(b+L)}$$

Since $b \gg L$, $E = \frac{1}{4\pi\varepsilon_0}\frac{\lambda_0 L}{b^2}$

For correctly substituting Q into the equation above — 1 point

$Q = \lambda_0 \mathrm{L}$

$$E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{b^2}$$

Question 2

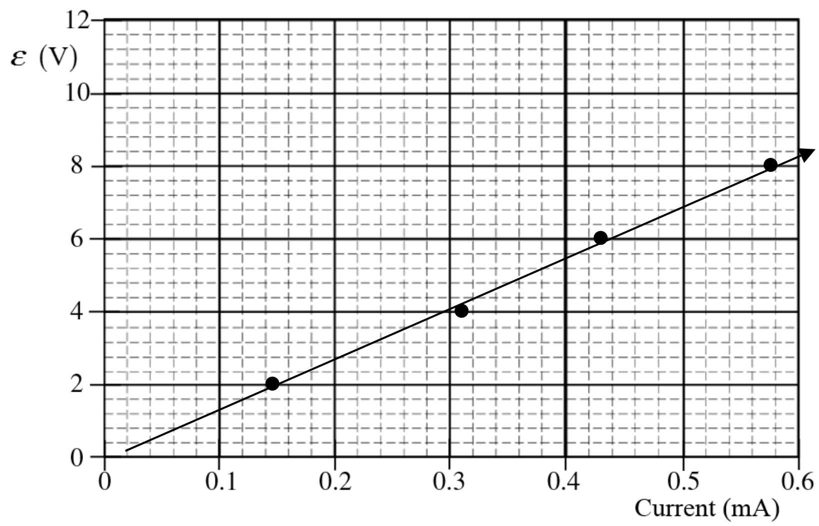
15 points total | **Distribution of points**

(a) 1 point

For indicating quantities that will yield a straight line that can be used to determine the resistance R_0 — 1 point

Example:
Horizontal axis: Current
Vertical axis: ε
Note: The axes can be reversed

(b) 4 points



For correctly labeling the axes with appropriate variables and units — 1 point
For a correct scale that uses more than half the grid — 1 point
For correctly plotting data indicated in part (a) — 1 point
For drawing a straight line consistent with the plotted data — 1 point

(c) 3 points

For correctly calculating slope using the best-fit straight line and not data points — 1 point

$$\text{slope} = \frac{(y_2 - y_1)}{(x_2 - x_1)} = \frac{(8.0 - 2.0)\ \text{V}}{(0.58 - 0.15)\ \text{mA}} = 13.95\ \text{V/mA}$$

Note: Linear regression gives slope $= 14.08\ \text{V/mA}$

To get credit for a linear regression, a response must indicate that the value comes from a linear regression from their calculator and the equation of the line must be shown.

For correctly relating R to the slope — 1 point

$\varepsilon = IR$ so $R =$ slope

For a correct answer — 1 point

$R = 13.95\ \text{k}\Omega$

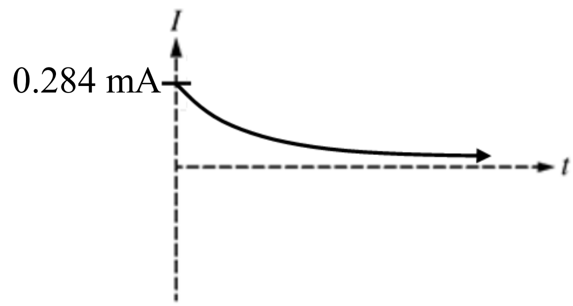
Note: Linear regression gives $R = 14.08\ \text{k}\Omega$

Question 2 (continued)

Distribution of points

(d)

i. 3 points



For a concave up curve in the first quadrant	1 point
For having the horizontal axis as an asymptote	1 point
For correctly labeling the initial current with units or algebraic expression	1 point

ii. 2 points

For correctly using the time constant to calculate the capacitance of the capacitor — 1 point

$\tau = RC$

$$C = \frac{\tau}{R} = \frac{(0.045\ \text{s})}{\left(13.95 \times 10^{3}\ \Omega\right)} = 3.23 \times 10^{-6}\ \text{F}$$

Note: Linear regression gives $C = 3.20 \times 10^{-6}$ F

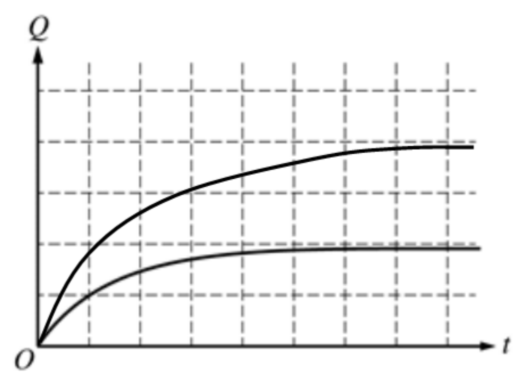
For a correct application of an expression for the energy stored in the capacitor — 1 point

$$U = \frac{1}{2}CV^2 = \left(\frac{1}{2}\right)\left(3.23 \times 10^{-6}\ \text{F}\right)(4\ \text{V})^2$$

$U = 2.58 \times 10^{-5}$ J

Note: Linear regression gives $U = 2.56 \times 10^{-5}$ J

iii. 2 points



For a concave down curve starting at the origin and above the original curve	1 point
For a curve that asymptotes later than the original and at twice the original value.	1 point

Question 3

15 points total — **Distribution of points**

(a) 2 points

For correctly using Ohm's law to calculate the current through the resistors — 1 point

$I = \dfrac{V}{R} = \dfrac{(20\text{ V})}{(200\ \Omega)} = 0.10\text{ A}$

Use Ohm's law to calculate the voltage across R_2

$V = IR = (0.10\text{ A})(100\ \Omega)$

For a correct answer — 1 point

$V = 10\text{ V}$

(b) 2 points

For correctly using the equation for the change in current in an inductor — 1 point

$\mathcal{E} = -L\dfrac{di}{dt}$

$\dfrac{di}{dt} = -\dfrac{\mathcal{E}}{L}$

Note: The minus sign may be omitted since the question asks for magnitude

For correctly using the voltage across R_2 to calculate the rate of change of current — 1 point

$\dfrac{di}{dt} = \dfrac{(10\text{ V})}{(3.0\text{ H})}$

$\dfrac{di}{dt} = 3.3\text{ A/s}$

(c)

i. 2 points

For correctly using Ohm's law to calculate the voltage across R_2 — 1 point

$V = IR = (0.020\text{ A})(100\ \Omega) = 2.0\text{ V}$

Use Ohm's law to calculate the current through R_3

$I = \dfrac{\mathcal{E} - V_2}{R_1 + R_3} = \dfrac{(20\text{ V} - 2.0\text{ V})}{(50\ \Omega + 50\ \Omega)}$

For a correct answer — 1 point

$I = 0.18\text{ A}$

ii. 2 points

For using the equation to calculate the energy stored in the inductor — 1 point

$U = \dfrac{1}{2}Li^2 = \left(\dfrac{1}{2}\right)(3.0\text{ H})(0.18\text{ A} - 0.020\text{ A})^2$

For an answer consistent with part (c)i — 1 point

$U = 0.0384\text{ J}$

Question 3 (continued)

Distribution of points

(d) 2 points

For correctly using Ohm's law to determine the current through the inductor — 1 point

$$I_L = \frac{\varepsilon}{R_1 + R_3} = \frac{(20\text{ V})}{(50\ \Omega + 50\ \Omega)}$$

For a correct answer — 1 point

$$I_L = 0.20\text{ A}$$

(e) 2 points

For using the loop rule to relate the inductor emf to the voltage drop across R_2 — 1 point

$$\varepsilon_L = V_{R_2}$$

For correctly expressing the loop equation as a differential equation — 1 point

$$-L\frac{di}{dt} = iR_2$$

(f) 3 points

For separation of variables in the differential equation above — 1 point

$$-L\frac{di}{dt} = iR_2$$

$$\frac{1}{i}di = -\frac{R_2}{L}dt$$

For attempting to integrate with the correct limits or the correct constant of integration — 1 point

$$\int_{i_0}^{i(t)} \frac{1}{i}\,di = \int_{t'=0}^{t'=t} -\frac{R_2}{L}\,dt'$$

$$\left[\ln(i)\right]_{i_0}^{i(t)} = \left[-\frac{R_2 t'}{L}\right]_{t'=0}^{t'=t}$$

$$\ln\left(\frac{i(t)}{i_0}\right) = -\frac{R_2}{L}(t-0)$$

$$i(t) = i_0 e^{-R_2 t/L} = (0.20\text{ A})\,e^{-(100\ \Omega)t/(3.0\text{ H})}$$

For a correct answer — 1 point

$$i(t) = (0.20\text{ A})\,e^{-33.3t}$$

Scoring Worksheet

The following provides a scoring worksheet and conversion table used for calculating a composite score of the exam.

2016 AP Physics C: Electricity and Magnetism Scoring Worksheet

Section I: Multiple Choice

$\_\_\_\_\_\_\_\_ \times 1.2857 = \_\_\_\_\_\_\_\_$

Number Correct (out of 35) — Weighted Section I Score (Do not round)

Section II: Free Response

Question 1 $\_\_\_\_\_\_\_\_ \times 1.0000 = \_\_\_\_\_\_\_\_$
(out of 15) (Do not round)

Question 2 $\_\_\_\_\_\_\_\_ \times 1.0000 = \_\_\_\_\_\_\_\_$
(out of 15) (Do not round)

Question 3 $\_\_\_\_\_\_\_\_ \times 1.0000 = \_\_\_\_\_\_\_\_$
(out of 15) (Do not round)

Sum = $\_\_\_\_\_\_\_\_$
Weighted Section II Score (Do not round)

Composite Score

$\_\_\_\_\_\_\_\_ + \_\_\_\_\_\_\_\_ = \_\_\_\_\_\_\_\_$

Weighted Section I Score — Weighted Section II Score — Composite Score (Round to nearest whole number)

AP Score Conversion Chart
Physics C: Electricity and Magnetism

Composite Score Range	AP Score
48-90	5
37-47	4
31-36	3
22-30	2
0-21	1

Question Descriptors and Performance Data

The following contains tables showing the content assessed,
the correct answer, and how AP students performed on each question.

2016 AP Physics C: Electricity and Magnetism
Question Descriptors and Performance Data

Multiple-Choice Questions

Questions	Topic	Key	% Correct
1	Magnetostatics	B	40
2	Magnetostatics	B	58
3	Magnetostatics	E	41
4	Conductors/Cpacitors/Dielectrics	D	43
5	Conductors/Cpacitors/Dielectrics	A	50
6	Conductors/Cpacitors/Dielectrics	E	34
7	Electric Circuits	A	75
8	Electric Circuits	E	13
9	Electrostatics	D	29
10	Electrostatics	C	19
11	Electrostatics	E	53
12	Conductors/Cpacitors/Dielectrics	A	19
13	Conductors/Cpacitors/Dielectrics	C	45
14	Conductors/Cpacitors/Dielectrics	C	86
15	Electric Circuits	E	29
16	Electric Circuits	E	70
17	Electric Circuits	B	35
18	Magnetostatics	C	39
19	Magnetostatics	D	28
20	Magnetostatics	E	71
21	Magnetostatics	B	42
22	Electromagnetism	E	55
23	Electromagnetism	C	42
24	Electric Circuits	D	67
25	Electric Circuits	C	43
26	Electrostatics	A	47
27	Electrostatics	B	58
28	Electrostatics	B	48
29	Magnetostatics	C	62
30	Magnetostatics	B	70
31	Magnetostatics	A	52
32	Magnetostatics	D	53
33	Conductors/Cpacitors/Dielectrics	E	36
34	Electrostatics	B	32
35	Electrostatics	C	53

AP Physics C: Electricity and Magnetism

The College Board

The College Board is a mission-driven not-for-profit organization that connects students to college success and opportunity. Founded in 1900, the College Board was created to expand access to higher education. Today, the membership association is made up of over 6,000 of the world's leading educational institutions and is dedicated to promoting excellence and equity in education. Each year, the College Board helps more than seven million students prepare for a successful transition to college through programs and services in college readiness and college success — including the SAT® and the Advanced Placement Program®. The organization also serves the education community through research and advocacy on behalf of students, educators, and schools. The College Board is committed to the principles of excellence and equity, and that commitment is embodied in all of its programs, services, activities, and concerns.