2020

AP® CollegeBoard

Please note: Some of the questions in this former practice exam may no longer perfectly align with the AP exam. Even though these questions do not fully represent the 2020 exam, teachers indicate that imperfectly aligned questions still provide instructional value. Teachers can consult the Question Bank to determine the degree to which these questions align to the 2020 Exam.

From the 2019 Administration

AP® | CollegeBoard

AP® Physics C: Electricity and Magnetism

Practice Exam

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Note: This publication shows the page numbers that appeared in the ***2018–19 AP Exam Instructions*** book and in the actual exam. This publication was not repaginated to begin with page 1.

AP Physics C: Electricity and Magnetism Exam

Regularly Scheduled Exam Date: Monday afternoon, May 13, 2019

Late-Testing Exam Date: Wednesday afternoon, May 22, 2019

Section I	**Total Time:** 45 minutes Calculator Allowed **Number of Questions:** 35 *(The number of questions may vary slightly depending on the form of the exam.)* **Percent of Total Score:** 50% **Writing Instrument:** Pencil required
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

Before Distributing Exams: Check that the title on all exam covers is ***Physics C: Electricity and Magnetism***. If there are any exam booklets with a different title, contact the AP coordinator immediately.

What Proctors Need to Bring to This Exam

- ☐ Exam packets
- ☐ Answer sheets
- ☐ AP Student Packs
- ☐ *2018-19 AP Coordinator's Manual*
- ☐ This book—*2018-19 AP Exam Instructions*
- ☐ AP Exam Seating Chart template
- ☐ School Code and Homeschool/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"
  - – "Phones of any kind are prohibited during the test administration, including breaks"

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 53 of the *2018-19 AP Coordinator's Manual*. See pages 50–53 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, they must hand copy, date, and sign the release statement on page 52 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 the regularly scheduled 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. (If administering Electricity and Magnetism during the late-testing administration, follow the schedule for late testing.)

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 295–296 for a seating chart template and instructions. See the *2018-19 AP Coordinator's Manual* for exam seating requirements (pages 56–59).

If you are giving the regularly scheduled exam, say:
It is Monday afternoon, May 13, 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 Wednesday afternoon, May 22, and you will be taking the AP Physics C: Electricity and Magnetism Exam.

Look at your exam packet and confirm that the exam title is "AP Physics C: Electricity and Magnetism." Raise your hand if your exam packet contains any title other than "AP Physics C: Electricity and Magnetism," and I will help you.

Once you confirm that all students have the correct exams, say:

In a moment, you will open the exam packet. By opening this packet, you agree to all of the AP Program's policies and procedures outlined in the *2018-19 Bulletin for AP Students and Parents*.

You may now remove the shrinkwrap from the outside only of your exam packet. Do not open the Section I booklet; do not remove the shrinkwrap from the Section II materials. Put the white seals and the shrinkwrapped Section II booklet aside. . . .

Carefully remove the AP Exam label found near the top left of your exam booklet cover. Place it on page 1 of your answer sheet on the light blue box near the top right 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.

Listen carefully to all my instructions. I will give you time to complete each step. Please look up after completing each step. Raise your hand if you have any questions.

Give students enough time to complete each step. Don't move on until all students are ready.

Read the statements on the front cover of the Section I booklet. . . .

Sign your name and write today's date. . . .

Now print your full legal name where indicated. . . .

Turn to the back cover of your exam booklet and read it completely. . . .

Give students a few minutes to read the entire cover.

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. You may never discuss the multiple-choice exam content at any time in any form with anyone, including your teacher and other students. If you disclose the multiple-choice exam content through any means, your AP Exam score will be canceled.

Open your answer sheet to page 2. 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 ______________ . **Note Stop Time** ______________ .

Check that students are marking their answers in pencil on their answer sheets and that they have not opened their shrinkwrapped Section II booklets. 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 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, faceup. 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, faceup. I will now collect your Section I booklet. . . .**

Collect a Section I booklet from each student. Check that each student has signed the front cover of the sealed Section I booklet.

SECTION II: Free Response

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 your pen, 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. . . .**
>
> **Now turn to the back cover. Using your pen, complete Items 1 through 3 under "Important Identification Information." . . .**
>
> **Read Item 4. . . .**
>
> **Are there any questions? . . .**

If this is your last AP Exam, you may keep your Student Pack. Place it under your chair for now. Otherwise if you are taking any other AP Exams this year, leave your Student Pack on your desk and I will collect it 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 from students who are taking any other AP Exams this year.

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 to complete your responses, raise your hand. At the top of each extra sheet of paper you use, write only:

- **your AP number,**
- **the exam title, and**
- **the question number you are working on.**

Do not write your name. Are there any questions? . . .

You may begin.

Note Start Time _______________. Note Stop Time _______________.

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, faceup. . . .

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 free-response exam booklets. Complete an Incident Report after the exam and return these free-response booklets with the extra sheets attached in the Incident Report return envelope (see page 68 of the *2018-19 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 their 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 the free-response exam content with anyone unless it is 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 content 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.

After-Exam Tasks

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.

NOTE: If you administered exams to students with accommodations, review the *2018-19 AP Coordinator's Manual* and the *2018-19 AP SSD Guidelines* for information about completing the Nonstandard Administration Report (NAR) form, and returning these exams.

The exam proctor should complete the following tasks if asked to do so by the AP coordinator. Otherwise, the AP coordinator must complete these tasks:

- Complete an Incident Report for any students who used extra paper for the free-response section. (Incident Report forms are provided in the coordinator packets sent with the exam shipments.) **These forms must be completed with a No. 2 pencil.** It is best to complete a single Incident Report for multiple students per exam subject, per administration (regular or late testing), as long as all required information is provided. Include all exam booklets with extra sheets of paper in an Incident Report return envelope (see page 68 of the *2018-19 AP Coordinator's Manual* for complete details).
- Return all exam materials to secure storage until they are shipped back to the AP Program. (See page 27 of the *2018-19 AP Coordinator's Manual* for more information about secure storage.) 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 *2018-19 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.

Name:________________________________

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

No.	Answer
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	
18	

No.	Answer
19	
20	
21	
22	
23	
24	
25	
26	
27	
28	
29	
30	
31	
32	
33	
34	
35	

AP® Physics C: Electricity and Magnetism Exam

SECTION I: Multiple Choice

2019

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 4PBP4-S

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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, $1 \text{ eV} = 1.60 \times 10^{-19}$ 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, $N_0 = 6.02 \times 10^{23}$ 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, $g = 9.8$ 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,	$1 \text{ atm} = 1.0 \times 10^{5} \text{ N/m}^2 = 1.0 \times 10^{5} \text{ Pa}$

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

$v_x = v_{x0} + a_x t$

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

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

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

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

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

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

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

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

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

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

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

$\Delta U_g = mg\Delta h$

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

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

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

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

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

$v = r\omega$

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

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

$\omega = \omega_0 + \alpha t$

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

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

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

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

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

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

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

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

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

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

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

$C_p = \sum_i C_i$

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

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

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

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

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

$I = Nev_d A$

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

$R_s = \sum_i R_i$

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

$P = I\Delta V$

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

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

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

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

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

$B_s = \mu_0 n I$

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

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

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

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

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

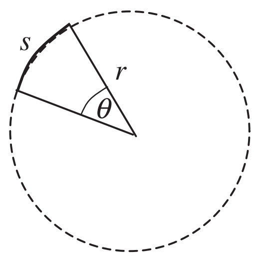
$a^2 + b^2 = c^2$

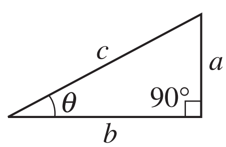
$\sin\theta = \frac{a}{c}$

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

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

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

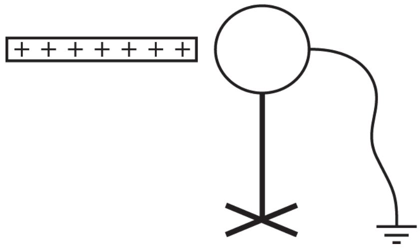
Time—45 minutes

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. Two positive point charges, both of magnitude 4.0×10^{-6} C, are situated along the *x*-axis at $x_1 = -2.0$ m and $x_2 = +2.0$ m. What is the electric potential at the origin of the *xy*-coordinate system?

(A) -3.6×10^4 V
(B) -1.8×10^4 V
(C) 0 V
(D) 1.8×10^4 V
(E) 3.6×10^4 V



2. A grounded spherical conductor is on an insulating stand. A positively charged rod is brought close to the sphere but does not touch the sphere, as shown above. The rod is moved far away and then the grounding wire is removed. Which of the following describes the resulting charge on the sphere?

(A) Positive
(B) Negative
(C) No net charge, but it is polarized with positive charges on the left side of the sphere
(D) No net charge, but it is polarized with negative charges on the left side of the sphere
(E) No net charge and no polarization

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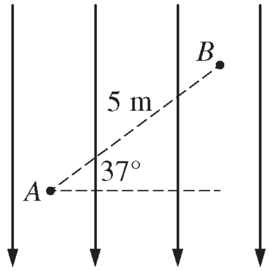
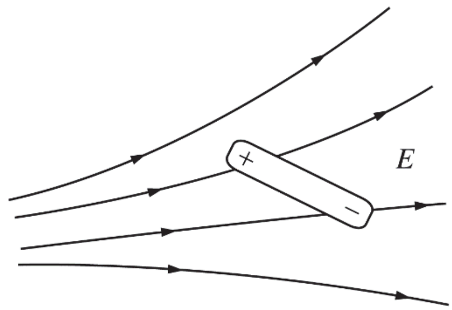


3. Points A and B shown above are in the plane of the page and 5 meters apart. The points are located in a uniform electric field of magnitude $1000\ \text{V/m}$ directed toward the bottom of the page. When a proton (of charge $+e$) moves from point A to point B, how much work is done on the proton by the electric field?

(A) −5000 eV
(B) −3000 eV
(C) +3000 eV
(D) +4000 eV
(E) +5000 eV



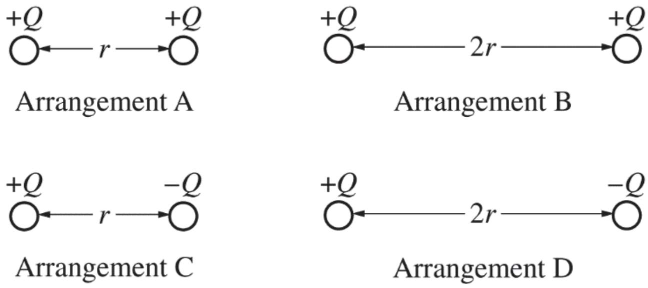
4. An electric dipole consisting of a positive charge and a negative charge held a fixed distance apart is at rest in an external, nonuniform electric field E, as shown in the figure above. Which of the following best describes the net torque and net force exerted on the dipole?

	Net Torque	Net Force
(A)	Clockwise	To the left
(B)	Clockwise	To the right
(C)	Counterclockwise	To the left
(D)	Counterclockwise	To the right
(E)	Zero	Zero

5. Which of the following must be true for a Gaussian surface through which the net flux is zero?

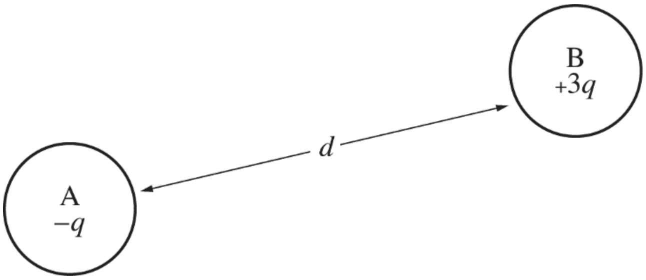
I. There are no charges inside the surface.
II. The net charge enclosed by the surface is zero.
III. The electric field is zero everywhere on the surface.

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



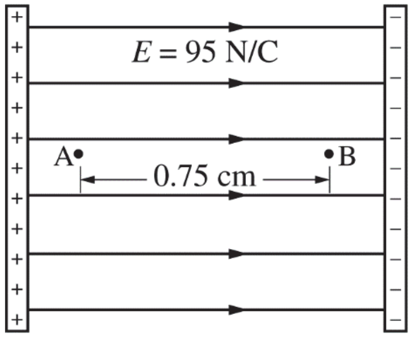
6. Four isolated arrangements of charged spheres are created for an experiment, as shown above. Which of the following correctly compares the electric potential energy U of the arrangements? Assume $U = 0$ when the charges are an infinite distance apart.

(A) $U_A > U_B > U_C > U_D$
(B) $U_A > U_C > U_B > U_D$
(C) $U_B > U_D > U_A > U_C$
(D) $U_D > U_C > U_B > U_A$
(E) $U_A > U_B > U_D > U_C$



7. Conducting spheres A and B of charges $-q$ and $+3q$, respectively, are separated by a distance d, as shown in the figure above. Which of the following statements is true about the two spheres?

(A) The magnitude of the force sphere A exerts on sphere B is three times larger than the magnitude of the force sphere B exerts on sphere A.
(B) The magnitude of the force sphere B exerts on sphere A is three times larger than the magnitude of the force sphere A exerts on sphere B.
(C) The force sphere B exerts on sphere A is equal in magnitude to the force sphere A exerts on sphere B.
(D) If the spheres are free to move, the magnitude of the force sphere B exerts on sphere A will decrease as the spheres move.
(E) If the spheres are brought into contact with each other and then returned to the positions shown, the two spheres will attract each other.



8. Two conducting plates hold equal and opposite charges that create an electric field of magnitude $E = 95\ \text{N/C}$ that is directed to the right, as shown in the figure above. Points A and B are 0.75 cm apart with A closer to the positive plate. A proton is released from rest at point A. What is the kinetic energy of the proton when it reaches point B ?

(A) 0
(B) $+1.14 \times 10^{-19}$ J
(C) $+1.52 \times 10^{-17}$ J
(D) $+1.92 \times 10^{-7}$ J
(E) +71 J

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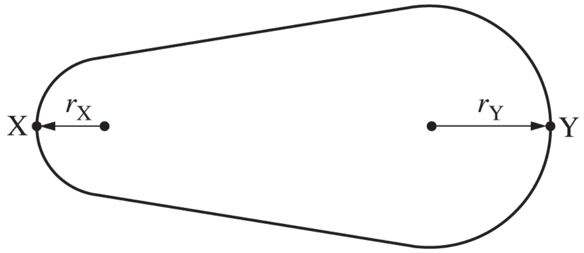
Questions 9-10



The figure above shows a cross section of a solid, isolated, metallic conductor in electrostatic equilibrium with a net charge $+Q$. The two ends of the conductor are spherical surfaces of radii r_X and r_Y, where $r_X < r_Y$. Points X and Y are on the conductor at each end.

9. Assuming that the electric potential is zero an infinite distance from the conductor, which of the following statements is true about the magnitude of the electric potential at points X and Y?

    (A) It is greater at point X than at point Y.
    (B) It is greater at point Y than at point X.
    (C) It is zero at both points X and Y.
    (D) It has the same nonzero value at both points X and Y.
    (E) There is not enough information to determine at which point, if either, the magnitude of the electric potential is greater.

10. Which of the following is true about the magnitude of the electric field just outside the surface of the conductor at points X and Y?

    (A) It is greater at point X than at point Y.
    (B) It is greater at point Y than at point X.
    (C) It is zero at both points X and Y.
    (D) It has the same nonzero value at both points X and Y.
    (E) There is not enough information to determine at which point, if either, the magnitude of the electric field is greater.

11. A parallel-plate capacitor is connected across a voltage V so that each plate of the capacitor collects a charge of magnitude Q. Which of the following is an expression for the energy stored in the capacitor?

    (A) QV
    (B) $\frac{Q}{V}$
    (C) $\frac{V}{Q}$
    (D) $\frac{1}{2}QV$
    (E) $\frac{1}{2}QV^2$

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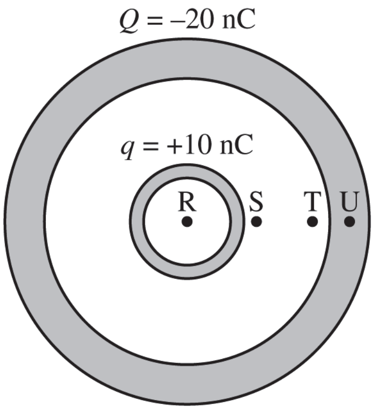
Questions 12-13



Two concentric spherical conducting shells and four labeled points are shown above. The outer shell has a net charge $Q = -20$ nC. The inner shell has a net charge $q = +10$ nC.

12. What is the charge on the outer surface of the outer shell?

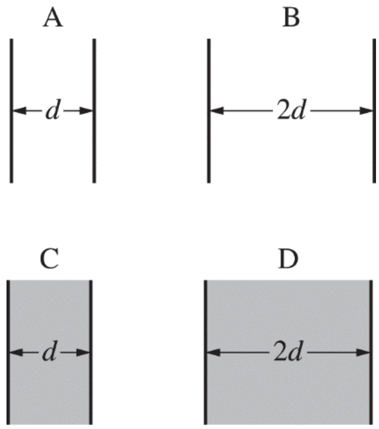
(A) –30 nC
(B) –20 nC
(C) –10 nC
(D) +10 nC
(E) +30 nC

13. The magnitudes of the electric fields at the four labeled points in the figure are E_R, E_S, E_T, and E_U, respectively. Which of the following correctly ranks the points according to the magnitude of their electric fields?

(A) $E_R = E_S = E_T = E_U$
(B) $E_S > E_T > (E_R = E_U)$
(C) $(E_S = E_T) > E_U > E_R$
(D) $E_T > E_S > E_R > E_U$
(E) $(E_S = E_T) > (E_R = E_U)$

14. A parallel plate capacitor is connected to a battery, fully charged, disconnected, and isolated from the battery. A dielectric slab is then inserted between the plates of the capacitor. Which of the following is a true statement about what happens when the dielectric slab is inserted?

(A) The magnitude of the electric field between the plates of the capacitor will increase.
(B) The potential difference between the plates of the capacitor will decrease.
(C) The capacitance of the capacitor will decrease.
(D) The charge stored on the capacitor will increase.
(E) The energy stored in the capacitor will increase.



15. Four parallel plate capacitors all have the same plate area and have the plate separations shown above. Both capacitors A and B have air between the plates, while the space between the plates of both capacitors C and D is filled with a dielectric slab of dielectric constant $\kappa = 2$. Which of the following correctly ranks the capacitors in order of their capacitance from largest to smallest ?

(A) B > (A = D) > C
(B) (A = C) > (B = D)
(C) C > (A = D) > B
(D) (B = D) > (A = C)
(E) D > C > B > A

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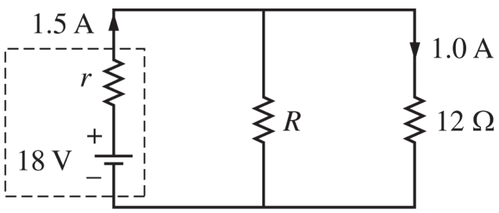
Questions 16-17



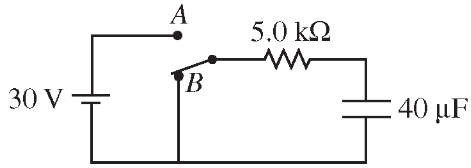
Two resistors of resistances R and 12 Ω are connected to a battery of emf 18 V, as shown in the figure above. The battery has an internal resistance of r. The current in the battery is 1.5 A, and the current in the 12 Ω resistor is 1.0 A.

16. What is the resistance R ?

(A) 7.2 Ω
(B) 12 Ω
(C) 18 Ω
(D) 24 Ω
(E) 45 Ω

17. What is the internal resistance of the battery?

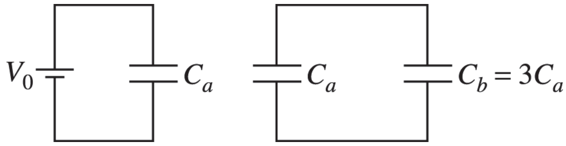
(A) 4.0 Ω
(B) 6.0 Ω
(C) 12 Ω
(D) 18 Ω
(E) 36 Ω



18. The capacitor in the circuit represented above is uncharged when the switch is at position B. The switch is then moved to position A. What is the energy stored by the capacitor when the current in the circuit is 2.0 mA?

(A) 0.8 mJ
(B) 1.2 mJ
(C) 8.0 mJ
(D) 16 mJ
(E) 18 mJ

Questions 19-20



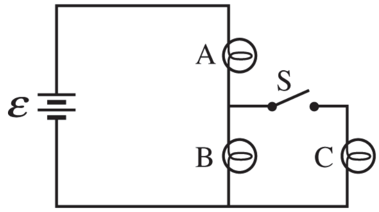
A capacitor of capacitance C_a is first charged to a voltage V_0, as shown above on the left. Without losing any charge, the capacitor is now disconnected from the voltage source and connected to a second initially uncharged capacitor of capacitance C_b that is three times C_a, and the circuit is allowed to reach equilibrium, as shown above on the right.

19. If Q_a is the new charge on capacitor C_a, the charge Q_b on capacitor C_b is given by

(A) 0
(B) $Q_a/3$
(C) $Q_a/2$
(D) Q_a
(E) $3Q_a$

20. The new voltage across capacitor C_a is V_a. How does this new voltage compare with the original voltage of V_0?

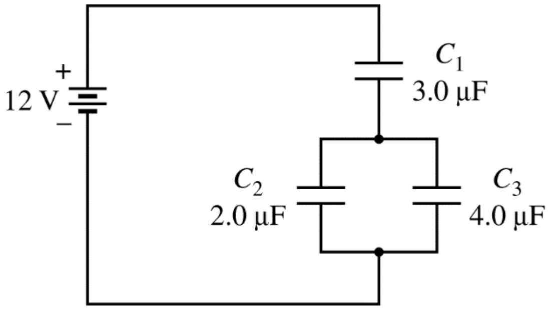
(A) $V_a > V_0$
(B) $V_a < V_0$
(C) $V_a = V_0$
(D) It depends on the value of C_a.
(E) It depends on the value of C_b.



21. A circuit contains three identical light bulbs and a switch S connected to an ideal battery of emf $\mathcal{E}$, as shown in the figure above. The switch is initially open and bulbs A and B have equal brightness, while C is not lit. What happens to the brightness of bulbs A and B when the switch S is closed and bulb C lights up?

	Bulb A	Bulb B
(A)	Remains the same	Becomes dimmer
(B)	Becomes dimmer	Becomes dimmer
(C)	Becomes brighter	Becomes dimmer
(D)	Becomes brighter	Not lit
(E)	Remains the same	Not lit

Questions 22-23



The circuit shown above has three capacitors and a 12 V battery. The capacitors are charged to steady state conditions.

22. What is the potential difference across capacitor C_1 ?

(A) 3.0 V
(B) 4.0 V
(C) 6.0 V
(D) 8.0 V
(E) 12 V

23. One of the capacitors is removed from the circuit and isolated. While it still holds all of its charge, a piece of ceramic with dielectric constant of 2 is inserted and completely fills the space between the plates. U_i is the energy stored in the capacitor before the dielectric was inserted, and U_f is the energy stored in the capacitor after the dielectric was inserted. What is the ratio U_f/U_i ?

(A) 1/4
(B) 1/2
(C) 1/1
(D) 2/1
(E) 4/1

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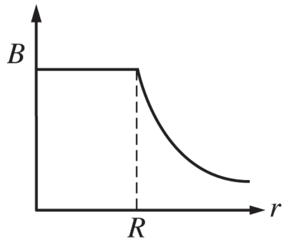
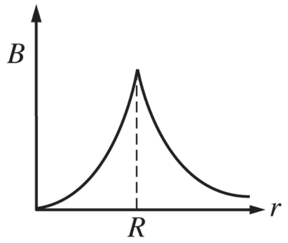
24. A long, straight wire of radius R carries current I. The current is distributed over the cross-sectional area of the wire with a uniform current density. Which of the following graphs best represents the magnetic field strength produced by the current as a function of the distance r from the center of the wire?

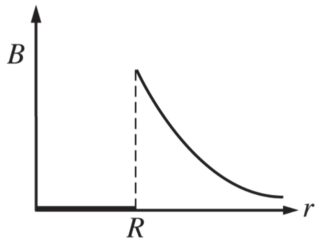
(A)



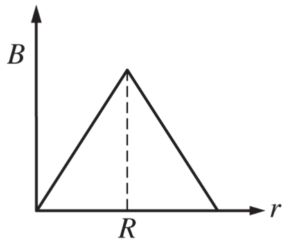
(B)



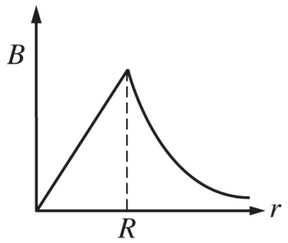
(C)



(D)



(E)



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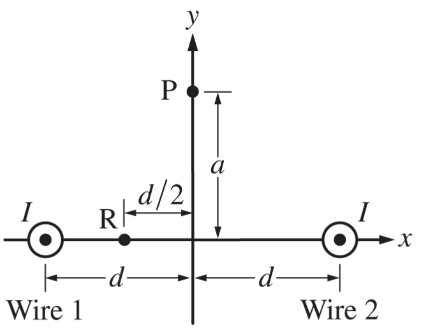
Questions 25-26



Two wires perpendicular to the x-axis have currents I directed out of the page, as shown above. Each wire is a distance d from the y-axis. Point P lies on the y-axis at the coordinate $(0, a)$, and point R lies on the x-axis at the coordinate $(-d/2,\ 0)$.

25. Which of the following expressions represents the magnitude of the magnetic field at point R?

(A) Zero

(B) $\dfrac{\mu_0 I}{2\pi d}$

(C) $\dfrac{\mu_0 I}{\pi d}$

(D) $\dfrac{4\mu_0 I}{3\pi d}$

(E) $\dfrac{2\mu_0 I}{3\pi d}$

26. Which of the following best represents the direction of the net magnetic field at point P?

(A) ↗

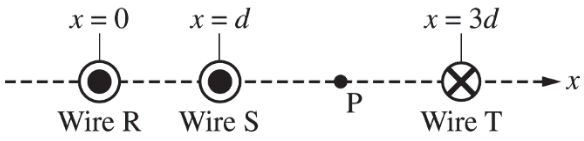
(B) →

(C) ↑

(D) ←

(E) ↓

Questions 27-28



Three long, current-carrying wires are shown in the cross-sectional view above. The currents in wires R and S are out of the page, and the current in wire T is into the page. The currents in the wires have equal magnitude, and the wires are in the positions shown. Point P is halfway between wires S and T.

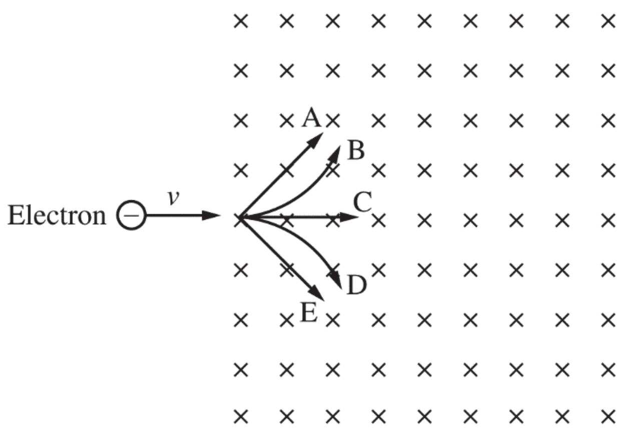
27. If B_S is the magnitude of the magnetic field at point P due to wire S, which of the following gives the magnitude and direction of the magnetic field at point P due to all three wires?

	Magnitude	Direction
(A)	$B_S/2$	Top of the page
(B)	$B_S/2$	Bottom of the page
(C)	B_S	Top of the page
(D)	$5B_S/2$	Top of the page
(E)	$5B_S/2$	Bottom of the page

28. To which of the following locations, if any, could wire S be moved so that the total magnetic force exerted on it by the other two wires is zero?

(A) $-d < x < 0$
(B) $0 < x < d$
(C) $d < x < 2d$
(D) $2d < x < 3d$
(E) There is no position in the vicinity of the wires at which the magnetic force on wire S would be zero.

Questions 29-30



An electron is traveling with speed v when it enters a uniform magnetic field that is directed into the page, as shown above. Five paths in the magnetic field are labeled A, B, C, D, and E.

29. Which labeled path best shows the path the electron will follow as it travels through the magnetic field?

(A) Path A
(B) Path B
(C) Path C
(D) Path D
(E) Path E

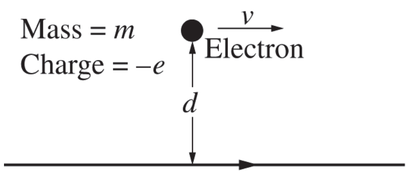
30. The electron is replaced with a proton that is traveling at the same speed v in the same direction as it enters the magnetic field. Which of the following best describes the motion of the proton as it passes through the magnetic field?

I. The speed of the proton changes less than the speed of the electron did.

II. The proton is deflected in the opposite direction.

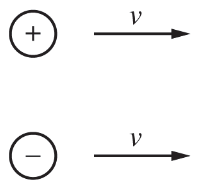
III. The proton is deflected more than the electron.

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



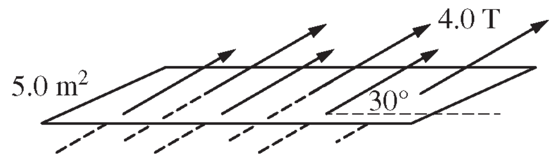
31. An electron of mass m and charge $-e$ is traveling to the right parallel to a wire with speed v . The electron is a distance d from the wire. The wire is carrying a current I to the right, as shown in the figure above. Which of the following gives the magnitude and direction of the force exerted on the electron by the current-carrying wire?

	Magnitude	Direction
(A)	$\frac{\mu_0 Iev}{2\pi d}$	Toward the top of the page
(B)	$\frac{\mu_0 Iev}{2\pi d}$	Out of the page
(C)	$\frac{\mu_0 Iev}{2\pi d}$	Into the page
(D)	$\frac{\mu_0 Iev}{2m\pi d}$	Toward the top of the page
(E)	$\frac{\mu_0 Iev}{2m\pi d}$	Out of the page



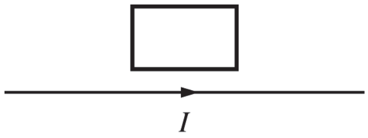
32. Two small spheres have equal and opposite charges and are travelling parallel to each other with speed v to the right, as shown above. What is the direction of the magnetic field midway between the spheres at the instant shown?

(A) Out of the page
(B) Into the page
(C) Toward the bottom of the page
(D) Toward the top of the page
(E) Undefined, since the magnitude of the magnetic field is zero.



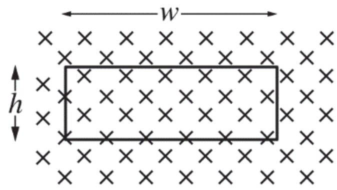
33. A magnetic field of magnitude 4.0 T is directed at an angle of $30°$ to the plane of a rectangular loop of area $5.0\ m^2$, as shown above. What is the magnetic flux through the loop?

(A) $10\ T \cdot m^2$
(B) $12\ T \cdot m^2$
(C) $17\ T \cdot m^2$
(D) $20\ T \cdot m^2$
(E) $40\ T \cdot m^2$



34. A rectangular conducting loop is located above a long, straight wire carrying a current I to the right, as shown in the figure above. The wire and loop are both in the plane of the page. Which of the following will induce a clockwise current in the loop?

(A) Decreasing the current in the wire
(B) Moving the loop to the right
(C) Moving the loop to the left
(D) Moving the loop up away from the wire
(E) Moving the loop down toward the wire



Magnetic field B into the page

35. A wire loop with width w and height h is in a magnetic field that is directed into the page, as shown in the figure above. The magnitude B of the magnetic field changes with time t. The magnitude of the resulting induced emf in the wire loop is given as a function of time by the equation $\mathcal{E} = \beta hwt^3$, where β is a positive constant in units of $\mathrm{T/s^4}$. Which of the following is a possible expression for the magnitude of the magnetic field?

(A) $\frac{1}{4}\beta t^3$

(B) $3\beta t^4$

(C) $3hw\beta t^2$

(D) $\frac{1}{4}hw\beta t^4$

(E) $\frac{1}{4}\beta t^4$

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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**

AP® Physics C: Electricity and Magnetism Exam

SECTION II: Free Response

2019

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
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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.
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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 4PBP4-S

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,	$1\ \text{atm} = 1.0 \times 10^{5}\ \text{N/m}^2 = 1.0 \times 10^{5}\ \text{Pa}$

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

$v_x = v_{x0} + a_x t$

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

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

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

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

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

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

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

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

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

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

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

$\Delta U_g = mg\Delta h$

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

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

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

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

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

$v = r\omega$

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

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

$\omega = \omega_0 + \alpha t$

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

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

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

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

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

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

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

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

$|\vec{F}_G| = \frac{Gm_1m_2}{r^2}$

$U_G = -\frac{Gm_1m_2}{r}$

ELECTRICITY AND MAGNETISM

$|\vec{F}_E| = \frac{1}{4\pi\varepsilon_0}\left|\frac{q_1q_2}{r^2}\right|$

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

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

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

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

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

$U_E = qV = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r}$

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

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

$C_p = \sum_i C_i$

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

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

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

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

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

$I = Nev_d A$

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

$R_s = \sum_i R_i$

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

$P = I\Delta V$

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

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

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

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

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

$B_s = \mu_0 nI$

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

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

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

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

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

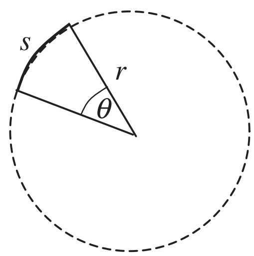
$a^2 + b^2 = c^2$

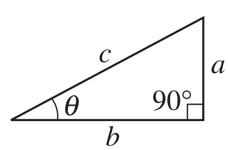
$\sin\theta = \frac{a}{c}$

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

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

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

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

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

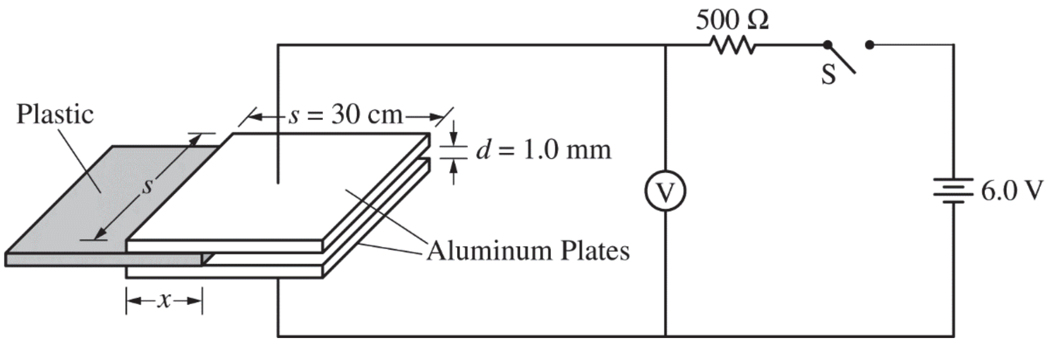
PHYSICS C: ELECTRICITY AND MAGNETISM

SECTION II

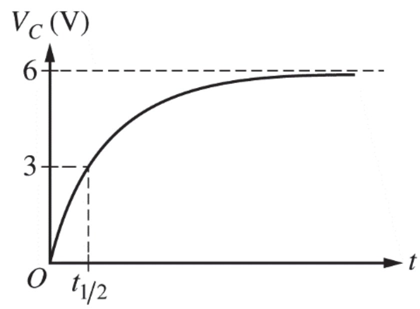
Time—45 minutes

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.



1. Students design an experiment to determine the unknown dielectric constant κ of a plastic material. A capacitor is created using two square aluminum plates of side length $s = 30$ cm that are separated by a distance $d = 1.0$ mm. This capacitor is placed in a circuit with an ideal 6.0-volt battery, a resistor of resistance $R = 500\ \Omega$, voltmeter V, and an open switch S, as shown above. A 1.0 mm thick piece of plastic is inserted between the aluminum plates. The distance x that the plastic is inserted between the plates can be varied, and the voltmeter is used to measure the potential difference V_C across the capacitor. The switch is closed, and readings from the voltmeter are recorded as a function of time t. The data are plotted to create the graph shown below.



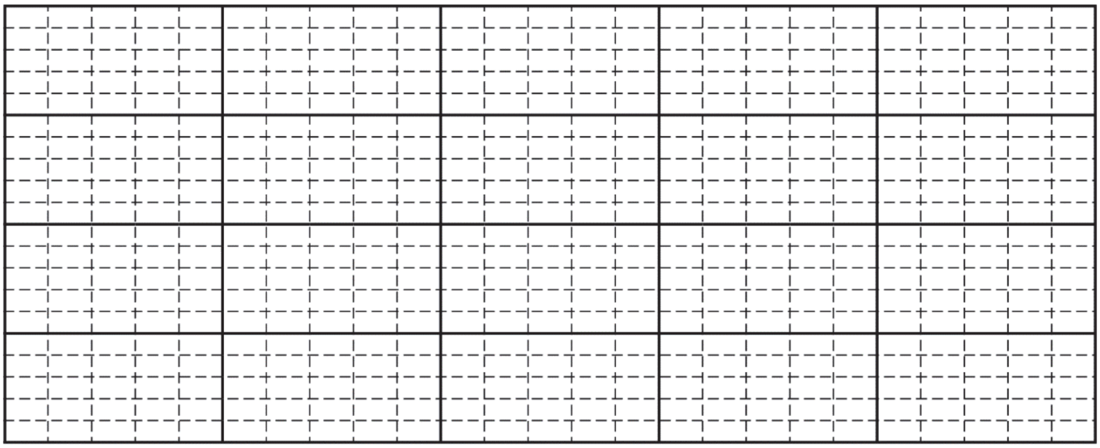
The time $t_{1/2}$ shown above is the time for the capacitor to charge to half the potential difference of the battery.

(a) The potential difference across the capacitor as a function of time is modeled by the equation $V_C = V_{MAX}\left(1 - e^{-t/RC}\right)$, where $V_{MAX} = 6$ V. Derive an expression for the capacitance C of the capacitor. Express your answer in terms of $t_{1/2}$, R, and physical constants, as appropriate.

The data for x and $t_{1/2}$ are recorded for several trials and the value of C for each trial is calculated. The results are shown in the chart below.

x (m)	0.050	0.10	0.15	0.20	0.25
$t_{1/2}$ (μs)	0.44	0.63	0.75	0.88	1.10
C (nF)	1.27	1.82	2.16	2.54	3.17

(b) Plot the experimental value of the capacitance C as a function of the distance x on the graph below. Clearly scale and label all axes, including units if appropriate. Draw a straight line that best represents the data.



(c) The capacitor in the lab can be treated as two capacitors in parallel, one with the dielectric and one with air between the plates. Show that the capacitance can be expressed as $C = \frac{\varepsilon_0 s}{d}(s + x(\kappa - 1))$.

Question 1 continues on the next page.

GO ON TO THE NEXT PAGE.

(d) Using the graph from part (b), calculate the value of the dielectric constant κ.

(e) The students now want to verify the value for the permittivity constant, ε_0. Using the graph from part (b), calculate an experimental value for ε_0.

(f) Assume the value found in part (e) is higher than the accepted value for the permittivity constant. State one possible physical reason for this error and explain how it could have caused this error.

THIS PAGE MAY BE USED FOR SCRATCH WORK.

GO ON TO THE NEXT PAGE.

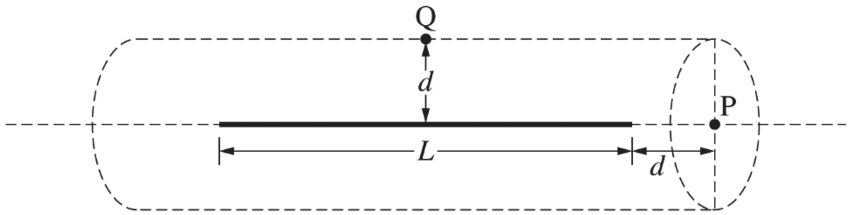


Figure 1

2. A thin wire of length L has a uniform charge density $+\lambda$. A cylindrical Gaussian surface of radius d is drawn with the wire along its central axis, as shown above. Point P is located at the center of one end of the cylinder, a distance d from the end of the wire. Point Q is on the edge of the cylinder directly above the center of the wire, as shown above.

A student says, “Gauss’s law can be used to find the electric flux Φ through the Gaussian surface.”

(a) Is the student’s statement correct or incorrect?

____ Correct ____ Incorrect

If you have chosen “Correct,” use Gauss’s law to find the electric flux Φ through the Gaussian surface.

If you have chosen “Incorrect,” explain why the student’s reasoning is incorrect and why Gauss’s law cannot be applied in this situation.

(b) Two students discuss whether or not they can use Gauss’s law to find the electric field at points P and Q. At which of the points, if either, is Gauss’s law a useful method for finding the electric field?

_____ At point P only ____ At point Q only

_____ At both points P and Q ____ At neither point P nor point Q

Justify your answer.

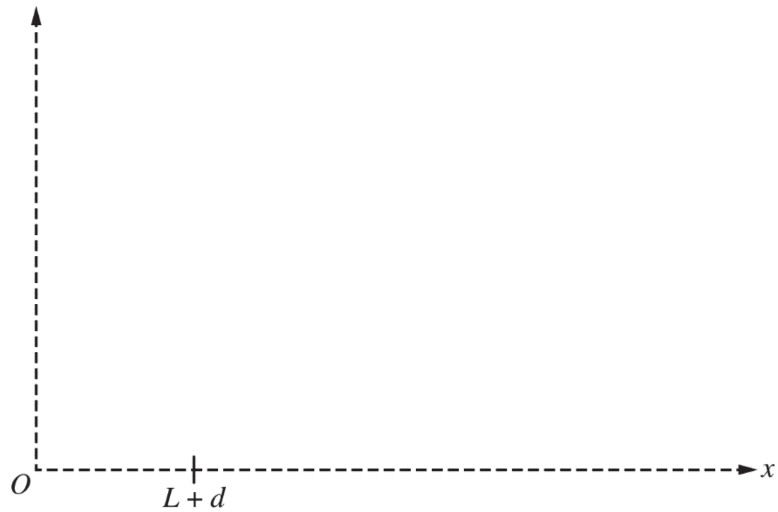
(c) Assuming the electric potential is zero at infinity, show that the value for the electric potential at point P is given by the following expression.

$$V = \frac{\lambda}{4\pi\varepsilon_0}\ln\left(\frac{L+d}{d}\right)$$

Figure 2

The wire is aligned along the x-axis with the origin at the left end of the wire, as shown in Figure 2 above.

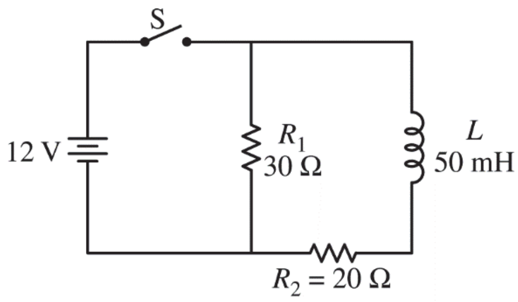
(d) A positively charged particle of charge $+e$ and mass m is released from rest at point P. On the axes below, sketch the kinetic energy K of the particle, the potential energy U of the wire-particle system, and the total energy E_{tot} of the wire-particle system as functions of the particle's position x. Clearly label each sketch with K, U, and E_{tot}. Explicitly label any maximum with numerical values or algebraic expressions, as appropriate.



Question 2 continues on the next page.

Figure 3

(e) Derive an expression for the magnitude of the electric field due to the wire as a function of the position along the x-axis, where $x > L$. Express your answer in terms of x, L, λ, and physical constants, as appropriate.



3. The circuit shown above is constructed using an ideal 12 V battery, an ideal switch S, and two resistors and an inductor with the values shown. Switch S is closed. After a long time, the circuit reaches steady-state conditions.

   (a) Calculate the current through R_1.

   (b) Calculate the current through the battery.

   The switch is then opened at time $t = 0$.

   (c) Determine the current in the inductor immediately after the switch is opened.

(d)

i. Determine the current in resistor R_1 immediately after the switch is opened.

ii. Which of the following statements is correct about the current through R_1 immediately after the switch is opened?

_____ The current is up through R_1.   _____ The current is down through R_1.

_____ There is no current through R_1.

Justify your answer.

(e) Immediately after the switch is opened, is the top end or bottom end of the inductor at the higher electric potential?

____ Top end   ____ Bottom end

Justify your answer.

Question 3 continues on the next page.

GO ON TO THE NEXT PAGE.

(f) On the axes below, sketch a graph of the potential difference V across the inductor as a function of time after the switch is opened. Explicitly label the vertical axis intercept with a numerical value.

(g) Write but DO NOT solve a differential equation that could be solved for the current through the inductor as a function of time after the switch is opened.

GO ON TO THE NEXT PAGE.

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.**

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

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

Multiple-Choice Section for Physics C: Electricity and Magnetism
2019 Course Framework Alignment and Rationales

Question 1

Skill	Learning Objective	Topic
6.C	CNV-1.A	Electrostatics — Electric Potential Due to Point Charges and Uniform Fields

(A)	Incorrect. This option is a result of substituting into the equation for electric potential but using negative values for both of the point charges.
(B)	Incorrect. This option calculates the electric potential difference for just one of the point charges and uses a negative value for the point charge.
(C)	Incorrect. This option adds the electric potentials for point charges as vectors similar to the electric field. However, the electric potential is a scalar variable.
(D)	Incorrect. This option calculates the electric potential difference for just one of the point charges.
(E)	**Correct**. Electric potential due to multiple point charges can be determined using the principle of superposition. Substituting into the equation for the electric potential yields $V = \frac{1}{4\pi\varepsilon_o}\sum_i \frac{q_i}{r_i}$ $V = \frac{1}{4\pi\varepsilon_o}\left[\frac{+4.0\times10^{-6}\ \text{C}}{+2.0\,\text{m}} + \frac{+4.0\times10^{-6}\ \text{C}}{+2.0\,\text{m}}\right]$ $V = 3.6\times10^{4}\ \text{V}$

Question 2

Skill	**Learning Objective**	**Topic**
7.A	ACT-2.C	Conductors, Capacitors, Dielectrics — Electrostatics with Conductors

(A)	Incorrect. This option describes a result of charging by conduction; however, the rod does not touch the sphere in this scenario. Additionally, the sphere would have to be ungrounded before the rod is moved away.
(B)	Incorrect. This option would result if the positively charged rod was moved away after the grounding wire was removed.
(C)	Incorrect. This option is a result of misunderstanding the idea that like charges repel and unlike charges attract as well as the effect of the order in which the rod is moved away and then the sphere is ungrounded.
(D)	Incorrect. This option correctly states that the sphere has no net charge. However, since the positively charged rod was moved far away from the sphere after being brought close to its left side, any initial negative charges moving toward the rod were freely able to move back since the external charged object inducing a charge was no longer present. Thus, the sphere has no net charge and no polarization.
(E)	**Correct**. As the positively charged rod is brought near the left side of the grounded spherical conductor, charge separation in the neutral sphere is induced and negative charges move toward the left side of the sphere. However, when the positively charged rod is moved far away from the sphere, the charges will move back to reestablish a neutral sphere and excess negative charges will flow back to the ground. Since the sphere is ungrounded after the rod is removed, the sphere is back to having no net charge and no polarization.

Question 3

Skill	Learning Objective	Topic
6.A	CNV-1.E	Electrostatics — Electric Potential Due to Point Charges and Uniform Fields

(A)	Incorrect. This option uses the equation for calculating work, $W = Fd = qEd$, and correctly determines that the work done on the proton is negative; however, it uses the distance shown between points A and B in its calculations. The value for d is only the component of the displacement parallel to the electric field.
(B)	**Correct**. Substituting into the equation for the work done by the electric field yields $W = FD\cos(\theta)$ $W = qED\cos(\theta)$ $W = (+e)(1000V / m)(5\,\text{m})(\cos(90° - 37°))$ $W = 3000\,\text{V}$. The proton is moving against the electric field; thus, the work done on the proton will be negative, so $W = -3000\,\text{e}V$.
(C)	Incorrect. This option correctly calculates the work done on the proton from point A to point B; however, it neglects that the work done by the electric force is negative, because the proton is moving against the electric field.
(D)	Incorrect. This option does not take into consideration that the work is negative and uses the component of the displacement that is perpendicular, not parallel, to the electric field to calculate the work done.
(E)	Incorrect. This option uses the equation for calculating work, $W = Fd = qEd$, but uses the distance shown between points A and B in its calculations. The value for d is only the component of the displacement parallel to the electric field. This option also does not take into consideration that the work is negative.

Question 4

Skill	Learning Objective	Topic
7.A	ACT-1.D	Electrostatics — Charge and Coulomb's Law

(A)	Incorrect. The direction of the net torque is correctly determined. However, because the positive side of the dipole is in a position where the electric field is stronger, the net force is to the right, not to the left.
(B)	**Correct**. The force on the top part of the dipole is to the right and on the bottom part is to the left; thus, the net torque will be clockwise. Also, because the positive side of the dipole is in a position where the electric field is stronger, the net force is to the right.
(C)	Incorrect. The force on the top part of the dipole is to the right and on the bottom part is to the left; thus, the net torque will be clockwise, not counterclockwise. However, because the positive side of the dipole is in a position where the electric field is stronger, the net force is to the right, not to the left.
(D)	Incorrect. This option determines the correct direction of net force. However, the force on the top part of the dipole is to the right and on the bottom part is to the left; thus, the net torque will be clockwise, not counterclockwise.
(E)	Incorrect. The net force cannot be zero because the external field is not uniform; thus, this option would be possible only if the field were uniform. Additionally, the net torque is not zero, but it could be mistaken as zero if the process of determining torque on an electric dipole in an electric field is misunderstood.

Question 5

Skill	Learning Objective	Topic
7.A	CNV-2.B	Electrostatics — Gauss's Law

(A)	Incorrect. This statement may be possible, but it is not necessary, since there can still be charges in a Gaussian surface where the net flux is zero, as long as the net charge enclosed is zero, meaning the number of positive charges present and number of negative charges present are equal; thus, I is not necessarily true.
(B)	**Correct**. The flux of an electric field through a closed surface is always zero if the net charge enclosed by the surface is zero. There could be charges inside the surface as long as they are equal and opposite charges. Also, there could be nonzero values of the electric field on the surface as long as the sum $\Sigma E \cdot dA$ is zero; thus, only II must be true.
(C)	Incorrect. This case also may be possible, but not necessary, since there can be a nonzero electric field everywhere on the surface, where the net flux is still zero. As long as the number of electric field lines entering the Gaussian surface is equal to the number of electric field lines exiting the Gaussian surface, the net flux equals zero; thus, III is not necessarily true.
(D)	Incorrect. There could be charges inside the surface as long as they are equal and opposite charges; thus, I is not necessarily true.
(E)	Incorrect. There could be charges inside the surface as long as they are equal and opposite charges. Also, there could be nonzero values of the electric field on the surface as long as the sum $\Sigma E \cdot dA$ is zero; thus, I and III are not necessarily true.

Question 6

Skill	**Learning Objective**	**Topic**
5.B	CNV-1.C	Electrostatics — Electric Potential Due to Point Charges and Uniform Fields

(A)	Incorrect. It is correct that $U_A > U_B$; however, the option places $U_C > U_D$. However, because C and D are negative, $U_D > U_C$.
(B)	Incorrect. This option correctly determines U_A as the greatest electric potential energy, as well as placing $U_B > U_D$, but incorrectly determines U_C as the second greatest electric potential energy. Because C is negative, U_C is the lowest electric potential energy.
(C)	Incorrect. This option has both U_B and U_D greater than U_A. However, because A is positive and has the smallest distance, U_A is the greatest electric potential energy.
(D)	Incorrect. This option has U_A as the lowest electric potential energy. However, because A is positive and has the smallest distance, U_A is the greatest electric potential energy.
(E)	**Correct**. The electric potential energy between two charges can be determined by using the equation for electric potential energy, $U = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r}$. For arrangement A: $U_A = \frac{1}{4\pi\varepsilon_0}\frac{(+Q)(+Q)}{r} = \frac{1}{4\pi\varepsilon_0}\frac{Q^2}{r} = 1\left(\frac{1}{4\pi\varepsilon_0}\frac{Q^2}{r}\right)$. For arrangement B: $U_B = \frac{1}{4\pi\varepsilon_0}\frac{(+Q)(+Q)}{2r} = \frac{1}{4\pi\varepsilon_0}\frac{Q^2}{2r} = \frac{1}{2}\left(\frac{1}{4\pi\varepsilon_0}\frac{Q^2}{r}\right)$. For arrangement C: $U_C = \frac{1}{4\pi\varepsilon_0}\frac{(+Q)(-Q)}{r} = -\frac{1}{4\pi\varepsilon_0}\frac{Q^2}{r} = -1\left(\frac{1}{4\pi\varepsilon_0}\frac{Q^2}{r}\right)$. For arrangement D: $U_D = \frac{1}{4\pi\varepsilon_0}\frac{(+Q)(-Q)}{2r} = -\frac{1}{4\pi\varepsilon_0}\frac{Q^2}{2r} = -\frac{1}{2}\left(\frac{1}{4\pi\varepsilon_0}\frac{Q^2}{2r}\right)$. Thus, $U_A > U_B > U_D > U_C$.

Question 7

Skill	**Learning Objective**	**Topic**
7.A	ACT-1.A	Electrostatics — Charge and Coulomb's Law

(A)	Incorrect. This option is a result of not applying Newton's third law to the situation. The forces acting on each charge are equal in magnitude and opposite in direction.
(B)	Incorrect. This option is a result of the misconception that the magnitude of force exerted by one charge on another charge is directly proportional to the larger charge.
(C)	**Correct**. The magnitude of force exerted by one charge on another charge can be determined by Coulomb's law. Coulomb's law states that the electrostatic force between two charges is directly proportional to the product of the magnitudes of charges and inversely proportional to the square of the distance between them. $\left\|\vec{F}\right\| = \frac{1}{4\pi\varepsilon_0}\left\|\frac{q_1 q_2}{r^2}\right\|$. The magnitude of force on sphere A is the same as the magnitude of force on sphere B, since there are only two charged spheres present, and only one value of force can be determined.
(D)	Incorrect. This option is a result of the misconception that moving two charges will change the force exerted on one of the charges but not on both equally.
(E)	Incorrect. This option is a result of the misconception that bringing two charged objects together will cause them to attract each other.

Question 8

Skill	Learning Objective	Topic
6.A	CNV-1.E	Electrostatics — Electric Potential Due to Point Charges and Uniform Fields

(A)	Incorrect. This option indicates that the proton will stop moving when it reaches point B; thus, the kinetic energy would be zero. However, because the proton starts at rest and moves through the electric field, it will gain kinetic energy as it moves to point B.
(B)	**Correct**. Setting the kinetic energy of the proton at point B equal to the change in the potential energy of the system as the proton moves from point A to point B yields the following. $\Delta U_E = qE\Delta d = K$ $K = \left(1.6 \times 10^{-19}\text{C}\right)\left(95N / C\right)\left(0.75cm \times \frac{1\text{m}}{100\,cm}\right)$ $K = 1.14 \times 10^{-17}$ J
(C)	Incorrect. This option uses the equation for change in the potential energy of the system but does not include the displacement in the calculation.
(D)	Incorrect. This option uses the equation for change in the potential energy of the system but divides by the displacement instead of multiplying by the displacement.
(E)	Incorrect. This option is the potential difference between the two points, not the change in the potential energy between the two points.

Question 9

Skill	**Learning Objective**	**Topic**
7.A	ACT-2.B	Conductors, Capacitors, Dielectrics — Electrostatics with Conductors

(A)	Incorrect. A conductor at electrical equilibrium is an equipotential surface. So the electric potential at point X cannot be greater than the electric potential at point Y.
(B)	Incorrect. Throughout a conductor at electrical equilibrium, there can be no net electric field, since charges would move to cancel out any field; thus, there can be no variation in electric potential. So the electric potential at point Y cannot be greater than the electric potential at point X.
(C)	Incorrect. There is a positive net charge on the conductor. Therefore, a positive test charge placed at the surface of the conductor would move away from the conductor; thus, the electric potential at points X and Y is not zero.
(D)	**Correct**. The electric field inside a conductor is zero; thus, the electric potential is the same at all points on the conductor's surface. There is a positive net charge on the conductor. Therefore, a positive test charge placed at the surface of the conductor would move away from the conductor; thus, the electric potential at points X and Y has a nonzero value.
(E)	Incorrect. Though there is not enough information to determine the value of the electric potential at points X and Y, there is enough information to determine the relative electric potential at those points.

Question 10

Skill	Learning Objective	Topic
7.A	ACT-2.A	Conductors, Capacitors, Dielectrics — Electrostatics with Conductors

(A)	**Correct**. On a solid conductor, all charges reside on the surface. More charges accumulate at locations of greater curvature because the force separating them, which is the only component of electrostatic force that is parallel to the surface, decreases with the greater curvature. Because more charges accumulate at these locations, the electric field just outside these sharply curved surfaces is strongest.
(B)	Incorrect. This option is based on the incorrect assumption that the total amount of charge, not the density of the charge, is responsible for the strength of the electric field at the conductor's surface.
(C)	Incorrect. There is a positive net charge on the conductor. Therefore, a positive test charge placed at the surface of the conductor would move away from the conductor; thus, the electric field at points X and Y is not zero.
(D)	Incorrect. The electric field is proportional to the electrostatic force, and the force separating charges, which is the only component of electrostatic force that is parallel to the surface, decreases with the greater curvature of the surface. The curvature at point X is not the same as the curvature at point Y; thus, the electric fields at the two points are not the same.
(E)	Incorrect. Though there is not enough information to determine the value of the electric field at points X and Y, there is enough information to determine the relative electric field at those points.

Question 11

Skill	Learning Objective	Topic
5.E	CNV-4.B	Conductors, Capacitors, Dielectrics — Capacitors

(A)	Incorrect. Because voltage is defined as the energy per unit charge, this option indicates that the energy stored on this capacitor is QV. However, this is only correct if the voltage between the plates is constant during the entire charging process.
(B)	Incorrect. This option uses an expression for the capacitance of the capacitor, not the energy stored in the capacitor.
(C)	Incorrect. This option uses an expression for the reciprocal of the capacitance of the capacitor, not the energy stored in the capacitor.
(D)	**Correct**. Energy stored in a capacitor is electrical potential energy. Electrical potential energy is related to charge and potential difference by $U_E = qV$. As the capacitor is being charged, the potential difference across the plates of the capacitor is zero, and when the capacitor is fully charged, the potential difference across the plates is V; thus, the average voltage on the capacitor while the capacitor charges is $\frac{1}{2}V$. Therefore, the energy stored in a capacitor with voltage V and charge Q is $\frac{1}{2}QV$.
(E)	Incorrect. The energy stored in a capacitor has several equivalent expressions since the capacitance C of a capacitor, charge Q, and voltage V can be related by $Q = CV$; thus, $E_{capacitor} = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{Q^2}{2C}$. Hence, this option is a result of incorrectly using the relationship between these three variables to derive the energy stored.

Question 12

Skill	**Learning Objective**	**Topic**
6.A	ACT-2.A	Conductors, Capacitors, Dielectrics — Electrostatics with Conductors

(A)	Incorrect. This option subtracts instead of adds the charge on the inner sphere from the charge on the outer sphere.
(B)	Incorrect. This option indicates that all of a conductor's charge resides on its surface but does not take into account the effect of the charge on the inner sphere.
(C)	**Correct**. A charge of $-10\,\text{nC}$ on the outer shell is drawn to the shell's inner surface by the $+10\,\text{nC}$ on the inner shell. The remainder of the charge on the outer shell distributes itself as far away as possible from the $-10\,\text{nC}$ on the shell's inner surface. Therefore, $-10\,\text{nC}$ is distributed on the outer surface of the outer shell.
(D)	Incorrect. This option indicates the charge on the outer surface is the opposite of, instead of equal to, the sum of the charges on the two spheres.
(E)	Incorrect. This option subtracts the charge on the outer sphere from the charge on the inner sphere. The charges should be added.

Question 13

Skill	**Learning Objective**	**Topic**
5.A	ACT-3.A	Conductors, Capacitors, Dielectrics — Electrostatics with Conductors

(A)	Incorrect. This option indicates that all four points have the same magnitude of electric field. This would be true if all four points were inside the conductors, but some of the points are in the space between the conductors.
(B)	**Correct**. Applying Gauss's law and using Gaussian surfaces as described, $E_R = E_U = 0$ because no charge is enclosed by the respective Gaussian sphere. (The sphere for point U is centered at the shells' center; the sphere for point R is centered slightly off the shells' center but still encloses no charge.) $E_s > E_U > 0$ because the same $+10\,\text{nC}$ charge is enclosed by the respective Gaussian spheres, but the sphere for point S is smaller than the sphere for point T. Therefore, the electric field magnitude, which is proportional to the enclosed charge divided by the sphere's surface area, is greater at point S than it is at point T.
(C)	Incorrect. This option indicates that the electric field is equal at points S and T. However, since points S and T are not inside the conductors but in the space between the conductors, and point S is closer to the center of the spheres than point T, the electric field is greater at point S than at point T. Also, since the electric field is zero at both points R and U, the electric field is equal at those two points.
(D)	Incorrect. This option indicates that the electric field is greater at point T than at point S. However, since point S is closer to the center of the spheres than point T is, the electric field is greater at point S than at point T. Also, since the electric field is zero at both points R and U, the electric field is equal at those two points.
(E)	Incorrect. This option indicates that the electric field is equal at points S and T. However, since points S and T are not inside the conductors but in the space between the conductors, and point S is closer to the center of the spheres than point T is, the electric field is greater at point S than at point T.

Question 14

Skill	**Learning Objective**	**Topic**
5.C	FIE-2.D	Conductors, Capacitors, Dielectrics — Dielectrics

(A)	Incorrect. The potential difference decreases when the dielectric is inserted between the plates; thus, the electric field will decrease, not increase, between the plates.
(B)	**Correct**. The parallel plate capacitor is connected to a battery to charge and then is isolated so the charge remains the same. Then, inserting a dielectric slab between the plates of the capacitor will result in the capacitance increasing; thus, since charge remains constant, the voltage across the parallel plate capacitor will decrease due to the following relationship: $Q = CV$. The potential energy will therefore decrease due to the following relationship: $U_C = \frac{1}{2}QV$.
(C)	Incorrect. The potential difference decreases when the dielectric is inserted between the plates; thus, the electric field will decrease, not increase, between the plates.
(D)	Incorrect. Since the parallel plate capacitor is disconnected from the battery after being fully charged, its isolation results in the charge remaining the same/constant; thus, the charge will not increase or decrease.
(E)	Incorrect. The energy in the capacitor actually would decrease as a result of the increase in capacitance, and decrease in voltage, as the charge remains the same, by the following relationship: $U_C = \frac{1}{2}QV$.

Question 15

Skill	Learning Objective	Topic
5.B	FIE-2.C	Conductors, Capacitors, Dielectrics — Dielectrics

(A)	Incorrect. This option lists the capacitances in order from smallest to largest, instead of largest to smallest.
(B)	Incorrect. This option is a result of using $C = \frac{\kappa \varepsilon_0 A}{d}$ for determining all of the capacitances, using $\kappa = 2$ for all four of the parallel plate capacitors, neglecting that capacitors A and B do not contain dielectric.
(C)	**Correct**. In order to calculate and compare the capacitance of the parallel plate capacitors with and without a dielectric material between the plates, the correct relationships should be used. Note that the plate areas for all of the plates are the same. For capacitors A and B, the capacitance of each can be determined using $C_A = \frac{\varepsilon_0 A}{d}$, since they are not filled with a dielectric slab. Therefore, $C_A = \frac{\varepsilon_0 A}{d} = (1)\left(\frac{\varepsilon_0 A}{d}\right)$ $C_B = \frac{\varepsilon_0 A}{2d} = \left(\frac{1}{2}\right)\left(\frac{\varepsilon_0 A}{d}\right)$. For capacitors C and D, the capacitance of each can be determined using $C = \frac{\kappa \varepsilon_0 A}{d}$, since they are filled with a dielectric slab of dielectric constant $\kappa = 2$. Therefore, $C_C = \frac{\kappa \varepsilon_0 A}{d} = \frac{2\varepsilon_0 A}{d} = (2)\left(\frac{\varepsilon_0 A}{d}\right)$ $C_D = \frac{\kappa \varepsilon_0 A}{2d} = \frac{2\varepsilon_0 A}{2d} = (1)\left(\frac{\varepsilon_0 A}{d}\right)$. Therefore, by comparing the coefficients of each of the capacitances calculated, the correct rank of the capacitors from largest to smallest is $C > (A = D) > B$.
(D)	Incorrect. This option is a result of using $C = \frac{\kappa \varepsilon_0 A}{d}$ for determining all of the capacitances, using $\kappa = 2$ for all four of the parallel plate capacitors, neglecting that capacitors A and B do not contain dielectric. The order also lists the capacitances in order from smallest to largest, instead of largest to smallest.
(E)	Incorrect. This option is the result of correctly indicating that the capacitance of the capacitors is inversely related to the distance between the plates; thus, the greater the distance, the lower the capacitance. However, it indicates that adding dielectric will decrease the capacitance instead of increasing it.

Question 16

Skill	**Learning Objective**	**Topic**
6.B	CNV-6.C	Electric Currents — Steady-State Direct - Current Circuits with Batteries and Resistors only

(A)	Incorrect. This option uses Ohm's law and divides the voltage of the battery by the sum of the two currents shown. However, Ohm's law would need the potential difference across and the current going through just the resistor in the middle branch.
(B)	Incorrect. This option indicates that the resistor must be equal to the other resistor. However, the current does not split equally between the two resistors; thus, the resistors are not equal.
(C)	Incorrect. This option uses Ohm's law and divides the voltage of the battery by the current shown in the right branch. However, Ohm's law would need the potential difference across and the current going through just the resistor in the middle branch.
(D)	**Correct**. The parallel branches must all have the same voltage, and the current flowing through R must be $0.5\,\text{A}$. Therefore, Eqn1 : $18\,\text{V} - (1.5\,\text{A})r = (1.0\,\text{A})(12\Omega)$ Eqn2 : $18\,\text{V} - (1.5\,\text{A})r = (0.5\,\text{A})R$ Eqn1 – Eqn2: $0 = (1.0\,\text{A})(12\Omega) - (0.5\,\text{A})R$ $R = \dfrac{(1.0\,\text{A})(12\Omega)}{(0.5\text{A})}$ $R = 24\Omega$
(E)	Incorrect. This option multiplies the voltage of the battery by the sum of the two currents shown. However, Ohm's law would divide the potential difference across and the current going through just the resistor in the middle branch.

Question 17

Skill	**Learning Objective**	**Topic**
6.C	CNV-6.C	Electric Currents — Steady-State Direct - Current Circuits with Batteries and Resistors only

(A)	**Correct**. The left and right parallel branches must both have the same voltage. $18\,\text{V} - (1.5\,\text{A})r = (1.0\,\text{A})(12\Omega)$ Therefore, $\dfrac{18\,\text{V} - (1.0\,\text{A})(12\Omega)}{1.5\,\text{A}} = r$ $r = 4\Omega.$
(B)	Incorrect. This option uses Ohm's law and divides the voltage of the battery by twice the current shown in the internal resistor. However, Ohm's law would need the potential difference across and the current going through just the internal resistor.
(C)	Incorrect. This option indicates that the internal resistance must be equal to the resistance of the other resistor. However, applying Ohm's law to the circuit shows that the two resistors are not equal.
(D)	Incorrect. This option uses Ohm's law and divides the voltage of the battery by the current shown in the right branch. However, Ohm's law would need the potential difference across and the current going through just the internal resistor.
(E)	Incorrect. This option indicates that the internal resistance must be equal to the sum of the resistances of the other two resistors. However, applying Ohm's law to the circuit shows that these values are not equal.

Question 18

Skill	**Learning Objective**	**Topic**
5.E	CNV-7.B	Capacitors in Circuits

(A)	Incorrect. This option is the correct numerical amount of charge (in μC), not the energy, on the capacitor when the current in the circuit is $2.0\,\text{m}A$.
(B)	Incorrect. This option is the correct numerical amount of charge (in μC) when the capacitor is fully charged, not the energy stored in the capacitor when the current in the circuit is $2.0\,\text{m}A$.
(C)	**Correct**. When the switch is closed to A, applying Kirchhoff's loop rule yields $\varepsilon - RI - V_C = 0$. Therefore, $V_C = (30\text{V}) - \left(5.0 \times 10^3\,\Omega\right)\left(2.0 \times 10^{-3}\,\text{A}\right) = 20\,\text{V}$. Then, substituting into an equation for potential energy yields $U = \frac{1}{2}CV^2 = \frac{1}{2}(40\mu\text{F})(20\text{V})^2 = 8.0\,\text{m}J$.
(D)	Incorrect. This option multiplies the values given for current, resistance, and capacitance instead of using the energy equation for when the current is $2.0\,\text{m}A$.
(E)	Incorrect. This option assumes that the voltage across the capacitor is the same as the battery's $\mathcal{E}$, but when the current in the circuit reaches $2.0\,\text{m}A$, the capacitor has not yet built up this voltage.

Question 19

Skill	**Learning Objective**	**Topic**
5.E	CNV-7.A	Capacitors in Circuits

(A)	Incorrect. This option is the initial charge on C_b, not the final charge on C_b.
(B)	Incorrect. This option sets the final potential differences of the two capacitors equal but then gets the reciprocal of the correct answer.
(C)	Incorrect. This option indicates that because the difference in the two capacitances is $2C$, the final charge on must be half the charge on C_a. However, the potential differences across the two capacitors must be set equal to solve for the charge on the two capacitors.
(D)	Incorrect. This option indicates that if the final potential differences for the two capacitors are equal, the charges on the two capacitors must be equal. However, because the two capacitances a C_b re not equal, the final charges are not equal.
(E)	**Correct**. The voltages of the two capacitors must be the same; therefore, $V_a = V_b$ $\frac{Q_a}{C_a} = \frac{Q_b}{C_b}$ $\frac{Q_a}{C_a} = \frac{Q_b}{3C_a}$. $3Q_a = Q_b$

Question 20

Skill		Learning Objective	Topic
5.A		CNV-7.A	Capacitors in Circuits
(A)	Incorrect. This option indicates that the potential difference across C_a increases. However, because some of the original charge on C_a is transferred to C_b, the potential difference across C_a decreases.		
(B)	**Correct**. In order to counter the battery, an initial charge Q_0 builds up on C_a. When C_a is transferred into the circuit with C_b, Q_0 is split between the two capacitors. Therefore, the charge on C_a is decreased. As a result, V_a, which is this reduced charge divided by C_a, is decreased.		
(C)	Incorrect. This option indicates that the potential difference across C_a stays the same. However, because some of the original charge on C_a is transferred to C_b, the potential difference across C_a decreases.		
(D)	Incorrect. To determine the numerical value of V_a, the value of C_a must be known. However, it can be determined that the potential difference across V_a decreases as the system reaches a new equilibrium with the potential drop for each capacitor being equal.		
(E)	Incorrect. To determine the value of V_a, the value of C_b must be known. However, it can be determined that the potential difference across V_a decreases because the initial charge is distributed among the two capacitors so that the potential difference is equal in both capacitors.		

Question 21

Skill		Learning Objective	Topic
7.A		CNV-6.C	Electric Currents — Steady-State Direct - Current Circuits with Batteries and Resistors only
(A)	Incorrect. This option results from incorrectly assuming that the equivalent resistance of the parallel branch is the same as the resistance of a single light bulb because the current would encounter the same resistance, regardless of which leg of the parallel branch it takes. Bulb A would therefore remain undimmed.		
(B)	Incorrect. This option could result from the faulty assumption that the battery's power output is constant. Therefore, when further load is placed on the battery, all previous loads receive less power.		
(C)	**Correct**. The brightness is indicative of power (I^2R.) When the switch is closed, bulb A has more current flowing through it than when the switch is open, and bulb B has less current flowing through it than when the switch is open. When the switch is open, bulb A and bulb B are in series. Each has a current of $\frac{\varepsilon}{2R}$ flowing through it, where R is the resistance of each light bulb. When the switch is closed, bulb A and bulb B are no longer in series. Though the ideal battery's ε remains the same, the circuit's resistance is now $\frac{3R}{2}$, whereas before it was $2R$. Bulb A now has a current $\frac{2\varepsilon}{3R}$ of flowing through it, an increase from before. Bulb B now has a current of $\frac{\varepsilon}{3R}$ flowing through it, a decrease from before. Therefore bulb A is brighter, and bulb B is dimmer.		
(D)	Incorrect. This option results from incorrectly assuming that all charges would take the path through bulb C , thereby shorting out bulb B.		
(E)	Incorrect. This option results from two errors. The first error is incorrectly assuming that the equivalent resistance of the parallel branch is the same as the resistance of a single light bulb because the current would encounter the same resistance, regardless of which leg of the parallel branch it takes. Bulb A would therefore remain undimmed. The second error is assuming that all charges would take the path through bulb C, ,thereby shorting out bulb B.		

Question 22

Skill		**Learning Objective**	**Topic**
6.B		CNV-7.A	Capacitors in Circuits
(A)	Incorrect. This option divides the voltage of the battery across all three capacitors. However, this would only occur for three equal capacitance in series. For this circuit, the capacitances are not equal, and two of the capacitors are in parallel.		
(B)	Incorrect. This option is the potential difference across the two capacitors in parallel, not the potential difference across C_1.		
(C)	Incorrect. Because this circuit can be reduced to two capacitors in series, this option indicates that the voltage of the battery is divided equally between the two capacitors. However, the equivalent capacitance of the two parallel capacitors is not equal to the C_1, the voltage of the battery does not divide equally.		
(D)	**Correct**. To calculate this, first determine the charge Q_{C_1} across capacitor C_1. The equivalent capacitance of the circuit is determined to be: $\frac{1}{C_{eq}} = \frac{1}{C_1 + C_2} + \frac{1}{C_3} = \frac{1}{20\ \mu\text{F}+40\ \mu\text{F}} + \frac{1}{30\ \mu\text{F}}\ C = 2.0\ \mu\text{F}.$ Therefore, $Q_{tot} = C_{eq}V = (2.0\mu\text{F})(12\ \text{V}) = 24\ \mu\text{C}.$ Capacitors in series $V_{C_1} = \frac{Q_{C_1}}{C_1} = \frac{24\ \mu\text{C}}{3\ \mu\text{F}} = 8\ \text{V}$ have the same charge on them; thus, $Q_{C_1} = 24\mu\text{C},$ and.		
(E)	Incorrect. This option indicates that the voltage of the battery is the potential difference across C_1. However, the voltage of the battery will divide between C_1 and the two parallel capacitors.		

Question 23

Skill	Learning Objective	Topic
5.B	CNV-4.G	Conductors, Capacitors, Dielectrics — Capacitors

(A)	Incorrect. This option would result if the energy stored in a capacitor is incorrectly remembered as $U = \frac{1}{2}\left(\frac{Q}{C}\right)^2$.
(B)	**Correct**. When a dielectric is inserted into a capacitor so that it completely fills the space between the capacitor's plates, $C_f = \kappa C_1$, where C_f is the capacitance after the dielectric is inserted, κ is the dielectric constant, and C_i is the capacitance without the dielectric. $U = \frac{1}{2}\frac{Q^2}{C}$; therefore, $U_f = \frac{1}{2}\frac{Q^2}{\kappa C}$; therefore, $\frac{U_f}{U_i} = \frac{1}{\kappa} = \frac{1}{2}$.
(C)	Incorrect. This option would result from incorrectly assuming that an inserted dielectric does not affect a capacitor's energy storage.
(D)	Incorrect. This option would result from the incorrect assumption that for a capacitor with a dielectric inserted between its plates, $C_{free\,of\,dielectric} = \kappa C_{inserted}$.
(E)	Incorrect. This option would result from two errors. The first error is the incorrect assumption that for a capacitor with a dielectric inserted between its plates, $C_{free\,of\,dielectric} = \kappa C_{inserted}$. The second error is incorrectly remembering the energy stored in a capacitor as $U = \frac{1}{2}\left(\frac{Q}{C}\right)^2$.

Question 24

Skill	Learning Objective	Topic
4.D	CNV-8.C	Magnetic Fields — Biot–Savart Law and Ampère’s Law

(A)	Incorrect. This option inaccurately shows that the magnetic field is constant and a positive value inside the wire, where $r < R$, and is proportional to $1/r$ outside the wire, where $r \geq R$.
(B)	Incorrect. This option inaccurately shows that the magnetic field is proportional to r^2 inside the wire, where $r < R$, and is proportional to $1/r$ outside the wire, where $r \geq R$.
(C)	Incorrect. This option inaccurately shows that the magnetic field is not proportional to the radius when inside the wire, where $r < R$, and is proportional to I/r for $r \geq R$.
(D)	Incorrect. This option inaccurately shows that the magnetic field is proportional to r for $r < R$ and negative r for $r \geq R$.
(E)	**Correct**. For a long, straight wire with uniform current density and radius R, the magnetic field strength produced by the current as a function of the distance from the center of the wire can be determined by drawing Amperian loops. Outside the wire, where $r \geq R$, the Amperian loop encircles current $I_{enc} = I$. Thus, using Ampere’s law, $\oint \vec{B} \cdot d\vec{S} = B \oint d\vec{S} = B(2\pi r) = \mu_0 I \;\; B = \frac{\mu_0 I}{2\pi r}.$ Inside the wire, where $r < R$, the current encircled is proportional to the area enclosed, $I_{enc} = \frac{\mu r^2}{\pi R^2}.$ So the closed integral of $\oint \vec{B} \cdot d\vec{S} = B \oint d\vec{S} = B(2\mu r) = \mu_0 I \left(\frac{\pi r^2}{\pi R^2}\right)$ $B = \frac{\mu_0 I r}{2\pi R^2}.$ Therefore, the $\vec{B}$ field is zero at the center of the wire and increases linearly with r for $r < R$. When it reaches $r = R$, the edge of radius of the wire (outside the wire), the $\vec{B}$ field falls off as $1/r$ for $r \geq R$. This graph appropriately shows this behavior, where B is proportional to r inside the wire and B is proportional to $1/r$ outside the wire.

Question 25

Skill	**Learning Objective**	**Topic**
5.E	FIE-5.B	Magnetic Fields — Fields of Long, Current-Carrying wires

(A)	Incorrect. This option would be correct if point R were placed at the center of the axis.
(B)	Incorrect. This option is a result of using the Biot-Savart law but substituting the distance d for R.
(C)	Incorrect. This option uses the Biot-Savart law correctly but only takes into account the wire closest to point R.
(D)	Incorrect. This option determines the magnitudes of the magnetic fields due to each of the current carrying wires. However, it is a result of adding the two magnetic fields due to the two wires instead of subtracting the vector pointing up from the vector pointing down.
(E)	**Correct**. Using the Biot-Savart law and superposition as well as the right-hand rule to determine the direction of the magnetic field due to the current carrying wires on a point, the magnitude of the magnetic field at point R due to wire 1 and wire 2 is determined to be the following: $B = \lvert\vec{B}\rvert = \left\lvert \frac{\mu_0 I}{2\pi(d/2)} - \frac{\mu_0 I}{2\pi(3d/2)} \right\rvert = B = \left\lvert \frac{\mu_0 I}{\pi d} - \frac{\mu_0 I}{3\pi d} \right\rvert \; B = \frac{2\mu_0 I}{3\pi d}$.

Question 26

Skill	**Learning Objective**	**Topic**
1.D	FIE-5.B	Magnetic Fields — Fields of Long, Current-Carrying wires

(A)	Incorrect. This would be true if wire 1 were not producing a magnetic field or were not in the figure and if wire 2 were carrying current into the page.
(B)	Incorrect. This would be true if both wire 1 and wire 2 carried current into the page instead of out of the page.
(C)	Incorrect. This would be true if wire 2 carried current into the page instead of out of the page.
(D)	**Correct**. Using the right-hand rule and drawing the circular magnetic field around the current carrying wire up to point **P**, the direction of the magnetic field due to wire 1 and wire 2 can be determined by taking the tangent vectors and adding them together. The magnetic field vector on point P due to wire 1 points upward and to the left. The magnetic field vector on point P due to wire 2 points downward and to the left. Thus by superposition, the net direction of the magnetic field at point P is to the left.
(E)	Incorrect. This would be true if point P were located at the same distance below the x-axis, wire 1 were carrying current into the page, and wire 2 were carrying current out of the page.

Question 27

Skill	Learning Objective	Topic
5.E	FIE-5.B	Magnetic Fields — Fields of Long, Current-Carrying wires

(A)	Incorrect. Although the direction of the magnetic field is correctly stated, this magnitude is only the magnetic field due to wire R . The direction of the magnetic field due to wire T was determined to be negative and opposite the magnetic field due to wire S, and since they are of equal magnitude, their magnetic field is incorrectly canceled out.
(B)	Incorrect. The magnitude stated is only the magnetic field due to wire R. The direction of the magnetic field due to wire T was determined to be negative and opposite the magnetic field due to wire S, and since they are of equal magnitude, their magnetic fields incorrectly canceled out. The overall direction toward the bottom of the page is a result of using the right-hand rule in the opposite direction.
(C)	Incorrect. This is only the magnetic field at point P due to wire S. This is a result of either the other two wires' magnetic fields canceling out in calculations or not being taken into account.
(D)	**Correct**. Since B_S is the magnetic field at point P due to wire S, which is a distance away, the magnetic fields due to the other wires can be determined in terms of B_S. $B_S = +\frac{\mu_0 I}{2\pi d}$. The magnetic field at point P due to wire R, a distance $2d$ from point P, is $B_R = +\frac{\mu_0 I}{2\pi(2d)} = \frac{1}{2}B_S$. The magnetic field at point P due to wire T, a distance d from point P, is $B_R = +\frac{\mu_0 I}{2\pi d} = B_S$. Thus, by the property of superposition, the total magnitude of the magnetic field at point P due to all three wires is $B_S + \frac{1}{2}B_S + B_S = \frac{5}{2}B_S$. Using the right-hand rule for determining the direction of the magnetic field at point P with respect to each of the wires shown, the magnetic field due to each of the wires is up toward the top of the page; thus, the net direction is toward the top of the page.
(E)	Incorrect. This is the correct magnitude of magnetic field at point P, but the direction is opposite. The right-hand rule was used in the opposite direction for each wire.

Question 28

Skill	Learning Objective	Topic
5.E	FIE-4.A	Magnetic Fields — Forces on Current-Carrying Wires in Magnetic Fields

(A)	Incorrect. The magnetic force between wires can be determined using a right-hand rule. Two parallel wires carrying current in the same direction, like wires S and R, will attract each other because the magneticorces due to each wire will face inward between the two wires. Two parallel wires carrying current in opposite directions will have magnetic forces facing outward, away from each other; thus, they will repel. The magnitude of the magnetic force is inversely proportional to the distance the wires are from each other. Therefore, placing wire S in this location will result in a net magnetic force due to the other wires.
(B)	Incorrect. Moving wire S to this location will mean that wire S will be closer to wire R, which is carrying current in the same direction. These will attract. Wire T will be located much farther away but will also repel wire S because it carries current in the opposite direction. Therefore, the force due to wires R and T will not balance, and there will be a net force on wire S.
(C)	Incorrect. Moving wire S to this location will cause wire S to equally attract to wire R and be repelled by wire T, which are of similar distances away from wire S. Therefore, there will be a net magnetic force exerted on wire S to the left.
(D)	Incorrect. Moving wire S to this location will mean that wire S will be closer to wire T, and wire T repels wire S. Wire S will still feel a force by wire R that will attract wire S, but the magnitude will be less. Therefore, there will be a net magnetic force exerted on wire S.
(E)	**Correct**. Since all of the positions shown result in a net magnetic force, there is no position in the vicinity of the wires at which the magnetic force on wire S would be zero.

Question 29

Skill	Learning Objective	Topic
1.D	CHG-1.B	Magnetic Fields — Forces on Moving Charges in Magnetic Fields

(A)	Incorrect. This path is incorrect because it does not take into account the acceleration due to the magnetic force acting on the charge. The electron would not deflect such that it continued to travel in a straight line. Additionally, the force is acting down on the electron, not up.
(B)	Incorrect. This path would be correct if the electron were a positively charged object such as a proton.
(C)	Incorrect. This path would be possible if the electron were an uncharged object moving through the magnetic field shown.
(D)	**Correct**. Using the right-hand rule for the magnetic force (from the Lorentz force equation), $\vec{F} = q\vec{v} \times \vec{B}$, the direction of velocity to the right crossed with the magnetic field perpendicular and into the page results in a magnetic force acting on the moving charge up toward the top of the page. However, since the charge is negative, the direction of the magnetic force acts down on the electron. Since force is being applied to the electron as soon as it enters the B field, it begins accelerating due the relationship $\vec{F} = m\vec{a}$. Since the electron is accelerating, the path that the electron deflects down is not linear but a curve, as shown by path D.
(E)	Incorrect. This path is incorrect because it does not take into account the acceleration due to the magnetic force acting on the charge. The electron would not deflect such that it continued to travel in a straight line.

Question 30

Skill	**Learning Objective**	**Topic**
7.A	CHG-1.B	Magnetic Fields — Forces on Moving Charges in Magnetic Fields

(A)	Incorrect. The speed of the particles is proportional to the force acting on the particle. Since the force is the magnetic force due to the magnetic field and the magnetic field does not change, the speed of the particles is the same. Also, speed is independent of the mass of an object.
(B)	Incorrect. Although statement II is an accurate description of the motion of the proton, statement I is not.
(C)	**Correct**. If the electron is replaced with a positive charge, the resulting force due to the magnetic field, the magnetic force, will act in the positive direction, or upward. This can be determined using the correct right-hand rule for the Lorentz force equation, $\vec{F} = q\vec{v} \times \vec{B}$. Since a force is acting on the charge, it is accelerating up as well. Also, since the mass of an electron is much smaller than the mass of a proton, then $m_{electron} < m_{proton}$. Since $a = \frac{F}{m}$, then $a_{electron} > a_{proton}$; thus, the proton would deflect less than an electron.
(D)	Incorrect. Statement II is a good description; however, statement III is not. The deflection of the particles is inversely proportional to the mass. Since the mass of an electron is much smaller than the mass of a proton, then $m_{electron} < m_{proton}$. Since $a = \frac{F}{m}$, then $a_{electron} > a_{proton}$; thus, the proton would deflect less than an electron.
(E)	Incorrect. Statements I and III are not accurate descriptions of the motion of the proton passing through the magnetic field.

Question 31

Skill		Learning Objective	Topic
5.E		FIE-4.A	Magnetic Fields — Forces on Current-Carrying Wires in Magnetic Fields
(A)	**Correct**. First, the magnitude of the magnetic field B, which is due to the current carrying wire, can be determined using the Biot-Savart Law, where $-e$ is the charge and v is the velocity of the charge. Thus, the magnetic field for this straight wire, where d is also the perpendicular distance from the charge to the wire, is as follows $dB = \frac{\mu_0}{4\pi}\frac{Id\,l\times r}{r^3}$ $B = \frac{\mu_0 I}{2\pi r}$. From the Lorentz force Law, the magnitude of $B = \frac{\mu_0 I}{2\pi d}$ the magnetic force on a moving charge can be determined as follows $F_M = qv\times B$ $F_M = qvB\sin\theta$ $F_M = -ev(\frac{\mu_0 I}{2\pi d})\sin(90^\circ)$. Using the right-hand rule for the $F_M = -ev(\frac{\mu_0 I}{2\pi d})\sin(90^\circ)$ $\lvert F_M \rvert = \frac{\mu_0 Iev}{2\pi d}$ magnetic force relationship, the direction of force due to the current carrying wire, carrying current to the right, crossed with the magnetic field that's out of the page at any point above the wire, is toward the bottom of the page. However, because of the way that the wire is oriented and because of the direction of the current, the magnetic field is directed toward the top of the page.		
(B)	Incorrect. The magnitude of the magnetic force on the charge is correct, however, the direction of the magnetic force is incorrect. In order for this direction to be correct, the magnetic field would have to be pointing down towards the bottom of the page. However, with how the wire is oriented and the direction of the current, the magnetic field is pointing out the page, perpendicular to the direction of the wire.		
(C)	Incorrect. Although the magnetic force is accurately determined, the right-hand rule for the magnetic force is not. This would be true if the magnetic field was pointing up toward the top of the page. However, because of the way the wire is oriented and because of the direction of the current, the magnetic field is directed out the page, perpendicular to the direction of the wire.		

Question 31 (continued)

(D)	Incorrect. This option correctly uses the right-hand rule to determine the direction of the magnetic force on the moving charge; however, in determining the magnitude of the magnetic force, the mass of the charge is misunderstood as being inversely related to the magnetic field.
(E)	Incorrect. The mass of the charge is independent of the magnetic field and force but is accounted for, and using the right-hand rule for the magnetic force relationship is also misunderstood.

Question 32

Skill	**Learning Objective**	**Topic**
1.D	FIE-5.B	Magnetic Fields — Fields of Long, Current-Carrying wires

(A)	Incorrect. This option uses the right-hand rule to determine the direction of the magnetic field; however, it indicates that the magnetic field is in the opposite direction for the motion of these charges.
(B)	**Correct**. Treating the moving charges as current in a wire results in the top charge resulting in a current to the right, and the bottom wire resulting a current to the left. The right-hand rule for the direction of the magnetic field would indicate that the magnetic field from both moving charges is directed into the page; thus, the magnetic field is midway between the spheres is directed into the page.
(C)	Incorrect. This option is only possible if the charges are moving into the page with positive charge on the left and the negative charge on the right. Only then the right-hand rule for the direction of the magnetic field would indicate that the magnetic field from both moving charges is directed toward the bottom of the page between them; thus, for the given situation the magnetic field cannot be toward the bottom of the page.
(D)	Incorrect. This option incorrectly assumes that the charges are moving out of the page with positive charge on the left and the negative charge on the right. Only then the right-hand rule for the direction of the magnetic field would indicate that the magnetic field from both moving charges is directed toward the top of the page between them. Under the given circumstances the field cannot be toward the top of the page.
(E)	Incorrect. The right-hand rule for the direction of the magnetic field would indicate that the magnetic field from both moving charges is directed into the page; thus, the magnetic field is not zero.

Question 33

Skill	Learning Objective	Topic
6.B	CNV-9.A	Electromagnetism — Electromagnetic Induction (Including Faraday's Law and Lenz's Law)

(A)	**Correct**. Using the equation for magnetic flux and taking into account the correct angle between a perpendicular vector to the area shown and the magnetic field lines, which would be $60°$, the magnetic flux can be determined by the following calculations. $\phi_m = \int B \cdot dA$ $\phi_m = B \cdot A \cdot \cos\theta$ $\phi_m = (4.0\,\text{T})(5\,\text{m}^2)(\cos(60^\circ))$ $\phi_m = 10\,\text{T} \cdot \text{m}^2$
(B)	Incorrect. This option is a result of the following calculation, where the area of the rectangular loop is $6\,\text{m}^2$ instead of the correct $5\,\text{m}^2$, which likely is a calculator error: $\phi_m = (4.0\,\text{T})(6\text{m}^2)(\cos(60^\circ))$.
(C)	Incorrect. This option is a result of performing the correct calculations but using the given angle in the problem $30°$; however, the correct angle is the measure from a perpendicular vector to the area shown with the magnetic field lines, which is $90° - 30° = 60°$.
(D)	Incorrect. This option is a result of neglecting the angle in which the magnetic field lines pass through the rectangular loop of area, which means that the direction of the vectors is not accounted for; thus, the calculation used is just $\phi_m = B \cdot A = (4.0\,\text{T})(5\,\text{m}^2) = 20\,\text{T} \cdot \text{m}^2$.
(E)	Incorrect. This option is four times greater than the correct answer. This option may result from forgetting that the magnetic field strength was already accounted for when the calculations were performed correctly and re-multiplied by $4.0\,\text{T}$, or it may result from performing the incorrect calculations and doubling the answer because of the misconception that the area needs to be accounted for twice; the vectors pass through both the top and the bottom of the area.

Question 34

Skill	Learning Objective	Topic
7.A	FIE-6.A	Electromagnetism — Electromagnetic Induction (Including Faraday's Law and Lenz's Law)

(A)	Incorrect. This option will have the same result as moving the loop away from the wire, which results in a decreasing magnetic field that is directed out of the page; thus the current induced in the loop would be counterclockwise.
(B)	Incorrect. The relative distance between the loop and the wire does not change when the loop is moved parallel to the wire to the right. Thus, the magnetic flux through the loop does not change. As a result, moving the loop to the right will not induce a current in the loop.
(C)	Incorrect. Flux does not change when the loop is moved parallel to wire to the left. Thus; moving the loop to the right will not induce a current in the loop.
(D)	Incorrect. While the flux changes when the loop is moved away from wire, this will cause the flux to be decreasing and out of the page; thus, a counterclockwise current, not a clockwise current, would be created in the loop.
(E)	**Correct**. Using one of the right-hand rules, it can be determined that the magnetic field due to the current-carrying wire it directed out of the page in the loop. Moving the loop closer to the wire will result in an increase in the magnetic field directed out of the page in the loop. By Lenz's law, the induced magnetic field will oppose this increase and will point into the page in the loop. As a result, using another right-hand rule, it can be determined that a clockwise current is induced in the loop.

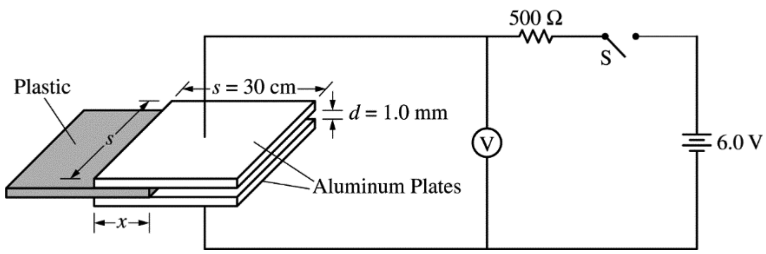
Question 35

Skill	Learning Objective	Topic
5.E	FIE-6.A	Electromagnetism — Electromagnetic Induction (Including Faraday's Law and Lenz's Law)

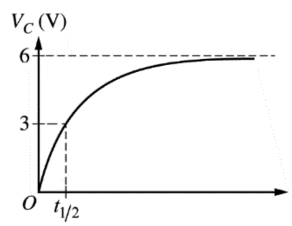
(A)	Incorrect. This option is a result of completing the correct calculations but not adding 1 to the exponent when integrating.
(B)	Incorrect. This option is a result of correctly setting up the mathematical equations, however, a misunderstanding of taking the integral could result with this.
(C)	Incorrect. This option is a combination of not finding the magnetic flux using the area of the loop to cancel out the term, as well as taking the derivative of with respect to t, not the integral.
(D)	Incorrect.
(E)	**Correct**. Given the induced emf $\varepsilon = \beta hwt^3$ and since the equation for emf is $\varepsilon = -\frac{d\varphi_B}{dt}$, one can set them equal to each other. The magnetic flux φ_B must first be determined through the wire loop. The magnetic flux through this loop is given by $\varphi_B = \mathrm{BAsin}(\theta)$, where A is the area of the loop, and the angle is 90 degrees since the magnetic field is perpendicular to the loop. Thus, $\varphi_B = Bwhsin(90) = Bwh$. Thus, by setting the given emf equal to the equation for emf, substituting in the magnetic flux, then integrating with respect to t, and taking the magnitude of the final answer results in this option. $\varepsilon = \varepsilon$ $\beta hwt^3 = -\frac{d\phi_B}{dt}$ $\beta hwt^3 dt = -d(Bwh)$ $\int \beta hwt^3 dt = \int -d(Bwh)$ $\frac{1}{4}\beta hwt^4 = -Bwh$

Question 1

15 points total **Distribution of points**



Students design an experiment to determine the unknown dielectric constant κ of a plastic material. A capacitor is created using two square aluminum plates of side length $s = 30$ cm that are separated by a distance $d = 1.0$ mm. This capacitor is placed in a circuit with an ideal 6.0-volt battery, a resistor of resistance $R = 500\ \Omega$, voltmeter V, and an open switch S, as shown above. A 1.0 mm thick piece of plastic is inserted between the aluminum plates. The distance x that the plastic is inserted between the plates can be varied, and the voltmeter is used to measure the potential difference V_C across the capacitor. The switch is closed, and readings from the voltmeter are recorded as a function of time t. The data are plotted to create the graph shown below.



The time $t_{1/2}$ shown above is the time for the capacitor to charge to half the potential difference of the battery.

(a) LO CNV-7.D.a, SP 5.E
2 points

The potential difference across the capacitor as a function of time is modeled by the equation $V_C = V_{MAX}\left(1 - e^{-t/RC}\right)$, where $V_{MAX} = 6$ V. Derive an expression for the capacitance C of the capacitor. Express your answer in terms of $t_{1/2}$, R, and physical constants, as appropriate.

For correctly substituting into given equation		1 point
$V_C = 6\left(1 - e^{-t/RC}\right) \therefore 3 = 6\left(1 - e^{-t_{1/2}/RC}\right)$		
For correctly solving the above equation		1 point
$\frac{3}{6} = 1 - e^{-t_{1/2}/RC} \therefore e^{-t_{1/2}/RC} = \frac{1}{2} \therefore -t_{1/2}/RC = \ln\left(\frac{1}{2}\right)$		
$C = \frac{t_{1/2}}{R\ln(2)}$		
Note: Answer point is earned with or without a negative sign		

Question 1 (continued)

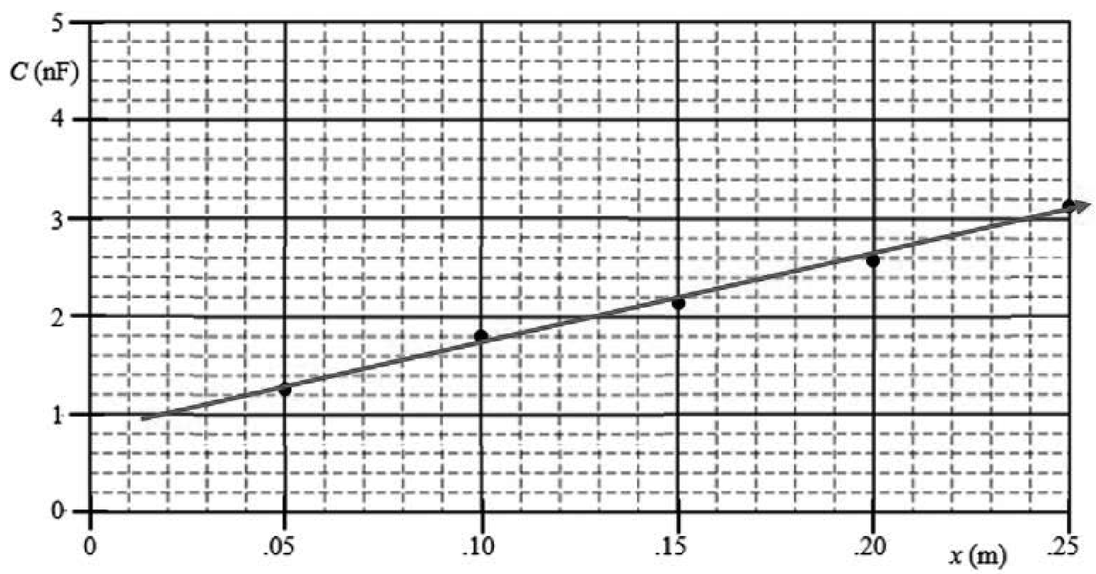
Distribution of points

The data for x and $t_{1/2}$ are recorded for several trials and the value of C for each trial is calculated. The results are shown in the chart below.

x (m)	0.050	0.10	0.15	0.20	0.25
$t_{1/2}$ (μs)	0.44	0.63	0.75	0.88	1.10
C (nF)	1.27	1.82	2.16	2.54	3.17

(b) LO CNV-7.D.a, SP 3.A, 4.C
3 points

Plot the experimental value of the capacitance C as a function of the distance x on the graph below. Clearly scale and label all axes, including units if appropriate. Draw a straight line that best represents the data.



For using a correct scale that uses more than half the grid and for correctly labeling the axes including units as appropriate		1 point
For correctly plotting the data		1 point
For drawing a straight line consistent with the plotted data		1 point

Question 1 (continued)

Distribution of points

(c) CNV-7.A.a, SP 5.A, 5.E
3 points

The capacitor in the lab can be treated as two capacitors in parallel, one with the dielectric and one with air between the plates. Show that the capacitance can be expressed as $C = \frac{\varepsilon_0 s}{d}(s + x(\kappa - 1))$.

For indicating that the capacitance is equal to the sum of the part with a dielectric and the part with air		1 point
$C = C_x + C_0$		
For correctly substituting for the part of the capacitor that has a dielectric		1 point
For correctly substituting for the part of the capacitor that has air		1 point
$C = \frac{\kappa\varepsilon_0 sx}{d} + \frac{\varepsilon_0 s(s - x)}{d} = \frac{\varepsilon_0 s}{d}(\kappa x + s - x) = \frac{\varepsilon_0 s}{d}(s + x(\kappa - 1))$		

(d) CNV-7.A.a, SP 4.D, 6.A, 6.C
3 points

Using the graph from part (b), calculate the value of the dielectric constant κ.

For calculating the slope using the best-fit line and not the data points unless they fall on the best fit line		1 point
$\text{slope} = \frac{\Delta y}{\Delta x} = \frac{(3-1)\text{nF}}{(.24 - .02)\text{m}} = 9.1 \times 10^{-9}\ \text{F/m}$		
For correctly relating the slope to the dielectric constant		1 point
$C = \frac{\varepsilon_0 s^2}{d} + \frac{\varepsilon_0 s(\kappa - 1)}{d}x \therefore \text{slope} = \frac{\varepsilon_0 s(\kappa - 1)}{d}$		
$\kappa = \frac{(d)(\text{slope})}{\varepsilon_0 s} + 1 = \frac{(1 \times 10^{-3}\ \text{m})(9.1 \times 10^{-9}\ \text{F/m})}{(8.85 \times 10^{-12}\ \text{C}^2/(\text{N}\bullet\text{m}^2))(.3\ \text{m})} + 1$		
For a correct answer		1 point
$\kappa = 4.4$		

Question 1 (continued)

Distribution of points

(e) CNV-7.A.a, SP 4.D, 6.C
2 points

The students now want to verify the value for the permittivity constant, ε_0. Using the graph from part (b), calculate an experimental value for ε_0.

For using an acceptable value for the *y*-intercept consistent with the best-fit line		1 point
For correctly relating the *y*-intercept to the permittivity constant		1 point
$C = \frac{\varepsilon_0 s^2}{d} + \frac{\varepsilon_0 s(\kappa - 1)}{d}x \therefore$ y-intercept $= \frac{\varepsilon_0 s^2}{d}$		
$\varepsilon_0 = \frac{(d)(\text{y-intercept})}{s^2} = \frac{(1 \times 10^{-3}\ \text{m})(8.4 \times 10^{-10}\ \text{F})}{(.3\ \text{m})^2} = 9.29 \times 10^{-12}\ \text{C}^2/(\text{N}\bullet\text{m}^2)$		

Units point
CNV-7.A.a, SP 7.A
1 point

For correct units in parts (d) and (e)		1 point

(f) CNV-7.A.a, SP 2.E
1 point

Assume the value found in part (e) is higher than the accepted value for the permittivity constant. State one possible physical reason for this error and explain how it could have caused this error.

For a correct explanation of an acceptable physical issue		1 point
Claim: The resistance in the wires would cause the experimental value to be higher than the accepted value of the permittivity constant. Evidence: The potential difference across the capacitor would be smaller. Reasoning: The wires could have nonnegligible resistance.		
Alternate Explanation		
Claim: The air between the plates of the capacitor would cause the experimental value to be higher than the accepted value of the permittivity constant. *Evidence: The air between the plates of the capacitor increases its capacitance.* *Reasoning: The air between the plates of the capacitor act as a dielectric.*		

Question 1 (continued)

Learning Objectives
CNV-7.A.a – Calculate the equivalent capacitance for capacitors arranged in series or parallel, or a combination of both, in steady-state situations.
CNV-7.D.a – Derive expressions using calculus to describe the time dependence of the stored charge or potential difference across the capacitor, or the current or potential difference across the resistor in an RC circuit when charging or discharging a capacitor.

Science Practices
2.E – Identify or describe potential sources of experimental error.
3.A – Select and plot appropriate data.
4.C – Linearize data and/or determine a best fit line or curve.
4.D – Select relevant features of a graph to describe a physical situation or solve problems.
5.A – Select an appropriate law, definition, or mathematical relationship or model to describe a physical situation.
5.E – Derive a symbolic expression from known quantities by selecting and following a logical algebraic pathway.
6.A – Extract quantities from narratives or mathematical relationships to solve problems.
6.C – Calculate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

Question 2

15 points total **Distribution of points**

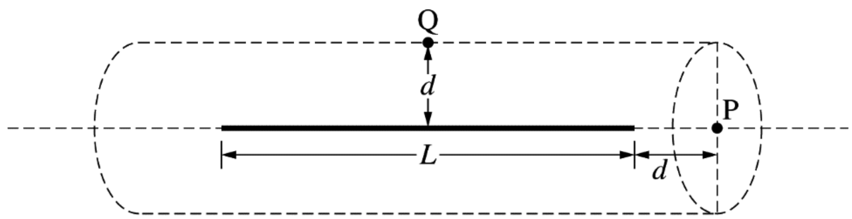


Figure 1

A thin wire of length L has a uniform charge density $+\lambda$. A cylindrical Gaussian surface of radius d is drawn with the wire along its central axis, as shown above. Point P is located at the center of one end of the cylinder, a distance d from the end of the wire. Point Q is on the edge of the cylinder directly above the center of the wire, as shown above.

A student says, "Gauss's law can be used to find the electric flux Φ through the Gaussian surface."

(a) LO CNV-2.C, SP 7.C
1 point

Is the student's statement correct or incorrect?
____ Correct
____ Incorrect

If you have chosen "Correct," use Gauss's law to find the electric flux Φ through the Gaussian surface.

If you have chosen "Incorrect," explain why the student's reasoning is incorrect and why Gauss's law cannot be applied in this situation.

Select "Correct"		
Note: If the wrong selection is made, the explanation is ignored.		
For using an appropriate equation to calculate the flux		1 point
$\Phi = \frac{q_{enc}}{\varepsilon_0} = \frac{\lambda L}{\varepsilon_0}$		
Claim: Student is correct. Evidence: A cylinder is useful for Gauss's law. Reasoning: A cylindrical surface has geometric symmetry.		

Question 2 (continued)

Distribution of points

(b) LO CNV-2.C, SP 7.C
1 point

Two students discuss whether or not they can use Gauss's law to find the electric field at points P and Q.

At which of the points, if either, is Gauss's law a useful method for finding the electric field?

_____ At point P only ____ At point Q only
_____ At both points P and Q ____ At neither point P nor point Q

Justify your answer.

Select "At neither point P nor point Q" or "At point Q only"		
Note: If the wrong selection is made, the justification is ignored.		
For a justification consistent with selection above		1 point
Example: There is no simple way to write the electric field at point P or Q in terms of the flux due to cylinder extending beyond the line of charge.		
Example: By drawing a new Gaussian cylinder that does not extend beyond the line of charge, Gauss's law can be used to calculate the electric field at point Q.		

(c) LO CNV-3.C.b, SP 5.A, 5.E
3 points

Assuming the electric potential is zero at infinity, show that the value for the electric potential at point P is given by the following expression.

$$V = \frac{\lambda}{4\pi\varepsilon_0}\ln\left(\frac{L+d}{d}\right)$$

For indicating an attempt to integrate to determine the electric potential at P		1 point
$V = \int \frac{1}{4\pi\varepsilon_0 r}dq$		
For integrating in terms of distance		1 point
$Q = \lambda L \therefore dq = \lambda dr \therefore V = \int_{r=d}^{r=d+L} \frac{\lambda}{4\pi\varepsilon_0 r}dr$		
For integrating using the correct limits or constant of integration		1 point
$V = \frac{\lambda}{4\pi\varepsilon_0}[\ln(r)]_{r=d}^{r=d+L} = \frac{\lambda}{4\pi\varepsilon_0}(\ln(d+L) - \ln(d)) = \frac{\lambda}{4\pi\varepsilon_0}\ln\left(\frac{d+L}{d}\right)$		

Question 2 (continued)

Distribution of points

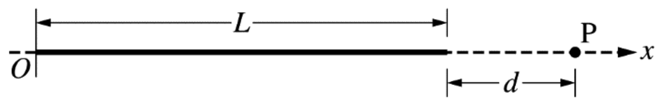
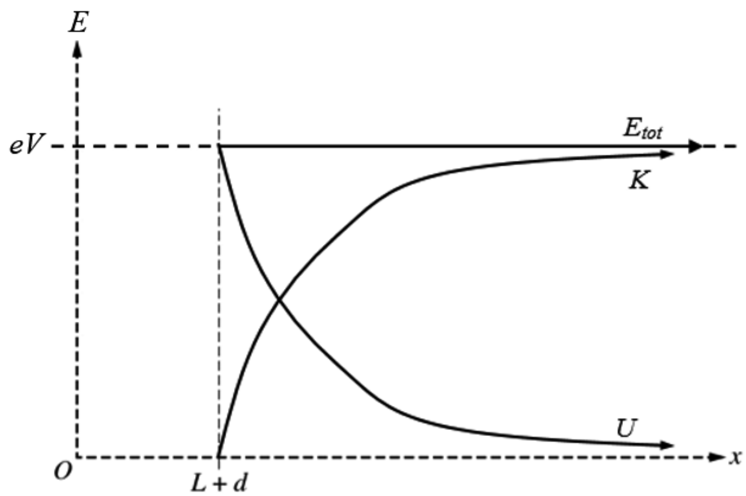


Figure 2

The wire is aligned along the x-axis with the origin at the left end of the wire, as shown in Figure 2 above.

(d) LO CNV-1.E, SP 3.C
6 points

A positively charged particle of charge $+e$ and mass m is released from rest at point P. On the axes below, sketch the kinetic energy K of the particle, the potential energy U of the wire-particle system, and the total energy E_{tot} of the wire-particle system as functions of the particle's position x. Clearly label each sketch with K, U, and E_{tot}. Explicitly label any maximum with numerical values or algebraic expressions, as appropriate.



For a curve in the first quadrant label K that is increasing in value for $x > L + d$		1 point
For a curve that is concave down curve starting at the point $(L + d,\ 0)$ and approaching a horizontal line		1 point
For a curve in the first quadrant label U that is decreasing in value for $x > L + d$		1 point
For a concave up curve at $L + d$ starting at or near the maximum value and approaching the x-axis		1 point
For a horizontal line labeled E_{tot} that is at the maximum value		1 point
For labeling and using correct asymptotes for the K and U curves		1 point

Question 2 (continued)

Distribution of points

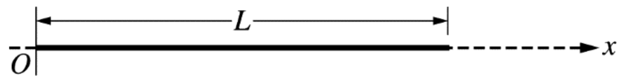


Figure 3

(e) LO CNV-3.E, SP 5.A, 5.E
4 points

Derive an expression for the magnitude of the electric field due to the wire as a function of the position along the x-axis, where $x > L$. Express your answer in terms of x, L, λ, and physical constants, as appropriate.

For indicating an attempt to integrate to determine the electric field		1 point
$E = \int \frac{1}{4\pi\varepsilon_0 r^2} dq$		
For integrating in terms of distance		1 point
$Q = \lambda L \therefore dq = \lambda dr \therefore E = \int_{r=x-L}^{r=x} \frac{\lambda}{4\pi\varepsilon_0 r^2} dr$		
For integrating using the correct limits or constant of integration		1 point
For correctly integrating		1 point
$E = \frac{\lambda}{4\pi\varepsilon_0}\left[-\frac{1}{r}\right]_{r=x-L}^{r=x} = \frac{\lambda}{4\pi\varepsilon_0}\left(\frac{1}{x-L} - \frac{1}{x}\right) = \frac{\lambda L}{4\pi\varepsilon_0 (x-L)x}$		
Alternate Solution		*Alternate Points*
For attempting to take the derivative of the electric potential to calculate the electric field		*1 point*
For substituting the expression from part (c) into the derivative		*1 point*
$E = -\frac{dV}{dx} = -\frac{d}{dx}\left[\frac{\lambda}{4\pi\varepsilon_0}\ln\left\lvert\frac{L+d}{d}\right\rvert\right]$		
For substituting $d = x - L$ into the above equation		*1 point*
$E = -\frac{d}{dx}\left[\frac{\lambda}{4\pi\varepsilon_0}\ln\left\lvert\frac{x}{x-L}\right\rvert\right]$		
For correctly differentiating the above equation		*1 point*
$E = -\frac{\lambda}{4\pi\varepsilon_0}\left(\frac{1}{x} - \frac{1}{x-L}\right) = \frac{\lambda L}{4\pi\varepsilon_0 (x-L)x}$		

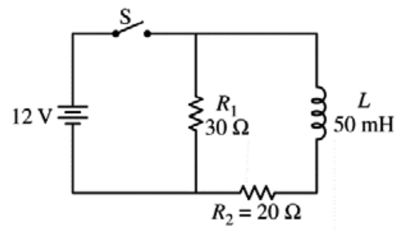
Question 2 (continued)

Learning Objectives
CNV-1.E – Calculate the work done or changes in kinetic energy (or changes in speed) of a charge particle when it is moved through some known potential difference.
CNV-2.C – State and use Gauss's law in integral form to derive unknown electric fields for planar, spherical, or cylindrically symmetrical charge distributions.
CNV-3.A – Derive expressions for the electric field of specified charge distributions using integration and the principle of superposition. Examples of such charge distributions include a uniformly charged wire, a thin ring of charge (along the axis of the ring), and semicircular or part of a semicircular arc.
CNV-3.C.b – Describe electric potential as a function of distance for the different types of symmetrical charge distributions.

Science Practices
3.C – Sketch a graph that shows a functional relationship between two quantities.
5.A – Select an appropriate law, definition, or mathematical relationship or model to describe a physical situation.
5.E – Derive a symbolic expression from known quantities by selecting and following a logical algebraic pathway.
7.C – Support a claim with evidence from physical representations.

Question 3

15 points total **Distribution of points**



The circuit shown above is constructed using an ideal 12 V battery, an ideal switch S, and two resistors and an inductor with the values shown. Switch S is closed. After a long time, the circuit reaches steady-state conditions.

(a) LO CNV-10.C.b, SP 6.B, 6.C
2 points

Calculate the current through R_1.

For using Ohm's law to calculate the current		1 point
$I = \frac{V_1}{R_1} = \frac{12\text{ V}}{30\ \Omega}$		
For a correct answer		1 point
$I = 0.40\text{ A}$		

(b) LO CNV-10.C.b, SP 6.A, 6.C
2 points

Calculate the current through the battery.

For correctly calculating the equivalent resistance of the circuit		1 point
$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{30\ \Omega} + \frac{1}{20\ \Omega}$		
$R_T = 12\ \Omega$		
For using Ohm's law to calculate the current		1 point
$I = \frac{V}{R_T} = \frac{12\text{ V}}{12\ \Omega} = 1.0\text{ A}$		

The switch is then opened at time $t = 0$.

(c) LO CNV-10.C.a, SP 6.B
1 point

Determine the current in the inductor immediately after the switch is opened.

For an answer consistent with parts (a) and (b)		1 point
$I = I_2 = \frac{12\text{ V}}{20\ \Omega} = 0.60\text{ A}$		

Question 3 (continued)

Distribution of points

(d)

i. LO CNV-10.C.a, SP 6.A
1 point

Determine the current in resistor R_1 immediately after the switch is opened.

For an answer consistent with part (c)		1 point
$I_1 = I_2 = 0.60$ A		
Note: Credit is earned even if no work is shown		

ii. LO CNV-10.C.a, SP 7.C
2 points

Which of the following statements is correct about the current through R_1 immediately after the switch is opened?

_____ The current is up through R_1.
_____ The current is down through R_1.
_____ There is no current through R_1.

Justify your answer.

Selecting "The current is up through R_1."		1 point
For a correct justification including inductors resisting changes in current		1 point
Example Justification: Conventional current would be going down through the inductor before the switch is opened. Inductors resists changes in current, so when the switch is opened, the current would continue to be down through the inductor and up through R_1.		
Note: If wrong selection is made, the justification is ignored.		

Question 3 (continued)

Distribution of points

(e) LO CNV-10.C.a, SP 7.C
1 point

Immediately after the switch is opened, is the top end or bottom end of the inductor at the higher electric potential?

____ Top end

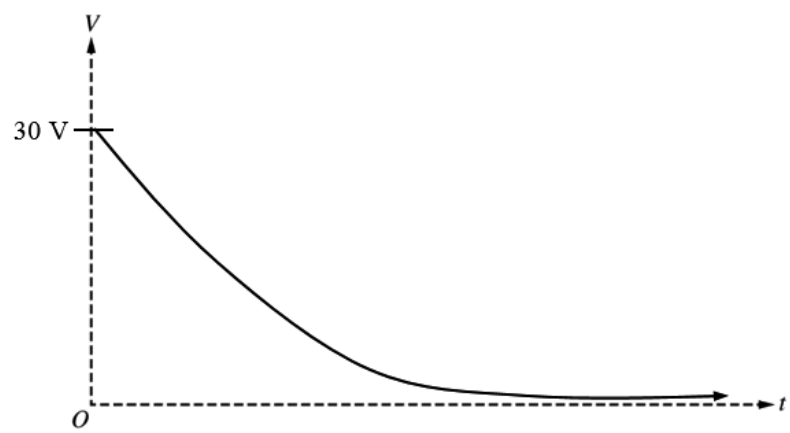
____ Bottom end

Justify your answer.

Select “Bottom end” or an answer consistent with part (d)(ii)		
For a relating the direction of the current/emf to the end of the inductor that is at the higher electric potential		1 point
Example Justification: The inductor will maintain a current going down through the inductor. Since conventional current comes out of the higher potential side, the bottom end of the inductor must be at the higher potential.		

(f) LO CNV-10.E, SP 3.C
3 points

On the axes below, sketch a graph of the potential difference *V* across the inductor as a function of time after the switch is opened. Explicitly label the vertical axis intercept with a numerical value.



For a concave up curve in the first quadrant		1 point
For a curve that has an asymptote at the horizontal axis		1 point
For correctly indicating the maximum value		1 point

Question 3 (continued)

Distribution of points

(g) LO CNV-10.D.a, SP 6.B, 6.C
3 points

Write but DO NOT solve a differential equation that could be solved for the current through the inductor as a function of time after the switch is opened.

For correctly applying Kirchoff's loop rule to the circuit		1 point
$V_L - V_{R2} - V_{R1} = 0$		
For correctly substituting into the above equation		1 point
For writing as a differential equation		1 point
$V_L = V_{R2} + V_{R1}$		
$-L\dfrac{dI}{dt} = I(R_1 + R_2)$ or $-\left(50\times 10^{-3}\ \text{H}\right)\dfrac{dI}{dt} = I(50\ \Omega)$		

Question 3 (continued)

Learning Objectives
CNV-10.C.a – Calculate initial transient currents and final steady-state currents through any part of a series or parallel circuit containing an inductor and one or more resistors.
CNV-10.D.a – Derive a differential equation for the current as a function of time in a simple LR series circuit.
CNV-10.E – Describe currents or potential differences with respect to time across resistors or inductors in a simple circuit containing resistors and an inductor, either in series or a parallel arrangement.

Science Practices
3.C – Sketch a graph that shows a functional relationship between two quantities.
6.A – Extract quantities from narratives or mathematical relationships to solve problems.
6.B – Apply an appropriate law, definition, or mathematical relationship to solve a problem.
6.C – Calculate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.
7.A – Make a scientific claim.
7.C – Support a claim with evidence from physical representations.

2019 AP Physics C: Electricity and Magnetism Scoring Worksheet

Section I: Multiple Choice

______________ × 1.2857 = __________________

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

Section II: Free Response

Question 1 ____________ (out of 15) × 1.0000 = ____________ (Do not round)

Question 2 ____________ (out of 15) × 1.0000 = ____________ (Do not round)

Question 3 ____________ (out of 15) × 1.0000 = ____________ (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
46-90	5
35-45	4
30-34	3
21-29	2
0-20	1

2019 AP Physics C: Electricity and Magnetism Question Descriptors and Performance Data

Multiple-Choice Questions

Question	Skill	Learning Objective	Topic	Key	% Correct
1	6.C	CNV-1.A	Electrostatics— Electric Potential Due to Point Charges and Uniform Fields	E	43
2	7.A	ACT-2.C	Conductors, Capacitors, Dielectrics – Electrostatics with Conductors	E	32
3	6.A	CNV-1.E	Electrostatics— Electric Potential Due to Point Charges and Uniform Fields	B	36
4	7.A	ACT-1.D	Electrostatics— Charge and Coulomb's Law	B	63
5	7.A	CNV-2.B	Electrostatics – Gauss's Law	B	61
6	5.B	CNV-1.C	Electrostatics— Electric Potential Due to Point Charges and Uniform Fields	E	52
7	7.A	ACT-1.A	Electrostatics— Charge and Coulomb's Law	C	80
8	6.A	CNV-1.E	Electrostatics— Electric Potential Due to Point Charges and Uniform Fields	B	60
9	7.A	ACT-2.B	Conductors, Capacitors, Dielectrics – Electrostatics with Conductors	D	40
10	7.A	ACT-2.A	Conductors, Capacitors, Dielectrics – Electrostatics with Conductors	A	39
11	5.E	CNV-4.B	Conductors, Capacitors, Dielectrics – Capacitors	D	74
12	6.A	ACT-2.A	Conductors, Capacitors, Dielectrics – Electrostatics with Conductors	C	65
13	5.A	ACT-3.A	Conductors, Capacitors, Dielectrics – Electrostatics with Conductors	B	48
14	5.C	FIE-2.D	Conductors, Capacitors, Dielectrics - Dielectrics	B	56
15	5.B	FIE-2.C	Conductors, Capacitors, Dielectrics - Dielectrics	C	88
16	6.B	CNV-6.C	Electric Currents – Steady-State Direct -Current Circuits with Batteries and Resistors only	D	73
17	6.C	CNV-6.C	Electric Currents – Steady-State Direct -Current Circuits with Batteries and Resistors only	A	61
18	5.E	CNV-7.B	Capacitors in Circuits	C	47
19	5.E	CNV-7.A	Capacitors in Circuits	E	60
20	5.A	CNV-7.A	Capacitors in Circuits	B	60
21	7.A	CNV-6.C	Electric Currents – Steady-State Direct -Current Circuits with Batteries and Resistors only	C	44
22	6.B	CNV-7.A	Capacitors in Circuits	D	39
23	5.B	CNV-4.G	Conductors, Capacitors, Dielectrics – Capacitors	B	36
24	4.D	CNV-8.C	Magnetic Fields – Biot–Savart Law and Ampère's Law	E	52
25	5.E	FIE-5.B	Magnetic Fields – Fields of Long, Current-Carrying Wires	E	43
26	1.D	FIE-5.B	Magnetic Fields – Fields of Long, Current-Carrying Wires	D	51
27	5.E	FIE-5.B	Magnetic Fields – Fields of Long, Current-Carrying Wires	D	51
28	5.E	FIE-4.A	Magnetic Fields – Forces on Current-Carrying Wires in Magnetic Fields	E	27
29	1.D	CHG-1.B	Magnetic Fields – Forces on Moving Charges in Magnetic Fields	D	75
30	7.A	CHG-1.B	Magnetic Fields – Forces on Moving Charges in Magnetic Fields	C	70
31	5.E	FIE-4.A	Magnetic Fields – Forces on Current-Carrying Wires in Magnetic Fields	A	56
32	1.D	FIE-5.B	Magnetic Fields – Fields of Long, Current-Carrying Wires	B	39
33	6.B	CNV-9.A	Electromagnetism – Electromagnetic Induction (Including Faraday's Law and Lenz's Law)	A	52
34	7.A	FIE-6.A	Electromagnetism – Electromagnetic Induction (Including Faraday's Law and Lenz's Law)	E	55
35	5.E	FIE-6.A	Electromagnetism – Electromagnetic Induction (Including Faraday's Law and Lenz's Law)	E	43

2019 AP Physics C: Electricity and Magnetism
Question Descriptors and Performance Data

Free-Response Questions

Question	Skill	Learning Objective	Topic	Mean Score
1	2.E|3.A|4.C|4.D|5.A|5.E|6.A|6.C|7.A	CNV-7.A.1|CNV-7.D.a	3.4	6.22
2	3.C|5.A|5.E|7.C	CNV-1.E|CNV-2.C|CNV-3.A|CNV-3.C.b	1.3|1.4|1.5	4.21
3	6.C|3.C|6.A|6.B|7.C	CNV-10.C|CNV-10.D|CNV-10.E	5.2	6.47