2019

AP® CollegeBoard

AP® Physics C: Electricity and Magnetism

Sample Student Responses and Scoring Commentary Set 1

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AP® PHYSICS
2019 SCORING GUIDELINES

General Notes About 2019 AP Physics Scoring Guidelines

1. The solutions contain the most common method of solving the free-response questions and the allocation of points for this solution. Some also contain a common alternate solution. Other methods of solution also receive appropriate credit for correct work.

2. The requirements that have been established for the paragraph-length response in Physics 1 and Physics 2 can be found on AP Central at https://secure-media.collegeboard.org/digitalServices/pdf/ap/paragraph-length-response.pdf.

3. Generally, double penalty for errors is avoided. For example, if an incorrect answer to part (a) is correctly substituted into an otherwise correct solution to part (b), full credit will usually be awarded. One exception to this may be cases when the numerical answer to a later part should be easily recognized as wrong, e.g., a speed faster than the speed of light in vacuum.

4. Implicit statements of concepts normally receive credit. For example, if use of the equation expressing a particular concept is worth 1 point, and a student's solution embeds the application of that equation to the problem in other work, the point is still awarded. However, when students are asked to derive an expression, it is normally expected that they will begin by writing one or more fundamental equations, such as those given on the exam equation sheet. For a description of the use of such terms as "derive" and "calculate" on the exams, and what is expected for each, see "The Free-Response Sections — Student Presentation" in the *AP Physics; Physics C: Mechanics, Physics C: Electricity and Magnetism Course Description* or "Terms Defined" in the *AP Physics 1: Algebra-Based Course and Exam Description* and the *AP Physics 2: Algebra-Based Course and Exam Description*.

5. The scoring guidelines typically show numerical results using the value $g = 9.8\text{ m/s}^2$, but the use of 10 m/s^2 is of course also acceptable. Solutions usually show numerical answers using both values when they are significantly different.

6. Strict rules regarding significant digits are usually not applied to numerical answers. However, in some cases answers containing too many digits may be penalized. In general, two to four significant digits are acceptable. Numerical answers that differ from the published answer due to differences in rounding throughout the question typically receive full credit. Exceptions to these guidelines usually occur when rounding makes a difference in obtaining a reasonable answer. For example, suppose a solution requires subtracting two numbers that should have five significant figures and that differ starting with the fourth digit (e.g., 20.295 and 20.278). Rounding to three digits will lose the accuracy required to determine the difference in the numbers, and some credit may be lost.

Question 2

15 points

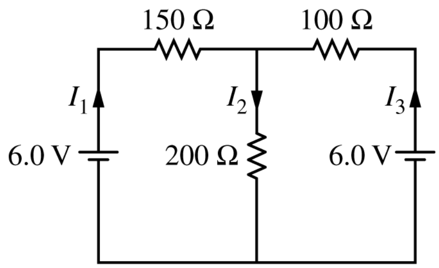


Figure 1

The circuit shown above is constructed with two 6.0 V batteries and three resistors with the values shown. The currents I_1, I_2, and I_3 in each branch of the circuit are indicated.

(a)

i. LO CNV-6.F.b, SP 6.A
3 points

Using Kirchhoff's rules, write, but DO NOT SOLVE, equations that can be used to solve for the current in each resistor.

For an equation representing the sum of the currents at one of the junctions		1 point
$I_1 - I_2 + I_3 = 0$		
For an equation representing the sum of the potential differences around one of the loops		1 point
For an equation representing the sum of the potential differences around a loop different from the above loop		1 point
$6 - 150I_1 - 200I_2 = 0$		
$6 - 100I_3 - 200I_2 = 0$		
$6 - 150I_1 + 100I_3 - 6 = 0$		
Note: Full credit is earned for two correct loop equations using loop currents.		

ii. LO CNV-6.F.b, SP 6.C
2 points

Calculate the current in the 200 Ω resistor.

For combining the equations from part (a)(i)		1 point
$I_1 - I_2 + I_3 = 0$ $-I_1 - 1.33I_2 = -.04 \therefore -4.33I_2 = -0.10$ $-I_3 - 2I_2 = -.06$		
Note: Credit is earned if students indicate they used a calculator function to solve the system of equations.		
For a correct answer with correct units		1 point
$-4.33I_2 = -0.10 \therefore I_2 = 0.023\text{ A}$		

Question 2 (continued)

(a) continued

iii. LO CNV-5.A.a, SP 6.C
1 point

Calculate the power dissipated by the $200\ \Omega$ resistor.

For using a correct equation to calculate the power in the $200\ \Omega$ resistor		1 point
$P = I^2R = (0.023\ \text{A})^2(200\ \Omega)\ \therefore\ P = 0.107\ \text{W}$		

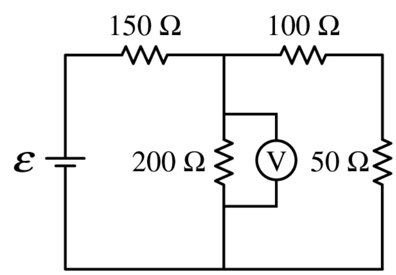


Figure 2

The two 6.0 V batteries are replaced with a battery with voltage $\mathcal{E}$ and a resistor of resistance $50\ \Omega$, as shown above. The voltmeter V shows that the voltage across the $200\ \Omega$ resistor is 4.4 V.

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

Calculate the current through the $50\ \Omega$ resistor.

For correctly calculating the equivalent resistance of the branch with the $50\ \Omega$ resistor		1 point
$R = 100\ \Omega + 50\ \Omega = 150\ \Omega$		
For using the correct potential difference in Ohm's law to calculate the current in the $50\ \Omega$ resistor		1 point
$I = \dfrac{V}{R} = \dfrac{(4.4\ \text{V})}{(100\ \Omega + 50\ \Omega)}\ \therefore\ I = 0.029\ \text{A}$		

Question 2 (continued)

(c) LO CNV-6.C.a, SP 6.A, 6.C
3 points

Calculate the voltage ε of the battery.

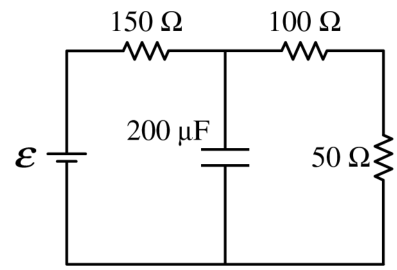
For using a correct equation to determine the current through the 150 Ω resistor		1 point
For correctly substituting the current from part (b) as I_3		1 point
$I_1 = I_2 + I_3 = \dfrac{(4.4\text{ V})}{(200\ \Omega)} + 0.029\text{ A} = 0.051\text{ A}$		
For using a correct equation to determine the emf of the battery		1 point
$\varepsilon = I_1 R_1 + V_2 = (0.051\text{ A})(150\ \Omega) + 4.4\text{ V} = 12.1\text{ V}$		
Alternate Third Point		
For calculating the equivalent resistance of the circuit and substituting this resistance into a correct equation to determine the emf of the battery		*1 point*
$R_T = 150\ \Omega + \dfrac{1}{\dfrac{1}{200\ \Omega} + \dfrac{1}{150\ \Omega}} = 236\ \Omega$		
$\varepsilon = I_1 R_T = (0.051\text{ A})(236\ \Omega) = 12.0\text{ V}$		
Alternate Solution		*Alternate Points*
For using a correct equation to determine the equivalent resistance of the parallel resistors		*1 point*
$\dfrac{1}{R_P} = \dfrac{1}{200\ \Omega} + \dfrac{1}{150\ \Omega}\ \therefore R_P = 86\ \Omega$		
For correctly substituting the given potential difference and the calculated equivalent resistance to determine the total current of the circuit		*1 point*
$I_T = \dfrac{(4.4\text{ V})}{(86\ \Omega)} = 0.051\text{ A}$		
For calculating the equivalent resistance of the circuit and substituting into a correct equation to determine the emf of the battery		*1 point*
$R_T = 150\ \Omega + 86\ \Omega = 236\ \Omega$		
$\varepsilon = I_1 R_T = (0.051\text{ A})(236\ \Omega) = 12.0\text{ V}$		

Question 2 (continued)

(d)

i. LO CNV-7.B.a, SP 6.A, 6.C
2 points

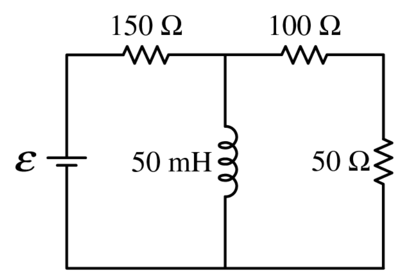
The 200 Ω resistor in the circuit in Figure 2 is replaced with a 200 μF capacitor, as shown on the right, and the circuit is allowed to reach steady state. Calculate the current through the 50 Ω resistor.



For substituting the voltage consistent with part (c) into Ohm's law		1 point
For correctly calculating the equivalent resistance of the circuit		1 point
$I = \dfrac{\mathcal{E}}{R_{tot}} = \dfrac{(12.1\ \text{V})}{(150\ \Omega + 100\ \Omega + 50\ \Omega)} = 40.3\ \text{mA}$		

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

The 200 Ω resistor in the circuit in Figure 2 is replaced with an ideal 50 mH inductor, as shown on the right, and the circuit is allowed to reach steady state. Is the current in the 50 Ω resistor greater than, less than, or equal to the current calculated in part (b)?



____ Greater than ____ Less than ____ Equal to

Justify your answer.

For correctly selecting "Less than" with an attempt at a relevant justification		1 point
For a correct justification		1 point
Example: Because steady state is reached, the inductor will act as a short circuit. So all the current will pass through the inductor and no current will pass through the 50 Ω resistor.		

Question 2 (continued)

Learning Objectives

CNV-5.A.a: Derive expressions that relate current, voltage, and resistance to the rate at which heat is produced in a resistor.
CNV-6.C.a: Calculate voltage, current, and power dissipation for any resistor in a circuit containing a network of known resistors with a single battery or energy source.
CNV-6.F.b: Set up simultaneous equations to calculate at least two unknowns (currents or resistance values) in a multi-loop circuit.
CNV-7.B.a: Calculate the potential difference across a capacitor in a circuit arrangement containing capacitors, resistors, and an energy source under steady-state conditions.
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.

Science Practices

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.

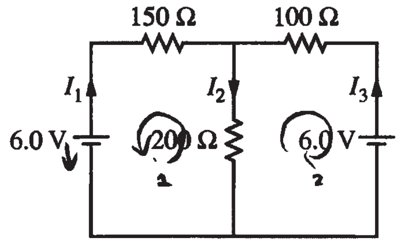


Figure 1

2. The circuit shown above is constructed with two 6.0 V batteries and three resistors with the values shown. The currents I_1, I_2, and I_3 in each branch of the circuit are indicated.

(a)

i. Using Kirchhoff's rules, write, but DO NOT SOLVE, equations that can be used to solve for the current in each resistor.

Loop 1: $6 - 150 I_1 - 200 I_2 = 0$

Loop 2: $6 - 100 I_3 - 200 I_2 = 0$

$I_1 + I_3 = I_2$

ii. Calculate the current in the 200 Ω resistor.

$I_1 = I_2 - I_3$

$6 - 150 I_2 + 150 I_3 - 200 I_2 = 0$

$6 - 150 I_3 - 200 I_2 = 0$

$-150 I_2 + 250 I_3 = 0$

$I_3 = 0.6 I_2$

$6 - 100 (0.6 I_2) - 200 I_2 = 0$

$6 = 260 I_2$

$I_2 =$ 0.023 (A)

iii. Calculate the power dissipated by the 200 Ω resistor.

$P = I^2 R = (0.023)^2 (200) =$ 0.107 (W)

E Q2 A p2

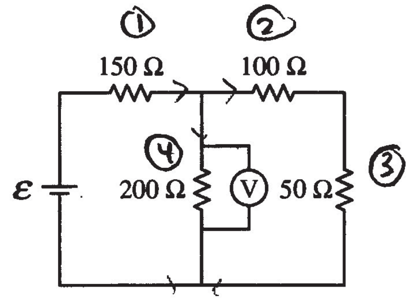


Figure 2

The two 6.0 V batteries are replaced with a battery with voltage $\mathcal{E}$ and a resistor of resistance 50 Ω, as shown above. The voltmeter V shows that the voltage across the 200 Ω resistor is 4.4 V.

(b) Calculate the current through the 50 Ω resistor.

$R_{23} = 100 + 50 = 150\ \Omega$

$V_{23} = V_4 = 4.4(V)$

$I_2 = I_3 = \frac{V_{23}}{R_{23}} = \frac{4.4}{150} = \boxed{0.029\ (A)}$

(c) Calculate the voltage $\mathcal{E}$ of the battery.

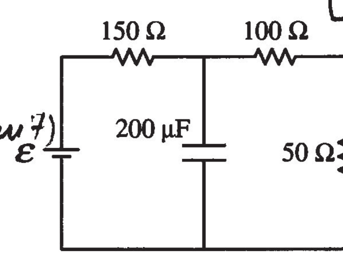
$I_1 = I_2 + I_4 = I_2 + \frac{V_4}{R_4} = 0.029 + \frac{4.4}{200}$

$= 0.051\ (A)$

$V_1 = I_1 R_1 = 0.051(150) = 7.7\ (V) \longrightarrow \mathcal{E} = V_1 + V_4 = 7.7 + 4.4 = \boxed{12.1\ (V)}$

(d)

i. The 200 Ω resistor in the circuit in Figure 2 is replaced with a 200 μF capacitor, as shown on the right, and the circuit is allowed to reach steady state. Calculate the current through the 50 Ω resistor.



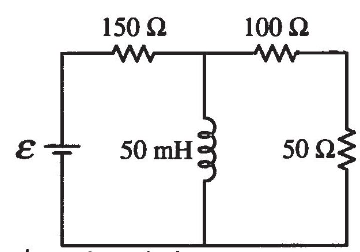
Capacitor is a broken circuit)

$\mathcal{E} = 12.1\ (V)$

$\Sigma R = 150 + 100 + 50 = 300\ (\Omega)$

$I_1 = I_2 = I_3 = \frac{12.1}{300} = \boxed{0.04\ (A)}$

ii. The 200 Ω resistor in the circuit in Figure 2 is replaced with an ideal 50 mH inductor, as shown on the right, and the circuit is allowed to reach steady state. Is the current in the 50 Ω resistor greater than, less than, or equal to the current calculated in part (b) ?



✓ Greater than ____ Less than ____ Equal to

Justify your answer.

Because the inductor is a short circuit at steady state, the loop is series - parallel, thus, the total resistance decreases, current increases.

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E Q2 B p1

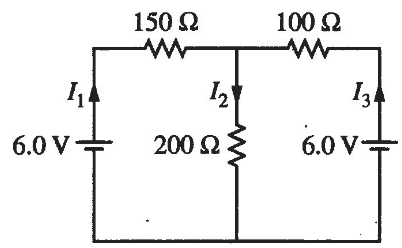

Figure 1

2. The circuit shown above is constructed with two 6.0 V batteries and three resistors with the values shown. The currents I_1, I_2, and I_3 in each branch of the circuit are indicated.

(a)

i. Using Kirchhoff's rules, write, but DO NOT SOLVE, equations that can be used to solve for the current in each resistor.

$6 - 150 I_1 + 100 I_3 - 6 = 0$

$-6 + 150 I_1 + 200 I_2 = 0$

ii. Calculate the current in the $200\ \Omega$ resistor.

$I_3 = \frac{200 I_2 - 6}{100}$

$I_3 = 2 I_2 - .06$

.03

$6 = 150 I_1 + 200 I_2$

$6 + 200 I_2 + 200 I_2 - 6$

$12 = 400 I_2$

$I_2 = .03$

iii. Calculate the power dissipated by the $200\ \Omega$ resistor.

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E Q2 B p2

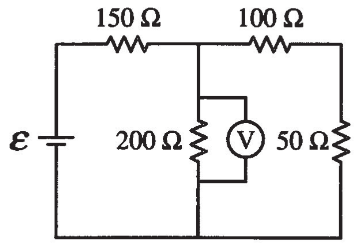


Figure 2

The two 6.0 V batteries are replaced with a battery with voltage $\mathcal{E}$ and a resistor of resistance 50 Ω, as shown above. The voltmeter V shows that the voltage across the 200 Ω resistor is 4.4 V.

(b) Calculate the current through the 50 Ω resistor.

V=IR

$\left(\frac{1}{150}+\frac{1}{200}\right)^{-1} = 85.71\ \Omega$

$\frac{4.4}{150} = .0293\text{A}$

(c) Calculate the voltage $\mathcal{E}$ of the battery.

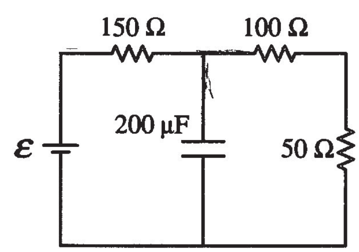
$85.71 + 150 = 235.71$

$\frac{4.4}{200} = .022 + .0293 = .0513\text{A}$

$.0513(235.71) = 12.09\text{v}$

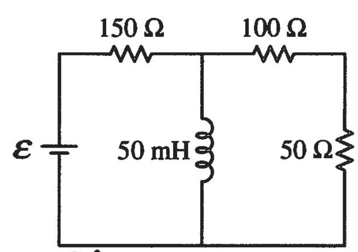
(d)

i. The 200 Ω resistor in the circuit in Figure 2 is replaced with a 200 μF capacitor, as shown on the right, and the circuit is allowed to reach steady state. Calculate the current through the 50 Ω resistor.



.0293A

ii. The 200 Ω resistor in the circuit in Figure 2 is replaced with an ideal 50 mH inductor, as shown on the right, and the circuit is allowed to reach steady state. Is the current in the 50 Ω resistor greater than, less than, or equal to the current calculated in part (b) ?



____ Greater than ____ Less than __✓__ Equal to

Justify your answer.

The capacitor and inductor have no effect on the 50 Ω resistor because they are not connected

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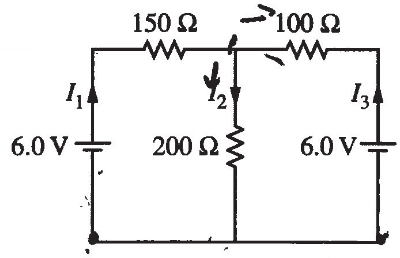

Figure 1

2. The circuit shown above is constructed with two 6.0 V batteries and three resistors with the values shown. The currents I_1, I_2, and I_3 in each branch of the circuit are indicated.

(a)

i. Using Kirchhoff's rules, write, but DO NOT SOLVE, equations that can be used to solve for the current in each resistor.

$+6V - I_1 150\Omega - I_2 200\Omega = 0$

$I_1 = I_2 + I_3$

$-6V - 100\Omega I_3 - 200\Omega I_2 = 0$

ii. Calculate the current in the 200 Ω resistor.

$+6 - (I_2 + I_3)150\Omega - I_2 200 = 0$

$+6 - I_2 150 - 150 I_3 - I_2 200 = 0$

$+6 - 350 I_2 - 150 I_3 = 0$

$-350 I_2 = 150 I_3 - 6$

$I_2 = -\left(\frac{150 I_3 - 6}{350}\right)$

$-6V - 100I_3 + 200\left(\frac{150 I_3 - 6}{350}\right) =$

$-6V - 100I_3 + \frac{30000 I_3 - 1200}{350}$

$-6V - 100I_3 + 85.71 I_3 - 3.4$

$-14.29 I_3 = 40.28$

$I_3 = 2.81\ A$

$6 - 350 I_2 - 150(2.81A) = 0$

$-350 I_2 = 421.5$

$I_2 = -1.187\ A$

iii. Calculate the power dissipated by the 200 Ω resistor.

$P = I^2 R$

$= (1.187)^2 (200)$

$= 281.86\ W$

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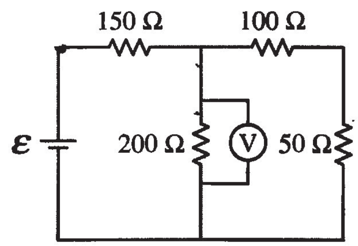


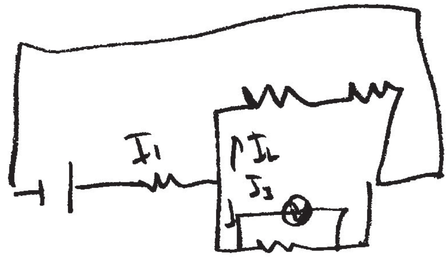


Figure 2

The two 6.0 V batteries are replaced with a battery with voltage ε and a resistor of resistance $50\ \Omega$, as shown above. The voltmeter V shows that the voltage across the $200\ \Omega$ resistor is 4.4 V.

(b) Calculate the current through the $50\ \Omega$ resistor.

$-I_1 150\Omega - 200\Omega I_2 + \varepsilon = 0$

$-I_1 150 - 4.4V + \varepsilon = 0$

$\left(\frac{1}{150} + \frac{1}{200}\right)^{-1} = 85.71$

$I_1 = \frac{\varepsilon}{85.71}$

$V_2 = 4.4V$

(c) Calculate the voltage ε of the battery.

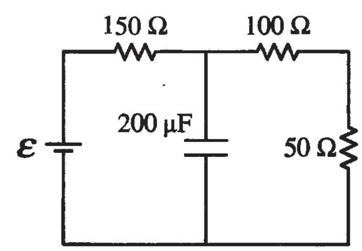
$V = I_2 R$

$I_2 = 0.022$

(d)

i. The $200\ \Omega$ resistor in the circuit in Figure 2 is replaced with a $200\ \mu F$ capacitor, as shown on the right, and the circuit is allowed to reach steady state. Calculate the current through the $50\ \Omega$ resistor.

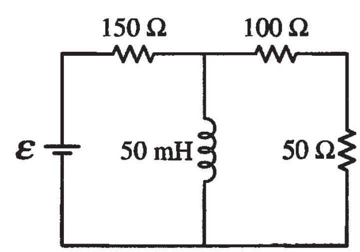
$I = \frac{\varepsilon}{300\Omega}$



ii. The $200\ \Omega$ resistor in the circuit in Figure 2 is replaced with an ideal 50 mH inductor, as shown on the right, and the circuit is allowed to reach steady state. Is the current in the $50\ \Omega$ resistor greater than, less than, or equal to the current calculated in part (b) ?

____ Greater than ✓ Less than ____ Equal to

Justify your answer.



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AP® PHYSICS C: ELECTRICITY AND MAGNETISM
2019 SCORING COMMENTARY

Question 2

Note: Student samples are quoted verbatim and may contain spelling and grammatical errors.

Overview

The responses to this question were expected to demonstrate the following:

- Derive a correct junction equation and at least two loop equations for a circuit with multiple sources of emf, paying attention to and using clear subscripts that were specified in the problem
- Use appropriate algebra skills to solve simultaneous equations with multiple unknowns
- Derive an expression to calculate the power dissipated by a specific resistor
- Solve for the current of any resistor and the voltage of a battery in a circuit with known resistors and a single source of emf
- Determine the total current in a circuit with multiple known resistors, a single source of emf, and a capacitor at steady state
- Recognize the effect of an inductor at steady state on a circuit with multiple known resistors with various types of connections

Sample: E Q2 A
Score: 13

Part (a)(i) has a correct junction equation and two correct loop equations, so 3 points were earned. Part (a)(ii) combines the equations from part (a)(i) and has a correct answer with units, so 2 points were earned. Part (a)(iii) uses a correct power equation, so 1 point was earned. Part (b) correctly calculates the equivalent resistance of the appropriate branch and then uses Ohm's law to calculate the current in the 50 Ω resistor, so 2 points were earned. Part (c) uses an appropriate method to calculate the emf of the battery, so 3 points were earned. Part (d)(i) correctly calculates the current in the 50 Ω resistor, so 2 points were earned. Part (d)(ii) has an incorrect selection and imprecise justification, so no points were earned.

Sample: E Q2 B
Score: 8

Parts (b) and (c) earned full credit, 2 points and 3 points, respectively. Part (a)(i) has two correct loop equations, but no junction equation, so 2 points were earned. Part (a)(ii) combines the equations from part (a)(i), but the answer is incorrect, so 1 point was earned. Part (a)(iii) is blank, so no points were earned. Part (b) uses the correct electric potential in Ohm's law but incorrectly calculates the equivalent resistance of the appropriate branch, so 1 point was earned. Part (d)(i) does not show appropriate work, so no points were earned. Part (d)(ii) has an incorrect selection with an incorrect justification, so no points were earned.

Sample: E Q2 C
Score: 4

Part (a)(i) has one correct loop equation, a second incorrect loop equation, and a junction equation with an ambiguous sign on I_2, so 1 point was earned. Part (a)(ii) combines the equations from part (a)(i), but the answer is incorrect, so 1 point was earned. Part (a)(iii) uses a correct power equation, so 1 point was earned. Part (b) does not calculate the equivalent resistance of the appropriate branch and does not provide evidence of using the correct potential difference in Ohm's law, so no points were earned. Part (c) is blank, so no points were earned. Part (d)(i) correctly calculates the equivalent resistance but did not substitute a correct potential difference into Ohm's law, so 1 point was earned. Part (d)(ii) has a correct selection but no justification, so no points were earned.