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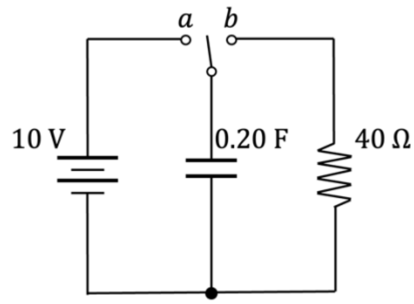
I. [60 pts] Multiple Choice: Mark your answer on BOTH the bubble sheet and this page.

1. [5 pts] The 0.20 F capacitor in the circuit at right is initially uncharged and the switch is open. First, the switch is flipped to position $\boldsymbol{a}$ and left there for a long time, allowing the capacitor to fully charge. We then flip the switch to position $\boldsymbol{b}$. What is the current through the 40 Ω resistor, exactly 6.0 s after the switch is flipped to position $\boldsymbol{b}$?



A. 0

B. 0.12 A

C. 0.36 A

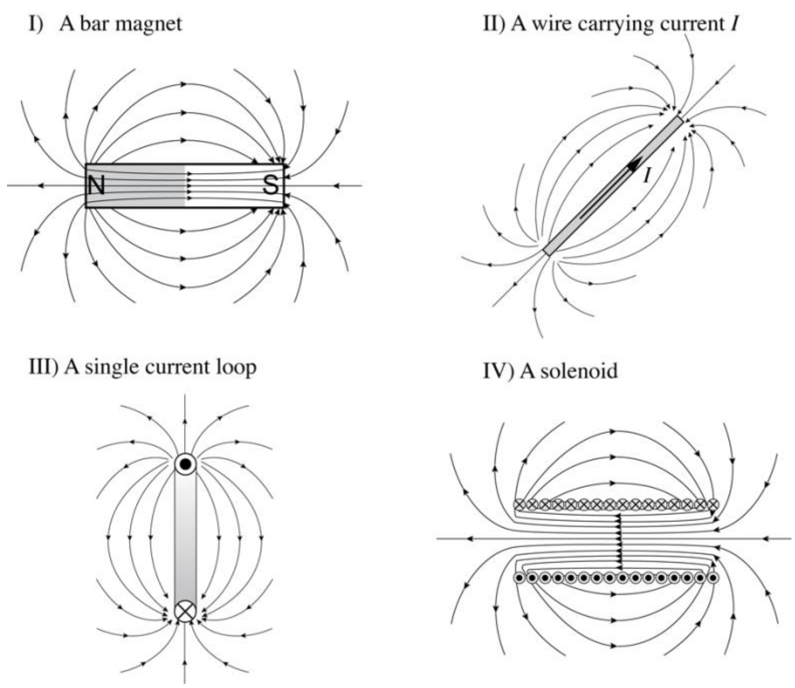
D. 4.3 A

E. 26 A

*Before flipping the switch to **b**, the capacitor is fully charged, and the voltage across is* $V_C = 10\ V$. *Immediately after flipping the switch to position **b**, the current in the resistor is* $I_0 = \frac{V_C}{R}$. *As we wait the current decays exponentially as:*

$$I(t) = I_0 e^{-t/(R\,C)} = \frac{V_C}{R} e^{-t/(R\,C)} = \frac{10\text{ V}}{40\ \Omega} e^{\frac{-(6\text{ s})}{(40\ \Omega)(0.2\text{ F})}} = 0.12\text{ A}.$$

2. [5 pts] The diagrams at right show four depictions of a magnetic field. Which of the field diagrams is most correct?



A. I only

B. II only

C. III only

D. IV only

E. None is correct

Only in figure D, the magnetic field lines are all forming closed loops.

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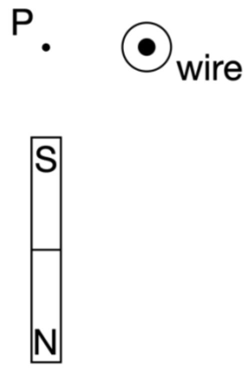
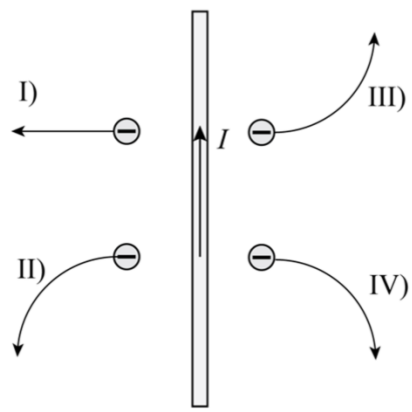
3. [5 pts] A long straight wire with a current out of the page is next to a bar magnet. Point P is directly to the left of the wire and directly above the bar magnet. The magnitudes of the magnetic fields from the wire and the magnet are the same at point P. What is the direction of the magnetic field at point P?



A. ↓
B. ↑
C. ↖
D. ↘
E. The magnetic field has zero magnitude at point P, and therefore, no direction.

The magnetic field of the magnet at point P is pointing down toward magnet, and so is the magnetic field from the wire. The total magnetic field is the sum of the two vectors, and it points down towards the magnet. The correct answer is ***A.***

4. [5 pts] A wire is carrying a positive current *I* as shown in the diagram at right. A negatively charged particle is moving in the magnetic field generated by the current in the wire. Which of the trajectories (I – IV) are possible?



A. I only
B. II and IV
C. II and III
D. III and IV
E. None is correct

On the right side of the wire, the magnetic field is pointing into the page. Using the right-hand rule, consider the particle is negatively charged and traveling to the right, the magnetic force should be pointing downward. So, the trajectory should bend downward. So, IV) is correct. The magnetic field on the left side of the wire is pointing out-of-the-page, using the same method to find that the magnetic force is also downward. So, II) is correct.

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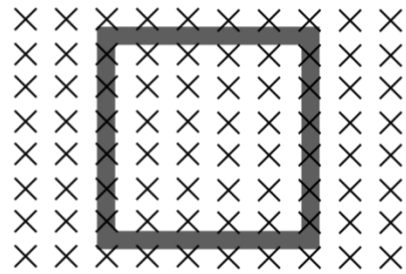
5. [5 pts] What is the magnitude of the total force on a square loop with width L that carries a clockwise current I in a uniform magnetic field B, in a configuration shown in the figure?



A. $4ILB$

B. $2ILB$

C. ILB

D. 0

E. Not enough information is given

The current in parallel edges of the loop are in opposite directions, the edges have the same length and they experience the same magnetic fields. Therefore, parallel edges experience magnetic forces of the same magnitude but in opposite directions. The net force on the square loop is therefore 0.

6. [5 pts] When running a full marathon race of 42.1 km, an elite runner has an average total metabolic power measured at 400 Watts. If the runner finishes the race with an average speed of 17.7 km per hour, how many Calories did the runner burn over the entire race?

A. 3.40×10^6 Calories

B. 14.0 Calories

C. 1320 Calories

D. 953 Calories

E. 818 Calories

The total time of the race is: $t = \frac{42.1\text{ km}}{17.1\text{ km/hr}} = 2.38\text{ hrs} \Longrightarrow 2.38\text{ hrs}\left(3600\ \frac{\text{s}}{\text{hr}}\right) = 8563\text{ s}$

Total energy consumption is: $E = 400\ \frac{\text{J}}{\text{s}} \times\ 8663\text{ s} = 3.42 \times 10^6\text{ J}$

Convert to Calories: $\frac{3.42\times10^6\text{ J}}{4186\text{ J/Cal}} = 818\text{ Calories}$

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7. [5 pts] The Global Seed Vault in Svalbard, located in the Arctic, safeguards over one million seed samples from the world's crop collections as a precaution against catastrophic losses. The vault is kept at −18.0°C to ensure optimal seed preservation. If American scientists were to communicate this temperature in Fahrenheit, what value would they report?

   A. -64.4 °F

   B. -27.8 °F

   C. -0.400 °F

   D. 7.80 °F

   E. 25.2 °F

$$T\ (°F) = \frac{9}{5}T(°C) + 32°C = \frac{9}{5}(-18.0°\text{C}) + 32°C = -0.4°\ \text{F}$$

8. [5 pts] A crane at a construction site uses an electric motor with 40% efficiency to lift things. How much electric energy in kWh does the crane use to lift a bundle of steel bars with a mass of 2000 kg from the ground level to a height of 10 meters? (Note: Utility company bills for electricity energy in unit of kWh, 1 kWh=1000 watts × 1 hour).

   A. 5×10^4 kWh

   B. 500 kWh

   C. 8.3 kWh

   D. 0.02 kWh

   E. 0.14 kWh

Potential energy gained by the steel bars after being lifted:

$$E = mg\Delta y$$

$$E = (2000\ \text{kg})(9.81\ \text{m/s}^2)(10\ \text{m}) = 1.96 \times 10^5\ \text{J}$$

The energy the crane will consume consider its efficiency: $E_{crane} = \frac{1.96\times10^5\ \text{J}}{0.4} = 4.98 \times 10^5\ \text{J}$

Convert energy in 1 kWh to Joule: $1\ kWh = 1000\ \text{Watt}\ \times 3600\ \text{s} = 3.6 \times 10^6\ \text{J}$

$$4.98 \times 10^5\ \text{J} = \frac{4.98 \times 10^5\ \text{J}}{3.6 \times 10^6\ \frac{\text{J}}{\text{kWh}}} = 0.14\ \text{kWh}$$

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9. [5 pts] A sealed container of boiling water is dropped in the ocean. We wait for some time for the temperatures to equilibrate. Determine whether the entropy change of the container (including the water in it) $\Delta S_{container}$, the entropy change of the ocean (including the air around it) ΔS_{ocean}, and the entropy change of the combined system $\Delta S_{container+ocean}$ increases (> 0), decreases (< 0), stays the same (= 0), or whether there is not enough information given to know.

   A. $\Delta S_{container} < 0, \Delta S_{ocean} > 0, \Delta S_{container+ocean} = 0$

   B. $\Delta S_{container} > 0, \Delta S_{ocean} < 0, \Delta S_{container+ocean} = 0$

   C. $\Delta S_{container} < 0, \Delta S_{ocean} > 0, \Delta S_{container+ocean} > 0$

   D. $\Delta S_{container} > 0, \Delta S_{ocean} = 0, \Delta S_{container+ocean} > 0$

   E. Not enough information is given.

   After equilibration, the temperature of the container decreases (i.e., $\Delta S_{container} < 0$), the temperature of the ocean increases, even though slightly, (i.e., $\Delta S_{ocean} > 0$), and since the entropy of the universe should increase (second law of thermodynamics), we have $\Delta S_{container+ocean} > 0$. The solution is ***C.***

10. [5 pts] A bottle contains 1 m^3 of pure nitrogen gas (formula: N_2) with a pressure of 2.0×10^5 Pascal and at temperature of 17 ºC. The atomic mass number of nitrogen is 14.

    What is the mass of N_2 gas in the bottle?

    A. 3.86×10^{-27} kg

    B. 6.58×10^{-26} kg

    C. 2.32 kg

    D. 38.6 kg

    E. 4.73×10^{3} kg

    From the ideal gas law: $PV = nRT$

$$n = \frac{PV}{RT} = \frac{2 \times 10^5 \times 1}{8.31 \times (273 + 17)} = 83\ mol$$

    The molar mass of N_2 is 28 grams/mol

    So, the mass of the gas in the bottle is:

$$m = 83\ \times\ 28 = 2324\ grams = 2.32\ kg$$

11. [5 pts] Two containers, A and B, are each filled with a different monatomic noble gas in thermal equilibrium: container A holds helium gas, and container B holds neon gas. The total thermal energies of the two gases are equal, and the helium and neon atoms have the same root-mean-square (rms) speed. What is the ratio of the number of moles of helium in container A to the number of moles of neon in container B, $\frac{n_A}{n_B}$?

    The atomic mass of Helium is 4 u, and the atomic mass of Neon is 20 u.

    A. 5

    B. 1/5

    C. 25

    D. 1/25

    E. Not enough information is given

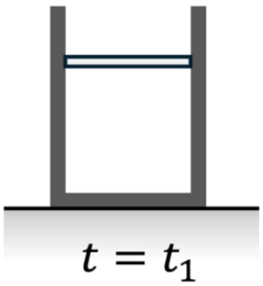
$E_{th} = \frac{3}{2}Nk_BT = \frac{3}{2}nRT$, and $v_{rms} = \sqrt{\frac{3K_BT}{m}}$

$E_{th}^A = E_{th}^B \rightarrow N_AT_A = N_BT_B \rightarrow T_A = (N_BT_B)/N_A$

Also we have $v_{rms}^A = v_{rms}^B \rightarrow \frac{T_A}{m_A} = \frac{T_B}{m_B} \rightarrow \frac{T_A}{u_A(1.66\times10^{-24}\text{ kg})} = \frac{T_B}{u_B(1.66\times10^{-24}\text{ kg})} \rightarrow \frac{T_A}{u_A} = \frac{T_B}{u_B}$

By substituting T_A, we will have: $\frac{(N_BT_B)/N_A}{u_A} = \frac{T_B}{u_B} \rightarrow \frac{N_A}{N_B} = \frac{u_B}{u_A} \rightarrow \frac{n_A}{n_B} = \frac{N_A}{N_B} = \frac{u_B}{u_A} = 5$

12. [5 pts] At $t = t_0$, a container seals a volume of ideal gas with a movable frictionless piston on the top. The piston is at rest and the gas pressure is p_0. At $t = t_1$, the container is placed above a flame and warmed slowly. Which of the following statements is FALSE?



    A. The internal energy of the gas in the container increases.

    B. The pressure of the gas in the container increases.

    C. The heat flow into the gas in the container is positive.

    D. The volume of the gas in the container increases.

    E. The gas in the container does positive work on the piston.

Since the gas is placed above a flame, the heat flowing into the gas is positive, which means choice C is true. The gas is warmed slowly, and the piston keeps the pressure of the gas constant. This means choice B is false. For a constant pressure expansion, both the volume and temperature increase. This means that choice D is true. Finally, as the gas pushes upward on the piston as the piston moves upward, it will do positive work on the piston. This means choice E is true.

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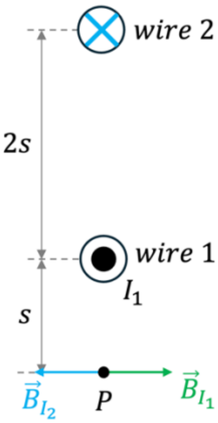
II. Lecture long-answer questions (20 points total)

13. [5 pts] Two current-carrying wires, 1 and 2, are arranged as shown at right. The current in wire 1 is flowing out of the page and has magnitude I_1. The distances of wires 1 and 2 from point *P* are *s* and 3*s* respectively, and the magnitude of the magnetic field at point *P* is zero.



What is the direction and the magnitude of the current in wire 2? Write the magnitude in terms of I_1. Explain your reasoning.

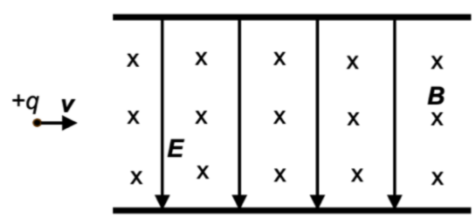
Based on the right-hand rule, wire 1 creates a magnetic field at point P that points to the right. Based on the principle of superposition, the field from wire 2 must have equal magnitude and be directed to the left for the net magnetic field to be zero at point P. The magnitude of the magnetic field at distance r from a long wire carrying a current I is $B_{wire} = \frac{\mu_0 I}{2\pi r}$. Now, wire 2 is three times as far from point P than wire 1, wire 2 must have current $3I_1$ and it must point into the page based on the right-hand rule.

$$|\vec{B}_{I_2}| = |\vec{B}_{I_1}|$$

$$\frac{\mu_0 I_2}{2\pi(3s)} = \frac{\mu_0 I_1}{2\pi s}$$

$$I_2 = 3I_1$$

14. [5 pts] A positive point charge +*q* moves with a speed v in the positive-*x* direction. The charge enters a region where the electric field is uniform and points in the negative-*y* direction as shown. The same region also contains a uniform magnetic field pointing into the page.



What is the ratio E/B of the magnitudes of the electric and magnetic fields, if the point charge moves through the region without deflection? You can ignore gravitational forces. Explain.

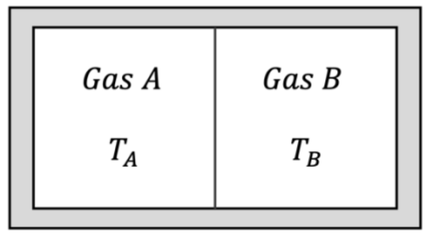
For the charge to move undeflected, the electric and magnetic forces must be equal in magnitude but point in opposite directions so that the net force is zero. The electric force $\vec{F}_{elec} = q\vec{E}$ points downward, which means that the magnetic force must point upward, which is the case in this situation based on the right-hand rule for the magnetic force. For the magnitude of the magnetic force $\vec{F}_{mag} = qv\vec{B}$ to be equal to the electric force, we require $qE = qvB \Rightarrow \frac{E}{B} = v$.

A small, closed syringe is filled with air that has been cooled down 5°C in a fridge. The syringe is then taken to a room that has an air temperature of 20°C. The syringe is allowed to come to thermal equilibrium with the room.

15. [4 pts] Now, the plunger of the syringe is pushed down very rapidly and the temperature of the air inside the syringe is observed to increase. How do you explain this observation?

    Positive work is done on the gas because a force is applied on the syringe, which moves in the direction of the force and compresses the gas. Since the process happens very quickly, the process is adiabatic $(Q = 0)$. *According to the first law of thermodynamics,* $\Delta E_{th} = W + Q = W + 0 = W > 0$, *which means that the thermal energy of the gas increased by the positive work. This corresponds to an increasing temperature.*

Two containers, A and B, contain ideal gases consisting of atoms of masses m_A and m_B, and root-mean-square speeds $v_{rms,A}$ and $v_{rms,B}$, respectively. The gases do not mix with each other, but they are in thermal contact. At $t = t_0$, the gases are at temperatures T_A and T_B, respectively.



16. [3 pts] In terms of the given quantities, what is the ratio of the average kinetic energies of the atoms in containers A and B at $t = t_0$? Show your work.

    For ideal gas at temperature T, *the average kinetic energy of the atoms can be expressed either as* $K_{avg} = \frac{3}{2}k_B T$ *or* $K_{avg} = \frac{1}{2}mv_{rms}^2$. *Thus, the ratio of average kinetic energies of the atoms in Gas A and Gas B at* $t = t_0$ is $\frac{K_{avg,A}}{K_{avg,B}} = \frac{T_A}{T_B}$, *which is also equivalent to* $\frac{K_{avg,A}}{K_{avg,B}} = \frac{m_A v_{rms,A}^2}{m_B v_{rms,B}^2}$

17. [3 pts] In terms of the given quantities, (i) what is the ratio of the average kinetic energies of the atoms in containers A and B and (ii) the ratio of their root-mean-square speeds a long time after $t = t_0$,? Show your work.

    (i) After a long time, the system has reached equilibrium, which means $T_A = T_B$. *We know from the previous problem that* $\frac{K_{avg,A}}{K_{avg,B}} = \frac{T_A}{T_B}$ *and since the temperatures have now equalized,* $\frac{K_{avg,A}}{K_{avg,B}} = 1$.

    (ii) Above, we also concluded that $\frac{K_{avg,A}}{K_{avg,B}} = \frac{m_A v_{rms,A}^2}{m_B v_{rms,B}^2}$. *Now, since* $\frac{K_{avg,A}}{K_{avg,B}} = 1$, *we get* $\frac{v_{rms,A}^2}{v_{rms,B}^2} = \frac{m_B}{m_A} \Rightarrow \frac{v_{rms,A}}{v_{rms,B}} = \sqrt{\frac{m_B}{m_A}}$.

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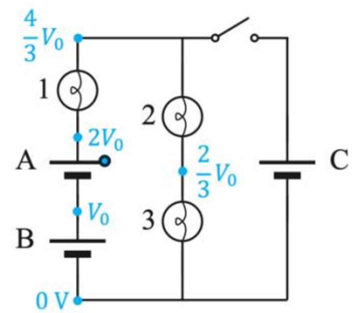
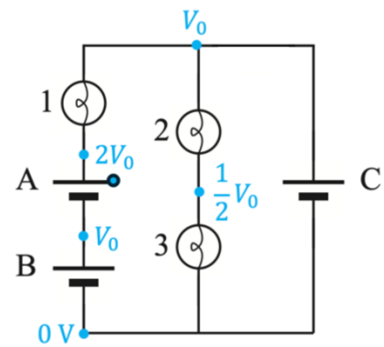
III. Tutorial and lab long answer questions (20 points total)

The circuit at right contains ideal identical batteries and identical bulbs.





18. [5 pts] When the switch is closed, does the brightness of bulb 3 *increase, decrease*, or *remain the same* compared to the brightness of bulb 3 when the switch is open?

    Switch open: Bulbs 1, 2 and 3 are in series, and batteries A and B are also in series. By Kirchhoff's loop law, if each battery has a voltage V_0, then the voltage across each bulb is $\frac{2}{3}V_0$.

    Switch closed: The sum of the voltage across bulbs 2 and 3 is the same as that of battery C since the network of bulbs 2 and 3 is connected across battery C. From Kirchhoff's loop law, the voltage across bulb 3 is $\frac{1}{2}V_0$.

    *Conclusion: The voltage across bulb 3 decreases from $\frac{2}{3}V_0$ to $\frac{1}{2}V_0$ when the switch is closed. This means that brightness of **bulb 3 decreases**.*

19. [5 pts] While the switch is closed, is bulb 1 *brighter than, dimmer than*, or *as bright as* bulb 2? Explain.

    With the switch closed, we know that the voltage across bulbs 2 and 3 is $\frac{1}{2}V_0$. In the left loop, the sum of the voltages across bulbs 1, 2 and 3 must equal that across batteries A and B, which is $2V_0$. The voltage across bulb 1 must therefore be V_0, which is greater than that across bulb 2. Bulb 1 is therefore brighter than bulb 2 when the switch is closed.

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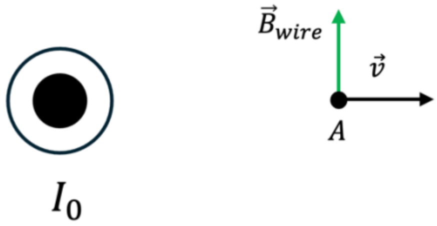
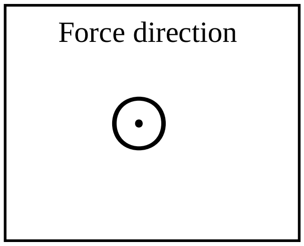
20. [5 pts] The diagram at right depicts a positively charged particle located near a current carrying wire (current is out of the page). The particle moves to the right at point A as shown. In the box provided, indicate the direction of the magnetic force experienced. If the force is either into or out of the page, use the appropriate symbols. Explain.

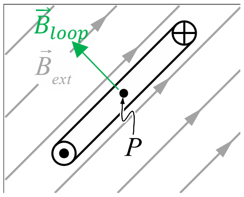


At point A, the wire creates a magnetic field that points up the page (positive y-direction).

Using the RHR rule, the force on the positively charged particle is ***out of the page****.*



21. [5 pts] A small loop of wire is placed in a region with a uniform magnetic field $\vec{B}_{ext}$ that does not change with time. The loop is attached to a battery (not shown) so that there is a current through it as shown in the cross-sectional diagram at right. The center of the loop is at point *P*.



Note: The symbol ⊗ indicates current into the page and the symbol ⊙ indicates current out of the page.

Is the magnitude of the net magnetic field at point *P* *greater than*, *less than*, or *equal to* the magnitude of $\vec{B}_{ext}$? Explain your reasoning.

Greater than*. Using the RHR for current loops, the magnetic field at the center of the loop ($\vec{B}_{loop}$) is up and to the left. The net magnetic field at point P is the vector sum of the $\vec{B}_{loop}$ and $\vec{B}_{ext}$. Since $\vec{B}_{loop}$ and $\vec{B}_{ext}$ are perpendicular, the magnitude of the net field is the Pythagorean sum of the two field magnitudes.*

$$|\vec{B}_{net}| = \sqrt{|\vec{B}_{loop}|^2 + |\vec{B}_{ext}|^2}$$

This means that the magnitude of the net magnetic field at point P is both greater than $\vec{B}_{loop}$ and $\vec{B}_{ext}$.