Electricity
Answers and Explanations

1. B

The difference between the magnitude of force exerted by the sphere on charge A vs. B is determined by their different distances from the center of the sphere and their respective charges. (A sphere upon which charge has been uniformly spread exerts force just as if its charge were concentrated at its center). The electrostatic force is inversely proportional to the square of the distance between each charge and the center of the sphere and directly proportional to the charge of each. Charge A is located a distance of 3r from the center of the sphere, and charge B is located a distance of 6r from the center of the sphere.

$$F = k\frac{q_1 q_2}{r^2}$$

$$F_A = k\frac{Q_0 q_{sph}}{(3r_A)^2} \qquad F_B = k\frac{2Q_0 q_{sph}}{(6r_A)^2}$$

$$F_A : F_B$$

$$\frac{1}{9} : \frac{1}{18}$$

$$2 : 1$$

2. A

The coulomb is the SI unit of electric charge, equal to the quantity of electricity conveyed in one second by a current of one ampere.

We would express the *capacitance* of the cloud in farads. The capacitance governs the relationship between the amount of charge stored in the cloud and the voltage between the cloud and the ground.

3. D

Each of these is a useful way to express one volt, but choice 'A', is especially helpful for understanding the energy description of an electrostatic system. When you say that the potential difference between two charged plates is 5 V, you are saying that the electric field between the plates can do 5 joules of work on 1 coulomb of charge. It would take 5 joules of work to move a coulomb from one plate to the other against the field. You're saying that a coulomb of positive charge has 5 joules more potential energy near the positive plate. Voltage is about the capability of a field to expend or store energy through work on charge between two locations within the field.

4. D

The negatively charged rod repels electrons in the metal sphere which then travel through the wire into the ground. Upon cutting the wire the sphere will now be positively charged on its surface. Excess charge collects along the surface of a conductor.

The potential difference between points A and B is defined as the change in potential energy per unit charge of a positive charge q moved from A to B. The potential difference between the ground and the sphere is positive. Next to the sphere is a place where a positive test charge would have a positive potential energy.

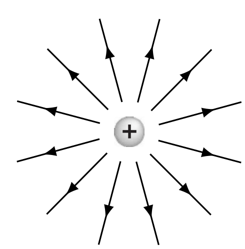
5. C

Both molten sodium chloride and metallic silver possess mobile charge carriers, ions and electrons respectively. They are good conductors. Fused quartz (glass) is a molecular solid. It is a poor conductor.

6. C

The electric field of a point charge represents the capability of that charge to exert force, a capability permeating the space around the charge, and just as the electric force exerted by a point charge decreases with the square of the distance (Coulomb's Law), the electric field intensity decreases with the square of the distance from a point charge

$$E = k\frac{q}{r^2}$$



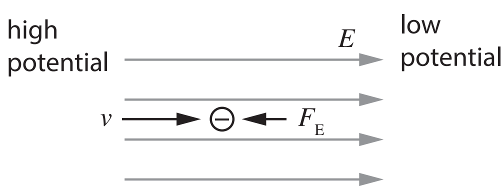
To determine the field intensity at a point 30 mm from a charge of 1×10^{-5} C:

$$E = \frac{(9.0 \times 10^{9}\ \mathrm{N \cdot m^2/C^2})(1 \times 10^{-5}\ \mathrm{C})}{(3 \times 10^{-2}\ \mathrm{m})^2}$$

$$E = 1\ \frac{\mathrm{N}}{\mathrm{C}}$$

7. A

A cathode ray is a beam of electrons. We are told in the question stem that after the electrons pass through the aperture of the electron gun they enter a zone of high potential, traveling towards a zone of low potential parallel to the electric field within the zone they have entered. The figure below shows an electron in a cathode ray traveling parallel to an electric field moving from a zone of high potential towards an area of lower potential.



Electric field lines are always drawn to show the orientation of the force that would be exerted on a *positive* test charge. The force on an electron will be in the opposite direction of the field lines.

From a dynamics/kinematics perspective the force on an electron within this electric field would cause an acceleration opposite the direction of particle velocity, so the electrons will slow down.

From a work and energy perspective, a zone of high potential is a location where a positive charge would have a high potential energy. Conversely, a negative charge has a low potential energy within a high potential zone, and a high potential energy where the electrical potential is low. In other words, as the electrons move through the field their kinetic energy is being transformed into potential energy in much the same way as would occur if you threw a ball straight up against the gravitational field.

8. C

As the α particles move from the higher to lower potential, electrostatic potential energy will be transformed into kinetic energy. To determine the amount of kinetic energy they gain, the first thing we need to do is convert the quantity of α particles given in moles into an SI quantity of electric charge in Coulombs.

$$\left(\frac{96{,}500\ \mathrm{C}}{\mathrm{mol\ e}}\right)\left(\frac{2\ \mathrm{mol\ e}}{\mathrm{mol\ He^{2+}}}\right) = 1.93 \times 10^{5}\ \mathrm{C}$$

The potential difference tells us how many joules per coulomb of work the field does through the potential drop. We can multiply the voltage by the charge to determine how much kinetic energy the α particles gained.

$$1.93 \times 10^{5}\ \mathrm{C}\left(\frac{1 \times 10^{-3}\ \mathrm{J}}{\mathrm{C}}\right) = 1.93 \times 10^{2}\ \mathrm{J}$$

From a thermodynamic perspective, the additional kinetic energy of the particles is a form of thermal energy. We can imagine this new thermal energy as the product of heat flow into the α particles to determine the temperature change.

$$Q = n\,C\,\Delta T$$

$$1.93 \times 10^{2}\ \mathrm{J} = (1\ \mathrm{mol})(12.6\ \mathrm{J\ mol^{-1}\ K^{-1}})\,\Delta T$$

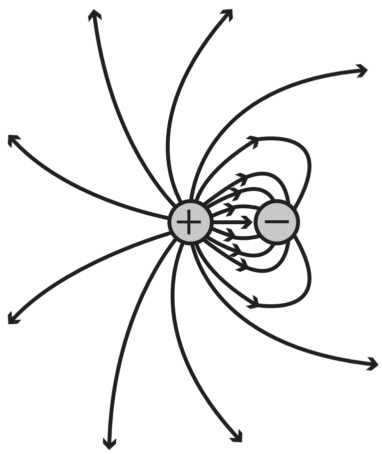
$$\Delta T = 15\ \mathrm{K}$$

Note that the question expects you to know the SI ideal gas constant, $R = 8.3\ \mathrm{J\ mol^{-1}\ K^{-1}}$. It's very difficult to tell the MCAT's disposition about the ideal gas constant . . . Also $R = 0.082\ \mathrm{L\ atm\ mol^{-1}\ K^{-1}}$.

Additionally, because the answers are widely spaced numerically, this is a safe problem for mental math. If instead of 1.93×10^{5} you use 2×10^{5} and instead of 12.6 for 3/2 R you just use 12, the answer will come out as 16 or 17K, which is okay!

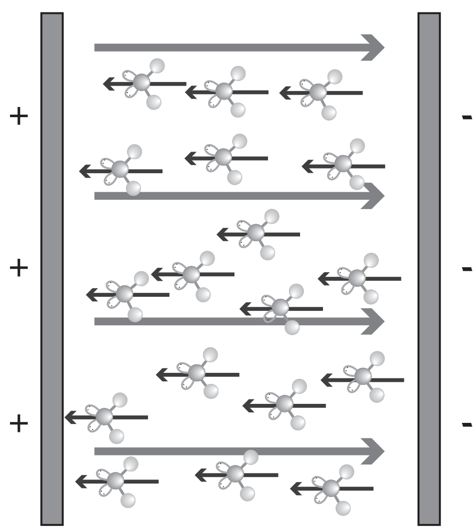
9. D

Two unlike point charges constitute a dipole. The net field of the two charges in the problem is that of a dipole with two unequal charges. Although such a point would exist if these were two like charges, there is no point on the axis between two unlike charges where the net field is zero.



10. A

Water is an example of a dielectric substance. With a dielectric substance the application of an external electric field causes the substance in bulk to polarize in opposition to the applied field.



Water molecules are polar. Under the influence of an external field they rotate with their negative poles towards the positive plate and positive poles towards the negative plate so that so that their dipole moment vectors are in alignment opposite the external field. Between the plates of a parallel plate capacitor the net result is to weaken the net electric field between the plates.

It should be noted that if the same charge densities on the plates now produces a weaker net field between the plates, the voltage across the plates is now lower ($V = Ed$ - the voltage is the product of the strength of the field and the distance of plate separation.) If there is a given charging voltage, this means that the plates can now store more charge before reaching that charging voltage. In other words, the introduction of the dielectric increased the capacitance of the capacitor.

The property of water to behave as a dielectric has consequences so far reaching it suffices to say you should basically always be thinking about it. It goes towards explaining how it is that salts can dissolve in water or how the hydration layer of proteins prevents protein precipitation. It goes towards understanding why voltage gated channels must be much closer on a nonmyelinated neuron than on a nonmyelinated neuron. Lots of important stuff!

11. D

It's a good heuristic approach for interpretation to remember that electrostatic potential energy *increases* in a system of charged particles if like charges are being forced closer together or unlike charges pulled further apart. It takes work to do those things. Imagine moving the charges yourself. Would it take work to do it? If you have two positive charges or two negative charges, it takes work to push them together against electrostatic force of repulsion, so you're storing energy in the system when you do that. Similarly, it takes work to pull a positive and a negative apart. It gets easier as you go, but you're storing energy the whole way.

Conversely, electrostatic potential energy *decreases* when things are happening in the opposite direction. When like charges are moving further apart, potential energy is decreasing, and when unlike charges are falling together, potential energy is also decreasing. Unlike charges fall together down into a well.

This is what's happening with choice 'A'. The sodium ion and the electron come together with a decrease in electrostatic potential energy. It would take work to pull the electron off the neutral atom. When they fall together it's a decrease.

Likewise it's a decrease in choice 'B' when negative charges introduced at a point on a neutral metal sphere spread over its surface area with uniform distribution. Like charges fall away from each other with decrease in electrostatic potential energy.

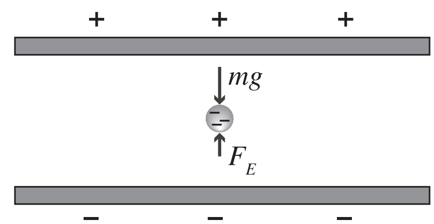
Choice 'C' is more complicated, obviously. We're priming some very important ideas, so don't hold it against yourself if it didn't seem obvious at first this is an electrostatic potential energy decrease. There are a few ways to think about it. Firstly, we know that the combustion occurs with heat flow out of the system. It's exothermic, and this is while the system is expanding. That means by the 1st law of thermodynamics that there must have been an internal energy decrease. ΔU is negative.

What is the form of that internal energy decrease? You have same charged particles on the left of the reaction as on the right, by which we mean carbon, hydrogen and oxygen nuclei and electrons. They have changed their configuration, their relationship in space. Electrons which had been in bonding orbitals between carbon and carbon and carbon and hydrogen are now in bonding orbitals between oxygen and carbon and oxygen and hydrogen. The internal energy decrease is electrostatic potential energy decrease as oxygen pulls the new electrons it has gained access to towards its big nucleus. Another way to say the same thing is that oxygen is oxidizing carbon and oxygen has a big positive reduction potential, so we know electrostatic potential energy is decreasing.

So choice 'D' is the answer. As the polypeptide unfolds, salt bridges come apart. A glutamate pulls away from a lysine. An aspartate pulls away from an arginine. Hydrogen bonds underlying secondary structure pull away from each other as α helices and β pleated sheets become disorganized. Water has to move away from itself to make room for exposed hydrophobic side chains. Across many domains throughout the polypeptide within its surroundings the electrostatic potential energy is increasing.

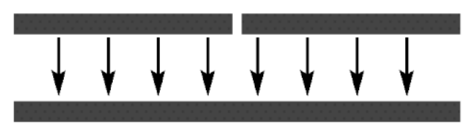
12. C

As the negatively charged oil droplet descends, it's gravitational potential energy decreases. However, it is moving *against* electrostatic force from a zone of positive potential to a zone of negative potential. It's electrostatic potential energy is increasing.



13. A

The best representation is a uniform electric field in the space between the plates with parallel electric field vectors directed downward. The larger the plates and the smaller the distance between them the more uniform the field.



Because electric field lines always show the force they would exert on a positive charge, the field as depicted would exert an *upward* force on a negative charge. We are told in the passage that the electric force is equal and opposite to the weight in the lower chamber, so the electric force must be upward. Millikan's findings report negatively charged droplets, so the field lines must be oriented downward. Additionally, the figure shows the positive plate connecting to the positive terminal of the voltage source which also corresponds to field lines oriented downward.

14. B

The voltage across parallel charged plates is the product of the strength of the uniform electric field between the plates and the distance between the plates.

$$V = Ed$$

$$E = \frac{V}{d}$$

$$E = \frac{1.2 \times 10^3 \text{ V}}{2 \times 10^{-2} \text{ m}}$$

$$E = 6.0 \times 10^4 \ \frac{\text{V}}{\text{m}}$$

The units of electric field may be expressed as either V/m or N/C. These are equivalent, though each gives you a different way to think about the field.

15. A

There is no net force on the droplet, neither when it is falling at terminal velocity in the upper chamber nor when it is suspended motionless in the lower chamber. In the upper chamber the equal and opposite forces on the droplet are the weight downwards and the frictional drag force upwards. In the lower chamber the equal and opposite forces on the droplet are the weight downwards and the electrostatic force upwards. Because both forces are equal and opposite to the weight, the drag force and the electrostatic force must be equal, so **I** is true.

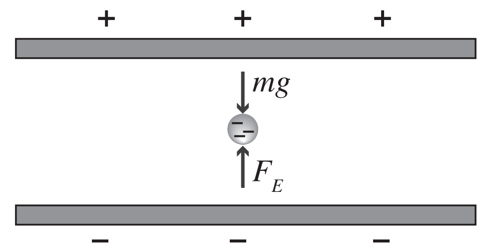
II is not true because friction forces are not conservative. Energy dissipates through friction, and **III** is not true because the friction force performs work (force times distance). As the droplet descends at terminal velocity its decrease in gravitational potential energy will equal the energy dissipated through friction (it's not becoming kinetic energy after all, as the speed is constant).

16. C

The quantum nature of charge means the magnitude of charge must be an integral multiple of *e*. It's actually a bit more complicated. It's not completely correct to say that *e* is the smallest possible charge in nature. In actuality, all known elementary particles, including quarks, have charges that are integer multiples of 1/3 *e*. Therefore, one can say that the "quantum of charge" is 1/3 *e*. . In this case, one says that the "elementary charge" is three times as large as the "quantum of charge". However all particles that can be isolated have charges that are integer multiples of *e*. Quarks only exist in collective states. In other words 'quantum of charge' may be ambiguous while 'elementary charge' is not.

17. A

When the droplet is suspended the free body diagram will be consistent with force equilibrium. The electrostatic force upwards is equal and opposite to the weight downwards.



The magnitudes of the two forces must be equal.

$$Eq = mg$$

The voltage between the plates is the product of the electric field and the distance of plate separation.

$$V = Ed$$

$$E = \frac{V}{d}$$

Substituting this into the force equilibrium expression allows us to express the voltage required as a function of droplet mass, charge and plate separation.

$$\frac{Vq}{d} = mg$$

$$V = \frac{mgd}{q}$$