1. Two large parallel metal plates are separated by a distance $L$ and have a uniform electric field between and perpendicular to them. An electron is released from the negatively charged plate at the same time as a proton is released from the positively charged plate. Neglecting the forces between the particles, find their distance from the positively charged plate when they pass each other. Assume that $m_p \approx 2000 m_e$, where $m_p$ is the proton mass and $m_e$ the electron mass.

(1) 0.0005$L$  (2) 0.001$L$  (3) 0.005$L$  (4) 0.01$L$  (5) 0.5$L$

2. In the figure a potential difference of $V = 6$V is applied across a capacitor arrangement with capacitances $C_1 = 1 \mu F$, $C_2 = 2 \mu F$, and $C_3 = 3 \mu F$. What is the charge on capacitor 2?

(1) 6$\mu C$  (2) 12$\mu C$  (3) 18$\mu C$  (4) 36$\mu C$  (5) 3$\mu C$

3. Three wires lie along the x axis (perpendicular to the page) as shown. Wires A and B each carry current $I$ into the page. When wire C carries current $I$ out of the page, wire B experiences a force $F$. With no other currents changed, in order for wire B to experience a force $F/4$ in the same direction as the original $F$, the current in wire C must be made:

(1) $I/2$, in  (2) 0  (3) $I$, in  (4) $I/4$, out  (5) 3$I/4$, out
4. A 1 mH inductor and a 30 Ω resistor are connected in series with a battery. After the current has reached a constant value, the energy stored in the magnetic field of the inductor is 45 µJ. What is the emf of the battery, in volts?

(1) 9  (2) 6  (3) 15  (4) 23  (5) 31

5. A conducting spherical shell of radius 2R has positive charge +Q. Concentrically nested inside the shell is a conducting sphere of radius R carrying charge −2Q. Which of the following is true, regarding the electric field $E_A$ at point $A$ slightly outside the shell and the electric field $E_B$ at point $B$ located in the gap between the shell and the sphere?

(1) Both $E_A$ and $E_B$ point inward
(2) $E_A$ points inward, $E_B$ outward
(3) $E_A$ points outward, $E_B$ inward
(4) $E_A = 0$ and $E_B$ is non-zero
(5) $E_A$ is non-zero and $E_B = 0$

6. A graph of the $x$ component of the electric field as a function of $x$ in a region of space is shown in the figure. The scale of the vertical axis is set by $E_{xs} = 20$ N/C. The $y$ and $z$ components of the electric field are zero in this region. If the electric potential at the origin is $-20$ V, for what value of $x$ (in meters) is the electric potential zero?

(1) 6  (2) 5  (3) 4  (4) 3  (5) 2

For this problem, answers (3) and (5) are correct. For all other problems, (1) is the correct answer.

7. In the figure the ideal batteries have emfs $E_1 = 12$ V and $E_2 = 6$ V, and the resistances are each 10 Ω. What is the value of the current in resistor 1, in amperes?

(1) 0.6  (2) 0.3  (3) 0.9  (4) 1.2  (5) 0

8. A loop of wire carrying current $I$ is placed in a uniform magnetic field as shown. What is the direction of the torque on the loop?

(1) $\vec{\tau}$  (2) $\vec{\tau}$  (3) $\vec{\tau}$  (4) $\vec{\tau}$  (5) the torque is zero

9. The figure gives, as a function of radial distance $r$, the magnitude $B$ of the magnetic field inside and outside four wires (a, b, c, and d), each of which carries a current that is uniformly distributed across the wire’s cross section. Overlapping portions of the plots are indicated by double labels. Rank the wires according to the magnitude of the current density, greatest first.

(1) $(a$ and $b) > (c$ and $d)$
(2) $(a$ and $c) > (b$ and $d)$
(3) $a > c > b > d$
(4) $a > b > c > d$
(5) $c > a > d > b$
10. The magnetic flux through a loop of wire increases according to the relation $\Phi_B = 6t^2 + 9t$, where $\Phi_B$ is in milliwebers and $t$ is in seconds. What is the magnitude, in millivolts, of the emf induced in the loop at $t = 5$ s?

(1) 69 (2) 195 (3) 15 (4) 34 (5) 127

11. The figure shows a driven $RLC$ circuit that contains two identical capacitors and two switches. The emf amplitude is set at 1.0 V, and the driving frequency is set at 60 Hz. With both switches open, the current leads the emf by 30°. With switch $S_1$ closed and switch $S_2$ still open, the emf leads the current by 15°. With both switches closed, the current amplitude is 0.50 A. What is the inductance $L$?

(1) 22 mH (2) 7.7 mH (3) 66 mH (4) 0.11 H (5) 0.33 H

12. The circuit in the figure consists of switch $S$, a 6.0 V battery, a 2.0 M$\Omega$ resistor, and an air-filled capacitor, which consists of two parallel circular plates of radius 7 cm, separated by 3 mm. At time $t = 0$, the switch is closed to begin charging the capacitor. The electric field between the plates is uniform. At $t = 10\mu$s, what is the magnitude of the magnetic field within the capacitor, at radial distance 5 cm?

(1) $5.5 \times 10^{-12}$ T (2) $7.8 \times 10^{-13}$ T (3) $4.1 \times 10^{-11}$ T (4) $5.3 \times 10^{-10}$ T (5) $6.7 \times 10^{-9}$ T

13. Suppose the prism of the figure has apex angle $\phi = 60^\circ$ and index of refraction $n = 1.6$. What is the smallest angle of incidence $\theta$ for which a ray can enter the left face of the prism and exit the right face?

(1) 36° (2) 31° (3) 25° (4) 18° (5) 13°

14. A system of thin symmetrical lenses consists of lens 1, with focal length $f_1 = +20$ cm, and lens 2, with focal length $f_2 = -20$ cm, as schematically shown in the figure. The lenses are separated by $d = 60$ cm, and an object is placed 15 cm to the left of lens 1. Find the position of the image produced by the lens system.

(1) 43 cm to the right of lens 1 (2) 8.6 cm to the left of lens 1 (3) 21 cm to the left of lens 1 (4) 6.9 cm to the right of lens 2 (5) 15 cm to the right of lens 2

15. A light ray is incident at angle $\theta = 60^\circ$ on a transparent plate comprising two parallel layers, as shown in the figure. The bottom layer, whose index of refraction is $n_2 = 1.5$, is 1.0 mm thick. How long does it take for the light to travel through this layer?

(1) 6.1 ps (2) 4.7 ps (3) 3.4 ps (4) 2.1 ps (5) 7.0 ps
16. Light of wavelength 520 nm is incident perpendicularly on a diffraction grating having 200 lines/mm. What is the highest order for which a sharp maximum occurs?

(1) 9  (2) 7  (3) 6  (4) 5  (5) 4

17. The figure shows the phasors for the driving emf of amplitude $E_m$ and the current of amplitude $I$ for three separate series RLC circuits. In which diagram is the driving frequency higher than the resonance frequency of the circuit?

(a)  (b)  (c)  

(1) c  (2) a  (3) b  (4) a and b  (5) a and c

18. Unpolarized light is sent into a system of five polarizing sheets, as shown. Their polarizing directions, measured counterclockwise from the positive direction of the $y$ axis, are the following: sheet 1, 35°; sheet 2, 0°; sheet 3, 0°; sheet 4, 110°; sheet 5, 45°. Sheet 3 is then rotated 180° counterclockwise about the light ray. During that rotation, what is the first angle (measured counterclockwise from the $y$ axis) at which the transmission of light through the system is eliminated?

(1) 20°  (2) 0°  (3) 35°  (4) 45°  (5) 65°

19. An object is placed 12 cm in front of a concave mirror of radius 30 cm. Is the resulting image real or virtual? Is the resulting image inverted or non-inverted?

(1) virtual, non-inverted  (2) real, inverted  (3) real, non-inverted  (4) virtual, inverted  (5) No image is formed

20. The figure shows four situations in which light reflects perpendicularly from a thin film of thickness $L$ sandwiched between much thicker materials. The indices of refraction are as given in the figure. When $L$ satisfies the condition $L = \lambda/(2n_f)$, where $\lambda$ is the wavelength of the light and $n_f$ is the index of refraction of the film, in which situations do you get maximum transmission of the light through the film?

(a)  (b)  (c)  (d)  

(1) c and d  (2) a and b  (3) a and c  (4) b and d  (5) b and c