Formulas:
Time dilation; Length contraction: $\Delta t = \gamma \Delta t' = \gamma \Delta t_p$; $L = L_p / \gamma$; $c = 3 \times 10^8 \text{m/s}$
Lorentz transformation: $x' = \gamma (x - vt)$; $y' = y$; $z' = z$; $t' = \gamma (t - vx/c^2)$; inverse: $v \rightarrow -v$
Spacetime interval: $(\Delta s)^2 = (c\Delta t)^2 - [\Delta x^2 + \Delta y^2 + \Delta z^2]$
Velocity transformation: $u'_x = \frac{u_x - v}{1 - u_x v/c^2}$; $u'_y = \frac{u_y}{\gamma(1 - u_x v/c^2)}$; inverse: $v \rightarrow -v$
Relativistic Doppler shift: $f_{\text{obs}} = f_{\text{source}} \sqrt{1 + v/c} / \sqrt{1 - v/c}$ (approaching)
Momentum: $\vec{p} = \gamma m \vec{u}$; Energy: $E = \gamma mc^2$; Kinetic energy: $K = (\gamma - 1)mc^2$
Rest energy: $E_0 = mc^2$; $E = \sqrt{p^2 c^2 + m^2 c^4}$
Electron: $m_e = 0.511 \text{MeV}/c^2$ Proton: $m_p = 938.26 \text{MeV}/c^2$ Neutron: $m_n = 939.55 \text{MeV}/c^2$
Atomic mass unit: $1 \text{u} = 931.5 \text{MeV}/c^2$; electron volt: $1 \text{eV} = 1.6 \times 10^{-19} \text{J}$
Stefan's law: $e_{\text{tot}} = \sigma T^4$, $e_{\text{tot}} = \text{power/unit area}; \sigma = 5.67 \times 10^{-8} \text{W/m}^2\text{K}^4$

$e_{\text{tot}} = cU/4$, $U = \text{energy density} = \int_0^\infty u(\lambda, T) d\lambda$; Wien's law: $\lambda_m T = \frac{hc}{4.96 k_B}$

Boltzmann distribution: $P(E) = Ce^{-E/(k_B T)}$
Planck's law: $u_j(\lambda, T) = N(\lambda) \times E(\lambda, T) = \frac{8\pi}{\lambda^4} \times \frac{hc/\lambda}{e^{hc/\lambda k_B T} - 1}$; $N(f) = \frac{8\pi f^2}{c^3}$
Photons: $E = hf = pc$; $f = c/\lambda$; $hc = 12,400 \text{eV} \cdot \text{A}$; $k_B = (1/11,600) \text{eV} / K$
Photoelectric effect: $eV_e = K_{\text{max}} = hf - \phi$, $\phi = \text{work function}$; Bragg equation: $n\lambda = 2d \sin \theta$
Compton scattering: $\lambda' - \lambda = \frac{h}{m_ec} (1 - \cos \theta)$; $\frac{h}{m_ec} = 0.0243 \text{A}$; Coulomb constant: $ke^2 = 14.4 \text{eV} \cdot \text{A}$

Force in electric and magnetic fields (Lorentz force): $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$; Drag force: $D = 6\pi \eta v$
Rutherford scattering: $\Delta n = \frac{C}{\sin^4(\phi/2)}$; $hc = 1,973 \text{eV} \cdot \text{A}$

Hydrogen spectrum: $\frac{1}{\lambda_{\text{min}}} = R \left( \frac{1}{m^2} - \frac{1}{n^2} \right)$; $R = 1.097 \times 10^7 \text{m}^{-1}$
Electrostatic force, energy: $F = \frac{kq_1 q_2}{r^2}$; $U = \frac{kq_1 q_2}{r}$ Centripetal force: $F_c = \frac{mv^2}{r}$
Bohr atom: $E_n = -\frac{ke^2 Z}{2r_n}$; $E_0 = \frac{ke^2}{2a_0} = 13.6 \text{eV}$; $K = \frac{mv^2}{2r}$; $U = -\frac{ke^2 Z}{r}$

$hf = E_i - E_f$; $r_n = n \hbar^2$; $r_0 = \frac{a_0}{Z}$; $a_0 = \frac{\hbar^2}{m_e k_e^2} = 0.529 \text{A}$; $L = m_y \nu = nh$ angular momentum
de Broglie: $\lambda = \frac{h}{p}$; $f = \frac{E}{h}$; $\omega = 2\pi f$; $k = \frac{2\pi}{\lambda}$; $E = h\omega$; $p = \hbar k$; $E = \frac{p^2}{2m}$
Wave packets: $y(x, t) = \sum_j a_j \cos(k_j x - \omega_j t)$, or $y(x, t) = \int dk a(k) e^{ikx - \omega(t)}$; $\Delta k \Delta x \sim 1$; $\Delta \omega \Delta t \sim 1$

Group and phase velocity: $v_g = \frac{d\omega}{dk}$; $v_p = \frac{\omega}{k}$ Heisenberg: $\Delta x \Delta p \sim h$; $\Delta t \Delta E \sim h$

Schrödinger equation: $-\frac{\hbar^2}{2m} \frac{\partial^2 \psi}{\partial x^2} + U(x) \psi(x, t) = i\hbar \frac{\partial \psi}{\partial t}$; $\Psi(x, t) = \psi(x) e^{\frac{iE}{\hbar}t}$
Time-independent Schrödinger equation: \[
-i\hbar \frac{\partial \psi}{\partial t} = H \psi
\]

\[
-\frac{\hbar^2}{2m} \frac{\partial^2 \psi}{\partial x^2} + U(x) \psi = E \psi
\]

∞ square well: \[
\psi_n(x) = \sqrt{\frac{2}{L}} \sin \left( \frac{n\pi x}{L} \right) ;
E_n = \frac{\pi^2 \hbar^2 n^2}{2mL^2} ;
\frac{\hbar^2}{2m_e} = 3.81 eV A^2 \text{ (electron)}
\]

Harmonic oscillator: \[
\Psi_n(x) = H_n(x) e^{-\frac{m \omega x^2}{\hbar}} ;
E_n = (n + \frac{1}{2}) \hbar \omega ;
E = \frac{p^2}{2m} + \frac{1}{2} m \omega^2 x^2 = \frac{1}{2} m \omega^2 A^2 ;
\Delta n = \pm 1
\]

Expectation value of \[Q\] : \[
\langle Q \rangle = \int \psi^* \langle Q \rangle \psi \ dx ;
\text{Momentum operator} : \ p = \frac{\hbar}{i} \frac{\partial}{\partial x}
\]

Eigenvalues and eigenfunctions: \[Q\] \[\Psi = q \Psi \] (q is a constant) ; uncertainty: \[
\Delta Q = \sqrt{\langle Q^2 \rangle - \langle Q \rangle^2}
\]

Step potential: reflection coef : \[
R = \left( \frac{k_1 - k_2}{k_1 + k_2} \right)^2 ,
T = 1 - R ;
k = \sqrt{\frac{2m}{\hbar^2} (E - U)}
\]

Tunneling : \[
\psi(x) \sim e^{-\alpha x} ;
T = e^{-2\alpha x} ;
T = e^{-\alpha} ;
\alpha(x) = \sqrt{\frac{2m[U(x) - E]}{\hbar^2}}
\]

Justify all your answers to all problems