4S ACADEMY • AP PHYSICS C • ELECTRICITY & MAGNETISM

The E&M Equations, Explained

Every core relationship with what it means and exactly when to reach for it

Knowing an equation is not knowing when to use it. This guide walks the E&M toolkit in the order the physics builds, from a single charge to Maxwell's induction, with an original plain-English note on each. Read it as a map, not a list.

Part 1. Electrostatics

fields, flux, potential

Force, field and Gauss

- $F = \dfrac{kq_1q_2}{r^2}, \qquad \mathbf{E} = \dfrac{\mathbf{F}}{q} = \dfrac{kq}{r^2}\hat{\mathbf{r}}$
  Coulomb's law and the field of a point charge. Use for point charges or as the building block for an integral over a continuous distribution.
- $\oint \mathbf{E} \cdot d\mathbf{A} = \dfrac{Q_{\text{enc}}}{\varepsilon_0}$
  Gauss's law. Use *instead of* integrating when the charge has spherical, cylindrical, or planar symmetry, it makes the field fall out in one line.

Potential

- $V = \dfrac{kq}{r}, \qquad U = qV, \qquad \mathbf{E} = -\dfrac{dV}{dr}, \qquad \Delta V = -\int \mathbf{E} \cdot d\mathbf{l}$
  Potential is energy per charge. Go from V to E by differentiating, from E to V by integrating. Potential is a *scalar*, so it adds without vector components, often easier than fields.

Part 2. Capacitance and circuits

storing charge and driving current

Capacitors

- $C = \dfrac{Q}{V}, \qquad C = \dfrac{\varepsilon_0 A}{d}, \qquad U = \tfrac{1}{2}CV^2 = \dfrac{Q^2}{2C}$
  Capacitance depends on geometry only. Series capacitors add reciprocally ($\frac{1}{C} = \sum \frac{1}{C_i}$); parallel add directly, the opposite of resistors.

Current, resistance, power

- $I = \dfrac{dQ}{dt}, \qquad R = \dfrac{\rho L}{A}, \qquad V = IR, \qquad P = IV = I^2R = \dfrac{V^2}{R}$
  Ohm's law and power. Series resistors add; parallel add reciprocally. Choose the power form that uses the two quantities you already know.

RC circuits

- $q(t) = Q\left(1 - e^{-t/RC}\right)$ (charging), $\qquad q(t) = Q\,e^{-t/RC}$ (discharging), $\qquad \tau = RC$
  The time constant $\tau = RC$ is the time to reach $\approx 63\%$ of the change. At $t = 0$ a capacitor acts like a wire; after a long time, like a break in the circuit.

Part 3. Magnetism and induction

moving charge and changing flux

Magnetic force and Ampère

- $\mathbf{F} = q\mathbf{v} \times \mathbf{B}, \qquad \mathbf{F} = I\mathbf{L} \times \mathbf{B}$
  Force on a moving charge and on a current. The cross product means the force is *perpendicular* to both $\mathbf{v}$ and $\mathbf{B}$; use the right-hand rule and note it does no work.
- $\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I_{\text{enc}}, \qquad B_{\text{solenoid}} = \mu_0 n I$
  Ampère's law, the magnetic analogue of Gauss. Use it for the field of a long wire, a solenoid, or a toroid, wherever the current has symmetry.

Faraday's law and inductance

- $\Phi_B = \int \mathbf{B} \cdot d\mathbf{A}, \qquad \varepsilon = -\dfrac{d\Phi_B}{dt}$
  Faraday's law: a *changing* magnetic flux drives an EMF. The minus sign (Lenz's law) says the induced current opposes the change that made it.
- $\varepsilon = -L\dfrac{dI}{dt}, \qquad U = \frac{1}{2}LI^2$
  An inductor opposes changes in current and stores energy in its field. In an RL circuit the current rises with time constant $\tau = L/R$.

The through-line. Gauss and Ampère both trade a hard integral for symmetry. Potential (a scalar) is often the easy road to a field. And induction is the one place a *rate of change* drives the physics, watch for "changing" in the question.