

Franklin in 1747 with his positive negative charge fluid theory, to Faraday in 1831 and ions, then to Maxwell in 1865 and EM Waves

The history of electromagnetism is a journey of connecting separate physical phenomena into a single, unified theory. Here is how these monumental milestones connect:

The Foundations of Charge and Field Theory

- **1747 – Benjamin Franklin’s Single-Fluid Theory:** Franklin proposed that electricity is a single, omnipresent electric fluid found in all matter. He defined a **positive charge** as an excess of this fluid and a **negative charge** as a deficiency. While we now know electrons move rather than a fluid, his positive/negative algebraic nomenclature remains the standard today.
- **1831 – Michael Faraday’s Ions and Induction:** Building on chemical discoveries, Faraday introduced the terms **ion** (from the Greek word for "goer"), *anion*, and *cation* to describe the charged particles that move through a chemical solution during electrolysis. In the same year, he discovered **electromagnetic induction**, proving that a changing magnetic field creates an electric current. He pioneered the concept of physical "lines of force" (or fields) stretching through space.
- **1860s (Published 1865) – James Clerk Maxwell’s EM Waves:** Maxwell took Faraday's intuitive visual concepts of electric and magnetic fields and translated them into rigorous mathematical equations. By unifying electricity, magnetism, and light, **Maxwell’s Equations** proved that changing electric fields create magnetic fields, and vice versa. This self-sustaining loop propagates through space as **electromagnetic waves**, moving at the speed of light.

The Evolution of Electromagnetism

Scientist & Year	Core Entity / Concept	Major Theoretical Shift
Benjamin Franklin (1747)	Electric Fluid	Shifted view from "types of electricity" to a single fluid balance (Positive/Negative).
Michael Faraday (1831)	Ions & Induction	Connected electricity to chemical matter (ions) and showed magnetism creates electricity.
James Clerk Maxwell (1865)	Electromagnetic Waves	Mathematically unified electricity and magnetism, proving light is an EM wave .

Which specific era or scientist's equations would you like to explore deeper? I can break down **Maxwell's mathematical derivations** or dive into **Faraday's laws of electrolysis**.

Both

Here is a deep dive into the foundational mathematics of **Faraday's Laws of Electrolysis** and **Maxwell's Equations**, bridging the gap between chemical matter and electromagnetic wave theory.

1. Faraday's Laws of Electrolysis (1834)

Faraday quantified how electric charge relates to chemical mass. His two laws explain how **ions** carry charge to electrodes, depositing or liberating matter.

The Governing Equations

Faraday's laws are synthesized into a single fundamental formula:

$$m = \left(\frac{Q}{F}\right) \cdot \left(\frac{M}{z}\right)$$

Where:

- m = Mass of the substance altered at an electrode (in grams)
- Q = Total electric charge passed through the solution ($Q = I \cdot t$, where I is current in amperes and t is time in seconds)
- F = **Faraday's constant** ($\approx 96,485$ C/mol), representing the magnitude of electric charge per mole of electrons
- M = Molar mass of the substance (g/mol)
- z = Valency number of the ions (electrons transferred per ion)

The term $\frac{M}{z}$ is known as the **equivalent weight** of the substance.

Physical Intuition

This equation shows that the amount of chemical change is directly proportional to the number of moles of electrons passed through the circuit ($\frac{Q}{F}$). To liberate one mole of a substance with a valency (z) of 2 (like Cu^{2+}), you need exactly 2 moles of electrons ($2F$ of charge).

2. Maxwell's Equations (1865)

Maxwell took Faraday's physical "lines of force" and turned them into the bedrock of classical electrodynamics. In his formulations, he noticed a logical asymmetry in the laws of electricity and magnetism and added a crucial missing link: **displacement current**.

The four equations are presented below in their modern differential form:

Equation Name	Differential Form	Physical Meaning
Gauss's Law for Electricity	$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$	Electric charges produce electric fields. Field lines diverge from positive charges and converge on negative charges.

Equation Name	Differential Form	Physical Meaning
Gauss's Law for Magnetism	$\nabla \cdot \mathbf{B} = 0$	Magnetic monopoles do not exist. Magnetic field lines always form continuous, closed loops.
Faraday's Law of Induction	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	A time-varying magnetic field curls to induce a spatially twisting electric field (the basis for electric generators).
Ampère-Maxwell Law	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$	Magnetic fields are generated by electric currents (J) and by time-varying electric fields (Maxwell's contribution).

Where:

- **E** and **B** are the electric and magnetic field vectors.
- ρ is the charge density, and **J** is the current density.
- ϵ_0 (vacuum permittivity) and μ_0 (vacuum permeability) are constants of space.

The Birth of EM Waves (The Derivation of Light)

In a vacuum where there are no charges ($\rho = 0$) and no currents (**J** = 0), Maxwell took the curl ($\nabla \times$) of Faraday's Law and substituted the Ampère-Maxwell Law into it. Through vector calculus identity ($\nabla \times (\nabla \times \mathbf{E}) = \nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E}$), he derived the **electromagnetic wave equation**:

$$\nabla^2 \mathbf{E} = \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

This is the standard mathematical form of a three-dimensional wave equation. The velocity (v) of any wave in such an equation is represented by the inverse square root of the coefficients multiplying the time derivative:

$$v = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

When Maxwell plugged in the laboratory-measured values for μ_0 and ϵ_0 , the calculated speed was approximately 300,000 km/s—exactly the speed of light. This allowed Maxwell to make the profound deduction that light itself is an electromagnetic wave.

Visualising the Waves

An electromagnetic wave consists of synchronized oscillations of electric and magnetic fields. They propagate perpendicular to each other and to the direction of energy travel.