

James Clerk Maxwell: his contribution to
Scotland's all-renewable electricity target
Scottish Solar Energy Group 5-3-19

Keith Barnham
Emeritus Professor of Physics,
Distinguished Research Fellow,
Imperial College London

The Burning Answer: a User's Guide to the Solar Revolution,
Weidenfeld & Nicolson (2015)

www.burninganswers.com

Maxwell's discovery of the laws of electro-magnetism
“the most significant event of the 19th century” Feynman

- How did Maxwell discover what sunlight is?
- How does his discovery change sunlight into electric power in a solar cell?
- Can solar cells contribute to Scotland's all-renewable electricity target in 2020?

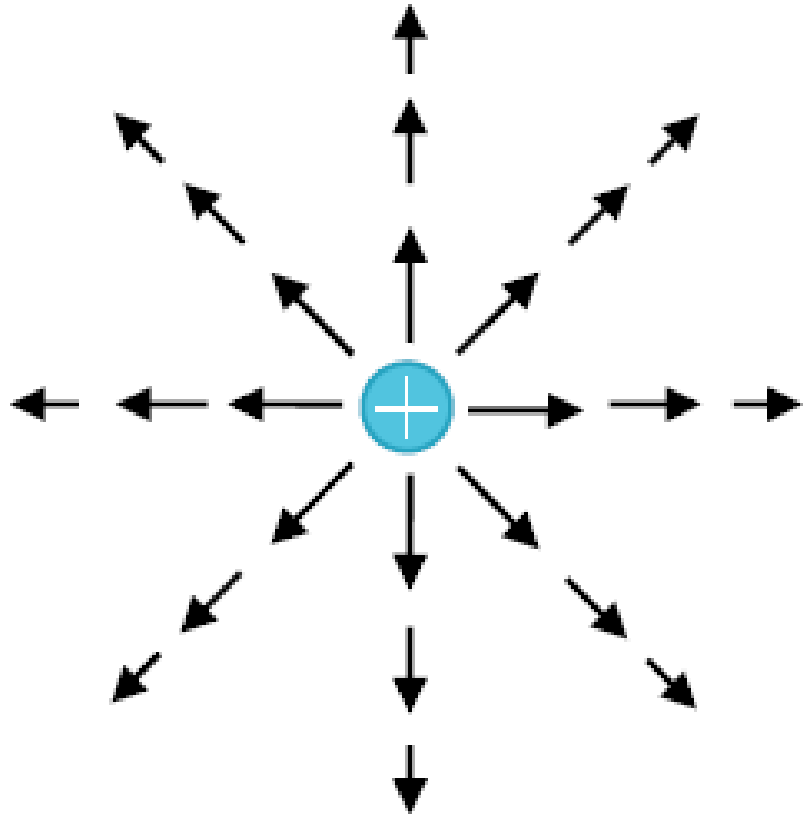
Why do so few people understand “the most significant event of the 19th century”?

- Often complex maths used e.g. Imperial Physics’ mural:

$$\begin{aligned}
 \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} &= \frac{1}{c} \left(4\pi j_x + \frac{\partial D_x}{\partial t} \right); \quad \frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = -\frac{1}{c} \frac{\partial B_x}{\partial t}; \quad \frac{\partial D_x}{\partial x} + \frac{\partial D_y}{\partial y} + \frac{\partial D_z}{\partial z} = 4\pi \rho; \quad v = L \frac{di}{dt} + Ri + \frac{q}{c} \cdot F = e(E + v \times B) \\
 \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} &= \frac{1}{c} \left(4\pi j_y + \frac{\partial D_y}{\partial t} \right); \quad \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -\frac{1}{c} \frac{\partial B_y}{\partial t}; \quad \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0; \quad \oint (\phi \nabla^2 \psi - \psi \nabla^2 \phi) d\tau = \int (\phi \frac{\partial \psi}{\partial n} - \psi \frac{\partial \phi}{\partial n}) ds \\
 \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} &= \frac{1}{c} \left(4\pi j_z + \frac{\partial D_z}{\partial t} \right); \quad \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -\frac{1}{c} \frac{\partial B_z}{\partial t}; \quad D = \epsilon E; \quad B = \mu H; \quad \frac{c}{4\pi} \operatorname{div}(E \times H) + \frac{1}{8\pi} \frac{\partial}{\partial t} (\epsilon E^2 + \mu H^2) + E j = 0
 \end{aligned}$$

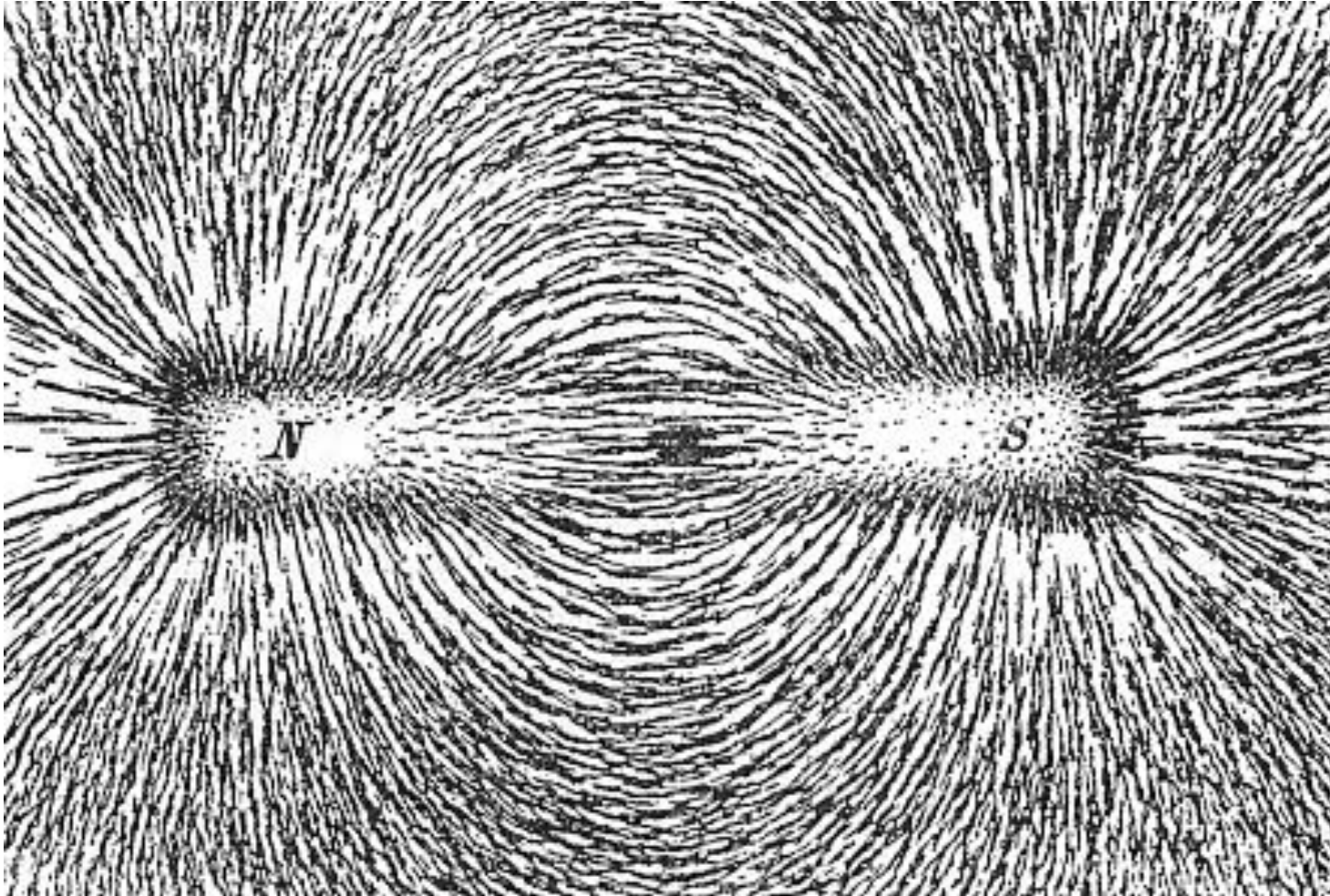
- *The Burning Answer*: Maxwell’s laws explained in words
Tonight I will explain them in pictures

1. Gauss' Law says electric field E diverges from a charge ρ



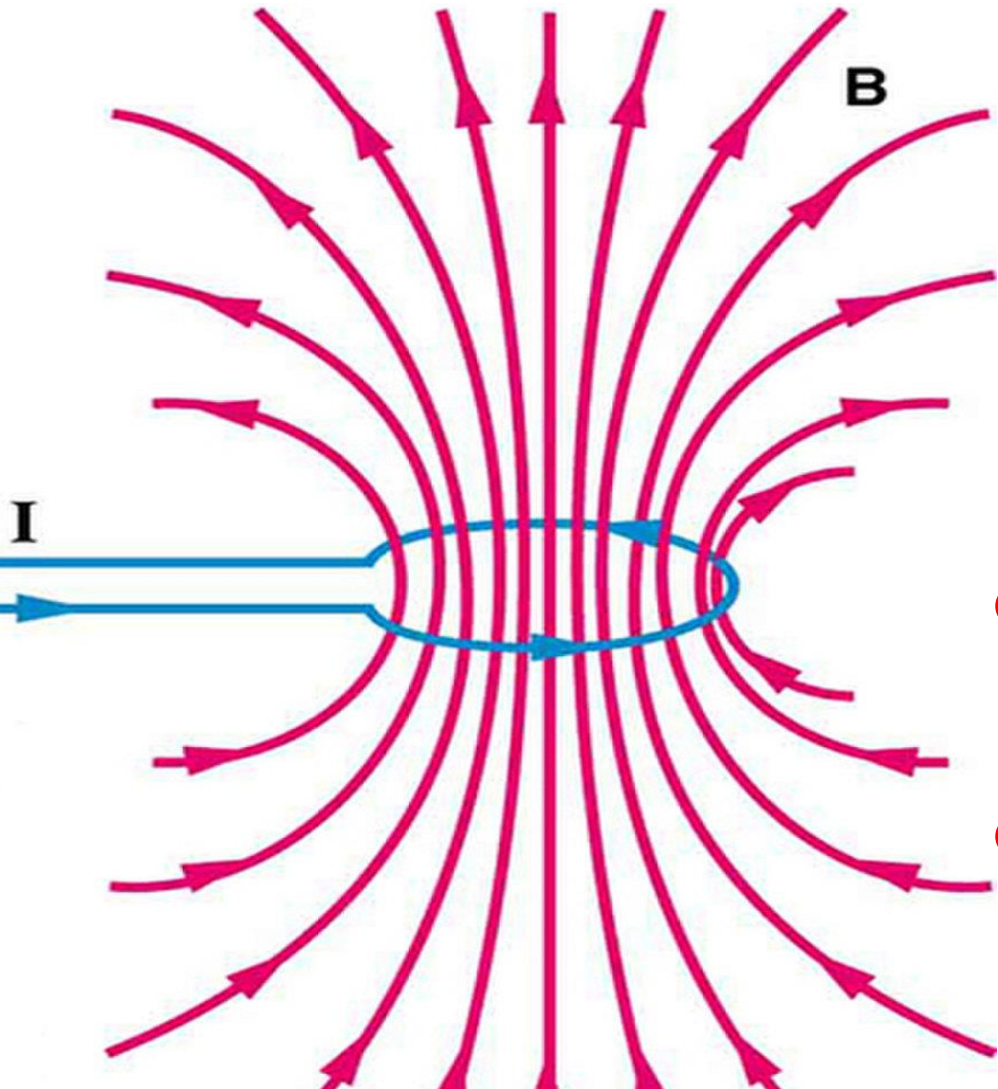
$$\nabla \cdot \mathbf{E} = \rho / \epsilon_0$$

2. Gauss' Law says magnetic field B forms loops



$$\nabla \cdot \mathbf{B} = 0$$

3. Faraday's Law says a magnetic field B changing with time generates a loop of E field

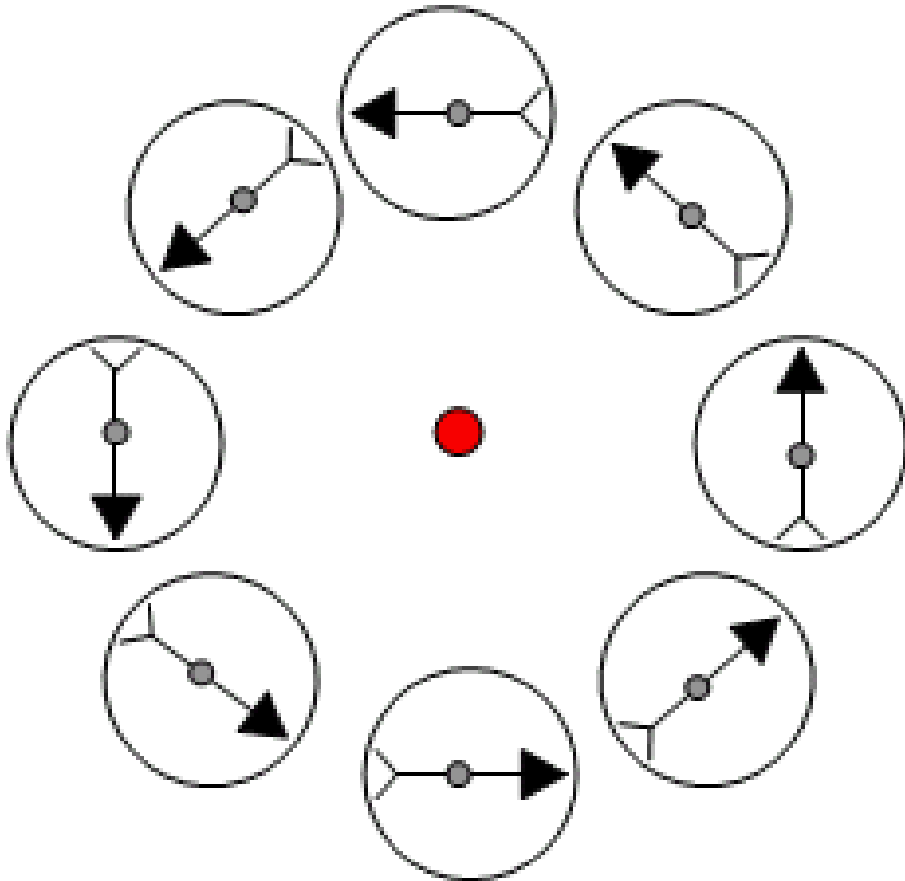


$$\nabla \times \mathbf{E} = - \frac{\partial \mathbf{B}}{\partial t}$$

- If E field generated in wire electrons pulled round circuit producing current
- This is the way *all* sources of electricity produce power - except for one

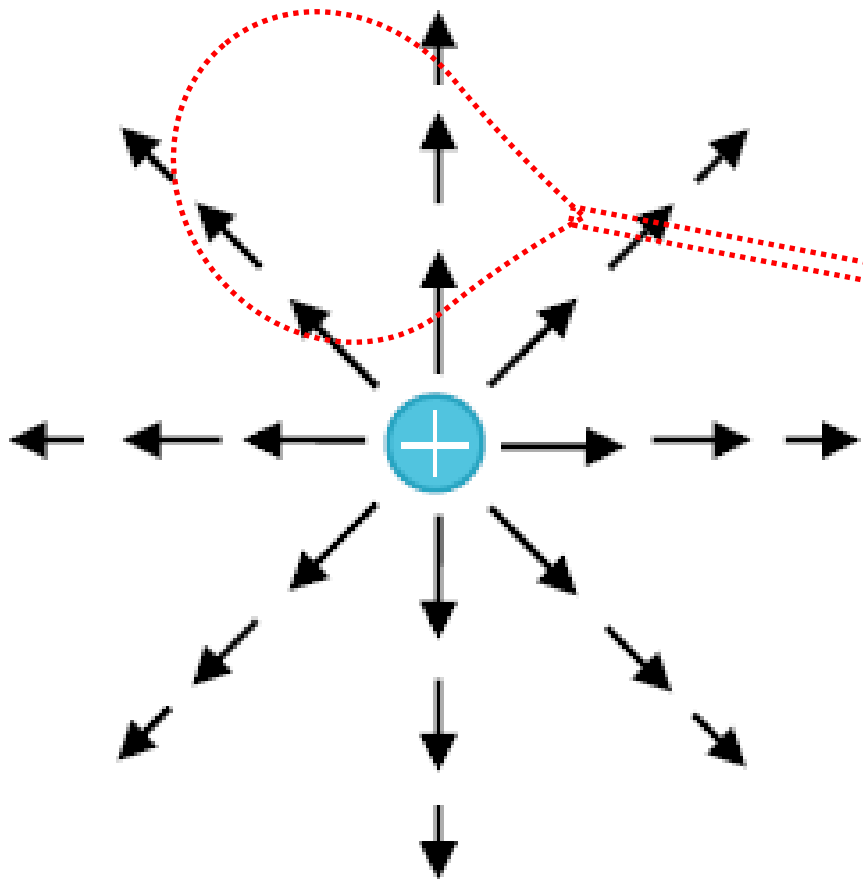
4. Ampere's law says magnetic field B loops round the current in a wire

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$



- Anything suspicious about the names of Maxwell's 4 laws?
- Maxwell discovered something missing from this equation

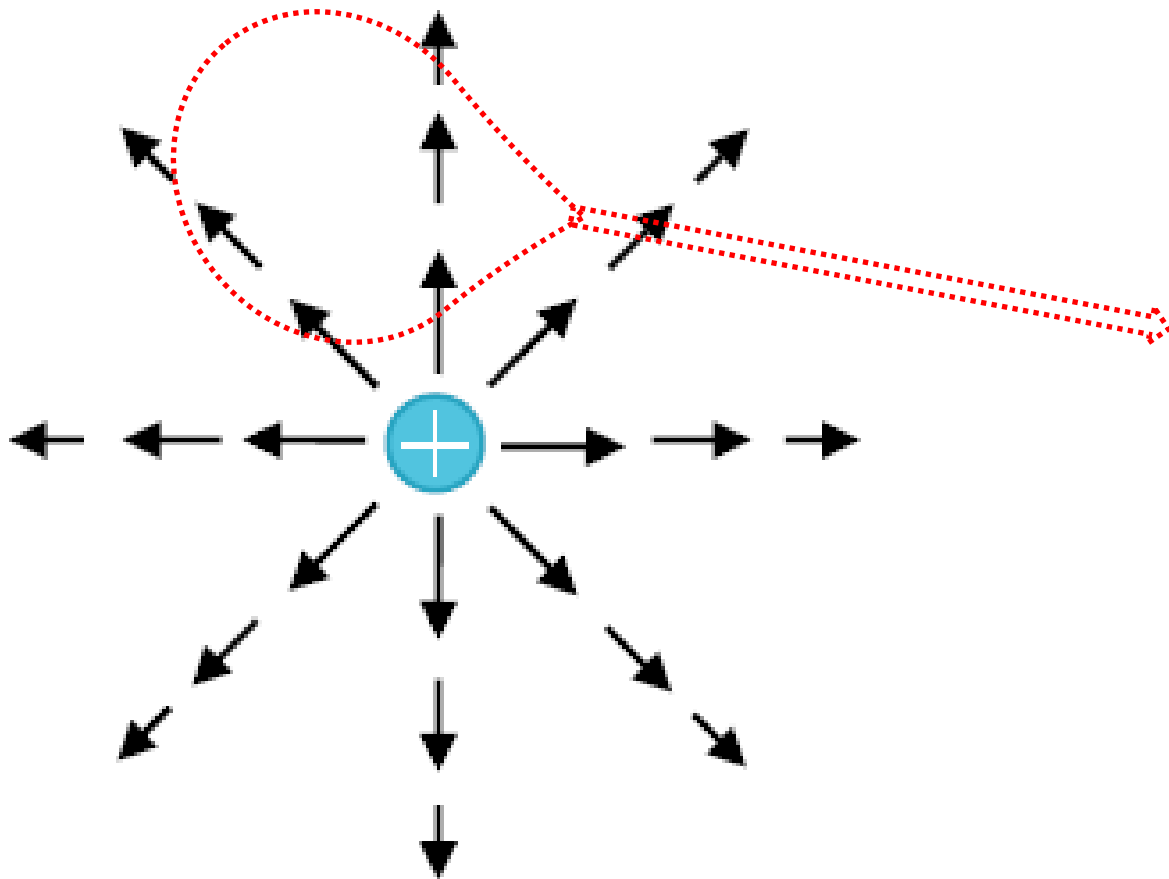
Is something missing from the lower equation when there is no current \mathbf{J} ?



$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = 0$$

JCM decided when circuit is broken the loop of E field takes time to die away



$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \epsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t}$$

Maxwell combined eqn. 3 and his new eqn. 4 and one surprising equation emerged

- Generations of physics undergrads have repeated this & shared his surprise that one equation emerges

A *wave equation* for electric and magnetic fields!

- Sound & water wave equations contain the *wave speed*

In Maxwell's case *speed of new wave* = $\frac{1}{\sqrt{\epsilon_0 \mu_0}}$

- If experimentalists could find a wave moving at this speed he would have discovered a new type of wave!
- Picture Maxwell's excitement searching for constants ϵ_0 & μ_0

JCM calculated the new wave speed & experienced the greatest Eureka moment in physics history

Maxwell's new wave had speed = 3.0×10^8 m/s

An extremely high number known extremely well:

The speed of light

- He didn't need to wait for experimentalist to confirm
- Only person to know: light is an **electromagnetic wave**
- He had explained a different branch of physics: optics
- He had unified two fundamental forces into one: EM
- Generations unified EM with other forces by symmetry

1865 Maxwell's Laws remain unchanged despite physics revolutions & unifications over 154 years

- **1887 Hertz** generated and detected EM waves in a lab
- **1905 Einstein's** relativity: JCM's laws already relativistic
- **1905** Sunlight emitted in quanta: **Einstein-Maxwell boson**
- **1947** Electromagnetism & quantum mechanics unified
- **1947** Positive electricity discovered in semiconductors
- **1964 Professor Peter Higgs boson** - unified theory of mass

1947 JCM & Einstein's pictures of sunlight gave us **positive electricity** which led to many revolutions.....

● **Positive electricity** has led to a revolution in the way this generation communicates



● Christy, Olan, Jude & Eliot have made a video showing how **positive electricity** & the **E-M boson** have revolutionised electricity generation