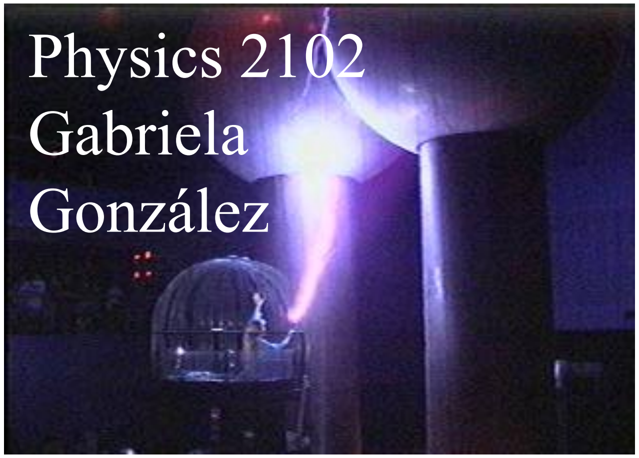
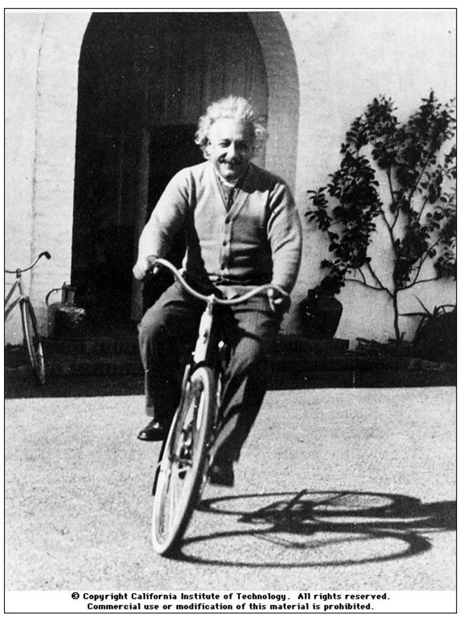
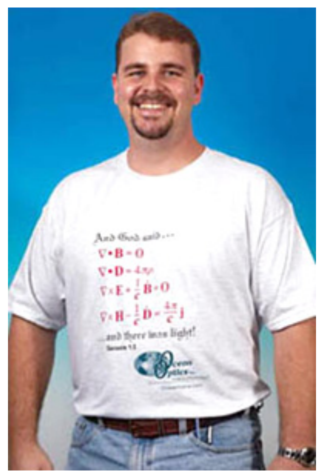


James Clerk Maxwell (1831-1879)

Maxwell’s equations
the dawn of 20th century physics

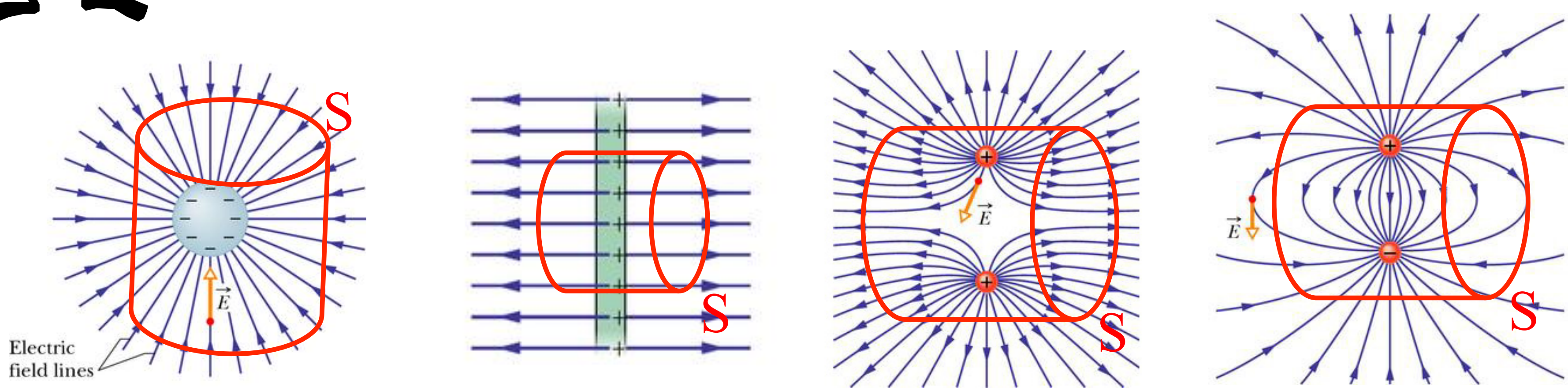




Gauss' Law:

charges produce electric fields,
field lines start and end in charges

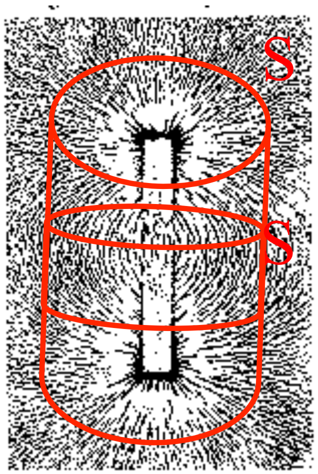
$$\oint_S E \bullet dA = q / \varepsilon_0$$



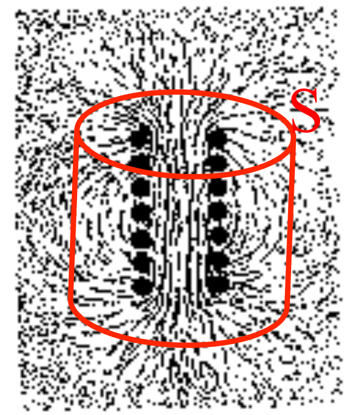
Gauss' law for magnetism:

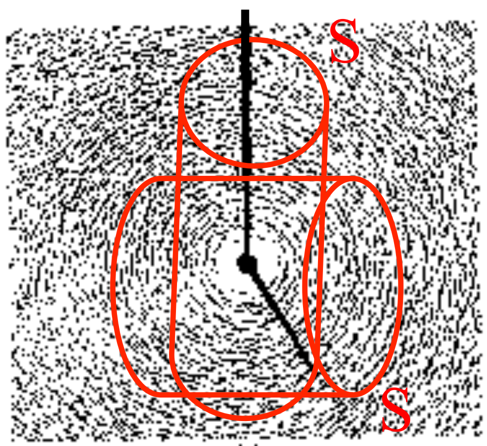
field lines are closed

or, there are no magnetic monopoles

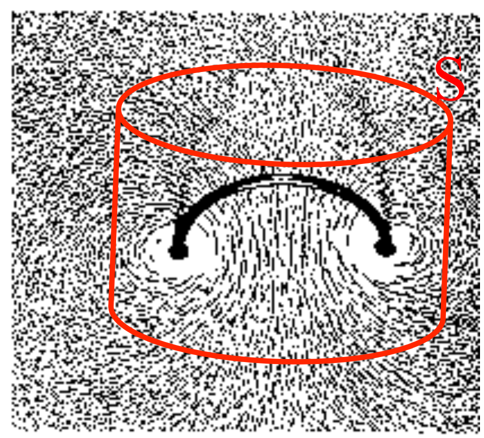


$$\oint_S B \bullet dA = 0$$





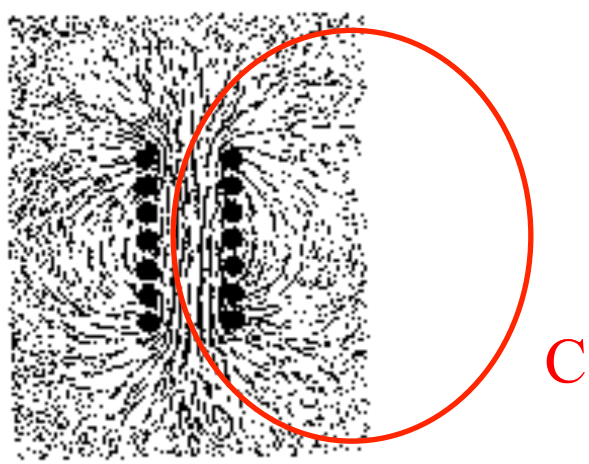
(a)



Ampere's law:

electric currents produce magnetic fields

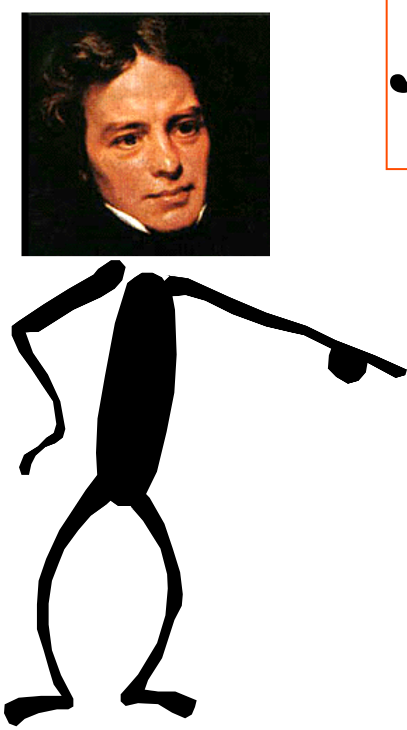
$$\oint_C B \bullet ds = \mu_0 i$$

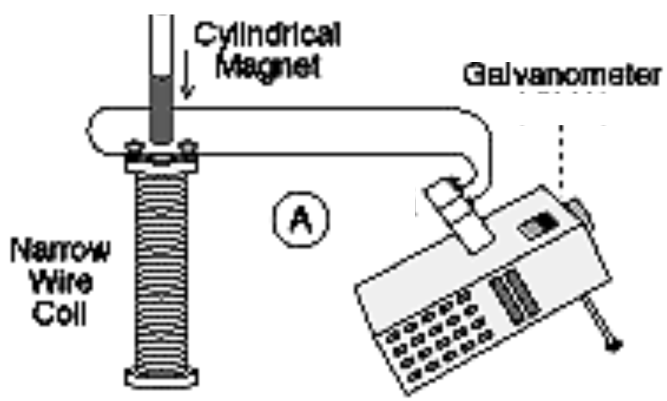


Faraday's law:

changing magnetic fields produce ("induce") electric fields

$$\oint_C E \bullet ds = -\frac{d}{dt}\int_S B \bullet dA$$





All together:

$$\oint_S E \bullet dA = q / \varepsilon_0$$

$$\oint_S B \bullet dA = 0$$

$$\oint_C B \bullet ds = \mu_0 i$$

$$\oint_C E \bullet ds = -\frac{d}{dt}\int_S B \bullet dA$$

No charges or currents:

$$\oint_S E \bullet dA = 0 \quad (q/\varepsilon_0)$$

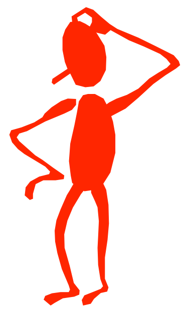
q=0

$$\oint_S B \bullet dA = 0$$

?

i=0

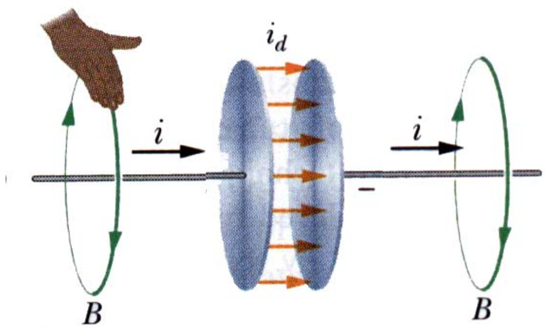
$$\oint_C B \bullet ds = 0 \quad (\mu_0 i)$$



…very suspicious…!

$$\oint_C E \bullet ds = -\frac{d}{dt}\int_S B \bullet dA$$

Something is not right…



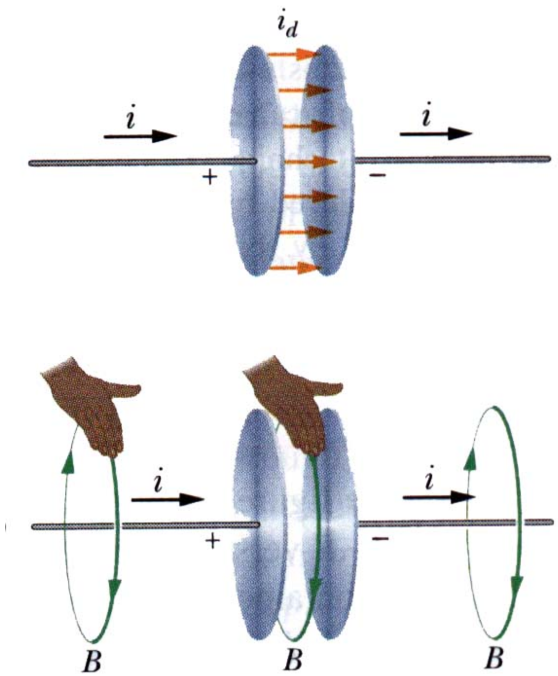
If we are charging a capacitor, there is a current left and right of the capacitor.

Thus, there is the same magnetic field right and left of the capacitor, with circular lines around the wires.

There is an electric field inside the capacitor. But no magnetic field there?

With a compass, we can verify there is indeed a magnetic field, equal to the field elsewhere.

But there is no current producing it! ?



Maybe **we can make it right…**

We calculate the magnetic field produced by the currents at left and at right using Ampere's law :

$$\oint_C B \bullet ds = \mu_0 i$$

We can write the current as:

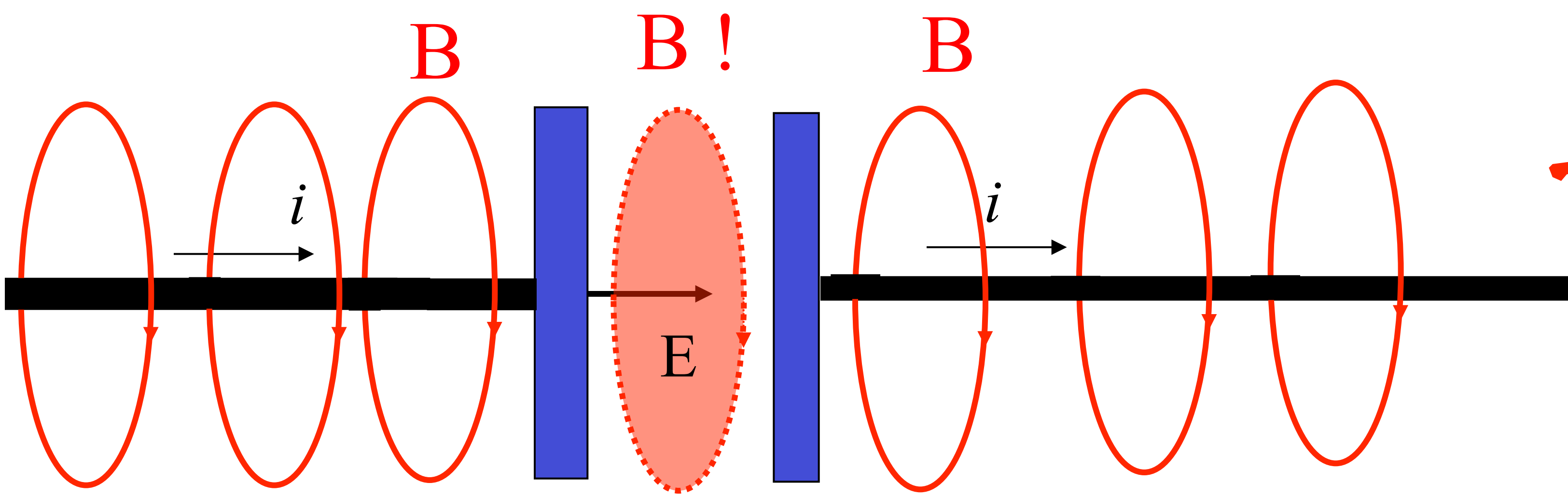
$$i = \frac{dq}{dt}$$

$q = CV$ $\quad C = \varepsilon_0 A/d$ $\quad V = Ed$ $\quad \Phi_E = EA$

Displacement current

Maxwell proposed it, and it was confirmed.

$$\oint_C B \bullet ds \neq 0 \; \mu_0 \varepsilon_0 \frac{d}{dt} \int_S E \bullet dA$$



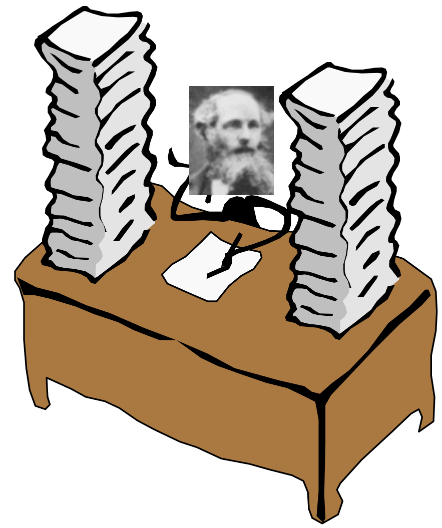
“Maxwell” equations:

$$\oint_S E \bullet dA = q/\varepsilon_0$$

$$\oint_S B \bullet dA = 0$$

$$\oint_C B \bullet ds = \mu_0 \varepsilon_0 \frac{d}{dt}\int_S E \bullet dA + \mu_0 i$$

$$\oint_C E \bullet ds = -\frac{d}{dt}\int_S B \bullet dA$$



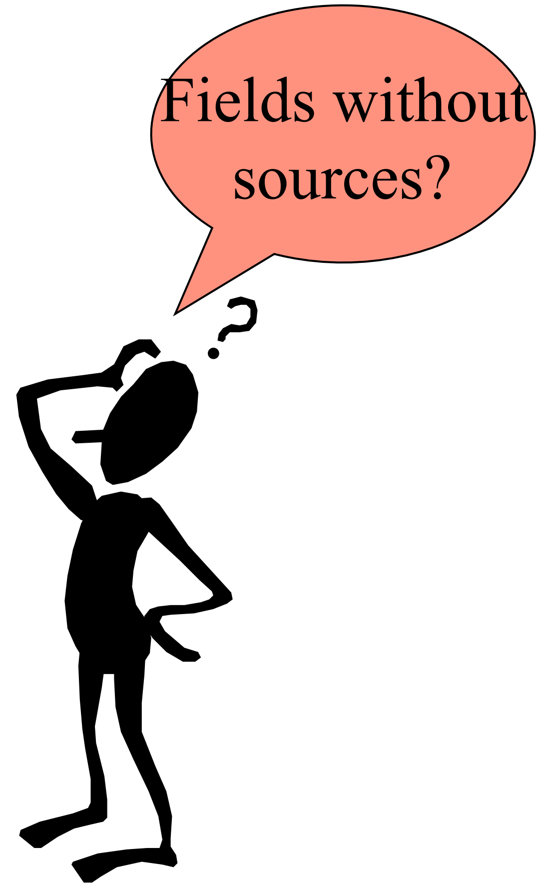
Maxwell equations in free space:

$$\oint_S E \bullet dA = 0$$

$$\oint_S B \bullet dA = 0$$

$$\oint_C B \bullet ds = \mu_0 \varepsilon_0 \frac{d}{dt} \int_S E \bullet dA$$

$$\oint_C E \bullet ds = -\frac{d}{dt} \int_S B \bullet dA$$



Maxwell, waves and light

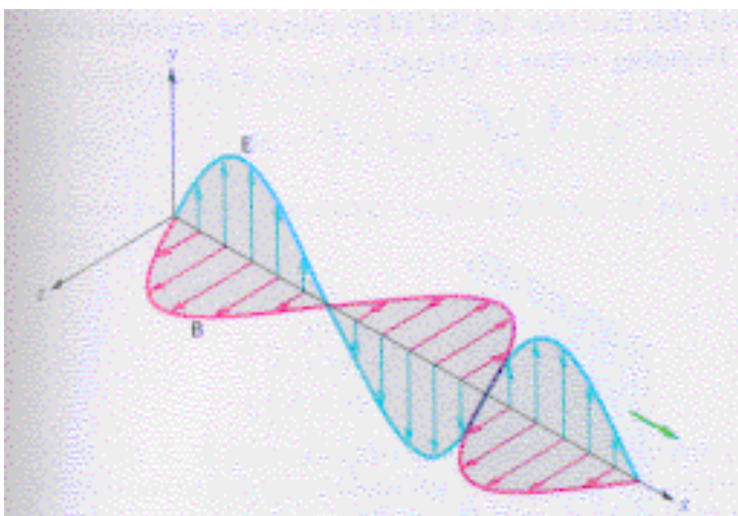
A solution to the Maxwell equations in free space is a "traveling wave"…

$\mu_0 = 1.256\ 10^{-6}$ Tm/A
$\varepsilon_0 = 8.854\ 10^{-12}\ C^2/Nm^2$
$[\mu_0\varepsilon_0] = (Tm/A)(C^2/Nm^2) = TsC/Nm$
$= (Ns/Cm)(sC/Nm)$
$= s^2/m^2$

$$\oint_C B \bullet ds = \mu_0 \varepsilon_0 \frac{d}{dt}\int_S E \bullet dA \qquad \oint_C E \bullet ds = -\frac{d}{dt}\int_S B \bullet dA$$

electric and magnetic "forces" can travel!

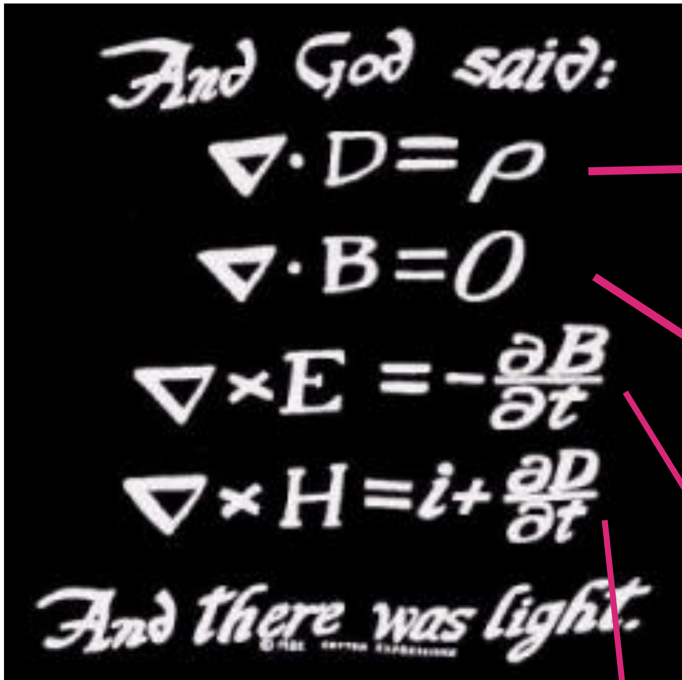
The velocity of the "Maxwell" waves is… $v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$ $= 3\ 10^8$ m/s

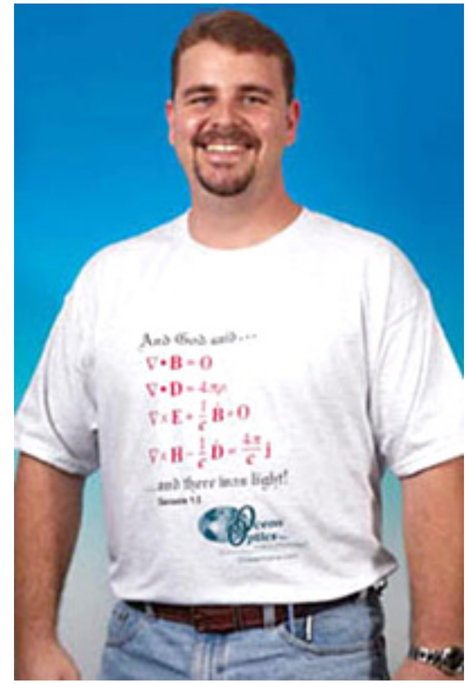


The "electric" waves travel at the speed of *light*!?

Light itself is a wave of electricity and magnetism!?

A physics t-shirt!





$$\oint_S E \bullet dA = q / \varepsilon_0$$

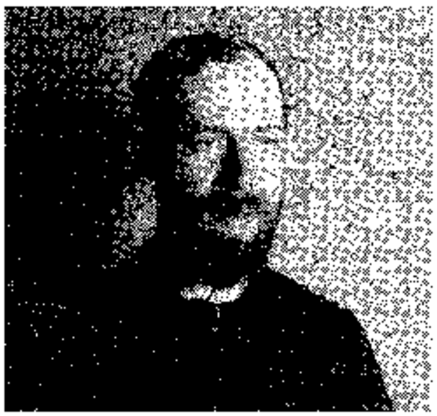
$$\oint_S B \bullet dA = 0$$

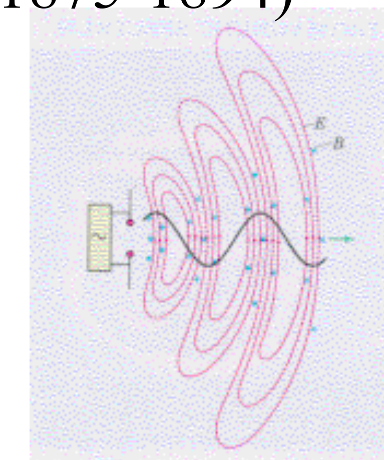
$$\oint_C E \bullet ds = -\frac{d}{dt}\int_S B \bullet dA$$

$$\oint_C B \bullet ds = \mu_0 \varepsilon_0 \frac{d}{dt}\int_S E \bullet dA + \mu_0 i$$

Electromagnetic waves

First person to prove that electromagnetic waves existed:
Heinrich Hertz (1875-1894)





First person to use electromagnetic waves for communications:
Guglielmo Marconi (1874-1937), 1909 Nobel Prize

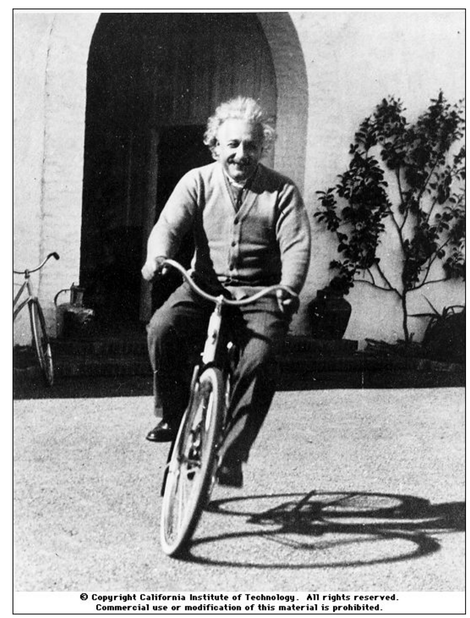
(first transatlantic commercial wireless service, Nova Scotia, 1909)

How do waves travel?

Is there an ether they ride on? Michelson and Morley looked and looked, and decided it wasn’t there. How do waves travel???

Electricity and magnetism are “relative”:
Whether charges move or not depends on which frame we use…

This was how Einstein began thinking about his “theory of special relativity”…



We’ll leave that theory for later…maybe.