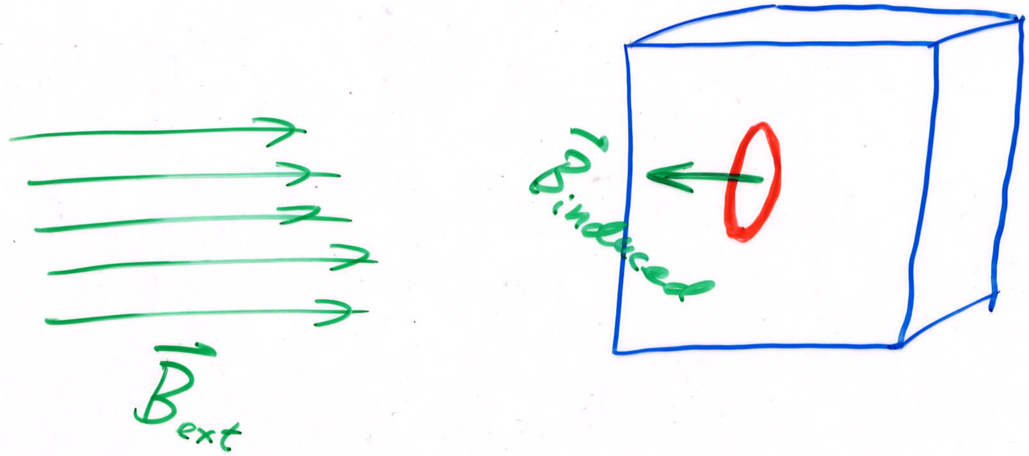
Diamagnetism

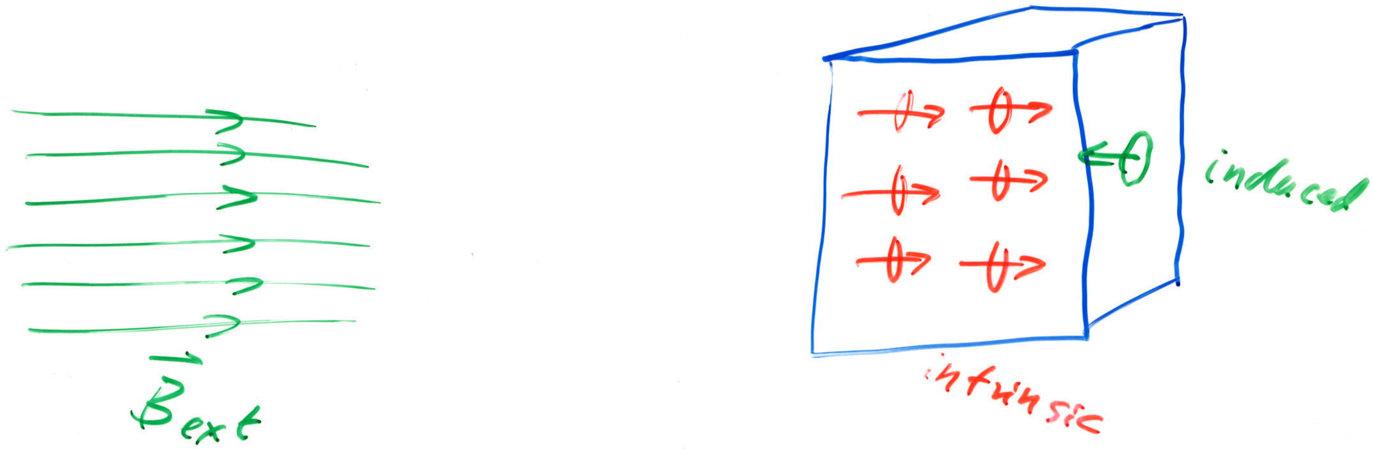
This is a consequence of Lenz's Law.



Magnetic dipoles are induced in the sample. This effect occurs in all substances to some extent. The result is a repulsion from the pole of a magnet.

Contrast this with the electrostatic case, where $\vec{E}_{ext}$ fields induce electric dipole moments in the sample and attract uncharged bits of paper and neutral metal objects.

Paramagnetism



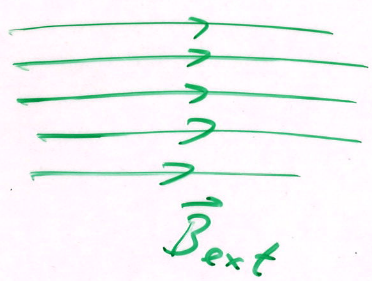
If the molecules of the sample already have an intrinsic magnetic dipole moment (not induced by the external $\vec{B}$ field), then those magnetic dipoles align with the external field and attraction results. This attraction is usually stronger than the diamagnetism repulsion.

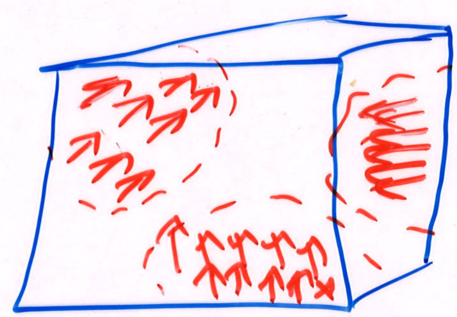
Heating the sample will randomize the dipoles and destroy the paramagnetism.

Ferromagnetism

This effect is like paramagnetism, but 10,000 → 100,000 times stronger.

In certain substances, the intrinsic magnetic dipole moments of the molecules are enormous and they tend to align with each other in "domains"





Again, heating will destroy the alignment and the ferromagnetism. The temperature at which all of the ferromagnetism disappears is called the "Curie temperature".

~1000 K

Ferromagnetic Elements

APPENDIX C

Periodic Table of the Elements*

Symbol — **Ca** 20 — Atomic number
Atomic mass † — 40.08
$4s^2$ — Electron configuration

Fe Co

Group I	Group II	Transition elements						
H 1 1.0080 $1s^1$								
Li 3 6.94 $2s^1$	**Be** 4 9.012 $2s^2$							
Na 11 22.99 $3s^1$	**Mg** 12 24.31 $3s^2$							
K 19 39.102 $4s^1$	**Ca** 20 40.08 $4s^2$	**Sc** 21 44.96 $3d^14s^2$	**Ti** 22 47.90 $3d^24s^2$	**V** 23 50.94 $3d^34s^2$	**Cr** 24 51.996 $3d^54s^1$	**Mn** 25 54.94 $3d^54s^2$	**Fe** 26 55.85 $3d^64s^2$	**Co** 27 58.93 $3d^74s^2$
Rb 37 85.47 $5s^1$	**Sr** 38 87.62 $5s^2$	**Y** 39 88.906 $4d^15s^2$	**Zr** 40 91.22 $4d^25s^2$	**Nb** 41 92.91 $4d^45s^1$	**Mo** 42 95.94 $4d^55s^1$	**Tc** 43 (99) $4d^55s^2$	**Ru** 44 101.1 $4d^75s^1$	**Rh** 45 102.91 $4d^85s^1$
Cs 55 132.91 $6s^1$	**Ba** 56 137.34 $6s^2$	57-71*	**Hf** 72 178.49 $5d^26s^2$	**Ta** 73 180.95 $5d^36s^2$	**W** 74 183.85 $5d^46s^2$	**Re** 75 186.2 $5d^56s^2$	**Os** 76 190.2 $5d^66s^2$	**Ir** 77 192.2 $5d^76s^2$
Fr 87 (223) $7s^1$	**Ra** 88 (226) $7s^2$	89-103**	**Unq** 104 (261) $6d^27s^2$	**Unp** 105 (262) $6d^37s^2$	**Unh** 106 (263)	**Uns** 107 (262)	**Uno** 108 (265)	**Une** 109 (266)

*Lanthanide series	**La** 57 138.91 $5d^16s^2$	**Ce** 58 140.12 $5d^14f^16s^2$	**Pr** 59 140.91 $4f^36s^2$	**Nd** 60 144.24 $4f^46s^2$	**Pm** 61 (147) $4f^56s^2$	**Sm** 62 150.4 $4f^66s^2$
**Actinide series	**Ac** 89 (227) $6d^17s^2$	**Th** 90 (232) $6d^27s^2$	**Pa** 91 (231) $5f^26d^17s^2$	**U** 92 (238) $5f^36d^17s^2$	**Np** 93 (239) $5f^46d^17s^2$	**Pu** 94 (239) $5f^66d^07s^2$

* Atomic mass values given are averaged over isotopes in the percentages in which they exist in nature.
† For an unstable element, mass number of the most stable known isotope is given in parentheses.

Ni

			Group III	Group IV	Group V	Group VI	Group VII	Group 0
							H 1 1.0080 $1s^1$	**He** 2 4.0026 $1s^2$
			B 5 10.81 $2p^1$	**C** 6 12.011 $2p^2$	**N** 7 14.007 $2p^3$	**O** 8 15.999 $2p^4$	**F** 9 18.998 $2p^5$	**Ne** 10 20.18 $2p^6$
			Al 13 26.98 $3p^1$	**Si** 14 28.09 $3p^2$	**P** 15 30.97 $3p^3$	**S** 16 32.06 $3p^4$	**Cl** 17 35.453 $3p^5$	**Ar** 18 39.948 $3p^6$
Ni 28 58.71 $3d^84s^2$	**Cu** 29 63.54 $3d^{10}4s^2$	**Zn** 30 65.37 $3d^{10}4s^2$	**Ga** 31 69.72 $4p^1$	**Ge** 32 72.59 $4p^2$	**As** 33 74.92 $4p^3$	**Se** 34 78.96 $4p^4$	**Br** 35 79.91 $4p^5$	**Kr** 36 83.80 $4p^6$
Pd 46 106.4 $4d^{10}$	**Ag** 47 107.87 $4d^{10}5s^1$	**Cd** 48 112.40 $4d^{10}5s^2$	**In** 49 114.82 $5p^1$	**Sn** 50 118.69 $5p^2$	**Sb** 51 121.75 $5p^3$	**Te** 52 127.60 $5p^4$	**I** 53 126.90 $5p^5$	**Xe** 54 131.30 $5p^6$
Pt 78 195.09 $5d^96s^1$	**Au** 79 196.97 $5d^{10}6s^1$	**Hg** 80 200.59 $5d^{10}6s^2$	**Tl** 81 204.37 $6p^1$	**Pb** 82 207.2 $6p^2$	**Bi** 83 208.98 $6p^3$	**Po** 84 (210) $6p^4$	**At** 85 (218) $6p^5$	**Rn** 86 (222) $6p^6$

Eu 63 152.0 $4f^76s^2$	**Gd** 64 157.25 $5d^14f^76s^2$	**Tb** 65 158.92 $5d^14f^86s^2$	**Dy** 66 162.50 $4f^{10}6s^2$	**Ho** 67 164.93 $4f^{11}6s^2$	**Er** 68 167.26 $4f^{12}6s^2$	**Tm** 69 168.93 $4f^{13}6s^2$	**Yb** 70 173.04 $4f^{14}6s^2$	**Lu** 71 174.97 $5d^14f^{14}6s^2$
Am 95 (243) $5f^76d^07s^2$	**Cm** 96 (245) $5f^76d^17s^2$	**Bk** 97 (247) $5f^86d^17s^2$	**Cf** 98 (249) $5f^{10}6d^07s^2$	**Es** 99 (254) $5f^{11}6d^07s^2$	**Fm** 100 (253) $5f^{12}6d^07s^2$	**Md** 101 (255) $5f^{13}6d^07s^2$	**No** 102 (255) $6d^07s^2$	**Lr** 103 (257) $6d^17s^2$

James Clerk Maxwell, *1831–18*79
Scottish physicist. He was professor
King's College, London, and later

Maxwell's Equations

(so far)

$$\oiint_S \vec{E}\cdot d\vec{A} = \frac{q_e^{\text{enclosed by } S}}{\varepsilon_0}$$

$$\oiint_S \vec{B}\cdot d\vec{A} = 0$$

Gauss' Laws

$$\oint_C \vec{E}\cdot d\vec{\ell} = -\frac{d}{dt}\Phi_B = -\frac{d}{dt}\iint_S \vec{B}\cdot d\vec{A}$$

Faraday's Law of Induction

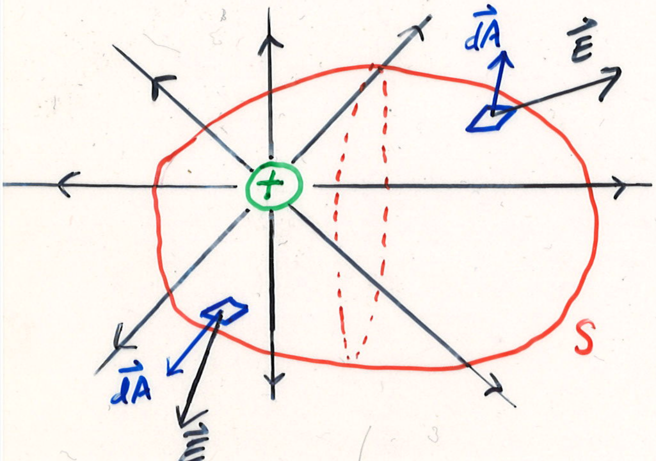
$$\oint_C \vec{B}\cdot d\vec{\ell} = \mu_0 \, i_{enc}^{\text{enclosed by } C}$$

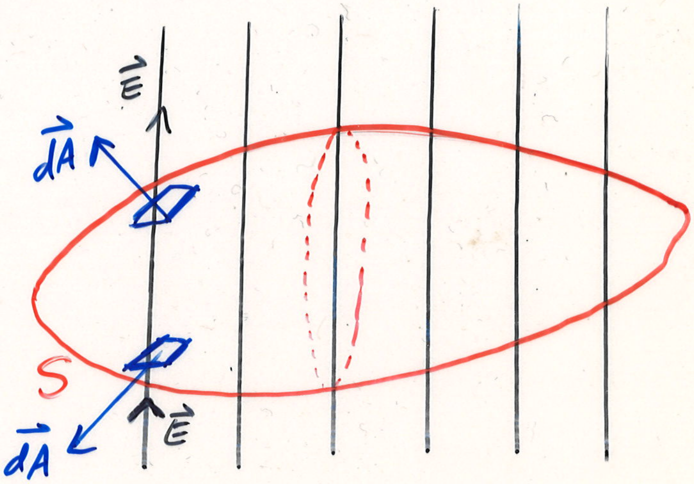
Ampere's Law

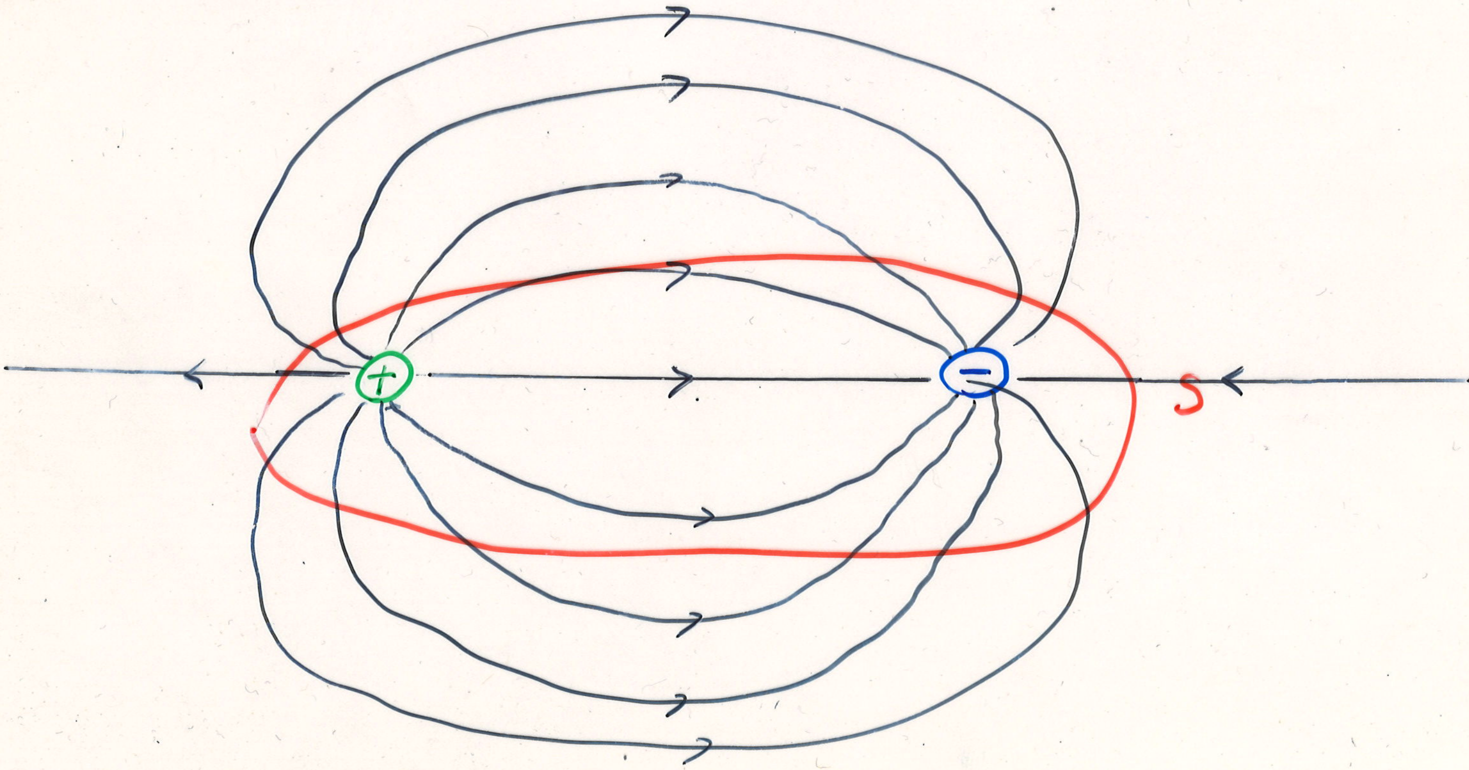
Why are these called Maxwell's equations?

Meaning of Gauss' Laws

$$\oint\!\!\!\oint_S \vec{E}\cdot d\vec{A} = \frac{q_e}{\epsilon_0}$$





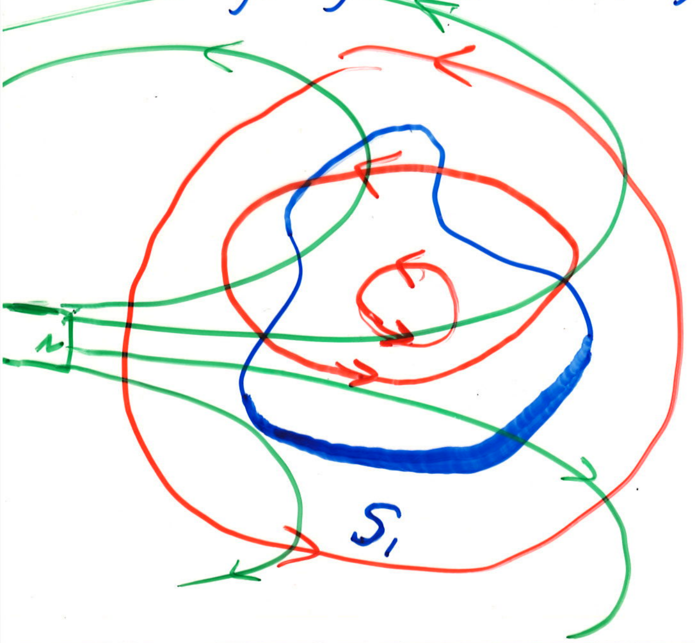


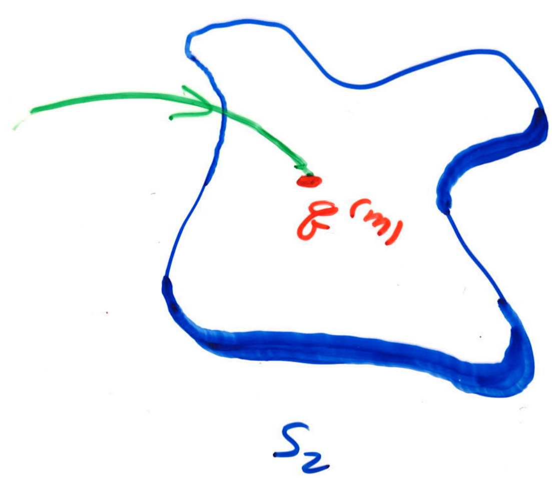
Gauss' Law

for Magnetism

$$\oint\!\!\!\oint_S \vec{B}\cdot d\vec{A} = 0$$

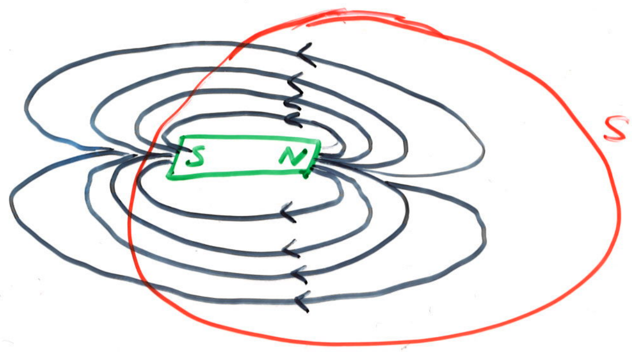
The **net** number of magnetic field lines going out through a **closed** surface is zero.





An Apparent Asymmetry

$$\oint\!\!\!\oint_S \vec{B} \cdot d\vec{A} = 0$$



There is no magnetic charge —

no "magnetic monopoles."

You can't isolate a north pole. 

$$\oint\!\!\!\oint_S \vec{B} \cdot d\vec{A} = \mu_0 \, q_m^{\text{enclosed by } S}$$

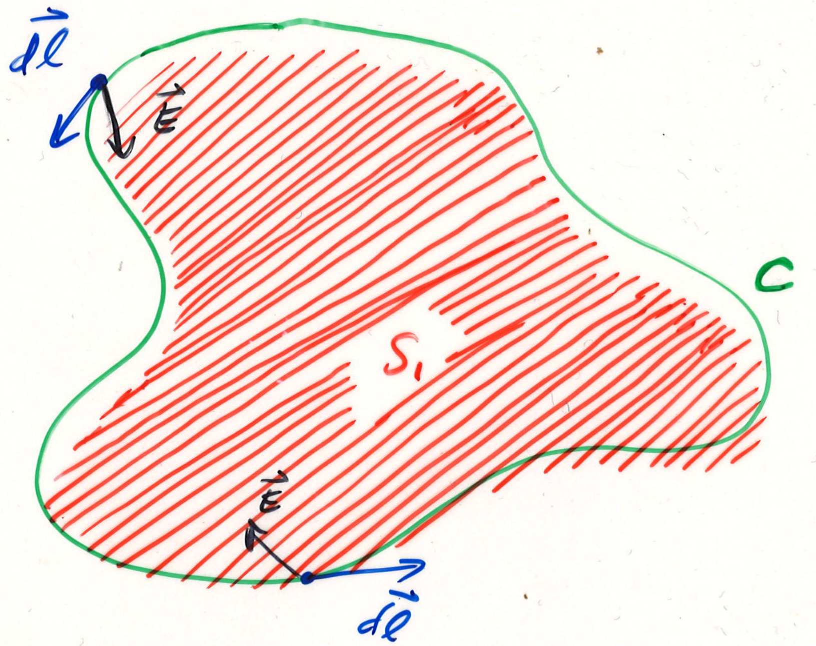
$q_m = 0$ is Nature's choice

Meaning of Faraday's Law

$$\oint_C \vec{E}\cdot d\vec{l} = -\frac{d}{dt}\Phi_B$$

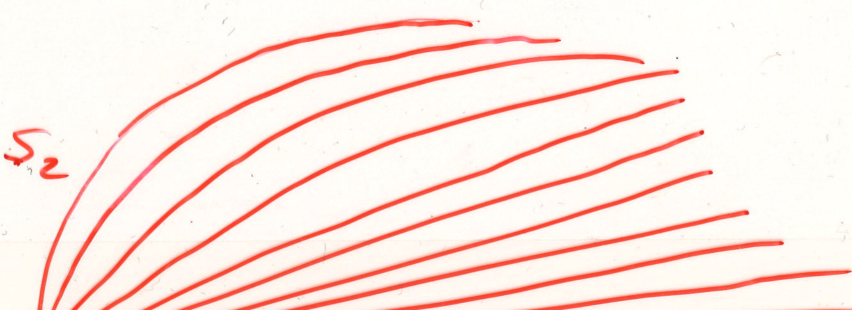
$$= -\frac{d}{dt}\iint_S \vec{B}\cdot d\vec{A}$$ ← Isn't this = 0?

← open



A changing magnetic ~~field~~ flux gives rise to an electric field on the curve C.

S is an open surface bounded by the closed curve C



Meaning of Faraday's Law

S_1

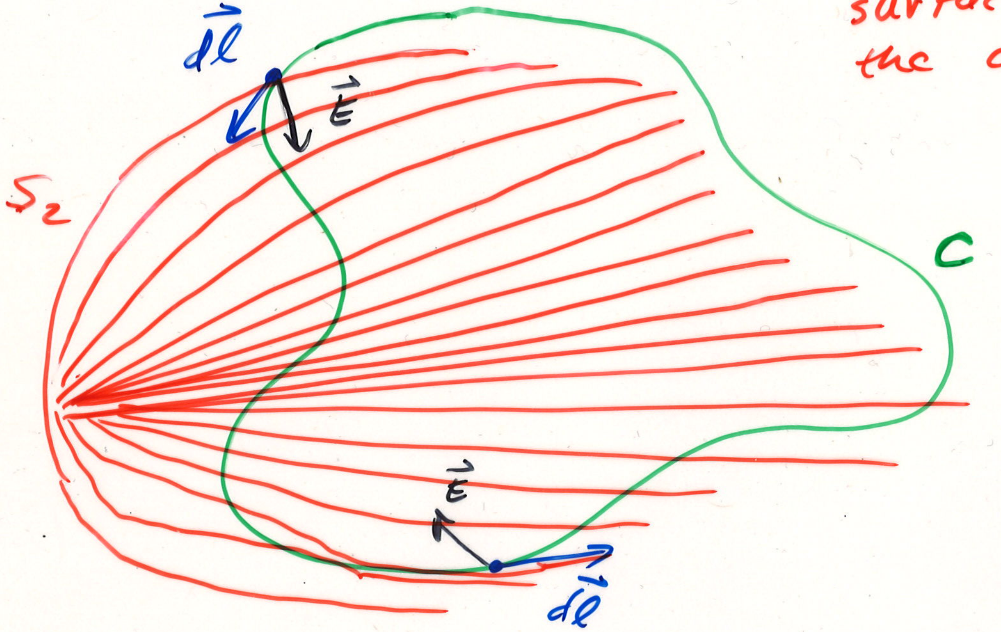
$$\oint_C \vec{E}\cdot d\vec{\ell} = -\frac{d}{dt}\Phi_B$$

$$= -\frac{d}{dt}\iint_S \vec{B}\cdot d\vec{A}$$

← Isn't this = 0?

← open

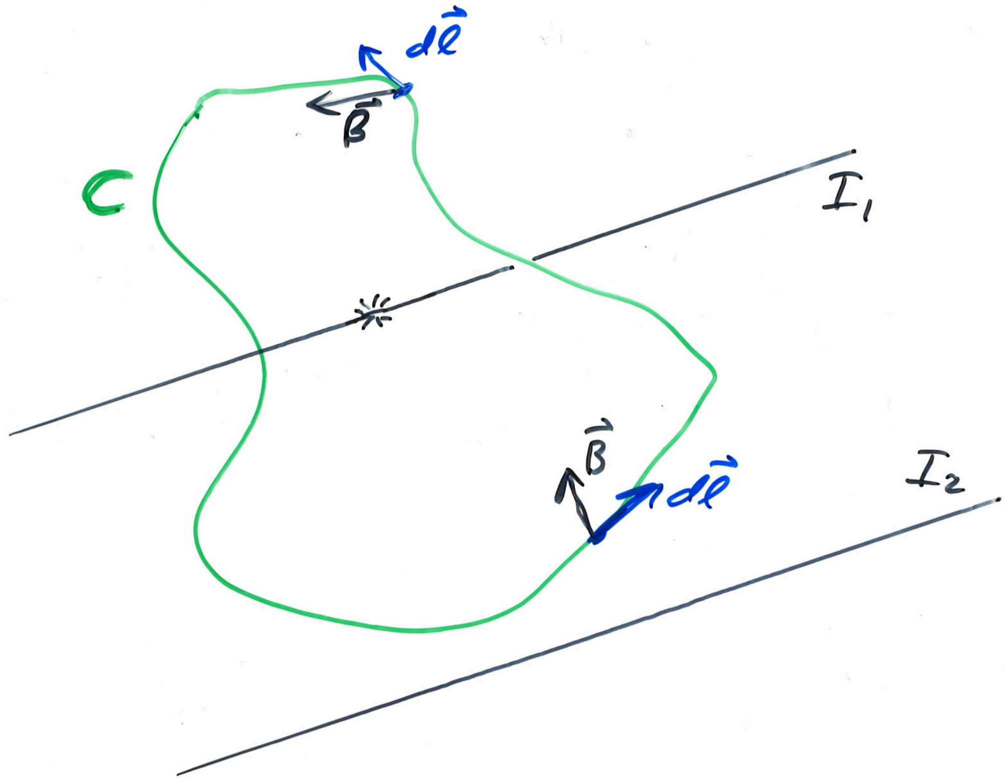
S is any open surface bounded by the closed curve C



A changing magnetic ~~field~~ flux gives rise to an electric field on the curve C.

Meaning of Ampere's Law

$$\oint_C \vec{B}\cdot d\vec{\ell} = \mu_0 I_e \text{ enclosed by C}$$



Another Apparent Asymmetry

$$\oint_C \vec{B} \cdot d\vec{l} = \mu_0 I_e$$

$$\oint_C \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \Phi_B + \frac{I_m}{\epsilon_0}$$

Since there are no magnetic charges, they cannot be put in motion to create "magnetic currents"

$$I_m = \frac{dq_m}{dt} = 0$$

again, this is Nature's choice

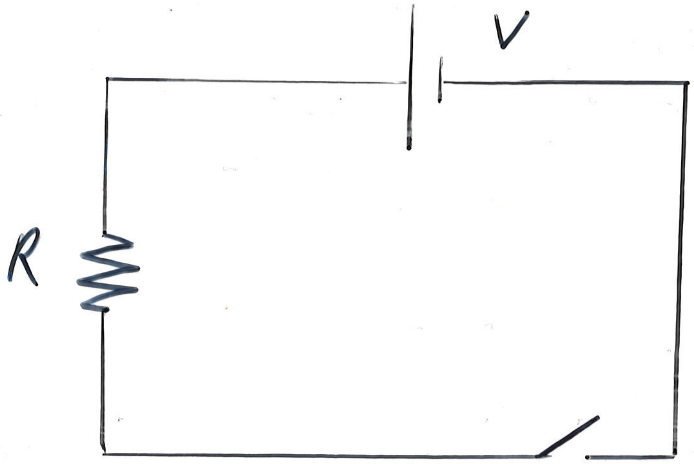
A real asymmetry

$$\oint_C \vec{E}\cdot d\vec{l} = -\frac{d}{dt}\Phi_B + \cancelto{0}{\frac{I_m}{\epsilon_0}}$$

$$\oint_C \vec{B}\cdot d\vec{l} = ??? + \mu_0 I_e$$

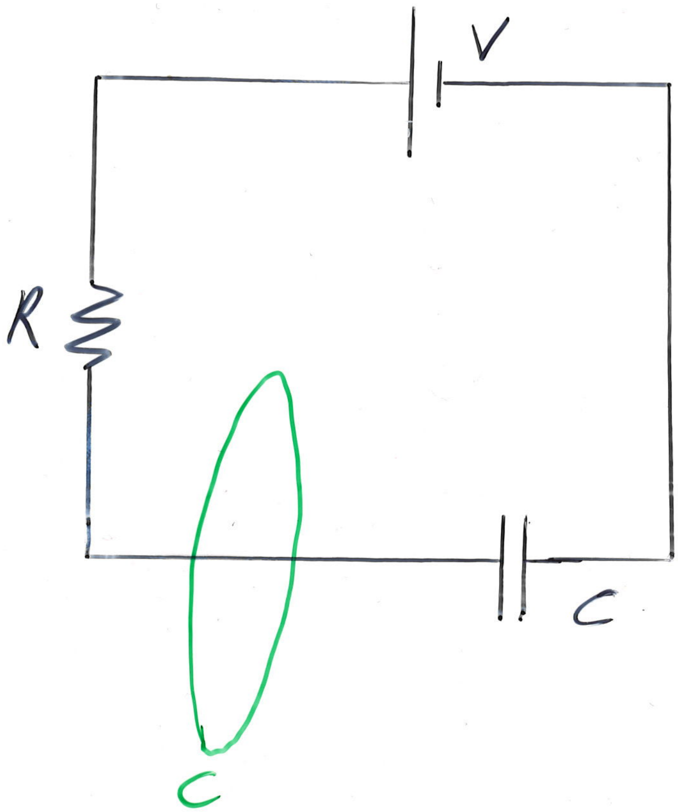
If a changing $\vec{B}$ field creates an $\vec{E}$ field (Faraday), then shouldn't a changing $\vec{E}$ field create a $\vec{B}$ field?

Enter James Clerk Maxwell ...

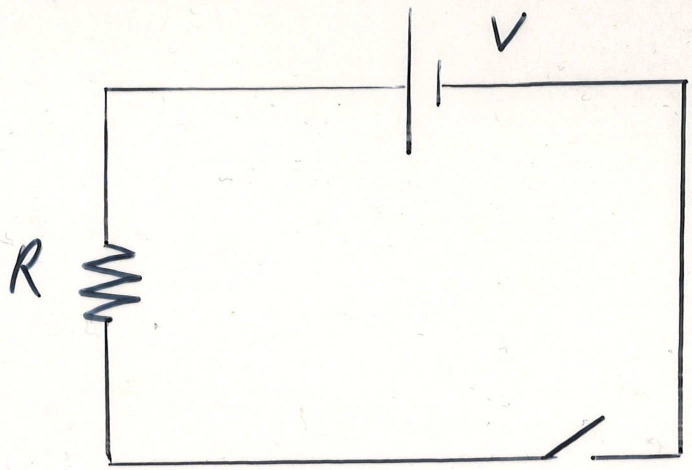


open circuit

limiting resistor

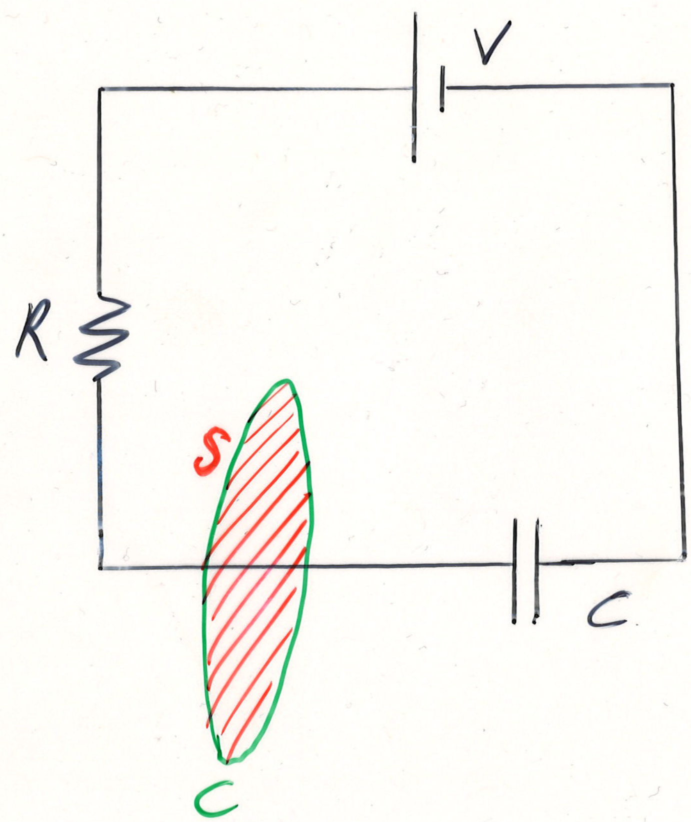


$$\oint_C \vec{B} \cdot d\vec{l} =$$

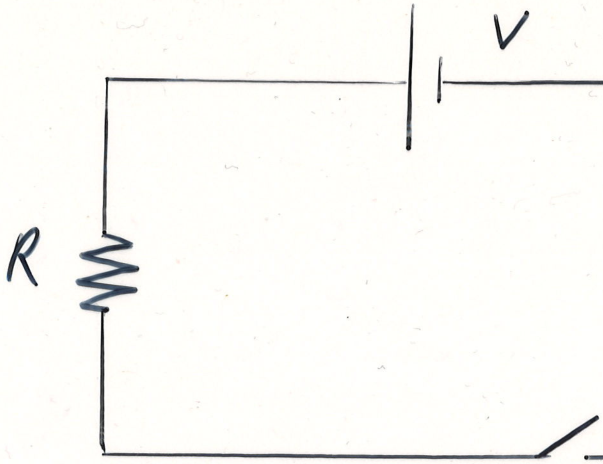


open circuit

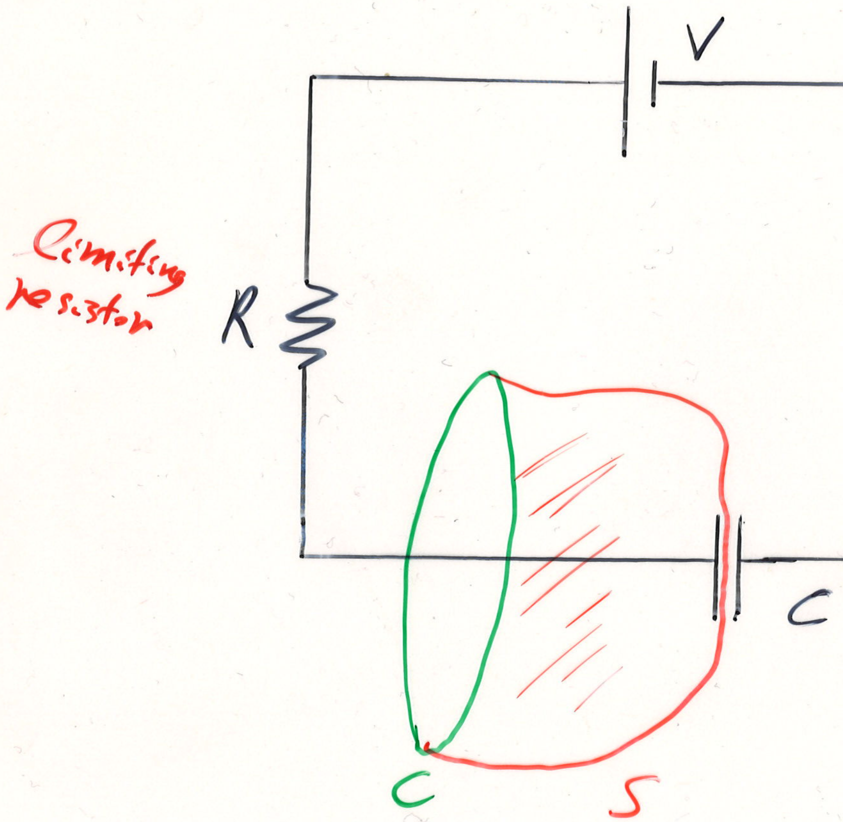
limiting resistor



$$\oint_C \vec{B}\cdot d\vec{\ell} = \mu_0 I$$



open circuit

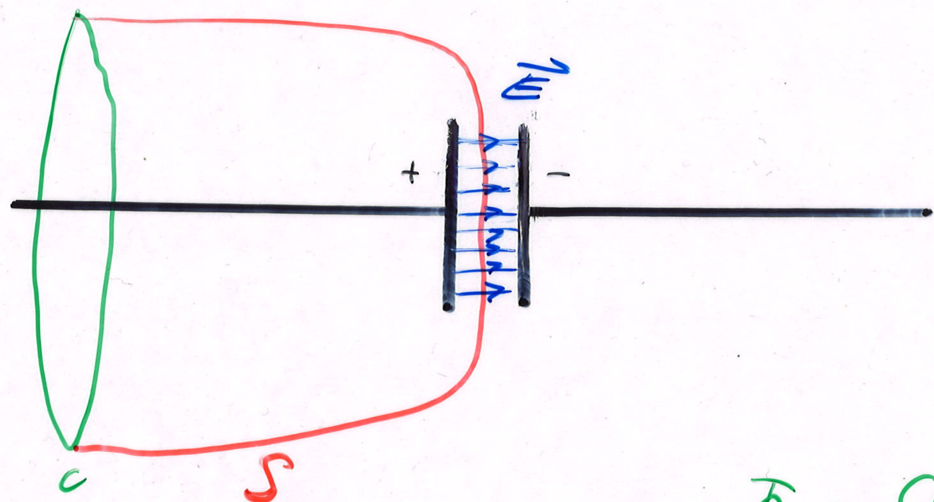


$$\oint_C \vec{B}\cdot d\vec{\ell} = 0$$

What if we include the term demanded by symmetry?

electric flux

$$\oint_C \vec{B}\cdot d\vec{\ell} = \mu_0 I_e + \mu_0\left(\epsilon_0 \frac{d}{dt}\Phi_e\right)$$



$$\Phi_e = \iint_S \vec{E}\cdot d\vec{A}$$

For a capacitor,

$$|\vec{E}| = \frac{Q}{\epsilon_0 A} \qquad \Phi_e = |\vec{E}|A = \frac{Q}{\epsilon_0}$$

$$\mu_0\left(\epsilon_0 \frac{d}{dt}\Phi_e\right) = \mu_0 \frac{dQ}{dt} = \mu_0 I$$

$$\left(\epsilon_0 \frac{d}{dt} \Phi_e\right)$$

is called the "displacement current,"

but it is not a real current.

Ampere-Maxwell Law

$$\oint_C \vec{B} \cdot d\vec{\ell} = \mu_0 \left[I_e + \epsilon_0 \frac{d}{dt} \Phi_e \right]$$

A changing electric ~~field~~ flux creates a magnetic field.

Maxwell's Equations

(complete set)

$$\oint\!\!\!\oint_S \vec{E}\cdot d\vec{A} = \frac{q}{\epsilon_0}$$

$$\oint\!\!\!\oint_S \vec{B}\cdot d\vec{A} = 0 + \mu_0 q_m$$

$$\oint_C \vec{E}\cdot d\vec{\ell} = -\frac{d}{dt}\Phi_B + \frac{I_m}{\epsilon_0}$$

$$\oint_C \vec{B}\cdot d\vec{\ell} = \mu_0\epsilon_0 \frac{d}{dt}\Phi_e + \mu_0 I$$

A changing $\vec{B}$ field creates a changing $\vec{E}$ field,
which creates a changing $\vec{B}$ field,
which creates a changing $\vec{E}$ field,
which ...

This is an electro-magnetic <u>wave</u>.

Speed?

Maxwell's Equations

(complete set)

$$\oiint_S \vec{E}\cdot d\vec{A} = \frac{q}{\epsilon_0}$$

$$\oiint_S \vec{B}\cdot d\vec{A} = 0$$

$$\oint_C \vec{E}\cdot d\vec{l} = -\frac{d}{dt}\Phi_B$$

$$\oint_C \vec{B}\cdot d\vec{l} = \mu_0\epsilon_0 \frac{d}{dt}\Phi_e + \mu_0 I$$

A changing $\vec{B}$ field creates a changing $\vec{E}$ field,
which creates a changing $\vec{B}$ field,
which creates a changing $\vec{E}$ field,
which ...

This is an electro-magnetic wave.

Speed?

Permittivity of free space:

$$\epsilon_0 = 8.85 \times 10^{-12}\ F/m \quad \left(\frac{C}{V m}\right)$$

Permeability of free space:

$$\mu_0 = 1.26 \times 10^{-6}\ H/m \quad \left(\frac{V \cdot s^2}{C\, m}\right)$$

$$\frac{1}{\epsilon_0 \mu_0} = 9 \times 10^{16}\ \frac{m^2}{s^2}$$

$$\sqrt{\frac{1}{\epsilon_0 \mu_0}} = 3 \times 10^{8}\ \frac{m}{s} = c$$

the speed of light!

Maxwell's equations have Special Relativity "built in." They do <u>not</u> need to be modified.