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The Beauty of Electromagnetism

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Outline

What is electricity?

Charge

- Some particles have *charge*, symbolized by q
  - Protons: $q = +e$
  - Electrons: $q = -e$
- Opposite charges attract, like charges repel

Coulomb's Law

- The force between charges is given by an inverse square law:

$$F = -k\frac{q_1 q_2}{r^2}$$

- Look familiar?

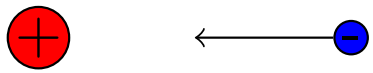
Electricity vs. Gravity

- The Saturn V rocket has more than enough thrust to escape the gravity of the entire Earth
- What if you remove the electrons from its nose?

Figure: The Saturn V rocket

Electrical Orbits

- Electricity acts like a stronger version of gravity
- Charged particles can orbit each other



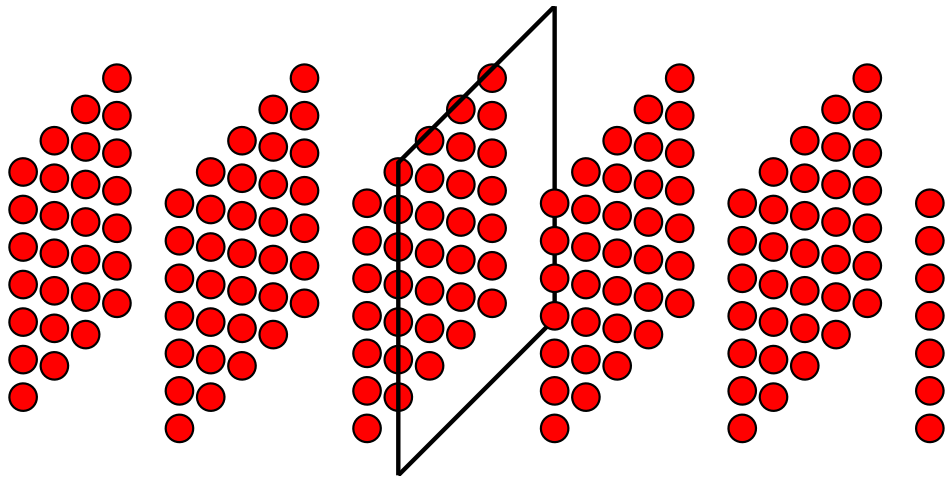
Lightning

- Electricity usually can't travel through air, so we use wires
- Thunderclouds can build up enough charge to split the electrical orbits in the atoms of air and force the particles to carry electricity

Current

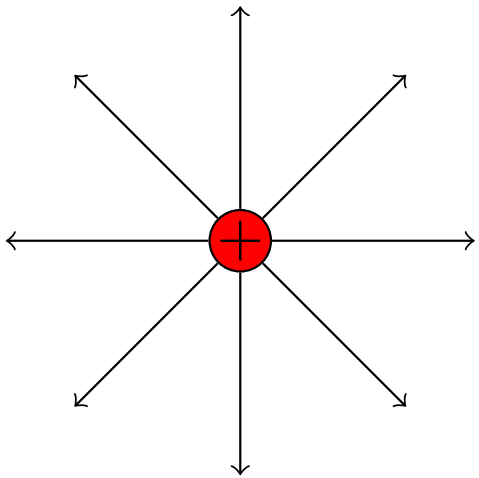
- Moving charges create currents

  $\boldsymbol{j}$ = amount of charge passing through unit of area per unit time

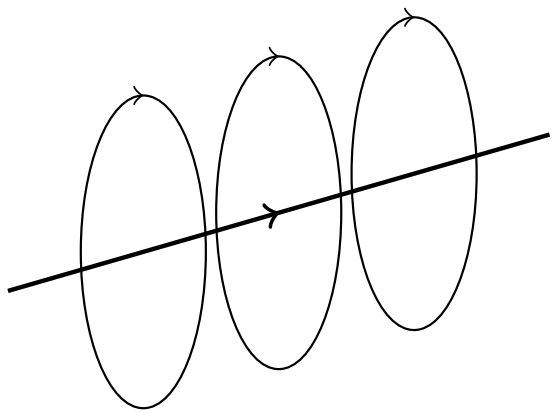


Fields

- Charges create rotation-free electric fields with a source
- $F = qE$

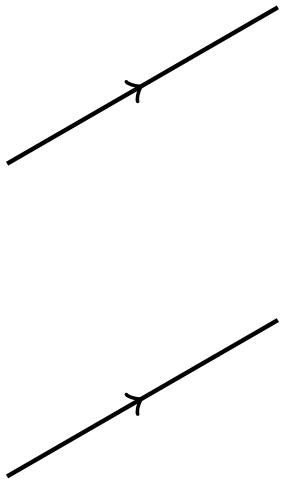


- Currents create source-free magnetic fields with rotation
- $F = qv \times B$



Force between Wires

- Do magnetic forces between parallel wires attract or repel?



Magnetic Orbits

- A particle in a magnetic field orbits the field itself, in a circle or a helix
- Rapidly rotating charged particles emit *synchrotron radiation*

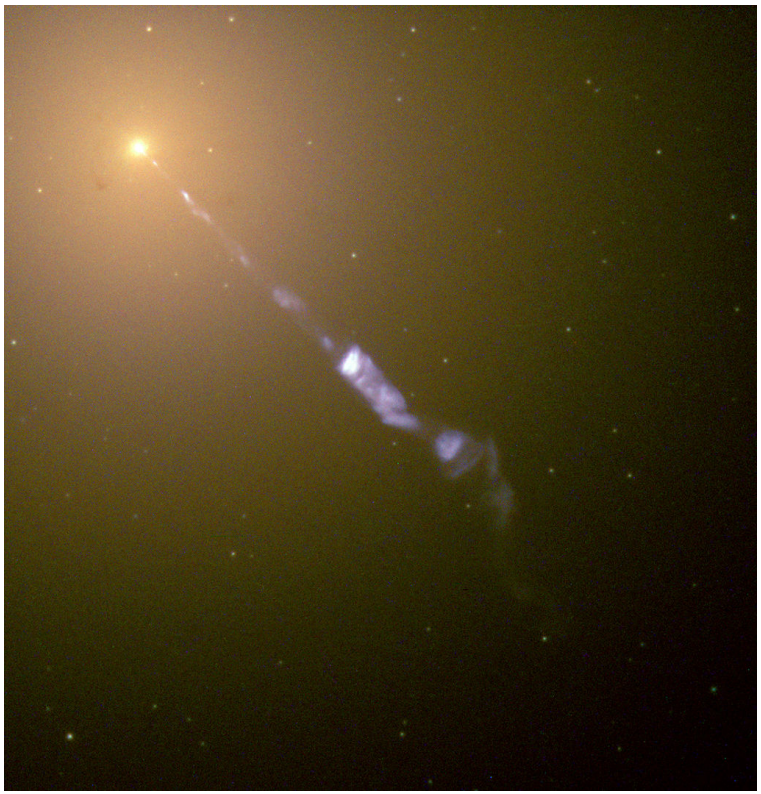


Figure: A Hubble image of a jet from elliptical galaxy M87.

Magnetic Orbits

- Another application: tabletop particle accelerators
- Cyclotrons combine magnetic and electric forces to bring charged particles to high speeds

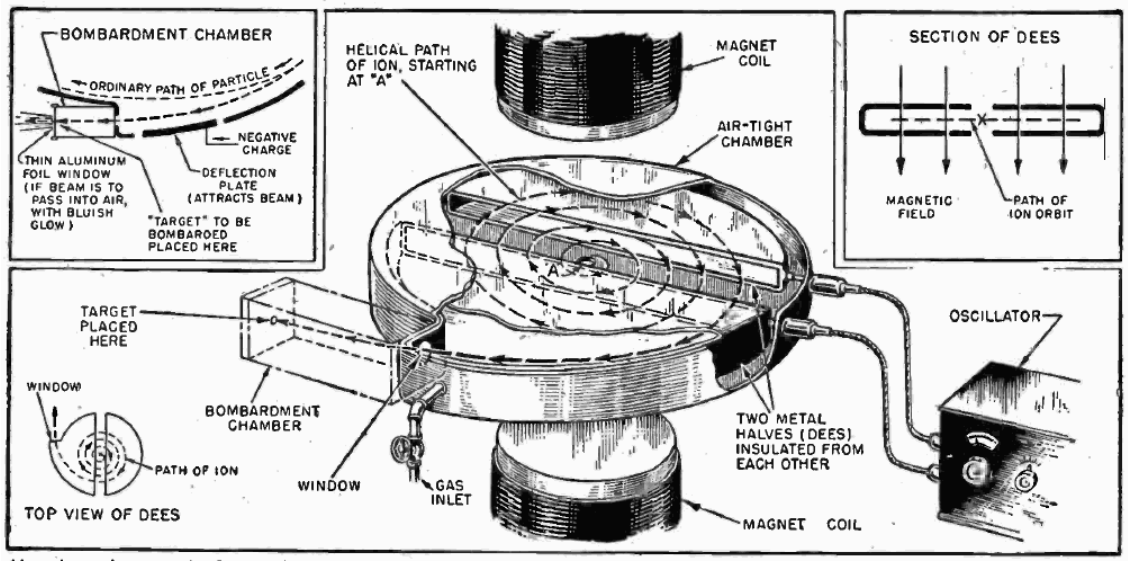


Figure: A diagram showing the operation of the cyclotron, the state-of-the-art until 1950.

The Missing Monopole

- Magnets always exist in dipoles; splitting a dipole magnet creates two new dipoles
- February 14, 1982: Blas Cabrera observes monopole event

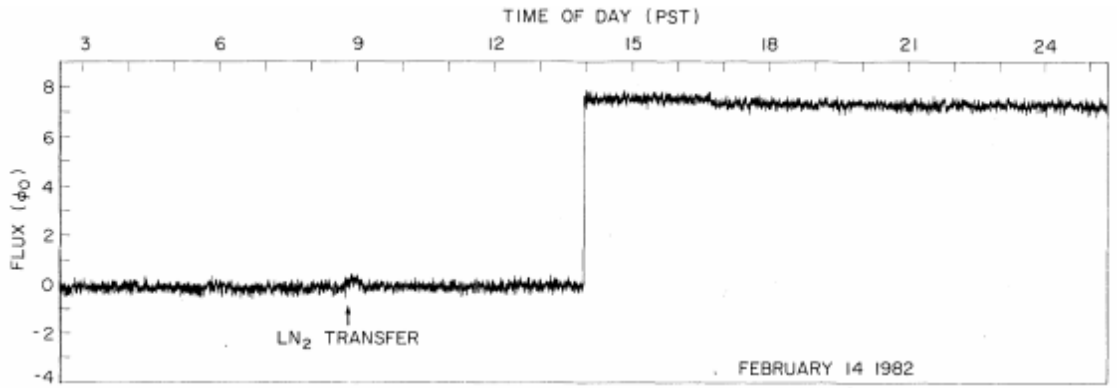
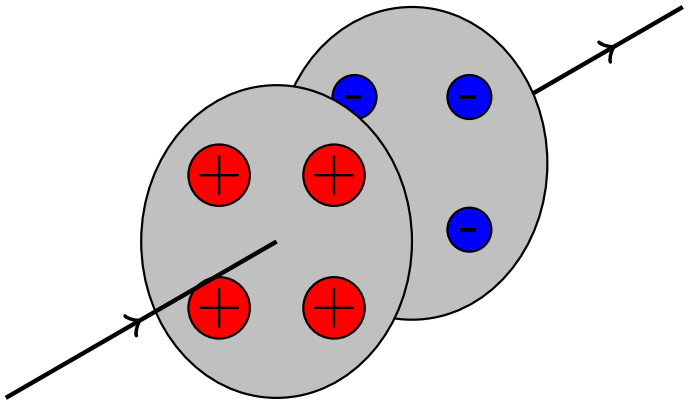


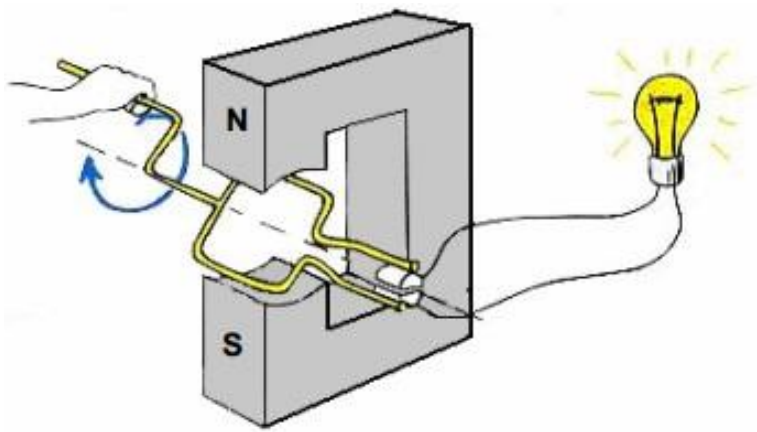
Figure: A detector readout showing the perfect signature of a magnetic monopole.

Electromagnetic Induction

- A changing electric field induces a magnetic field



- A changing magnetic field induces an electric field



Self-Propagating Fields

- These effects combined allow electric and magnetic fields to support one another, even in the absence of charges and currents
- Working through the math shows that electric and magnetic fields in a vacuum obey the *wave equation*

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

- The speed of a wave is given by $\frac{1}{\sqrt{\epsilon_0 \mu_0}}$

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- The value of $\frac{1}{\sqrt{\epsilon_0 \mu_0}}$ is $2.998 \times 10^8\,\mathrm{m/s}$

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- This was known, even over 100 years ago, to be the speed of light
- "From a long view of the history of mankind, seen from, say, ten thousand years from now, there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics. The American Civil War will pale into provincial insignificance in comparison with this important scientific event of the same decade." – Richard P. Feynman

Index of Refraction

- Inside materials, Maxwell's equations take a more complicated form
- In the simplest case, light moves at a speed $\frac{c}{n}$
  - Water: $n = 1.33$
  - Glass: $n = 1.5$

Fermat's Principle

- Light takes a path of least time from point A to point B
- If a material forces light to slow down, it will bend in order to take the shortest path

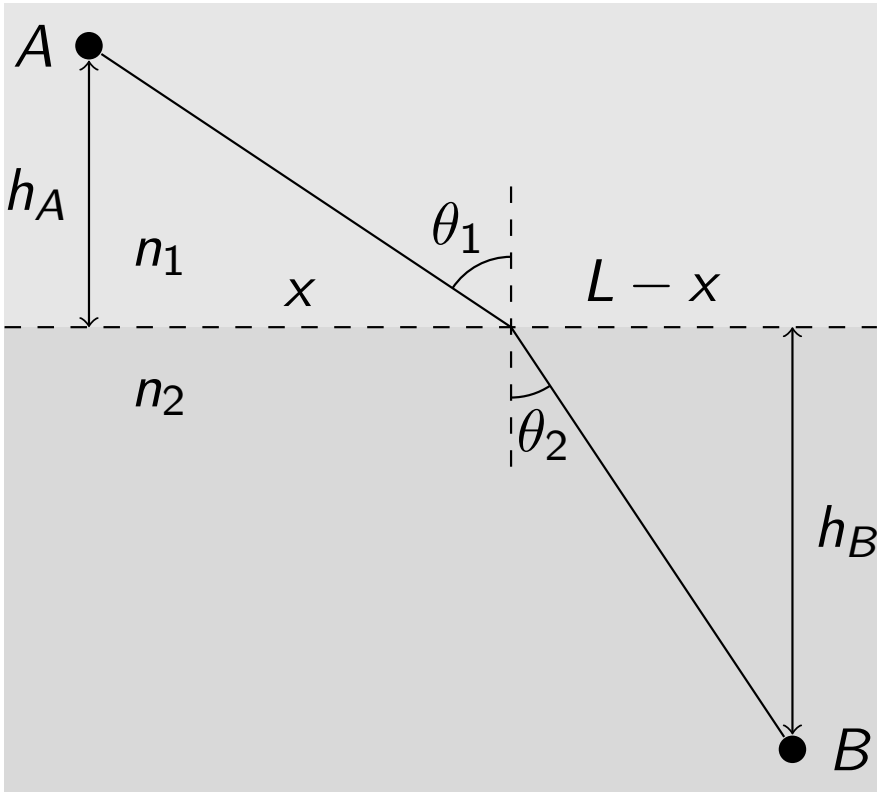
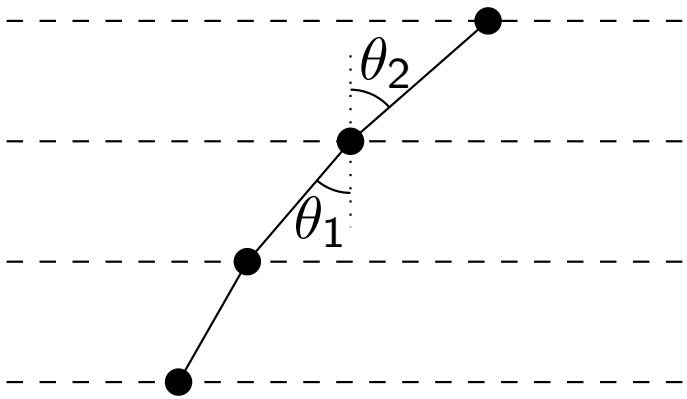


Image credit: Balasubramanian & Dempsey, Mechanics: An Extended Introduction (2016)

Turning Light Around

- If the index of refraction in a material varies, light can smoothly bend all the way around



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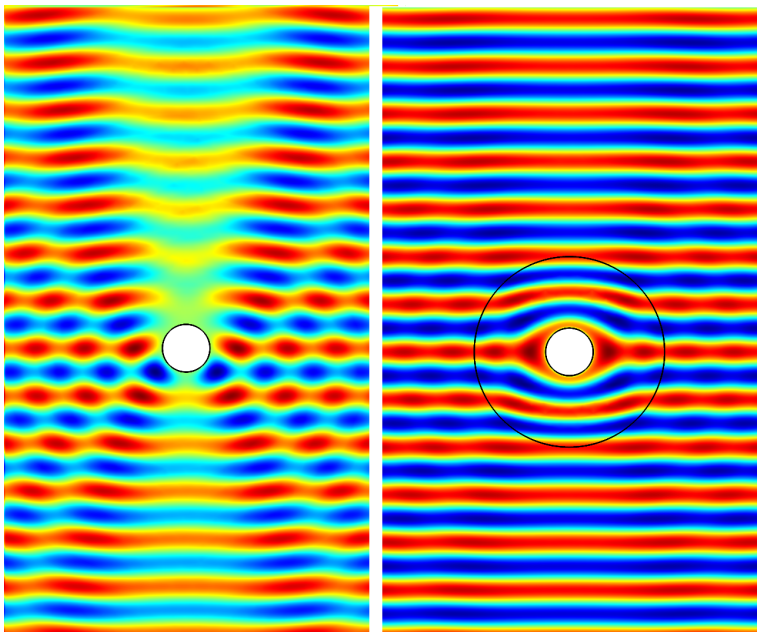
Metamaterial Cloaking

- Carefully designed materials may be able to bend light around objects inside them



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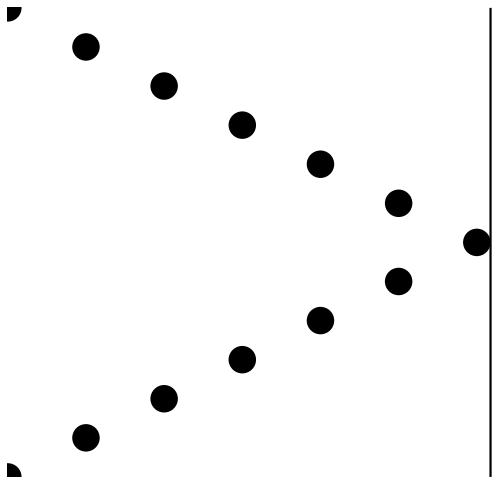
Particles of Light

- Light is made of *photons*, which are massless but carry momentum
- Force = rate of change of momentum



Solar Sailing

Microwave Plasma