From Last Time...

- Electromagnetic waves
- Charges, current and forces: Coulomb’s law.
- Accelerating charges produce an electromagnetic wave
- The idea of the electric field.

Today...

Electric fields, magnetic fields, and their unification

Eventually transatlantic signals!

Gulgielmo Marconi’s transatlantic transmitter

Electromagnetic Waves

- A Transverse wave.
- Electric and magnetic fields are perpendicular to propagation direction
- Can travel in empty space

\[ f = \frac{v}{\lambda}, \quad v = c = 3 \times 10^8 \text{ m/s} \ (186,000 \text{ miles/second!}) \]

The idea of electric fields

- EM wave made up of oscillating electric and magnetic fields.
- But what is an electric field?
- Electric field is a way to describe the force on a charged particle due to other charges around it.
- Force = charge \( \times \) electric field
- The direction of the force is the direction of the electric field.

Question

- Direction of force between two particles of the same charge (use next slide).

The electric field

\[ F = k \frac{Q_1 Q_2}{r^2} \]

...due to this charge
**Visualizing the electric field**

- Faraday invented the idea of field lines following the force to visualize the electric field.

> Local electric field is same direction as field lines.  
> Force is parallel or antiparallel to field lines.  
> Charged particle will move along these field lines.  
> Field lines emanate from positive charge and terminate on negative charge.

**Why bother?**

- Why invent fields - why not just use forces?
- Think of the EM wave. A spark is an accelerating current flow, producing the wave.
- The wave continues to propagate even when the spark is gone.
- No charges anywhere, but time-varying fields propagate as a wave.

**Electric field: summary**

- Presence of electric field means that there will be a force on a charged particle.  
- This force (and electric field) can arise from electric charges (via Coulomb’s law).  
- Is a way to determine forces on a charged particle without thinking about the charges that give rise to the forces.

**But wait... there’s more**

- Energy can be stored in the field.  
- Energy density proportional to \((\text{Electric field})^2\) \((\text{Magnetic field})^2\)  
- Electromagnetic forces aren’t felt instantaneously, the propagate at speed of electromagnetic wave (speed of light)  
- Object transfers momentum to the field, which later transfers it to another object.

**Magnetic forces**

- Clearly magnets interact with each other  
- Sometimes attracting, sometimes repelling  
- But the magnetic particles are sort of a ‘composite’ positive and negative ‘magnetic charge’.  
- Visualized as a bar with positive pole (North) at one end and negative pole (South) at other.  
- These ‘magnetic charges’ cannot be broken apart — always appear in N-S pairs.

**Magnetism: Permanent magnets**

- North Pole and South Pole  
- This is the elementary magnetic particle  
- Called magnetic dipole (North pole and South pole)  
- Poles interact with each other similar to charges.
Magnetic field

- Similar in spirit to electric field
- Used to determine the ‘orientational’ force on a magnetic dipole:
  - Magnetic field exerts a force on a dipole that aligns it with magnetic field lines.
  - Uniform magnetic field only rotates dipole: doesn’t cause it to move.
- Static magnetic field arises from permanent magnets (or currents).
- But, as electric field, can exist in an EM wave even without magnetic dipoles.

Field lines of a magnet

- Field lines indicate direction of field
- Density indicates strength of field
- Similar to electrostatic force, but force is felt by magnetic dipole

The Earth is a magnet!

Earth is a magnetic dipole.
North magnetic pole - at south geographic pole
A compass is a magnetic dipole
Compass needle aligns with local Earth field

Surprise! Electric current produces magnetic field

- Current (flow of electric charges) in wire produces magnetic field.
- That magnetic field aligns compass needle

Magnetic field from a current

Iron filings align with magnetic field lines
Magnetic field loops around the current.

Forces between currents

- Which of these pairs of currents will attract each other?

A. A
B. A & C
C. B
Magnetic field from a current loop

- One loop: field still loops around the wire.
- Many loops: same effect

Solenoid electromagnet

- Sequence of current loops can produce strong magnetic fields.
- This is an electromagnet

Superconducting Magnets

- Solenoid as in conventional electromagnet.
- But once current is injected, power supply turned off, current and magnetic field stays forever... ...as long as $T < T_c$

Magnetic Field Ranges

<table>
<thead>
<tr>
<th>Field Size</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>850 T</td>
<td>the strongest declassified plutonium 1.0 T</td>
</tr>
<tr>
<td>60 T</td>
<td>60 T long Tesla magnet</td>
</tr>
<tr>
<td>33 T</td>
<td>MIT continuous field magnet</td>
</tr>
<tr>
<td>2 T</td>
<td>MRI machine</td>
</tr>
<tr>
<td>0.5 T</td>
<td>Strong speaker magnet</td>
</tr>
</tbody>
</table>

Magnets for MRI

- Magnetic Resonance Imaging typically done at 1.5 T
- Superconducting magnet to provide static magnetic field
- Spatial resolution of positions of tracer atomic nuclei.

Large scale applications

- Superconducting magnet
- Plasma confinement torus
- Proposed ITER fusion test reactor
Time-varying magnetic field

- Up to this point, electric and magnetic fields constant in time
- Constant electric current produces constant magnetic field.
- Constant magnetic field produces nothing in particular!
- But changing the magnetic field in time produces an electric field!
- This effect is called induction.

Faraday’s law of induction

Faraday’s law:
- time-varying magnetic field produces electric field
- Strength of electric field proportional to how fast magnetic field changes.

In this experiment:
- Magnetic field is largest close to the bar magnet, drops off farther away.
- Moving magnet toward coil causes magnetic field through coil to increase with time, producing electric field
- Since coil is conducting, this electric field produces a current in the wire of the coil and through the meter.

One step further: Lenz’s law

- This induced current produces a magnetic field, which interacts with the bar magnet just as another bar magnet would.
- Lenz’s law describes the direction of the induced field (or equivalently, the direction of the induced currents)
  - The induced current circulates in such a way as to generate a magnetic field that tends to cancel the change in the field.
  - Causes repulsive force on original moving bar magnet.

Time-varying electric field

- Can also produce a time-varying magnetic field with a time-varying current in an electromagnet.
- Faraday’s law: time-varying magnetic field produces electric field, electric field produces electric current (in a metal).
- Just as before, the current is induced in such a way that the resulting magnetic dipole repels the changing flux that produced the current.
- This is the principle of an electromagnetic ‘gun’.

Maxwell’s unification

- Intimate connection between electricity and magnetism
- Time-varying magnetic field induces an electric field (Faraday’s Law)
- Time-varying electric field generates a magnetic field

\[
\nabla \times E = \frac{1}{c^2} \frac{\partial B}{\partial t} \\
\n\nabla \times B = \frac{1}{c^2} \frac{\partial E}{\partial t}
\]

In vacuum:

This is the basis of Maxwell’s unification of electricity and magnetism into Electromagnetism

Electromagnetic Waves

Current (up and down) creates electromagnetic wave consisting of oscillating electric and magnetic fields
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