Magnetostatics

Compare to electrostatics:
- Sources of fields
  - \( \vec{E} \): Coulomb's law
  - \( \vec{B} \): Biot-Savart law

- Forces due to the fields
  - \( \vec{E} \): \( \vec{F} = q \vec{E} \)
  - Magnetic: \( \vec{F} = q \vec{v} \times \vec{B} \)

Hall effect
For positive charge carriers

\[ \vec{E} = \nu \vec{v} \times \vec{B} \]
By measuring the polarity of the Hall voltage, we can determine the sign of the carriers.

One important thing to notice about the magnetic force. It doesn’t do any work!

\[ \mathbf{F} = q \mathbf{v} \times \mathbf{B} \quad \perp \mathbf{v} \]

Magnetic force on a current carrying wire

\[ \mathbf{F} = n q v A \]

\( q \) & \( v \) can be positive or negative.

For a small piece of the wire \( dl \):

\[ d\mathbf{Q} = n q A dl \]

\[ d\mathbf{F} = d\mathbf{Q} \mathbf{v} \times \mathbf{B} = (n q A dl) \mathbf{v} \times \mathbf{B} \]

\[ = n q v A \, dl \times \mathbf{B} = I \, dl \times \mathbf{B} \]
For a wire from A to B:
\[ F = I \int_A^B \vec{dl} \times \vec{B} \]

For a straight wire in uniform \( \vec{B} \):
\[ F = I \vec{L} \vec{B} \]

If you have a loop:
\[ F = I \int \vec{dl} \times \vec{B} \]

When and only when \( \vec{B} \) is a constant:
\[ F = I (\oint \vec{dl}) \times \vec{B} = 0 \]
\[ \oint \vec{dl} = 0 \text{ for any loop!} \]

Let's look at a rectangular loop in a \( \vec{B} \)-field:

\[ F_1 + F_3 = 0 \]
\[ F_2 + F_4 = 0 \]

Total force is 0.
Will the loop be set in motion by these forces? - Torque

\[ T = F_1 \frac{a}{2} \sin \theta + F_3 \frac{a}{2} \sin \theta \]
\[ = F a \sin \theta = I b B a \sin \theta = I \vec{A} B \sin \theta \]
Define the magnetic moment
\[ \vec{m} = NIA \hat{n} \] # of turns

Then \[ \vec{F} = \vec{m} \times \vec{B} \]. Vector, direction (right hand rule), magnitude.

We derived this equation for a rectangular loop, but it's general. A current-carrying loop is like a magnet: electromagnet.

\[ \Delta \text{ The unit of } B \]
\[ F = q \vec{v} \times \vec{B} \]

[unit of B] = \[ \frac{N}{C \text{ m}^2} = \frac{N}{Am} \equiv T \]

For the E field \[ F = qE \]

\[ \therefore \text{B and E have the same unit} \]

[unit of B] = \[ \frac{V}{m \text{s}} = \frac{V}{m^2} \equiv T \]

\[ \Delta \text{ We will revisit this later, giving you other forms of the unit T.} \]

We have discussed the force exerted by the magnetic field on a moving charge.

Notice the word moving...
Now, question: does a charge gain any energy from a magnetic field?

Ok, now we discuss the source of the magnetic field.
Again we use the electric field analogy.
For the $E$ field, we have Coulomb's law.
\[
d\vec{E} = \frac{1}{4\pi\varepsilon} \frac{P dV}{R^2} \hat{R}
\]
For the magnetic field, we have the Biot-Savart law.
\[
d\vec{H} = \frac{1}{4\pi} \frac{I d\vec{l} \times \hat{R}}{R^2}
\]
\[
B = \mu_0 \mu H.
\]

Similarities: Both carry French names with weird pronunciations.
Both proportional to $1/R^2$.
Difference:
\[
d\vec{E} \parallel \hat{R}
\]
\[
d\vec{H} \perp \hat{R}
\]

For a point charge
\[
\text{Archetypical pictures/models}
\]
To appreciate the shape of the magnetic field read on your own: example 5-2, p.p. 244 in 6/E. 

Magnetic field of a current-carrying wire

Personally, I don't like this example too much, coz it's physically not very realistic — the current gotta go somewhere.

The big picture is like this.

\[ \frac{1}{H} = \frac{I}{2\pi r^2} \]

Take this to the limit, let's say the straight wire is infinitely long, then, will show how to get this in an easier way later.

Before we go further, let's consider the unit of H. It is \( \frac{A}{m} \).
For any loop \( \oint \vec{d}l = 0 \) \( \oint \frac{\vec{d}l}{R} = 0 \)

OK, from that picture we see currents always flow in circuits, which means loops.

So, let's look at a more realistic example to illustrate the application of Biot-Savart law.

Let's say we have a loop like this:

When the gap is small enough, you can ignore it, and oh, the loop is like the one in the example in the textbook.

For simplicity, we only attempt to find the \( H \) field along the axis of the loop. Call it the \( y \) axis.

\[
\vec{d}H = \frac{I}{4\pi R^2} \vec{d}l \times \vec{R}
\]

Notice that \( \vec{d}l \perp \vec{R} \Rightarrow |\vec{d}l \times \vec{R}| = \delta \vec{dl} \)

The horizontal components of the field due to any pair of diametrical elements always cancel each other, so we only need to consider the vertical component.

\[
dH_3 = \frac{I \delta l}{4\pi R^2} \cos \theta
\]
\[ H = H_3 = \oint \frac{I \, dl}{4\pi R^2} \cos \theta = \frac{I \cos \theta}{4\pi R^2} \frac{\oint dl}{g} \]

\[ = \frac{I \cos \theta}{4\pi R^2} \geq \pi a \]

\[ = \frac{I}{2R^2} \cos \theta \]

\[ = \frac{I a}{2(a^2 + z^2)^{3/2}} \cdot \frac{a}{\sqrt{a^2 + z^2}} = \frac{Ia^2}{2(a^2 + z^2)^{3/2}} \]

\[ H(3=0) = \frac{Ia^2}{2a^3} = \frac{I}{2a} \]

\[ H(3 \gg a) = \frac{Ia^2}{2 |3|^{3}} \]

Recall that we defined the magnetic moment

\[ m = IA = I\pi a^2 \]

\[ \therefore H(3 \gg a) = \frac{m}{2\pi l|3|^{3}} \]

\[ \vec{H}(3 \gg a) = \frac{\vec{m}}{2\pi l|3|^{3}} \]

Far from the loop, the shape of the loop doesn’t matter.
Any current carrying loop has a magnetic moment, and the loop is called a magnetic dipole.

There's no need for a physical wire. For example, an electron orbiting a nucleus forms a magnetic dipole.

We call such a loop a magnetic dipole because its H field has the same shape as the E field of the electric dipole. When we only consider the far field.

Here, I stress the far field.

If you zoom in and look at the near field, you'll see a big difference.

Have you noticed the difference?
We will comeback to this after a necessary digression.

When we studied the electric field, we defined \( \vec{D} \) and \( \vec{E} \), where \( \vec{D} = \varepsilon\varepsilon_0 \vec{E} = \varepsilon_\varepsilon_0 \vec{E} \).

\[ \vec{D} = \varepsilon_0 \vec{E} + \vec{P} \quad \nabla \cdot \vec{D} = \rho \]

Here for the mag field, similarly, we have

\[ \vec{B} = \mu\mu_0 \vec{H} = \mu_r \mu_0 \vec{H} \quad \vec{B} = \mu_0 \vec{H} + \vec{M} \quad \nabla \times \vec{H} = \vec{J} \]

\( \mu_r \) is a property of the material, and \( \mu_0 \) is a physical constant.

\( \mu_r \) is dimensionless, which means it's just a number without a unit.

There is an important difference between \( \mu_r \) and \( \varepsilon_r \): \( \varepsilon_r \) has a big range.

\( \varepsilon_r \approx 1 \) for air, \( \varepsilon_r \approx 2 \times \) for many polymers.

\( \varepsilon_r = 3.9 \) for SiO2

and for dielectric materials it can be about 10, or 10's, or even hundreds.

There are materials \( \varepsilon_r \) in 1000's.

But for \( \mu_r \), it's either \( \approx 1 \), or huge.

Those materials with huge \( \mu_r \)'s are called ferromagnetic, such as iron.

They can be permanently magnetized,
which means, when there's no current flowing around, there can be a residual B field in them. For other materials, it's more than sufficient to use \( \mu_r = 1 \) for most practical purposes.

Now, let's go back and look at an important difference between the magnetic and electric fields.

As we can see from these pictures of the electric dipole and the magnetic dipole, and as I emphasized many times, the electric field line come from the positive charge and end at the negative charge, while the magnetic field lines form loops.

In the mathematical language,

\[ \nabla \cdot \mathbf{D} = \rho \quad \text{or} \quad \oint \mathbf{D} \cdot d\mathbf{S} = \int \rho dV \]

but

\[ \nabla \cdot \mathbf{B} = 0 \quad \text{or} \quad \oint \mathbf{B} \cdot d\mathbf{S} = 0 \]

There's no such thing as a magnetic charge or monopole.

Let's now give an example to draw the analogy between the electric & mag fields.
First, for the electric field, what's the force per area between the two plates of an infinitely large parallel plate capacitor?

\[ E = \frac{P_A}{\varepsilon} \]

\[ \therefore \frac{E}{A} = \frac{P_A}{A} \cdot \frac{P_A}{\varepsilon} = \frac{P_A^2}{\varepsilon} \]

Is this right?

Now, let's look at two wires, carrying currents \( I_1 \) and \( I_2 \), respectively.

Similarly to the \( E \) field situation, here we consider one wire in the field of the other.

The field due to \( I_1 \) at the position of wire 2 is

\[ B = \frac{I_1}{2\pi d} \]

Of course, the field is a vector.

\[ \frac{F}{l} = \frac{1}{l} - \frac{I_2}{l} \cdot \frac{M_0 I_1}{2\pi d} = \frac{M_0 I_1 I_2}{2\pi d} \text{ (direction)} \]
Notice that two currents flowing in the same direction attract each other.

Since the \( \nabla \times \vec{E} \) field must point from the positive charge to the negative charge, there can be no loops. Mathematically:

\[
\nabla \times \vec{E} = 0 \quad \text{or} \quad \oint \vec{E} \cdot d\vec{l} = 0
\]

(conservative)

But for the magnetic field, since there's no magnetic monopole, it must form loops:

\[
\nabla \times \vec{H} = \vec{J} \quad \text{or} \quad \oint \vec{H} \cdot d\vec{l} = \int \vec{J} \cdot d\vec{S} = I
\]

(Ampere's law)

This is the physics no matter how small the loop is.

Define

\[
\text{curl } \vec{H} = \lim_{\Delta S \to 0} \frac{\oint \vec{n} \phi \vec{H} \cdot d\vec{l}}{\Delta S}
\]

In the Cartesian coordinates,

\[
\vec{H} = H_x \hat{x} + H_y \hat{y} + H_z \hat{z}
\]

\[
\nabla = \hat{x} \frac{\partial}{\partial x} + \hat{y} \frac{\partial}{\partial y} + \hat{z} \frac{\partial}{\partial z}
\]

\[
\nabla \times \vec{H} = \begin{vmatrix}
\hat{x} & \hat{y} & \hat{z} \\
\frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\
H_x & H_y & H_z
\end{vmatrix}
= \hat{x} \left( \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \right) + \hat{y} \left( \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} \right) + \hat{z} \left( \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \right)
\]

determinant
Stoke's Theorem \[\nabla \times \vec{E} \cdot \mathbf{d}l \]

\[\iint_S (\nabla \times \vec{E}) \cdot \mathbf{d}S = \oint_C \vec{E} \cdot \mathbf{d}l \]

Compare:

\[\iint_S (\nabla \times \vec{H}) \cdot \mathbf{d}S = \oint_C \vec{H} \cdot \mathbf{d}l \]

\[\iint_S (\nabla \times \vec{H}) \cdot \mathbf{d}S = \oint_C \vec{J} \cdot \mathbf{d}l \]

\[
= \sum (\nabla \times \vec{H}) \cdot \mathbf{d}S = \int (\nabla \times \vec{H}) \cdot \mathbf{d}S = \int \vec{J} \cdot \mathbf{d}S
\]

Now go back to the physics:

\[\nabla \times \vec{H} = \vec{J}\]

\[\oint \vec{H} \cdot \mathbf{d}l = \int \vec{J} \cdot \mathbf{d}l = I\]

Example:

\[\vec{J} = \frac{I}{\pi a^2}\]

For \( r < a \)

\[\oint \vec{H} \cdot \mathbf{d}l = H(2\pi a) = \frac{I}{\pi a^2} \cdot \pi r^2 = I \left( \frac{r}{a} \right)^2\]

\[\therefore H = \frac{I}{2\pi a^2} \left( \frac{r}{a} \right)^2 = \frac{Ir}{2\pi a^2}\]

For \( r > a \)

\[\oint \vec{H} \cdot \mathbf{d}l = 2\pi r H = I\]

\[\therefore H = \frac{I}{2\pi r}\]

Same result as from Biot-Savart law.
For other geometries, read the following examples on your own:

Ex 5-5 (5-6 in 5/E) Toroidal coil.

5-6 (5-7 in 5/E) Infinite current sheet. (Think: what about a slab?)

Sect. 5-7.1 (5-8.1 in 5/E) Solenoid. Go thru the mathematical details. But more importantly, get the visual sense of B field generated by a current in these different geometries. Look at the figures and think. Make sure they stay in your head.

We will defer the discussion of the inductance to the next chapter, because L is about a changing current. Defining the L in the context of a dc current is not really meaningful.