

Physics 1C Notes

Kyle Chui

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1 Lecture 1

1.1 Electromagnetism

In Physics 1B, we discussed how

$$\text{charge} \rightarrow \text{electric fields} \begin{cases} \text{Coulomb's Law} \\ \text{Gauss' Law} \end{cases}.$$

Furthermore, we know that moving charge \rightarrow magnetic field (Ampere's Law).

$$\text{Gauss' Law: } \oint_{\text{surface}} \vec{E} \cdot d\vec{A} = \frac{q}{\epsilon_0} \qquad \text{Ampere's Law: } \oint_{\text{loop}} \vec{B} \cdot d\vec{\ell} = \mu_0 I.$$

There are two other main laws for electromagnetism, and all of these laws give us magnets, motors, power generators, etc.

1.2 Electromagnetic Waves

These four laws also lead to electromagnetic waves, examples of which are radio waves, visible light, etc.

Definition. *Speed of Light*

We define the speed of light c to be

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 3 \cdot 10^8 \text{ m/s}.$$

1.3 Light and Optics

Light and matter gives us the ideas of reflection and refraction, which lead to prisms, lens, and mirrors. In 1905, Einstein noticed that space and time depend on the observer, and that energy and momentum are different from what we thought.

2 Lecture 2

Definition. *Magnetic field*

The *magnetic field* is denoted by \vec{B} , and its units are given in Tesla (which is a large unit!).

2.1 Demonstrations

- A current through a magnetic field experiences a force (the jumping wire). We observed that the force \vec{F} was perpendicular to the magnetic field \vec{B} , which was also perpendicular to the current \vec{I} .
- The lodestone is a magnet.
- Opposite poles attract, same poles repel (bar magnets).
- We visualised the magnetic field by looking at the alignment of iron filings in a viscous fluid.

2.2 Equations

1. The force due to a magnetic field is given by

$$\vec{F}_m = q\vec{v} \times \vec{B}.$$

This force is a part of the electromagnetic force,

$$\vec{F}_{EM} = q\vec{E} + q\vec{v} \times \vec{B}.$$

Note (Cross Products). Suppose we have two vectors \vec{a} and \vec{b} . Then $\vec{a} \times \vec{b}$ is a vector perpendicular to both \vec{a} and \vec{b} . If θ is the angle between the two vectors, then

$$|\vec{a} \times \vec{b}| = |\vec{a}| |\vec{b}| \sin \theta = ab \sin \theta.$$

The direction of the vector is given by the “right hand rule”.

3 Lecture 3

3.1 Gauss' Law for Magnetic Fields

In Physics 1B, we learned Gauss' Law for electric fields:

$$\oint \vec{E} \cdot d\vec{A} = \frac{q_{\text{enclosed}}}{\epsilon_0}.$$

We have a similar equation for magnetic fields:

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

The reason why this is zero is because there are “no magnetic monopoles”, i.e. every magnet has two poles.

Note. This can also be interpreted to mean that for a given surface, the number of magnetic field lines coming out must equal the number of magnetic field lines going in.

3.2 The Motion of Charged Particles in a Magnetic Field

There are [some] cases:

- i) When the particle is at rest, we have

$$\vec{F} = q\vec{v} \times \vec{B} = 0.$$

- ii) For a particle in 2D motion with a constant magnetic field, we have

$$\vec{F} = q\vec{v} \times \vec{B},$$

which is perpendicular to both \vec{v} and \vec{B} (by the properties of the cross product). We use the right hand rule to get the actual direction of the force (when the charge is positive).

Note. Since the magnetic force is perpendicular to the motion of the particle, we have uniform circular motion.

To get the radius of the motion, we solve:

$$\begin{aligned} F_C &= F_B \\ \frac{mv^2}{r} &= qvB \\ r &= \frac{mv^2}{qvB} \\ \boxed{r = \frac{mv}{qB} = \frac{p}{qB}.} \end{aligned}$$

- iii) For a particle in 3D motion with a constant magnetic field, \vec{v}_0 is not necessarily perpendicular to \vec{B} . Thus we first decompose \vec{v}_0 into $\vec{v}_0 = \vec{v}_{0\parallel} + \vec{v}_{0\perp}$. Then we have

$$\begin{aligned} \vec{F} &= q(\vec{v}_{0\parallel} + \vec{v}_{0\perp}) \times \vec{B} \\ &= qv_{0\parallel} \times B + q\vec{v}_{0\perp} \times \vec{B} \\ &= q\vec{v}_{0\perp} \times \vec{B}. \end{aligned}$$

Note. The movement of the particle is circular relative to the perpendicular plane to the magnetic field, but the velocity of the particle parallel to the magnetic field is constant. Thus the particle moves in a helix (or spiral) pattern.

3.3 Force Equation for a Current-Carrying Wire

We define $\vec{\ell}$ to be the length of the wire in the direction of \vec{v} . From earlier, we know that

$$\vec{F} = N \cdot q\vec{v} \times \vec{B}.$$

Furthermore, we have

$$I = \frac{Q}{t} = \frac{Nq}{t} = \frac{Nq}{\frac{\ell}{v}} = \frac{Nqv}{\ell}.$$

Thus we have

$$\begin{aligned}\vec{F} &= N \cdot q\vec{v} \times \vec{B} \\ &= N \cdot qv \cdot \frac{\vec{\ell}}{\ell} \times \vec{B} \\ &= I\vec{\ell} \times \vec{B}.\end{aligned}$$

Alternatively, if things are always changing, then

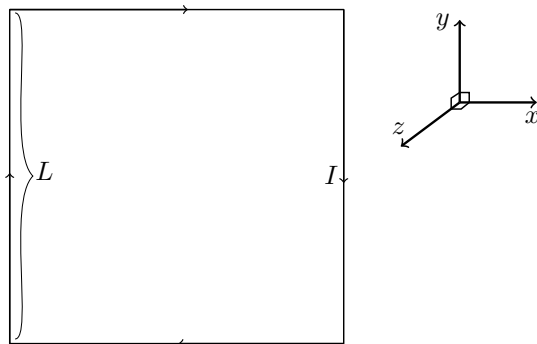
$$\vec{F} = \int_{\text{wire}} I \, d\vec{\ell} \times \vec{B}.$$

4 Lecture 4

4.1 Current Loops in Magnetic fields: Force and Torque

4.1.1 Uniform Magnetic Field Perpendicular to the Loop

Consider a fictional square loop of wire with side L , where the current flowing through the loop is I . We denote \odot to be out of the page, and \otimes to be into the page. We will use the equations $\vec{F} = I\vec{L} \times \vec{B}$ and $\vec{\tau} = \vec{r} \times \vec{F}$, and assume that we have a constant, uniform \vec{B} field.



\vec{B}	\vec{F}_{left}	\vec{F}_{top}	\vec{F}_{right}	\vec{F}_{bottom}	\vec{F}_{net}	$\vec{\tau}_{\text{net}}$
\otimes	\leftarrow	\uparrow	\rightarrow	\downarrow	0	0
\uparrow	0	\odot	0	\otimes	0	$\hat{i} \left(\frac{L}{2} BIL \cdot 2 \right) = (BIL^2)\hat{i}$

The magnetic moment μ is given by $\mu = IA$, where A is the area of the loop (in this case, $L = A^2$). We use this μ to find the torque, and we have $\tau = \mu B$ or $\vec{\tau} = \vec{\mu} \times \vec{B}$. The magnetic moment is defined as perpendicular to the surface of the loop.

For the example above, the magnetic moment must be *into the page*. We can find this by using the right hand rule, where you point your thumb in the direction of the current and curl your fingers around to find the direction of the moment.

4.1.2 Generalisation to a Loop of Any Shape

We can approximate an irregularly shaped loop of wire by breaking it into smaller, rectangular loops of wire.

Note. If the currents of the rectangular loops are all travelling in the same direction, the currents inside of the outer loop will cancel, leaving only the current around the perimeter of the outside loop.

5 Lecture 5

Last week, we studied the force due to a \vec{B} . This week, we will study how to produce a \vec{B} .

5.1 Biot-Savart Law

Point charge observations:

- When you have a point charge, you have an electric field \vec{E} that radiates outwards from the point charge.
- This is slightly different from the magnetic field, which is generated by a *moving* point charge.
 - The closer you are to the point charge, the larger the magnetic field.

Theorem — Coulomb's Law

Given the charge and distance from a point charge, we may find the electric field:

$$\vec{E} = \frac{q\hat{r}}{4\pi\epsilon_0 r^2}.$$

Biot-Savart Law precursor:

$$\vec{B} = \frac{\mu_0}{4\pi} \cdot \frac{q\vec{v} \times \hat{r}}{r^2}.$$

Note. In the equation for the magnetic field, we see that it is both orthogonal to the velocity vector and \hat{r} (due to the cross product).

Points:

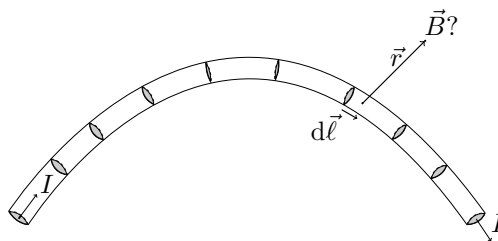
- Both are inversely proportional to the square of the distance.
- $\mu_0 := 4\pi \cdot 10^{-7} \text{ Tm/A}$, and is used in the definition of the ampere (and so the Coulomb).

Note. This means that the \vec{E} is very large, but \vec{B} is quite small.

Theorem — Biot-Savart Law

Given the current through a wire, and the displacement from a point to the wire, we can find the magnetic field:

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{\ell} \times \hat{r}}{r^2}.$$

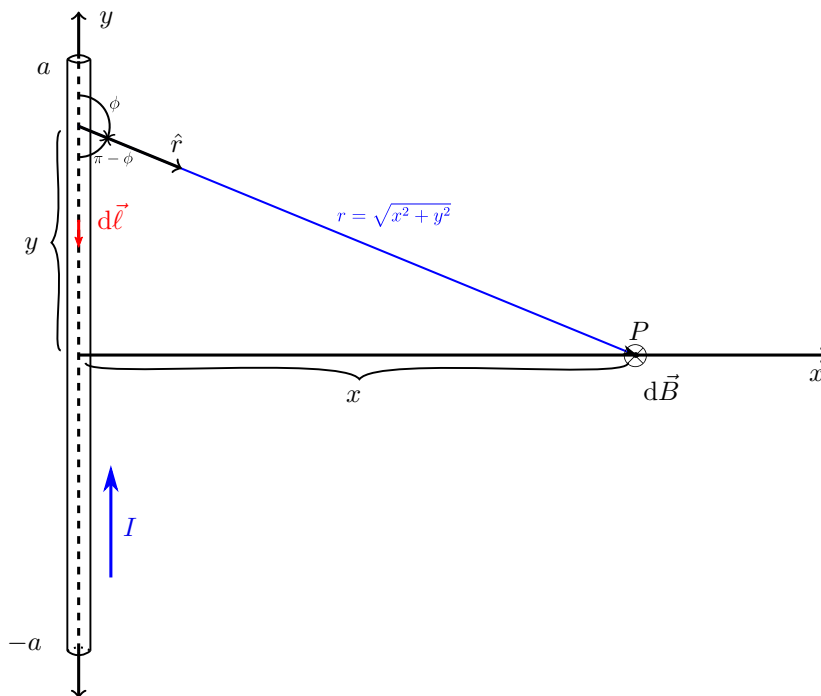


In the above diagram, you can see how the cross product of $d\vec{\ell}$ and \vec{r} is in the direction of the magnetic field. Furthermore, we can integrate the Biot-Savart Law to get

$$\vec{B} = \int_{\text{wire}} d\vec{B}$$

5.2 Magnetic Field of a Straight Current-Carrying Wire

For a long, straight current-carrying wire, we try to find the field on some point P from locations $-a$ to a on the wire.



From the diagram, we can see that $r = (x^2 + y^2)^{\frac{1}{2}}$, and

$$\hat{r} = \frac{x\hat{i} - y\hat{j}}{(x^2 + y^2)^{\frac{1}{2}}}. \quad (\text{Scale down } \vec{r})$$

Furthermore, $d\vec{\ell} = dy\hat{j}$. The hard part is calculating the following:

$$\begin{aligned} \frac{d\vec{\ell} \times \hat{r}}{r^2} &= \frac{dy\hat{j} \times (x\hat{i} - y\hat{j})}{(x^2 + y^2)^{\frac{3}{2}}} \\ &= \frac{-\hat{k}x dy}{(x^2 + y^2)^{\frac{3}{2}}}. \end{aligned}$$

We then integrate over the length of the wire:

$$\vec{B} = -\hat{k} \frac{\mu_0 I}{4\pi} \int_{-a}^a \frac{x dy}{(x^2 + y^2)^{\frac{3}{2}}}$$

Letting $y = x \tan \theta$, and going through some algebra, we get

$$= -\hat{k} \frac{\mu_0 I}{4\pi} \left(\frac{2a}{x\sqrt{a^2 + x^2}} \right).$$

For an infinitely long wire, we see what happens when $a \rightarrow \infty$. In this case, we have

$$\vec{B} = -\hat{k} \frac{\mu_0 I}{4\pi} \left(\frac{2}{x} \right) = -\hat{k} \frac{\mu_0 I}{2\pi x}.$$

We started with a special point P on the wire, which is on the perpendicular bisector of the wire. However, when $a \rightarrow \infty$, we have an infinite amount of wire on either side, so the y becomes irrelevant and all we care about is the distance x to the wire. Thus to find the magnitude of the wire, we have

$$B = \frac{\mu_0 I}{2\pi r},$$

where r is the distance to the wire. If we were to look at the wire from the top (the xz -plane), we would have that \vec{B} circles the wire.

Note. Another right-hand rule is to put your thumb in the direction of the current, and your thumbs will curl to form the magnetic field.

6 Lecture 6

The force between long parallel wires defines the ampere. As a reminder, last class we found the formula

$$B = \frac{\mu_0 I}{2\pi r}.$$

Consider two parallel, infinitely-long wires that are carrying current. If the currents are going in the same direction, then we use the right-hand rule to find that the wires have an attractive force between them. We find that the force acting on wire 2 is

$$\begin{aligned}\vec{F} &= I_2 \vec{L} \times \vec{B}_1 \\ &= I_2 L \frac{\mu_0 I_1}{2\pi r} \text{ to the left,}\end{aligned}$$

so we have

$$F_2 = \frac{\mu_0}{2\pi} \cdot \frac{I_1 I_2 L}{r}.$$

Rearranging some more, we get

$$\frac{F_2}{L} = (2 \cdot 10^{-7}) \frac{I_1 I_2}{r} \text{ Newtons.}$$

What happens when we have $I_1 = I_2$? Well, we get that

$$\frac{F}{L} = (2 \cdot 10^{-7}) \frac{I^2}{r},$$

which we can rearrange to get

$$I = \underbrace{\left(r \cdot \frac{F}{L} \cdot \frac{1}{2 \cdot 10^{-7}} \right)^{\frac{1}{2}}}_{\text{defines the Ampere}}.$$

6.1 Ampere's Law

Just like Coulomb's Law leads to Gauss' Law (which is an integral), the Biot-Savart Law leads to Ampere's Law (also an integral). Remember the Biot-Savart Law from before:

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{\ell} \times \hat{r}}{r^2}.$$

Theorem — Ampere's Law

The amount of magnetic field in a loop can give you the current, given by

$$\oint_{\text{loop}} \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{enc}}.$$

The analogue to the Gaussian surface is what we call an *Ampereum loop*. There is no radial component to \vec{B} because there are no monopoles. Thus we have that $\vec{B} \parallel d\vec{\ell}$, and $\vec{B} \cdot d\vec{\ell} = B d\ell$. Then

$$\begin{aligned}\oint B d\ell &= B \oint d\ell \\ &= B \cdot 2\pi r \\ &= \mu_0 I,\end{aligned}$$

so

$$B = \frac{\mu_0 I}{2\pi r}.$$

The differential form of Ampere's Law is given by:

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J},$$

where \vec{J} is the current density.

6.1.1 Ampere's Law Example—Long Wire, Thin but Finite Thickness

Consider a wire with radius R that has uniform current density J . We define current density to be the current per unit area, in other words

$$J = \frac{I}{\pi R^2}, \text{ a constant.}$$

We have a few cases here:

(a) Outside the wire, i.e. $r > R$.

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{encl}}$$

$$2\pi r B = \mu_0 I$$

$$B = \frac{\mu_0 I}{2\pi r}.$$

(b) Inside the wire, i.e. $r < R$.

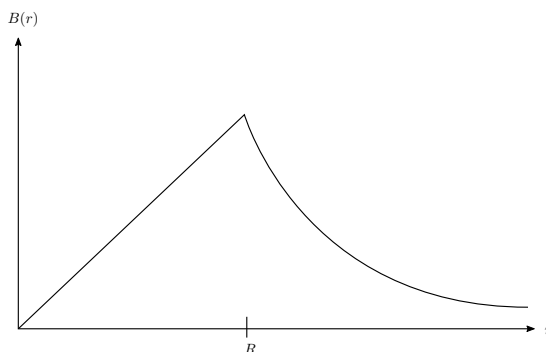
$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{encl}}$$

$$2\pi r B = \mu_0 I \cdot \frac{\pi r^2}{\pi R^2}$$

$$2\pi r B = \mu_0 I \cdot \frac{r^2}{R^2}$$

$$B = \frac{\mu_0 I r}{2\pi R^2}.$$

Pictorially, we can draw a graph for the magnetic field as a function of the distance to the centre of the wire as follows:



6.1.2 Ampere's Law Example—Plane of Current

If we have two parallel wires next to each other with the currents moving in the same direction, by superposition of field lines we generate a space with zero field between the wires. Extending this idea to more than just two wires (read: an infinite number, creating a plane of current), we create a planar magnetic field.

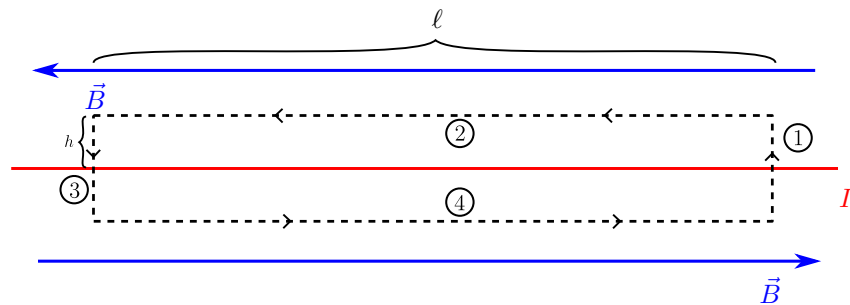


Figure 1: Plane of Current

Definition. *Winding Density*

We define the *winding density* n to be the number of wires per unit length, or

$$n = \frac{N}{\ell}.$$

Applying Ampere's Law, we have

$$\begin{aligned} \oint \vec{B} \cdot d\vec{\ell} &= \mu_0 I_{\text{encl}} \\ \int_1 + \int_2 + \int_3 + \int_4 &= \mu_0 NI \\ 2 \int_4 \vec{B} \cdot d\vec{\ell} &= \mu_0 NI \\ 2B\ell &= \mu_0 NI \\ B &= \frac{\mu_0 n I}{2}. \end{aligned}$$

7 Lecture 7

7.1 Magnetic Field from a Solenoid

Definition. *Solenoid*

A *solenoid* is the winding of wire in a helix shape.

If you take a 2D cross-section of the solenoid, you can see how the inside of the solenoid has parallel magnetic field lines due to the superposition of the field lines. This is analogous to the parallel electric field lines found between parallel, charged plates. In the infinite case, the magnetic field can be calculated with the equation

$$B = \mu_0 \cdot \frac{nI}{2}.$$

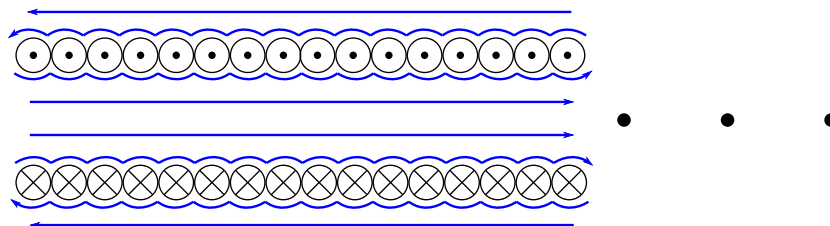


Figure 2: Cross Section of a Solenoid

Using Ampere's Law, with a box around all of the currents shown, we have

$$\begin{aligned} \oint_{\text{loop}} \vec{B} \cdot d\vec{\ell} &= \mu_0 I_{\text{encl}} \\ &= \int_1 + \int_3 \\ &= 0. \end{aligned} \quad (\text{The currents cancel})$$

From our diagram we see that the magnetic field outside of the solenoid is in one direction, regardless where you are, so $\int_1 = \int_3 = 0$. Restricting our attention to only the top half of the currents, we have

$$\begin{aligned} \oint_{\text{loop}} \vec{B} \cdot d\vec{\ell} &= \mu_0 NI \\ B \cdot L &= \mu_0 nLI \\ B &= \mu_0 nI. \end{aligned}$$

The magnetic field lines outside the solenoid cancel out.

7.2 Magnetic Field from a Toroid

To get a toroid, you basically bend a solenoid into a loop. Consider a toroid with inner radius a and outer radius b . Then applying Ampere's Law, we get

$$\oint_{\text{loop}} \vec{B} \cdot d\vec{\ell} = 2\pi r B \\ = \mu_0 N I,$$

so $B = \frac{\mu_0 N I}{2\pi r}$ (here we have $n = \frac{N}{2\pi a}$ when $a < r < b$). Outside of the toroid, the enclosed current is zero.

8 Lecture 8

8.1 Magnetism in Matter—Atoms

For a series of loops, we know that the magnetic moment is given by

$$\vec{\mu} = NIA \cdot \hat{n},$$

where N is the number of loops, I is the current, and A is the area enclosed by the loop. Furthermore, the torque on the loop(s) in an external \vec{B} field is given by $\vec{\tau} = \vec{\mu} \times \vec{B}$. This is analogous to a dipole in an electric field, where we had

$$\vec{p} = q \cdot \vec{\ell} \quad \text{and} \quad \vec{\tau} = \vec{p} \times \vec{E}.$$

Question. What happens if dipoles go to minimum potential energy U ?

If we call the *electric field generated by the dipole* \vec{E}' , then we see that it tends to point in the opposite direction to \vec{E}_0 , the original electric field. Then we have that the net electric field is given by $\vec{E} = \vec{E}_0 + \vec{E}'$.

In contrast, the magnetic field created by the solenoid is usually in the *same* direction as \vec{B}_0 , so the magnetic field usually gets *amplified*.

8.2 Describing Magnetic Materials

The textbook goes over the “Bohr magneton” for a single atom. We have the equations

$$\vec{M} = \frac{\vec{\mu}_{\text{total}}}{V} \quad \text{and} \quad \vec{B} = \vec{B}_0 + \mu_0 \vec{M}.$$

However, the above equations are usually not that useful, so we ignore them. More interestingly, we have

$$\begin{aligned} \mu_0 \rightarrow \mu &= K_m \cdot \mu_0 \\ \oint B \cdot d\ell &= \mu I \\ B \cdot 2\pi r &= \mu I. \end{aligned}$$

The K_m constant referenced above is called “permeability”. We replace all of the μ_0 ’s in the previous equations with just μ .

Note. This is analogous to the dielectric constant for capacitors.

Example. The permeability of iron is approximately 1000, so when you fill a solenoid with iron, you increase its magnetic field output by a factor of 1000. This is similar to filling the space between the plates of a capacitor with a dielectric, which increased the capacitor’s capacitance.

Note. Most materials have a permeability K_m that is close to 1.

We define a new constant called “susceptibility” given by $\chi_m := K_m - 1$. This makes it such that have a “susceptibility” close to zero are the items that are not very magnetic.

If atomic loops perfectly align, then the currents inside the magnet perfectly cancel out, leaving only a net current along the boundary of the magnet. This generates the same effect as a solenoid, which just has a current looping around and around its boundary.

8.3 Three Types of Magnetic Materials

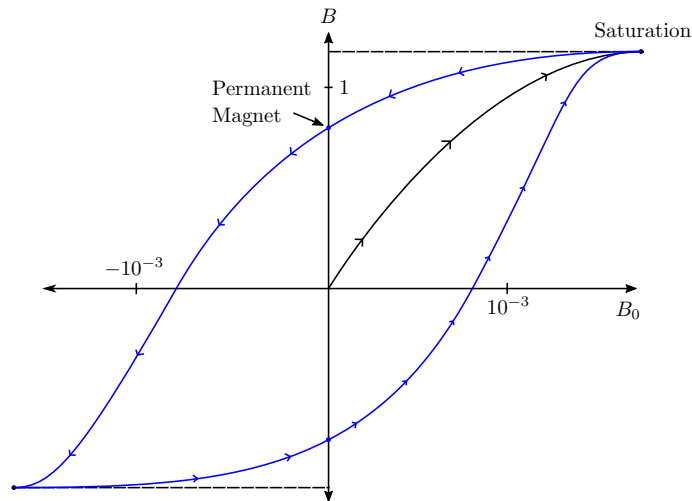
1. Iron-like: Ferromagnetic materials have $K_m \gg 1$ (much greater than one).
2. Paramagnetic materials have $K_m = 1 + \underbrace{\chi_m}_{\text{around } 10^{-4}}$.

3. Diamagnetic materials have $K_m = 1 - \underbrace{|\chi_m|}_{\text{around } 10^{-5}}$.

Ferromagnetic materials are useful:

- They have big K_m due to atoms aligning better than thermally expected (they are usually in disarray).

In the following diagram (hysteresis curve), the x -axis represents the applied magnetic field, and the y -axis is the induced magnetic field. If you apply a strong magnetic field to a ferromagnetic material, it will also create its own magnetic field, amplifying the effects of the original magnetic field. What's interesting here is that when you remove the external magnetic field, the ferromagnetic field will settle into being a permanent magnet. If you apply a negative magnetic field to the object, the same happens, but in the other direction.

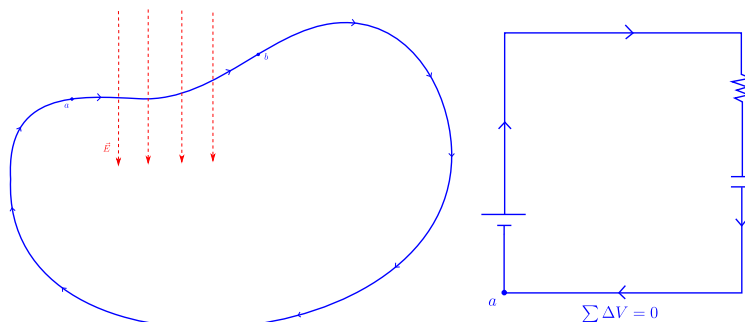


The black curve above traces the induced field as you apply an external \vec{B} , and the blue curves show how the induced magnetic field changes with the external field after the initial application.

9 Lecture 9

9.1 A New Fundamental Law of Nature—Faraday’s Law

A changing magnetic field produces *loops* in the electric field. Recall for voltage:



$$\Delta V_{ab} = - \int_a^b \vec{E} \cdot d\vec{\ell} \quad \text{and} \quad \oint_{\text{loop}} \vec{E} \cdot d\vec{\ell} = 0.$$

Theorem — Faraday’s Law

If Φ_m is the magnetic flux, given by

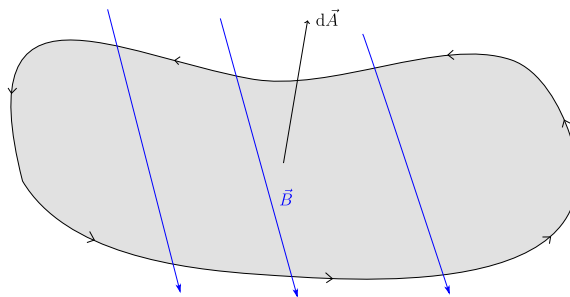
$$\Phi_m = \oint_{\text{surface}} \vec{B} \cdot d\vec{A},$$

then we have

$$\oint \vec{E} \cdot d\vec{\ell} = - \frac{d}{dt} \Phi_m = - \frac{d\Phi_m}{dt}.$$

Alternatively, we have the differential form of Faraday’s Law, given by

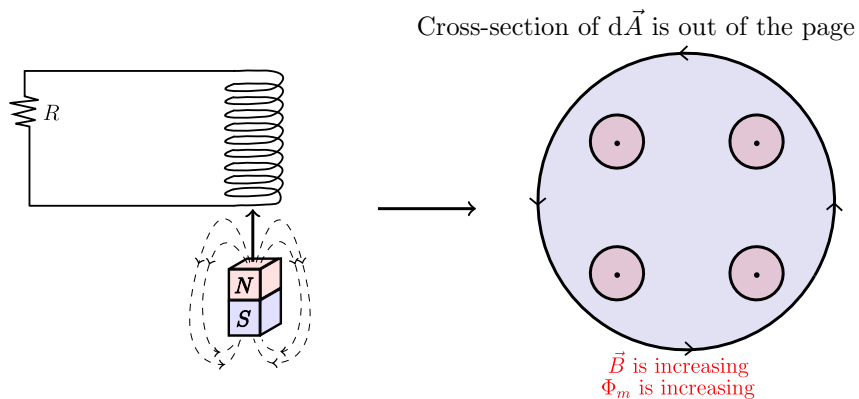
$$\vec{\nabla} \times \vec{E} = - \frac{d\vec{B}}{dt}.$$



Note. Note that for Gauss’ Law, we needed a potential difference in order to be able to generate an electric field, but for Faraday’s Law we just need a changing magnetic flux.

9.2 Moving a Magnet Into Coil: EMF

When we move the north pole of a magnet into a coil of wire, we are increasing the magnetic field through the same area, so the magnetic flux is increasing.



Applying Faraday's Law, we have

$$\oint \vec{E} \cdot d\vec{\ell} < -\frac{d}{dt}\Phi_m < 0.$$

From this, we know that \vec{E} is clockwise, and the current is also in the clockwise direction.

9.3 Rotating Coil in a Magnetic Field

Suppose we were to rotate a square coil in a magnetic field, as follows:

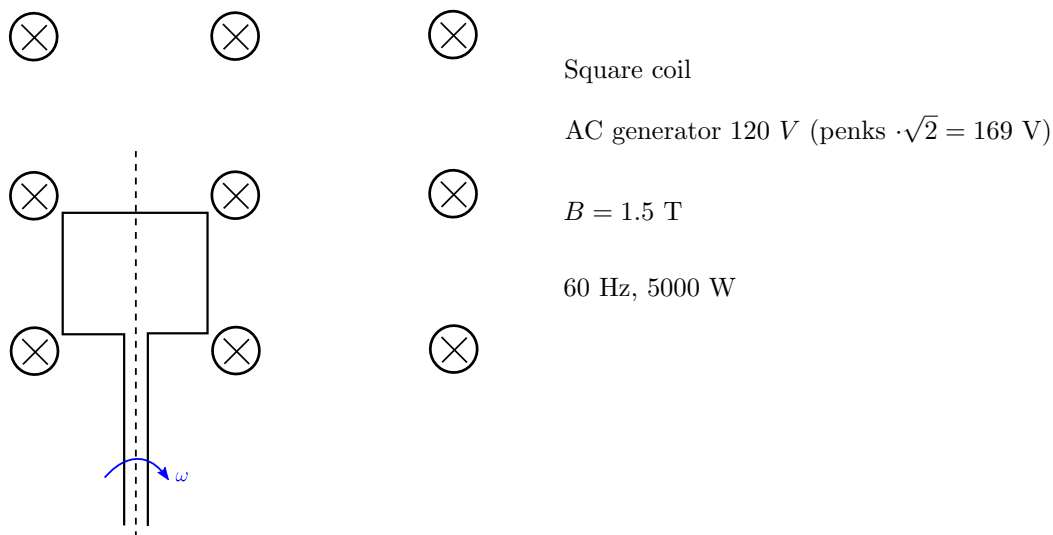


Figure 3: Top view of the loops of wire

Suppose that there are $N = 169$ loops of wire, so there is one loop of wire per volt needed. We can find the

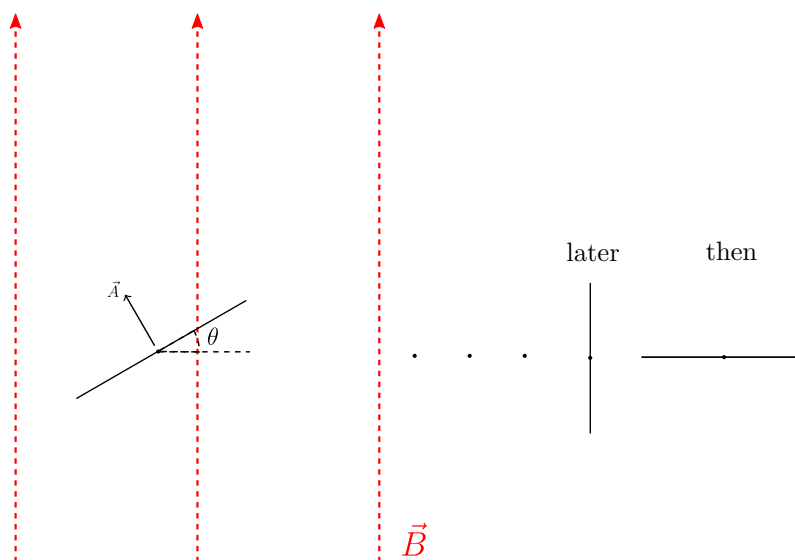


Figure 4: Side view of the loops of wire

angular velocity from the frequency, given by $\omega = 2\pi f = 377$ rad/s. We see from our diagram that

$$\Phi_m = BA \cdot \cos \theta = BA \cos(\omega t),$$

so

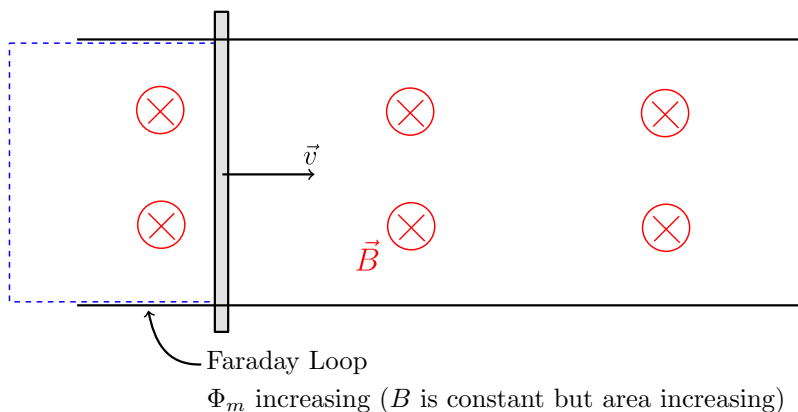
$$\frac{d\Phi_m}{dt} = -BA\omega \sin(\omega t).$$

The electromotive force $\varepsilon = BA\omega$ should be equal to 1 volt (because each of the 169 loops contributes 1 volt to the net potential). Thus we can solve for the area:

$$A = \frac{\varepsilon}{B\omega} \approx 26.5 \text{ cm}^2.$$

9.4 Motional EMF

Consider a wire laying on rails, with magnetic field between the rails, as shown:



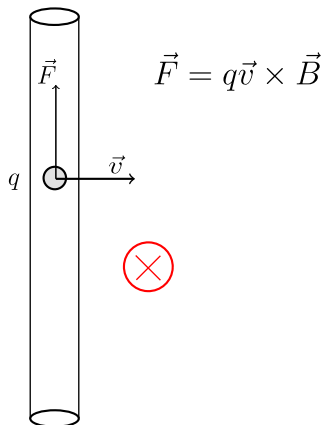
If the width of the Faraday loop is x , then the area is

$$A = xL, \text{ and } \Phi_m = B \cdot A = B \times Lx.$$

Furthermore, we have

$$\varepsilon = -\frac{d\Phi_m}{dt} = -BL \cdot \frac{dx}{dt} = -BLv$$

across the end of the slider. From another point of view, we see



The magnetic force on the charges inside the rod move the positive charges upwards, and the negative charges downwards. This creates an electric field in the rod from top to bottom, which counteracts the magnetic force. From either perspective, we reach the same conclusion that there is a potential difference across the rod.

10 Lecture 10

10.1 Lenz's Law, Eddy Currents

This is useful for determining the sign and direction of things in a system involving magnetic fields/forces.

Note. When changing a magnetic system, forces and currents act in the direction to *oppose* the change.

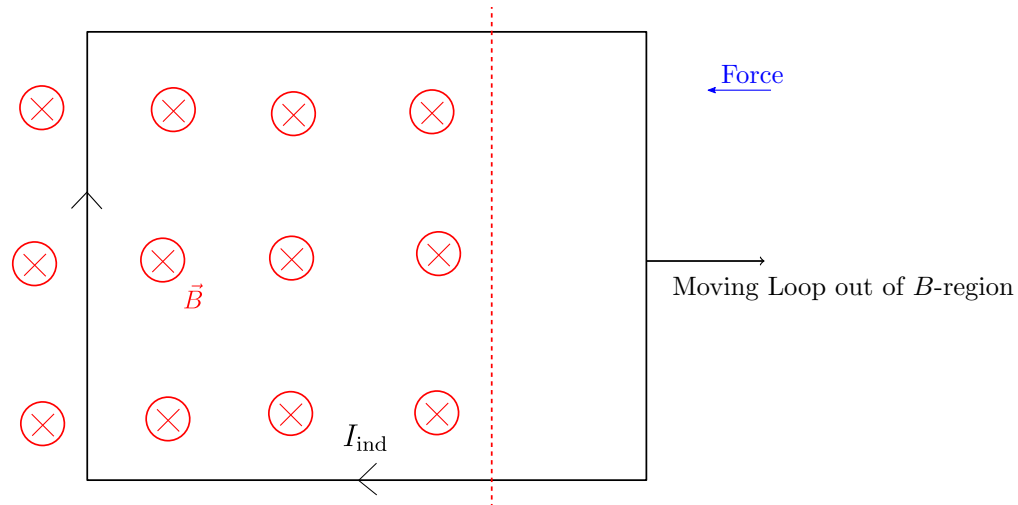


Figure 5: Pulling a Loop of Wire out of a Magnetic Field

As you pull the loop of wire out of the magnetic field that is into the page, the area of the loop that is in the constant magnetic field will decrease. Thus the loop of wire will have an induced current such that it will generate more field into the page. By the right-hand rule, we can see that the induced current should run clockwise. Furthermore, the magnetic forces on the top and bottom portions of the wire are equal and in opposite directions, and so cancel out. There is a force on the left part of the loop that is pointing to the left, which opposes the force that is pulling the loop out of the magnetic field.

11 Lecture 11

11.1 Motional EMF—Conductors Moving in Magnetic Fields

See the diagram in section 9.4. From the Lorentz force equation, we have

$$\vec{F} = q\vec{v} \times \vec{B}.$$

The electric field generated by the separation of charges (positives to the top, negatives to the bottom) in the conductor will create a force equal to and opposing the magnetic force. In other words,

$$\vec{F}_E = q\vec{E} = -q\vec{v} \times \vec{B} = -\vec{F}_M,$$

so $\vec{E} = -\vec{v} \times \vec{B}$. If the conductor is connected to metal rails, we see that this electric field will actually send the charges through the loop. The magnitude of this EMF is given by $\varepsilon = BLv$, which agrees with what we got in section 9.4.

We can generalise this to an arbitrary loop of wire with segments all moving in random directions, by cutting the loop up into small segments of length $d\vec{\ell}$ and integrating:

$$\varepsilon = \oint (\vec{v} \times \vec{B}) d\vec{\ell}.$$

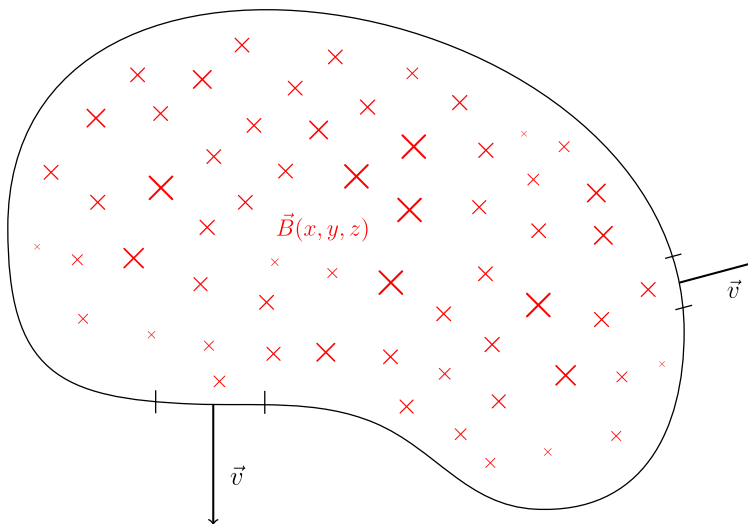


Figure 6: Arbitrary Loop of Wire in Magnetic Field

11.2 Eddy Current Demonstrations

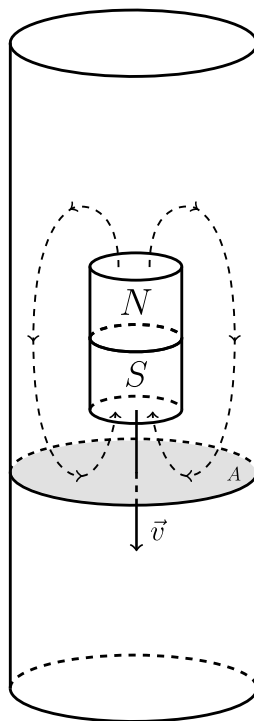


Figure 7: Magnet Falling Through a Conducting Tube

Notice that as the magnet falls, the magnetic flux through the area A is increasing upwards. By Lenz's Law, there will be an induced magnetic field pointing downwards, opposing the change in magnetic flux. This induced magnetic field exerts a force on the magnet, causing it to slow down and fall through the tube more slowly. As the tube gets thicker and more conductive, the eddy currents and induced magnetic field also get larger, causing the magnet to fall even more slowly.

12 Lecture 12

12.1 Magnetic Induction in Circuits

Take \vec{B} uniform, increasing with $B = \alpha \cdot t$ into the page. We choose the area vector \vec{A} to be out of the page, resulting in

$$\Phi = \int \vec{B} \cdot d\vec{A} = \vec{B} \cdot \vec{A} = -BA < 0,$$

and

$$\frac{d\Phi}{dt} = -A \cdot \frac{dB}{dt} = -A\alpha < 0.$$

Then $\varepsilon = -\frac{d\Phi}{dt} = A \cdot \alpha > 0$. We know that ε is defined by

$$\varepsilon = \oint \vec{E} \cdot d\vec{\ell} > 0,$$

and the direction of the loop is set by the direction of \vec{A} . By the right hand rule, this direction must be counter-clockwise. Thus having a positive ε means \vec{E} is in the same direction as $d\vec{\ell}$, so \vec{E} is also counter-clockwise.

Note. Just like motional EMF: charges will accumulate almost instantaneously since $\vec{E} = 0$ inside the conductor.

Let's make this a circuit by attaching a resistor: If we look at the direction of this current, it will induce a magnetic field B' inside of the loop, that is pointing out of the page. This opposes the B that is going into the page.

12.2 Concept of Self-inductance L , Solenoid Example

We know that the magnetic field inside a solenoid is

$$B_{\text{in}} = \mu \frac{N}{\ell} I = \mu n I, \quad (n := \frac{N}{\ell})$$

where N is the number of turns, ℓ is the length of the solenoid, and I is the current. The flux inside the solenoid is given by

$$\Phi_B = B_{\text{in}} \cdot A \cdot N = (\mu n I) AN.$$

We differentiate this to get the electromotive force (and assume the current is the only one that changes),

$$\varepsilon = -\frac{d\Phi_B}{dt} = -\mu n AN \cdot \frac{dI}{dt}.$$

We define the self-inductance L by $L := \mu n AN$, which simplifies the above into

$$\varepsilon = -L \cdot \frac{dI}{dt}.$$

For other geometries:

- $B = (\text{constant of geometry}) \cdot I$
- $\Phi_B = (\text{another constant of geometry}) \cdot I$
- $\varepsilon = -\frac{d\Phi_B}{dt} = -(\text{some constant}) \cdot \frac{dI}{dt} = -L \cdot \frac{dI}{dt}$

12.3 Magnetic Field Energy

Consider a voltage V sending a current I through an inductor L . To find the power dispersed across the inductor, we use

$$P = |I\varepsilon| = IL \cdot \frac{dI}{dt} \quad (\text{into/out of the inductor})$$

Suppose V starts at zero, then increases. The back ε opposes the increase of current—power needs to be supplied. We use the equation

$$\text{Energy} = \int_0^t \text{Power} \cdot dt' \quad (t' \text{ is dummy variable})$$

to find the energy stored in the inductor (U). Thus we have

$$\begin{aligned} U &= \int_0^t P \, dt' \\ &= \int_0^t IL \cdot \left(\frac{dI}{dt'} \right) dt' \\ &= \int_0^I I' L \, dI' \quad (\text{Change dummy variable}) \\ &= \frac{1}{2} I^2 L. \end{aligned}$$

Note. This is similar to the equation for the energy of a capacitor, which was $U = \frac{1}{2} CV^2$.

Note. Just as how we think of energy stored in a capacitor as being stored in the electric field between the plates, we may think of energy stored in an inductor as being stored in the magnetic field generated by the inductor.

12.4 Magnetic Field Energy Density—Use Solenoid Calculation

We use the three equations we derived earlier:

$$\begin{aligned} \varepsilon &= -L \cdot \frac{dI}{dt} \\ U &= \frac{1}{2} LI^2 \\ B_{\text{in}} &= \mu n I \end{aligned}$$

Plugging in the definition of L , we have

$$\begin{aligned} U &= \frac{1}{2} \mu n N A I^2 \\ &= \frac{1}{2} \mu n N A \cdot \frac{B^2}{\mu^2 n^2} \\ &= \frac{1}{2} N A \cdot \frac{B^2}{\mu n} \\ &= \frac{\ell A B^2}{2\mu}. \quad (n = \frac{N}{\ell}) \end{aligned}$$

Since the volume of the solenoid is $A \cdot \ell$, we have

$$\frac{U}{\text{volume}} = \frac{B^2}{2\mu}.$$

Note. This is analogous to the capacitor's energy density, given by

$$\frac{U}{\text{volume}} = \frac{\varepsilon}{2} E^2.$$

13 Lecture 13

13.1 R-L Circuits

These are circuits with both a resistor (R) and an inductor (L). This is going to be a time dependent circuit with a switch. The switch, resistor, inductor, and battery are all in series. At time $t = 0$, the switch is closed. Let the voltage across the battery be V . We want to find the current i through the circuit as a function of time t . If there was no inductor, the current would be $i(t) = \frac{V}{R}$.

In the inductor, we have an induced voltage $\varepsilon = -L \cdot \frac{di}{dt}$. Furthermore, we know that the current $i = 0$ when $t = 0$. By Kirchoff's Loop Rule, we know that the sum of the voltages in the loop must be zero, in other words

$$\begin{aligned} V - iR - \varepsilon &= 0 \\ V - iR - L \cdot \frac{di}{dt} &= 0 \\ \frac{di}{dt} &= \frac{V - iR}{L} \\ \frac{di}{V - iR} &= \frac{1}{L} dt \\ -\frac{1}{R} \ln(V - iR) &= \frac{1}{L} t + C_1 \\ \ln(V - iR) &= -\frac{R}{L} t + C_2 \\ V - iR &= C_3 e^{-\frac{R}{L} t} \\ iR &= V - C_3 e^{-\frac{R}{L} t} \\ i &= \frac{V}{R} - C_4 e^{-\frac{R}{L} t}. \end{aligned}$$

We also know that $i(0) = 0$, so

$$i(t) = \frac{V}{R} - \frac{V}{R} e^{-\frac{R}{L} t} \quad \text{or} \quad \frac{V}{R} \left(1 - e^{-\frac{R}{L} t}\right).$$

If we define a new time constant $\tau = \frac{L}{R}$, then we have

$$i(t) = \frac{V}{R} \left(1 - e^{-\frac{t}{\tau}}\right).$$

Note. This is analogous to the RC time constant for capacitors.

If we were to instead connect a charged inductor to a resistor, closing the switch would *discharge* the inductor. In this case, we would have

$$i(t) = \frac{V}{R} e^{-\frac{t}{\tau}}.$$

13.2 L-C Circuits

These are circuits with both an inductor (L) and a capacitor (C). We know that the voltage drop across the circuit is zero, just like before, so

$$-L \cdot \frac{di}{dt} - \frac{q}{C} = 0.$$

I'm too lazy to solve this differential equation, so just know that

$$q(t) = A \cos(\omega t + \phi),$$

where $\omega = \frac{1}{\sqrt{LC}}$. We may also write $q(t) = q_{\max} \cos(\omega t)$. The current is then

$$i(t) = \frac{dq}{dt} = -q_{\max} \cdot \omega \sin(\omega t).$$

14 Lecture 14

14.1 Transformers: Mutual Inductance

Consider a toroid with two different sections with loops of wire. Let the first section have N_1 turns and current i_1 , and the second section have N_2 turns and current i_2 . Since the toroid is made of iron, there is a magnetic field \vec{B} flowing through it (it is “captured” in the iron because $\frac{\mu}{\mu_0} \approx 1000$).

For our ideal transformer, we assume that all of the magnetic field \vec{B} goes around the toroid. The magnetic field is constant in the toroid, so Φ_m is the same for every loop. We have

$$\begin{aligned}\varepsilon_2 &= N_2 \cdot \frac{d\Phi_m}{dt} \\ \varepsilon_1 &= N_1 \cdot \frac{d\Phi_m}{dt} \\ \frac{\varepsilon_2}{\varepsilon_1} &= \frac{N_2}{N_1}.\end{aligned}$$

Note. This only works if the magnetic flux is time-varying (AC).

If we look at the power transfer, we get

$$P_{\text{in}} = VI = \varepsilon_1 i_1 = P_{\text{out}} = \varepsilon_2 i_2.$$

To find the current, we can manipulate the above equation to get

$$\frac{i_2}{i_1} = \frac{\varepsilon_1}{\varepsilon_2} = \frac{N_1}{N_2}.$$

For mutual inductance, we have

$$N_2 \Phi_{B2} \equiv M_{21} i_1 \quad \text{and} \quad N_1 \Phi_{B1} \equiv M_{12} i_2.$$

We won't prove this in this class, but $M_{12} = M_{21} = M$, which we call the mutual inductance.

15 Lecture 15

15.1 Why Would We Want an RLC Circuit?

1. RLC Circuits are useful when you want to generate a specific frequency *or* you want to select a specific frequency.

Note. Used in cell phones, internet, TV, radio, etc. for receiving and transmitting.

2. There is always some resistance in a circuit.
3. Electrical Engineering: All circuits also have capacitance and inductance.
4. Damped oscillation

15.2 RLC Circuits—Damped Oscillation

Suppose that at time $t = 0$, we close the circuit such that the charged capacitor, resistor, and inductor are in series. When the RLC circuit is underdamped, we get

$$-\frac{q}{c} - iR - L \cdot \frac{di}{dt} = 0.$$

Substituting $i = \frac{dq}{dt}$, we have

$$L \cdot \frac{d^2q}{dt^2} + \underbrace{R \cdot \frac{dq}{dt}}_{\text{damping term}} + \frac{1}{c} \cdot q = 0.$$

The general solution to this differential equation is given by

$$q(t) = q_0 e^{-\frac{t}{2L/R}} \cos(\omega t + \phi),$$

where $\omega = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$.

Note. You have two parameters in the above equation, namely q_0 and ϕ .

15.3 RLC Circuits—Forced Oscillation

16 Lecture 16

16.1 AC Circuits—Motivation and History

There is power loss in normal circuits when the voltage is low, so we use transformers with “high-voltage lines” in order to reduce the power loss (not possible with DC power) when getting electricity from the source to destination. We have the equation

$$\frac{P_{\text{loss}}}{P} = \frac{PR}{\varepsilon^2}.$$

Note. The power loss decreases with the square of the voltage, so high-voltage lines are used.

16.2 RMS Voltages and Currents

Note. RMS stands for “root mean square”.

Alternating currents follow a sinusoidal path, in other words

$$I = I_0 \sin(\omega t + \phi),$$

where $f = \frac{\omega}{2\pi}$, which is 60 Hz for Americans or 50 Hz for Europeans. If we square the current, we have

$$\begin{aligned} I^2 &= I_0^2 \sin^2(\omega t + \phi) \\ &= \frac{I_0^2}{2} (1 - \cos(2\omega t + 2\phi)), \end{aligned}$$

which is also sinusoidal (but stays positive). Furthermore, we know that the power in a resistor is $P = I^2 R$. The average power is thus

$$P_{\text{avg}} = (I^2)_{\text{avg}} R = \frac{I_0^2}{2} \cdot R = I_{\text{RMS}}^2 R. \quad (I_{\text{RMS}} := \frac{I_0}{\sqrt{2}})$$

Similarly, we define V_{RMS} by $V_{\text{RMS}} := \frac{V_0}{\sqrt{2}}$.

For $V_{\text{RMS}} = 120$ V, we have $V_0 = V_{\text{RMS}}\sqrt{2} \approx 170$ V (the voltage fluctuates between -170 and 170 volts).

16.3 The *Driven* RLC Circuit

We take a typical RLC circuit and add a time-varying EMF to it. There are two solutions to this:

1. Transitory (sinusoidal but amplitude approaching zero)
2. Steady-state (oscillates sinusoidally forever)

To make things simple for ourselves, we choose a phase such that $q = A \sin(\omega t)$. Then we know the voltage across the capacitor,

$$V_C = \frac{q}{C} = \frac{A}{C} \sin(\omega t).$$

The current can then be found by differentiating:

$$I = \frac{dq}{dt} = A\omega \cos(\omega t) = A\omega \sin\left(\omega t + \frac{\pi}{2}\right).$$

And so the voltage across the resistor is given by

$$V_R = RI = RA\omega \sin\left(\omega t + \frac{\pi}{2}\right).$$

Finally, we find the voltage across the inductor:

$$V_L = L \cdot \frac{dI}{dt} = -LA\omega^2 \sin(\omega t) = LA\omega^2 \sin(\omega t + \pi).$$

We use the mnemonic “ELI the ICE man”. For “ELI”, we see that in an inductor (L) the EMF precedes the current. And for “ICE”, we see that in a capacitor (C) the current precedes the EMF.

17 Lecture 17

17.1 Reactance in the Driven RLC Circuit

Using the equations from last class, notice that

$$\frac{V_C(\max)}{I(\max)} = \frac{A/C}{A\omega} = \frac{1}{\omega C} = \frac{V_C(\text{RMS})}{I(\text{RMS})}.$$

Definition. *Capacitive Reactance*

We define the *capacitive reactance* by the equation:

$$X_C := \frac{1}{\omega C}.$$

Similarly for an inductor, we have

$$\frac{V_L(\max)}{I(\max)} = \frac{LA\omega^2}{A\omega} = \omega L.$$

Definition. *Inductive Reactance*

We define the *inductive reactance* by the equation:

$$X_L := \omega L.$$

By Kirchoff's Loop Rule, we have

$$\begin{aligned} \varepsilon &= V_C + V_R + V_L \\ &= X_C I_{\max} \sin(\omega t) + I_{\max} R \sin\left(\omega t + \frac{\pi}{2}\right) + X_L I_{\max} \sin(\omega t + \pi) \\ &= I_{\max} \left(X_C \sin(\omega t) + R \sin\left(\omega t + \frac{\pi}{2}\right) + X_L \sin(\omega t + \pi) \right). \end{aligned}$$

Dividing both sides by I_{\max} , we get

$$\frac{\varepsilon}{I_{\max}} = X_C \sin(\omega t) + R \sin\left(\omega t + \frac{\pi}{2}\right) + X_L \sin(\omega t + \pi).$$

17.2 Phasors in the Driven RLC Circuit

If we graphed out all of these values as vectors and added them up, we would see that

$$\frac{\varepsilon_{\max}}{I_{\max}} = \sqrt{R^2 + (X_C - X_L)^2}.$$

Note. This is because if you pay attention to the angles in the original equation for $\frac{\varepsilon}{I_{\max}}$, you see that the middle term is perpendicular to the X_C and X_L terms, which are acting in opposition. Thus we may use the Pythagorean Theorem to get the above.

17.3 Impedance Z in the Driven RLC Circuit

Definition. *Impedance*

We define the *impedance* (units given in Ω) to be

$$Z := \sqrt{R^2 + (X_C - X_L)^2}.$$

Furthermore, for the initial phase, we have

$$\tan \phi = \frac{X_L - X_C}{R}.$$

The power consumed by this circuit is given by

$$P_{\text{avg}} = I_{\text{RMS}} V_{\text{RMS}} \cdot \underbrace{\cos \phi}_{\text{“Power factor”}}.$$

Note. To maximise the power of the motor, we want $\cos \phi$ to be as close to 1 as possible. Thus we should add just the right amount of capacitance.

18 Lecture 18

Note. Impedance is a generalisation of resistance for AC circuits.

From last lecture, we learned that

$$I_{\max} = \frac{\varepsilon_{\max}}{Z} = \frac{\varepsilon_{\max}}{\sqrt{R^2 + \left(\frac{1}{\omega C} - \omega L\right)^2}}.$$

If ω can vary, the maximum value of I_{\max} occurs when $\frac{1}{\omega C} = \omega L$ (and so $I_{\max} = \frac{\varepsilon_{\max}}{R}$). Note that solving for ω yields

$$\omega = \frac{1}{\sqrt{LC}}, \quad \text{or} \quad f = \frac{1}{2\pi\sqrt{LC}}.$$

When R is small and $\omega = \frac{1}{\sqrt{LC}}$, I_{\max} approaches infinity. Furthermore, when the frequency is high the inductor dominates, and when it is low the capacitor dominates.

18.1 Low-pass Filter

Consider an AC circuit that consists of a voltage source ε , and a resistor and capacitor in series (order matters!). We consider the output of this circuit to be the voltage drop across the capacitor, i.e. V_C . Since there is no inductor, we know that

$$Z = \sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}.$$

Then we have

$$\begin{aligned} V_{C,\max} &= X_C \cdot I_{\max} \\ &= \frac{1}{\omega C} \cdot \frac{\varepsilon_{\max}}{Z} \\ &= \frac{1}{\omega C} \cdot \frac{\varepsilon_{\max}}{\sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}} \\ &= \frac{\varepsilon_{\max}}{\sqrt{(RC\omega)^2 + 1}}. \end{aligned}$$

Notice that when ω is small ($RC\omega \ll 1$), we have that $V_{C,\max} \approx \varepsilon_{\max}$, and that when ω is large ($RC\omega \gg 1$), $V_{C,\max} \approx 0$. Thus we see that this circuit is a “low-pass filter” because it allows lower frequencies to get through the circuit virtually unchanged, while mitigating or removing higher frequencies.

18.2 High-pass Filter

There are two examples of this: we could switch the order of the resistor and capacitor from the last section (so the output is V_R instead of V_C), or we could swap the capacitor with an inductor. Since there is no capacitor, we have

$$Z = \sqrt{R^2 + (\omega L)^2}.$$

Thus we have

$$\begin{aligned} V_{L,\max} &= X_L \cdot I_{\max} \\ &= \omega L \cdot \frac{\varepsilon_{\max}}{\sqrt{R^2 + (\omega L)^2}} \\ &= \frac{\varepsilon_{\max}}{\left(\frac{R}{\omega L}\right)^2 + 1}. \end{aligned}$$

Notice that when ω is small ($\frac{R}{\omega L} \gg 1$), we have $V_{L,\max} \approx 0$, and when ω is large ($\frac{R}{\omega L} \ll 1$), $V_{L,\max} \approx \varepsilon_{\max}$. This circuit is thus a “high-pass filter” because it allows high frequencies through while blocking lower frequencies.

19 Lecture 19

19.1 Displacement Current

Recall Ampere's Law:

$$\oint_{\text{loop}} \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{encl}}.$$

When we say I_{encl} to mean enclosed current, we mean that the current goes through the surface. The main thing to take note of is that the surface doesn't need to be planar—it can be any surface.

Consider a current flowing into a capacitor, with an amperium loop that goes around half of the capacitor. There is seemingly no current flowing across the capacitor, a contradiction. What Maxwell notices is that charges build up on the plates of the capacitor—maybe a changing \vec{E} field could produce a current. He modified Ampere's Law to get

$$\oint_{\text{loop}} \vec{B} \cdot d\vec{\ell} = \mu_0 (I_{\text{encl}} + I_{\text{disp}}).$$

His idea was that I_{disp} should be proportional to $\frac{dE}{dt}$ and proportional to the area A of the parallel plates.

Remember that for capacitors, $E = \frac{V}{d}$ and $C = \epsilon_0 \cdot \frac{A}{d}$. Thus

$$\begin{aligned} A \cdot \frac{dE}{dt} &= \left(\frac{Cd}{\epsilon_0} \right) \cdot \frac{1}{d} \cdot \frac{dV}{dt} \\ &= \frac{1}{\epsilon_0} C \cdot \frac{dQ}{dt} \cdot \frac{1}{C} \\ &= \frac{1}{\epsilon_0} \cdot \frac{dQ}{dt}. \end{aligned}$$

Rearranging the above, we get

$$\frac{dQ}{dt} = I_{\text{disp}} = \epsilon_0 \cdot A \cdot \frac{dE}{dt}.$$

Thus Maxwell's modification of Ampere's Law takes the form

$$\oint_{\text{loop}} \vec{B} \cdot d\vec{\ell} = \mu_0 \left(I_{\text{encl}} + \epsilon_0 A \cdot \frac{dE}{dt} \right).$$

Note. We can substitute $A \cdot \frac{dE}{dt}$ for $\frac{d\Phi_E}{dt}$.

This forms a parallel with Faraday's Law, which states that a changing Φ_B generates \vec{E} , whereas this says that a changing Φ_E generates \vec{B} .

Note. A magnetic field (although possibly not large) is generated when charging up a capacitor, parallel to the plates of the capacitor.

Note. This exhibits *exactly* the same behaviour as the wire of radius R from Lecture 6.

19.2 Maxwell's Equations

1. Gauss' Law for \vec{E} :

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{\text{encl}}}{\epsilon_0}$$

2. Gauss' Law for \vec{B} :

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

3. Faraday's Law for a stationary integration path:

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

4. Ampere's law for a stationary integration path:

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 \left(i_C + \varepsilon_0 \frac{d\Phi_E}{dt} \right)_{\text{encl}}$$

Note. In empty space (with no charges nor currents), Maxwell's equations are highly symmetric.

19.3 Plane Electromagnetic Waves (in Vacuum)

19.3.1 Recap on Waves

Given a “wave number” k , we have the equation

$$f(x) = A \sin(kx).$$

We know that the wavelength must satisfy $k\lambda = 2\pi$, so $\lambda = \frac{2\pi}{k}$. If we take $f(x - vt)$, the wave is moving to the *right*. If the function is $f(x + vt)$, then the function is moving to the *left*.