We’ve seen that electrical current can produce magnetic fields.

Can magnetic fields be used to produce electrical current?

The answer, as discovered by Michael Faraday, is YES:

Applications include electrical generators, ground-fault interrupters, microphones
Faraday’s Experiments
Faraday’s Experiments

Close switch: immediately after switch closed, ammeter measures current in secondary circuit
Faraday’s Experiments

After the switch has been closed for a while, ammeter has returned to zero.
Faraday’s Experiments

Open switch: immediately after opening switch, ammeter registers a current in the OPPOSITE direction.
Faraday’s Experiments

After the switch has been opened for a while, ammeter has returned to zero.
Conclusions from Faraday’s experiment:

B-field going from OFF to ON -- induces a current in secondary circuit

B-field going from ON to OFF -- induces a current (opposite sign) in secondary circuit.

B-field level constant (zero or non-zero) -- no current induced!

Conclusion: The B-field itself does not induce any current -- only a CHANGE in B-field.
Electromagnetic Induction

While a magnet is moving toward a loop of wire, the ammeter shows the presence of a current.

While the magnet is held stationary, there is no current.

While the magnet is moving away from the loop, the ammeter shows a current in the opposite direction.
Electromagnetic Induction

If the magnet is held stationary and the LOOP is moving, you get the same effect.

A current is induced whenever there exists RELATIVE motion between the magnet & loop.

Direction of current depends on direction of motion.
Magnetic Flux

Assume B-field is uniform.
Area of loop = A.

Magn. Flux $\Phi_B$ through an area A:

$\Phi_B = B\perp A = BA\cos\theta$

SI unit: Weber (Wb) = $T\times m^2$

$\Phi_B$ is proportional to the total number of lines passing through the loop
Magnetic Flux

Edge view of loop in uniform B-field:

\( \theta = 0^\circ: \Phi_B \) is maximized: \( \Phi_B = BA \)

\( \theta = 90^\circ: \Phi_B \) is zero

Change B-field direction so \( \theta = 180^\circ: \Phi_B = -BA \)
Example: A hexagon-shaped loop with area 0.5 $m^2$ is placed in a uniform B-field of 2 T such that the loop’s normal is parallel to B. Calculate $\Phi_B$.

$$\Phi_{B1} = BA \cos \theta = BA \cos 0^\circ = (2T)(0.5 \ m^2) = 1.0 \ \text{Wb}$$

Suppose the B-field strength is halved. Calculate $\Phi_B$ now. Calculate $\Delta \Phi_B$.

$$\Phi_{B2} = \Phi_{B1} / 2 = 0.5 \ \text{Wb}$$

$$\Delta \Phi_B = \Phi_{B2} - \Phi_{B1} = (1.0 - 0.5)\text{Wb} = 0.5 \ \text{Wb}$$
Example: Go back to B=2.0 T. Suppose the loop is rotated 45° as shown. Calculate $\Phi_B$ & $\Delta \Phi_B$.

$$\Phi_{B2} = BA \cos \theta = BA \cos 45^\circ = (2\text{T})(0.5 \text{ m}^2)(0.707) = 0.707 \text{ Wb}$$

$$\Delta \Phi_B = \Phi_{B2} - \Phi_{B1} = (1.0-0.707) \text{ Wb} = 0.293 \text{ Wb}$$
No magnetic monopoles

If we were to apply an analog of Gauss’ law to MAGNETIC field lines for a Gaussian surface in any region of space, we’d find:

No magnetic monopoles means there’s no “magnetic charge” to enclose

All B-field lines which enter the surface, must also leave it. So net $\Phi_B$ is zero.
FARADAY’S LAW OF MAGNETIC INDUCTION

The instantaneous EMF induced in a circuit equals the time rate of change of MAGNETIC FLUX through the circuit.

If a circuit contains N tightly wound loops and the magnetic flux changes by $\Delta \Phi_B$ during a time interval $\Delta t$, the average EMF induced is given by Faraday’s Law:

$$\varepsilon = -N \frac{\Delta \Phi_B}{\Delta t}$$
FARADAY’S LAW OF MAGNETIC INDUCTION

$$\Phi_B = BA \cos \theta$$

So EMF can be induced by changing any of $B$, $A$ or $\theta$.

- **B**: increase/decrease B-field strength
- **A**: change area of loop inside B-field
- **\( \theta \)**: rotating coil in the field.
A singular circular coil with a radius of 20 cm is in a B-field of 0.2 T with the plane of the coil perpendicular to the field lines. If the coil is pulled out of the field in 0.30 s find the magnitude of the average emf induced during this interval.

\[ \varepsilon = -N \frac{\Delta \Phi_B}{\Delta t} = -N \frac{\Phi_{B2} - \Phi_{B1}}{\Delta t} \]

\[ \Phi_{B1} = BA = (0.2T)(\pi(0.2m)^2) = 0.025 \text{ Wb} \]

\[ \Phi_{B2} = 0 \]

\[ N = 1 \]

\[ \varepsilon = 1(0.025\text{Wb})/(0.3\text{s}) = 0.084\text{V}. \]
Another example:
A 25-turn circular coil of wire with a diameter of 1.0 m is placed with its axis aligned with the Earth's B-field, which has a magnitude of \(0.5 \times 10^{-4} \text{T} = 0.5 \text{G}\). During a time interval of 0.2 s, it's flipped 180°. What's the magnitude of the average EMF generated during this time?

\[
\Phi_{B1} = BA \\
\Phi_{B2} = -BA \\
\Delta \Phi_B = \Phi_{B2} - \Phi_{B1} = -2BA \\
\varepsilon = -N \Delta \Phi_B / \Delta t = -25(2BA) / \Delta t \\
\varepsilon = -25(2)(0.5 \times 10^{-4} \text{T})(\pi(0.5 \text{m})^2) / 0.2 \text{ s} \\
\varepsilon = 9.8 \times 10^{-3} \text{V}.
\]
Application: Electric Guitars

changing magnetic flux induces voltage in pickup coil
Microphones / acoustic pick-ups

(me in 1998, BTW)
Ground Fault Interrupters

(a)

Hair dryer

Wall outlet

Ground fault interrupter

120 V
Ground Fault Interrupters

If a connection to ground is accidently made…
Ground Fault Interrupters

... the ground fault interrupter shuts off the device
Ground Fault Interrupters

Under normal operation, $I_1$ & $I_2$ are equal and opposite. Net B-field through Fe ring is zero.
Ground Fault Interrupters

But if there’s a short …
Ground Fault Interrupters

… wire 1 induces a net B-field in Fe ring
Ground Fault Interrupters

… wire 1 induces a net B-field in Fe ring

The sudden increase in B induces a current in sensing coil, which triggers the circuit breaker
Lenz’s Law:

\[ \mathcal{E} = -N \frac{\Delta \Phi_B}{\Delta t} \]

Determines the direction the induced current flows.

The current caused by the induce EMF travels in the direction that creates a magnetic field whose flux opposes the change in the original magnetic flux.

i.e., the induced current will flow to try to maintain the original magnetic flux thru the loop.
Lenz’s Law:

Induced B-field $B_{\text{ind}}$ “shores up” original $\Phi_B$ if original $\Phi_B$ is shrinking with time, or opposes the original $\Phi_B$ if original $\Phi_B$ is growing with time.

$\Phi_B$ increasing with time. $B_{\text{ind}}$ points in opposite direction to $B_{\text{orig}}$. 
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$\Phi_B$ (now defined as flux towards the left) is decreasing with time. $B_{\text{ind}}$ points in same direction to $B_{\text{orig}}$. 
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Example 20.2

Given: a square coil with 25 turns. Each side is 1.8 cm. The total resistance of the coil 0.35 Ω. A uniform B-field is applied in the +z direction.

a) If B changes from 0 T to 0.5 T in 0.8 s, find $\varepsilon_{\text{ind}}$.

First, find $\Phi_{\text{B initial}}$ & $\Phi_{\text{B final}}$:

$\Phi_{\text{B initial}} = B_{\text{init}} A \cos 0^\circ = 0$

$\Phi_{\text{B final}} = B_{\text{final}} A \cos 0^\circ = 0.5 \text{T}(0.018 \text{m})^2 = 1.62 \times 10^{-4} \text{ Wb}$

$\Delta \Phi_B = \Phi_{\text{B final}} - \Phi_{\text{B initial}} = 1.62 \times 10^{-4} \text{ Wb}$

Then use Faraday’s Law:

$\varepsilon_{\text{ind}} = -N \frac{\Delta \Phi_B}{\Delta t} = -25(1.62 \times 10^{-4} \text{ Wb}) / 0.8 \text{ s} = -5.06 \times 10^{-3} \text{ V}$
Example 20.2

Given: a square coil with 25 turns. Each side is 1.8 cm. The total resistance of the coil 0.35 Ω. A uniform B-field is applied in the +z direction.

b) Find the magnitude & direction of the current induced while the field is changing.

Use Ohm’s Law to find the magnitude of I

\[ I = \frac{\Delta V}{R} = \frac{5.06 \times 10^{-3} \text{ V}}{0.35 \Omega} = 1.45 \times 10^{-2} \text{ A} \]

The direction is found from Lenz’s Law: \( \vec{B} \) is increasing up through the loop. \( \Phi_B \) is also positive and increasing. The induced B-field will thus point downward. The induced current will circulate clockwise (right-hand rule with thumb pointing downward).
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