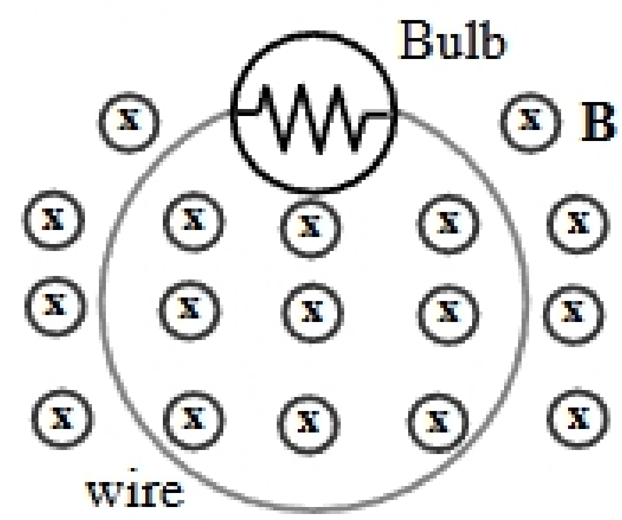
## Faraday's Law:

A steady **E** field pushes charges around, makes *currents* flow. We've used the word "EMF" for this occasionally, an EMF is any voltage difference capable of generating electric currents.
Think of EMF = $\Delta V$ (=E $\Delta$**x**, remember that relation between V and E?)
(Note: batteries have an EMF, but resistors do NOT. Even though an R can have a voltage difference across it, it is not *generating* it! Resistors don't make currents spontaneously flow, batteries can.)

Michael Faraday, a British physicist (at the same time as Joseph Henry, an American, but Faraday published first) about 180 years ago discovered a remarkable new property of nature:

**Changing magnetic fields (not steady ones) can make EMF's.**
In other words, a time-varying **B** field can make currents flow.

Imagine a wire loop sitting in a **B** field, like this:




If the **B** field is steady then there is NO CURRENT, the bulb is dark.

But, if the **B** field *changes* with time, the bulb lights up, a current flows through that wire (!)

You might do this by e.g. just moving a big magnet closer, or farther away (yes, weakening the **B** field is still a *change*)... or move the coil itself closer (or farther) from the magnet face.

There's no battery here, no external voltage source, but the bulb still glows! This effect is surprising, it's something new...

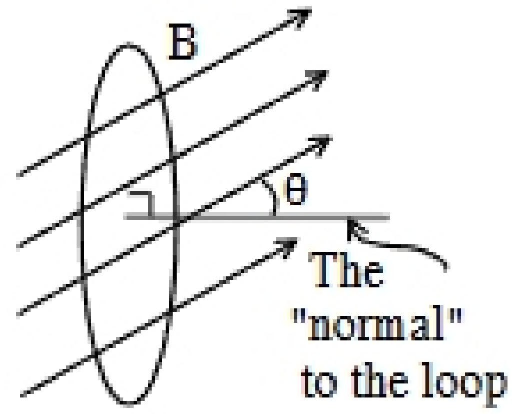
Faraday spent only 10 days of (intensive) work on these experiments, but they changed the world radically.
This is how most of modern society's electricity is now generated!

Faraday worked out an equation (Faraday's Law) which quantifies the effect (how *much* current do you get?)
But before we can write it down, we need to first define one relevant quantity we haven't seen yet.

Imagine a **B** field whose field lines "cut through" or "pierce" a loop.

Define θ as the angle between **B** and the "normal" or "perpendicular" direction to the loop.

We will now define a new quantity, the **magnetic flux through the loop**, as




Magnetic Flux, or $\Phi = B_\perp A = B\,A\cos\theta$

$B_\perp$ is the component of B perpendicular to the loop:

$B_\perp = B\cos\theta$.

The UNIT of magnetic flux = $[\Phi]$ = T m^2 = Weber = Wb.

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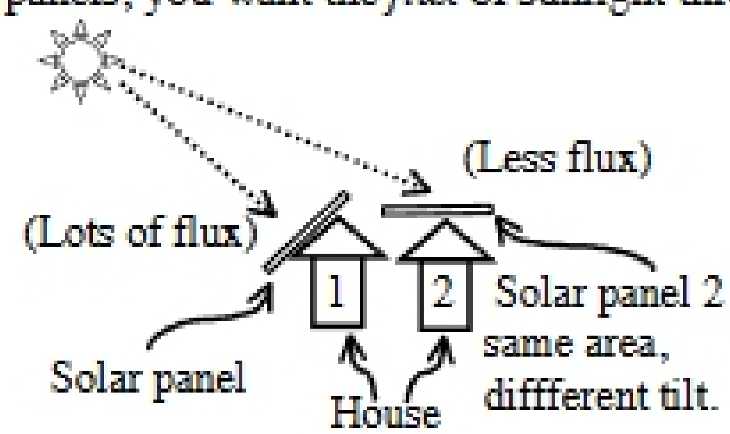
Flux is a useful concept, used for *other* quantities besides B, too. E.g. if you have solar panels, you want the *flux* of sunlight through the panel to be large. House #2 has poorly designed panels. Although the AREA of the panels is the *exact same*, and the sunshine brightness is the *exact same*, panel 2 is less useful: fewer light rays "pierce" the panel, there is less FLUX through that panel.

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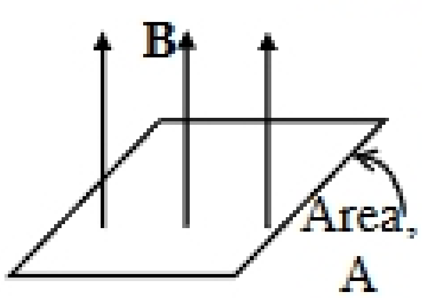
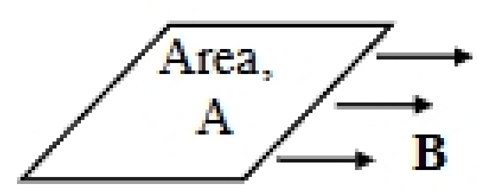
<u>Examples of calculating magnetic flux:</u>

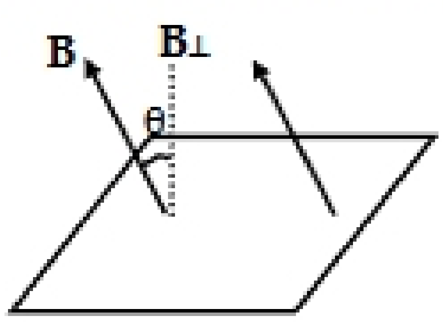



Here (picture to the left) $\Phi = B\,A$, because B is perpendicular to the area. ($\theta=0$)

Here (picture to the right), $\Phi = 0$, because B is parallel to the area. ($\theta=90$.)

No flux: the B field lines don't "pierce" this loop at ALL, they "skim" past it... (That's zero flux!)




Here, (picture to the left), $\Phi = B\,A\cos\theta$. The flux is reduced a bit because it's not perfectly perpendicular.

**Faraday's Law**: The induced EMF in any loop is

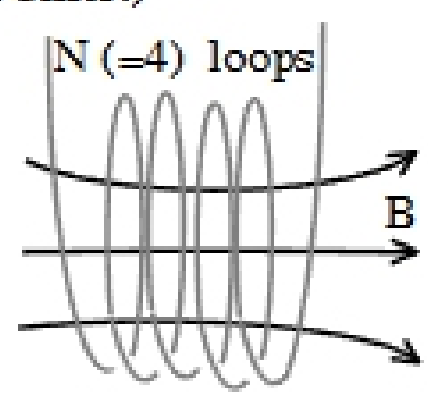
EMF = $-\Delta\Phi/\Delta t$ ($\Phi$ is magnetic flux, t is time.)

• If you put a loop into a B field, and then *change the flux* through that loop over time, there will be an EMF (basically, a voltage difference) induced. Current flows, if you have a *conducting* loop.

• The formula says it is only the *change* in flux through the loop that matters. A huge B field (lots of flux) does NOT make the EMF, it's the *change* in B with time that does the trick.

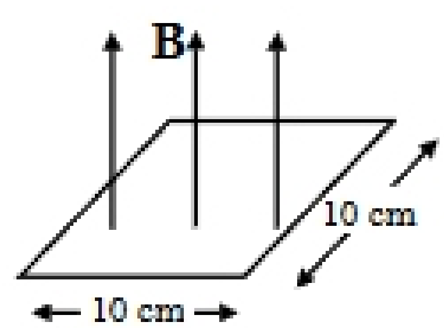
• This equation has not been derived - it's just an experimental fact!

• Units are $\frac{\text{Wb}}{\text{sec}} = \frac{\text{Tm}^2}{\text{sec}} = \left(\frac{\text{N}}{\text{Am}}\right)\frac{\text{m}^2}{\text{sec}} = \frac{\text{Nm}}{\text{Asec}} = \frac{\text{J}}{\text{C}} = \text{Volt}$ (yikes! It's a mess, but it works out. The formula gives the correct units.)




• If you were to "pile up" N loops on top of each other, the effective flux will be increased by a factor of N, the formula becomes EMF=$-N\Delta\Phi/\Delta t$. (Do you see why?)

• Since $\Phi = B\,A\cos\theta$, *you can change the flux in many ways: you could change B,* or *area,* or *the angle between **B** and the loop.*




**Example:** **B** is perp. to this loop, $\theta=0$, as shown. (Remember, $\theta$ is the angle from the *normal*)
The area is A= (0.1m)^2 = .01 m^2
Suppose B is 1 Tesla, as shown, and then you turn it off, taking a time of 2 seconds to do so...

Faraday's law says there will be an "induced EMF", or voltage, around the loop,
$|\text{EMF}|=|\Delta\Phi/\Delta t|$ = [ (1 T * 0.01 m^2) cos(0) - 0 / (2 sec) = .005 V

If you had N=1000 coils (loops) of wire, all stacked (coiled) up around that same perimeter, you'd get |EMF|=5 V, enough to light up a small bulb. But remember, you'd only have this voltage for those 2 seconds while B was changing! Once B reaches 0 (and presumably stays there), there is no more *change*, and so |EMF| goes back to 0.