Magnetic flux and induction – a new teaching concept

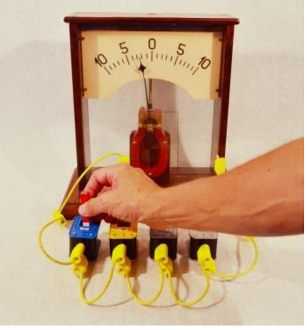
Traditionally, the laws of induction are shown by qualitative experiments, eq. by moving magnets in or out of coils and measure the maximal induced voltage. Using instrumental amplifiers it is now possible to make quantitative measurements, and thereby verify Faraday’s Law of Induction. The same equipment also gives us the opportunity to measure the magnetic flux of magnets passing through coils. In this way we can establish and verify Faraday’s law of induction and Lenz’ law on basis of experiments. Another phenomenon depending on Faraday’s law of induction is the producing of eddy currents in conducting materials, either when moving magnets near the material or when moving the conducting material relative to the magnet. Using video cameras we can measure the time needed for magnets to fall through conducting pipes, and thereby show that the size of the braking eddy currents depends on the magnets strength, the dimensions of the magnet and the conducting tube, and on the resistivity of the conducting material.

Faraday’s Law of Induction: The classic way

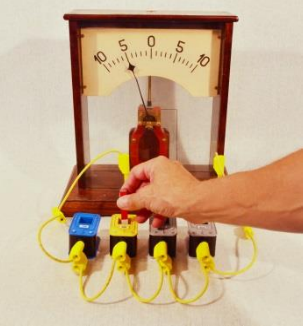
Traditionally, the laws of induction are shown by qualitative experiments, eq. by moving bar magnets in or out of coils and measure the maximal induced voltage by means of a galvanometer, acting as an analog voltmeter.

It is also possible to move the coils relative to the magnets, change the shape or the size of the coils, or change the direction of the magnet relative to the coils. You could also use a coil to produce the magnetic field.

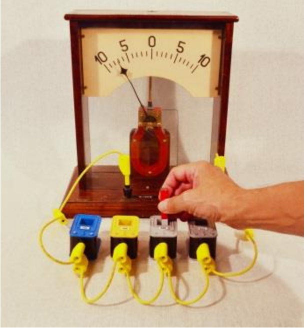
The next four pictures shows the maximal induced voltage when moving a bar magnet into coils with 200, 400, 600 and 800 turns. The coils are connected in series.



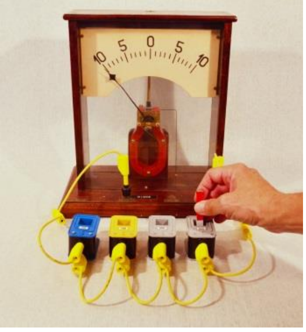
200 turns



400 turns



600 turns



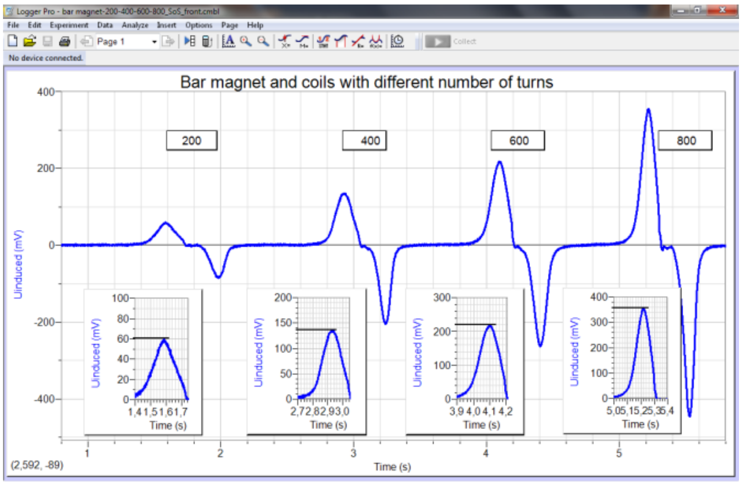
800 turns

We see that the maximal induces voltage is proportional to the number of turns in the coils.

The results above looks like a quantitative result, but it isn’t. In fact, you need a skilled experimenter to get nice results in experiments like this! The problem is *how to move the magnet*.

Faraday’s Law of Induction: New opportunities

The new way is to use an instrumental amplifier (eg. Vernier INA-BTA) to measure the induced voltage.



The magnet induces a voltage in one direction when entering the coil, and in the opposite direction when leaving the coil.

The maximum induced voltage depends on the number of turns in the coil.

In the results shown the maximum voltages are not directly proportional to the number of turns in the coils.

Explanation: The experimenter was not able to move the magnet into the four different coils in the same way. Again: The problem is *how to move the magnet*.

Instead of moving the magnets, one could move the coil relative to the magnet, change the size (eg. the length) of the coil, the shape of the coil, or the angle between the magnet and the coil.

Faraday’s Law of Induction: Magnetic flux

Faradays law of induction states that

$$U_{induced} = -\frac{d\Phi}{dt} = -\Phi'$$

Φ is the magnetic flux produced by the magnetic field B through a surface with area A. The minus sign in Faraday’s law of induction states that *The direction of the induced voltage is such that it tends to oppose the change that produced it.*

By calculus we have

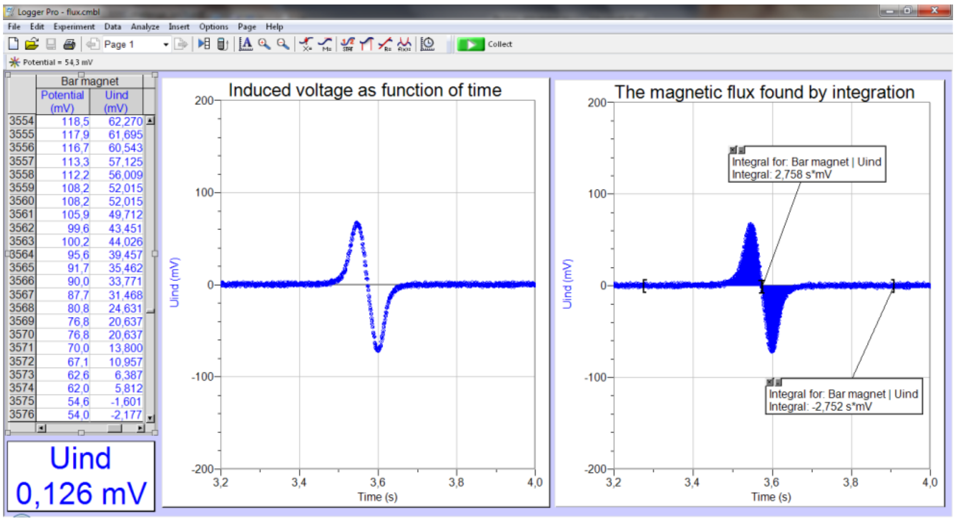
$$\Phi = -\int U_{induced}(t)dt$$

which means that we can calculate the magnetic flux Φ by integration.

To the right: We measured the induced voltage from a magnet falling through a coil, and found the values of the two integrals:

2,758 mV·s and
-2,752 mV·s

The numerical values equals as expected.



Potential = 54,3 mV

	Bar magnet	
	Potential (mV)	Uind (mV)
3554	118,5	62,270
3555	117,9	61,695
3556	116,7	60,543
3557	113,3	57,125
3558	112,2	56,009
3559	108,2	52,015
3560	108,2	52,015
3561	105,9	49,712
3562	99,6	43,451
3563	100,2	44,026
3564	95,6	39,457
3565	91,7	35,462
3566	90,0	33,771
3567	87,7	31,468
3568	80,8	24,631
3569	76,8	20,637
3570	76,8	20,637
3571	70,0	13,800
3572	67,1	10,957
3573	62,6	6,387
3574	62,0	5,812
3575	54,6	-1,601
3576	54,0	-2,177

Uind
0,126 mV

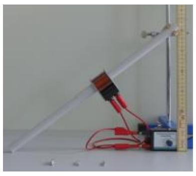
Integral for: Bar magnet | Uind
Integral: 2,758 s*mV

Integral for: Bar magnet | Uind
Integral: -2,752 s*mV

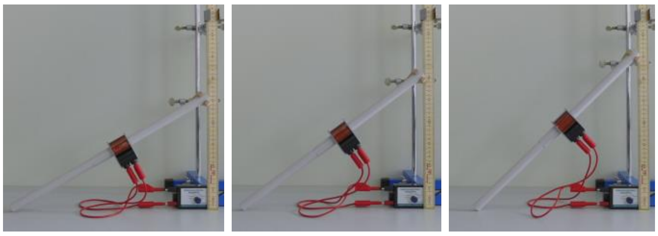
Verifying Faraday’s law of Induction in three steps

Faraday’s law of induction can be verified by a setup in three steps. The setup consist of a PVC pipe (length 50cm) inside the coil, and small (but strong) neodymium magnets that slide through the pipe:

1) PVC pipe with one end raised 30cm, one magnet
   - Slide the magnet through the PVC pipe, use coils with 200, 400, 600 and 800 turns.

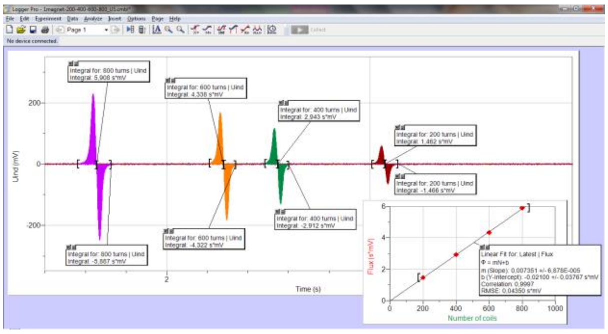


2) PVC pipe with one end raised 30cm, coil 800 turns
   - Slide 1, 2 or 3 neodymium magnets through the pipe. When using 2 or 3 magnets, they must be made “parallel” to enhance the magnetic strength

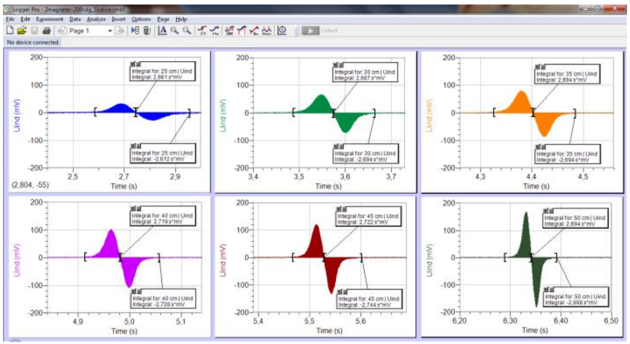


3) PVC pipe, 1 magnet, coil 800 turns
   - Change the velocities of the magnet by raising one end of the PVC pipe to different heights.

Results for step 1 and step 3:



Step 1: The magnetic flux Φ is directly proportional to the number of turns in the coil.

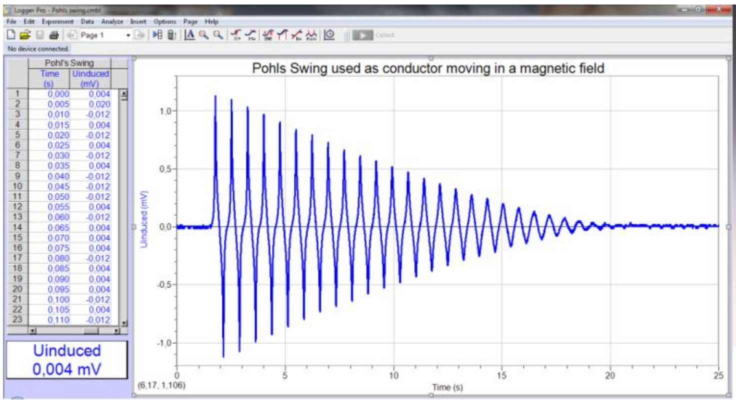


Step 3: Changing the velocity of the magnet doesn’t change the magnetic flux Φ.

The minus sign in Faraday’s law of induction is easiest shown in the next experiment.

Faraday’s Law of Induction: Moving the conductor

Using an experimental apparatus known as “Pohl’s Swing” (which is ordinarily used to show the direction of the Lorentz force on a conductor in a magnetic field), it is easy to verify the minus sign in Faraday’s law of induction.



Pohl's Swing

	Time (s)	Uinduced (mV)
1	0,000	0,004
2	0,005	0,020
3	0,010	-0,012
4	0,015	0,004
5	0,020	-0,012
6	0,025	0,004
7	0,030	-0,012
8	0,035	0,004
9	0,040	-0,012
10	0,045	-0,012
11	0,050	-0,012
12	0,055	0,004
13	0,060	-0,012
14	0,065	0,004
15	0,070	0,004
16	0,075	0,004
17	0,080	-0,012
18	0,085	0,004
19	0,090	0,004
20	0,095	0,004
21	0,100	-0,012
22	0,105	0,004
23	0,110	-0,012

Uinduced
0,004 mV

Lenz' Law

Lenz' law states that *The induced current produces a magnetic field which tends to oppose the change in the magnetic flux that induces the current.*

This is in good agreement with the minus sign in Faradays law of induction:
If you push a magnetic pole into a conducting coil, the induced voltage will produce a current in a direction creating a magnetic field in the opposite direction. The direction is easily found by the right hand rule.

Eddy currents

Eddy currents are produced by magnets moving near conductors, magnetic fields that change near conductors, or by conductors moving near magnets.
By using video analysis or dataloggers it is now possible to make quantitative measurements on these phenomena.

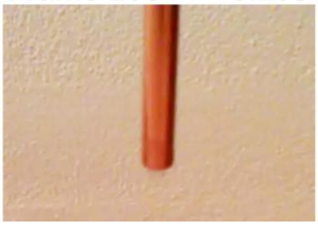
1) Magnets falling through conducting pipes (eg. aluminum, copper or brass)

We used video from a smartphone to find the time used for a magnet to fall through a conducting pipe (copper, length 1,00m). By identifying the frames where the magnet enters and leaves the conducting pipe, it is possible to determine the time used for the magnet to fall through the pipe and calculate the velocity.

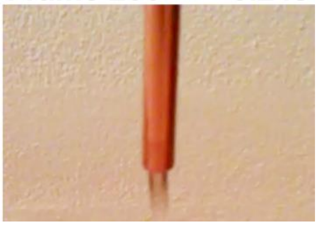
Frame 046 **1.84s**

Frame 047 **1.88s**

Frame 205 **8.20s**



Frame 206 **8.24s**



Finding $t_{enter} = 1{,}86s \pm 0{,}02s$ and $t_{leave} = 8{,}22s \pm 0{,}02s$

we get $t_{fall,Copper} = 6{,}56s \pm 0{,}04s \Rightarrow v_{fall,Copper} = 1{,}52m/s \pm 0{,}01m/s$

We bring tubes of different materials (aluminum, copper, brass), to show that the velocity depends on the material, the radius and the wall thickness of the tubes.

2) Magnet rolling through an U- or H-shaped profile

Use video analysis to show that the velocity is constant.

3) Waltenhofens pendulum

Homemade version using strong neodymium magnets instead of the traditionally used electromagnets.

Closing remarks

The concept is developed as part of the reintroduction of electric and magnetic fields in the danish curriculum. The experiments were developed for 17-18 years old students on A-level, but many of the experiments can be used on lower levels too. The danish students learn calculus. The use of calculus to find "the new concept" for experiments with Faraday's law of induction works well for these students.

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