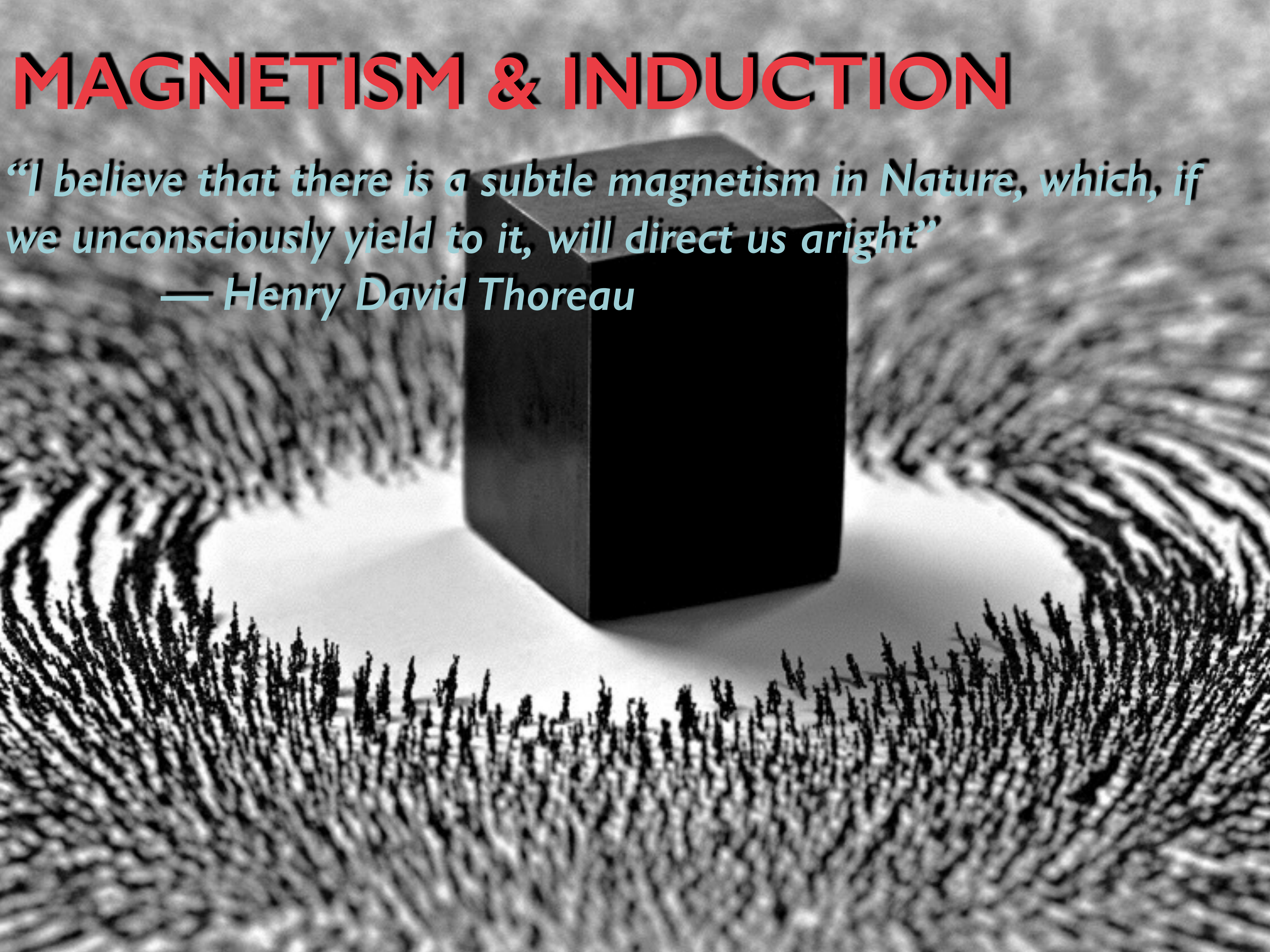
# MAGNETISM & INDUCTION



> *"I believe that there is a subtle magnetism in Nature, which, if we unconsciously yield to it, will direct us aright"*
>
> *— Henry David Thoreau*

# MAGNETS

- **Ancient civilizations discovered special rocks in a region known as Magnesia, rocks which would attract each other when brought close**

- **These rocks were dubbed “magnets” after their place of discovery**

# MAGNETIC POLES

- Every magnet, no matter its shape, has two ends or faces, called ***poles***
    - The poles are where the magnetic effect is the strongest
- If a magnet is suspended by a thread, one pole will always point towards the north
- By the 11th Century the Chinese were already taking advantage of this effect to aid in navigation

# MAGNETIC POLES

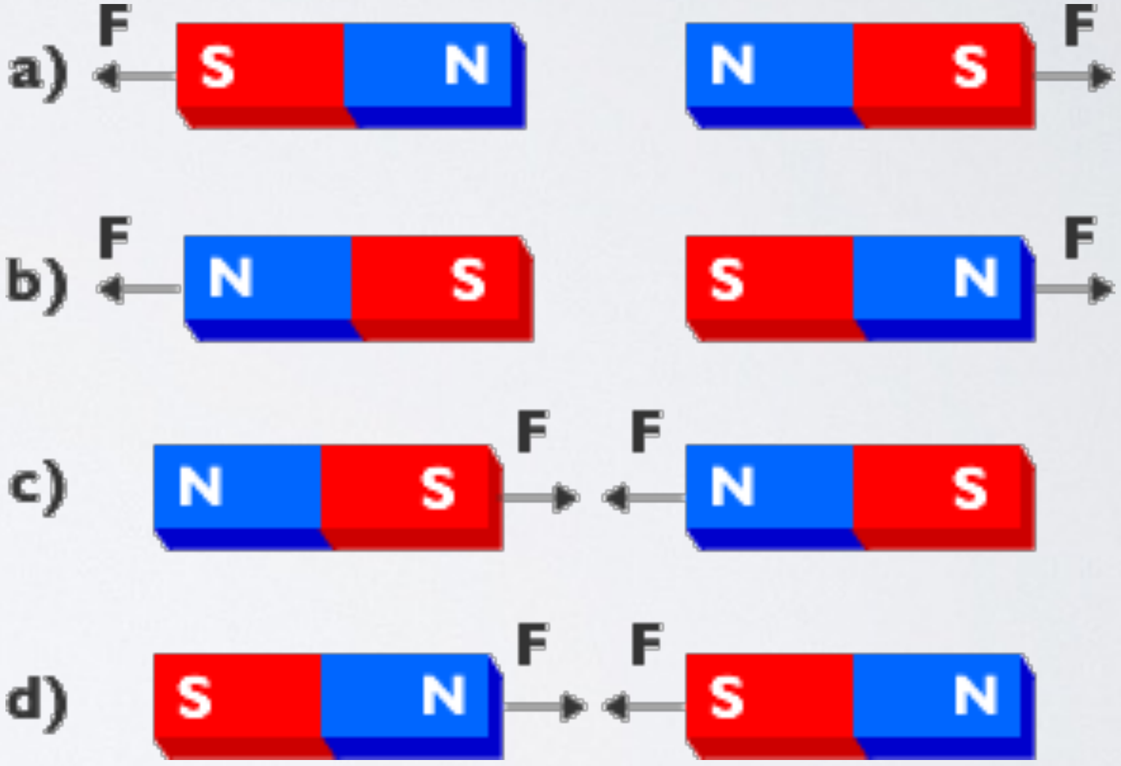
- Every magnet has a ***north pole*** and a ***south pole***

- Like poles repel

- Unlike pole attract

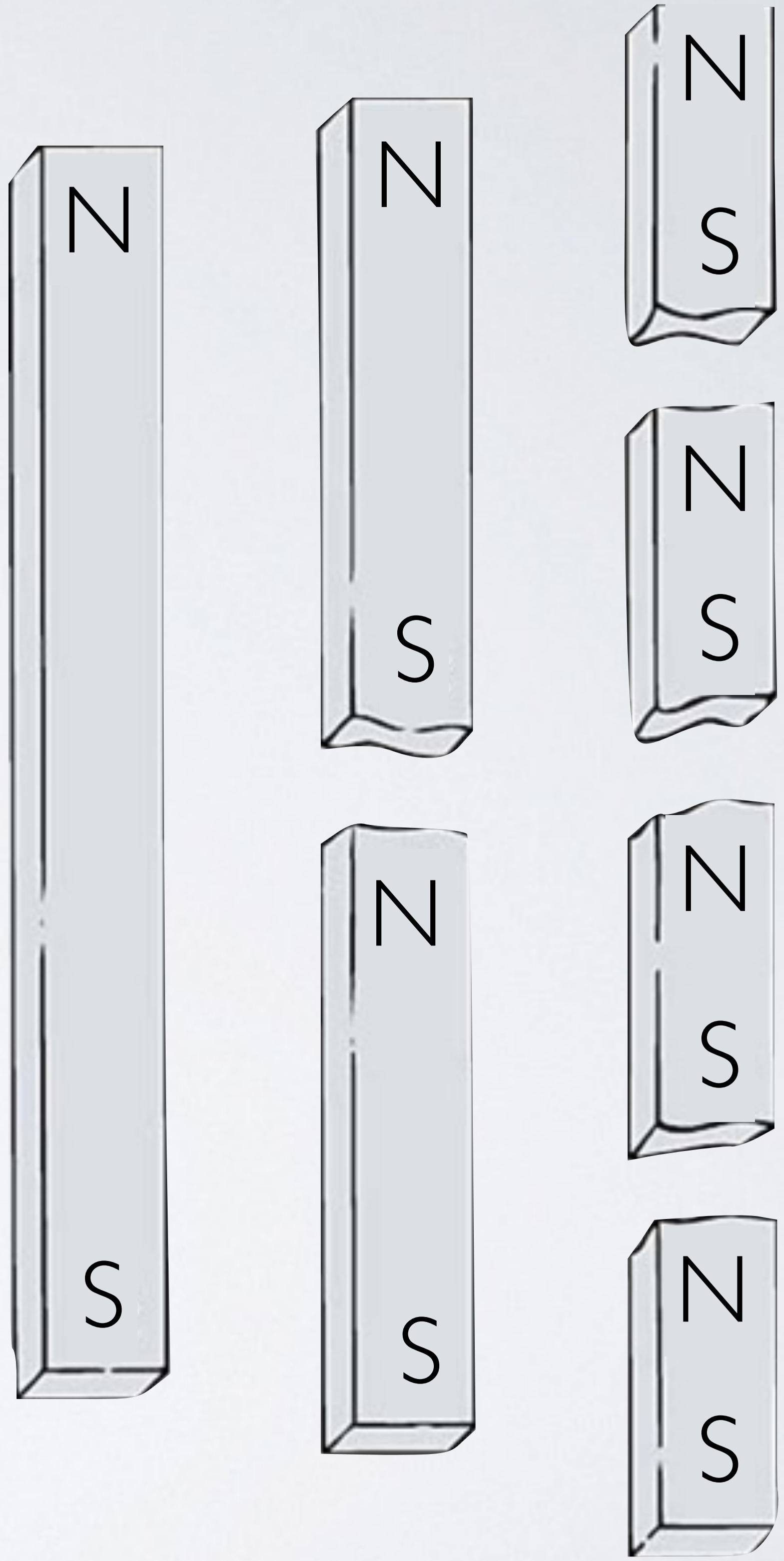
  - A lot like electric charge

  - ***But with one very important difference***



# MAGNETIC POLES

- While you can easily separate positive from negative charges, you *cannot* separate north from south poles
  - You will *always* have both
  - Just like every coin has two sides, "heads" and "tails"
- There's no such thing as a magnetic monopole (as far as we can tell)



# MAGNETIC FIELDS

- Just like it can useful to talk about the electric field surrounding an electric charge, we can also imagine a ***magnetic field*** surrounding a magnet
- The shape of the field is revealed by the ***magnetic field lines***
  - (They will look very reminiscent of electric field lines)

# MAGNETIC FIELDS

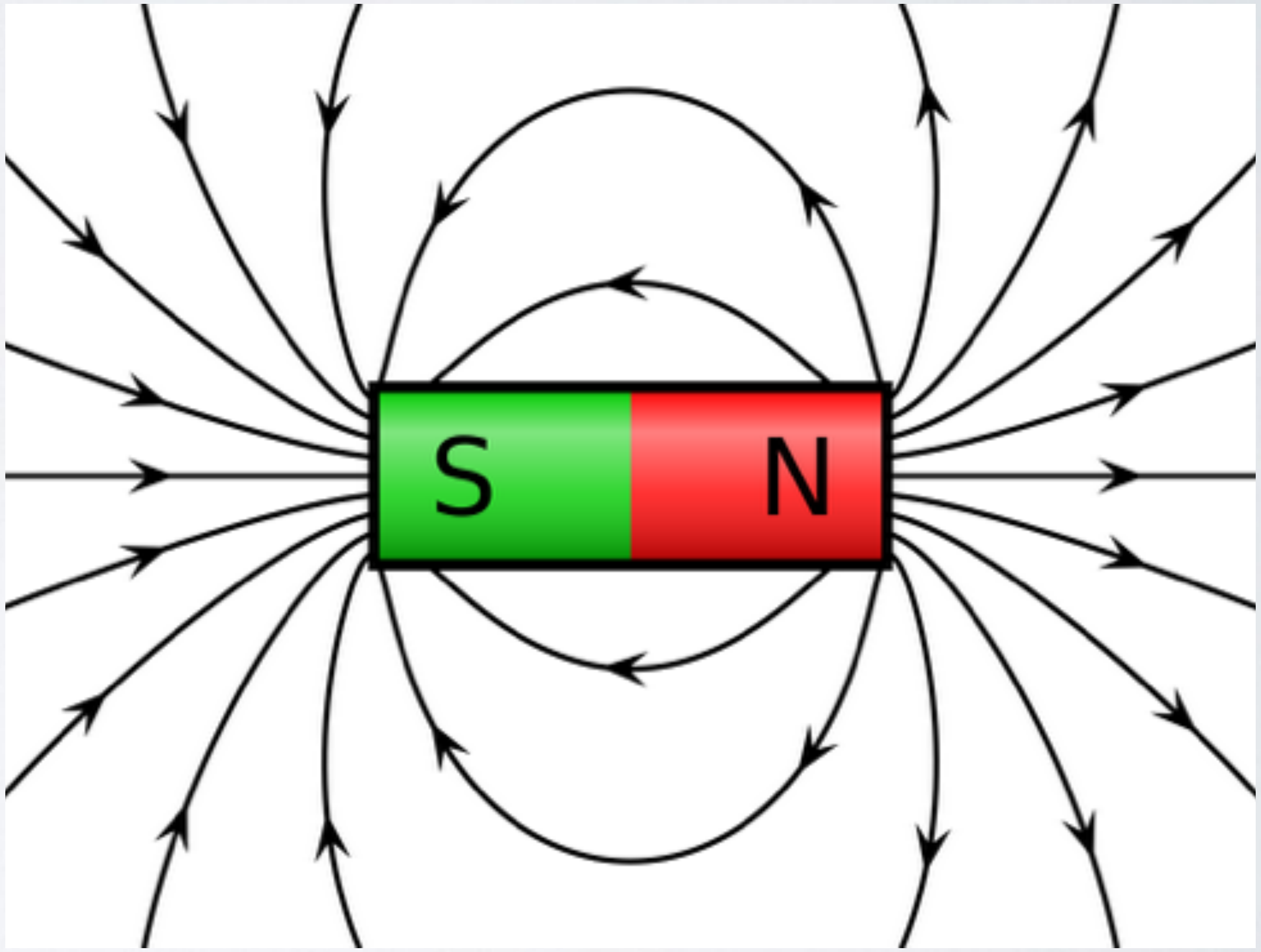
- Facts:

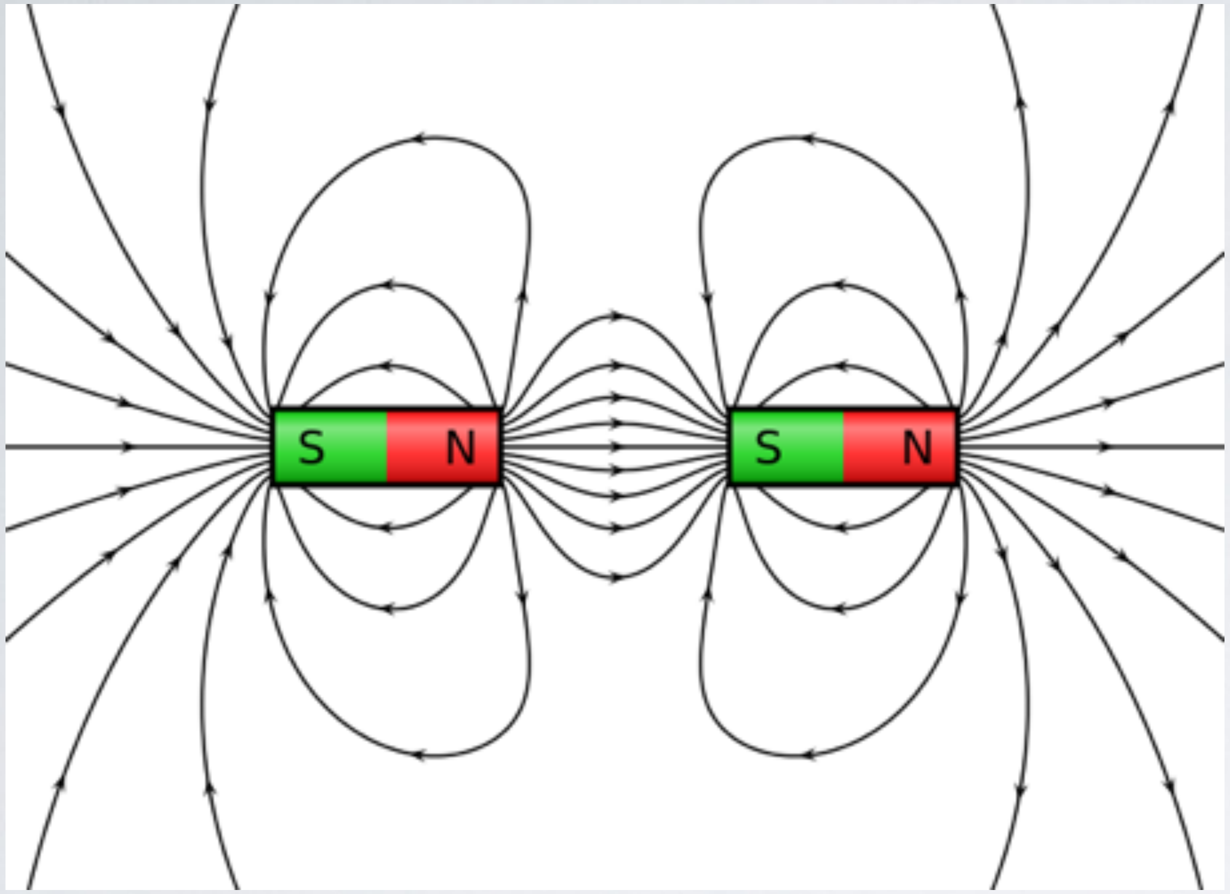
  1. field lines point from north to south

     - (the direction a compass needle would point)

  2. field lines never cross

  3. density of field lines is proportional to the strength of the field

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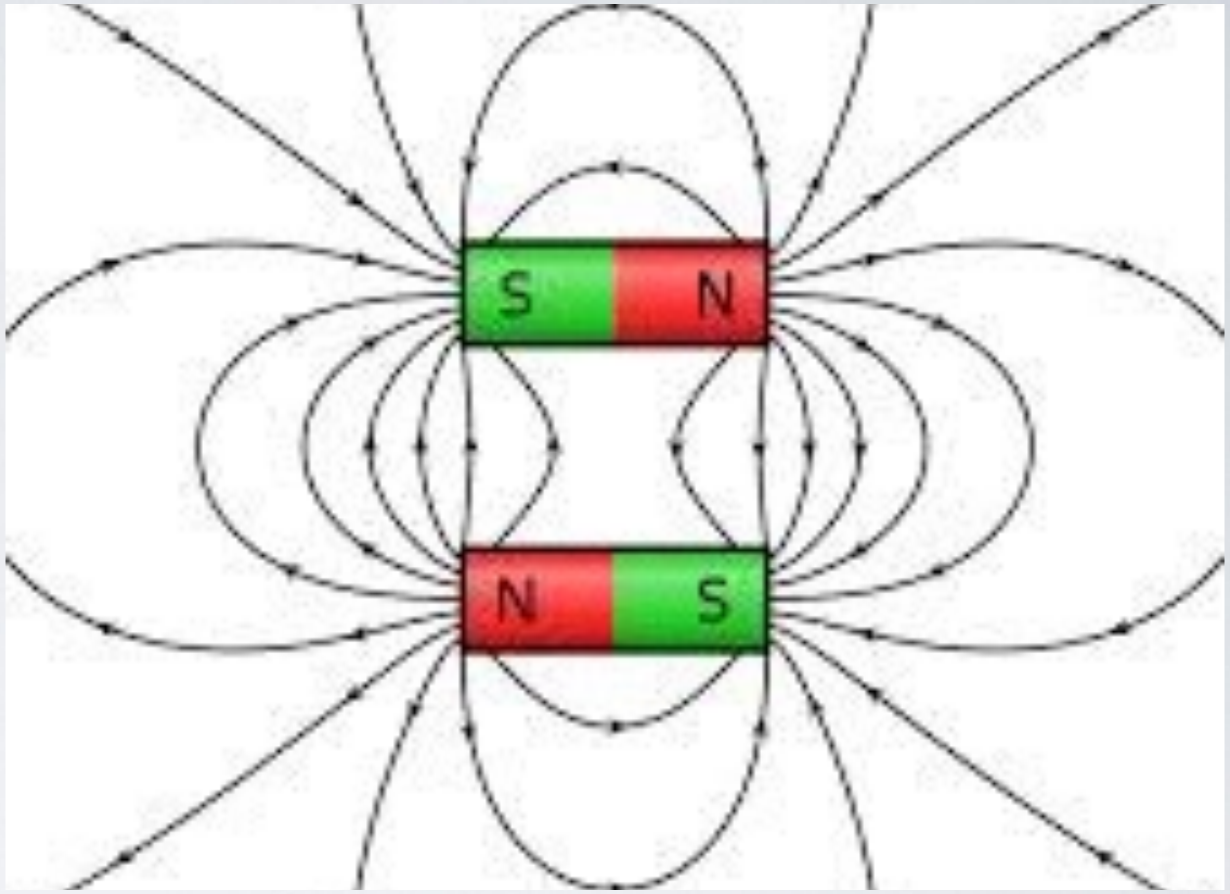
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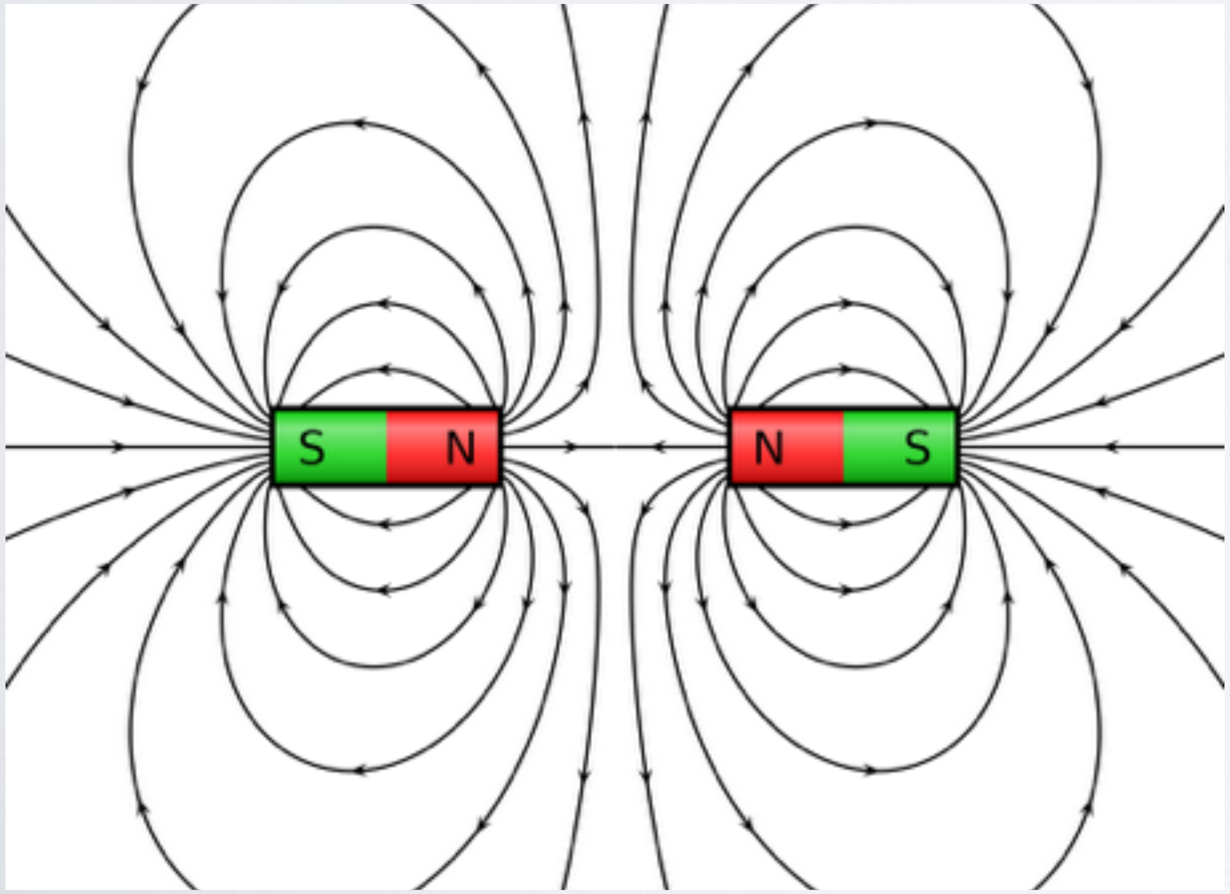
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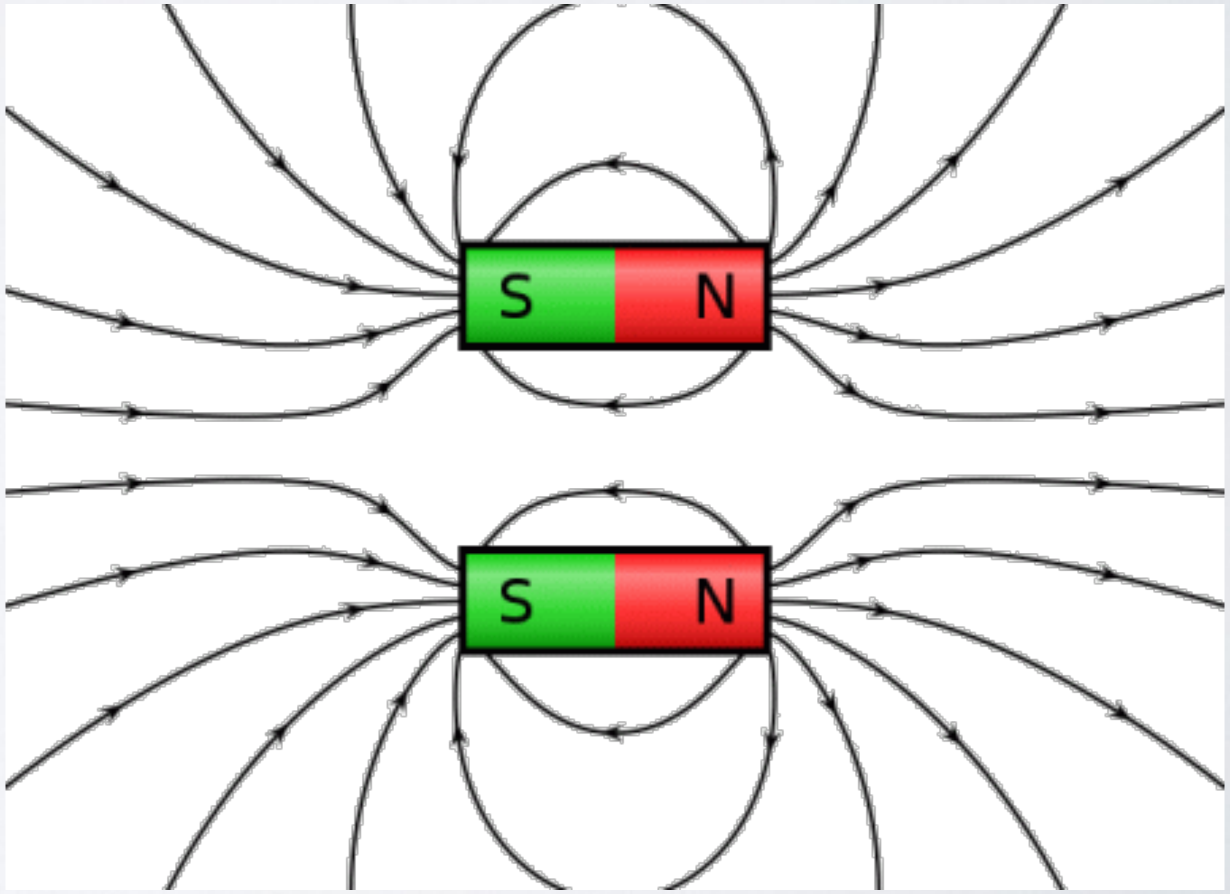
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# MAKING MAGNETISM

- Only iron and a few other materials such as cobalt, nickel, and gadolinium show strong magnetic effects
  - These materials are called ***ferromagnets***
- All other materials show *slight* magnetic effects that can be detected only the most sensitive instruments

# MAKING MAGNETISM

- In 1820, Hans Christian Oersted was experimenting with electricity and magnetism

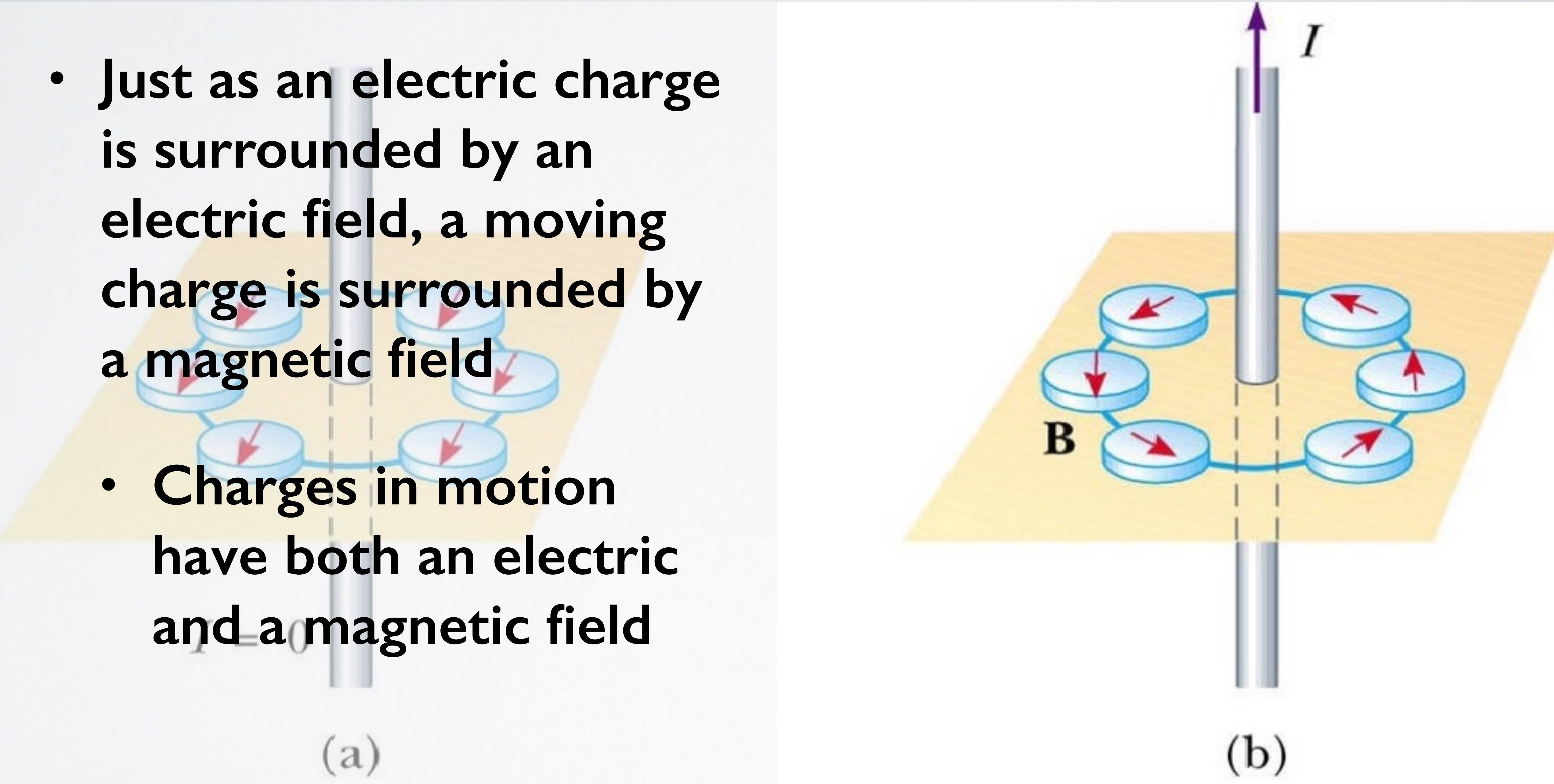
- A stationary charge and a magnet won't influence each other

- But! when he placed a compass near a wire, as soon as he connected the battery and current began to flow, the compass needle deflected!

- ***A magnetic field is produced by the motion of electric charge***

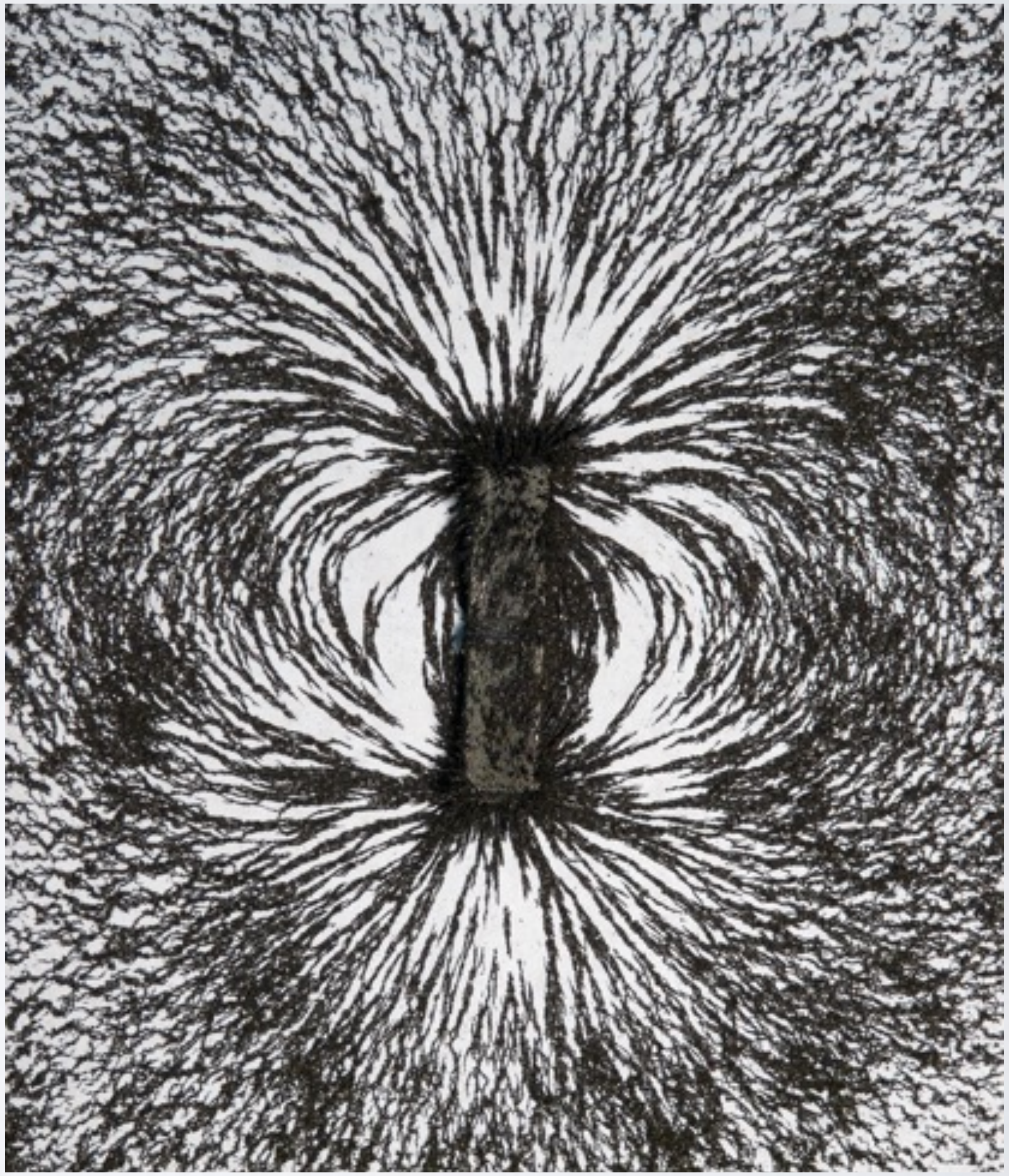
# MAKING MAGNETISM

- **Just as an electric charge is surrounded by an electric field, a moving charge is surrounded by a magnetic field**
  - **Charges in motion have both an electric and a magnetic field**



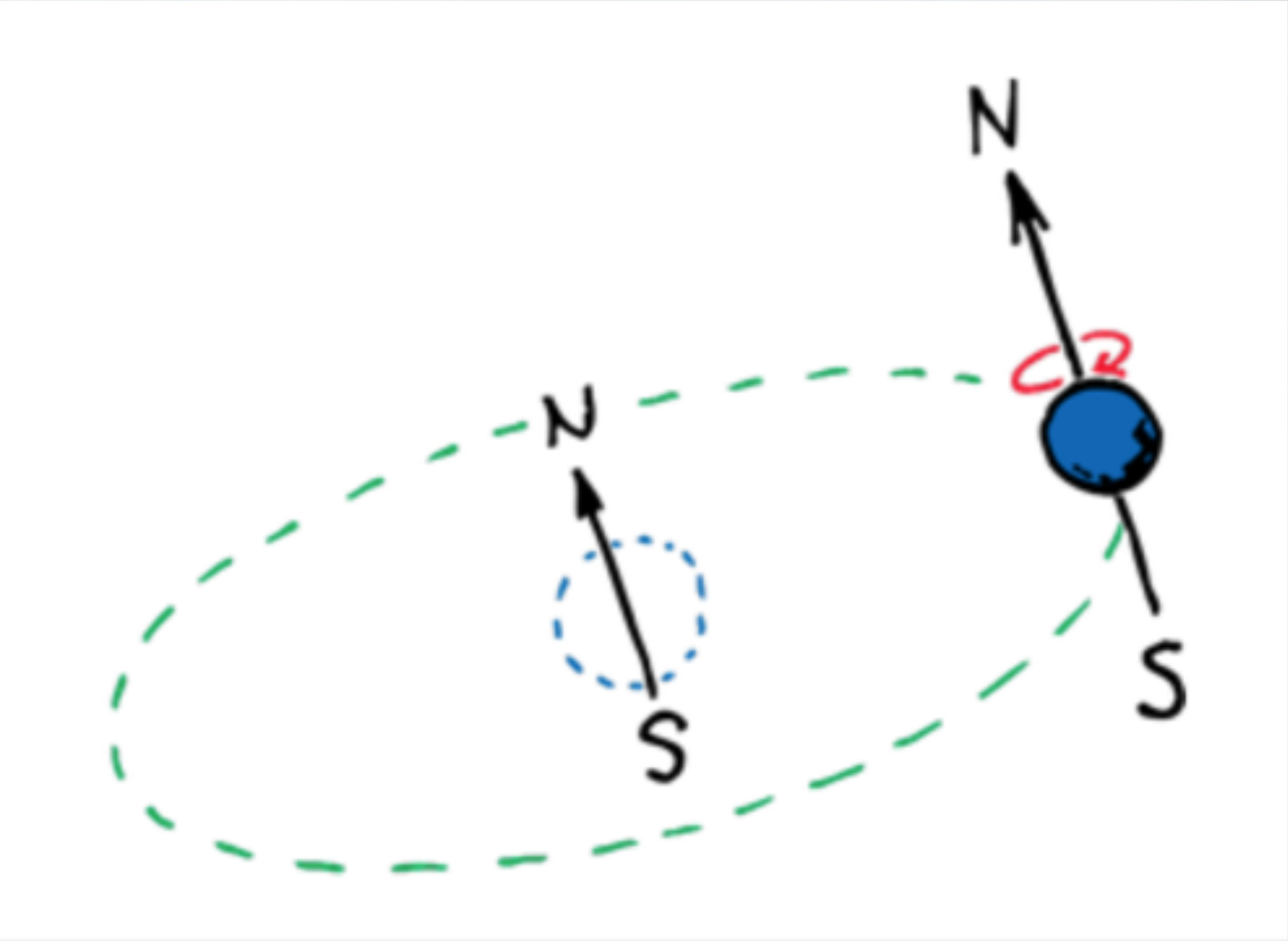
# SANITY CHECK

- So where's the motion of electric charge in a bar magnet?



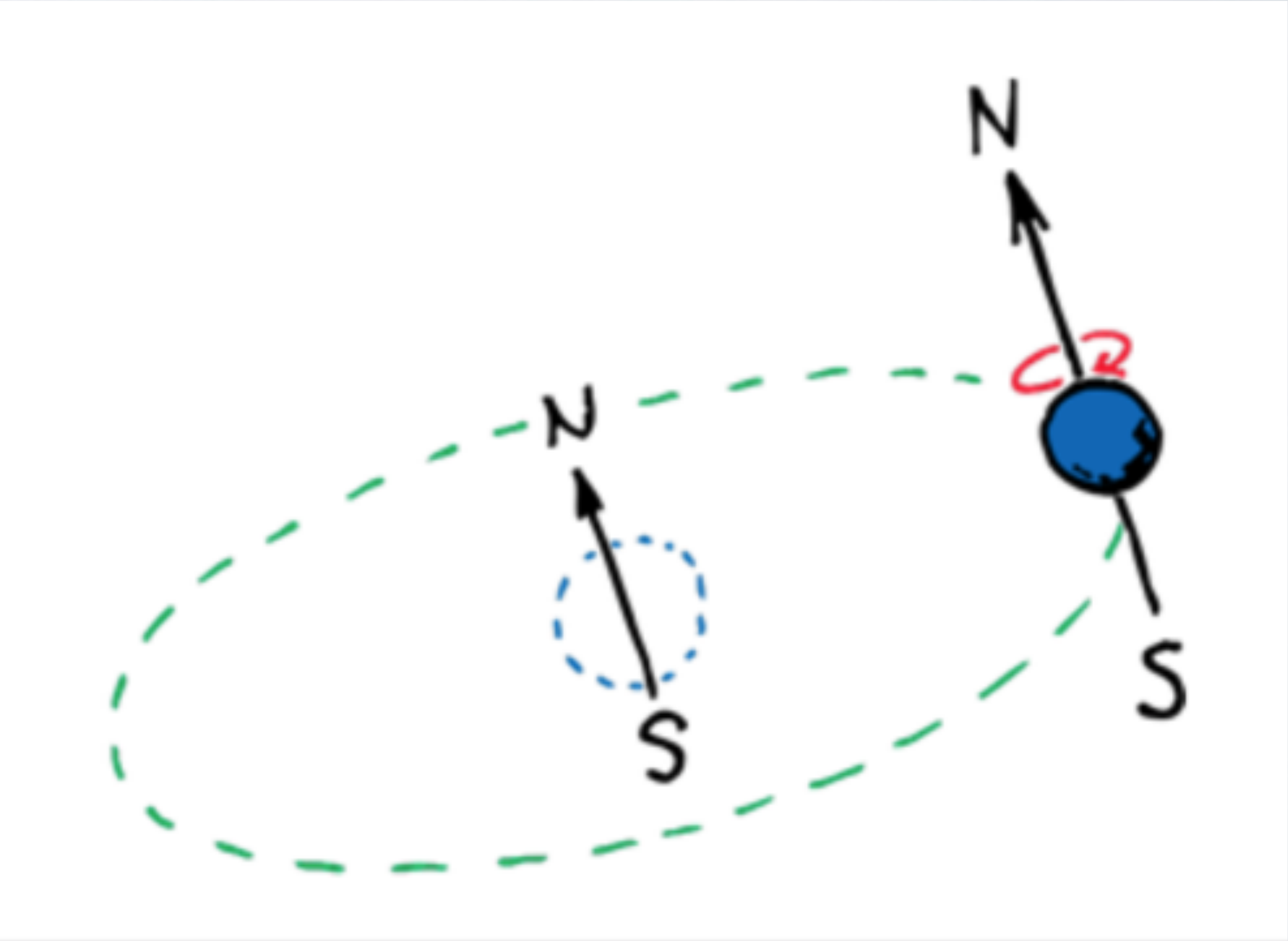
# SANITY CHECK

- So where's the motion of electric charge in a bar magnet?
  - *While the magnet as a whole may be stationary, it is made of atoms whose electrons are in constant motion around the atomic nuclei*
  - *This moving charge constitutes a tiny current and produces a magnetic field*

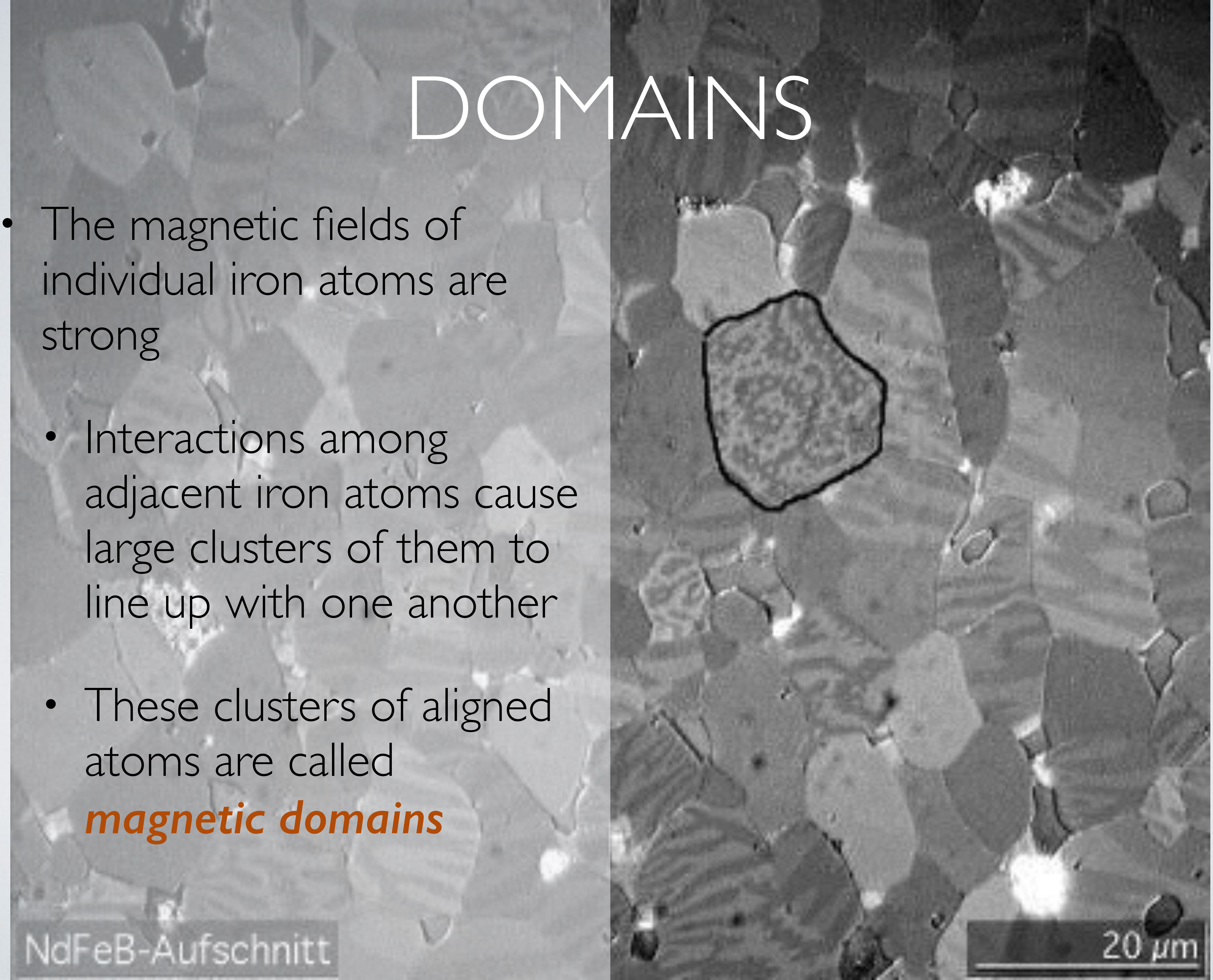


# SANITY CHECK

- *More important, electrons can be thought of as spinning about their own axes like tops*
  - *The spinning electron creates another magnetic field*
- *Typically, the field due to the electron spin predominates over the field due to orbital motion*



# DOMAINS

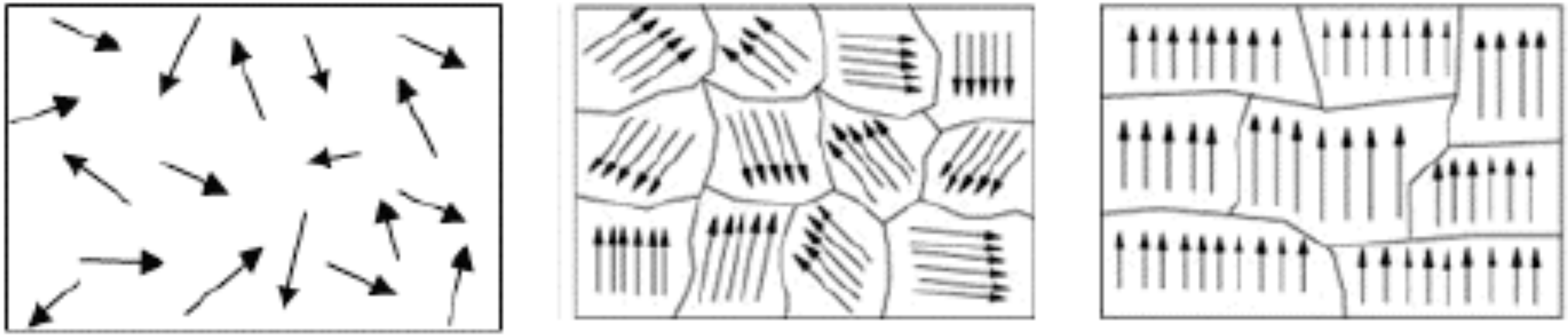


- The magnetic fields of individual iron atoms are strong
  - Interactions among adjacent iron atoms cause large clusters of them to line up with one another
  - These clusters of aligned atoms are called ***magnetic domains***

# DOMAINS

- The difference between an ordinary piece of iron and an iron magnet is the alignment of the domains
  - In common iron nail = randomly oriented
  - But in presence of a strong magnetic field, the aligned domains grow
- If a permanent magnet is dropped or heated, the domains may jostle out of alignment

# DOMAINS



**Non-Magnetic Material**
(no domains)

**Magnetic Material**
(domains, but not lined up)

**Magnet**
(domains, and all are lined up)

# MORAL OF THE STORY

- *Magnetic fields are produced by the motion of electric charge*

# MAGNETISM & ELECTRIC CURRENTS

- Since moving charges produce a magnetic field, we can expect there to be a magnetic field around any and all current-carrying wires

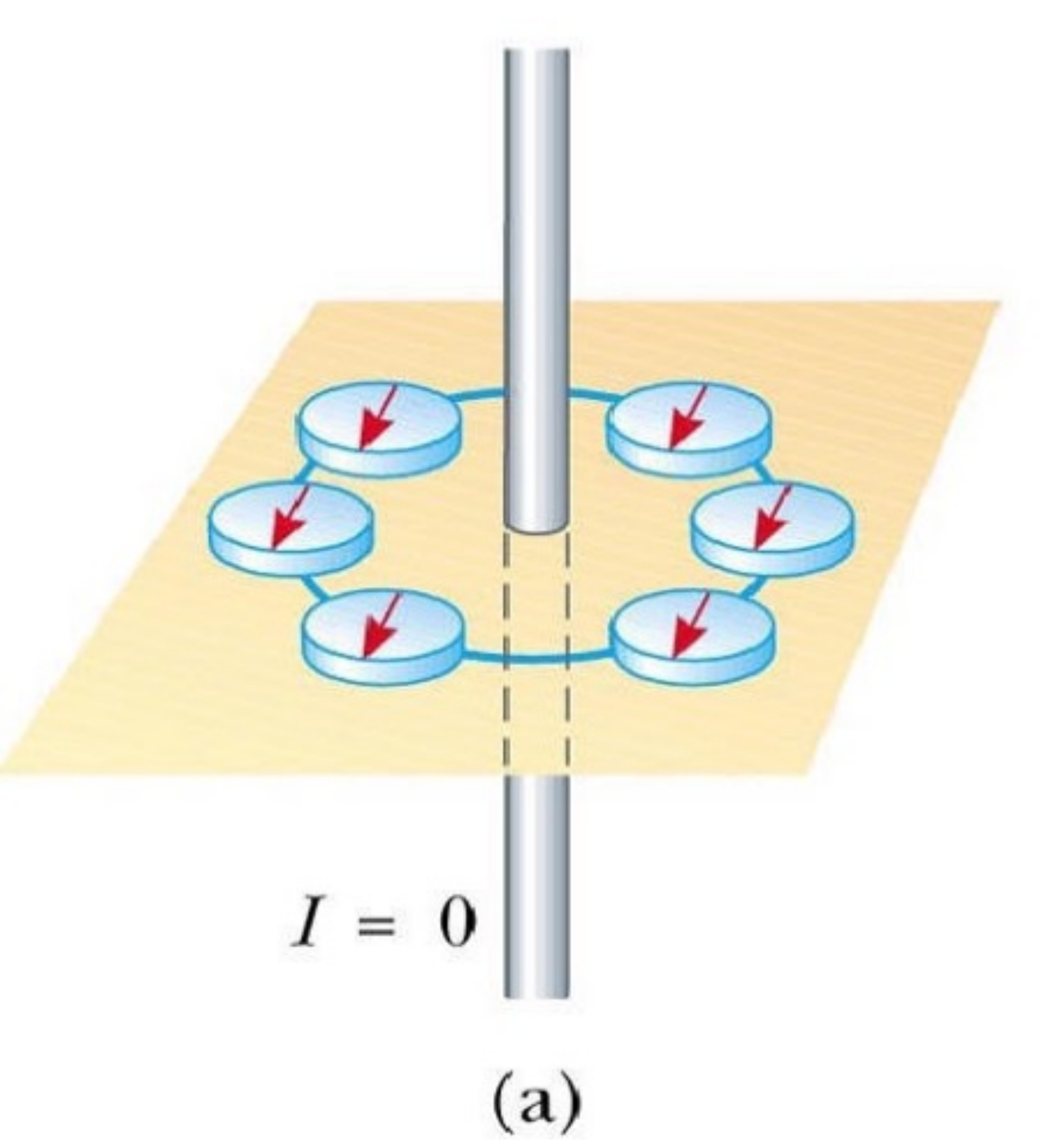
- If you arrange a bunch of compasses around a current-carrying wire, the compasses will line up with the magnetic field

    - a pattern of concentric circles around the wire

- If the current reverses direction, the compasses turn around, showing that the direction of the magnetic field changes also

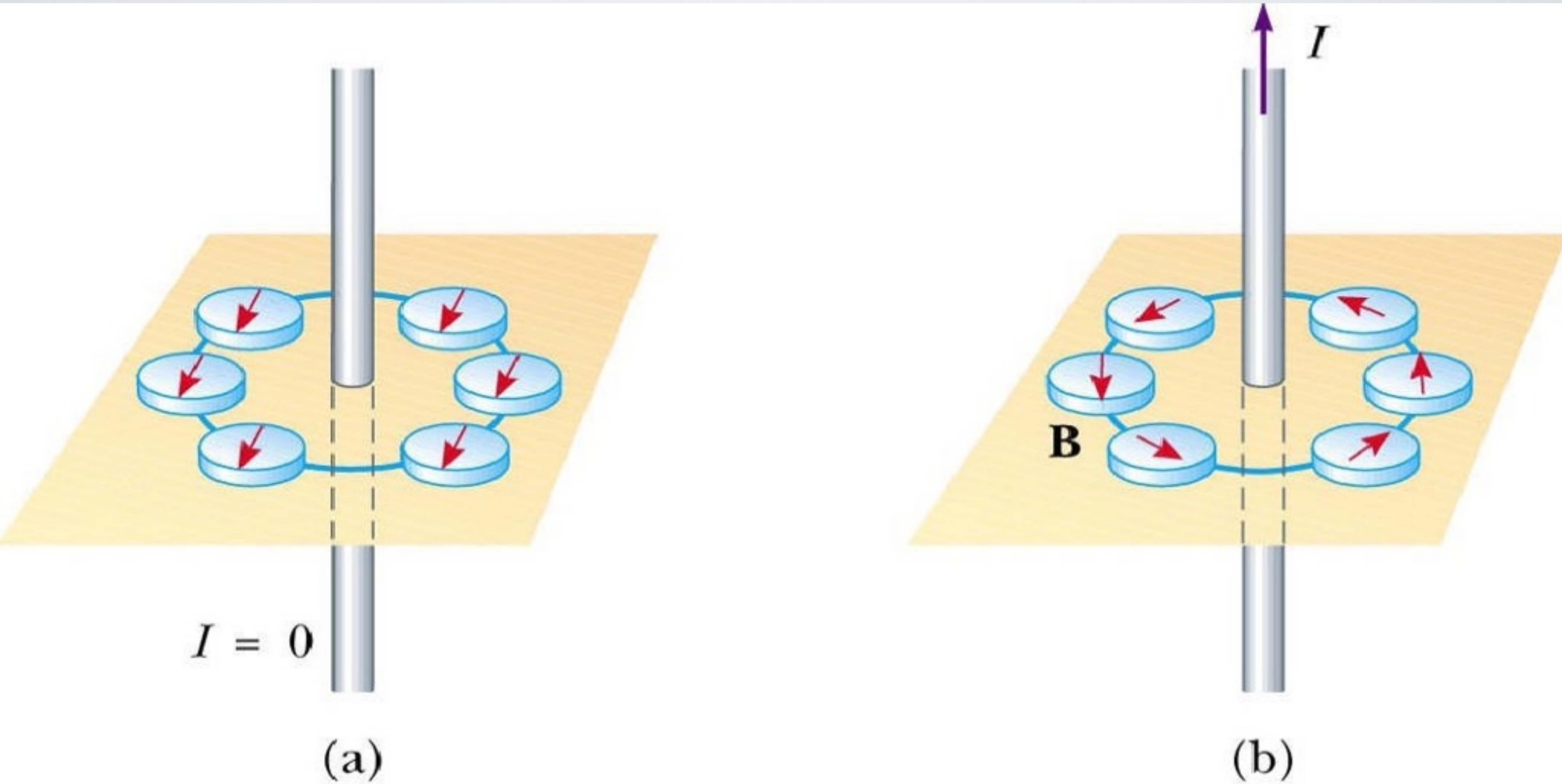
# MAGNETISM & ELECTRIC CURRENTS

(a) When there is no current in the wire, the compasses align with Earth's magnetic field



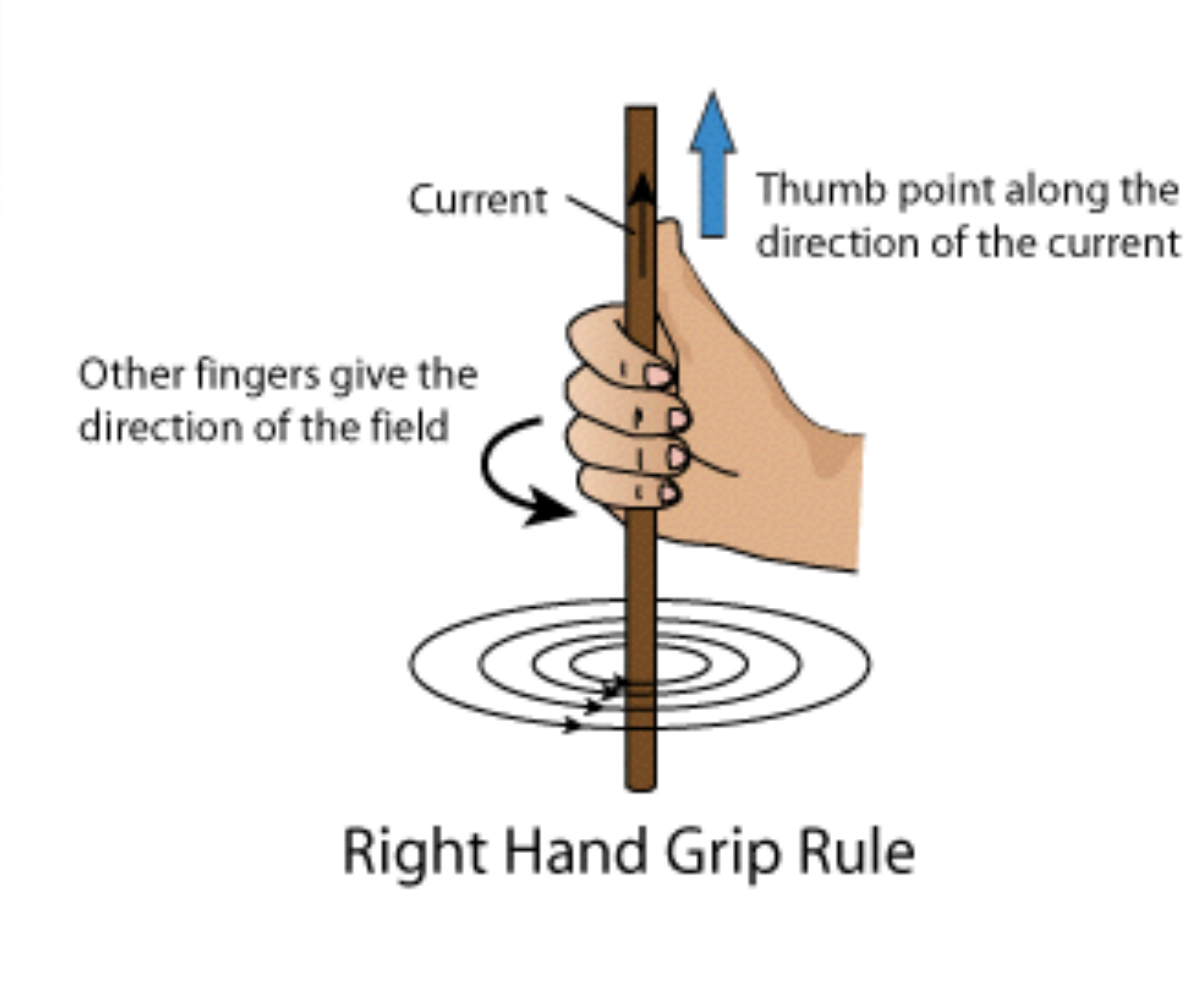
# MAGNETISM & ELECTRIC CURRENTS

(b) When there is a current in the wire, the compasses align with the stronger magnetic field near the wire



# RIGHT HAND RULE, PART 1

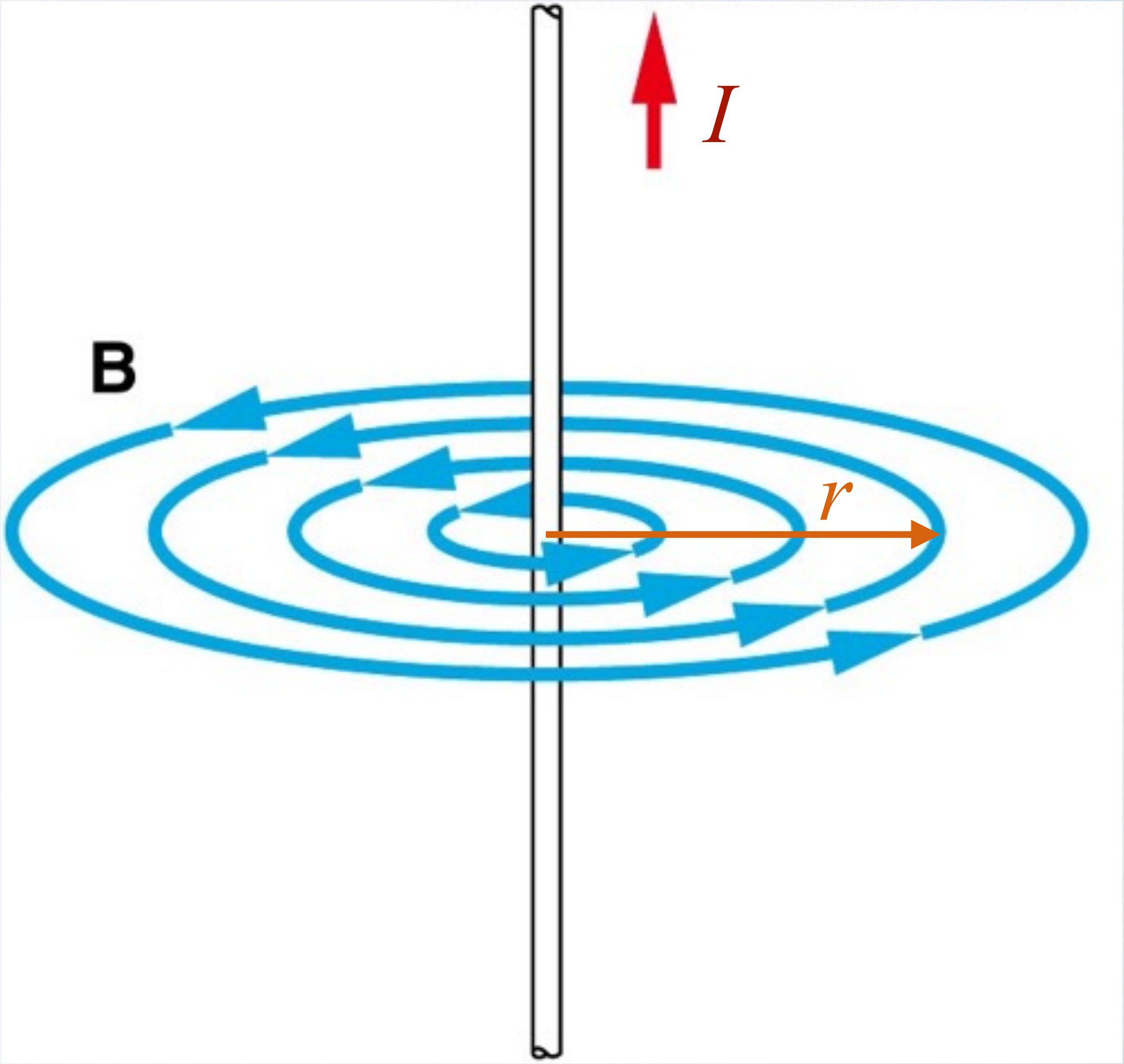
- The ***right hand rule*** is a tool to help us figure out the *direction* of the magnetic field relative to the current



Right Hand Grip Rule

# MAGNETISM & ELECTRIC CURRENTS

- The strength of the magnetic field around a current-carrying wire depends on two quantities:
    1. How much current passes through the wire: $I$
    2. How you are from the wire: $r$

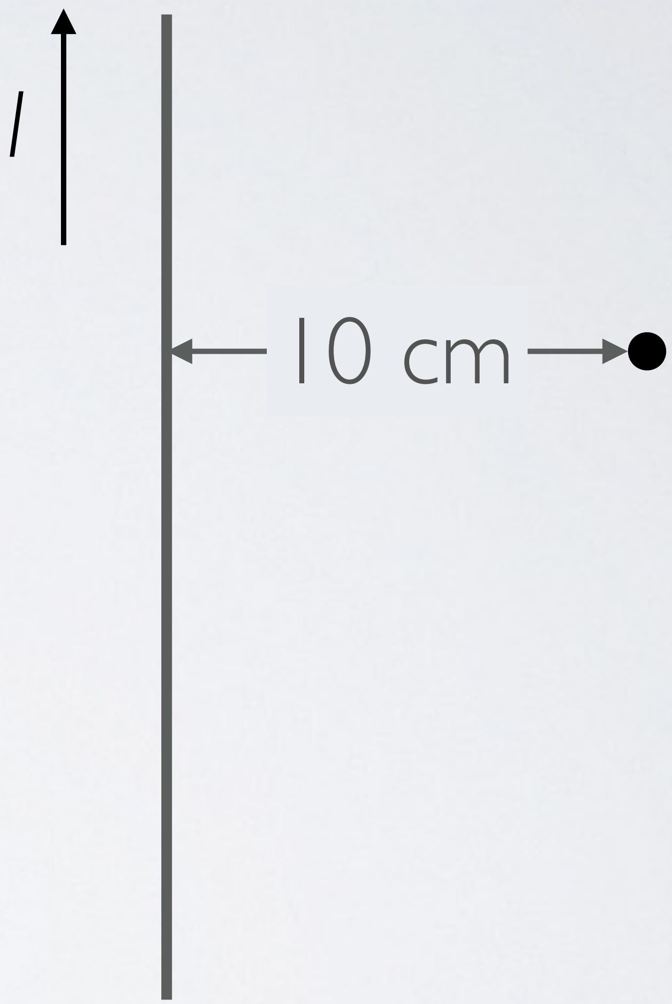


# MAGNETISM & ELECTRIC CURRENTS

- $\boxed{B = \frac{\mu_0 I}{2\pi r}}$
  - $B$ represents the magnetic field
  - Measured in ***Teslas*** (**T**)
- $\mu_0$ is called the ***permeability of free space***
  - $\mu_0 = 4\pi \times 10^{-7}$ Tm/A
  - It's a measure of how accepting a vacuum is of a magnetic field

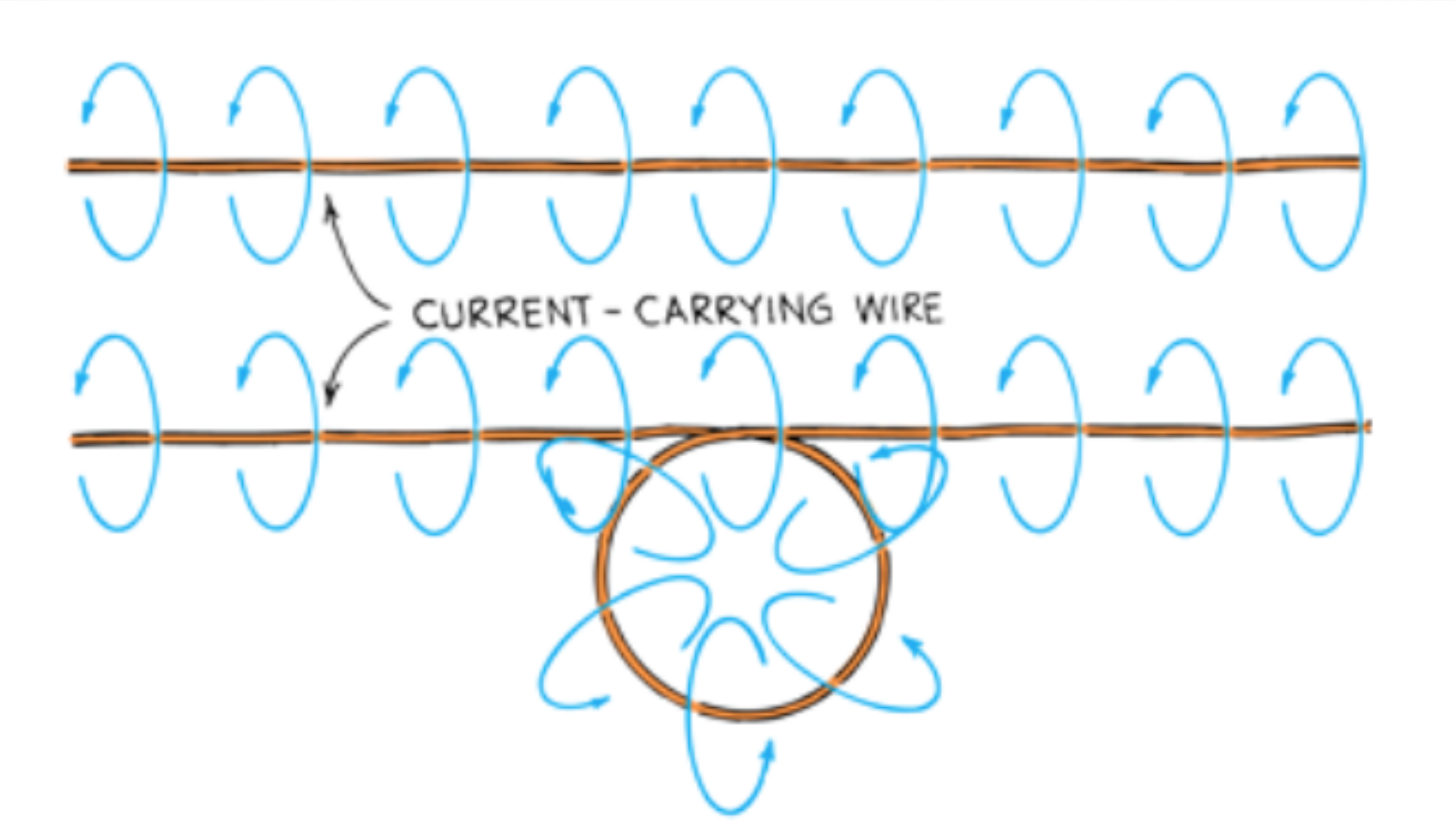
# EXAMPLE 1

- A vertical electric wire in the wall of a building carries a current of 25 A upward. What is the magnitude and direction of magnetic field at a point 10 cm to the right of the wire?
  - *Ans.* $B = 5.0 \times 10^{-5}$ T *into the page*



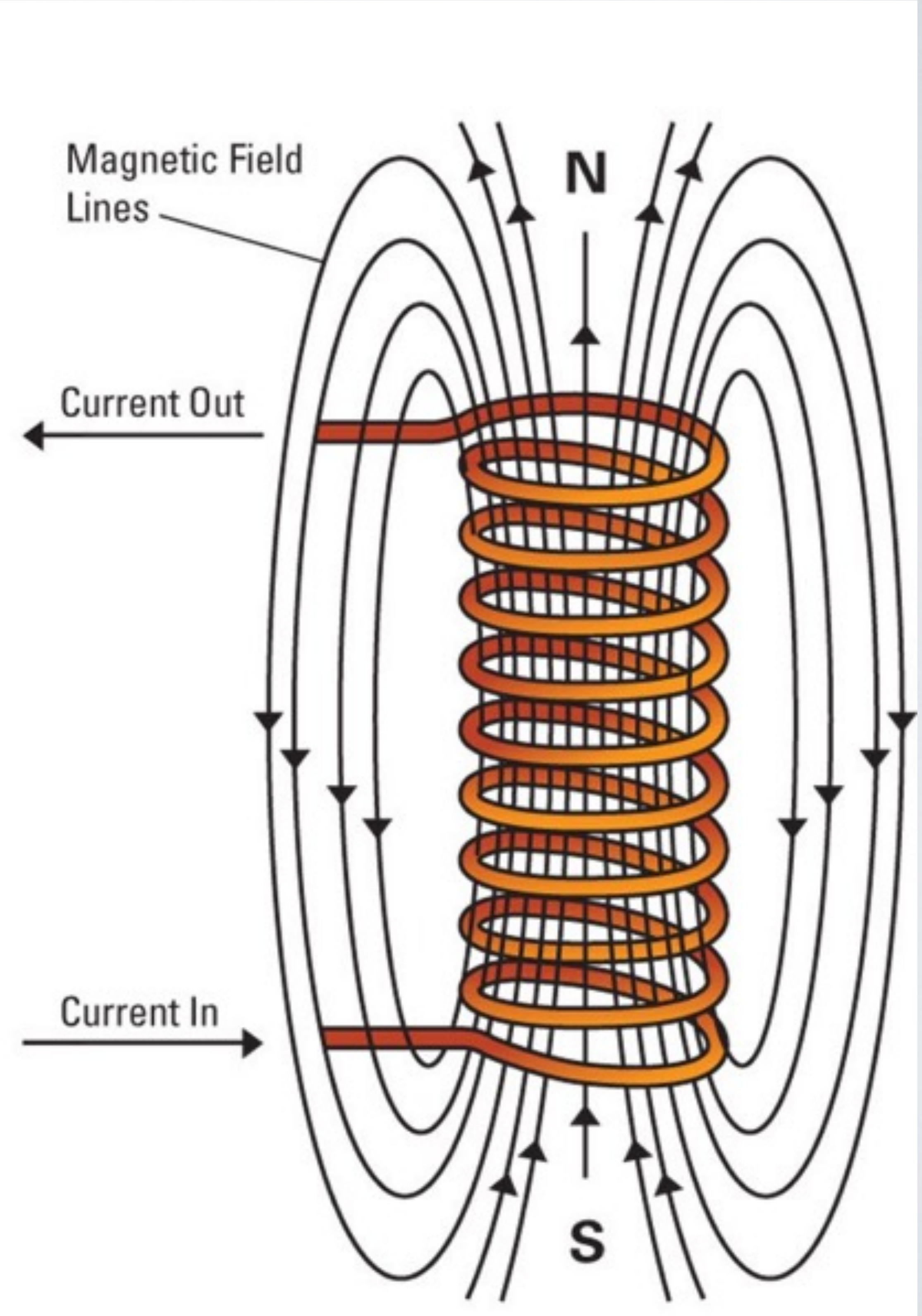
# MAGNETISM & ELECTRIC CURRENTS

- If the wire is bent into a loop, the magnetic field lines become bunched up inside the loop
- Bend it into another loop and the concentration of field lines inside becomes twice that of the single loop
- The magnetic field intensity is proportional to the number of loops



# MAGNETISM & ELECTRIC CURRENTS

- A current-carrying coil of wire is an ***electromagnet***

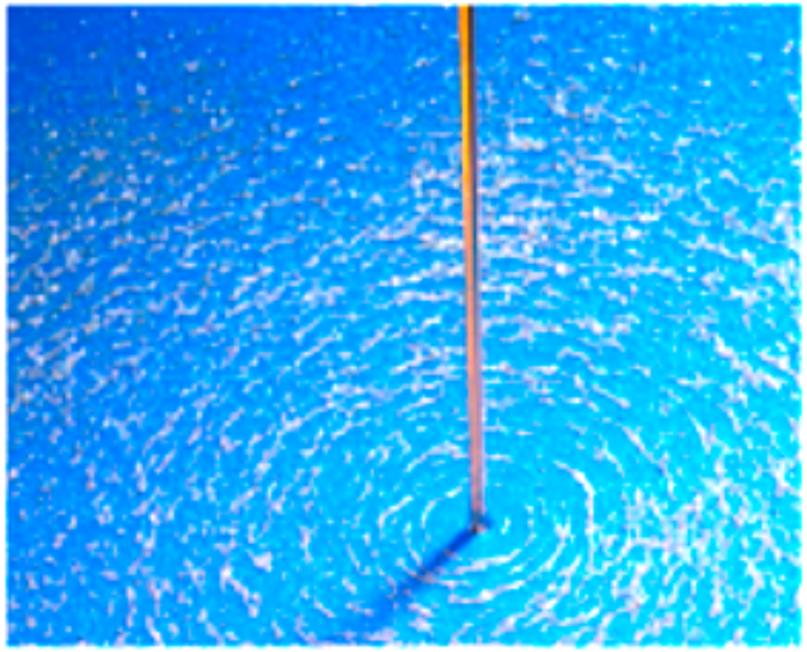


# MAGNETISM & ELECTRIC CURRENTS

a) current-carrying wire

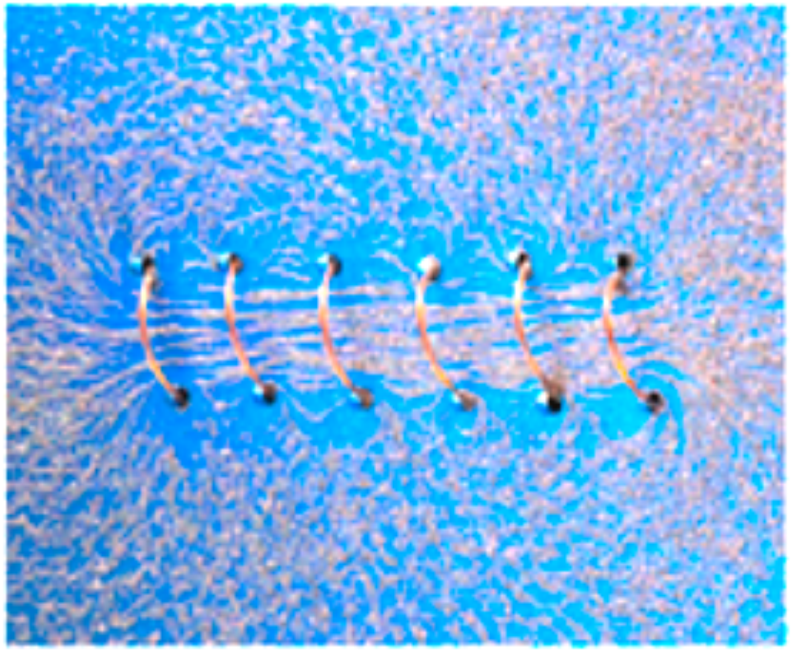
b) current-carrying loop

c) coil of loops



a

b



c

# MAGNETISM & ELECTRIC CURRENTS

- Sometimes a piece of iron is placed inside the coil of an electromagnet
- The magnetic domains in the iron are induced into alignment, increasing the magnetic field intensity
- Beyond a certain limit, the magnetic field in the iron "saturates," so iron isn't used in the cores of the strongest electromagnets

# MAGNETISM & ELECTRIC CURRENTS

- A superconducting electromagnet can generate a powerful magnetic field indefinitely without using any power

- At Fermilab near Chicago, superconducting electromagnets guide high-energy particles around the four-mile-circumference accelerator

- Superconducting magnets can also be found in magnetic resonance imaging (MRI) devices in hospitals

# MAGNETISM & ELECTRIC CURRENTS

https://www.youtube.com/watch?v=zPqEEZa2Gis

# MAGNETIC FORCES ON ELECTRIC CURRENT

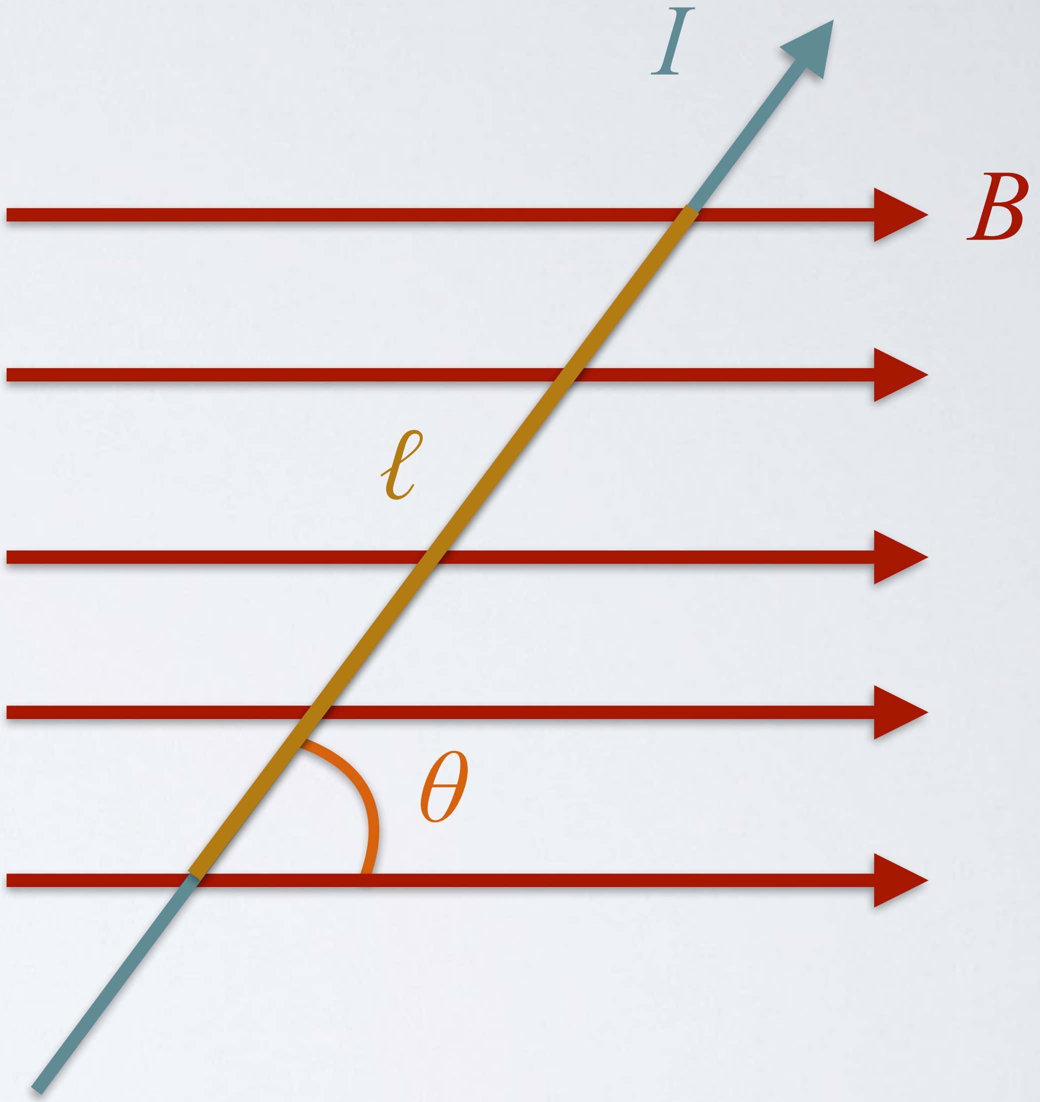
- An electric current exerts a force on a magnet, such as a compass needle

- By Newton's Third Law, the reverse must be true as well: *a magnet exerts a force on a current-carrying wire*

# MAGNETIC FORCES ON ELECTRIC CURRENT

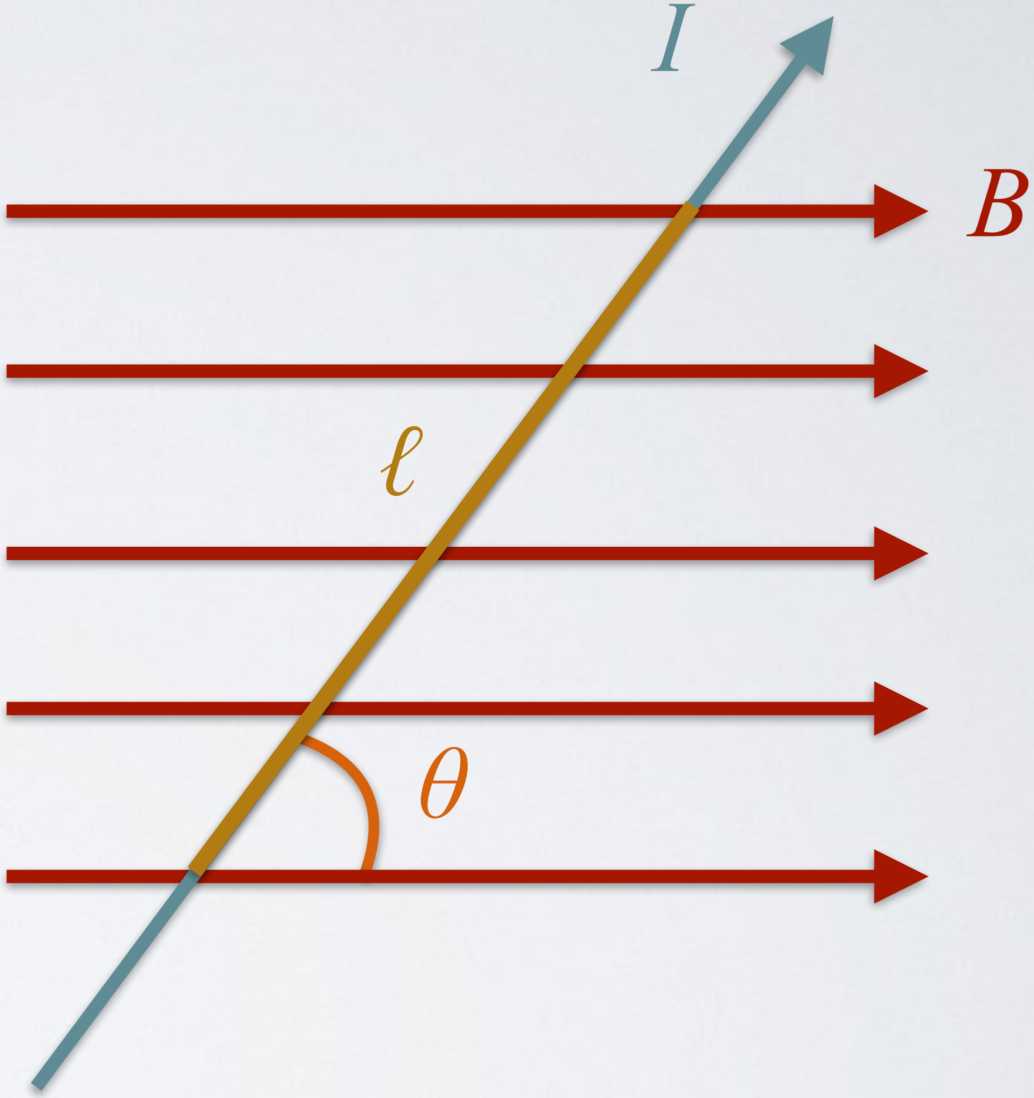
- The magnitude of the force on electric current due to a magnetic field depends on 4 quantities:

1. Strength of the magnetic field: $B$
2. Current in the wire: $I$
3. Length of wire in the magnetic field: $\ell$
4. Angle the wire makes with the magnetic field: $\theta$

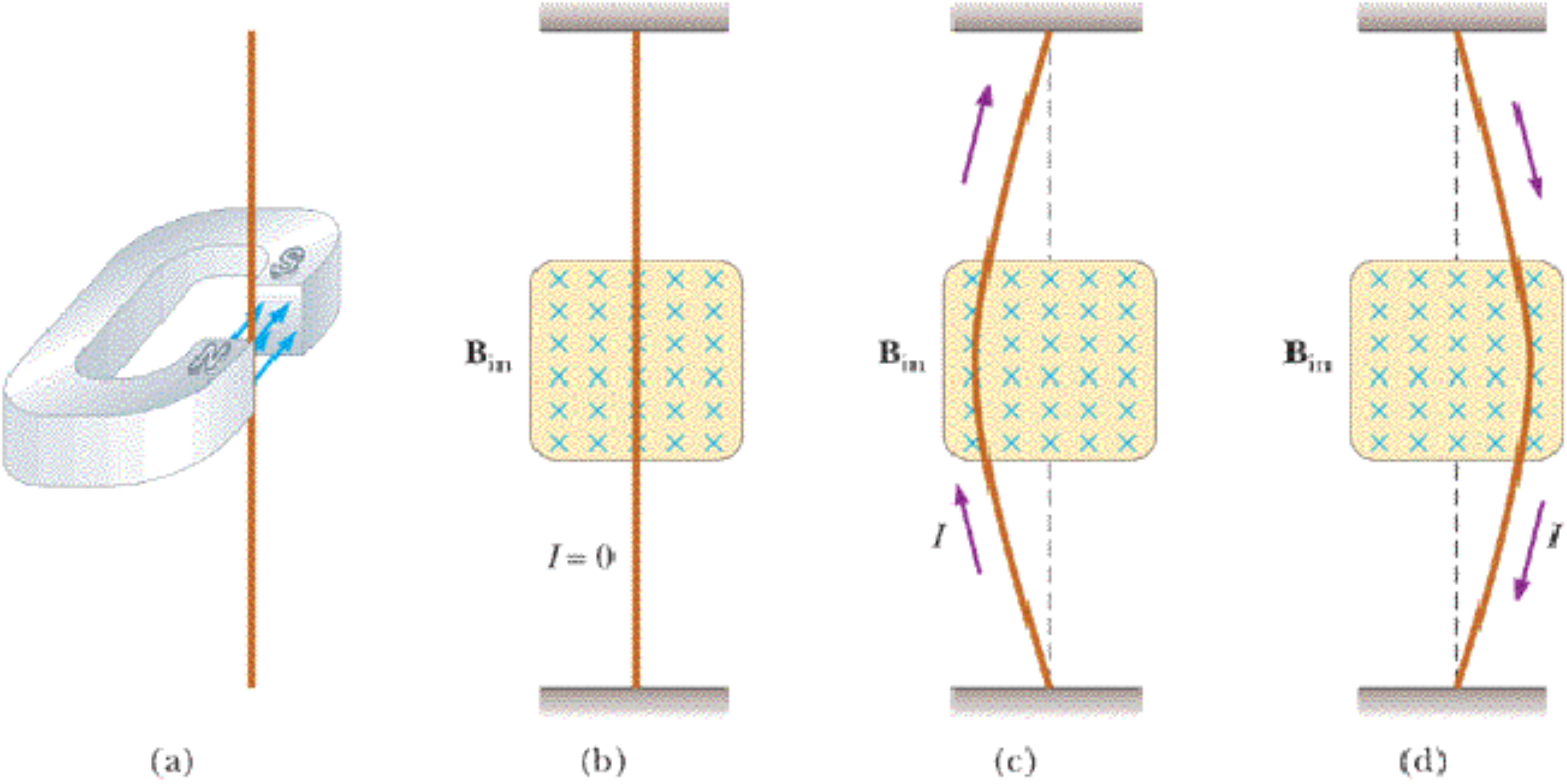


# MAGNETIC FORCES ON ELECTRIC CURRENT

- $\boxed{F_B = I\ell B\,\sin\theta}$

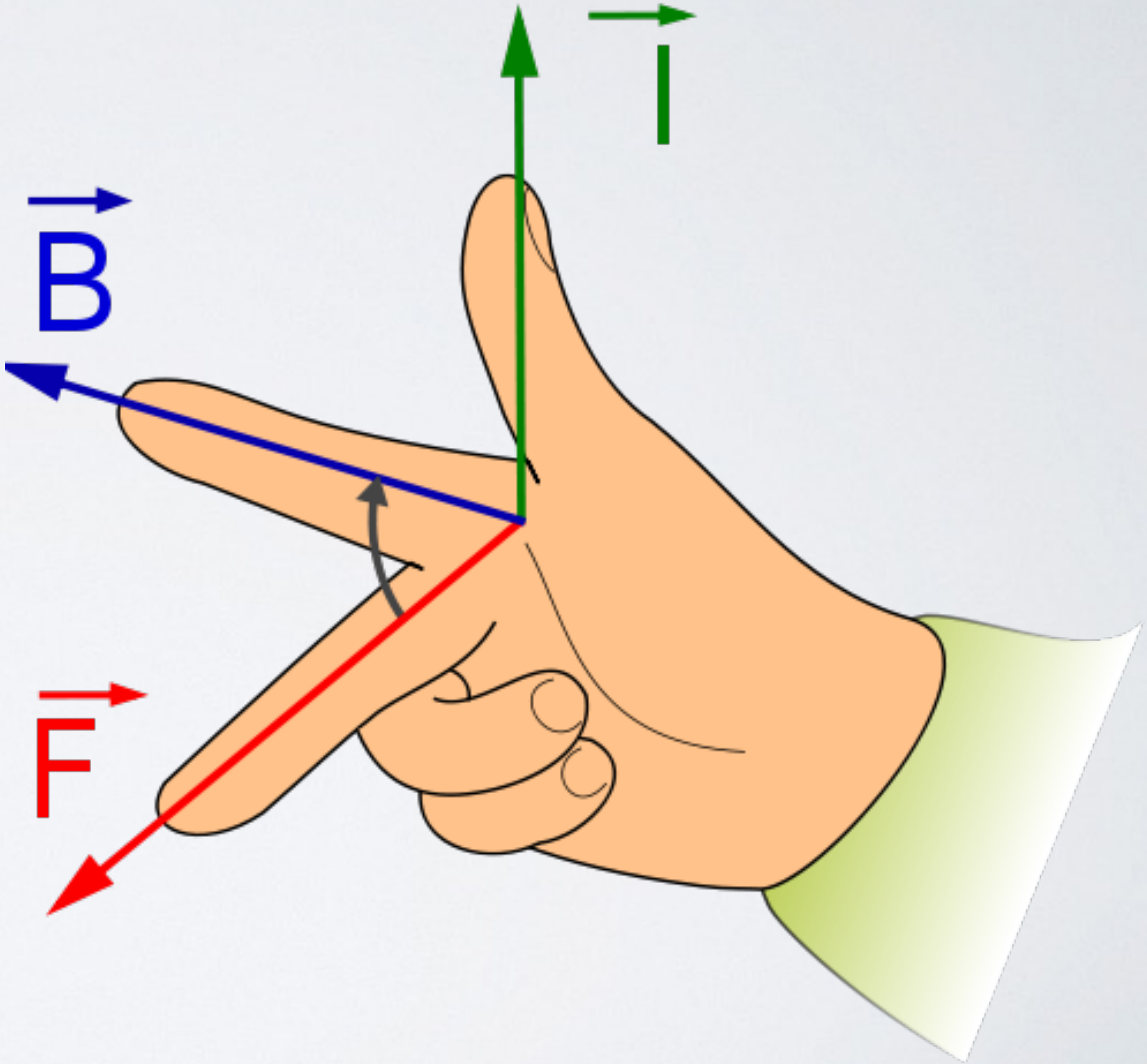


# MAGNETIC FORCE ON ELECTRIC CURRENT



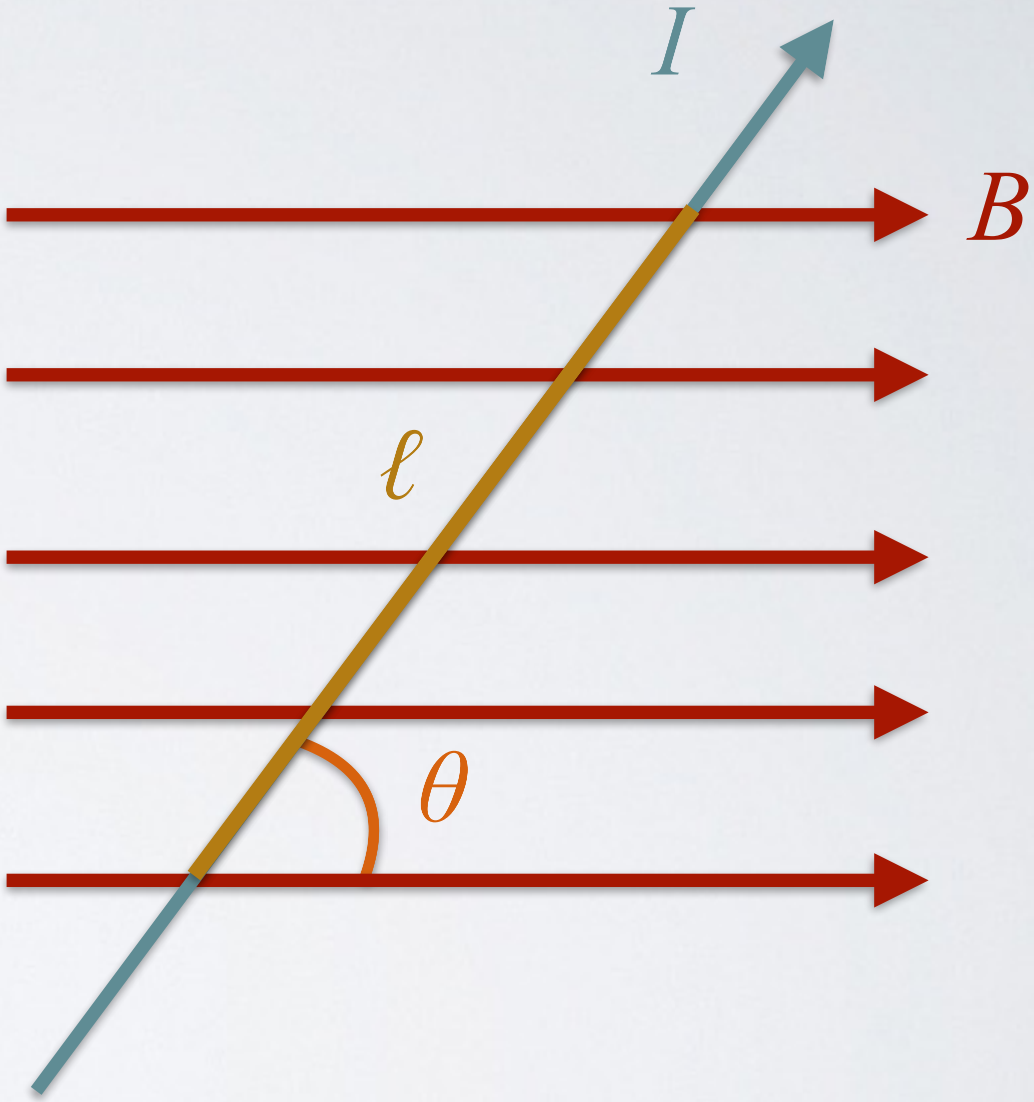
# RIGHT HAND RULE, PART 2

- The magnetic force will *always* be perpendicular to both the direction of the current and the direction of the magnetic field



# EXAMPLE 2

- A wire carrying a 30-A current has length $\ell = 12$ cm between the pole faces of a magnet at an angle $\theta = 60°$. The magnetic field is approximately uniform at 0.90 T. What is the force on the wire?
  - *Answer:* $F_B = 2.8$ *N into the board*



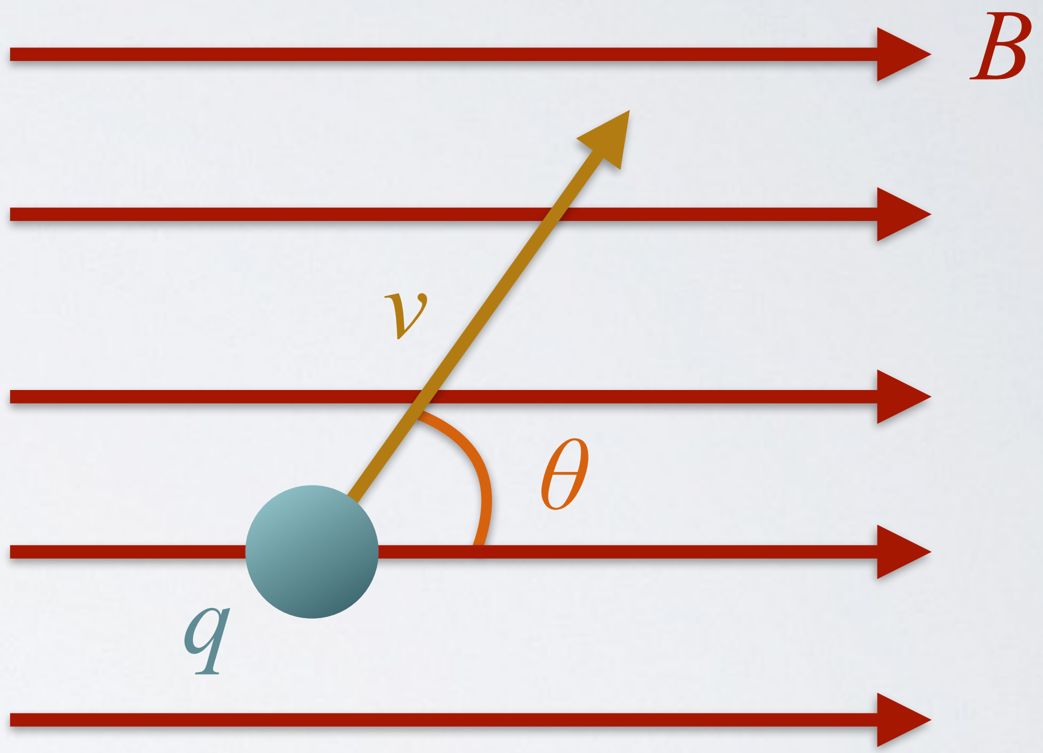
# MAGNETIC FORCE ON MOVING CHARGES

- Magnetic fields exert a force on electric current
- That's the same as saying magnetic field exert a force on moving charges

# MAGNETIC FORCE ON MOVING CHARGES

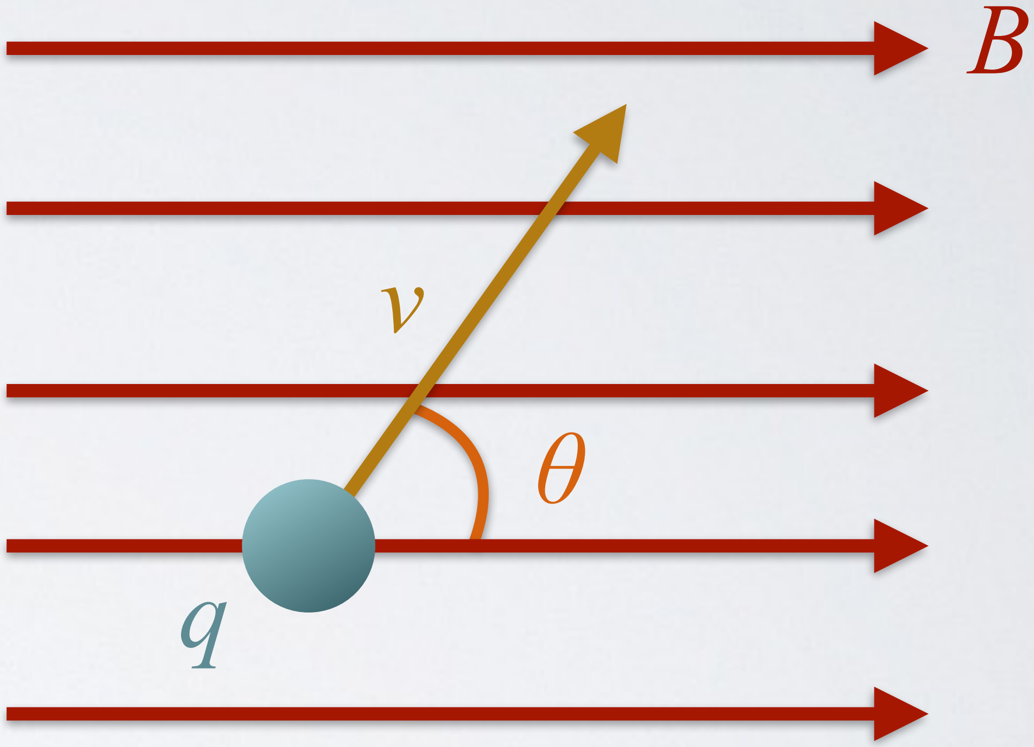
- The magnitude of the force on a moving charge due to a magnetic field depends on 4 quantities:

1. Strength of the magnetic field: $B$
2. Charge of the particle: $q$
3. Velocity of the particle: $v$
4. Angle the velocity makes with the magnetic field: $\theta$



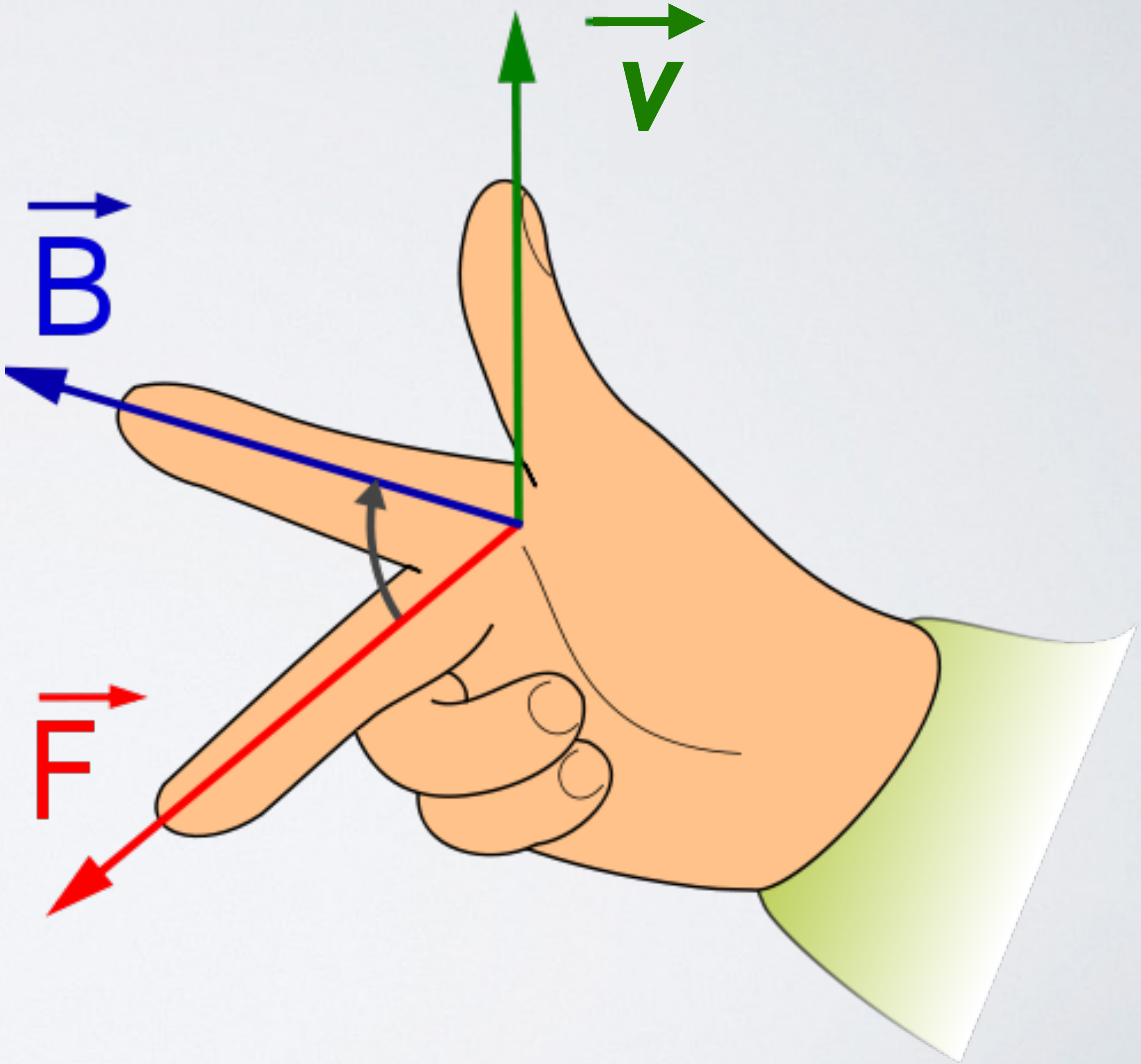
# MAGNETIC FORCE ON MOVING CHARGES

- $\boxed{F_B = qvB\ \sin\theta}$



# RIGHT HAND RULE, PART 2½

- Only work for *positive* charges!
- For negative charges, either remember that the force will be in the opposite direction of whatever the right hand rule yields
- Or use your left hand



# EXAMPLE 3

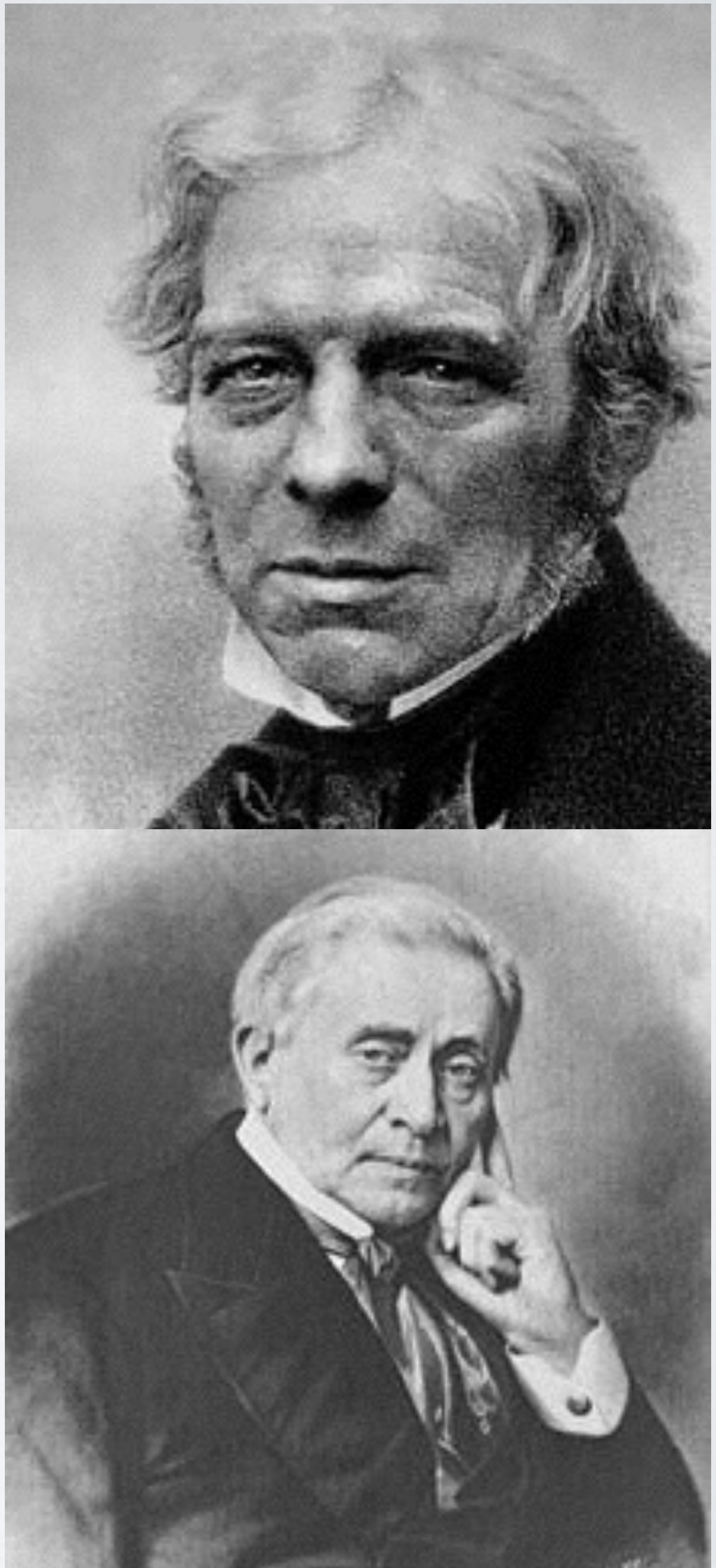
- A proton having a speed of $5.0\times10^6$ m/s in a magnetic field feels a force of $8.0\times10^{-14}$ N toward the west when it moves vertically upward. When moving horizontally in a northerly direction, it feels zero force. What is the magnitude and direction of the magnetic field in this region?
    - *Answer: B = 0.10 T north*

# EXAMPLE 4

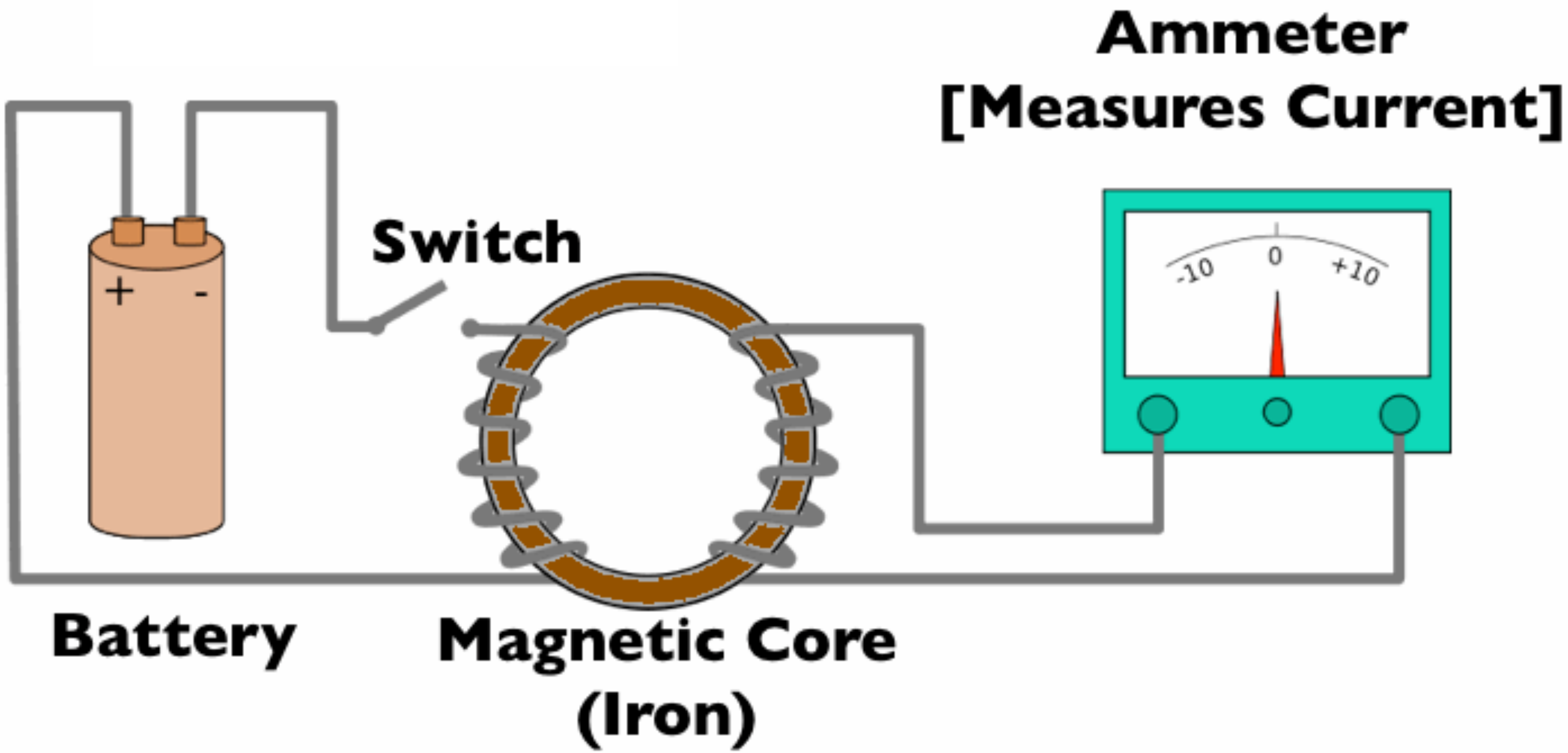
- An proton travels at $2.0 \times 10^{7}$ m/s in a plane perpendicular to a 0.010-T magnetic field. Describe its path. ($q_{\mathrm{p}} = 1.6 \times 10^{-19}$ C, $m_{\mathrm{p}} = 1.67 \times 10^{-27}$ kg)
  - *Answer: circle with radius $r = 20.9$ m*

# ELECTROMAGNETIC INDUCTION

- In 1831, two physicists, Michael Faraday in England and Joseph Henry in the United States, independently discovered that magnetism could produce an electric current in a wire



# ELECTROMAGNETIC INDUCTION



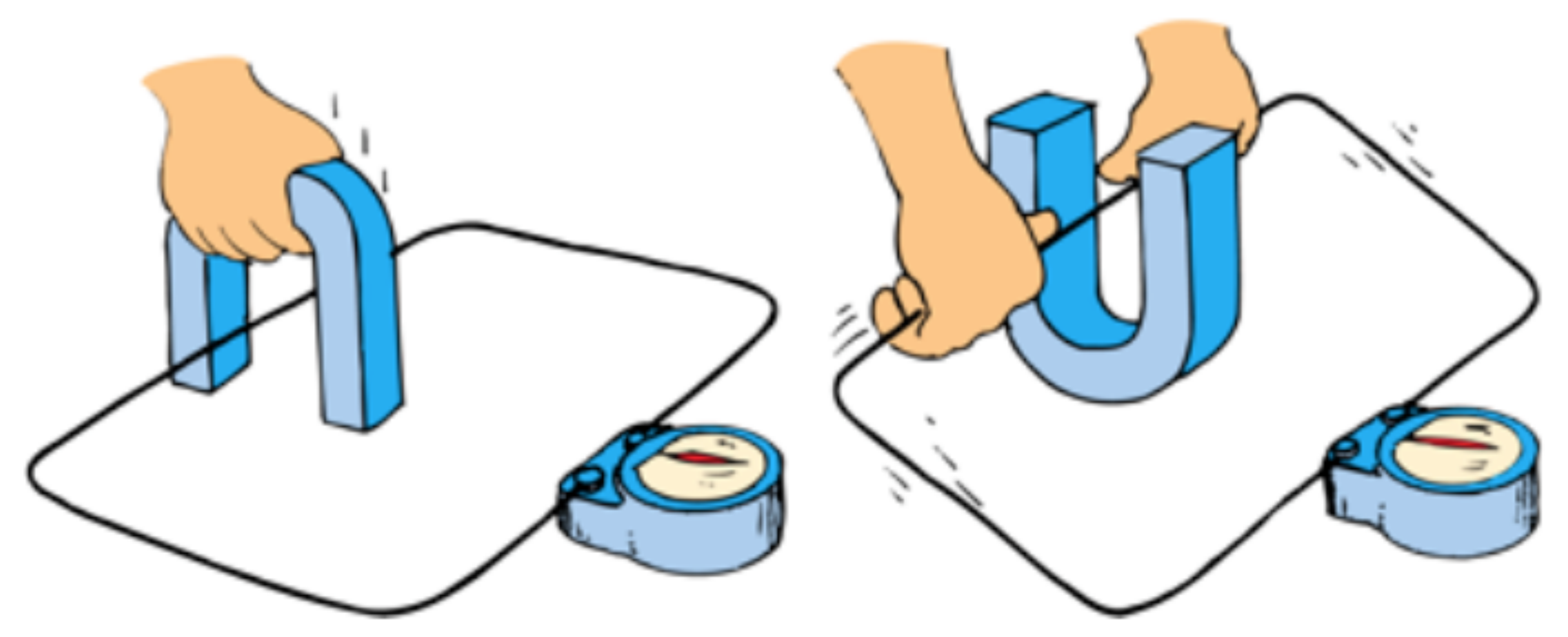
# ELECTROMAGNETIC INDUCTION

- A *changing* magnetic field will produce a voltage
- This phenomenon is known as ***electromagnetic induction***

# ELECTROMAGNETIC INDUCTION

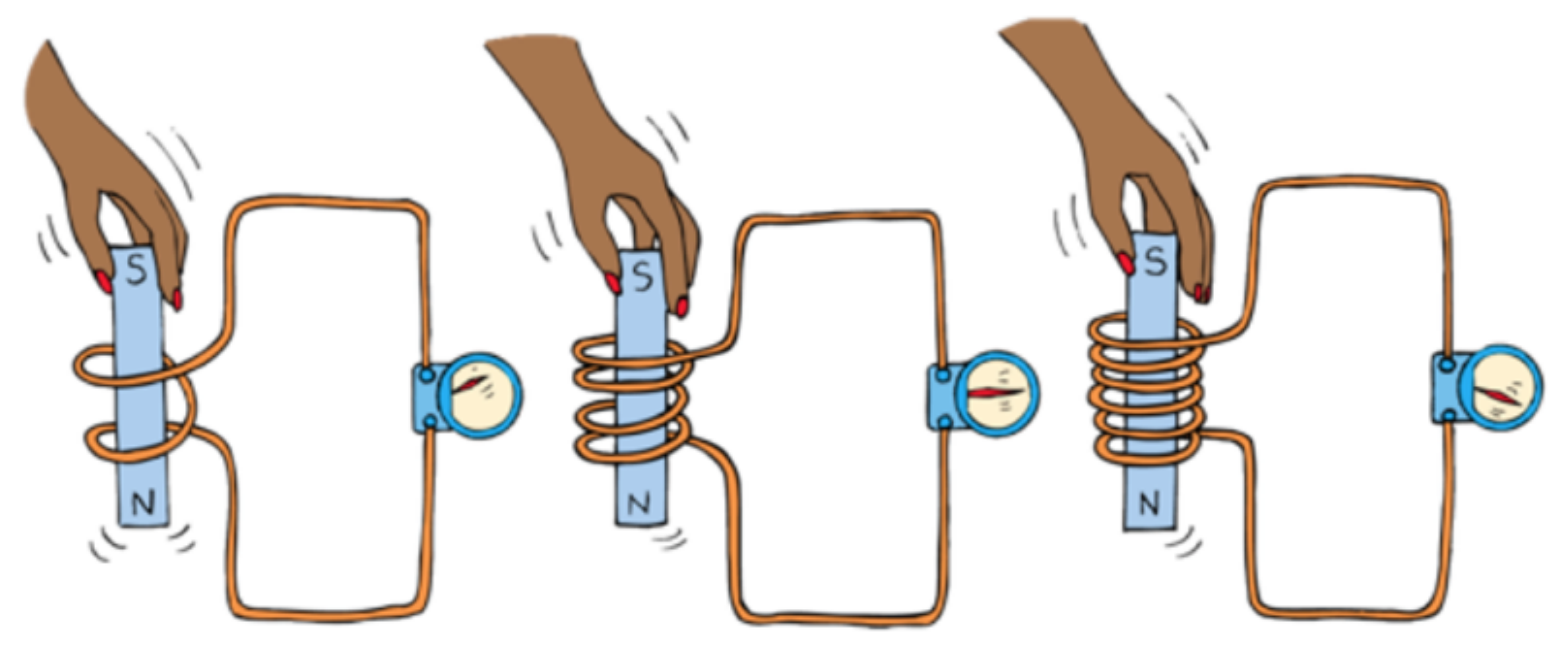
- The production of voltage depends only on the relative motion of the conductor with respect to the magnetic field

- Whether the magnetic field moves past the conductor or the conductor moves through the magnetic field, the results are the same



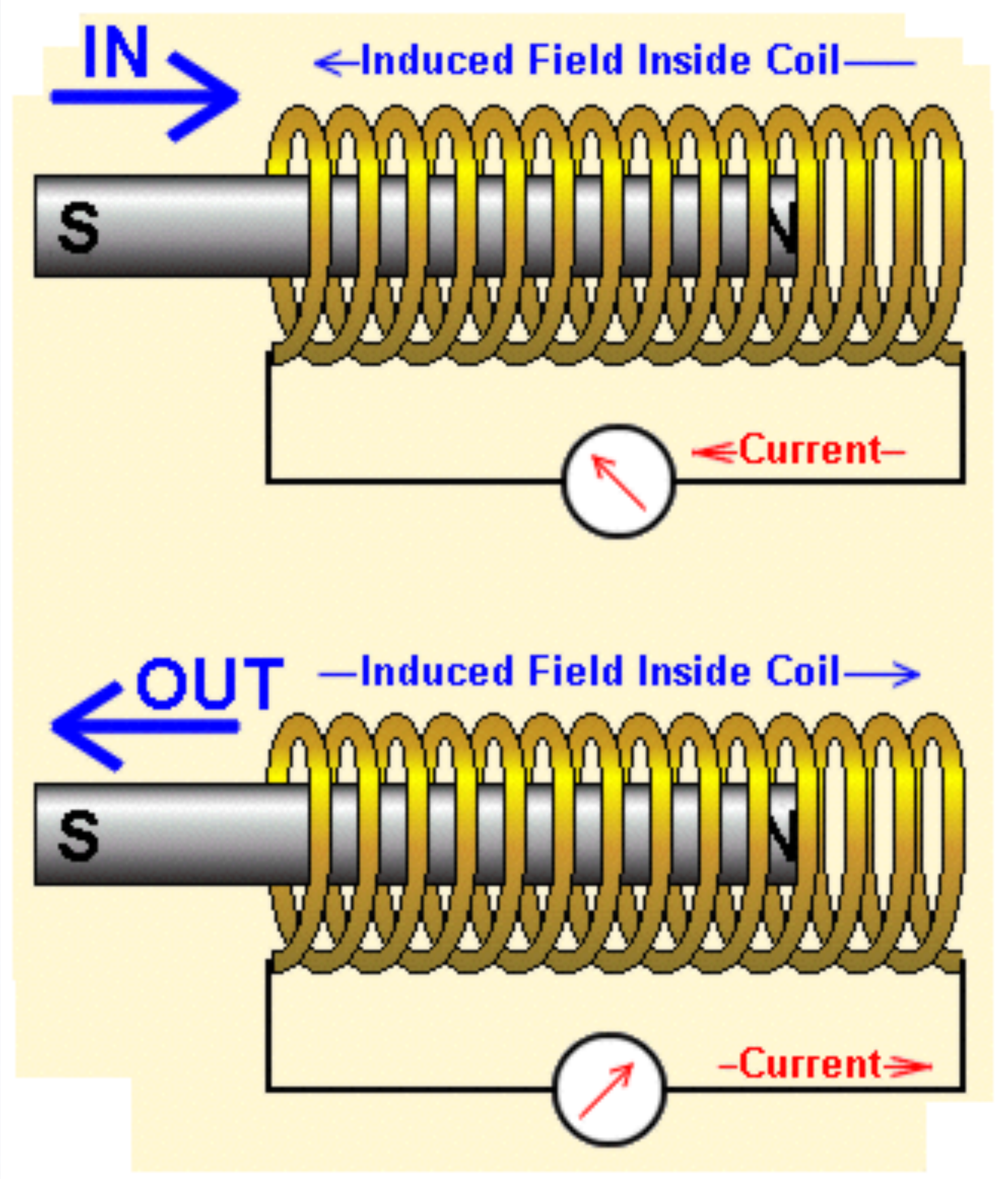
# ELECTROMAGNETIC INDUCTION

- The voltage induced depends on how quickly the wire traverses the magnetic field
  - The faster the motion, the greater the voltage
- Also depends on the number of loops in the wire that the magnetic field passes through
  - Doubling the number of loops doubles the voltage induced



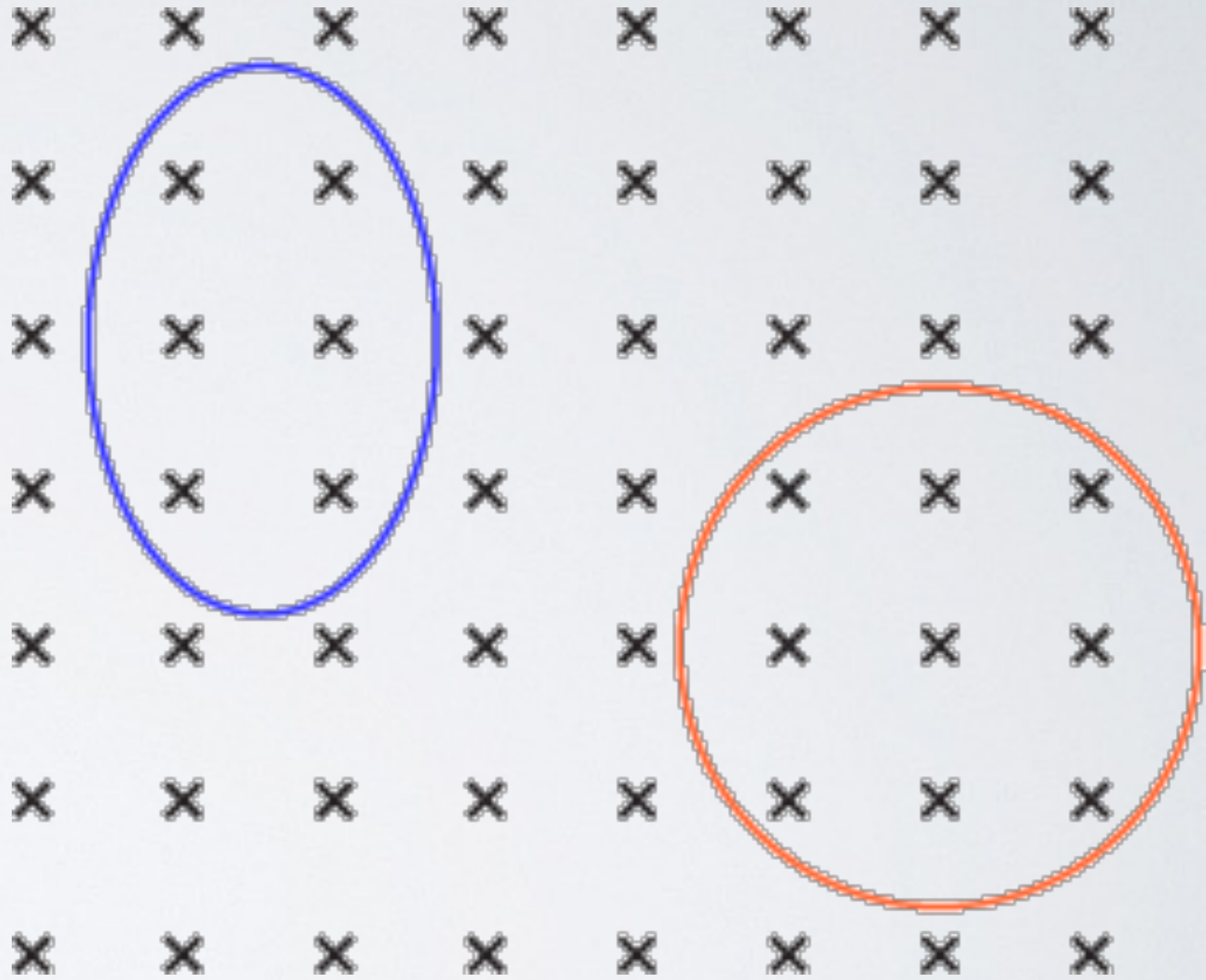
# ELECTROMAGNETIC INDUCTION

- Nothing comes for free!
  - The induced current in the wire creates its own magnetic field that will always resist the motion of the magnet
  - So, pushing a magnet into a coil with more loops requires more work



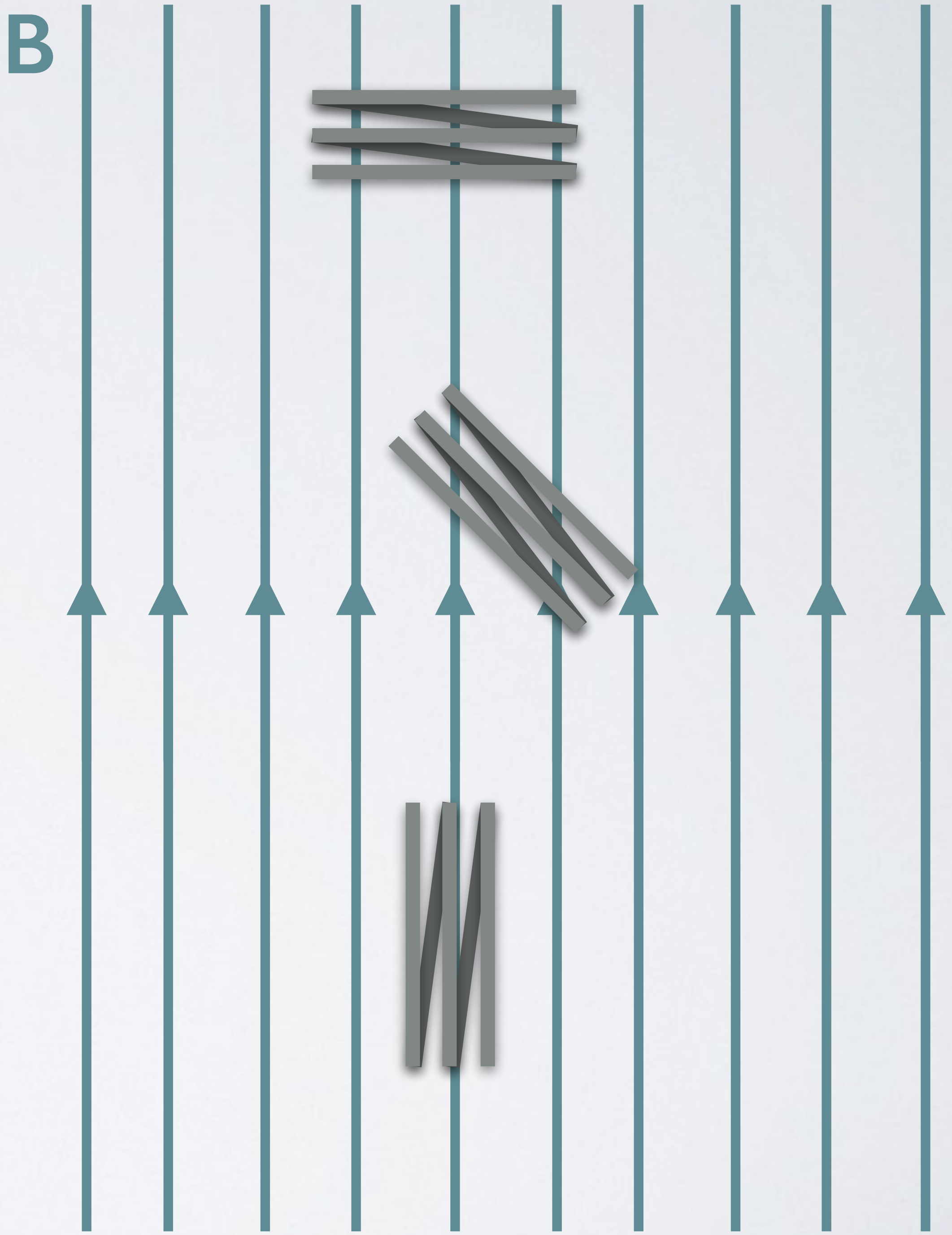
# FARADAY'S & LENZ'S LAWS

- Faraday investigated what factors influence the magnitude of the voltage induced
- He found that it depends on how much of a magnetic field is able to pass through the coil
- This can be achieved two ways:
    - Change the strength of the magnetic field
    - And/or change cross-sectional area of the coil



# FARADAY'S & LENZ'S LAWS

- Product of the magnetic field and cross-sectional area is called the ***magnetic flux***
- $\boxed{\Phi = B_{\perp}A = BA \sin\theta}$
  - Measured in ***webers*** (**Wb**)
- The induced voltage will be proportional the *rate of change* of the magnetic flux



# FARADAY’S & LENZ’S LAWS

- Faraday’s Law of Induction:
    - $\boxed{V = N\Delta\Phi/\Delta t}$
    - $V$ is the voltage induced
    - $N$ is the number of loops
    - $\Delta\Phi/\Delta t$ is the change in flux per time

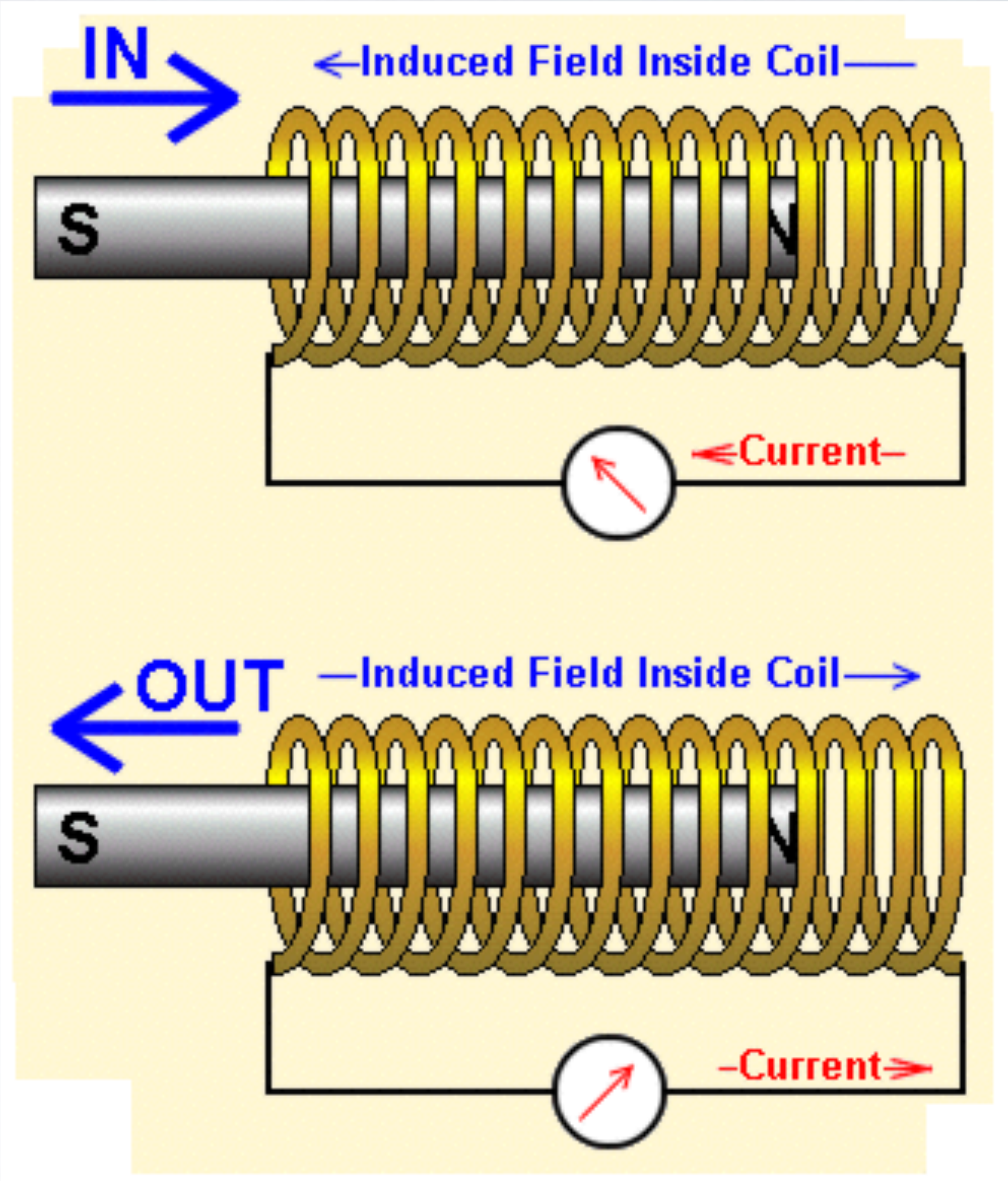
# FARADAY'S & LENZ'S LAWS

- ***An induced voltage always gives rise to a current whose magnetic field opposes the original magnetic field which produced it***
    - This is known as ***Lenz's Law***

# FARADAY’S & LENZ’S LAWS

- Try to push the magnet *into* the coil and current will counter-clockwise, creating a magnetic field that *repels* the incoming magnet

- Try to pull the magnet *out of* the coil and current will run clockwise, creating a magnetic field that *attracts* the outgoing magnet

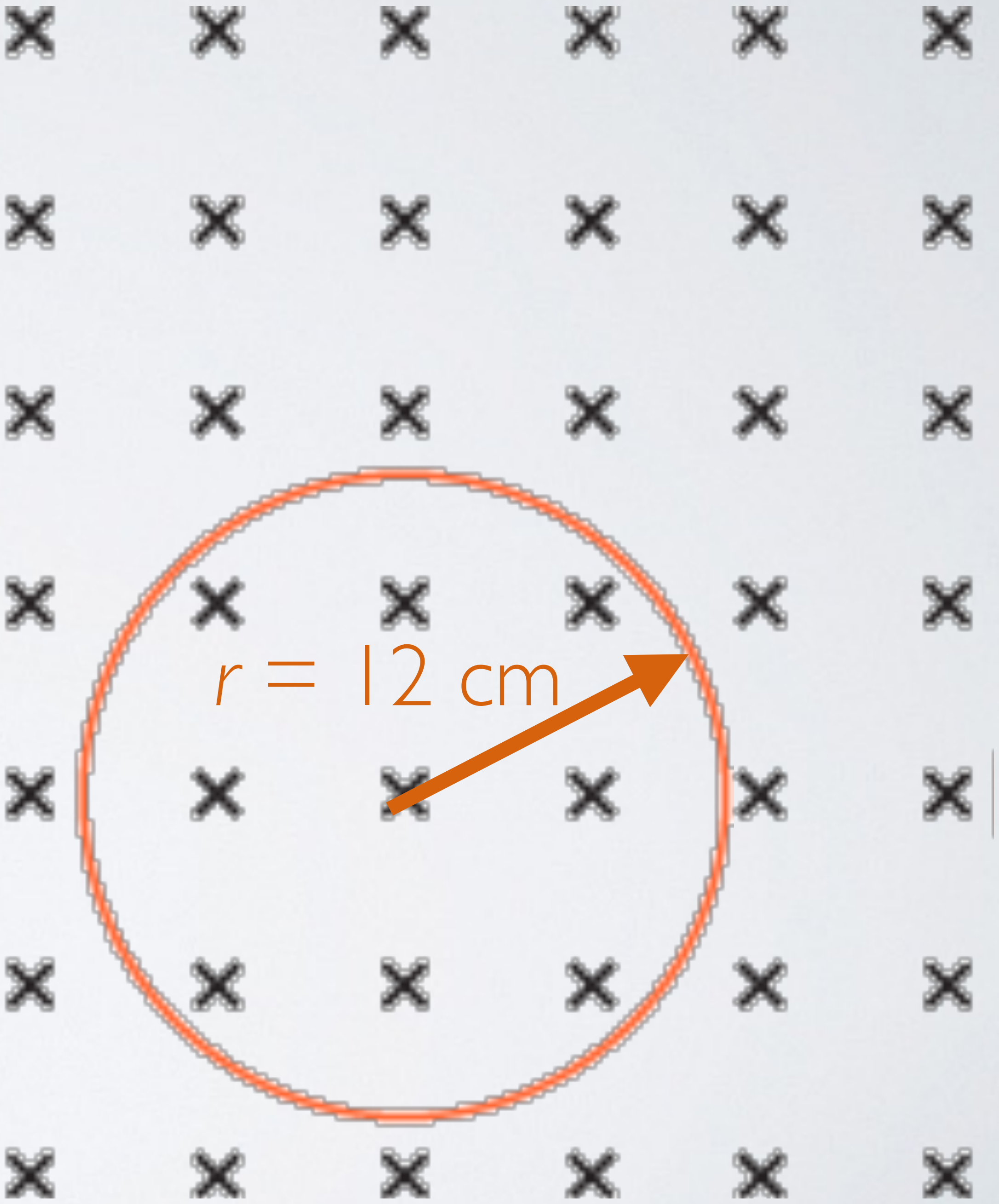


# SANITY CHECK

- Some modern stove burners are based on induction. That is, an AC current passes around a coil that is the burner. Why will it heat a metal pan but not a glass container?
  - *Answer*: the AC current sets up a changing magnetic field which induces current in the bottom of the pan
  - The pan offers resistance, so electric energy is transformed to heat
  - The glass offers very high resistance, so very little current flows

# EXAMPLE 5

- A circular, 100-loop coil of wire has a radius of 12 cm. it is exposed to a perpendicular magnetic field which grows at a steady rate of 0.33 T/s. What is the induced voltage, and in what direction will current flow?
  - *Answer:* $V = 1.49\text{ V}$
  - Current will flow counter-clockwise



# ELECTRIC GENERATORS

- The discoveries that current produces a magnetic field *and* changing magnetic fields induce a current has allowed us to harness electric energy in unprecedented ways

- Enter the electric generator and electric motor

- These two inventions launched human civilization into one powered by electricity in a way batteries alone could never hope to do

# ELECTRIC GENERATORS

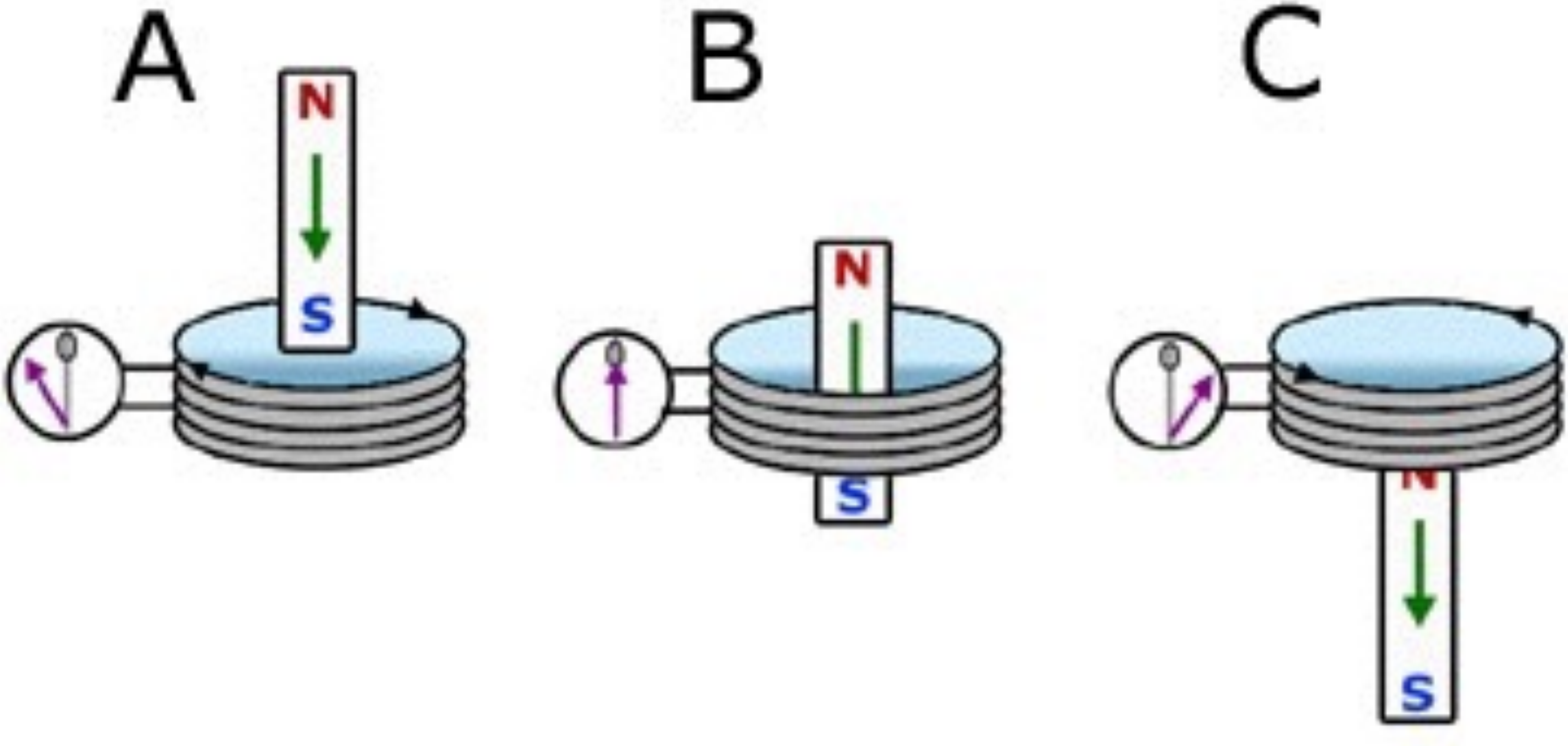
- ***Electric motors*** convert electrical energy into mechanical energy

- ***Electric generators*** convert mechanical energy into electrical energy

# ELECTRIC GENERATORS

- *How to build an electric generator:*
- Plunge a magnet into and out of a coil of wire
  - Magnet enters → field strength inside coil increases, induce voltage directed one way
  - Magnet exits → field strength diminishes, voltage induced in opposite direction
  - Greater frequency of field change = greater voltage
  - Frequency of alternating voltage = frequency of changing magnetic field in loop

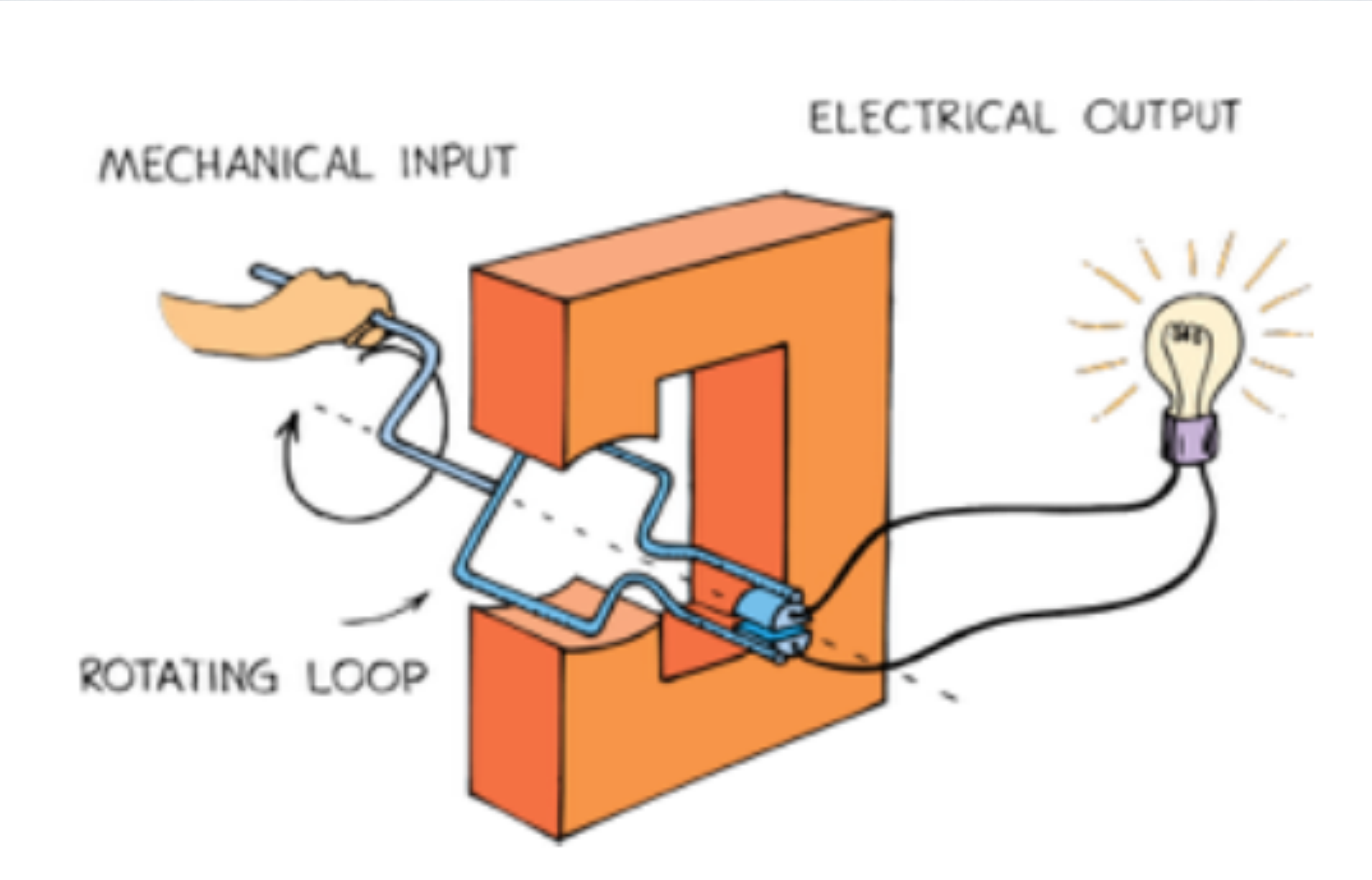
# ELECTRIC GENERATORS



# ELECTRIC GENERATORS

- *More practical:*
  - Rotate coil in stationary magnetic field
    - When loop is perpendicular to the field, the max field lines pass through it
    - As it rotates, the loop encircles fewer and fewer field lines until it's parallel, when it encloses none at all
    - Rotation continues, it encloses an increasing number of field lines until it's perpendicular again, when it's made a half rotation

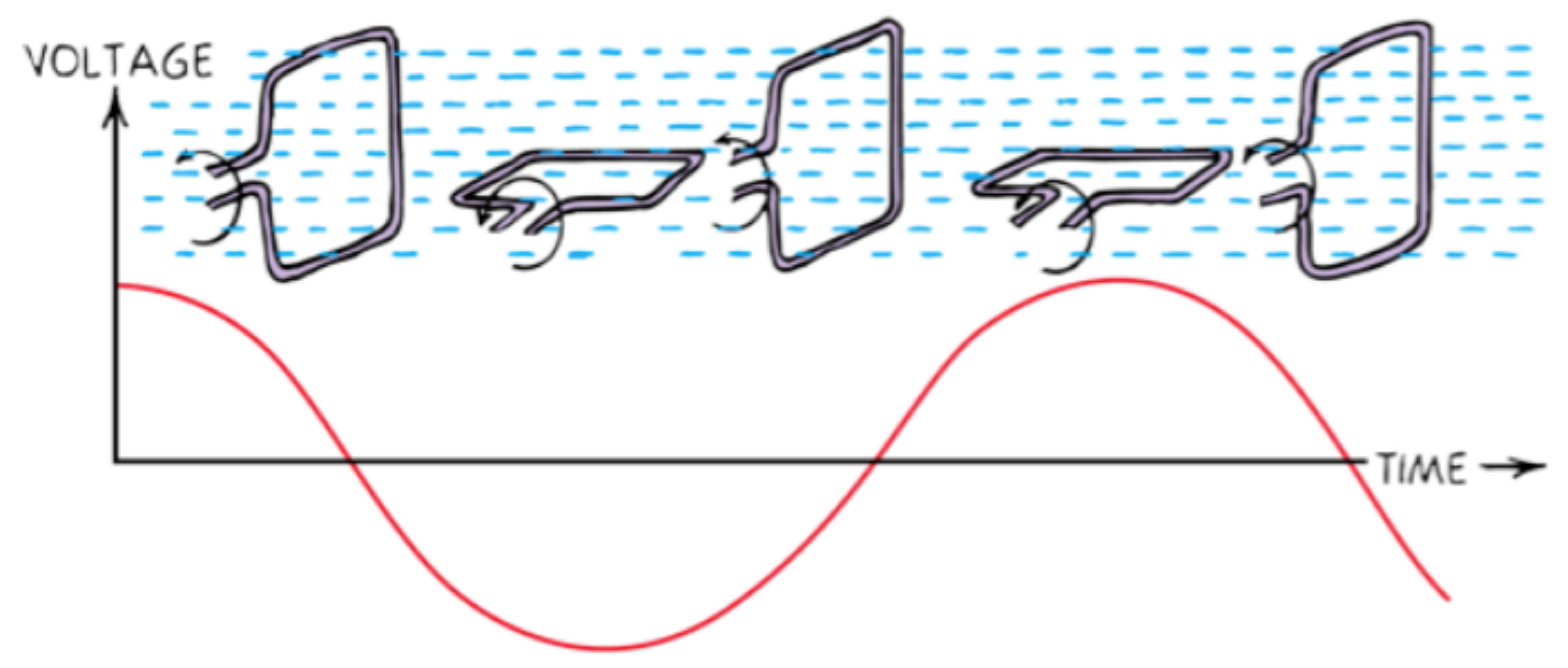
# ELECTRIC GENERATORS



# ELECTRIC GENERATORS

- As the loop rotates, the magnitude and direction of the voltage (and current) change

- One complete voltage cycle is produced for every full rotation of the loop



# ELECTRIC GENERATORS

- The voltage induced by the generator alternates and produces an ***alternating current*** (***AC***)

- Current changes magnitude and direction periodically

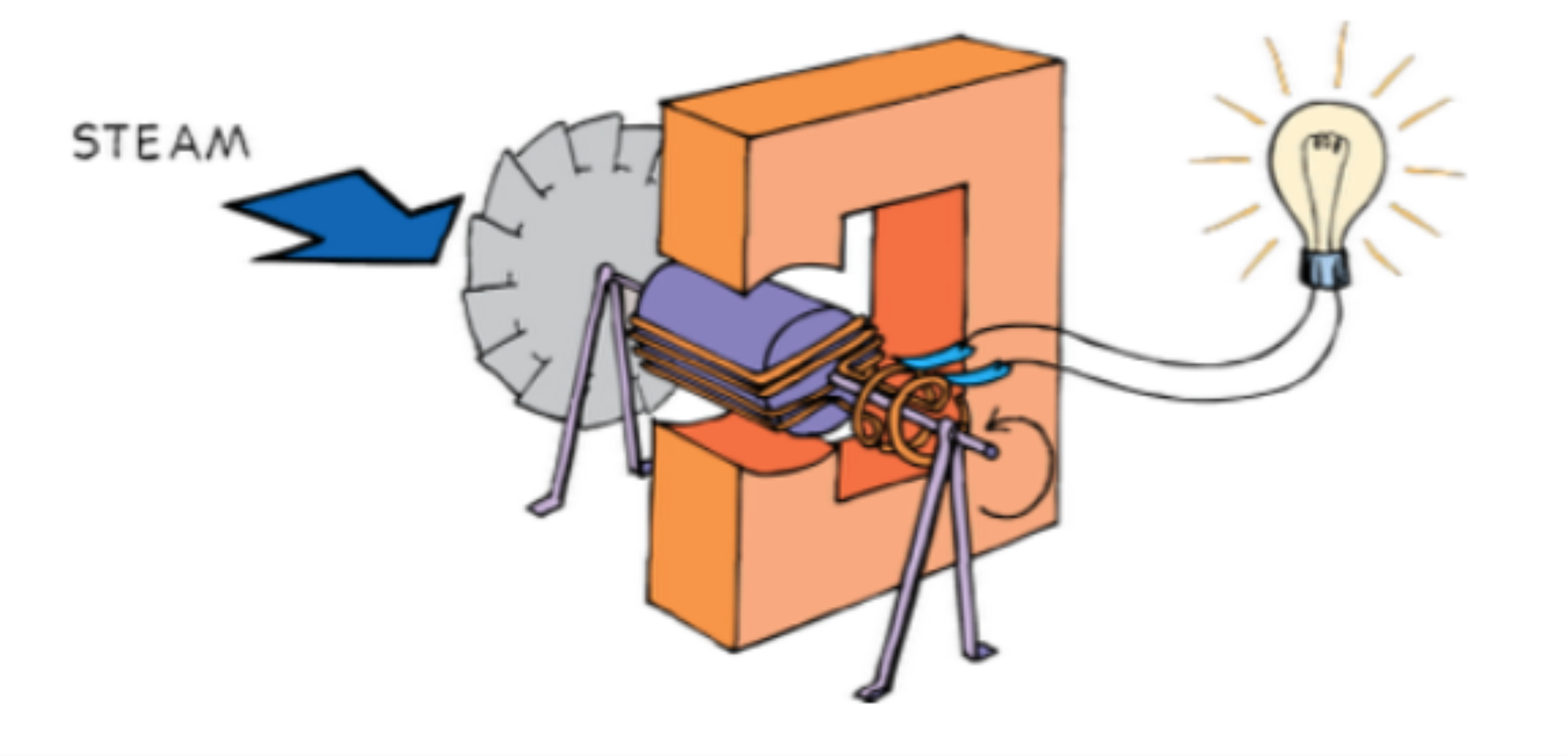
- Standard AC in North America cycles through magnitude and direction 60 times every second — 60 Hz

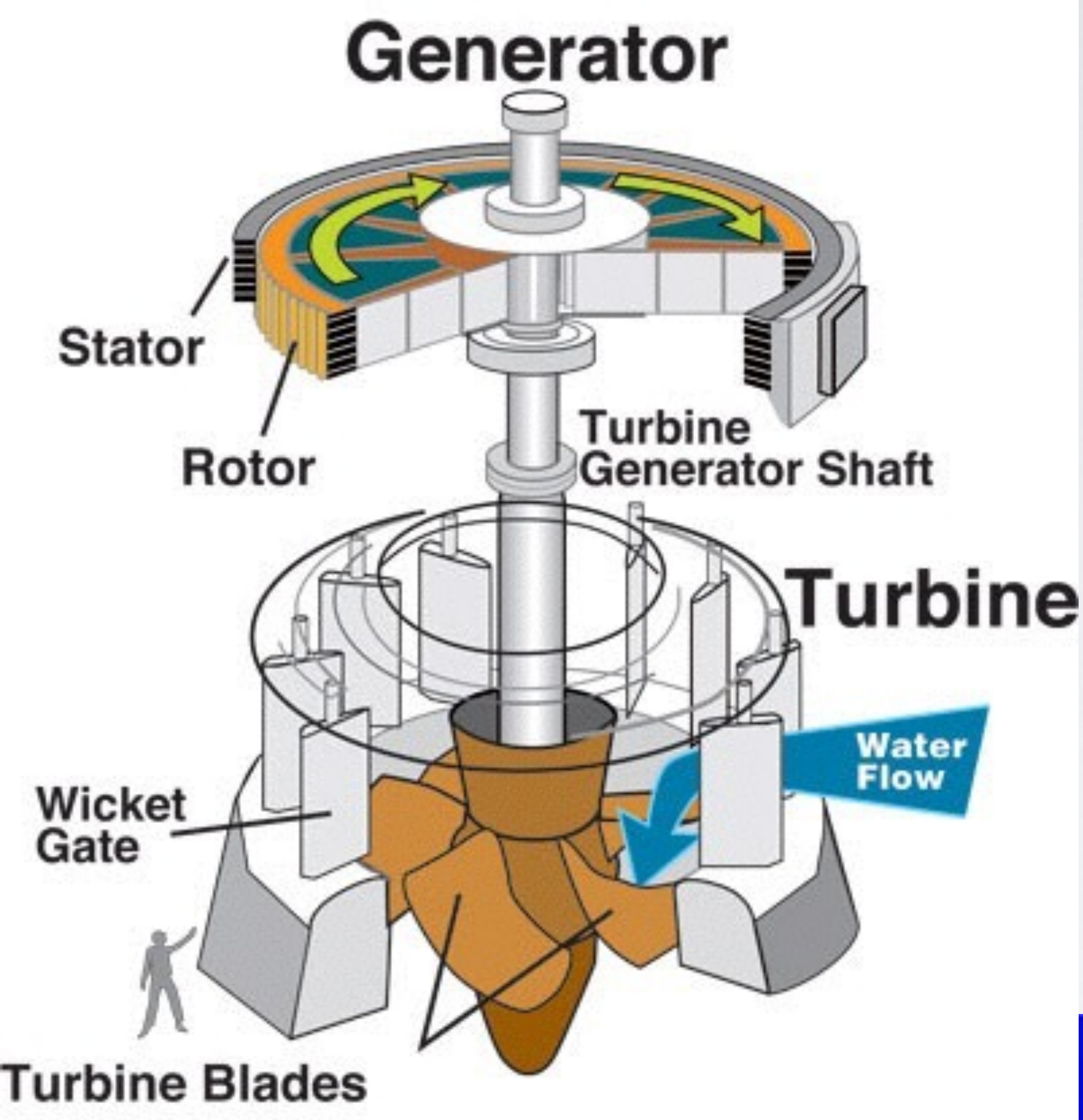
# ELECTRIC GENERATORS

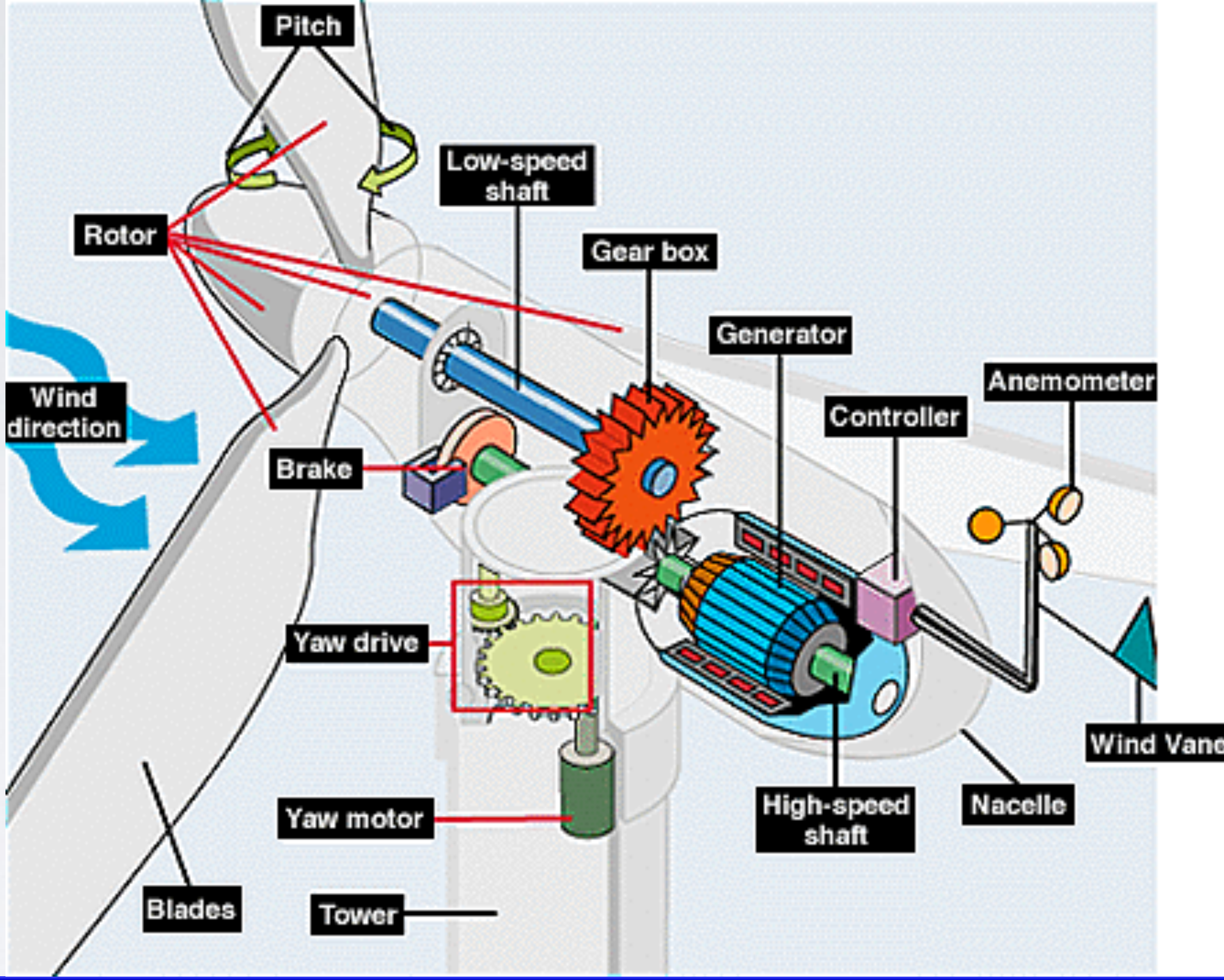
- *Complex generators:*
- To make your generator even better:
  - use a coil with many loops
  - add an iron core
  - produce the external magnetic field using powerful electromagnets

# ELECTRIC GENERATORS

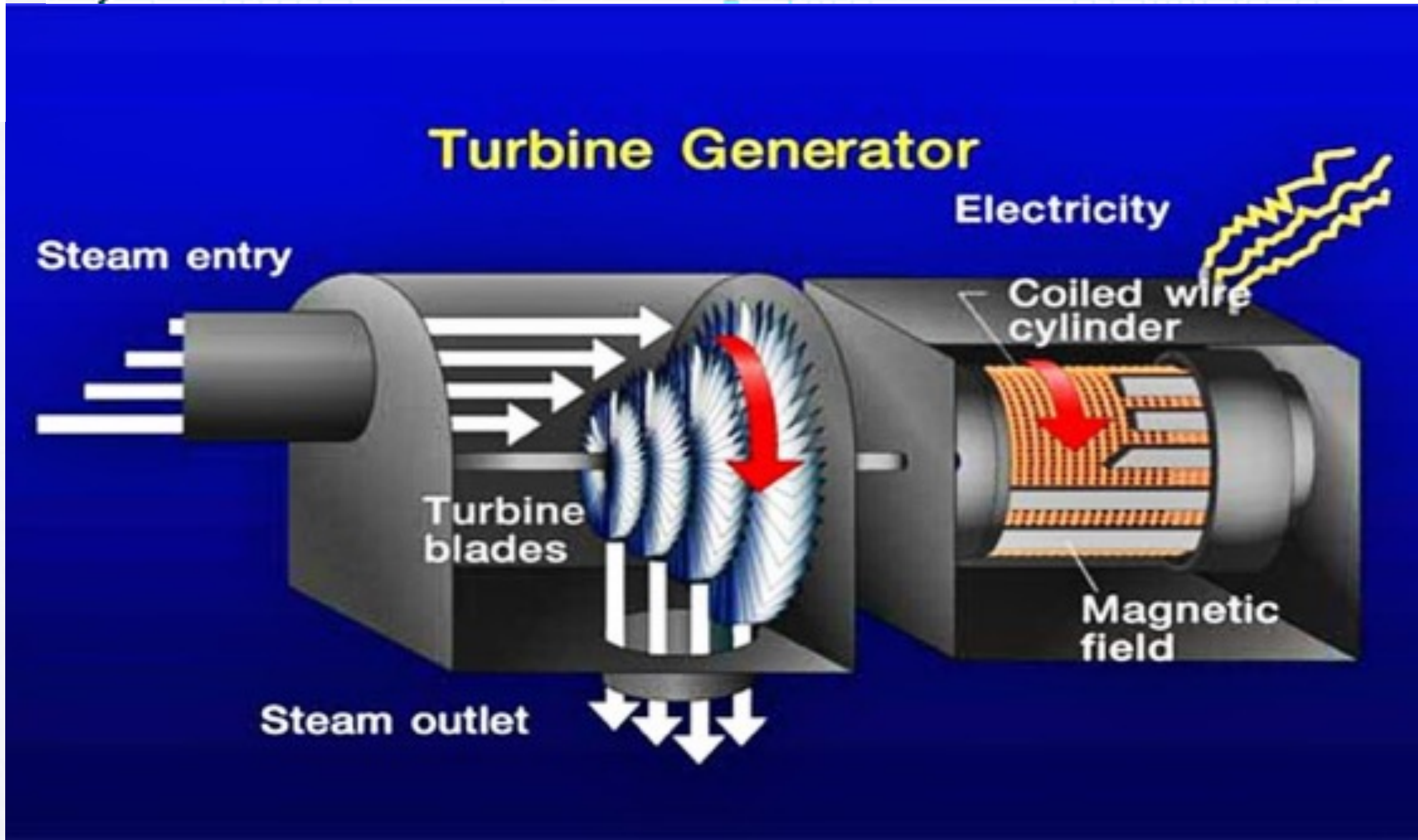
- Attach the armature of your assembly to a turbine
- Rotate the turbine using wind, falling water, or (most typically) steam





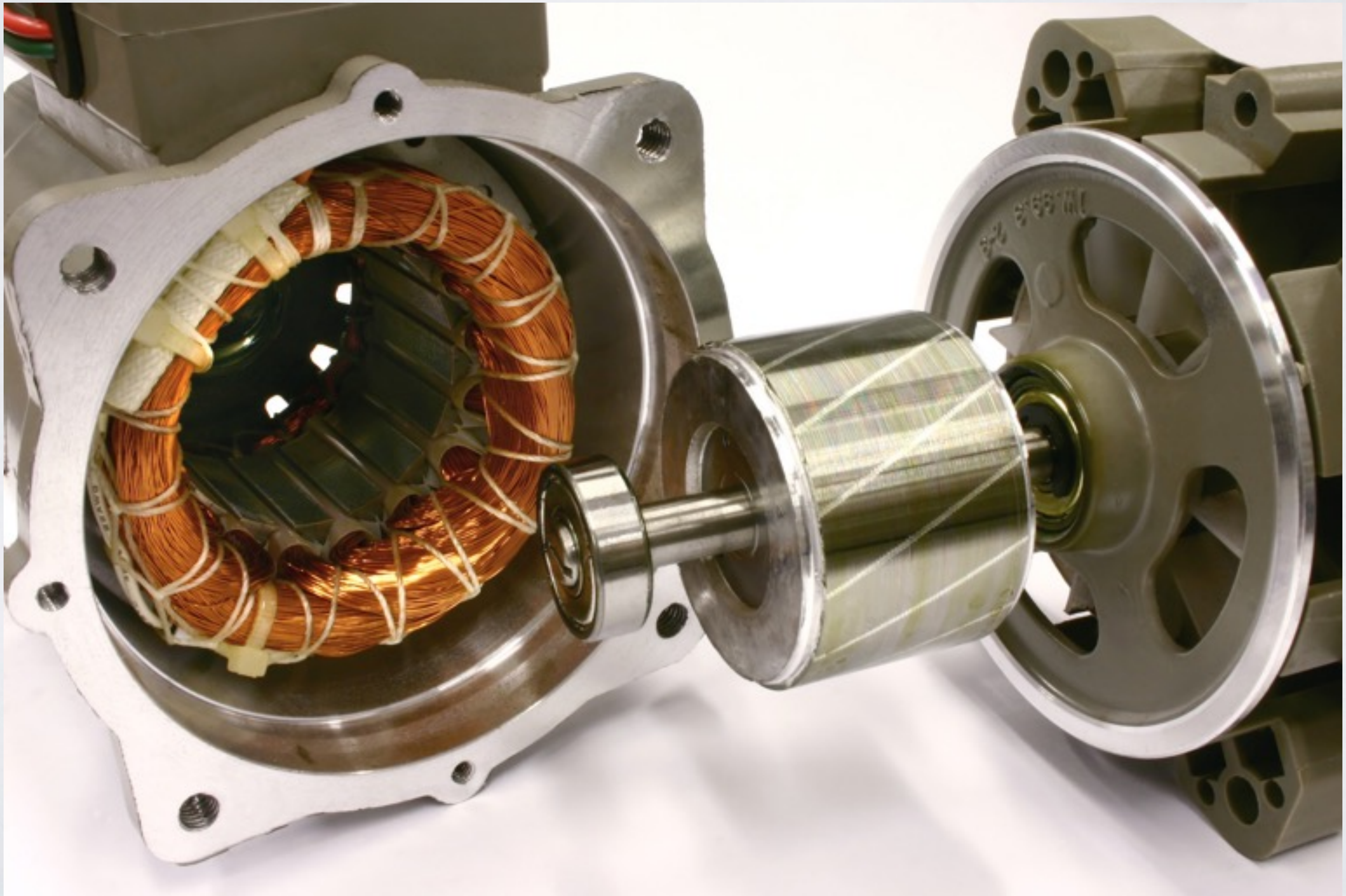


What's the source of energy?



# ELECTRIC MOTORS

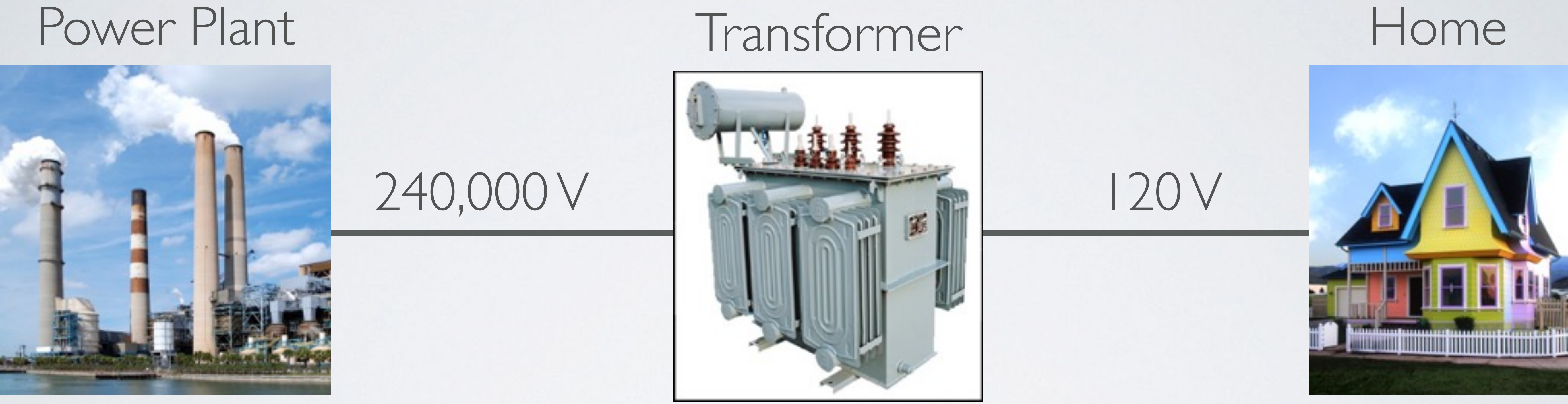
- An electric motor is simply a generator run in reverse



# ELECTRIC MOTORS/ GENERATORS

- In fact, cars have devices that function as both a motor and a generator
    - When extra power is needed for accelerating or going uphill, this device draws current from a battery and acts as a motor
    - Braking or rolling downhill cause the wheels to exert a torque on the device so it acts as a generator and recharges the battery

# TRANSFORMERS



Power Plant

Transformer

Home

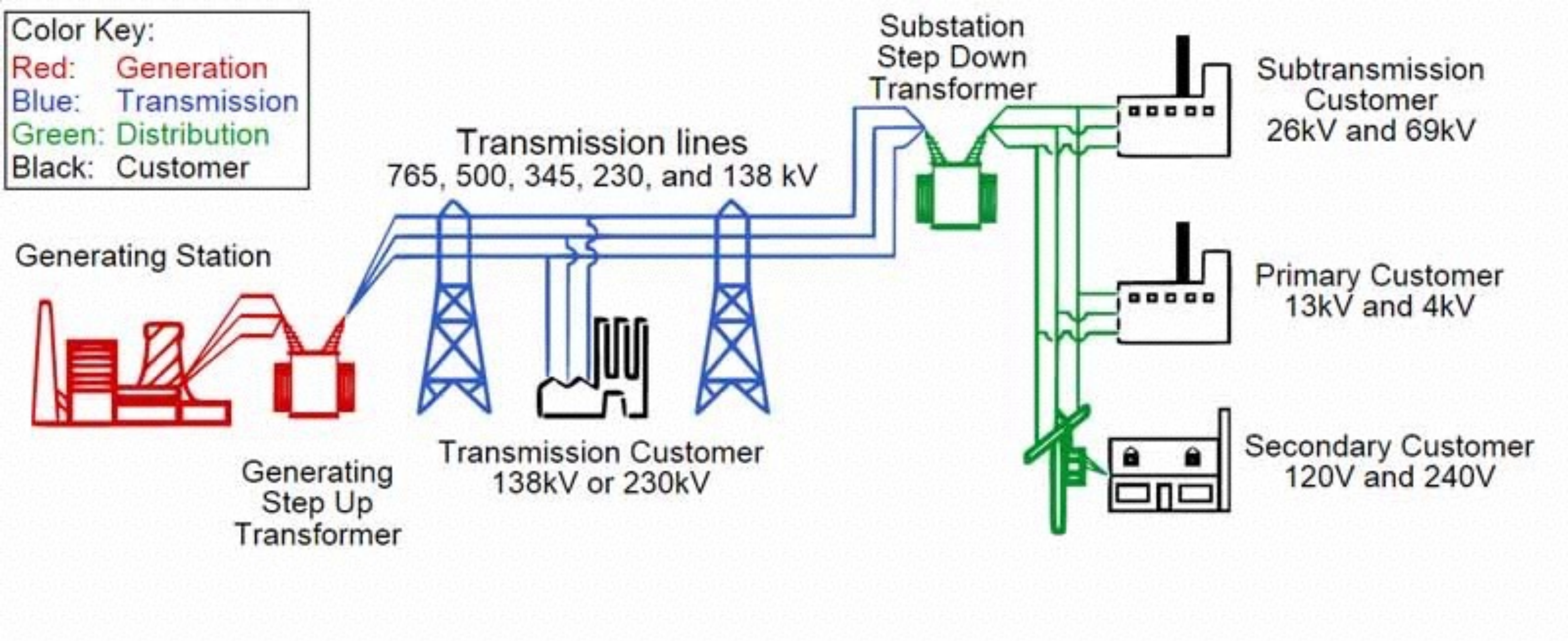
240,000 V

120 V

# TRANSFORMERS

- A ***transformer*** is a device for increasing or decreasing an AC voltage

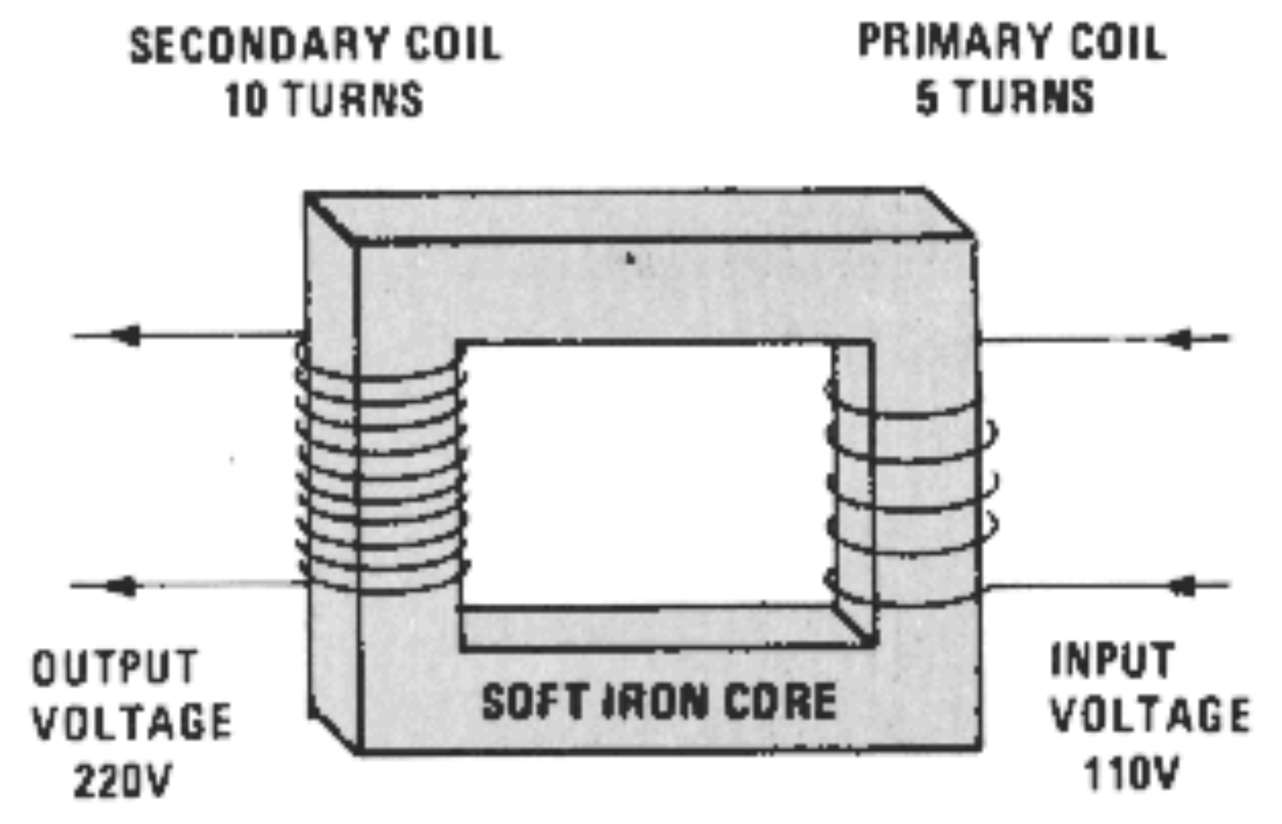
# TRANSFORMERS




50
4.8 / 16

# TRANSFORMERS

- A transformer consists of two coils of wire known as the ***primary*** and ***secondary*** coils
- The two coils can be interwoven (with insulated wire) or linked by a soft iron core
- Transformers are built so that (nearly) all magnetic flux produced by current in the primary also passes through the secondary



# TRANSFORMERS

- Faraday's Law tells us that induced voltage is proportional to the number of loops in the coil
- $\frac{\text{primary voltage}}{\text{number of primary turns}} = \frac{\text{secondary voltage}}{\text{number of secondary turns}}$
- $\boxed{V_P/N_P = V_S/N_S}$

# TRANSFORMERS

- If the secondary coil has *more* loops than the primary, the secondary voltage will be *greater* than the primary
  - Called a ***step-up transformer***
- If the secondary coil has *less* loops than the primary, the secondary voltage will be *less* than the primary
  - Called a ***step-down transformer***

# TRANSFORMERS

- You still don't get something for nothing! Energy is always conserved

- A transformer actually transfers energy from one coil to the other. The rate at which energy is transferred is the power

- The power used in the secondary is supplied by the primary

  - $P = I_P V_P = I_S V_S$

  - If the secondary has more voltage, it will have less current, and vice versa

# EXAMPLE 6

- A transformer in a portable radio reduces 120-V to 9.0 V. The secondary contains 30 turns and the radio draws 400 mA.

  a) How many turns in the primary?

  b) What's the current in the primary?

  c) Calculate the power transferred.

*a) Answer:* $N_P = 400$ loops

*b) Answer:* $I_P = 0.030$ A

*c) Answer:* $P = 3.6$ W