Magnetic Fields and Sources

photo courtesy of
Mr. White

Relativity and Magnetism

--Newton's Classical Mechanics demands that the speed of light depend upon the relative motion between the *frame of reference* of the light source and the observer's frame (think of about a passing car's speed on the freeway—how fast it passes you depends upon how fast *you* are going).

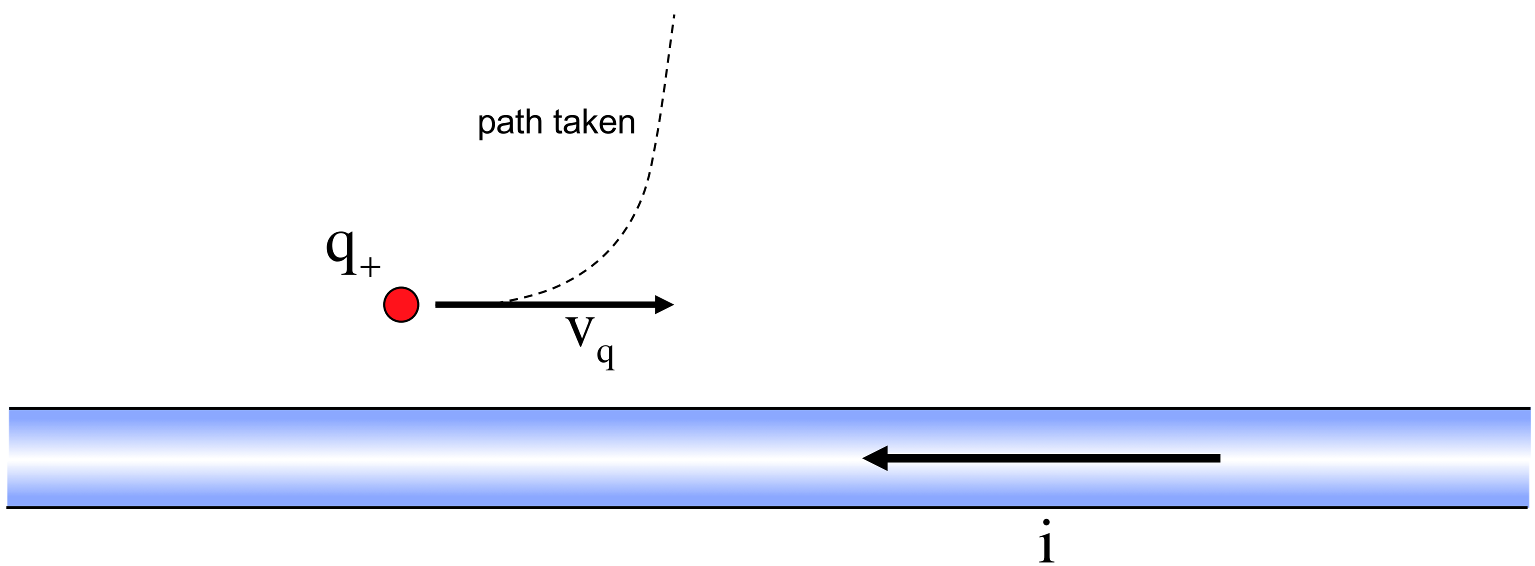
--Yet because alternating magnetic fields (B-flds) induce electric fields (E-flds), and alternating E-flds induce B-flds, the only way an alternating E-fld can coupled with an alternating B-fld to produce an electromagnetic wave (i.e., a wave in which the alternating E-fld feeds the B-fld and the alternating B-fld feeds the E-fld), is if, according to Maxwell's equations, the wave's velocity is 3×10^8 m/s, *the speed of light*.

--You can't have it both ways. The *speed of light* is either frame-of-reference dependent alla Newton, or it's a fixed value independent of frame-of-reference alla Maxwell.

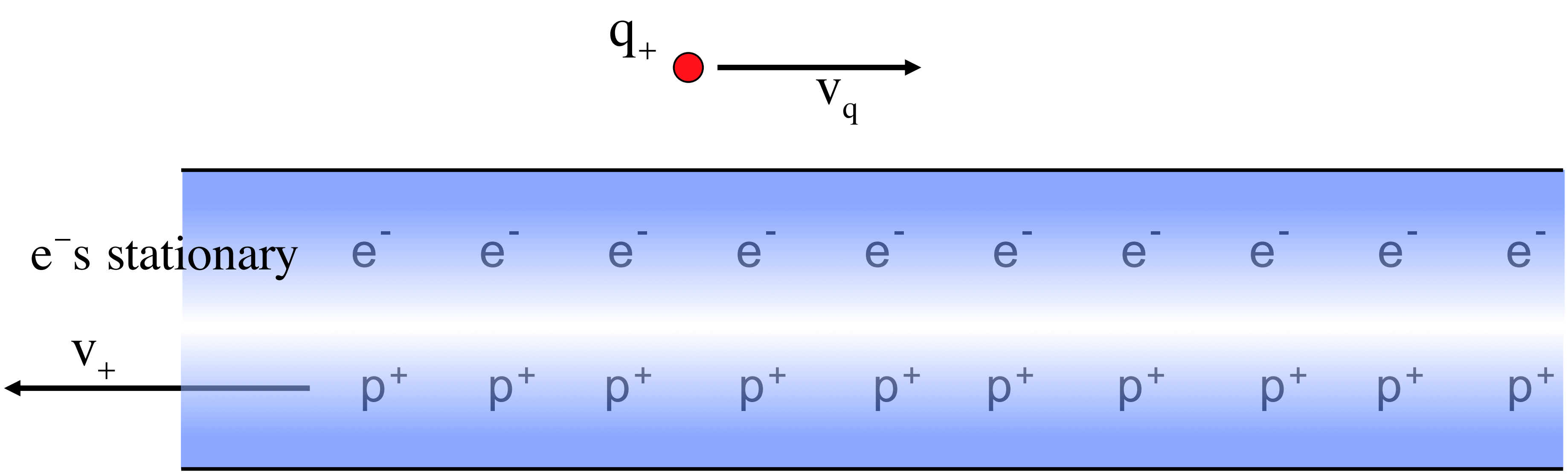
--This conundrum is what motivated Einstein to develop his Theory of Special Relativity, a form of Mechanics that assume that the speed of light is the same in all frames of reference.

--One of the stranger characteristics of *Special Relativity* is that if you have an object that is approaching at relativistic speeds, it will *length contract*. And, in fact, this length contraction phenomenon will occur even at classical speeds (though observing it at classical speeds is difficult).

--With this in mind, consider a wire with conventional current flowing through it (i.e., assume positive charge flow). If you fire a positive charge opposite the direction of current flow, an interesting thing is observed. The charge will feel a force that motivates it to veer away from the wire. So what's going on?

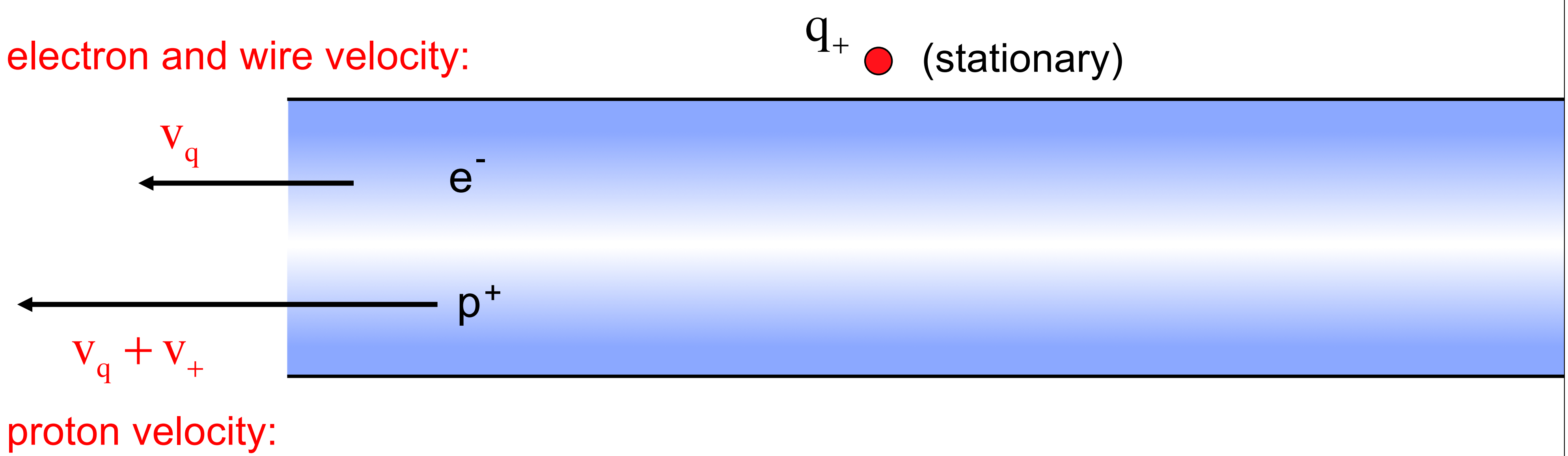


As positive charge carriers move onto the wire (with electrons assumed stationary), an equal number of positive charge carriers move off the wire. That means the number of positive and negative charge stays even throughout time, the wire stays electrically neutral, and there's no good reason for the moving test charge to feel a force. But it does. This led early theorists to conclude that there must be a force, a *magnetic* force, affecting the moving charge . . . except that isn't what's really happening here. To see this, we have to look at the situation through the perspective of the moving charge q_+.

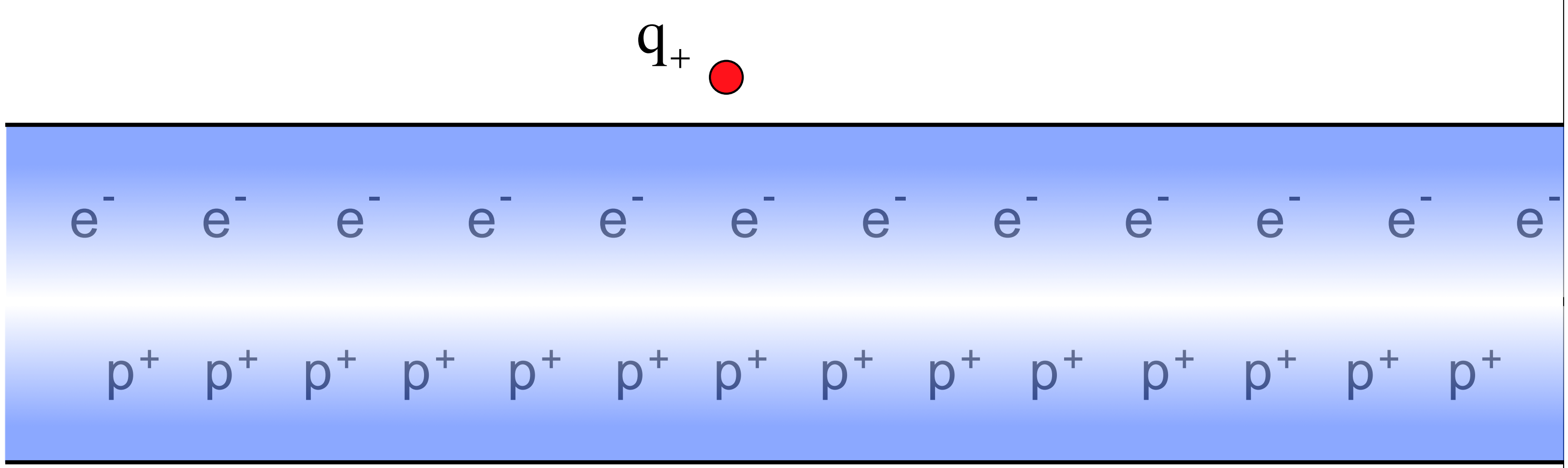


assume velocity of positive charge is v_+

In the frame of reference attached to q_+ ,q_+ is not moving. What's more, as far as q_+ is concerned, both the electrons and the wire are seen to be moving to the left with velocity v_q , and the protons are seen to be moving to the left with velocity $v_q + v_+$. The sketch below show all of this.

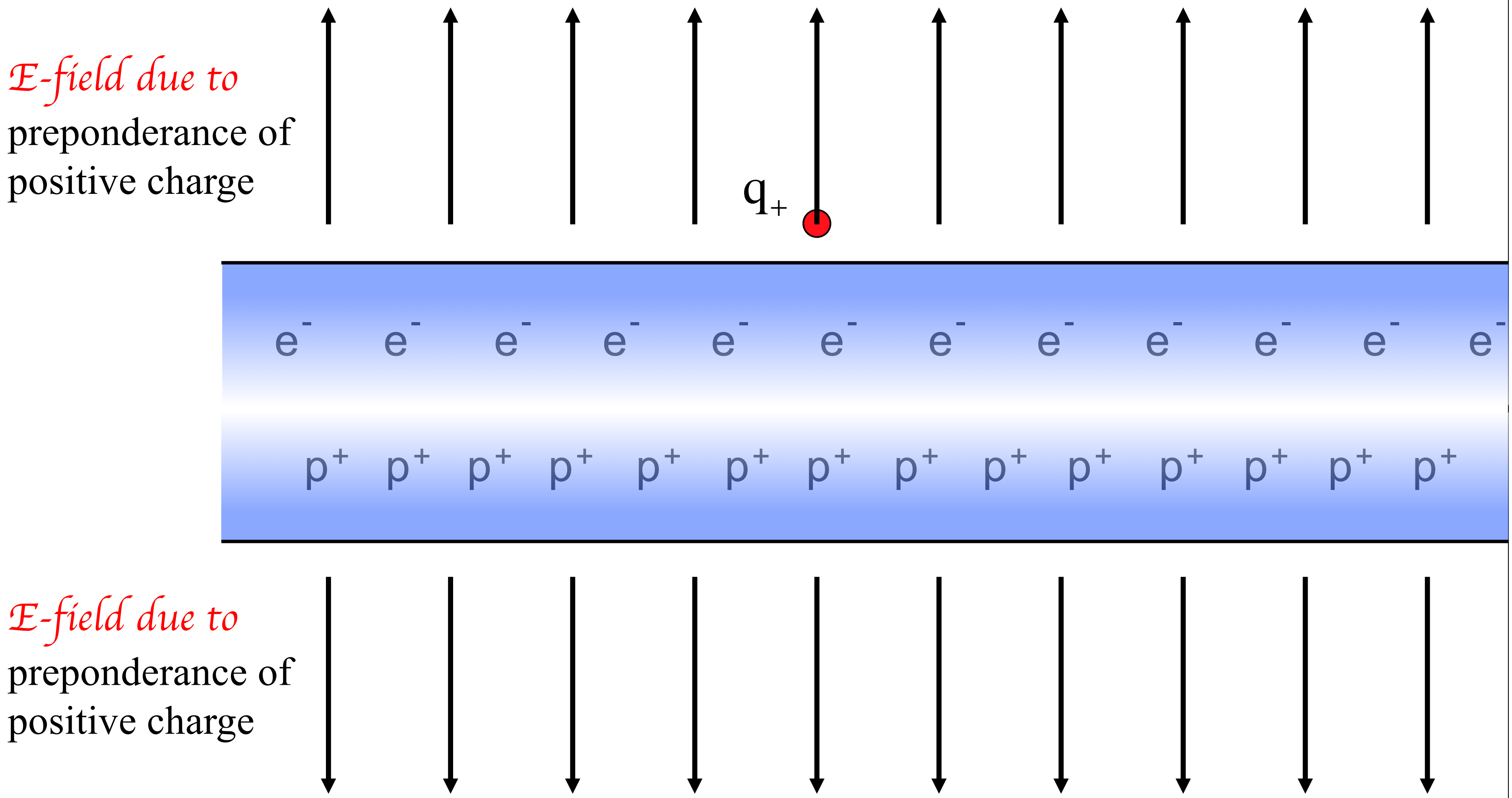


What's important to notice here is that because the *protons are moving faster than the electrons*, they will *length contract* more than will the electrons. When they do so, from the moving charge's perspective, there appears to be more protons on the wire than electrons.



Protons length contract more than electrons. More protons means the wire looks electrically positive and an electric field is set up pointing outward from the wire.

With more protons apparently on the wire, there is an electric field generated emanating outward from the wire. It is that electric field that the q_+ responds to.



In short, what was described by early researchers as a MAGNETIC EFFECT was (and is) really a RELATIVISTIC EFFECT.

Still, the Classical Theory of Magnetism is a good theory in the everyday world (just as is the case with Newtonian Mechanics), so that's what you will be spending the next several weeks learning.

What do you know about magnets?

- From previous experience, there are certain things we all seem to pick up about magnetism before we ever step foot in physics class. They are:
  - Magnets have **poles** - what are they? What do you know about them?
  - Magnets exert forces on some objects - what kind(s)?
  - Compasses are magnets - what does that tell us?

- We need to figure out the <u>why</u> and the <u>what</u> for each of these, and define them carefully to connect to the physics we already know. So pay attention - some definitions might be a little different than what you use in real life!

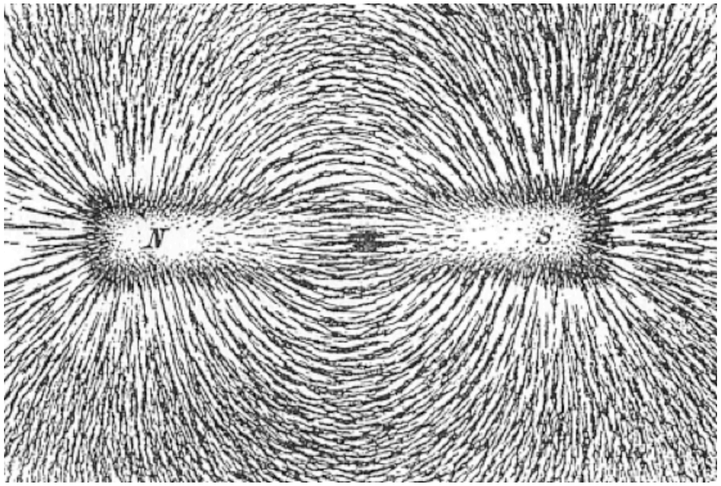
Magnetic poles

- What is a magnetic pole?
  - It's where the magnetic field is **strongest**
  - On a bar magnet, the poles are on the two ends
    - Non-bar magnets also have poles! We'll see that later.
  - Every magnet has <u>both</u> a north and south pole. You can't isolate one pole from another - even if you cut the magnet in half!
    - **this is different than electricity! You <u>can</u> separate positive and negative charges. Magnetism is NOT the same as electricity - even though they are related.

- North and South poles attract each other; like poles repel each other
- We talk both about "north" and "south" poles, as well as "north-seeking" and "south-seeking" poles. What's the difference?

Magnetic poles and Bar Magnets

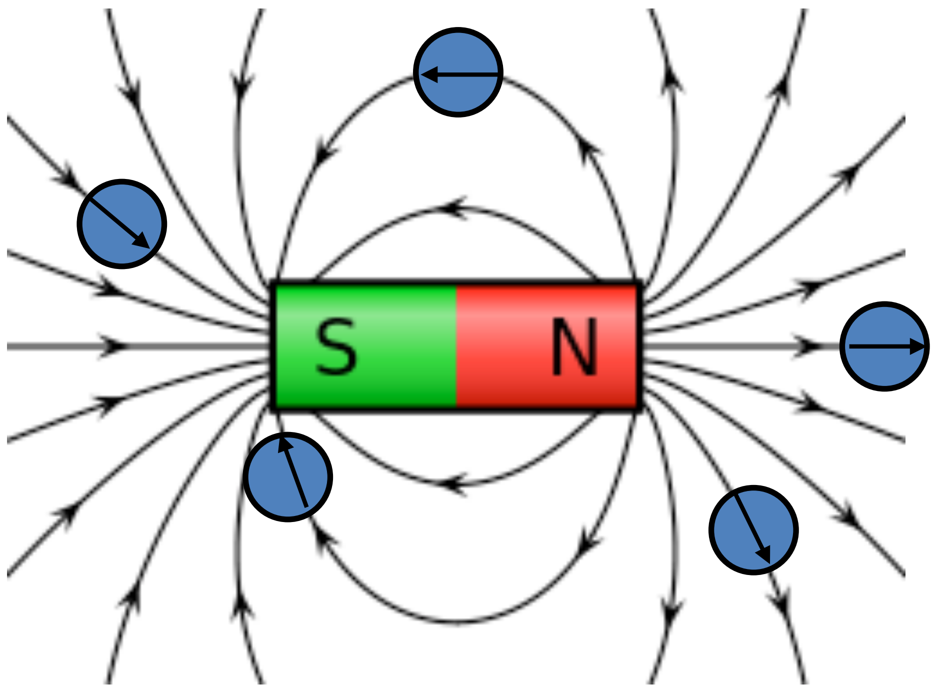
- A magnetic north-seeking pole is the part of magnet that is attracted to a north geographic hemisphere. That is usually the part of the compass with the arrowhead.
- Magnetic north poles are attracted to magnetic south poles.
- To tell if one side of a bar magnet is a north or south poles, look at the direction of its **magnetic field lines**. Field lines LEAVE north poles and ENTER south poles (think about how a compass would point if put at the end of the bar magnet).



Magnetic field lines

- Put a little differently, if you put a magnet in a magnetic field, it will align itself with that field!
  - Consider the magnetic field around the bar magnet, below. If I put a compass at the indicated points, what will the needle do?

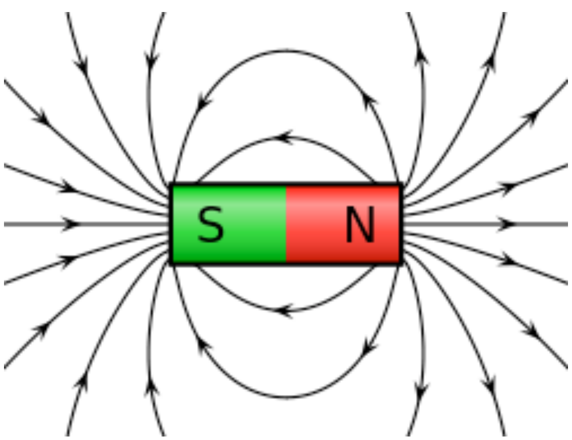
A compass needle aligns in the direction of the magnetic field line at that point.

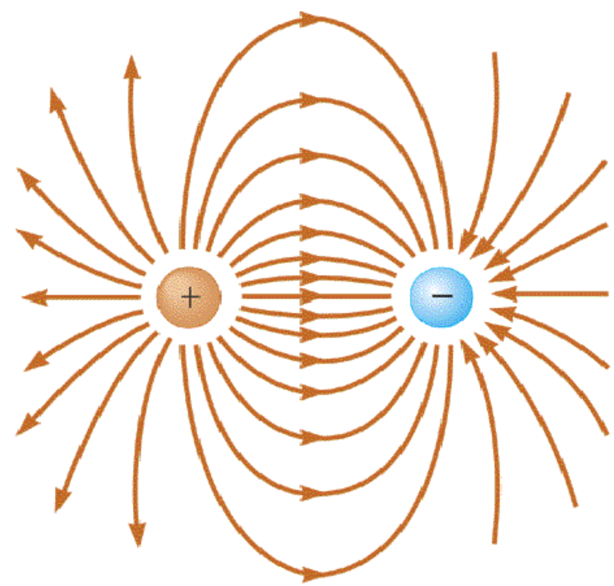


The compass needle points in the direction of the field - the field lines point the way a north magnetic pole would orient itself.

Magnetic field lines

- So again, magnetic field lines point **out from the north pole** and **into the south pole**.
- At any point, the direction of the magnetic field is tangent to the field line at that point.
- The number of lines per unit area is proportional to the field strength.
  - Hey, doesn't this sound familiar….?





Magnetic fields vs electric fields

- Obviously, magnetic field lines and electric field lines have things in common:
  - Both indicate strength of the field with density of lines
  - Both indicate a direction something will occur

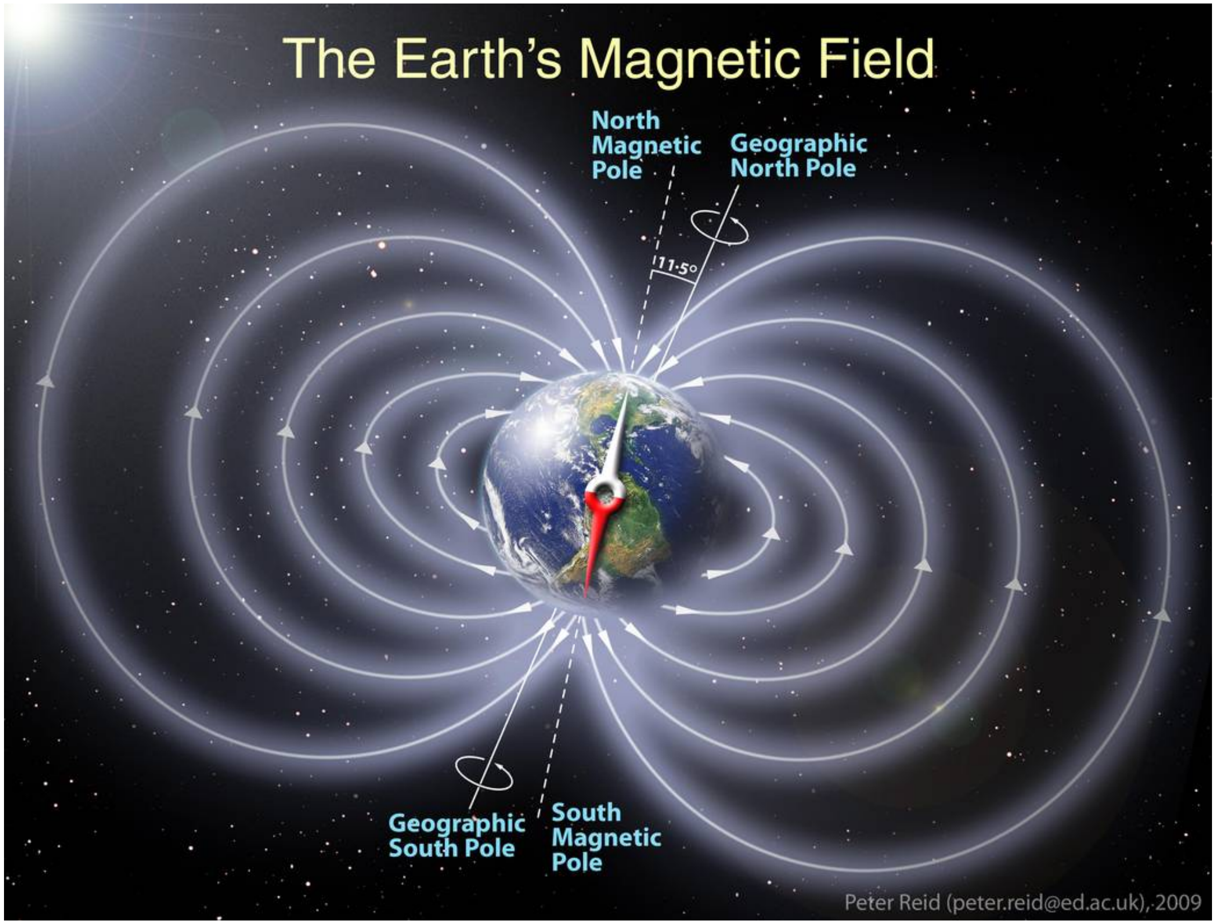
- **HOWEVER**, electric fields and magnetic fields are very different things! First off:
  - Magnets always have paired north and south poles. You can't separate them.
    - You can have isolated positive or negative charges
  - Magnetic field lines are <u>closed loops</u> that exit the north pole and enter the south pole.
    - Electric field lines emanate from + charges and terminate on - charges. They have starts and ends!
- There's one more BIG DIFFERENCE…

E vs. B field differences

- Imagine a charged particle. It's placed in a uniform electric field. What happens?
  - It accelerates - because an electric field is the force per unit charge at any given point.
- That same charged particle is placed in a uniform magnetic field. What happens?

Earth's magnetic field

- Earth obviously has a magnetic field surrounding it - otherwise, compasses would be useless in helping us navigate!
- What does the "north" label of a compass needle really mean?



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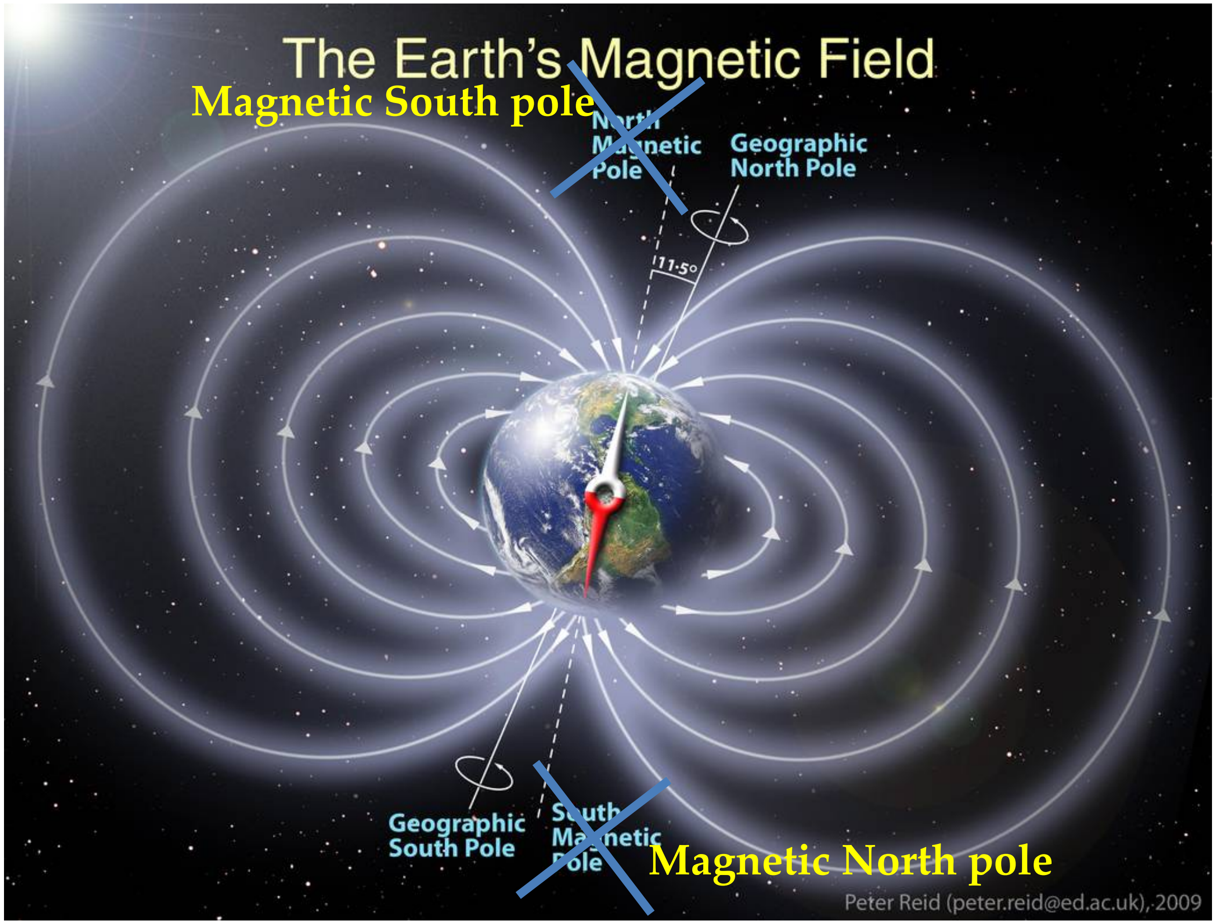
Earth's magnetic field

- Earth's magnetic field can be approximated by imagining a large bar magnet running through the planet, with poles roughly aligned to the geographic north and south poles.
  - The geographic and magnetic poles are actually off by quite a bit - several hundred kilometers! The magnetic poles also wander about, drifting tens of kilometers each year.
- The side of a compass needle painted and labeled "N" points to the magnetic pole that is located near the geographic north pole. This is often called the "geographic-north-seeking pole" of the compass needle.
- However, let's look at that picture again - which way are the field lines going???

Earth's magnetic field + compasses



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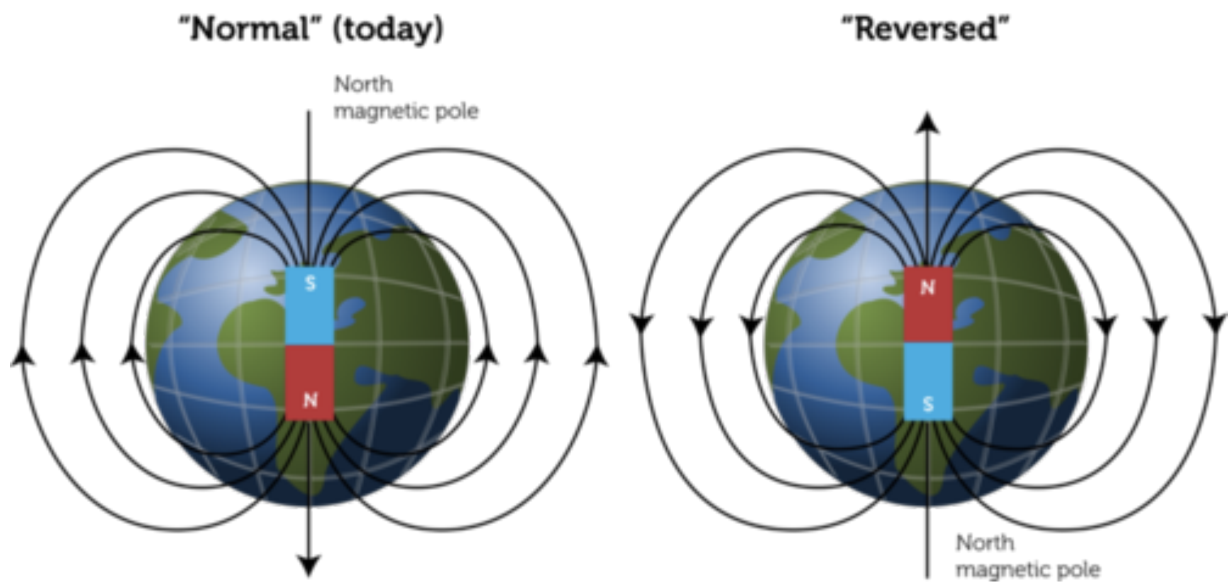
The Earth's field lines are going <u>into</u> the Earth at geographic north. That makes it a **<u>south magnetic pole</u>** by definition!

Thus, a **geographic-north-seeking compass needle** is itself a **north magnetic pole**, because it points to a **south magnetic pole** up in Canada somewhere.

Earth's magnetic field is complicated!

- Earth's magnetic field isn't always the same - the poles wander about, strengthen/weaken over time, and even flip!
- Right now, we are in what is called a "normal polarity" period - in a "reversed" polarity period, our compasses would point to Antarctica!

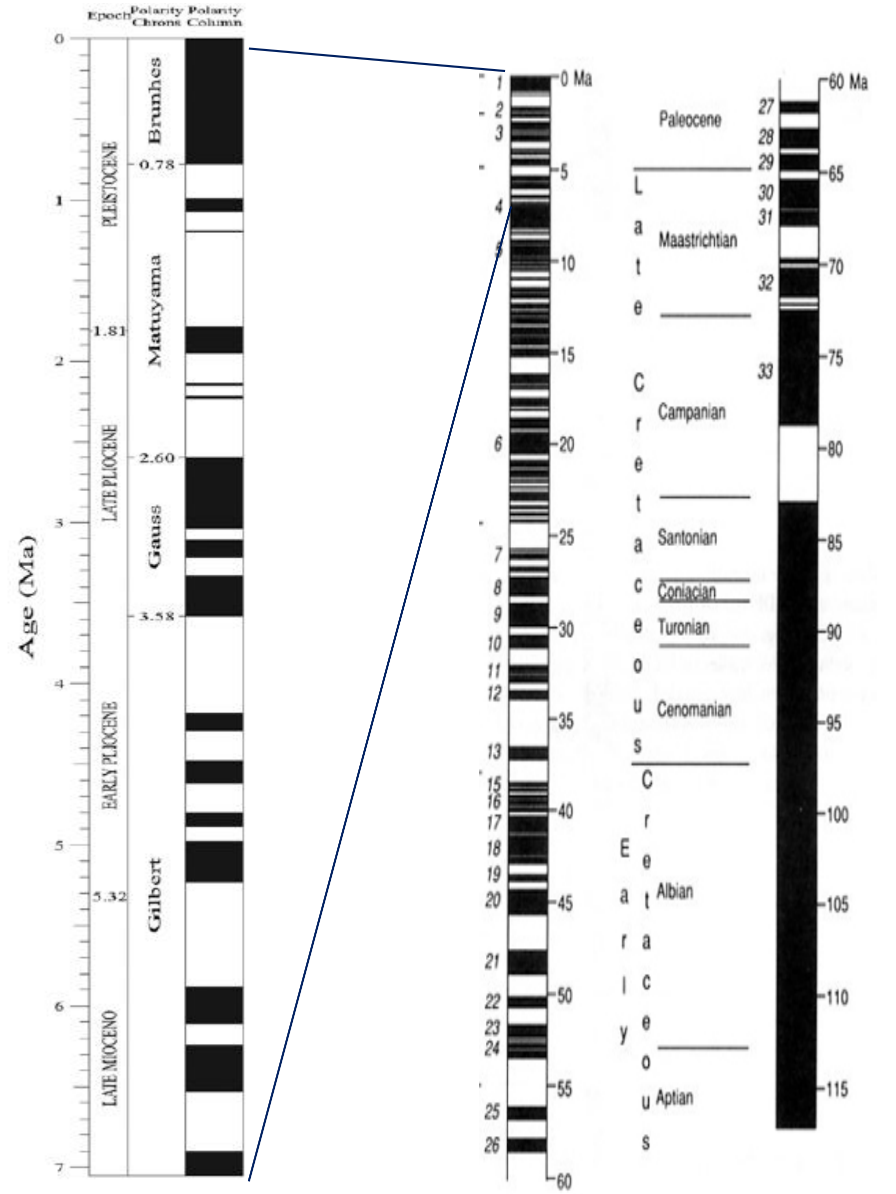
❑ There's a pretty strong record of magnetic reversals over time - anywhere from a few thousand to hundreds of thousands of years between reversals.



https://www.ck12.org/book/CK-12-Physical-Science-Concepts-For-Middle-School/section/5.81/

Magnetic reversals

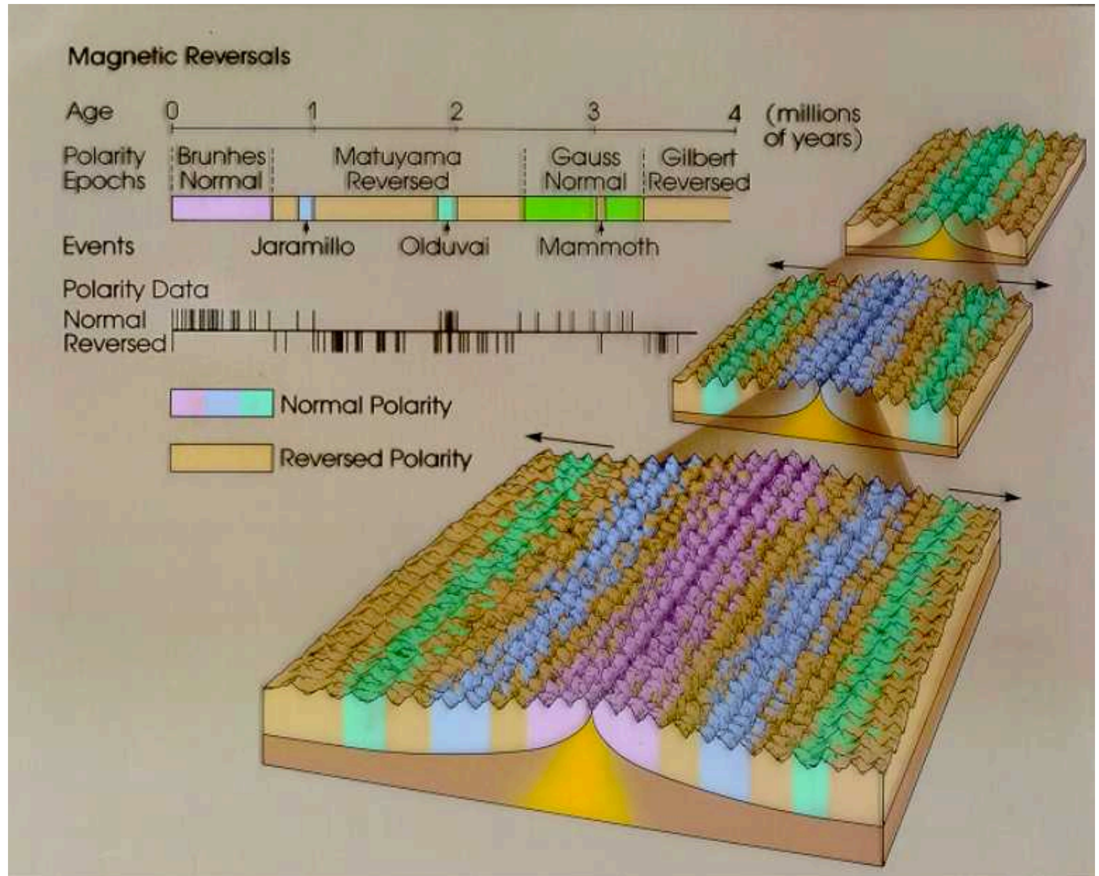
- Geologists can create “calendars” of reversals that help correlate rock ages around the world, and look for patterns related to reversals
- Each black stripe on this calendar represents a time period of ”normal” polarity (like today). The white stripes are the “reversed” polarity times.
- Notice there have been both abnormally long and abnormally short “chrons,” just in the last 7 million years (left image). There have been some <u>really</u> long chrons before, though! (right image)



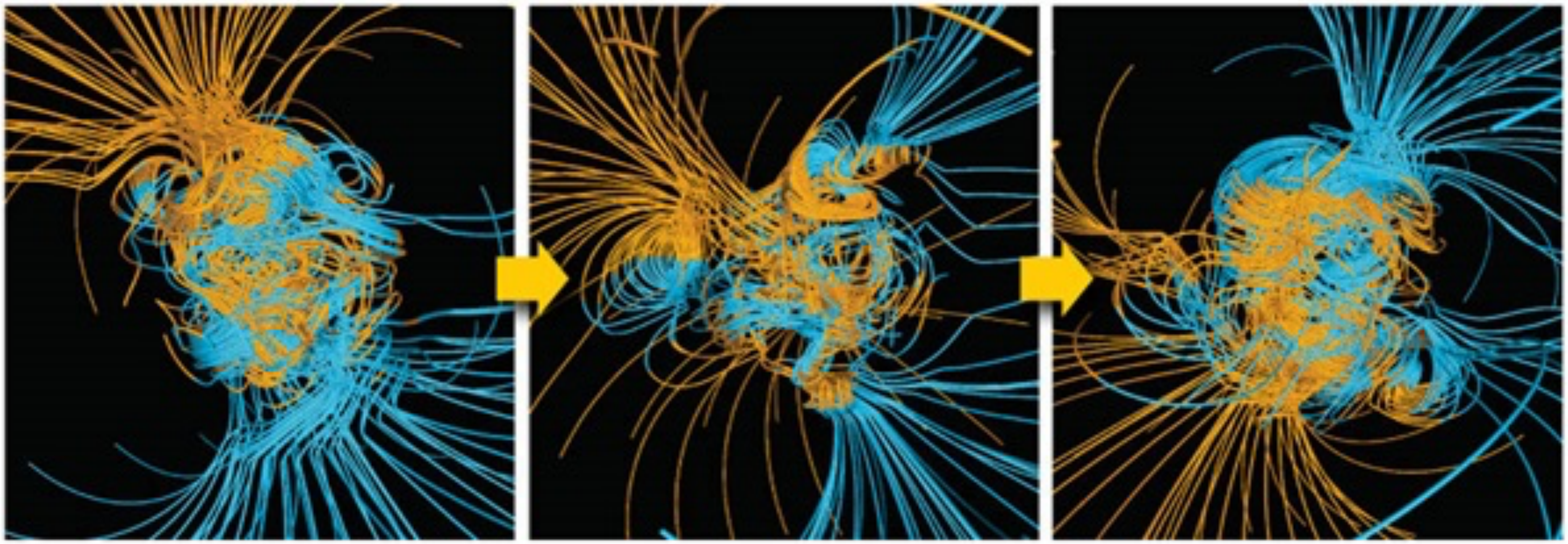
https://www.geol.umd.edu/~jmerck/geol342/lectures/20a.htm

Magnetic reversals in the rock record

- We see in the rock record that the magnetic field has changed polarity over time.
- Changes in polarity appear to be preceded by decreases in magnetic field strength and appearances of magnetic anomalies (north poles in the south region and vice versa).
- We are seeing some of these things occurring today – are we going into a reversal?



What does a reversal look like?



This is a model produced by Gary Glatzmaier at UC Santa Cruz a few years ago. It made big news, because it was the first model to really show what could happen in a reversal in a way that can be measured and tested (and because it looks super cool!)

https://websites.pmc.ucsc.edu/~glatz/pub/glatzmaier_coe_tog_2015.pdf

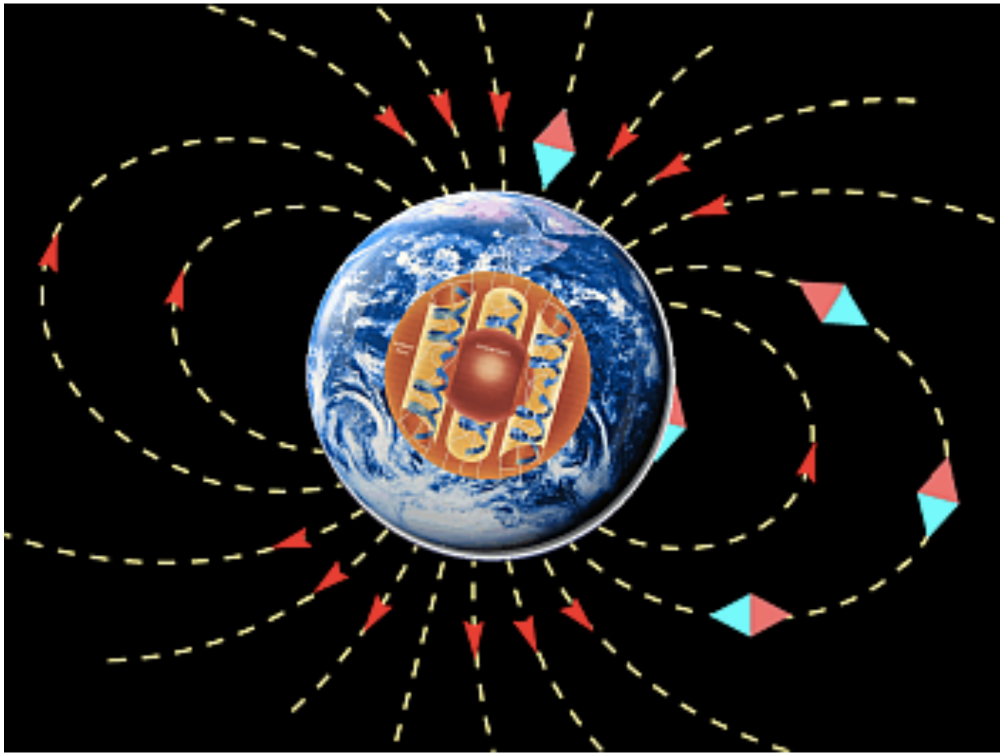
What produces this field?

- Earth doesn't actually have a giant bar magnet inside it. Where does our magnetic field come from?

The accepted theory is that convection currents in the liquid outer core produce our magnetic field! What kind of liquid are we talking about?

Metal! The outer core is liquid iron, nickel, and other metals. What happens when metal flows…?

You get a **current**! So magnetism appears to be connected to electric currents…hmmm…



http://www.conrad-observatory.at/cmsjoomla/en/magnetism-overviev