Magnetism is a very important force in physics: one half of electromagnetism.

Originally discovered in rocks called "lodestone" (a type of iron), one has two "poles" in magnetism, a north and south pole. Historically, the right type of rocks were found to point toward the North Pole.

Iron filings sprinkled around a simple bar magnet fall into a well defined shapes following the magnetic field.

A field in physics is a model to help scientists think about how to deal with "action at a distance".

In magnetism, the field lines are directed from north to south magnetic pole.

Like poles repel and unlike poles attract.

Some objects are permanently magnets whilst others retain their magnetism for a short time.

A fundamental observation is that wires carrying currents have a magnetic field.

Further, motion in a magnetic field produces an electrical current (generator) and an electrical current in a magnetic field produces motion (electric motor).

In fact electromagnetism is a fundamental physics force: light is an electromagnetic wave.

So perhaps at formation there were some lumps of rock that had magnetism. In contracting, the proto-Earth started to spin and maybe some of its inner parts were already molten and had some charged particles. The initial rotation in the Earth’s initial magnetic field led to some current. This current in a magnetic field leads to motion and so on. This is a self-sustaining dynamo.

Based on the Earth’s size, if this "self-sustaining" feature was not present, any initial magnetism would have died away in only 20,000 years.

Magma coming through volcanos, after its solidifies retains the polarization of the magnetic field when it started to cool.
This paleomagnetic record indicates the Earth’s magnetic field has existed for $3 \times 10^9$ years at least. Thus there has to be some renewal process. The temperature in the core (say 6000K) is too hot to retain a permanent magnet without renewal. Heating a permanent magnet destroys its magnetism (Curie temperature).

- Solid inner core about the size of the moon, temp 6000K, consisting of mainly Fe.

- Convection is a very efficient way of transporting heat.

- Initially when you heat a gas or a liquid, the heat travels through by conduction or even radiation. But if sufficient heat is input, the temperature gradient gets very steep and the only way heat can be transported fast enough is convection - the fluid boils over. Steep temperature gradients in stars/planets lead to convection.

- The temperature gradient in the Earth’s outer core is too steep to satisfy the ”Schwarzschild criterion”: its convectively unstable.

- Also, as the core cools, iron in the fluid outer core solidifies onto the inner core and leaves behind lighter elements which rise up - convection again.

- Additional heating due to radioactive decay by potassium-40.

- Consider children sitting around a roundabout with the roundabout in motion. They roll a ball to each other. To the children, as they roll the ball to someone, it appears to travel in a curved path due to the motion of the roundabout. To someone outside, the ball moves in a straight line.

- Thus people in a ”rotating frame of reference” postulate this curved path as due to a force, a fictitious force called the Coriolis force. For example, as air moves from high to low pressure in the Northern hemisphere, it is deflected to the right by the Coriolis force, the result of the Earth’s rotation. In the Southern hemisphere, air is deflected to the left. Someone not in the Earth’s rotating frame of reference would see the air moving in a straight line.

- Thus in the outer core, light fluid does not rise straight up and heavy liquid does not sink straight down but follows curved trajectories.

- This fluid is electrically conducting. Its curved path in the ambient existing magnetic field produces an electromotive force by Faraday’s law of induction which drives large electric currents.

- These electric currents produce new magnetic fields through Amperes law that compensate for the decay of ambient magnetic field (Lenz’s law).
The detailed analysis of this problem is a complicated problem in 3D magnetohydrodynamics.

Simulations show that a dipolar magnetic field like the Earth’s can be maintained by convection driven by the Earth’s interior reservoir of heat energy.

Inside the core, the field is very complicated but outside its very much like a bar magnet field ie dipole dominated. Outside the core the field is much weaker.

These models find that the core rotates slightly faster than the mantle and the Earth’s crust: perhaps by as much as 2-3 degrees of longitude per year.

This could be how the drift in the precise location of the Earth’s magnetic North Pole comes about.

After a period of some 36,000 years, the model underwent a flip in polarity.

The inner and outer core have different polarities and the outer core is always trying to invade the inner core and change its polarity. More often than not it can change a small part of the inner core’s polarity before the core re-establishes itself with the existing polarity. However, sometimes when the inner core field is low, the outer core field ”invades” the inner core and flips it causing a general polarity reversal.

If you have a uniform heat flux at the core-mantle boundary, then the flips happen about every 100000-300000 years apart taking about 1-2000 years to occur.

Evidence of this magnetic pole reversal is in the geologic record: magma retains the polarity of the prevalent magnetic field when it cooled.

Some rocks in Oregon have suggested that at times $16 \times 10^6$ years ago, the magnetic polarity was moving by about 6 degrees/day.

The paleomagnetic record proves such reversals happened many times over the past billion years.

Some reversals occurred within a few 10,000 years whilst at other times there are no reversals for millions of years. The last reversal happened approxiametly seven hundred thousand years ago.

Currently there is evidence that the strength of the Earth’s magnetic field has declined by 10% in say a few hundred years. This is a much greater decline than would be expected if the dynamo inside the Earth’s core stopped working.
For example, the paper, "Paleomagnetic Study of a Reversal of the Earth’s Magnetic Field" by Dunn J. R., Fuller M., Ito H., and Schmidt V. A., (Science 21 May 1971, vol 172, no. 3985, pp.840-845) looked at the natural remanent magnetization of the Tatoosh Intrusion in Mt. Rainier Park, Washington. They found this reversal took place 14.7 ± 1 million years ago from reverse to normal. They found that just before the reversal, the intensity dropped by an order of magnitude with an unchanged orientation. During the reversal, the pole traced a path across the Pacific. The reversal process lasted about 500 years and the drop in intensity before about 100 years.

There are other variations: diurnal variations due to induced current loop’s in the Earth’s atmosphere (ionosphere) caused by the Solar wind.

There is an effect due to the gravitational effect of the moon on Earth’s atmosphere.

Variations in the Solar wind striking the Earth can also cause short lived larger variations, mostly in the higher latitude areas.

Affect on mankind of a magnetic reversal?

- Increased amount of dangerous particles arriving the surface would generate more auroral activity, perhaps knock out power grids widen ozone holes.
- Many feel it wont have too much of an effect, Animals will adapt. More cancer rates etc. but the atmosphere provides good protection from dangerous particles.
- Project?
- Radioactive decay in the Earth’s interior by Thorium, Uranium and Potassium decay. This produces roughly $38 \times 10^{12} W$. The energy consumption of the US is $3.0 \times 10^{11} W$. Spread out over the Earth’s surface area this is $0.075 W/m^2$. That is a piece of land 1000 square meters would yield enough heat to light up a 75 watt bulb. Not very efficient.
- This heat flow is not uniform: its concentrated in certain hot spots. Most is released through volcanism associated with ocean ridges, geysers mountain belts etc.
- This energy makes its way to the surface and radiates into outerspace.
- Project: Find out how much Potassium-40 may be inside the Earth and hence estimate the timescale on which such a heat source could continue and compare to the lifetime of the Sun.
– You need to look up things on Geothermal heat flow.
– Core/mantle boundary lies at a depth of about 2900km (radius of the Earth is roughly 6400km), Inner core has a radius of about 1700km. Mantle consists of silicate rocks whilst the core is predominantly Iron.
– Under these extreme conditions, minerals squeezed into extreme conditions eg. squeeze the mineral olivine (ie subject it to ultra-high pressures and temperatures, it undergoes sudden phase transitions involving sudden transitions of its crystal structure.
– These transitions change its properties eg. how it transmits seismic waves (waves generated by earthquakes). Analysis of earthquake data then permits scientists to say where, that is the depth, of such transitions in the Earth. This tells us the pressure, temperature and density.
– So a sudden change in the seismic properties of the mantle are associated with a phase transition of the minerals comprising the mantle.
– New mineral postpervoskite likely to appear in the mantle. A phase transition occurs from postpervoskite to pervoskite near the core/mantle boundary. Mineral appears and then disappears forming a layer of post-pervoskite.
– Detected such a layer in the lower mantle southeast of Hawaii. Upwelling of hot mantle rock may be responsible for the volcanos there.
– Temperature at the bottom of the postpervoskite layer is 2500K (4000 degrees Farenheit). At the lower boundary, its 3500K.
– Two points imply a temperature gradient and hence a measurement of heat flux upwards in that layer! Amounts to 13 trillion watts at the surface. Sun’s luminosity is about $10^{26}$W.
– Upwelling of hot mantle material from core/mantle boundary makes a significant contribution to mantle convection which moves tectonic plates.
– Core is solidifying from inside out - so such a high heat flux implies the core is quite young - perhaps only a billion years old.
– Surface heat flux is between $23.5 - 37.7 \times 10^{-3} Wm^{-2}$