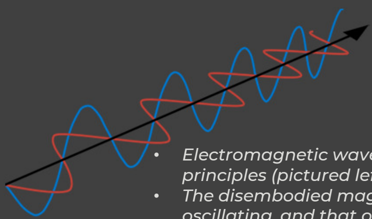
ELECTRICITY AND MAGNETISM – TWO SIDES OF THE SAME COIN

SEAN MATA

Electromagnetism – it means that electricity and magnetism are simply different aspects of the same thing. But is this actually true?

Intro

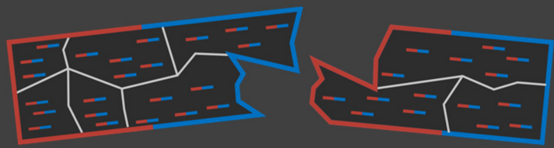
- Electricity and magnetism have many similar properties, and because of this we created a unified theory for them in the 19th century
- There also exist many electric monopoles - fundamental particles with a net electric charge (a familiar one is the electron)
- Electricity and magnetism share many properties - but can you think of a magnetic monopole?

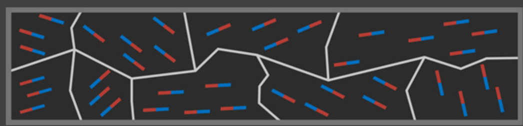


- *Electromagnetic waves are a demonstration of electromagnetic principles (pictured left)*
- *The disembodied magnetic field produces an electric field while oscillating, and that oscillating electric field produces a magnetic field, and so on and so on… infinitely*
- *Using this, Maxwell showed how electromagnetic waves could exist by themselves, with no mass, no charge etc. by dynamically regenerating each other while moving*

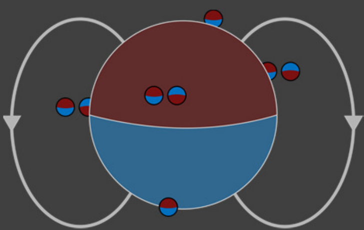
To help answer this question, let's try breaking a bar magnet in half - it is a dipole magnet since it has two poles, a north and a south pole:

When breaking the bar we end up with chunks of domains. These are regions of uniform magnetization, and have their own magnetic North and South poles. So we end up with two new dipole magnets.



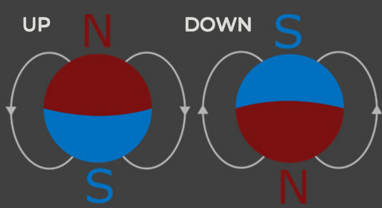


(In non magnetised materials, domains are aligned in differing directions and cancel each other out)



If we keep trying to break up the magnet, we'll get to atoms. These are dipole magnets.

They get an overall weak magnetic field from unpaired electrons. (Nickle structure represented here)



If we look even closer we see electrons, which also have two poles.

Electrons get their magnetic charge from spin:

- Spin is their intrinsic angular momentum
- Electrons also have an intrinsic electric charge
- So the moving electric charge creates a magnetic field, which has two poles because of symmetry laws
- These electrons have two possible spin states with opposite magnetic charge, spin-up and spin-down

And then we can't breakdown the electrons as they're fundamental particles, so all parts of the magnet are magnetic dipoles. It's a bit harder to find a monopole than you might expect…

So magnetism in bar magnets is not caused by magnetic monopoles, and interestingly not in electromagnets either.

In reality, there is no experimental evidence magnetic monopoles exist! And we've been looking for a long time, more than 40 years!

This is observation is quantified in one of Maxwell's equations – Gauss' Law for magnetism, which would have to be changed if magnetic monopoles were found.

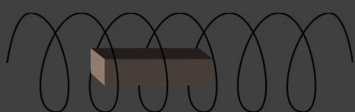
There are some other interesting results if they do exist:

- Paul Dirac proved if magnetic monopoles exist, all electric charge must be quantised, which would explain why it is not continuous in our universe [1]
- Many modern particle theories, such as string theories, grand unified theories and M-theories require magnetic monopoles to exist, and their discovery would be a step in the right direction for them

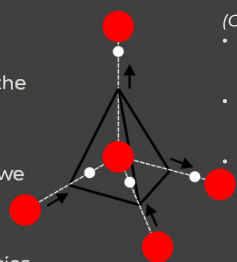
Joseph Polchinski, a leading string-theorist, called their existence "one of the safest bets that one can make about physics not seen", so while sensational, the discovery of magnetic monopoles probably won't be surprising too many physicists [2].

While no fundamental particle magnetic monopole has been discovered, there is a way to create emergent magnetic monopoles. And in the same way how moving a magnet through a coil (in one direction) induces a direct current, moving a magnetic monopole through a coil induces a direct current.

A representation of what the SQUID detector looks like



Using this principle a Super Conducting Quantum Interference Device, SQUID, (pictured top-right) is able to detect monopoles to a very high precision. These magnetic monopoles are created at 2 Kelvin in $DY_2Ti_2O_7$, also called spin ice, which the monopoles move within. The category spin ice is named for its lowest energy state having the magnetic moment of ions, their spins, pointing – two in and two out – of each tetrahedron, and for its analogy to hydrogen configuration in frozen water (pictured right). However the density of these monopoles in spin ice is very high, so we have yet to detect a single monopole [3].



(Oxygen-RED Hydrogen-WHITE)

- *(pictured left) A representation of the tetrahedral structure of ice, analogous to the structure of spin ice*
- *The "two-in two-out" structure here comes from the differing lengths of O-H bonds and hydrogen bonds (two-in on bottom left, two-out on up/right)*
- *In spin ice, the ions are in the hydrogen positions and their most stable state contains "two-in two-out" of the magnetically oppositely charged spins, it can also be thought of "two-up two-down"*

While not fundamental, the monopoles in spin ice essentially have the same properties as normal magnetic monopoles. Possible applications include more efficient classical computation involving the creation and manipulation of "magnetricity" – the magnetic equivalent of electricity! We are able to create logic gates out of artificial spin ices, and computers made with them could operate close to the Landauer Limit – the fundamental theoretical maximum of computation [4]. These monopoles also could lead to more efficient and less-intrusive MRI scanning [5]!

References

[1] P. Dirac, Proceedings Of The Royal Society Of London. Series A, Containing Papers Of A Mathematical And Physical Character 133, (1931).

[2] J. Polchinski, International Journal Of Modern Physics A 19, (2004).

[3] R. Dusad, F. Kirschner, J. Hoke, B. Roberts, A. Eyal, F. Flicker, G. Luke, S. Blundell and J. Davis, Nature 571, (2019).

[4] L. Heyderman, *Artificial Spin Ice-Applications*, Mesosys.Mat.Ethz.Ch (2020).

[5] R. McDermott, S. Lee, B. Haken, A. Trabesinger, A. Pines and J. Clarke, Proceedings Of The National Academy Of Sciences 101, (2004).