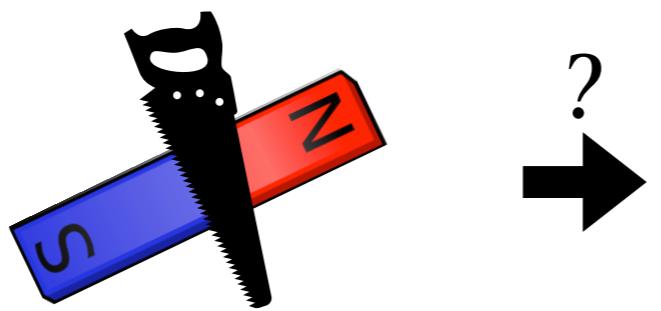


Story centres around the idea of chopping a magnet in half - separating a dipole into a pair of disconnected monopoles. This is the start of a surprisingly deep idea, not just about magnetism, but about the nature of electricity, quantum mechanics, and indeed it will lead us to question the very notion of “fundamental” in physics.

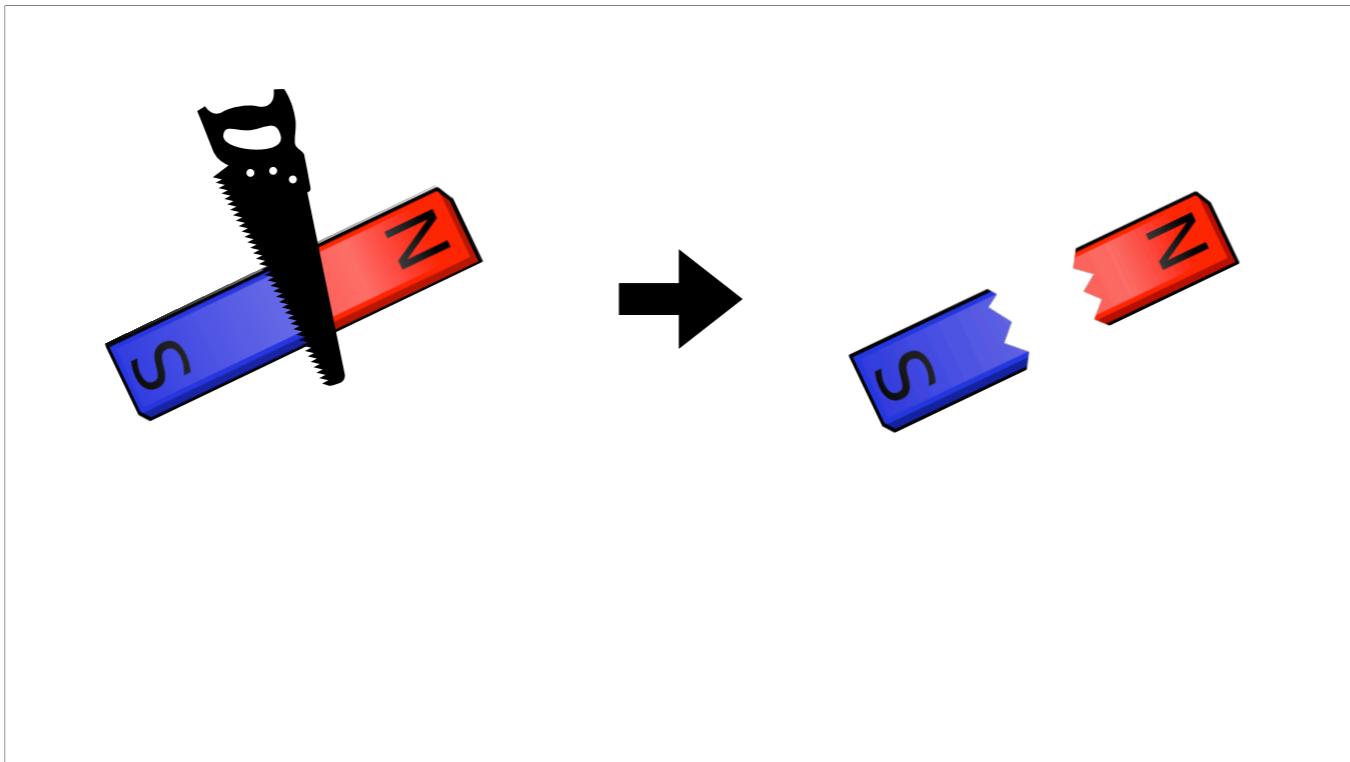
If you've ever played with magnets, you'll appreciate that they're odd.



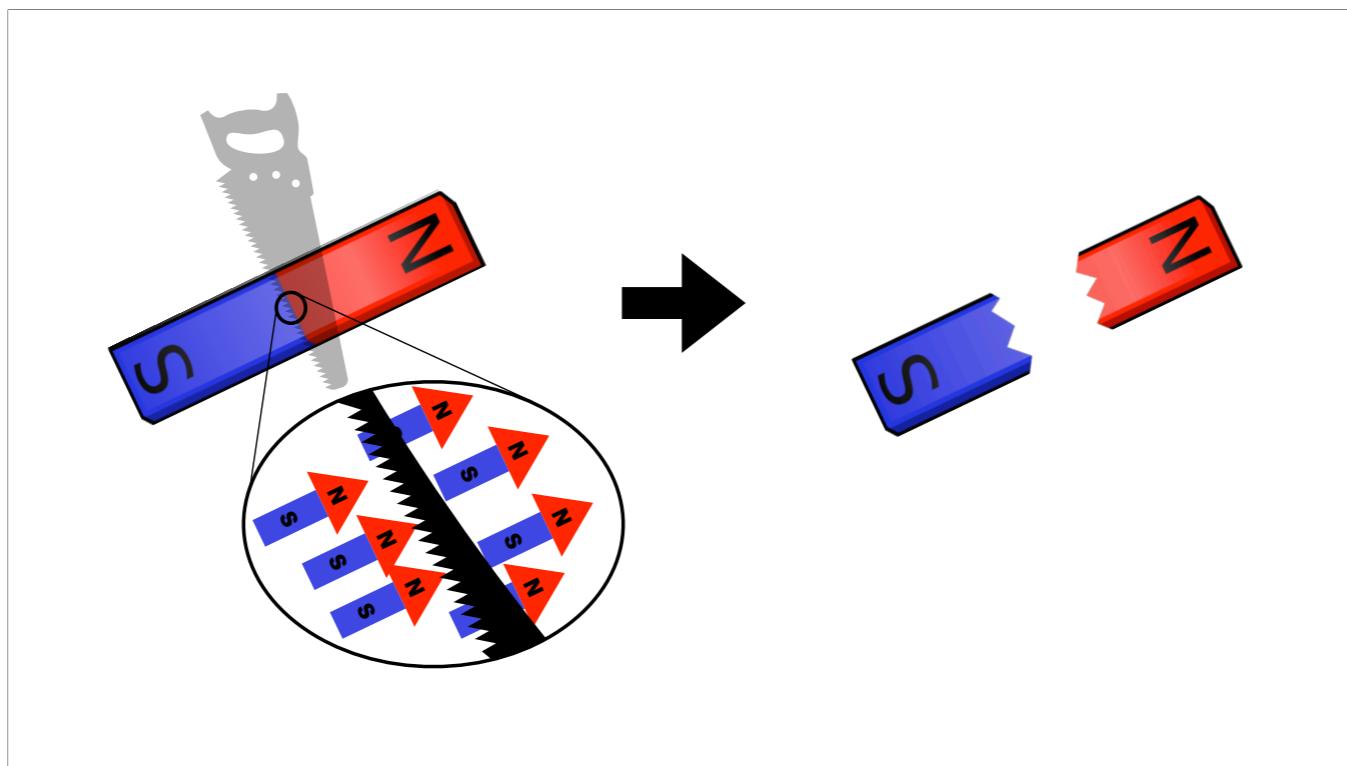
# **Dividing the Indivisible**

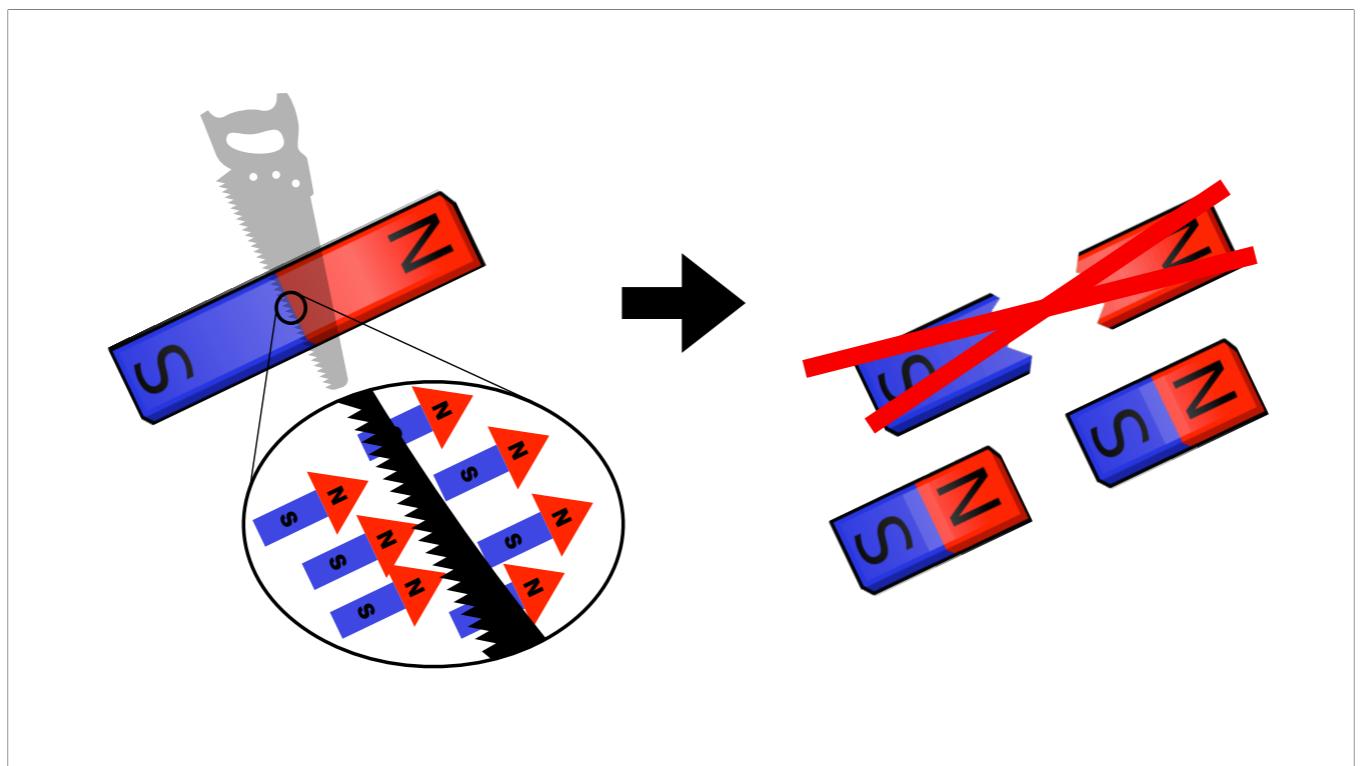
## **Magnetism, Quantum Mechanics and the Origin of Matter**

Alaric Sanders, 14/11/2023

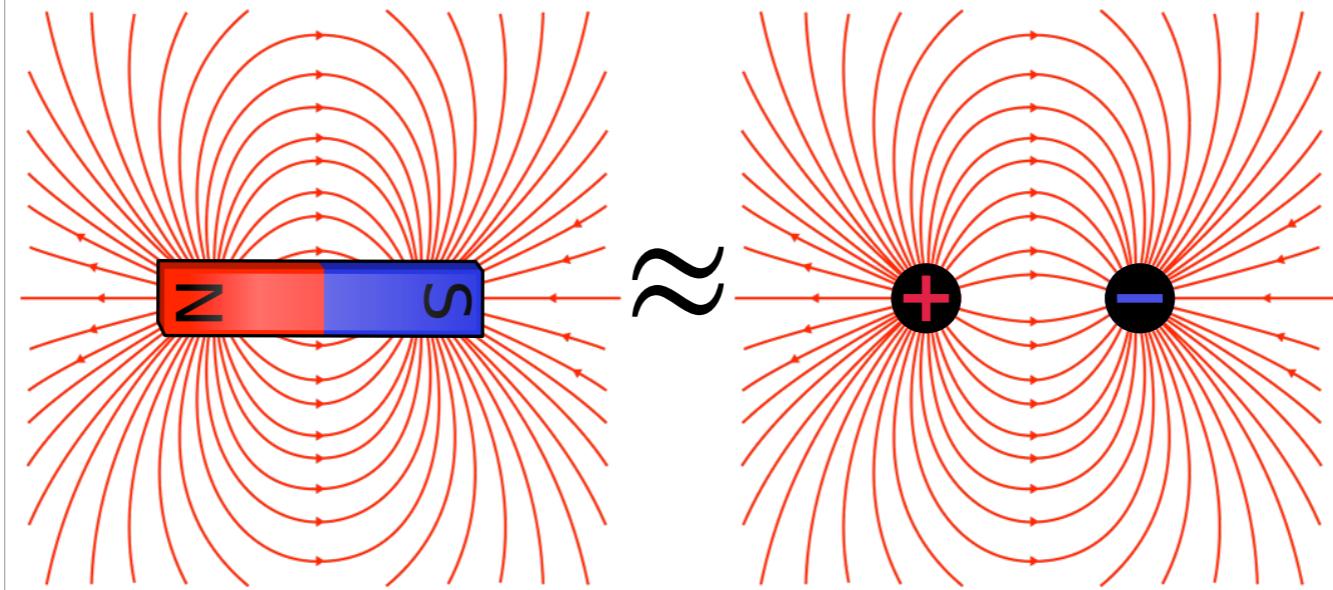


- I want you to do a thought experiment with me:
  - Take the north end of a magnet, and try to separate it from the south end.
- How can we avoid this?





## A Dipole is like Two Monopoles



The insight, due to Paul Dirac, is that the magnet needs not to be cut, but to be stretched.

## Moving Monopoles by Cancellation

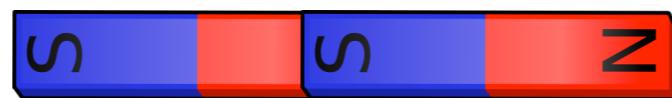


P.A.M. Dirac, 1902-1984

The insight, due to Paul Dirac, is that the magnet needs not to be cut, but to be stretched.

By stacking magnets one on top of the other, north on top of south, we kill the magnetic charge at the end (and so can move the monopoles around).

## Moving Monopoles by Cancellation



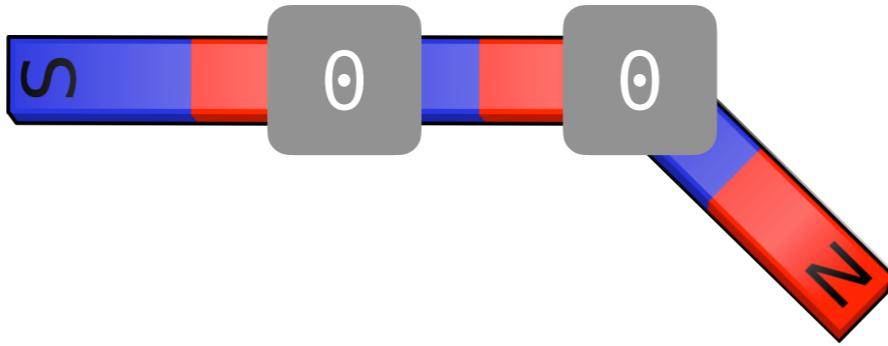
P.A.M. Dirac, 1902-1984

# Moving Monopoles by Cancellation



P.A.M. Dirac, 1902-1984

## Moving Monopoles by Cancellation

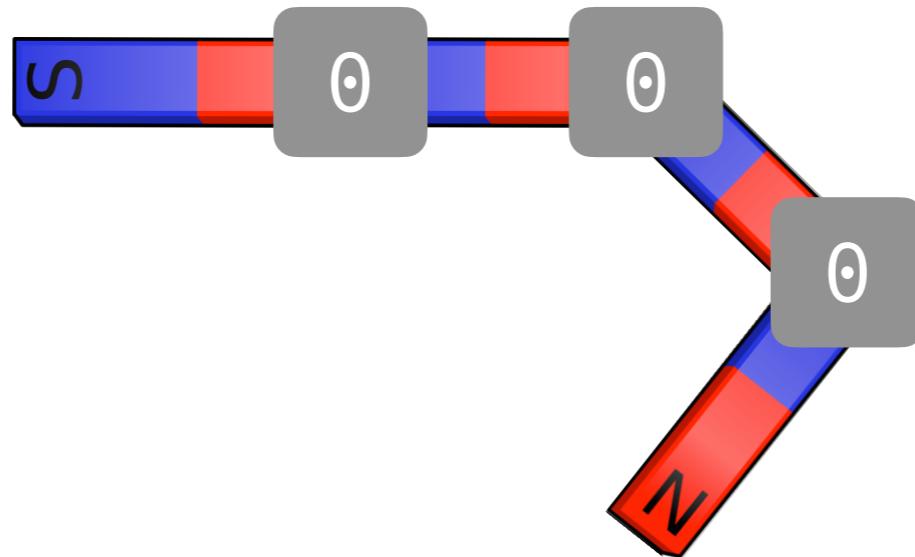


P.A.M. Dirac, 1902-1984

## Moving Monopoles by Cancellation



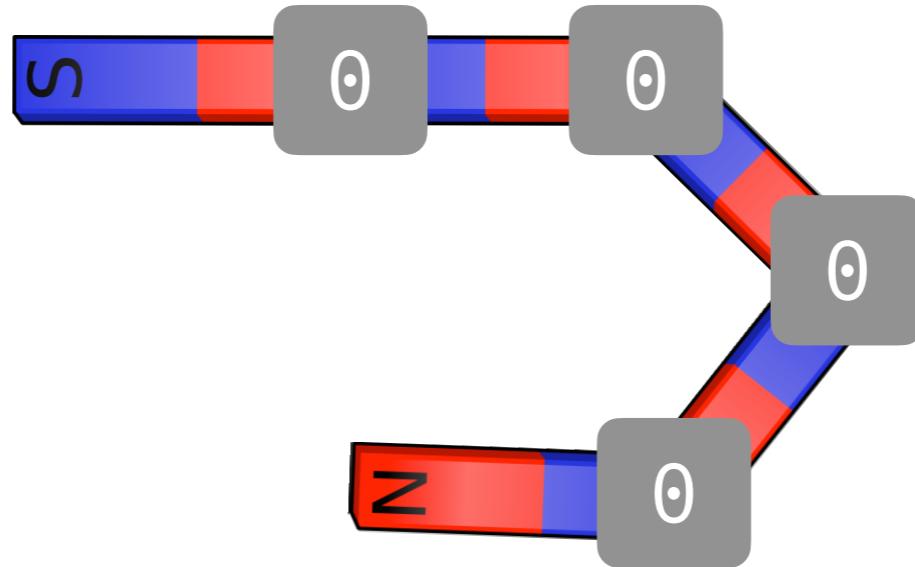
P.A.M. Dirac, 1902-1984

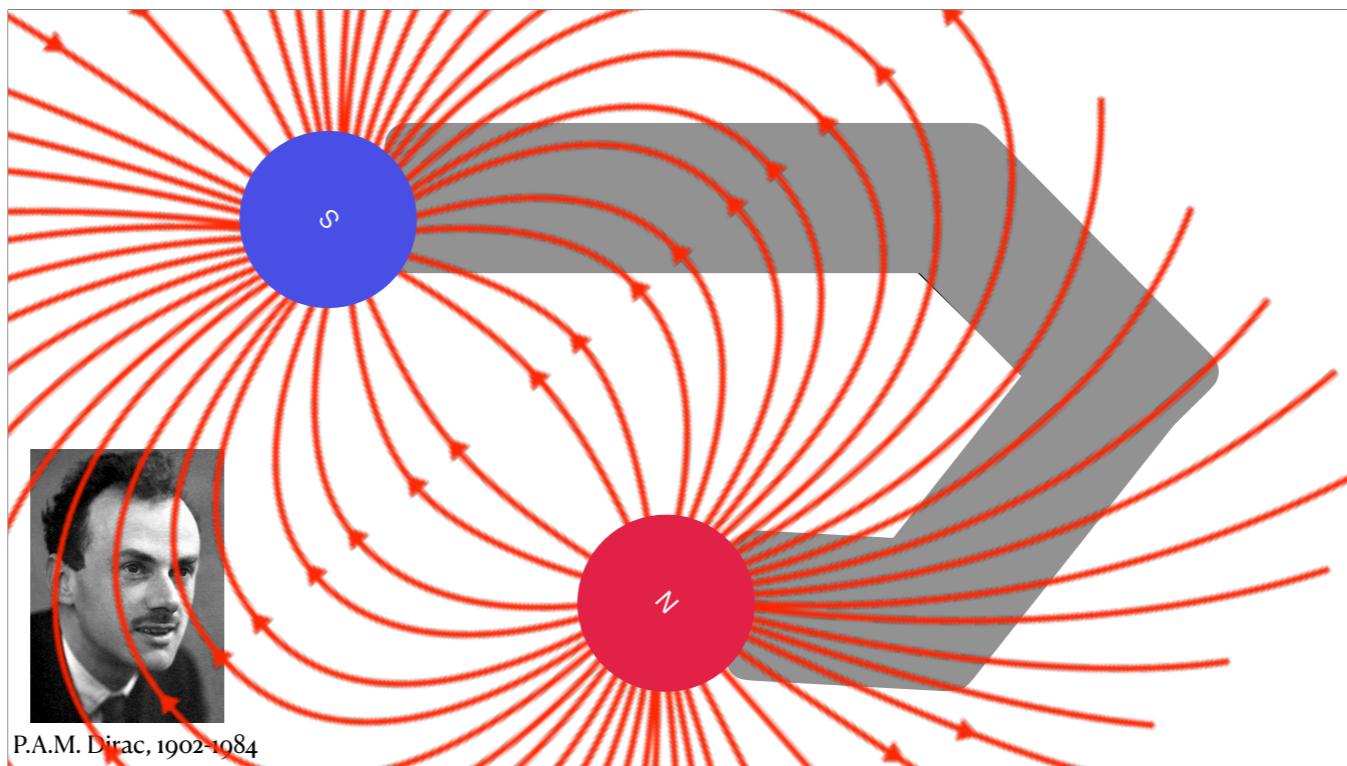


## Moving Monopoles by Cancellation



P.A.M. Dirac, 1902-1984



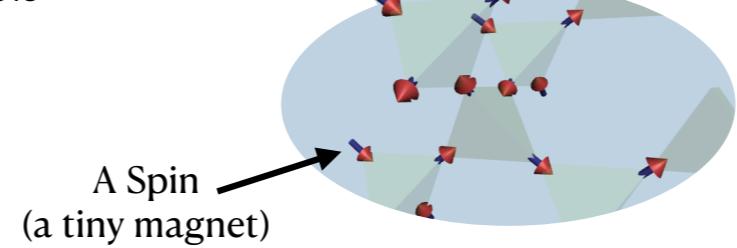


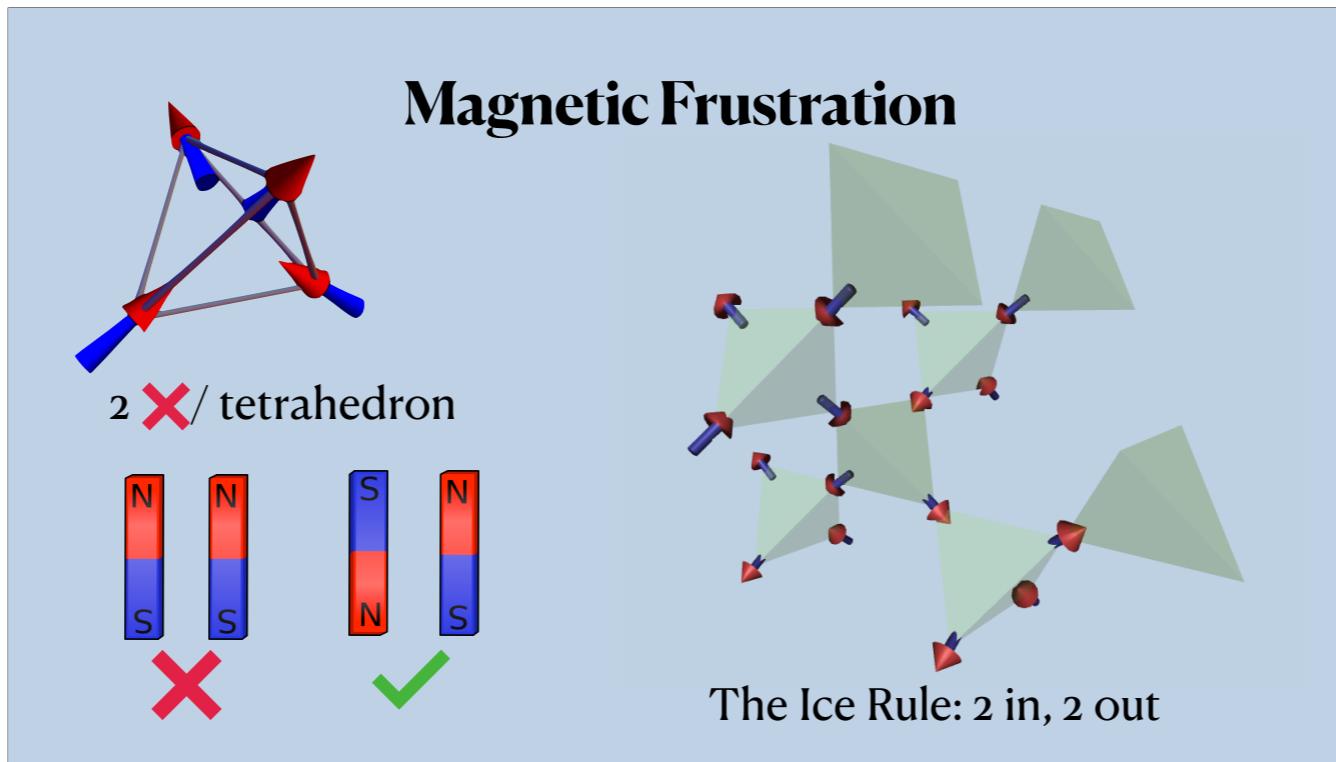
The insight, due to Paul Dirac, is that the magnet needs not to be cut, but to be stretched.

# Making it Real: Dysprosium Titanate

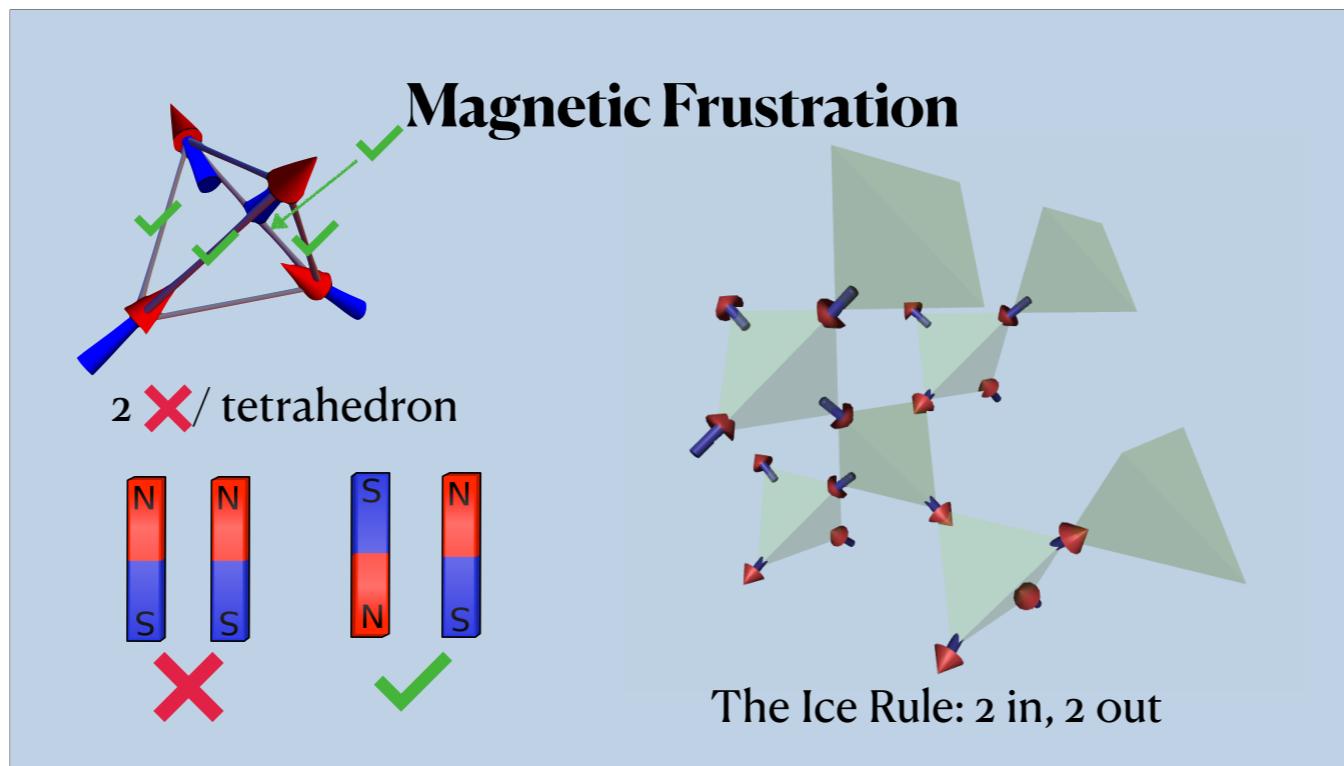


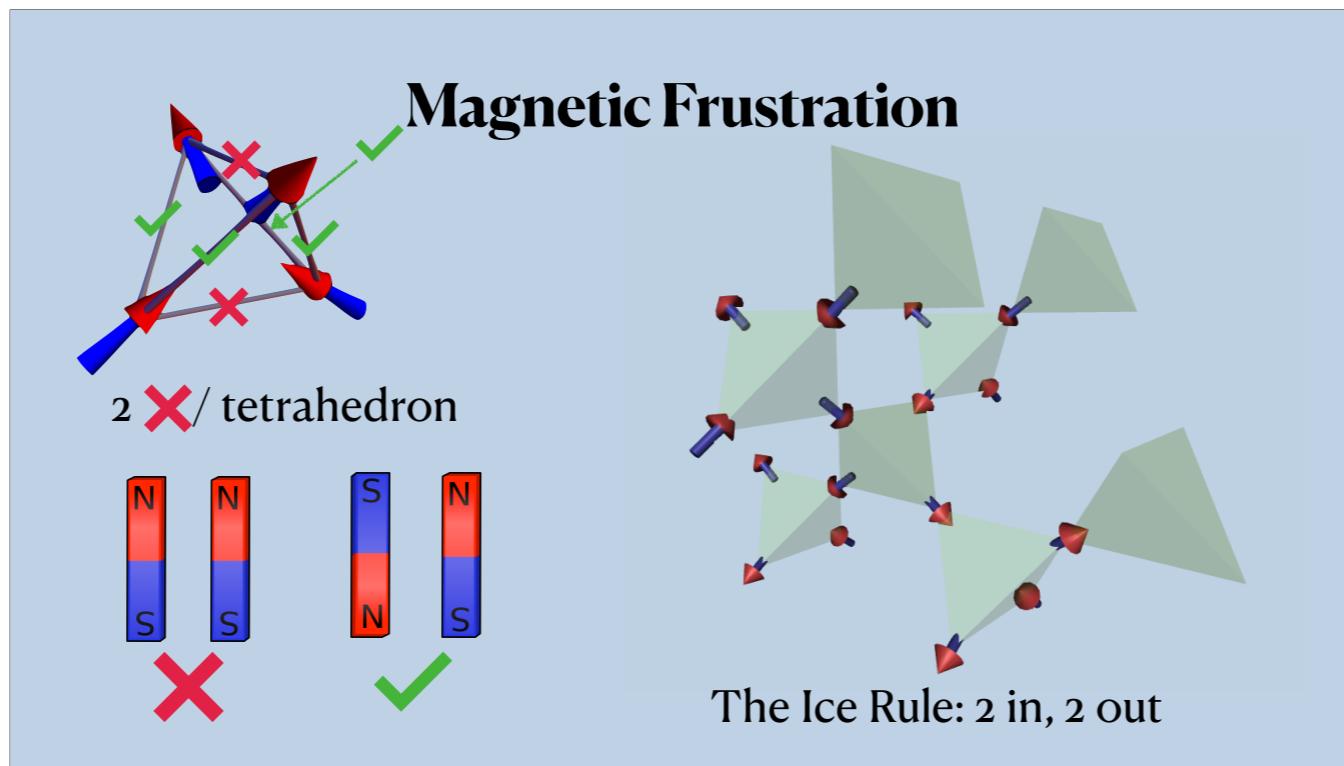
Timothy Munsie, 31 Oct 2013





I've tiled this configuration of magnets through all of space. Just like you might expect, north poles repel each other - they want to align north to south. Every north-north costs some energy, and I'll call them 'X bonds' because they're bad. The system wants only 'tick' bonds.





# Why "Ice"?

## THE JOURNAL OF CHEMICAL PHYSICS

VOLUME 1

AUGUST, 1933

NUMBER 8

A Theory of Water and Ionic Solution, with Particular Reference to Hydrogen and Hydroxyl Ions

J. D. BERNAL AND R. H. FOWLER, *University of Cambridge, England*  
(Received April 29, 1933)

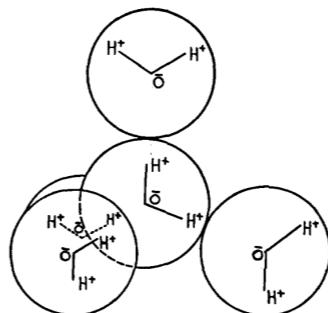


FIG. 4. Tetrahedral coordination of water molecules. The four molecules surrounding one water molecule are shown. Of these, two are in the plane of the paper, one above and one below it.

# Why “Ice”?

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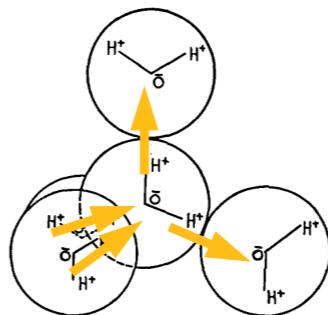
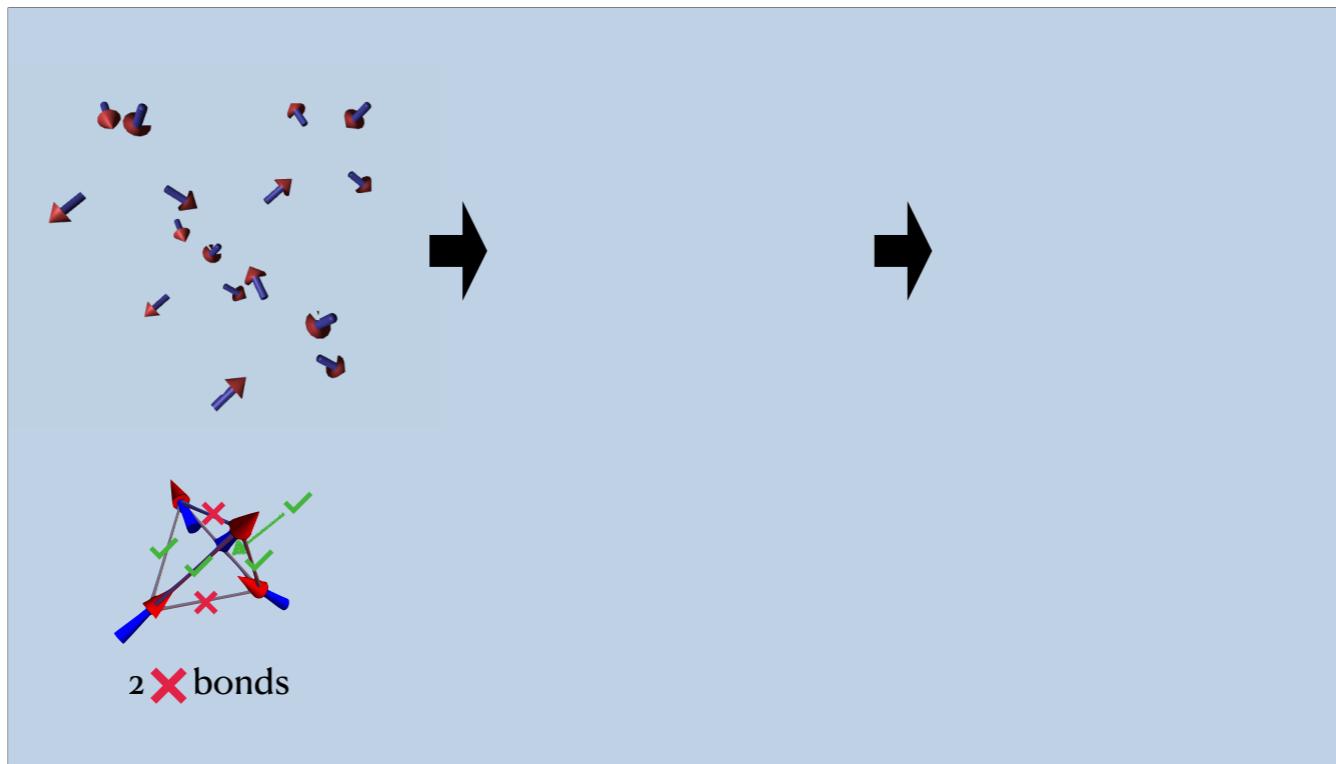


FIG. 4. Tetrahedral coordination of water molecules. The four molecules surrounding one water molecule are shown. Of these, two are in the plane of the paper, one above and one below it.



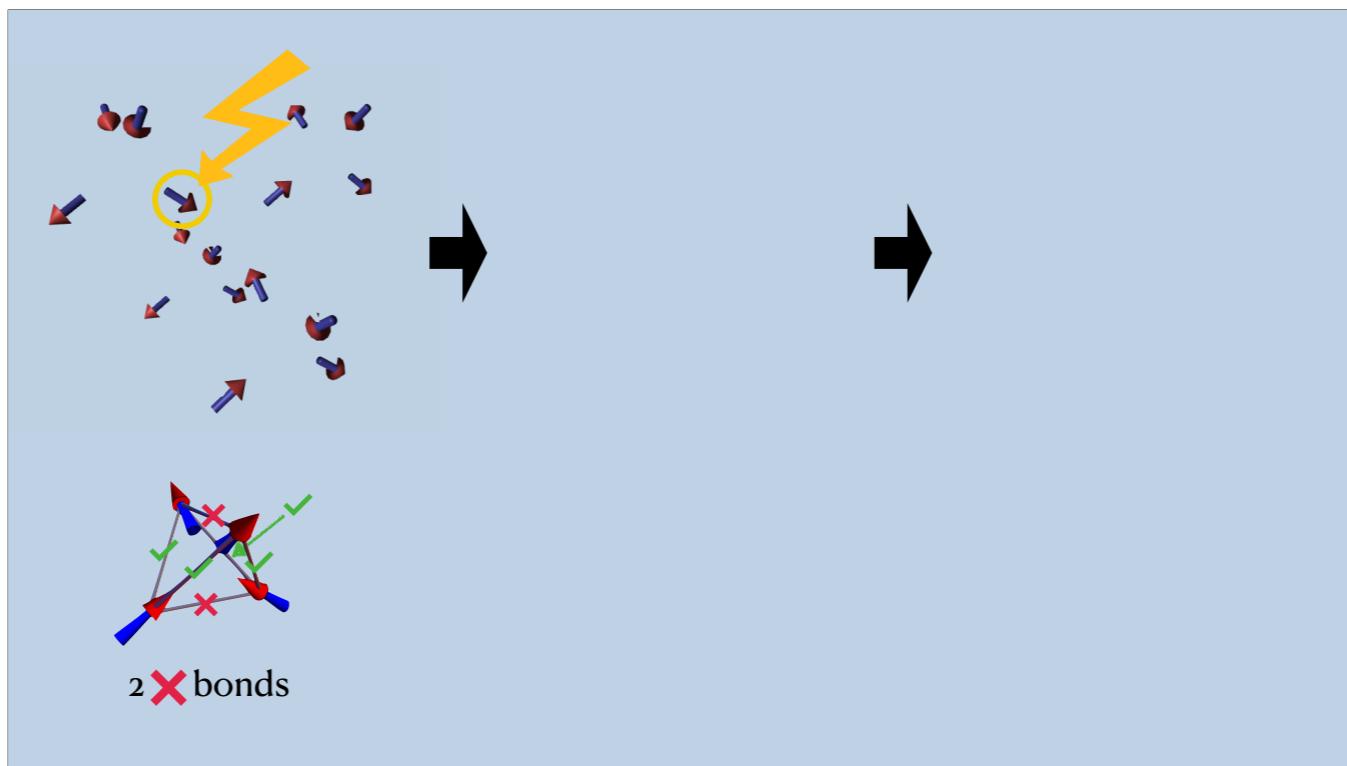
Created two excitations - the red and blue tetrahedra, each with three repulsive 'X' bonds.

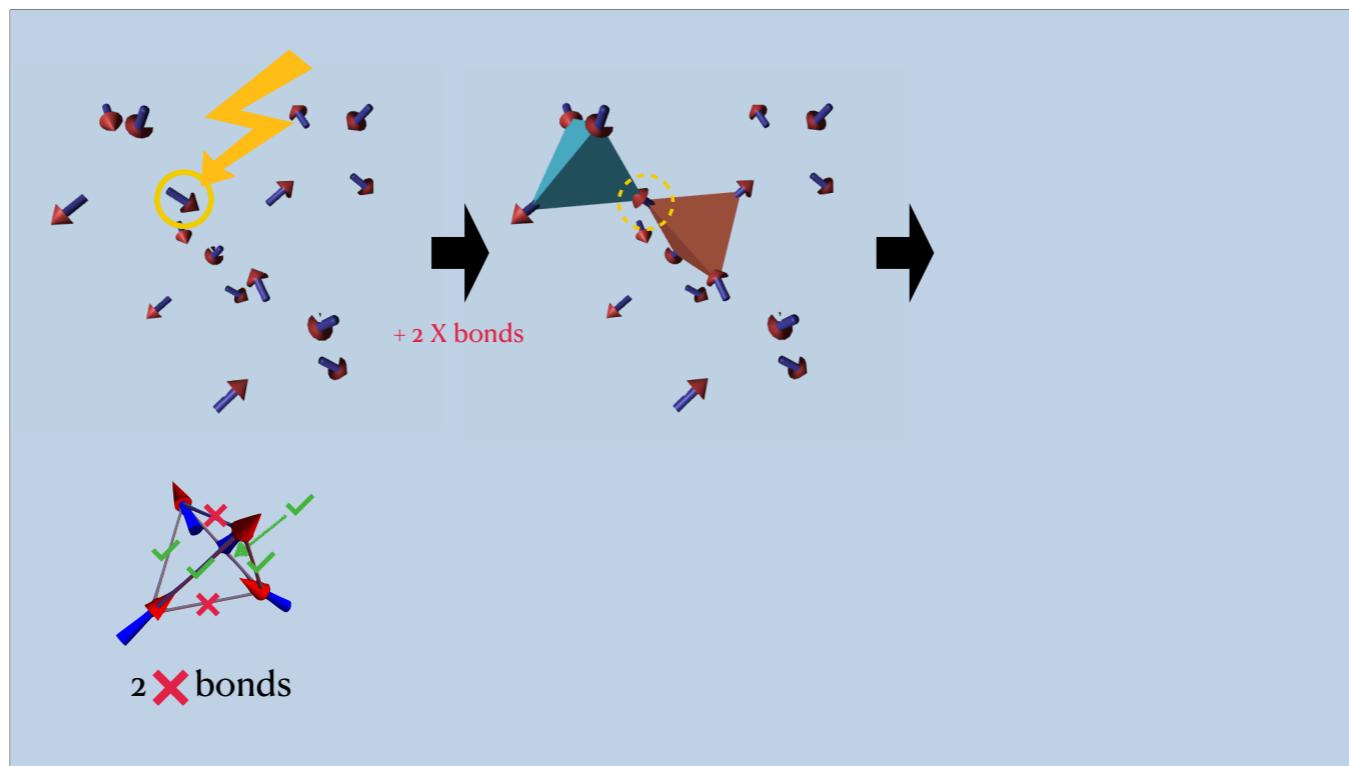
That cost energy.

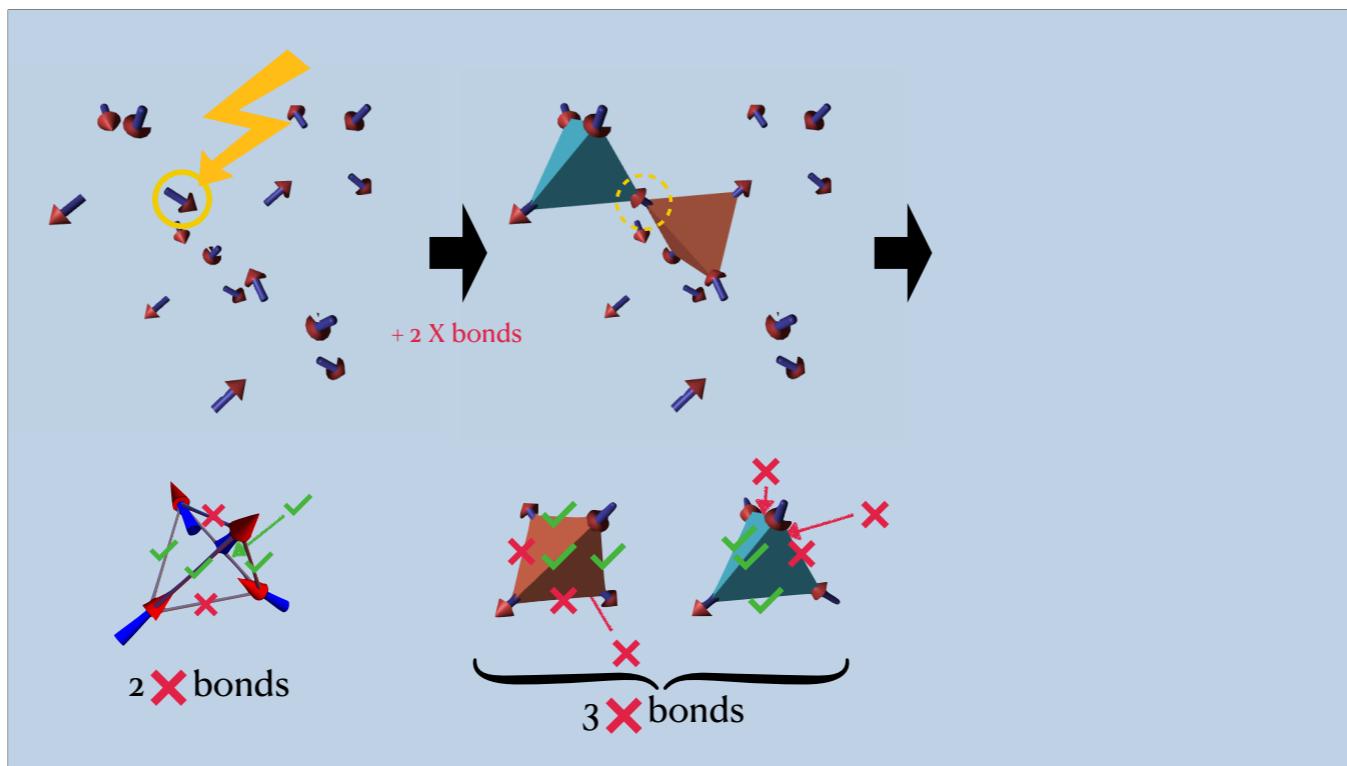
Now flip another arrow - created two X bonds, but also removed two - in total, it's free

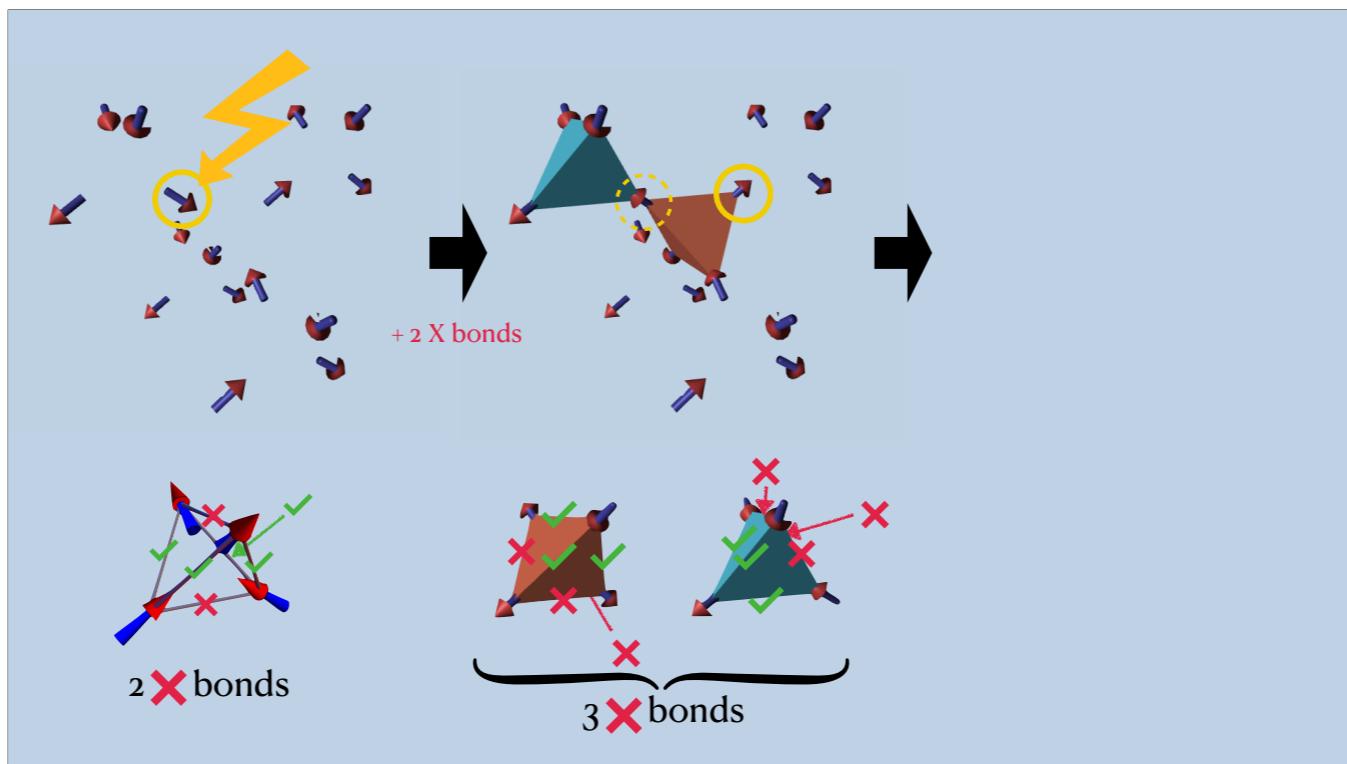
.. let's say we do this a few times - essentially we have red and blue blobs moving around.

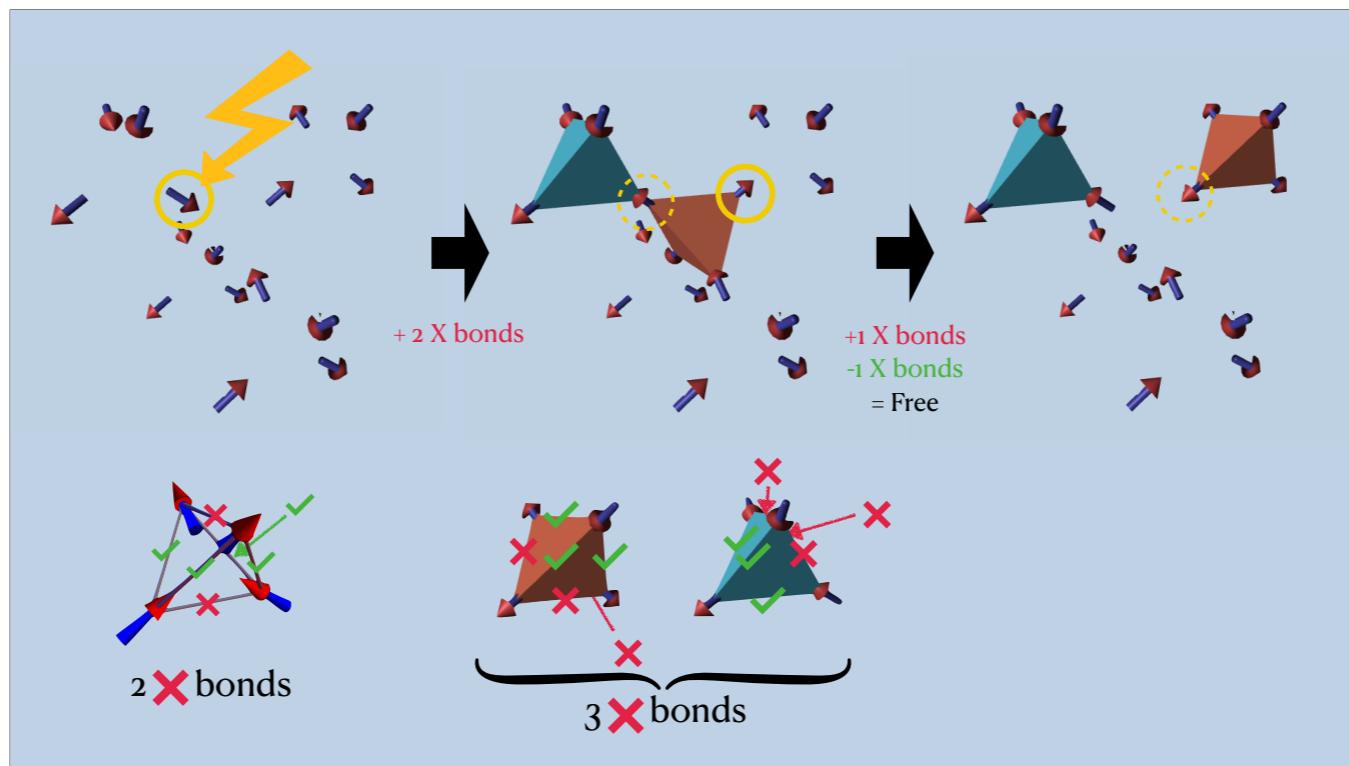
Exactly like my long magnet, except because the whole universe is made of magnets, you don't really notice it.

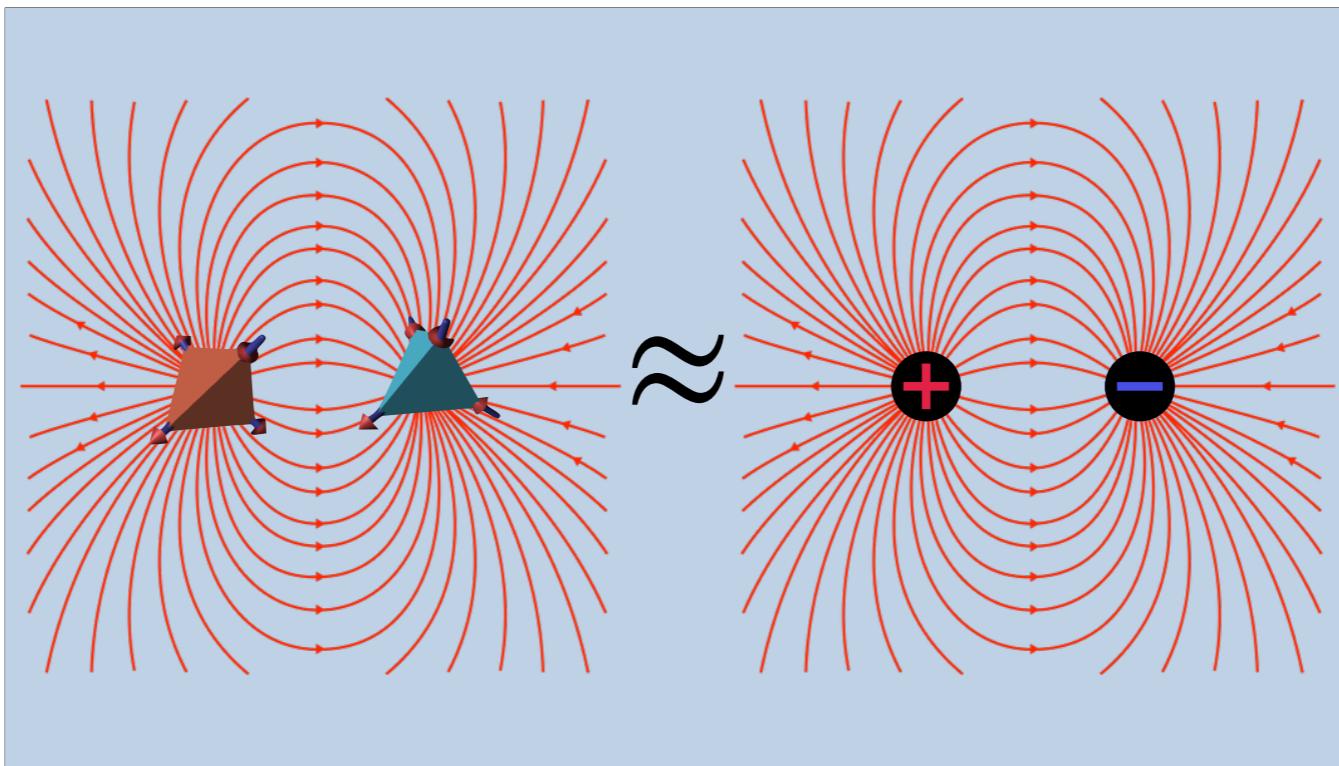








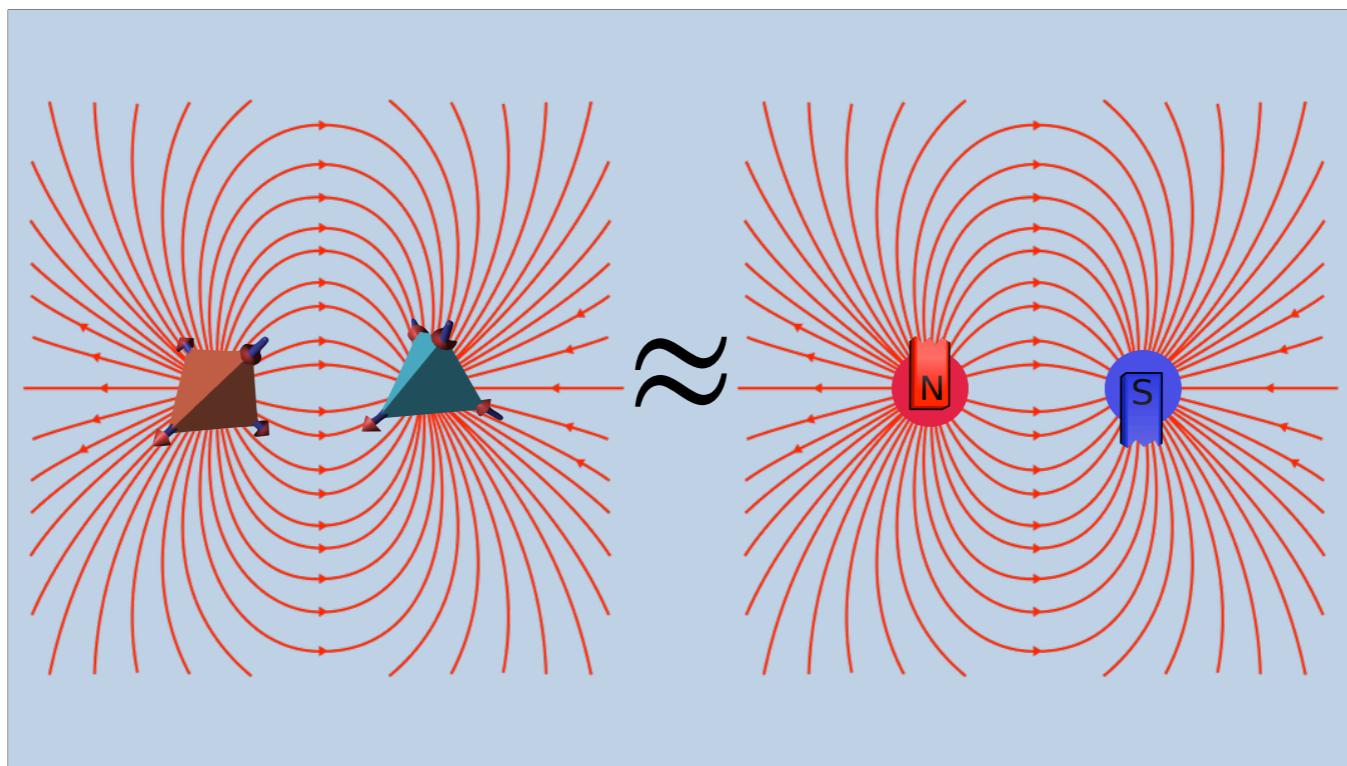


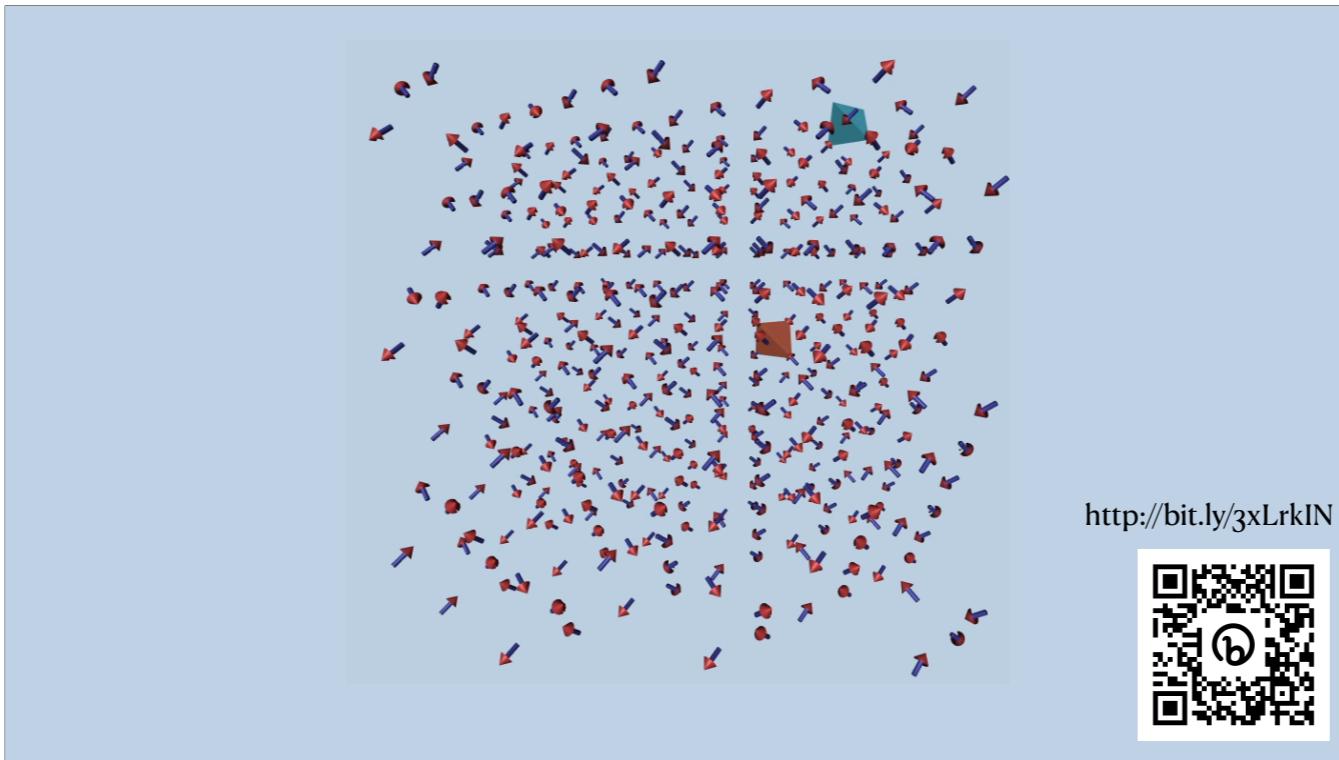


Red guys have more arrow ‘out’ than ‘in’

If you squint your eyes a bit, the magnetic field that the ‘red’ and ‘blue’ guys make looks exactly like the field made by two charges (magnetic or electric)  
These are monopoles “for all intents and purposes”

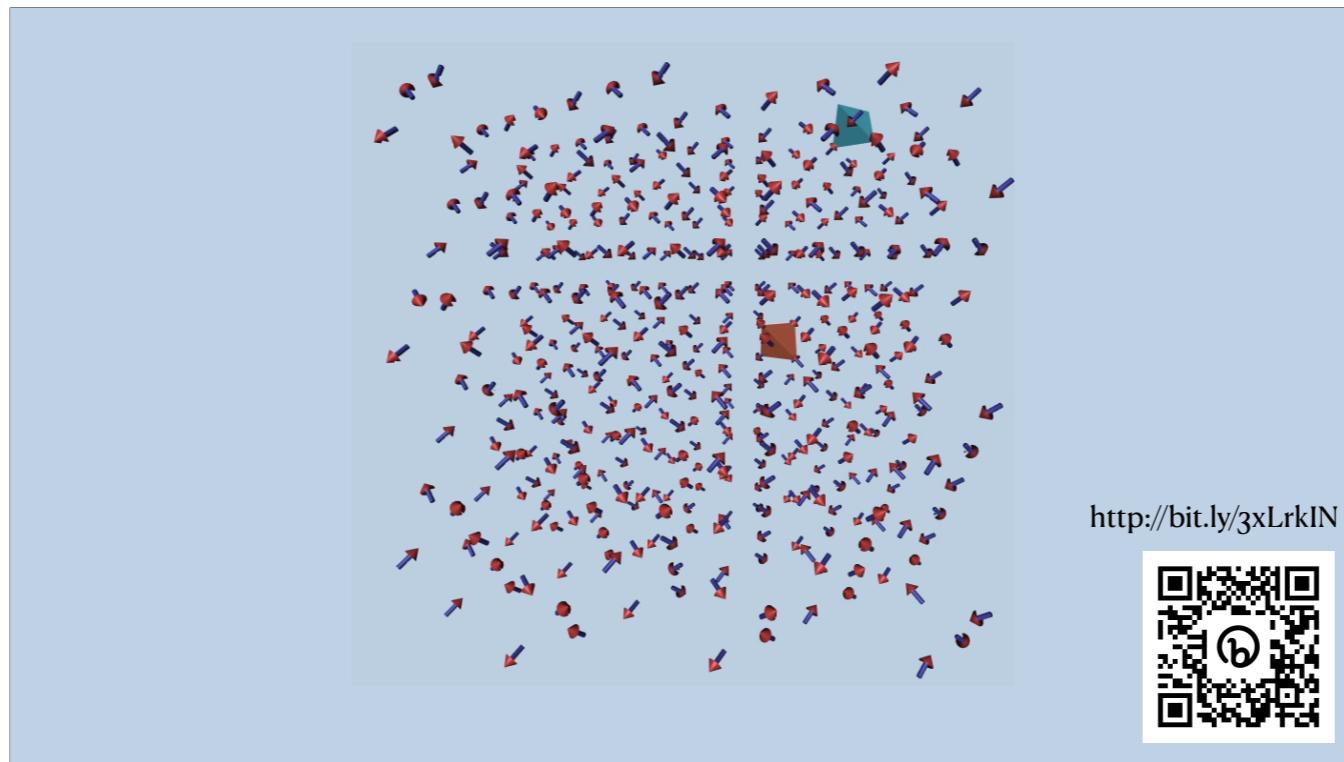
Crucially, they \_emerged\_ from a deeper, more fundamental theory.





What you're seeing here is a computer simulation of monopoles moving in time (at low temperature). Every so often, the computer randomly flips a spin, making the monopoles 'hop' in random directions.

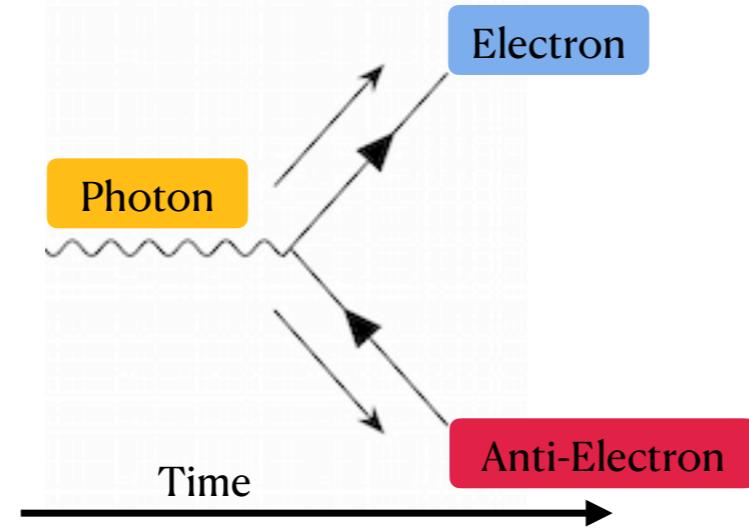
Zoom out - forget about the tiny magnets, only focus on the excited tetrahedra, the red blobs and blue blobs



<http://bit.ly/3xLrkIN>

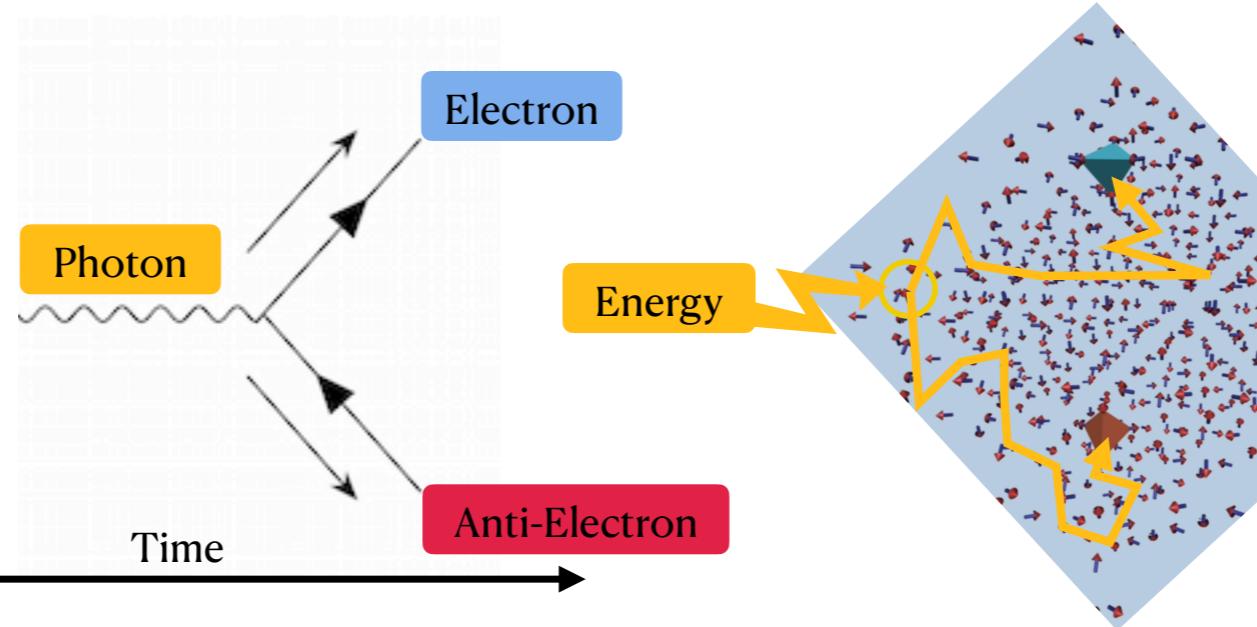


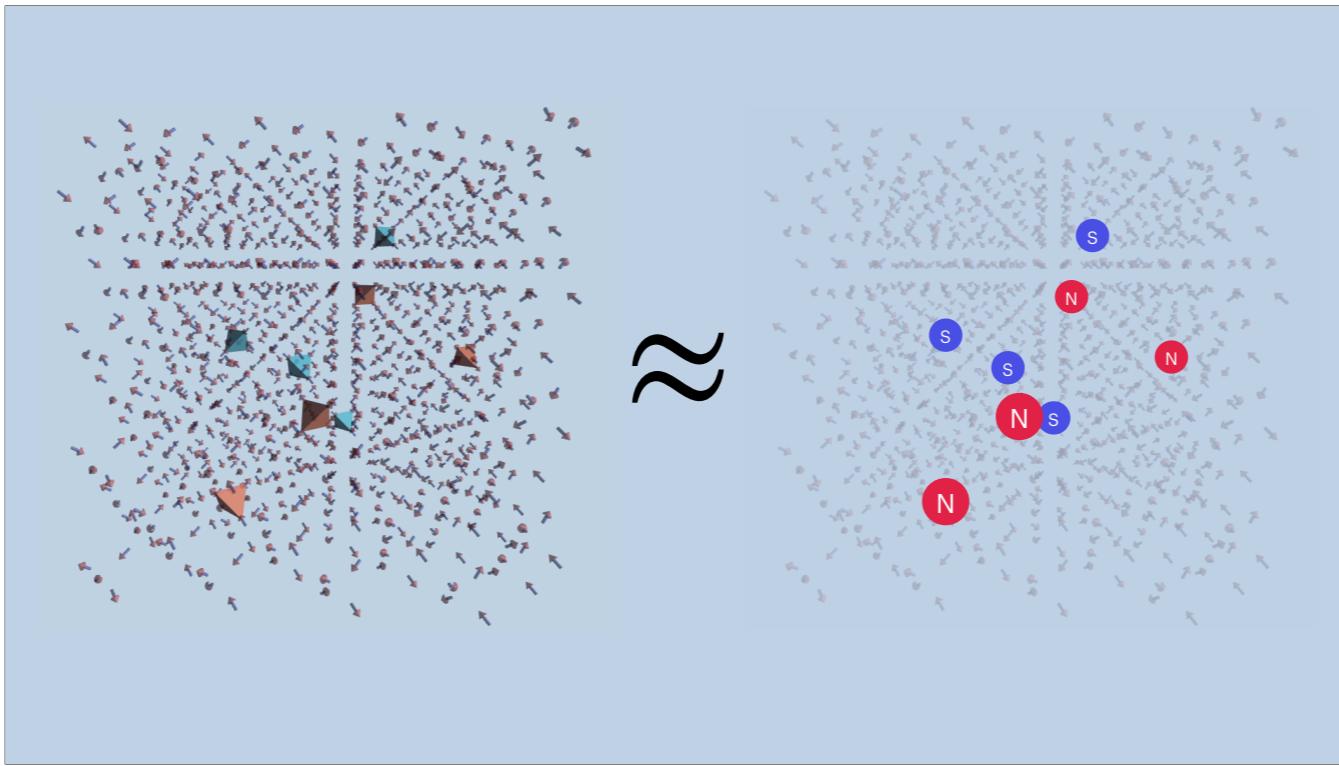
## Quantum Electrodynamics (QED)



It's at this point that I should really draw attention to a parallel with QED, the theory of how electricity and magnetism interact in our quantum world.

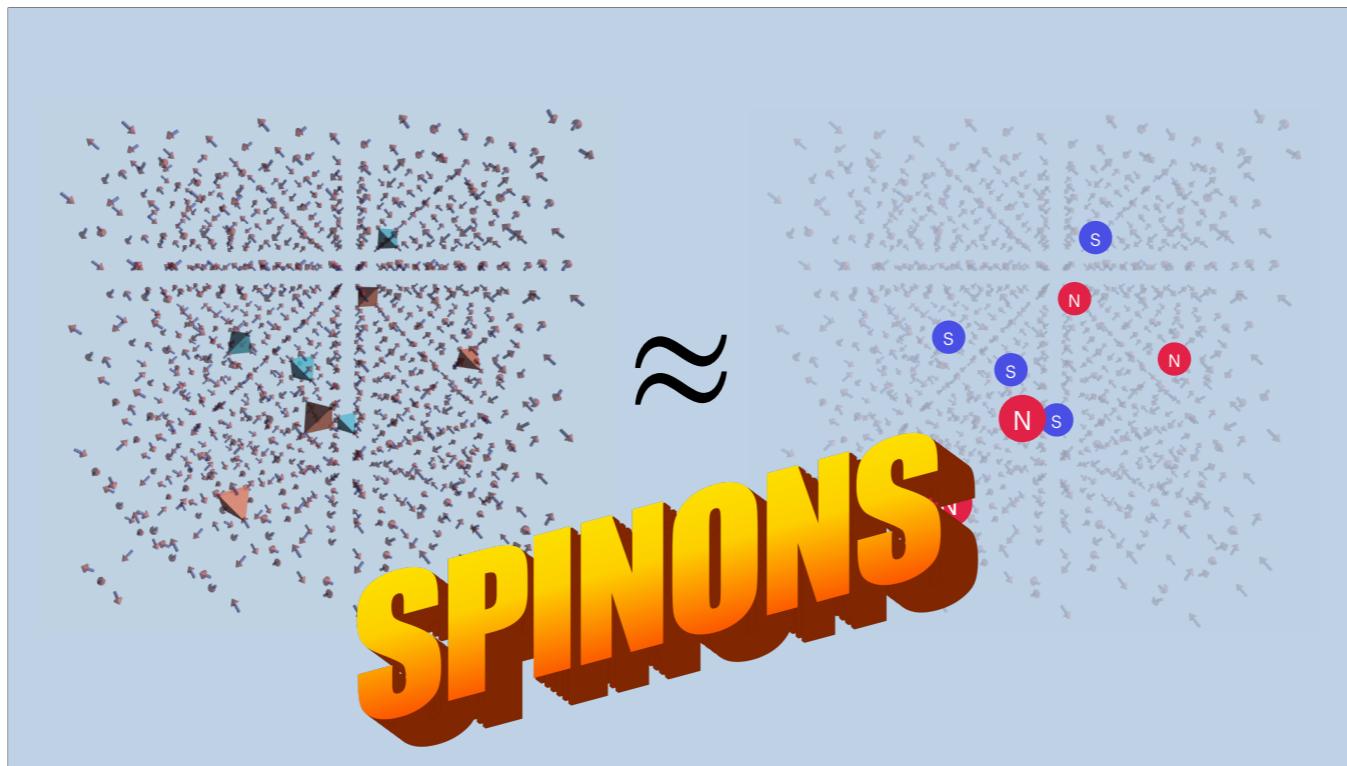
# Quantum Electrodynamics (QED)





We have something that looks, smells, and acts like a particle, so we call it a particle.

In physics, particles end with “-on” (e.g. photon, electron, positron...)

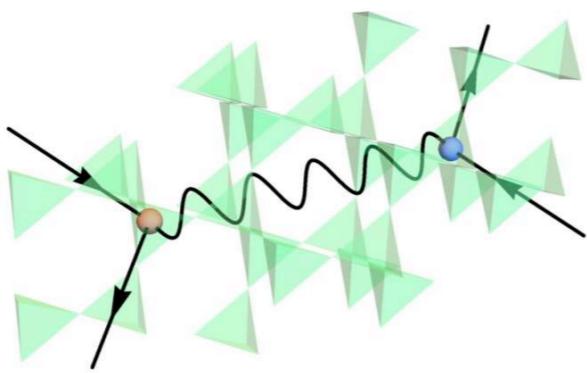


## Summary: Classical Spin Ice

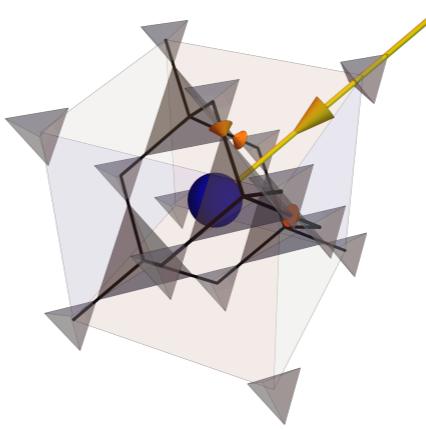
- The base model: spins in a crystal
- Magnetism is frustrated
- 2 in, 2 out constraint à la H<sub>2</sub>O
- Elementary excitations of the system are, for most intents and purposes, magnetic monopoles
- These monopoles move at random in the bulk.



# Quantum Spin Ice

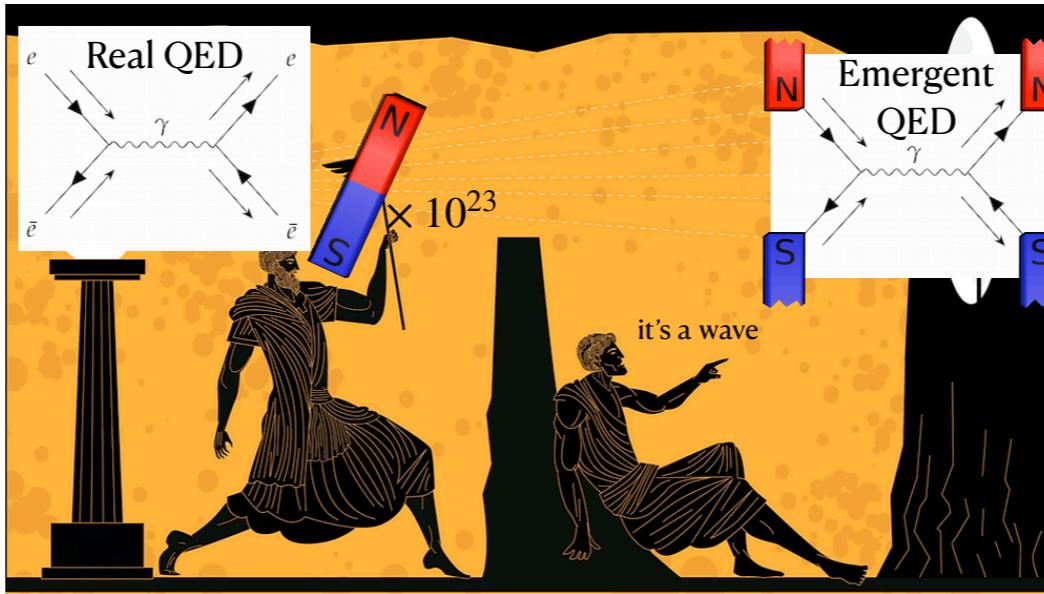


Salvatore D. Pace, Siddharth C. Morampudi, Roderich Moessner and Chris R. Laumann  
"Emergent fine structure constant of quantum spin ice is large"



ALS, Claudio Castelnovo  
"Vison crystal in quantum spin ice on the breathing pyrochlore lattice"

# Emergence

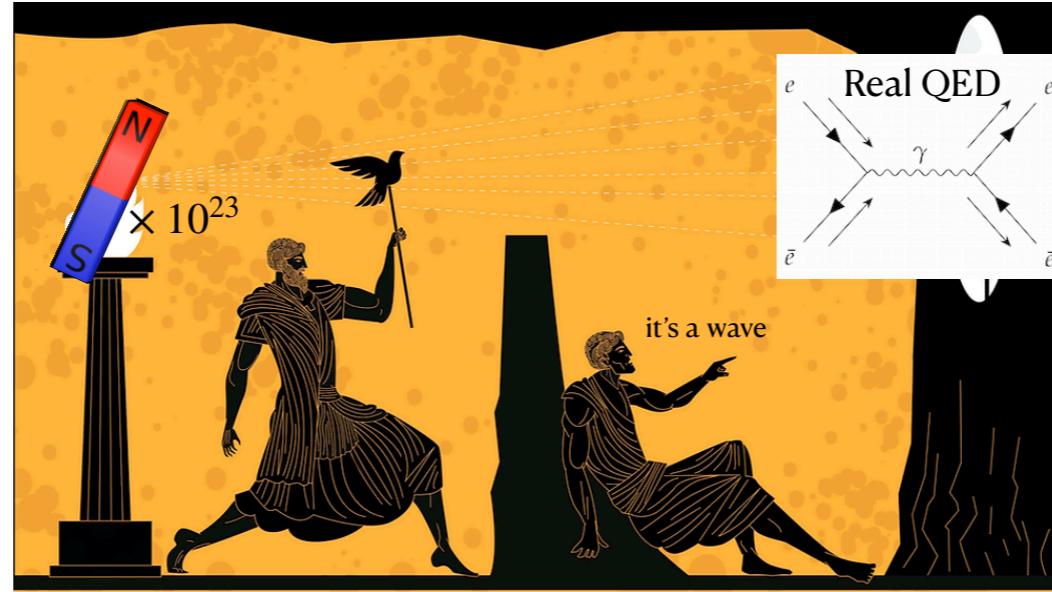


You might well say ...

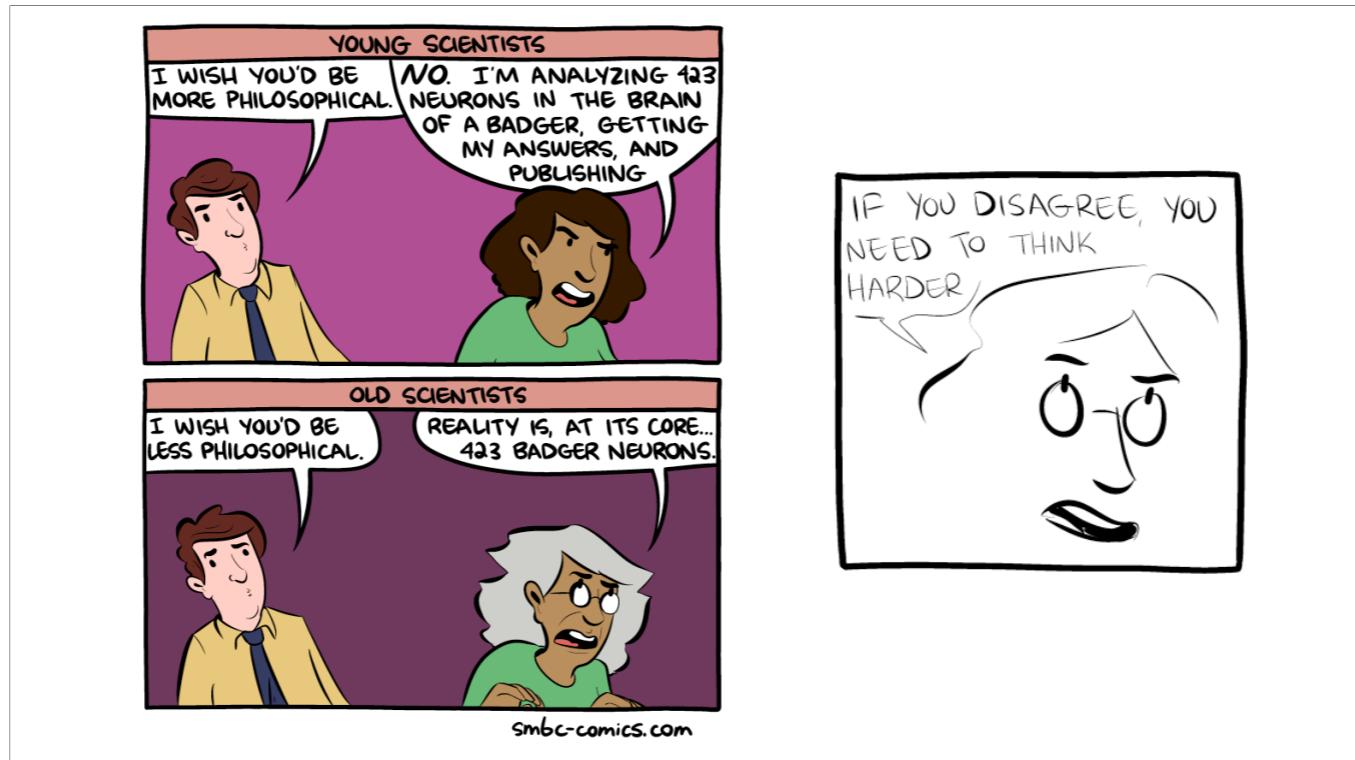
Alright I've just written down some effective theory, this says nothing about the universe

True to an extent, but I'd counter that by asking - "How real do you believe electrons to be?"

# Emergence



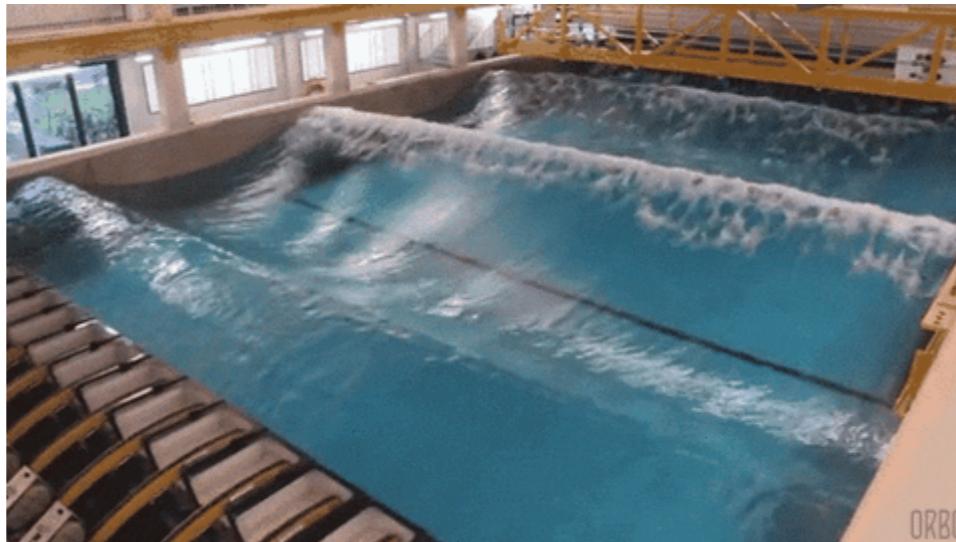




# **Emergence**



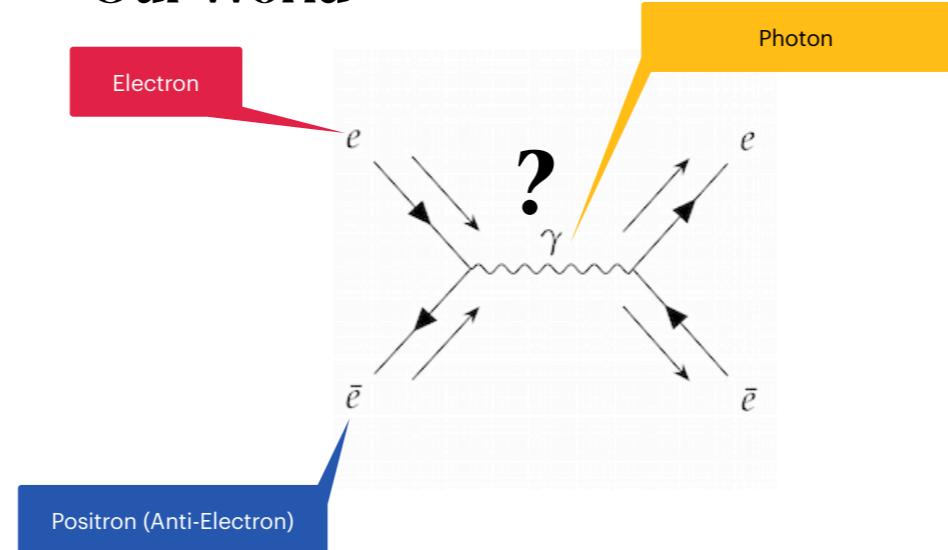
# **Emergence**



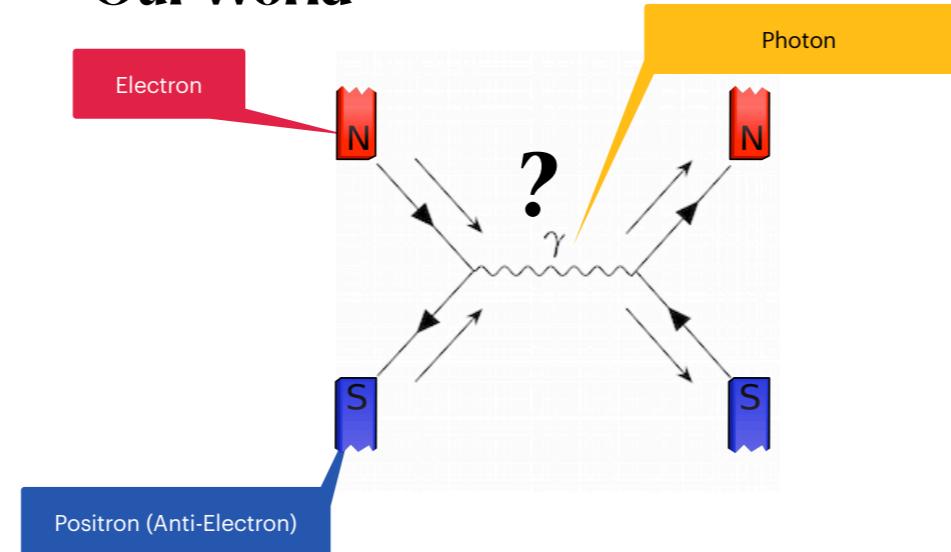
# Phenomenology

	Electrons / Positrons	Spinons / Antispinons
<b>Created and annihilated in pairs</b>	✓	✓
<b>Force between particles</b>	$-\frac{q_1 q_2}{r^2}$ (Electric)	$-\frac{q_1 q_2}{r^2}$ (Magnetic)
<b>Propagation</b>	Ballistic (like a billiard ball)	Diffusive (like a random walk)
<b>Force Carrier</b>	Photons	Entropy

# Our World



# Our World



## **Electricity and Magnetism**

$$\frac{\partial}{\partial t} E = \text{curl } B$$

$$-\frac{\partial}{\partial t} B = \text{curl } E$$

Demonstration Time

# Electricity and Magnetism

$$\frac{\partial}{\partial t} E = \text{curl } B$$

Time-Varying

$$-\frac{\partial}{\partial t} B = \text{curl } E$$

# Electricity and Magnetism

$$\frac{\partial}{\partial t} E = \text{curl } B$$

Time-Varying      Electric Field

$$-\frac{\partial}{\partial t} B = \text{curl } E$$

# Electricity and Magnetism

$$\frac{\partial}{\partial t} E = \text{curl } B$$

Time-Varying      Electric Field      Is A

$$-\frac{\partial}{\partial t} B = \text{curl } E$$

# Electricity and Magnetism

$$\frac{\partial}{\partial t} E = \text{curl } B$$

Time-Varying      Electric Field      Is A      Space-Varying

$$-\frac{\partial}{\partial t} B = \text{curl } E$$

# Electricity and Magnetism

$$\frac{\partial}{\partial t} E = \text{curl } B$$

Time-Varying      Electric Field      Is A      Space-Varying      Magnetic Field

$$-\frac{\partial}{\partial t} B = \text{curl } E$$

# Electricity and Magnetism

$$\frac{\partial}{\partial t} E = \text{curl } B$$

Time-Varying      Electric Field      Is A      Space-Varying      Magnetic Field

$$-\frac{\partial}{\partial t} B = \text{curl } E$$

Time-Varying

# Electricity and Magnetism

$$\frac{\partial}{\partial t} E = \text{curl } B$$

Time-Varying      Electric Field      Is A      Space-Varying      Magnetic Field

$$-\frac{\partial}{\partial t} B = \text{curl } E$$

Time-Varying      Magnetic Field

The diagram illustrates the Faraday's law of induction equation:  $\frac{\partial}{\partial t} E = \text{curl } B$ . Annotations provide context for each term:

- The first term  $\frac{\partial}{\partial t}$  is labeled "Time-Varying".
- The electric field  $E$  is labeled "Electric Field".
- The right side " $\text{curl } B$ " is labeled "Is A".
- The second term  $-\frac{\partial}{\partial t} B$  is labeled "Space-Varying".
- The magnetic field  $B$  is labeled "Magnetic Field".

Below the equation, another instance of the law is shown:  $-\frac{\partial}{\partial t} B = \text{curl } E$ , where the first term  $-\frac{\partial}{\partial t}$  is also labeled "Time-Varying".

# Electricity and Magnetism

$$\frac{\partial}{\partial t} E = \text{curl } B$$

Time-Varying      Electric Field      Is A      Space-Varying      Magnetic Field

$$-\frac{\partial}{\partial t} B = \text{curl } E$$

Time-Varying      Magnetic Field      Is A

# Electricity and Magnetism

$$\frac{\partial}{\partial t} E = \text{curl } B$$

Time-Varying      Electric Field      Is A      Space-Varying      Magnetic Field

$$-\frac{\partial}{\partial t} B = \text{curl } E$$

Time-Varying      Magnetic Field      Is A      Space-Varying

# Electricity and Magnetism

$$\frac{\partial}{\partial t} E = \text{curl } B$$

Time-Varying      Electric Field      Is A      Space-Varying      Magnetic Field

$$-\frac{\partial}{\partial t} B = \text{curl } E$$

Time-Varying      Magnetic Field      Is A      Space-Varying      Electric Field