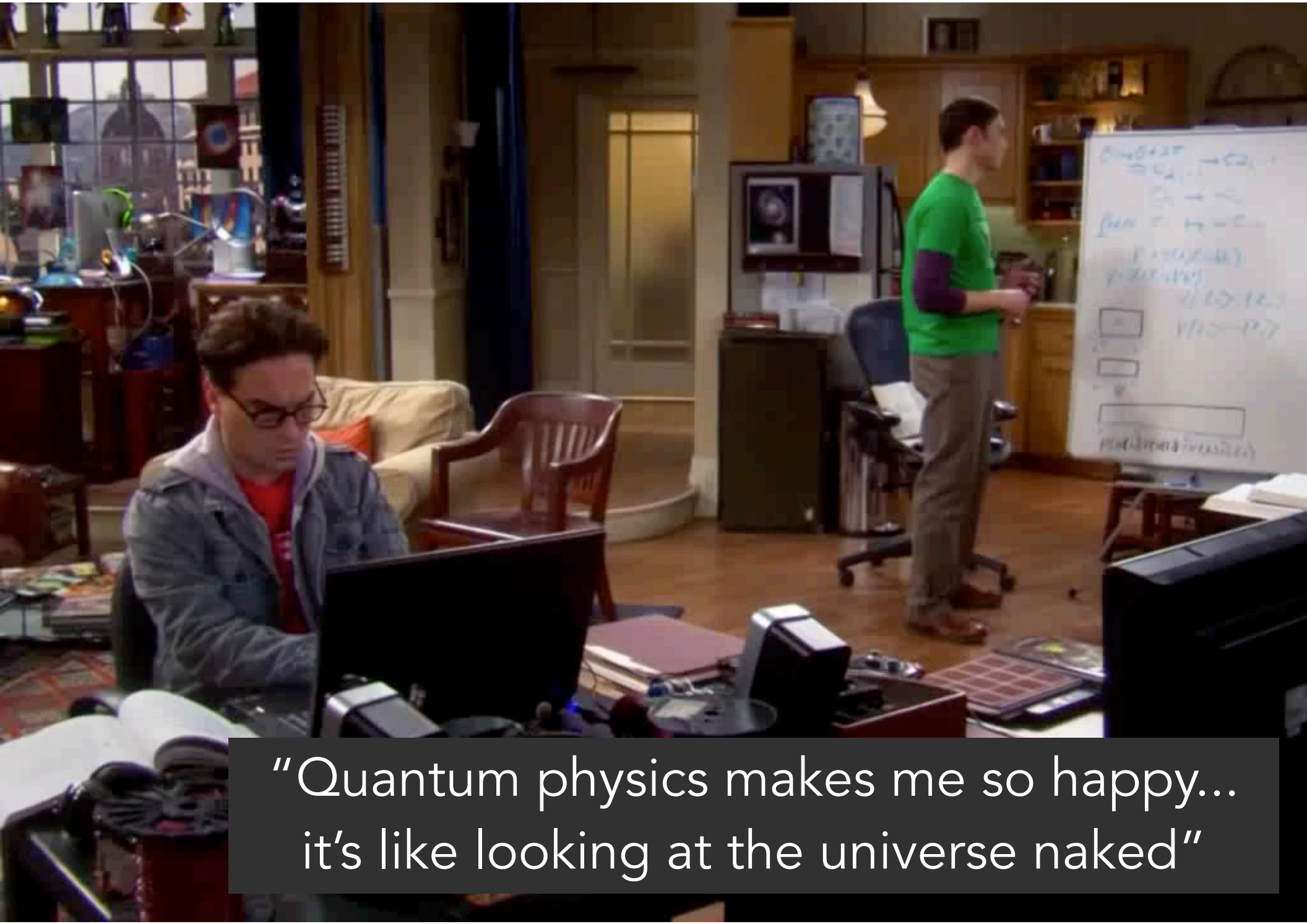
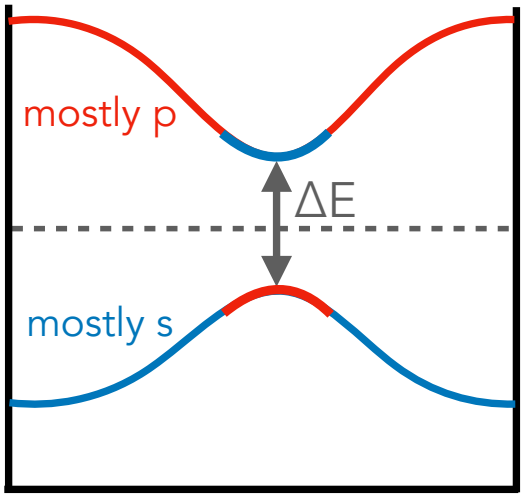
Quantum physics in crystals: spins, magnetism, and entanglement

Leon Balents, KITP

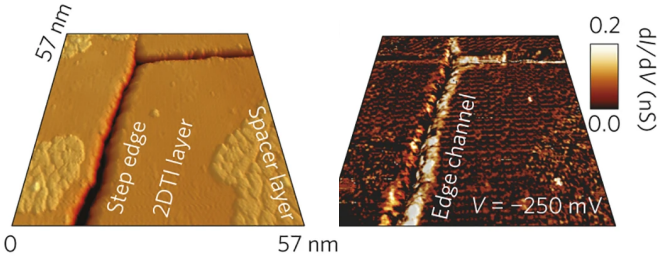
KITP teacher's conference, April 1, 2023
What's in a crystal? A quantum universe!


“Quantum physics makes me so happy...
it’s like looking at the universe naked”

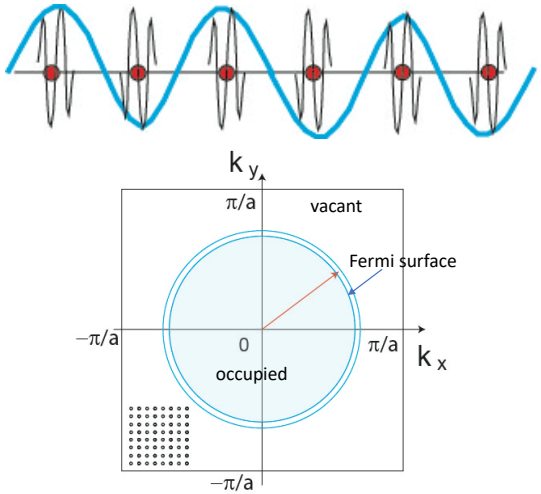
Previous Science Talks

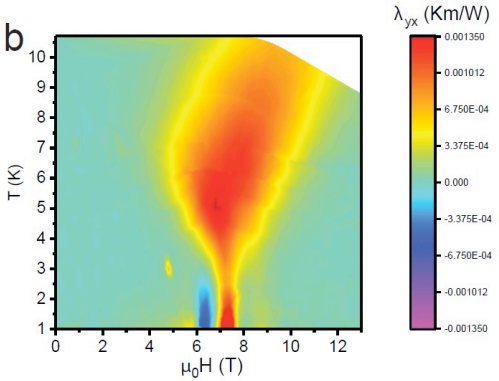


"Topological" insulator

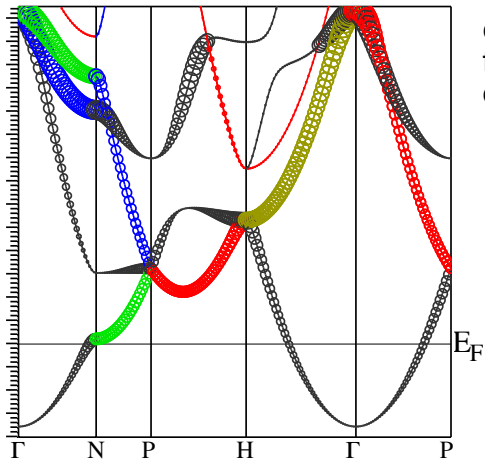


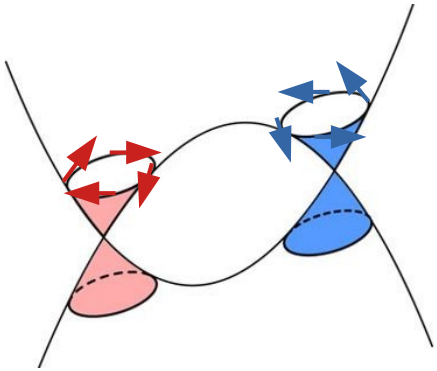
J Cano





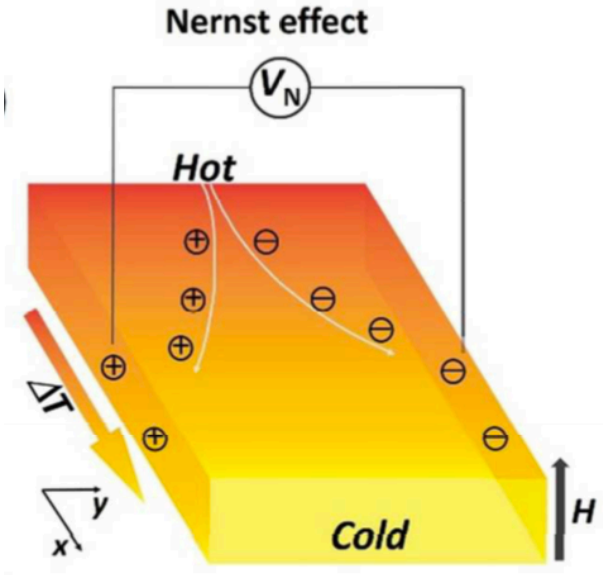
NP Ong



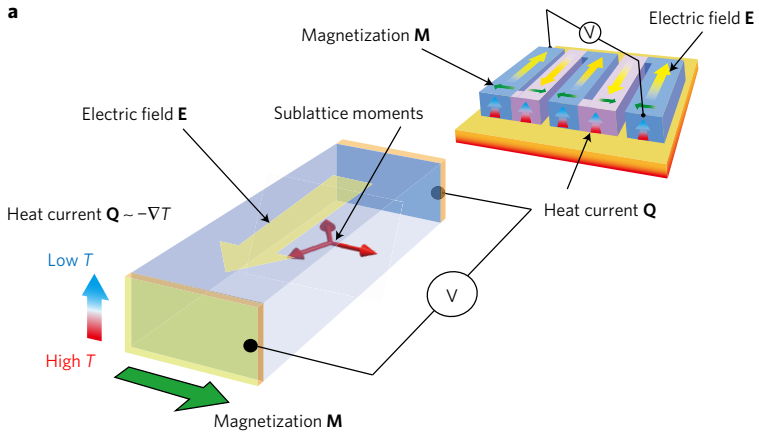


S Bühler-Paschen

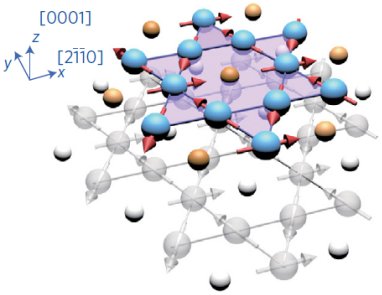
Thermoelectric Hall effect



Force (electric field) perpendicular to *heat* current



Mn_3Sn

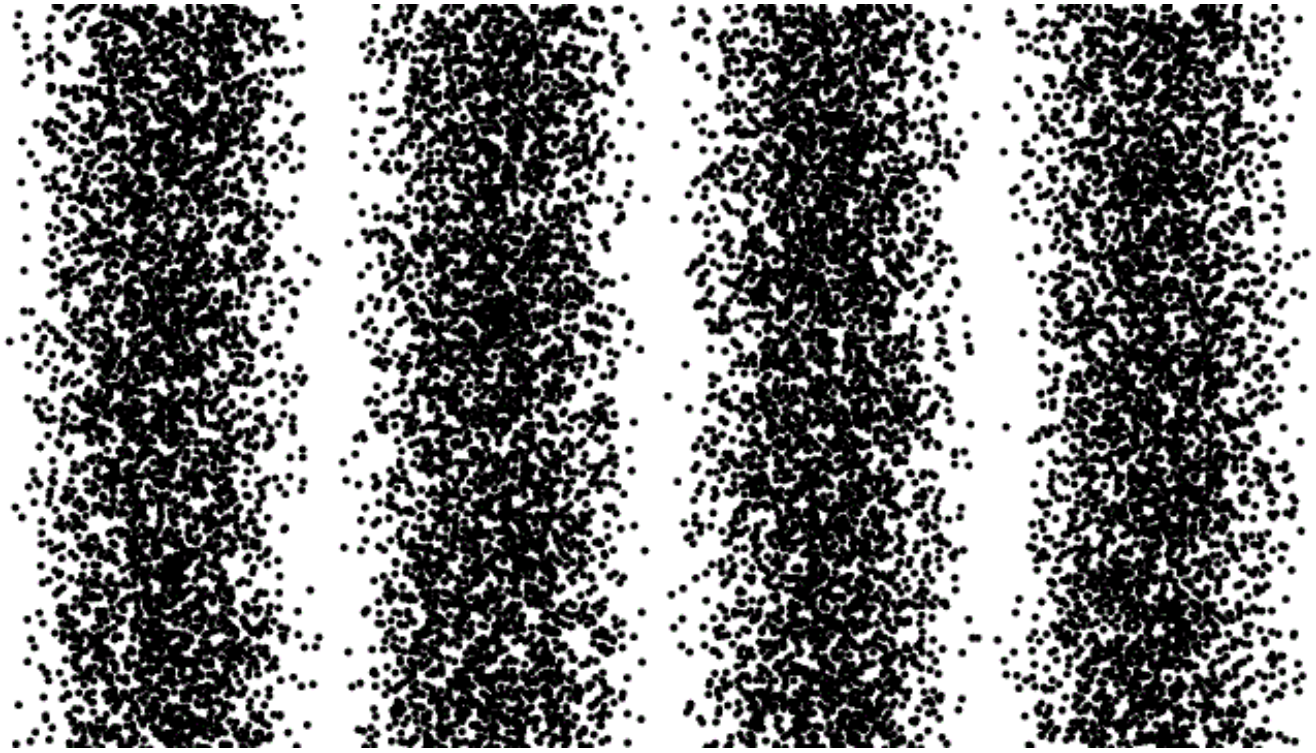


Huge effect w/o magnetic field

©Satoru Nakatsuji

thermopile: heat -> electricity

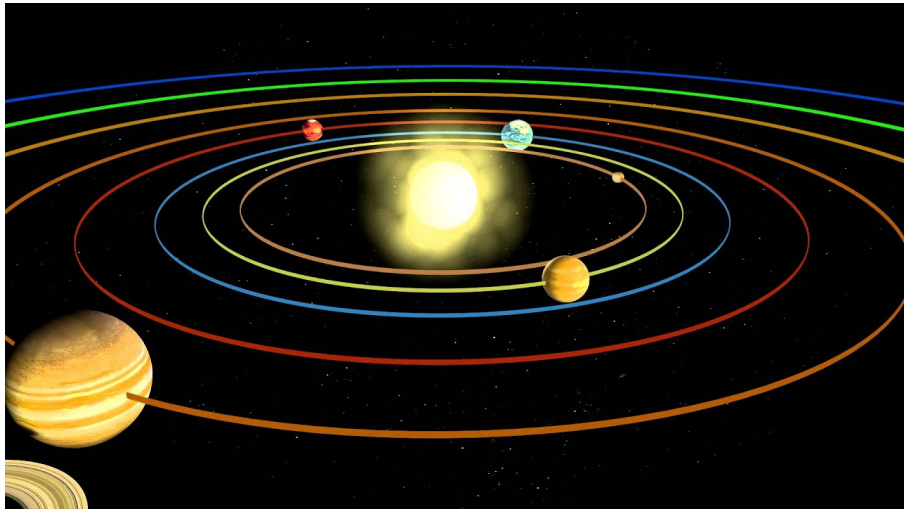
Wave-Particle Duality

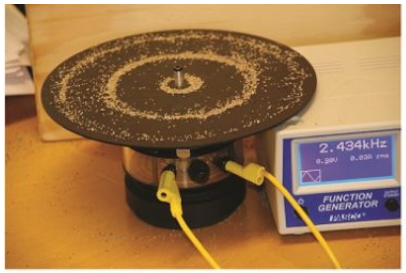


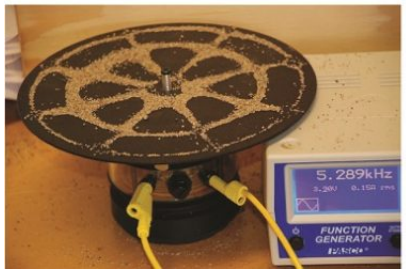
$$\Delta x \times \Delta v > \frac{h}{4\pi m}$$

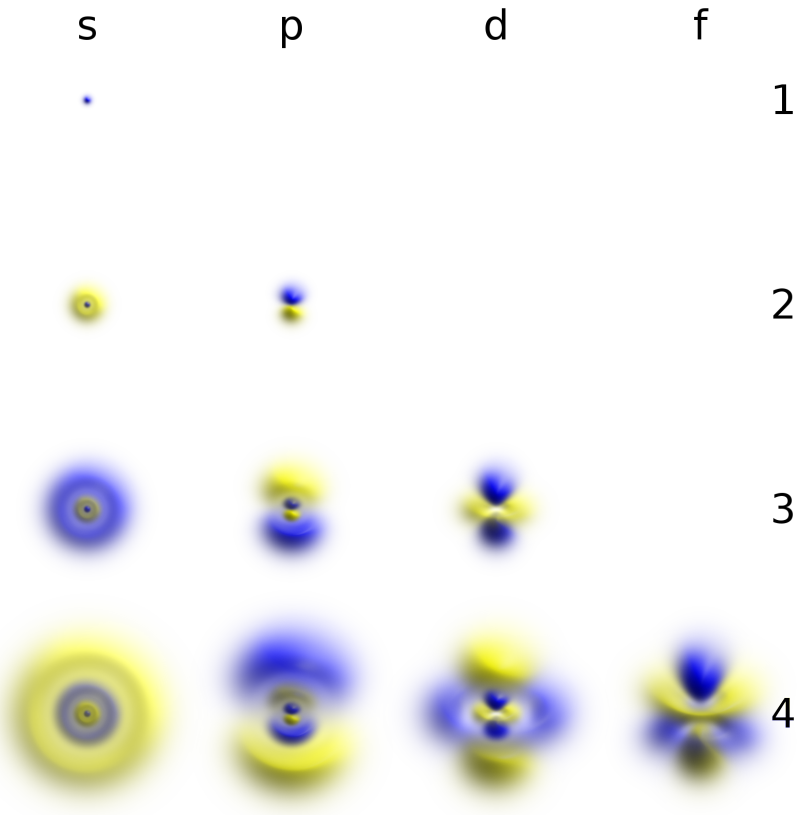
h=6.626 x 10^{-34} Js

Wave-Particle Duality



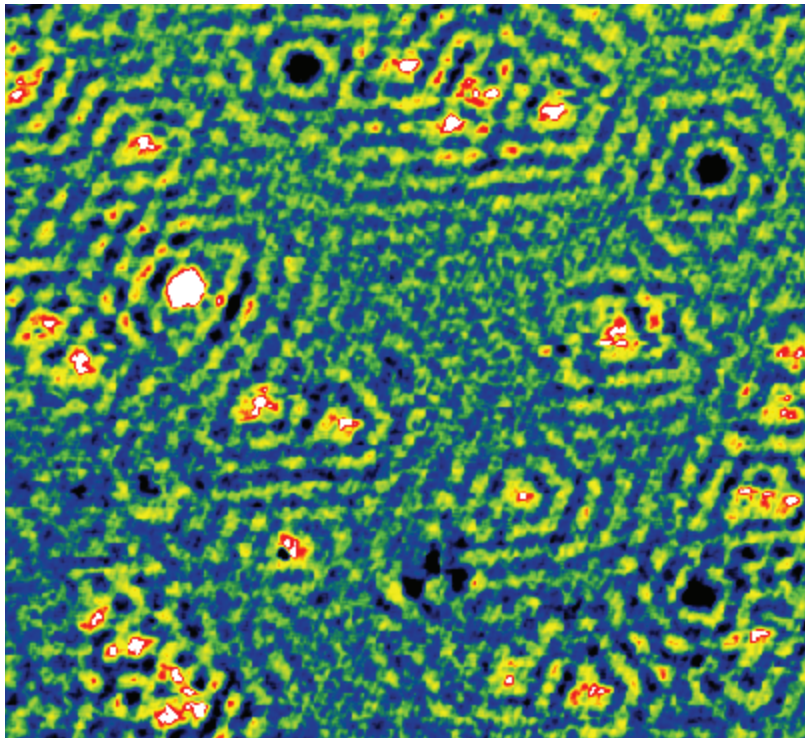






Orbitals

Wave-Particle Duality



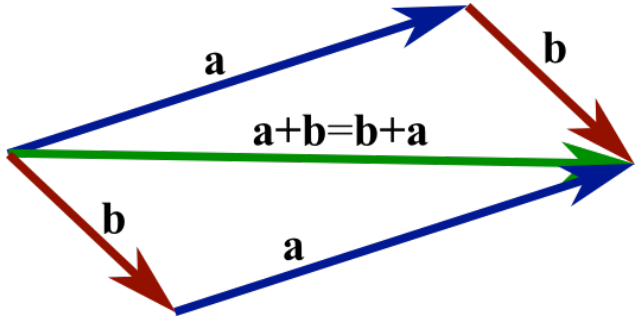
STM image of bismuth metal
Hoffman lab, Harvard

Typical electron speed = c/300 = 3,000,000 mi/hr!

Quantum Superpositon

Adding numbers: 7+5 = 12

Adding vectors:



In quantum physics, we can add "states"

Quantum Superpositon

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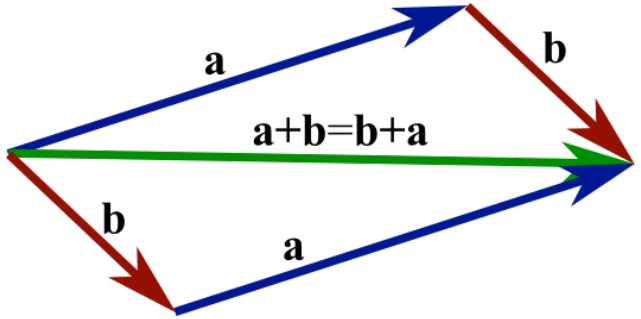

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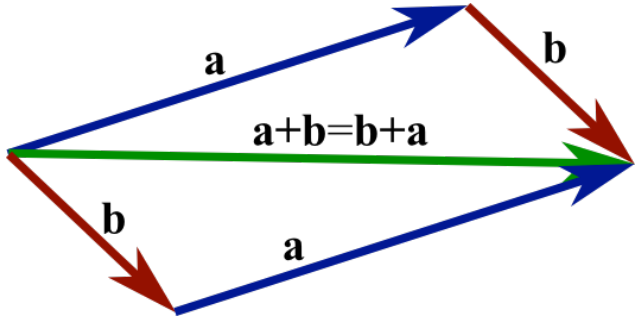

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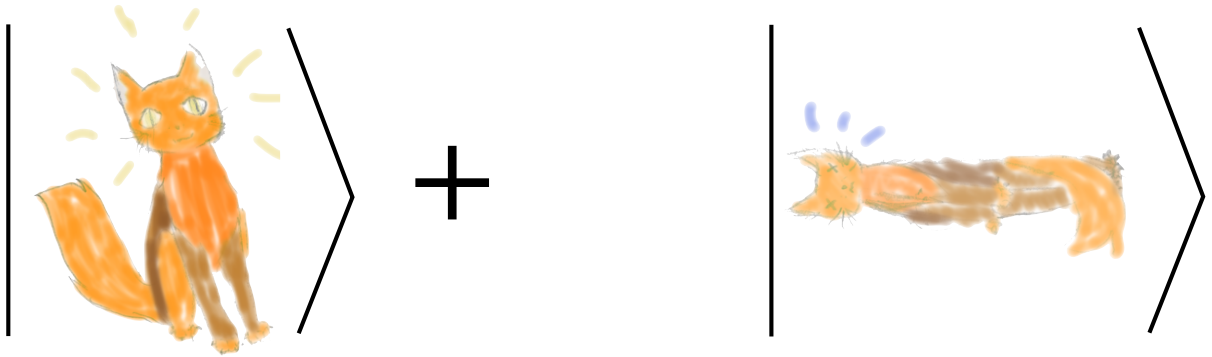

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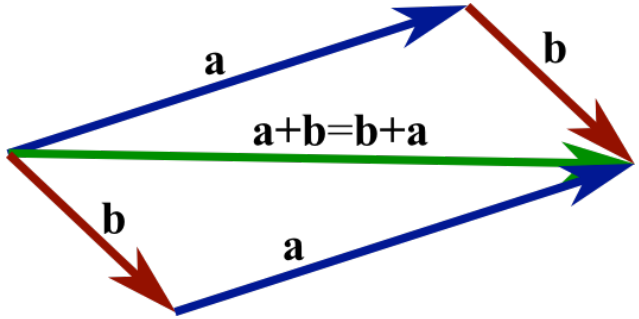
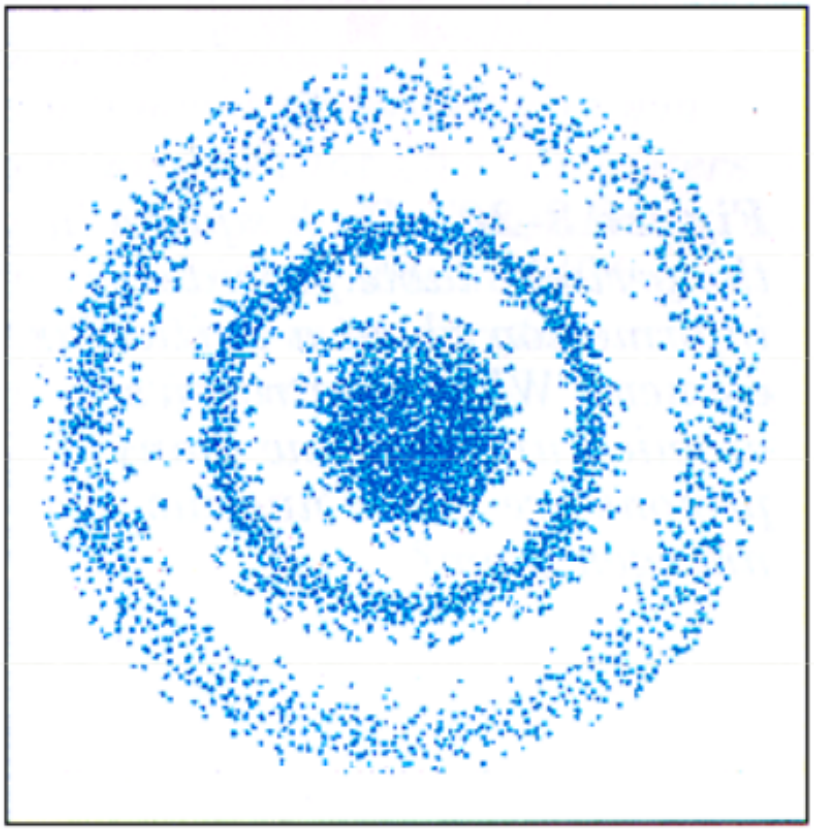
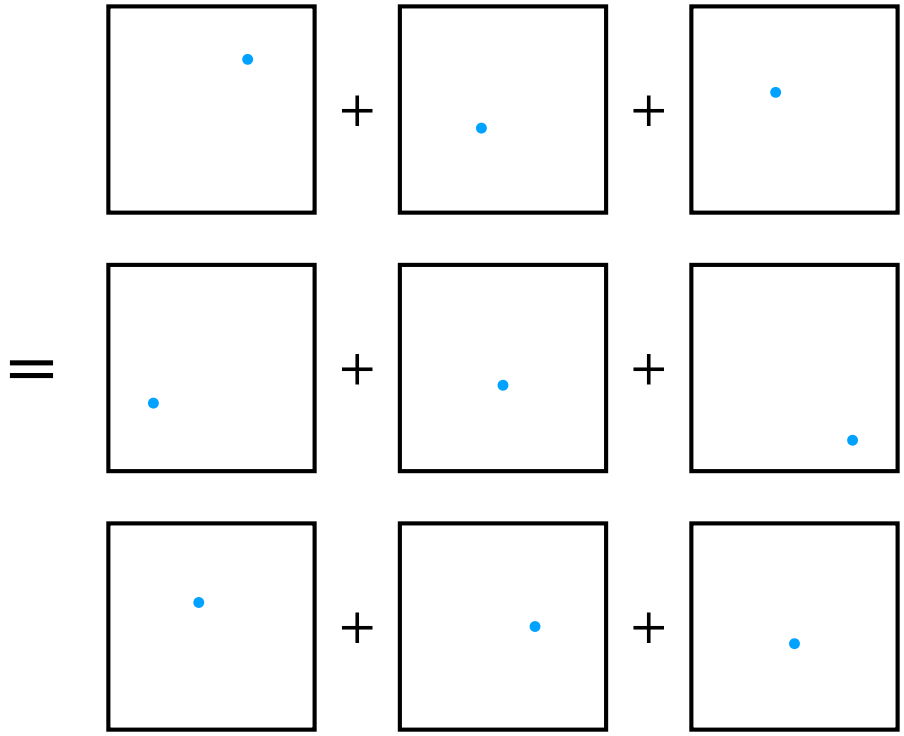


And multiply them by (complex) numbers

$$0.5 \times |\text{cat}\rangle + 0.7i \times |\text{cat}\rangle$$

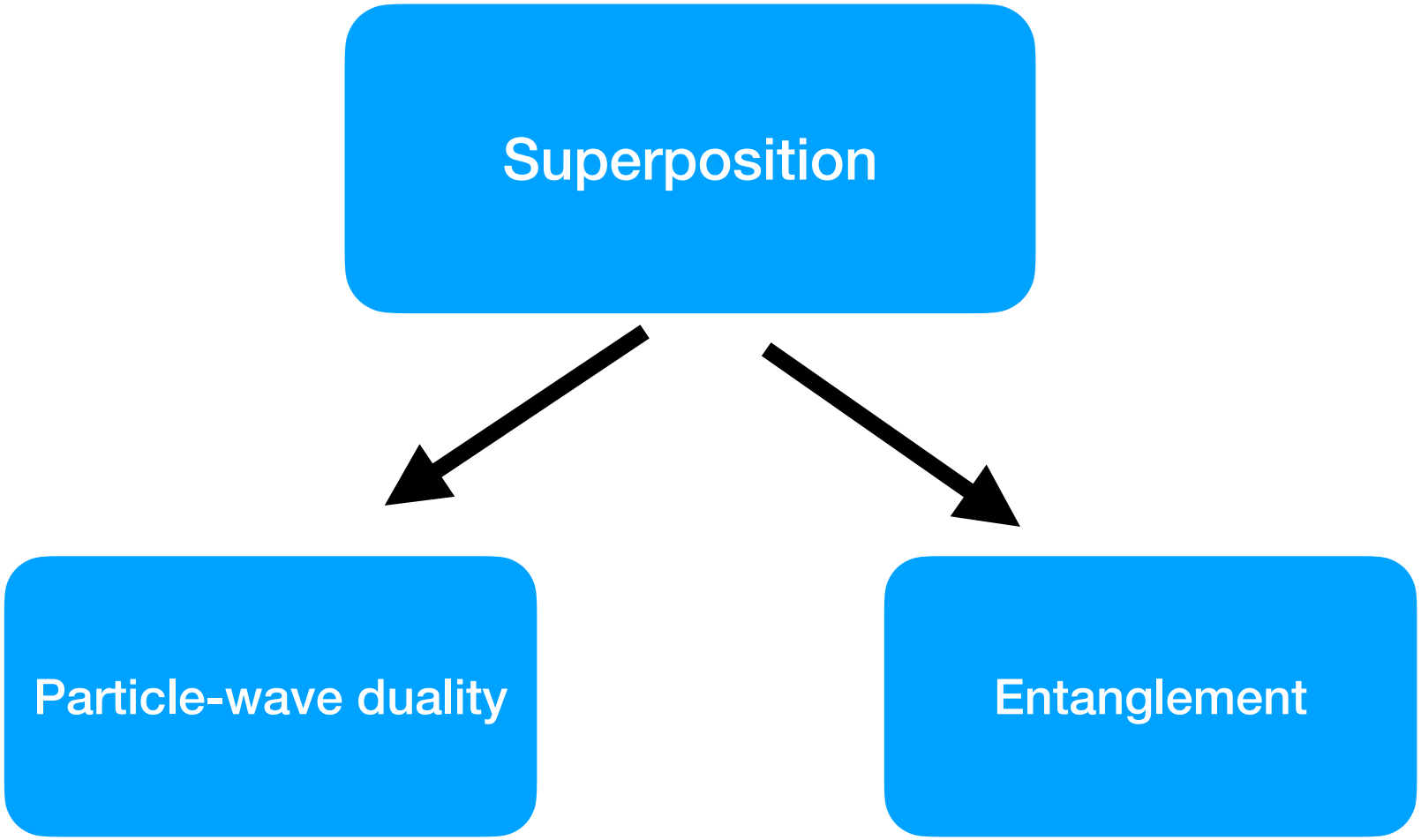
Quantum Superposition





Quantum superposition applied to single particles leads to their wavelike nature

Quantum entanglement



2 or more particles

Qubits

Basic building blocks for entanglement: quantum bits

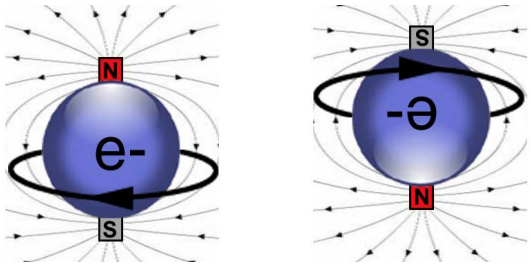
Classical bit

$$b = 0,1$$

Qubit

$$|b\rangle = \alpha|0\rangle + \beta|1\rangle$$

Nature's qubit: electron spin



$$|e\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$$

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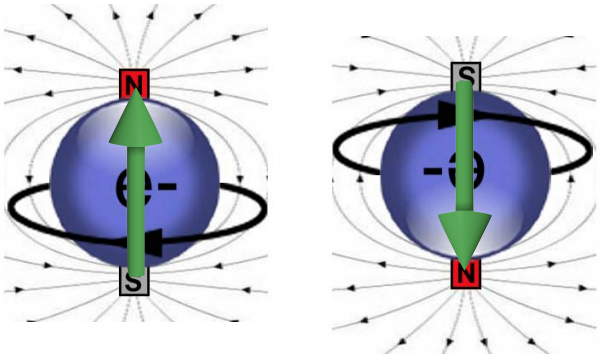

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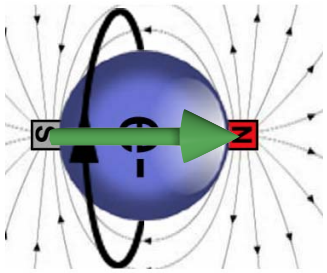
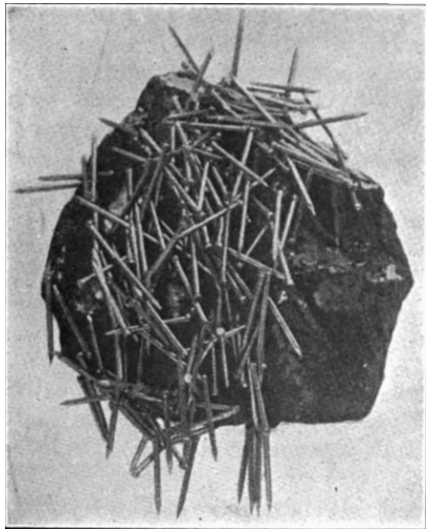
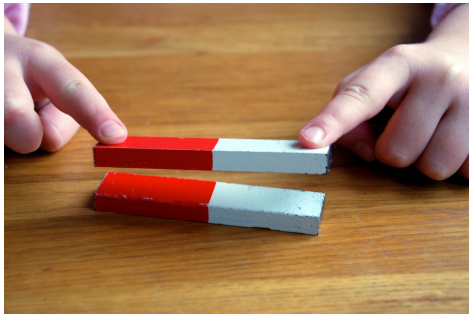
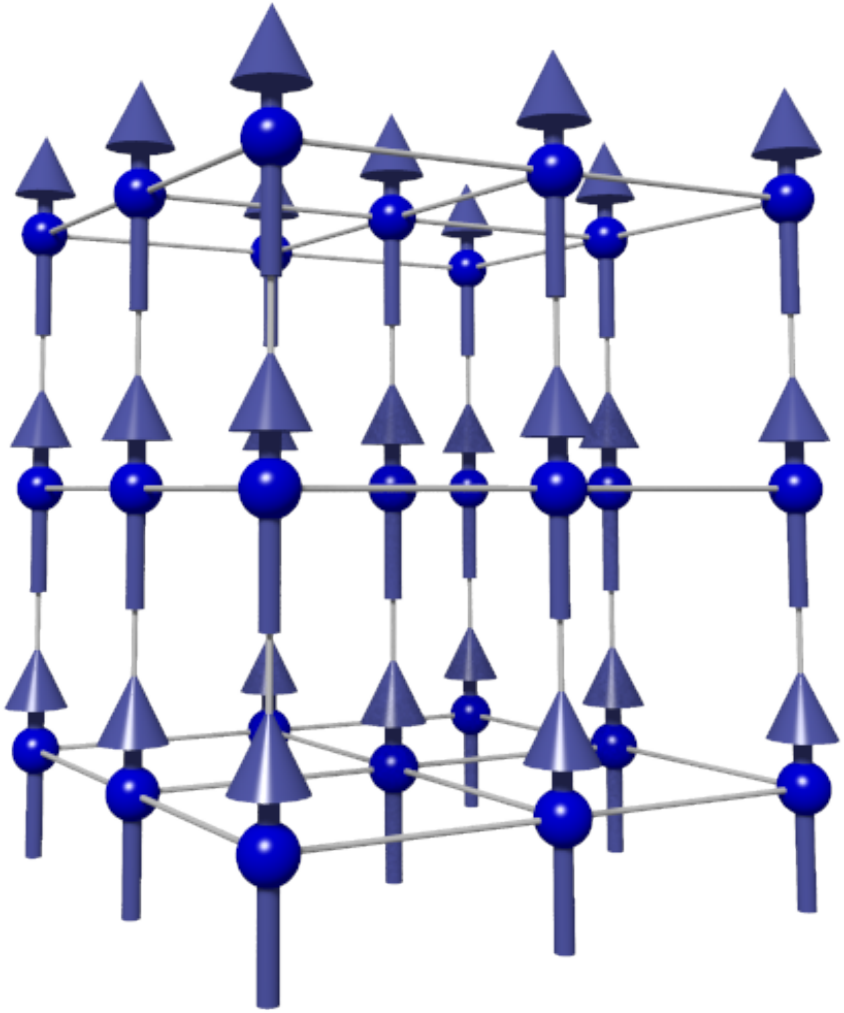


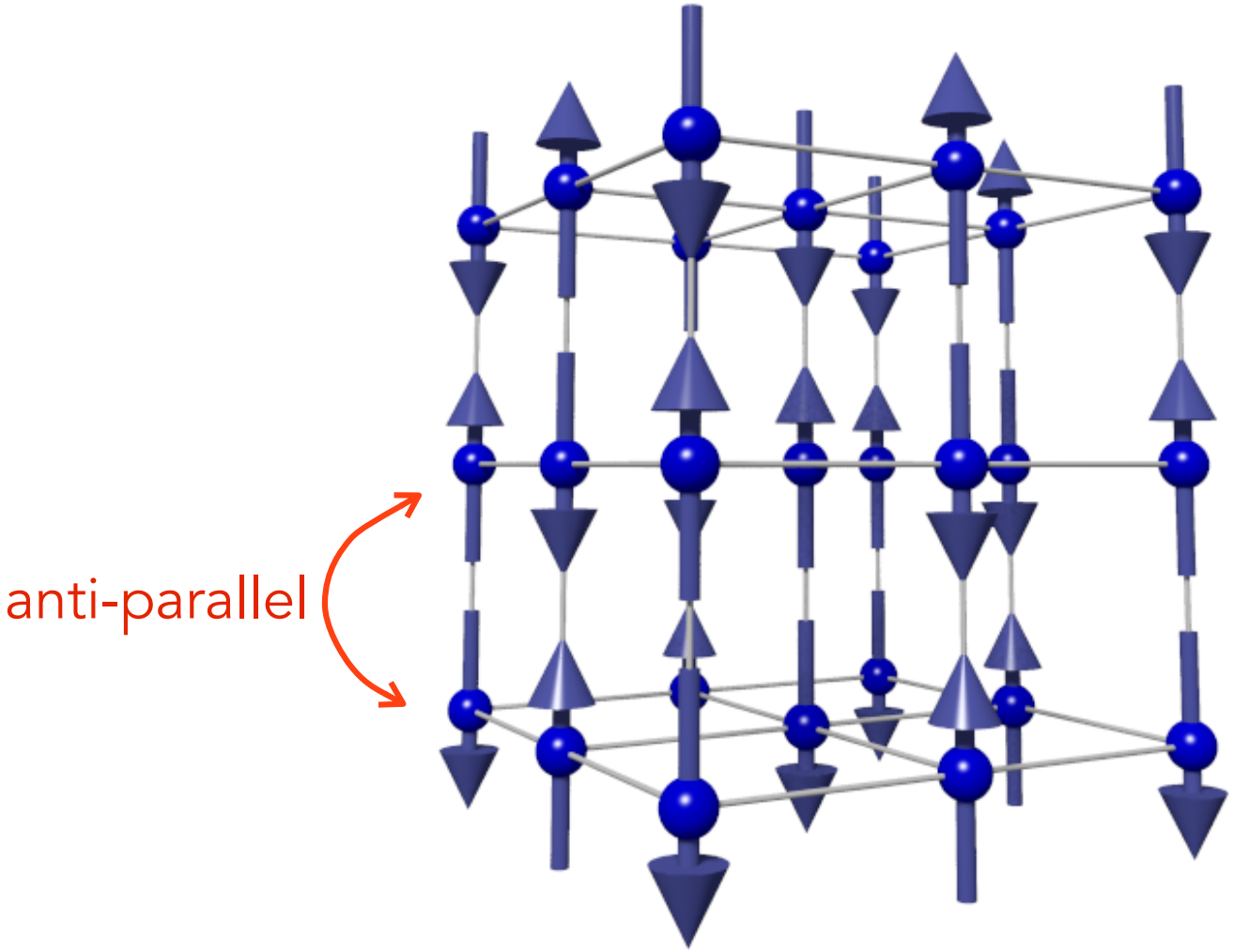
$$|\rightarrow\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle$$



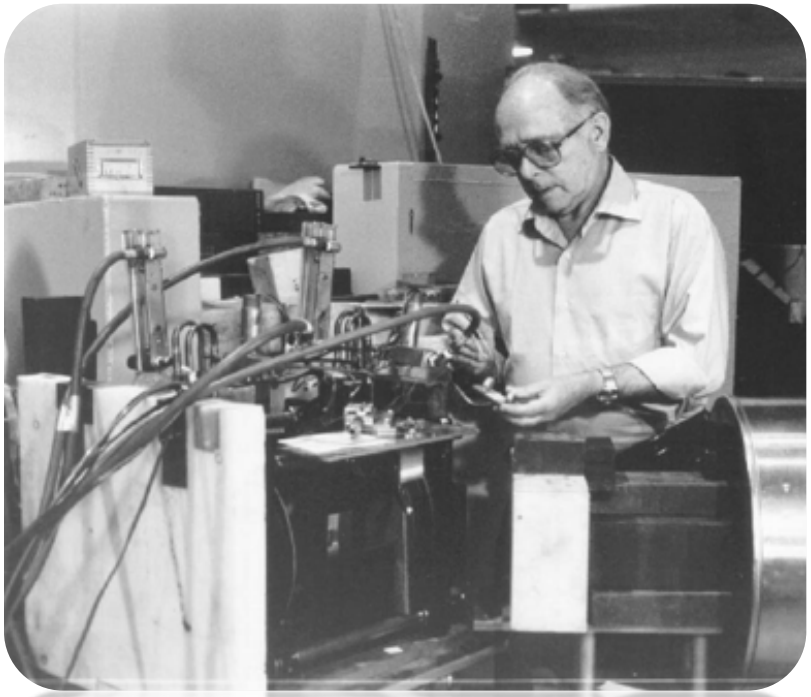




Ferromagnet



antiferromagnet

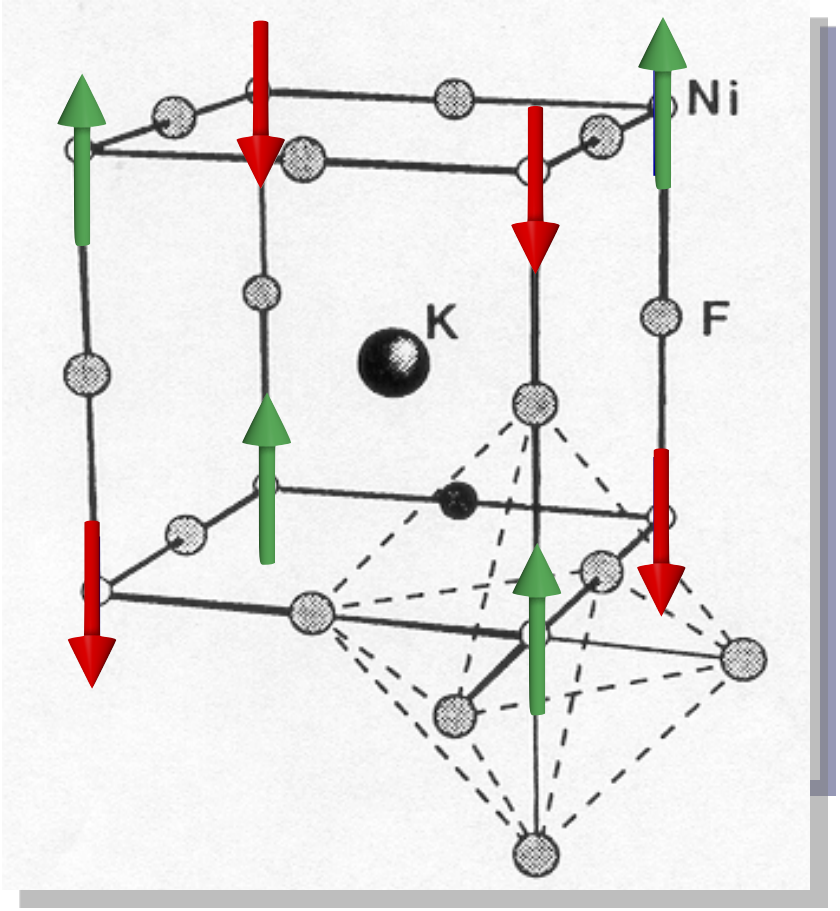


1994 Nobel prize

Detection of Antiferromagnetism by Neutron Diffraction*

C. G. SHULL
Oak Ridge National Laboratory, Oak Ridge, Tennessee
AND
J. SAMUEL SMART
Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland

August 29, 1949



Entanglement

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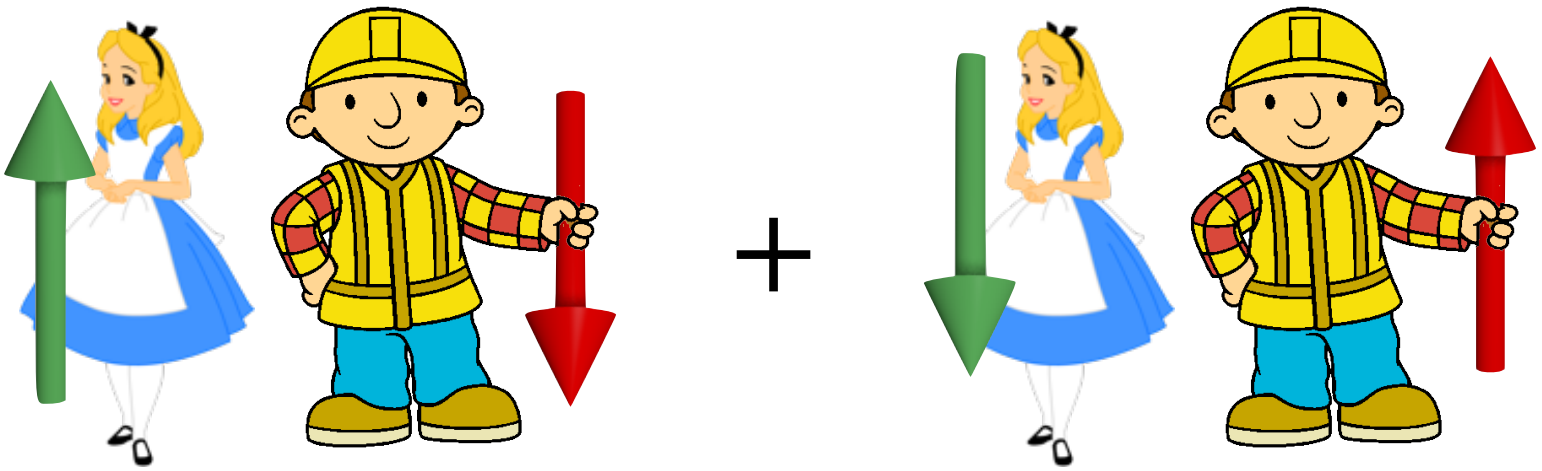
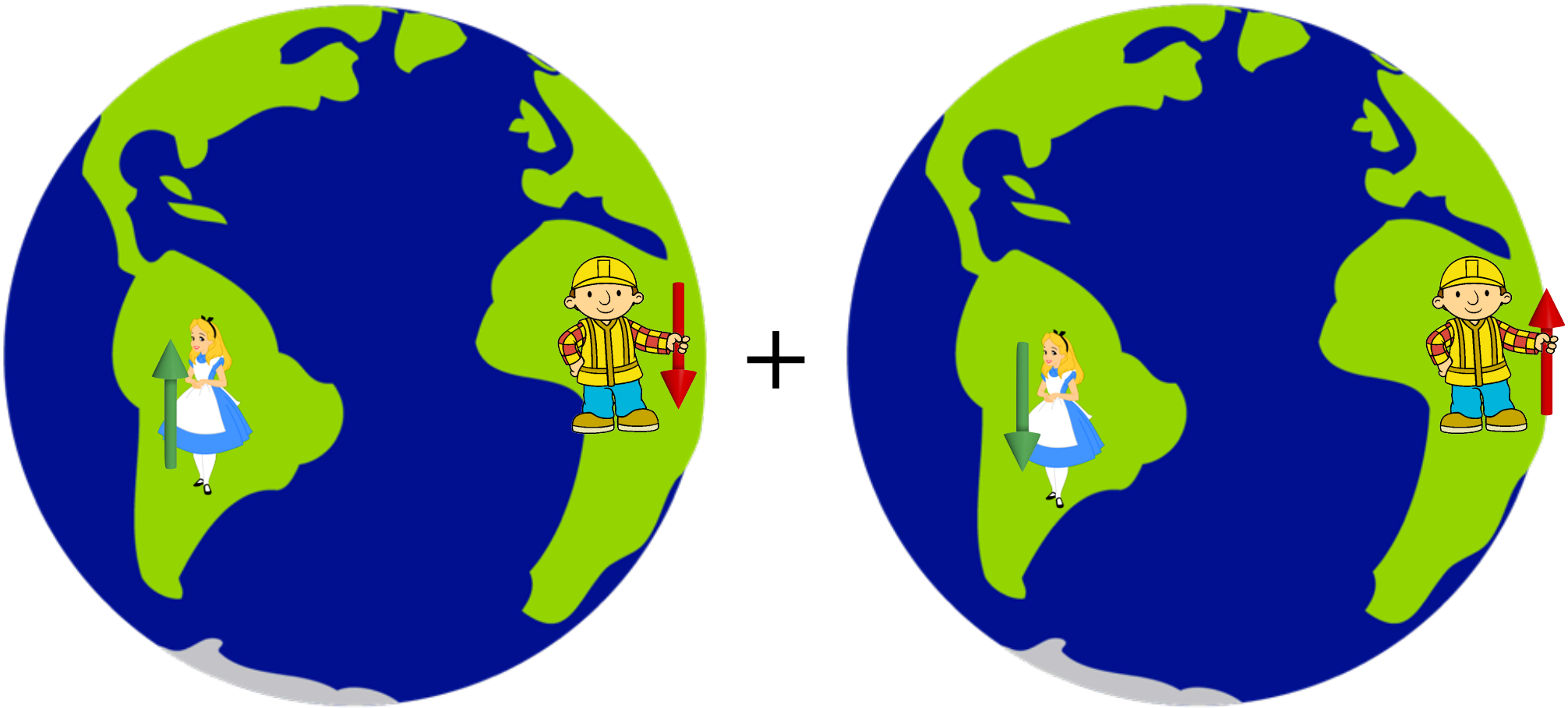
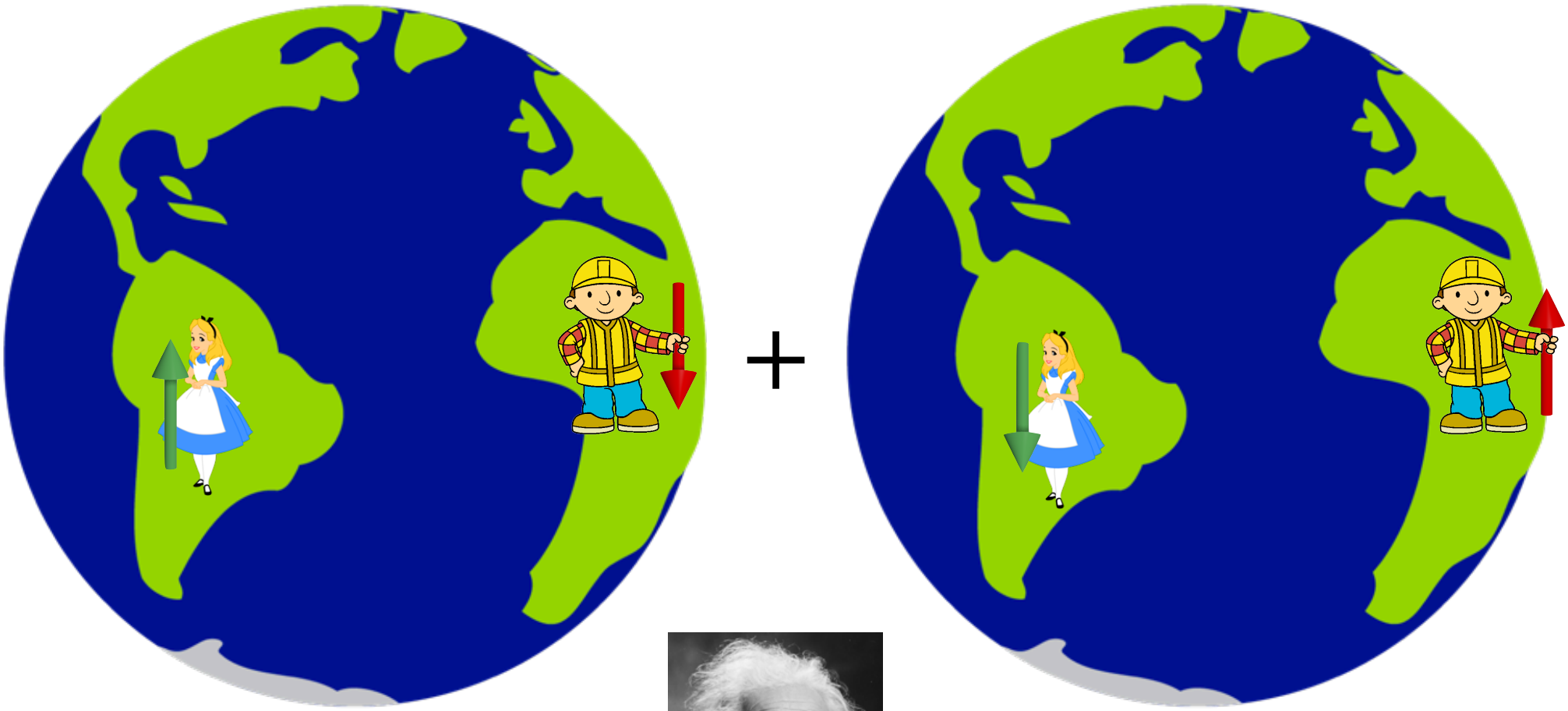
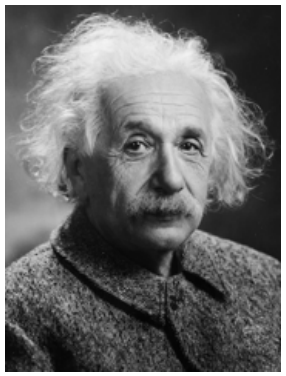


Entanglement



Einstein-Podolsky-Rosen Pair





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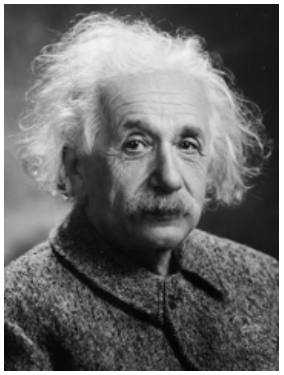
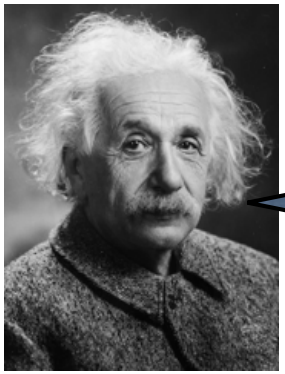


"quantum non-locality"

Einstein-Podolsky-Rosen Pair



spukhafte Fernwirkung!

Entanglement and information

Two qubits $|\psi\rangle = c_1|\uparrow\uparrow\rangle + c_2|\uparrow\downarrow\rangle + c_3|\downarrow\uparrow\rangle + c_4|\downarrow\downarrow\rangle$

Three qubits $|\psi\rangle = c_1|\uparrow\uparrow\uparrow\rangle + c_2|\uparrow\uparrow\downarrow\rangle + c_3|\uparrow\downarrow\uparrow\rangle + c_4|\uparrow\downarrow\downarrow\rangle + c_5|\downarrow\uparrow\uparrow\rangle + c_6|\downarrow\uparrow\downarrow\rangle + c_7|\downarrow\downarrow\uparrow\rangle + c_8|\downarrow\downarrow\downarrow\rangle$

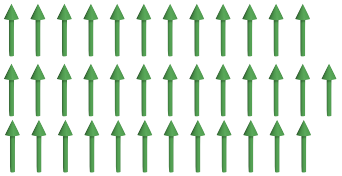
N qubits $|\psi\rangle = c_1|\uparrow\cdots\uparrow\rangle + \cdots + c_{2^N}|\downarrow\cdots\downarrow\rangle$

** A system of N qubits stores 2^N complex numbers in its physical state

Entanglement and information

My Mac: 16GB memory = 1.3×10^{11} bits

37 qubits store more numbers than this



~ $1.5nm^3$ cube of $KNiF_3$

<u>500 qubits = more numbers than atoms in the universe</u>

Google Quantum AI 2.5mi away

Quantum processors with
~50 qubits

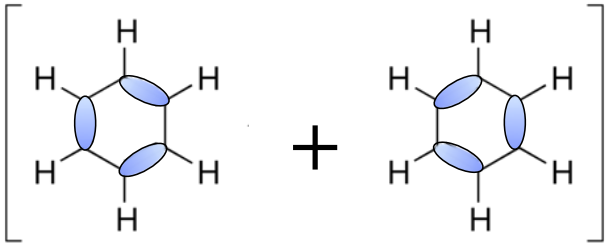
thequantuminsider.com

Aiming for nearly full control of ~100 qubits

Entanglement in matter

Nearby spins are often entangled

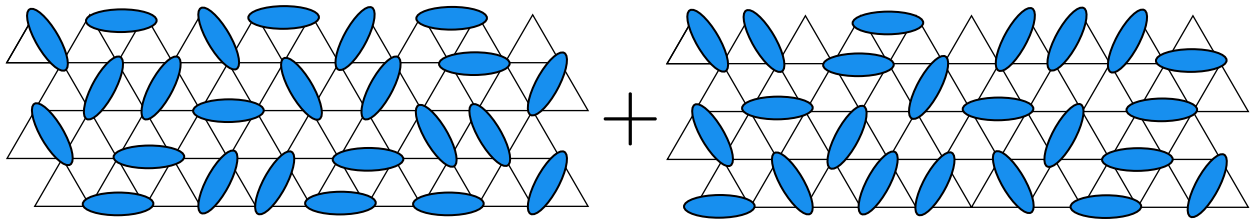
chemical bond
= EPR pair!



benzene

Long-range entanglement of many spins?

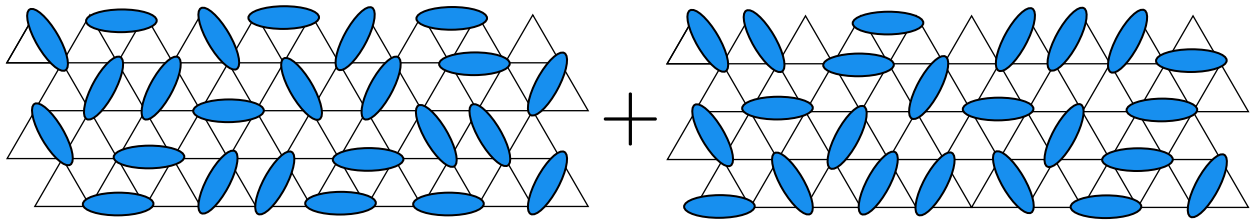
Ψ =



+...

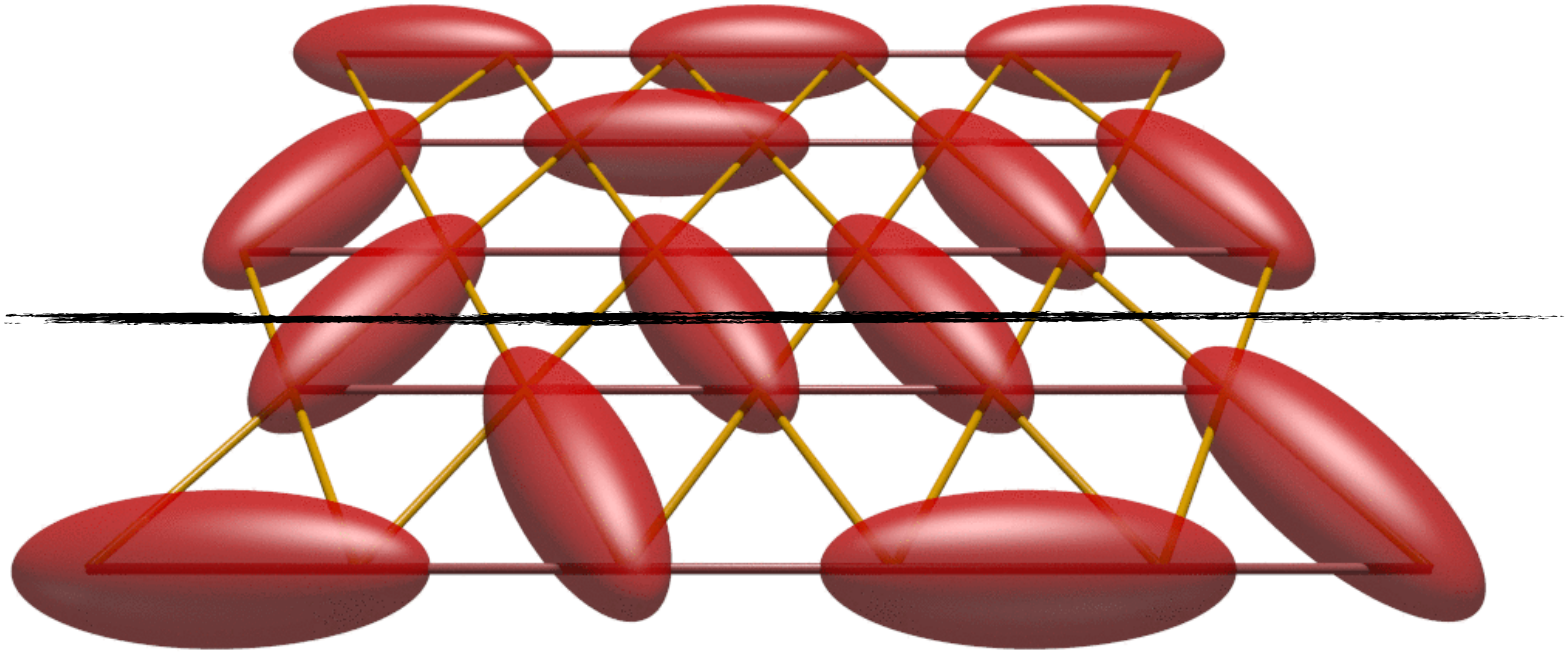
"A quantum spin liquid"

Entanglement and Emergence

Ψ =  +...

- We cannot hope to control $2^{10^{20}}$ coefficients
- Instead, we study what sort of structures of entanglement can be created and what phenomena they engender

A hint of topology



The *parity* of the number of crossings of the line is *invariant.*

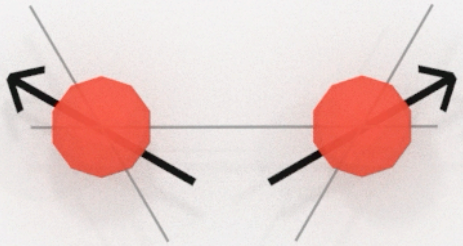
Teachers' Conference: What's in a crystal? – A quantum universe

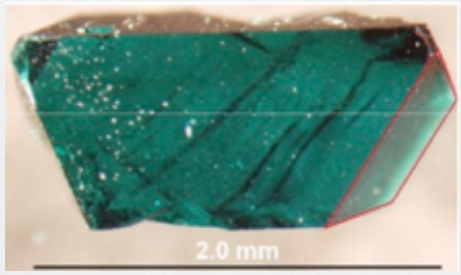
Coordinators: Jennifer Cano and Qimiao Si

Carl Sagan is famous for saying that there are more stars in our Universe than there are grains of sand covering the world's beaches. What Sagan didn't say is that a single grain of sand has more electrons than stars in the Universe. What do these many electrons do in a crystal? They form a quantum universe.

- New types of particles?
- New forces?
- Models for the origin of particles and forces in our world?

Fractionalization





"Spinon"

QuantumMadeSimple.com

Possible applications

Electrically insulating materials that conduct heat like metals?

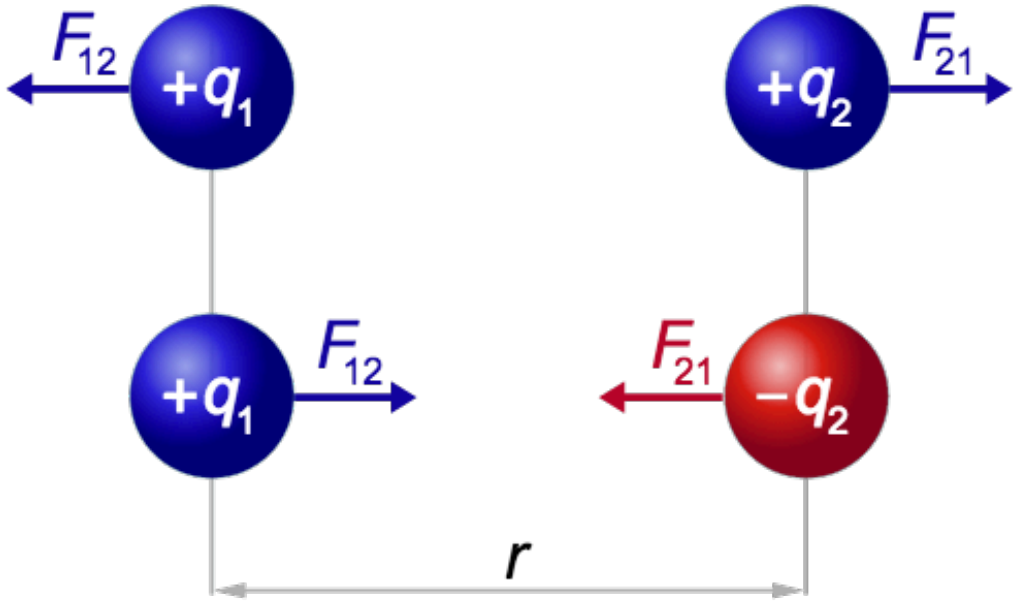
Insulating magnetic field sensors?

Computing elements, thermoelectrics, …

Coulomb, 1785

DES recherches qui précèdent, il réſultera :

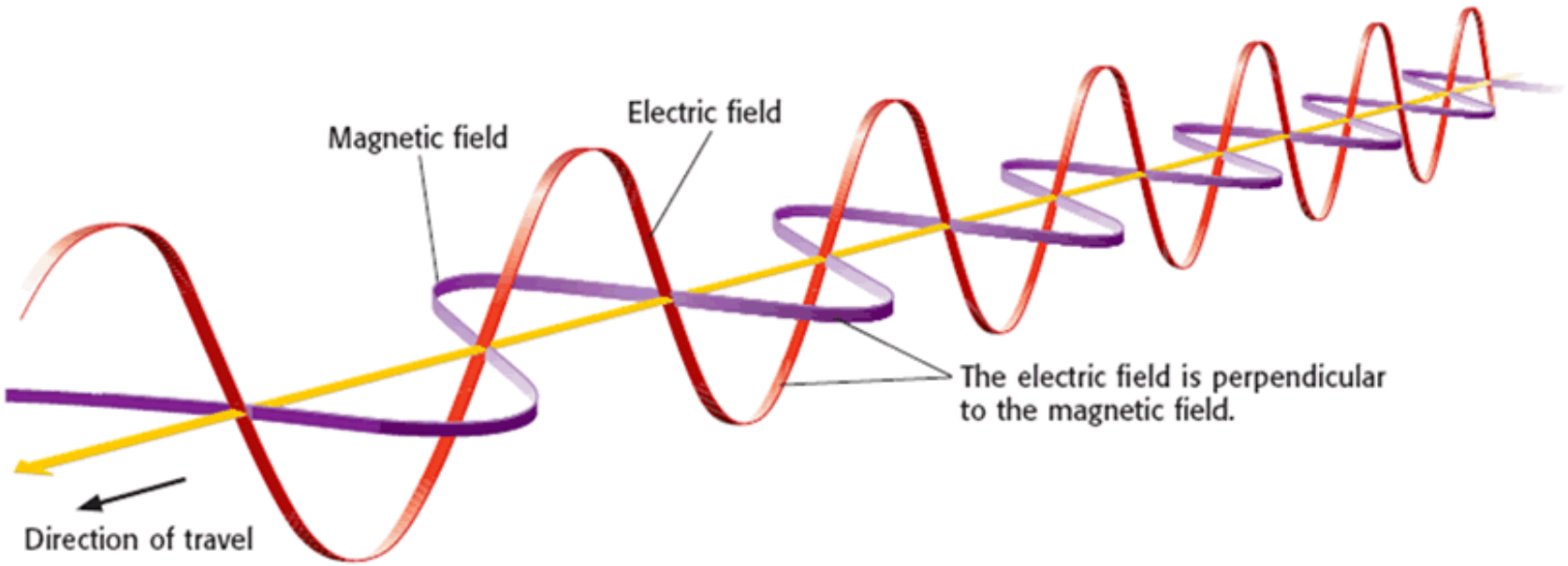
1.° Que l'action, ſoit répulſive, ſoit attractive de deux globes électriſés, & par conſéquent de deux molécules électriques, eſt en raiſon compoſée des denſités du fluide électrique des deux molécules électriſées, & inverſe du carré des diſtances.



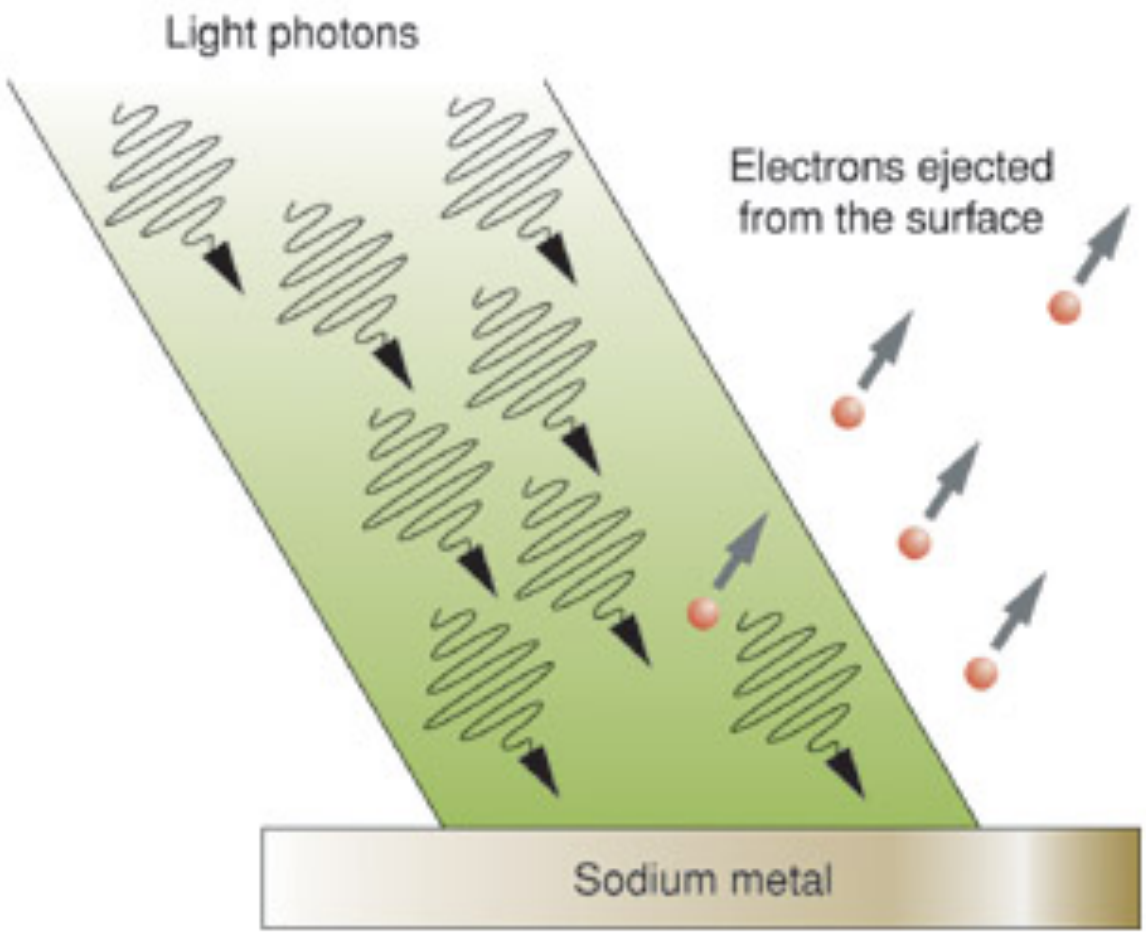
$$F_{12} = F_{21} = k \frac{q_1 q_2}{r^2}$$

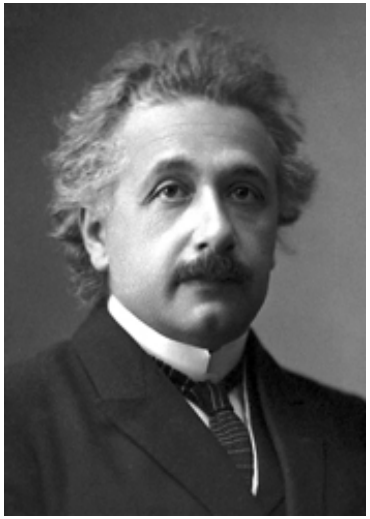
Electromagnetism

James Clerk Maxwell

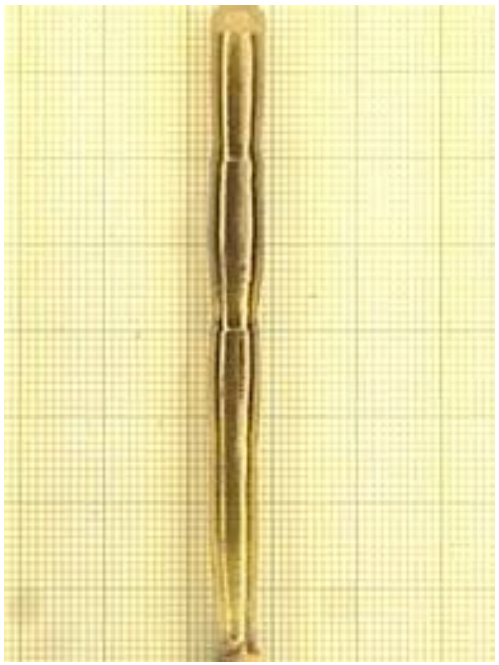


Photoelectric effect



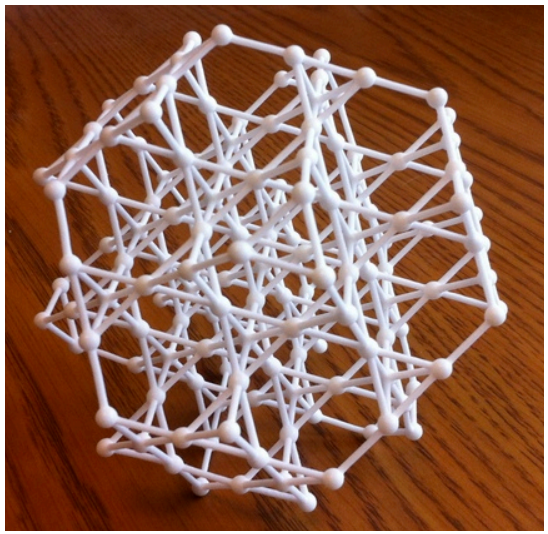


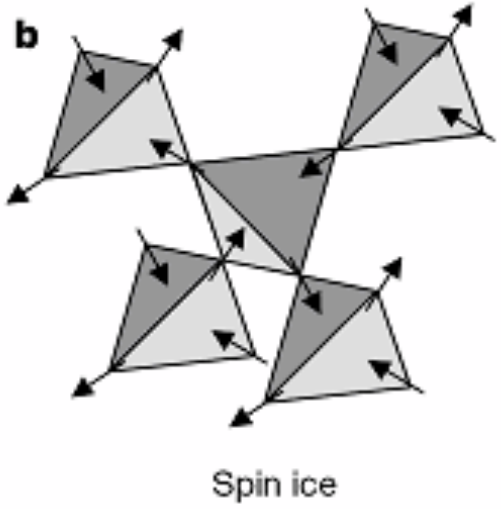
Quantum spin ice



$A_2B_2X_7$

"Pyrochlore" lattice



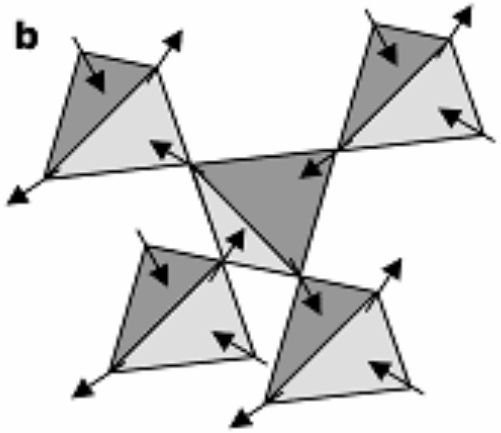


Spin ice

Forces between spins: strongly prefer "2 in - 2 out"

But otherwise the spins can take many configurations

Quantum spin ice



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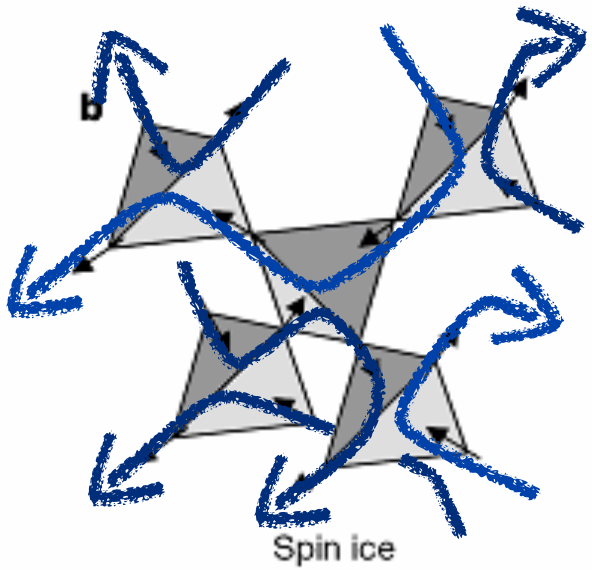
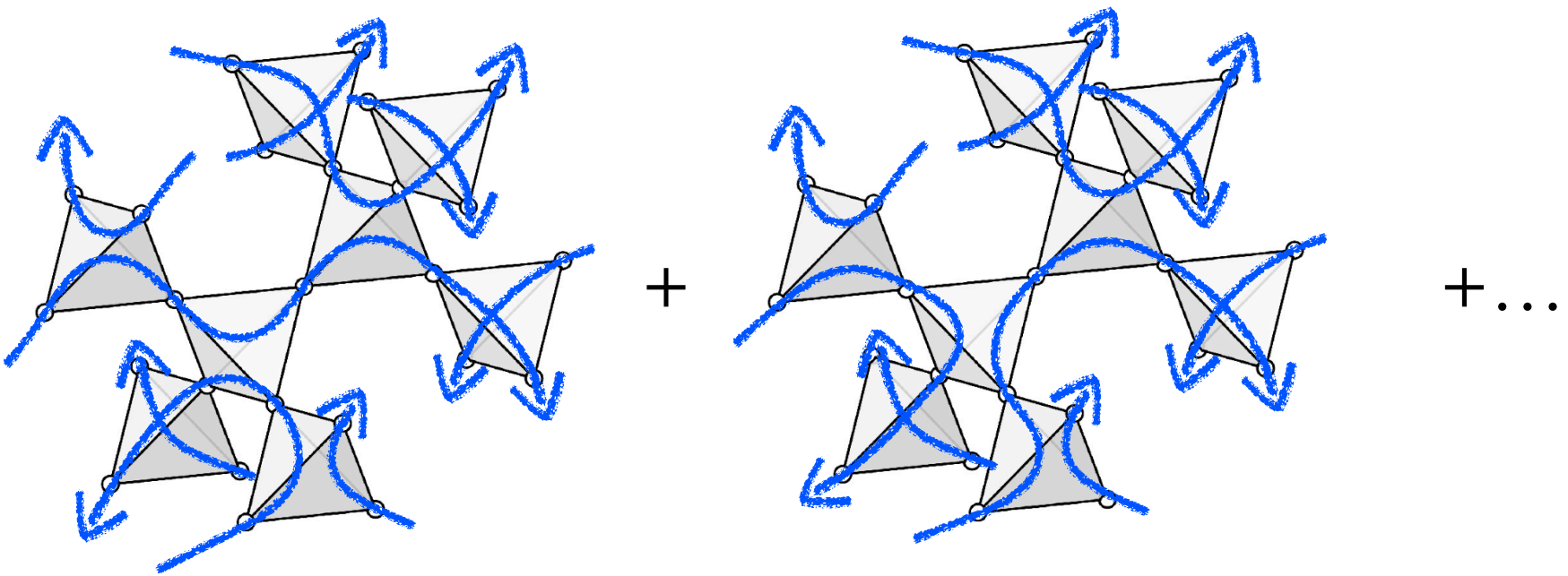


These spin configurations can be represented as lines that do not end — like magnetic field lines!

The “unbreakable” nature of these lines is another example of topology entering quantum materials.

Quantum spin ice

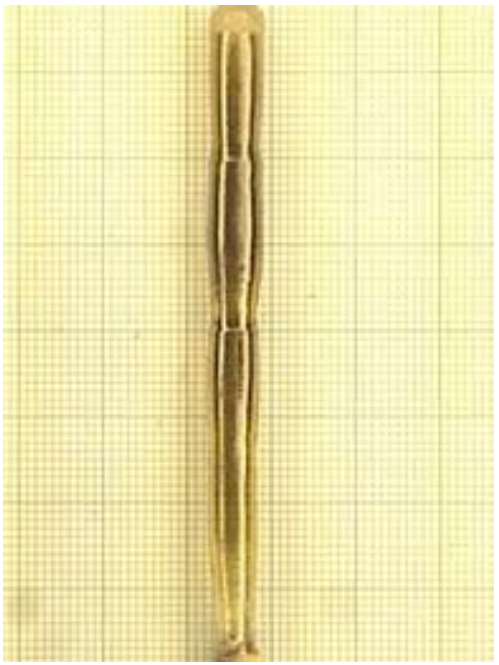


And under the right conditions, this quantum superposition really acts like the “vacuum fluctuations” of an electromagnetic field!

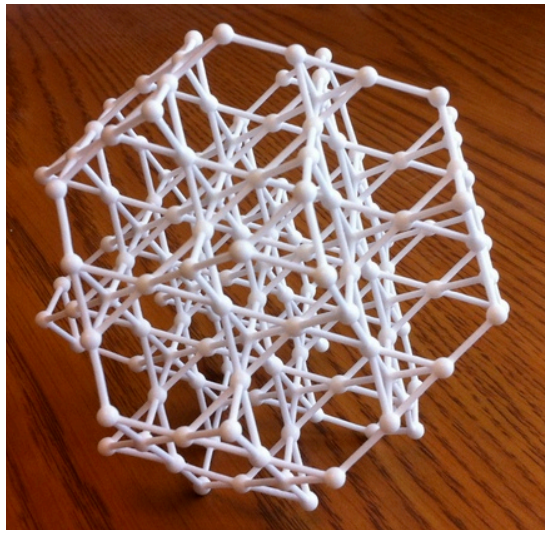
Lucile Savary

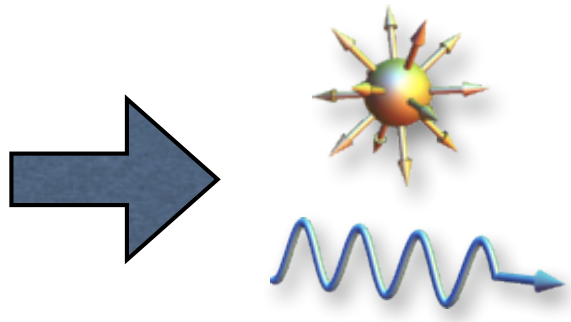
SungBin Lee

Quantum Spin Ice



$A_2B_2X_7$



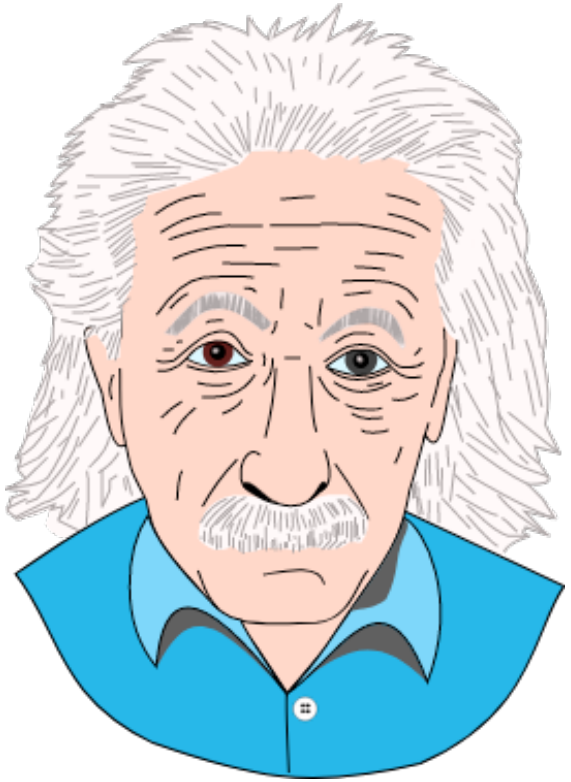


Movement of entangled spins behaves like emergent electromagnetism!

Teachers' Conference: What's in a crystal? – A quantum universe

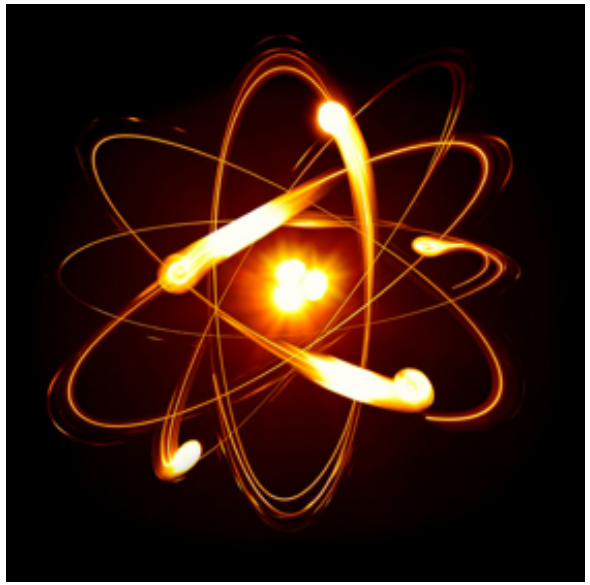
Coordinators: Jennifer Cano and Qimiao Si

Carl Sagan is famous for saying that there are more stars in our Universe than there are grains of sand covering the world's beaches. What Sagan didn't say is that a single grain of sand has more electrons than stars in the Universe. What do these many electrons do in a crystal? They form a quantum universe.



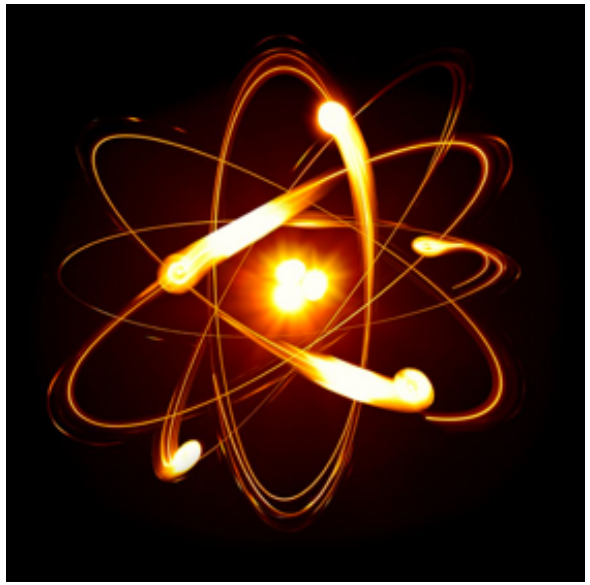
Gravity inside a crystal?

How about a black hole?



Electrons

Black holes



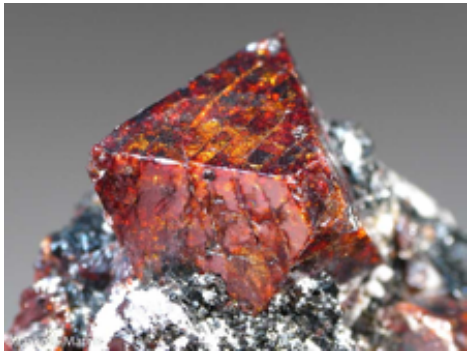
Electrons

.000000000000000000000000000009kg

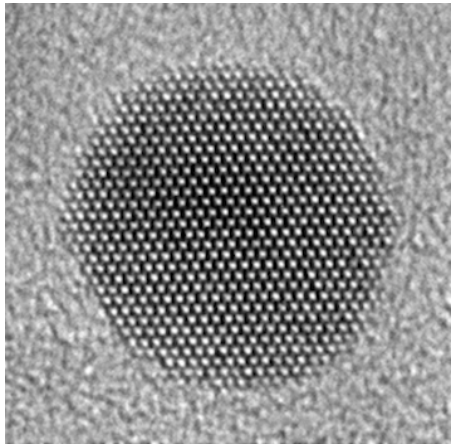
Black holes

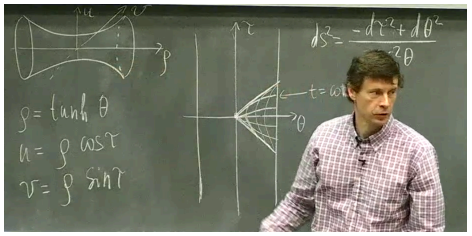
60000000000000000000000000000kg

Emergent Forces



electromagnetism

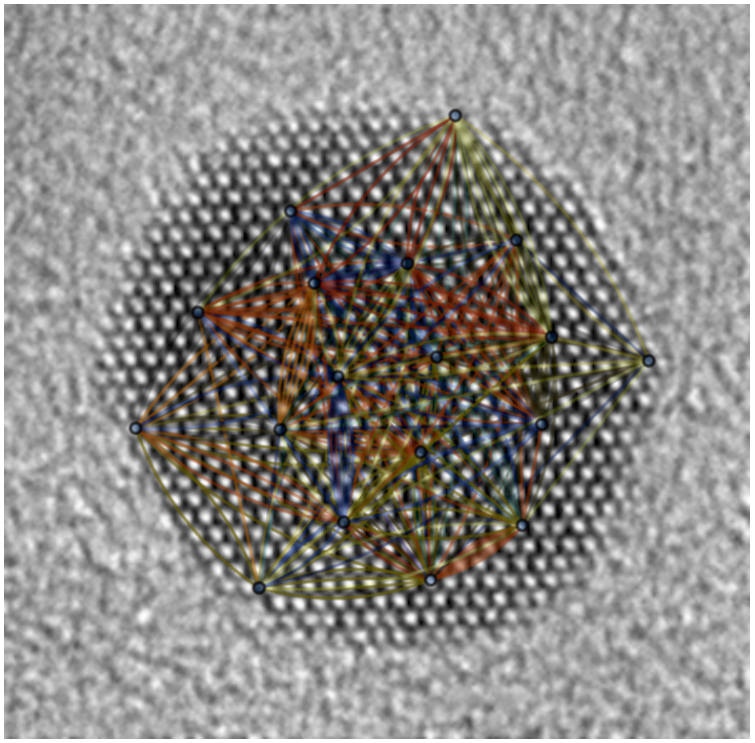




A. Kitaev, 2015

1+1-dimensional gravity in anti-de Sitter space

Sachdev-Ye Kitaev Model



NEWS AND VIEWS | 30 November 2022

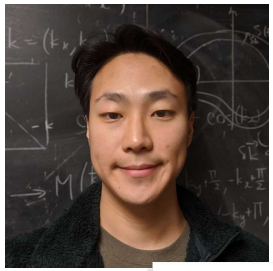
A holographic wormhole traversed in a quantum computer

A system of nine quantum bits has been used to simulate a state known as a holographic wormhole, a concept that features in attempts to reconcile quantum mechanics with the general theory of relativity.

Adam R. Brown ✉ & Leonard Susskind

n.b. this is a bit farfetched.

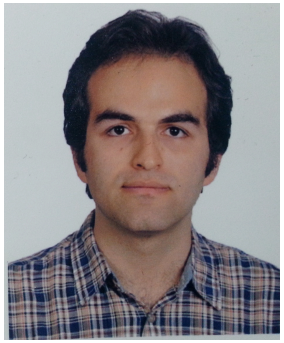
Many thanks

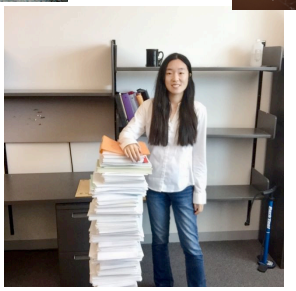
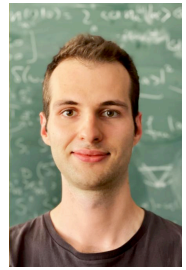








The end

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