

Quantum Mechanics

(what it is, what it's good for, why it's weird)

Claude Bernard
Washington University

TWA
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- Nose to nose with quantum weirdness.

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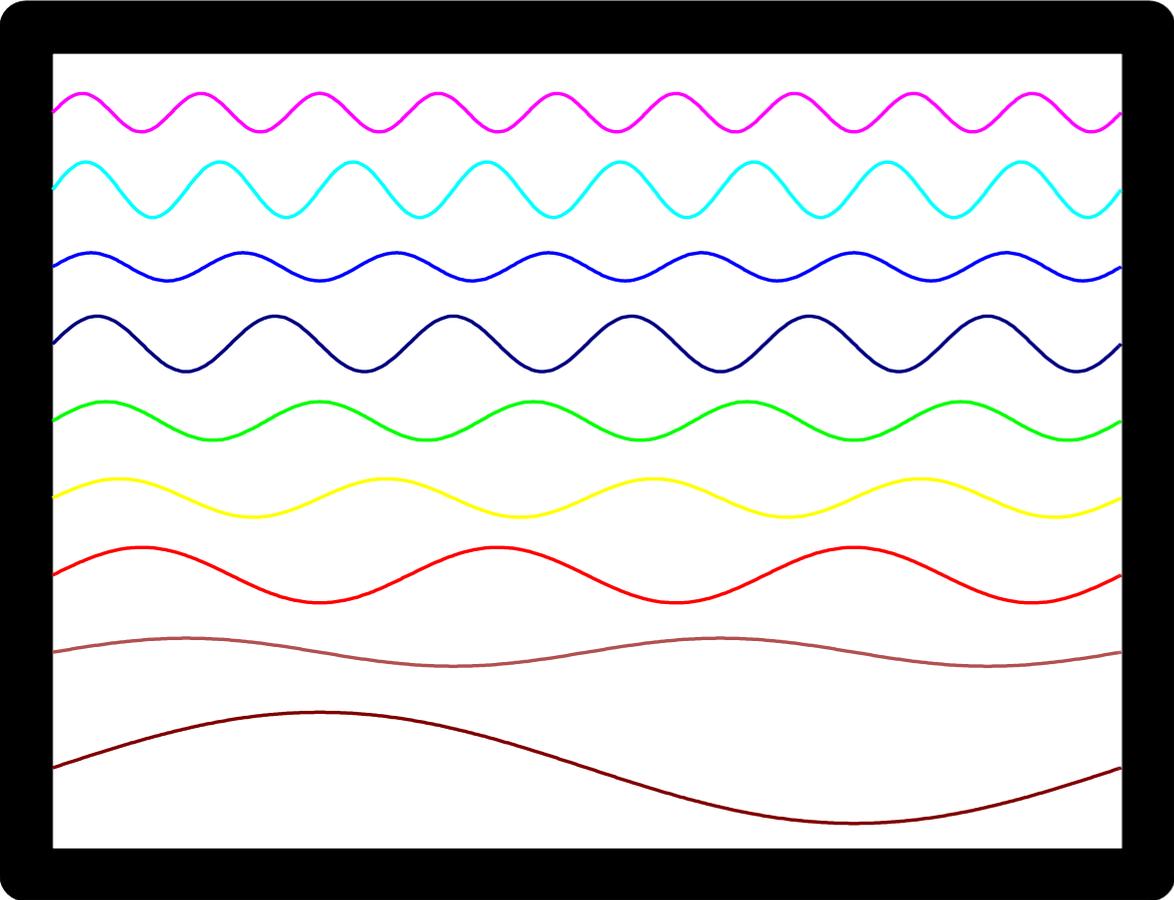


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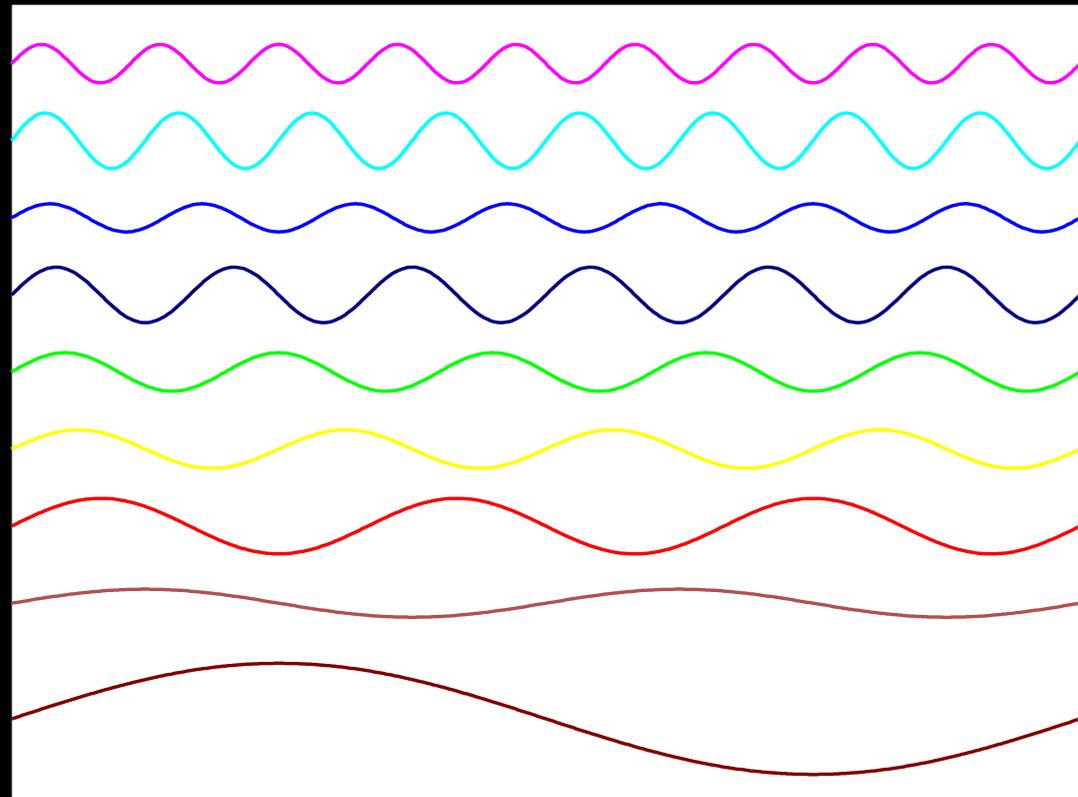
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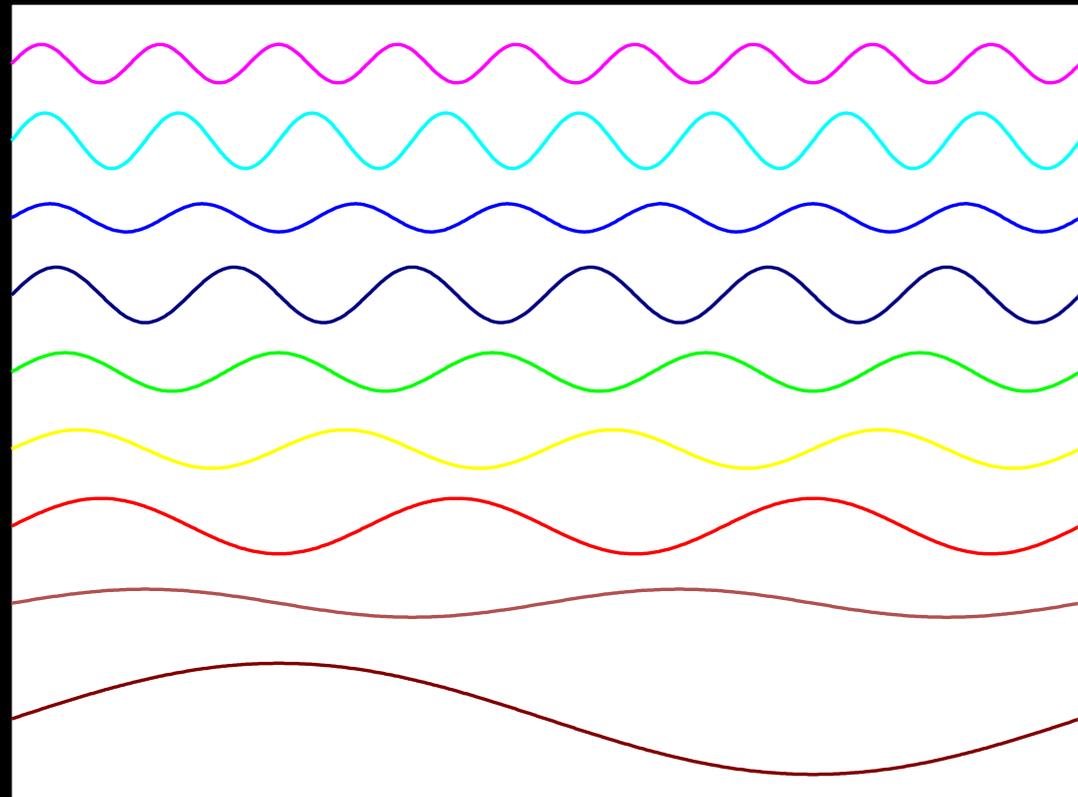
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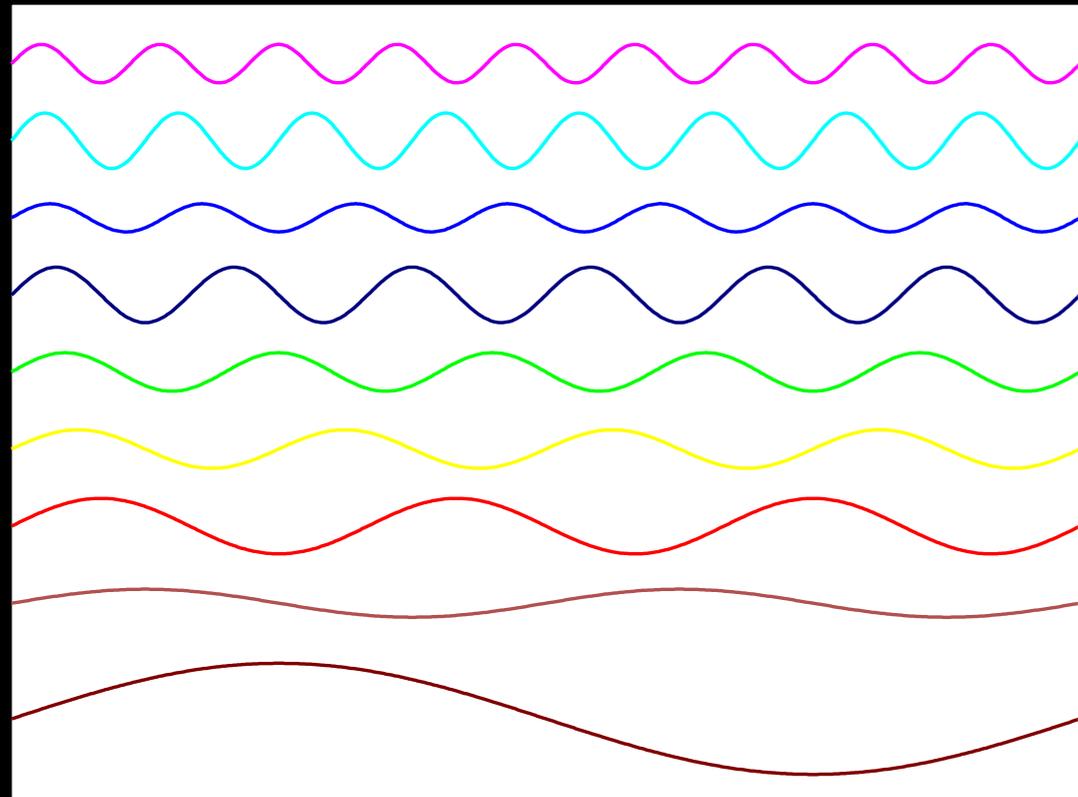
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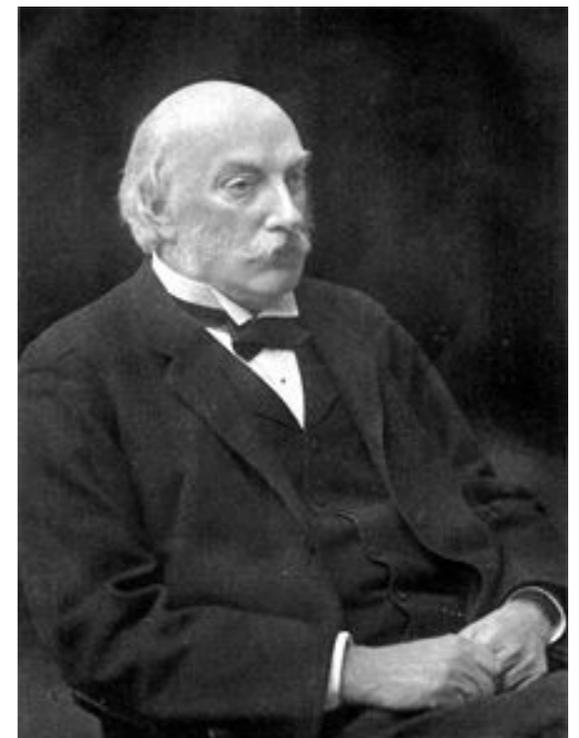
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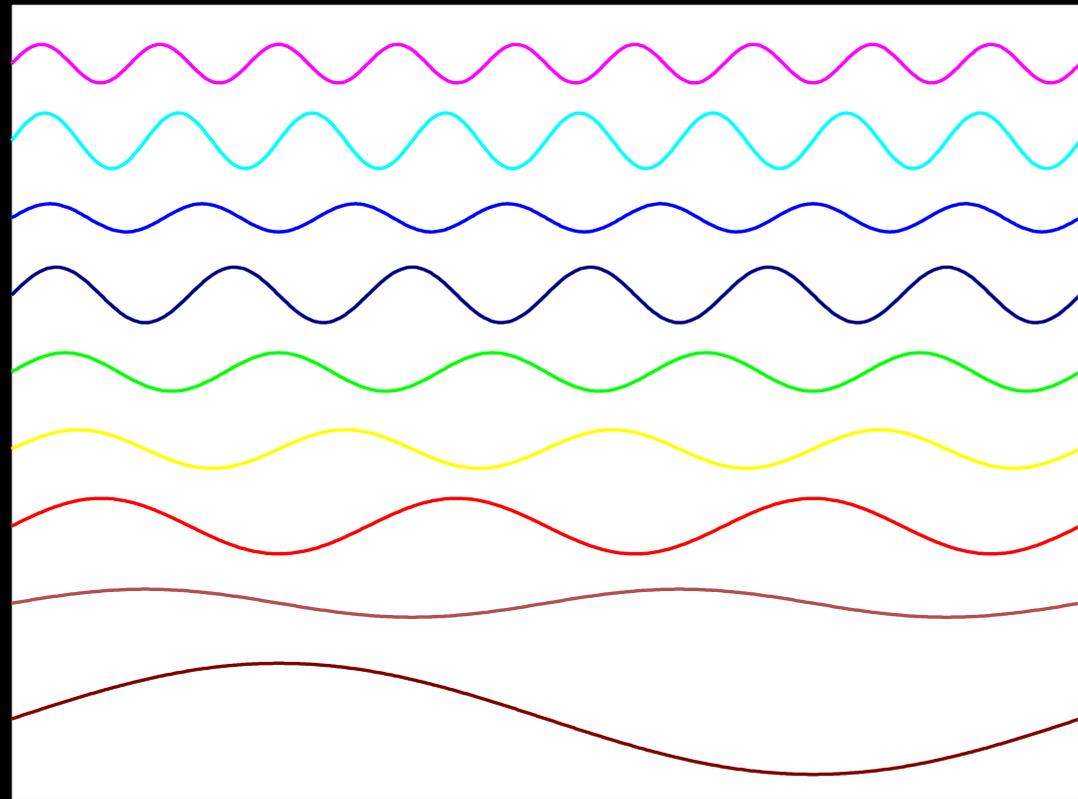
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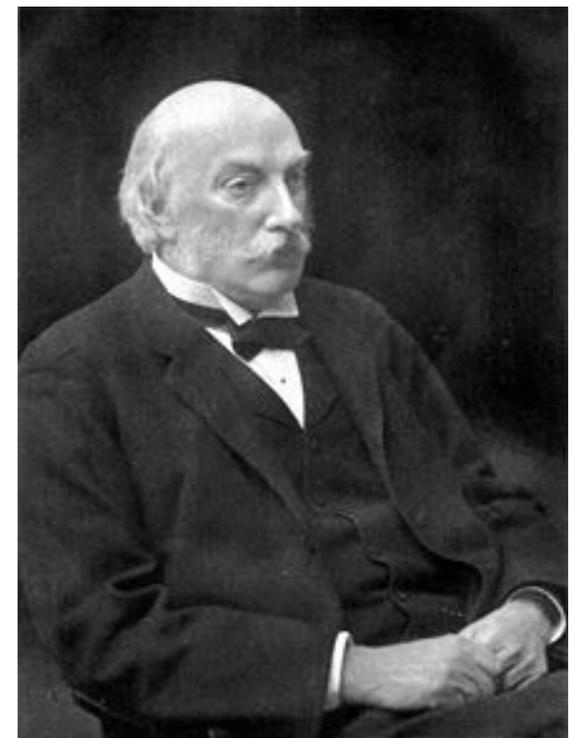
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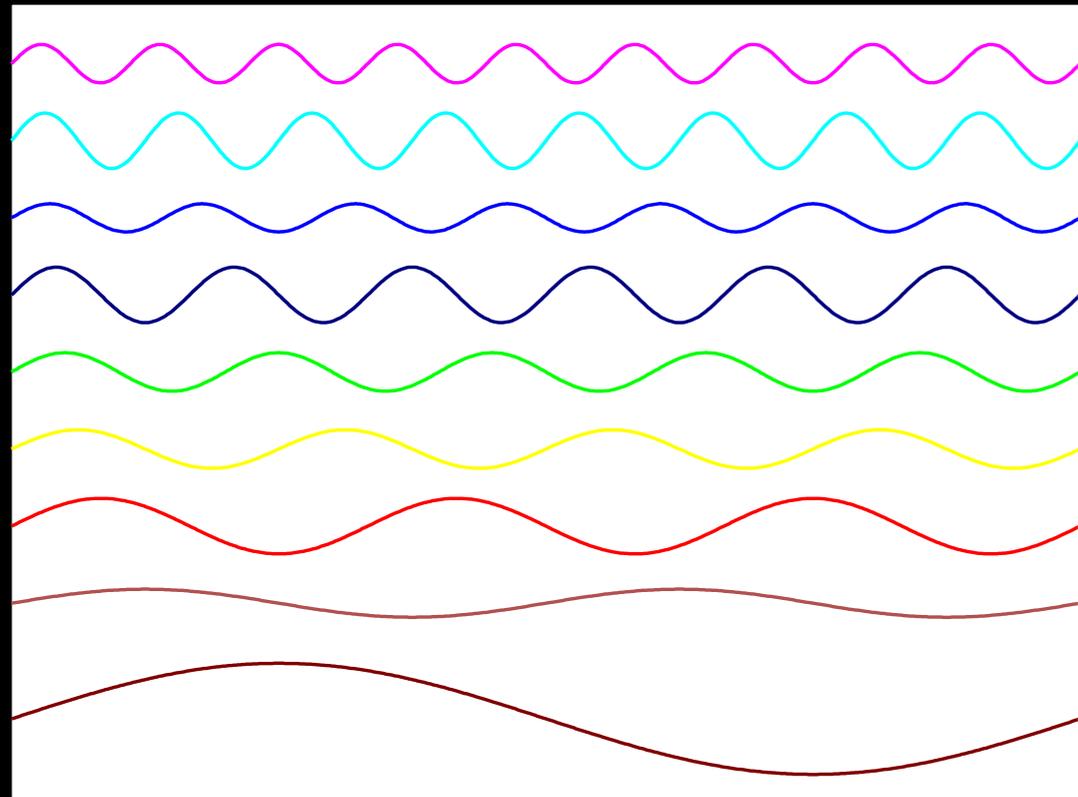
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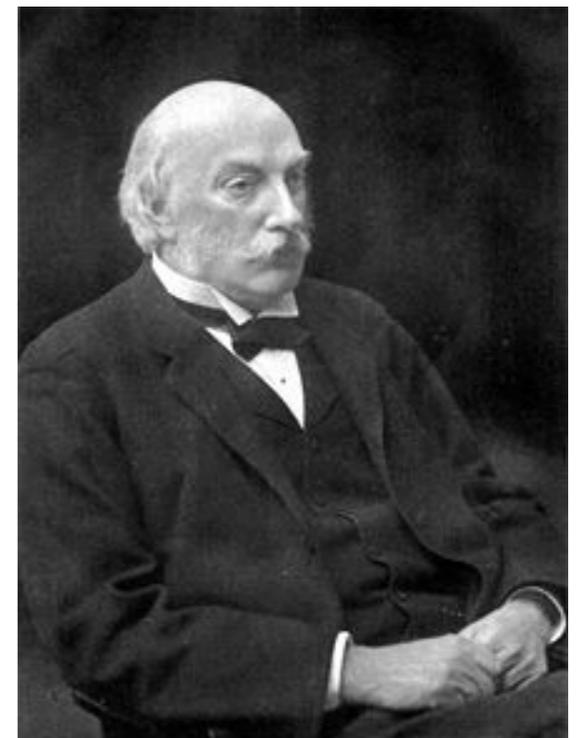
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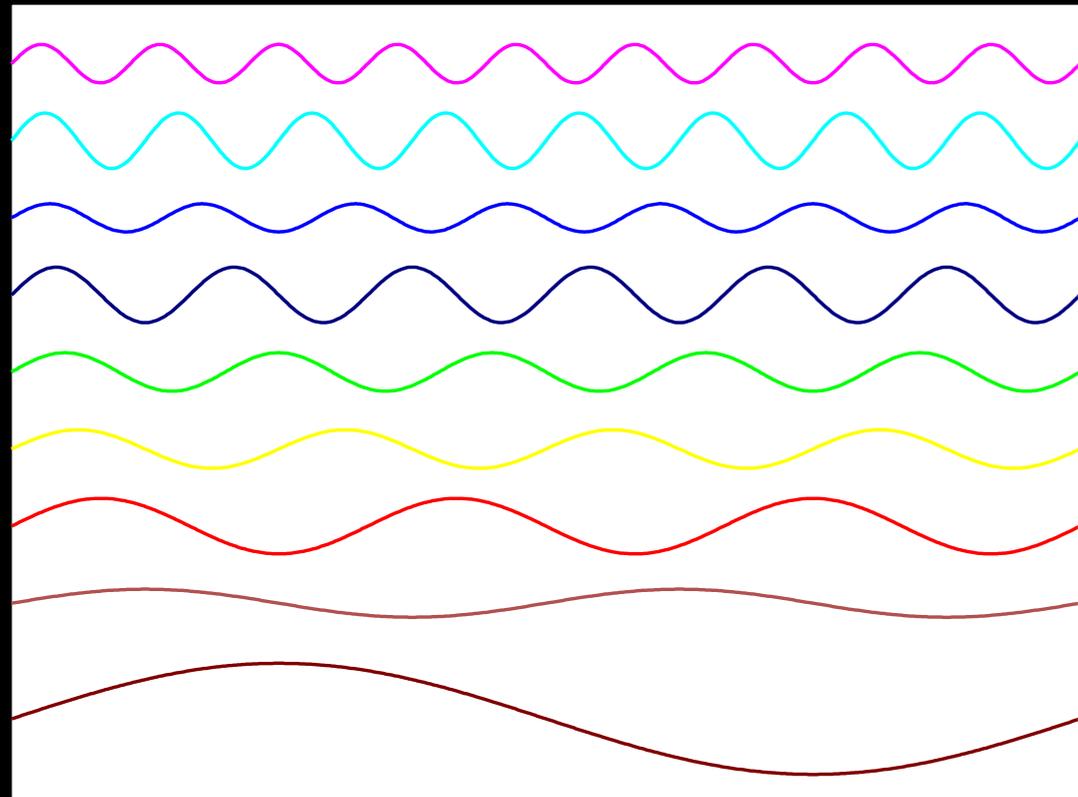
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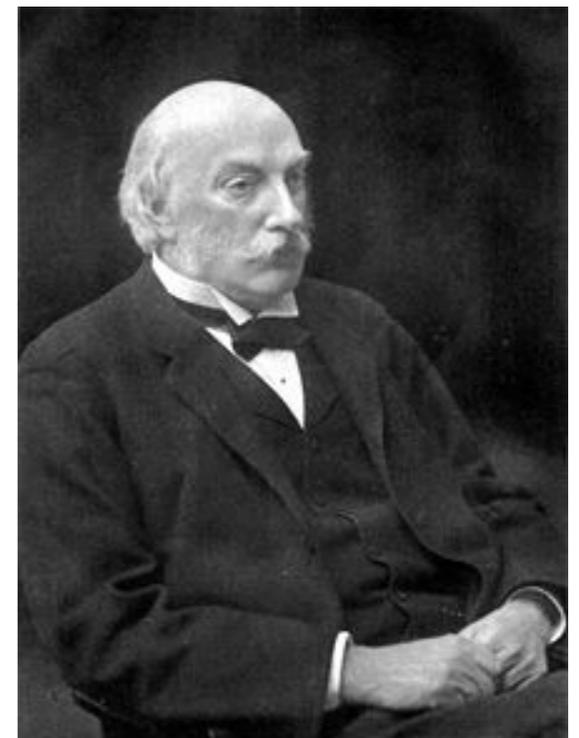
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 - (Not literally a catastrophe — boxes don’t really have infinite energy — but catastrophe of understanding.)



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 - Note: combination $\frac{h}{2\pi}$ appears a lot in QM, physicists give it special symbol: \hbar (pronounced “h-bar”).



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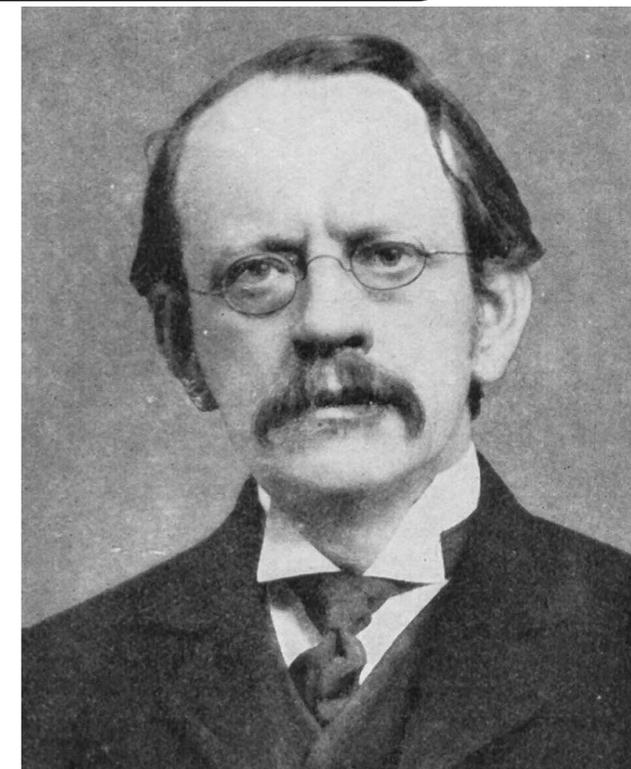


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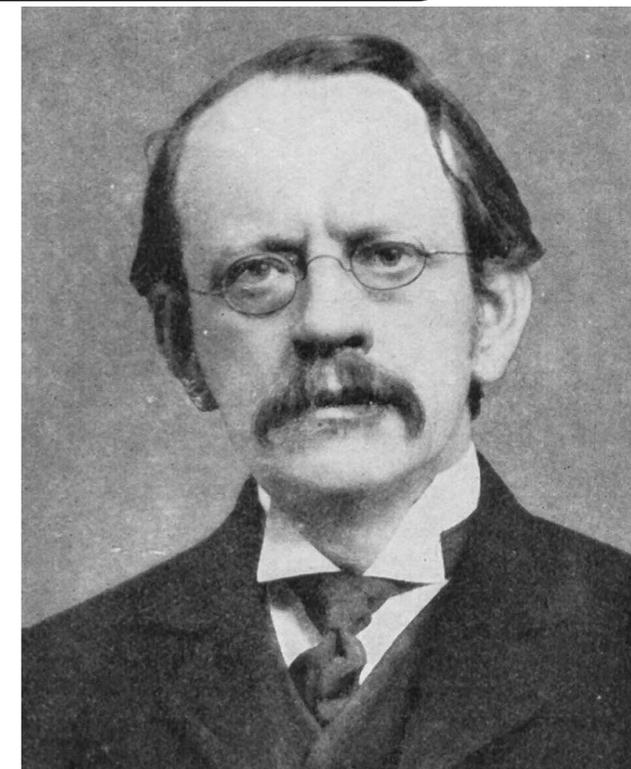


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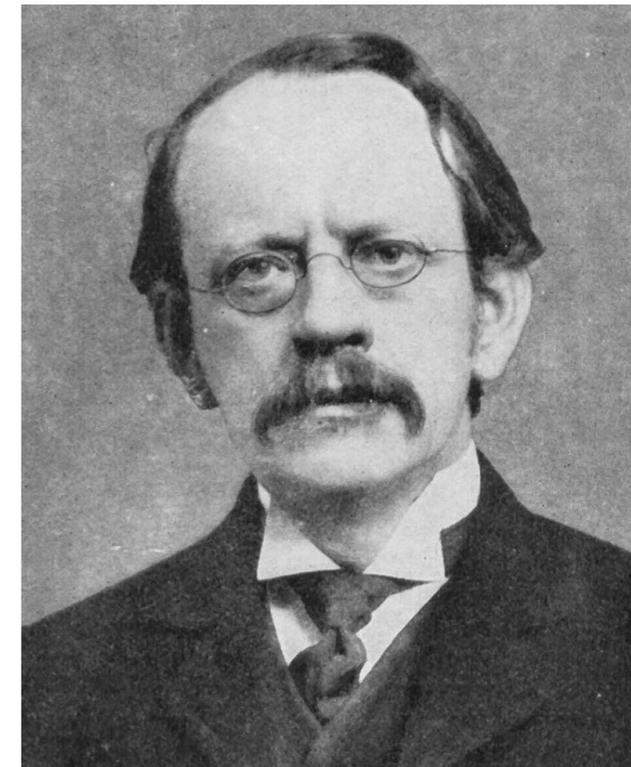


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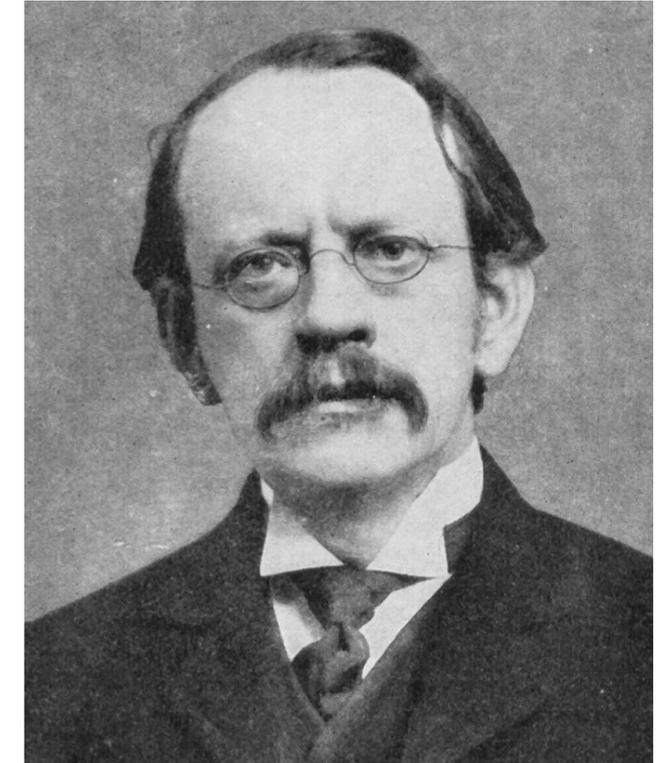


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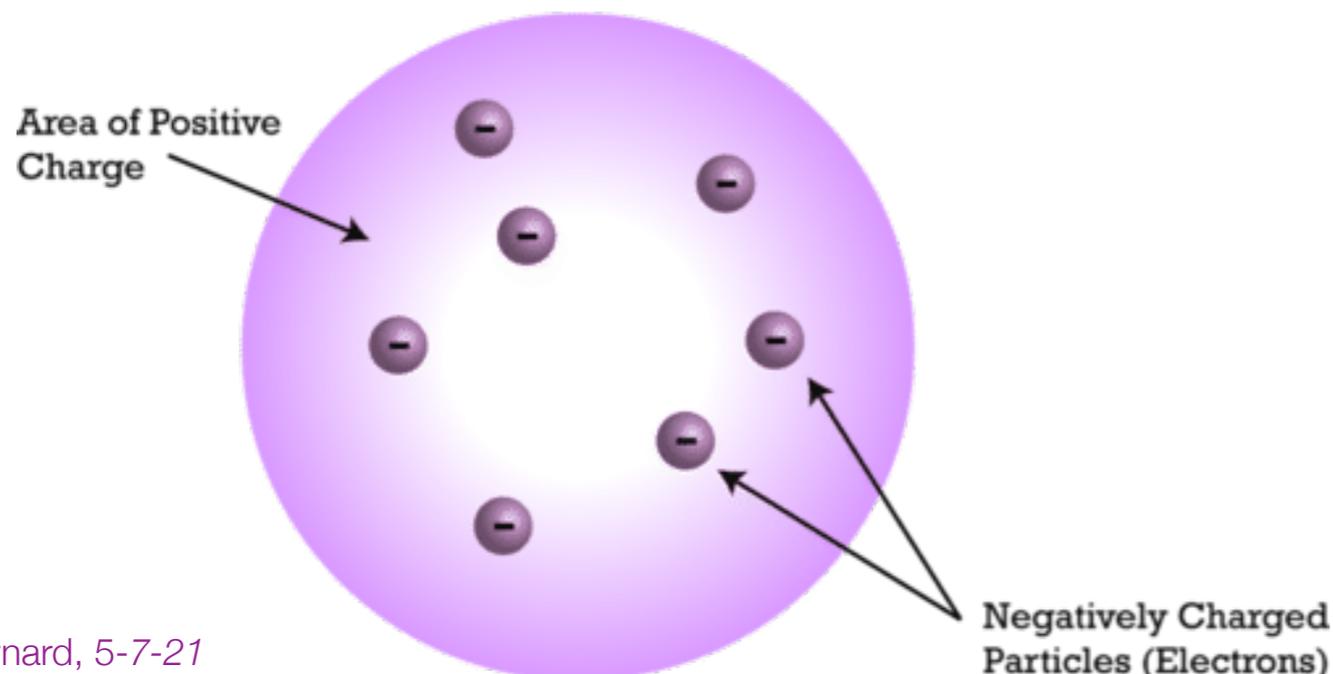
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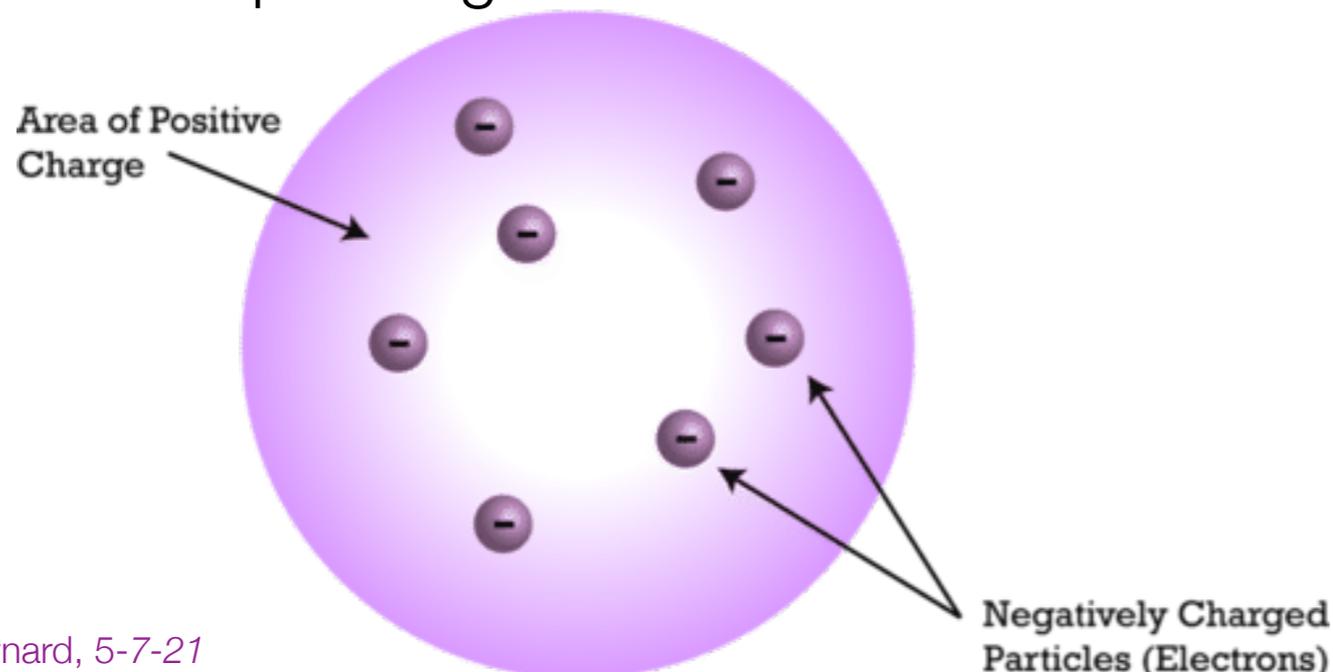
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- ▶ “Plum pudding” model of the atom.

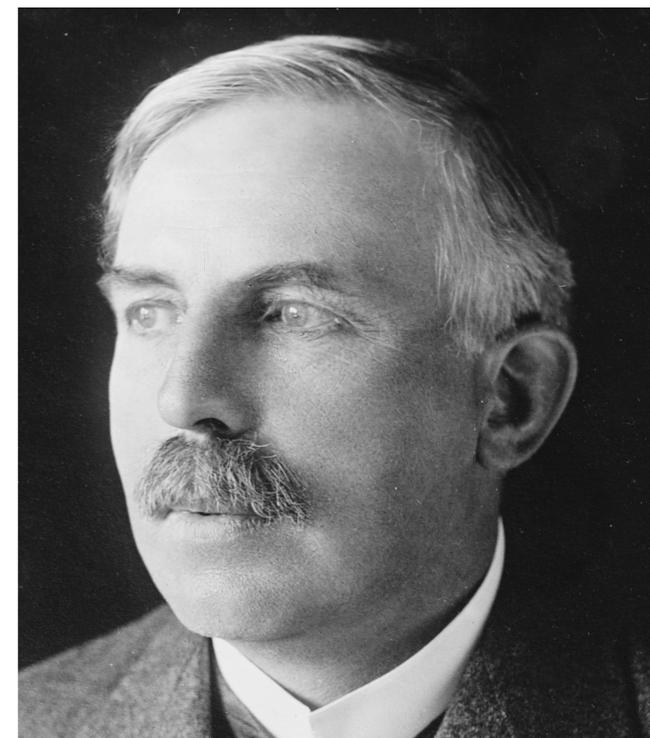


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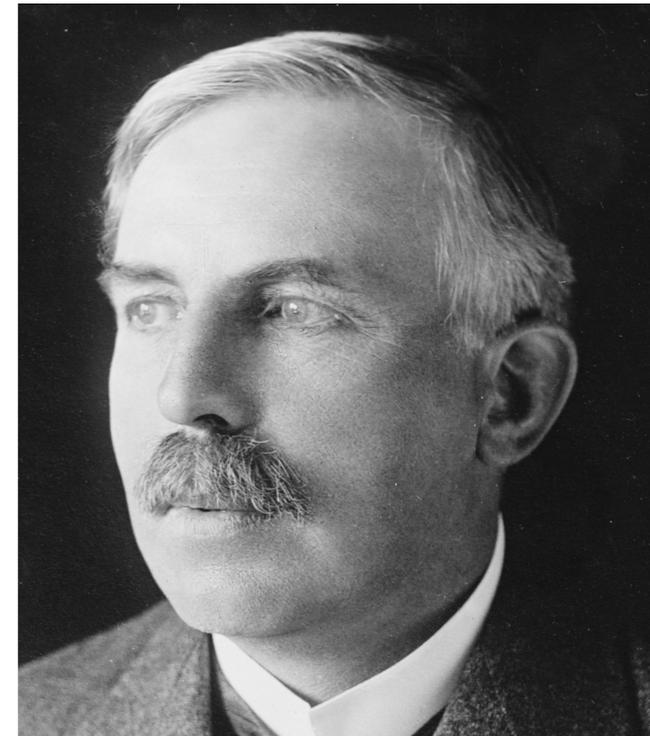
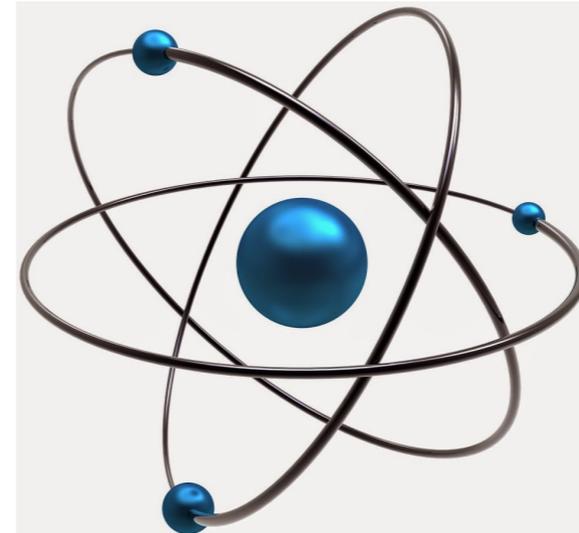
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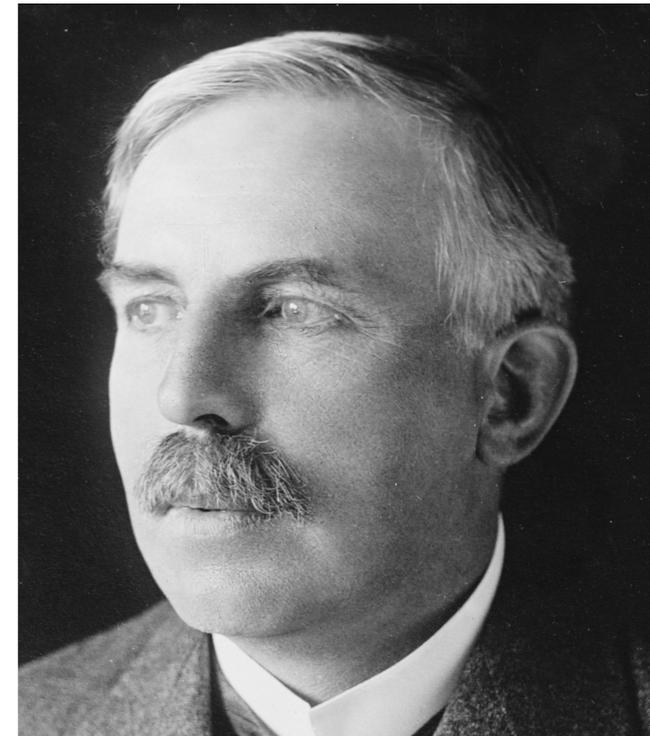
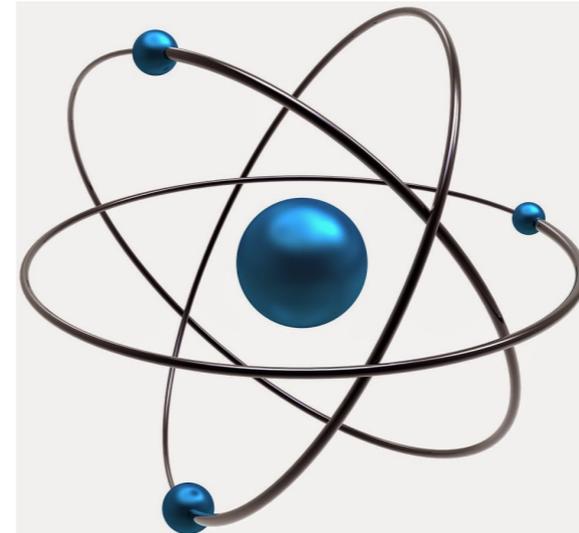
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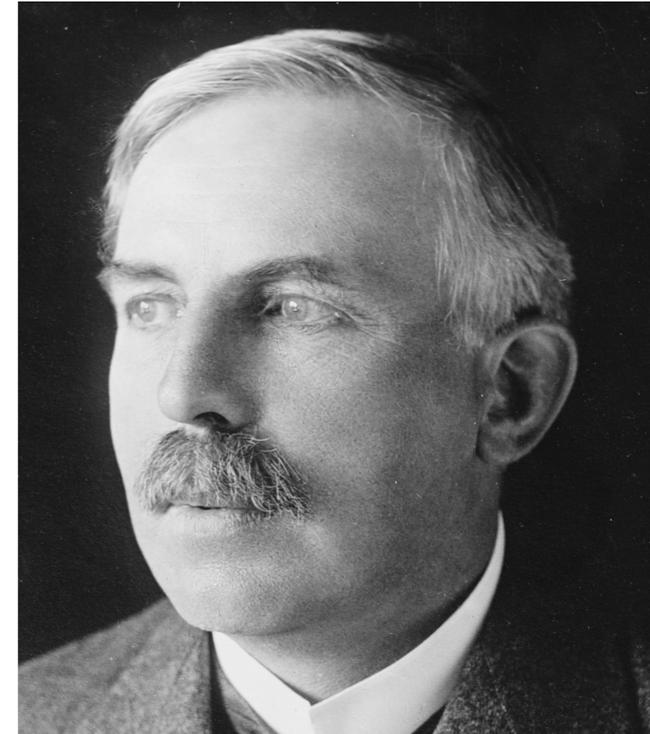
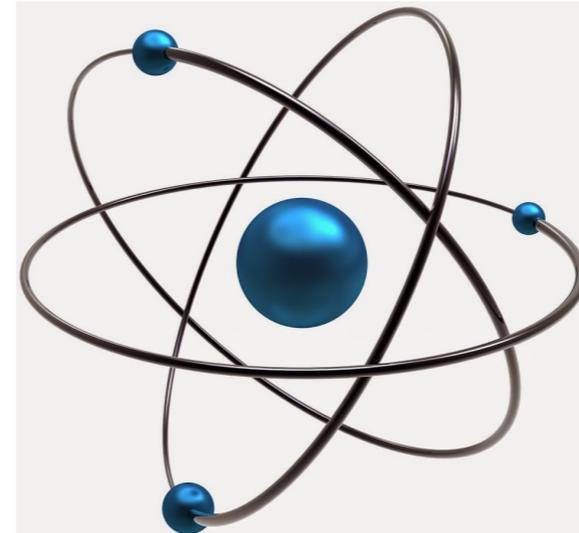
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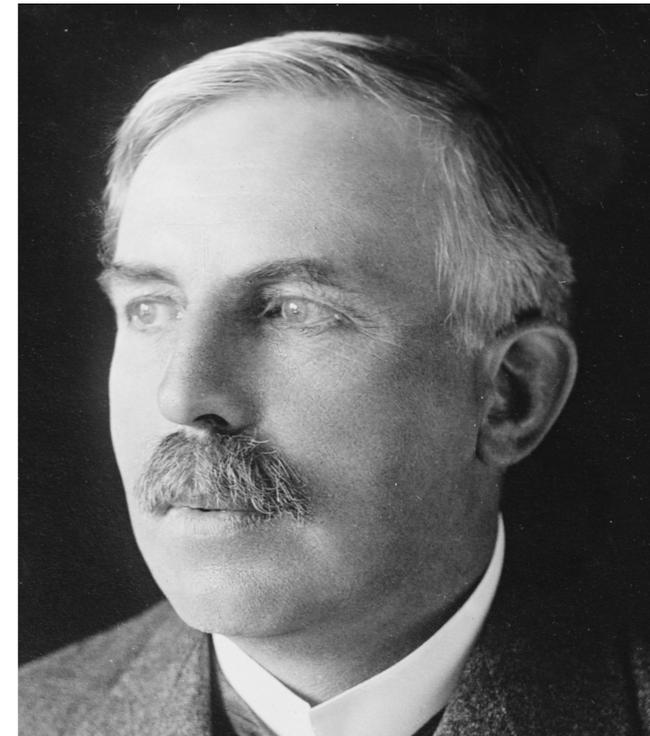
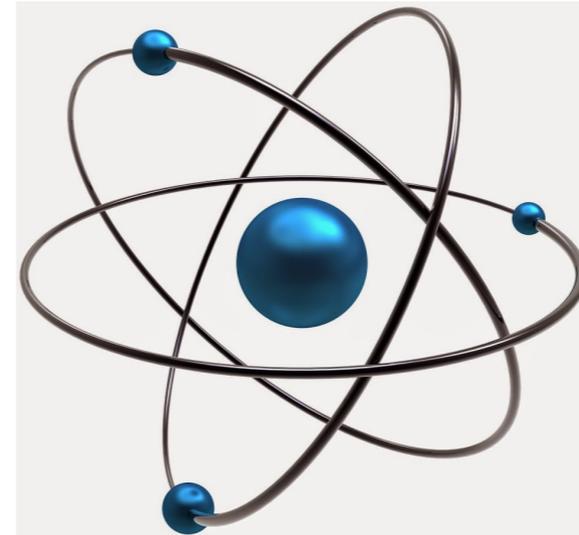
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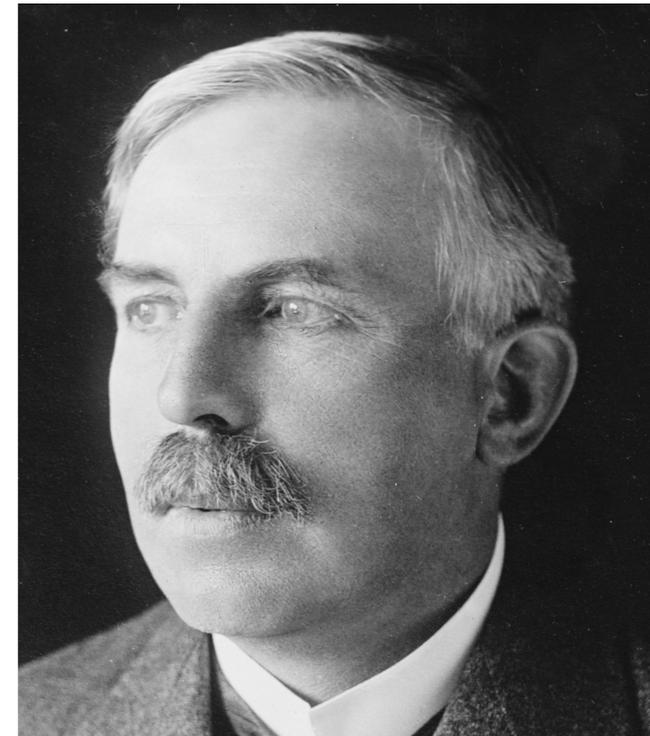
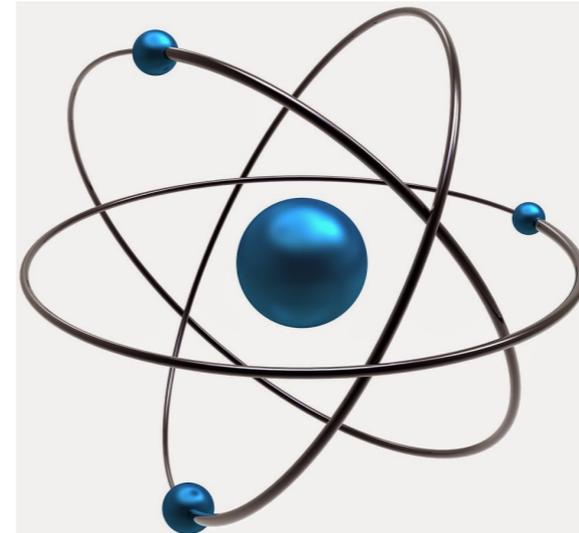
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Old Quantum Theory: Structure of the Atom



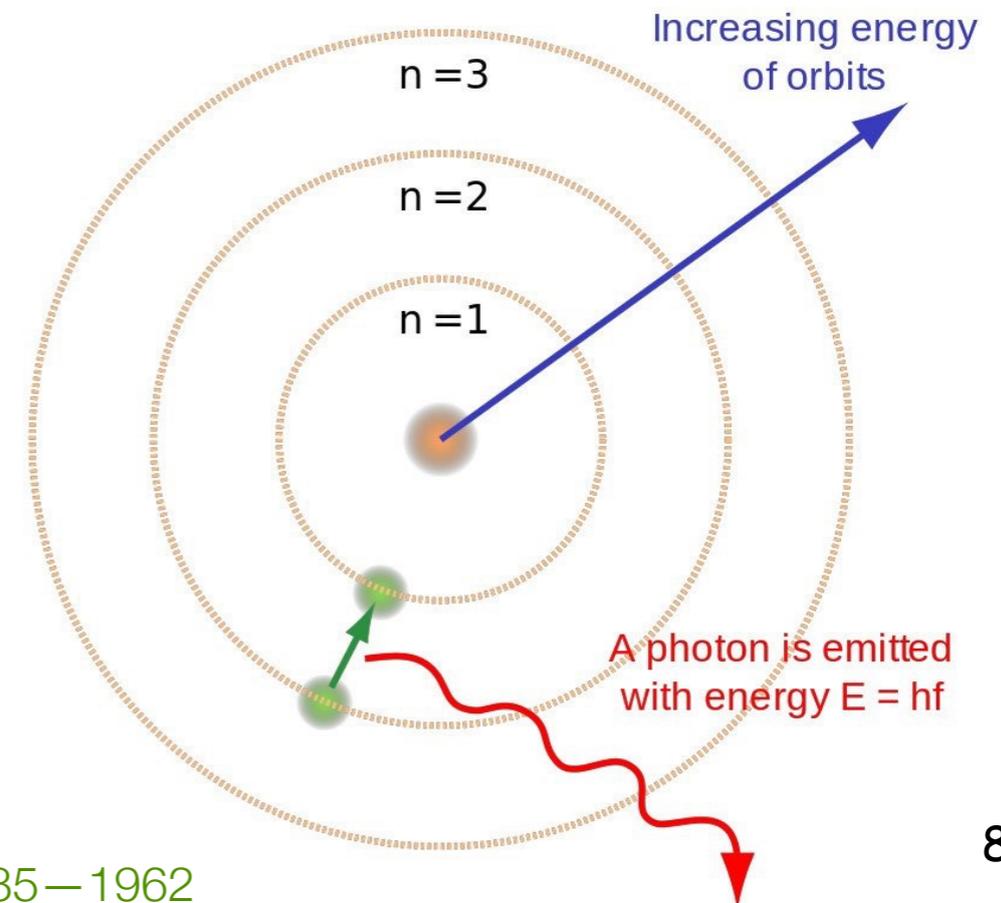
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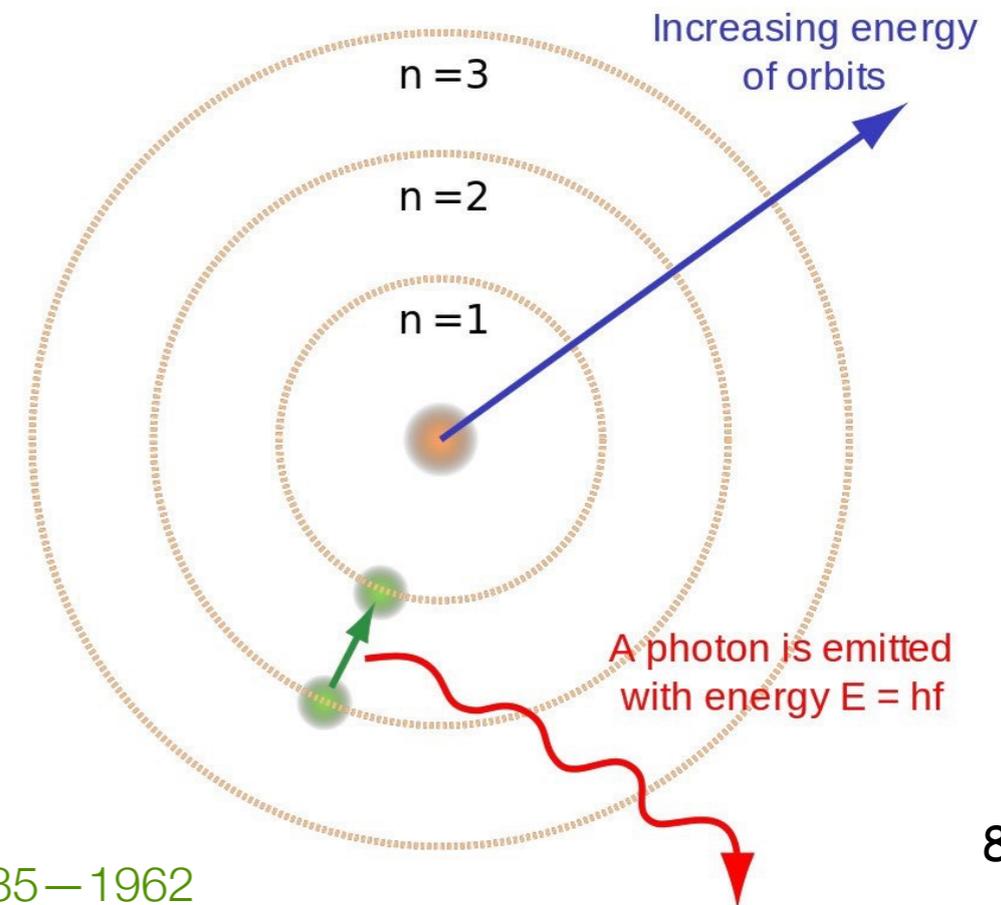
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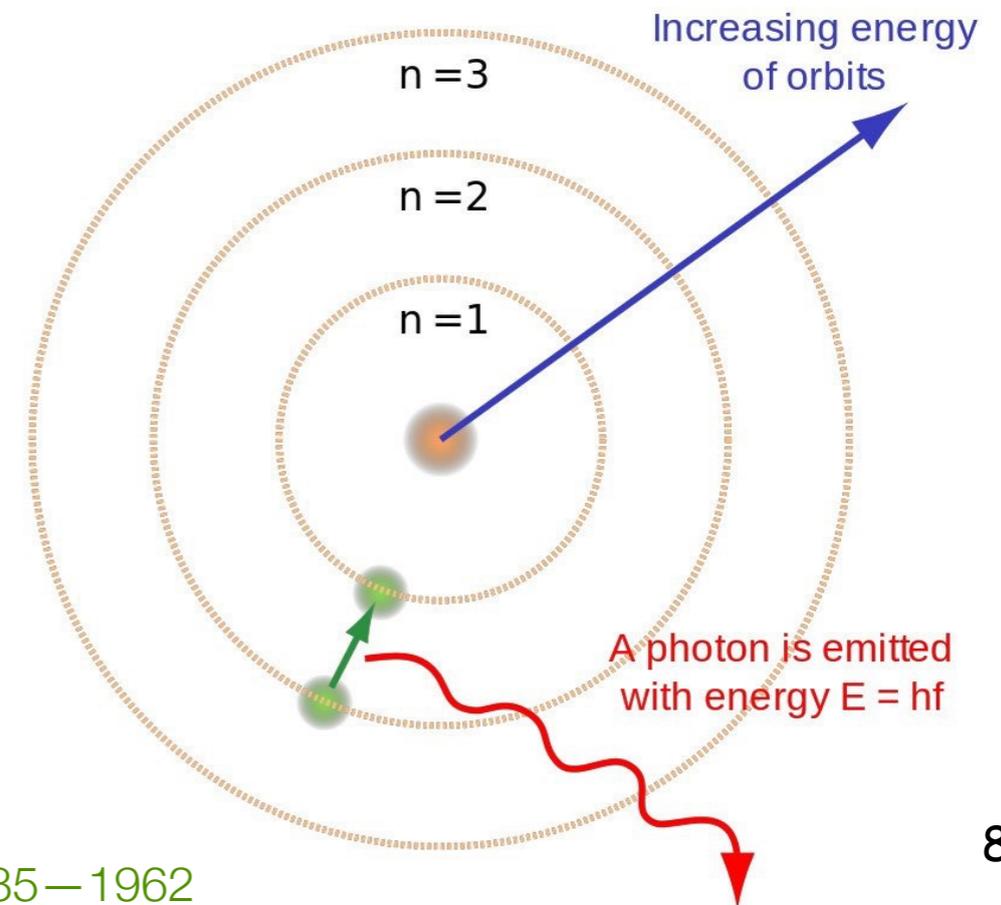
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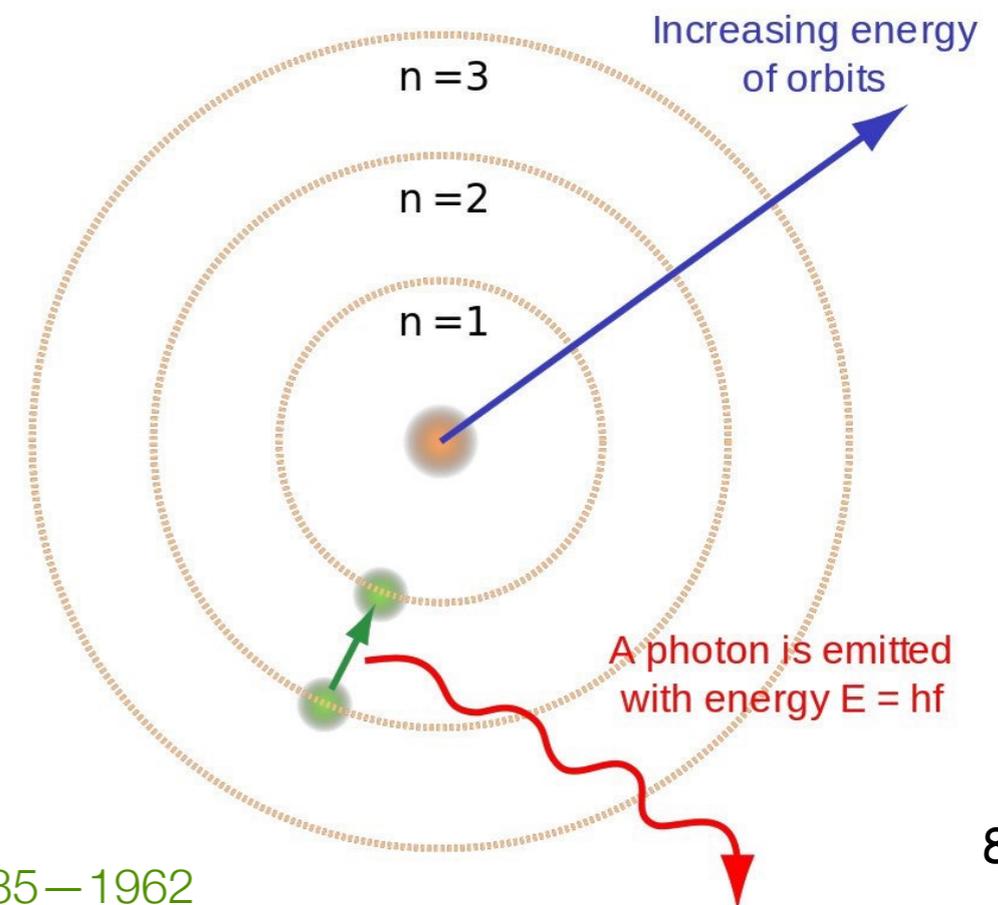
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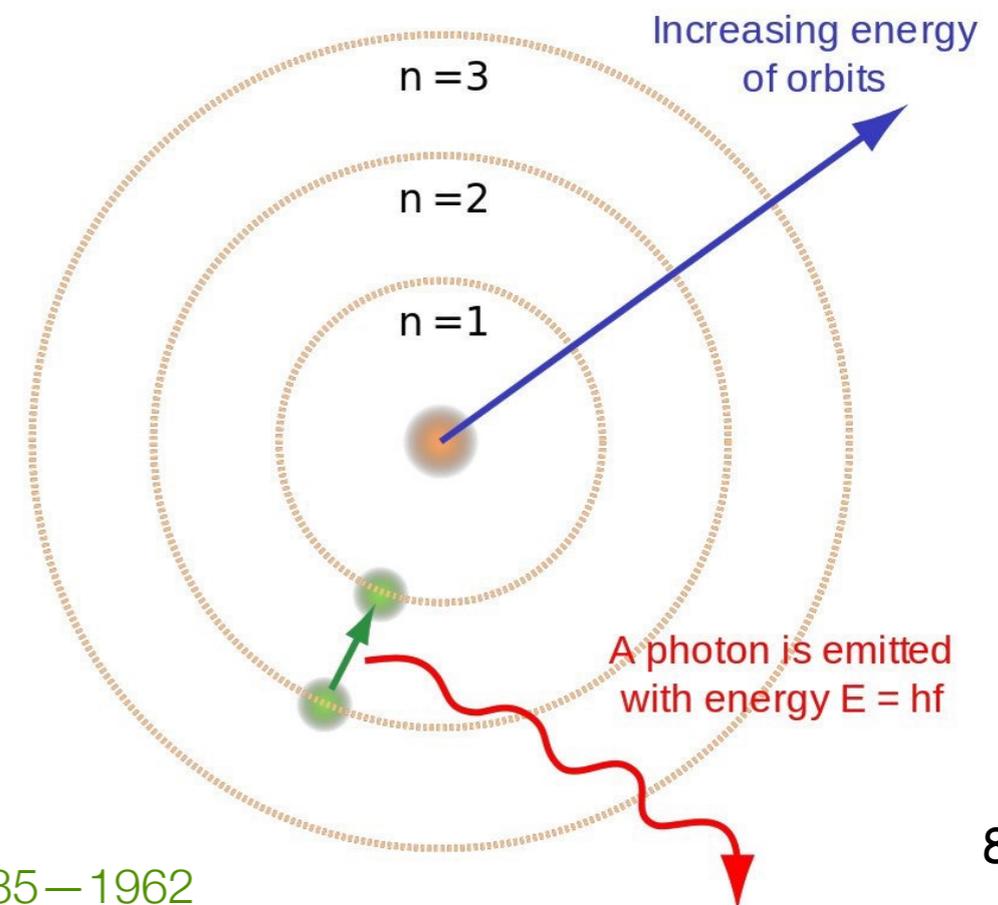
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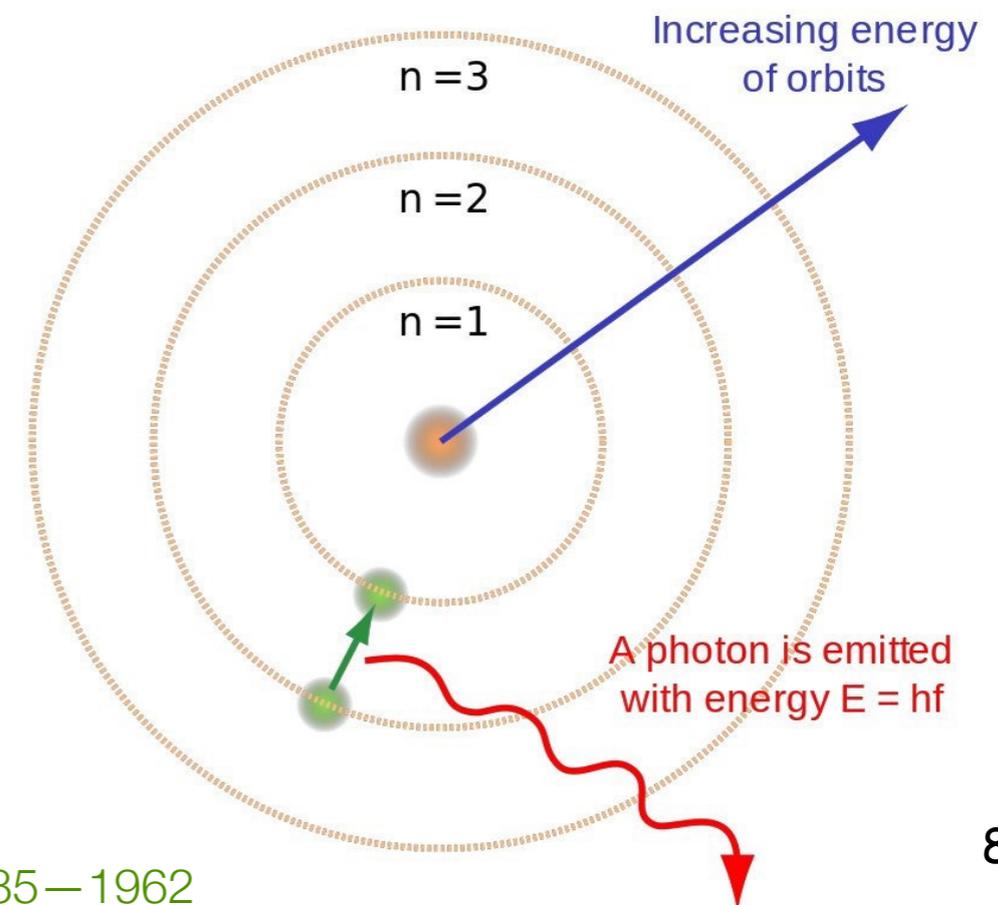
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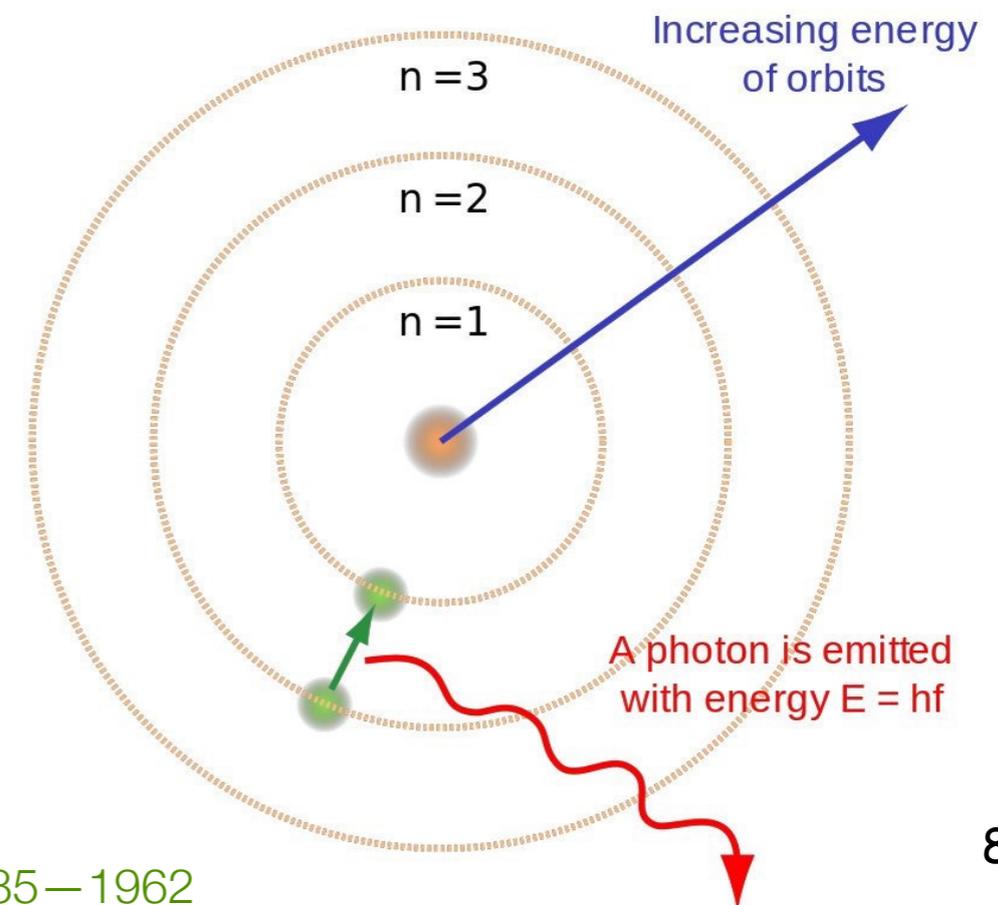
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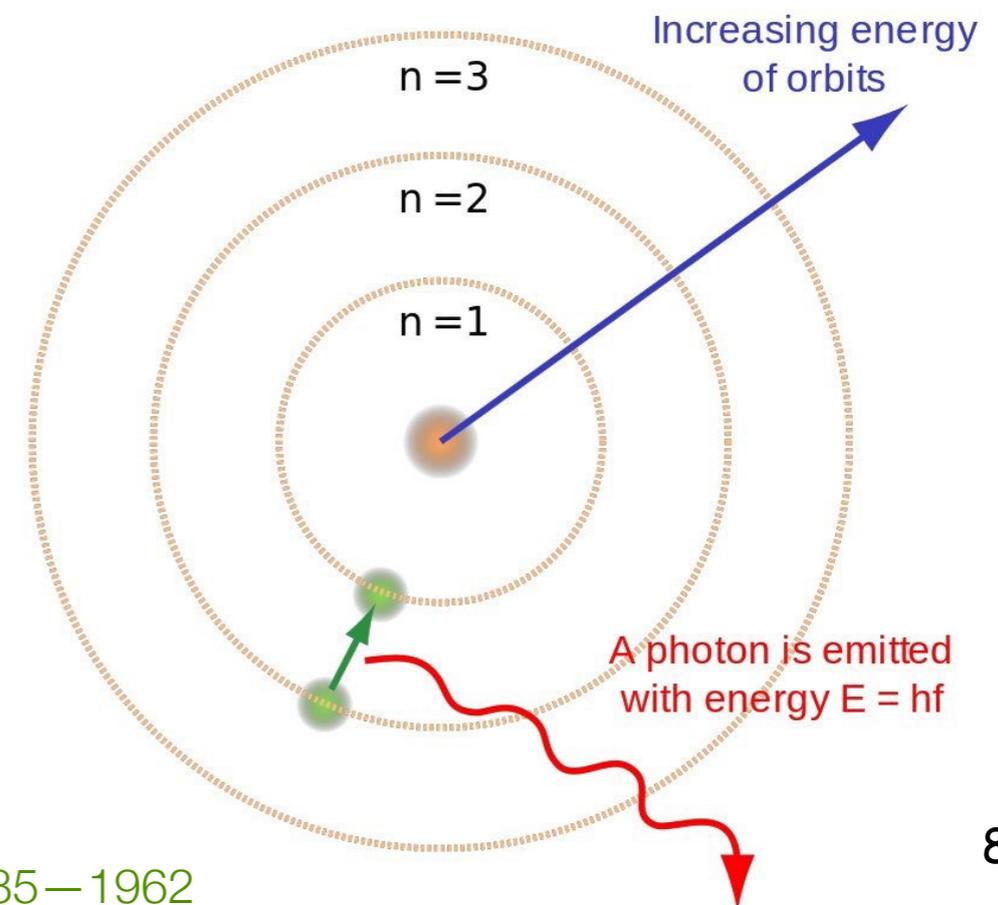
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 - No way to justify or improve it.



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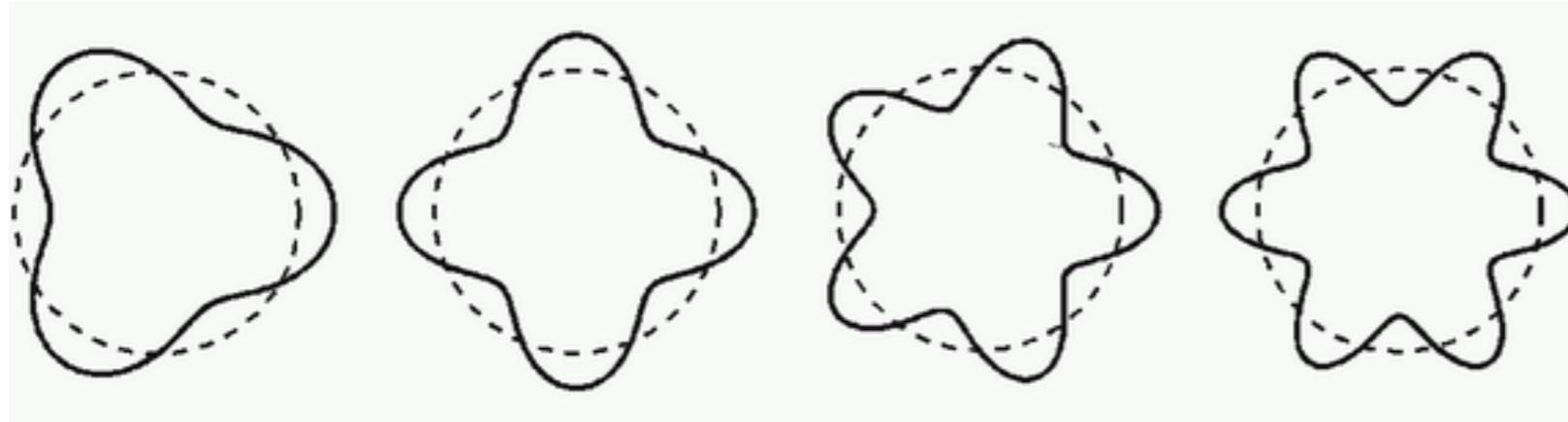
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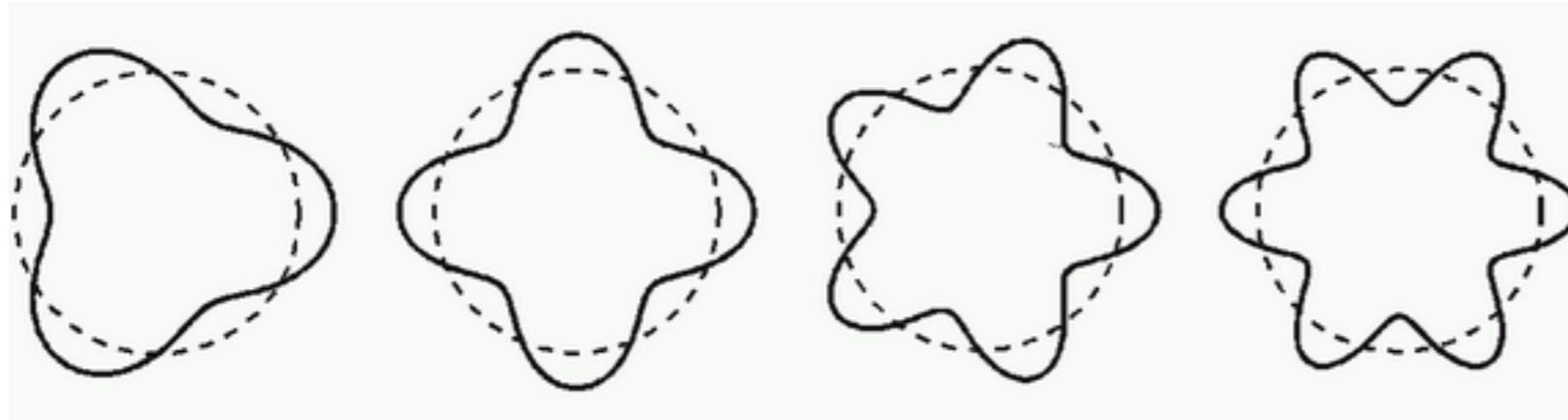
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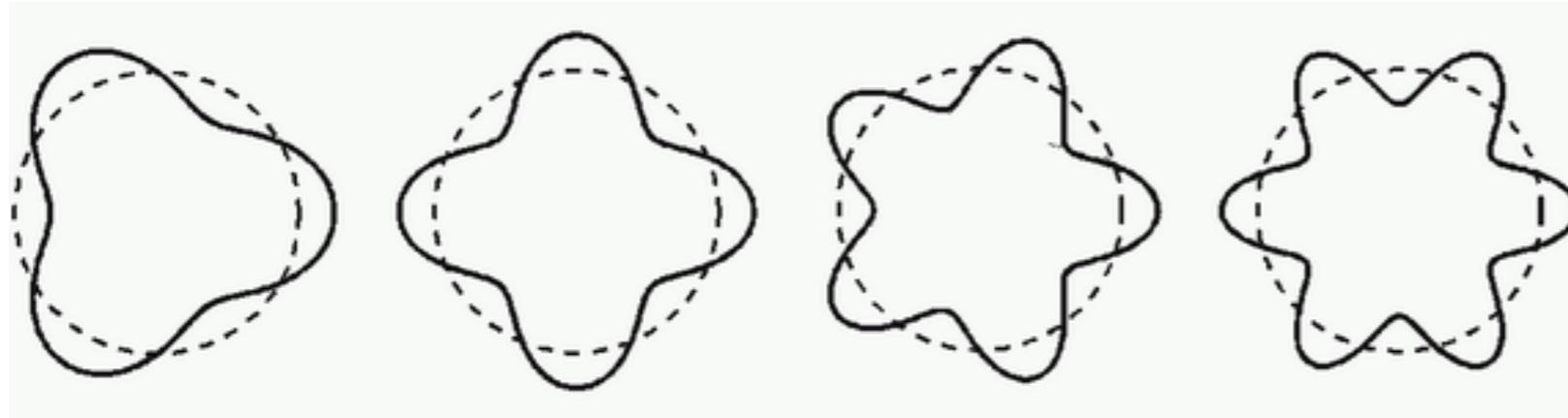
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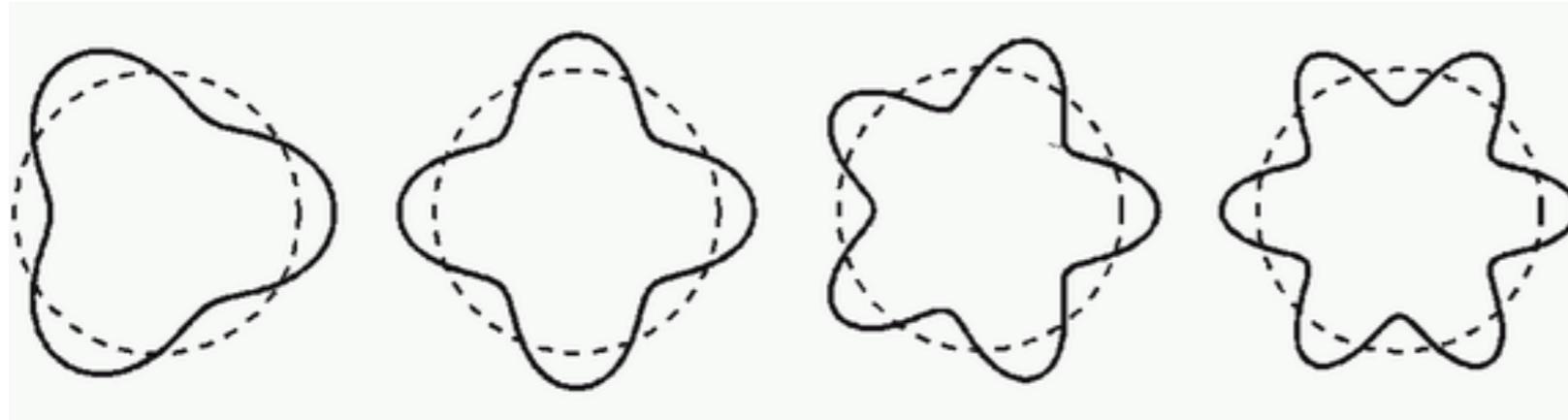
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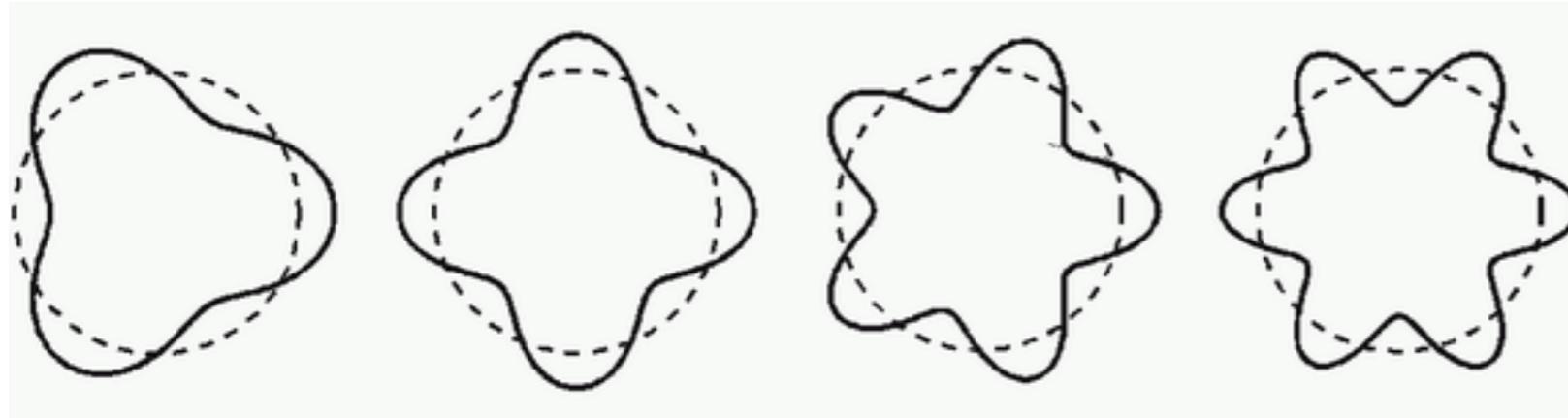
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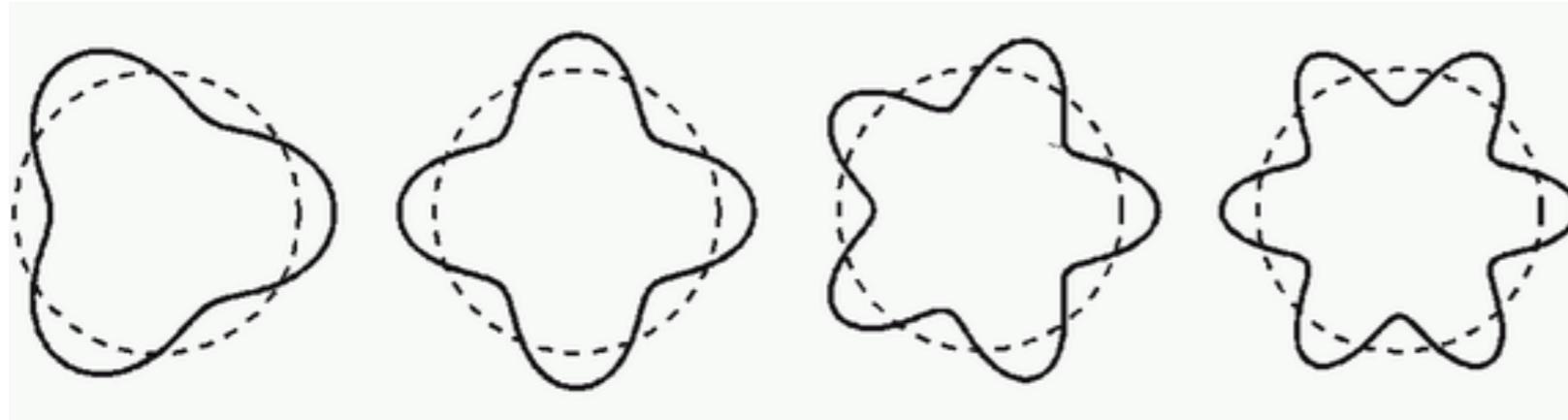
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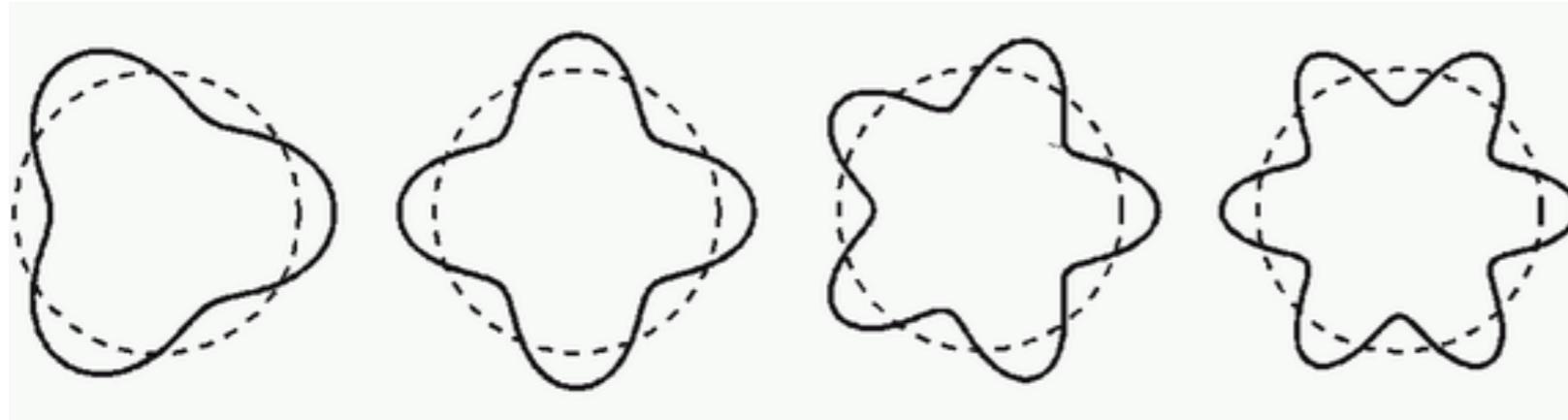
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Schrödinger's grave, with his equation



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 - Forget about what *we* can *measure*: precise values of position & momentum of electron **do not exist** at same time.



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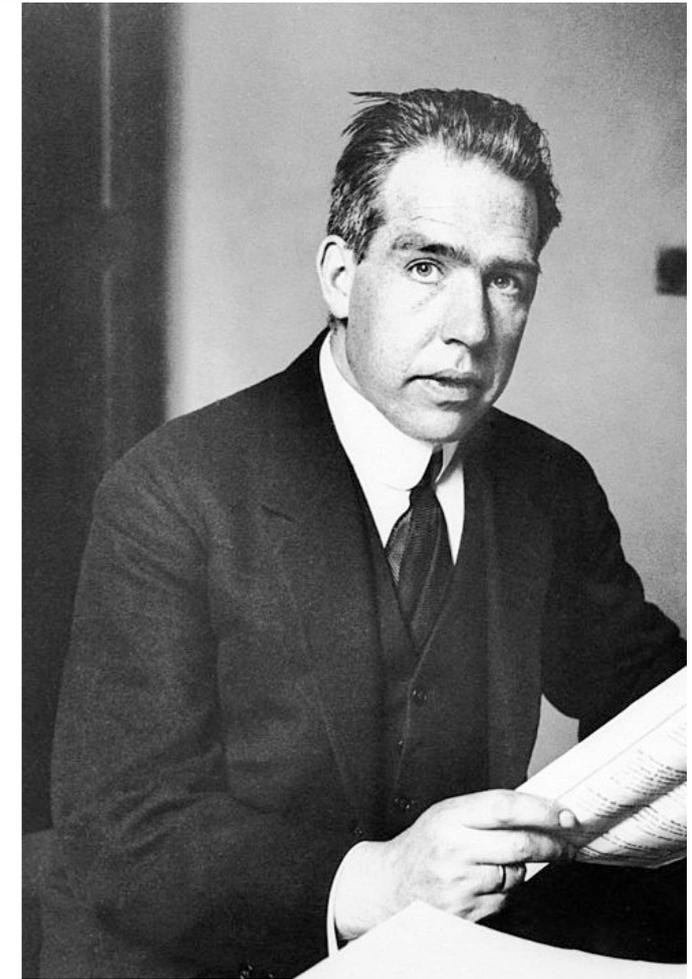
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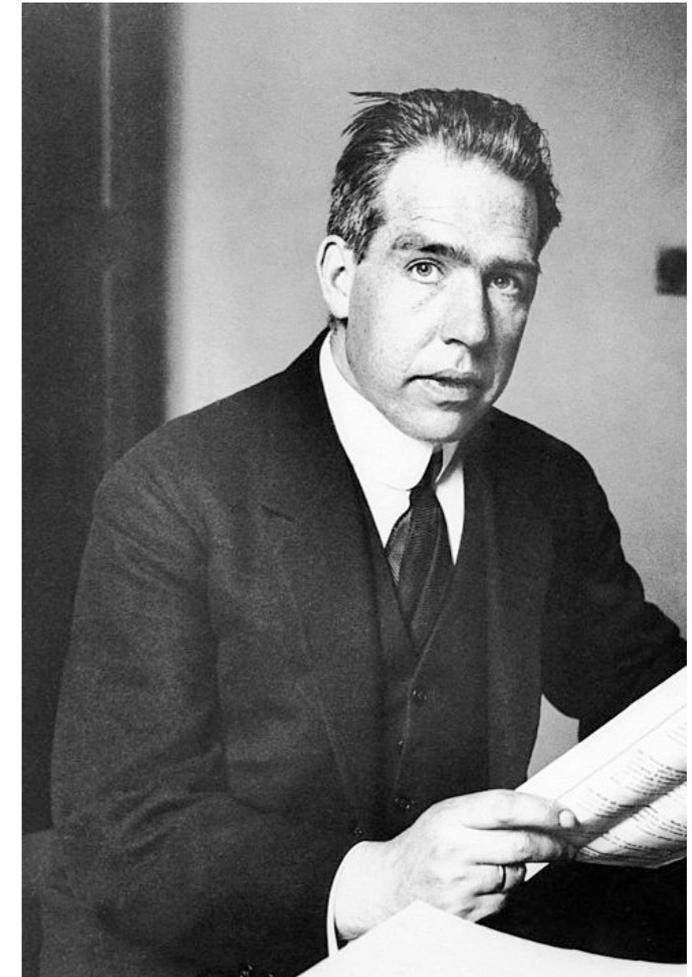
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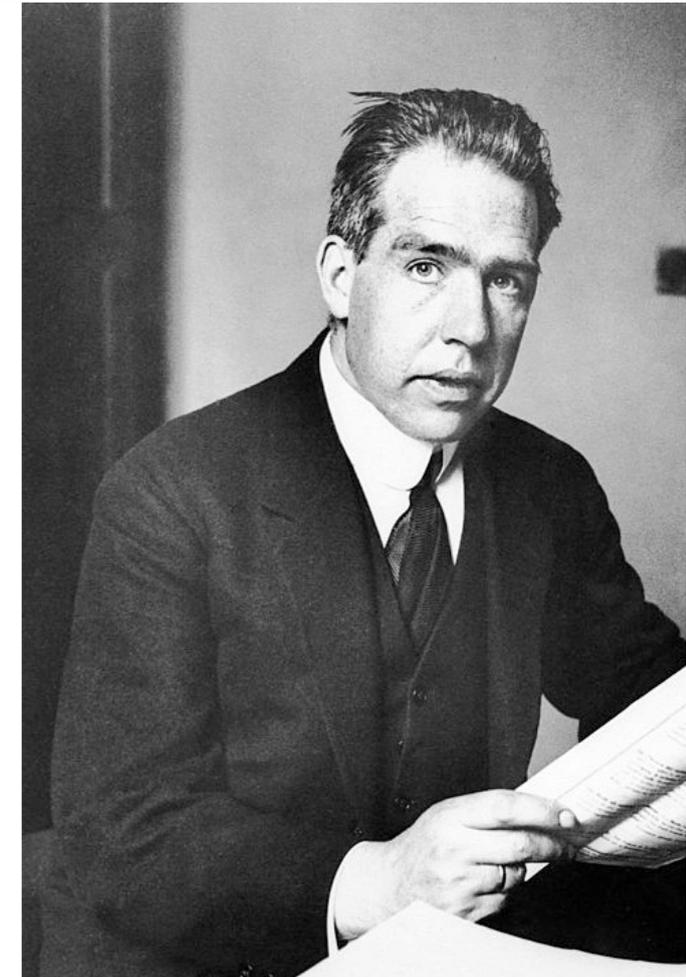
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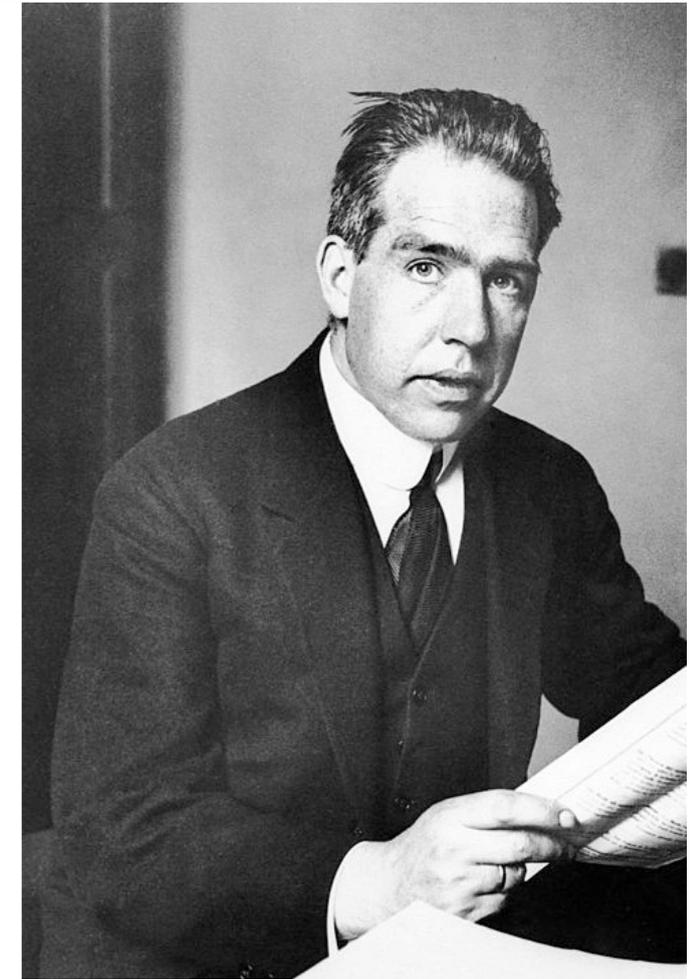
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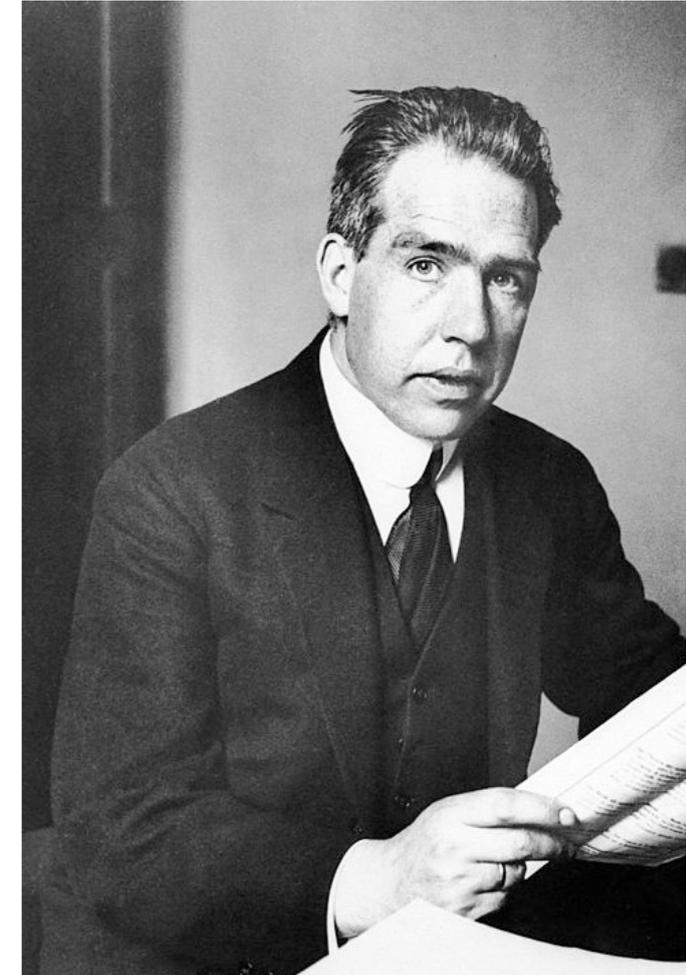
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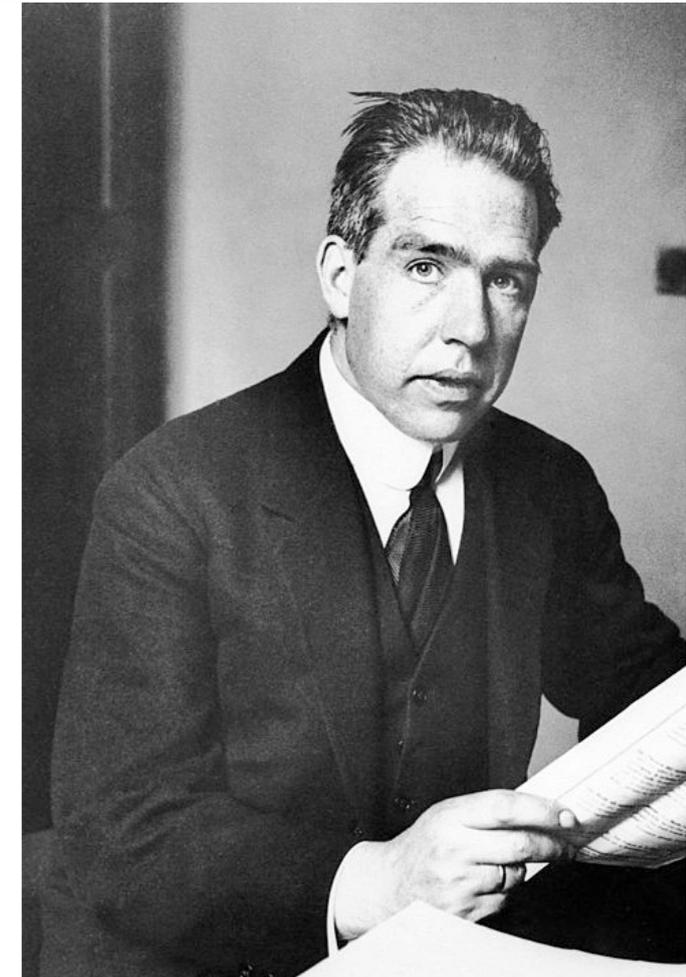
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 - E.g., position and momentum of an electron (or other atomic-scale object).



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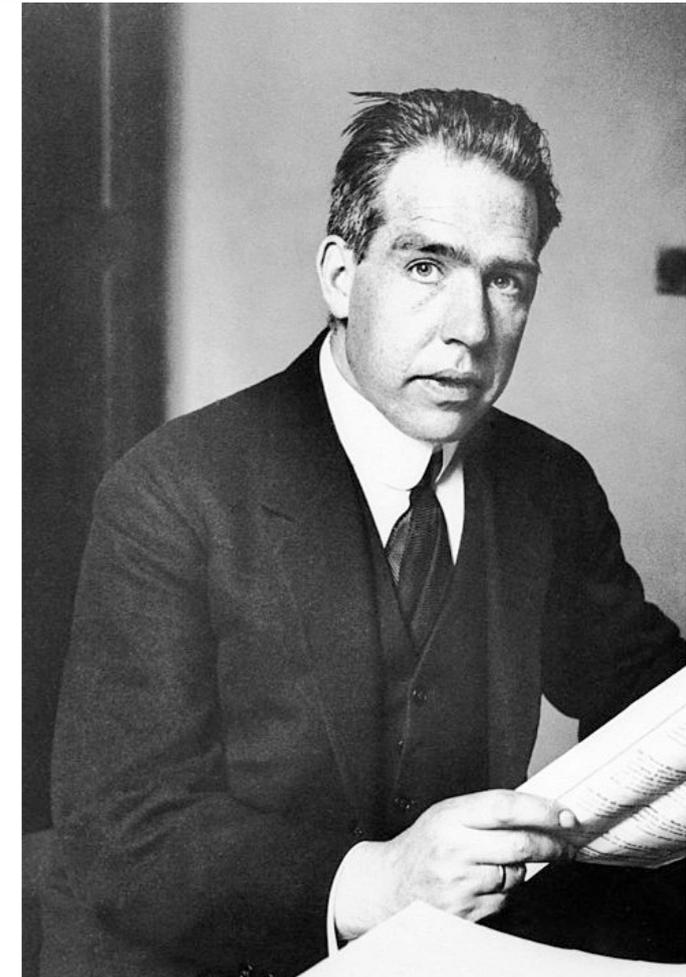
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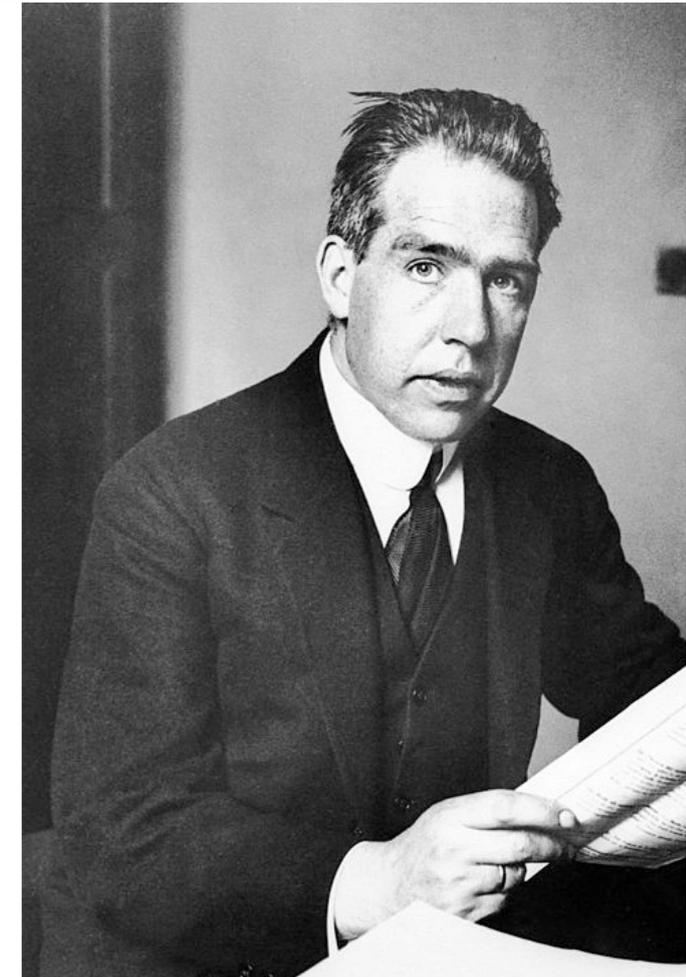
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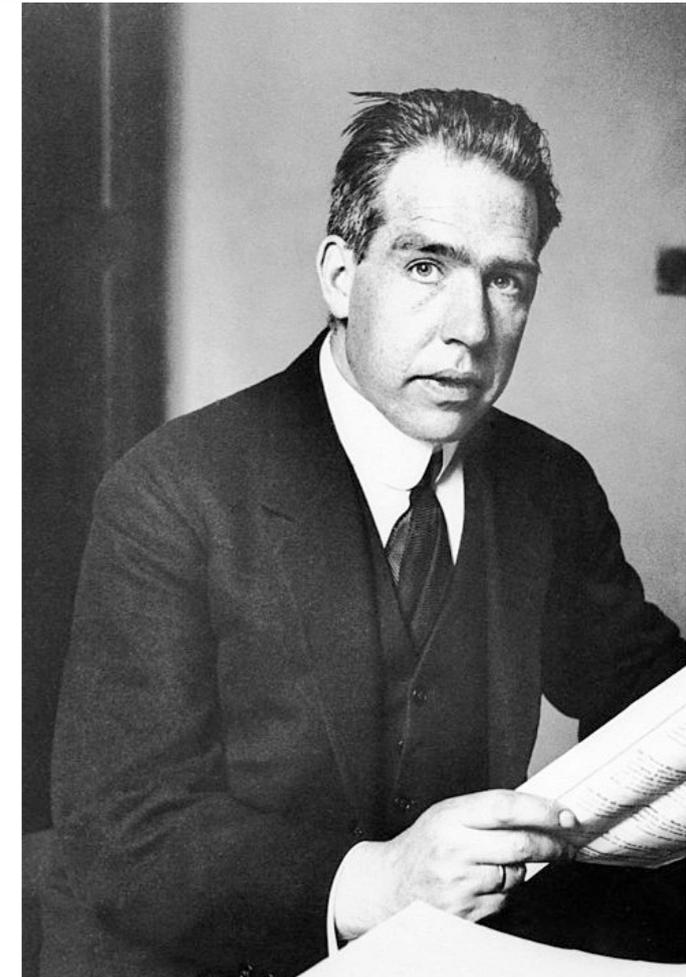
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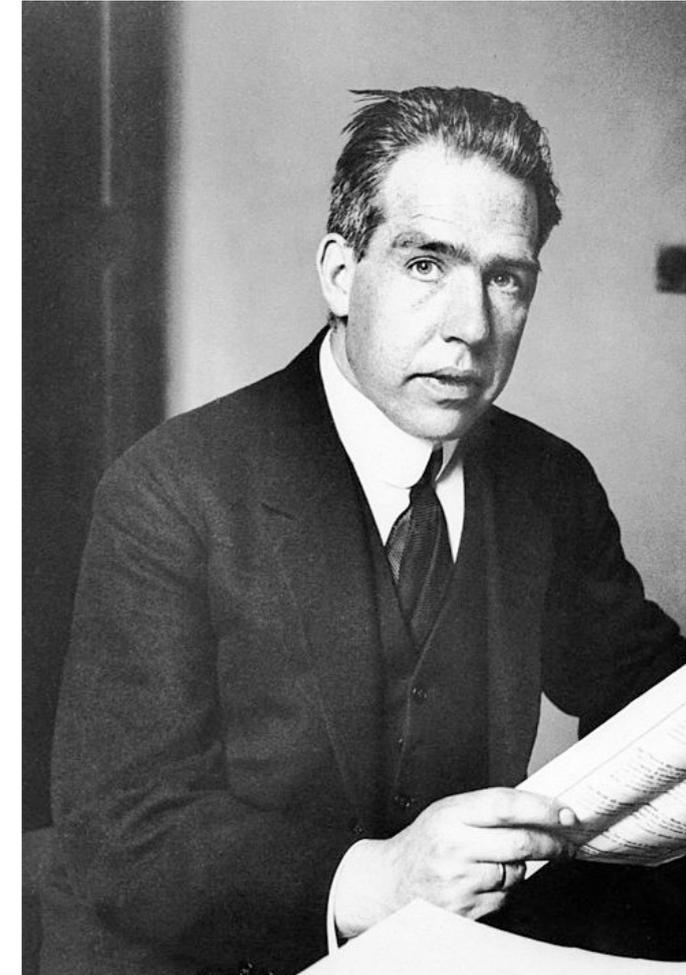
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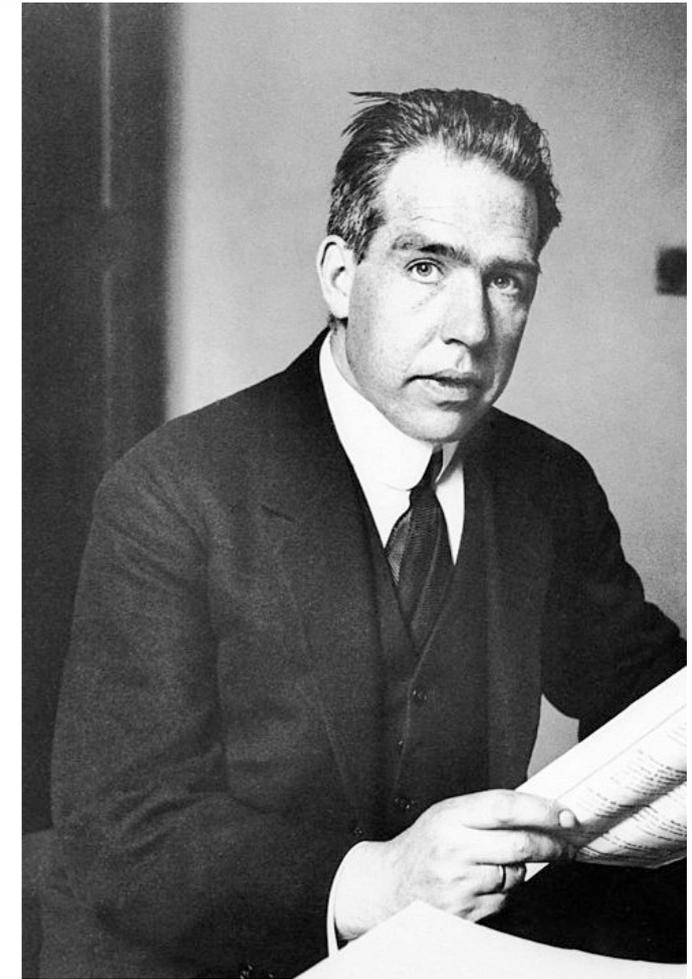
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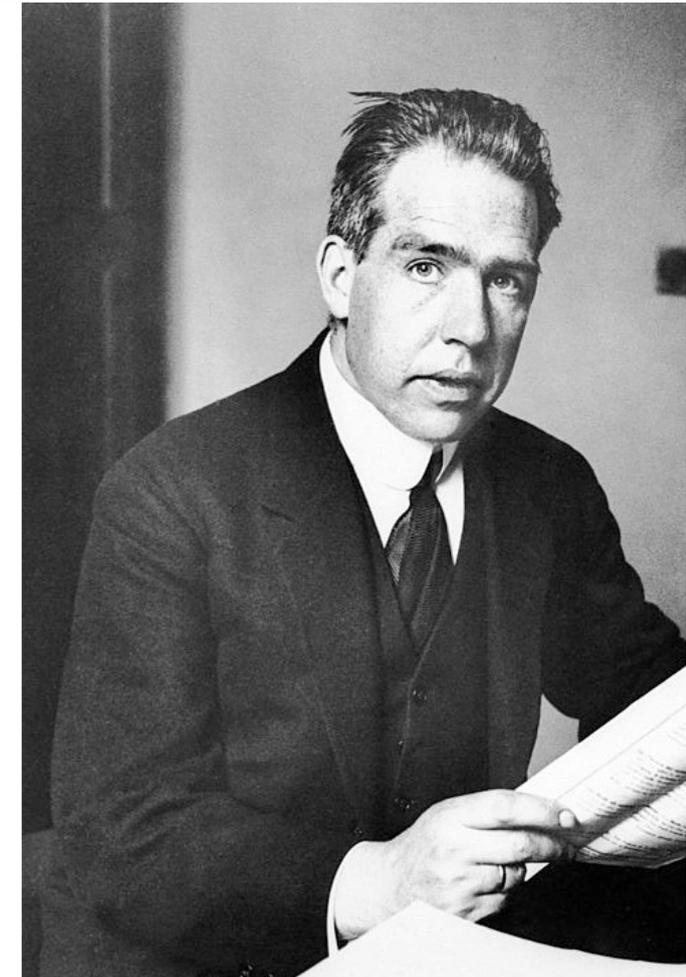
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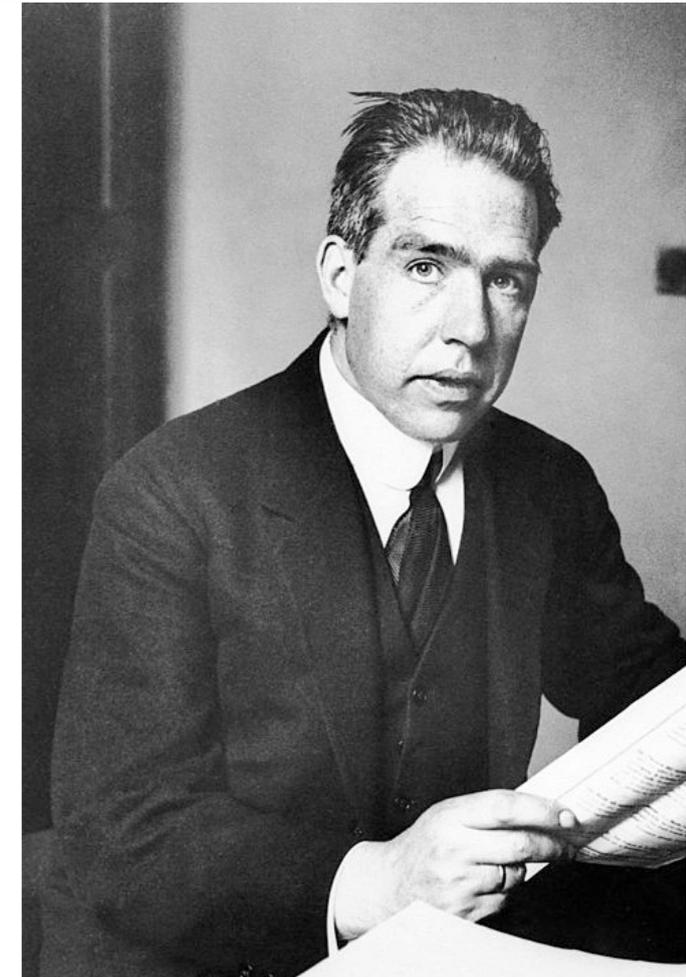
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 - ▶ Copenhagen Interpretation is “orthodox” quantum mechanics: more or less what we teach students.



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Einstein & Quantum Mechanics



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 - But later experiments[†]: essentially ruled out possibility of hidden variables & confirmed indeterminism!



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Uses of Quantum Mechanics



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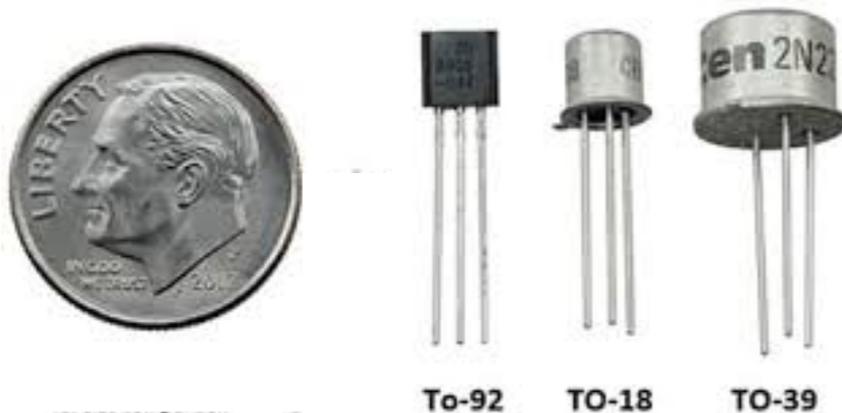
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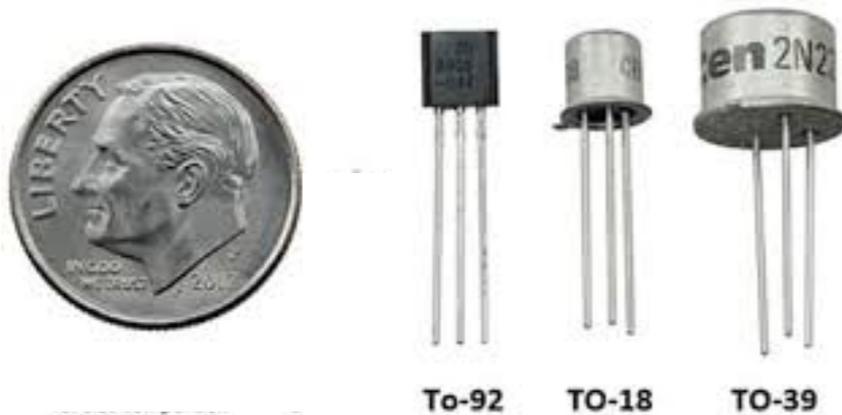
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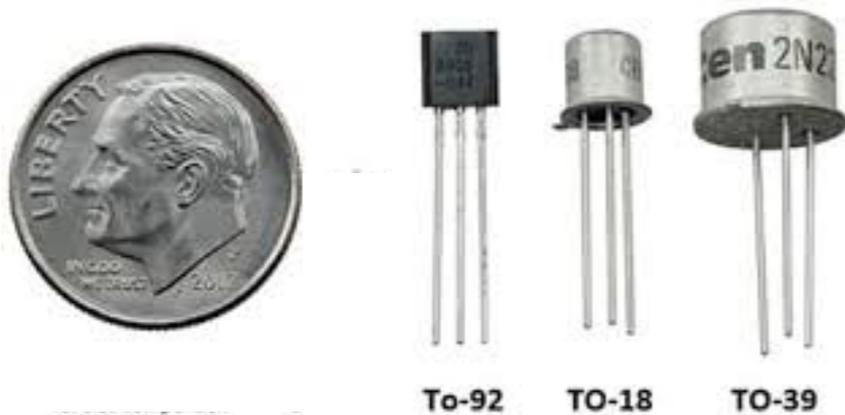
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- began to replace vacuum tubes in 1950s.

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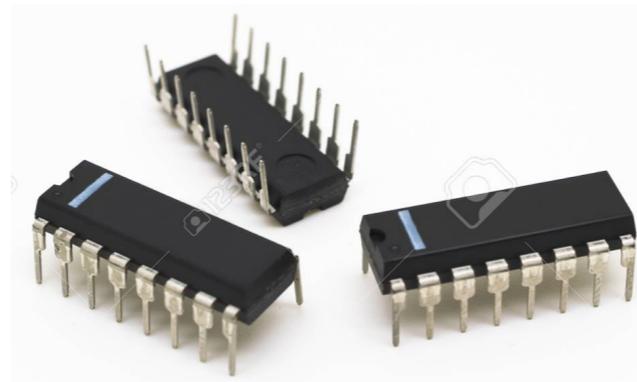
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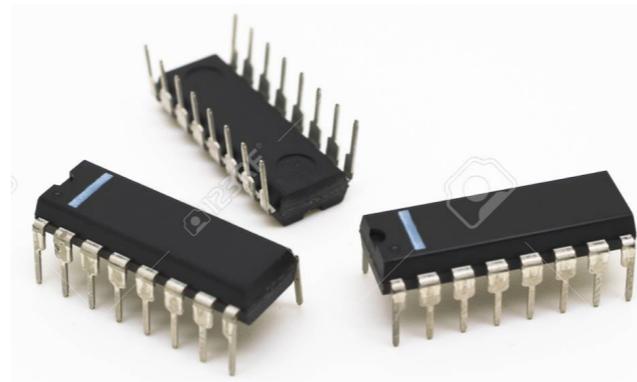
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Immigrants: We get the job done!

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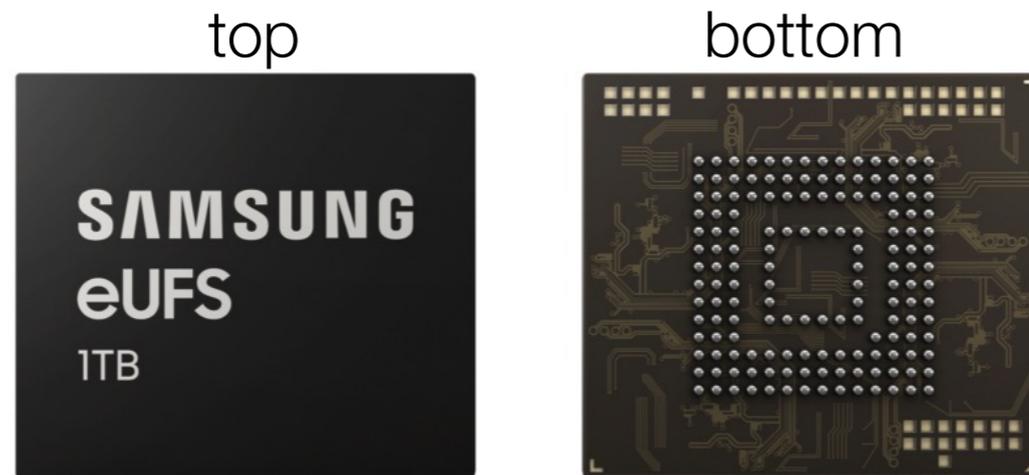
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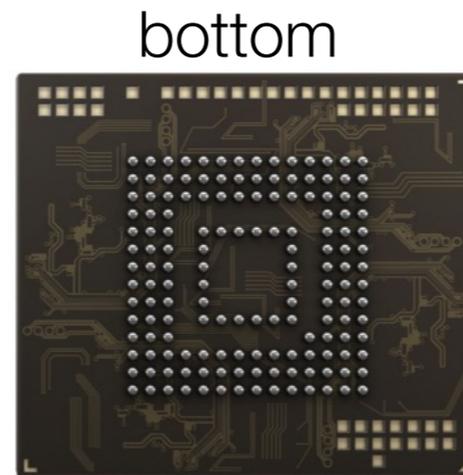
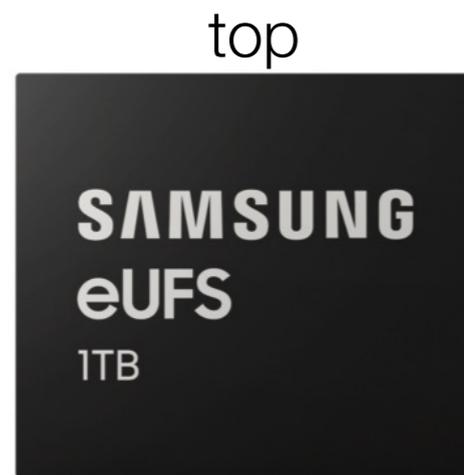
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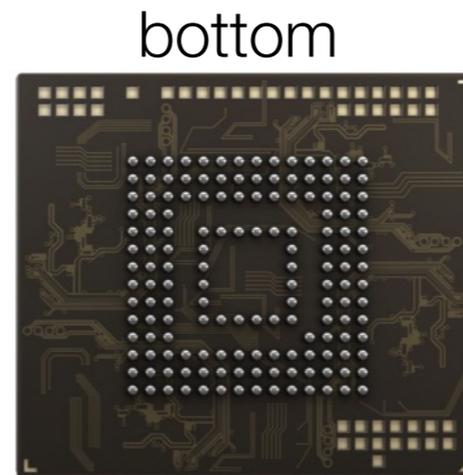
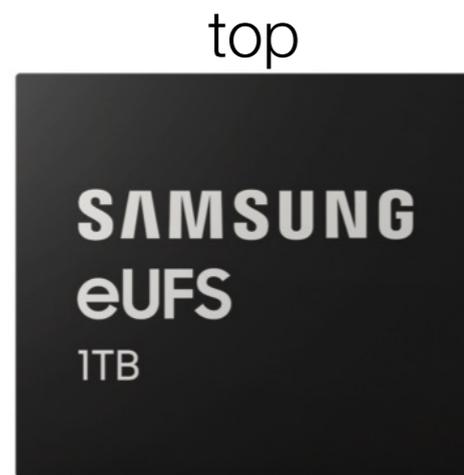
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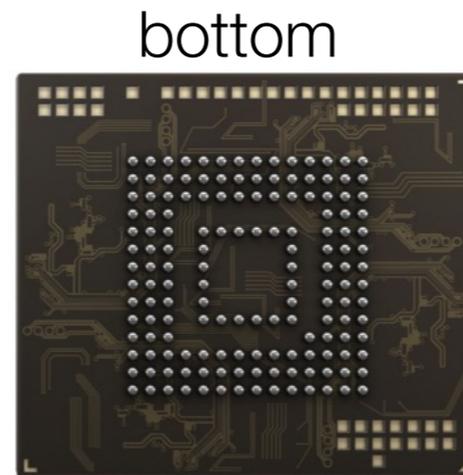
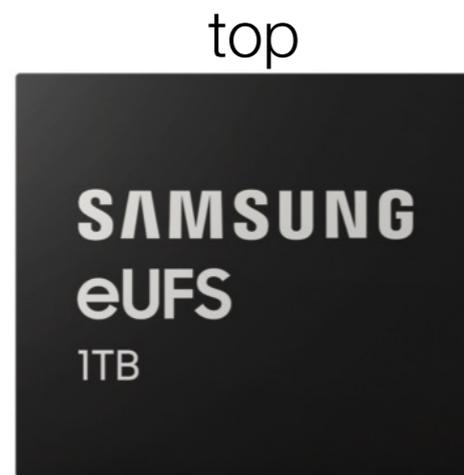
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- ▶ ~10x more transistors than there are stars in Milky Way galaxy!

Some Other QM Uses



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◆ Lasers.

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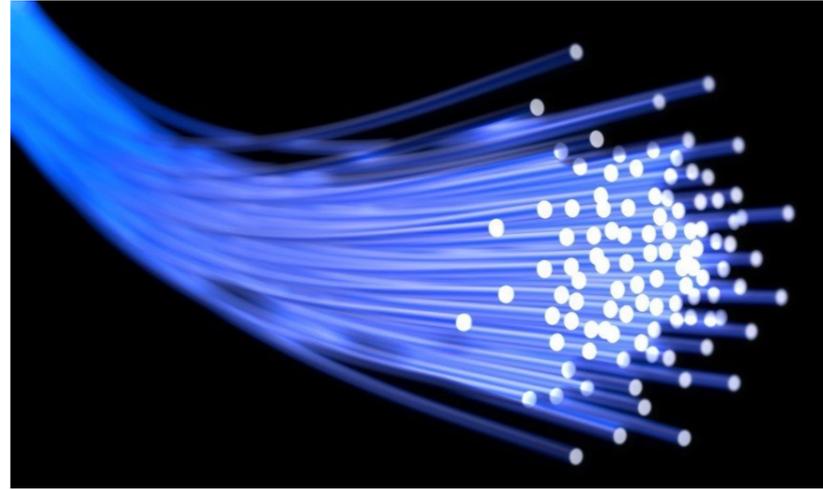
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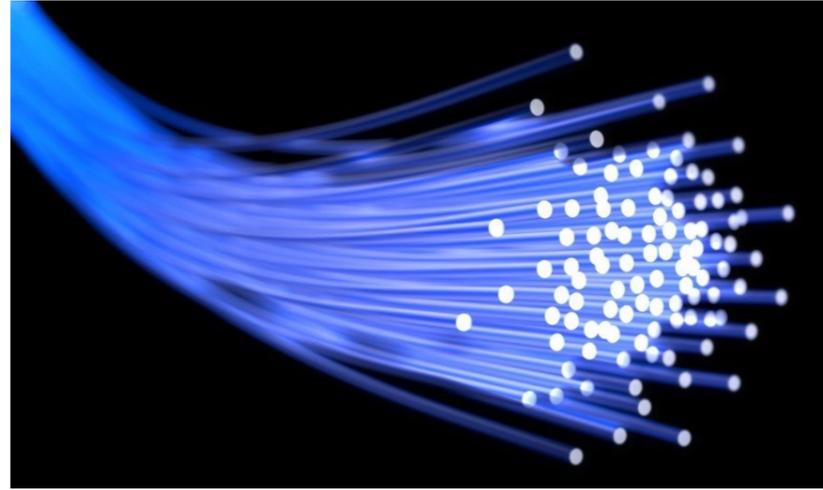
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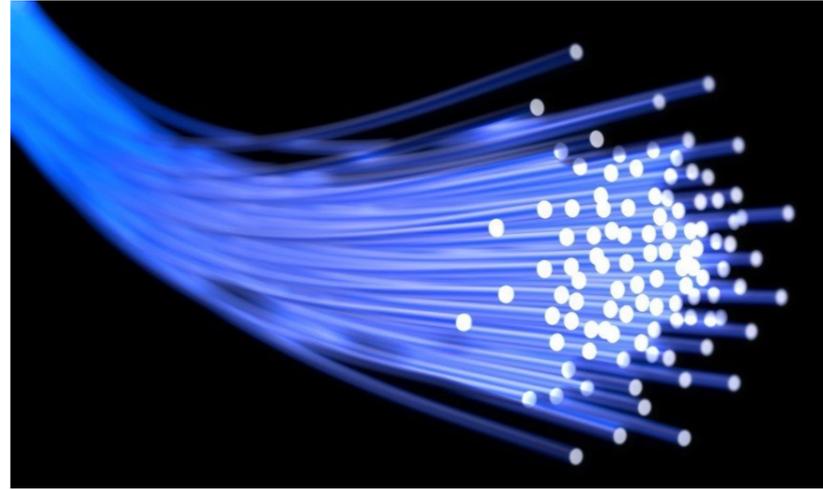
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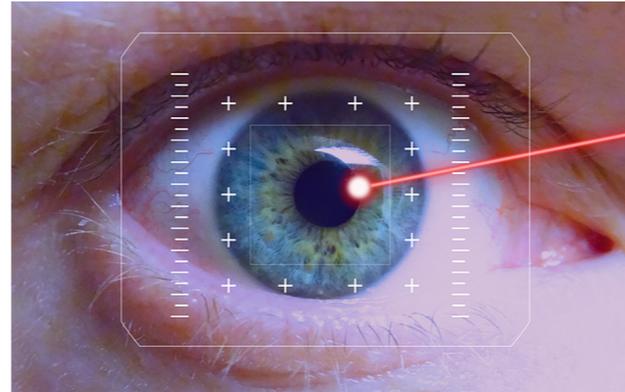
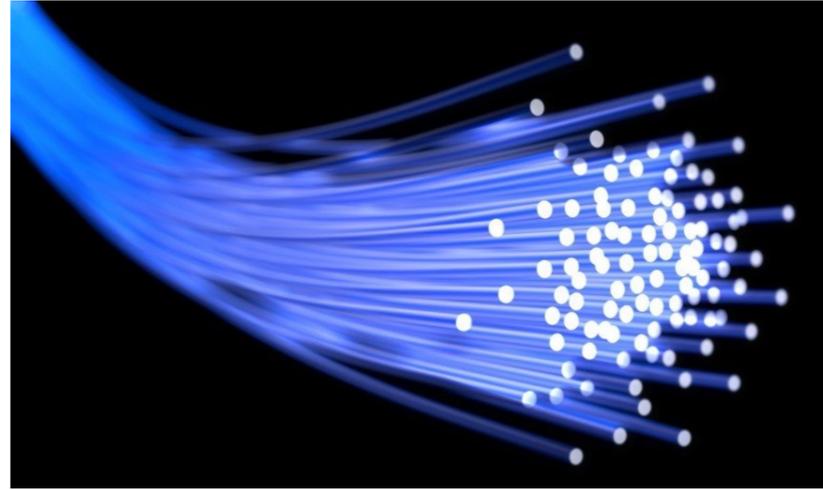


credit: Cathedral eye clinic

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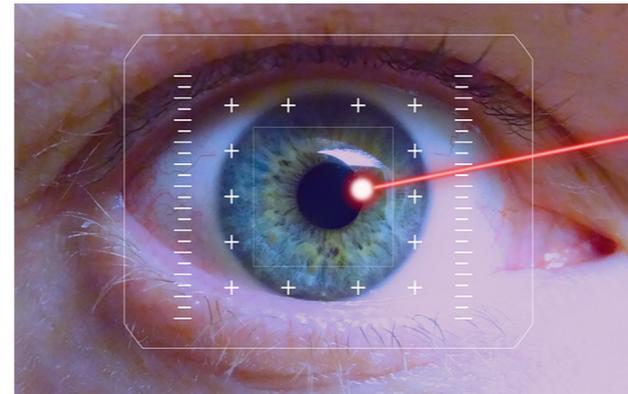
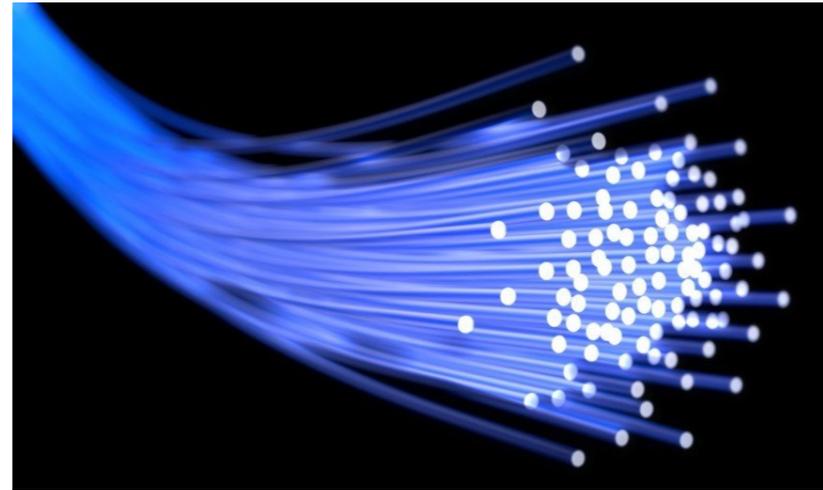
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Some Other QM Uses

◆ Lasers.

- Ubiquitous. E.g.:
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 - ▶ CD/DVD players
 - ▶ laser surgery, ...



credit: Cathedral eye clinic

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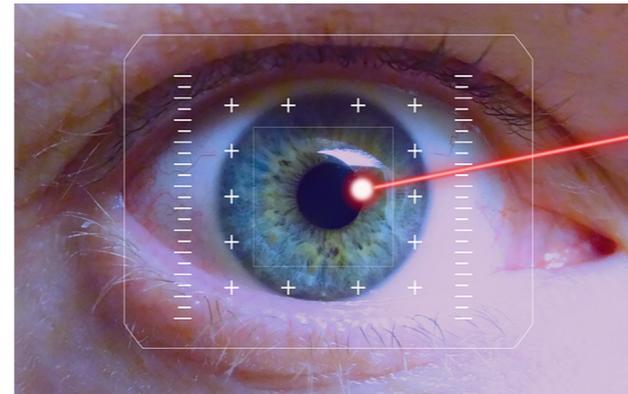
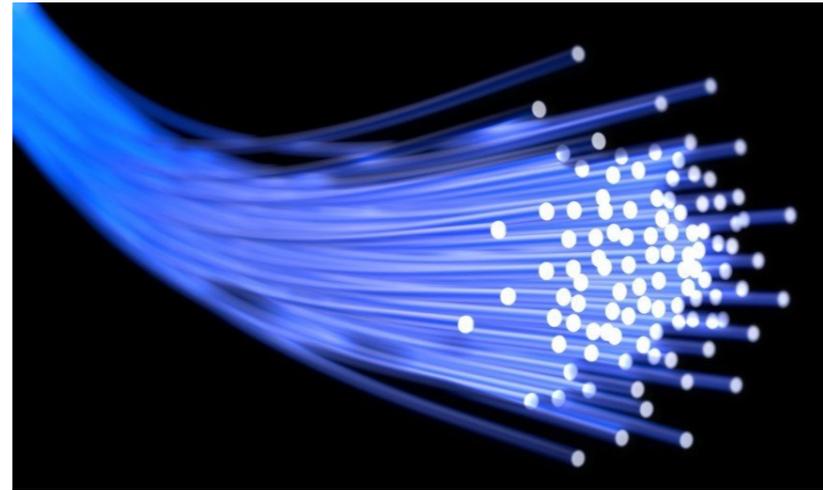


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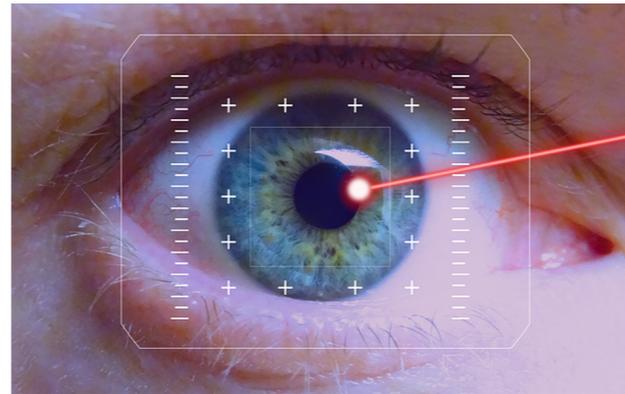
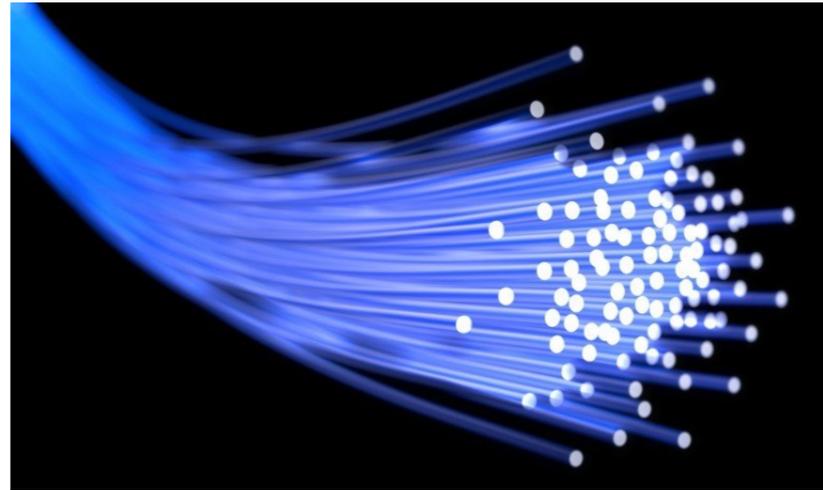
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 - ▶ So in practice, needs atomic clocks, which do depend on QM.



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 - Corresponds precisely to possible QM setup, but we'll imagine that it applies to macroscopic objects (instead of obscure properties of electrons, photons, ...).

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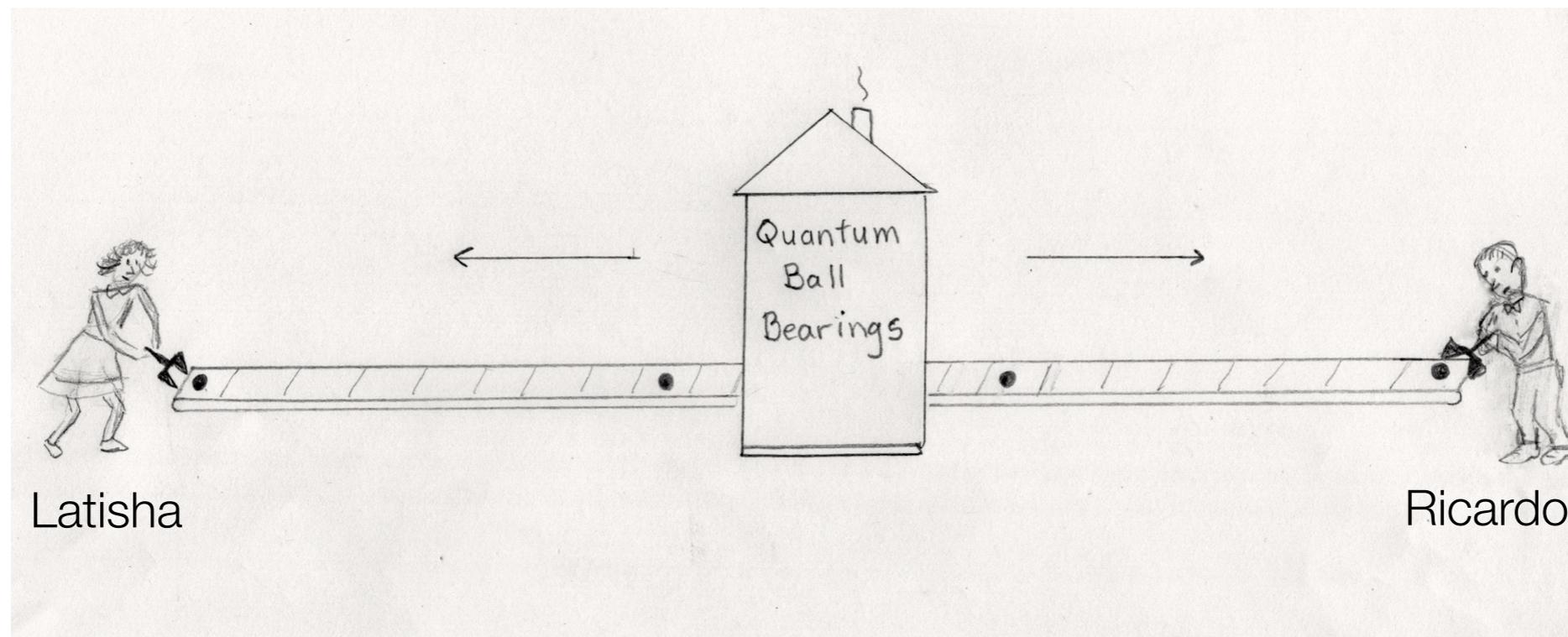
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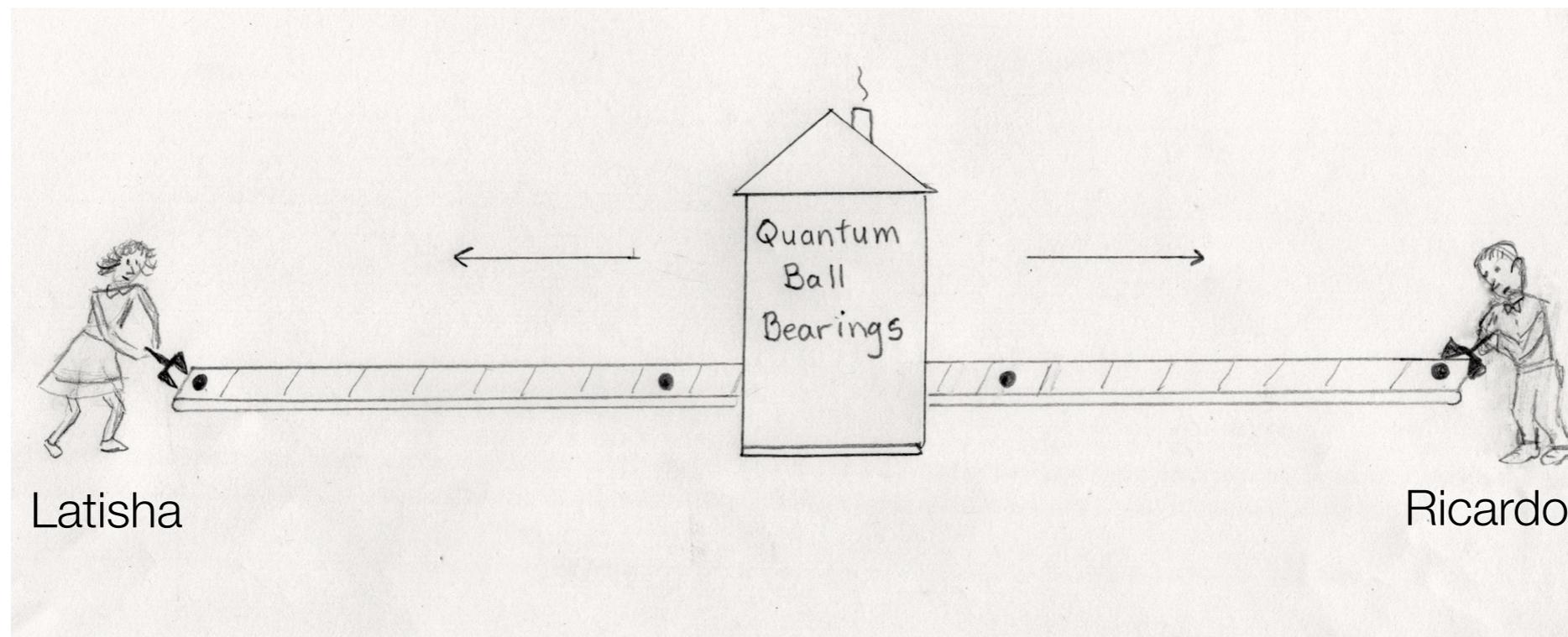
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drawing by J. Walker

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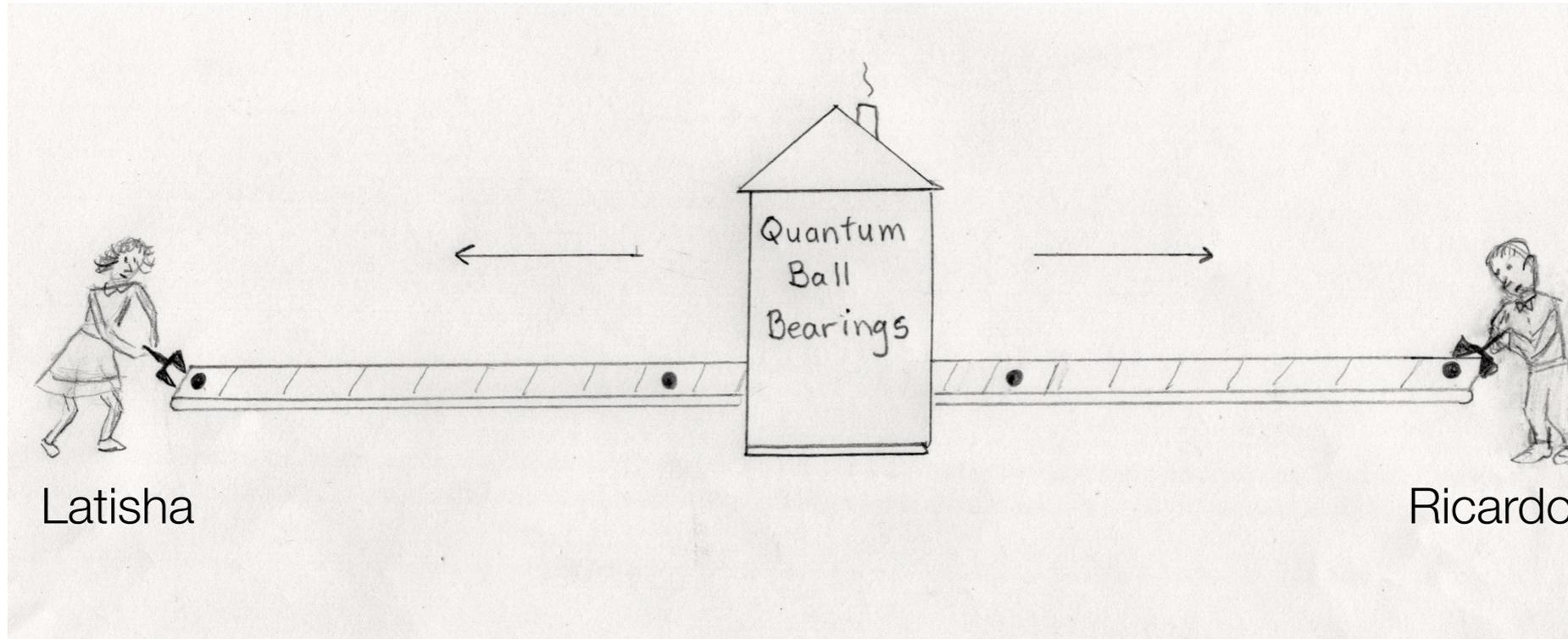
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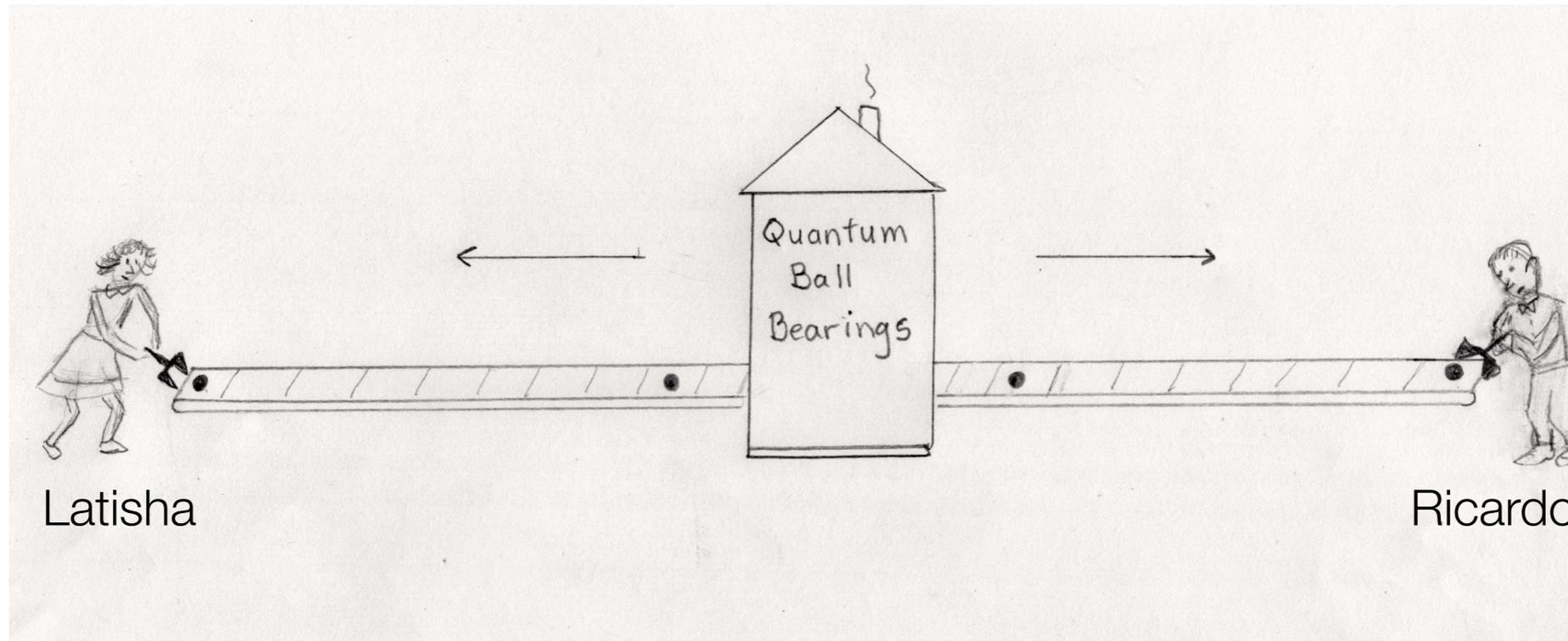
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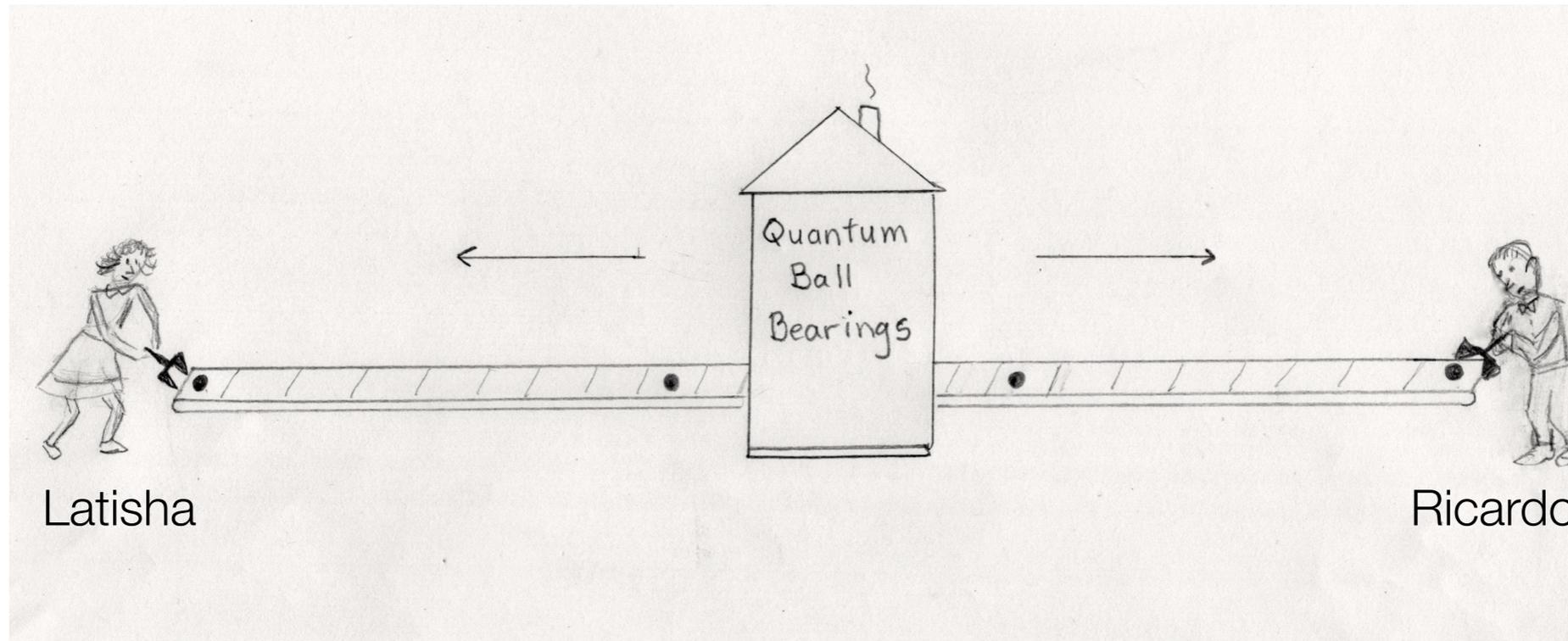
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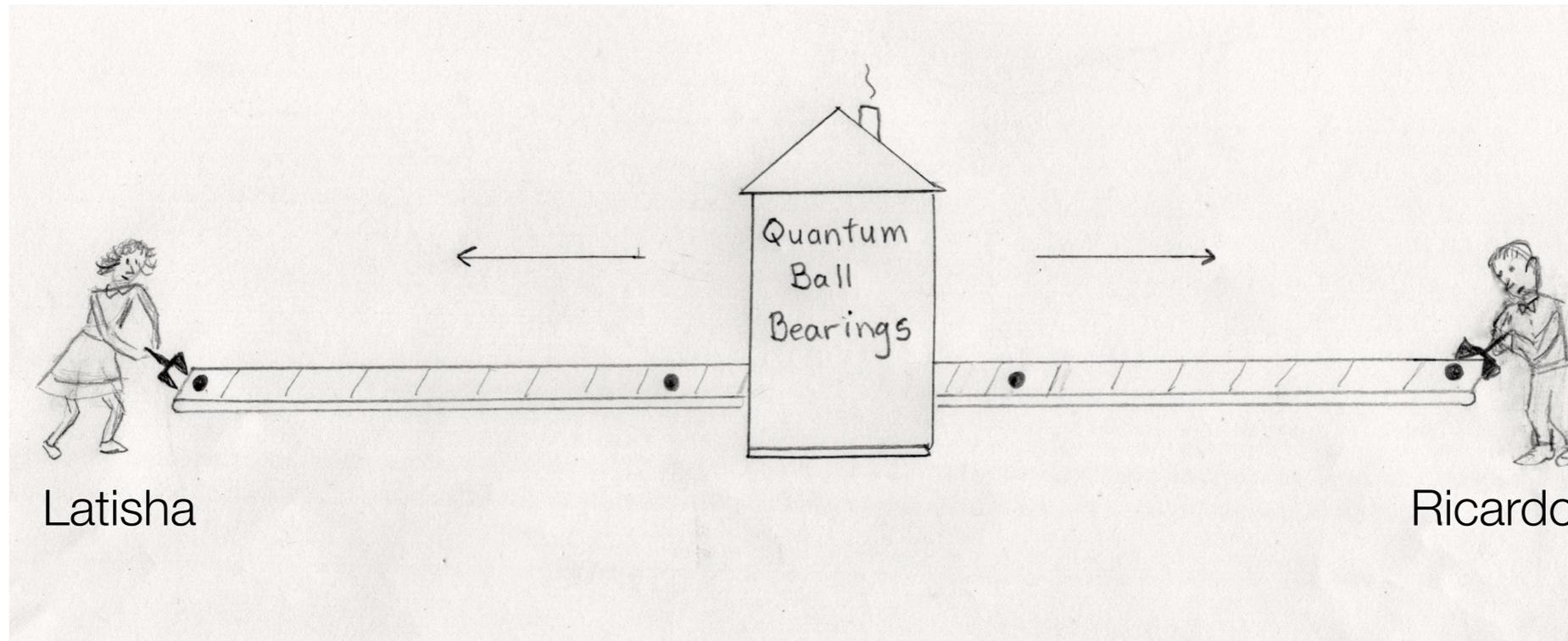
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 - In reality, ball bearings much too large (composed of too many atoms) for QM effects to be evident.

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 - “Elves” in factory adjust hidden variables for each ball bearing they send out ⇒ ensure two R’s never sent out at same time.

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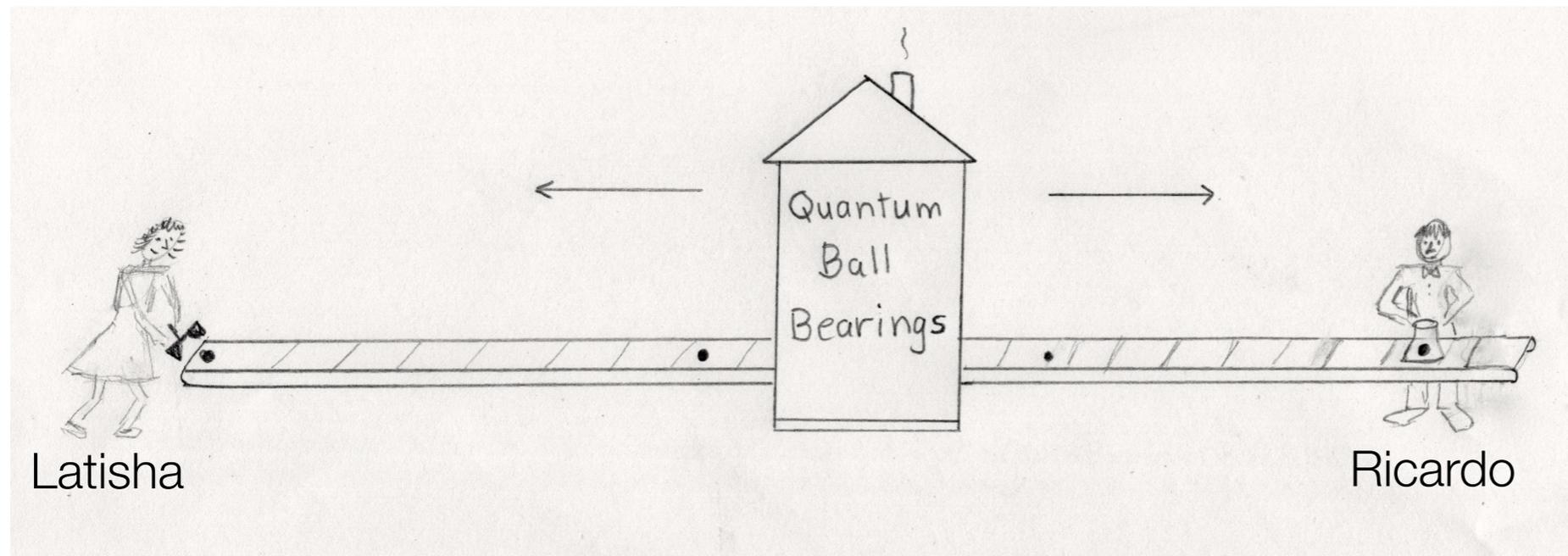
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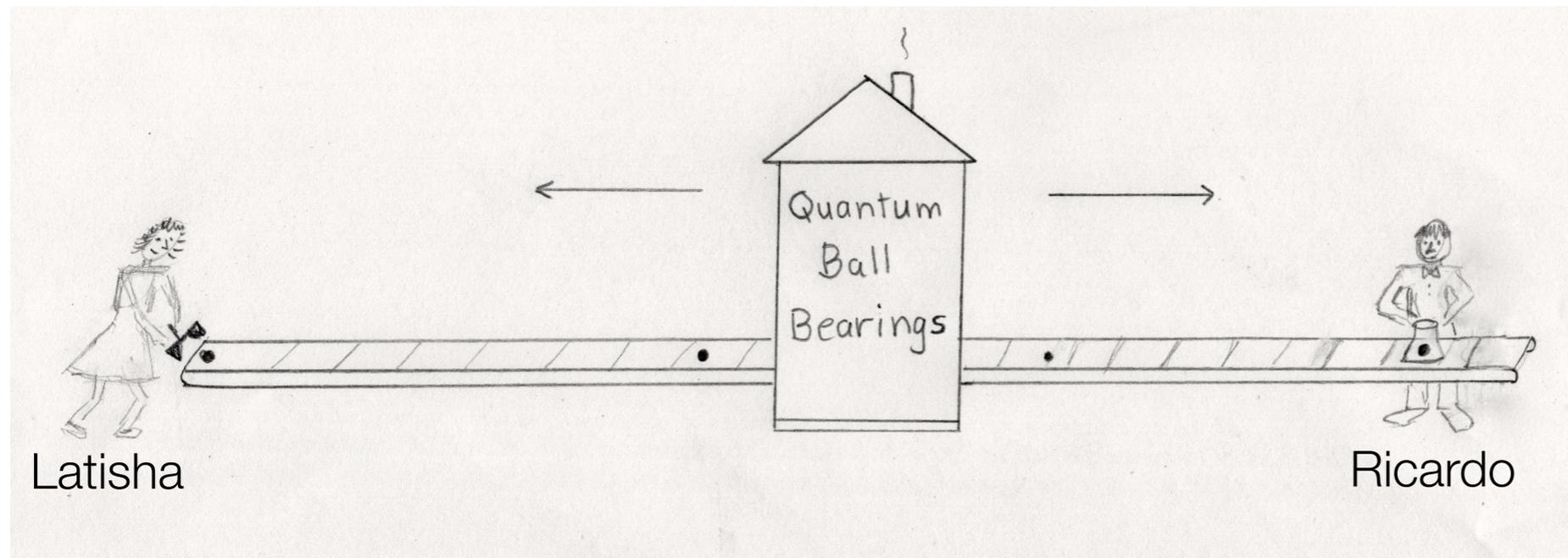
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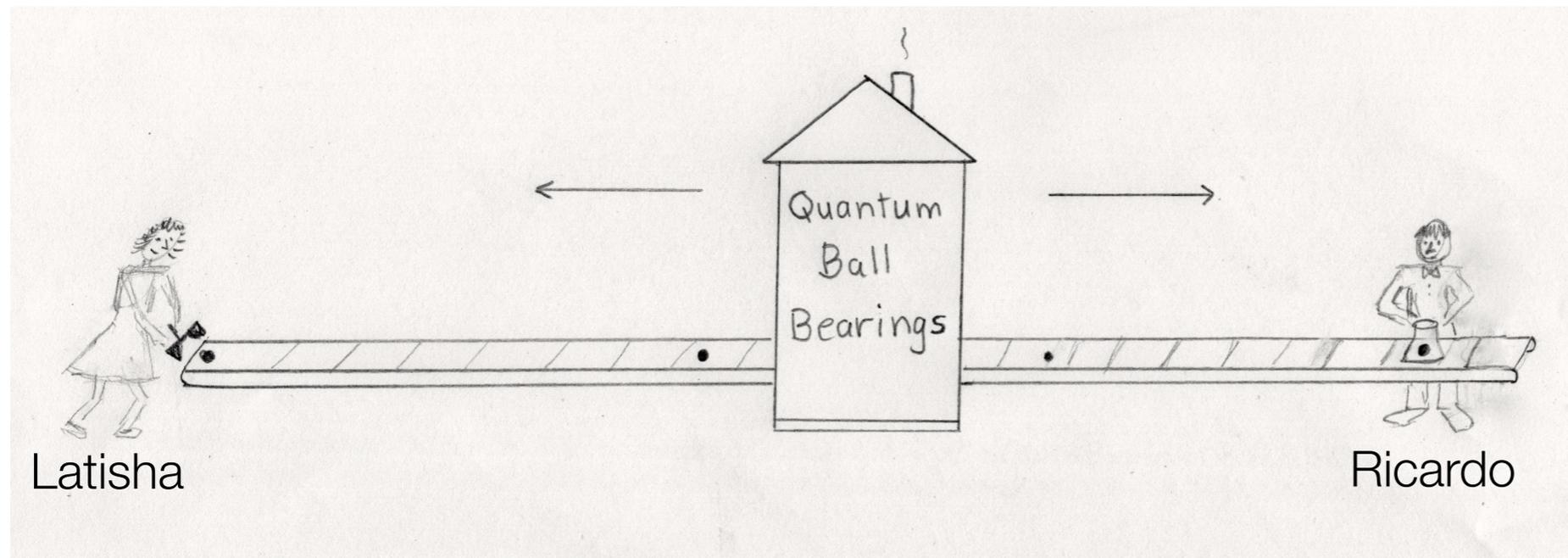


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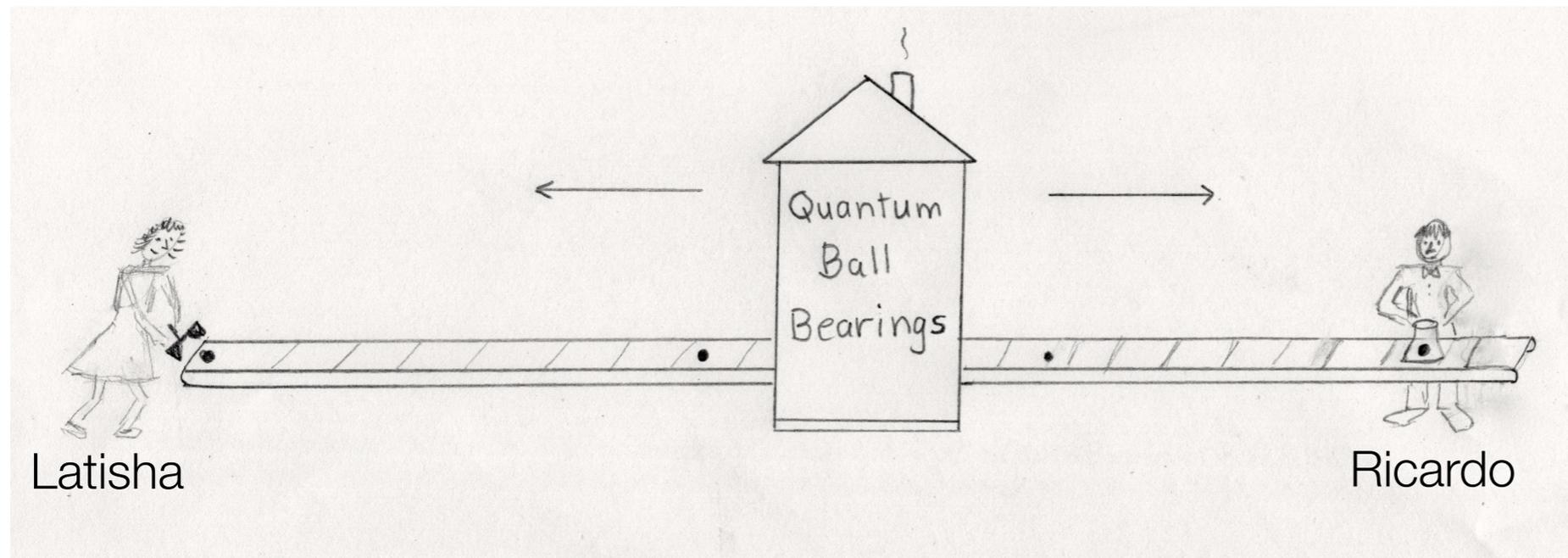
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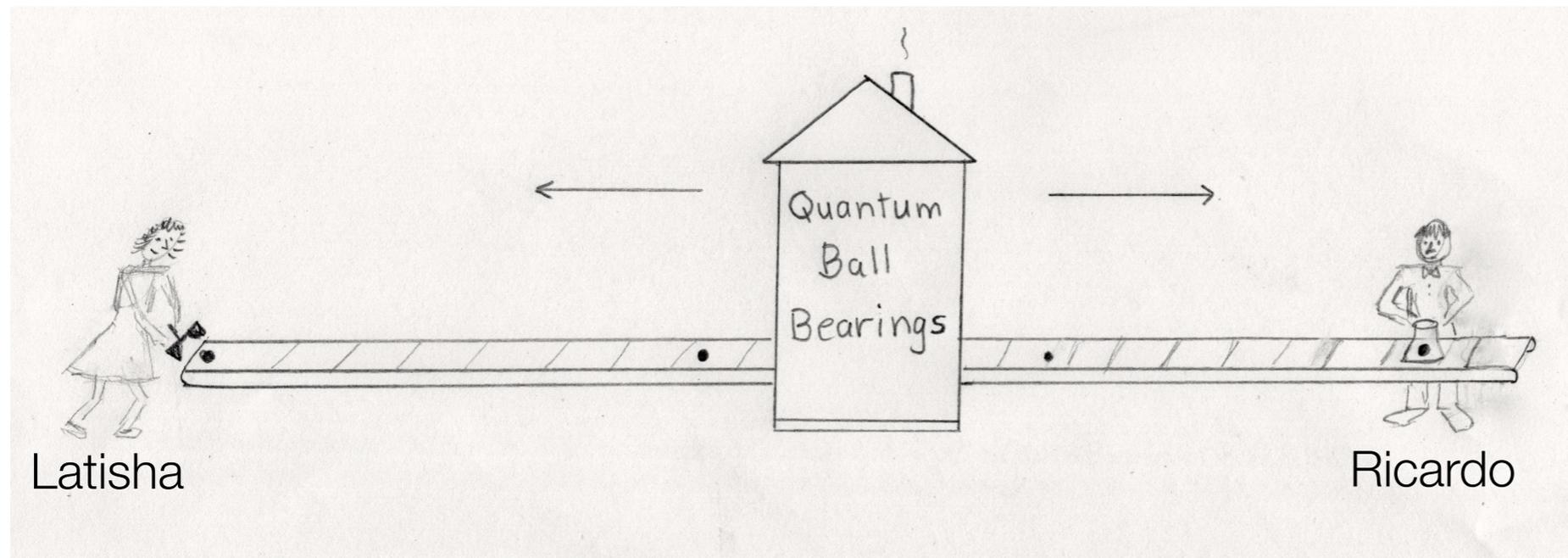
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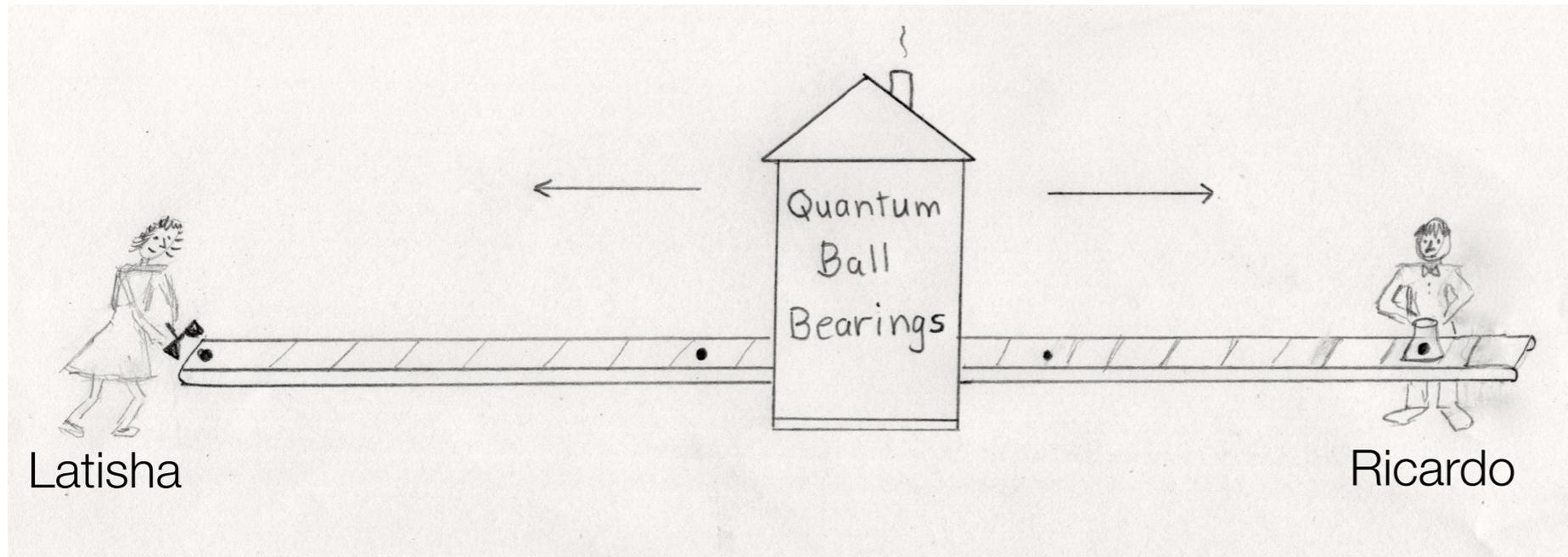
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28	I			B
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10	I			B
17	I			B
22	R			B
24	I			B
28	I			B
34	R			G
35	I			B
39	R			B
42	I			B
47	R			G
51	R			B
55	I			B
61	I			B

◆ When Ricardo finds composition of his ball bearing to be good (G), Latisha always finds her ball bearing to be round (R)!

- [When Ricardo finds bad composition (B), Latisha may get either round (R) or irregular (I).]

◆ Works same way when Latisha measures composition & Ricardo measures roundness:

“Quantum Ball Bearing Factory”

◆ Look at cases where Latisha measures roundness & Ricardo measures composition.

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“Quantum Ball Bearing Factory”



“Quantum Ball Bearing Factory”



◆ The plot thus far:

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- ◆ The plot thus far:
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 - ▶ But that is impossible, by 1.

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◆ **NO** possible choice of hidden variables that could make this happen (along with the results of the other tests).

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 - The two ball bearings are sent out “entangled”:
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 - ▶ Once there is a result of a measurement on one side, the possible results on the other side are instantaneously affected!

Conclusions



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Extra Slides



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- ◆ “Spooky action at a distance” seems to violate a principle of relativity, colloquially stated as “nothing can go faster than the speed of light.”
 - Actually, relativity only \Rightarrow **objects** can't move faster than the speed of light, & **signals** can't be transmitted faster than the speed of light.
 - “Spooky action at a distance” can't be used to transmit information \Rightarrow doesn't violate relativity.
 - ▶ Latisha & Ricardo can choose which test to make, but can't choose what results they get.
 - ▶ Tests on one side always have right probabilities (independent of what property other tester measures).
 - ▶ Can't send information to each other in real time using QM.

EM Waves

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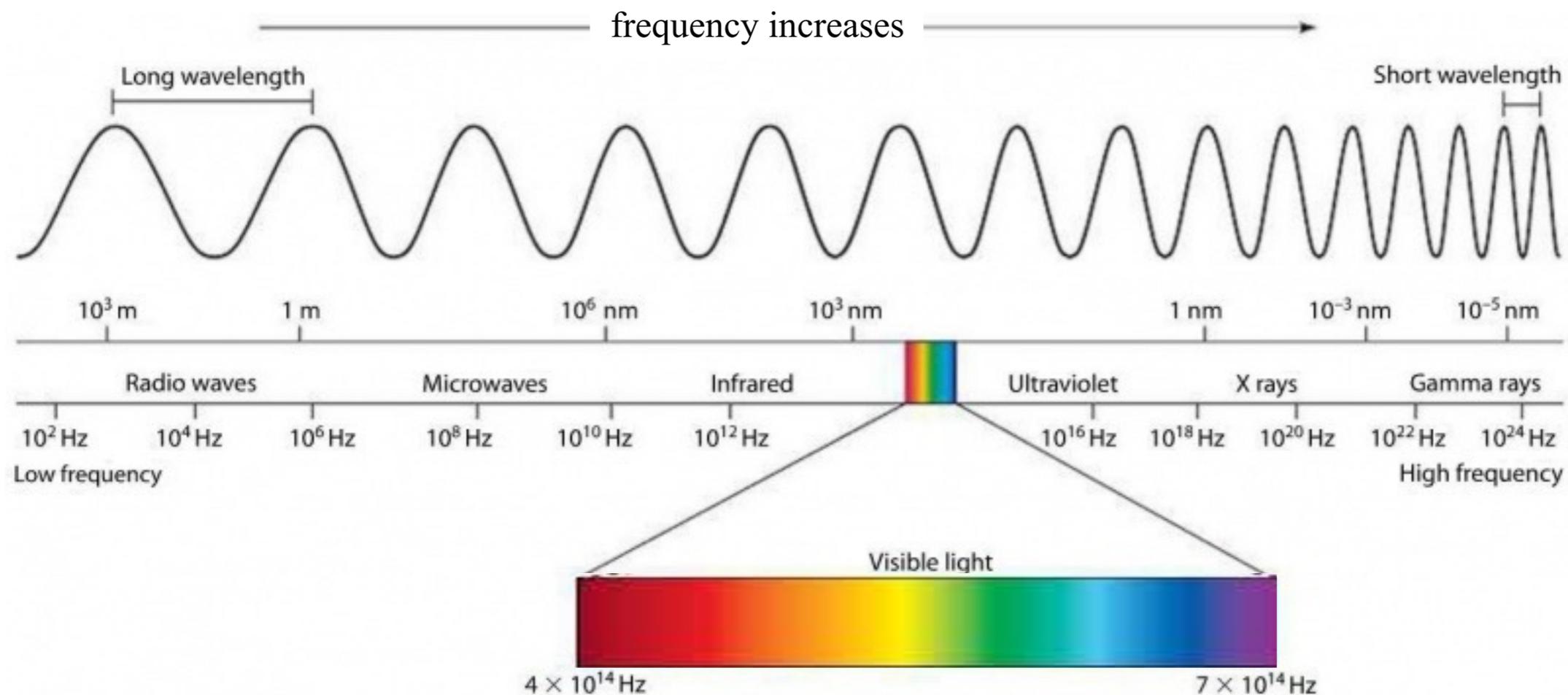
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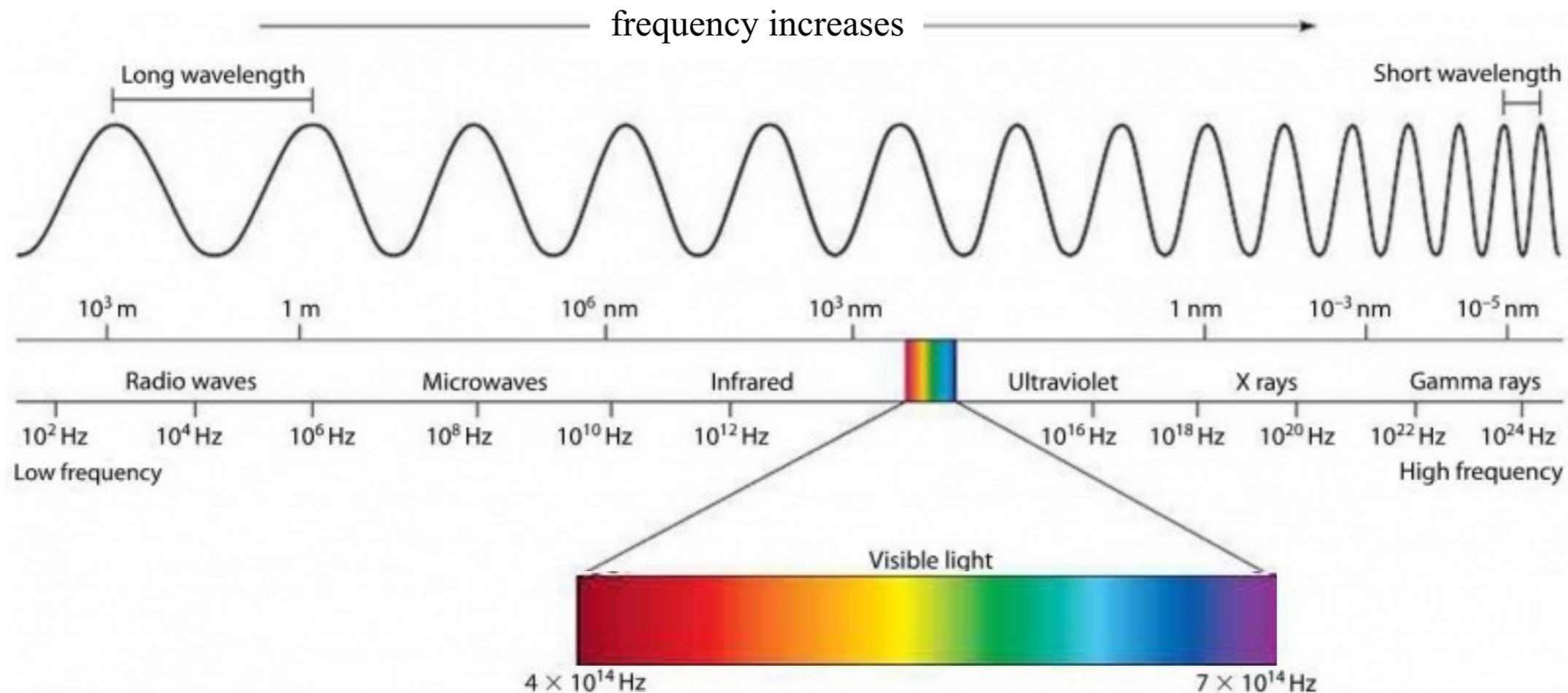
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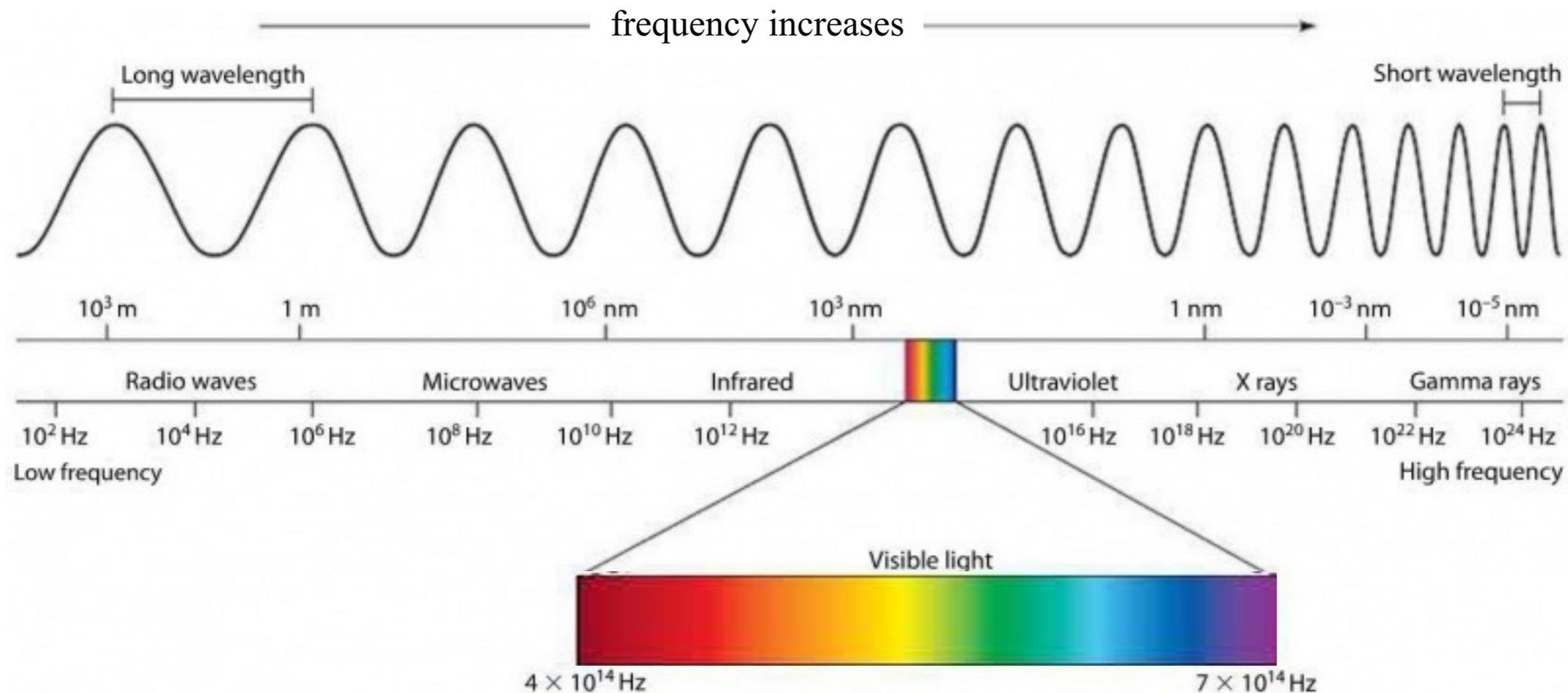


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- Visible light: a small range of frequencies
- Physicists often say “light” when they really mean any electromagnetic wave.

Uses of Quantum Mechanics



- ◆ “The beautiful aspect to this is the scientists who developed this were not trying to make a cell phone; they were not trying to invent a CD player. If you went to Schrödinger in 1926 and said, “Nice equation, Erwin. What's it good for?” He's not going to say, “Well, if you want to store music in a compact digital format...”
 - James Kakalios [physicist], author of *The Amazing Story of Quantum Mechanics*, interview with John Matson, *Scientific American*, Nov 2, 2010.

Old Quantum Theory: Electromagnetic Waves



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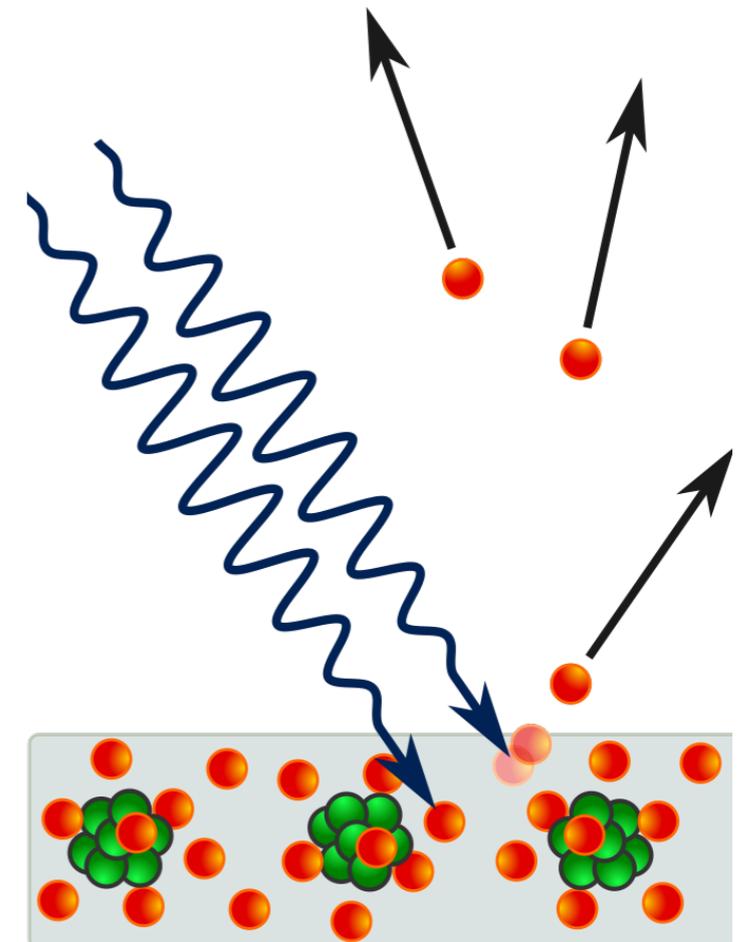
Credit: journal *Nature*

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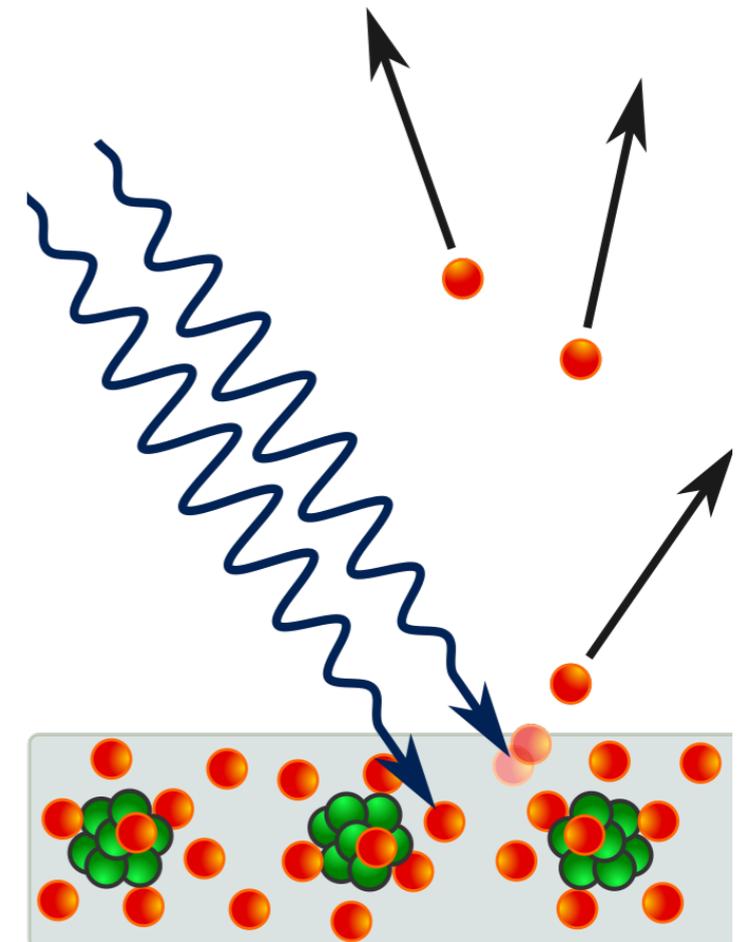


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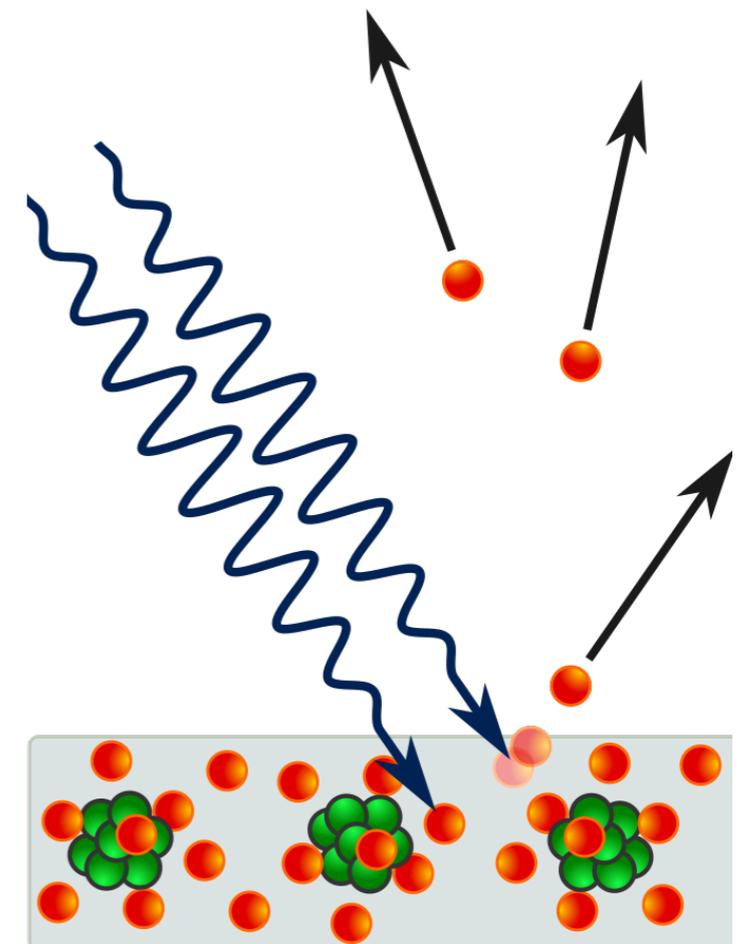


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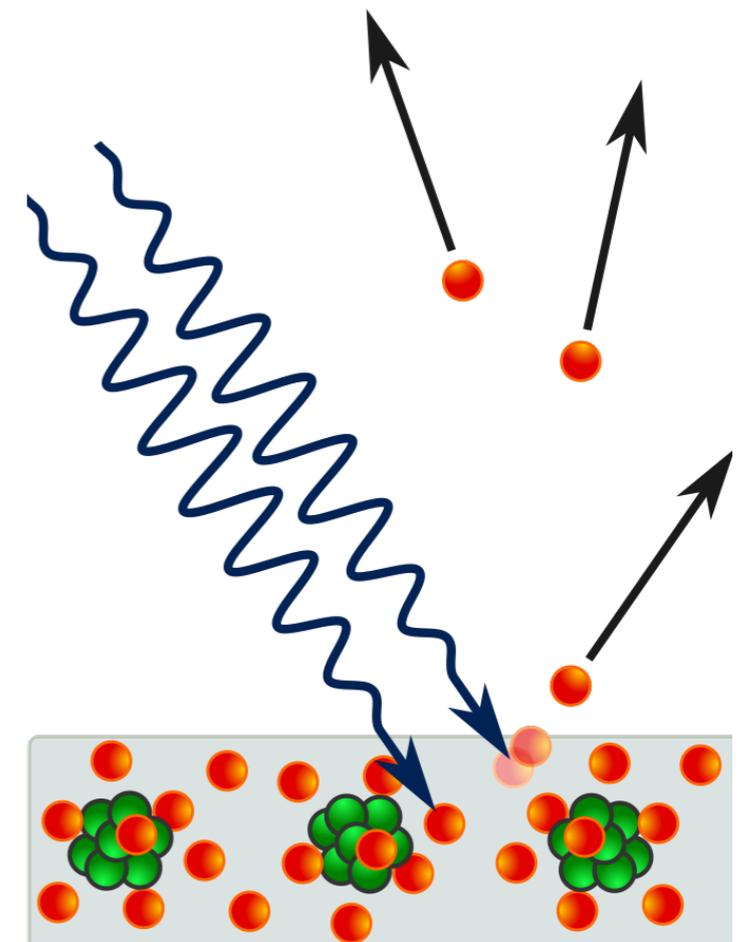


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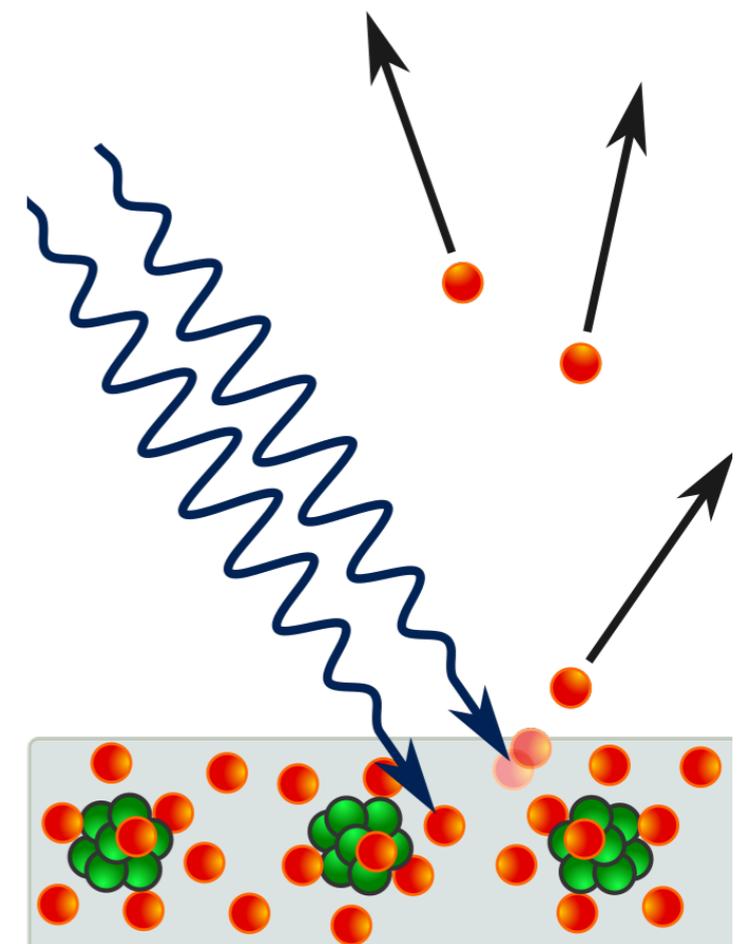


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 - A low frequency wave (e.g. red light) can't knock out electrons, no matter how much total energy it has.
 - None of the photons can knock out an electron, so it doesn't matter how many photons there are.



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Computers & Quantum Computers

- ◆ While QM is necessary for understanding how a transistor works, a transistor still represents only a “classical” bit:
 - either 0 or 1 (not some combination — “superposition” — of them).
- ◆ A true quantum bit (“qubit”) is inherently quantum mechanical and can be in a superposition state.
 - Technically very hard to achieve.
 - But potentially very powerful if we can take advantage of superposition states and entanglement to do many calculations at once.
 - “Quantum computing” is in its infancy.
 - Largest quantum computers today have only ~60 or 70 qubits. [IBM, Google, University of Science & Technology (China), ...]
 - IBM has promised a 1000 qubit quantum computer by 2023.
 - Key potential use of quantum computers would be to factor very large numbers, which would allow them to crack digital encryption codes in use today.
 - E.g., estimated that a 4000 qubit quantum computer could crack Bitcoin’s encryption.

Schrödinger's Cat

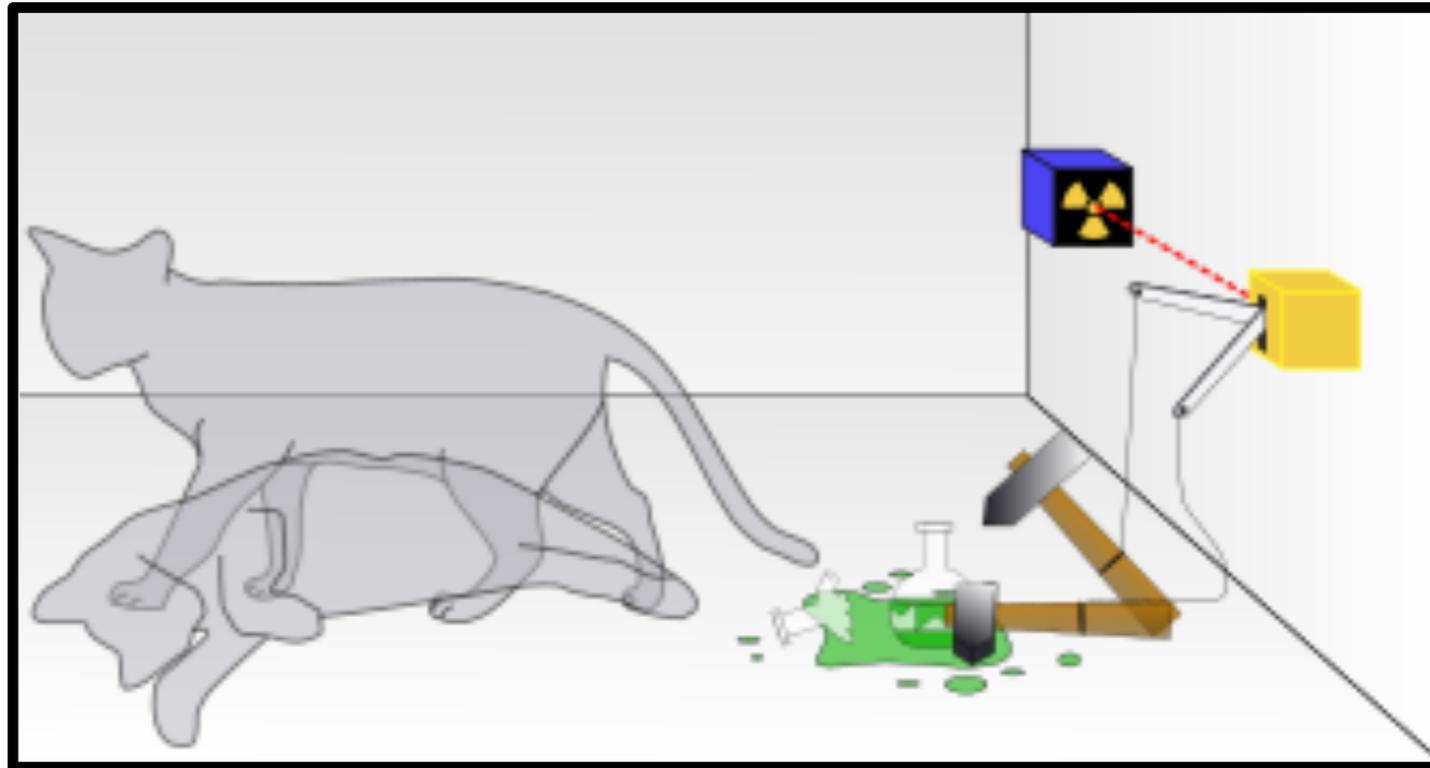


Schrödinger's Cat

- ◆ Another quantum mechanics thought experiment.

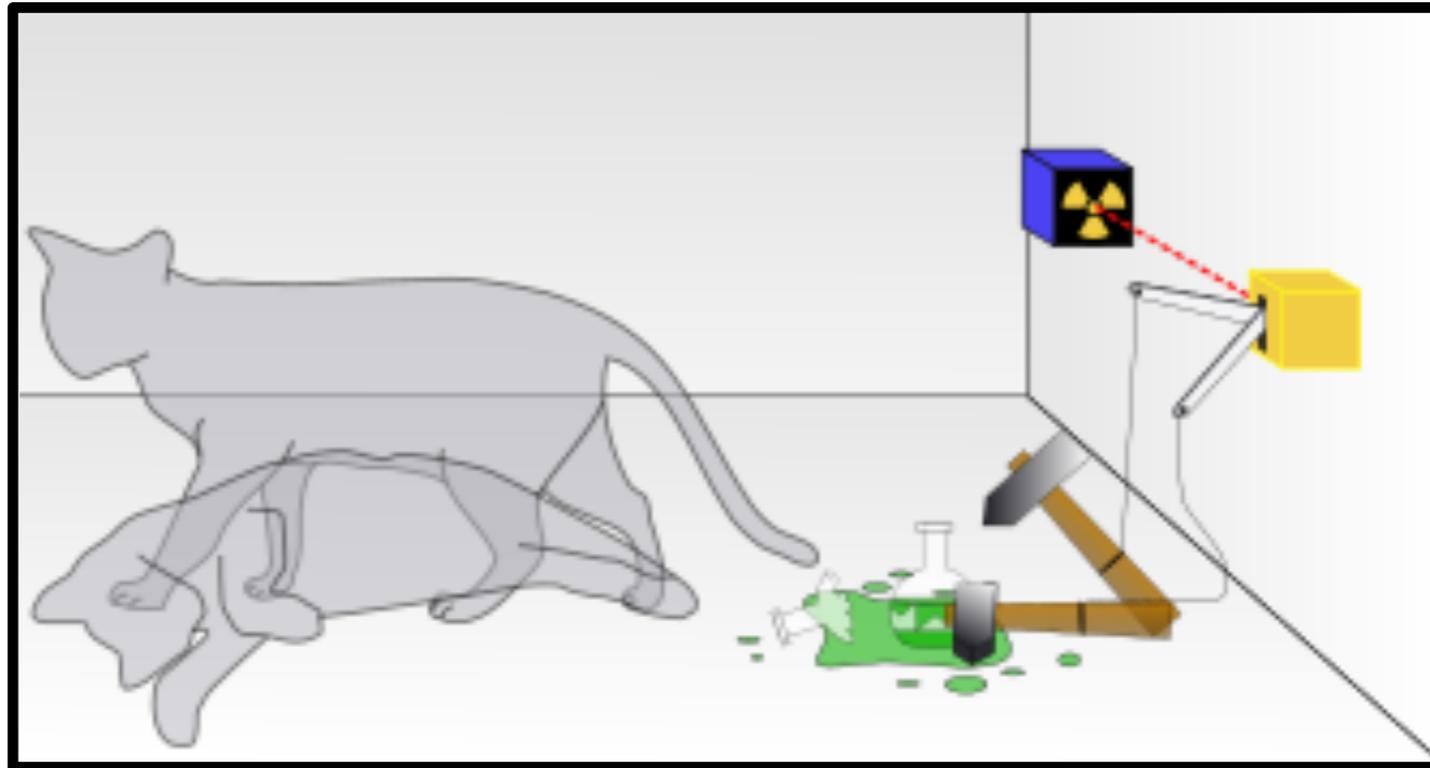
Schrödinger's Cat

- ◆ Another quantum mechanics thought experiment.



Schrödinger's Cat

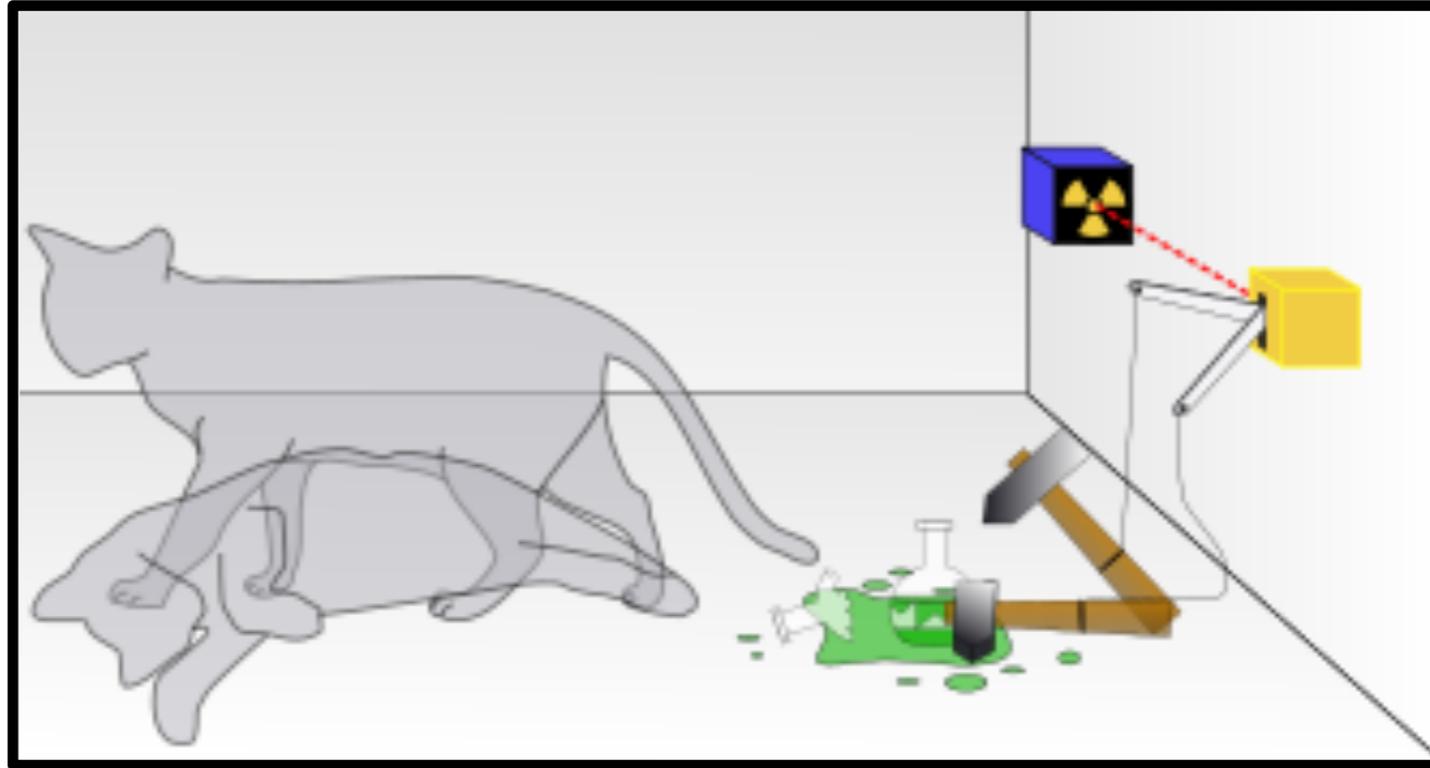
- ◆ Another quantum mechanics thought experiment.



- ◆ Introduced by Schrödinger to argue against the Copenhagen Interpretation.

Schrödinger's Cat

- ◆ Another quantum mechanics thought experiment.



- ◆ Introduced by Schrödinger to argue against the Copenhagen Interpretation.
- ◆ Has led to lots of heat, but little light.

Transistors



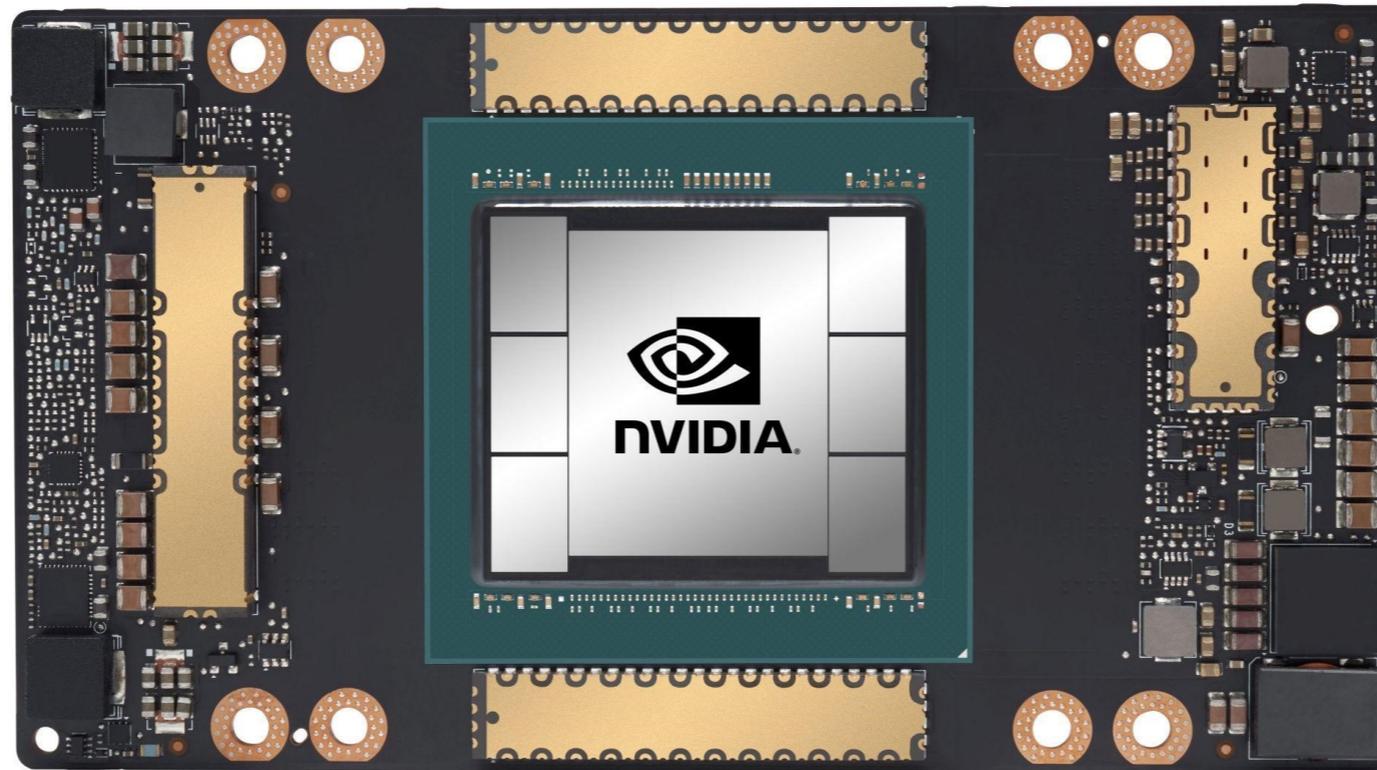
Transistors



- ◆ As of 2020, record for number of transistors in a single processor chip is NVIDIA's A100 chip.

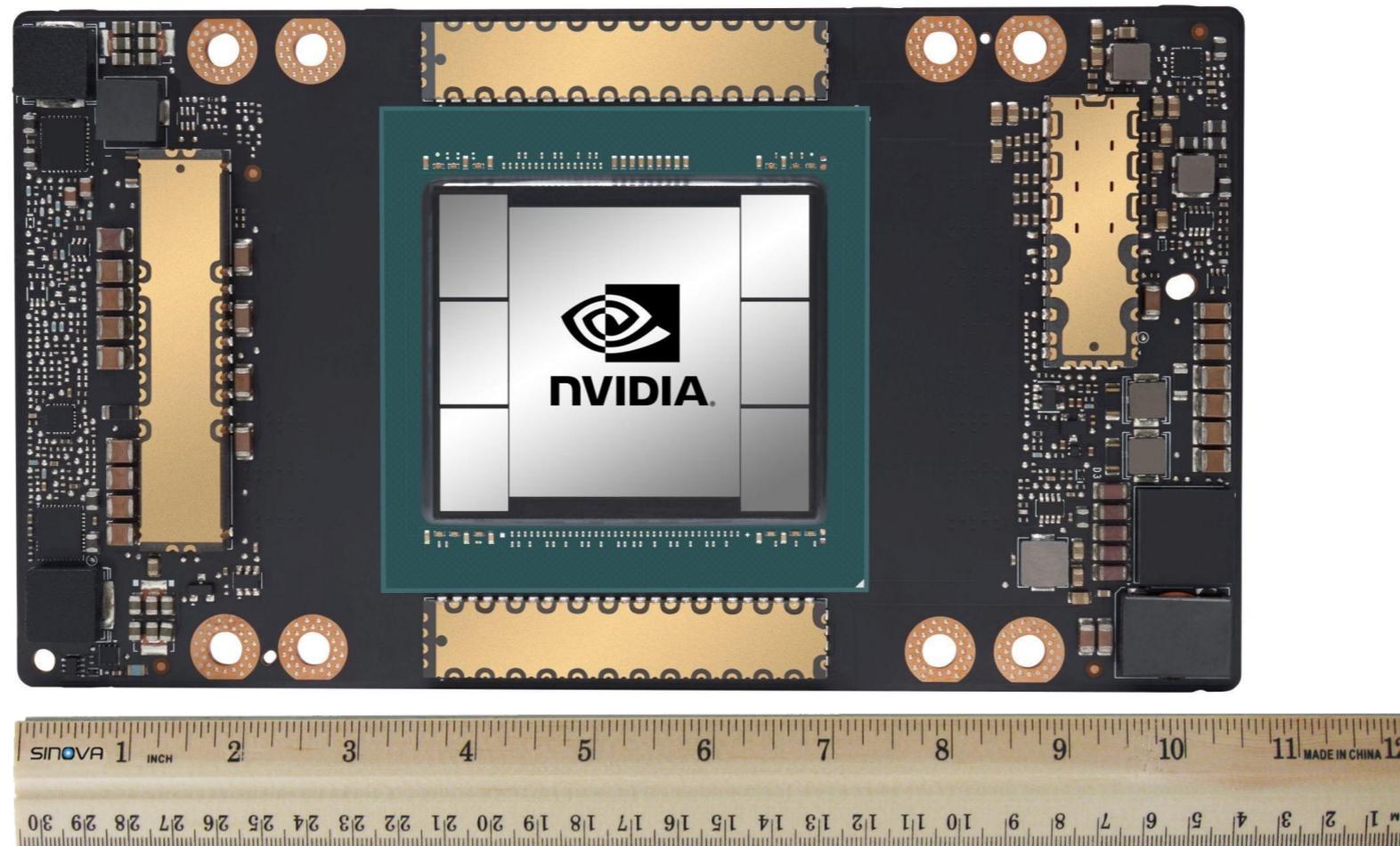
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 - shown here in a GPU (graphical processing unit).



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Transistors

- ◆ As of 2020, record for number of transistors in a single processor chip is NVIDIA's A100 chip.
 - shown here in a GPU (graphical processing unit).
 - chip itself is about a square inch; has 54 billion transistors.

