Hands-on Quantum Computing

Daniel Bowring
Fermilab
Ask-a-Scientist
April 7, 2019

QC is getting lots of hype.

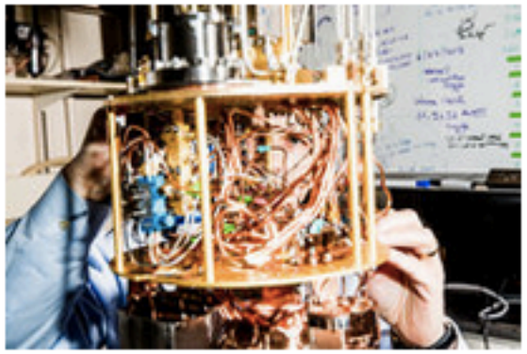
Nov. 13, 2017

NY Times

TECHNOLOGY

Yale Professors Race Google and IBM to the First Quantum Computer

Robert Schoelkopf helped create technology that promises to deliver the machines of tomorrow at Google and IBM. Now, he is giving them some competition.



Dec. 3, 2018

TECHNOLOGY

The Race Is On to Protect Data From the Next Leap in Computers. And China Has the Lead.

China is investing in quantum encryption that could be far tougher to crack than today's security methods. Now the United States is trying to catch up.

Oct. 21, 2018

TECHNOLOGY

The Next Tech Talent Shortage: Quantum Computing Researchers

By some estimates, only 1,000 or so researchers can claim to understand the technology. Finding more could become a national security issue.

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Scientists Worldwide Are Getting Serious About Quantum Internet

Ryan F. Mandelbaum

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U. of I. joins 'milestone' quantum tech research hub with University of Chicago

By Adam Thorp@AdamKThorp | email

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Technology

Forget the Trade War. China Wants to Win Computing Arms Race

By Susan Decker and Christopher Yasiejko

April 8, 2018, 6:00 PM CDT *Updated on April 9, 2018, 9:50 AM CDT*

- Next wave could transform everything from medicine to crops
- China is racing with U.S. companies for the quantum tech lead

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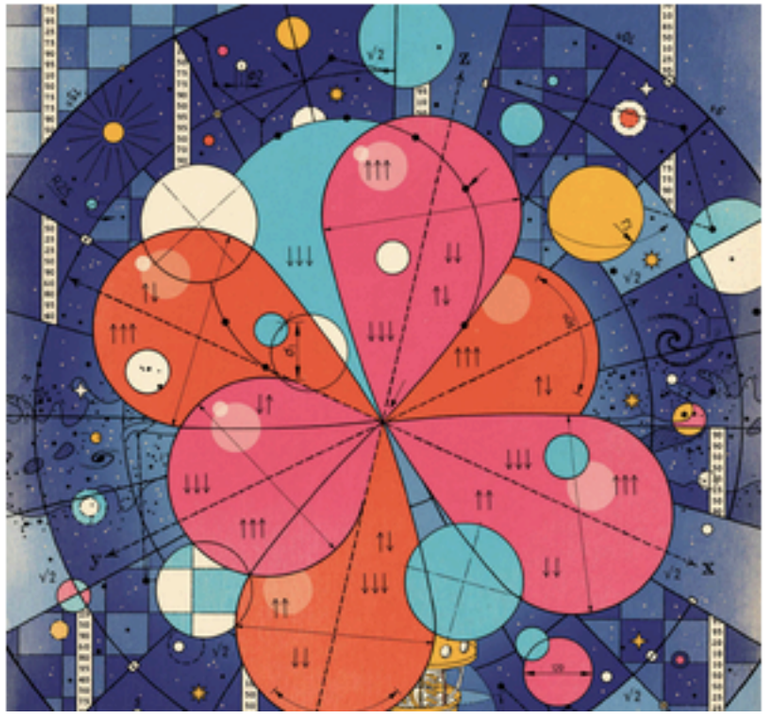
The Case Against Quantum Computing

The proposed strategy relies on manipulating with high precision an unimaginably huge number of variables

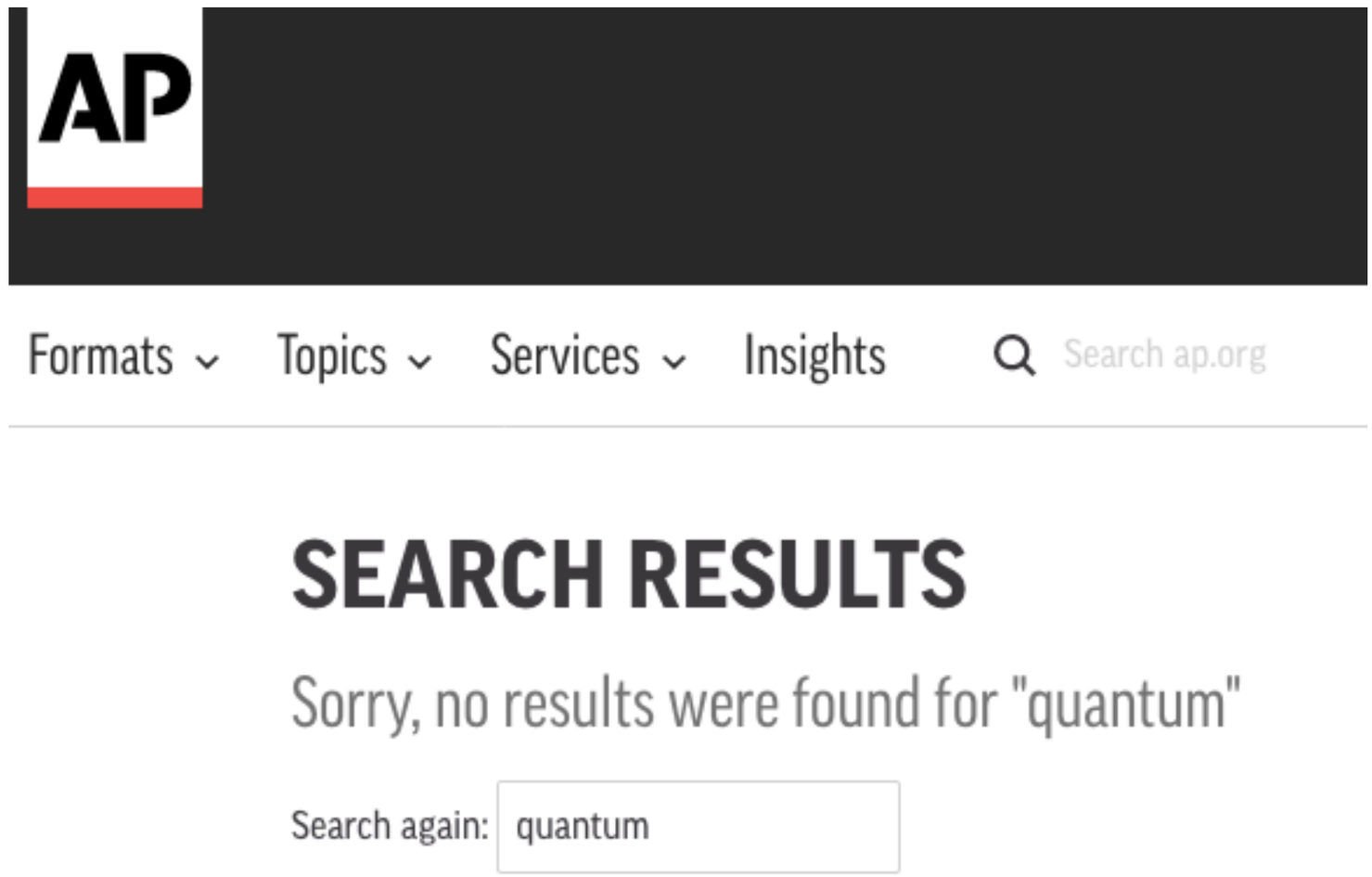
By **Mikhail Dyakonov**

Quantum computing is all the rage. It seems like hardly a day goes by without some news outlet describing the extraordinary things this technology promises. Most commentators forget, or just gloss over, the fact that people have been working on quantum computing for decades—and without any practical results to show for it.

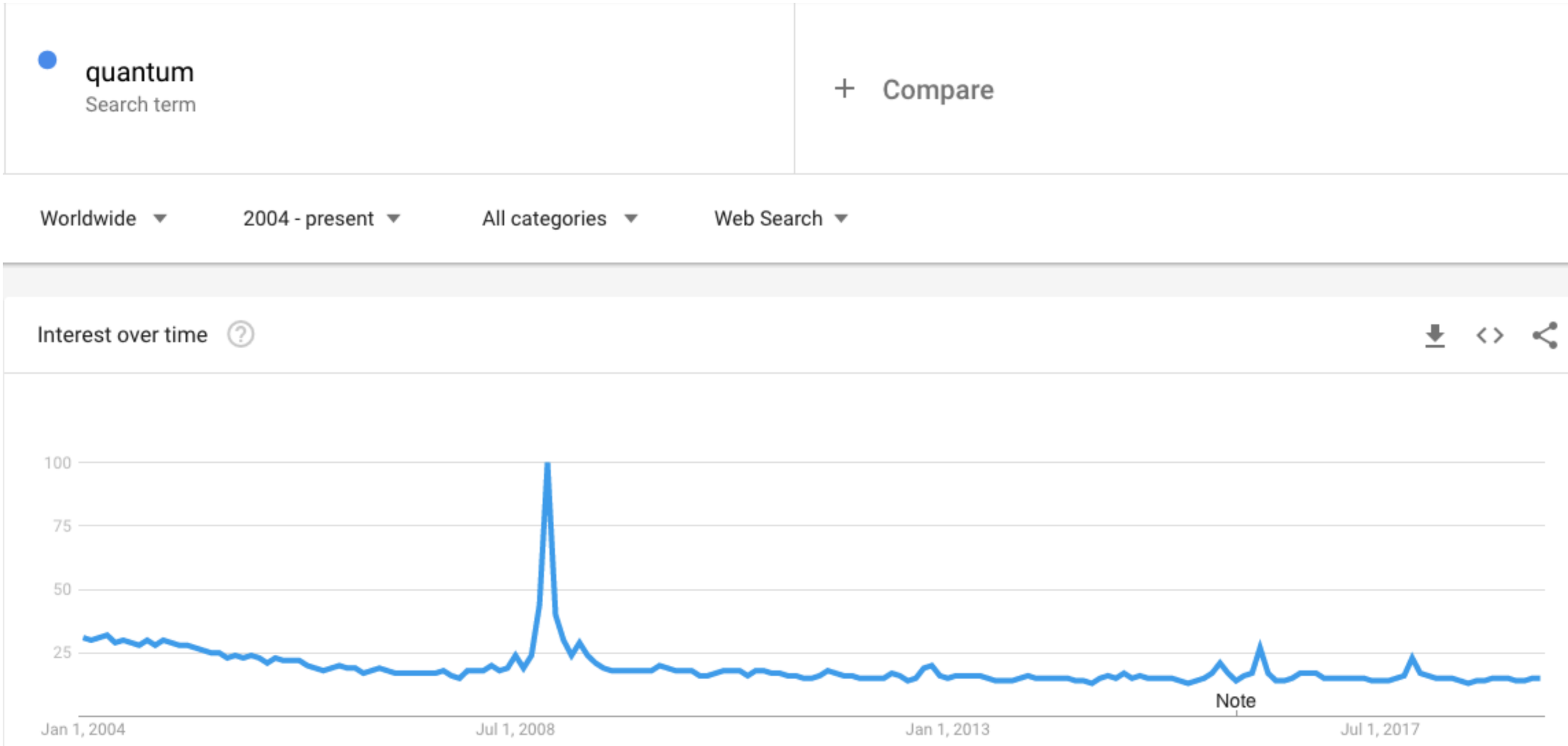


We've been told that quantum

QC is getting lots of hype.



QC is getting lots of hype.



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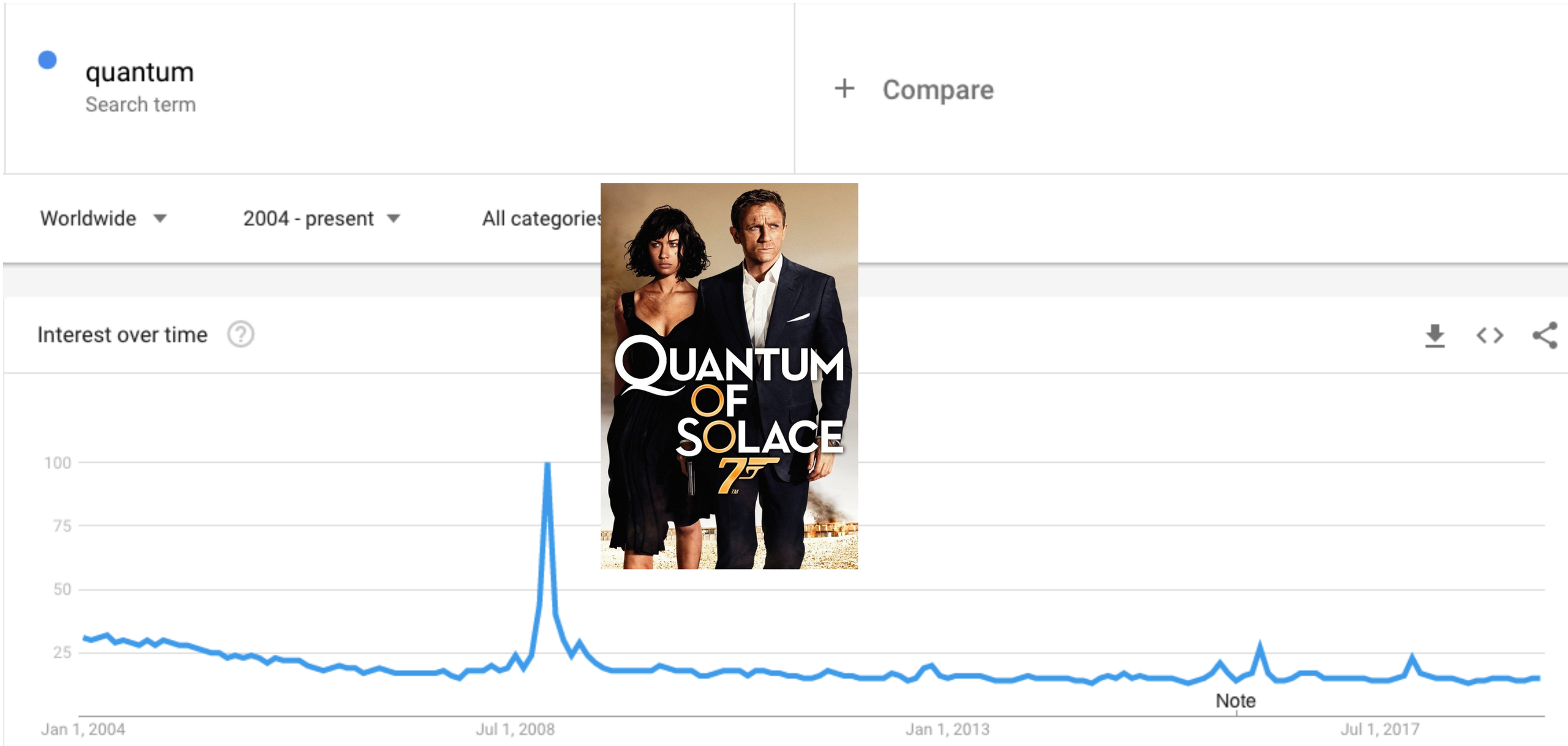


QC is getting lots of hype.

ars TECHNICA

BIZ & IT TECH SCIENCE POLICY CARS GAMING & CULTURE

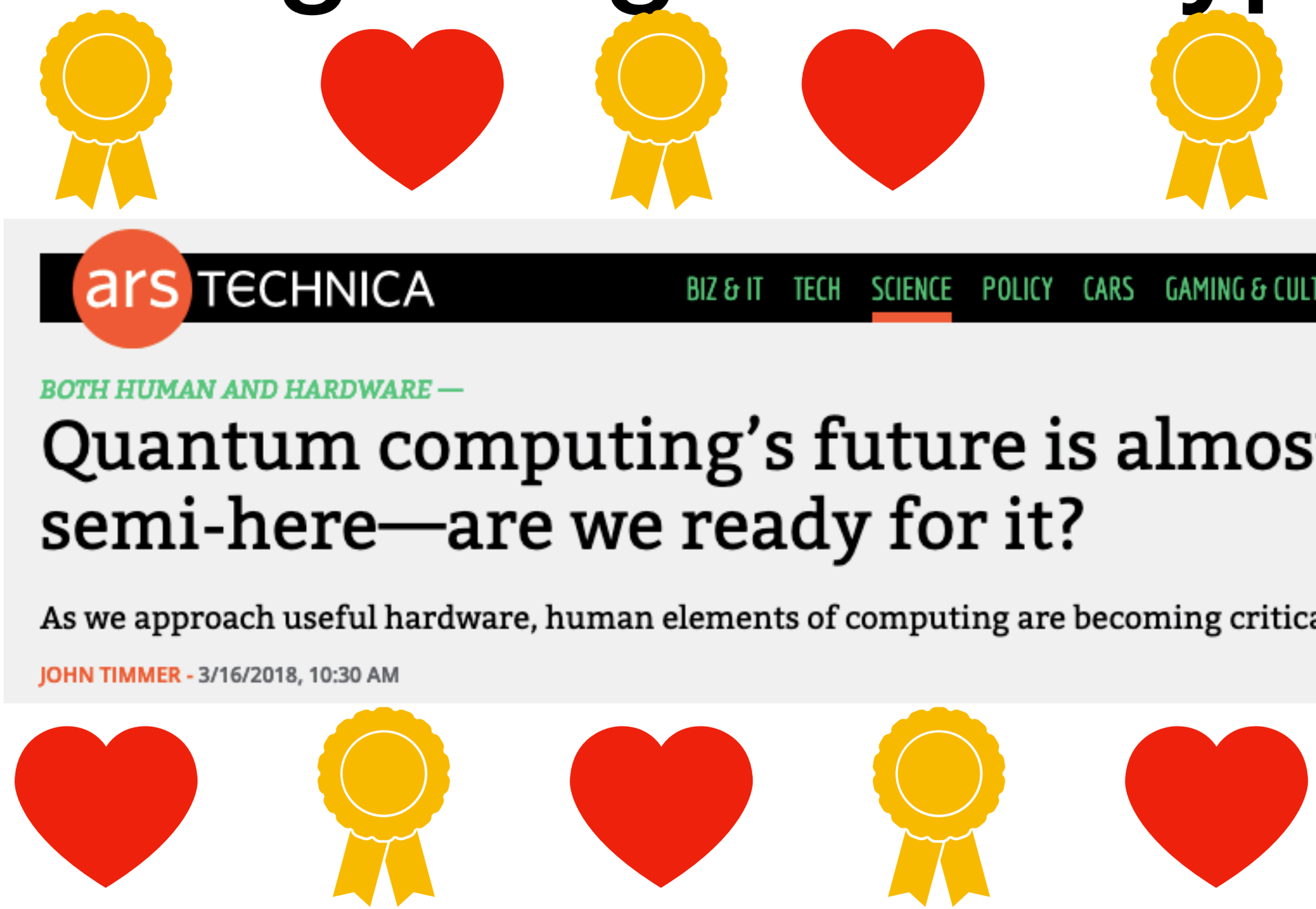
BOTH HUMAN AND HARDWARE —

Quantum computing's future is almost semi-here—are we ready for it?

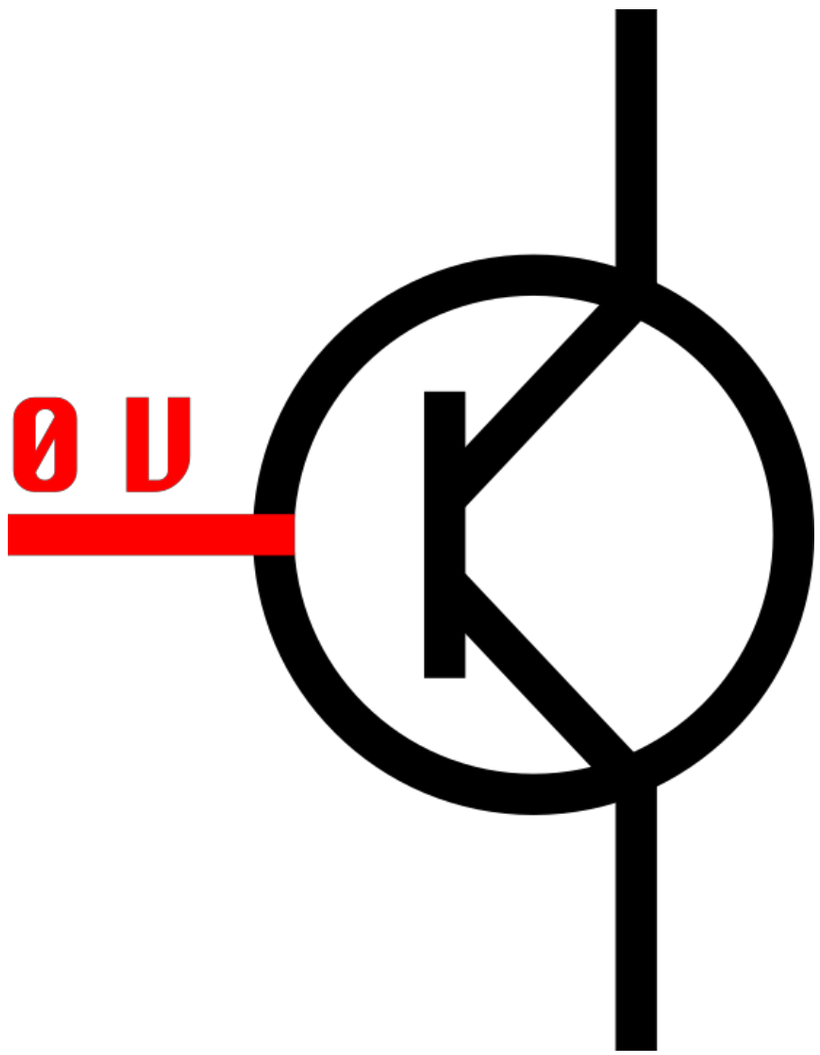
As we approach useful hardware, human elements of computing are becoming critical.

JOHN TIMMER - 3/16/2018, 10:30 AM

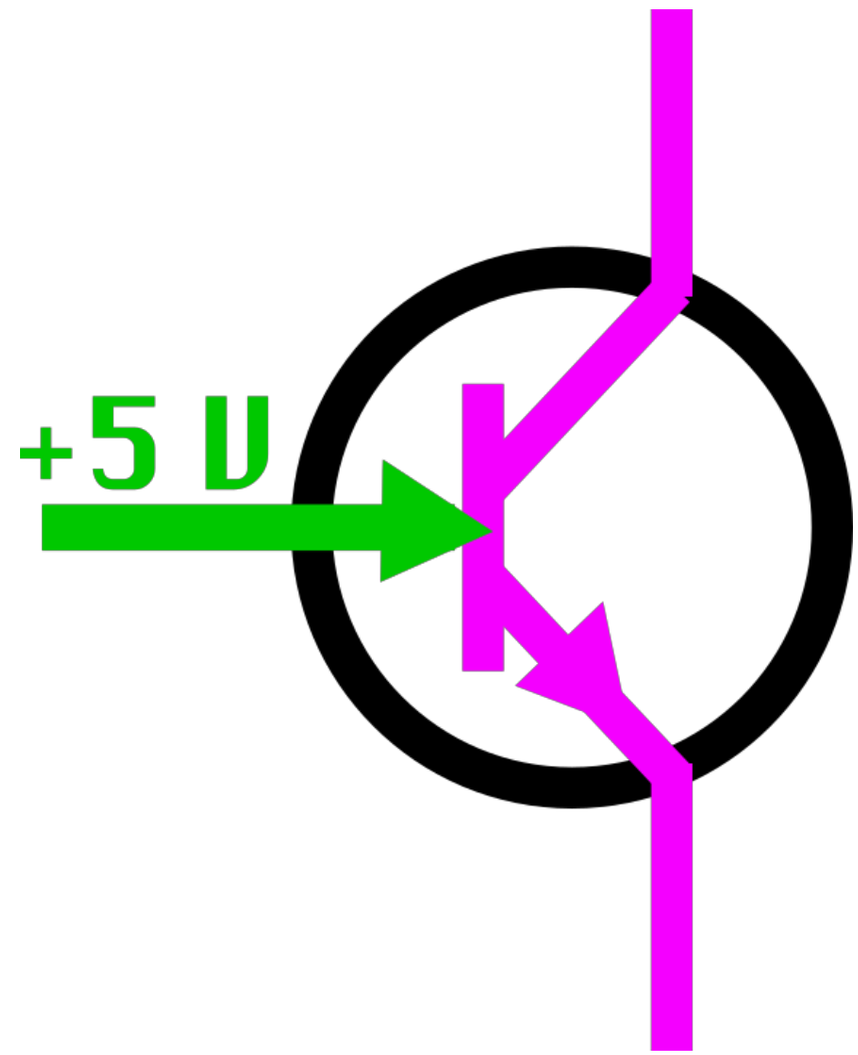
QC is getting lots of hype.



Transistors As Switches

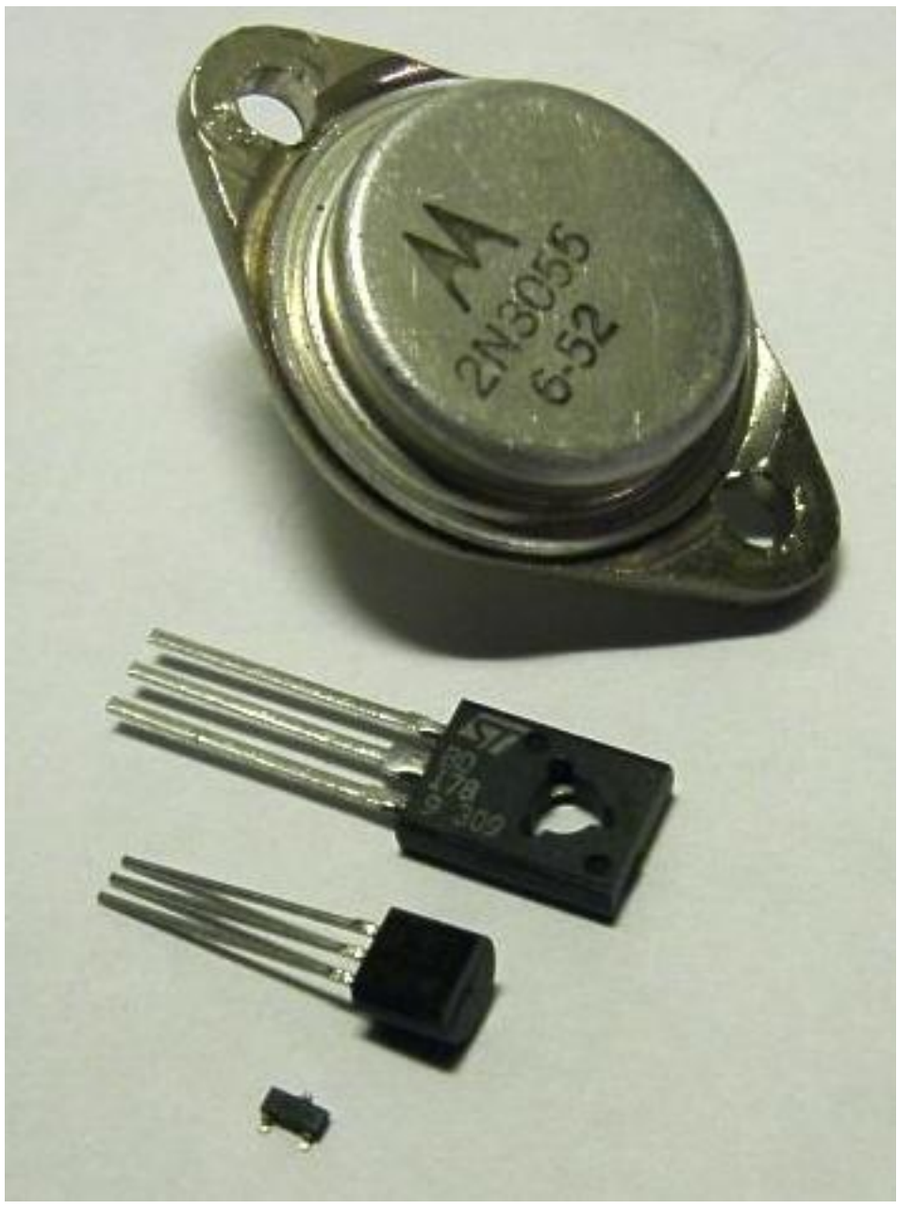


$|0\rangle$

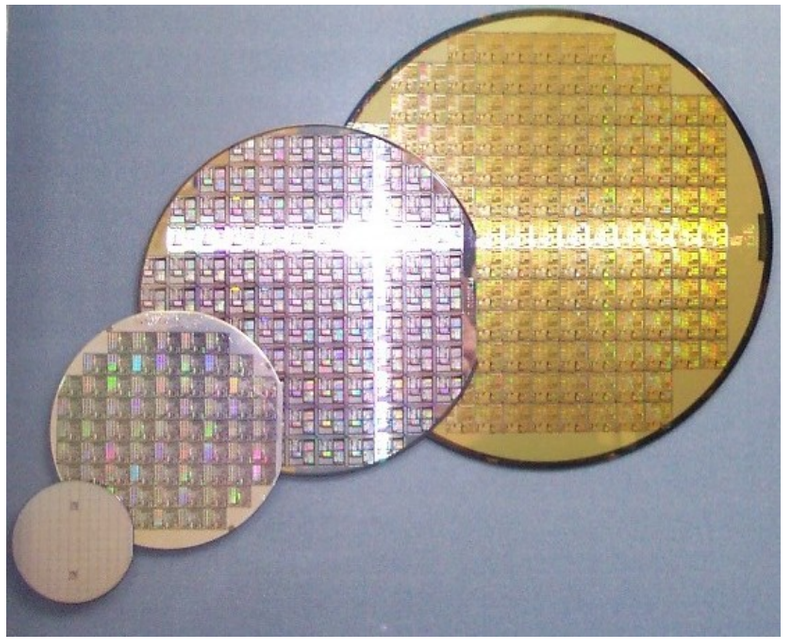


$|1\rangle$

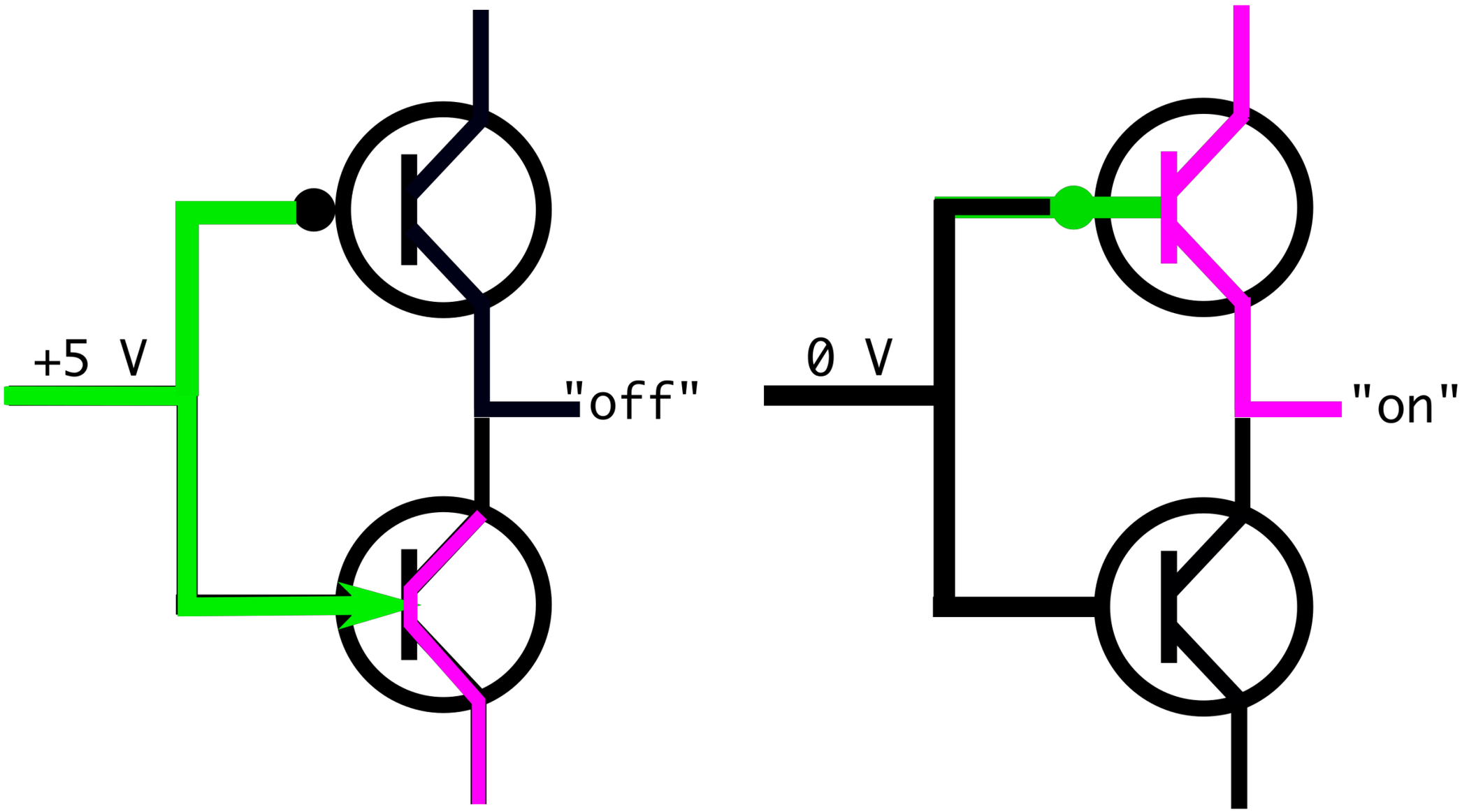
Transistors As Switches



- Many shapes, sizes power ratings
- They can also be used as amplifiers!
- They are *everywhere.*
- Want to guess how many are in your phone?



“Not Gate” From Transistors



Some Basic Gate Tables

NOT

IN	OUT
0	1
1	0

AND

IN	OUT
00	0
01	0
10	0
11	1

OR

IN	OUT
00	0
01	1
10	1
11	1

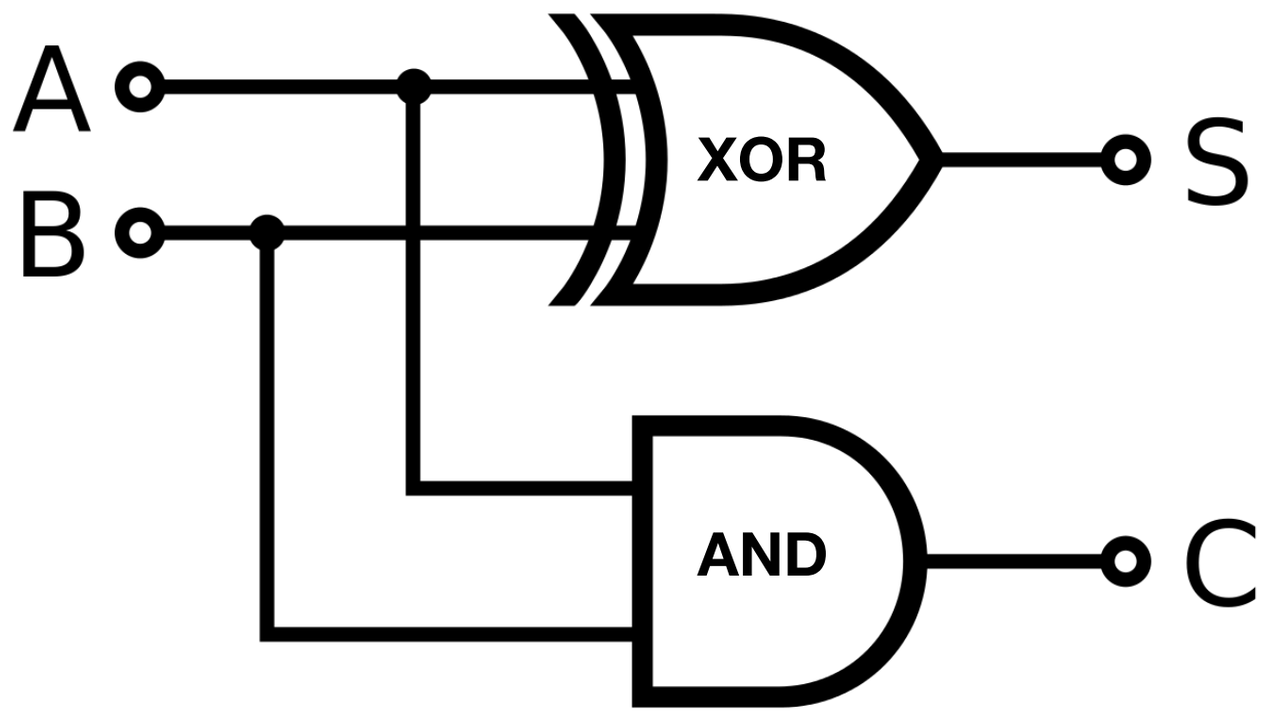
XOR

IN	OUT
00	0
01	1
10	1
11	0

How computers add

AND

IN	OUT
00	0
01	0
10	0
11	1



XOR

IN	OUT
00	0
01	1
10	1
11	0

Question: What are computers good at?

An answer: Following long, complicated instructions related to large data sets.

Example: video games

From Johnathan Blow's "The Witness" (Thekla Inc., 2016)

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From Johnathan Blow's "The Witness" (Thekla Inc., 2016)

The computer controls the color of every pixel on your screen. It follows a complex set of instructions to decide how every pixel should change in response to the players' (and other objects, and NPCs, etc.) tiniest movements.
… This is not a great job for a person.

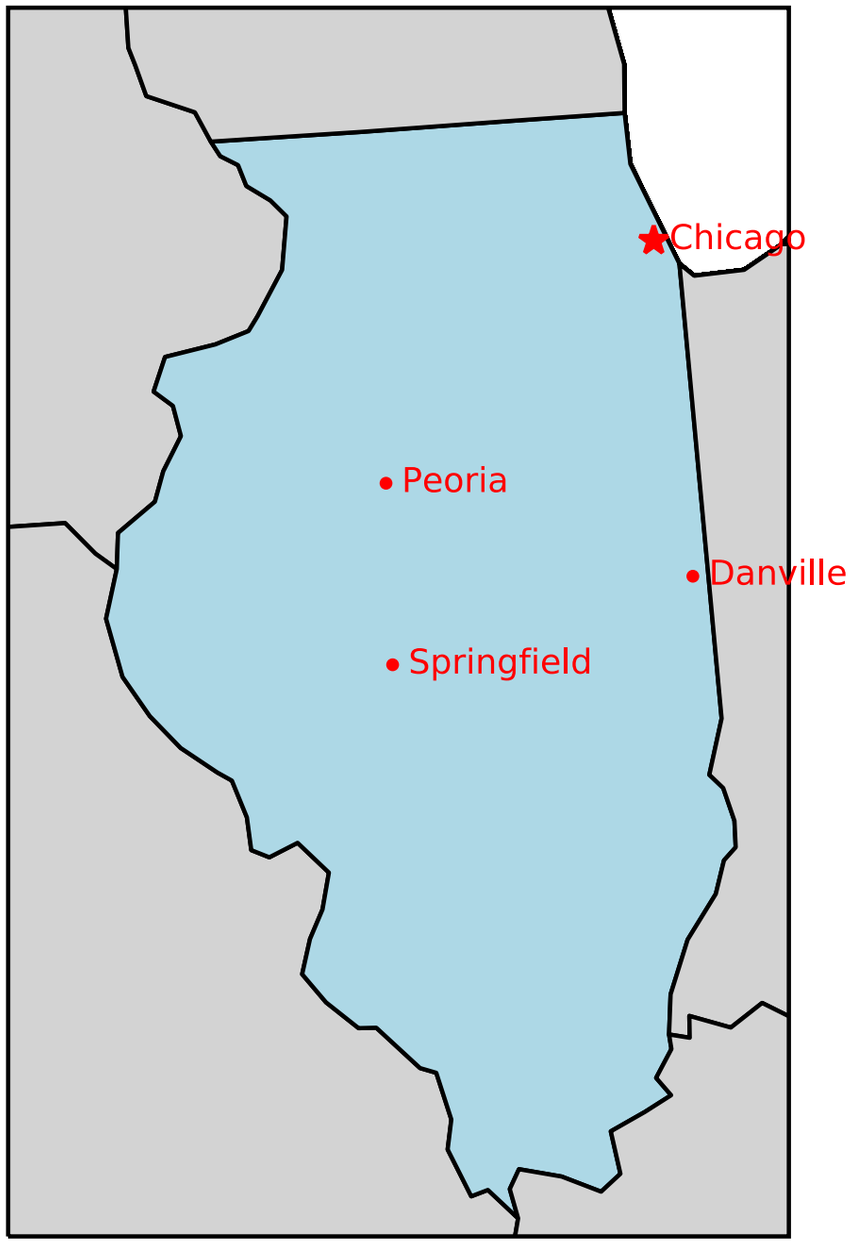
Example: video games

From Johnathan Blow's "The Witness" (Thekla Inc., 2016)

The computer controls the color of every pixel on your screen. It follows a complex set of instructions to decide how every pixel should change in response to the players' (and other objects, and NPCs, etc.) tiniest movements.
… This is not a great job for a person.
… And a computer does it using logic gates!

Maybe an interesting question:
What jobs are *computers* bad at?

Let’s talk about the “traveling salesman problem”.



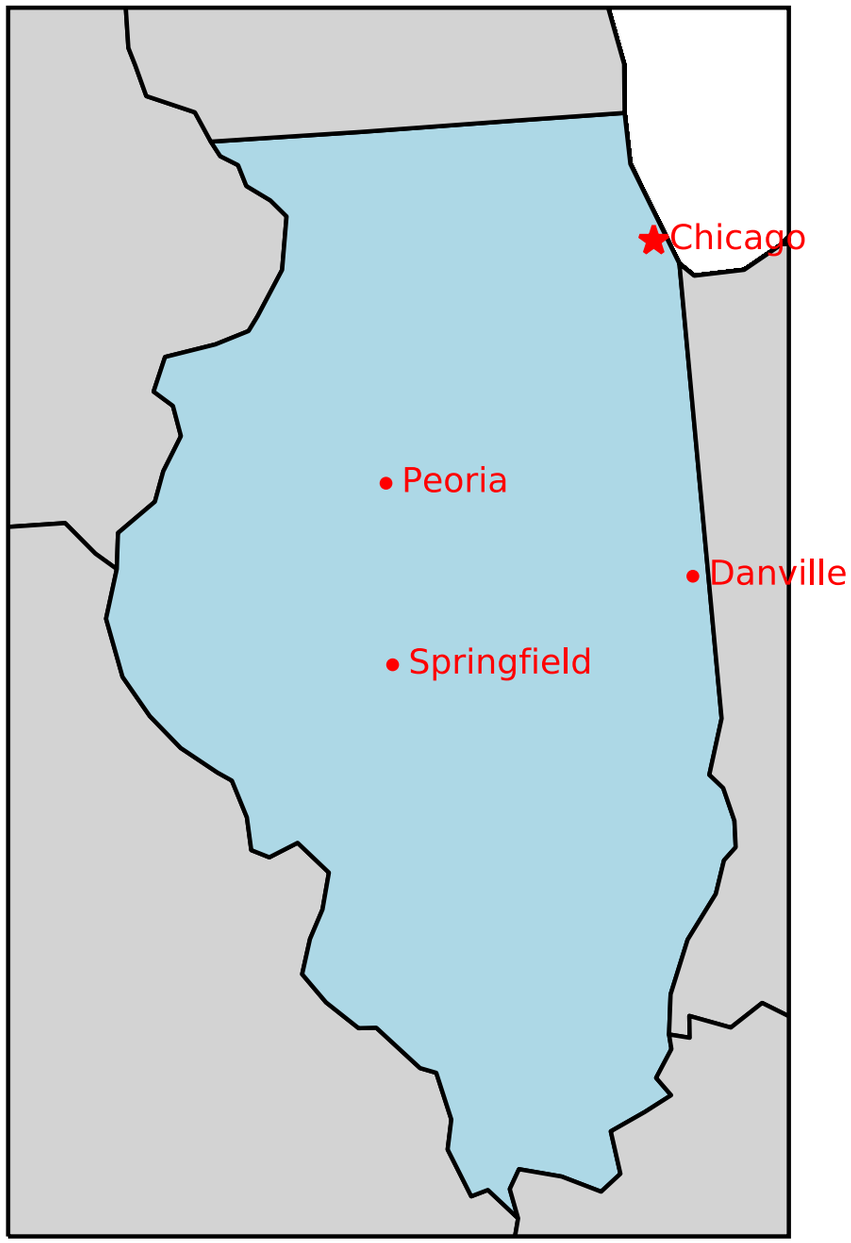
You have four cities on your sales route. Try to optimize your trip:

- **depart from Chicago**
- **visit each city exactly once**
- **visit every city on your route**
- **end up back in Chicago**

How would you plan your route?

Simplification: traveling salesbird

Let’s talk about the “traveling salesman problem”.



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- **depart from Chicago**
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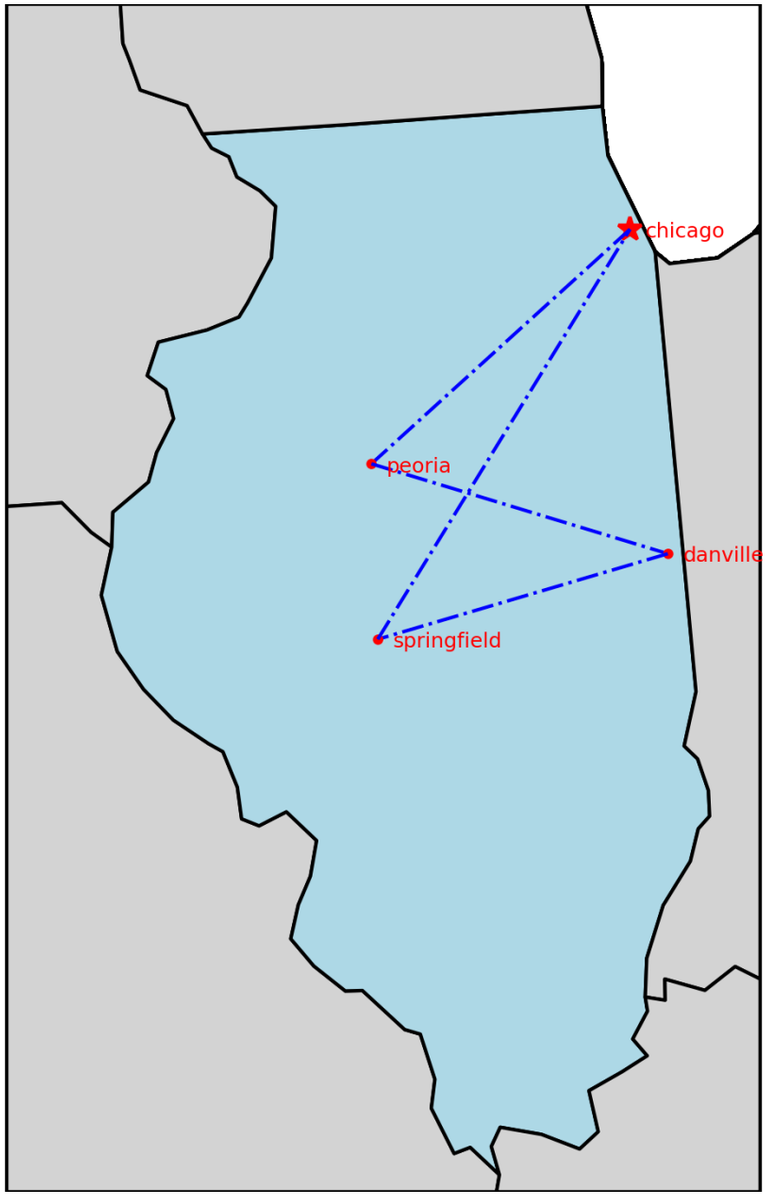
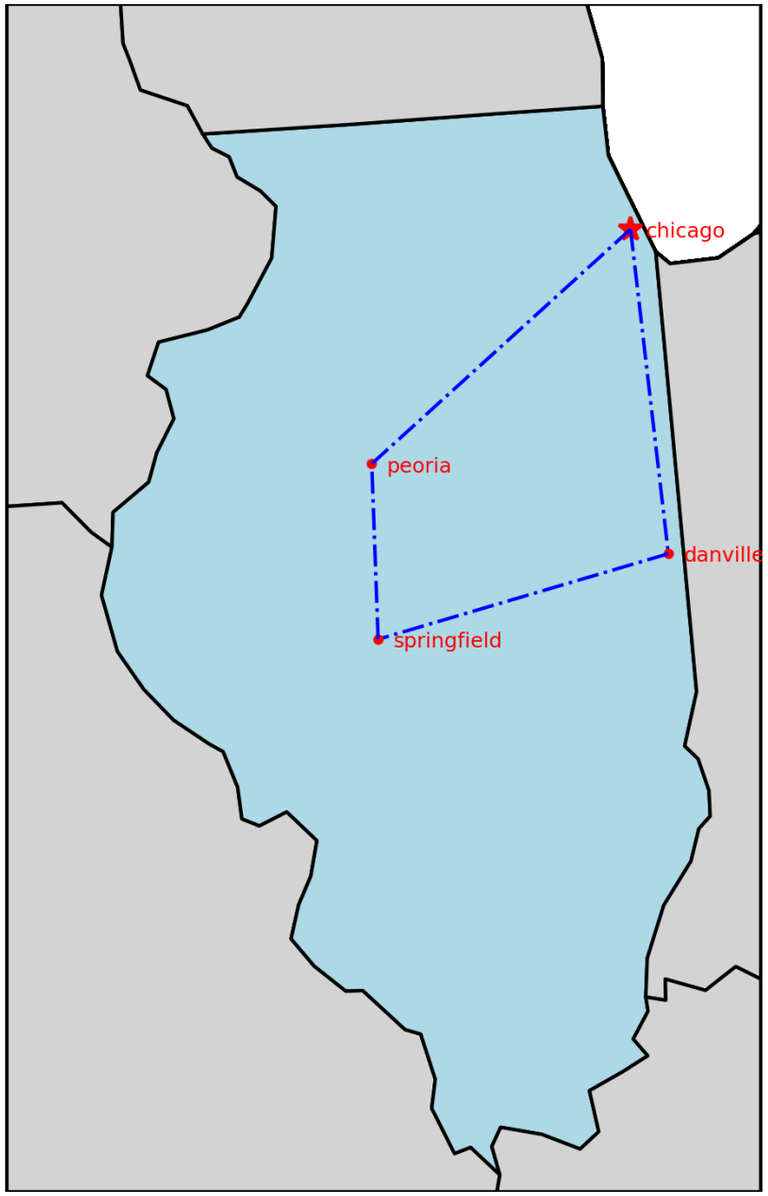
How would you plan your route?

Let’s start “easy”, with four cities.





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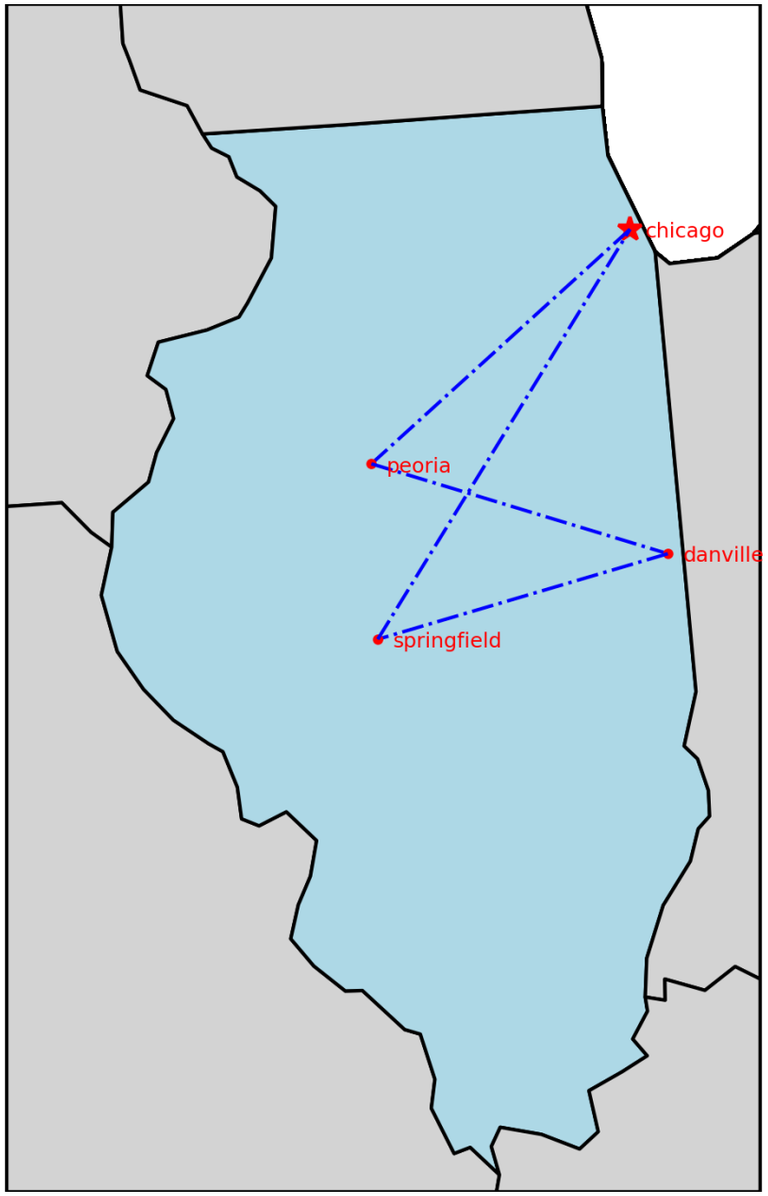
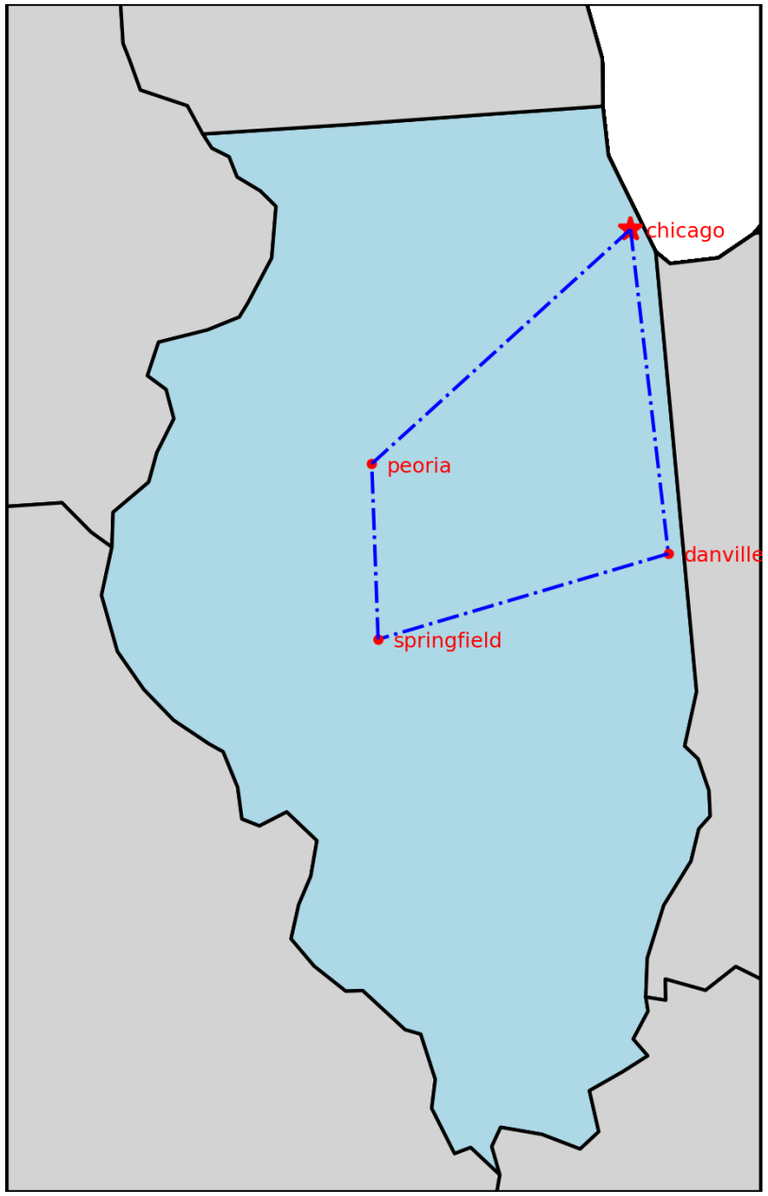
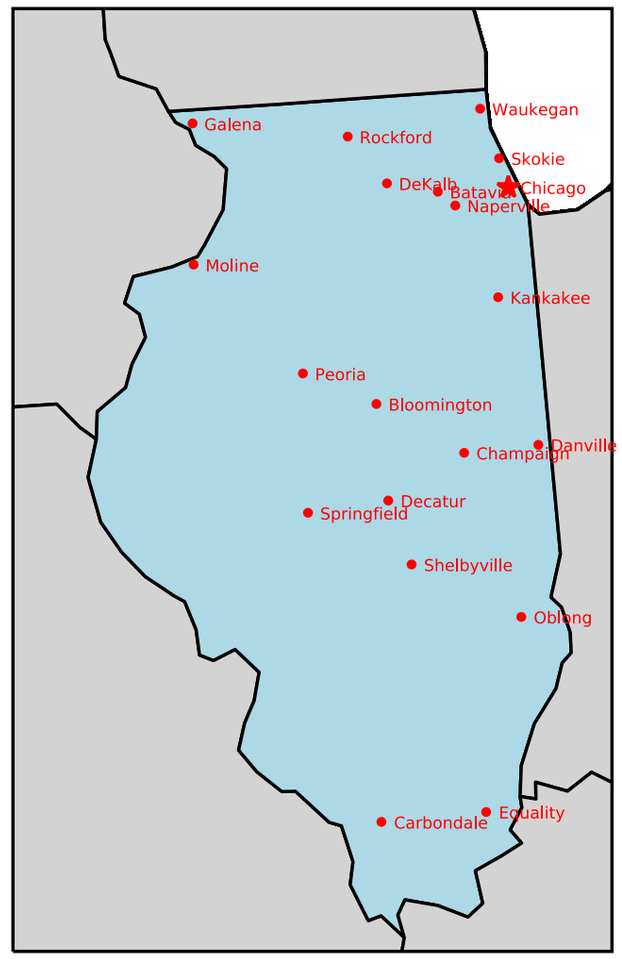


754 km



673 km (11% improvement)

What if you had more cities on your route?



This is still a simplified example. But what if:

- **the price of gas was different in different cities and/or**
- **you had to visit some cities before others and/or**
- **you were doing this not just for yourself but for a whole team?**

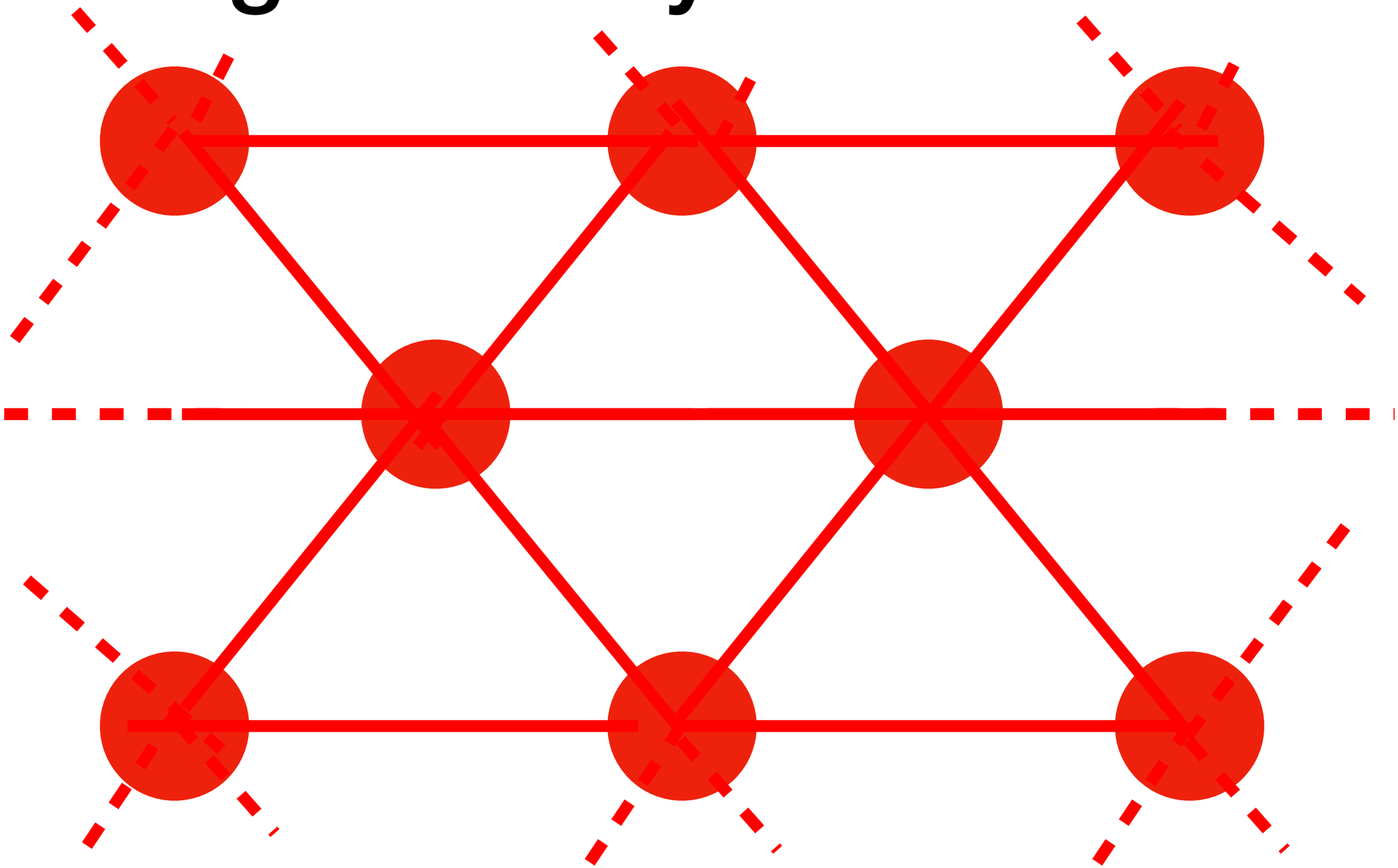
Lots of ways to make this more complicated.

“Simulated Annealing” is our solution.

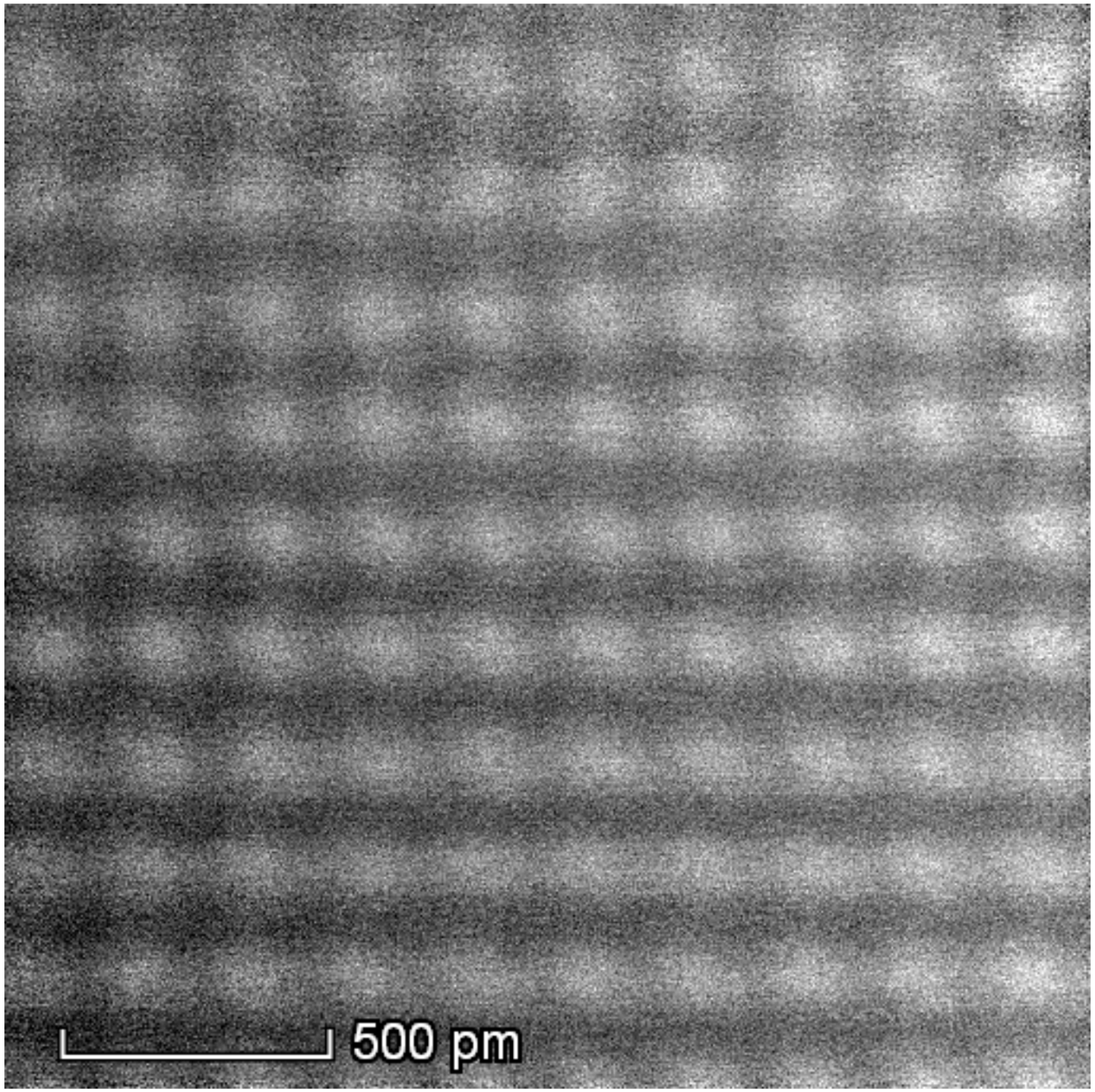
What is regular annealing?

Working hardens a metal, increasing the chance of cracking, tearing, or other failure modes.

Metals are made from very regular arrays of atoms.

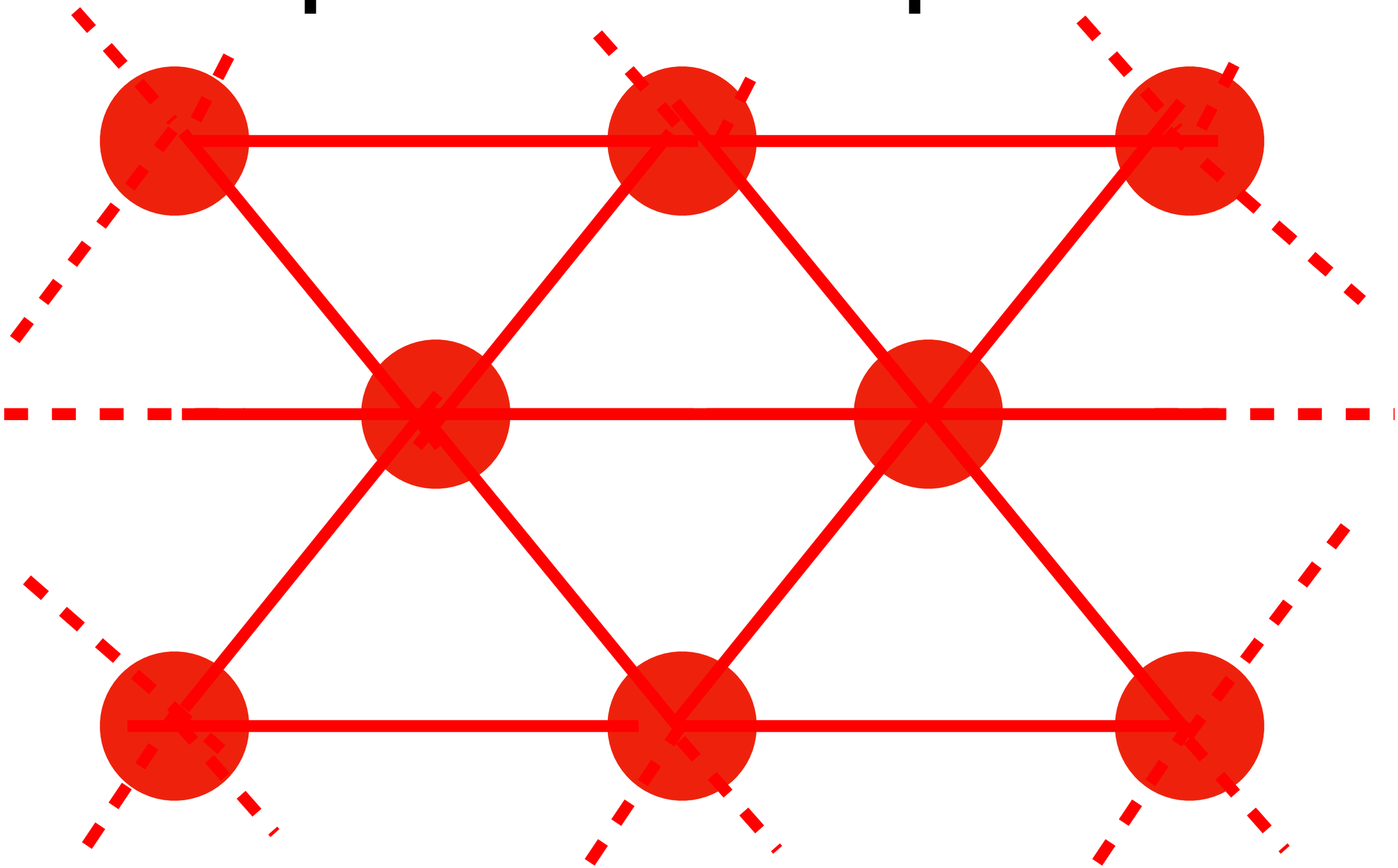


Aluminum, via scanning tunneling electron microscope!



Matheustunes [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)]

Atoms jiggle in their array, in response to temperature.



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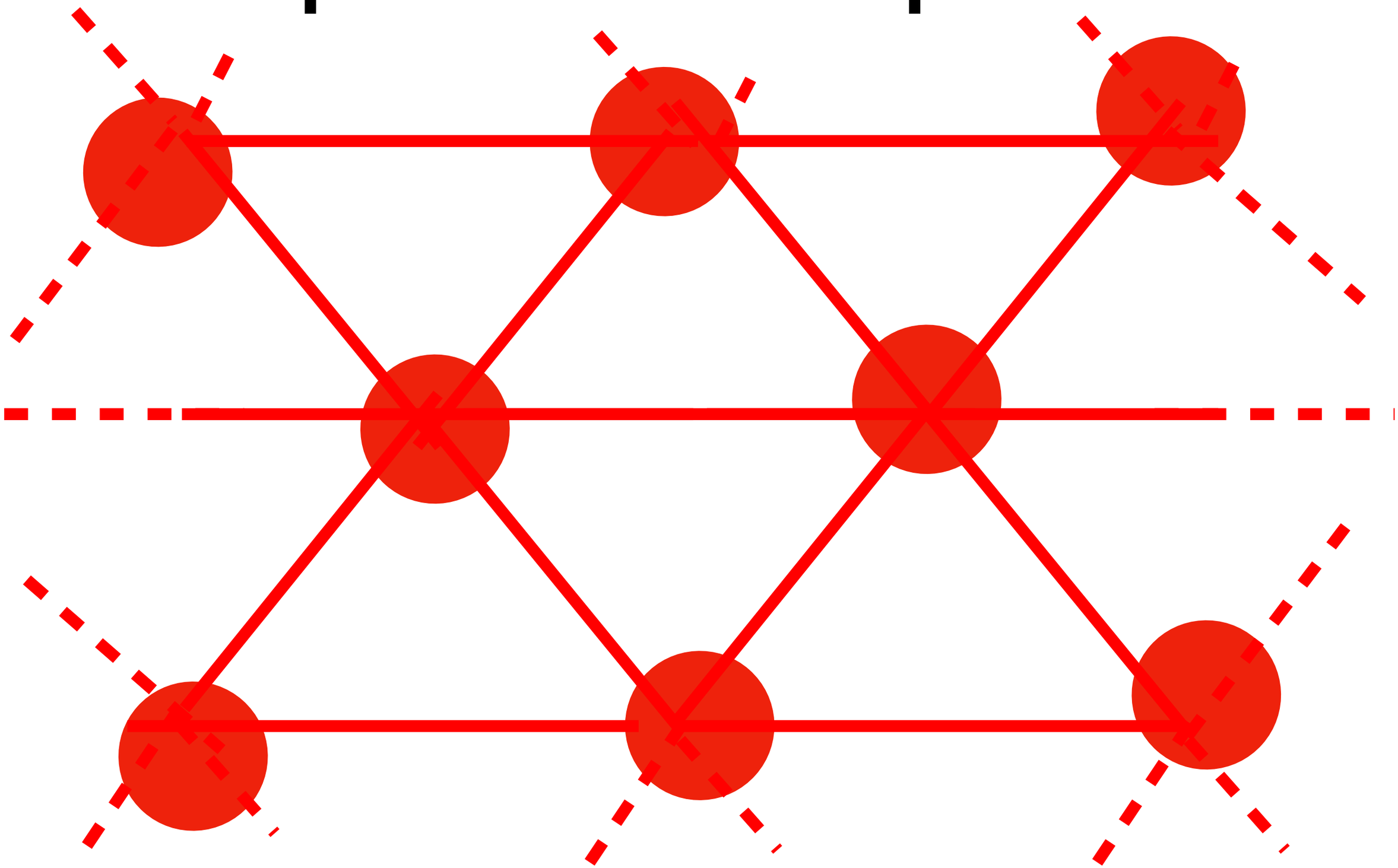

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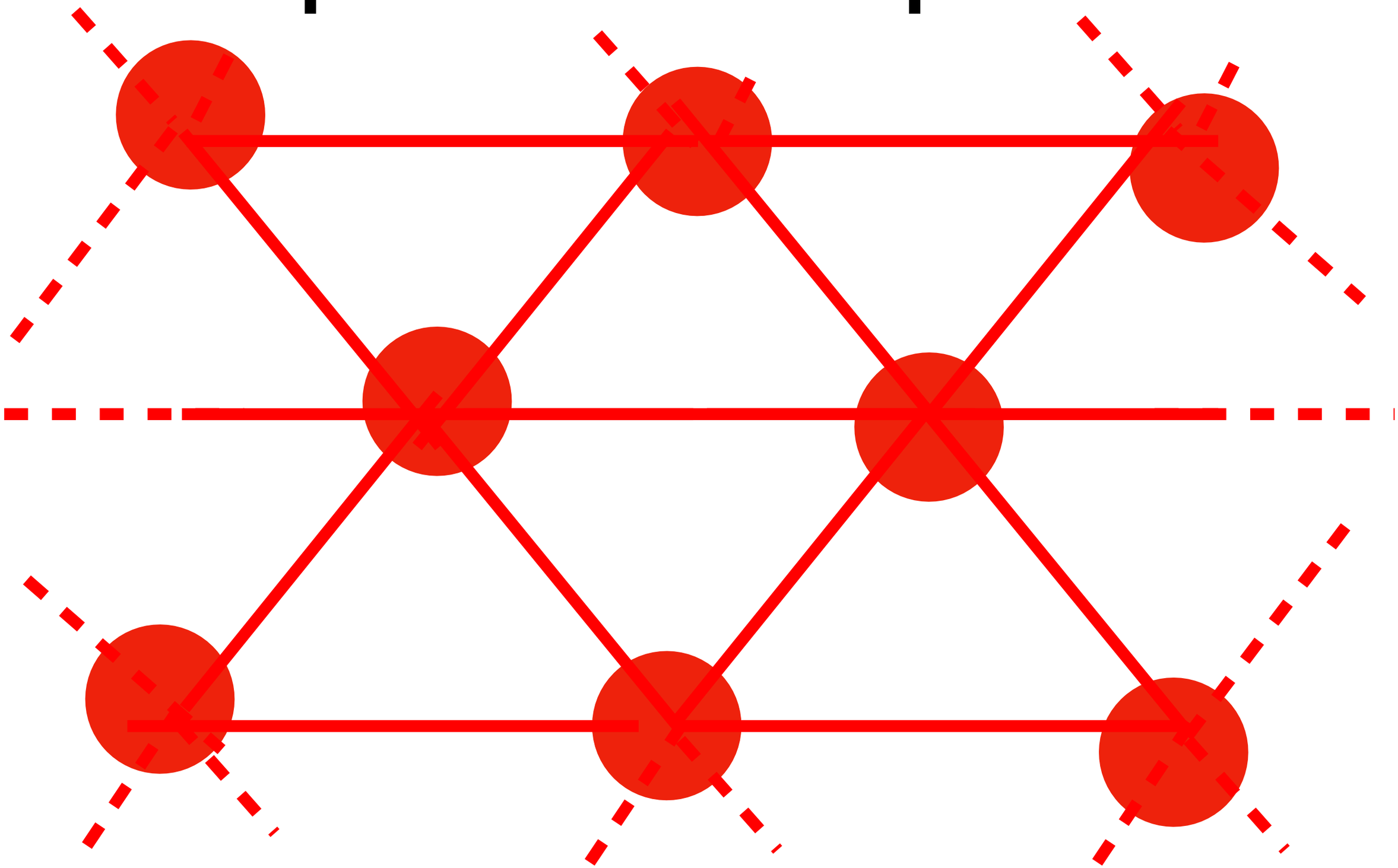
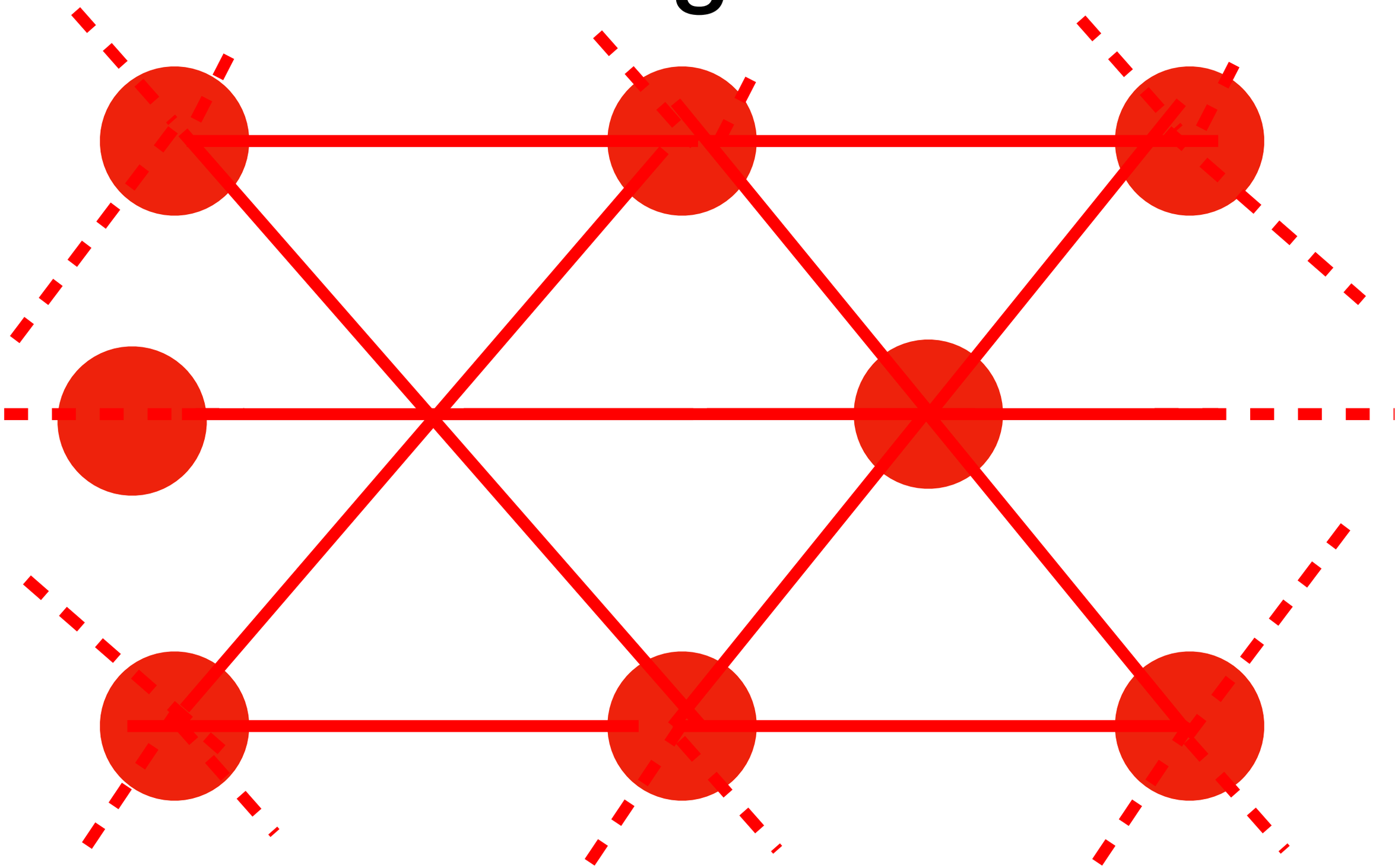
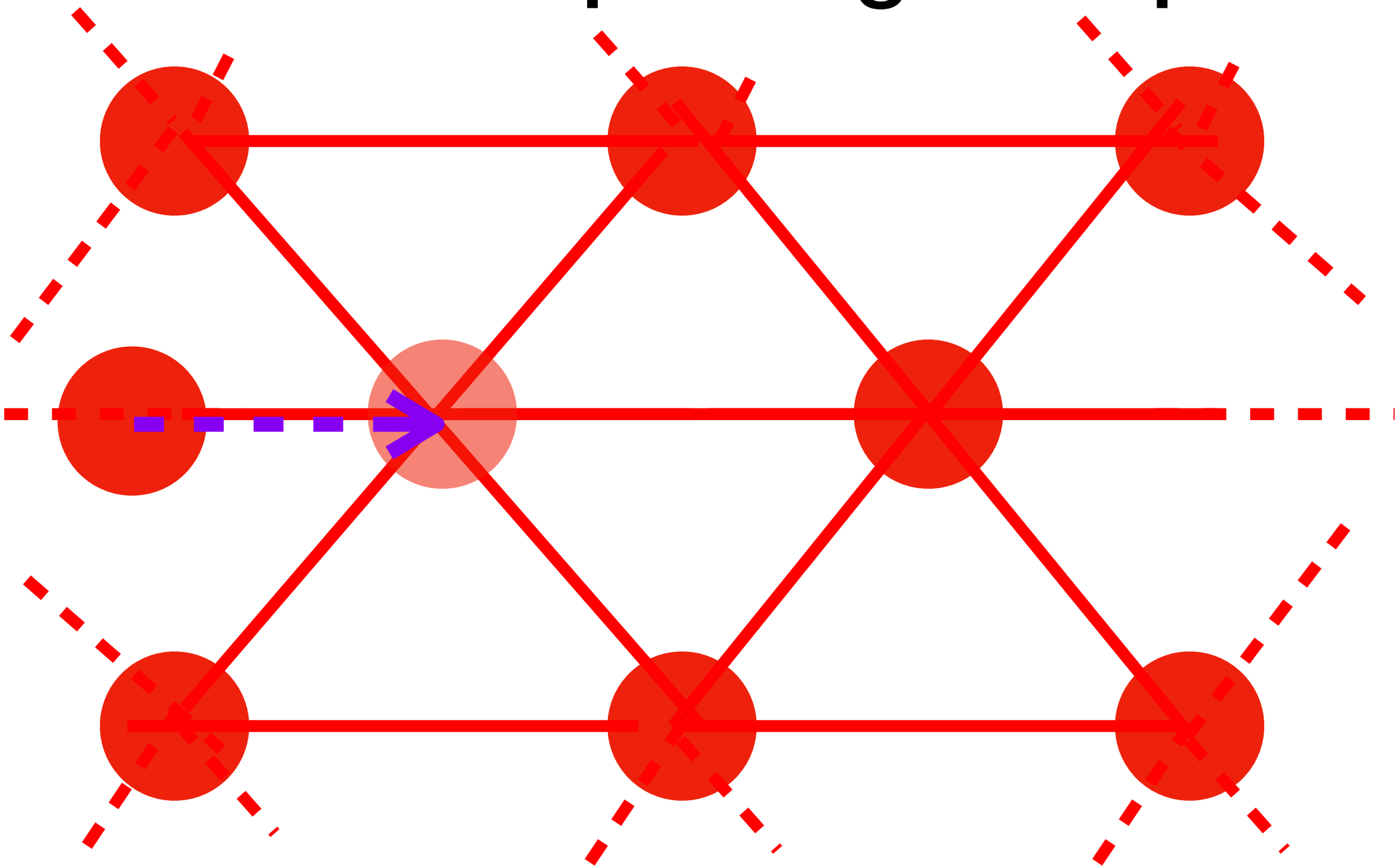


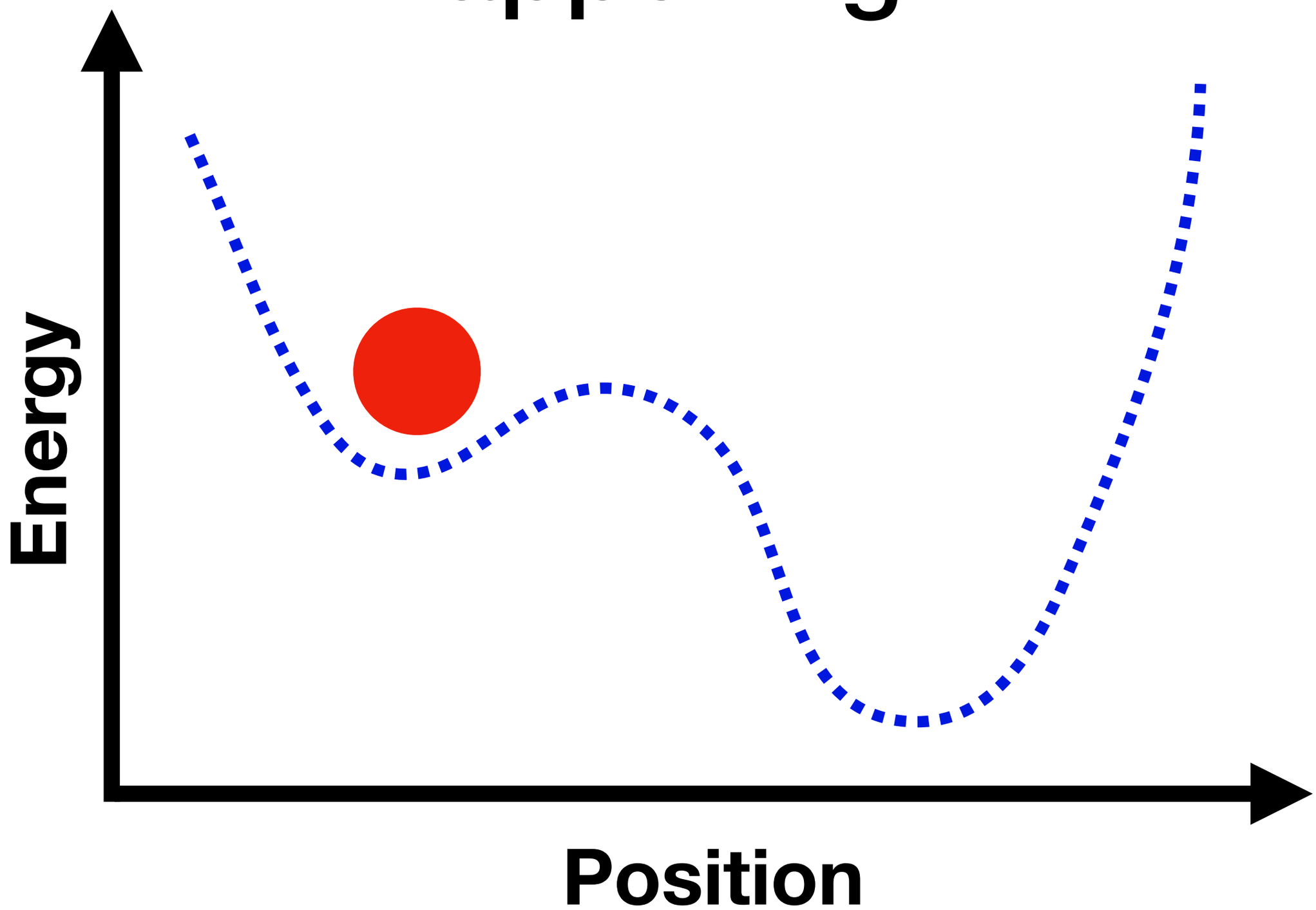
Sometimes the array is not so regular.



With enough temperature, the atom can hop to a good spot.



In terms of energy, what is happening?



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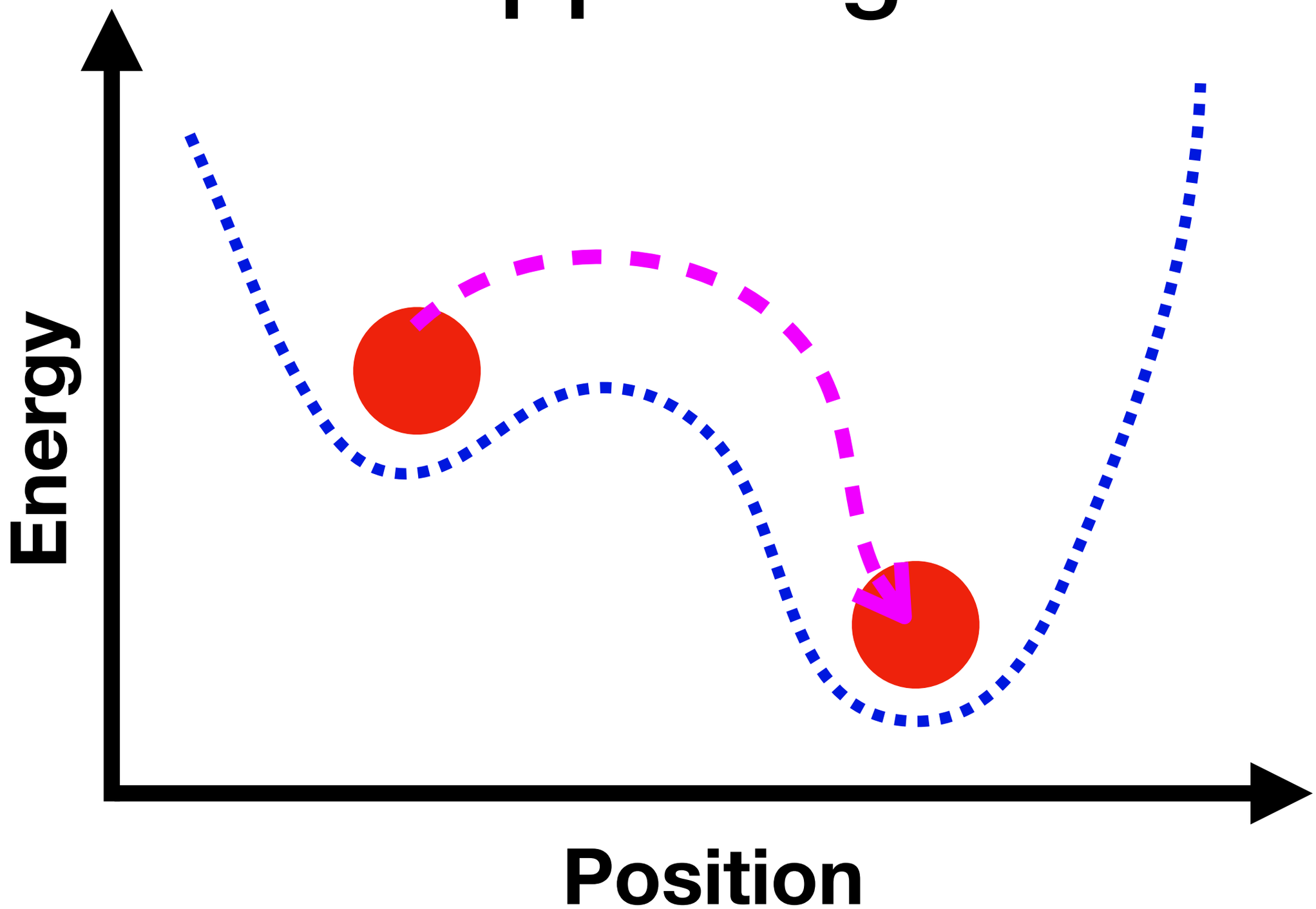
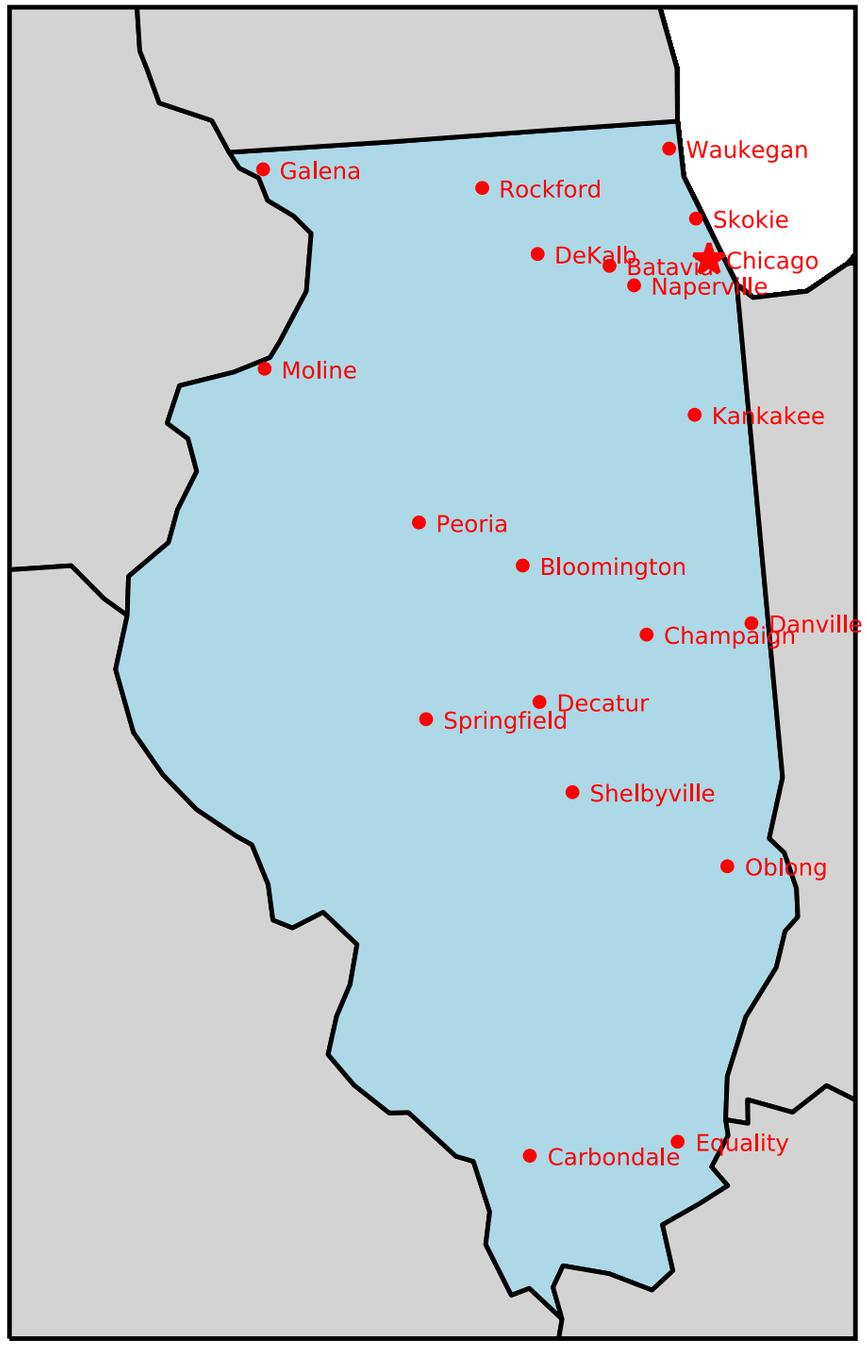


Annealing helps atom lattices to find their *minimum energy configuration.*

(But don’t put in so much energy that your metal melts.)

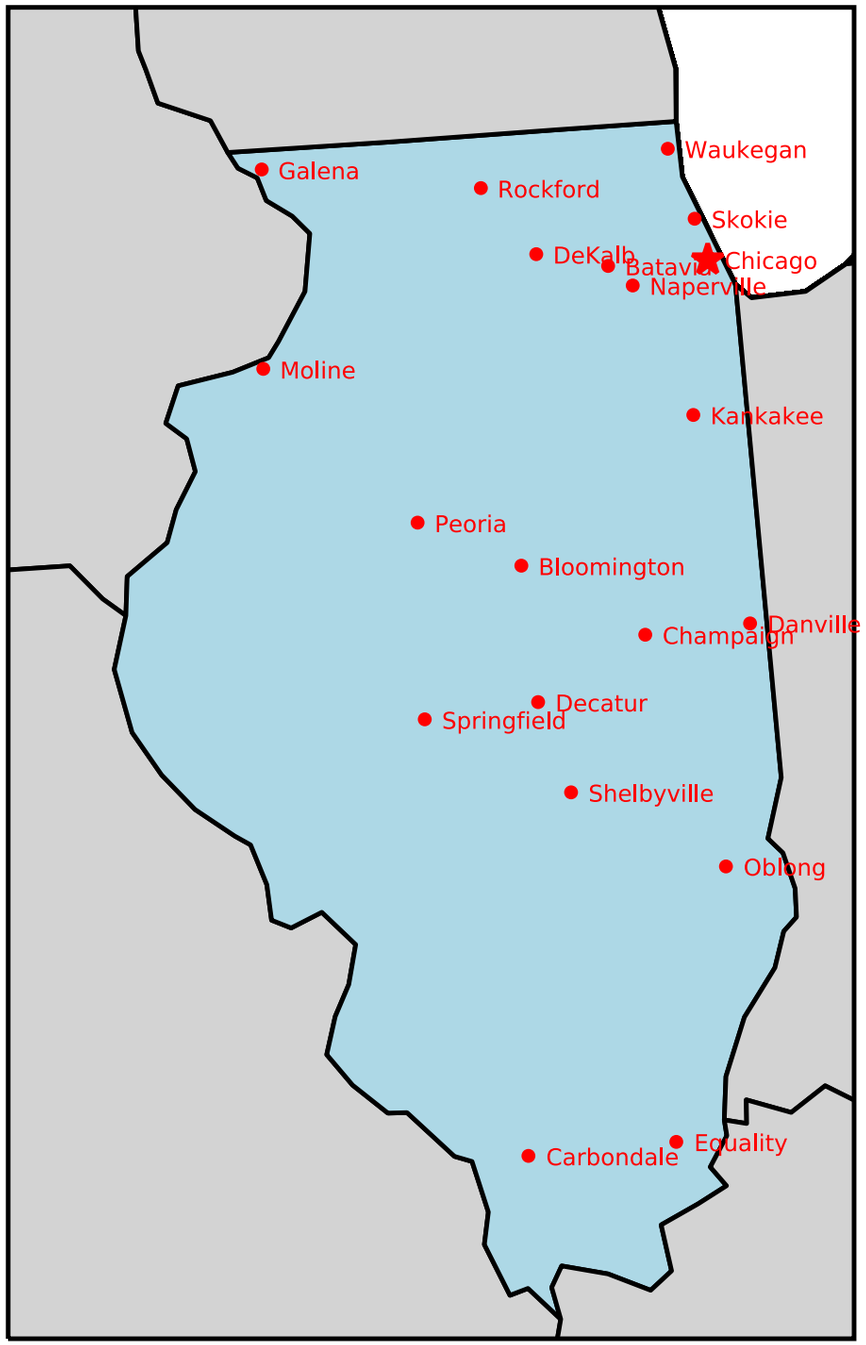
Simulated annealing can help us find the minimum-energy configuration of other systems.

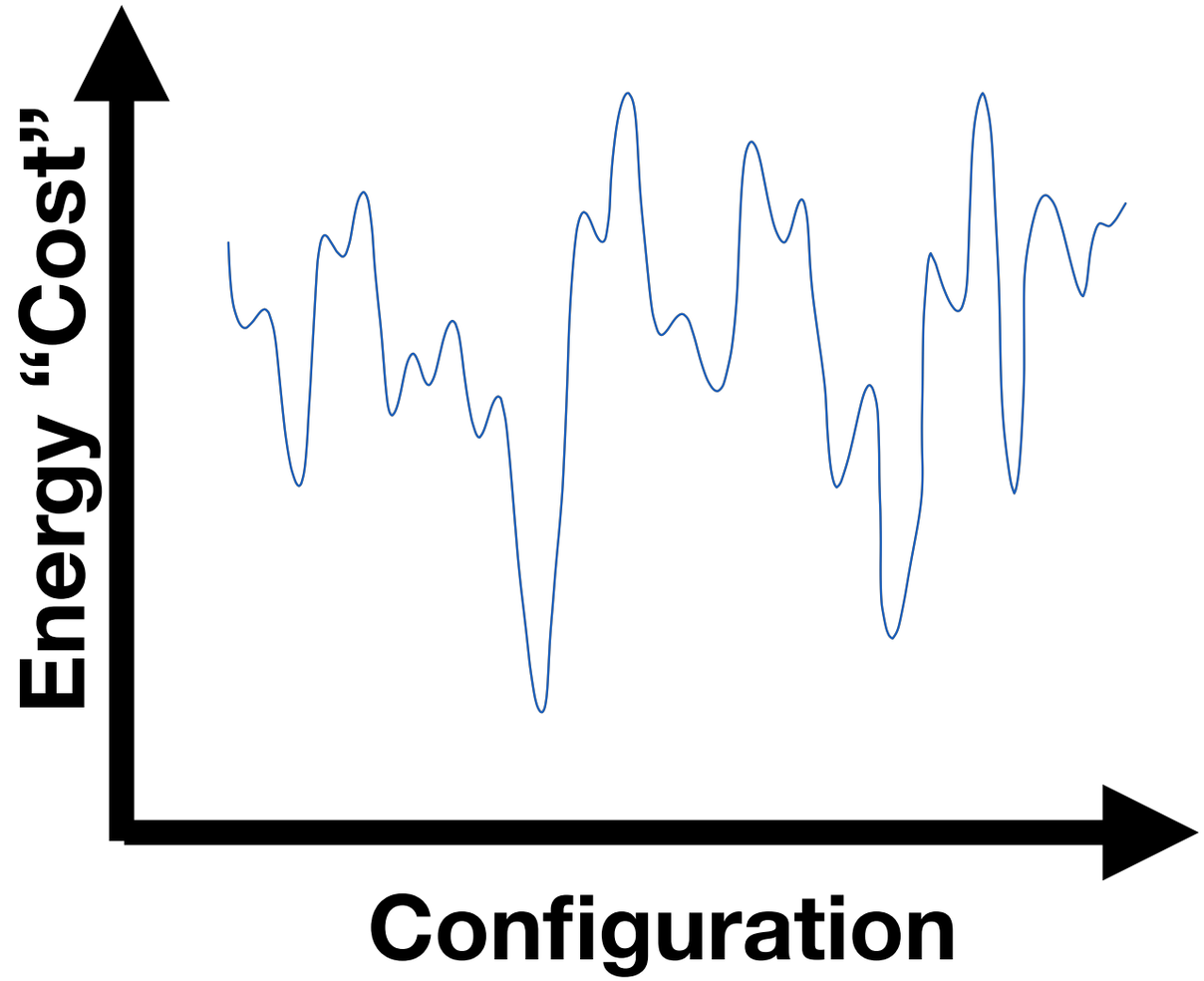


What do I mean by “configuration”?

- The salesbird visits cities in a specific order.
- I’m calling that order the **configuration of the system.**
- If the salesbird makes a bunch of round trips downstate, that’s a lot of miles traveled! This configuration is expensive.
- A more efficient route (configuration) uses less energy (money, time, fuel, whatever).
- We want to find the **lowest-energy configuration.**

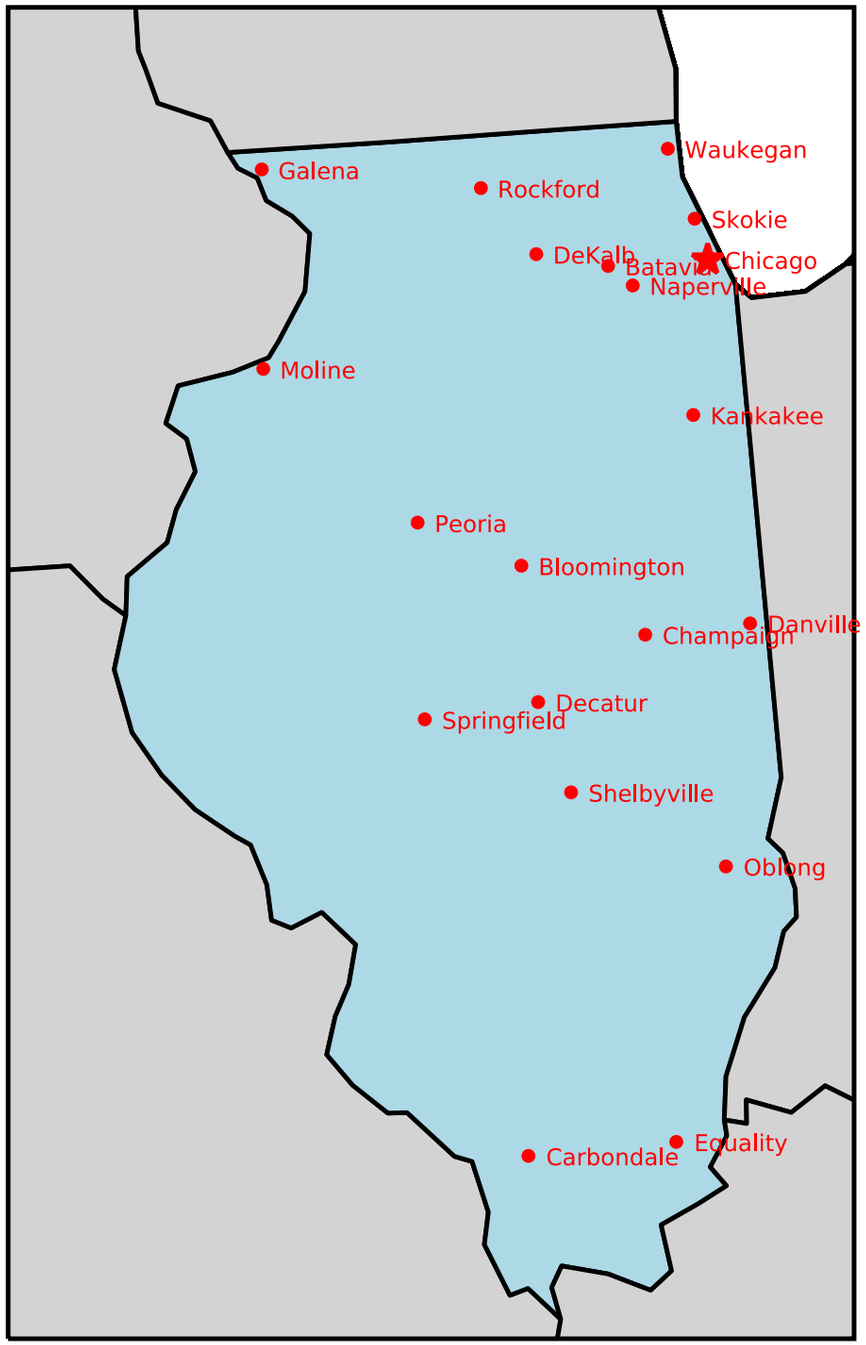
All the possible trips take some amount of "energy". How do we find the minimum?

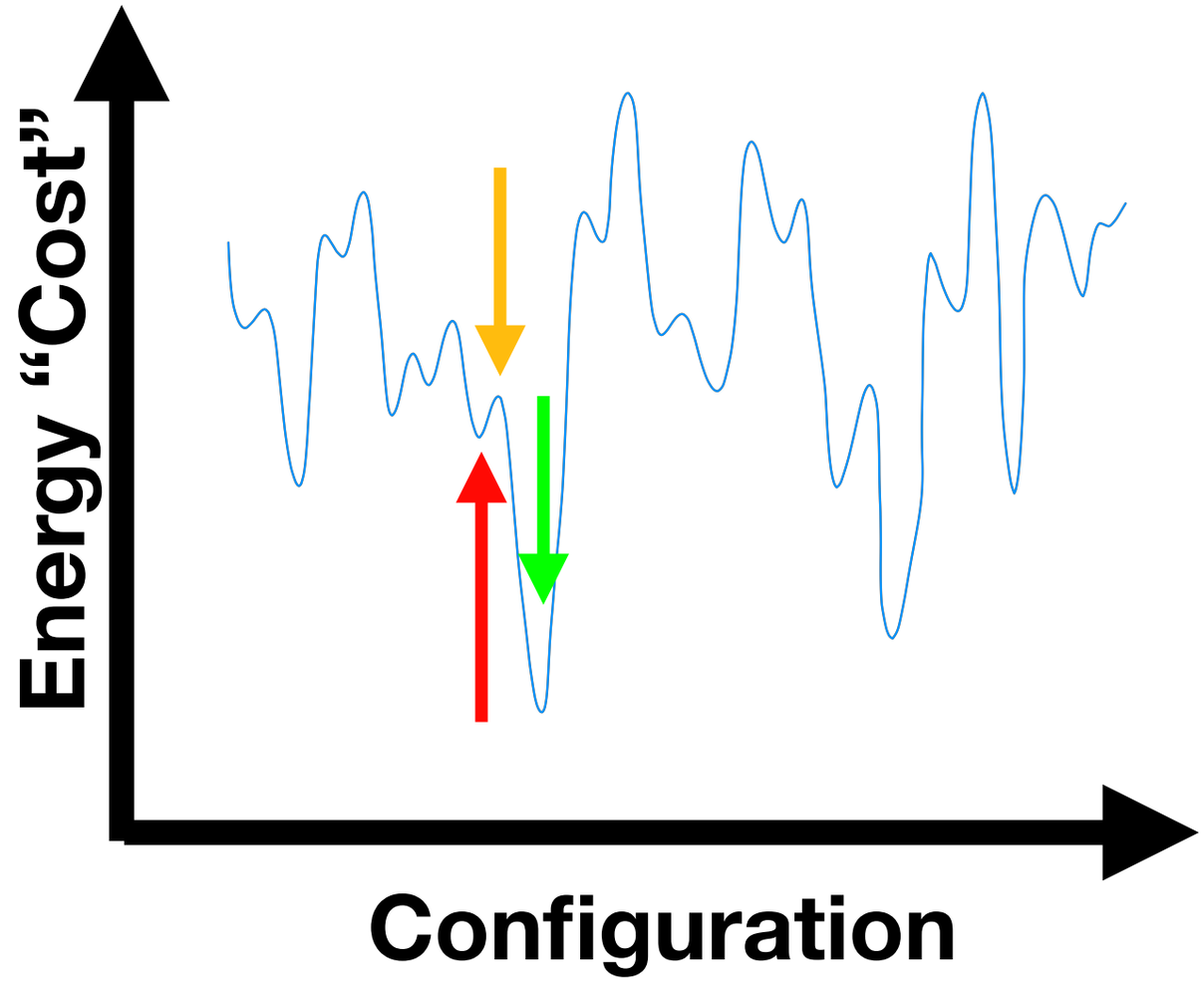




More generally, this could be a HUGE function defined over way, way more than one dimension.

All the possible trips take some amount of "energy". How do we find the minimum?

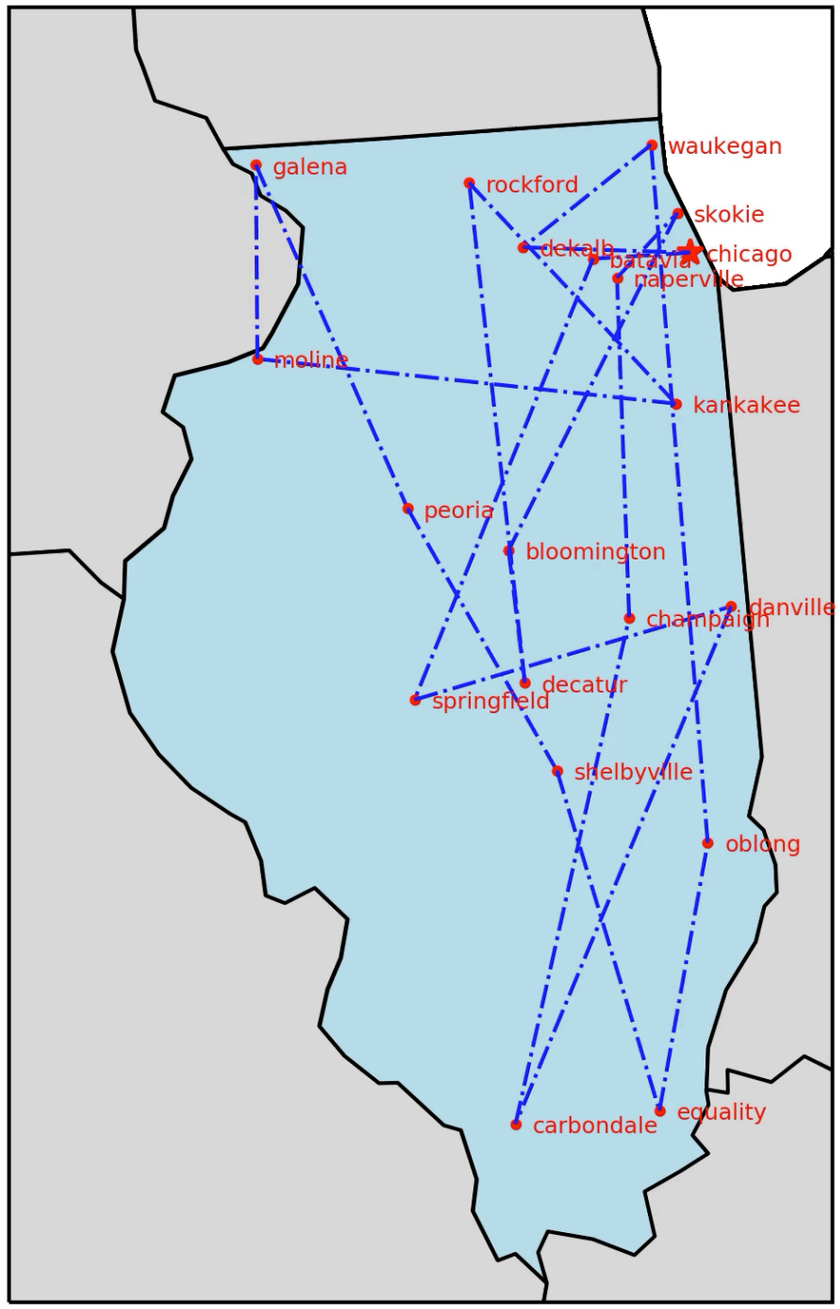




Probability to hop to a new configuration:

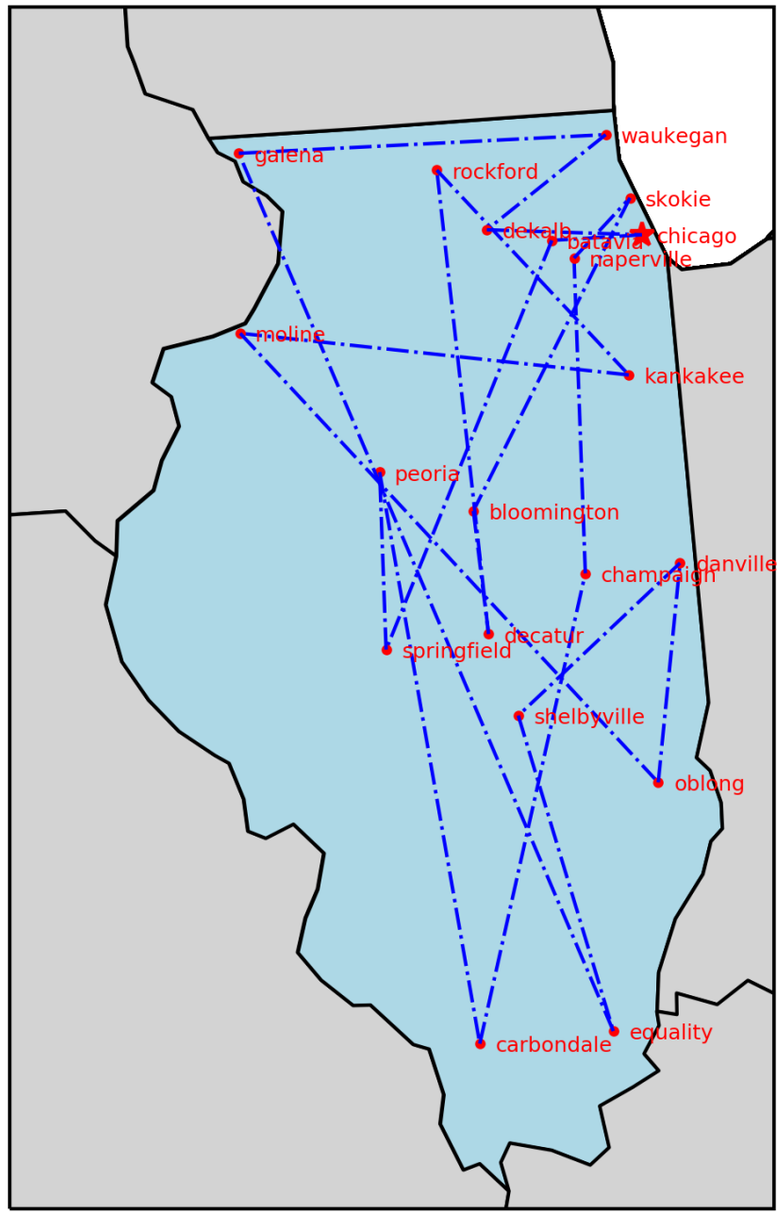
$$P = \begin{cases} 1 & E_{new} < E_{current} \\ Ae^{-\Delta E/kT} & E_{new} \geq E_{current} \end{cases}$$

Simulated Annealing Solution to T.S.P.

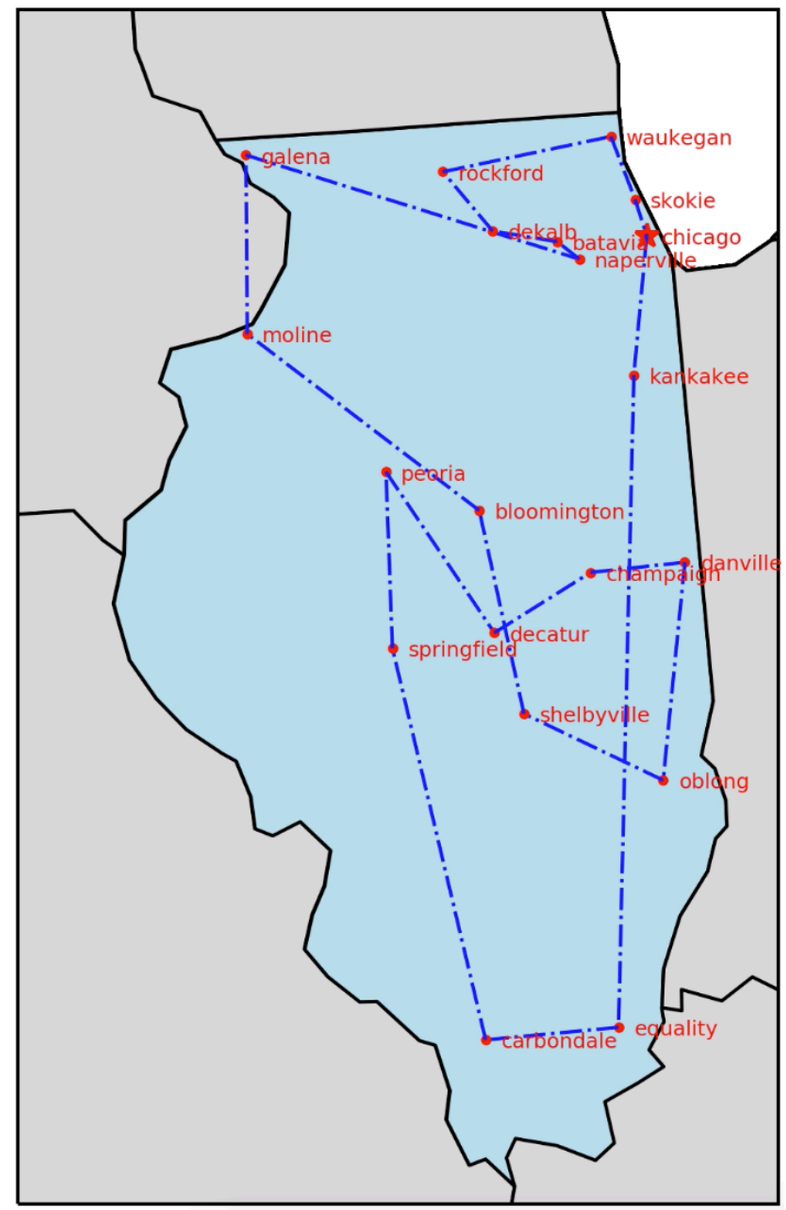


http://github.com/goossaert/algorithms/raw/master/simulated_annealing/annealing.py

Simulated annealing cuts our trip time almost in half.



Before: 20 cities, random order, 3646 km



After simulated annealing: 1914 km (48% improvement)

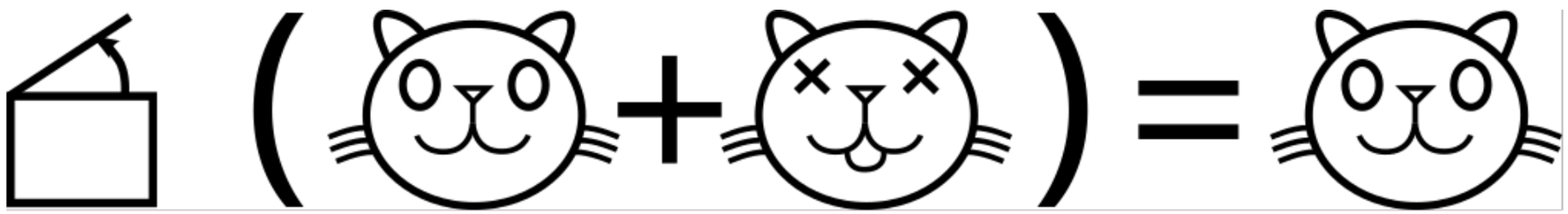
Quick Review

- TSP is a hard problem for computers.
- My program has to try lots of solutions in a kind-of-sensible way, throw away bad solutions, and keep good ones.
- But switching only two cities can make the difference between a good solution and a bad one!
- There’s got to be a better way…

New Topic: Quantum Mechanics

Erwin Schrödinger (1933)
Nobel foundation [Public domain]

Schrödinger’s Cat

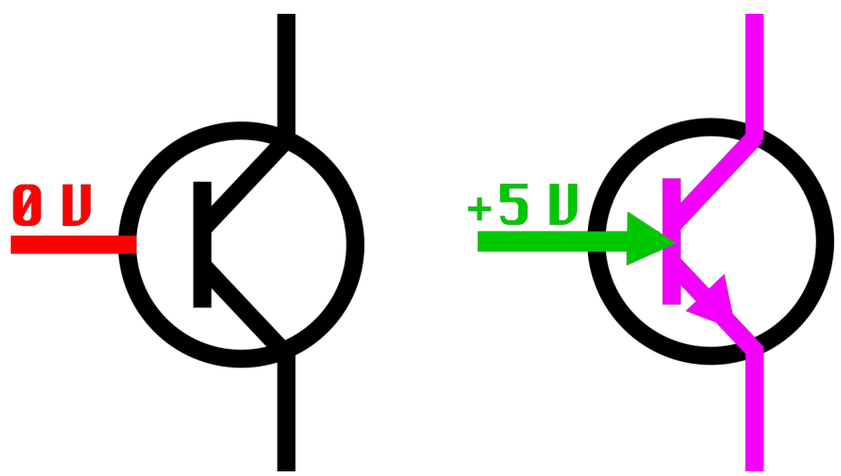


Quantum Superposition

- In the box, the only correct way to describe the cat's *state* is that it is *both alive and dead.*
- *This is not because we are bad at measuring.*
- We say that the cat is in a superposition of two states, alive and dead. It's both.
- A more humane example: quantum bits!

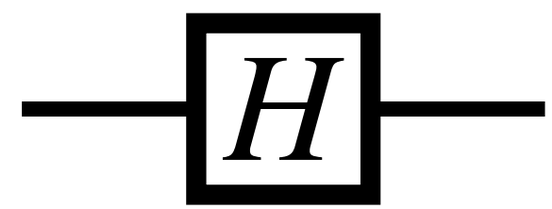
Quantum Superposition

Classical Computing



$|0\rangle$ $|1\rangle$

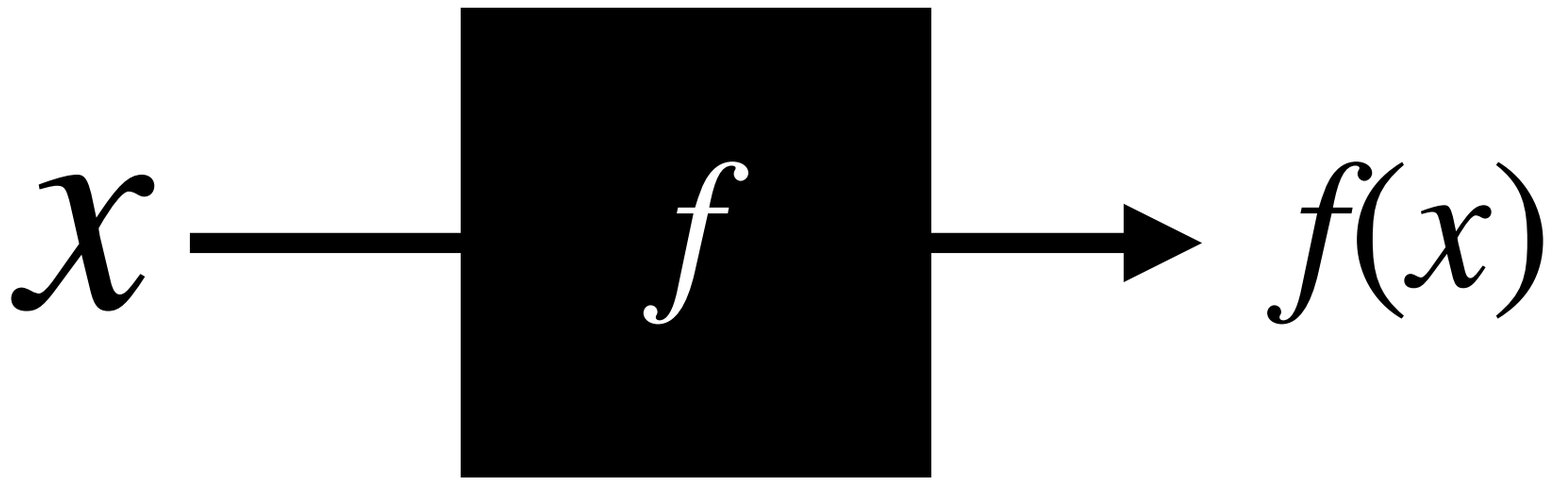
Quantum Computing



$$|0\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$$

If we can exploit the properties of quantum mechanics, then maybe some new and interesting computing possibilities open up for us.

The Deutsch-Jozsa Algorithm: a “toy problem”



f(x) is *constant* if:

X	f(X)
0	1
1	1

f(x) is *balanced* if*:*

X	f(X)
0	1
1	0

The Deutsch-Jozsa Algorithm: a “toy problem”

f(x) is *constant* if:

X	f(X)
0	1
1	1

f(x) is *balanced* if:

X	f(X)
0	1
1	0

With a classical computer (or using your classical brain) how many tries do you need before you know whether *f(x)* is constant or balanced?

The Deutsch-Jozsa Algorithm: a “toy problem”

f(x) is *constant* if:

X	f(X)
0	1
1	1

f(x) is *balanced* if:

X	f(X)
0	1
1	0

With a quantum computer, you only need to make one measurement to know this! The Deutsch-Jozsa algorithm requires superposition in order to work.

This is what scientists mean when they talk about “quantum superiority”.

The Deutsch-Jozsa Algorithm: a “toy problem”

f(x) is *constant* if:

X	f(X)
0	1
1	1

f(x) is *balanced* if:

X	f(X)
0	1
1	0

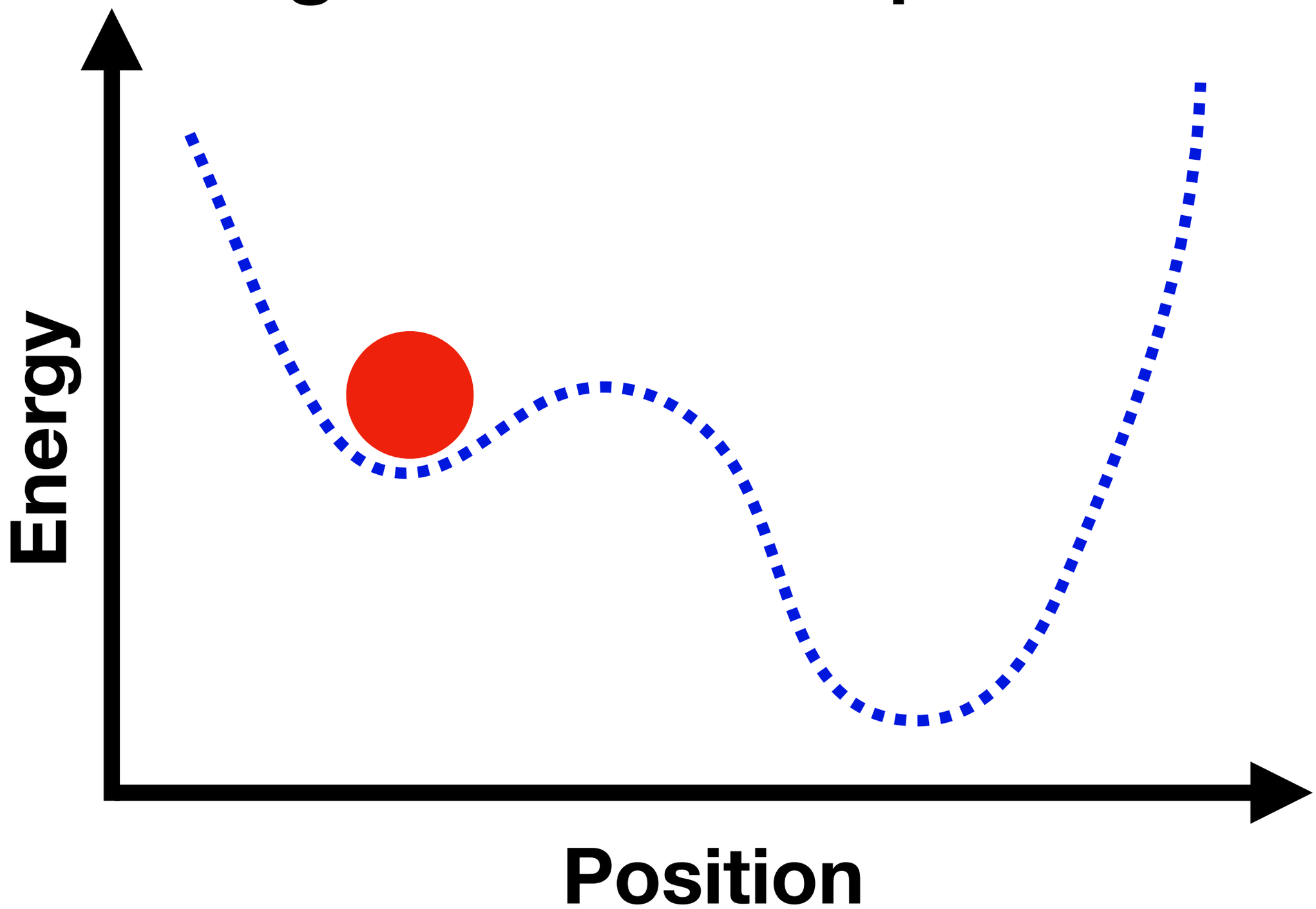
If you want to see the math:

http://math.uchicago.edu/~may/REU2012/REUPapers/Krahn.pdf

Or you can get a lecture from David Deutsch:

https://www.youtube.com/watch?v=3I3OBFlJmnE

In quantum mechanics, jumping *through* barriers is possible!



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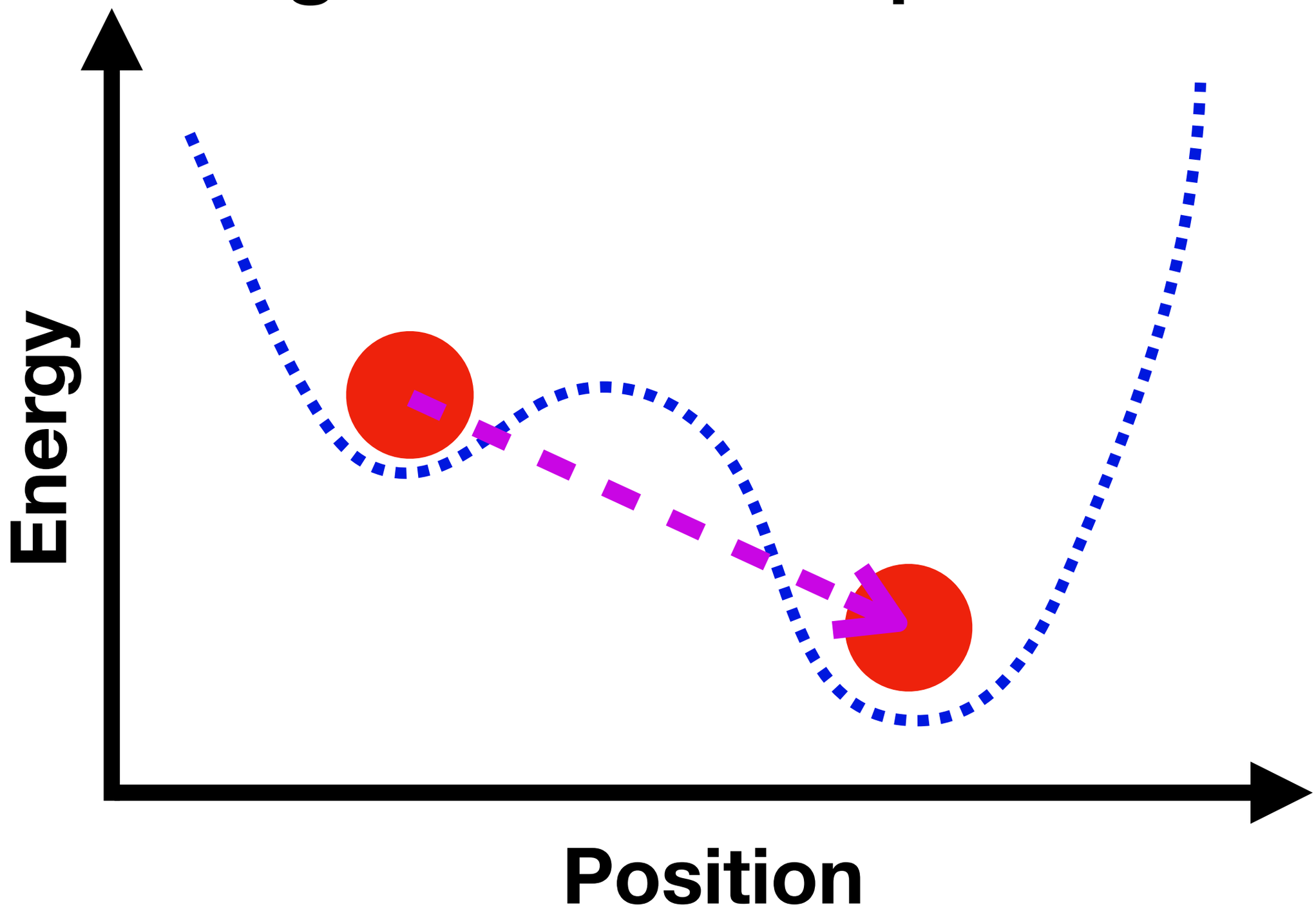
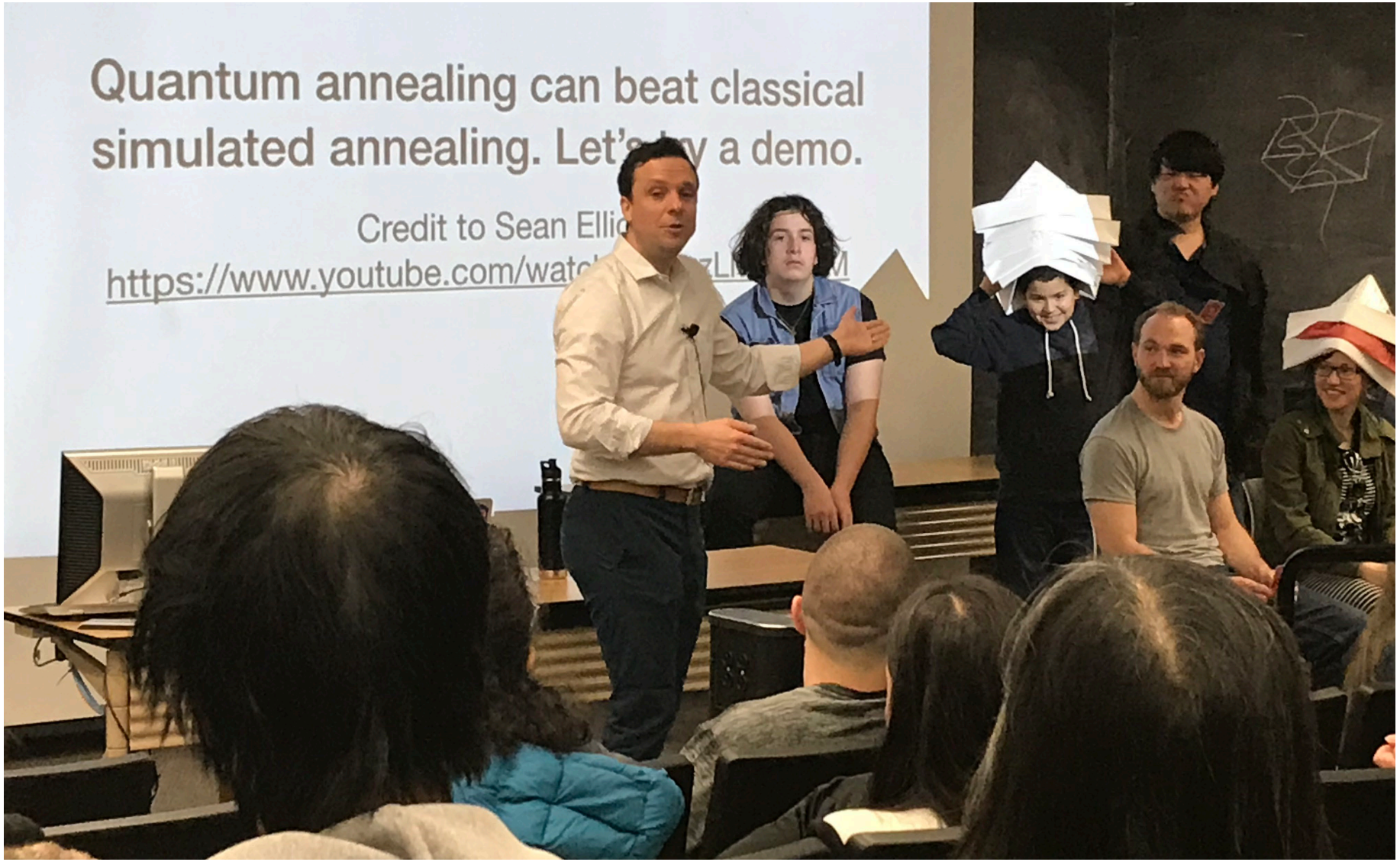


Quantum annealing can beat classical simulated annealing. Let’s try a demo.

Credit to Sean Elliot:
https://www.youtube.com/watch?v=PqzLM3I9pcM

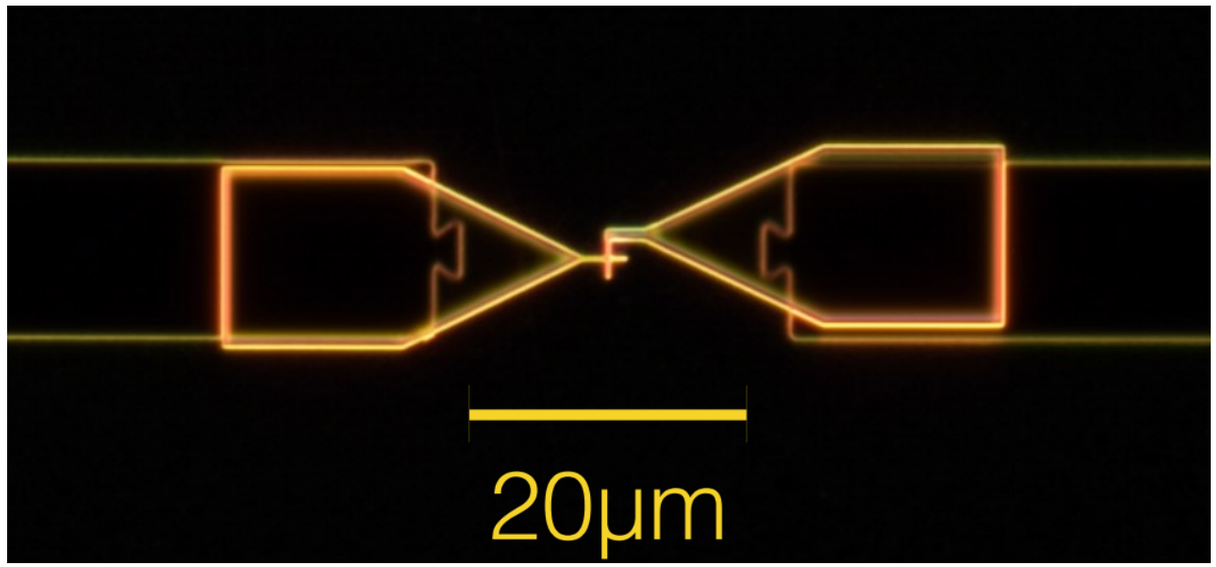
David Tejada wins the quantum annealing optimization contest!
lowest number => most hats



Ok, but what is a qubit, actually?

- A **two-state** device which obeys quantum mechanics and can be manipulated in a controllable way.
- Superconducting electron pairs, sets of atomic spins, photons polarized in one of two ways …

What does a quantum computer look like?



Thanks to A. Dixit and A. Agrawal at U. Chicago for these images and their excellent work!
http://schusterlab.uchicago.edu/

THE UNIVERSITY OF CHICAGO

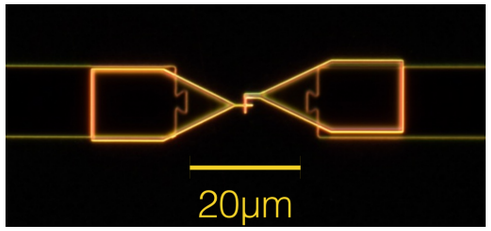
The promise of quantum computing?

- Using *superposition*, we can use *n* qubits to explore 2^n states very quickly.
- Quantum computers can be very powerful tools for search, optimization, and some aspects of machine learning.

The problems with quantum computing?

- Qubits are very fragile! They don't live very long, and they're prone to errors.

- **Physical qubits** are the actual devices



- **Logical qubits** are the essential units that run quantum algorithms.

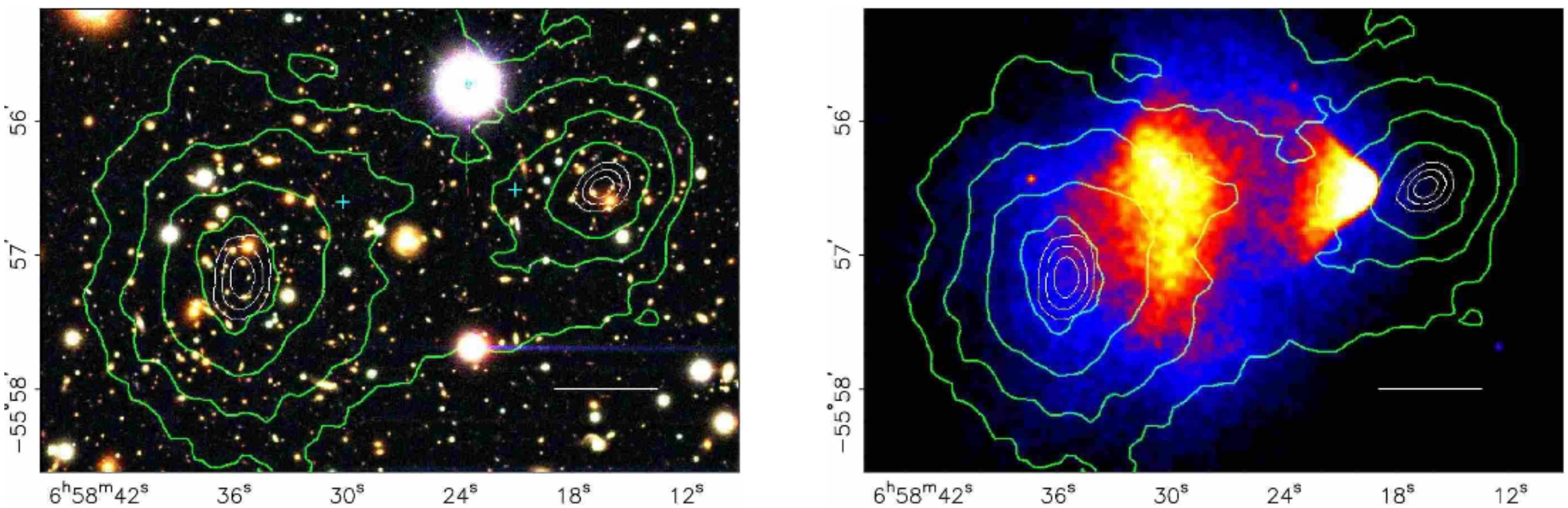
- Errors and finite qubit lifetimes means that you need several (many?) physical qubits to represent one logical qubit.

- **Fault tolerance** is a huge area of research in quantum computing right now.

At Fermilab, we’re borrowing tech from quantum computing so we can look for dark matter.

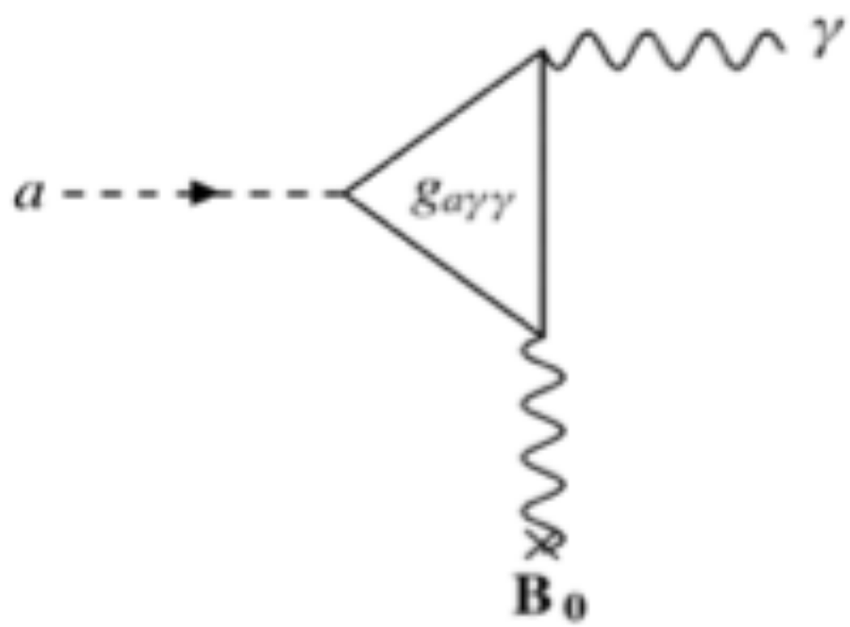
We’re still getting the lab set up…

At Fermilab, we're borrowing tech from quantum computing so we can look for dark matter.

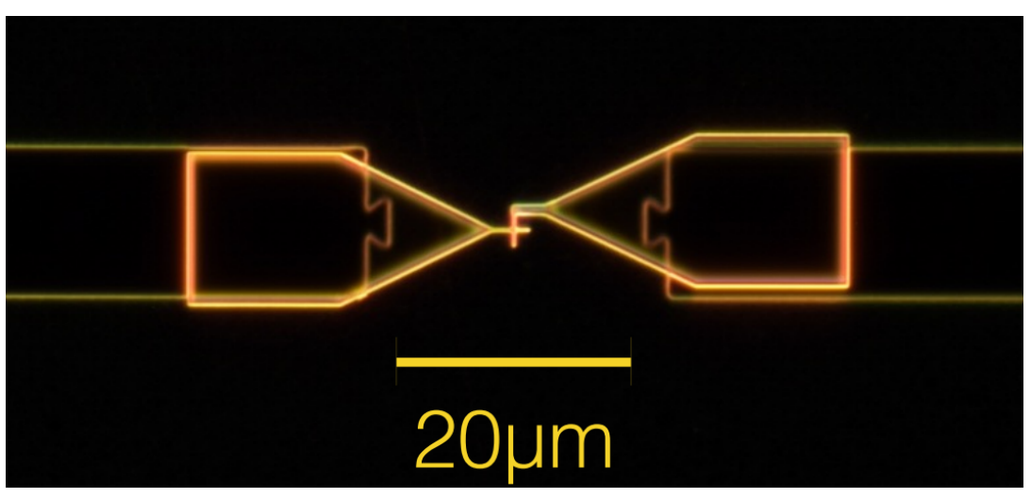


https://arxiv.org/pdf/astro-ph/0608407.pdf

Our dark matter signal is very, very faint light.

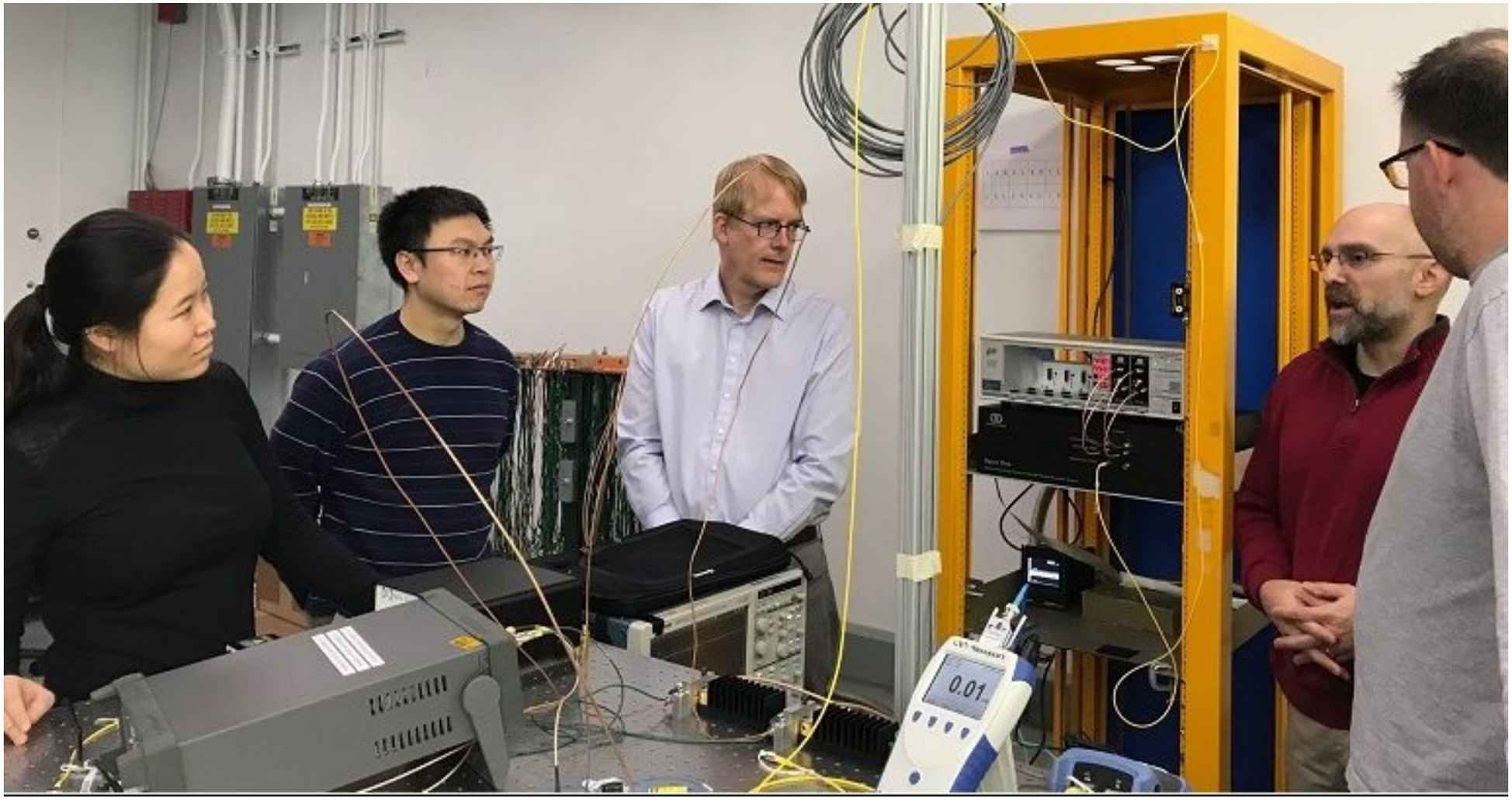


10^{-23} W photons X-(



We can use quantum bits to measure this light!

We're also working on quantum "teleportation". (*Communication* might be a more clear term.)



https://qis.fnal.gov/quantum-teleportation-experiment/

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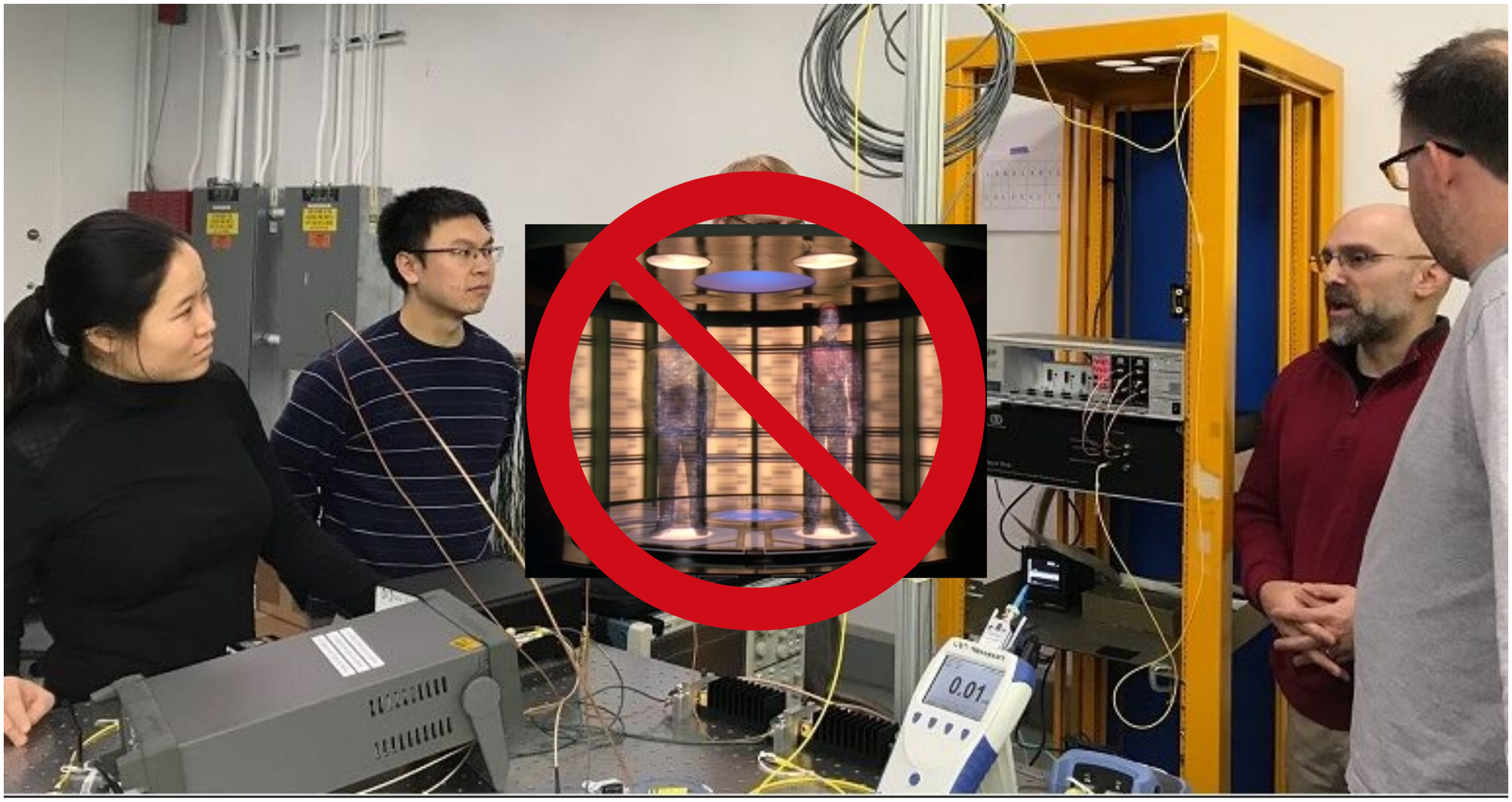

https://qis.fnal.gov/quantum-teleportation-experiment/

We're building up our quantum science program!

http://news.fnal.gov/2018/09/department-of-energy-awards-fermilab-more-than-10-million-for-quantum-science/

Lastly, a few resources in case you want to try your hand:

- A Python “quantum toolbox”: *http://qutip.org/*
- IBM has a 5-qubit machine you can actually* run code on: *https://www.research.ibm.com/ibm-q/technology/devices/#ibmqx4*

Thanks for your attention!