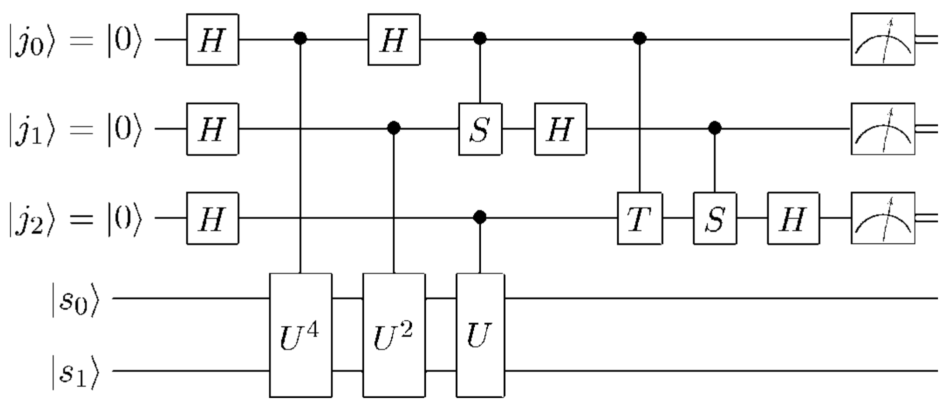
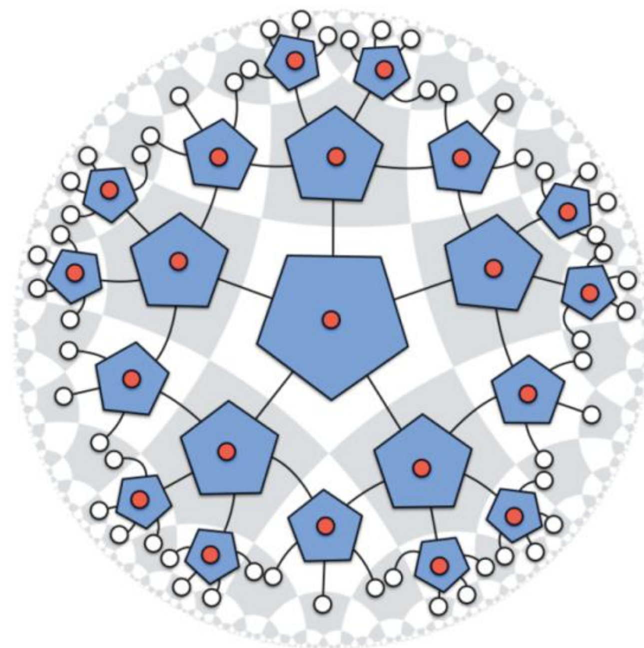
# Entanglement Explained!



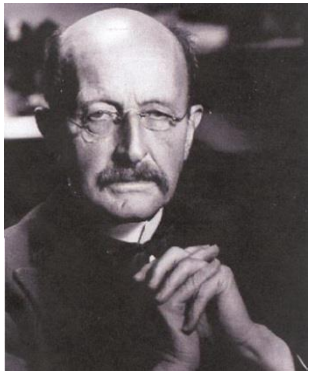
INSTITUTE FOR QUANTUM INFORMATION AND MATTER

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891


John Preskill

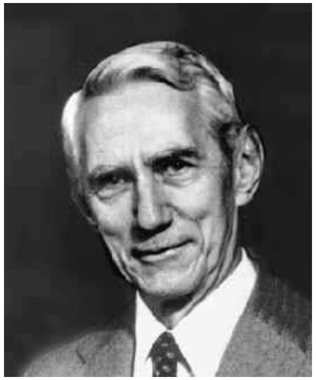
KITP Teachers' Conference
18 January 2020

# Quantum Information Science



Planck

Turing



Shannon

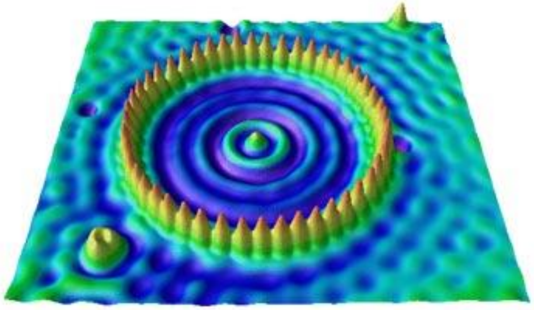
quantum theory

\+ computer science

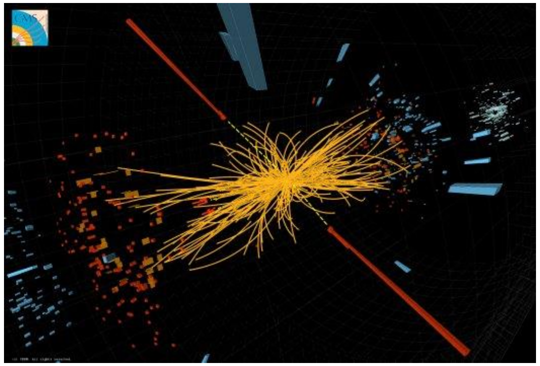
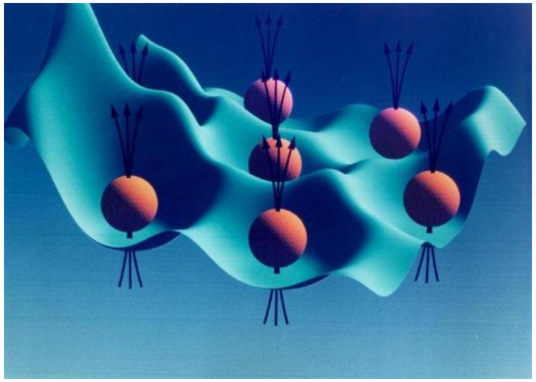
\+ information theory

↓

quantum information science



# Frontiers of Physics

| short distance | long distance | complexity |
| --- | --- | --- |
|  |  |  |
| Higgs boson | Large scale structure | “More is different” |
| Neutrino masses | Cosmic microwave background | Many-body entanglement |
| Supersymmetry | Dark matter | Phases of quantum matter |
| Quantum gravity | Dark energy | Quantum computing |
| String theory | Gravitational waves | Quantum spacetime |

# Shell Game

# Shell Game

# Shell Game

# Shell Game

# Shell Game

# Shell Game

1 2 3

When the Gorilla give thumbs up, and you look under Cup Number 1, you *always* find the ball.

# Shell Game


1 2 3

What if the Gorilla gives thumbs up, and you look under Cup Number 2?

# (Classical) Shell Game

When the Gorilla gives thumbs up & you look under Cup Number 1, you *always* find ball.


When the Gorilla gives thumbs up & you look under Cup Number 2, you find the ball ...

A. Always
B. Never
C. Sometimes

# (Classical) Shell Game

When the Gorilla gives thumbs up & you look under Cup Number 1, you *always* find ball.

When the Gorilla gives thumbs up & you look under Cup Number 2, you find the ball ...

A. Always

B. Never

C. Sometimes

# (Quantum) Shell Game

When the Gorilla gives thumbs up & you look under Cup Number 1, you *always* find ball.


When the Gorilla gives thumbs up & you look under Cup Number 2, you find the ball ...

A. Always
B. Never
C. Sometimes

# (Quantum) Shell Game

When the Gorilla gives thumbs up & you look under Cup Number 1, you *always* find ball.

When the Gorilla gives thumbs up & you look under Cup Number 2, you find the ball ...

A. Always
B. Never
C. Sometimes

# (Quantum) Shell Game

Secret of the Quantum Gorilla:

Before deciding whether to give thumbs up, he checks the cups *collectively*, rather than one at a time.

# (Quantum) Shell Game

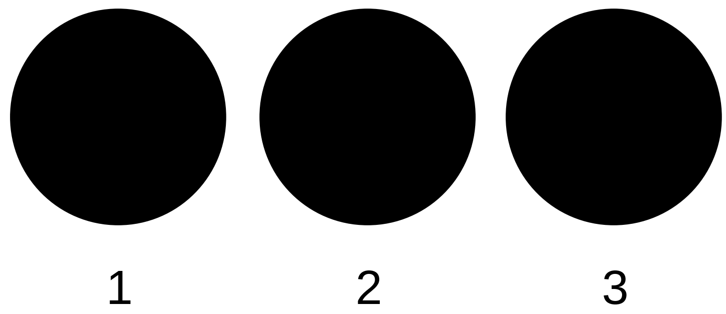
Initial state of the ball: $$\frac{1}{\sqrt{3}}(e_1 + e_2 + e_3)$$

Thumbs up if projected onto: $$\frac{1}{\sqrt{3}}(e_1 + e_2 - e_3)$$

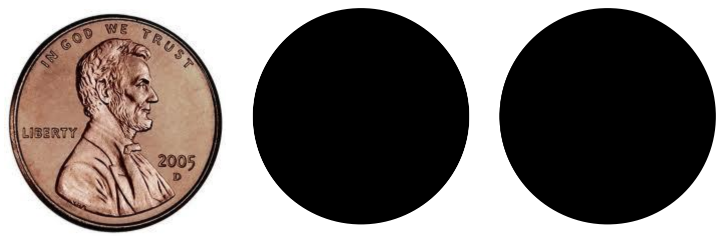
If ball not under cup #1: $$\frac{1}{\sqrt{2}}(e_2 + e_3)$$

If ball not under cup #2: $$\frac{1}{\sqrt{2}}(e_1 + e_3)$$

Before deciding whether to give thumbs up, the gorilla checks the cups *collectively*, rather than one at a time.

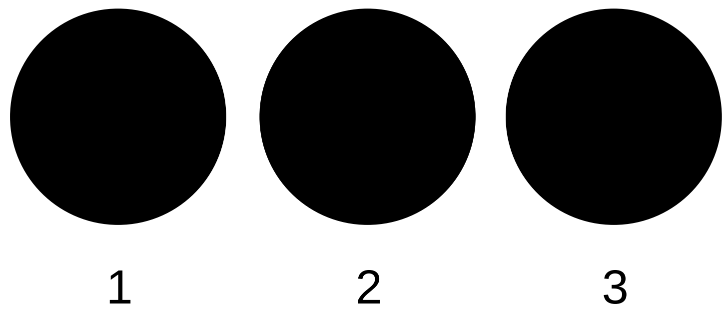



Three coins on the table. Each is either heads or tails. You can uncover any one of the three coins, revealing whether it is heads of tails, but when you do the other two coins disappear --- you’ll never know whether those other two coins are heads or tails.




1 2 3

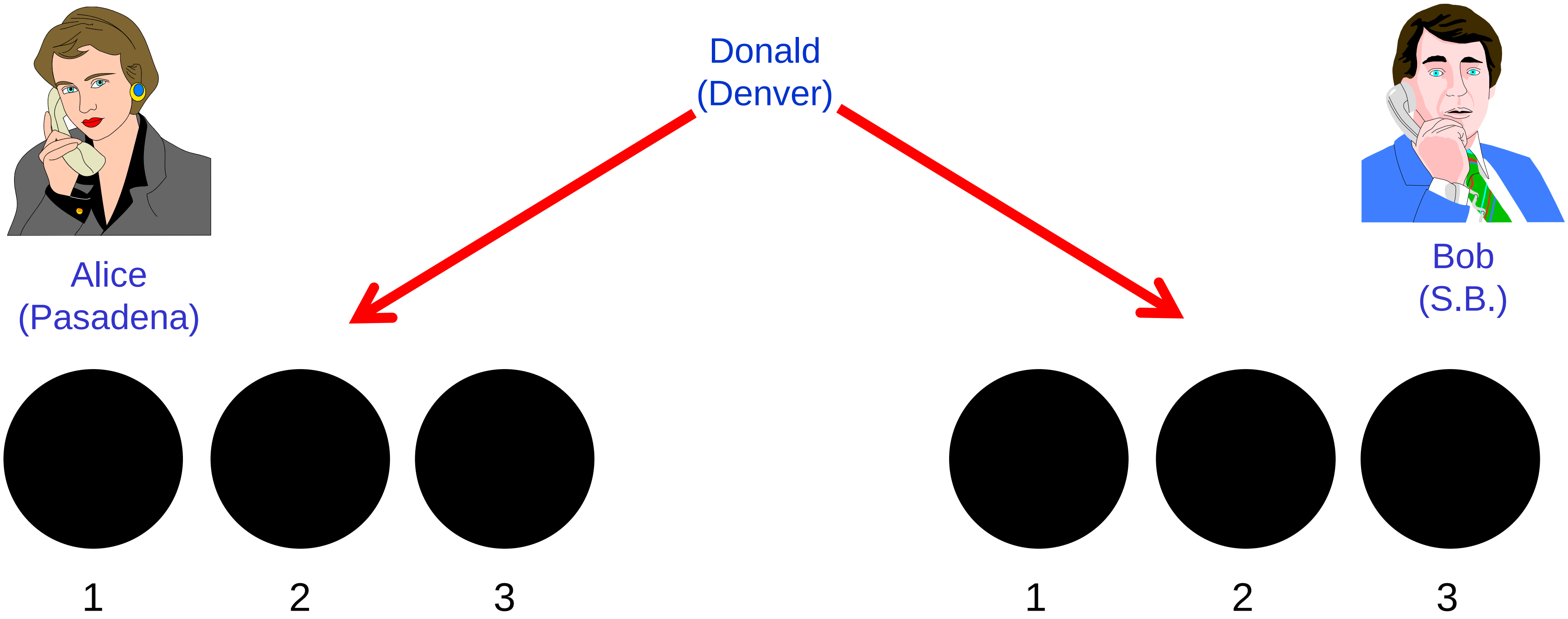
Three coins on the table. Each is either heads or tails. You can uncover any one of the three coins, revealing whether it is heads of tails, but when you do the other two coins disappear --- you'll never know whether those other two coins are heads or tails.




Three coins on the table. Each is either heads or tails. You can uncover any one of the three coins, revealing whether it is heads of tails, but when you do the other two coins disappear --- you’ll never know whether those other two coins are heads or tails.

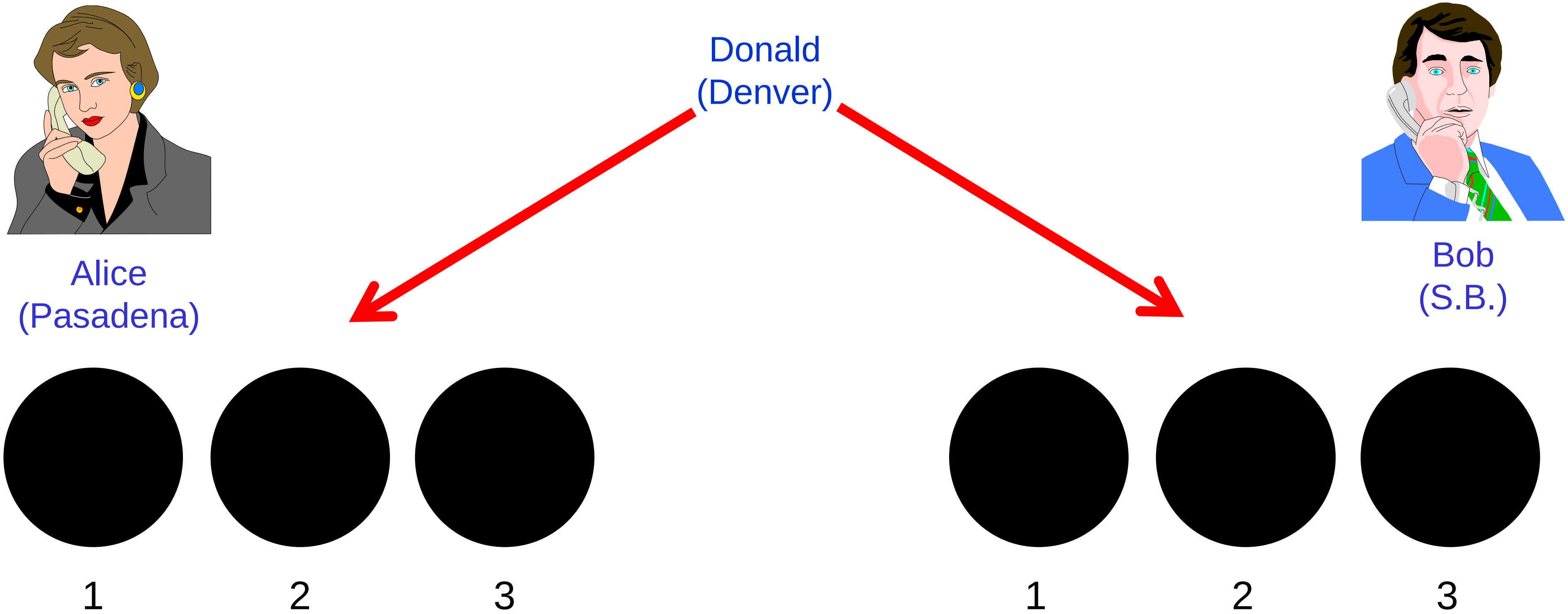

1 2 3

Three coins on the table. Each is either heads or tails. You can uncover any one of the three coins, revealing whether it is heads of tails, but when you do the other two coins disappear --- you’ll never know whether those other two coins are heads or tails.




There are many sets of coins, identically prepared by Donald.

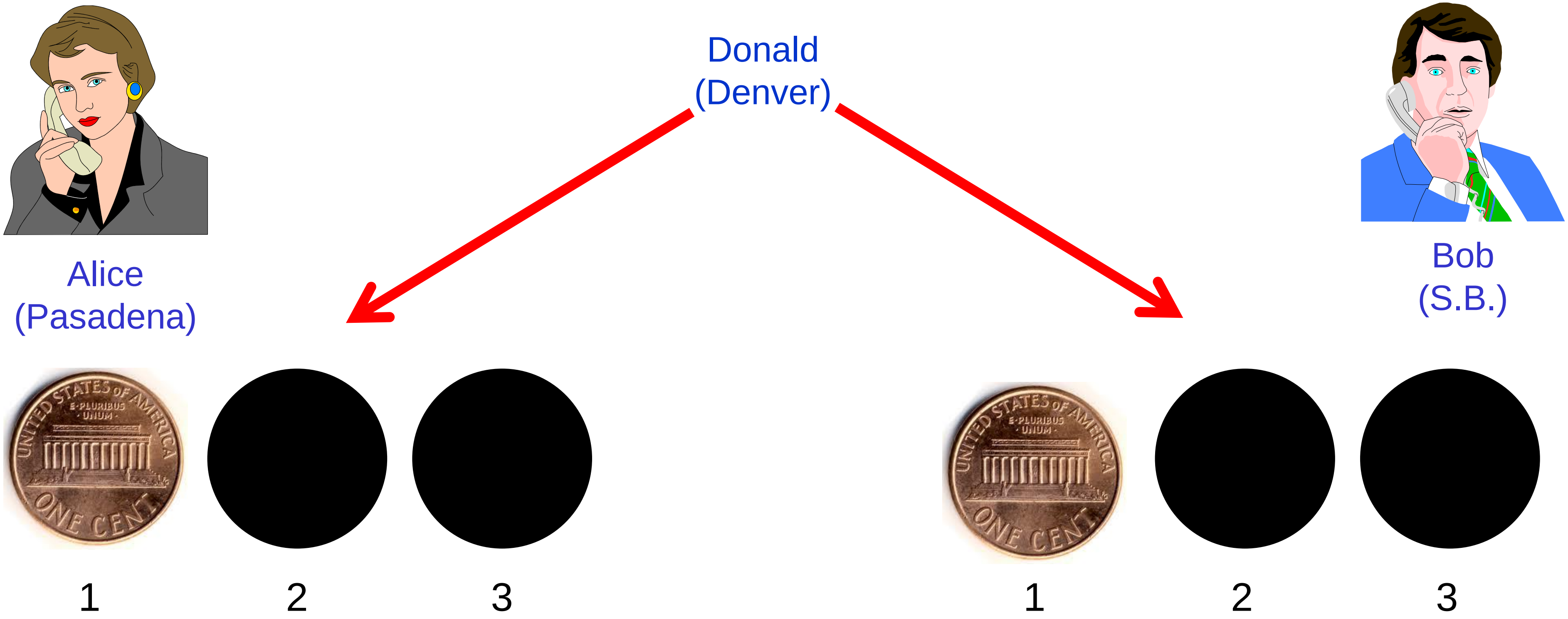
For each of the three coins, in Pasadena or Santa Barbara, the probability is ½ that the coin is heads or tails.




There are many sets of coins, identically prepared by Donald.

For each of the three coins, in Pasadena or Santa Barbara, the probability is ½ that the coin is heads or tails.

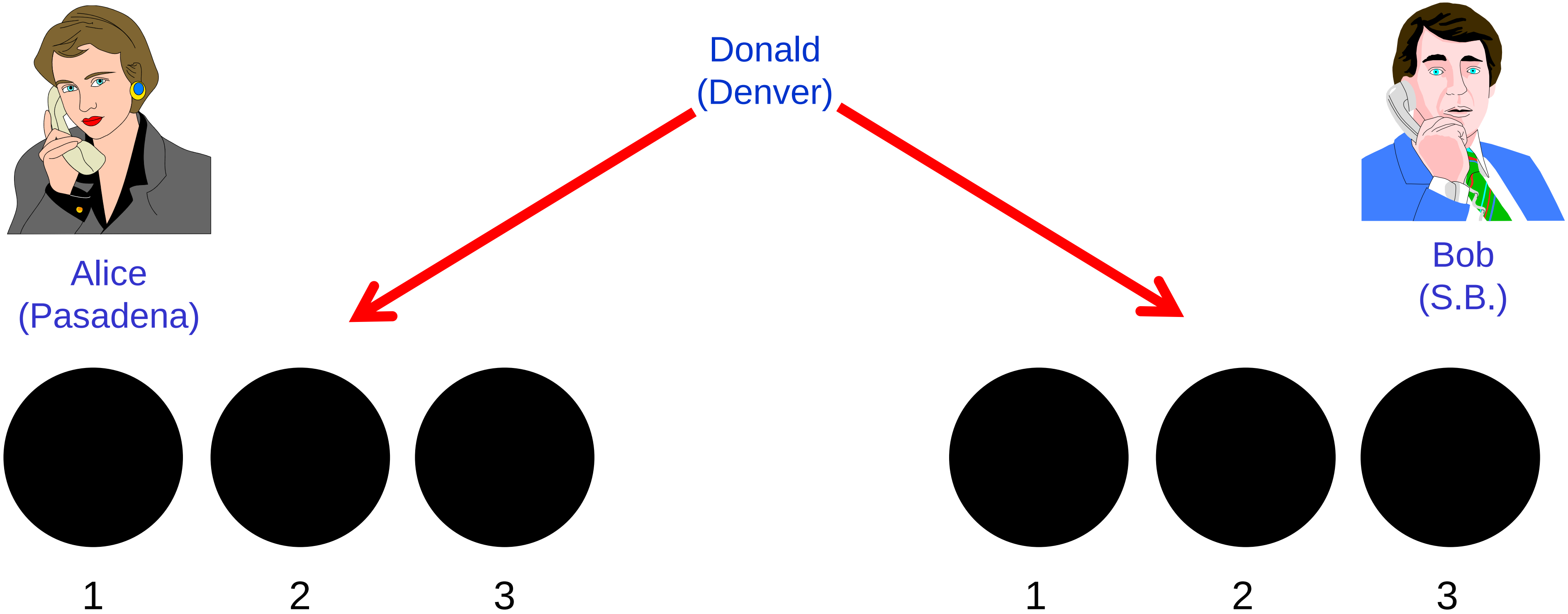
But, if Alice and Bob both uncover the same coin, the outcomes are perfectly correlated.




There are many sets of coins, identically prepared by Donald.

For each of the three coins, in Pasadena or Santa Barbara, the probability is ½ that the coin is heads or tails.

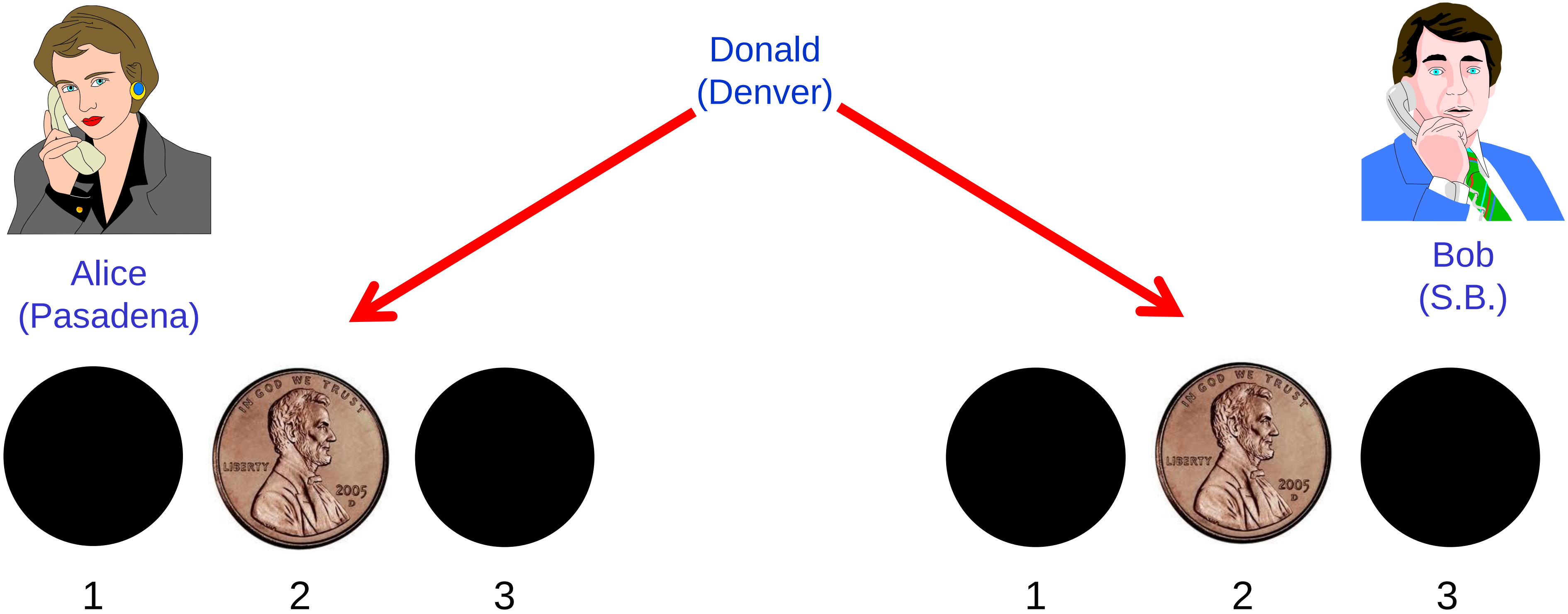
But, if Alice and Bob both uncover the same coin, the outcomes are perfectly correlated.




There are many sets of coins, identically prepared by Donald.

For each of the three coins, in Pasadena or Santa Barbara, the probability is ½ that the coin is heads or tails.

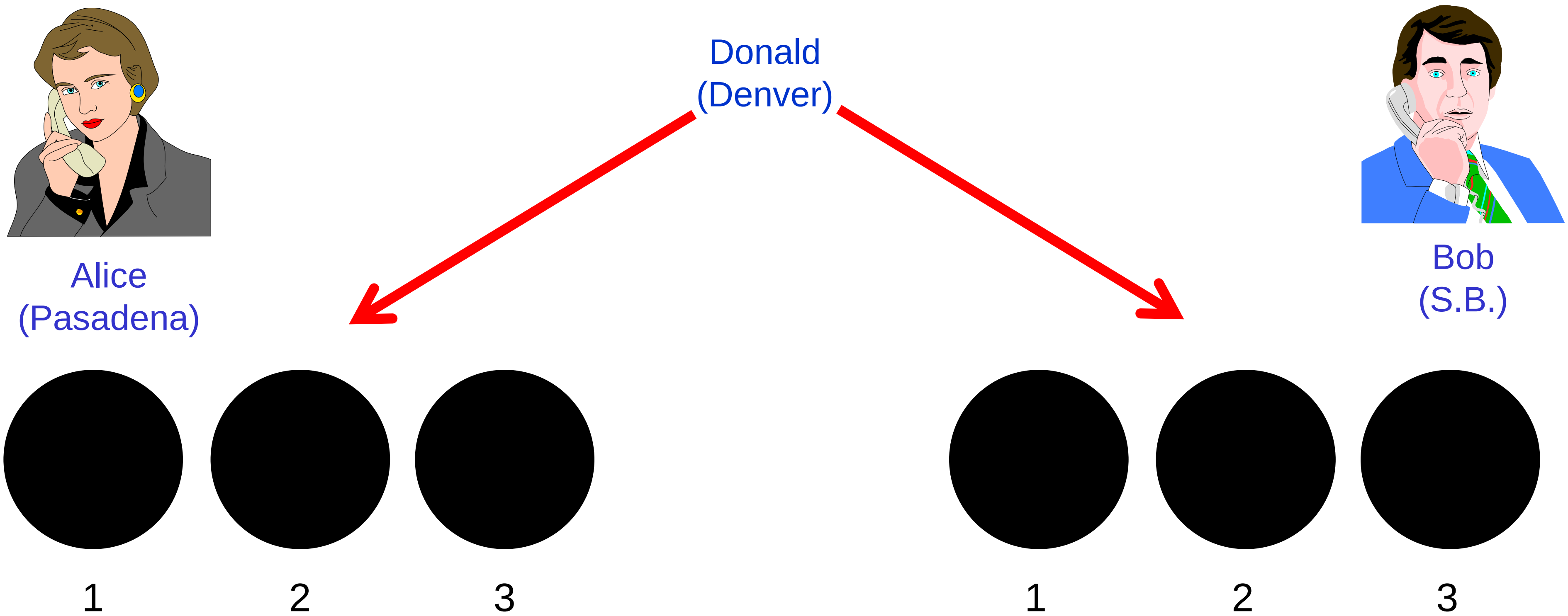
But, if Alice and Bob both uncover the same coin, the outcomes are perfectly correlated.




There are many sets of coins, identically prepared by Donald.

For each of the three coins, in Pasadena or Santa Barbara, the probability is ½ that the coin is heads or tails.

But, if Alice and Bob both uncover the same coin, the outcomes are perfectly correlated.

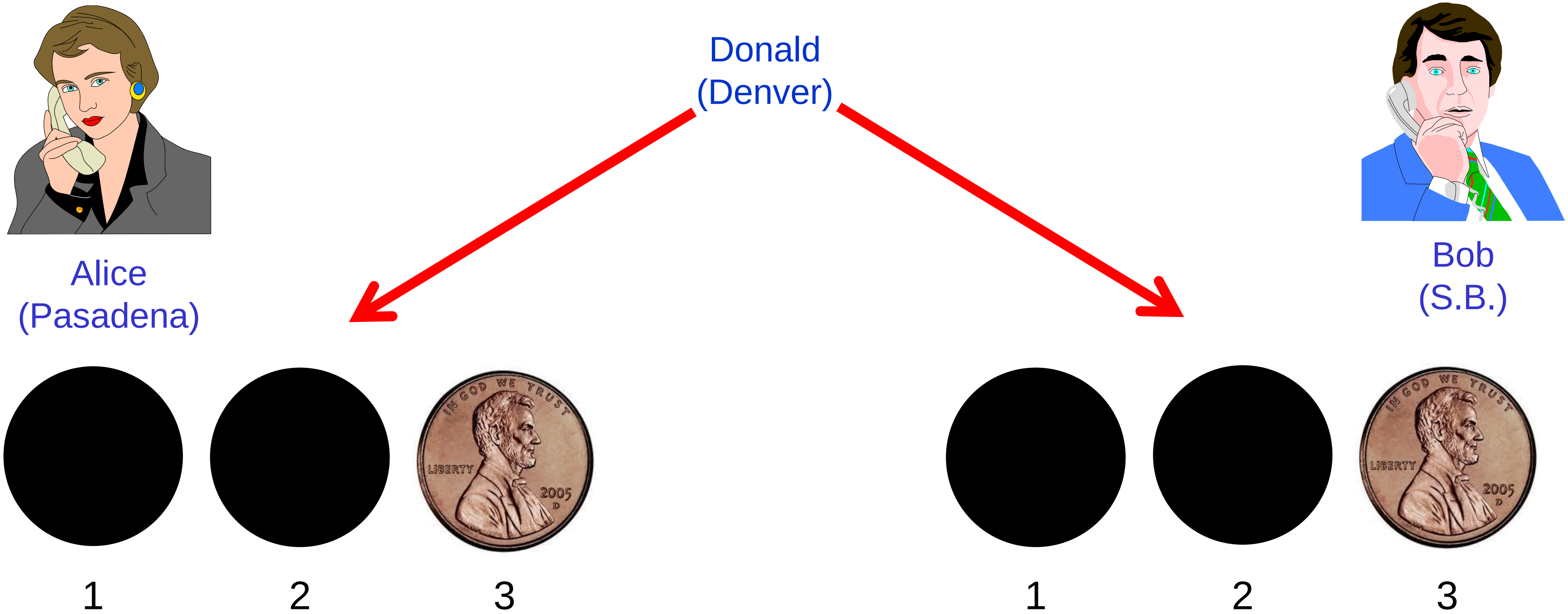



There are many sets of coins, identically prepared by Donald.

For each of the three coins, in Pasadena or Santa Barbara, the probability is ½ that the coin is heads or tails.

But, if Alice and Bob both uncover the same coin, the outcomes are perfectly correlated.

We know it always works – we’ve checked it a million times.

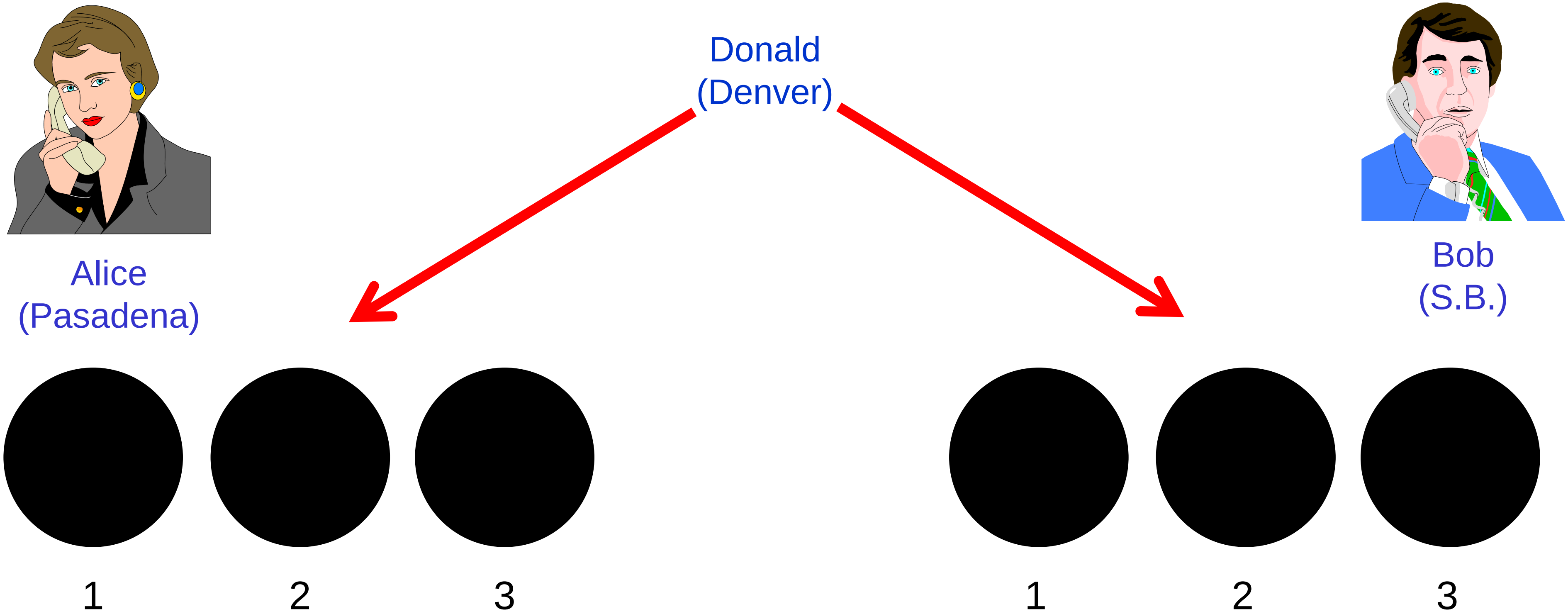



There are many sets of coins, identically prepared by Donald.

For each of the three coins, in Pasadena or Santa Barbara, the probability is ½ that the coin is heads or tails.

But, if Alice and Bob both uncover the same coin, the outcomes are perfectly correlated.

We know it always works – we’ve checked it a million times.

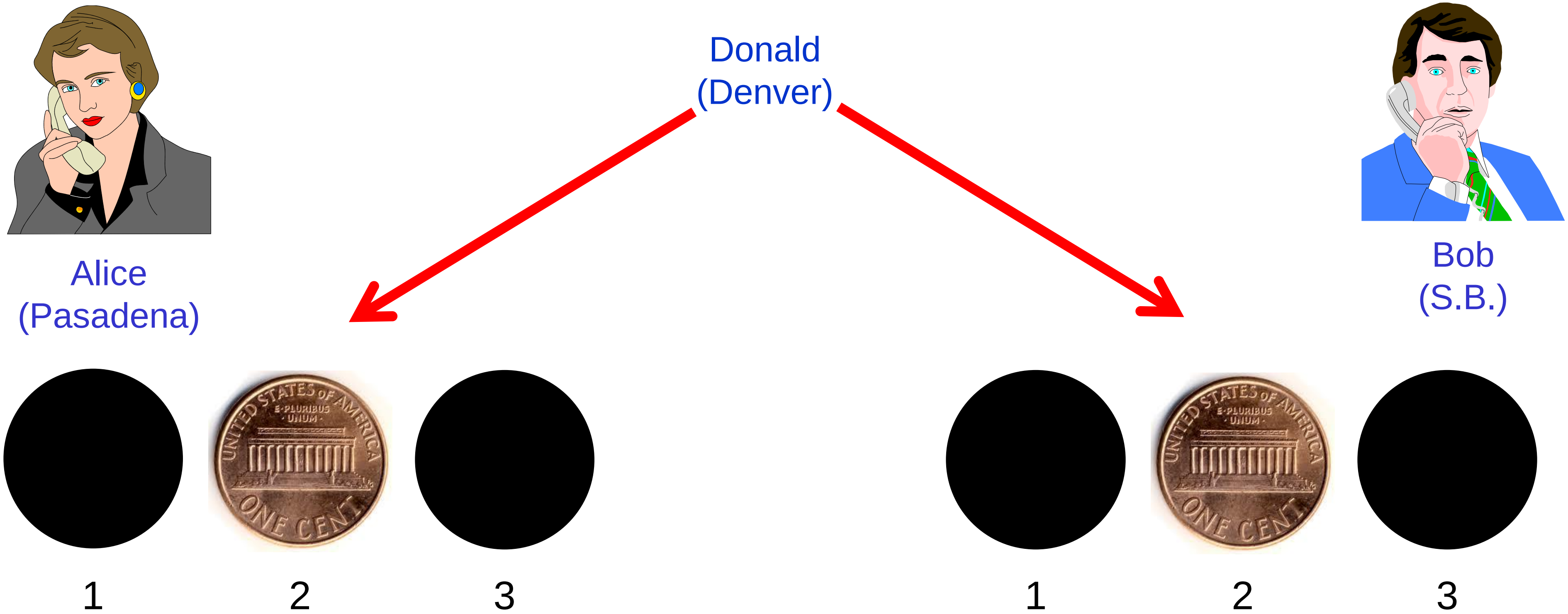



There are many sets of coins, identically prepared by Donald.

For each of the three coins, in Pasadena or Santa Barbara, the probability is ½ that the coin is heads or tails.

But, if Alice and Bob both uncover the same coin, the outcomes are perfectly correlated.

We know it always works – we've checked it a million times.

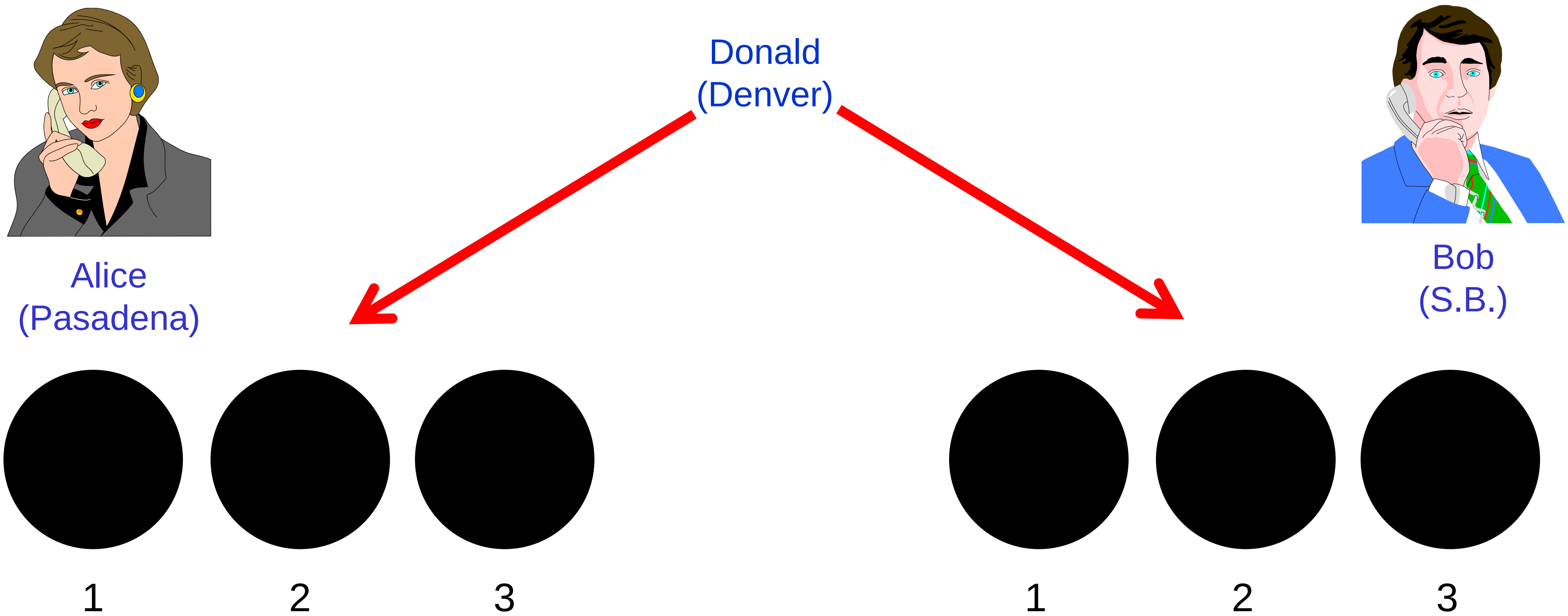



There are many sets of coins, identically prepared by Donald.

For each of the three coins, in Pasadena or Santa Barbara, the probability is ½ that the coin is heads or tails.

But, if Alice and Bob both uncover the same coin, the outcomes are perfectly correlated.

We know it always works – we’ve checked it a million times.

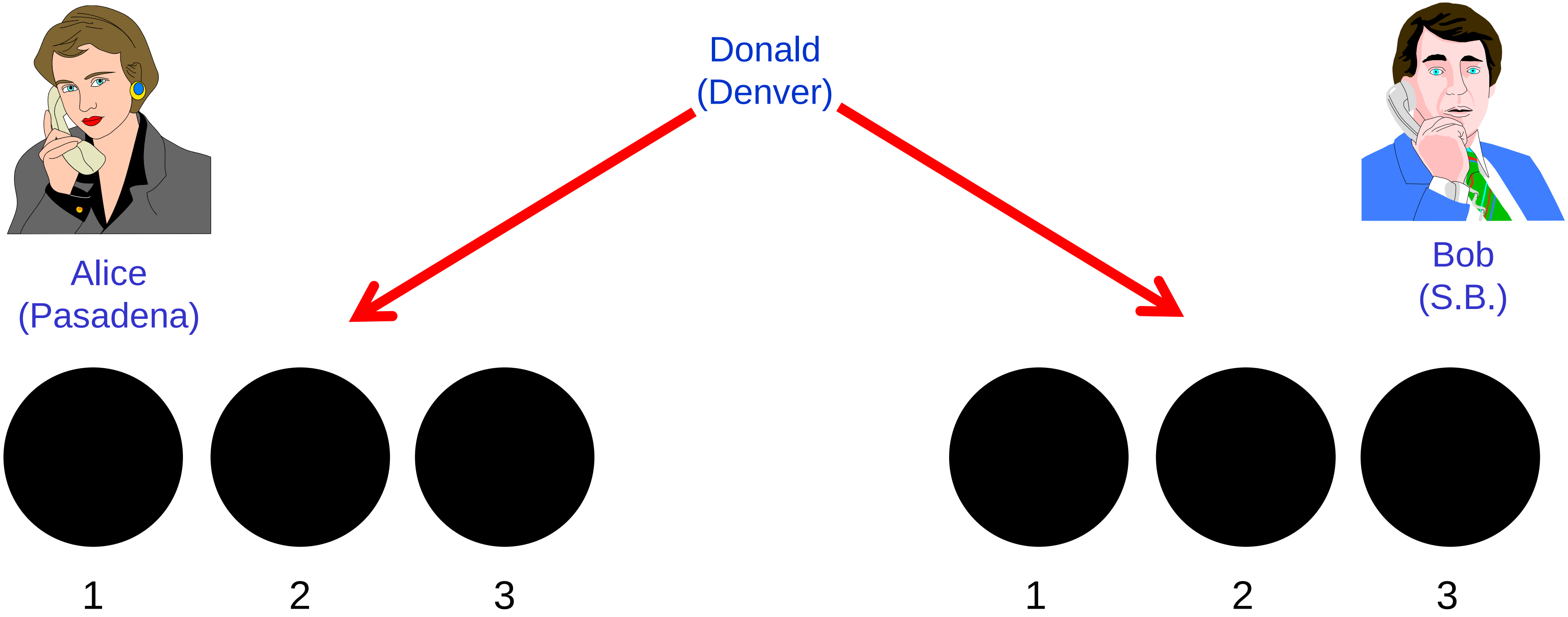



There are many sets of coins, identically prepared by Donald.

For each of the three coins, in Pasadena or Santa Barbara, the probability is ½ that the coin is heads or tails.

But, if Alice and Bob both uncover the same coin, the outcomes are perfectly correlated.

We know it always works – we’ve checked it a million times.

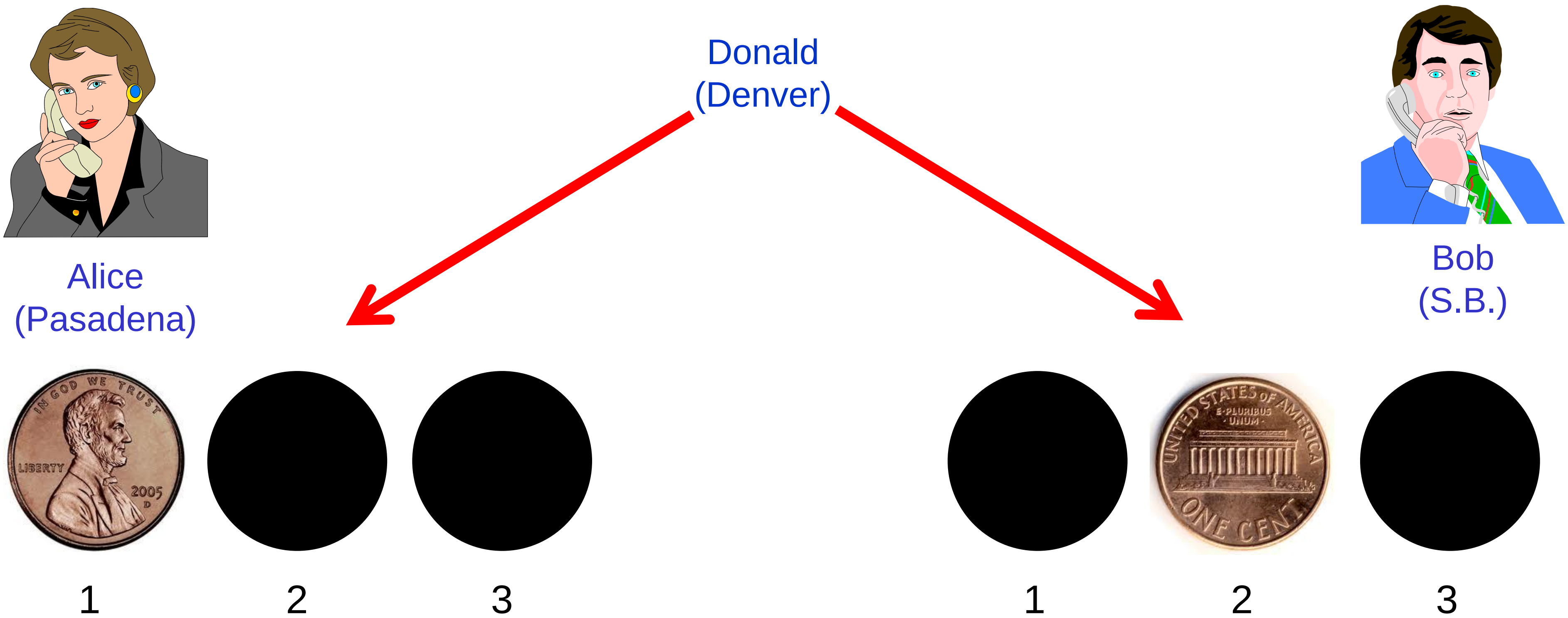



Bob reasons:

-- We know the correlation is always perfect,

-- And surely what Alice does in Pasadena exerts no influence on what Bob finds when he uncovers a coin in Santa Barbara.

-- So, in effect, Alice and Bob, working together, can learn the outcome when any two of the coins are uncovered in Santa Barbara.

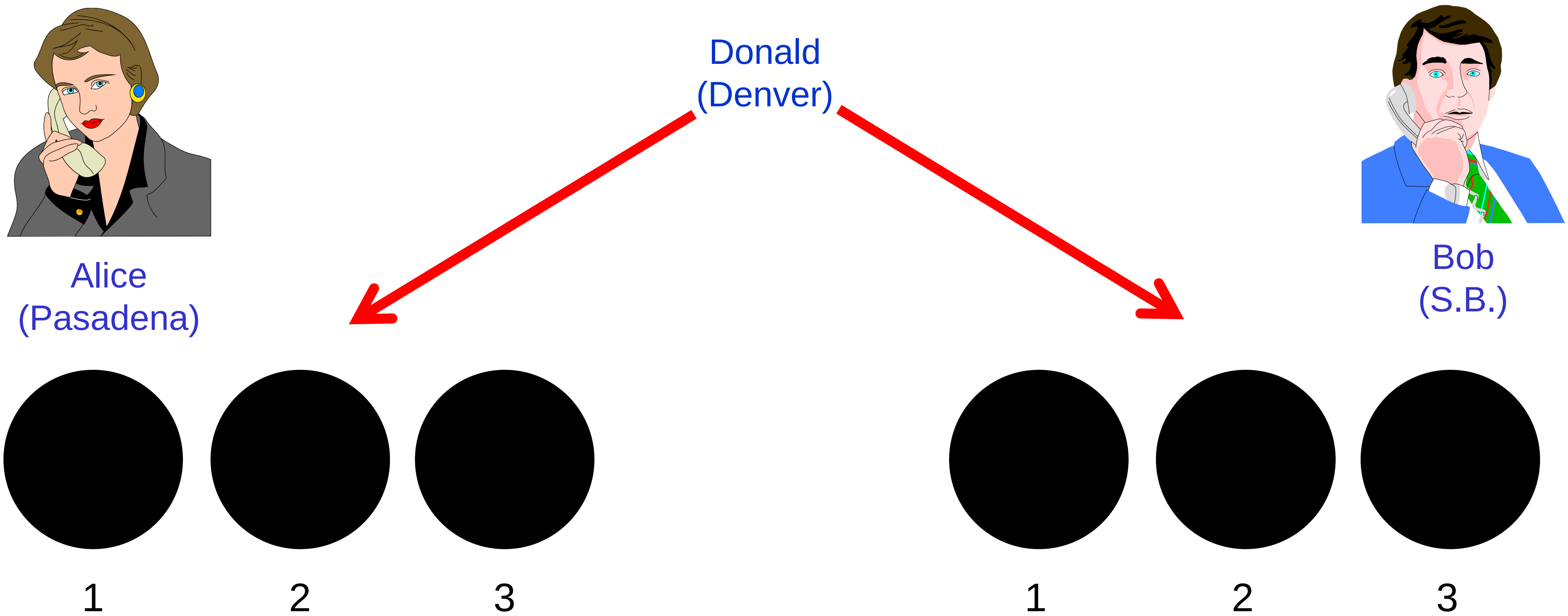



Bob reasons:

-- We know the correlation is always perfect,

-- And surely what Alice does in Pasadena exerts no influence on what Bob finds when he uncovers a coin in Santa Barbara.

-- So, in effect, Alice and Bob, working together, can learn the outcome when any two of the coins are uncovered in Santa Barbara.

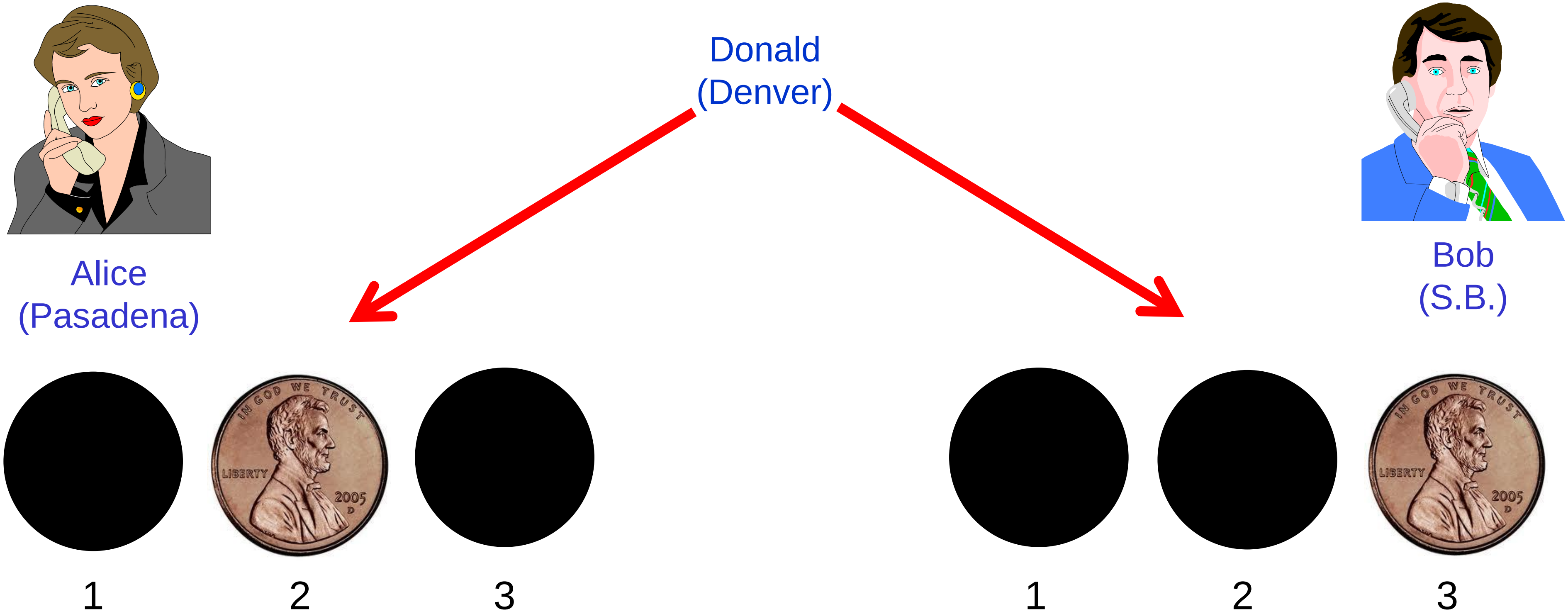



Bob reasons:

-- We know the correlation is always perfect,

-- And surely what Alice does in Pasadena exerts no influence on what Bob finds when he uncovers a coin in Santa Barbara.

-- So, in effect, Alice and Bob, working together, can learn the outcome when any two of the coins are uncovered in Santa Barbara.



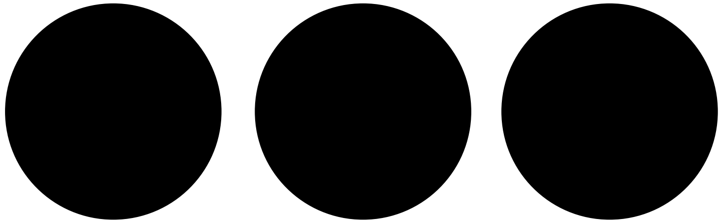

Bob reasons:

-- We know the correlation is always perfect,

-- And surely what Alice does in Pasadena exerts no influence on what Bob finds when he uncovers a coin in Santa Barbara.

-- So, in effect, Alice and Bob, working together, can learn the outcome when any two of the coins are uncovered in Santa Barbara.

Alice
(Pasadena)



Bob
(S.B.)

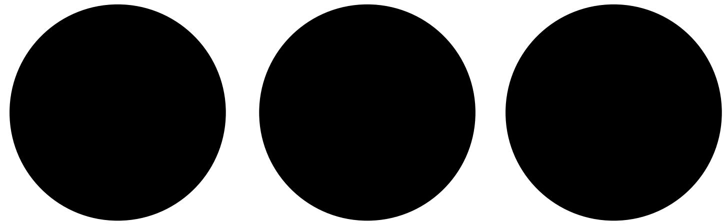
Bell reasons: $$\sum_{x,y,z\in\{H,T\}} P(x,y,z)=1\,.$$

$$P_{\text{same}}(1,2)=P(HHH)+P(HHT)+P(TTH)+P(TTT),$$
$$P_{\text{same}}(2,3)=P(HHH)+P(THH)+P(HTT)+P(TTT),$$
$$P_{\text{same}}(1,3)=P(HHH)+P(HTH)+P(THT)+P(TTT).$$

$$P_{\text{same}}(1,2)+P_{\text{same}}(2,3)+P_{\text{same}}(1,3)=1+2P(HHH)+2P(TTT)\geq 1$$

Why? Because if you uncover all three coins, at least two have to be the same!

Alice
(Pasadena)



$$P_{\text{same}}(1,2)+P_{\text{same}}(2,3)+P_{\text{same}}(1,3)\geq 1$$

Bob
(S.B.)

Alice and Bob did the experiment a million times, and found …

$$P_{\text{same}}(1,2)=P_{\text{same}}(2,3)=P_{\text{same}}(1,3)=\frac{1}{4}$$

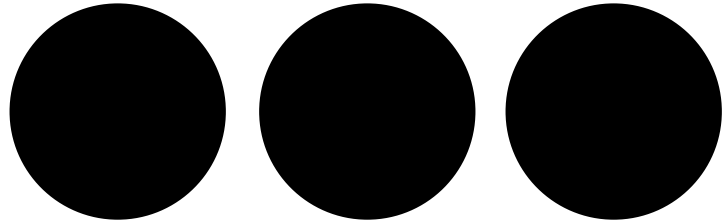
How could Bell's prediction be wrong? Bell assumed the probability distribution describes our ignorance about the actually state of the coins under the black covers, and that there is no "action at a distance" between Pasadena and Santa Barbara. The lesson:

-- Don't reason about "counterfactuals" ("I found H when I uncovered 1; I would have found either H or T if I had uncovered 2 instead, I just don't know which.") When the measurements are incompatible, then if we do measurement 1 we can't speak about what would have happened if we had done measurement 2 instead.

-- Quantum randomness is not due to ignorance. Rather, it is intrinsic, occurring even when we have the most complete knowledge that Nature will allow.

-- Note that the quantum correlations do not allow A and B to send signals to one another.

Alice
(Pasadena)



Bob
(S.B.)

$$P_{\text{same}}(1,2) + P_{\text{same}}(2,3) + P_{\text{same}}(1,3) \geq 1$$

However, Alice and Bob did the experiment a million times, and found …

$$P_{\text{same}}(1,2) = P_{\text{same}}(2,3) = P_{\text{same}}(1,3) = \frac{1}{4}$$

Bell inequality violations are seen in experiments with qubits encoded in photons, atoms, and superconducting circuits.

There are “loopholes”:

1. Detection efficiency
2. Causality
3. “Free will”

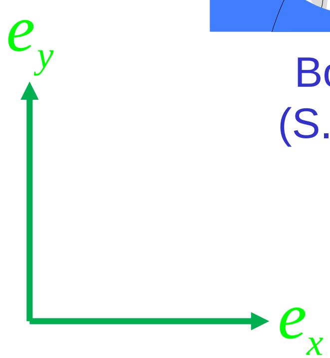
Bell inequality violation has been verified experimentally since the 1980s, but the first “loophole free” experiments were first achieved in 2015.

Alice and Bob shared a maximally entangled (Bell) pair of qubits, and each could perform a two-outcome measurement on her/his qubit in one of three possible ways. What did they measure?

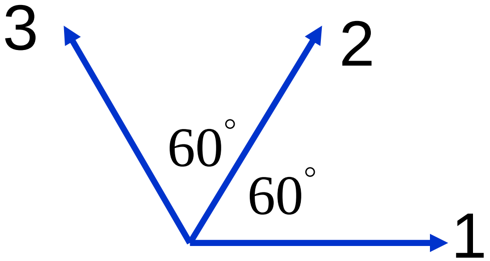
Alice
(Pasadena)


$$\frac{1}{\sqrt{2}}\left(e_x \otimes e_y - e_y \otimes e_x\right)$$

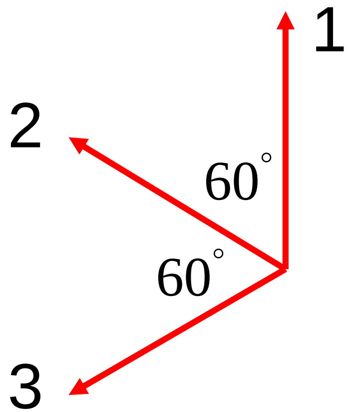
Bob
(S.B.)



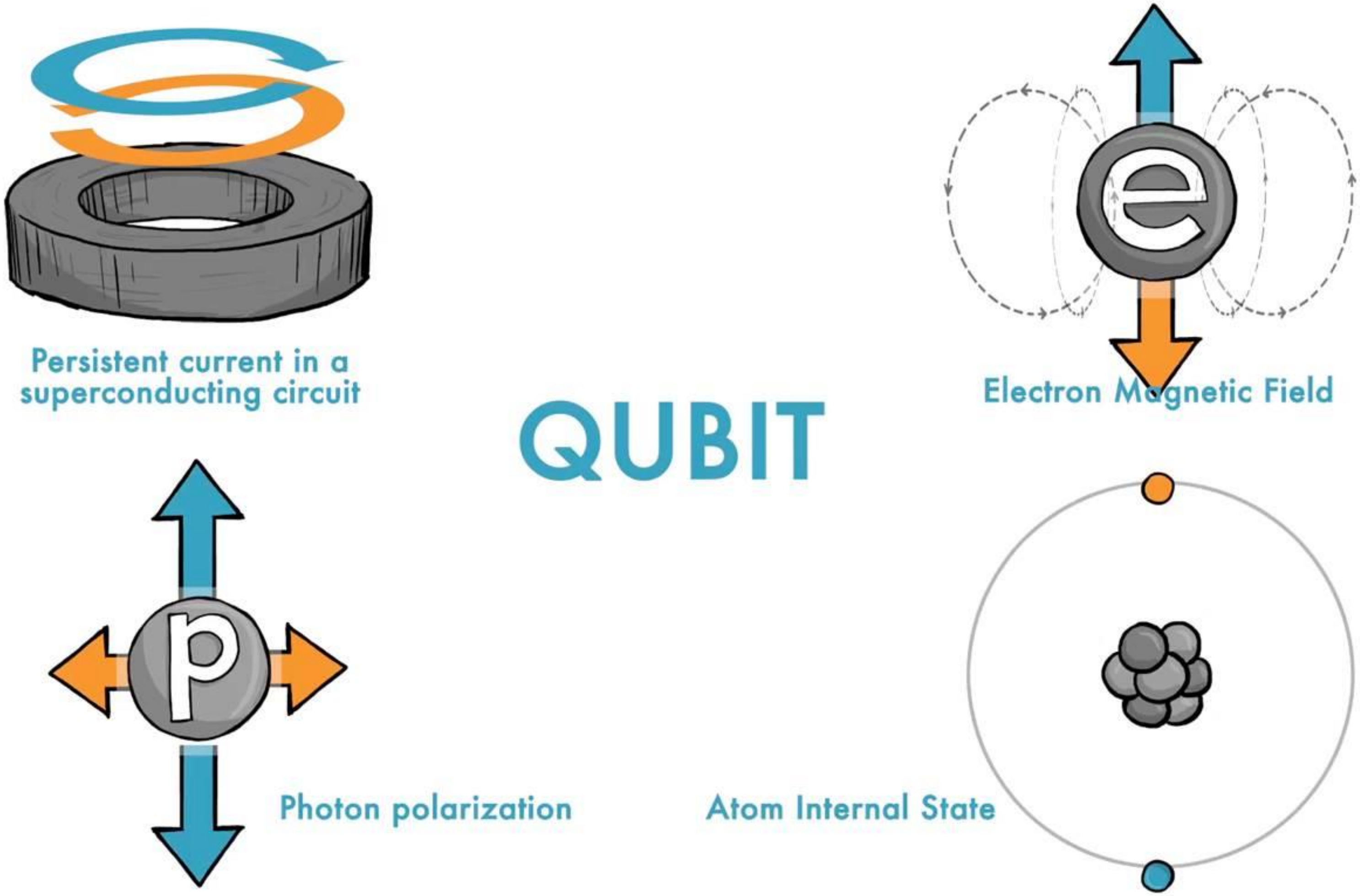

Alice Heads

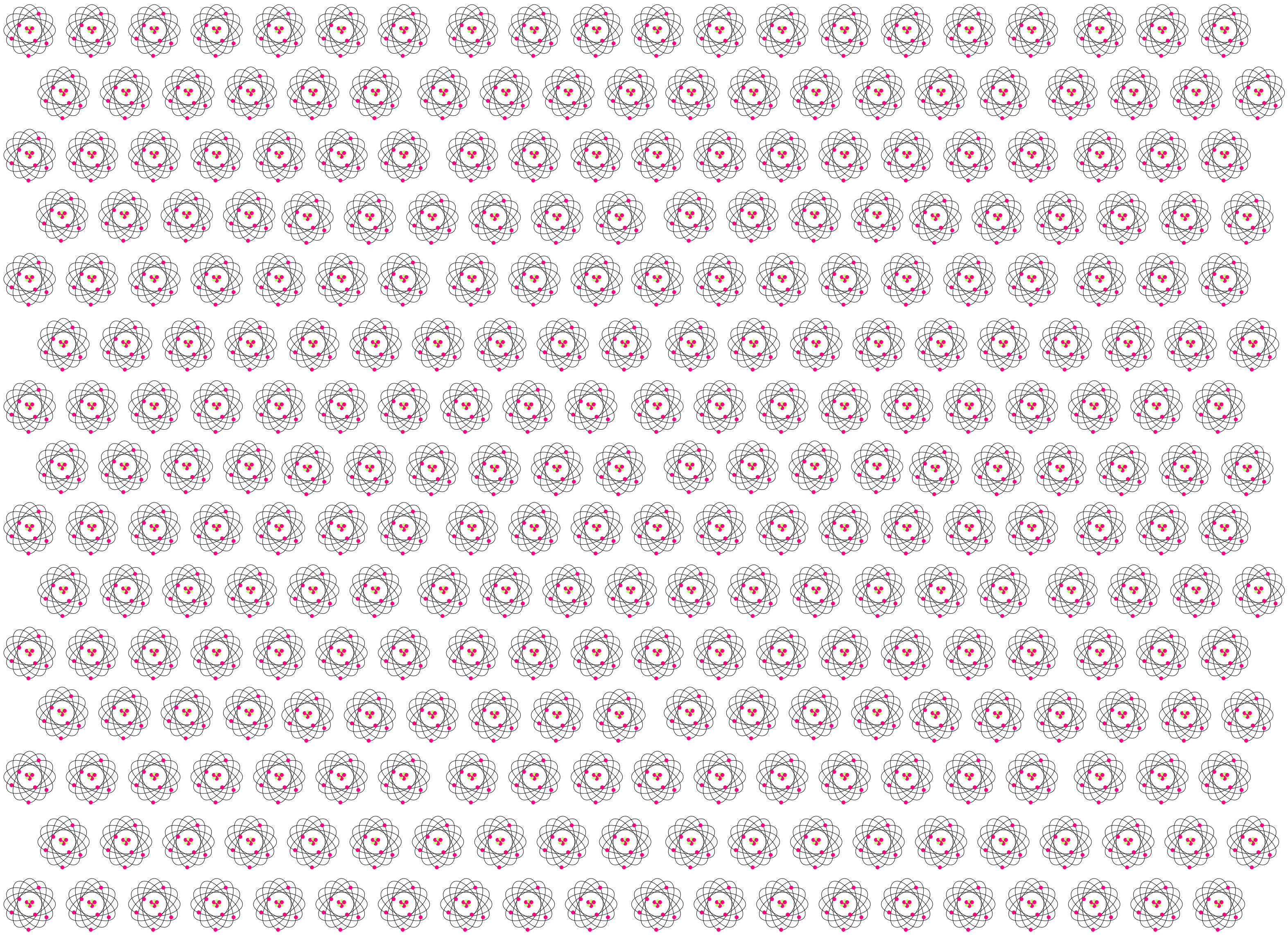



Bob Heads




| | Alice Heads | Bob Heads |
|---|---|---|
| 1 | $e_x$ | $e_y$ |
| 2 | $\frac{1}{2}e_x + \frac{\sqrt{3}}{2}e_y$ | $-\frac{\sqrt{3}}{2}e_x + \frac{1}{2}e_y$ |
| 3 | $-\frac{1}{2}e_x + \frac{\sqrt{3}}{2}e_y$ | $-\frac{\sqrt{3}}{2}e_x - \frac{1}{2}e_y$ |


QUBIT
Persistent current in a superconducting circuit
Electron Magnetic Field
Photon polarization
Atom Internal State
e
p

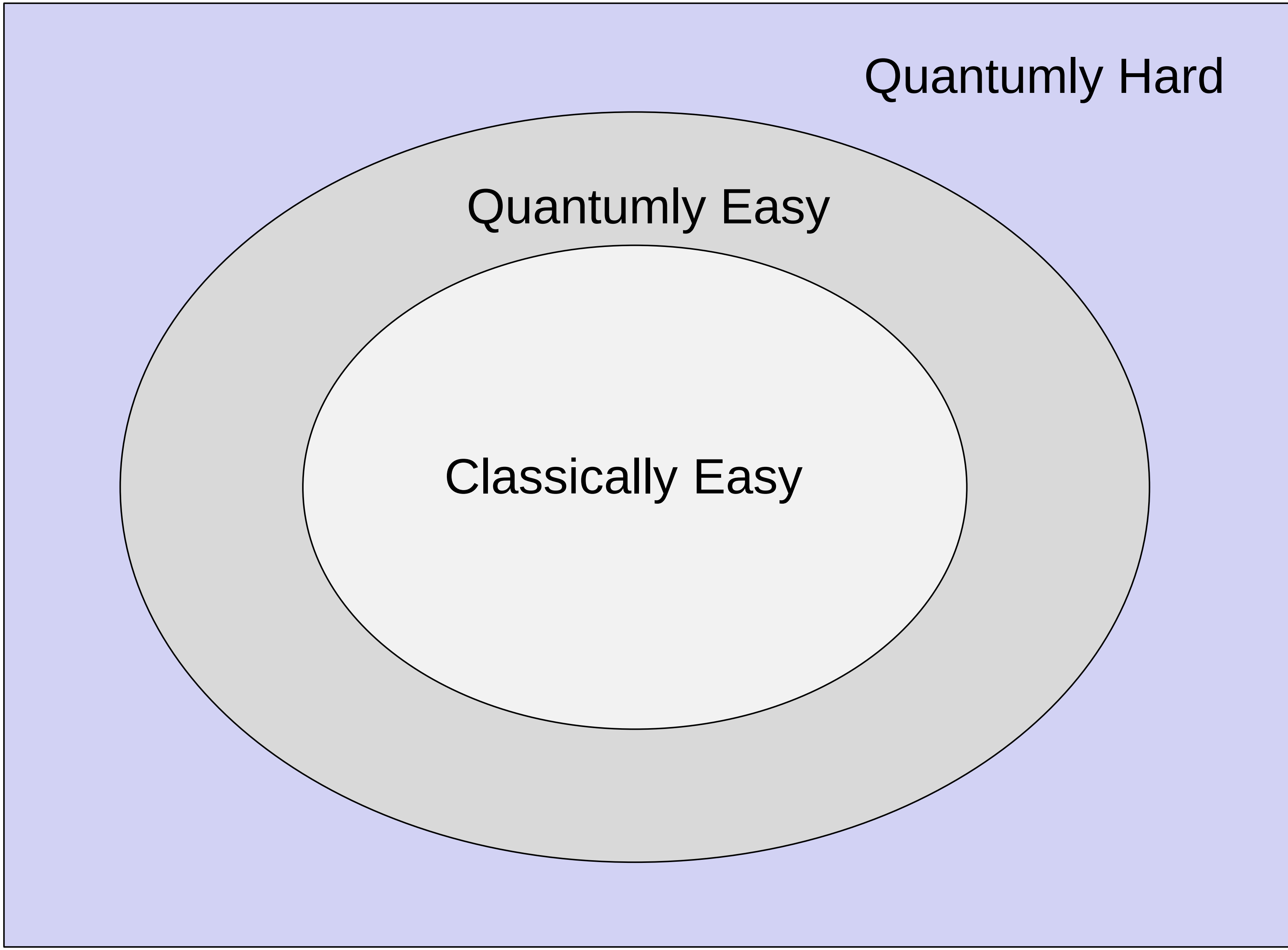


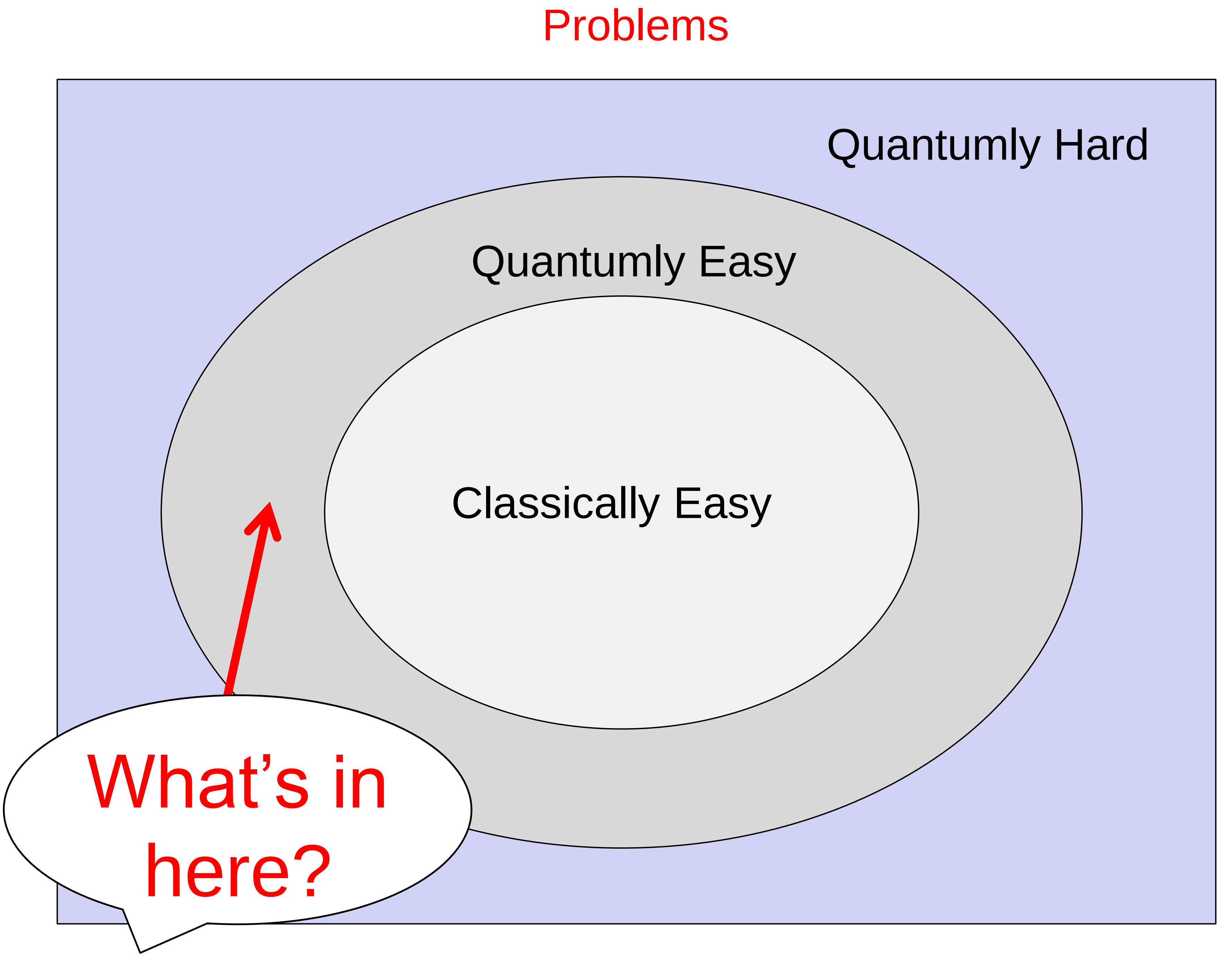
A complete description of a typical quantum state of just 300 qubits requires more bits than the number of atoms in the visible universe.

*Classical systems cannot simulate quantum systems efficiently (a widely believed but unproven conjecture).*

Arguably the most interesting thing we know about the difference between quantum and classical.

# Problems

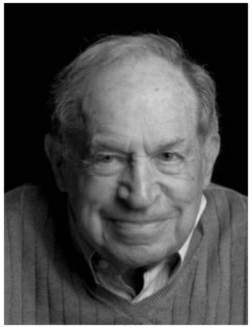


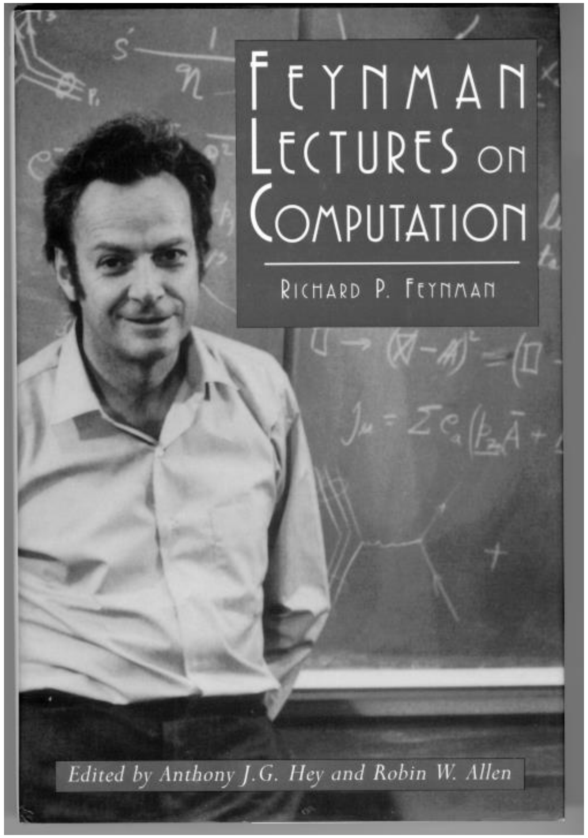

Problems
Quantumly Hard
Quantumly Easy
Classically Easy
What’s in here?

# "The theory of everything?"

"The Theory of Everything is not even remotely a theory of every thing … We know this equation is correct because it has been solved accurately for small numbers of particles (isolated atoms and small molecules) and found to agree in minute detail with experiment. However, it cannot be solved accurately when the number of particles exceeds about 10. No computer existing, or that will ever exist, can break this barrier because it is a catastrophe of dimension … We have succeeded in reducing all of ordinary physical behavior to a simple, correct Theory of Everything only to discover that it has revealed exactly nothing about many things of great importance."

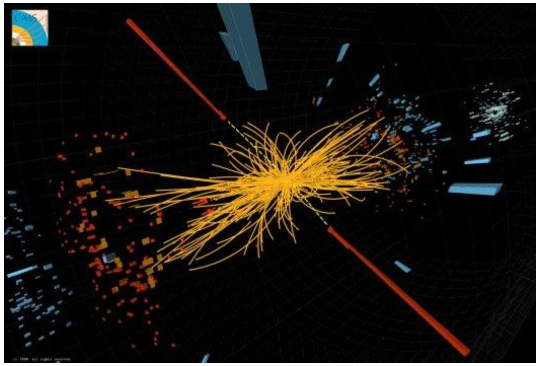
R. B. Laughlin and D. Pines, PNAS 2000.



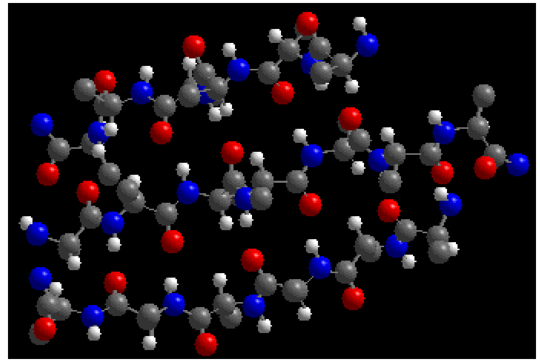



"Nature isn't classical, dammit, and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look so easy."

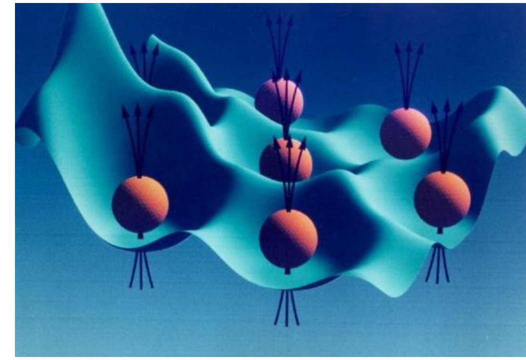
R. P. Feynman, 1981



particle collision



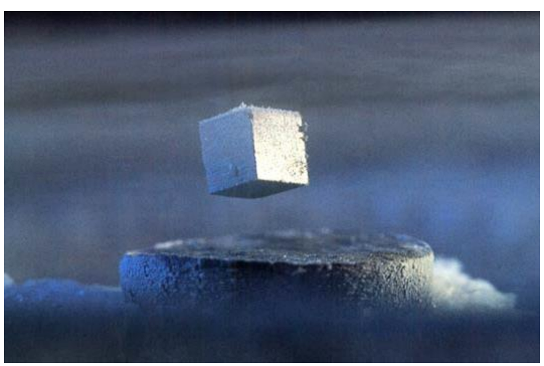
molecular chemistry



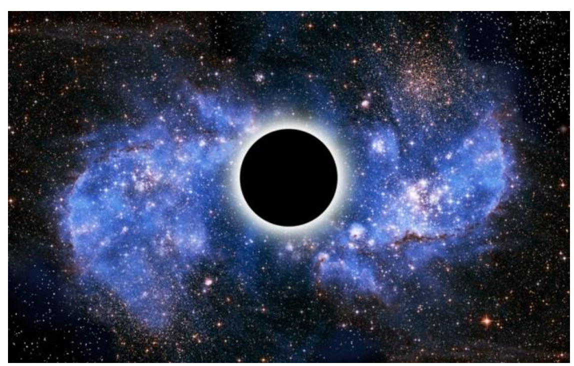
entangled electrons

A quantum computer can simulate efficiently any physical process that occurs in Nature.

(Maybe. We don’t actually know for sure.)



superconductor



black hole

early universe

# Why quantum computing is hard

We want qubits to interact strongly with one another.

We don't want qubits to interact with the environment.

Except when we control or measure them.

Article
*Nature* **574**, pages 505–510 (2019), 23 October 2019

# Quantum supremacy using a programmable superconducting processor

https://doi.org/10.1038/s41586-019-1666-5

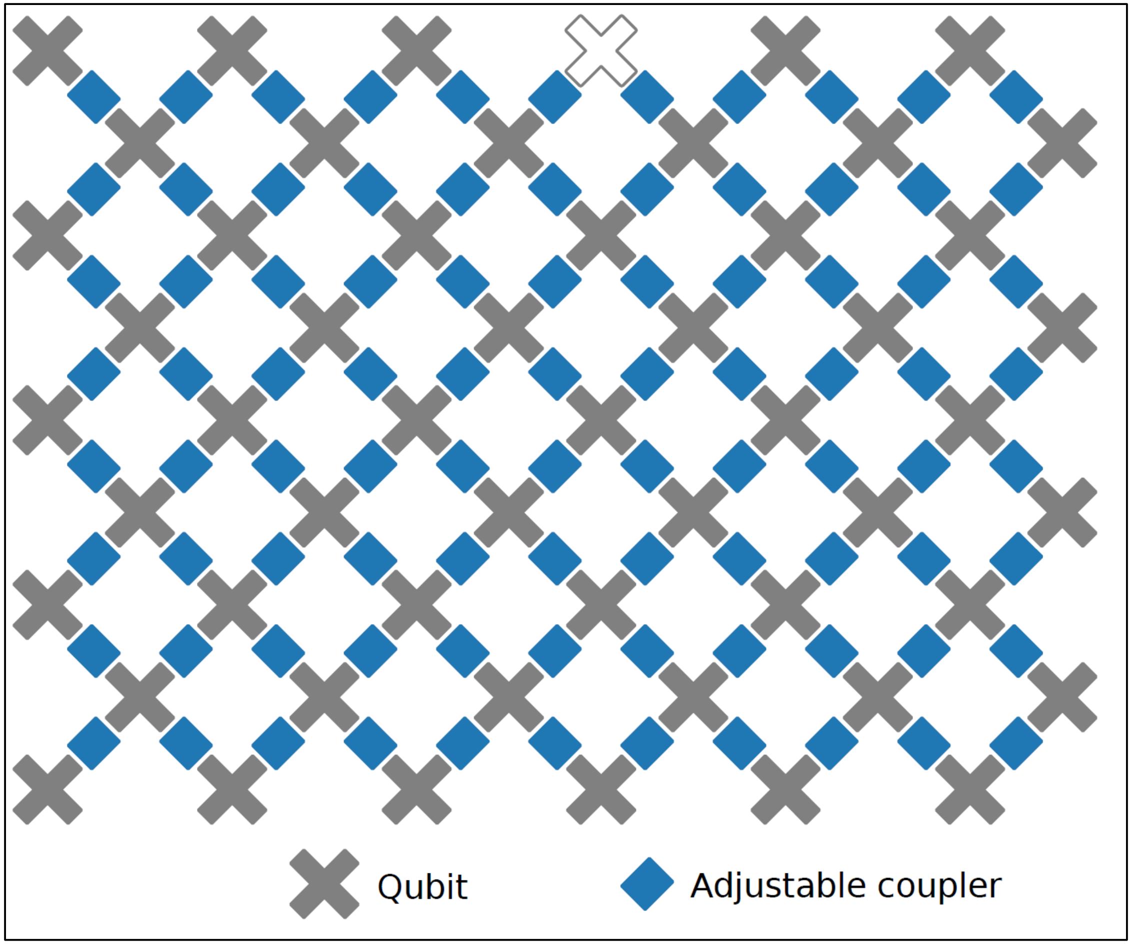
Received: 22 July 2019

Accepted: 20 September 2019

Published online: 23 October 2019

Frank Arute[1], Kunal Arya[1], Ryan Babbush[1], Dave Bacon[1], Joseph C. Bardin[1,2], Rami Barends[1], Rupak Biswas[3], Sergio Boixo[1], Fernando G. S. L. Brandao[1,4], David A. Buell[1], Brian Burkett[1], Yu Chen[1], Zijun Chen[1], Ben Chiaro[5], Roberto Collins[1], William Courtney[1], Andrew Dunsworth[1], Edward Farhi[1], Brooks Foxen[1,5], Austin Fowler[1], Craig Gidney[1], Marissa Giustina[1], Rob Graff[1], Keith Guerin[1], Steve Habegger[1], Matthew P. Harrigan[1], Michael J. Hartmann[1,6], Alan Ho[1], Markus Hoffmann[1], Trent Huang[1], Travis S. Humble[7], Sergei V. Isakov[1], Evan Jeffrey[1], Zhang Jiang[1], Dvir Kafri[1], Kostyantyn Kechedzhi[1], Julian Kelly[1], Paul V. Klimov[1], Sergey Knysh[1], Alexander Korotkov[1,8], Fedor Kostritsa[1], David Landhuis[1], Mike Lindmark[1], Erik Lucero[1], Dmitry Lyakh[9], Salvatore Mandrà[3,10], Jarrod R. McClean[1], Matthew McEwen[5], Anthony Megrant[1], Xiao Mi[1], Kristel Michielsen[11,12], Masoud Mohseni[1], Josh Mutus[1], Ofer Naaman[1], Matthew Neeley[1], Charles Neill[1], Murphy Yuezhen Niu[1], Eric Ostby[1], Andre Petukhov[1], John C. Platt[1], Chris Quintana[1], Eleanor G. Rieffel[3], Pedram Roushan[1], Nicholas C. Rubin[1], Daniel Sank[1], Kevin J. Satzinger[1], Vadim Smelyanskiy[1], Kevin J. Sung[1,13], Matthew D. Trevithick[1], Amit Vainsencher[1], Benjamin Villalonga[1,14], Theodore White[1], Z. Jamie Yao[1], Ping Yeh[1], Adam Zalcman[1], Hartmut Neven[1] & John M. Martinis[1,5*]

The promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here we report the use of a processor with programmable superconducting qubits to create quantum states on 53 qubits, corresponding to a computational state-space of dimension 253 (about 1016). Measurements from repeated experiments sample the resulting probability distribution, which we verify using classical simulations. Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times—our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years. This dramatic increase in speed compared to all known classical algorithms is an experimental realization of quantum supremacy for this specific computational task, heralding a much anticipated computing paradigm.




Each qubit is also connected to its neighboring qubits using a new adjustable coupler [31, 32]. Our coupler design allows us to quickly tune the qubit-qubit coupling from completely off to 40 MHz. Since one qubit did not function properly the device uses 53 qubits and 86 couplers.

[31] Martinis group, UCSB, 2014 (inductor coupled).
[32] Oliver group, MIT Lincoln Laboratory, 2018 (capacitor coupled)

# About Sycamore

*Greg Kuperberg: "Quantum David vs. Classical Goliath"*

A fully programmable circuit-based quantum computer. $n$= 53 working qubits in a 2D array with coupling of nearest neighbors.

Entangling 2-qubit gates with error rate .6% (in parallel), executed in 12 ns.

Estimated global circuit fidelity F = .2% for circuit with 20 "cycles" of 2-qubit gates: 430 2-qubit gates and 1113 1-qubit gates.

A circuit with fixed 2-qubit gates and randomly-chosen 1-qubit gates is chosen and executed millions of times; Each time, all qubits are measured, generating a 53-bit string.

The collected sample of 53-bit strings is not uniformly distributed. Comparing with classical simulations one can verify "heavy output generation" --- that the average probability of strings in the sample is greater than $2^{-n}$.

Because a random circuit has no structure, and the Hilbert space is exponentially large in $n$, simulation using a classical supercomputer is hard. (At least days, while the Sycamore generates a large sample in minutes.)

Experiment verifies that the hardware is working well enough to produce meaningful results in a regime where classical simulation is very difficult.

# What quantum computational supremacy means

*"Quantum David vs. Classical Goliath"*

It's a programmable circuit-based quantum computer.

An impressive achievement in experimental physics and a testament to ongoing progress in building quantum computing hardware;

We have arguably entered the regime where the extravagant exponential resources of the quantum world can be validated.

This confirmation does not surprise (most) physicists, but it's a milestone for technology on planet earth.

Building a quantum computer is merely *really, really hard,* not *ridiculously hard*. The hardware is working; we can begin a serious search for useful applications.

Other takes:
John Martinis and Sergio Boixo on Google QI Blog, 23 October 2019.
Scott Aaronson's "Quantum Supremacy FAQ" on Shtetl Optimized.
Scott's New York Times Op-Ed, 30 October 2019.
My column in Quanta Magazine, 2 October 2019.

# Quantum computing in the NISQ Era

The (noisy) 50-100 qubit quantum computer has arrived.
(*NISQ* = noisy intermediate-scale quantum.)

NISQ devices cannot be simulated by brute force using the most powerful currently existing supercomputers.

Noise limits the computational power of NISQ-era technology.

NISQ will be an interesting tool for exploring physics. It *might* also have other useful applications. But we're not sure about that.

NISQ will not change the world by itself. Rather it is a step toward more powerful quantum technologies of the future.

Potentially transformative scalable quantum computers may still be decades away. We're not sure how long it will take.

*Quantum 2, 79 (2018), arXiv:1801.00862*

# Department of unlikely headlines (Gizmodo 22 Nov. 2019)

PHYSICS

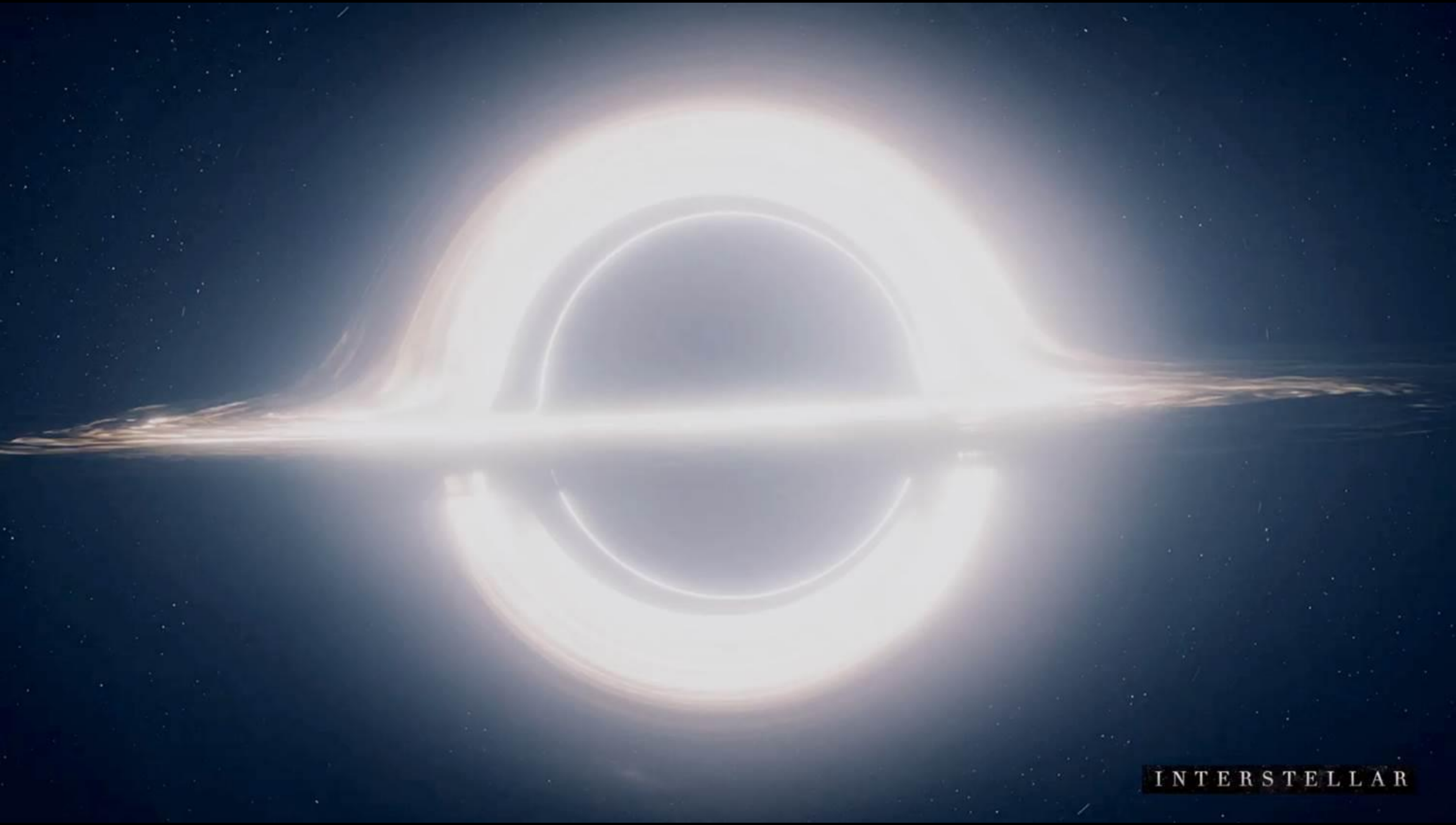
## Google Scientists Are Using Quantum Computers to Study Wormholes

Ryan F. Mandelbaum
Yesterday 1:15PM • Filed to: GOOGLE

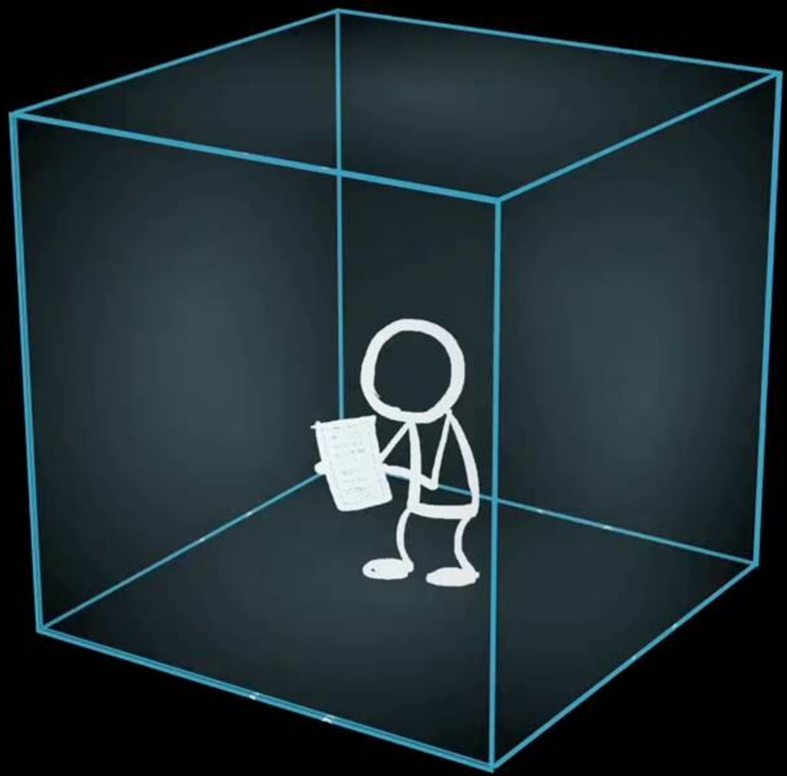
19.7K 8 Save

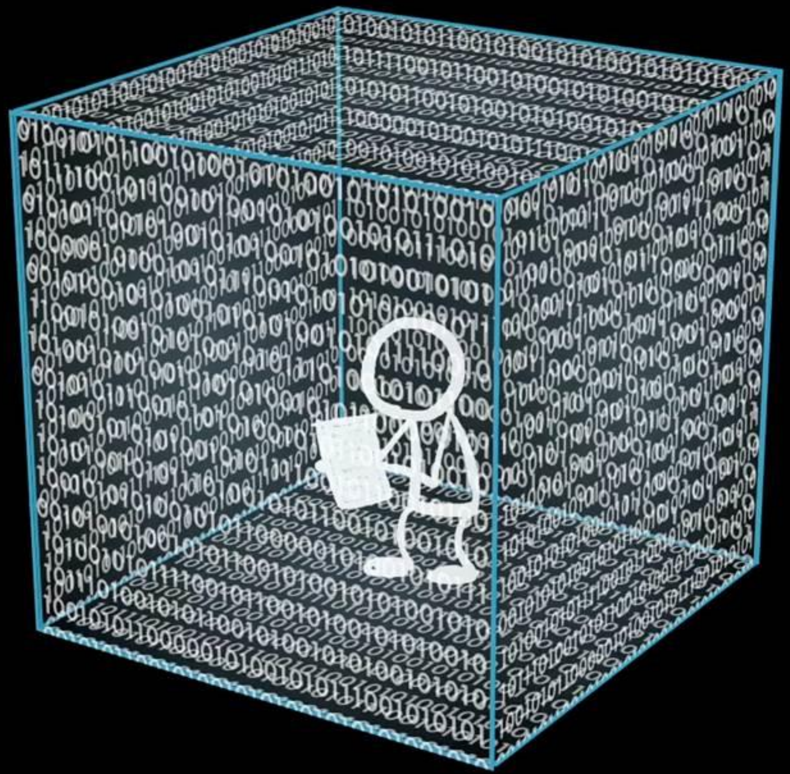
Artist's concept of information falling into a black hole
Illustration: E. Edwards/JQI

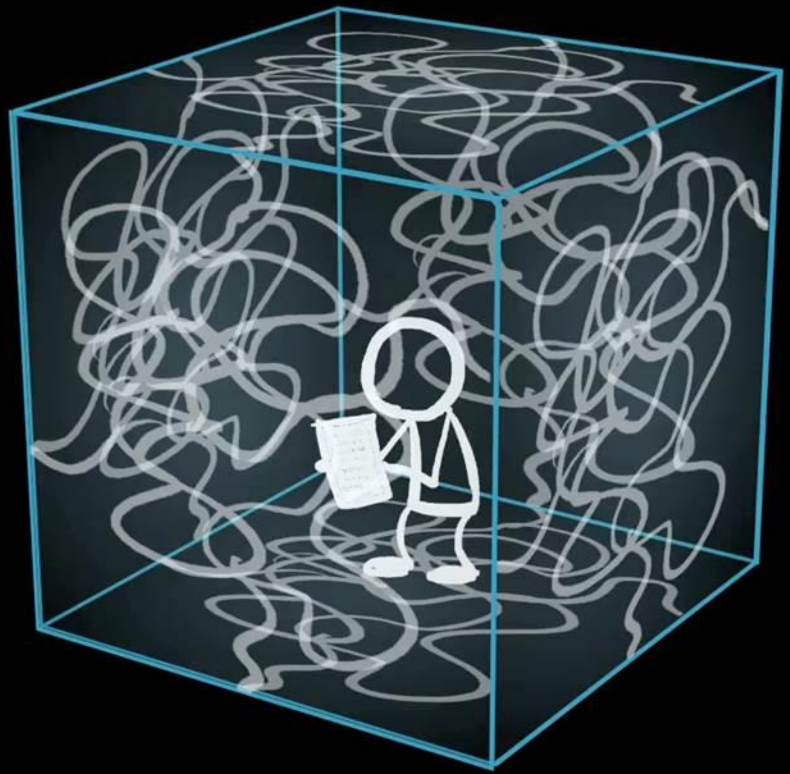
Google researchers are figuring out how to study some of the weirdest theorized physics phenomena, like wormholes that link pairs of black holes, using experiments in a lab.

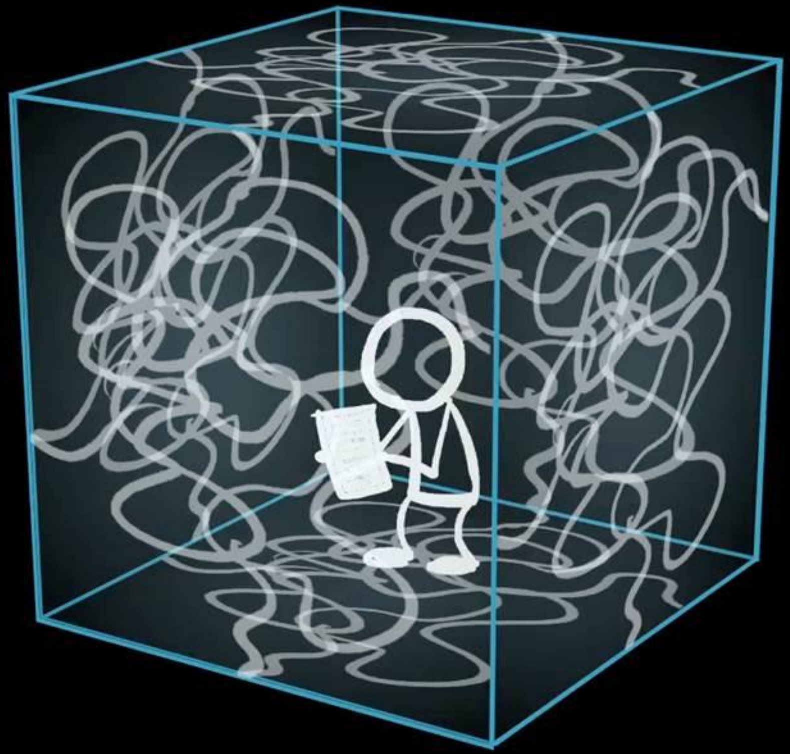

INTERSTELLAR

# THE HOLOGRAPHIC PRINCIPLE



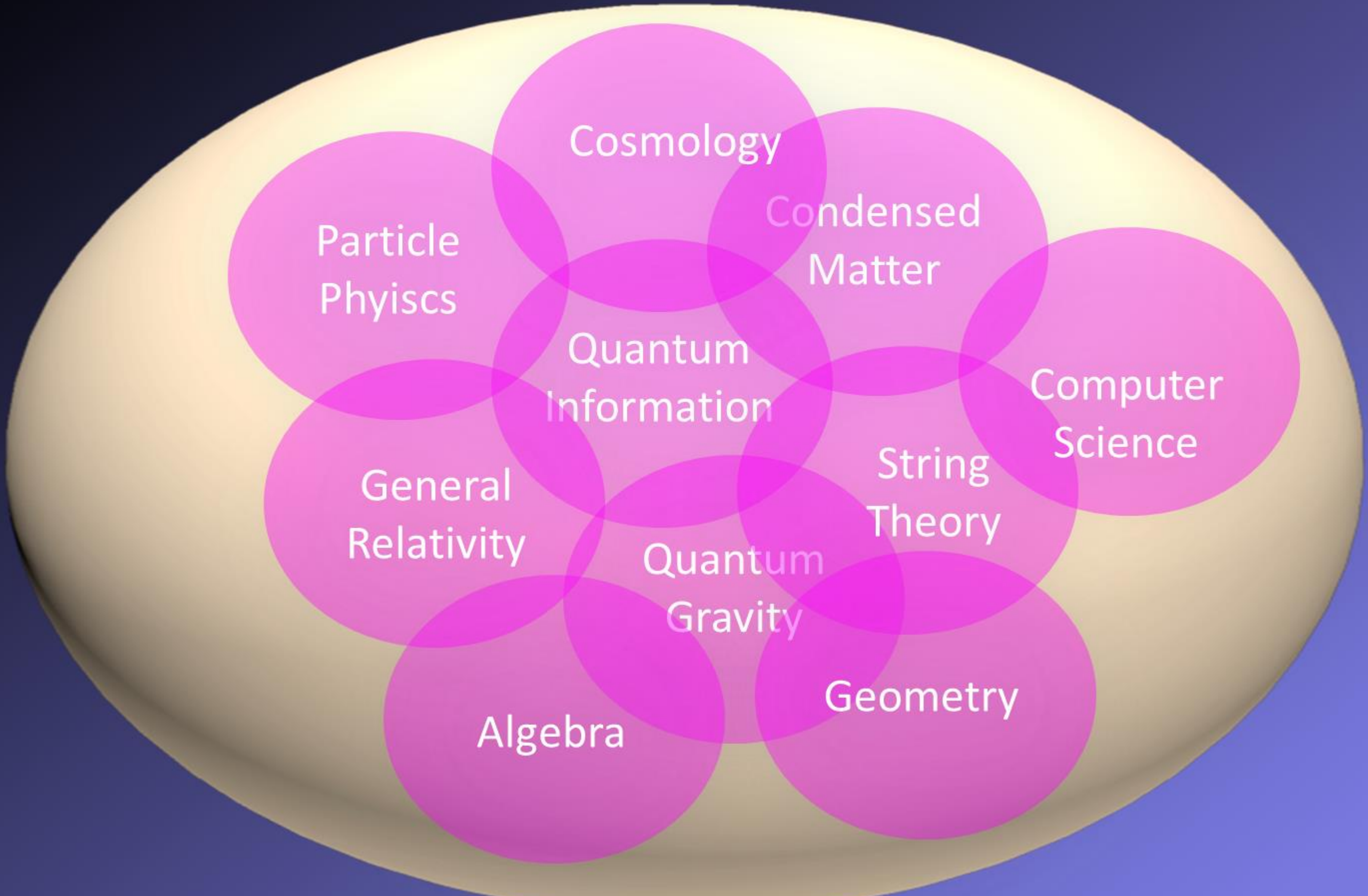






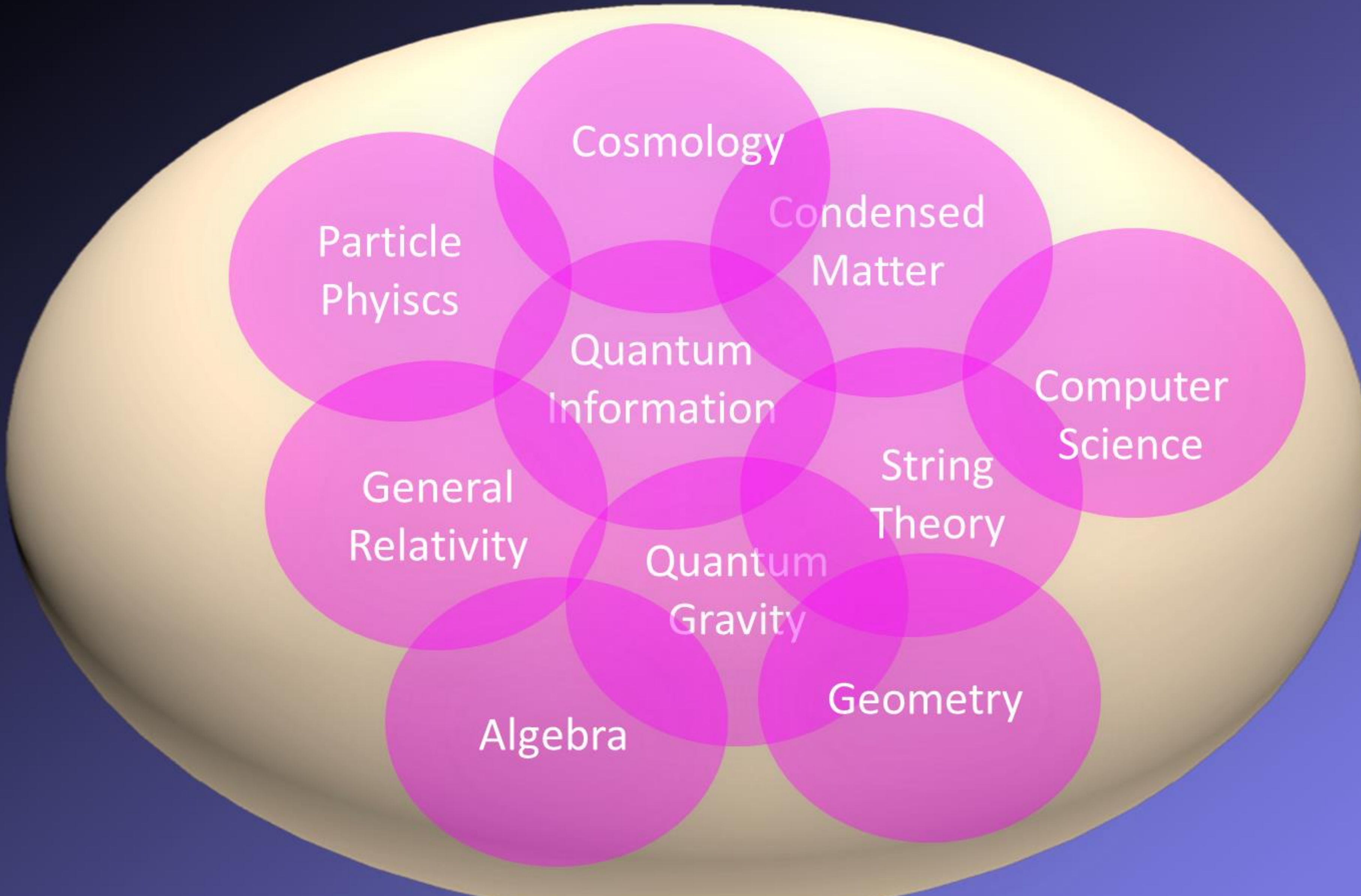
Entanglement is what holds space together.

# Unity of Theoretical Physics




From: Robbert Dijkgraaf at the inauguration of Caltech's Burke Institute.

# Unity of ~~Theoretical~~ Physics

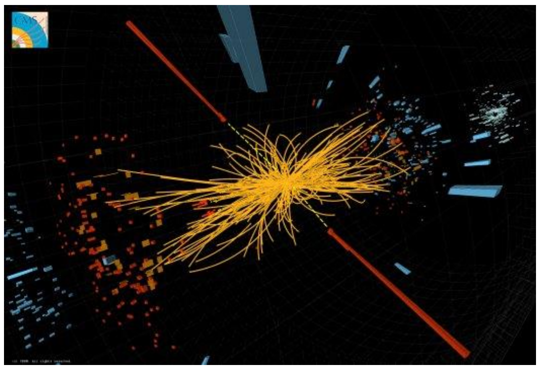



From: Robbert Dijkgraaf at the inauguration of Caltech’s Burke Institute.

Deep insights into the quantum structure of spacetime will arise from laboratory experiments studying highly entangled quantum systems.

# Frontiers of Physics

## short distance



Higgs boson

Neutrino masses

Supersymmetry

Quantum gravity

String theory

## long distance

Large scale structure

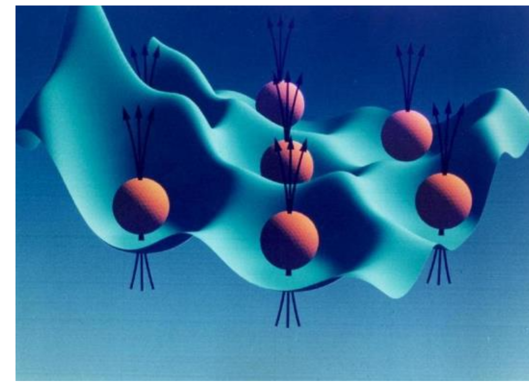
Cosmic microwave background

Dark matter

Dark energy

Gravitational waves

## complexity



"More is different"

Many-body entanglement

Phases of quantum matter

Quantum computing

Quantum spacetime