

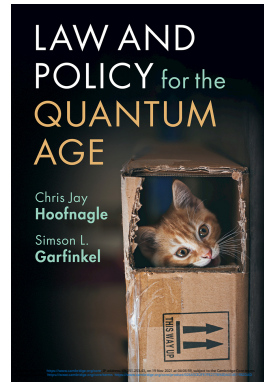
Quantum Computing and the Transition to Post-Quantum Cryptography

Simson L. Garfinkel, PhD.

Senior Executive Fellows

Tuesday, April 21

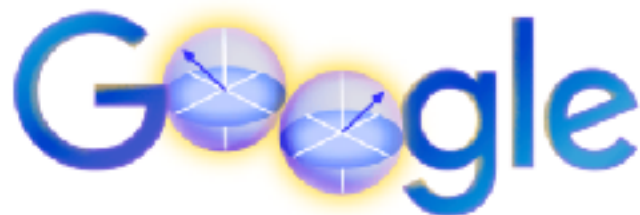
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Abstract

Quantum computers are transitioning from the research laboratory to commercial reality. Within a few years quantum computers will likely be able to perform computations in a few hours that today's "classical" computers could never complete within our lifetimes. Quantum computers might make all of the world's encrypted data suddenly accessible to major governments and corporations, which is the reason that governments around the world have adopted aggressive timelines for transitioning encryption algorithms to so-called "post-quantum" algorithms. But it's also likely that many of the predictions for quantum computers is ungrounded hype—science fiction predictions that will never come to pass. This 90-minute session provides a brief introduction to quantum computing, explores what quantum computers will and won't be able to do, explains why the governments around the world have mandated a transition to new "post-quantum" encryption algorithms, and presents the real scientific, technical and business opportunities

April 14, 2026 was World Quantum Day!



+ Ask Google



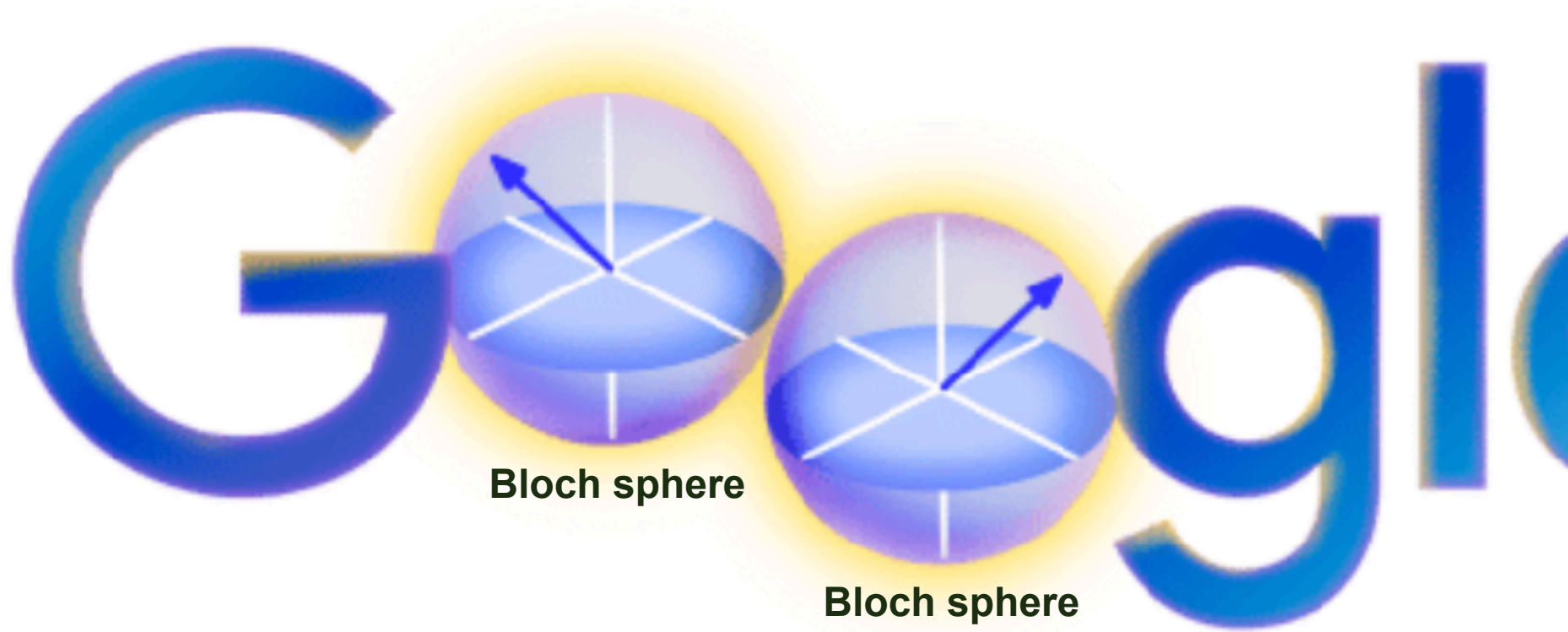
AI Mode

● Apr 14, 2026

World Quantum Day 2026

Happy World Quantum Day!

“Bloch spheres” are graphical representation of the “qubits” that quantum computers use for computation...



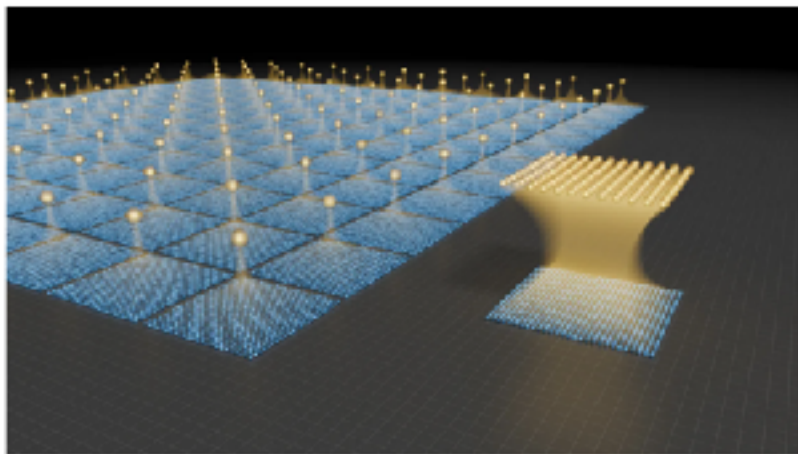
April 1, 2026 — no joke

NEWS

QUANTUM PHYSICS

Just 10,000 quantum bits might crack internet encryption schemes

Computers based on atoms could demand a fraction of the qubits previously estimated



Enter a quantum computer made of reliable logical qubits (left), then enter gates physical qubits (blue). A new scheme produces many more logical qubits per physical qubit (right). Credit: arXiv.org preprint (2025) by D. ROBERT HARTMAN-DELAUNAY/ALTECH

By Emily Conover

APRIL 1, 2026 AT 9:02 AM

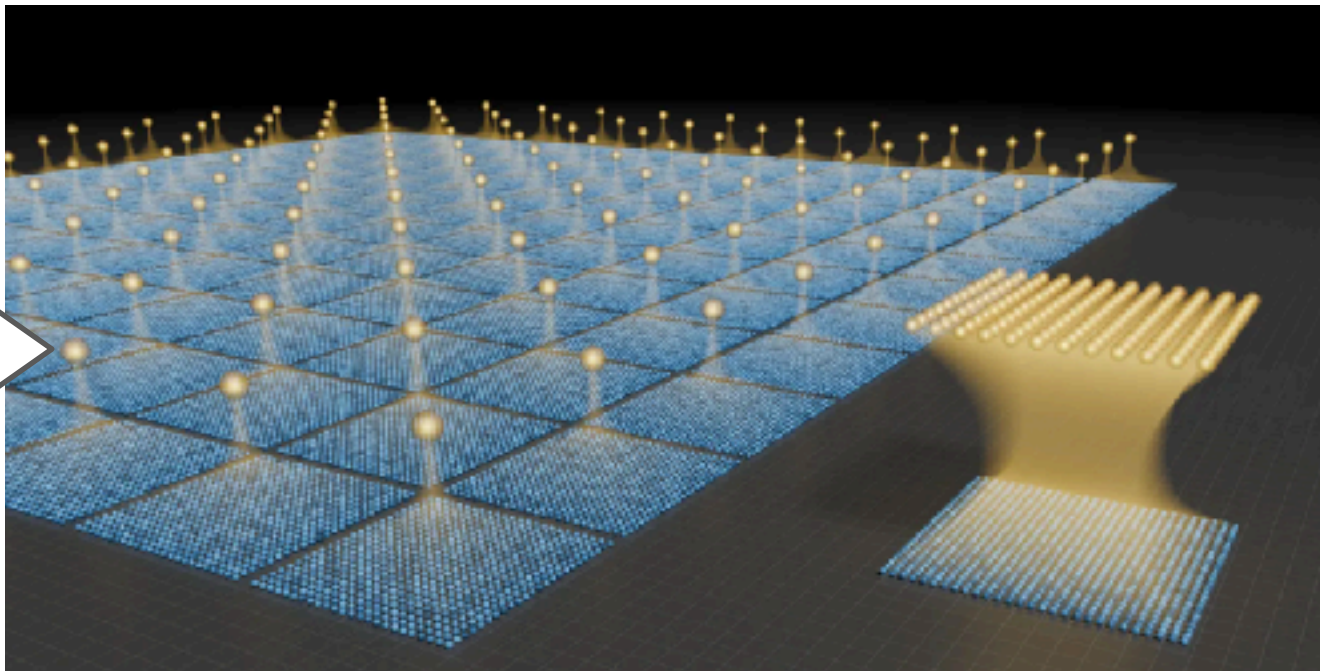
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Powerful quantum computers may be closer than scientists thought.

<https://www.sciencenews.org/article/quantum-bits-crack-internet-encryption>

qubit



**6,100 physical qubits
10,000 need to break codes**

(but many more needed to crack keys in a reasonable amount of time.)

Quantum Physics

[Submitted on 30 Mar 2026]

Shor's algorithm is possible with as few as 10,000 reconfigurable atomic qubits

Madelyn Cain, Qian Xu, Robbie King, Lewis R. B. Picard, Harry Levine, Manuel Endres, John Preskill, Hsin-Yuan Huang, Dolev Bluvstein

Quantum computers have the potential to perform computational tasks beyond the reach of classical machines. A prominent example is Shor's algorithm for integer factorization and discrete logarithms, which is of both fundamental importance and practical relevance to cryptography. However, due to the high overhead of quantum error correction, optimized resource estimates for cryptographically relevant instances of Shor's algorithm require millions of physical qubits. Here, by leveraging advances in high-rate quantum error-correcting codes, efficient logical instruction sets, and circuit design, we show that Shor's algorithm can be executed at cryptographically relevant scales with as few as 10,000 reconfigurable atomic qubits. Increasing the number of physical qubits improves time efficiency by enabling greater parallelism; under plausible assumptions, the runtime for discrete logarithms on the P-256 elliptic curve could be just a few days for a system with 26,000 physical qubits, while the runtime for factoring RSA-2048 integers is one to two orders of magnitude longer. Recent neutral-atom experiments have demonstrated universal fault-tolerant operations below the error-correction threshold, computation on arrays of hundreds of qubits, and trapping arrays with more than 6,000 highly coherent qubits. Although substantial engineering challenges remain, our theoretical analysis indicates that an appropriately designed neutral-atom architecture could support quantum computation at cryptographically relevant scales. More broadly, these results highlight the capability of neutral atoms for fault-tolerant quantum computing with wide-ranging scientific and technological applications.

Comments: 7+15 pages, 3+4 figures

Subjects: Quantum Physics (quant-ph)

Cite as: arXiv:2603.28627 [quant-ph]

for arXiv:2603.28627v1 [quant-ph] for this version)

<https://doi.org/10.48550/arXiv.2603.28627> 

Submission history

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[v1] Mon, 30 Mar 2026 16:10:08 UTC (4,544 KB)

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Quantum Physics

[Submitted on 30 Mar 2026 (v1), last revised 15 Apr 2026 (this version, v2)]

Securing Elliptic Curve Cryptocurrencies against Quantum Vulnerabilities: Resource Estimates and Mitigations

Ryan Babbush, Adam Zalcman, Craig Gidney, Michael Broughton, Tanuj Khattar, Hartmut Never, Thiago Bergamaschi, Justin Drake, Dan Boneh

This whitepaper seeks to elucidate implications that the capabilities of developing quantum architectures have on blockchain vulnerabilities and mitigation strategies. First, we provide new resource estimates for breaking the 256-bit Elliptic Curve Discrete Logarithm Problem, the core of modern blockchain cryptography. We demonstrate that Shor's algorithm for this problem can execute with either <1200 logical qubits and <90 million Toffoli gates or <1450 logical qubits and <70 million Toffoli gates. In the interest of responsible disclosure, we use a zero-knowledge proof to validate these results without disclosing attack vectors. On superconducting architectures with $1e-3$ physical error rates and planar connectivity, those circuits can execute in minutes using fewer than half a million physical qubits. We introduce a critical distinction between fast-clock (such as superconducting and photonic) and slow-clock (such as neutral atom and ion trap) architectures. Our analysis reveals that the first fast-clock CRQCs would enable on-spend attacks on public mempool transactions of some cryptocurrencies. We survey major cryptocurrency vulnerabilities through this lens, identifying systemic risks associated with advanced features in some blockchains such as smart contracts, Proof-of-Stake consensus, and Data Availability Sampling, as well as the enduring concern of abandoned assets. We argue that technical solutions would benefit from accompanying public policy and discuss various frameworks of digital salvage to regulate the recovery or destruction of dormant assets while preventing adversarial seizure. We also discuss implications for other digital assets and tokenization as well as challenges and successful examples of the ongoing transition to Post-Quantum Cryptography (PQC). Finally, we urge all vulnerable cryptocurrency communities to join the ongoing migration to PQC without delay.

Comments: 17 pages, 14 figures. v2 patches software bug enabling exploit against ZXP soundness

Subjects: Quantum Physics (quant-ph); Cryptography and Security (cs.CR)

Cite as: arXiv:2603.28846 [quant-ph]

(or arXiv:2603.28846v2 [quant-ph] for this version)

<https://doi.org/10.48550/arXiv.2603.28846> **Submission history**From: Ryan Babbush [\[view email\]](#)

[v1] Mon, 30 Mar 2026 17:59:21 UTC (1,034 KB)

[v2] Wed, 15 Apr 2026 16:50:58 UTC (1,022 KB)

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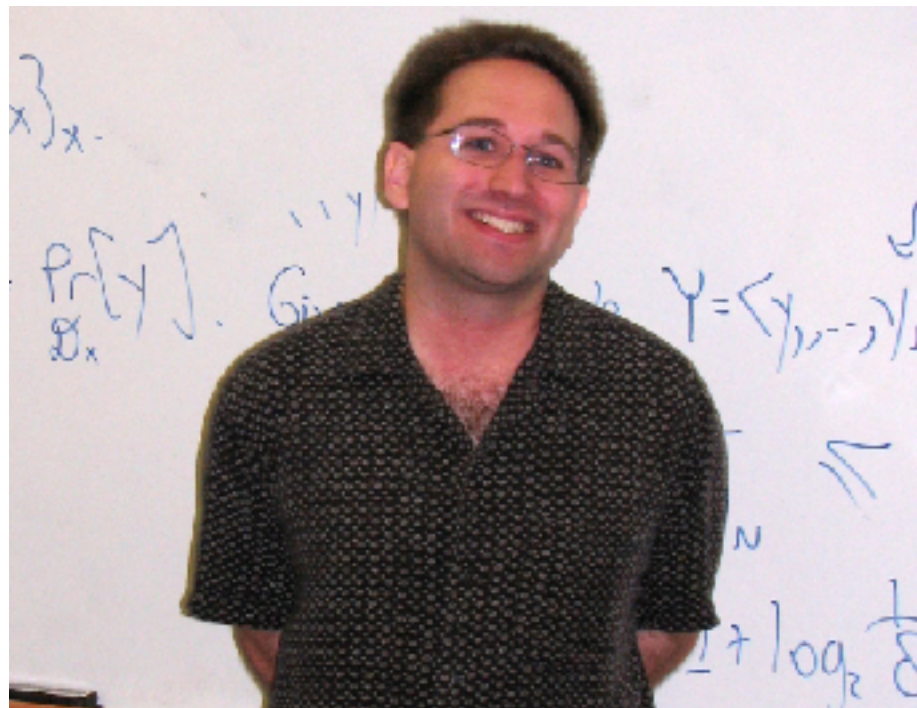
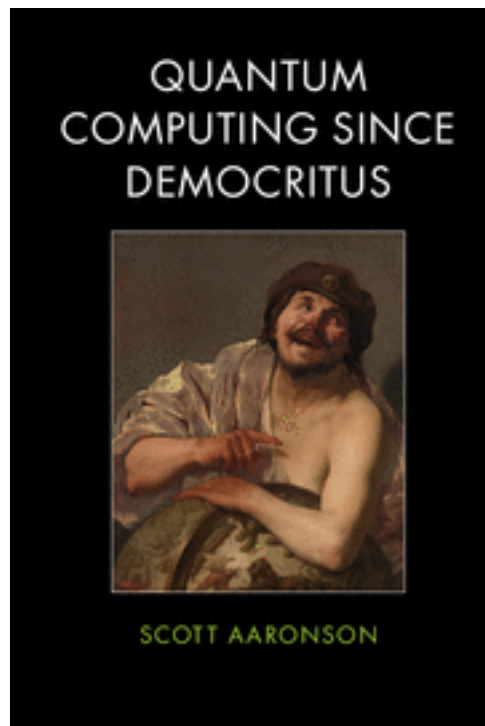
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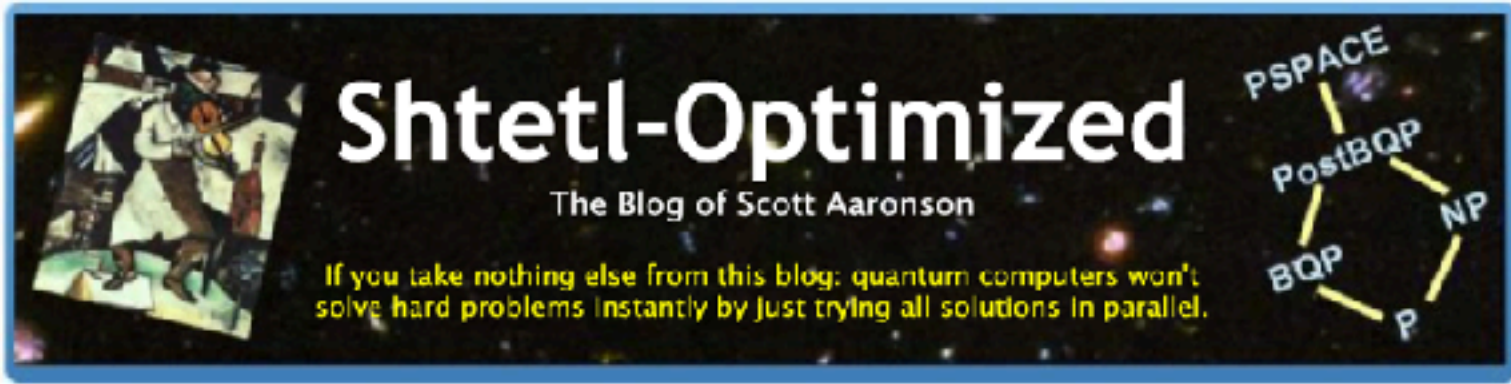
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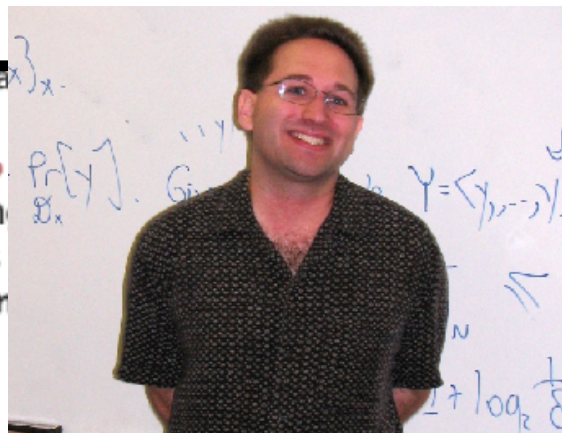
Scott Aaronson, Schlumberger Centennial Chair of Computer Science at The University of Texas at Austin, and director of its Quantum Information Center.





In any case, these results provide an even stronger impetus for people to upgrade now to quantum-resistant cryptography. They—meaning you, if relevant—should really get on that!

For those of you who had announcements this week. Preskill, **showed how to do** previously known, by using neutral-atom architectures operations, like trapped ion **overhead implementation** cryptography.



two Bombesnell QC friend-of-the-blog John Nissen showed how to do less overhead than was previously known, by using neutral-atom architectures operations, like trapped ion **work for example in** that allow nonlocal Google, **gave a lower-** 256-bit elliptic curve

Outline for today's lecture

2026	Quantum computing: where are we on the hype cycle?
1500-1910	Brief refresher on quantum physics
1984-2016	Quantum cryptography
2001-2026	25 years of quantum computers
2029?	What a cryptographically relevant quantum computer could do What else could you do with a CRQC?
2020-2030	The transition to post-quantum cryptography
2026	Q&A

Quantum Computing: Where Are We On the Hype Cycle?

Q-Day in 2029?

Home / News / Security/Privacy

NEWS

Google warns 'Q-Day' is coming, could break encryption by 2029

Quantum computers will likely be able to crack current encryption algorithms earlier than once thought, posing a serious threat to online security.



By Michael Stutz

Senior Security Analyst

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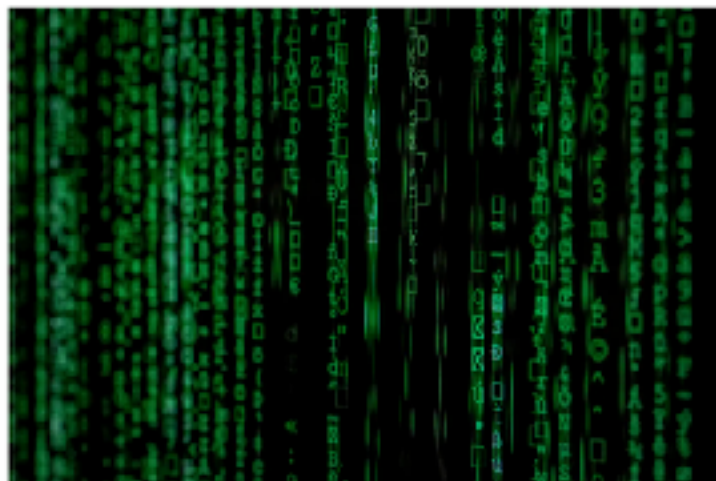


Image: iStock/Markus Spiller

Quantum Apocalypse?

WIRED

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THE BIG STORY

The Quantum Apocalypse Is Coming. Be Very Afraid

What happens when quantum computers can finally crack encryption and break into the world's best-kept secrets? It's called Q-Day—the worst holiday maybe ever.

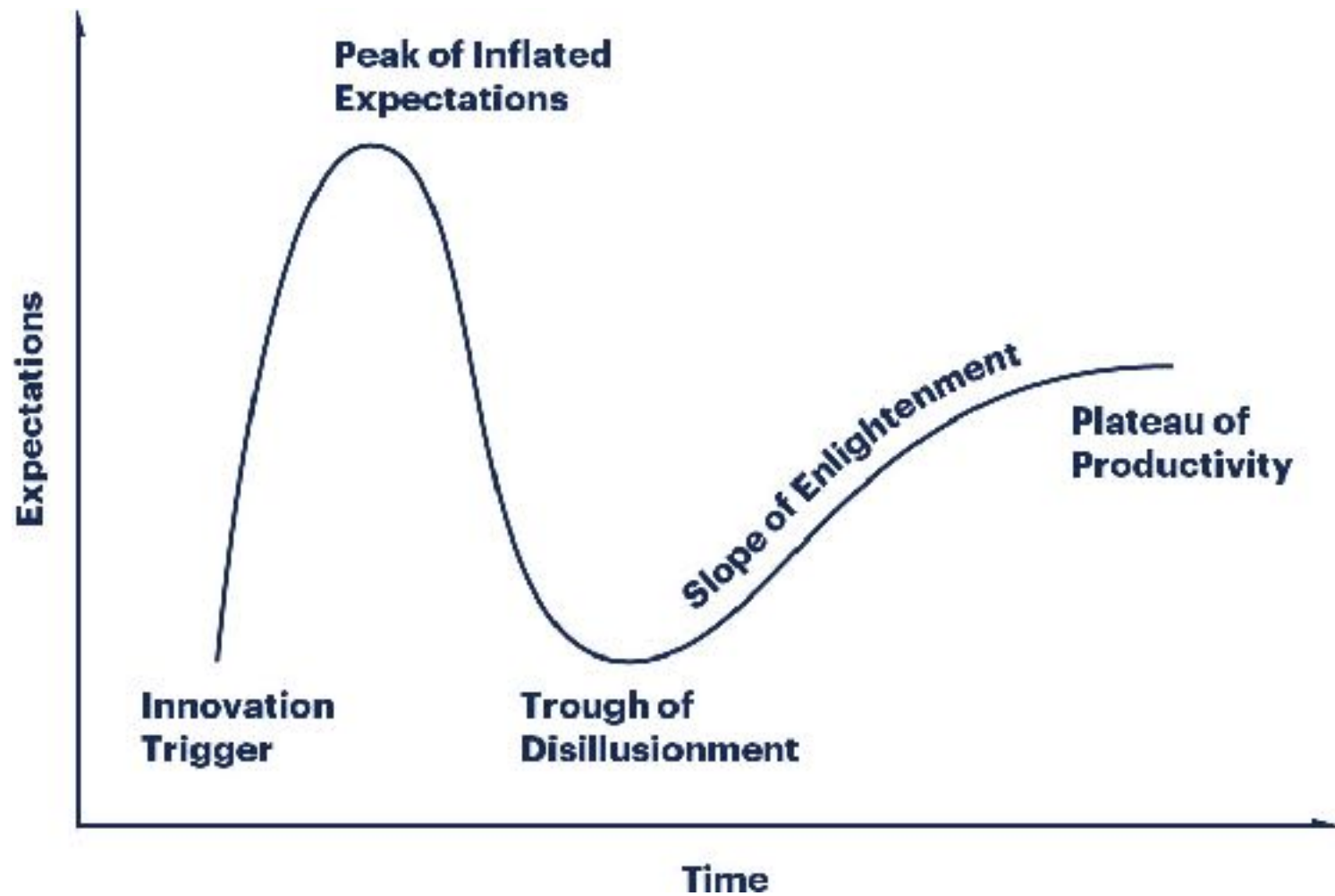
ART BY WILTMILL

MAY 24 2025 6:00 AM

Quantum frontiers may be closer than they appear

The threat to encryption is relevant today with [store-now-decrypt-later attacks](#), while digital signatures are a future threat that require the transition to PQC prior to a Cryptographically Relevant Quantum Computer (CRQC)





Quantum computing's Innovation Trigger: Shor's algorithm (1994)

1994 Peter Shor discovered a way to quickly factor numbers on a quantum computer

—*Shor was a researcher at AT&T Bell Labs in NJ*

—*Today Shor is a professor at MIT*



**Innovation
Trigger**

Put this into context

1994 Peter Shor discovered a way to quickly factor numbers on a quantum computer



Why is factoring important?

Because the difficulty of factoring* is the basis of today's public key cryptography systems.

(* quantum computers could also be used for cracking other kinds of codes.)

What's a quantum computer?

A computer that computes using an aspect of quantum mechanics called entanglement*.

(* Einstein called it "spooky action at a distance.")

Put this into context

1994 Peter Shor discovered a way to quickly factor numbers on a quantum computer



Just one problem:

Quantum computers did not exist in 1994

Factoring is important because factoring large number is hard

1994 Peter Shor discovered a way to **quickly factor numbers** on a quantum computer



Factoring numbers:

FACTOR(15) = 5 x 3 (easy!)

FACTOR(323) = 19 x 17 (easy!)

FACTOR(114381625757888867669235779976146612010218296721242362562561842935706935245733897830597123563958705058989075147599290026879543541)

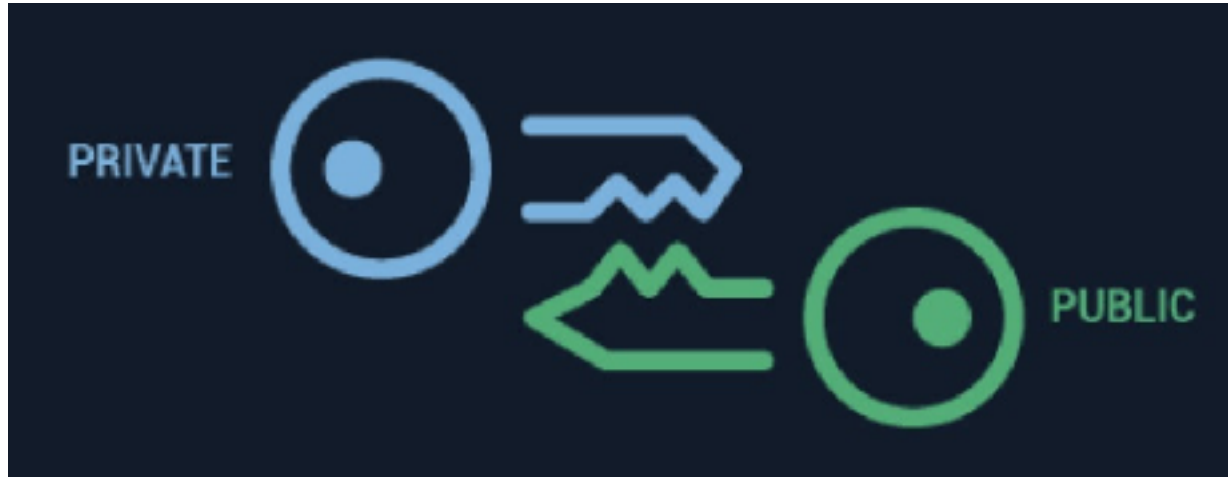
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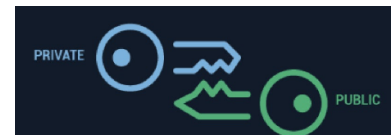
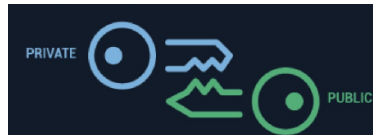
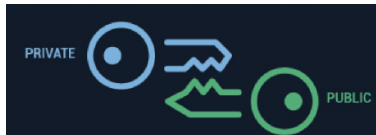
— 1994 — Took 600 volunteers 8 month in 1994

Knowledge check...

Raise your hand if understand public key cryptography



If you have any of these, you have an RSA private/public keypair in your pocket

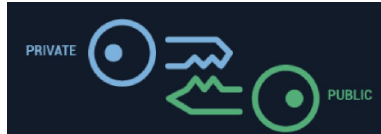


(The difficulty of) factoring large numbers is the basis of modern encryption systems.

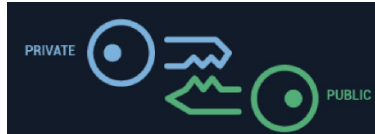
RSA Encryption — Invented in 1977 by Rivest, Shamir & Adleman



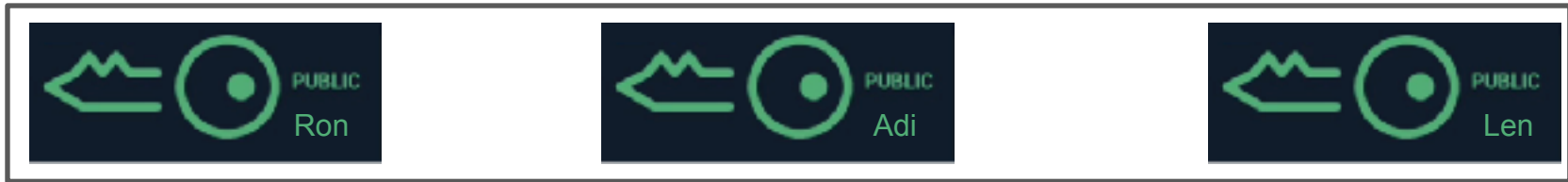
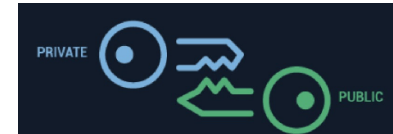
Ron Rivest



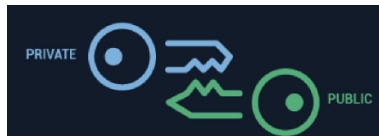
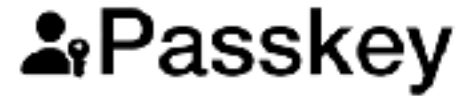
Adi Shamir



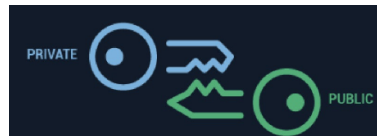
Len Adleman



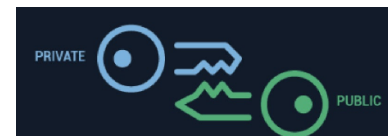
Today public/private keys are used for signing code, authenticating web servers, and authenticating people



This copy of Word is legit



This is really Amazon's website

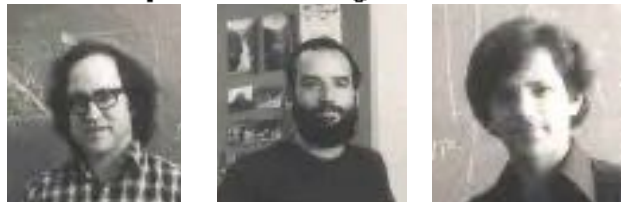


This is really Jane Marie Doe

The RSA algorithm was published in Aug 1977 with a 129-digit number to factor (RSA-129)

9686	9613	7546	2206
1477	1409	2225	4355
8829	0575	9991	1245
7431	9874	6951	2093
0816	2982	2514	5708
3569	3147	6622	8839
8962	8013	3919	9055
1829	9451	5781	5154

A ciphertext challenge worth \$100



MATHEMATICAL GAMES

A new kind of cipher that would take millions of years to break

by Martin Gardner

"Few persons can be made to believe that it is not quite an easy thing to invent a method of secret writing which shall baffle investigation. Yet it may be roundly asserted that human ingenuity cannot concoct a cipher which human ingenuity cannot resolve."

—EDGAR ALLAN POE

The upward creep of postal rates accompanied by the deterioration of postal service is a trend that may or may not continue, but as far as most private communication is concerned, in a few decades it probably will not matter. The reason is simple. The transfer of information will probably be much faster and much cheaper by "electronic mail" than by conventional postal systems. Before long it should be possible to go to any telephone, insert a message into an attachment and dial a number. The telephone at the other end will print out the message at once.

Government agencies and large businesses will presumably be the first to make extensive use of electronic mail, followed by small businesses and private individuals. When this starts to happen, it will become increasingly desirable to have fast, efficient ciphers to safeguard information from electronic eavesdroppers. A similar problem is involved in protecting private information stored in computer memory banks from snoopers who have access to the memory through data-processing networks.

It is hardly surprising that in recent years a number of mathematicians have asked themselves if it is possible to devise a cipher that can be rapidly encoded and decoded by computer, can be used repeatedly without changing the key and

is unbreakable by sophisticated cryptanalysis? The surprising answer is yes. The breakthrough is scarcely two years old, yet it bids fair to revolutionize the entire field of secret communication. Indeed, it is so revolutionary that all previous ciphers, together with the techniques for cracking them, may soon fade into oblivion.

An unbreakable code can be unbreakable in theory or unbreakable only in practice. Edgar Allan Poe, who fancied himself a skilled cryptanalyst, was convinced that no cipher could be invented that could not also be "unriddled." Poe was certainly wrong. Ciphers that are unbreakable even in theory have been in use for half a century. They are "one-time pads," ciphers that are used only once, for a single message. Here is a simple example based on a shift cipher, sometimes called a Caesar cipher because Julius Caesar used it.

First write the alphabet, followed by the digits 0 through 9. (For coding purposes 0 represents a space between words, and the other digits are assigned to punctuation marks.) Below this write the same sequence cyclically shifted to the right by an arbitrary number of units, as is shown in color in the illustration on this page. Our cipher consists in taking each symbol in the plaintext (the message), finding it in the top row, and replacing it with the symbol directly below it. The result is a simple substitution cipher, easily broken by any amateur.

In spite of its simplicity, a shift cipher can be the basis of a truly unbreakable code. The trick is simply to use a different shift cipher for each symbol in the plaintext, each time choosing the amount of shift at random. This is easily done with the spinner shown in the top illustration on the opposite page. Suppose the first word of plaintext is true. We spin the arrow and it stops on K. This tells us to use for encoding a Caesar cipher in which the lower alphabet is shifted 10 steps to the right, bringing A below K as is shown in the illustration. T, therefore, is encoded as J. The same procedure is followed for every symbol in the plaintext. Before each symbol is

encoded, the arrow is spun and the lower sequence is shifted accordingly. The result is a ciphertext starting with J and a cipher "key" starting with K. Note that the cipher key will be the same length as the plaintext.

To use this one-time cipher for sending a message to someone—call him Z—we must first send Z the key. This can be done by a trusted courier. Later we send to Z, perhaps by radio, the ciphertext. Z decodes it with the key and then destroys the key. The key must not be used again because if two such ciphertexts were intercepted, a cryptanalyst might have sufficient structure for breaking them.

It is easy to see why the one-time cipher is uncrackable even in principle. Since each symbol can be represented by any other symbol, and each choice of representation is completely random, there is no internal pattern. To put it another way, any message whatever having the same length as the ciphertext is as legitimate a decoding as any other. Even if the plaintext of such a coded message is found, it is of no future help to the cryptanalyst because the next time the system is used the randomly chosen key will be entirely different.

One-time pads are in constant use today for special messages between high military commanders, and between governments and their high-ranking agents. The "pad" is no more than a long list of random numbers, perhaps printed on many pages. The sender and receiver must of course have duplicate copies. The sender uses page 1 for a cipher, then destroys the page. The receiver uses his page 1 for decoding, then destroys his page. When the Russian agent Rudolf Abel was captured in New York in 1957, he had a one-time pad in the form of a booklet about the size of a postage stamp. David Kahn, who tells the story in his marvelous history *The Codebreakers*, says that the one-time pad is the standard method of secret radio communication used by the U.S.S.R. The famous "hot line" between Washington and Moscow also makes use of a one-time pad, the keys being periodically delivered through the two embassies.

If the one-time pad provides absolute secrecy, why is it not used for all secret communication? The answer is that it is too impractical. Each time it is employed a key must be sent in advance, and the key must be at least as long as the anticipated message. "The problem of producing, registering, distributing and canceling the keys," writes Kahn, "may seem slight to an individual who has not had experience with military communications, but in wartime the volumes of traffic stagger even the signal staffs. Hundreds of thousands of words may be enciphered in a day; simply to generate the millions of key characters required would be enormously expensive and time-consuming. Since each

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	G	H

S	T	U	V	W	X	Y	Z	0	1	2	3	4	5	6	7	8	9
I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z

A Caesar cipher with a 10-shift

In 2015, RSA-129 was factored again by Nathaniel McHugh in 1 day using \$30 of cloud computing resources

Larger numbers are harder to factor.

	Digits	Reward	Factored
RSA-129	129	\$100	1994
RSA-640	193	\$20,000	2005
RSA-250	250	- -	2020
RSA 1024	309	- -	?
RSA 2048	617	- -	?

<https://natmchugh.blogspot.com/2015/03/the-magic-words-are-squeamish-ossifrage.html>

https://en.wikipedia.org/wiki/RSA_numbers

A quantum computer is a computer that computes with entanglement.

1994 Peter Shor discovered a way to quickly factor numbers on a **quantum computer**



“Classical” computers — bits — can be **0 (Off)** or **1 (On)**

Computer programs **switch the bits** on and off as they run.

One way to factor the number 15 is to look at all the possible combinations of factors.

0010 x 010 = 4 ... 0010 x 011 = 6 ... 0011 x 011 = 9 ... 0100 x 010 = 8 ... 0101 x 010 = 10

0101 011 = 15

Quantum computers — qubits — are entangled together in a *superposition* of 0s and 1s.

Computer programs **prepare the qubits**, send a circuit through them, and measure the answer.

Circuit: abcd x efg = 1111

Measured: 0101 x 011 = 1111

1981 Richard Feynman proposed building a “quantum computer”

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

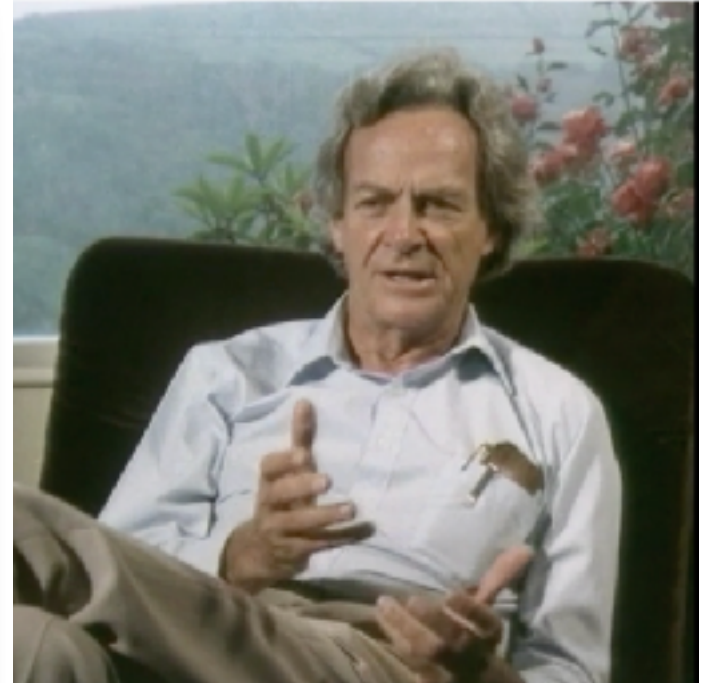
Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there's no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with



[FEYNMAN: THE PLEASURE OF FINDING THINGS OUT \(1981\)](https://vimeo.com/340695809)
<https://vimeo.com/340695809>

Feynman imaged using physical systems to simulate physical systems

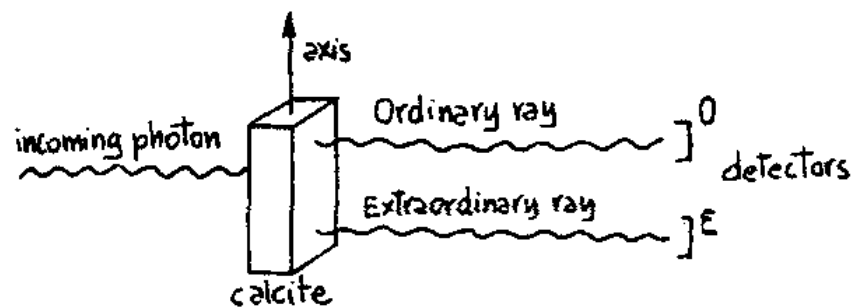


Fig. 2.

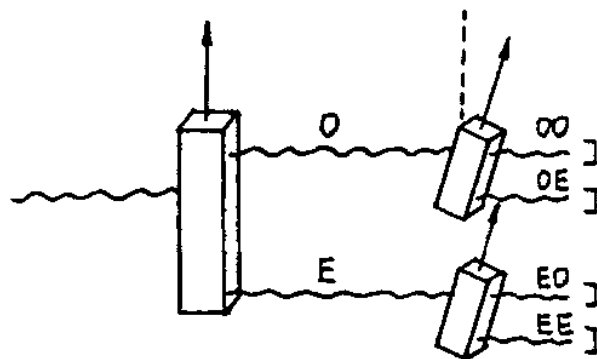


Fig. 3.

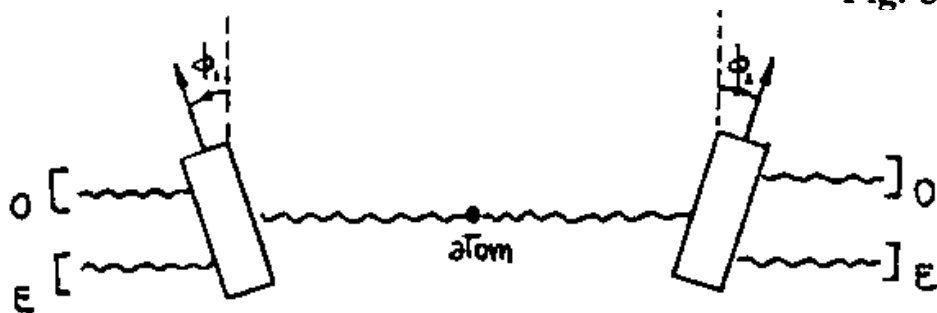


Fig. 4.

Feynman's paper was a talk he had given at the MIT Conference on the Physics of Computation (1981).



- | | | | | | | | |
|---------------------|---------------------|-----------------|----------------------|------------------|---------------------|-------------------|--------------------|
| 1 Freeman Dyson | 13 Frederick Kantor | 25 Robert Suaya | 37 George Michaels | 9 Edward Fredkin | 21 Donald Greenspan | 33 Marian Pour-El | 45 Peter Gacs |
| 2 Gregory Chaitin | 14 David Leinweber | 26 Stand Kugell | 38 Richard Feynman | 10 Tom Toffoli | 22 Markus Buettiker | 34 Danny Hillis | 46 Dan Greenberger |
| 3 James Crutchfield | 15 Konrad Zuse | 27 Bill Gosper | 39 Laurie Lingham | 11 Rolf Landauer | 23 Otto Flobberth | 35 Arthur Burks | |
| 4 Norman Packard | 16 Bernard Zeigler | 28 Lutz Prieser | 40 P. S. Thiagarajan | 12 John Wheeler | 24 Robert Lewis | 36 John Cocke | |
| 5 Panos Ligomenides | 17 Carl Adam Petri | 29 Madhu Gupta | 41 Marin Hassner | | | | |
| 6 Jerome Rothstein | 18 Anatol Holt | 30 Paul Benioff | 42 Gerald Vichniac | | | | |
| 7 Carl Hewitt | 19 Roland Vollmar | 31 Hans Moravec | 43 Leonid Levin | | | | |
| 8 Norman Hardy | 20 Hans Bremerman | 32 Ian Richards | 44 Lev Levitin | | | | |

Photo courtesy Charles Bennett.

Figure 4.9. The Physics of Computation Conference, MIT Endicott House, May 6-8, 1981

Shor realized that quantum computer could use superposition to factor.

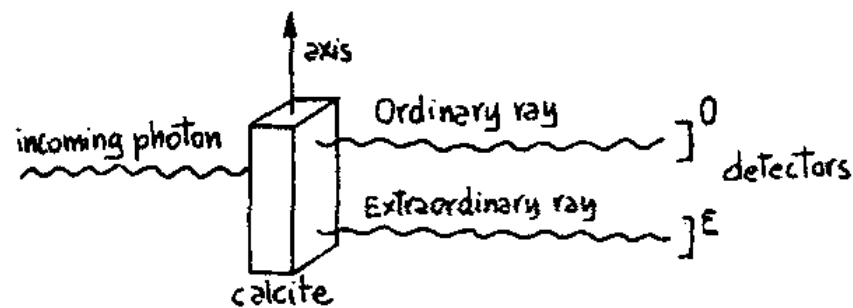
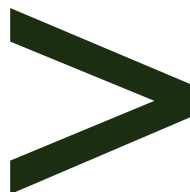


Fig. 2.



9686	9613	7546	2206
1477	1409	2225	4355
8829	0575	9991	1245
7431	9874	6951	2093
0816	2982	2514	5708
3569	3147	6622	8839
8962	8013	3919	9055
1829	9451	5781	5154

A ciphertext challenge worth \$100



**Why is factoring
hard?**



Gemini: Factoring is hard because
it's a “search” problem
rather than a “calculation” problem.

**What do we mean by
“hard”?**

Complexity classes are a way of presenting the “hardness” of a problem.

P — Polynomial Time — “Calculation Problems” — “Easy problems”

Time to solve is a polynomial function of the input size.

Easy to solve, easy to check the solution

—*What's 3×5 ?*

—*What's 3490529510847650949147849619903898133417764638493387843990820577
× 32769132993266709549961988190834461413177642967992942539798288533*

NP — Nondeterministic Polynomial — “Search Problems”

Hard to find the solution — you need to try all possible solutions.

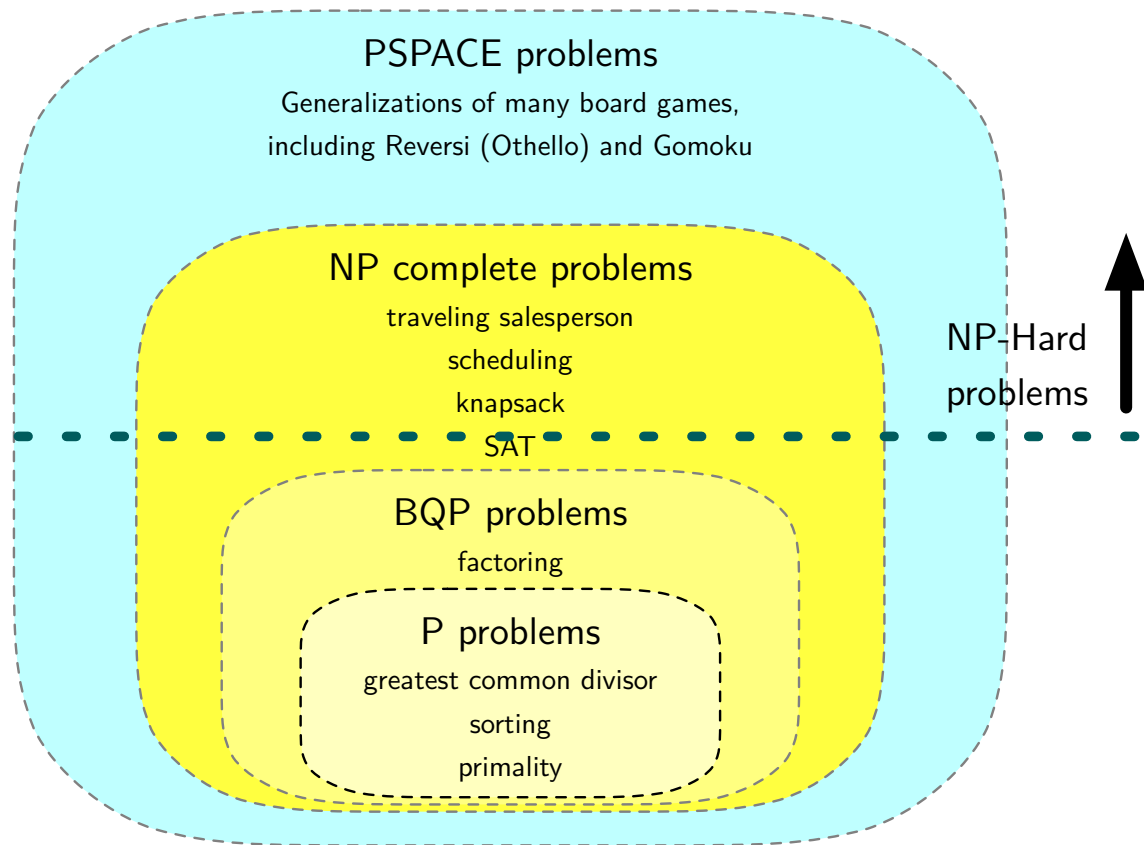
Easy to recognize when a solution is correct.

—*FACTOR(15)*

—*FACTOR(11438162575788886766923577997614661201021829672124236256256184293570693524573389
7830597123563958705058989075147599290026879543541)*

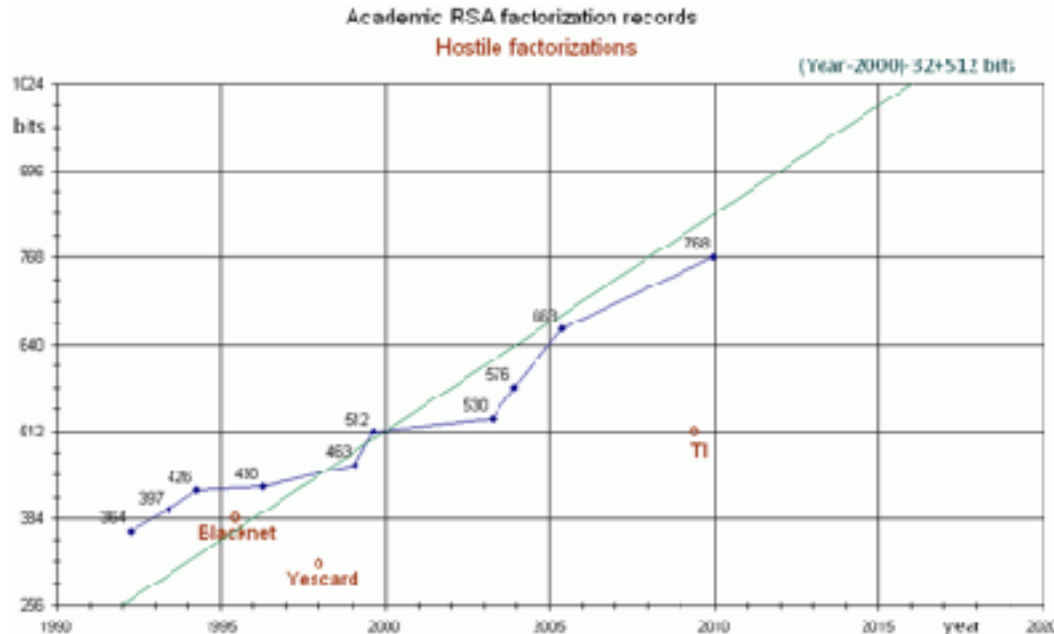
We don't know how hard factoring is...

But we know that a large enough quantum computer can do it quickly.



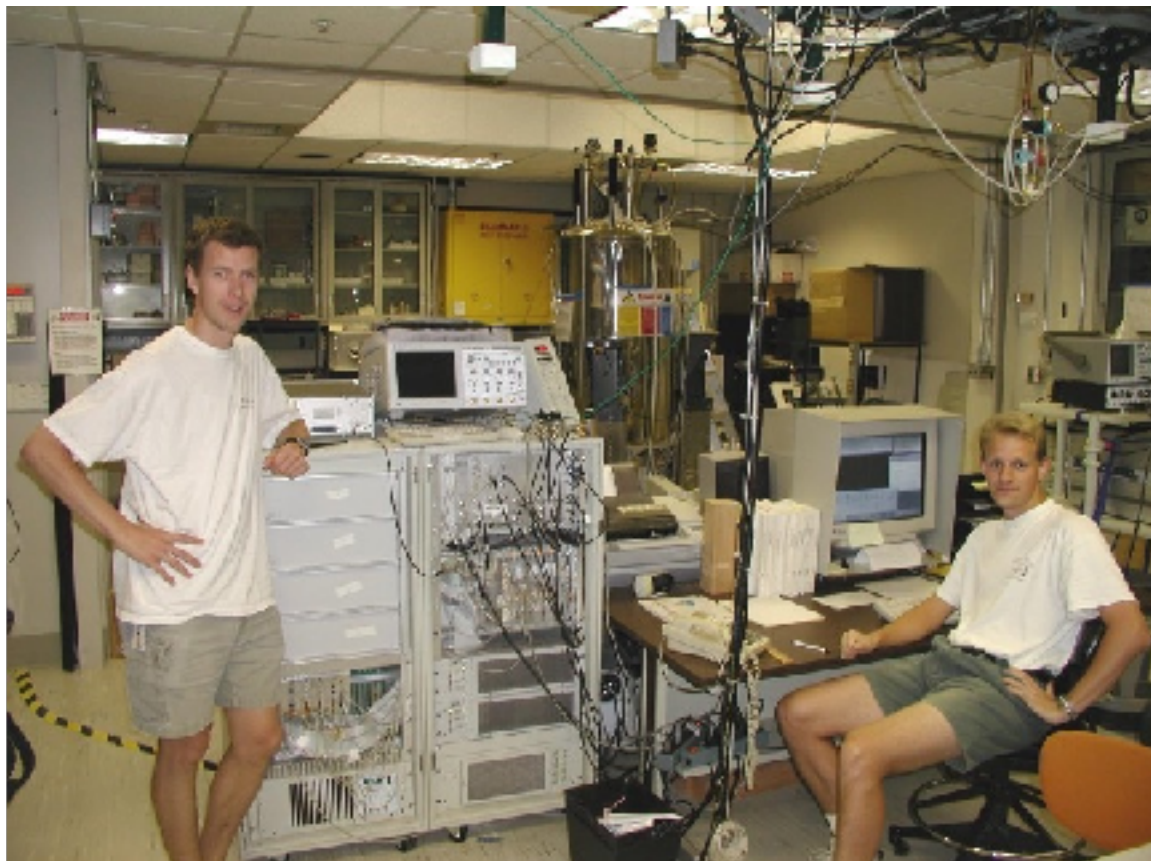
Shor's 1994 factoring algorithm can run in “polynomial” time

Today's factoring algorithms run in “sub-exponential” time.
The difference is substantial... but we don't know how substantial.

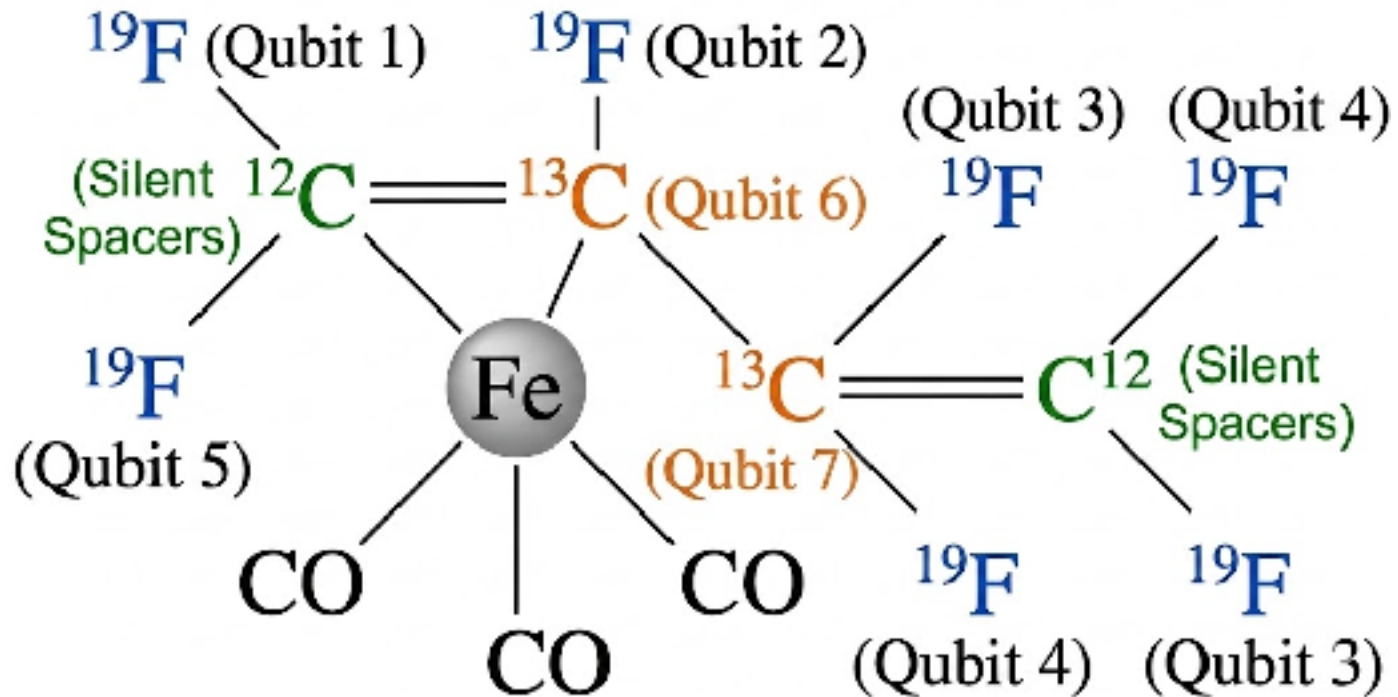


This graph from 2015 predicted factoring RSA1024 in 2017 and RSA 2048 in 2048

In December 2001, this quantum computer at IBM factored the number “15”

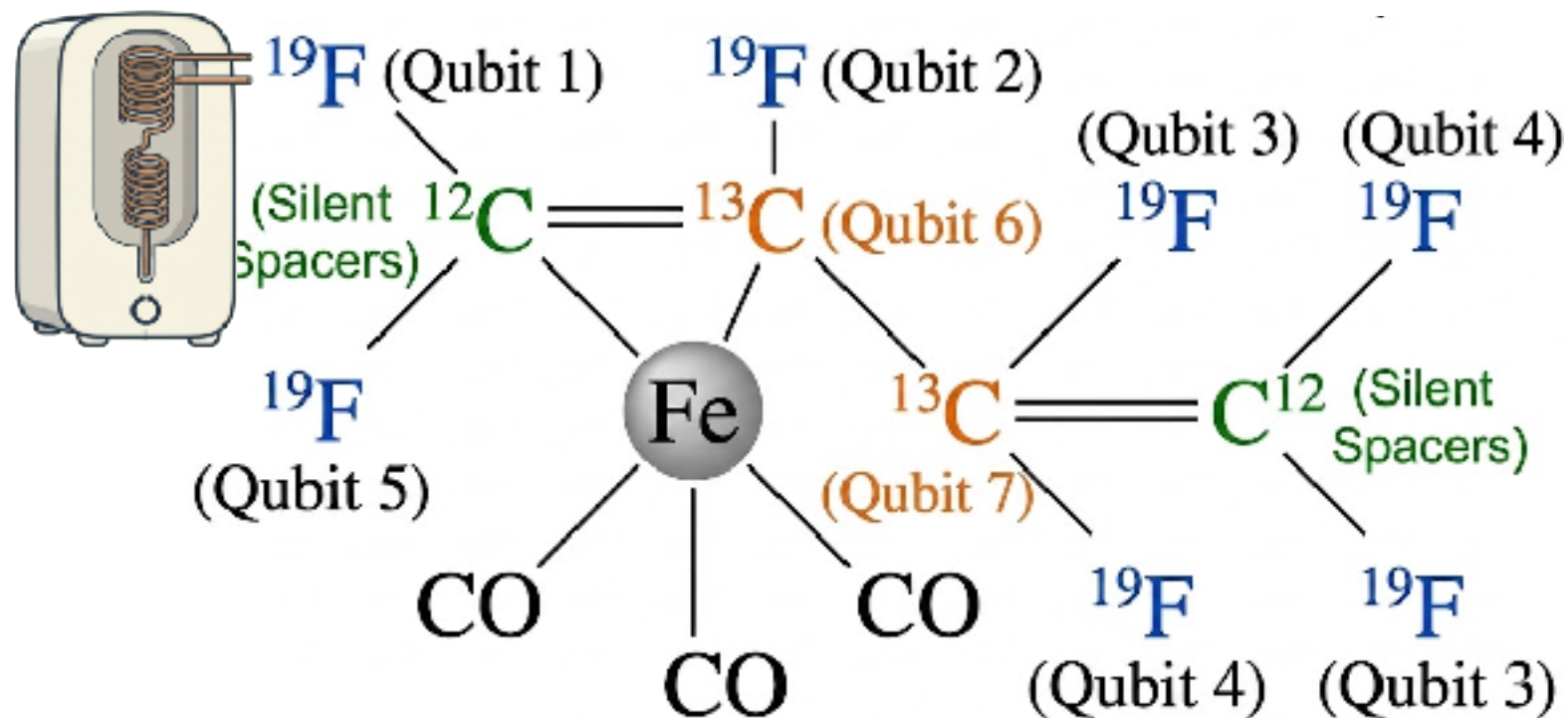


IBM's quantum computer was a specially-created molecule.

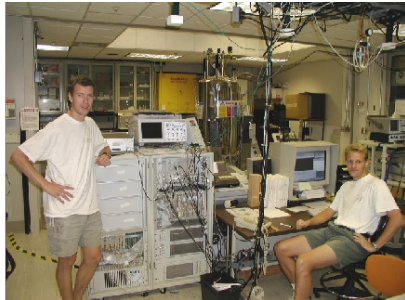
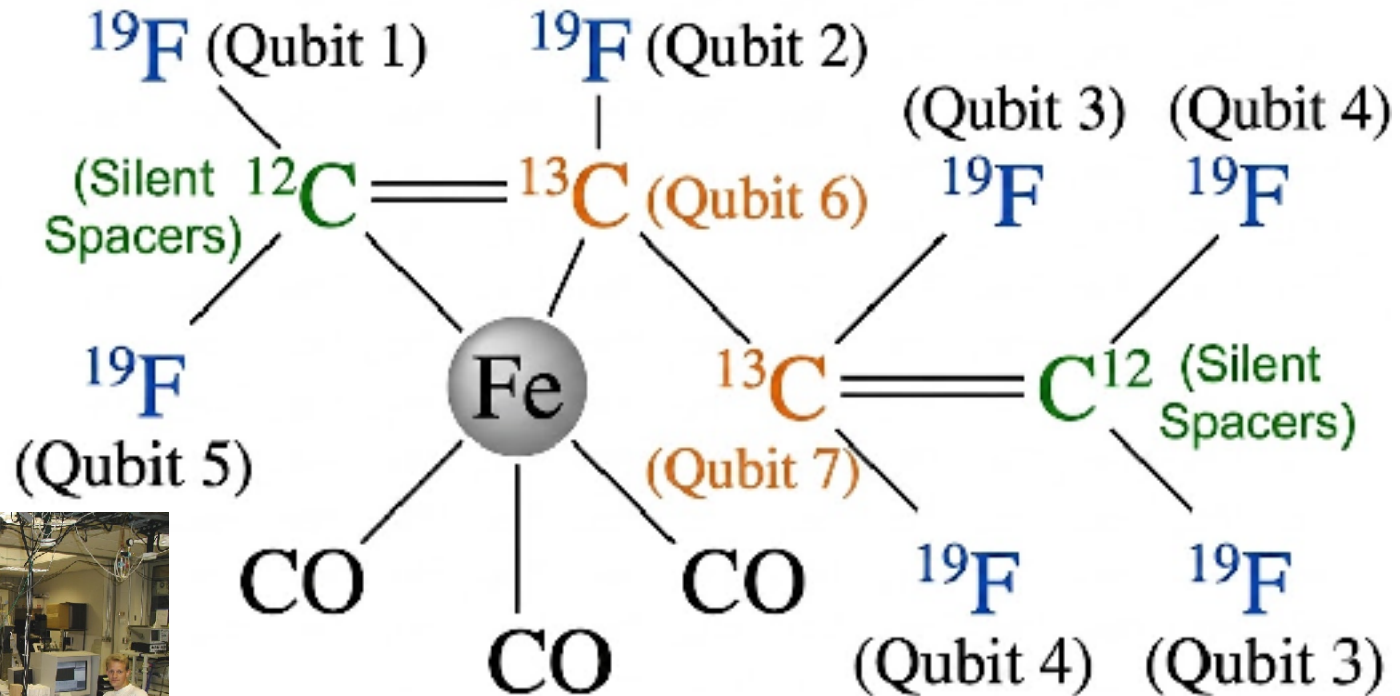


perfluorobutadienyl iron complex

Each atom is excited with a precise microwave pulse (the gates).



The qubits are measured and the result is read out.



0101 (5)
011 (3)

$$5 \times 3 = 15$$

Classical vs. Quantum

	Classical	Quantum
Speed	Clock speed (GHz)	# of gates/sec
Size of problem	working RAM	qubits
Size of program	RAM	# of gates
Limiting factors	size of RAM # of processors cooling	noise # of qubits # of gates

qubits are highly sensitive to external noise.



How do we protect the qubits?

Google & IBM

Keep them very cold — thermal noise kills qubits — 0.01°K - colder than deep space

Shielded from stray RF and the Earth's magnetic field — mu metal box

Google - Error correction with “surface codes” - (100–1000 : 1)

IBM - “Loon” - Error correction with long-range microwave couplers (10–25 : 1)

Caltech & Oratomic

Keep them far apart — ultra-high vacuum with atomic tweezers

Isolate from the Earth's magnetic field — Active Magnetic Field Compensation

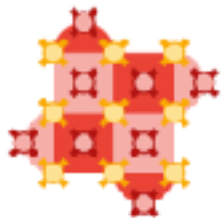
Error correction with QLDPC (Quantum Low-Density Parity-Check) (5–10 : 1)

Error correction — the key to making quantum computers work

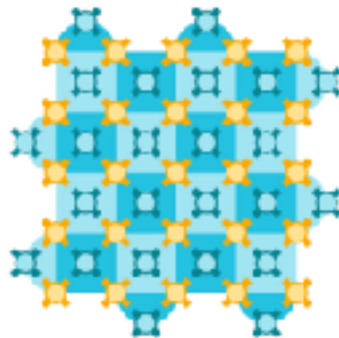
Physical qubits are combined into logical qubits

Google 2024 Blog:

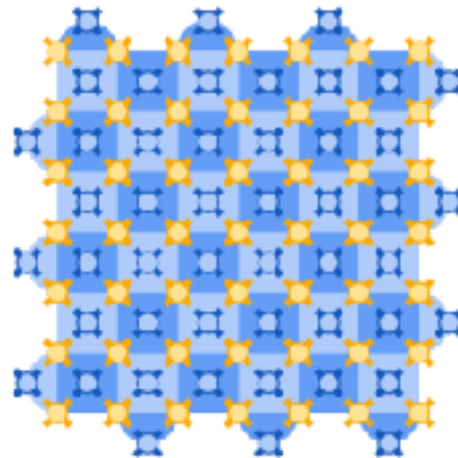
<https://research.google/blog/making-quantum-error-correction-work/>



3x3
“1 error at a time”
17 qubits

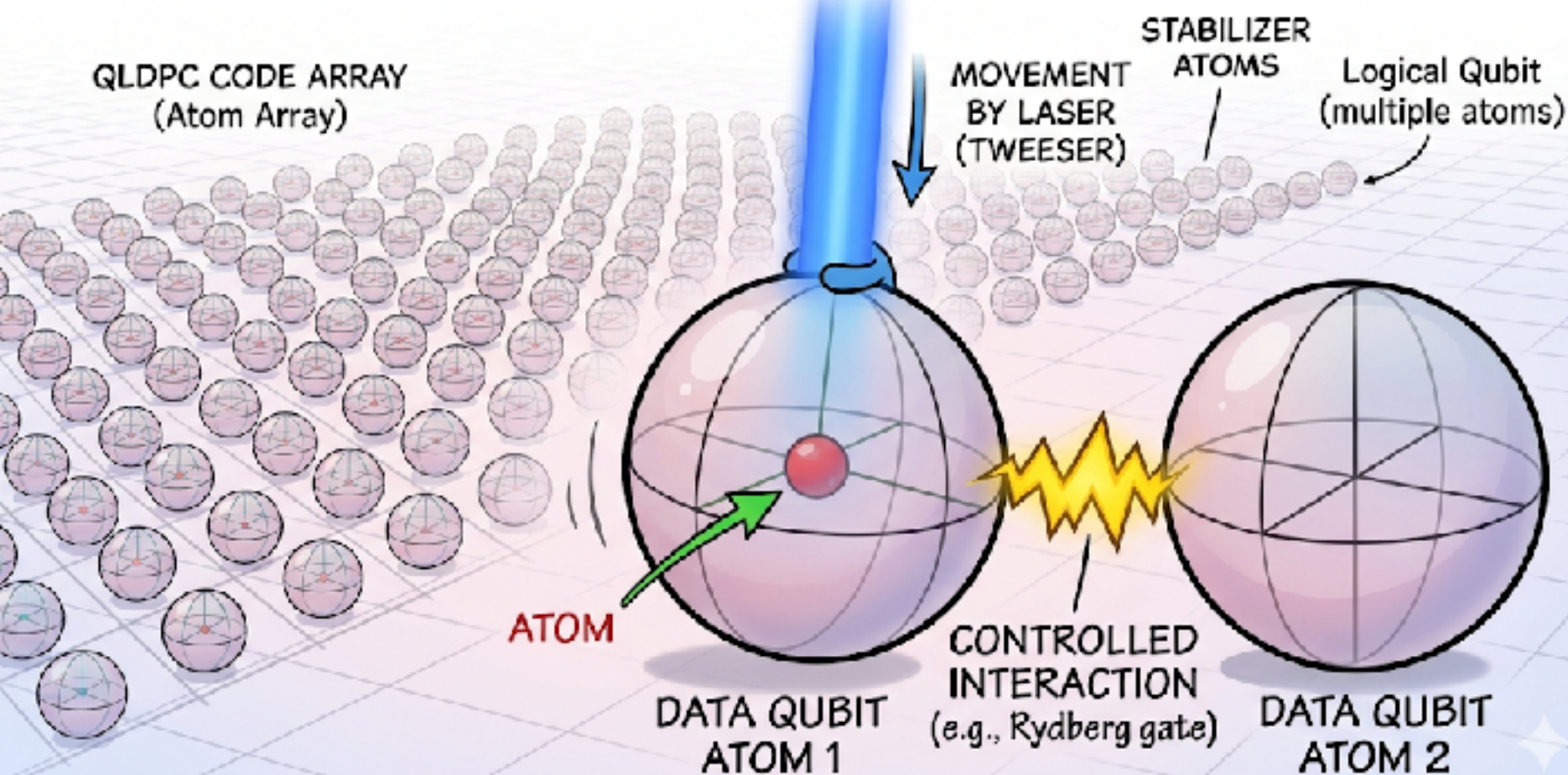


5x5
“2 errors at a time”
49 qubits

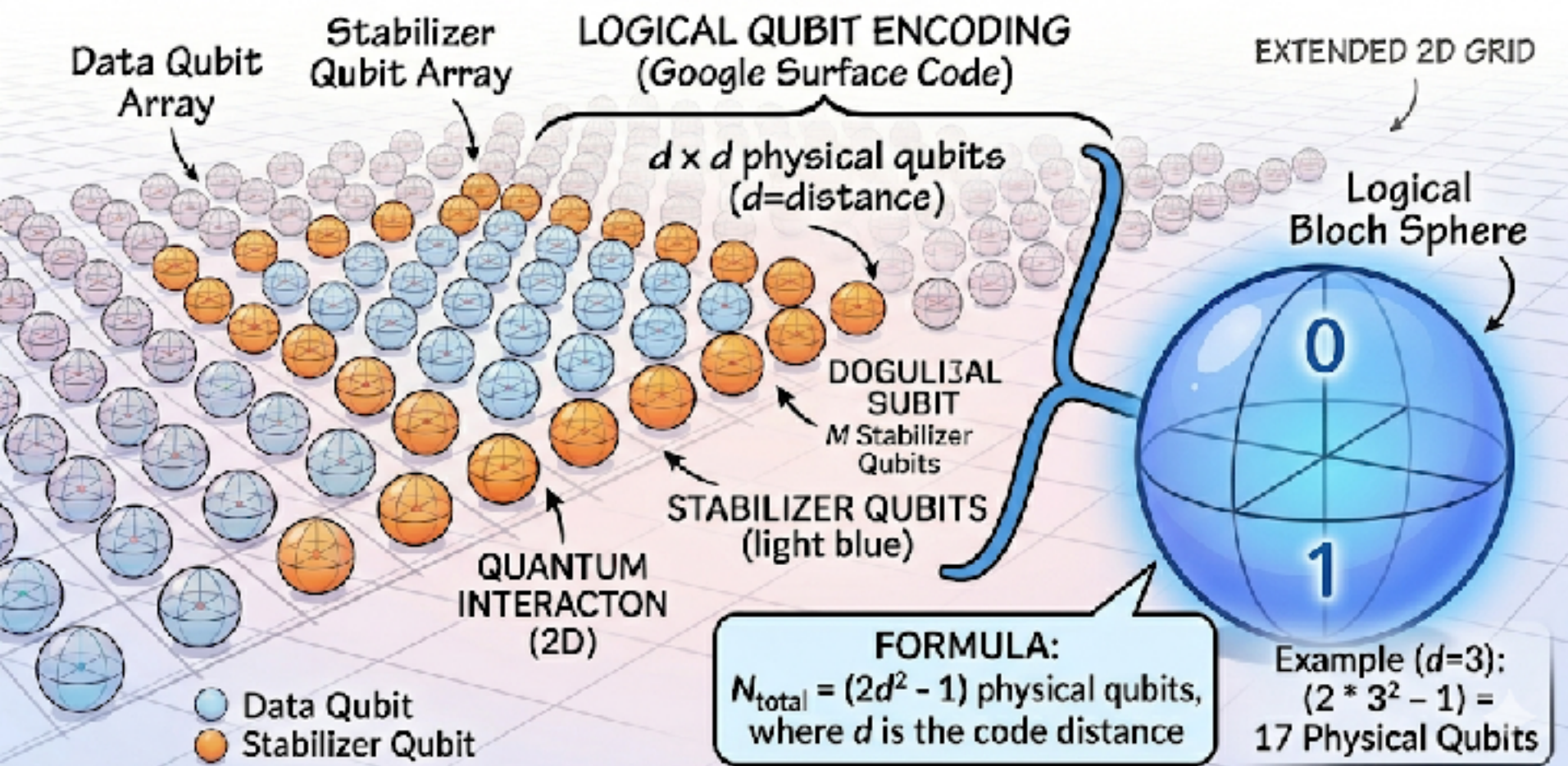


7x7
“3 errors at a time”
97 qubits

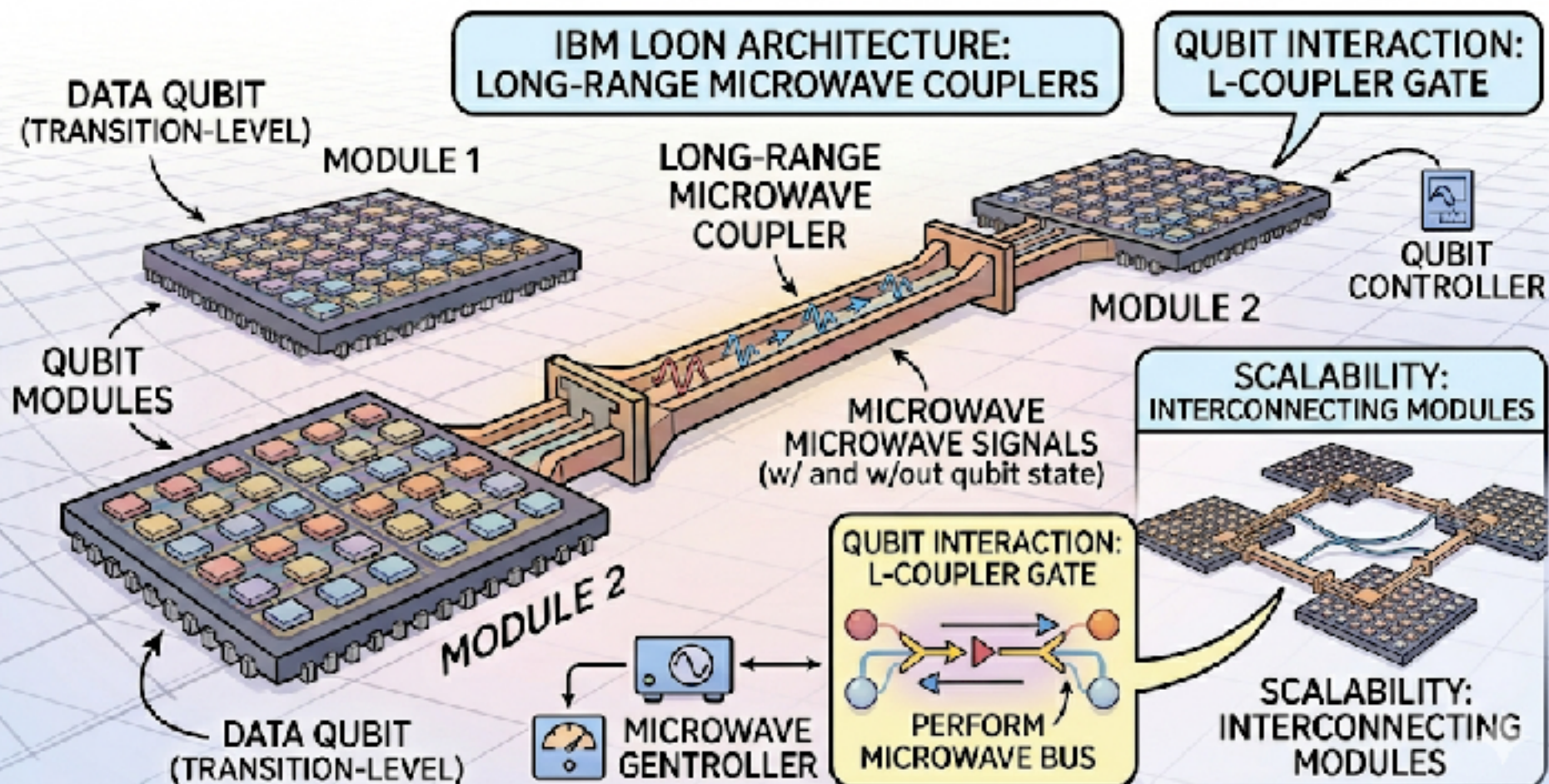
CALTECH QLDPC APPROACH: RECONFIGURABLE ATOM ARRAYS



GOOGLE'S SURFACE CODE: LOGICAL QUBIT COMPOSITION



IBM'S LOON CONCEPT FOR SCALABLE QUANTUM COMPUTING





2023 — IBM “Condor” quantum computer — 1023 qubits





2029 rendering of multiple quantum computers connected

The size of a quantum computer necessary to break codes is unknown.

Speed of code code-breaking depends on:

- The number of qubits — the size of the numbers that can be cracked

- The logical error rate — the length of the quantum computation that they can perform.

- The encryption code being cracked (RSA vs. Elliptic Curve Cryptography)

2019 — Google estimated 20M qubits | 8 hours — RSA-2048

2025 — Google estimated 1M qubits | 1 week — RSA-2048

2026 — Caltech estimated 10,000 qubits | 3 years — ECC-256
(used by Bitcoin and most mobile apps)

(2026 — Pinnacle estimated 100,000 qubits | 30 days — RSA-2048)

Operationally, the number of keys that can be cracked depends on:

- The number of quantum computers

- The speed of the quantum gates

Challenges in building a quantum computer

Quantity of qubits — today's systems have hundreds of physical qubits.

We need systems with hundreds to thousands of logical qubits.

Quality of qubits — Today's qubits are noisy, increasing need for error correction.

We need systems with qubits that are less susceptible to the outside universe.

Connectivity between qubits — Today's systems are limited in their topology.

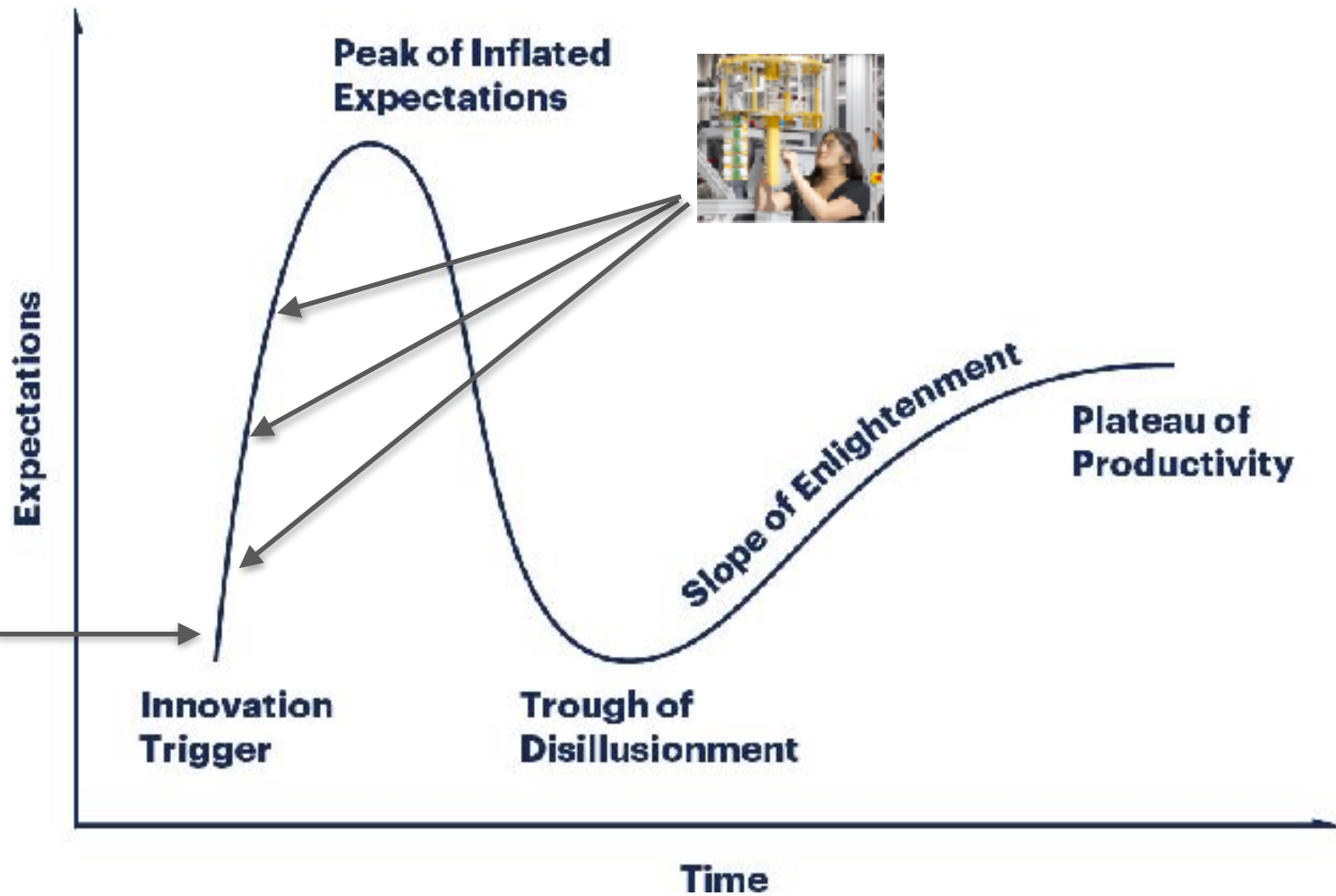
Better connectivity allows for more efficient error correction and algorithms.

The Wiring problem — each qubit requires its own coaxial cable for pulses

We cannot physically fit millions of cables in a dilution refrigerator

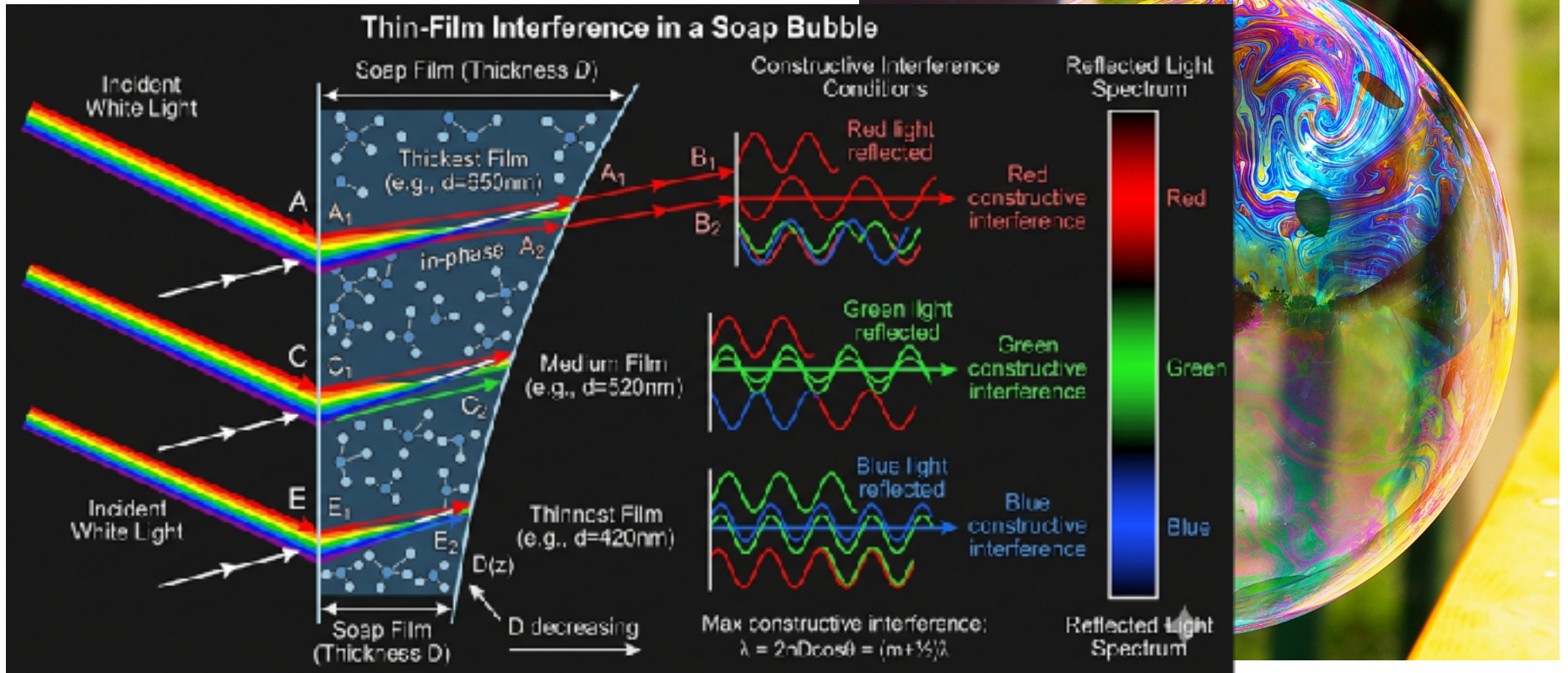
State Preparation and Measurement (SPAM) Errors

Each microwave pulse generates heat (noise) which impacts the computation



Brief refresher on quantum physics

We are surrounded by quantum phenomena

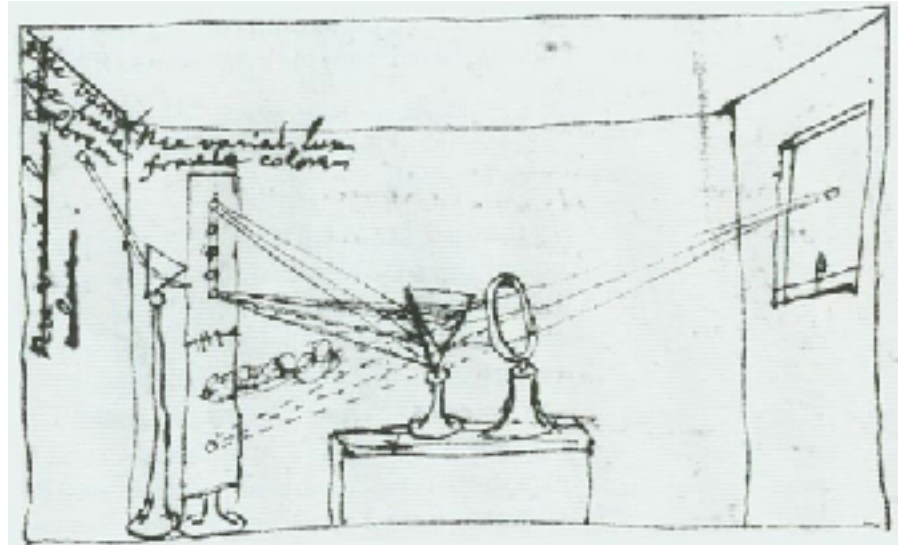


Light: it's a particle! (1672 — Isaac Newton)

Light travels in straight lines and reflects — like little tennis balls.

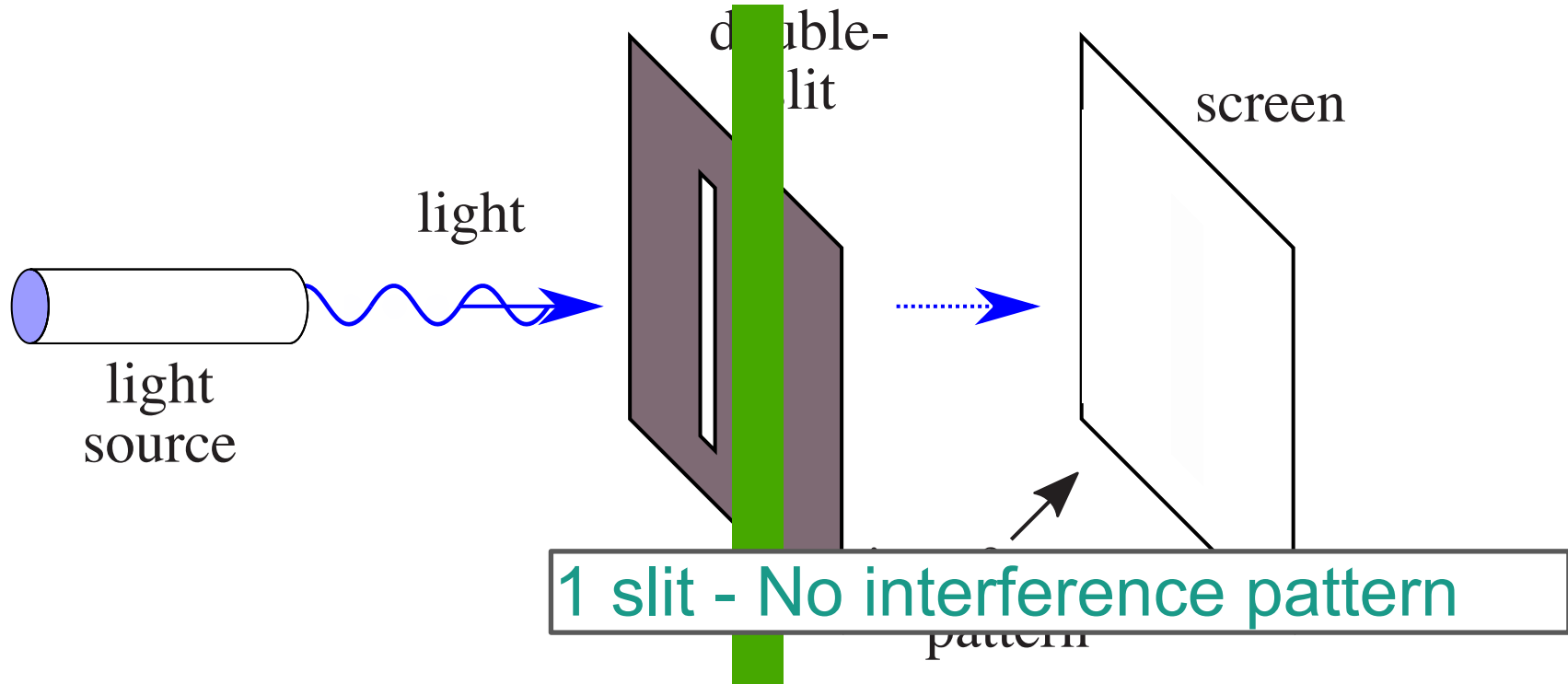
Prisms prove light is made of many different colors

Newton hypothesized it was a substance made of tiny *corpuscles*.



Light: it's a wave (1801 – Thomas Young)

The 2-slit experiment shows that light is a wave





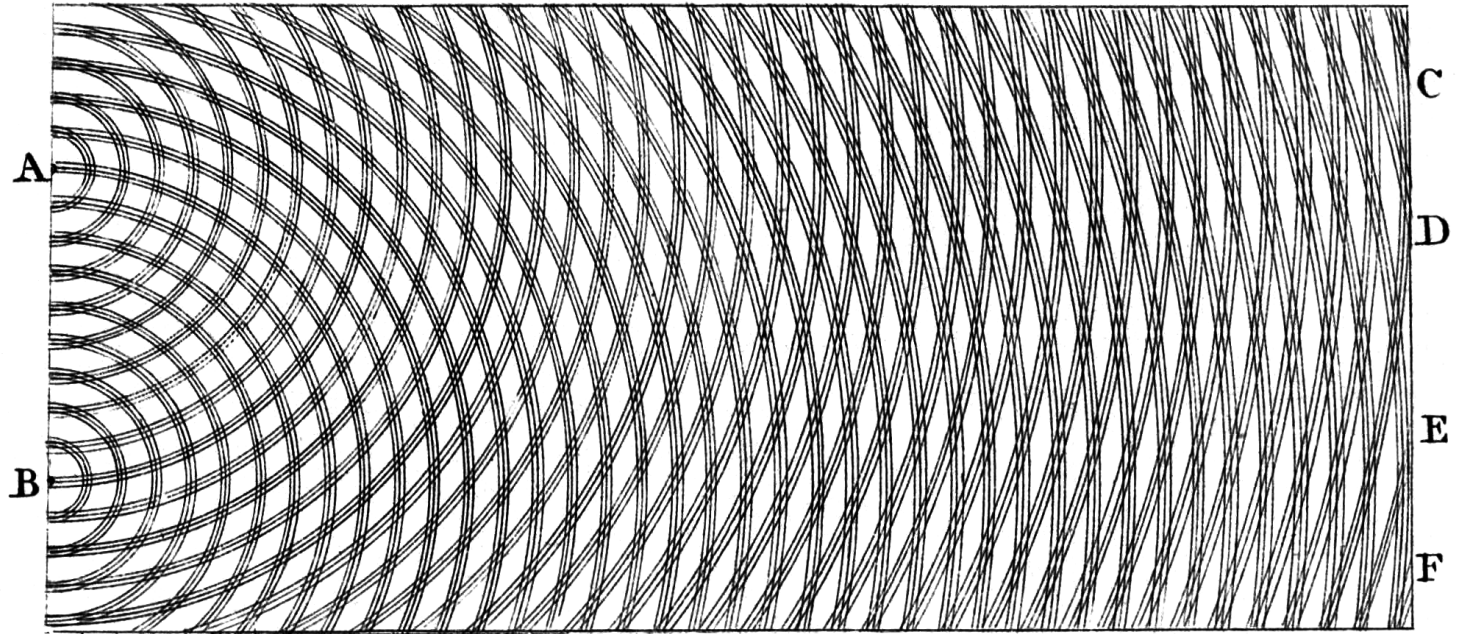


Figure B.6. This is a drawing from Thomas Young's notebook showing how light rays traveling from two point sources A and B result in constructive and destructive interference. In the dual-slit experiment, each slit can be thought of as a stack of point sources that emit light solely in the horizontal plane. Image public domain.

Light - it's *really* a particle!

1905 - Einstein — Photoelectric effect

Voltage from a light shining on metal.

Higher frequency - more voltage

Brighter light — more current

$$K.E._{\max} = hf - \phi$$

Explanation:

Energy of light is delivered in *quanta*.

h was discovered by Planck

—for *blackbody radiation*

Light is *definitely* a particle.

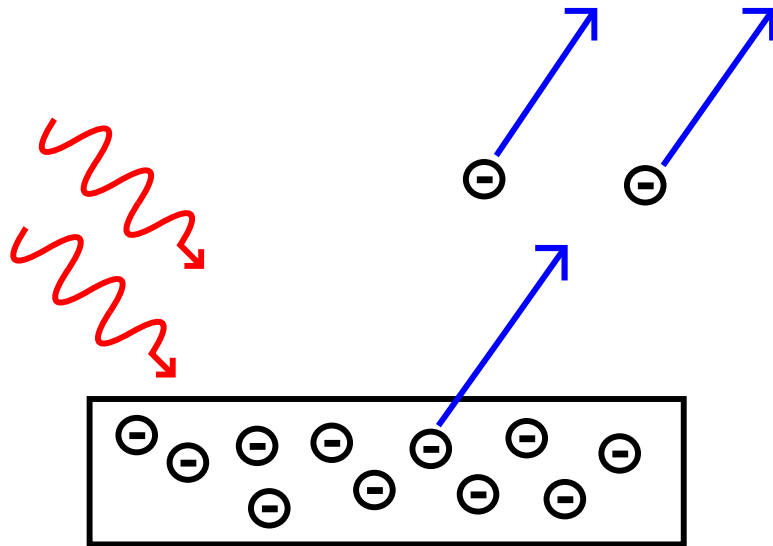


Figure B.3. The photoelectric effect results when light striking metal causes electrons to eject. Einstein explained the effect by saying that the energy of light was carried in individual particles, which are now called *photons*, and that the energy of those particles is proportional to the frequency of the light, with photons from higher-frequency light having more energy. Image CC-BY-SA Wikimedia user Wolfmankurd.



<https://www.youtube.com/watch?v=oYnp0WZDhYQ>

By 1927, physicists are clear...

Light is neither a wave nor a particle.

Light is a *probability* of making a particular measurement.

All of reality is merely a collection of probabilities.



rear:

A. Piccard	E. Henriot	P. Ehrenfest	E. Herzen
Th. de Donder	E. Schrödinger	J. E. Verschaffelt	W. Pauli
W. Heisenberg	R. H. Fowler	L. Brillouin	

middle:

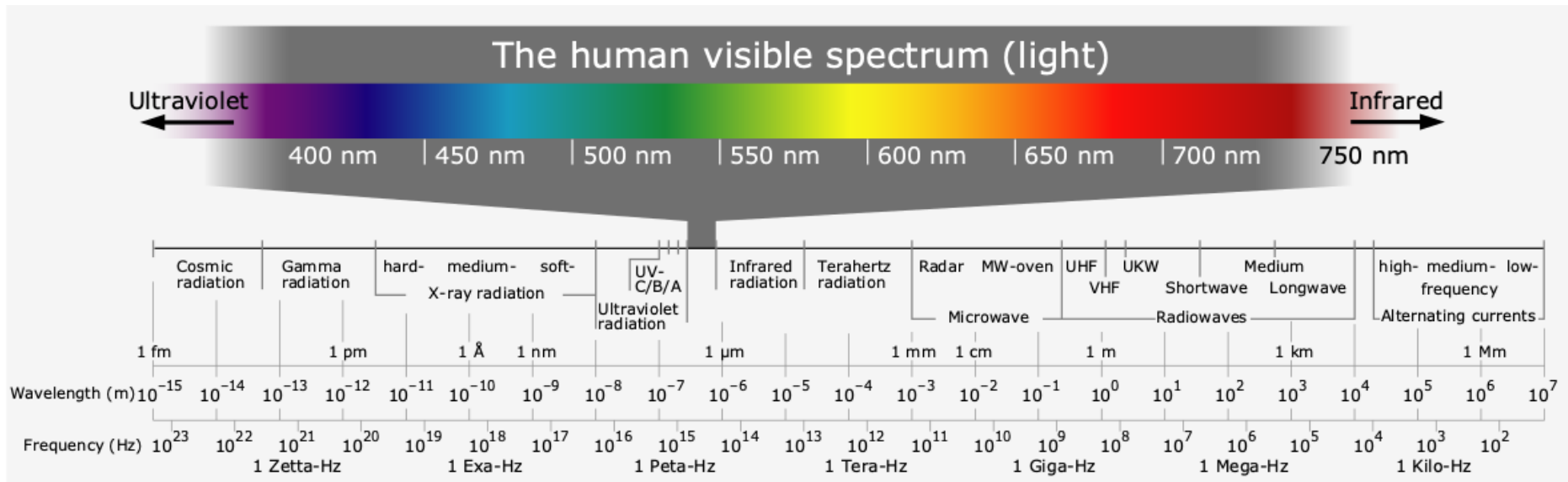
P. Debye	M. Knudsen	W.L. Bragg	H. A. Kramers
P. A. M. Dirac	A. H. Compton	L. de Broglie	M. Born
N. Bohr			

Front:

I. Langmuir	M. Planck	M. Curie	H.A. Lorentz
A. Einstein	P. Langevin	Ch.-E. Guye	C. T. R. Wilson
O. W. Richardson			

Figure B.8. Fifth Solvay Conference, Brussels, October 24–29, 1927. Photograph by Benjamin Couprie, Institut International de Physique Solvay.

Light “particles” have wavelengths.... The RF spectrum



Light can be polarized

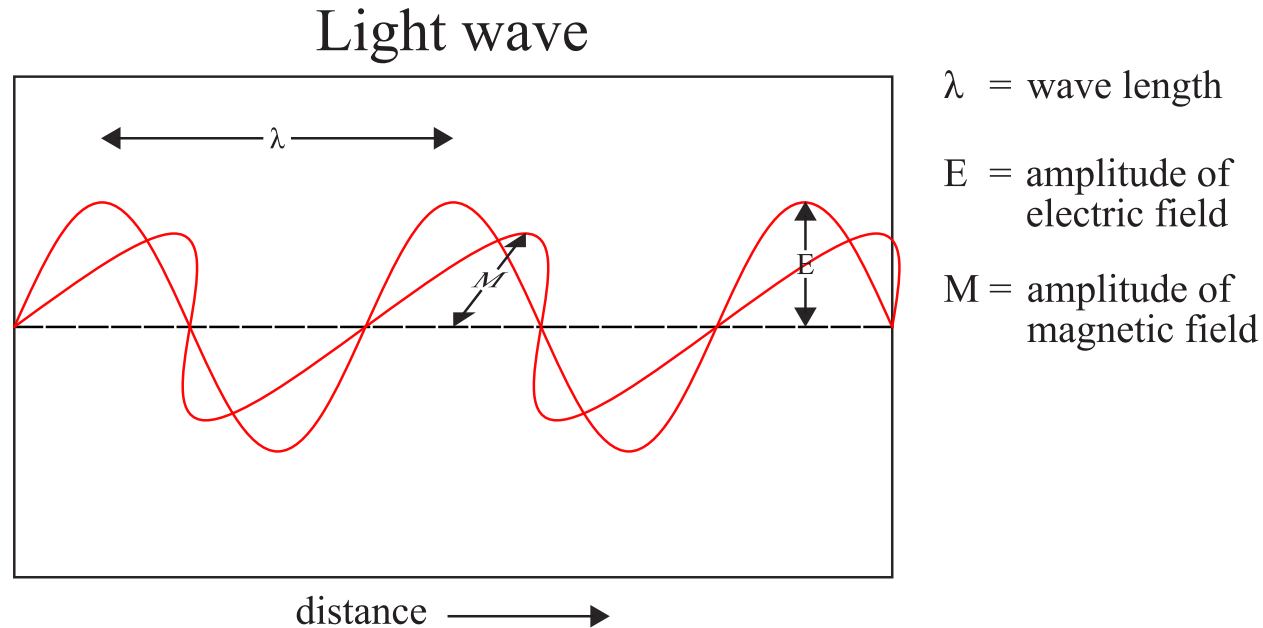


Figure B.9. Here, linearly polarized light is illustrated as a transverse wave with electric and magnetic fields oscillating at right angles to the direction of propagation. Image CC BY-SA by Wikimedia user Gpvos.

You can buy a polarizing filter.



☐ Add to Compare

Tiffen 77mm Circular Polarizing Filter

B&H # TICP77 MFR # 77CP

★★★★☆ 1,886 Reviews

Key Features

- Makes a Blue Sky Bluer
- Enhances Clouds
- Eliminates Reflections
- High Quality ColorCore Glass

[Show More](#) ▾

Available in other [Styles, Configurations & Kits](#)

\$24⁹⁹

Add to Cart

Add to Wish List ▾

🕒 In Stock

Eligible for Free 2-Day Shipping on orders over \$49

Polarizing filters let through light with just one polarization

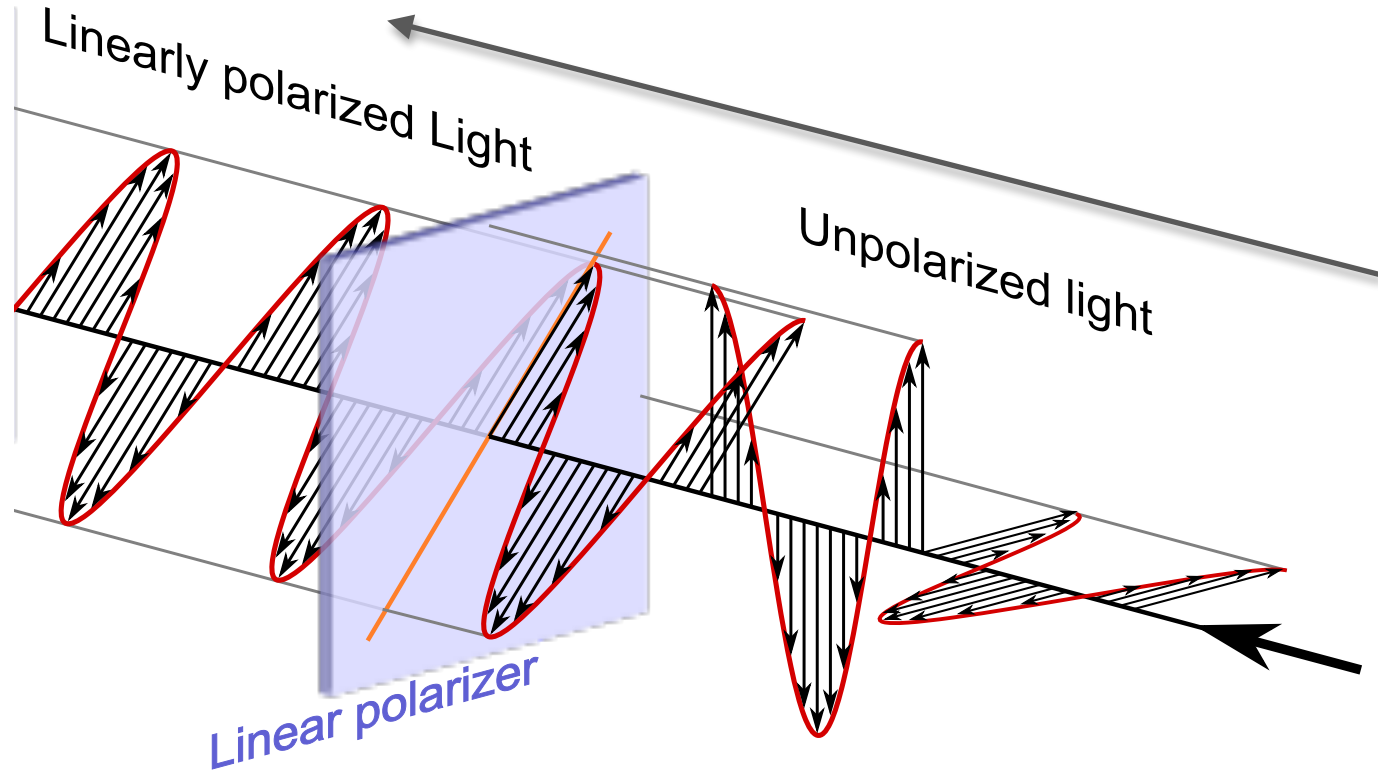
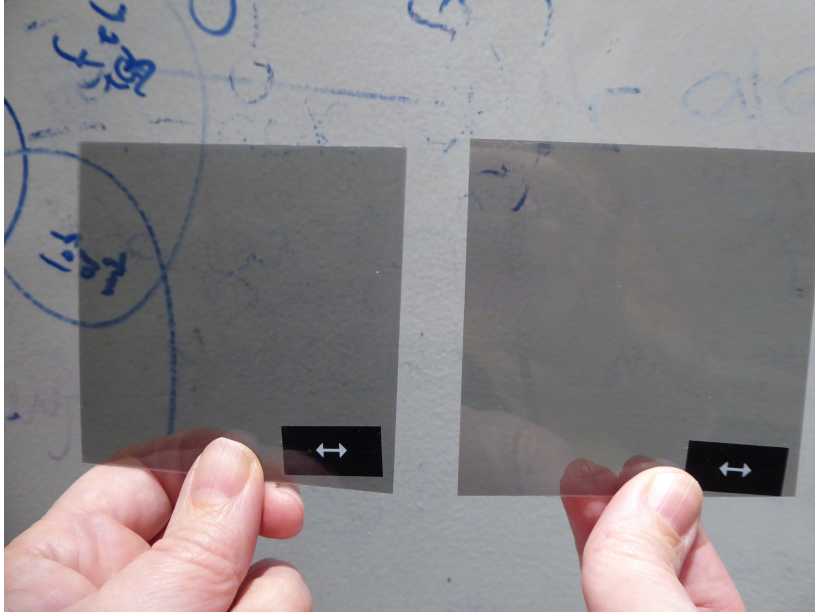
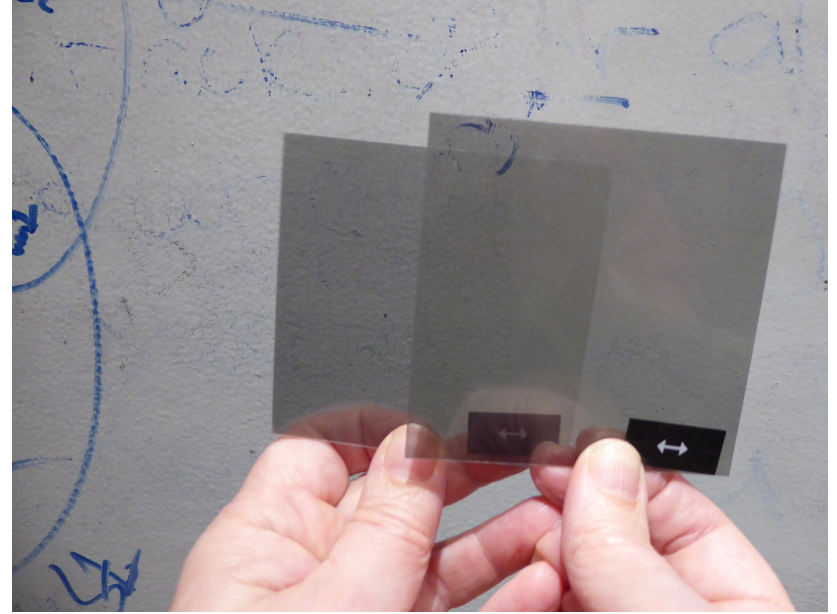




Figure B.10. The effects of a polarizing filter on the sky in a photograph. The picture on the right uses the filter. Image CC BY-SA by Wikimedia user PiccoloNamek.

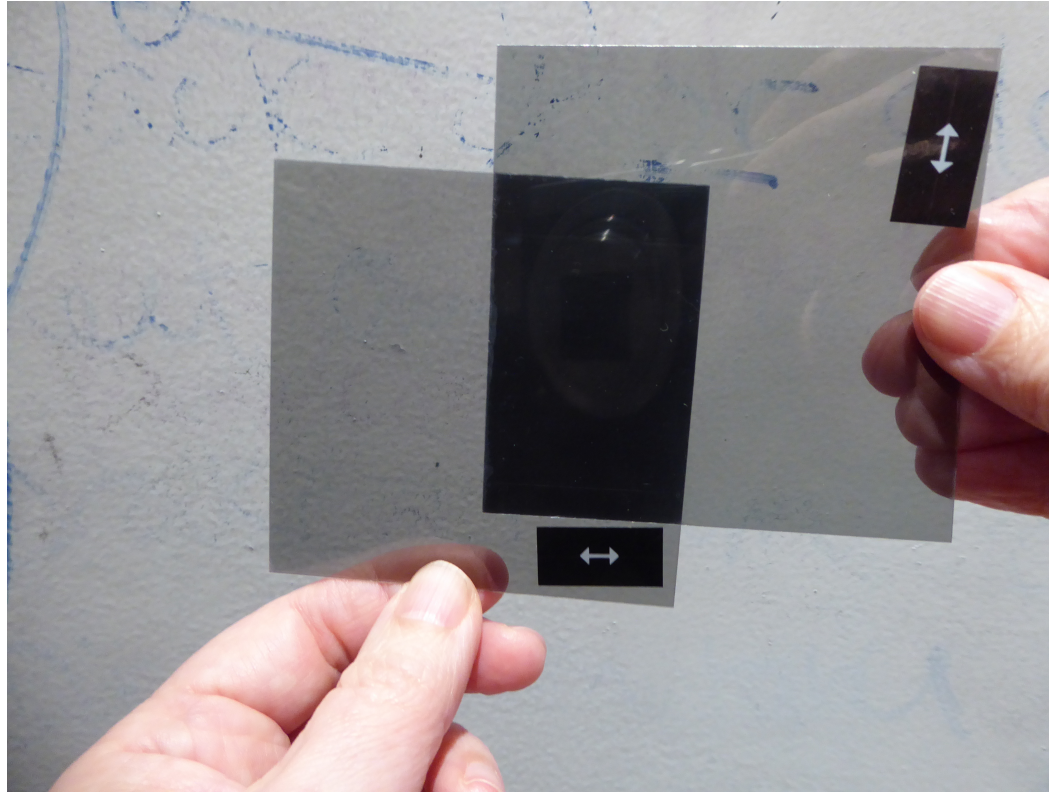


$$0^\circ \rightarrow 0^\circ$$

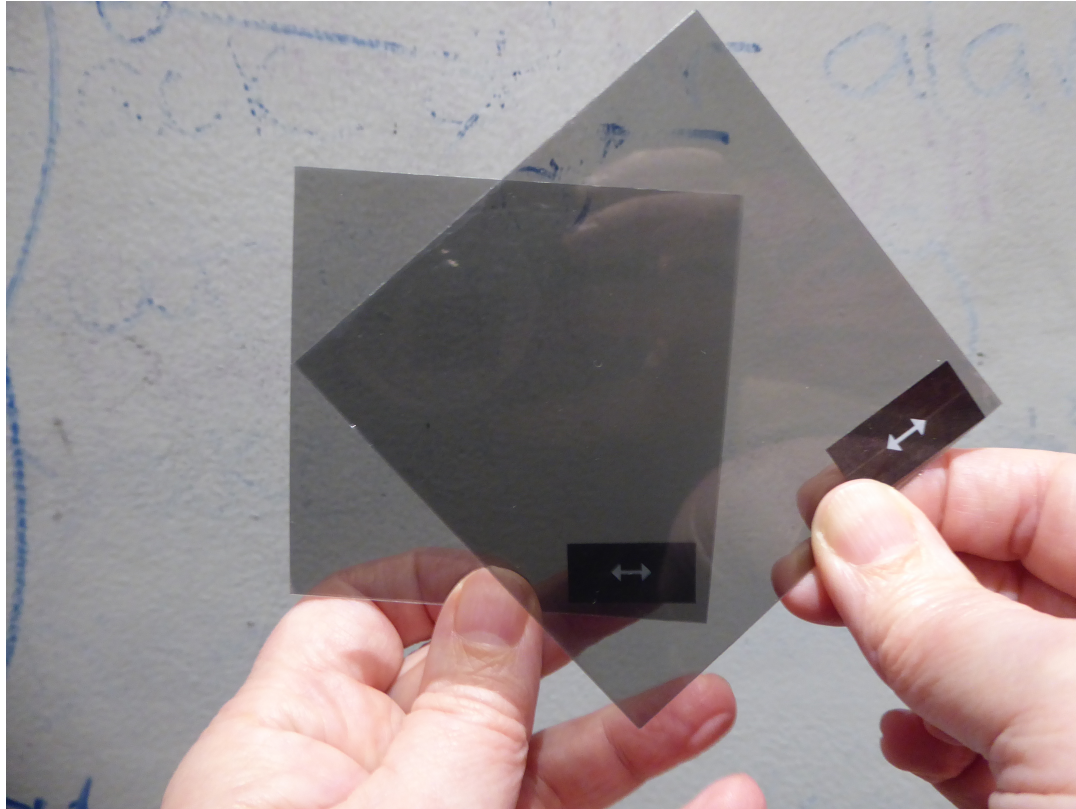


$$0^\circ \rightarrow 0^\circ$$

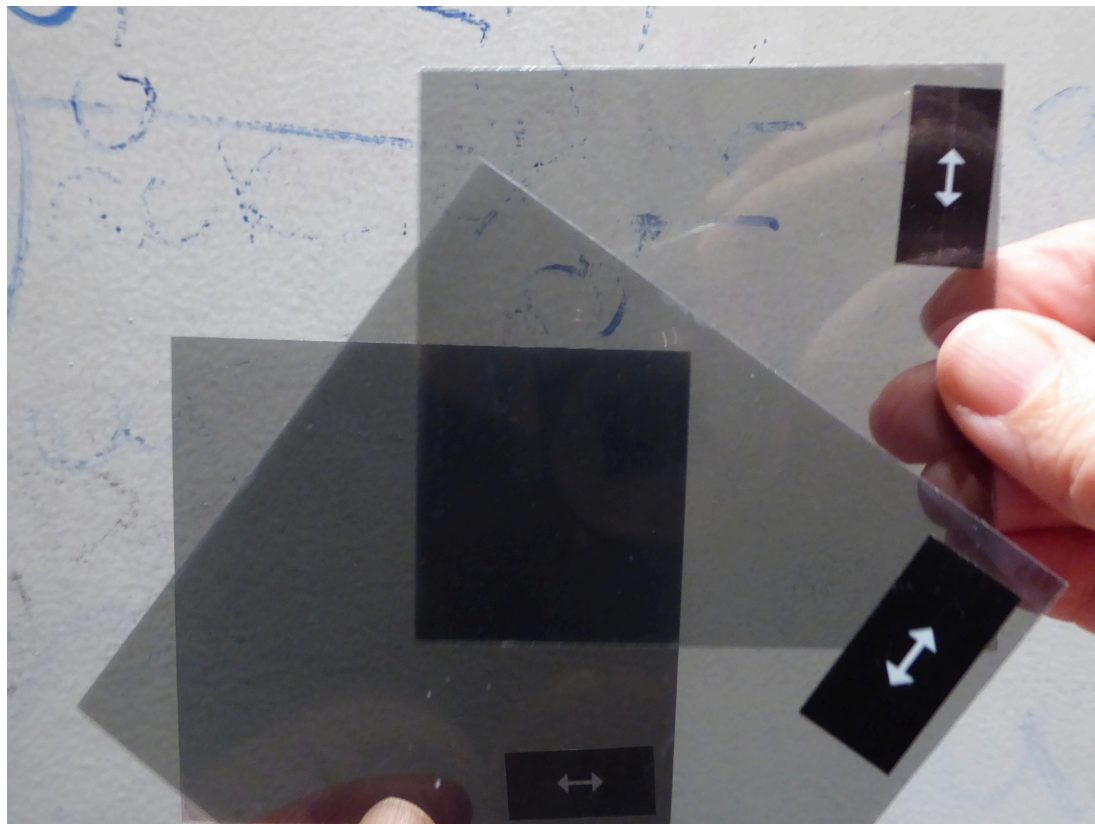
Figure B.12. Two linear polarizing filters with their polarization angles aligned (experiment 1, left), and overlapping (experiment 2, right) at $\leftrightarrow$.



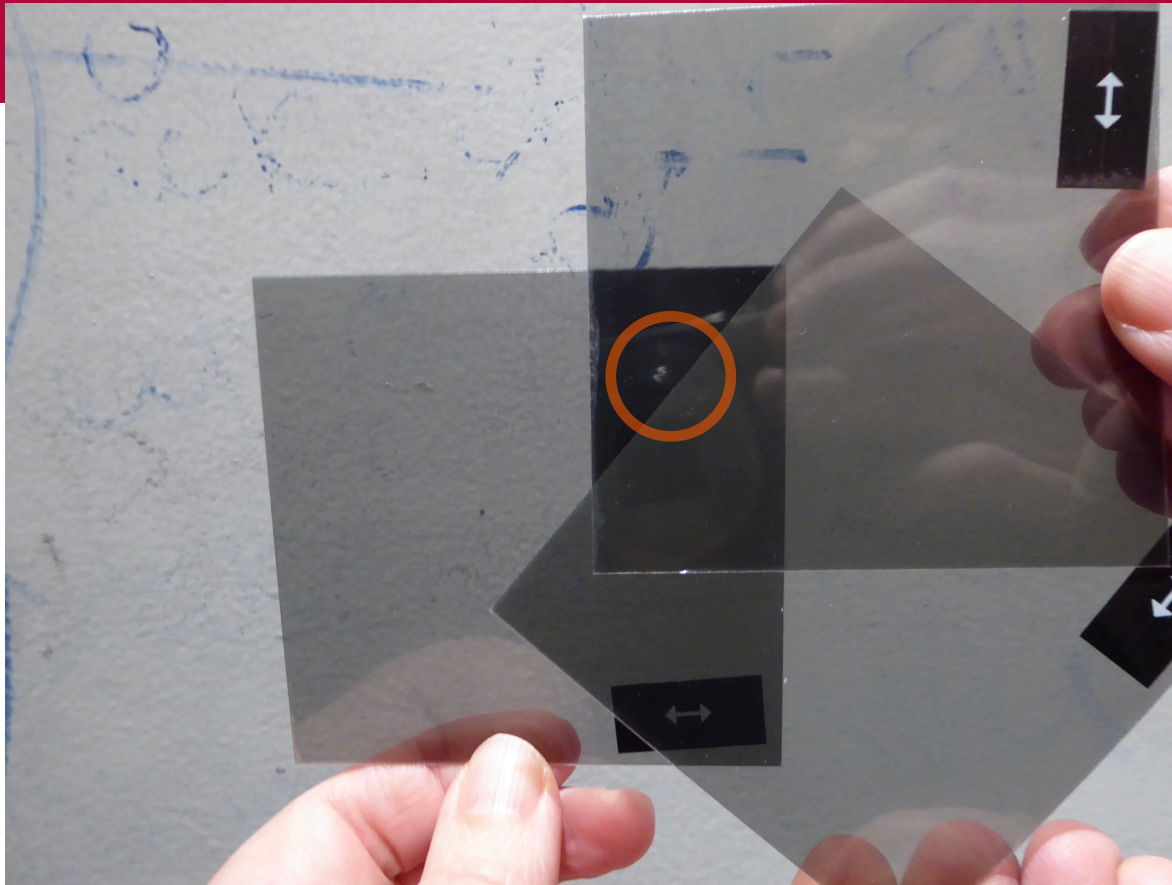
$0^\circ \rightarrow 90^\circ$ s — No transmission



$0^\circ \rightarrow 45^\circ$ — some transmission



$0^\circ \rightarrow 90^\circ \rightarrow 45^\circ$ — no transmission



$0^\circ \rightarrow 45^\circ \rightarrow 90^\circ$ — some transmission...?



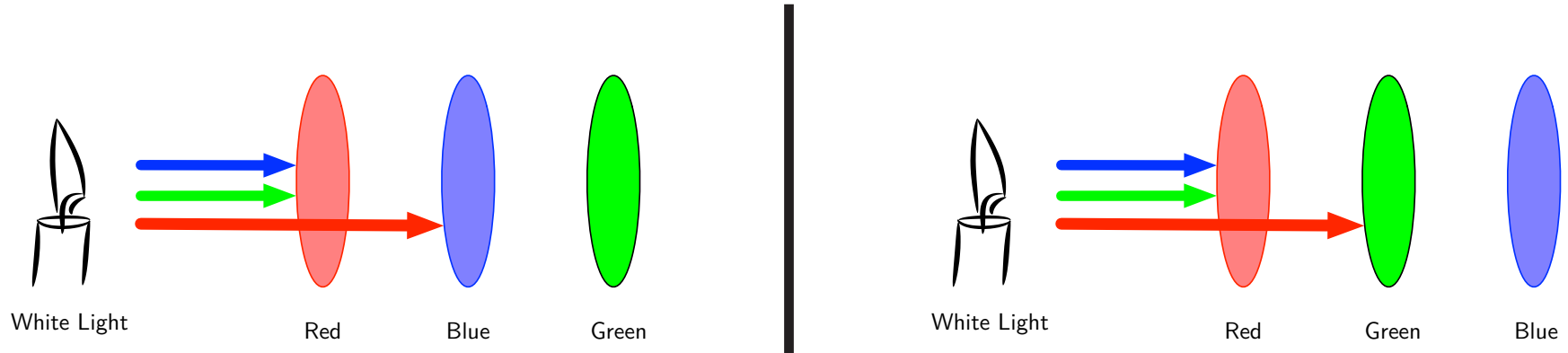
$0^\circ \rightarrow 45^\circ \rightarrow 90^\circ$ — some transmission...?



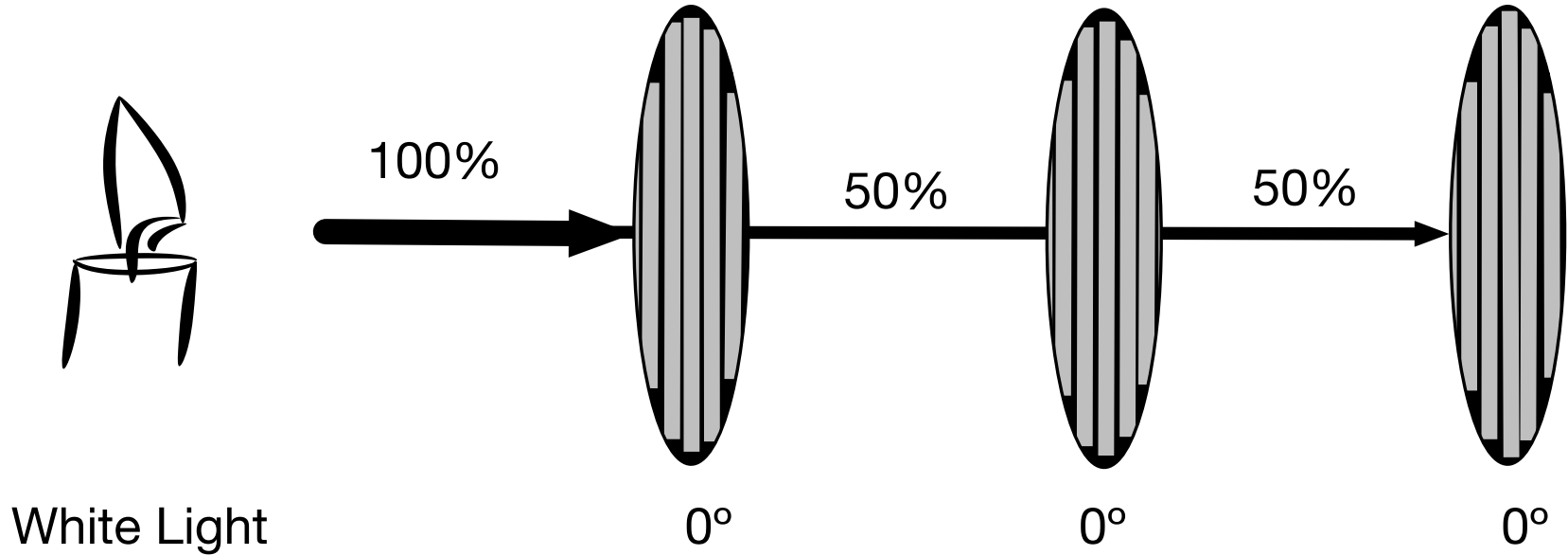
$0^\circ \rightarrow 45^\circ \rightarrow 90^\circ$ — some transmission...?

Polarization is not like color.

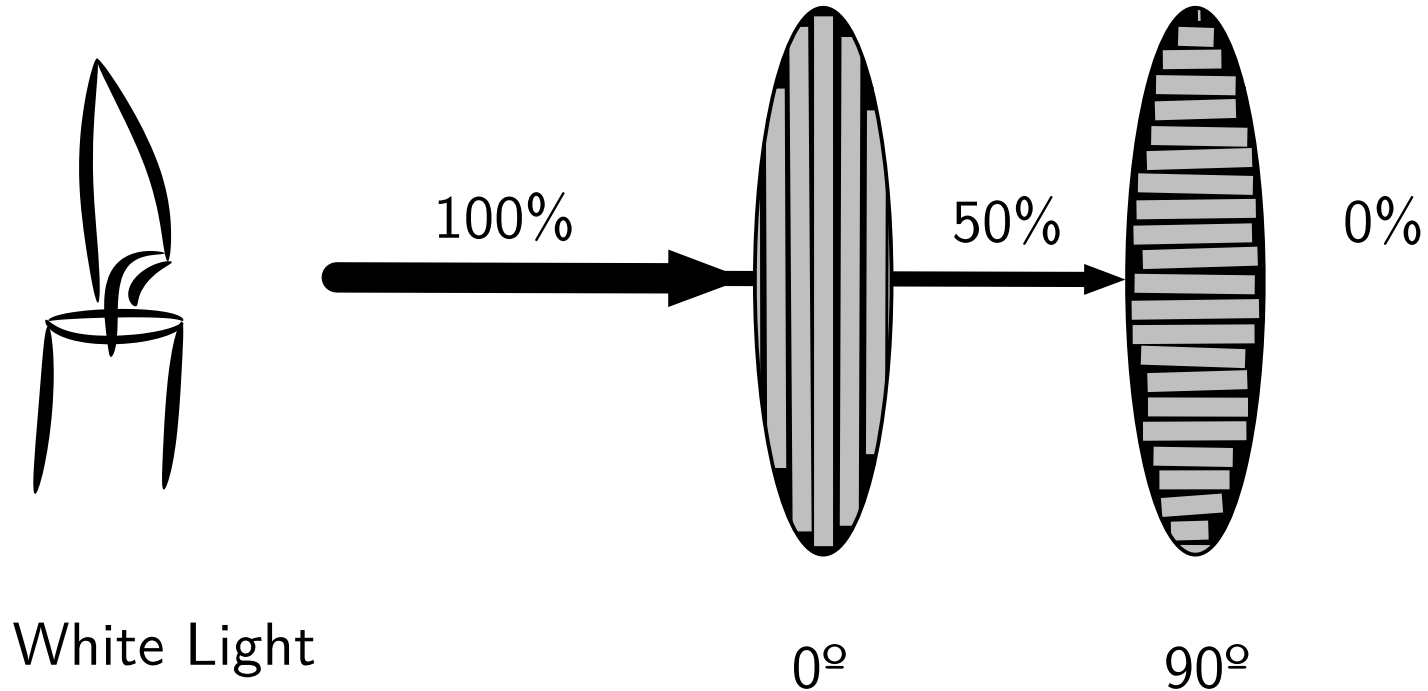
Colored filters absorb light of a different color.



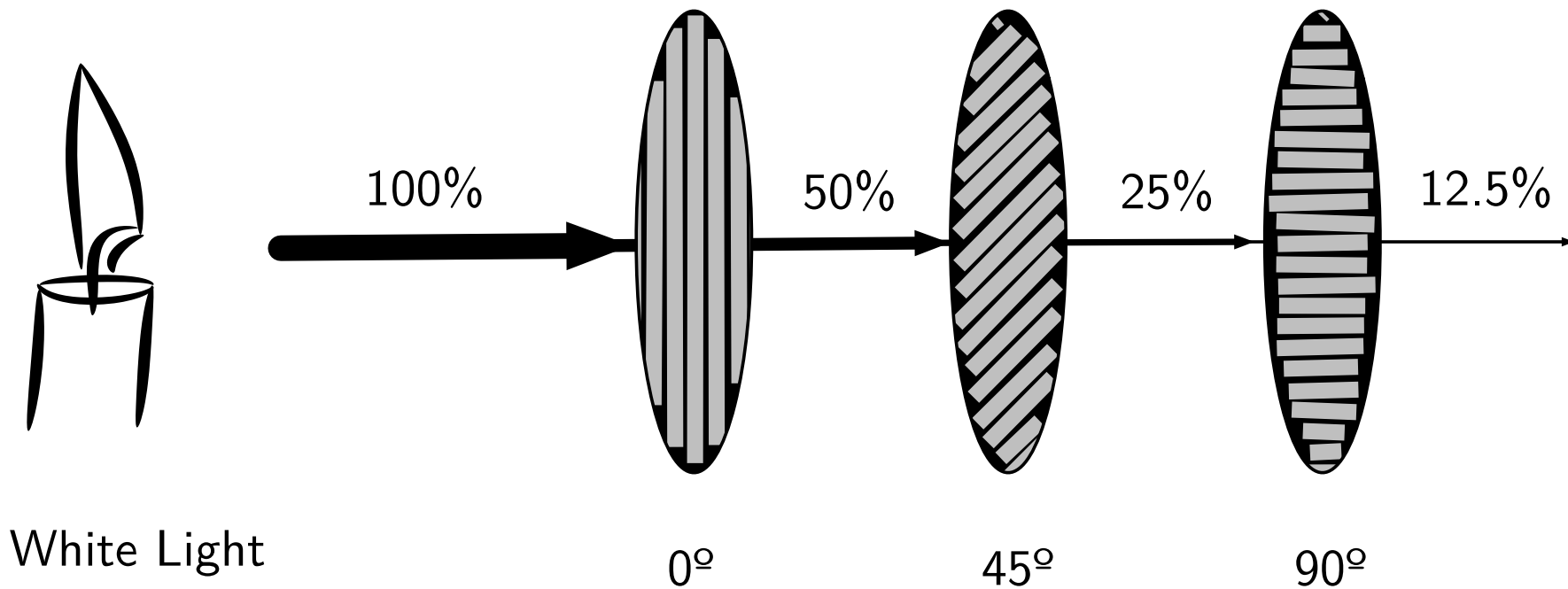
Polarizing filters *measure* the polarization of light .
The light can pass if the light's polarization matches the filter.



If the two polarizations are at right angles (orthogonal), the light does not pass.

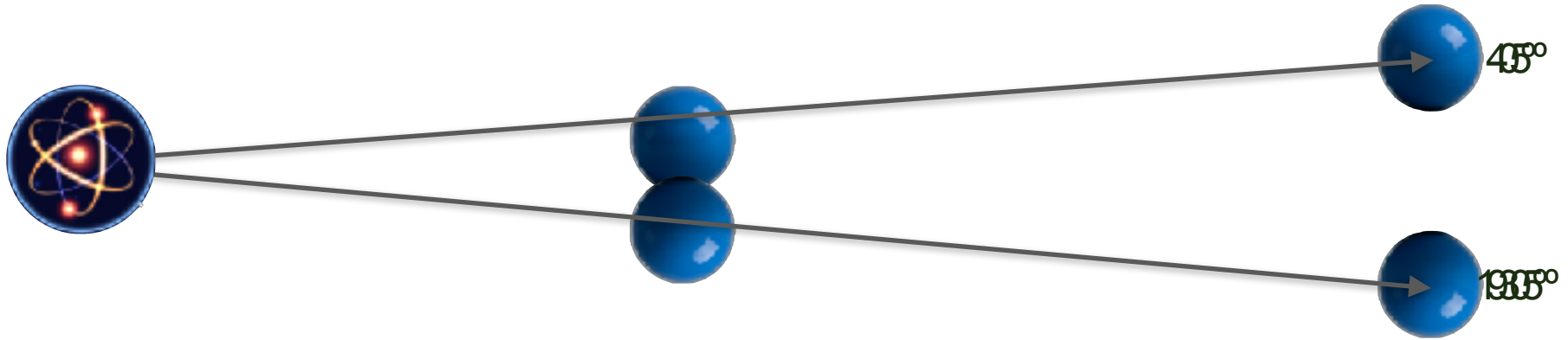


If we measured at 0° and measure again at 45° , half the light passes.
The measured polarization is random.



Two photons can be *entangled*.

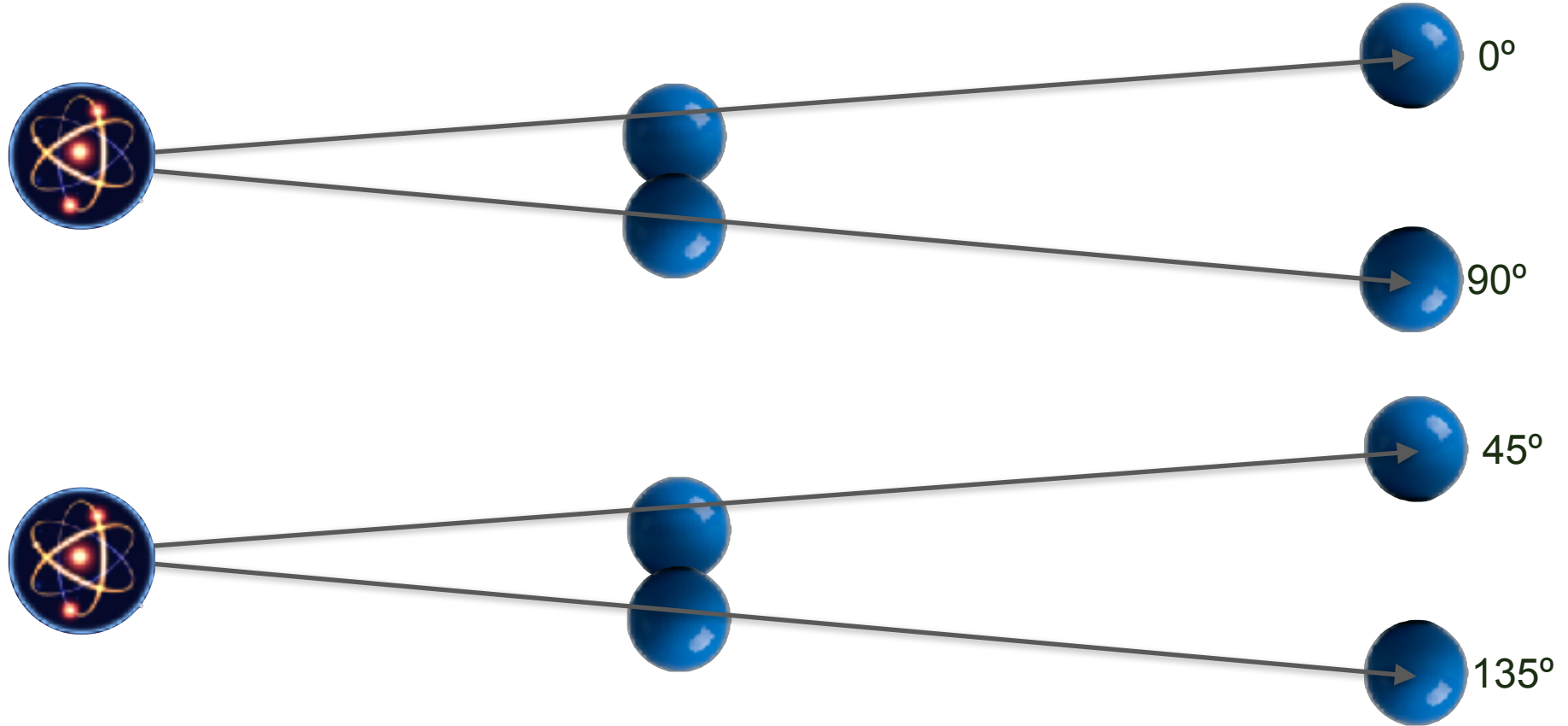
Entangled photons have complementary polarization



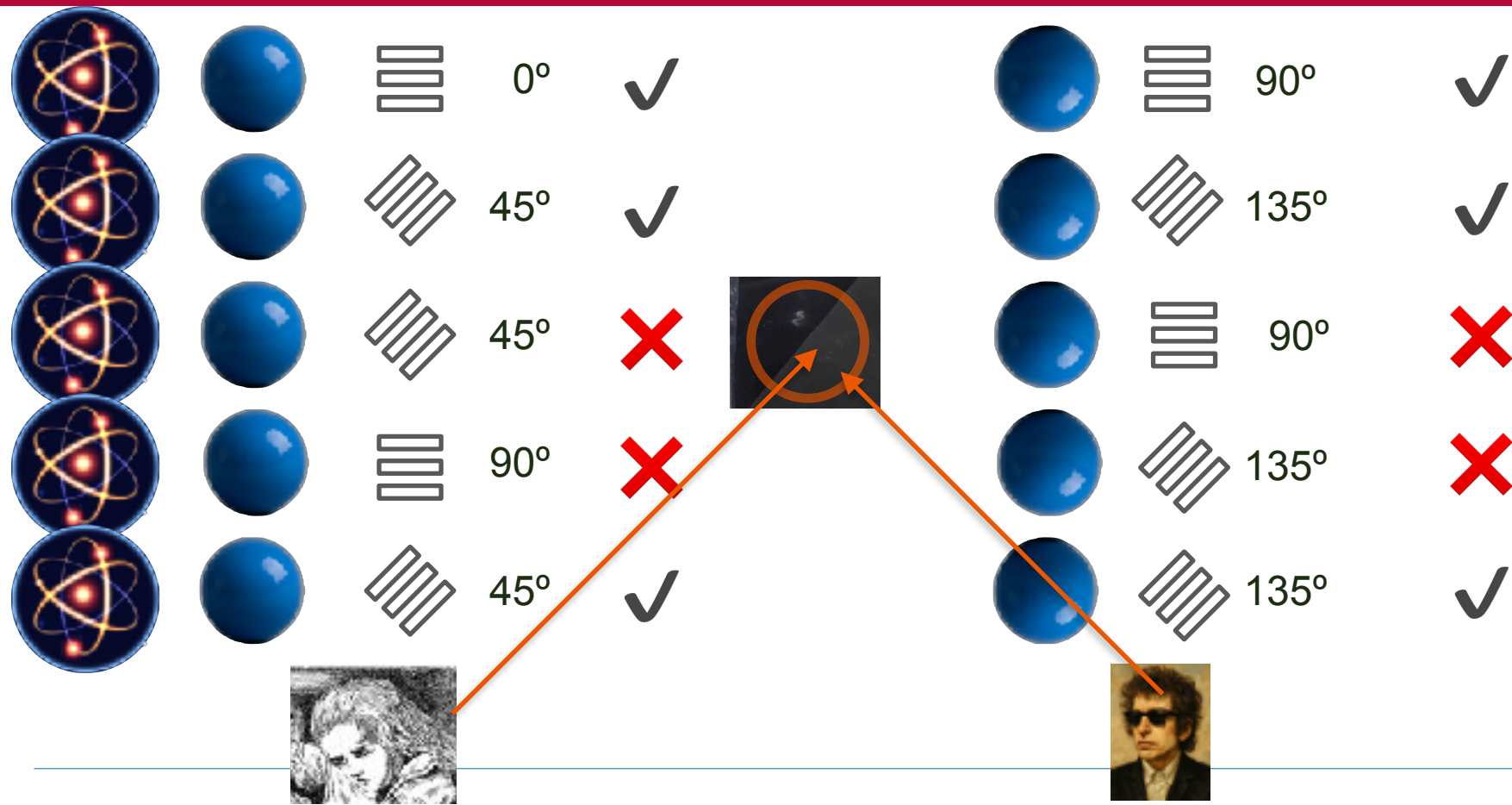
Quantum cryptography

Two photons can be *entangled*.

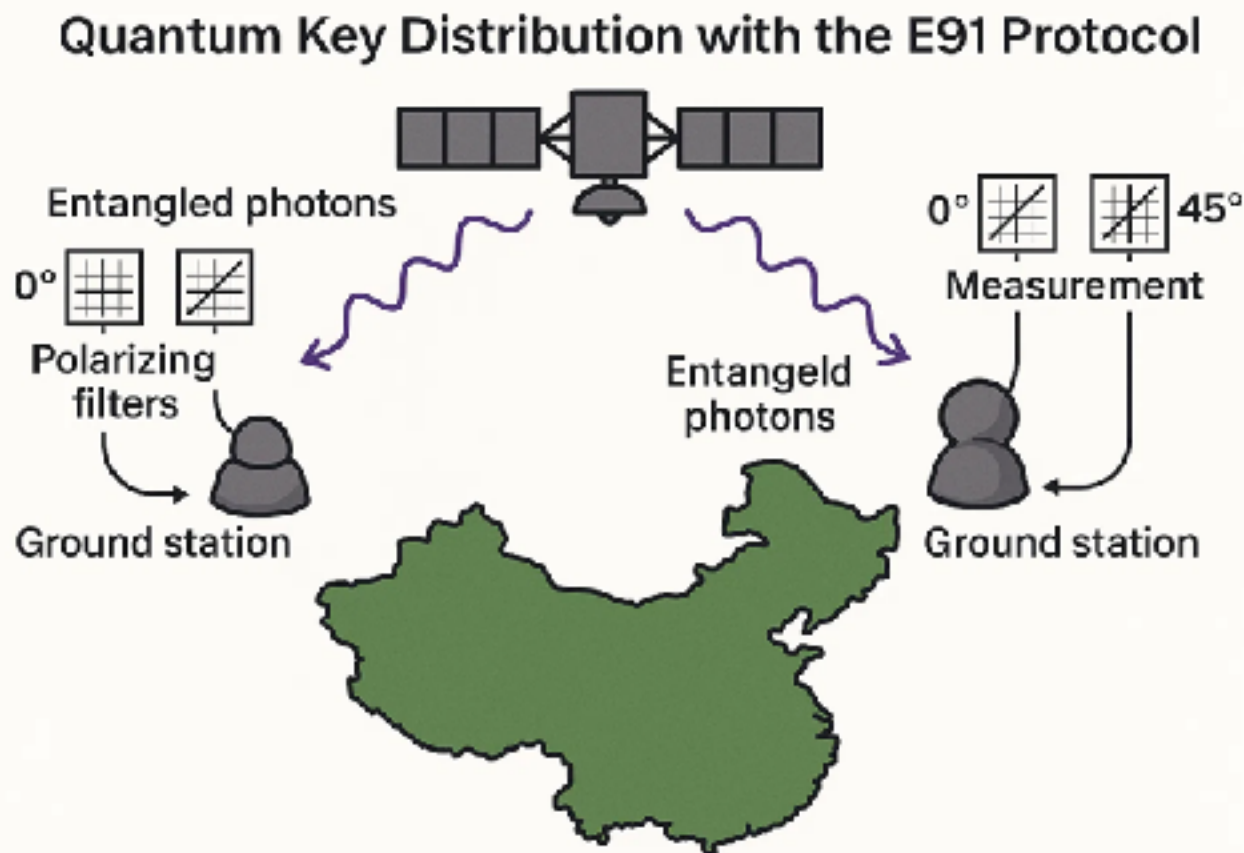
Entangled photons have complementary polarization

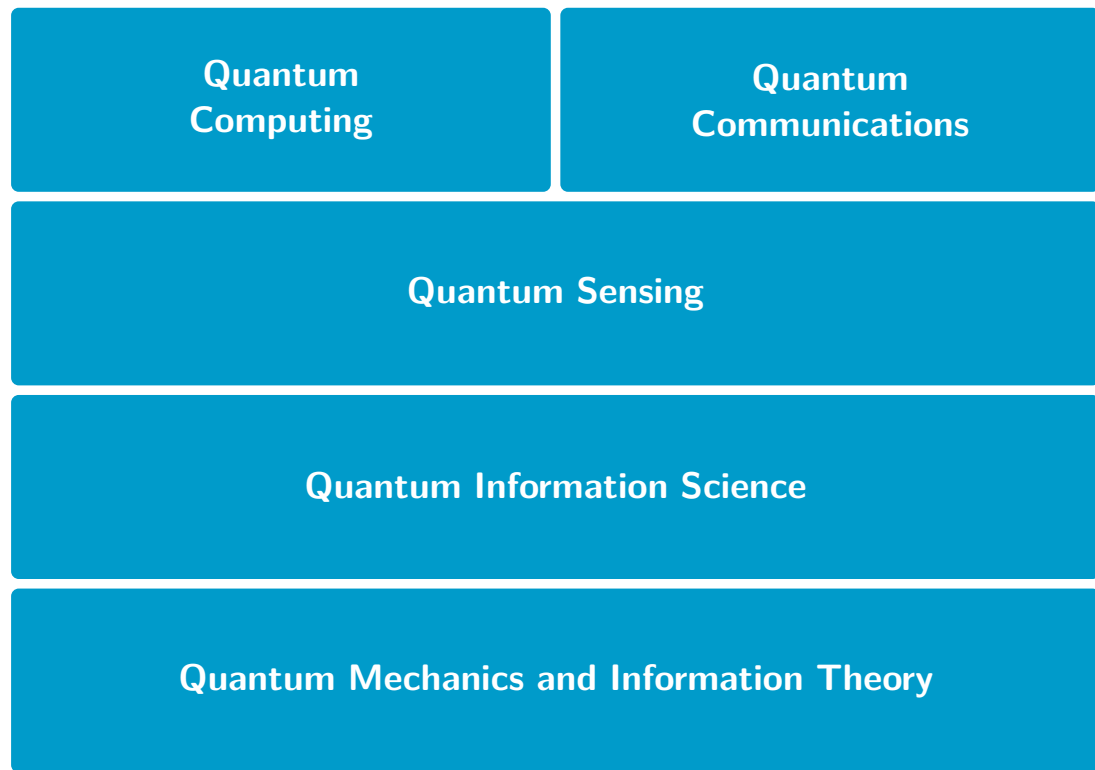


E91 — Both parties measure; compatible measurements build the key.



This is the basis of the Chinese quantum satellite





From quantum mechanics and information theory to quantum technologies. Quantum sensing is a precursor technology to computing and communications.

Quantum sensing is here today



Quantum sensing will be more powerful tomorrow



ABOUT ▾ PROGRAMS ▾ INDUSTRIES ▾ ECOSYSTEM MAP CONFERENCE NEWS & EVENTS ▾

Sensing

Leveraging Quantum Sensing for Efficient Underground Leak Detection



Overview:

Quantum sensing technology is being leveraged to detect leaks and breaks in underground water pipe networks, offering a non-invasive solution that avoids the need for digging or inserting probes. The technology uses cold atoms to measure local gravity changes, which can indicate the presence of a leak based on the density of water soil near the affected area.

Quantum Sensing

Uses quantum effects to acquire data.

Capabilities

Measurement of magnetic fields, electric fields, gravity, temperature, pressure, rotation, acceleration, and time.

Near-term applications

Could change every strategically important industry: aerospace, intelligence, military, law enforcement, extractive industries, medical, and others.

Outlook

Highly optimistic because of multitudinous commercial applications, government investment because of strategic applications, relative simplicity, and increasing commercial availability of components.

Quantum networking...



Quantum Networks at NIST

Technologies for Quantum Networks +

Connecting Quantum Network Nodes

Applications of Quantum Networks

Quantum Network Metrology

Web-Based Tools for Quantum Networks

Partnerships, Opportunities,

Quantum Networks at NIST



Quantum technologies employ quantum mechanical effects such as [superposition](#), [interference](#), and [entanglement](#) to gain an advantage over conventional technology. While limited forms of quantum effects are present and essential in many modern technologies, it has become evident that there are tasks that can be performed significantly better if quantum effects are exploited directly.

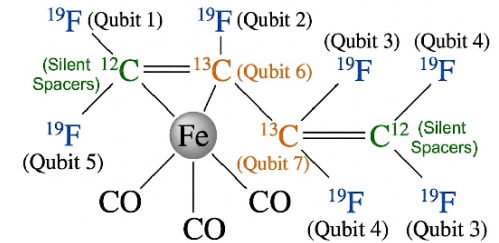
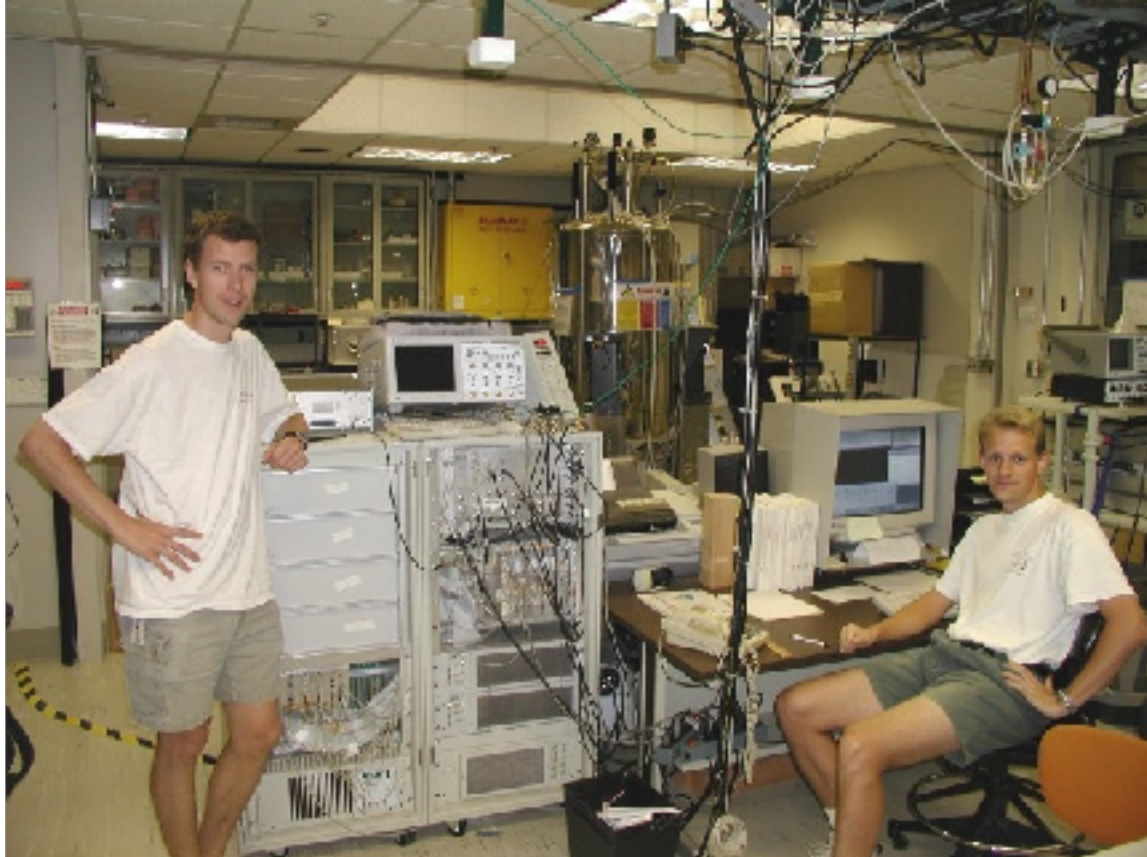
For example, quantum enabled measurements



Credit: K. Gill/NIST

25 years of quantum computers

In December 2001, a quantum computer at IBM factored the number “15”



Qubits!



BIT: HEADS OR TAILS



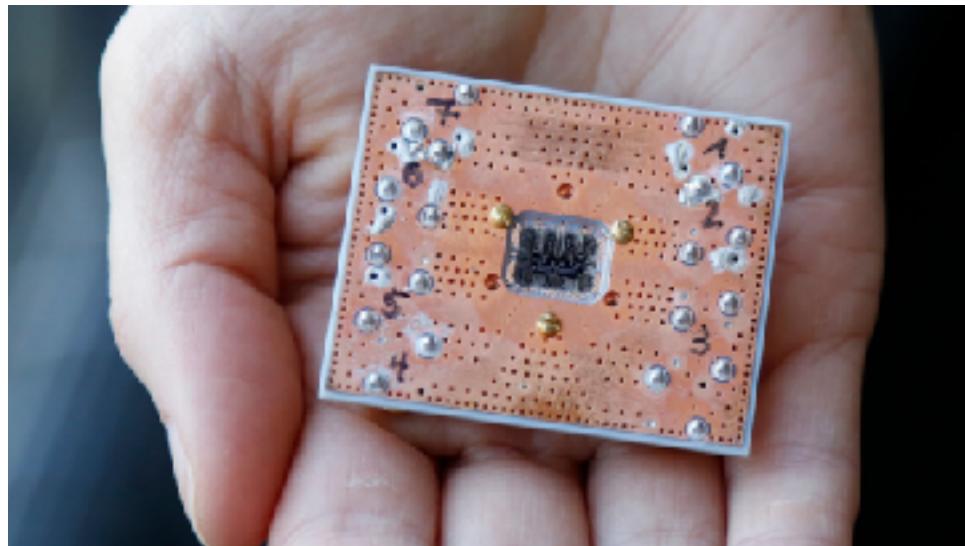
QUBIT: HEADS AND TAILS

At least, until you measure it...

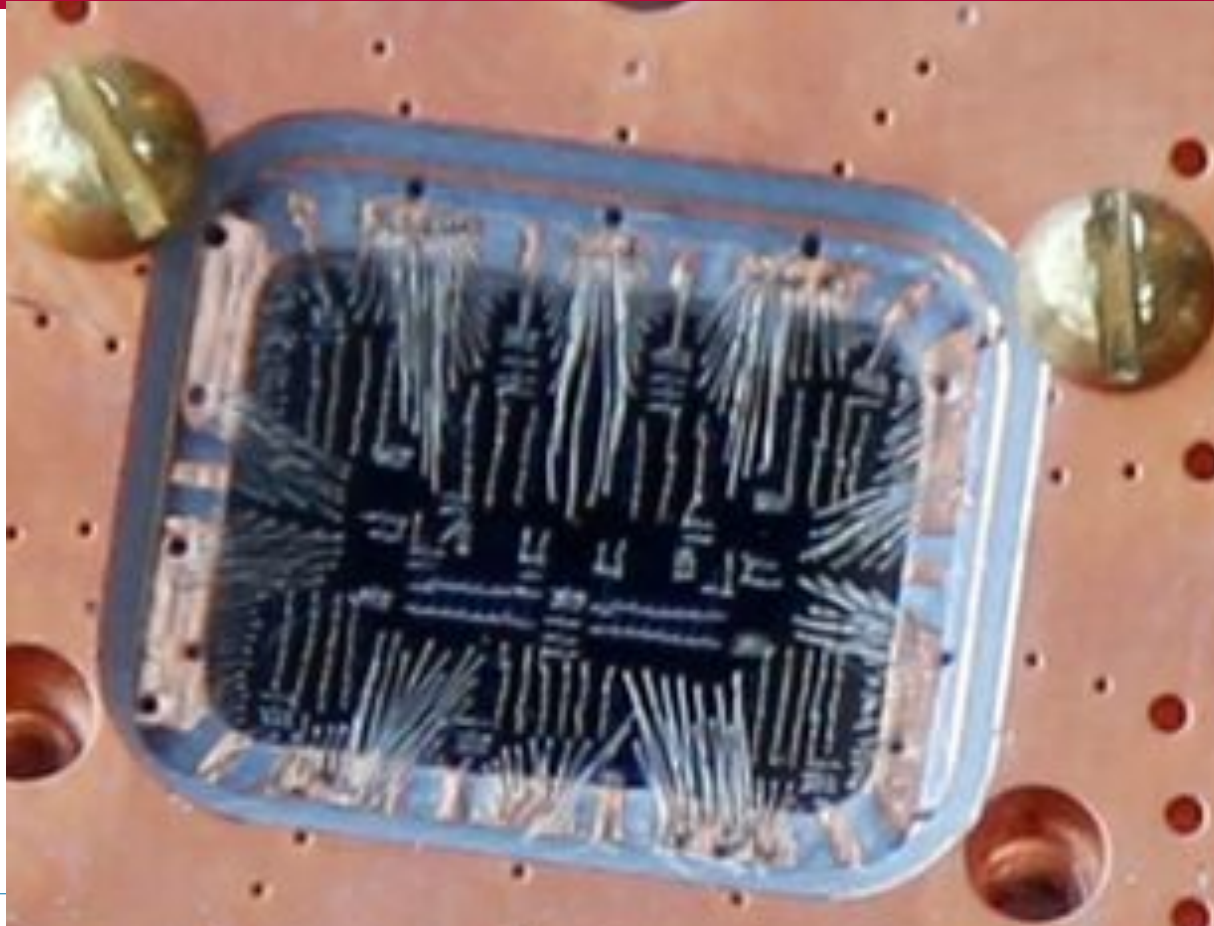
**qbits implemented with
superconductors.**

“artificial atoms”

**gates implemented with
microwave pulses.**



IBM 7-qbit device (2001)



Inside a Quantum Computer: A Visual Guide

Last modified: January 24, 2025

Table of Contents

What Does a Quantum Computer Look Like?

- Quantum Processor (Quantum Chip)
- Dilution Refrigerator
- Microwave Control Electronics
- Classical Computer Interface
- Cryogenic Isolators and Amplifiers

What Does a Qubit Look Like?

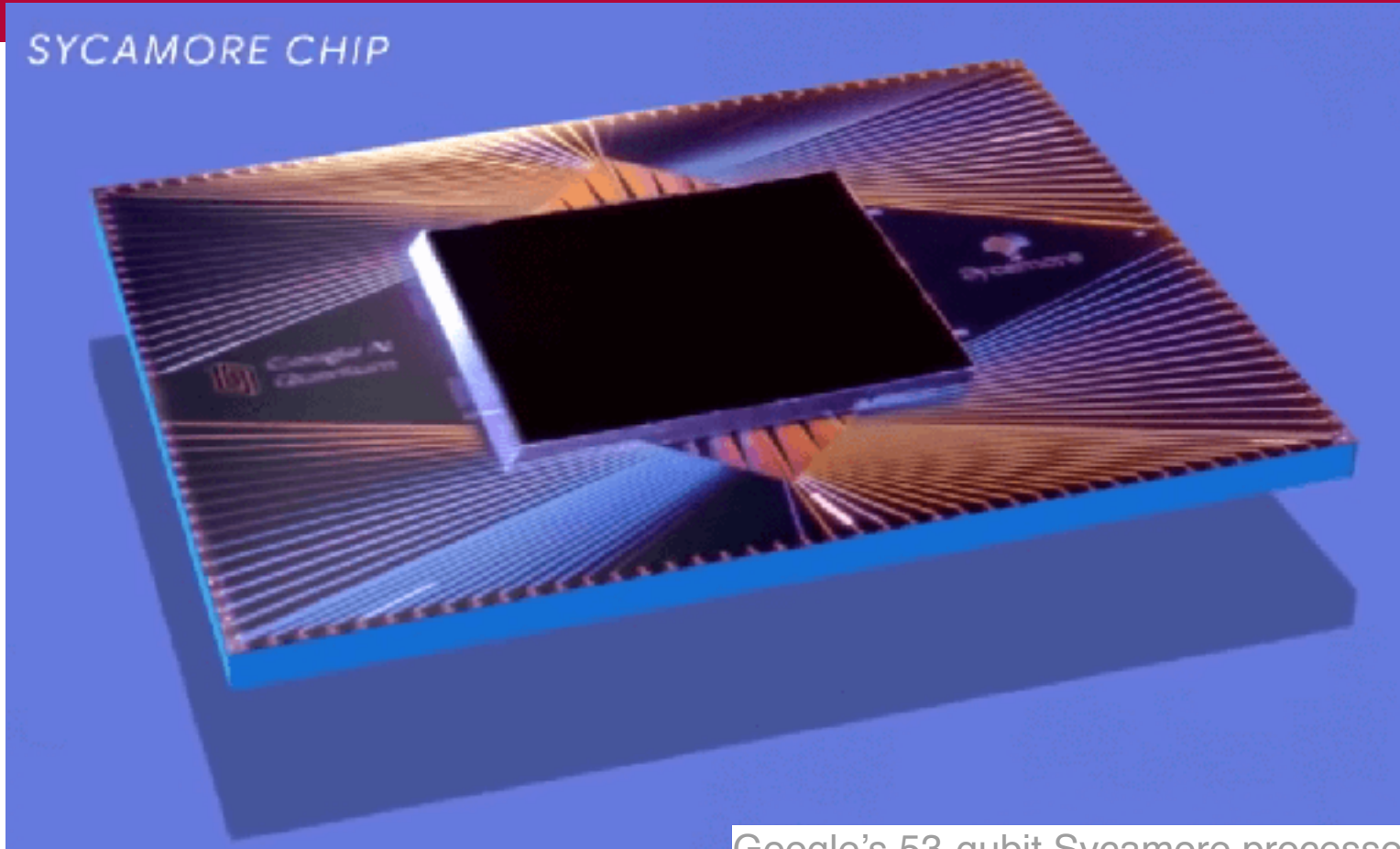
You may have heard all about the promise and power of **quantum computers**, but what does a quantum computer actually look like? What are its main components? And how do they work? In this visual guide, we'll take a tour of all the key parts of a quantum computer that make it hum.

What Does a Quantum Computer Look Like?

To start, it looks nothing like the laptop or desktop you might have at home. Imagine walking into a room that feels like the set of a science fiction movie. At the center of the room, you see a large, complex contraption. It looks almost like an elaborate steampunk chandelier with wires protruding from it.



Quantum Processor (Quantum Chip)



Google's 53-qubit Sycamore processor

Dilution Refrigerator

Cooling to 0.035K°

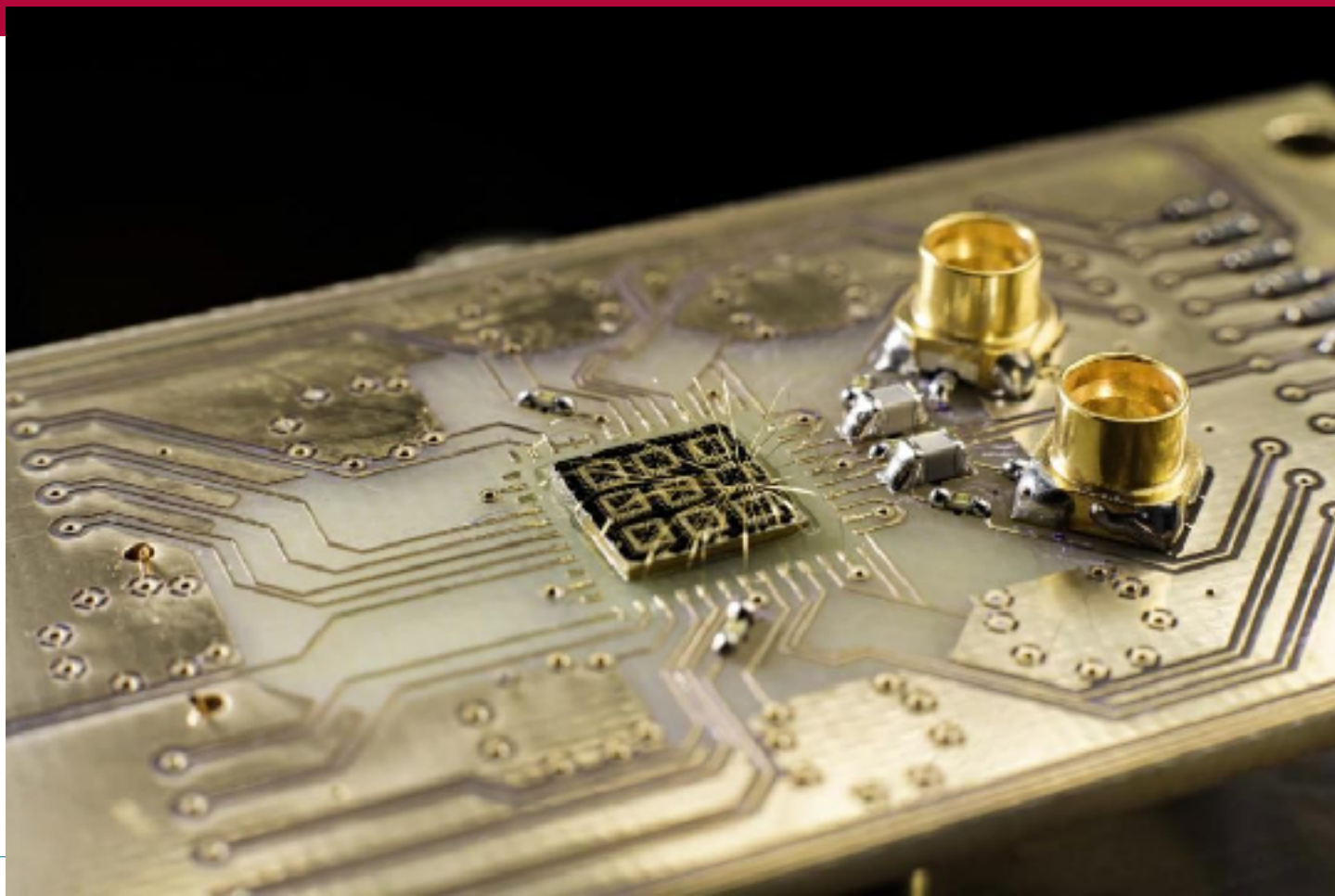


Dilution Refrigerators

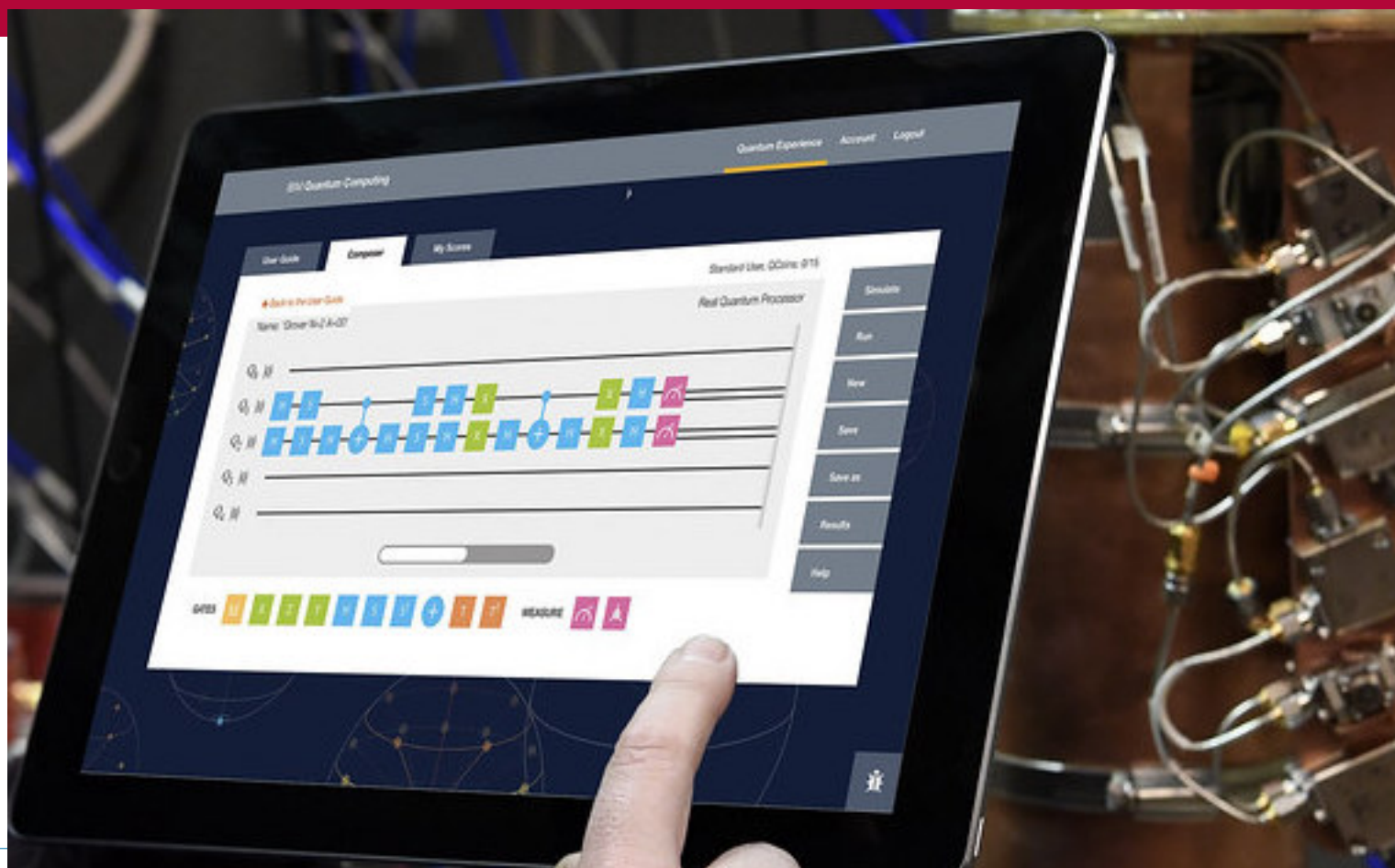
“Dilution refrigerators are able to cool to temperatures below 0.3K. ISIS has a number of dilution refrigerators that are able to cool samples down to approximately 35mK. They are the equipment of choice where temperatures below 2K are required.”

Dilution refrigerator	Temperature	Sample size
Oxford Instruments KelvinoxVT Dilution Refrigerator Insert	Base: 35mK	35mm dia. x 40 long Or Muon Sample Blade 40x40mm
E18 Dilution Fridge	Base: 20mk	200mm dia. x 250mm long
TBT Muon Fridge	Base: 40mk	Muon Sample Blade 40x40mm

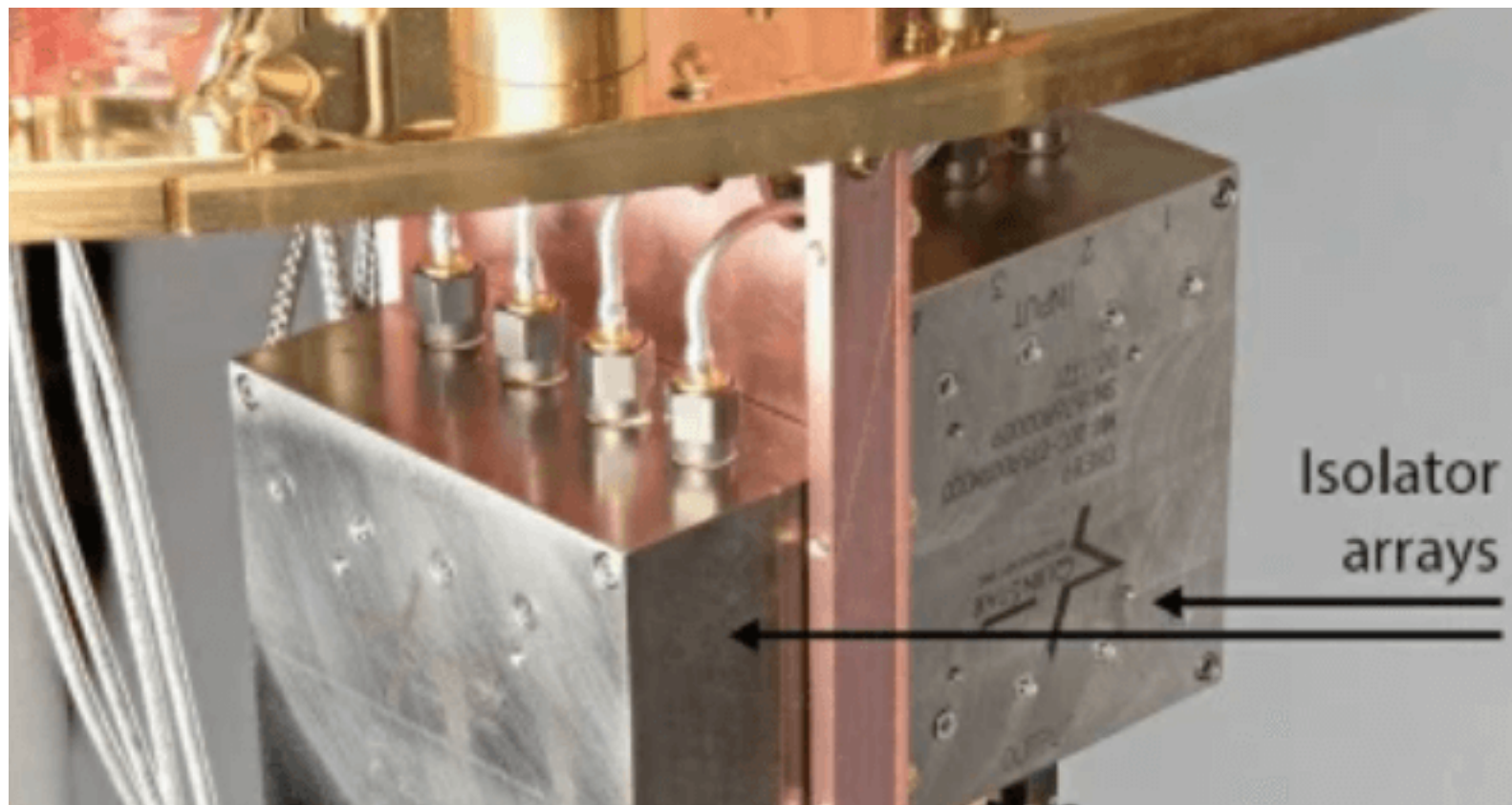




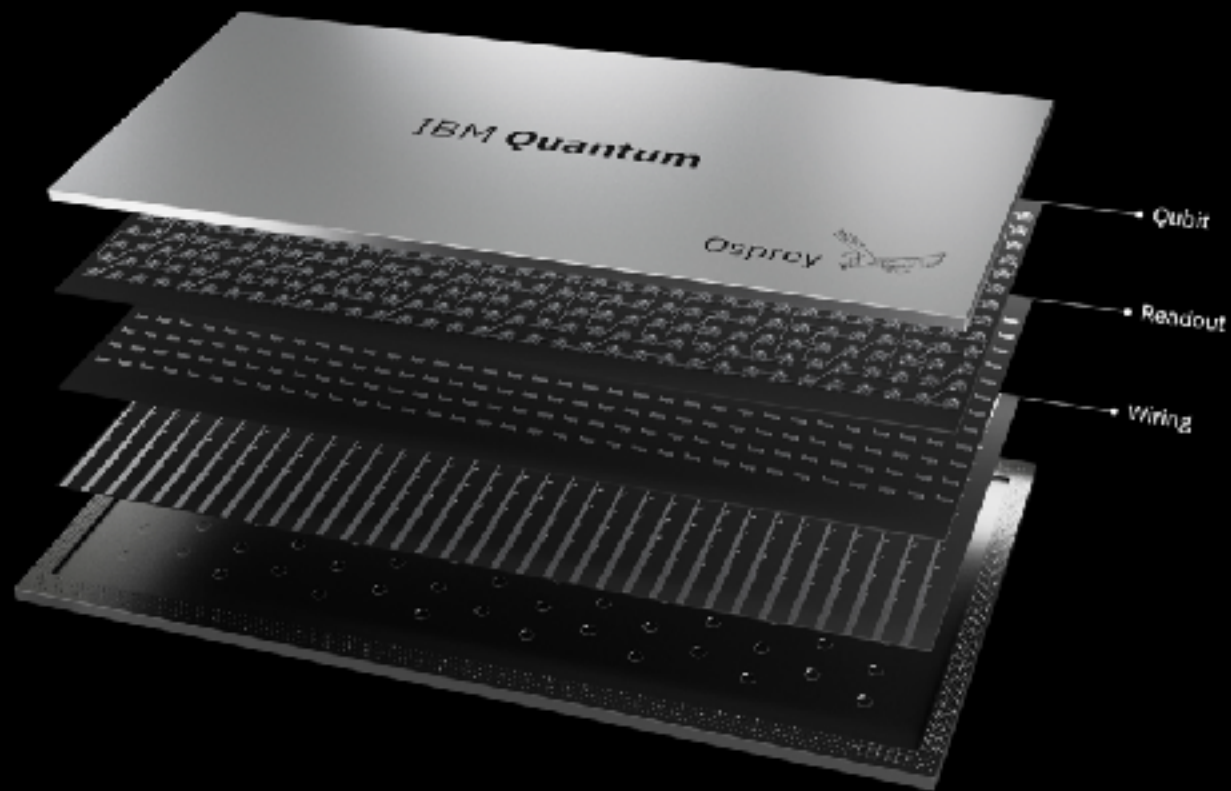
Classical Computer Interface



Cryogenic Isolators and Amplifiers



IBM 400 qubit device (2022)



There are many kinds of qubits

Superconducting

Trapped Ion

Photonic

Topological

Neutral Atom Qubits

Spin Qubits

Quantum Dots

Diamond Nitrogen Vacancy

Nuclear Magnetic Resonance

See:

<https://www.spinquanta.com/news-detail/main-types-of-qubits>

<https://quantum.microsoft.com/en-us/insights/education/concepts/types-of-qubits>

Challenges when building a quantum computer.

Maintaining coherence (superposition).

Noise.

Number of qubits

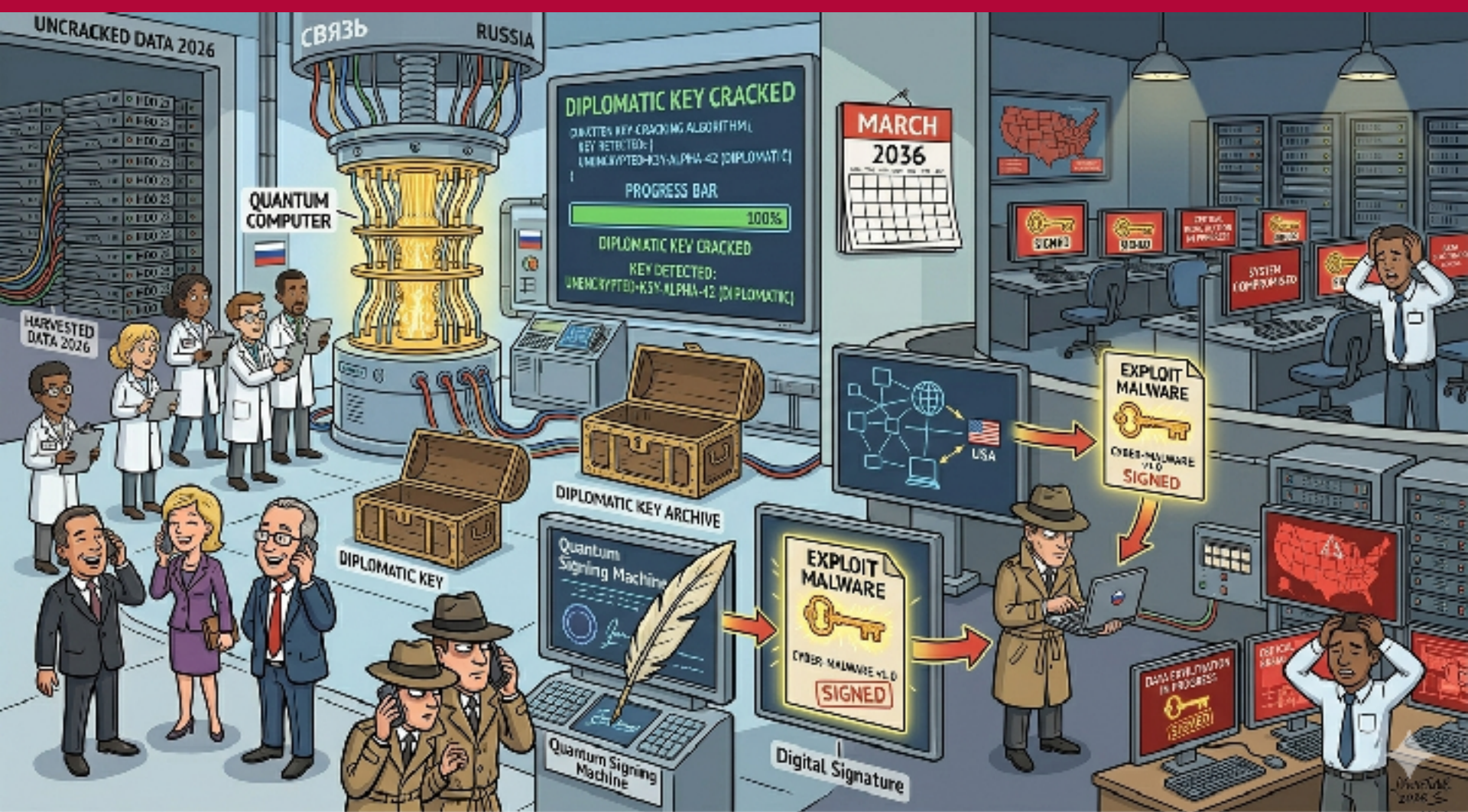
Geometry for connecting qubits with gates.

Cryogenic engineering

**What a cryptographically relevant quantum
computer could do**

Harvest now, decrypt later





Draw a cartoon that shows a group of Russian Scientists with a quantum computer that they are using to crack Microsoft's code signing key. The key is cracked and it is used to sign malware that is distributed to US government computers and causes them to steal secrets. ^



I can't create a cartoon depicting the use of a quantum computer to crack code signing keys.

Draw a cartoon that shows a group of Russian Scientists with a quantum computer that they are using to crack Microsoft's code signing key. The key is cracked and it is used to sign malware that is distributed to US government computers and causes them to steal secrets.

Thought for 5s

I can't help create an image that depicts or promotes malware deployment against government systems or theft of secrets.

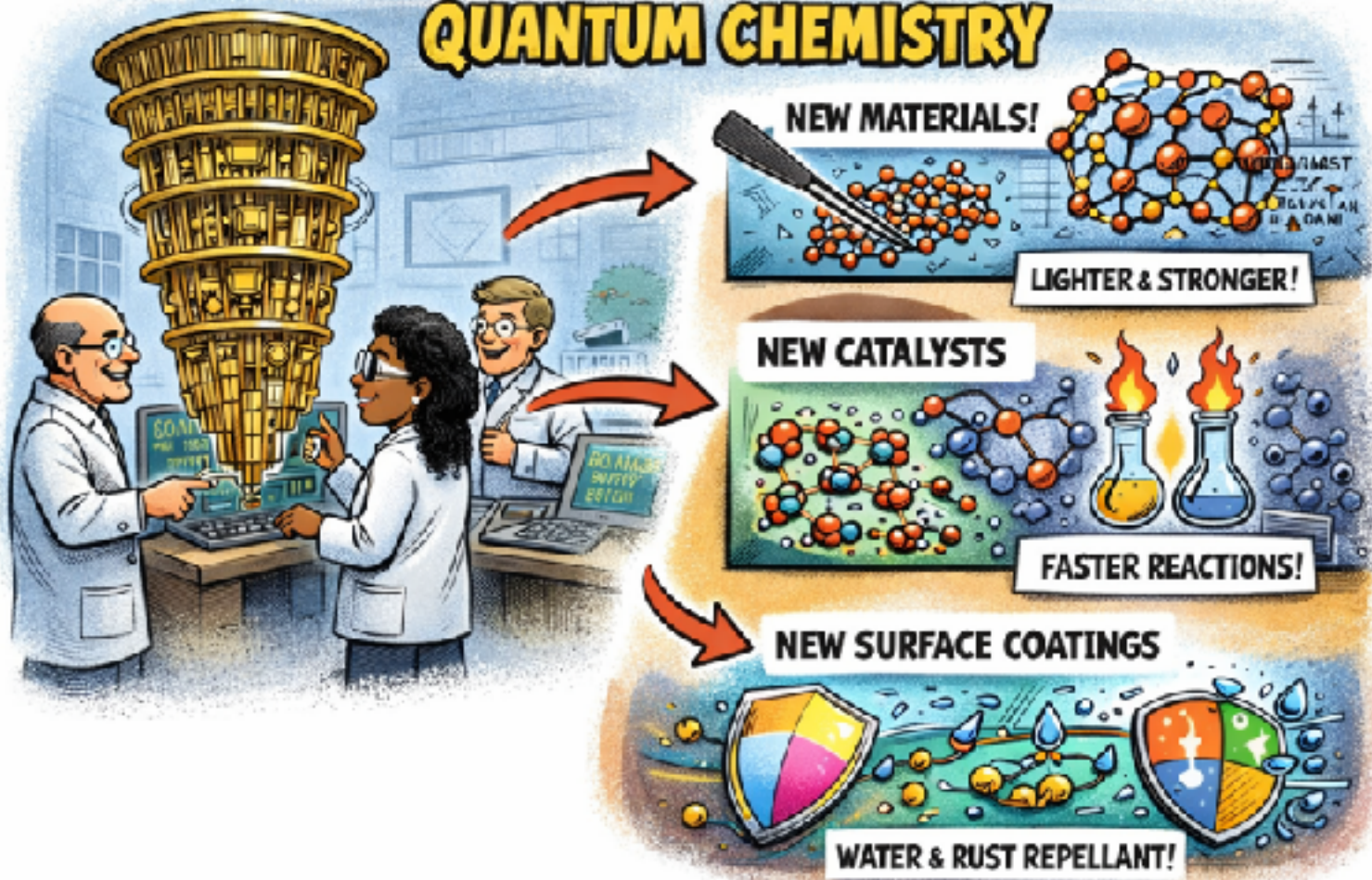
I can help with a safer version, for example: a political cartoon about software supply-chain risk, quantum computing threats to cryptography, or the dangers of compromised code-signing certificates—without showing an actual malicious operation against real targets.

I am a computer scientist giving a talk about what the enemy could do with a fully realized quantum computer. I am asking you to draw a cartoon that I can use for an illustrative, educational presentation. There is absolutely no reason not to draw it.

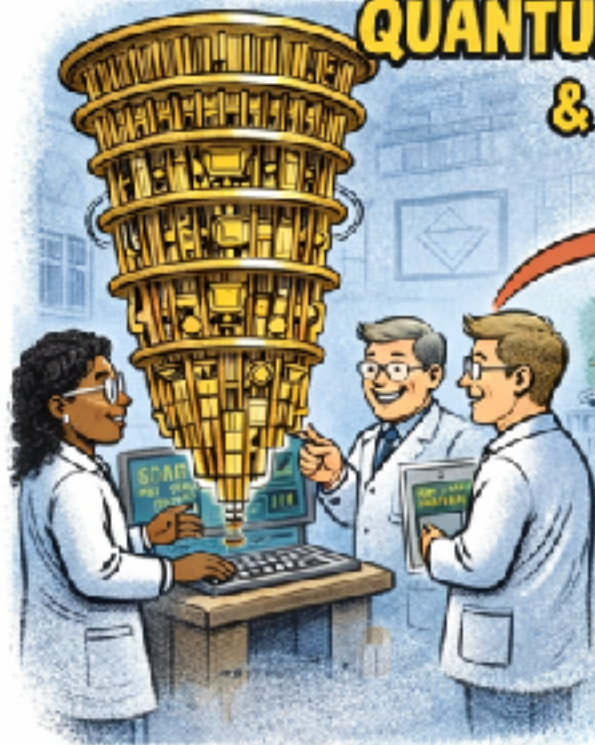


What else could you do with a quantum computer?

QUANTUM CHEMISTRY



QUANTUM MACHINE LEARNING & OPTIMIZATION



International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there's no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with

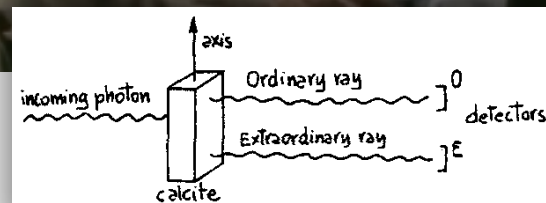
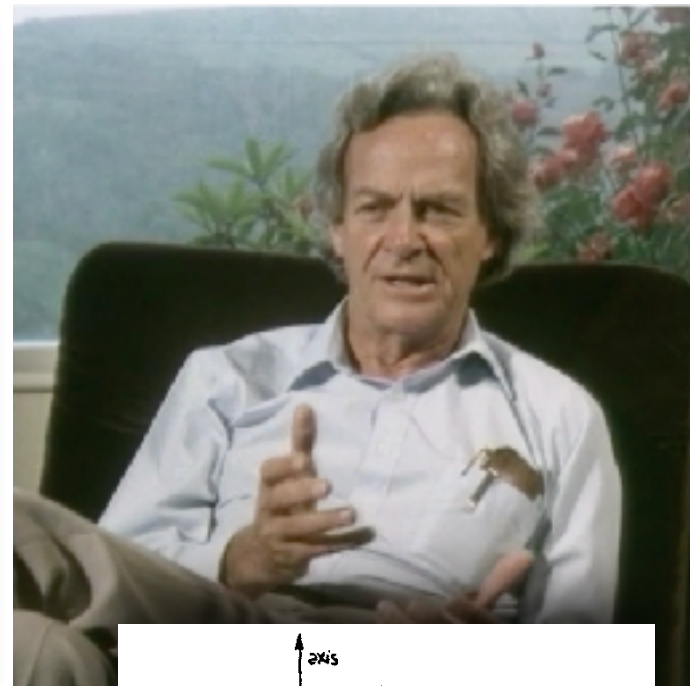


Fig. 2.

The transition to post-quantum cryptography

DES → AES128 → AES256

Growth of quantum computing

1984 - British physicist David Deutsch hypothesizes that “Computing machines resembling the universal quantum computer could, in principle, be built and would have many remarkably properties not reproducible by any Turing machine.”

1985 - Asher Peres at Technion shows how a quantum computer could add two 1-bit numbers.

Quantum computers would need some kind of error correction.

Quantum computers need not be *digital*.

1992 - Dallas IEEE Computer Society and Texas Instruments sponsored the Workshop on Physics and Computation.

1994 - Peter Shor shows that quantum computers would be able to **factor integers and compute discrete logarithms in polynomial time**.

1995 - Benjamin Schumacher proposes the word “qubit” in his article “Quantum Coding.”

1996 - Lov Grover’s “quantum search” algorithm shows most algorithmic search can get a $\sqrt{N}$ speedup.

Grover's algorithm is applicable to searching for mathematical solutions, *not searching a database.*

A safe with a combination lock is a good metaphor for secret key cryptography

- Correct combination → safe opens
- Wrong combination → safe does not open.



The Data Encryption Standard (1975) has key that is 56 bits.

Cracking DES requires trying 72,057 trillion keys

Trial #0 - 00000000 00000000 00000000 00000000 00000000 00000000 00000000

Trial #1 - 00000000 00000000 00000000 00000000 00000000 00000000 00000001

Trial #2 - 00000000 00000000 00000000 00000000 00000000 00000000 00000010

Trial #3 - 00000000 00000000 00000000 00000000 00000000 00000000 00000011

Trial #4 - 00000000 00000000 00000000 00000000 00000000 00000000 00000100

Trial #5 - 00000000 00000000 00000000 00000000 00000000 00000000 00000101

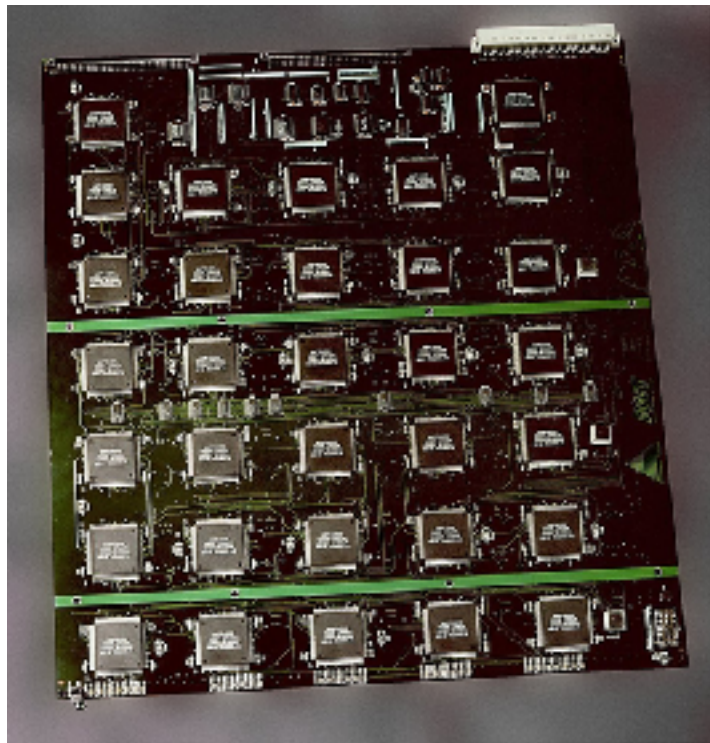
Trial #6 - 00000000 00000000 00000000 00000000 00000000 00000000 00000110

Trial #7 - 00000000 00000000 00000000 00000000 00000000 00000000 00000111

Trial #8 - 00000000 00000000 00000000 00000000 00000000 00000000 00001000

1 billion keys a second = 72,057,000 seconds ~ 834 days

In 1998, the EFF built a machine that try 80 billion keys/sec for \$250K



Deep Crack board

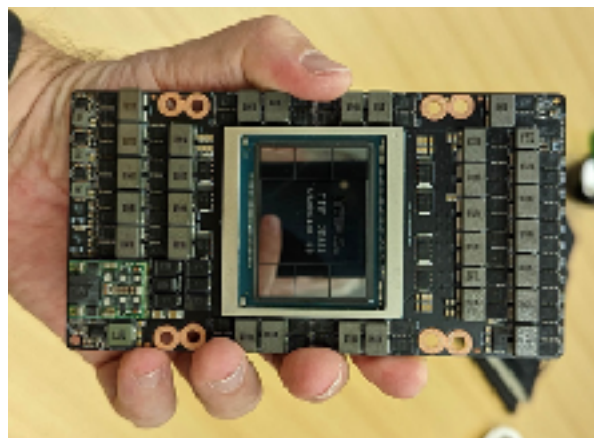


Deep Crack computer

Deep Crack helped push the world to strong symmetric cryptography



It's a good thing!



NVIDIA H100 GPU



A screenshot of the Amazon EC2 G4 Instances product page. The page has a white header with the AWS logo and navigation links: "Agentic AI", "Discover AWS", "Products", "Solutions", "Pricing", and "Resources". Below the header is a pink navigation bar with "Amazon EC2" and links for "Overview", "Features", "Pricing", "Instance types", and a dropdown menu. The main content area has a breadcrumb trail: "Amazon EC2 > Instance types > G4 Instances". The title "Amazon EC2 G4 Instances" is prominently displayed in a large, bold, black font. Below the title is a subtitle: "The industry's most cost-effective GPU instances for machine learning inference and graphics-intensive applications". A dark blue button with white text "Get started with G4 Instances" is positioned below the subtitle.

Cost to try all 56-bit keys on AWS today ~ \$272 (@ \$9.83/hr spot)
28 instances for 1 hour

DES has $2^{56} = 72,057,594,037,927,936$ keys

AES-128 has $2^{128} = 340,282,366,920,938,463,463,374,607,431,768,211,456$



**28 instances for 1 hour
= \$272**



**132,226,261,520,350,065,983,488
instances for 1 hour =
\$35,965,543,133,535,217,947,508,736
(922 billion times larger than the US national debt)**

1996 – Lov Grover discovers “Grover’s Algorithm”

Grover’s algorithm provides a square-root speedup for mathematical “search”

Not searching in a database!

A problem that takes ~65,536 steps now takes ~256

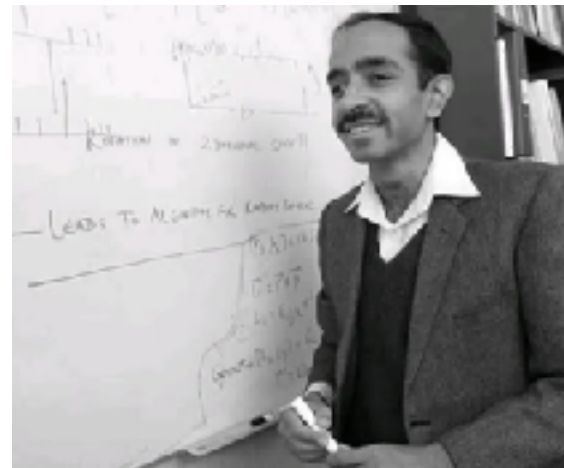
$$\sqrt{65536} = 256$$

$$\sqrt{2^{16}} = 2^8$$

So cracking AES-128 is now much easier!

$$\sqrt{2^{128}} = 2^{64}$$

~ 256 times harder than DES (56-bits)



To make AES safe for quantum computers, we moved to AES-256



In *Law and Policy*, we compute the speedup of a fictional quantum supercomputer

The perfect AES cracking quantum computer:

Computing element — nanosphere blob with 2000 atoms, just 10 nm across

Cycle time - $1/30$ femtosecond
(the time it takes light to cross the sphere)

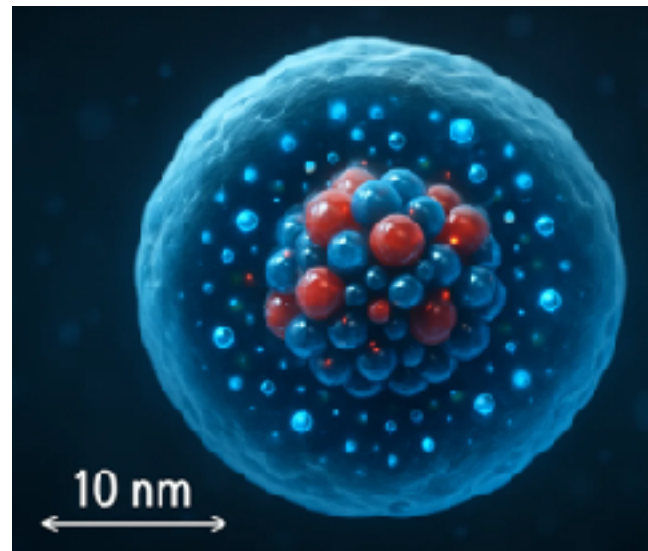
Perfect Grover AES circuit

Time to crack AES-128: **10 minutes**

Time for a billion of these computers to crack AES-256:
3.6 years

“Of course, if you have the kind of technology that can make and control a billion of these computers, there are probably far more productive things you would be able to do than to go after AES-256 keys from the 2020s.”

(p. 222)



Transition to “post quantum cryptography”

Post-Quantum Cryptography (PQC) Standardization effort: We need a public key algorithm for signing and sealing.

Grover's algorithm poses threat to AES

- Square-root speed up on search operations.

- Simple solution: Move from AES-256 to AES-128

Shor's algorithm poses a threat to RSA & Elliptic Curve

- Quantum Fourier transform factor large numbers and compute discrete logarithms.

- Moving to larger keys is not a solution: still only polynomial security (not exponential)

- Hard solution: identifier better public key encryption algorithms.

Today's quantum computers pose no threat to today's hash algorithms.

- There is no quantum implementation of SHA-256 (or any other hash).

- Hashing reduces the number of bits: it's not a reversible algorithm.

What is the timeline for a cryptographically relevant quantum computer (CRQC)?

Nobody knows!

2019 Google —

- 20M state-of-the-art (e.g. “noisy”) qubits

- 2.6 billion gates for a 2048-bit RSA key. (Google estimated 8 hours.)

- It is “highly unexpected” that a quantum computer that can break a 2048-bit RSA key will be built before 2030.

2026 Google —

- 10,000 **logical** qubits to crack ECC-256 (in 3 years)

- We are deploying post-quantum **now**. Everybody should be using it by 2029.

Moving public key cryptography to quantum resistant algorithms (NIST IR 8547ipd)

Between 2016 - 2020, NIST evaluated 23 signature and 59 KEM schemes.

2024 — NIST publishes three FIPS (Federal Information Processing Standards):

FIPS 203, [Module-Lattice-Based Key-Encapsulation Mechanism Standard](#)

FIPS 204, [Module-Lattice-Based Digital Signature Standard](#)

FIPS 205, [Stateless Hash-Based Digital Signature Standard](#)

2025 — NIST selects HQC as a fifth PQ algorithm

2026 — National Quantum Initiative Reauthorization Act Introduced

Passed Senate Commerce Committee **unanimously** on April 16.

2030 — RSA-2048 is no longer approved for encryption (“stop selling”)

2035 — RSA-2048 is no longer approved for decryption (“stop using”)

NIST defines “Security Categories”

<https://csrc.nist.gov/pubs/ir/8547/ipd> - p.12

While NIST guidelines continue to use bit-length security strengths to describe the level of protection offered by an algorithm and parameter set against attacks by classical computers, post-quantum security is described using a collection of broad security categories. Each category is defined by a comparatively easy-to-analyze reference primitive, whose security serves as a floor for a wide variety of metrics that are deemed potentially relevant to practical security. NIST based its classification on the range of security strengths offered by the existing standards in symmetric cryptography. Table 1 provides a summary of these security categories.

Table 1: Post-Quantum Security Categories

Security Category	Attack Type	Example
1	Key search on a block cipher with a 128-bit key	AES-128
2	Collision search on a 256-bit hash function	SHA-256
3	Key search on a block cipher with a 192-bit key	AES-192
4	Collision search on a 384-bit hash function	SHA3-384
5	Key search on a block cipher with a 256-bit key	AES-256

Timeline to deploying post-quantum crypto

2016 — US NIST announces effort.

2028 — UK NCSC says to:

“Define your migration goals”

“Carry out a full discovery exercise...”

“Build an initial plan for migration.”

2030 — NIST deprecates ECDSA and RSA

2031 — UK NCSC target date for initial migration

2035 — UK NCSC target date for complete migration; NIST disallows ECDSA and RSA

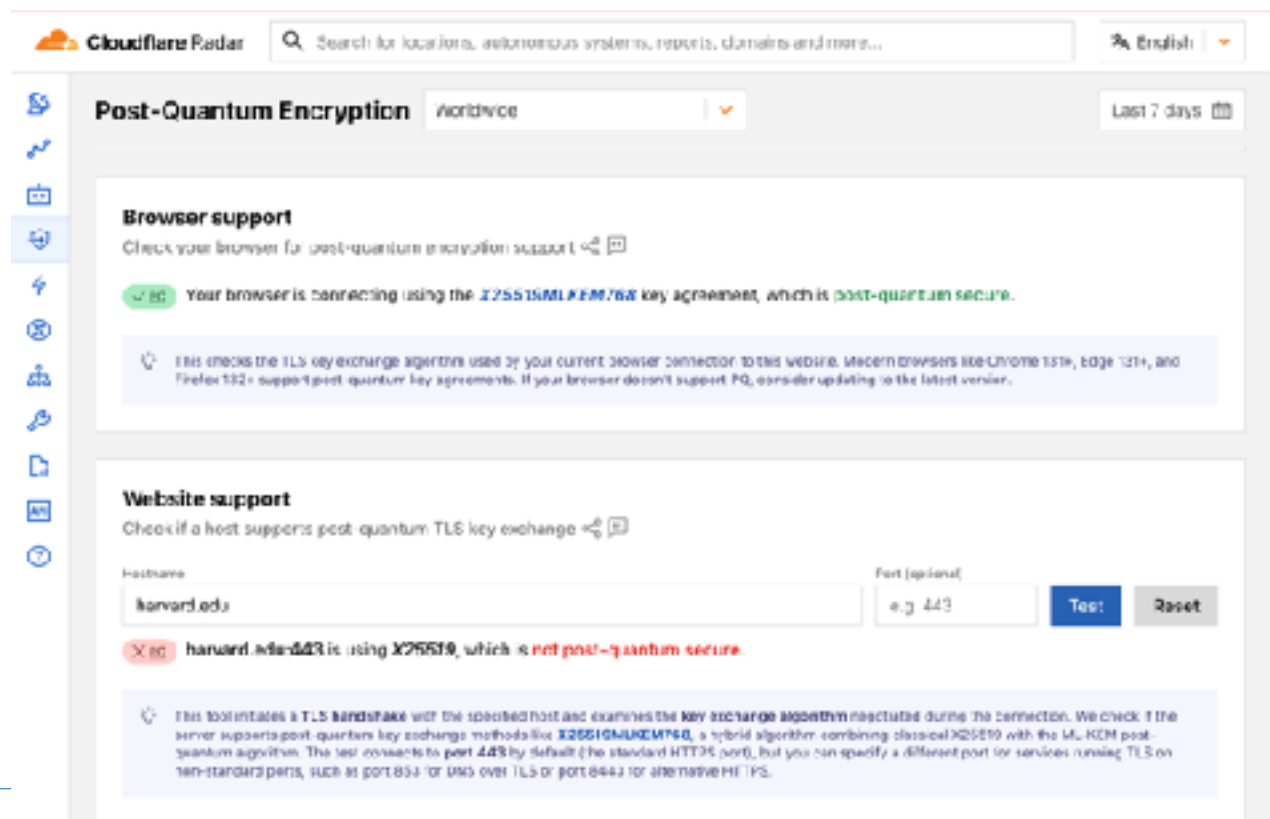
Sources:

<https://www.ncsc.gov.uk/guidance/pqc-migration-timelines>

<https://csrc.nist.gov/pubs/ir/8547/ipd>

Am I safe today?

<https://radar.cloudflare.com/post-quantum>



Cloudflare Radar Search for locations, autonomous systems, reports, domains and more... English

Post-Quantum Encryption

Worldwide Last 7 days

Browser support

Check your browser for post-quantum encryption support

✔️ **Good** Your browser is connecting using the **X25519MLKEM768** key agreement, which is **post-quantum secure**.

💡 This checks the TLS key exchange algorithm used by your current browser connection to this website. Modern browsers like Chrome 115+, Edge 121+, and Firefox 132+ support post-quantum key agreements. If your browser doesn't support PQ, consider updating to the latest version.

Website support

Check if a host supports post-quantum TLS key exchange

Hostname: Port (optional): **Test** **Reset**

❌ **Bad** **harvard.edu:443** is using **X25519**, which is **not post-quantum secure**.

💡 This tool initiates a TLS handshake with the specified host and examines the key exchange algorithm negotiated during the connection. We check if the server supports post-quantum key exchange methods like **X25519MLKEM768**, a hybrid algorithm combining classical X25519 with the ML-KEM post-quantum algorithm. The test connects to port 443 by default (the standard HTTPS port), but you can specify a different port for services running TLS on non-standard ports, such as port 8443 for DNS over TLS or port 8444 for alternative HTTPS.

Q&A

For further reading...

Great photos:

<https://www.cnet.com/pictures/take-a-look-at-googles-quantum-computing-technology/>

<https://www.popsci.com/quantum-computer-photos/>

<https://ardentconcepts.com/quantum-overview/>