Quantum Information, the Ambiguity of the Past, and the Complexity of the Present

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I. Information is Quantum:

How physics has helped explain the nature of information and what can be done with it

Like other parts of mathematics, the theory of information processing originated as an abstraction from everyday experience

Calculation = manipulation of pebbles
Digit = a finger or a toe

Today's digital information revolution is based on these abstractions, crystallized in the mid- 1900's by Turing, Shannon, von Neumann…

But these notions are now known to be too narrow.

Quantum theory, developed by physicists in the early 1900's, and spectacularly successful in its own field, also provides a more complete and natural arena for developing concepts of communication and computation.

Conventionally, information carriers have been viewed as what a physicist would call ***classical*** systems:

• Their states in principle are reliably distinguishable, and can be observed without disturbing the system

• To specify the joint state of two or more systems, it is sufficient to specify the state of each one separately.

But for quantum systems like atoms or photons:

• Attempting to observe a particle's state in general disturbs it, while obtaining only partial information about the state (uncertainty principle).

• Two particles can exist in an *entangled* state, causing them to behave in ways that cannot be explained by supposing that each particle has some state of its own.

For most of the 20th century, quantum effects in information processing were regarded mainly as a nuisance, because the uncertainty principle makes quantum devices behave less reliably than the classical ideal.

Now it is known that quantum effects also have positive consequences, making possible new kinds of information processing such as quantum cryptography, and dramatically speeding up some classically hard computations.

These positive effects are chiefly due to entanglement. Moreover, entanglement helps explain why quantum effects are so inconspicuous, and remained undiscovered until the 20th century.

Despite the differences there are important similarities between classical and quantum information

All (classical) information is reducible to bits **0** and **1**.

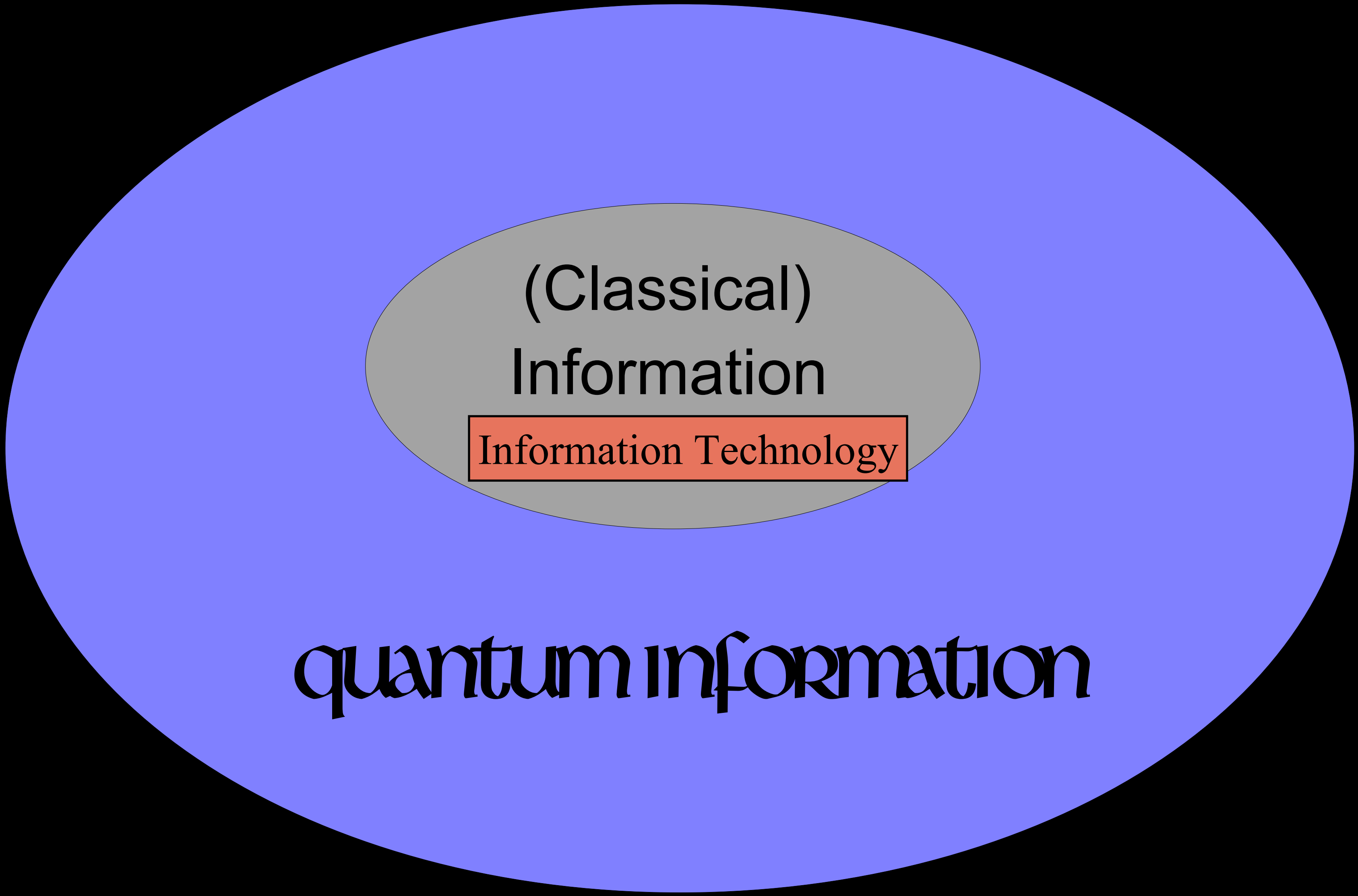
All processing of it can be done by simple logic gates (**AND, NOT**) acting on bits one and two bits.

Bits and gates are fungible (independent of physical embodiment), making possible Moore's law.

Quantum information is reducible to **qubits** i.e. two-state quantum systems such as a photon's polarization or a spin-1/2 atom.

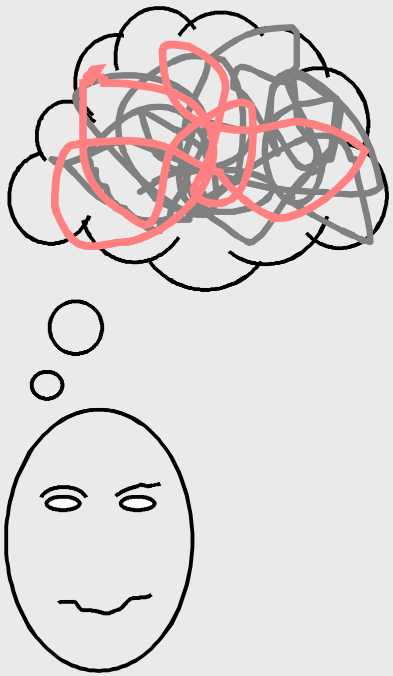
Quantum information processing is reducible to one- and two-qubit gate operations.

Qubits and quantum gates are fungible among different quantum systems


(Classical)
Information
Information Technology
quantum information

Ordinary classical information, such as one finds in a book, can be copied at will and is not disturbed by reading it.

Quantum information is more like the information in a dream



- Trying to describe your dream changes your memory of it, so eventually you forget the dream and remember only what you've said about it.

- You cannot prove to someone else what you dreamed.

- You can lie about your dream and not get caught.

But unlike dreams, quantum information obeys well-known laws.

1. A linear vector space with complex coefficients and inner product

$$< \phi \mid \psi > \;=\; \Sigma\, \phi_i^* \psi_i$$

2. For polarized photons two, e.g. vertical and horizonal

$$\leftrightarrow = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad \updownarrow = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

3. E.g. for photons, other polarizations

$$\swarrow\!\!\!\nearrow = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad \nwarrow\!\!\!\searrow = \begin{pmatrix} +1 \\ -1 \end{pmatrix}$$

$$\circlearrowright = \begin{pmatrix} i \\ 1 \end{pmatrix} \quad \circlearrowleft = \begin{pmatrix} i \\ -1 \end{pmatrix}$$

4. Unitary = Linear and inner-product preserving.

quantum laws

I. To each physical system there corresponds a Hilbert space [1] of dimensionality equal to the system's maximum number of reliably distinguishable states. [2]

2. Each direction (ray) in the Hilbert space corresponds to a possible state of the system. [3]

3. Spontaneous evolution of an unobserved system is a unitary transformation on its Hilbert space. [4]

-- more --

4. The Hilbert space of a composite sysem is the tensor product of the Hilbert spaces of its parts. 1

5. Each possible measurement 2 on a system corresponds to a resolution of its Hilbert space into orthogonal subspaces $\{\mathbf{P}_j\}$, where $\sum \mathbf{P}_j = 1$. On state ψ the result j occurs with probability $|\mathbf{P}_j\,\psi|^2$ and the state after measurement is

$$\frac{\mathbf{P}_j\,|\psi>}{|\mathbf{P}_j\,|\psi>|}$$

1. Thus a two-photon system can exist in "product states" such as $\leftrightarrow\leftrightarrow$ and $\leftrightarrow\nearrow$ but also in "entangled" states such as

$$\frac{\leftrightarrow\leftrightarrow - \updownarrow\updownarrow}{\sqrt{2}}$$

in which neither photon has a definite state even though the pair together does

2 Believers in the "many worlds interpretation" reject this axiom as ugly and unnecessary. For them measurement is just a unitary evolution producing an entangled state of the system and measuring apparatus. For others, measurement causes the system to behave probabilistically and forget its pre-measurement state, unless that state happens to lie entirely within one of the subspaces $\mathbf{P}_j$.

The central principle of quantum mechanics is the

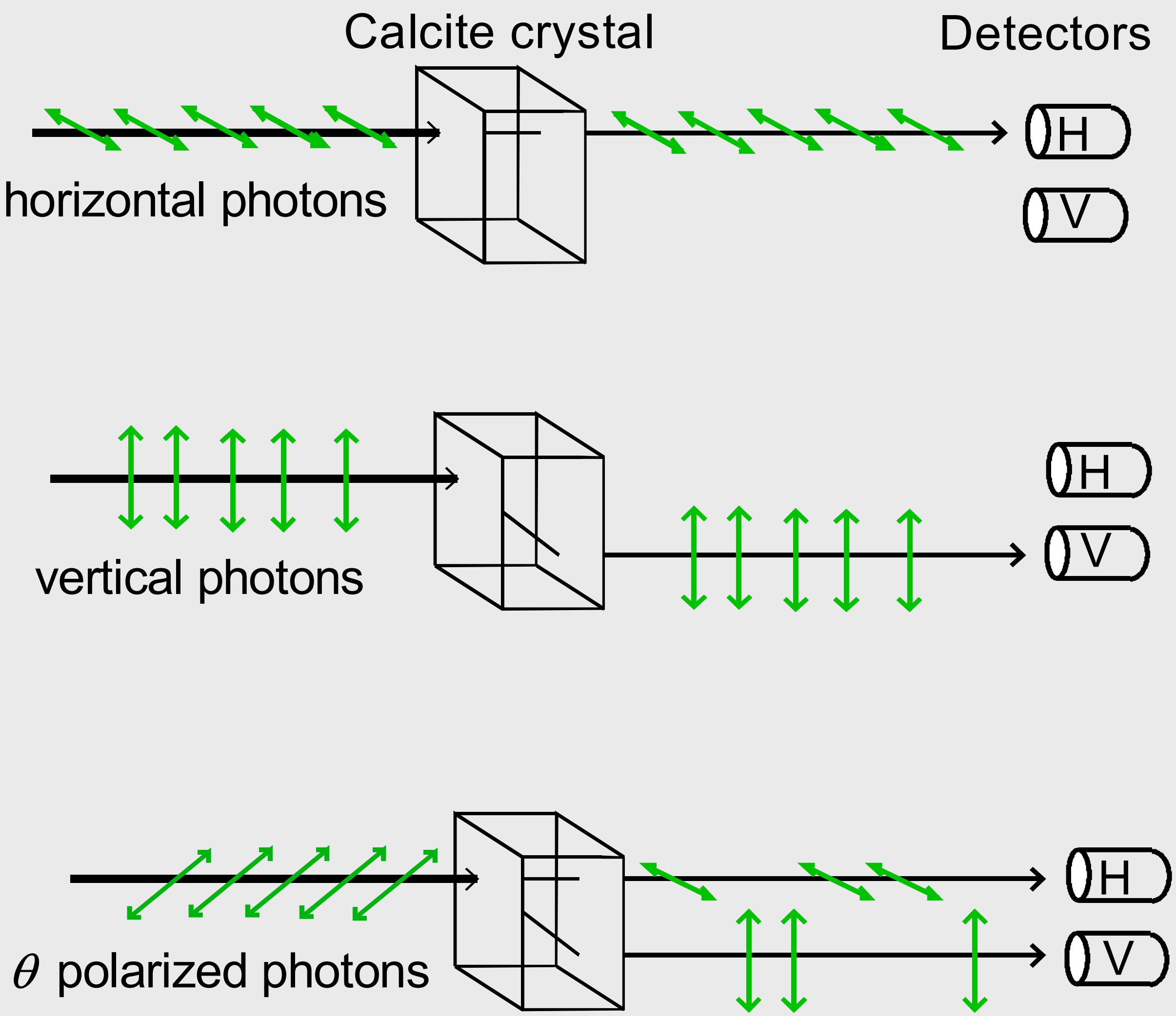
Superposition Principle:

• Between any two reliably distinguishable states of a physical system (for example vertically and horizontally polarized single photons) there are intermediate states (for example diagonal photons) that are not reliably distinguishable from either original state

• The possible physical states of a system correspond to directions in a space. The dimensionality of this space is equal to the system's maximum number of reliably distinguishable states.

• Any direction is a possible state, but two states are reliably distinguishable if only if their directions are perpendicular.

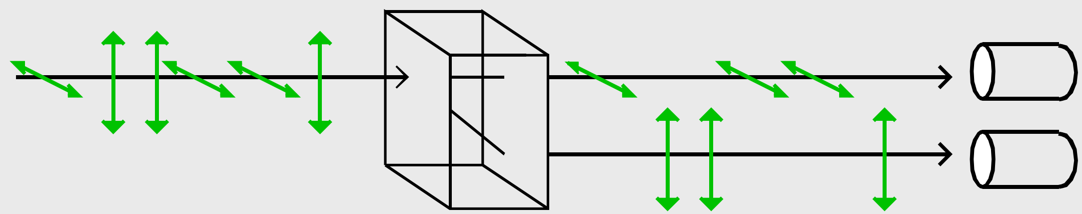
Using Polarized Photons to Carry Information



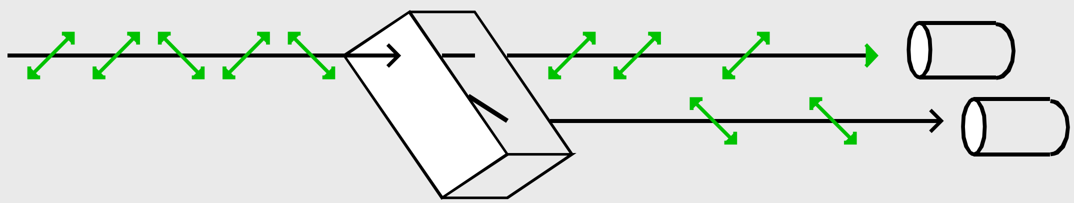
Photons behave reliably if measured along an axis parallel or perpendicular to their original polarization.
Used in this way, each photon can carry one reliable bit of information.

But measuring the photons along any other axis causes them to **behave randomly**, forgetting their original polarization direction.

A rectilinear (ie vertical vs horizontal) measurement distinguishes vertical and horizontal photons reliably, but randomizes diagonal photons.



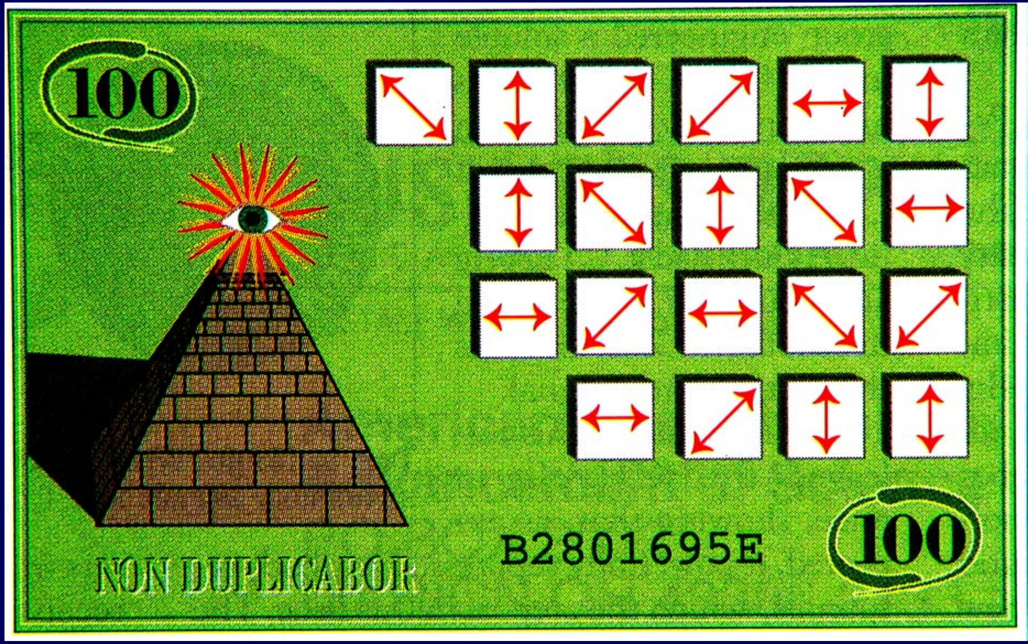
A diagonal measurement distinguishes diagonal photons reliably but randomizes rectilinear photons.

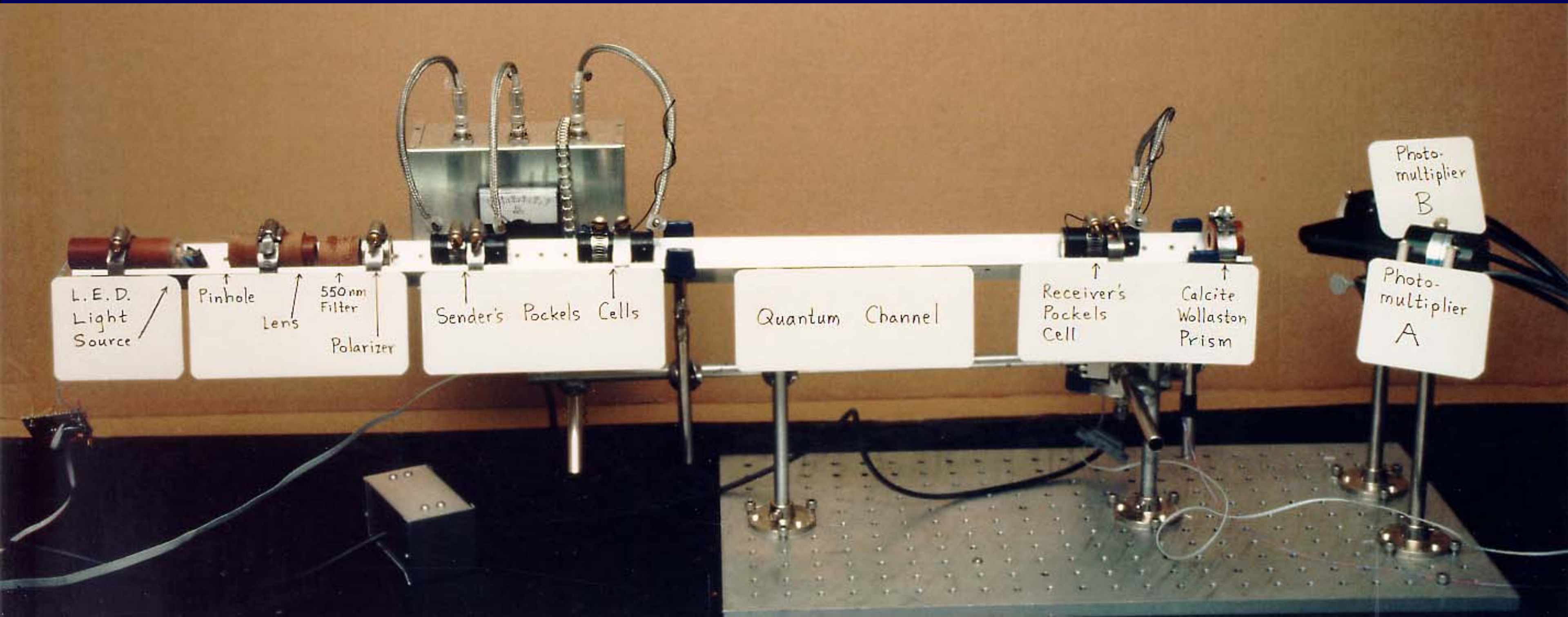


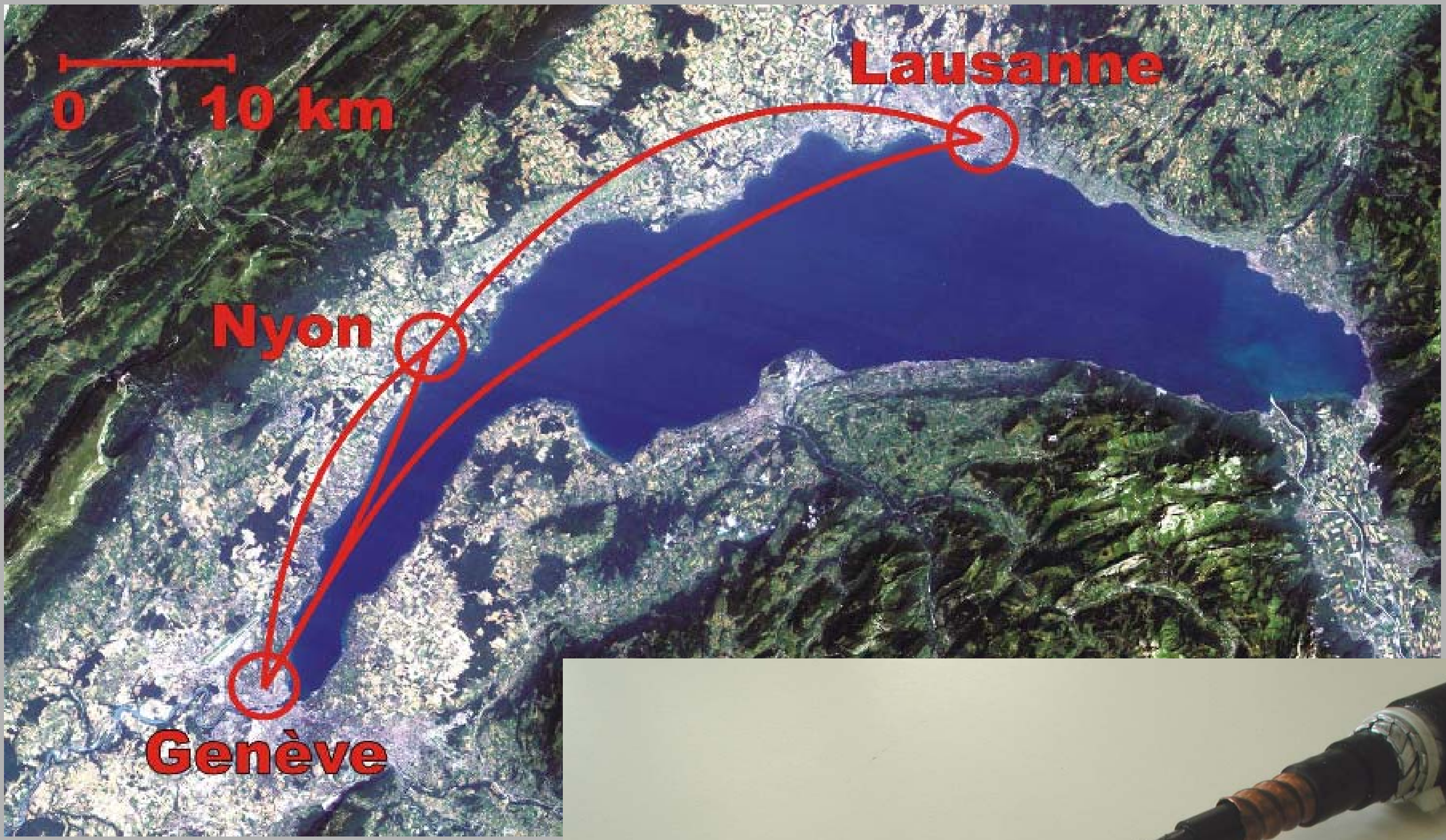
No measurement can distinguish all four kinds. This is not a limitation of particular measuring apparatuses, but a fundamental consequence of the uncertainty principle. This fundamental limitation gives rise to the possibility of quantum money and quantum cryptography.

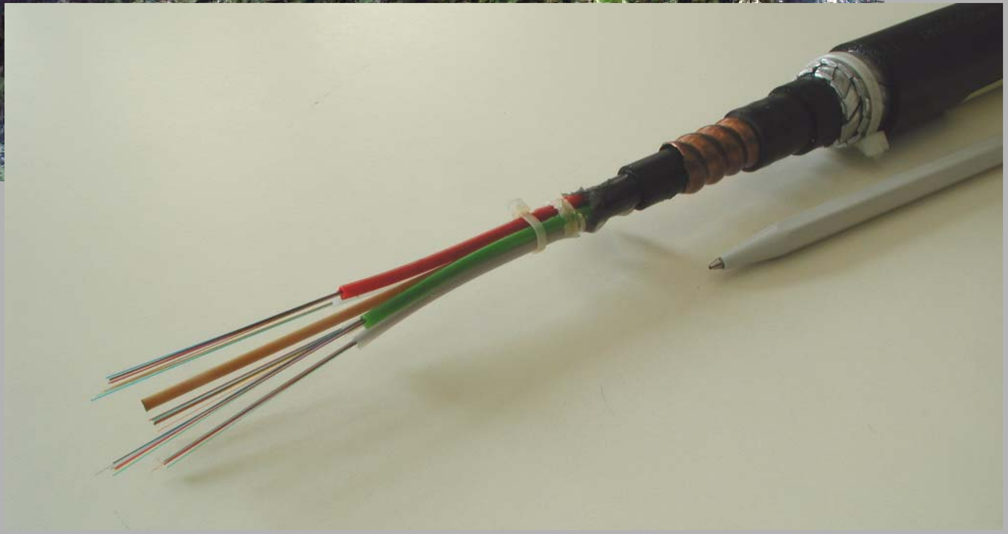
Quantum money (Wiesner '70, '83) cannot be copied by a counterfeiter, but can be checked by the bank, which knows the secret sequence of polarized photons it should contain.

Quantum cryptography uses polarized photons to generate shared secret information between parties who share no secret initially (BB84, E91…)





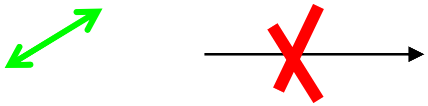




Modern Quantum Crypto Key Distribution at University of Geneva

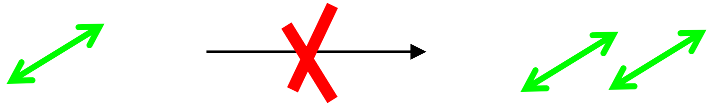
Also experiments at several other labs, in free space, and commercial systems.

Measuring an unknown photon's polarization exactly is impossible (no measurement can yield more than 1 bit about it).

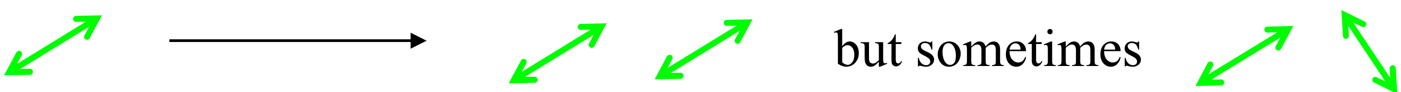


28.3^o

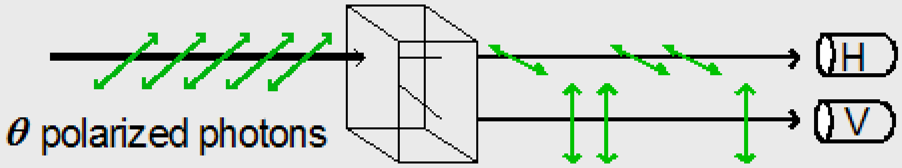
Cloning an unknown photon is impossible. (If either cloning or measuring were possible the other would be also).



If you **try** to clone an unknown photon by sending it into an ideal laser, the output will be polluted by just enough noise (due to spontaneous emission) to be no more useful than the input in figuring out what the original photon's polarization was.



Prof. William Wootters' pedagogic analogy for quantum measurement



Like a pupil confronting a strict teacher, a quantum system being measured is forced to choose among a set of distinguishable states (here 2) characteristic of the measuring apparatus.

Teacher: Is your polarization vertical or horizontal?

Pupil: Uh, I am polarized at about a 55 degree angle from horizontal.

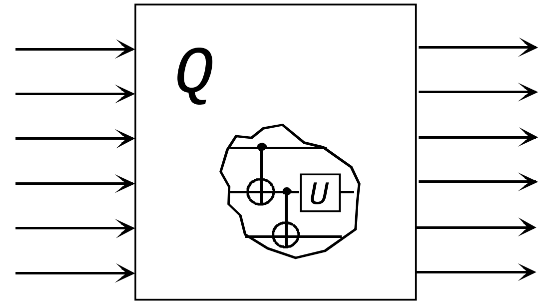
Teacher: **I believe I asked you a question.** Are you vertical or horizontal?

Pupil: Horizontal, sir.

Teacher: Have you ever had any other polarization?

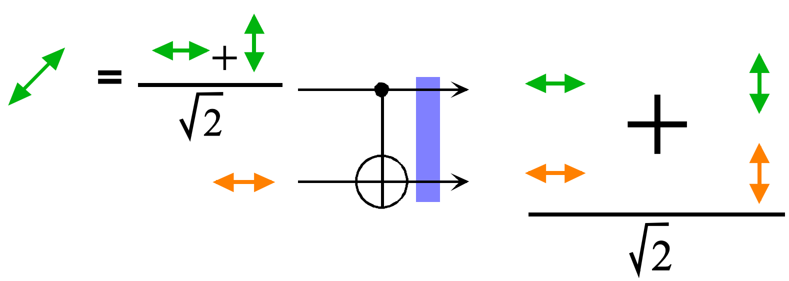
Pupil: No, sir. I was always horizontal.

Any quantum data processing can be done by 1- and 2-qubit gates acting on qubits.



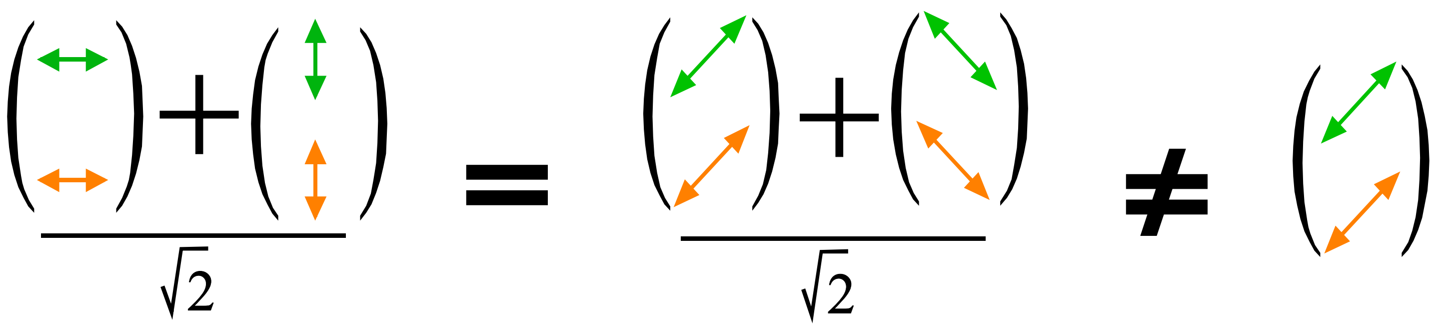
The 2-qubit XOR or "controlled-NOT" gate flips its 2nd input if its first input is 1, otherwise does nothing.

A superposition of inputs gives a superposition of outputs.



An entangled state

This entangled state of two photons behaves in ways that cannot be explained by supposing that each photon has a state of its own.



The two photons may be said to be in a definite state of *sameness* of polarization even though neither photon has a polarization of its own.

Entanglement allows two particles to be in a perfectly definite joint state, even though each by itself is completely random.

Like two hippies who are know they are, like, in perfect harmony, even though neither has an opinion on anything.

Hippies believed that with enough LSD, everyone could in perfect harmony with everyone else.

Now we have a quantitative theory of entanglement and know that it is *monogamous*: the more entangled two systems are with each other, the less entangled they can be with anything else.

Pedagogic analog of entanglement:

Twin pupils Remus and Romulus, who are each completely ignorant of all subjects, answering every question randomly, but they always give the same answer, even when questioned separately.

Teacher A: Remus, what color is growing grass?

Remus: Pink, sir.

Teacher B (in another classroom): Romulus, what color is growing grass?

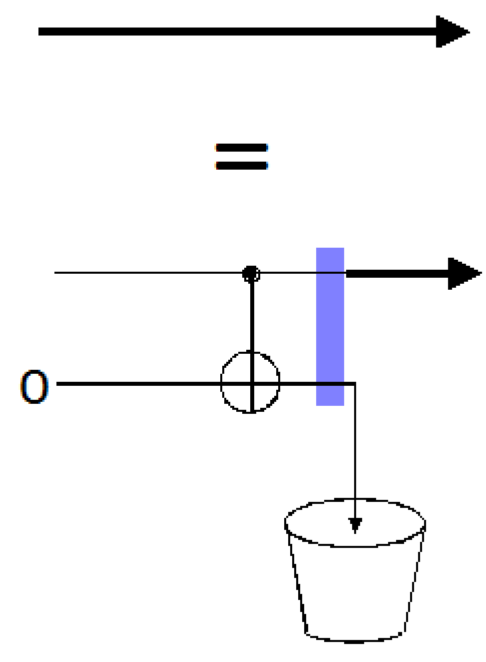
Romulus: Pink, ma’am.

Expressing Classical Data Processing in Quantum Terms

A Classical Bit is a qubit with one of the Boolean values 0 or 1

A classical wire is a quantum channel that conducts 0 and 1 faithfully but randomizes superpositions of 0 and 1.

This happens because the data passing through the wire interacts with its environment, causing the environment to acquire a copy of it, if it was 0 or 1, and otherwise become entangled with it.



A classical channel is a quantum channel with an eavesdropper.

A classical computer is a quantum computer handicapped by having eavesdroppers on all its wires.

Using entanglement

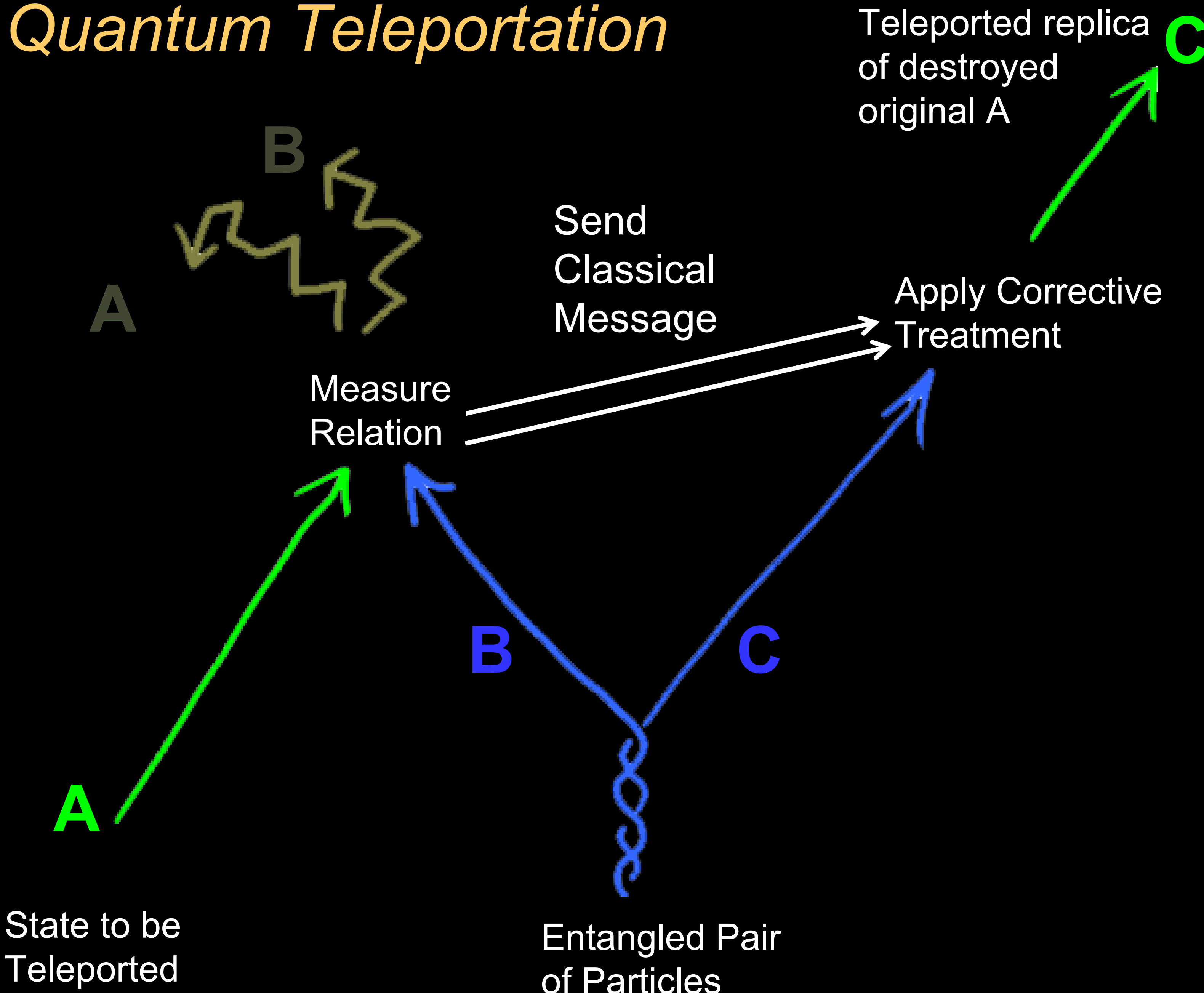
Measure

Send Partial Information

Prepare an approximate copy

It would seem that the uncertainty principle prevents complete information about a particle's state being extracted from the particle and transferred to another particle, which has never been anywhere near the first particle. But quantum teleportation permits us to make an end run around that logic.

Quantum Teleportation



Human analog of quantum teleportation

Suppose Alice has witnessed a complicated crime with possible terrorist implications where she lives, in Boston. The FBI in Washington know that her memory of the crime is in a fragile form and don't want to ask her questions that might spoil it. They especially don't want to leave the investigation to the Boston police, who will ask her stupid questions and confuse her, so they invite her to Washington to be interviewed by a panel of experts, who will ask her just the right questions in just the right order.

Unfortunately Alice dislikes travel and refuses to go. Fearing she will become uncooperative if they subpoena her, the FBI agrees to send one of their agents to Boston.

But there is still a problem. The FBI experts all have strong opinions about the case, and don't trust each other to conduct the interview alone.

Finally Remus volunteers, “I know nothing about this case, so I am less likely to influence her than any of you. Besides, I like to travel. Just ask my brother.” Romulus concurs.

So Remus goes to Boston to meet Alice. The meeting is a sort of speed date, with the parties instructed not to talk about anything substantive, just to concentrate on their relationship. The date goes badly, with Alice emerging a few minutes later saying, “I can’t stand him, and for some reason, this has all been so stressful that now I don’t remember anything about the crime.” The Boston police thank Alice and tell her she can go home.

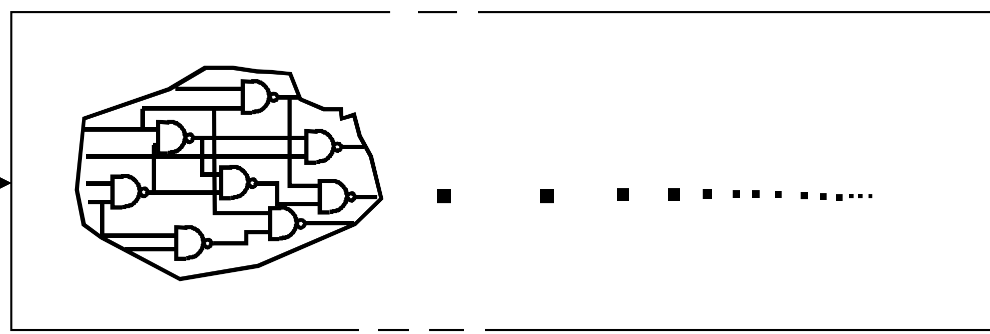
Then they phone Washington and tell the FBI that Alice and Remus don’t get along. The FBI experts go to Romulus and say, "Well, it seems that Alice and your brother don’t get on. So any question we would have asked Alice, we can ask you. We know that whenever you say yes, she would have said no." They proceed with their careful questioning, reversing every one of Romulus' answers to get what Alice would have answered."

But the biggest reason there is so much interest in quantum information processing is **quantum computing**: the fact that a quantum computer, if we could build one, would greatly speed up some hard computations, including some that would take longer than the age of the universe on an ordinary classical computer.

Factoring large integers is an example. This 129-digit number, nicknamed RSA 129, took 8 months to factor on hundreds of computers.

RSA 129

1143816257578888676
6923577997614661201
0218296721242362562
5618429357069352457
3389783059712356395
8705058989075147599
290026879543541



Factors

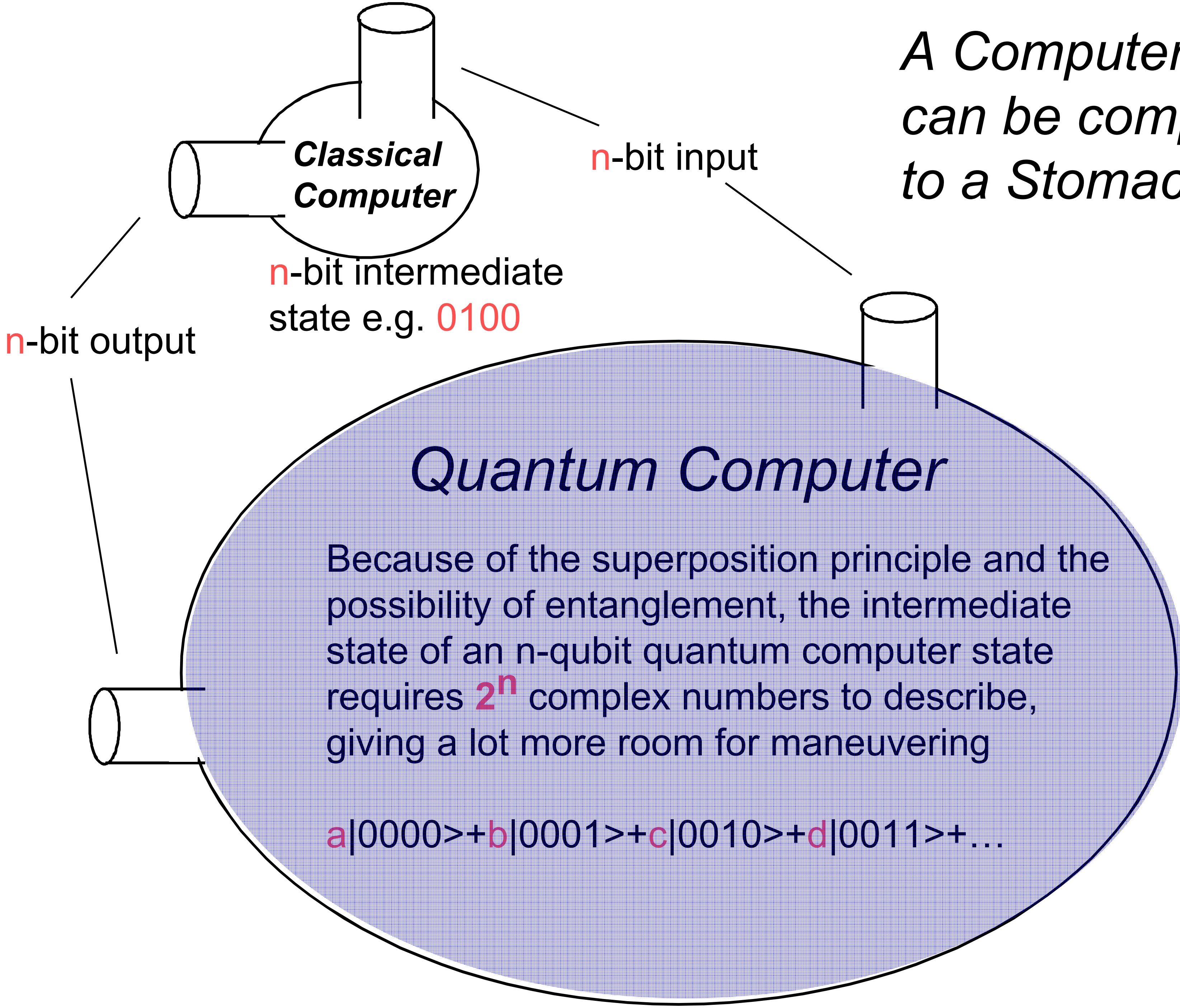
3490529510847650949
1478496199038981334
1776463849338784399
0820577

x

3276913299326670954
9961988190834461413
1776429679929425397
98288533

For classical computers, by the best known algorithms, factoring is exponentially harder than its reverse, multiplying two numbers together. For quantum computers, both jobs would be easy.

A Computer can be compared to a Stomach



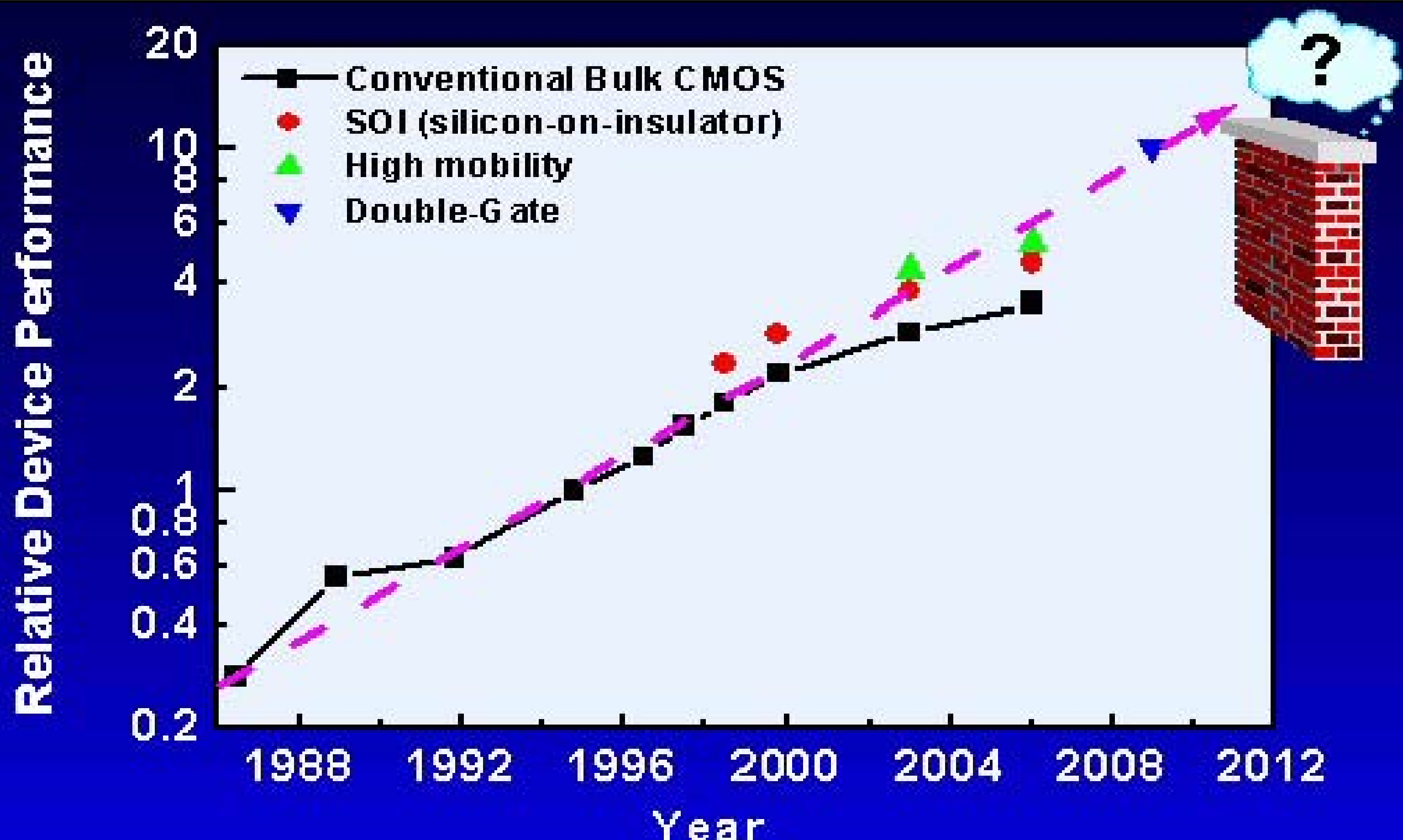
How Much Information is "contained in" ***n*** qubits, compared to ***n*** classical bits, or ***n*** analog variables?

	Digital		Analog		Quantum
Information required to specify a state	***n*** bits	<<	***n*** real numbers	<<	2^{n} complex numbers
Information extractable from state	***n*** bits	<<	***n*** real numbers	>>	***n*** bits
Good error correction	yes		no		yes

But because analog data lacks good error correction, it behaves more like classical digital data than like quantum

	Digital		Analog		Quantum
Information required to specify a state	$\boldsymbol{n}$ bits	$\approx$	$O(\boldsymbol{n})$ bits	$<<$	$2^{\boldsymbol{n}}$ complex numbers
Information extractable from state	$\boldsymbol{n}$ bits	$\approx$	$O(\boldsymbol{n})$ bits	$\approx$	$\boldsymbol{n}$ bits
Good error correction	yes		no		yes

Computer performance has been increasing exponentially for several decades (Moore's law). But this can't go on for ever. Can quantum computers give Moore's law a new lease on life? If so, how soon will we have them?



Physical systems actively considered for quantum computer implementation

- Liquid-state NMR
- NMR spin lattices
- Linear ion-trap spectroscopy
- Neutral-atom optical lattices
- Cavity QED + atoms
- Linear optics with single photons
- Nitrogen vacancies in diamond
- Topological defects in fractional quantum Hall effect systems
- Electrons on liquid helium
- Small Josephson junctions
  - "charge" qubits
  - "flux" qubits
- Spin spectroscopies, impurities in semiconductors
- Coupled quantum dots
  - Qubits: spin, charge, excitons
  - Exchange coupled, cavity coupled

Executive Summary

• A Quantum computer can probably be built eventually, but not right away. Maybe in 20 years. We don't know yet what it will look like.

• It would exponentially speed up a few computations like factoring, thereby breaking currently used digital signatures and public key cryptography (Shor algorithm)

• It would speed up many important optimization problems like the traveling salesman quadratically, not exponentially. (Grover algorithm). But this is still quite an accomplishment.

• There would be no speedup for many other problems. For these computational tasks, Moore's law would still come to an end, even with quantum computers.

But quantum information is good for many other things besides quantum cryptography and speeding up classical math problems.

- A quantum computer could simulate quantum systems found in nature or proposed on paper by engineers, some of which are intractable to simulate on classical computers, with applications to chemistry, biology, and materials science.

- Communication and secure distributed computing, such as sending one's data to be processed on untrusted servers.

- Metrology, precision measurement and time standards.

Most importantly, quantum information is an exciting area of basic science, which has deepened our understanding of nature, helped unify physics and mathematics, and attracted undergraduates to careers in science.
It continues to yield surprises.


II. The Ambiguity of the Past

Reasoning from classical mechanics, Laplace thought the future and past were fully determined by the present, but attributed the perceived ambiguity of the future to our imperfect knowledge of the present, and/or our lack of sufficient computing power to calculate the future. An omniscient God would know past, present, and future.

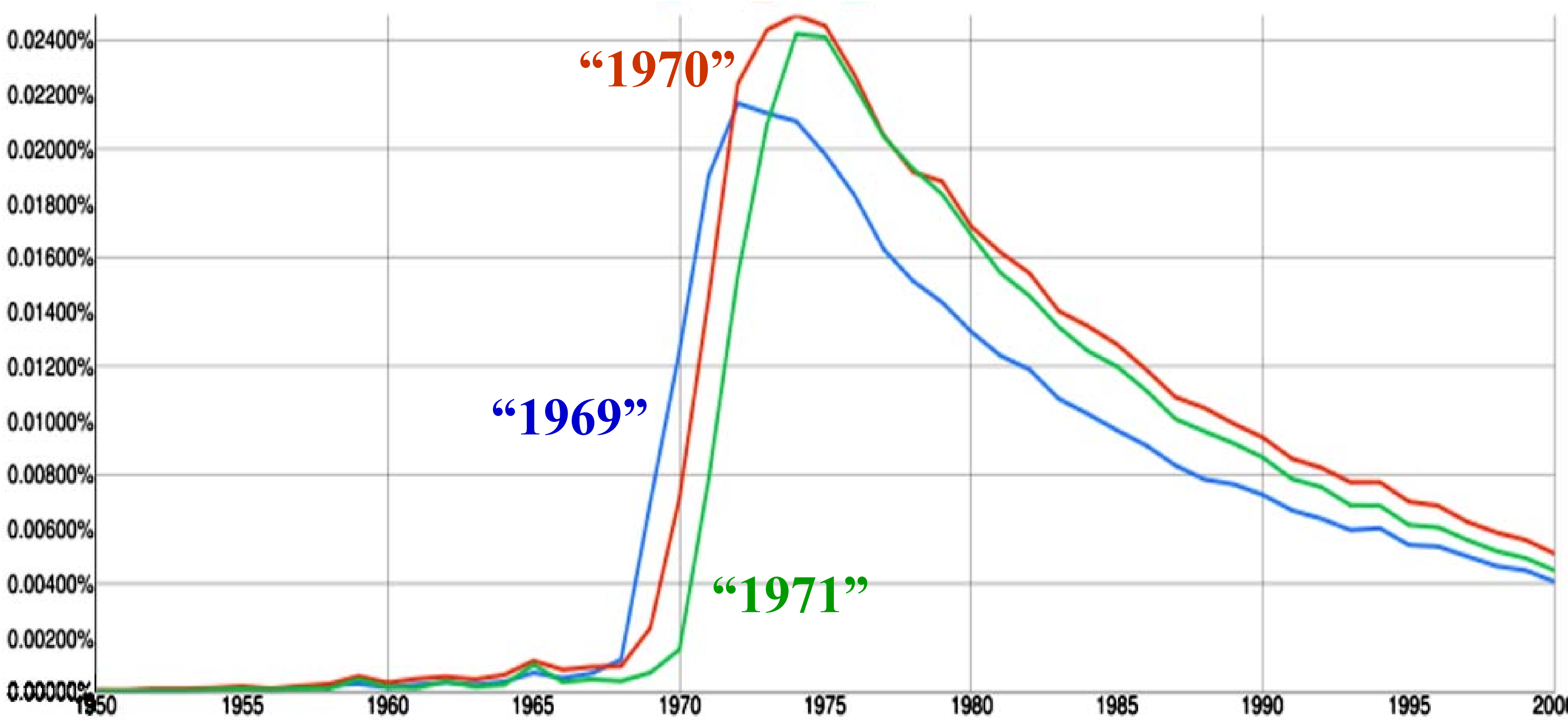
Quantumly, the future is less determined than Laplace imagined. Even an omniscient God would not be able to predict whether a particular radioactive atom will decay within its half life.

In our macroscopic world, we remember the past much better than we can predict the future. One can now scan all the books in Google Books to see how the frequency of various phrases have varied over time. The phrase "1970" is mentioned rarely before that year, often immediately after, then with declining frequency.

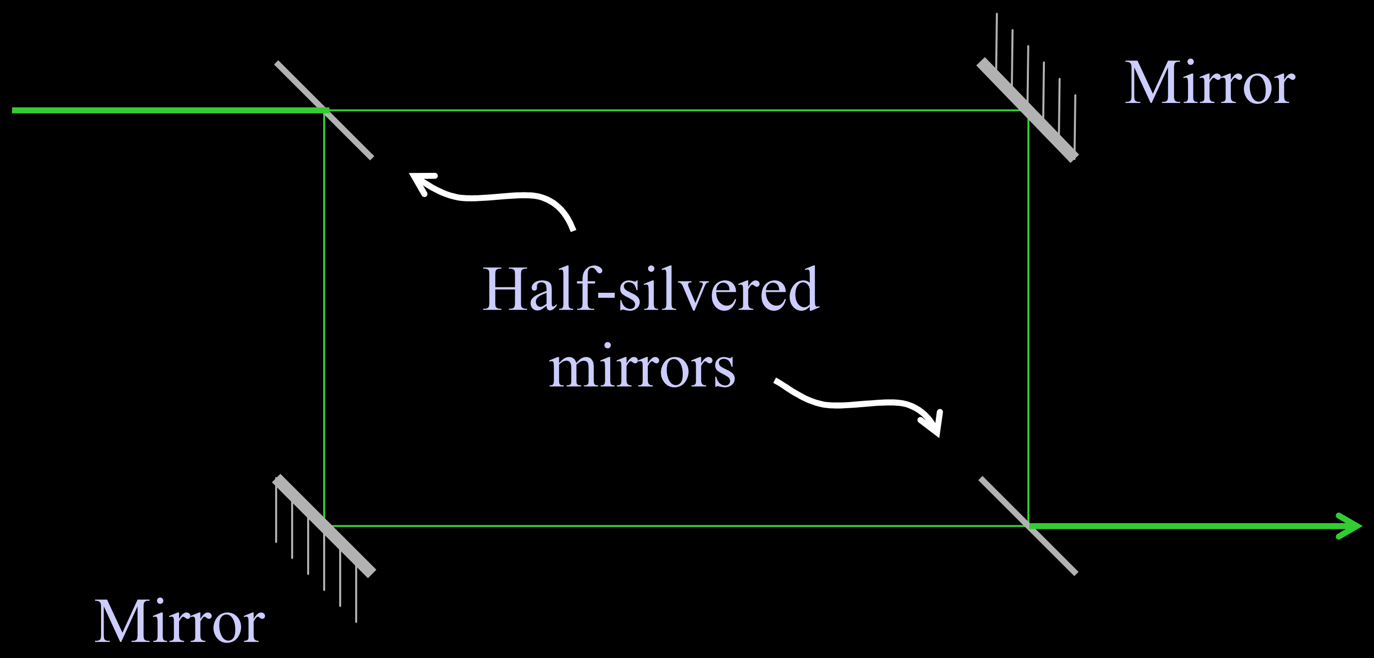
Google books Ngram Viewer

Year of publication:

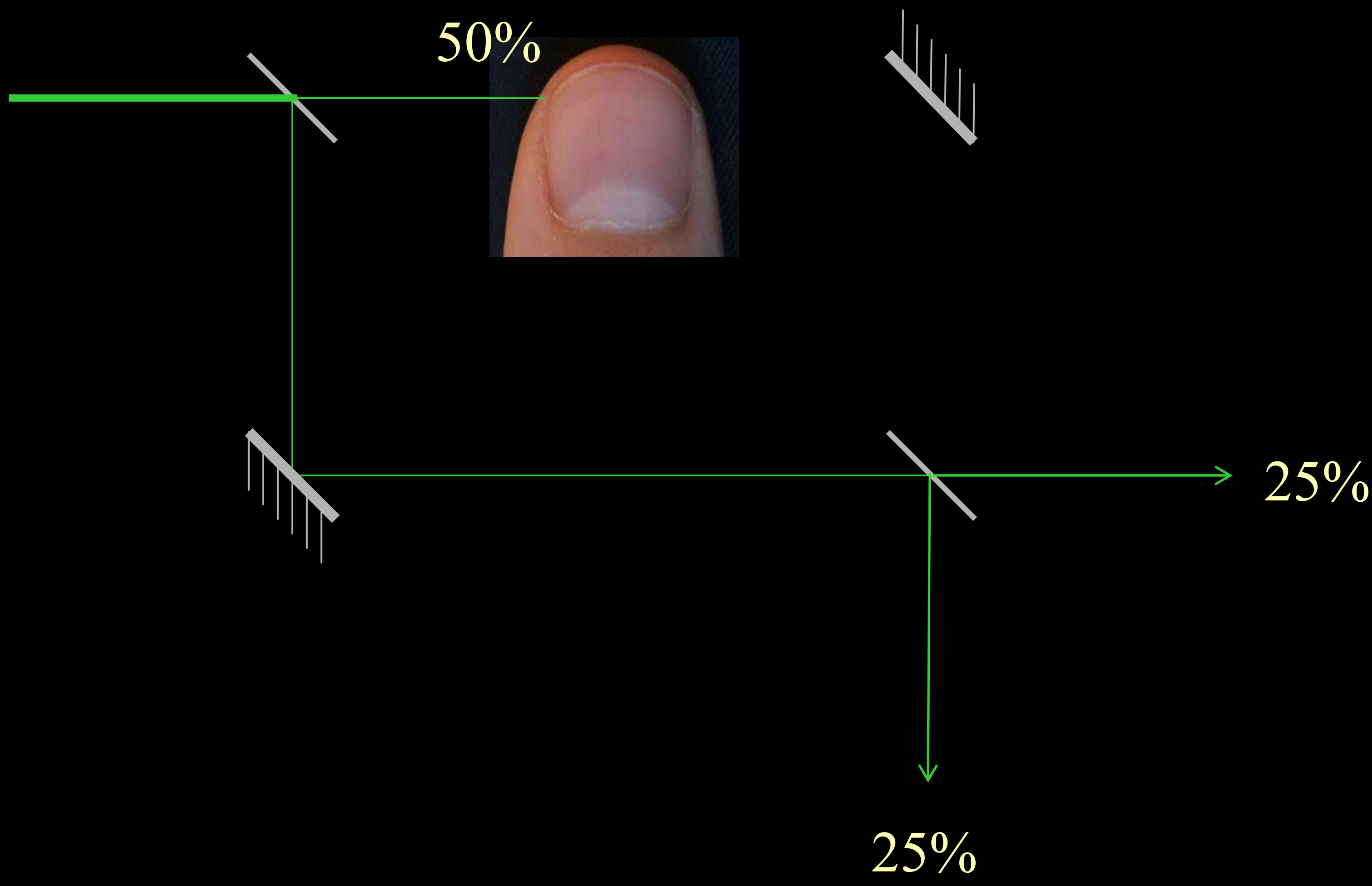
1960 1970 1980 1990



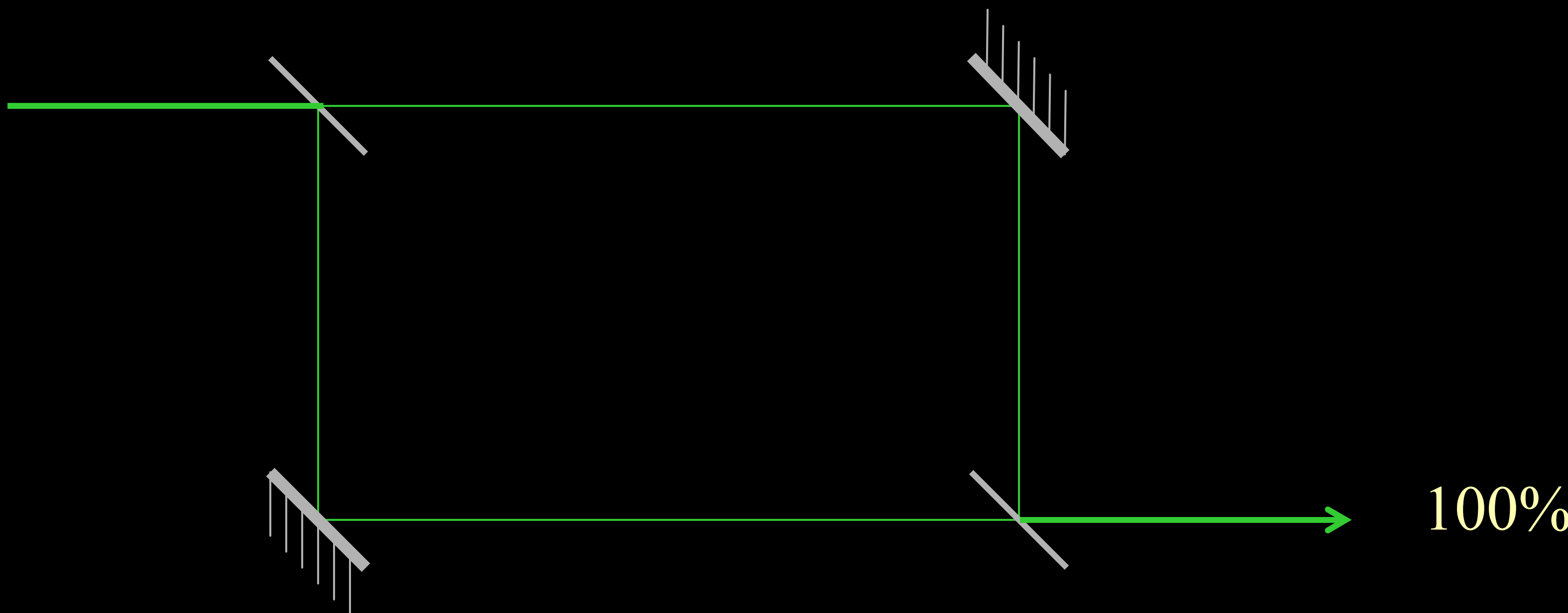
Unlike the future, past macroscopic events are generally regarded as definite and unambiguous. Of course some *microscopic* “events” in the past (e.g. which path an unobserved photon followed through an interferometer) are regarded as being ambiguous, not because of ignorance, but because they are ill-defined in principle.



If either path through the interferometer is blocked, the photon leaves both exits equally often.

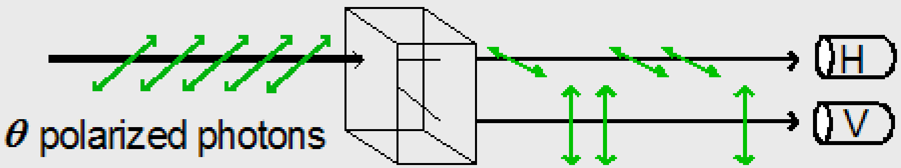


But with both paths left open, the photon always leaves by the same exit, indicating that while passing unobserved through the apparatus, it followed a **superposition** of both paths.



After the experiment is over, even God doesn't remember which path the photon followed.

Contrast this evanescence with the brutal irreversibility of measurement



Like a pupil confronting a strict teacher, a quantum system being measured is forced to choose among a set of distinguishable states characteristic of the measuring apparatus (analogy due to Bill Wootters).

Teacher: Is your polarization vertical or horizontal?

Pupil: Uh, I am polarized at about a 55 degree angle from horizontal.

Teacher: **I believe I asked you a question.**
Are you vertical or horizontal?

Pupil: **Horizontal, sir.**

Teacher: Have you ever had any other polarization?

Pupil: No, sir. I was always horizontal.

These views can be harmonized by the notion of entanglement, in particular its monogamy.

Most systems in nature, other than tiny ones like photons, interact so strongly with their environment that they soon become massively entangled with it.

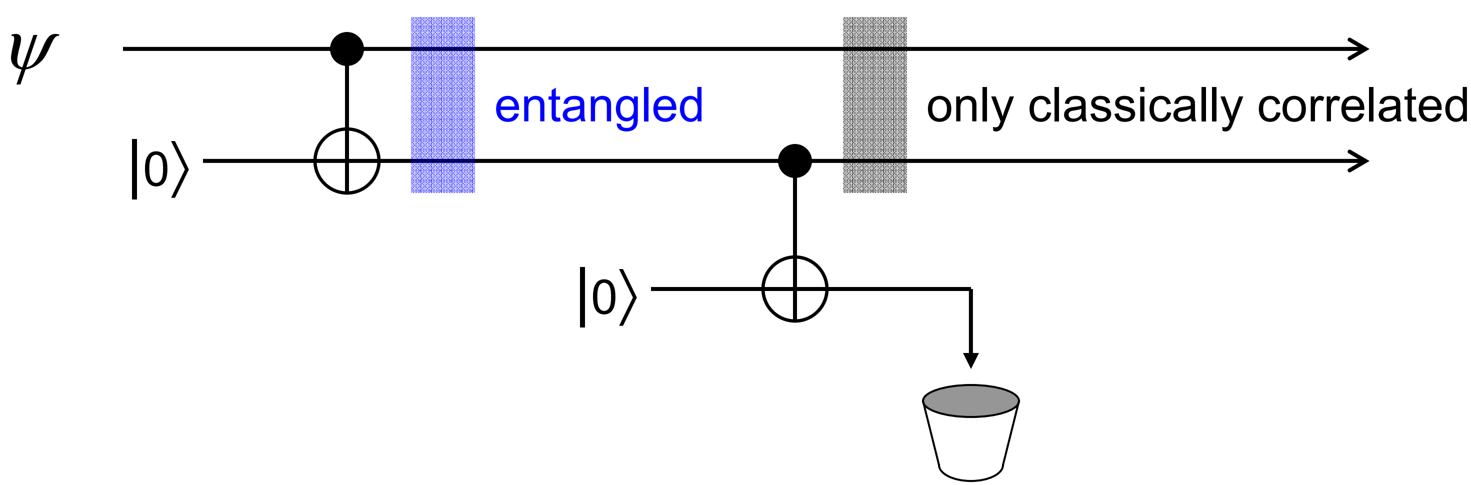
This destroys any previous entanglement that may have existed between internal parts of the system, degrading it into mere correlated randomness. Contrary to the hopes of the hippies, the parts of the system can no longer be entangled with each other.

Monogamy of Entanglement

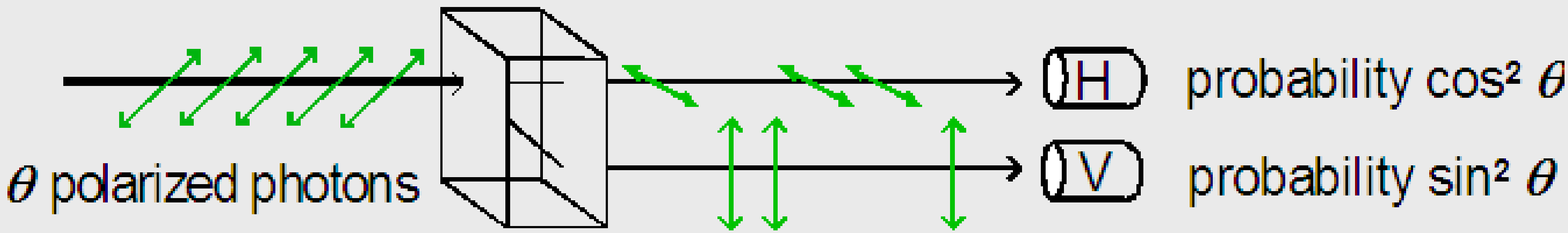
• If A and B are perfectly entangled with each other, they cannot be even classically correlated with anyone else.

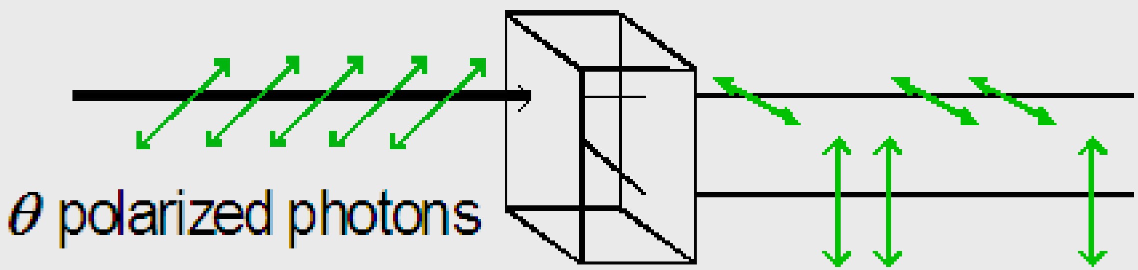
• If B tries to share his entanglement with a third party, or lets it get eavesdropped on by the environment, his entanglement with A becomes degraded into mere classical correlation.

"Two is a couple. Three is a crowd".

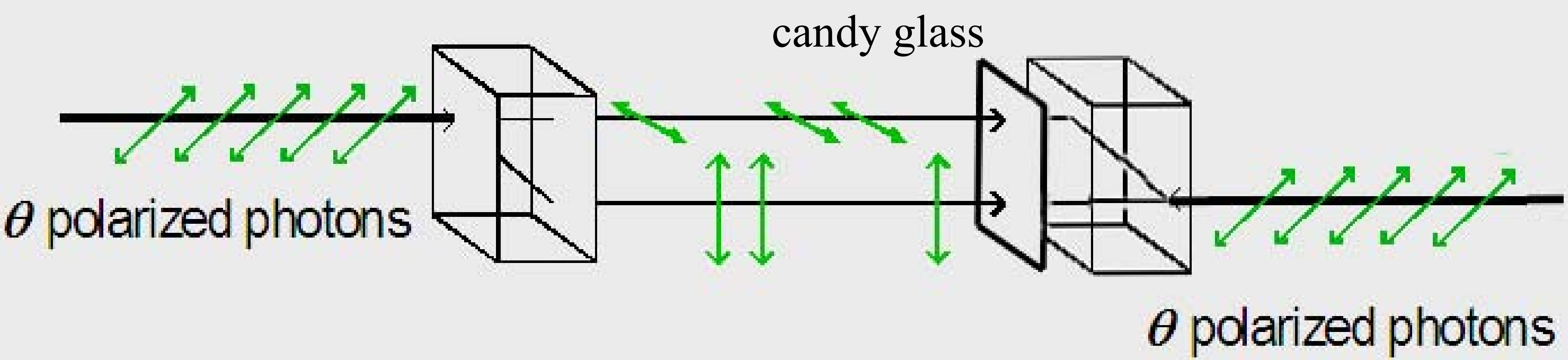


Entanglement and the origin of Quantum Randomness



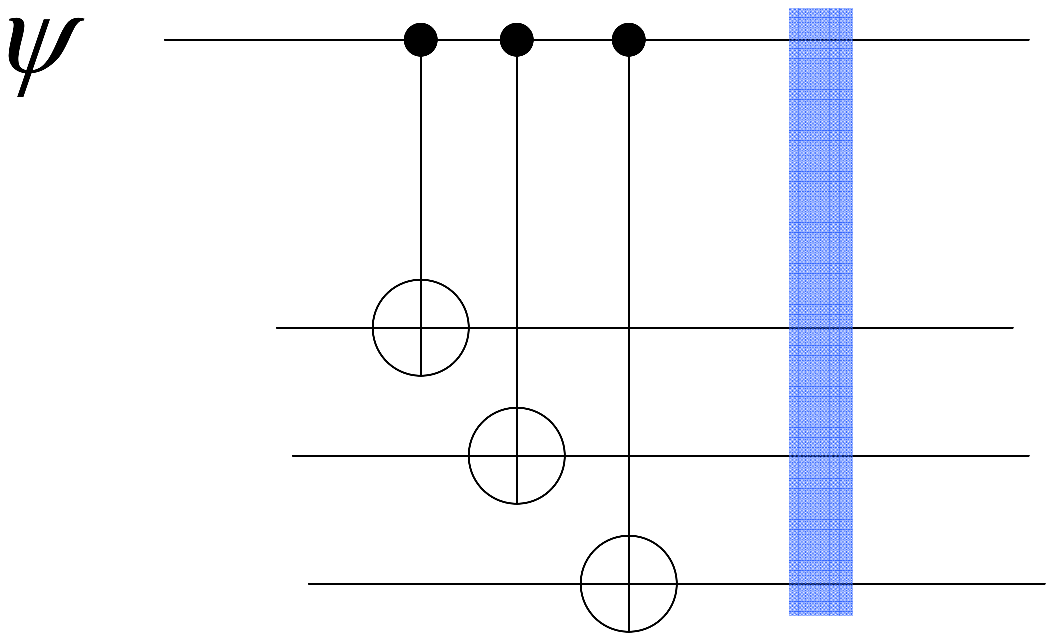


If no one observes the photons, their random "behavior" can be undone.



Metaphorically speaking, it is the **public embarrassment** of the pupil, in front of the whole class, that makes him forget his original polarization.

What does it mean for information to be "classical" anyway?



System

Environment:

Along one measurement axis, the system is correlated with each sub-environment.
Along other axes it is correlated only with the whole environment

Information becomes classical by being replicated redundantly throughout the environment.

"Quantum Darwinism" Blume-Kohout, Zurek quant-ph/0505031; Riedel, Zurek1001.3419v3. *A better name would be **Quantum Spam.***

Information becomes *more classical* by becoming *less private.*

Speaking of Privacy, it seems to be in short supply nowadays.

Cheap, easy-to-use video cameras and cheap data storage lead to the temptation to record everything happening in public or even private places and save it forever, with ensuing loss of privacy, and potential loss of liberty, if despotic rulers get control of the data.

But these recordings are sometimes good, deterring governmental as well as individual misconduct. In many situations the bad guys want privacy for their misdeeds, while the good guys want publicity, with authenticity.

To the amazement of most of the rest of the world, some Americans think it is good for society for everyone to carry a gun.

A better idea would be for everyone to carry a camera.

Public policy would then encourage amateurs to make audiovisual recordings, but restrict how the recordings could legally be used. (Yes for exposing crime and injustice; No for blackmail).

CNN billboard in Delhi:

If you see it, shoot it—
Every citizen a photojournalist.

Returning to Science, it seems there are 3 levels of privacy.

- **Quantum:** Information like the path of an unobserved photon, that exists only temporarily, and afterward can best be thought of as never having existed.

- **Classically Private:** Information that has been amplified to the point of becoming classical, but is not widely distributed in easily recoverable form. Humans can erase it, then lie about it with impunity, although perhaps not without guilt.

- **Public:** Information that is so widely distributed that it is infeasible to conceal. Lying about it only makes you look foolish.

Nowadays, it is tempting to believe that once information has become public, and entered the blogosphere, it can never be wholly destroyed.

The modern world appears very different in this regard from the ancient pre-Gutenberg era, when major literary works were written down, performed, and widely known, but then lost.

Ancient Greek poet Sappho, ca 620-525 BC, as depicted by Gustav Klimt ca 1900.

In China, the Classic of Music, or Sixth Classic, is thought to have been lost in the book-burning instigated by Emperor Qin Shi Huang in the 3rd century BC, though some general knowledge about it survives. Fortunately, Confucian scholars had memorized, and later managed to reconstruct, many of the other destroyed works.

Sappho's poems were lost more gradually, through neglect : once widely reproduced and taught, they fell out of favor when her Aeolian dialect of Greek died out. They were no longer taught, and the existing manuscripts were discarded or repurposed.

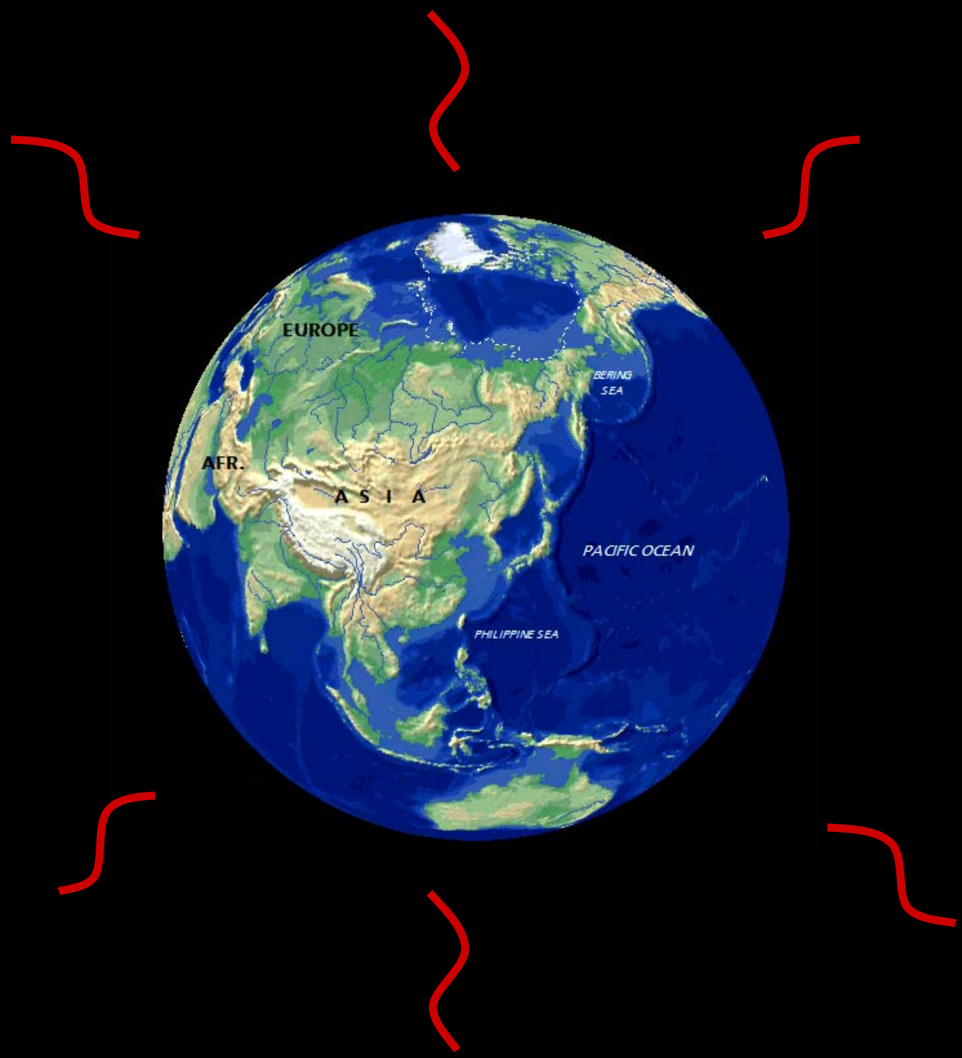
More recently, after surviving over 1000 years in India, the Carvaka school of philosophy is thought to have died out around the 15th century, along with all its original texts, except for fragments quoted in the writings of its Hindu and Buddhist opponents, who disliked it because of its denial of the afterlife, reincarnation, and gods.

But I think some information really is lost, not from the universe but from the world (i.e. the planet Earth). Why? Because most information we might care about is washed away by much larger entropy flows into and out of the Earth.

The Earth has finite information storage capacity, but it exports a lot of randomness (generates a lot of entanglement with its environment, in the quantum way of speaking) in the form of thermal radiation into the sky.

Thermal entropy export rate $\approx$ 300 watts/sq meter at 300K
$\approx 10^{30}$ bits per square meter per year.

Geological information capture rate in "hard" degrees of freedom, stable for geological times against thermal motion (e.g. atomic substitutional disorder and crystal lattice defects in solid rock of earth's crust) = crust thickness ($\approx$10 km) $\times$
rock information density ($\approx$1 bit/cubic nm) / rock lifetime ($\approx 10^8$ yr)
$\approx$ **10^{22}** bits / per square meter per year.



To catch up with the thermal radiation leaving Earth, one would need to travel faster than light.   So the information is still in the universe, but not recoverable by us.

So we are motivated to add a new level of privacy.

- **Quantum:** Information like the path taken in an interferometer, that exists only temporarily, and afterward can best be thought of as never having existed.

- **Classical but Escaped:** Information that has been amplified to the point of becoming classical, but has escaped from Earth in thermal radiation. Humans have no way of recovering it.

- **Classically Private:** Information that has been amplified to the point of becoming classical, and still resides on earth in a few places, though it may be infeasible to recover with current technology.

- **Public and Permanent** Information that is so widely distributed that it is infeasible to erase all the copies.

Mysteries of the Past:

Still recorded on earth, though unknown to any human and inaccessible with current technology:

- Locations of gold rings, dropped in an annual ceremony into the Venice Lagoon over a period of several centuries, to symbolize Venice's marriage to the Sea.

Maybe still recorded on earth, maybe escaped:

- Lost classic writings of many cultures
- Fates of mysteriously disappeared persons, such as
  - Physicist Ettore Majorana disappeared 1938
  - Labor leader Jimmy Hoffa disappeared 1975
  - Computer Scientist Jim Gray disappeared 2007

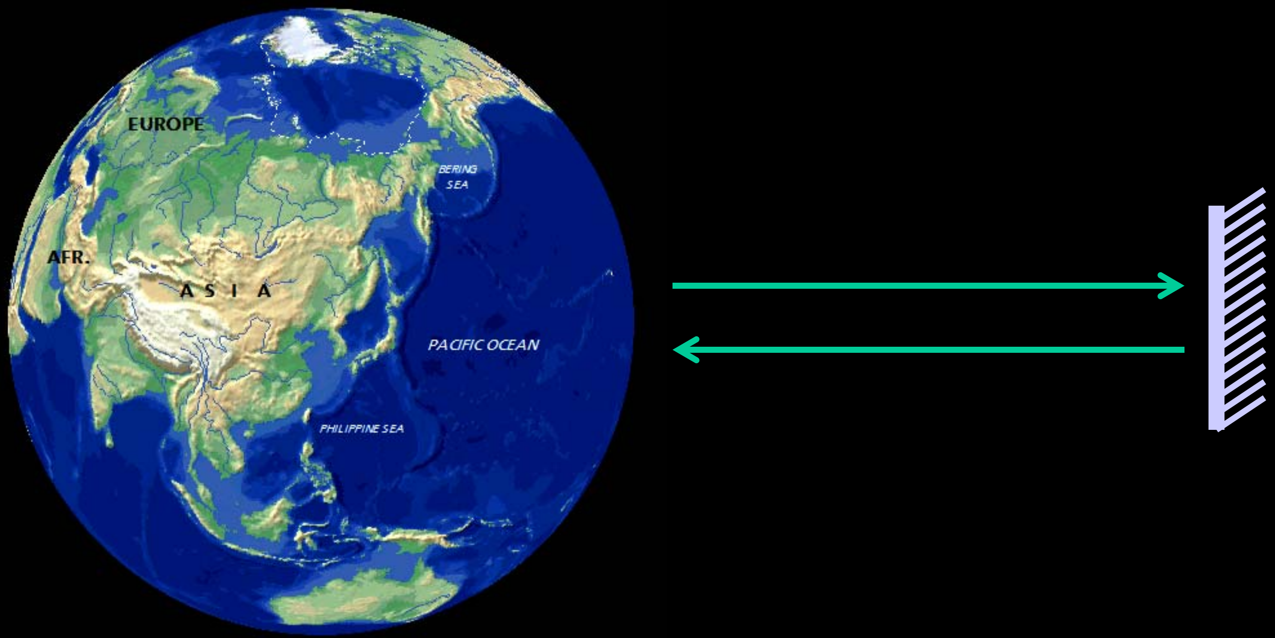
Escaped:

- Unrecorded raindrops from past rain storms.
- Pattern of rice grains in today's lunch.

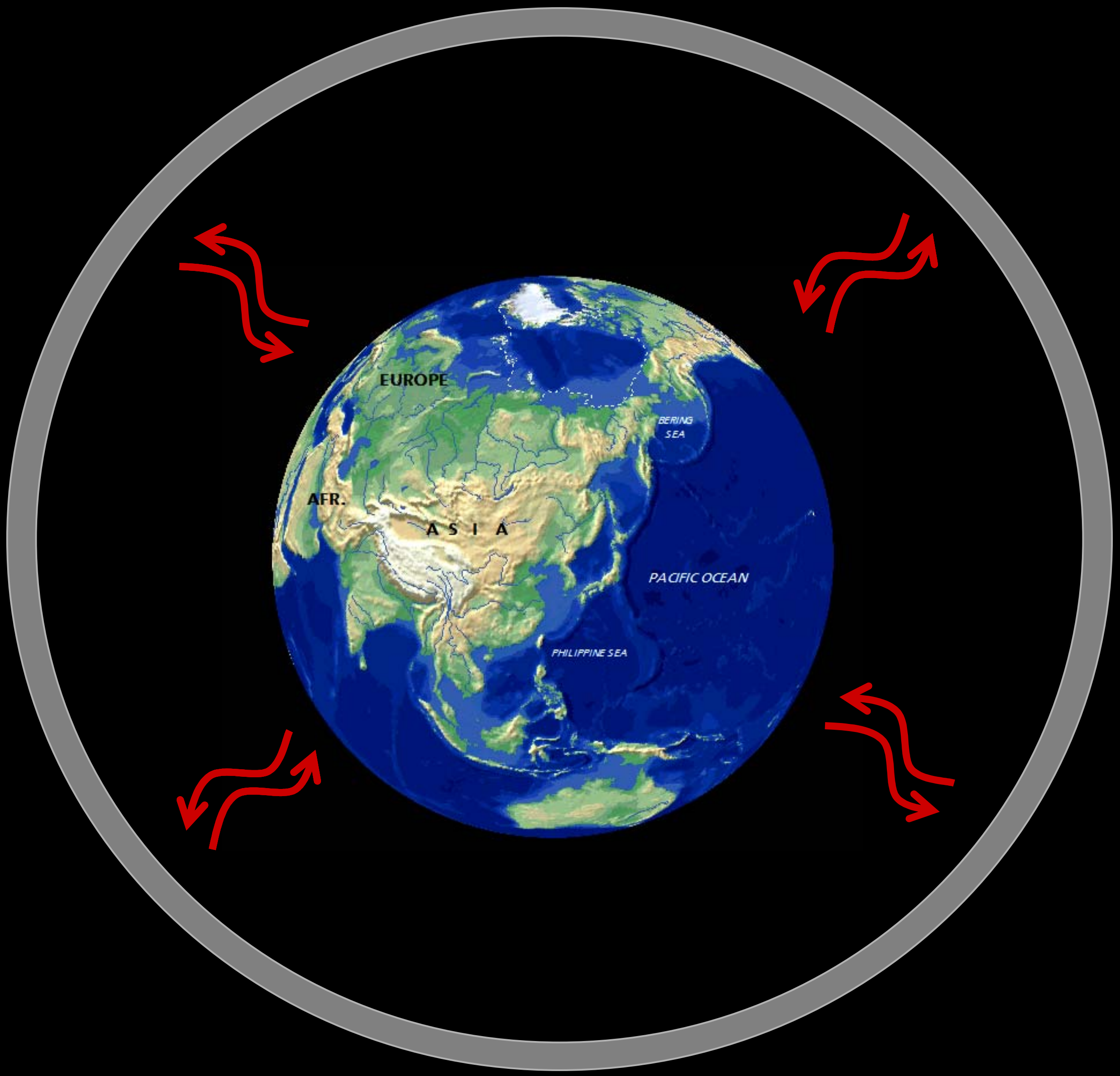
How to obliterate earthly evidence of Jimmy Hoffa's demise? (Former US labor leader disappeared in 1975, presumed murdered by the New York City Mafia, but body was never found. Police are still searching.)

- Cremate his body and let the smoke and heat escape
- Dissolve the ashes to make a clear liquid, with no solid fragments, then pour the liquid into the ocean
- Don't tell anyone you did it, even on your deathbed
- For good measure, have yourself cremated and your ashes dissolved to make sure physical traces of your memory are thoroughly gone.

Can we arrange for escaped information to be reflected back to us later, making it again accessible?

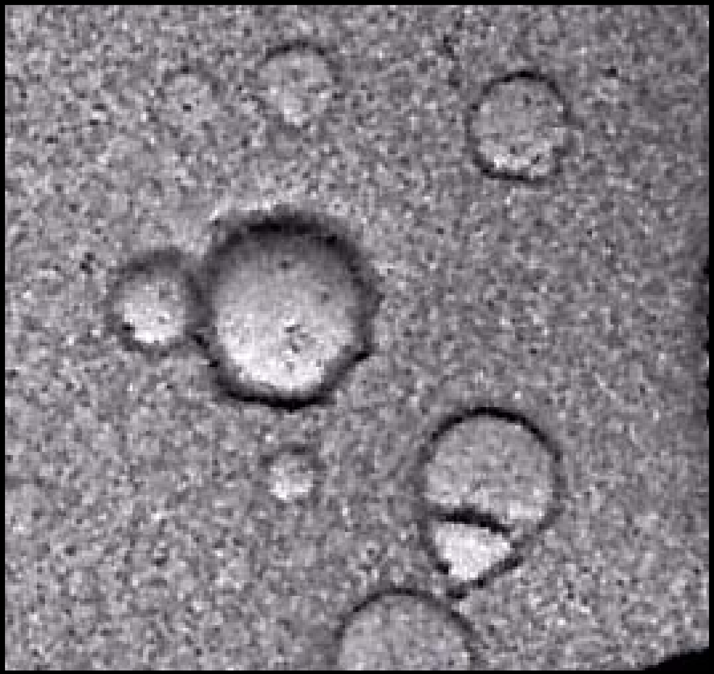


Yes. For specific items of non-thermalized outgoing radiation (e.g. optical earth views, old TV broadcasts) , this could be arranged, with advance planning, or it might happen accidentally. Such information could be called extraterrestrial fossils.



But for fully thermalized radiation, we would have to catch and reflect back so much of it, to reconstruct any particular item of interest, that the earth would have a serious climate change problem.

Randomizing dynamics in a representative case.



Though the raindrop originates in quantum and thermal fluctuations, it does not fall in a superposition of places. Independent observers would agree where it fell, and as long as the drop or its crater exists, reflected light will generate a torrent of replicas of the information that escape into space.

However, unless the crater is lucky enough to get fossilized, it will be washed away, and its former location will then lose any stable earthly embodiment. The torrent of optical replicas will cease, and the old optical replicas will escape into space. So it would appear that the classical information, of where it formerly was, remains in the universe, but not on Earth.

Ontological Status of Escaped Information

Consider a raindrop that may fall in one of 2 locations **L** or **R**.
Suppose that it forms, falls, and finally evaporates, so that all earthly record of where it fell is lost as radiation into the sky.

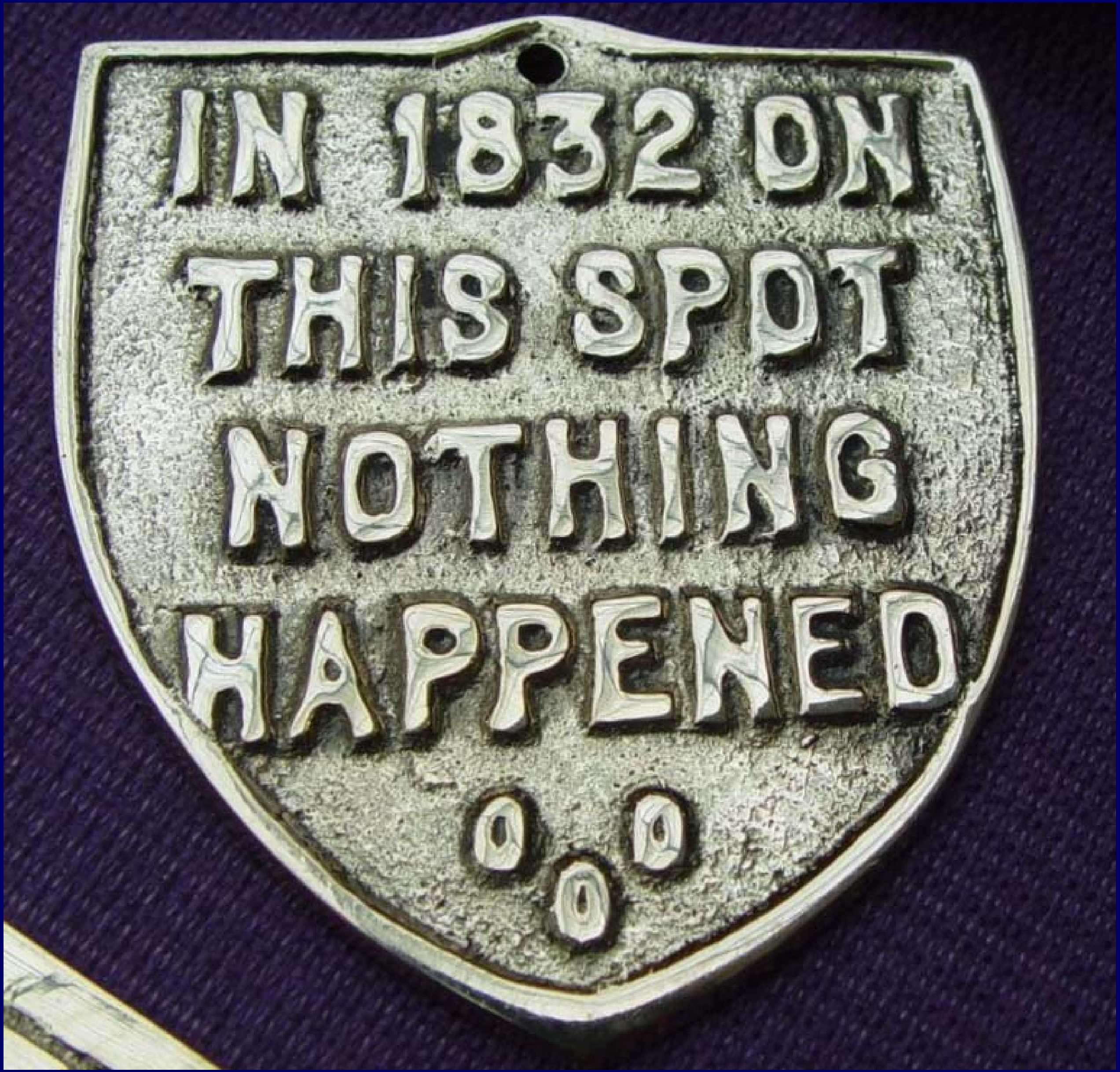
(LLLL+RRRR) $/\sqrt{2}$ Drop forms, falls and begins to emit radiative replicas into space. All observers, terrestrial and celestial, will see the drop as having fallen in one of two places. God sees a cat state-like superposition in which both outcomes happen.

(LLLLL+RRRRR $/\sqrt{2}$ Drop begins to evaporate, emitting further radiative replicas.

(LLLLL+RRRRR $/\sqrt{2}$ Drop has entirely evaporated. No terrestrial information remains about where it fell.

Conclusion: Escape of last replica from Earth restores terrestrial observers to a more detached, Olympian viewpoint in which both outcomes are equally real. Escaped information is not so different, after all, from which-path information.

J. A. Wheeler: "The past exists only insofar as it is recorded in the present."


IN 1832 ON
THIS SPOT
NOTHING
HAPPENED

III. Complexity

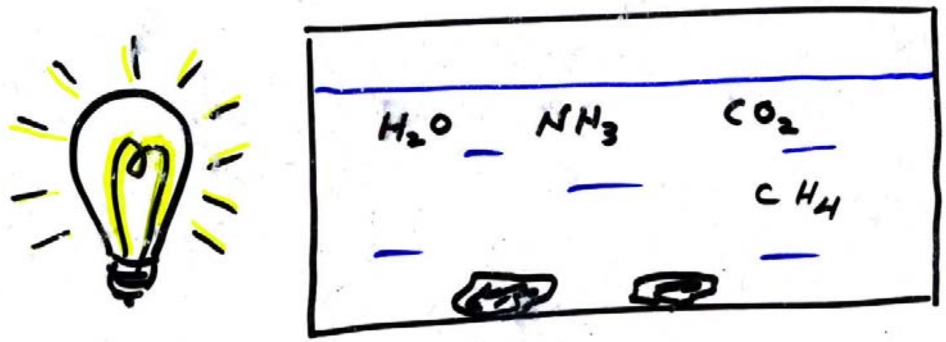
Enough about information & remembering and forgetting.

Can we find a non-anthropocentric definition of what kind of information is *worth* remembering?

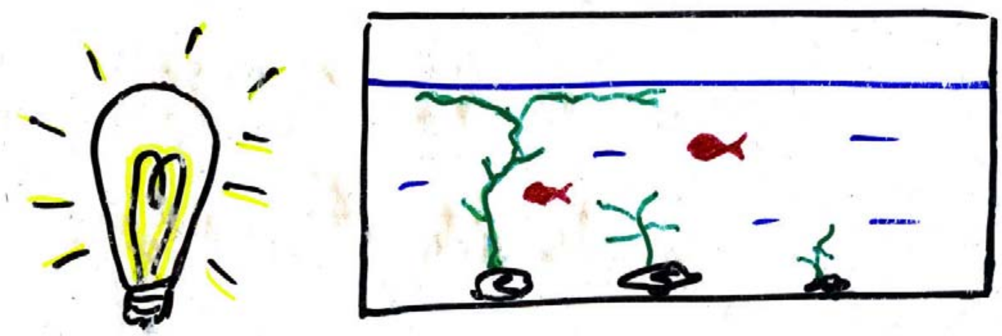
How should *complexity* be defined?

What is its connection with the universe not being at thermal equilibrium?

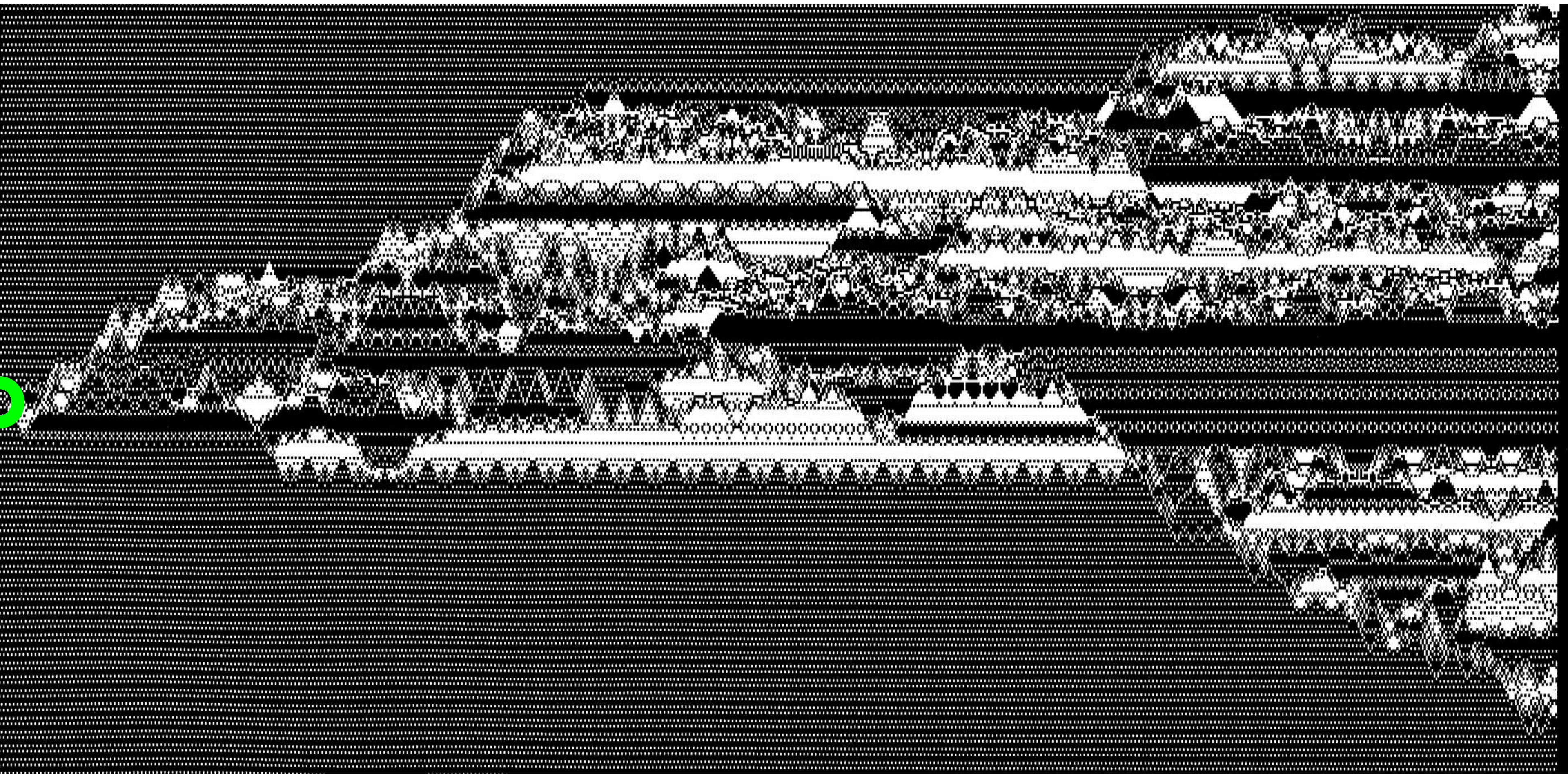
A simple cause can have a complicated effect, but not right away.



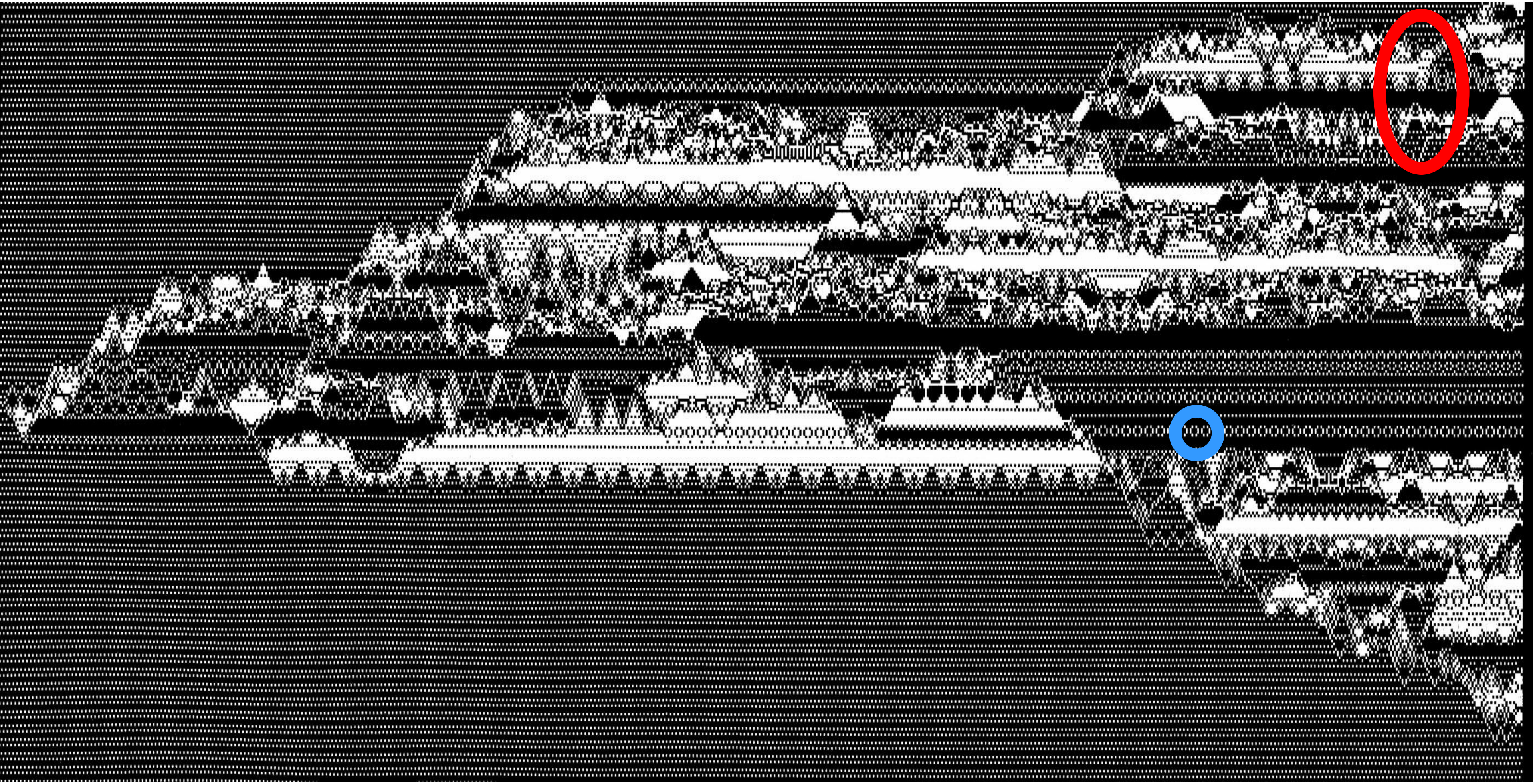
Much later



Self-organization, the spontaneous increase of complexity: A simple dynamics (a reversible deterministic cellular automaton) can produce a complicated effect from a simple cause.



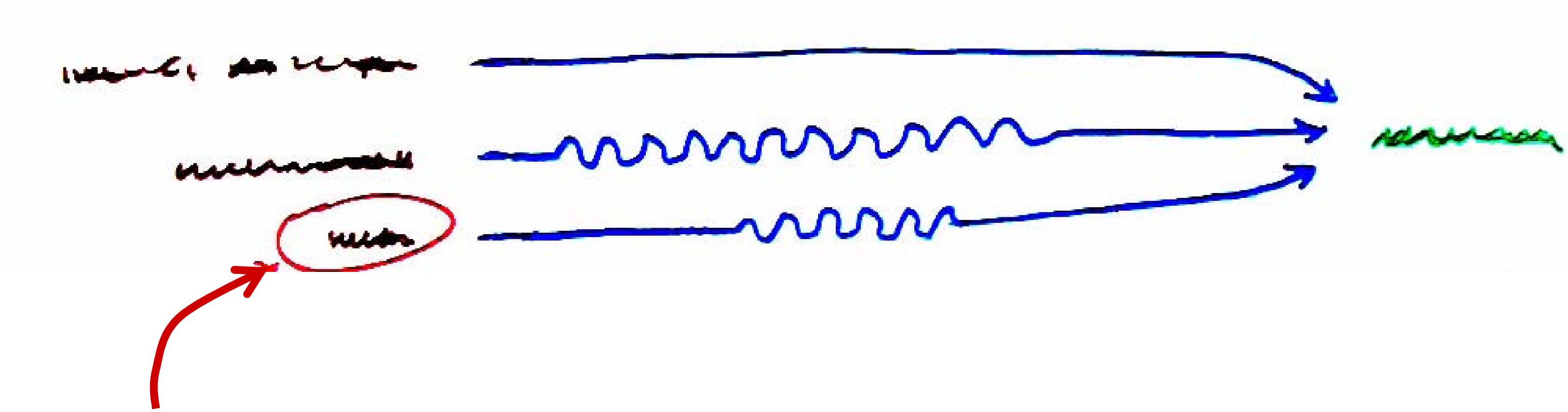
Small irregularity (green) in initial pattern produces a complex deterministic "wake" spreading out behind it.



A sufficiently big piece of the wake (red) contains enough evidence to infer the whole history. A smaller pieces (blue) does not.

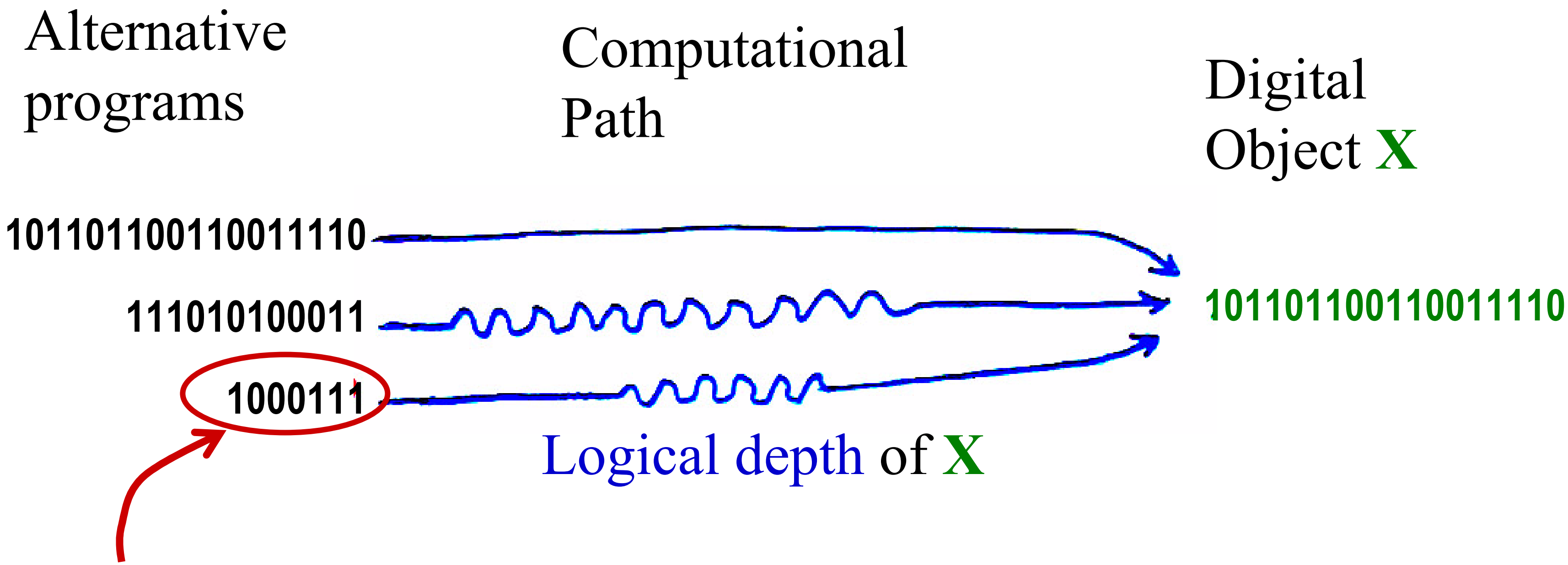
In the philosophy of science, the principle of Occam's Razor directs us to favor the most economical set of assumptions able to explain a given body of observational data.

Alternative hypotheses | Deductive path | Observed Phenomena



The most economical hypothesis is preferred, even if the deductive path connecting it to the phenomena it explains is long and complicated.

In a computerized version of Occam's Razor, the hypotheses are replaced by alternative programs for a universal computer to compute a particular digital or digitized object **X**.

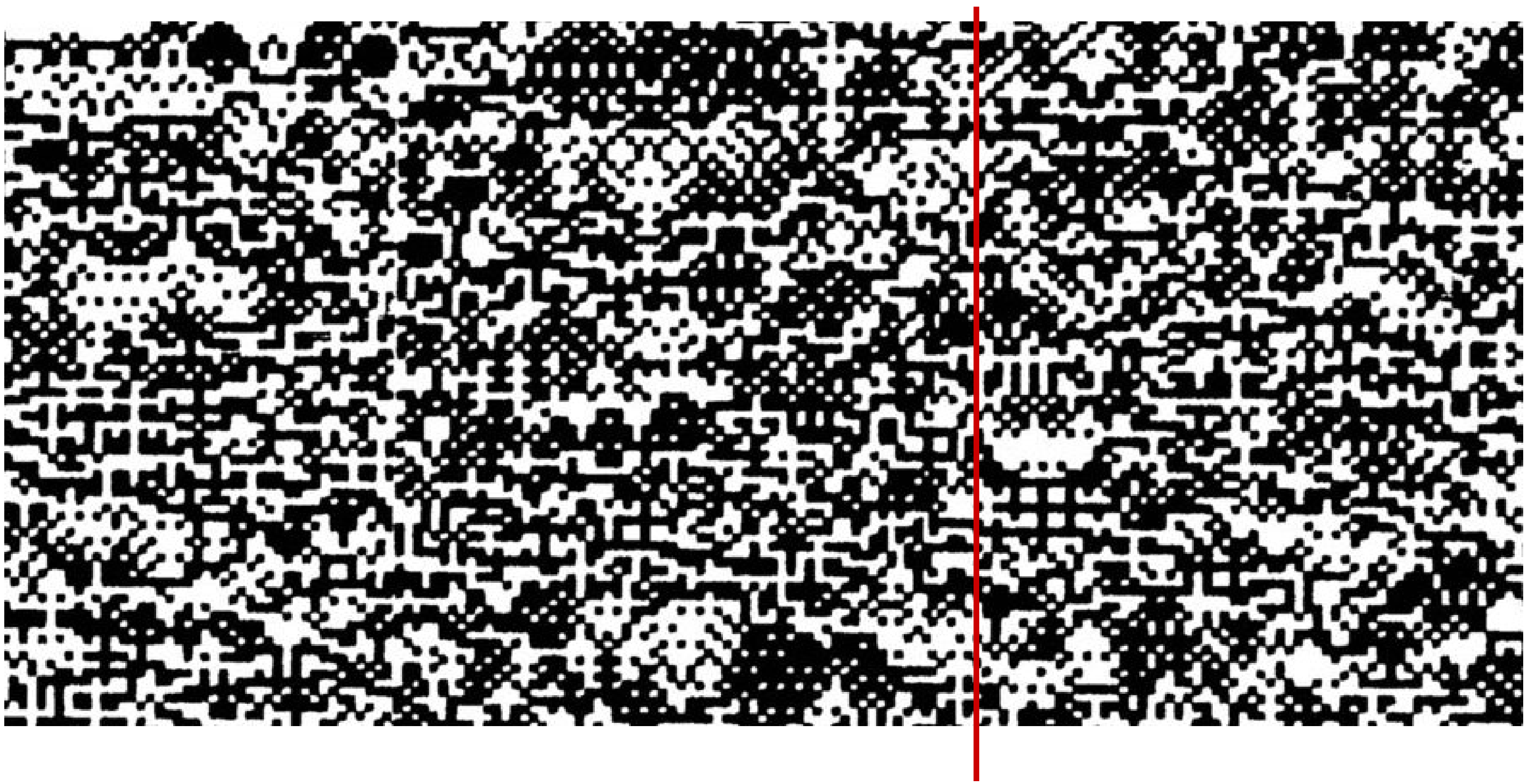


The shortest program is most plausible, so its *run time* measures the object's logical depth, or plausible amount of computational work required to create the object.

A trivially orderly sequence like 111111… is logically shallow because it can be computed rapidly from a short description.

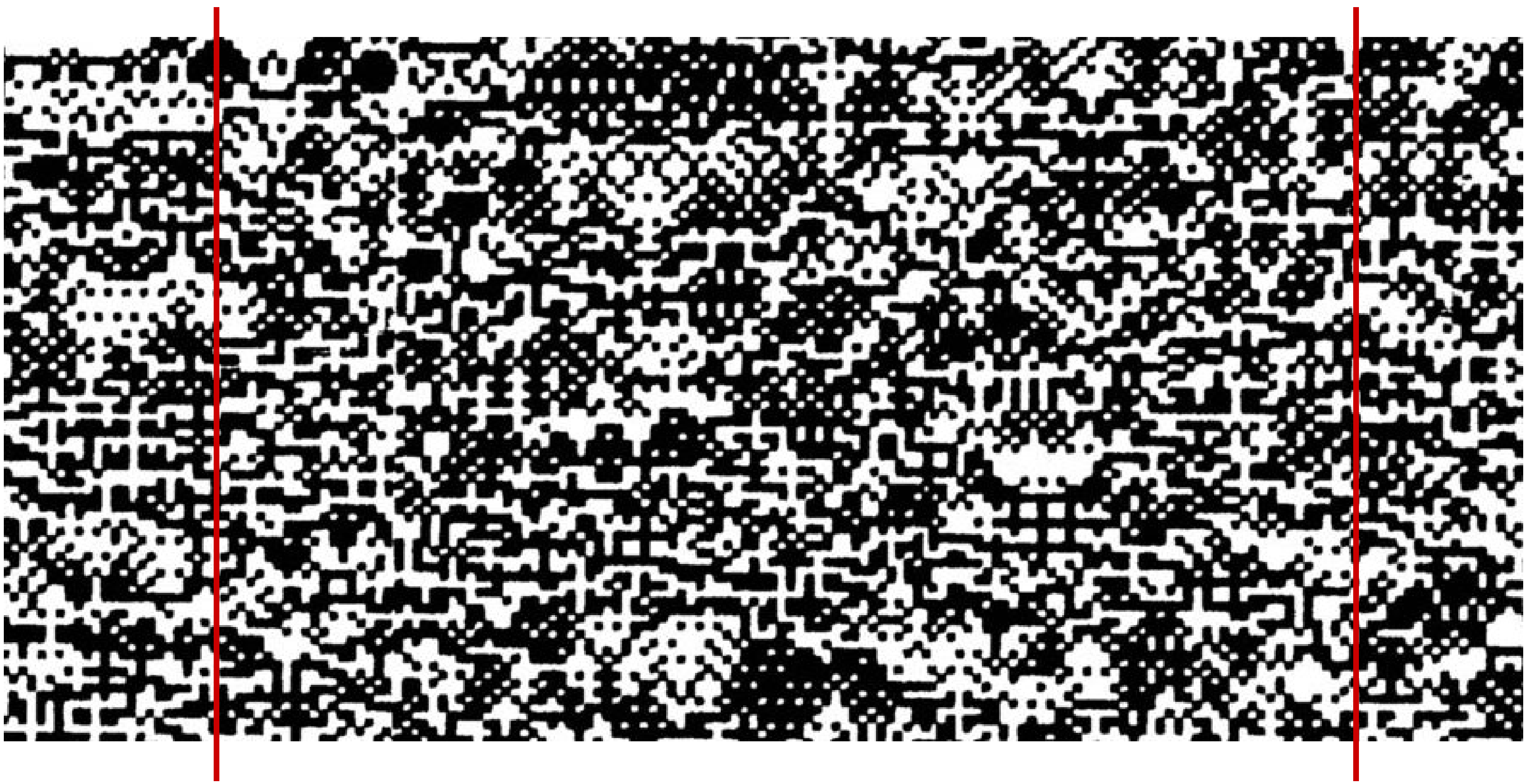
A typical random sequence, produced by coin tossing, is also logically shallow, because it essentially *its own* shortest description, and is rapidly computable from that.   Depth thus differs from Kolmogorov complexity or algorithmic information, defined as the *size* of the shortest description, which is high for random sequences.

If a reversible local dynamics (e.g. the 1d system considered earlier) is allowed to run long enough in a closed system, the state becomes trivial and random, a discrete version of "heat death" in thermodynamics. Our world is complex only because it is still out of equilibrium.



After equilibration, typical time slice is shallow, with only local correlations.

At equilibrium, complexity still persists in 2-time correlations. Two time slices of the equilibrated system contain internal evidence of the intervening dynamics, even though each slice itself is shallow. The inhabitants of this world, being confined to one time slice, can't see this complexity. (Also they'd be dead.)



complex intervening dynamics

In an equilibrium world with local interactions (e.g. a thermal ensemble under a local Hamiltonian) correlations are generically local, mediated through the present.

Equilibrium correlations mediated through present only

time

By contrast, in a non-equilibrium world, local dynamics can generically give rise to long range correlations, mediated not through the present but through a V-shaped path in space-time representing a common history.

QE I

Grenada 1999

Canada 2002

Conclusions – in place of Laplacian determinism, quantum mechanics gives us a world where:

• Many aspects of the future are inherently ambiguous: even God doesn’t know which radioactive atoms will decay, or who will win next year’s elections. It is unreasonable to want to know some of these things.

• In a world out of thermal equilibrium, the monogamy of entanglement leads to the emergence of classical correlations, and paradoxically makes overtly quantum phenomena hard to notice.

• Even though the earth retains a great deal of deep information about its past, a much larger amount escapes into space, making many aspects of the earth’s past nearly as ambiguous as its future.

• Thermal disequilibrium enables both complexity and classicality.