Title: Quantum information, the ambiguity of the past, and the complexity of the present

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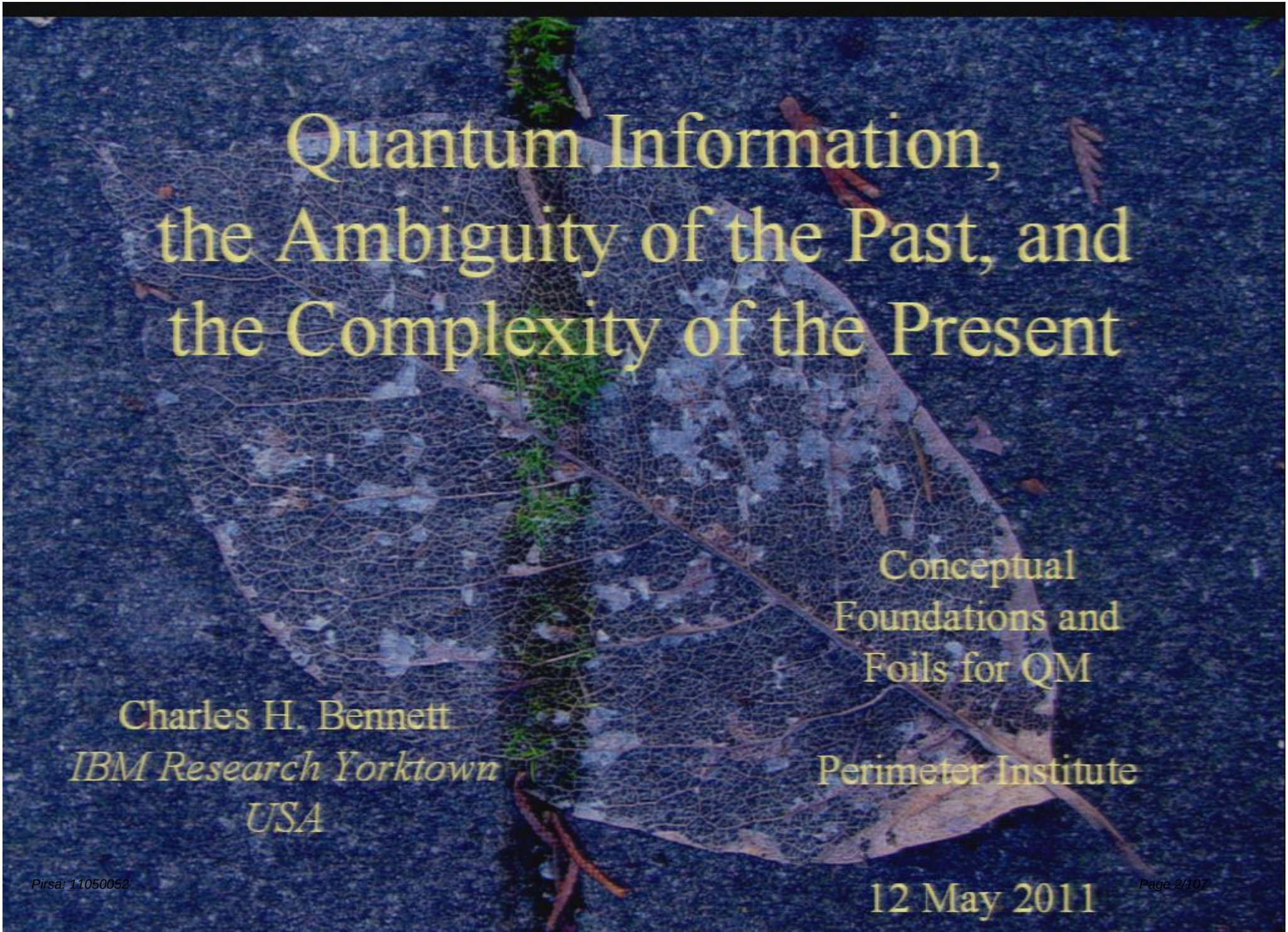
Abstract: Entanglement provides a coherent view of the physical origin of randomness and the growth and decay of correlations, even in macroscopic systems exhibiting few traditional quantum hallmarks. It helps explain why the future is more uncertain than the past, and how correlations can become macroscopic and classical by being redundantly replicated throughout a system's environment. The most private information, exemplified by a quantum eraser experiment, exists only transiently: after the experiment is over no record remains anywhere in the universe of what "happened". At the other extreme is information that has been so widely replicated as to be infeasible to conceal and unlikely to be forgotten. But such conspicuous information is exceptional: a comparison of entropy flows into and out of the Earth with estimates of the planet's storage capacity leads to the conclusion that most macroscopic classical information---for example the pattern of drops in last week's rainfall---is impermanent, eventually becoming nearly as ambiguous, from a terrestrial perspective, as the transient result of a quantum eraser experiment. Finally we discuss prerequisites for a system to accumulate and maintain in its present state, as our world does, a complex and redundant record of at least some features of its past. Not all dynamics and initial conditions lead to this behavior, and in those that do, the behavior itself tends to be temporary, with the system losing its memory, and even its classical character, as it relaxes to thermal equilibrium.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Charles H. Bennett
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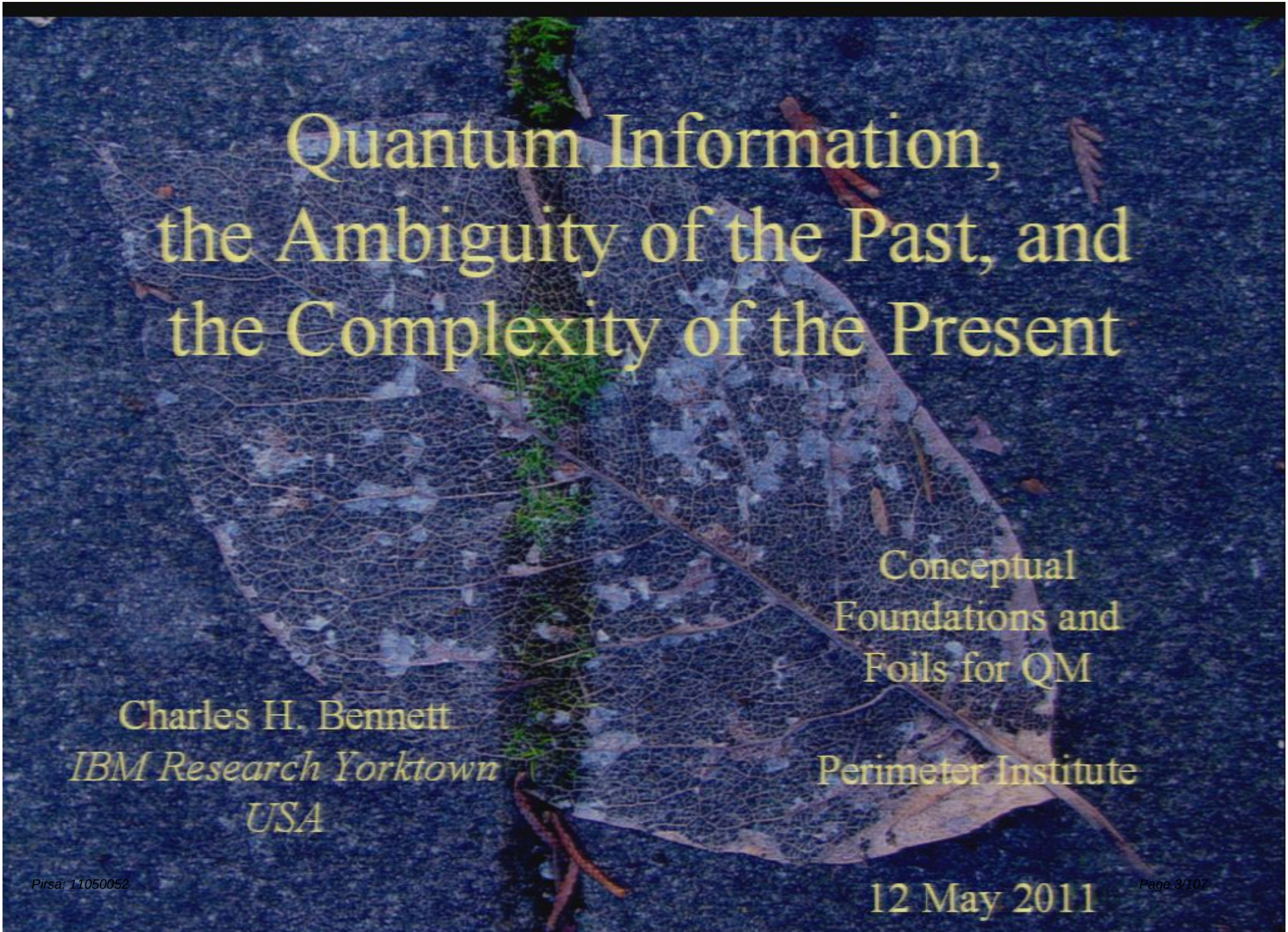
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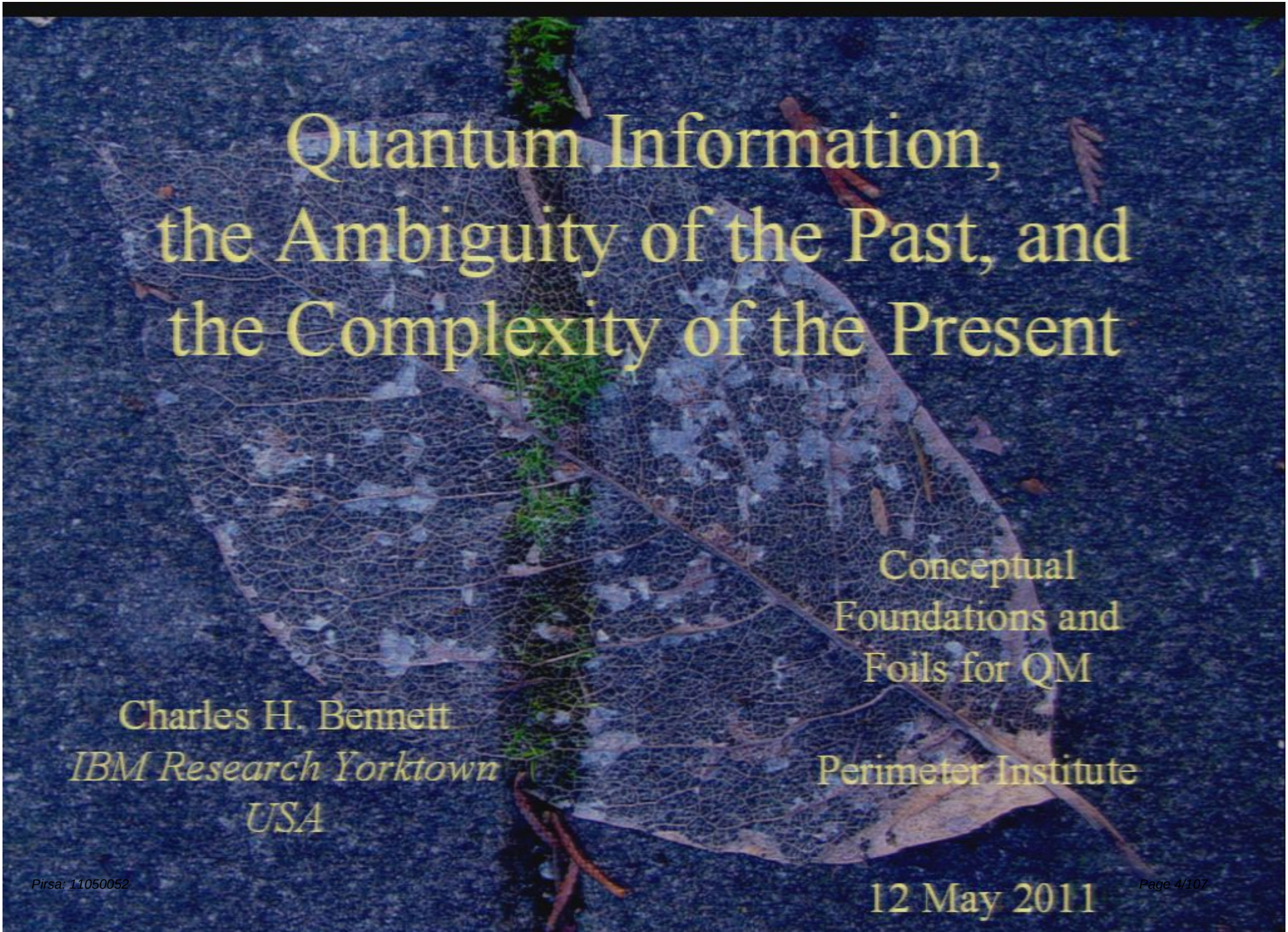
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Will accept the Dowry of standard quantum mechanics

Will argue that standard QM, especially the "Monogamy of Entanglement", provides a satisfying explanation of many features of the macroscopic world, even seemingly non-quantum ones

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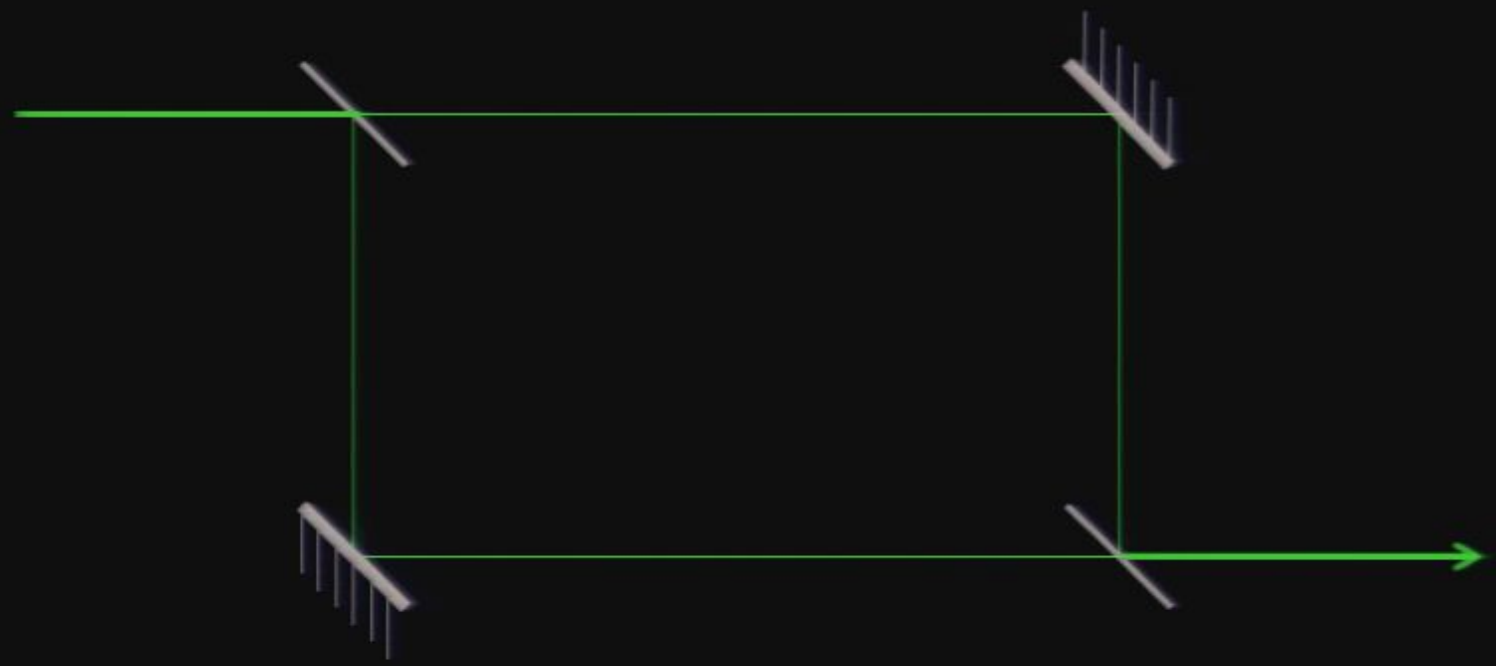
Reasoning from classical mechanics, Laplace thought the future and past were fully determined by the present, but attributed the perceived ambiguity of the future to our imperfect knowledge of the present, and/or our lack of sufficient computing power to calculate the future. An omniscient God would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

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.



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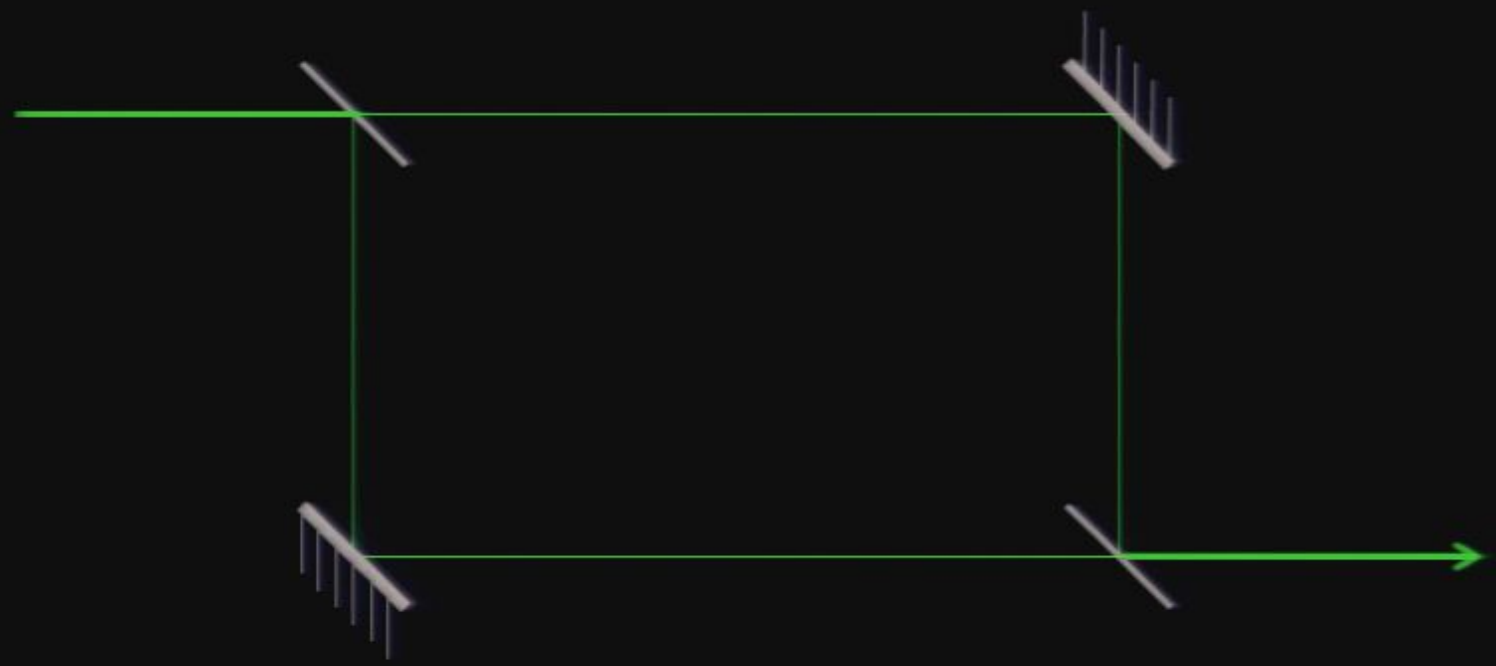

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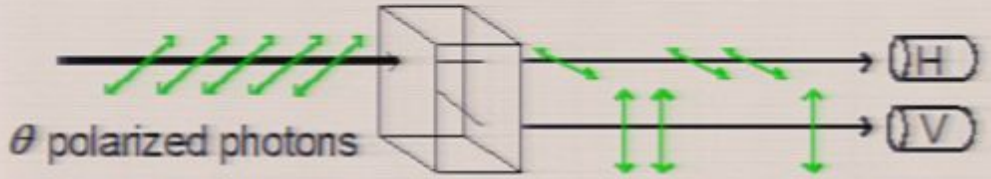
Bill Wootters' pedagogic analog of collapse



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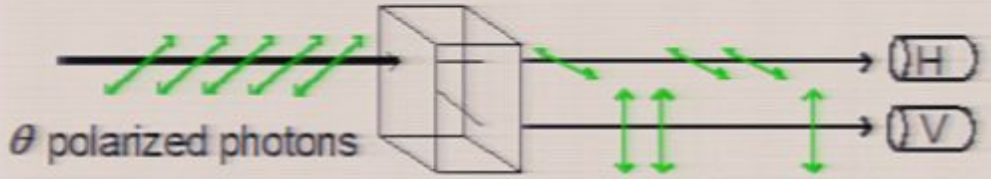

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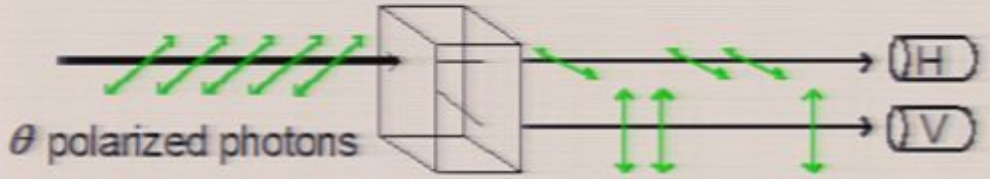

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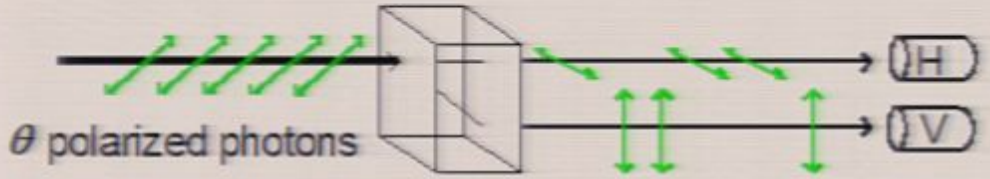

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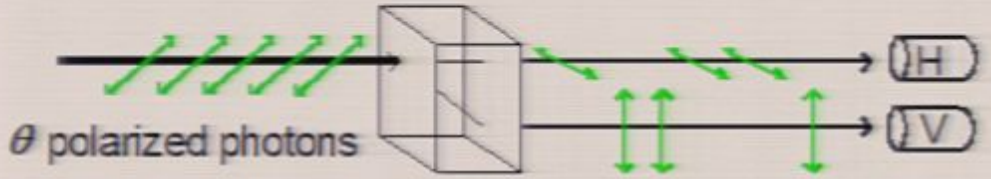

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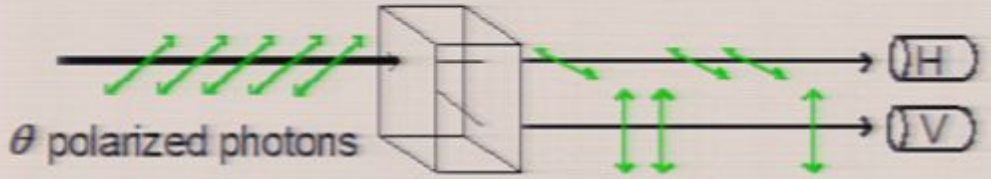

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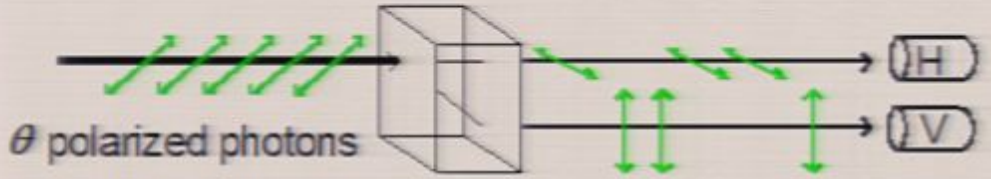

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Teacher: Have you ever had any other polarization?

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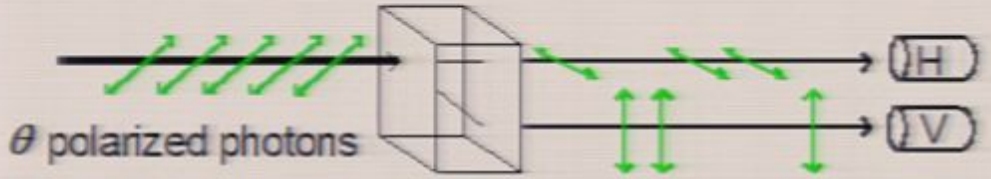

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Pupil: Horizontal, sir.

Teacher: Have you ever had any other polarization?

Pupil: No, sir. I was always horizontal.

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• 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.

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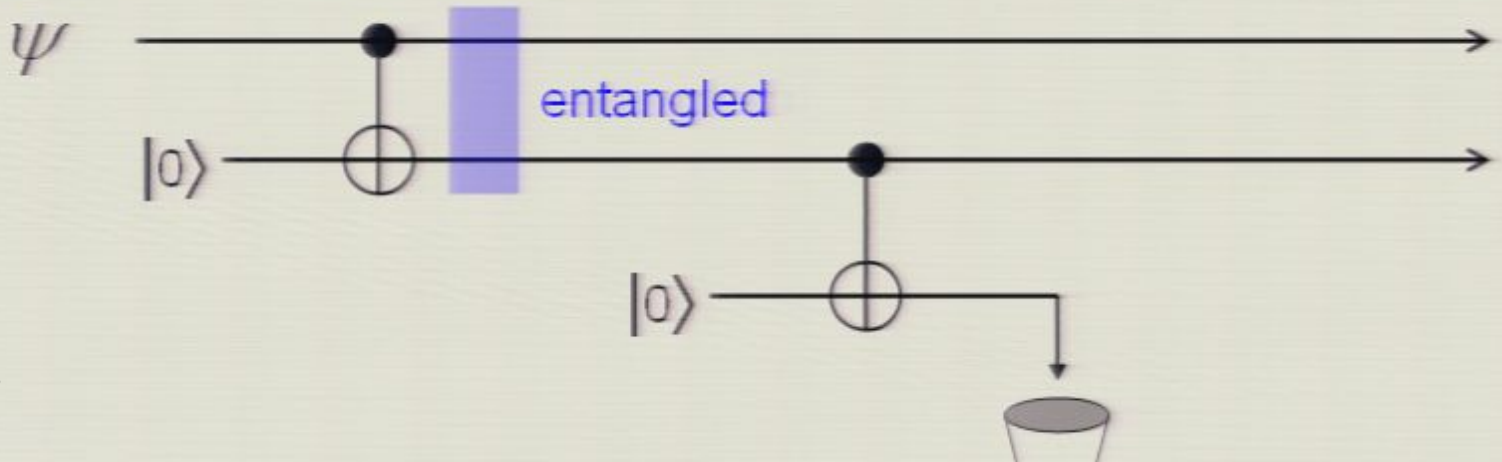

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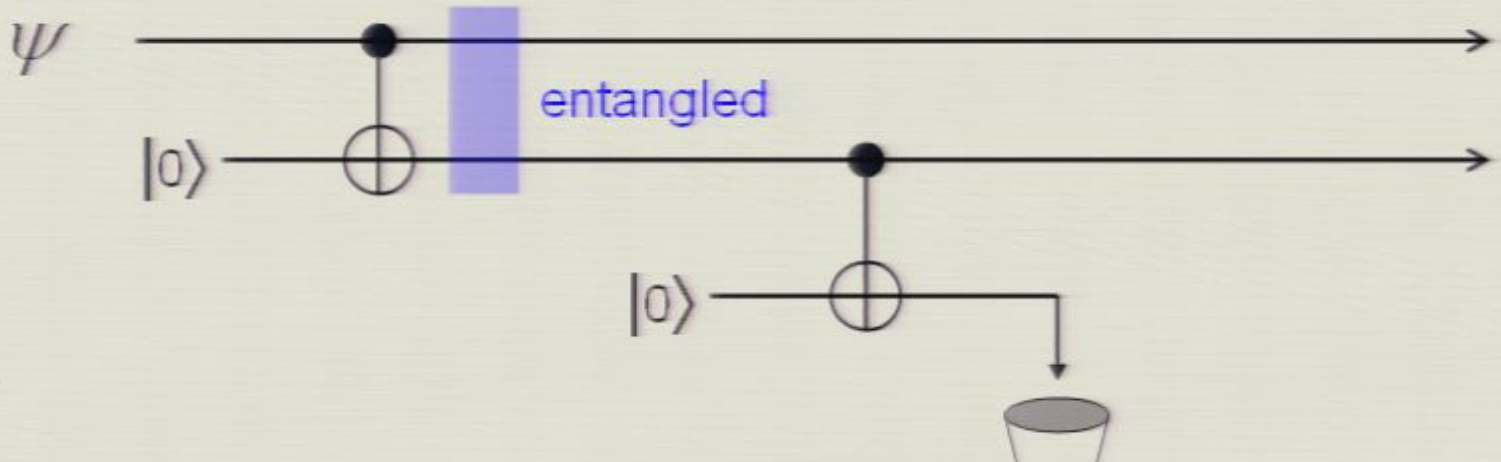

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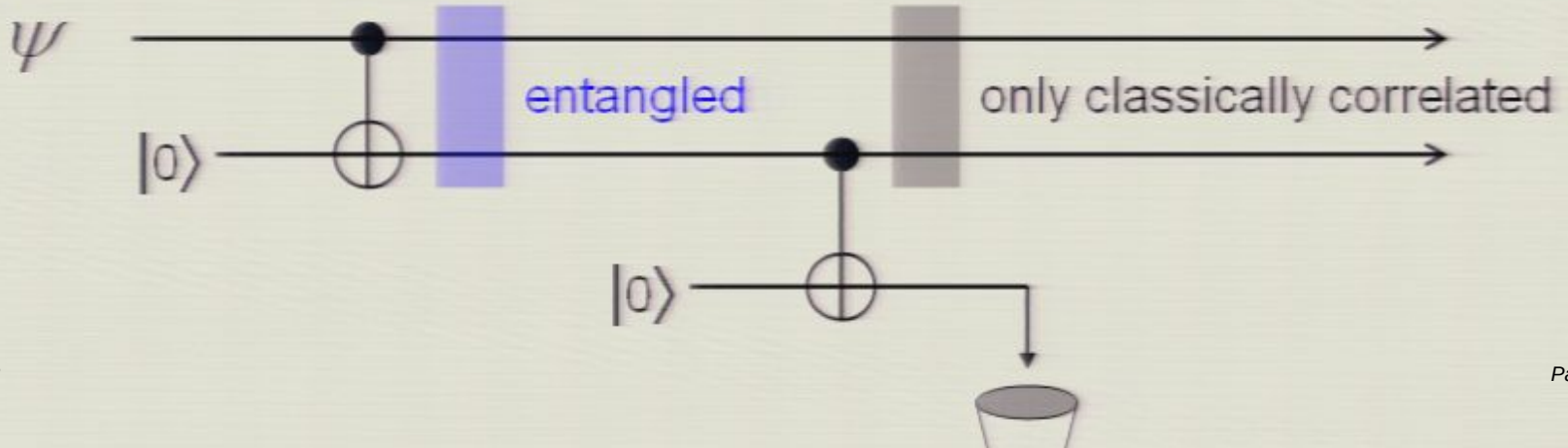

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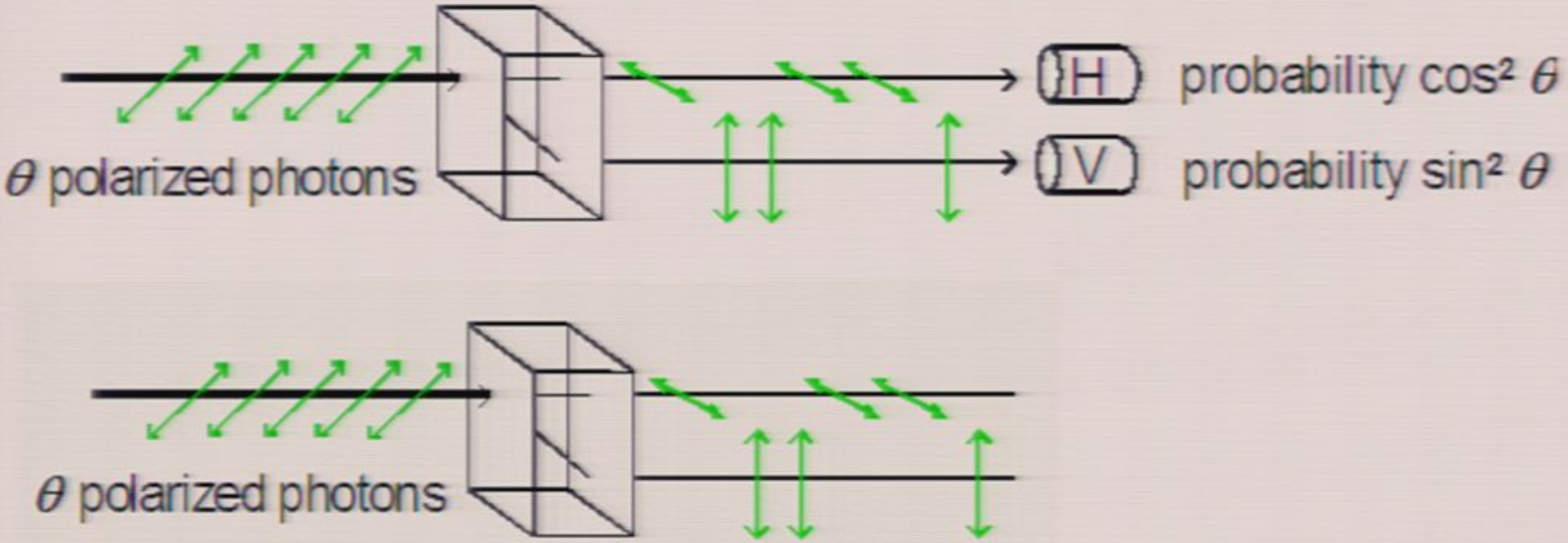

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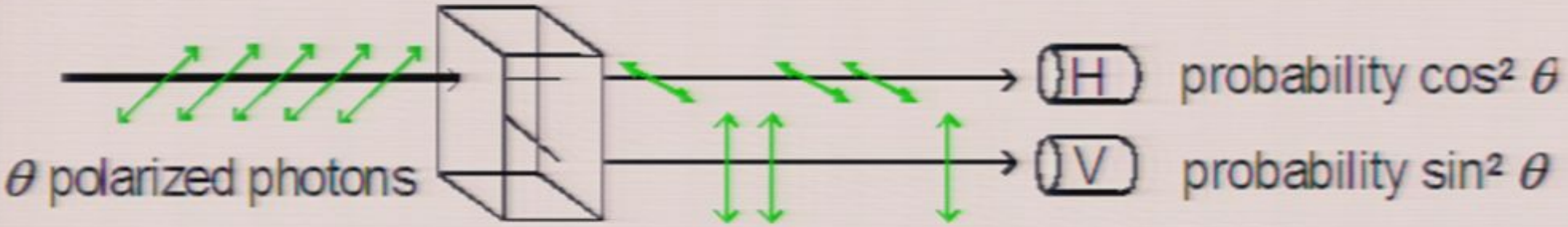

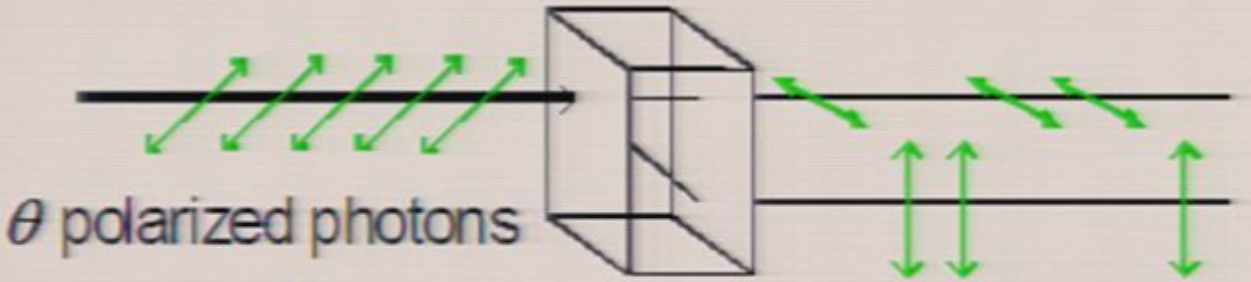

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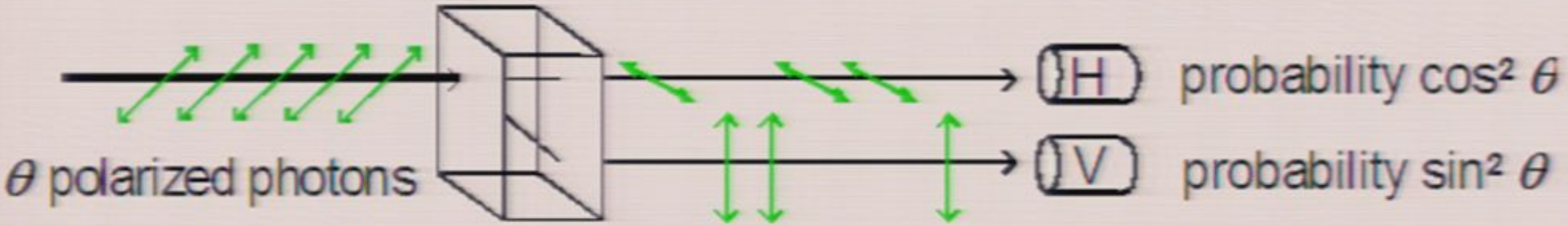

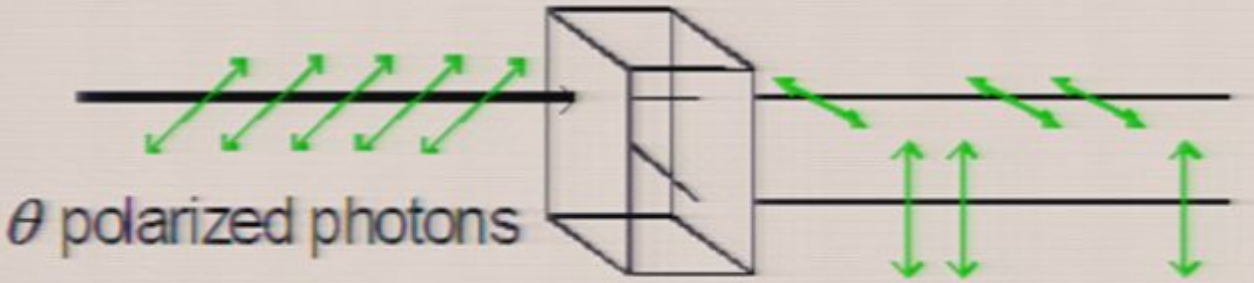

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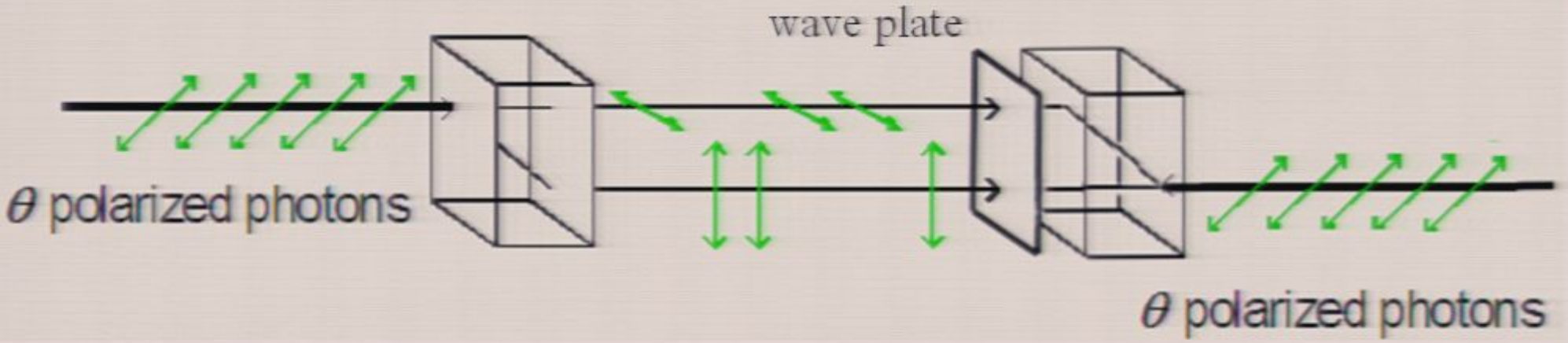

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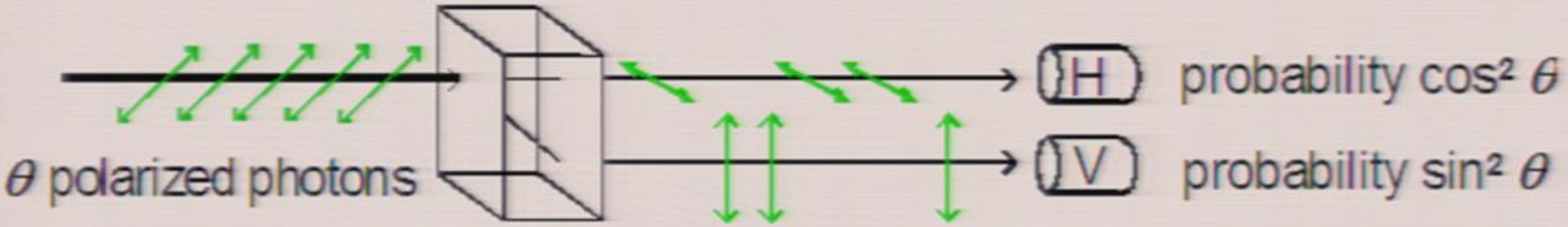

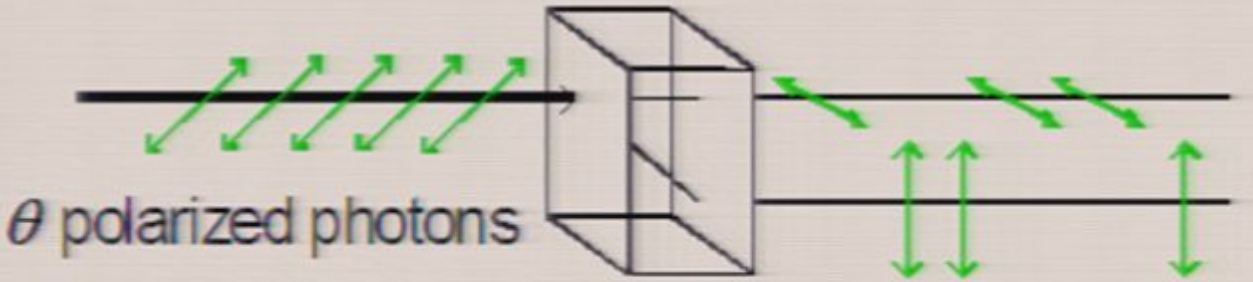

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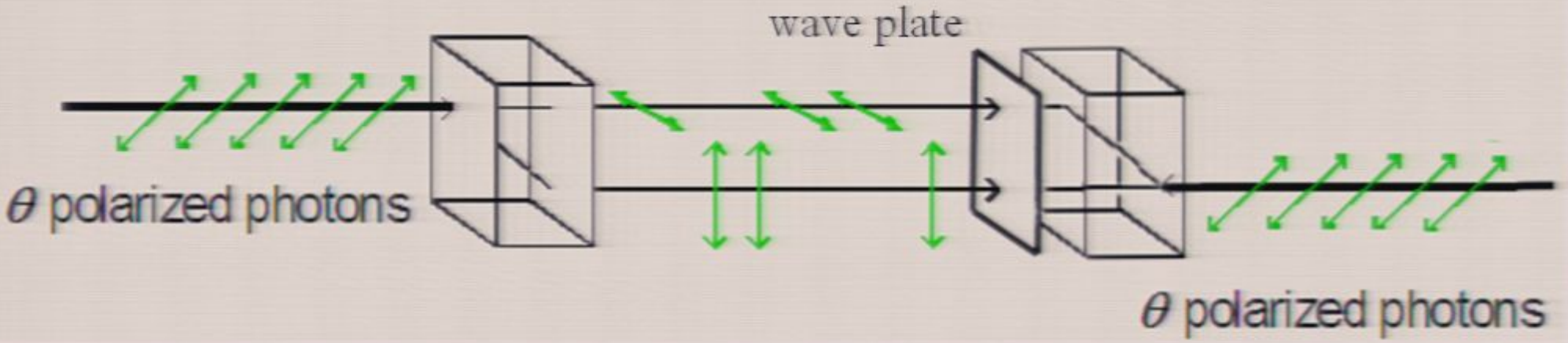

Metaphorically speaking, it is the **public embarrassment** of the pupil, in

Meaning of the Density Matrix:

The density matrix represents all and only that information that can be obtained by sampling the ensemble or observing the A part of the compound system. Ensembles with the same ρ are indistinguishable. Pure states $\Psi(A,B)$ with the same $\rho(A)$ are indistinguishable by observing the A part.

If Alice and Bob share a system in pure state $\Psi(A,B)$, then for any ensemble $\{\psi_i, p_i\}$ compatible with $\rho(A)$, there is a measurement Bob can do on his subsystem alone, without Alice's knowledge or consent, that *remotely generates* the ensemble in her lab, in the sense that for each i, Bob gets measurement outcome i with probability p_i and if he obtains that outcome, he knows that Alice's subsystem is in pure state ψ_i. (Schroedinger called this "steering," but that is a bad name for it, because Bob merely learns, but can't control, which state Alice gets.)

The Church of the Larger Hilbert Space

This is the name given by John Smolin to the habit of always thinking of a mixed state as a pure state of some larger system, and of any stochastic evolution as being embedded in a unitary evolution of a larger system. No one can stop us from thinking this way, and Church members find it satisfying and helpful to their intuition.

This doctrine only makes sense in a quantum context, where because of entanglement a pure whole can have impure parts. Classically, a whole can be no purer than its most impure part.

Most religions view impurity classically and unfavorably

"If thy hand or thy foot offend thee, cut them off, and cast them from thee: it is better for thee to enter into life [heaven] halt or maimed, rather than having two hands or two feet to be cast into everlasting fire." (Matthew 18:8)

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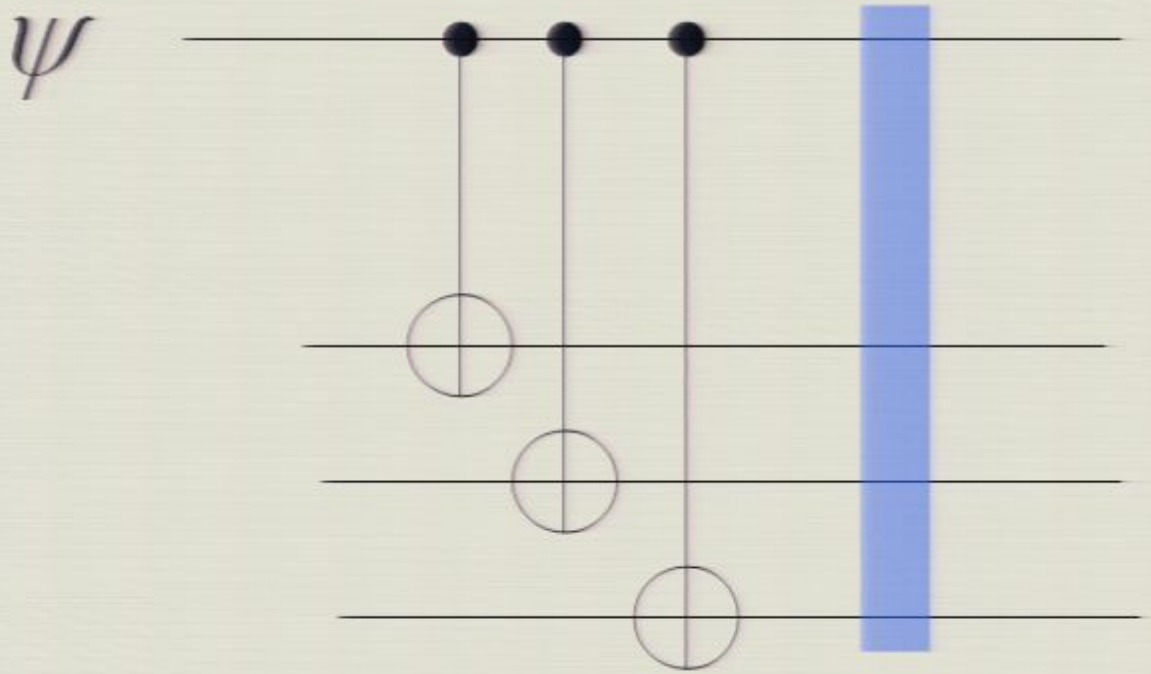

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In 0/1 basis, system is correlated with each sub-environment. In other bases it is correlated only with the whole environment

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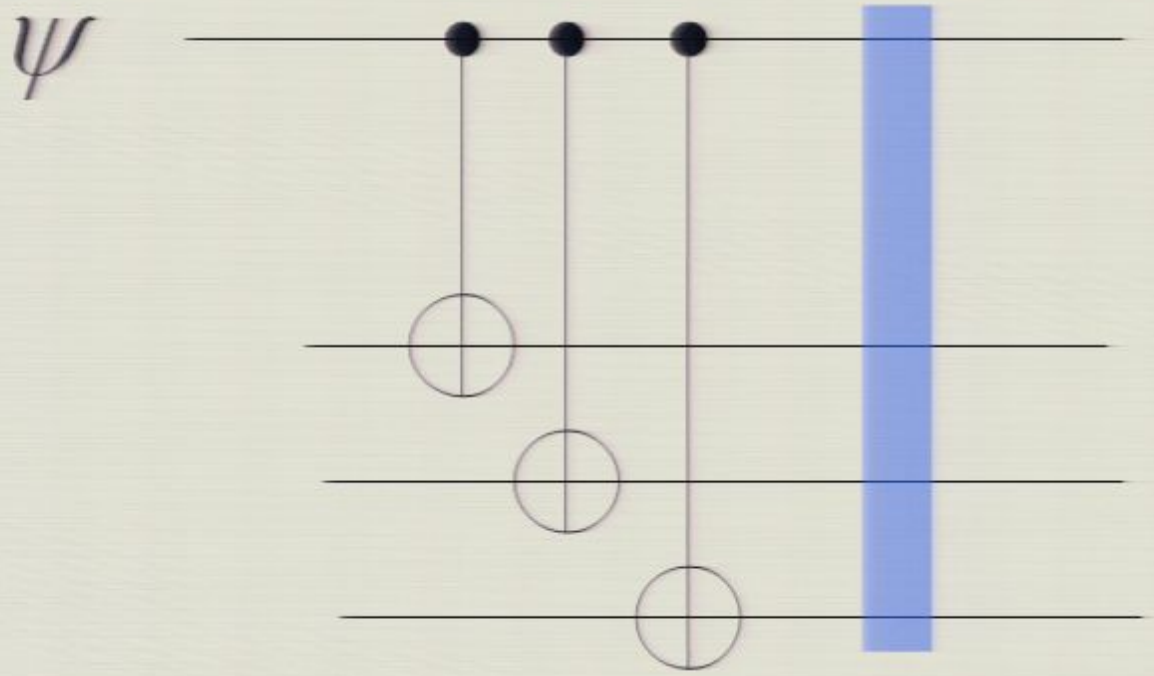

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Information becomes classical by being replicated redundantly throughout the environment. "Quantum Darwinism"

Blume-Kohout, Zurek quant-ph/0505031; Riedel, Zurek 1001.3419v3

(This typically happens when the environment is ***not*** *at thermal equilibrium, and when it contains many subsystems that interact more strongly with the*

It seems there are 3 levels 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.

- **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.

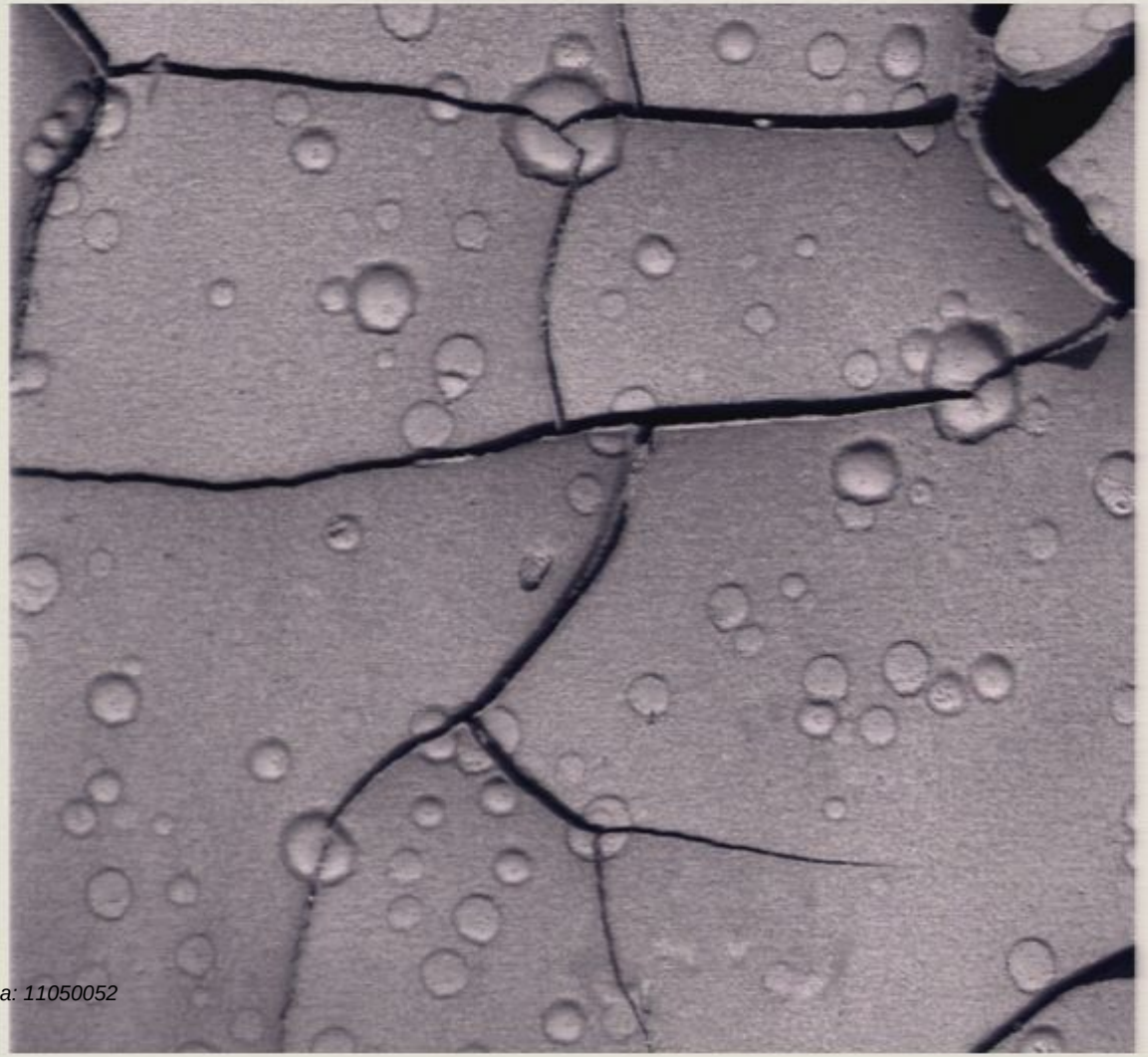
- **Public:** Information that is so widely distributed that it is infeasible to conceal. Lying about it only makes you look foolish.

Nowadays, it is tempting to believe that once information has become public, 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 620-625 BC, as depicted by Gustav Klimt ca 1900

Yet even in today's world, much macroscopic, publicly accessible information is seemingly lost because no person, nor any natural process, happens to record it in a durable medium.



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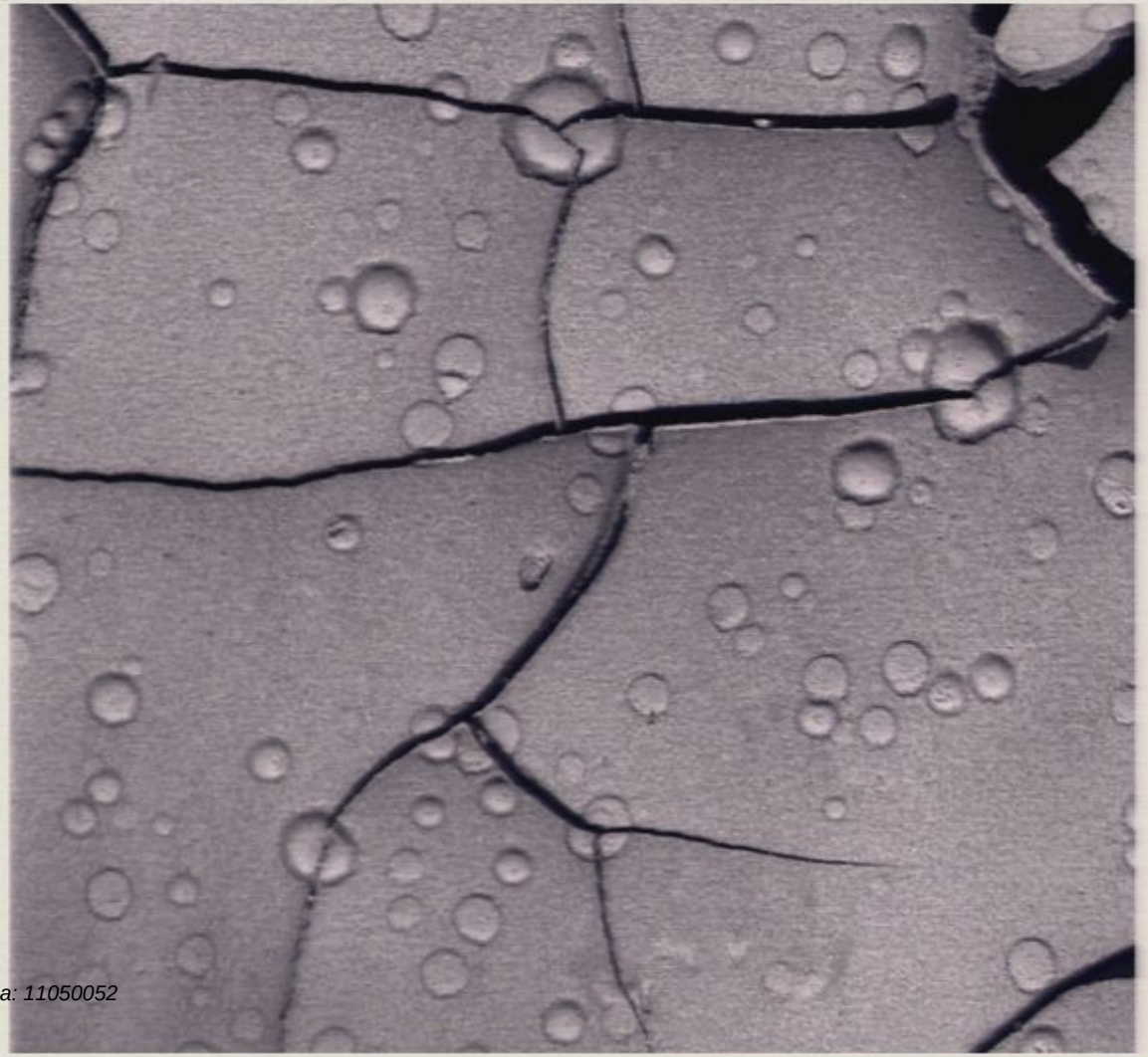

Dried mud with cracks and raindrop craters in a river bed in Las Vegas, USA in 1965. A few days later these details were washed away by a subsequent rain.

If no one had photographed them, would a physical record of them still exist?

It is tempting to believe that such macroscopic information is not really lost, just that it becomes so diffusely and complexly spread out as to be irrecoverable in practice while being still recoverable in principle. When a book is burned, its contents are in principle still recoverable from the exact state of the smoke, ash, and heat it generates.

Could it be that every macroscopic past phenomenon, say Sappho's lost poems, or the fate of mysteriously disappeared persons like labor leader Jimmy Hoffa or computer scientist Jim Gray, can be recovered from physical evidence in principle, if not in practice?

To believe otherwise is venturing dangerously close to the postmodernist view, abhorred by most scientists as arrogantly anthropocentric, that the past (or maybe even the present) has no objective reality independent of human belief systems, and therefore that it is pointless to inquire what "actually" happened.

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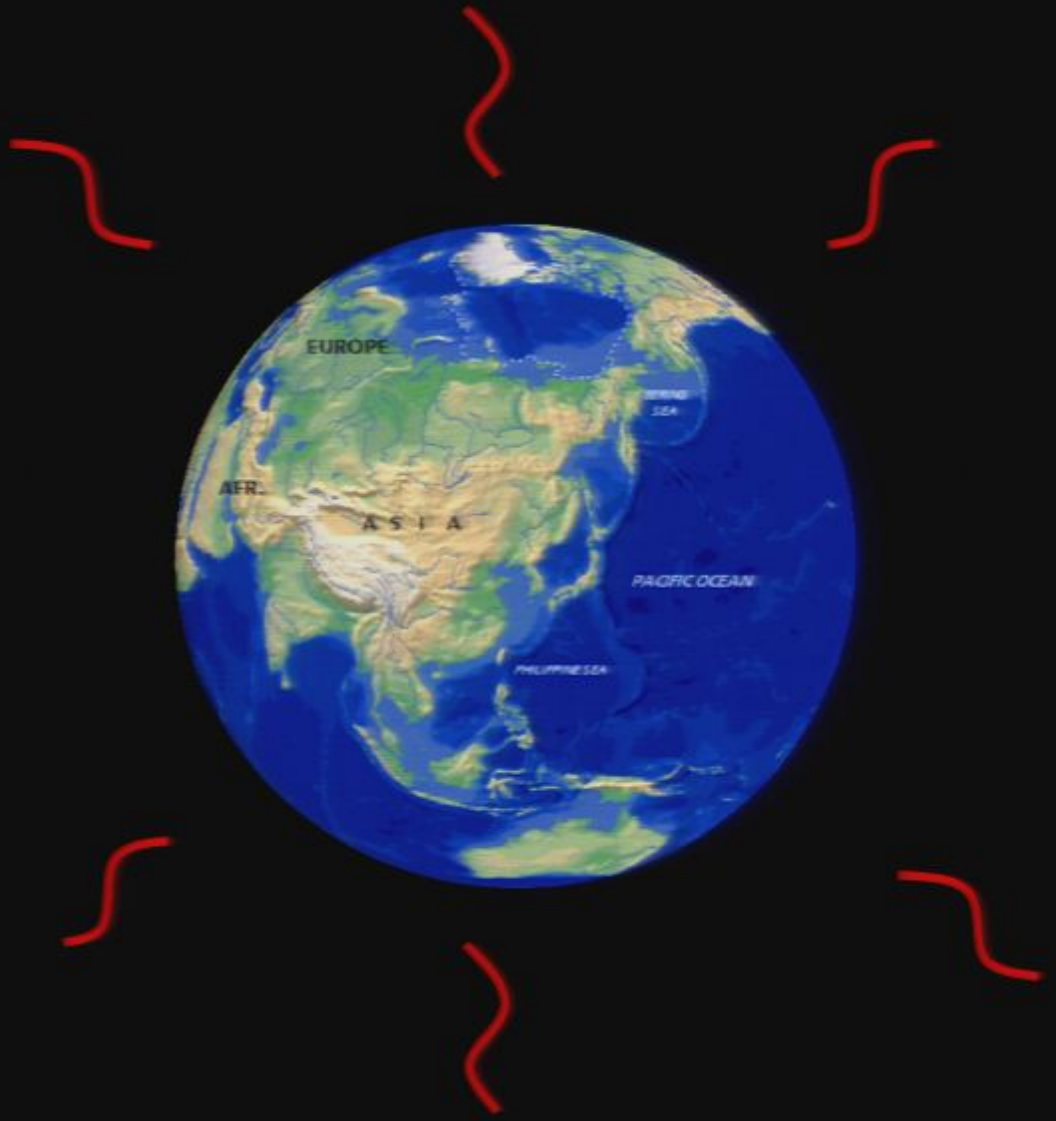
Human digital information capture rate 100GB/person x 10^9 people who are heavy information users ≈10^{21} bits per year

(that's for the whole world, not per sq meter)



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.

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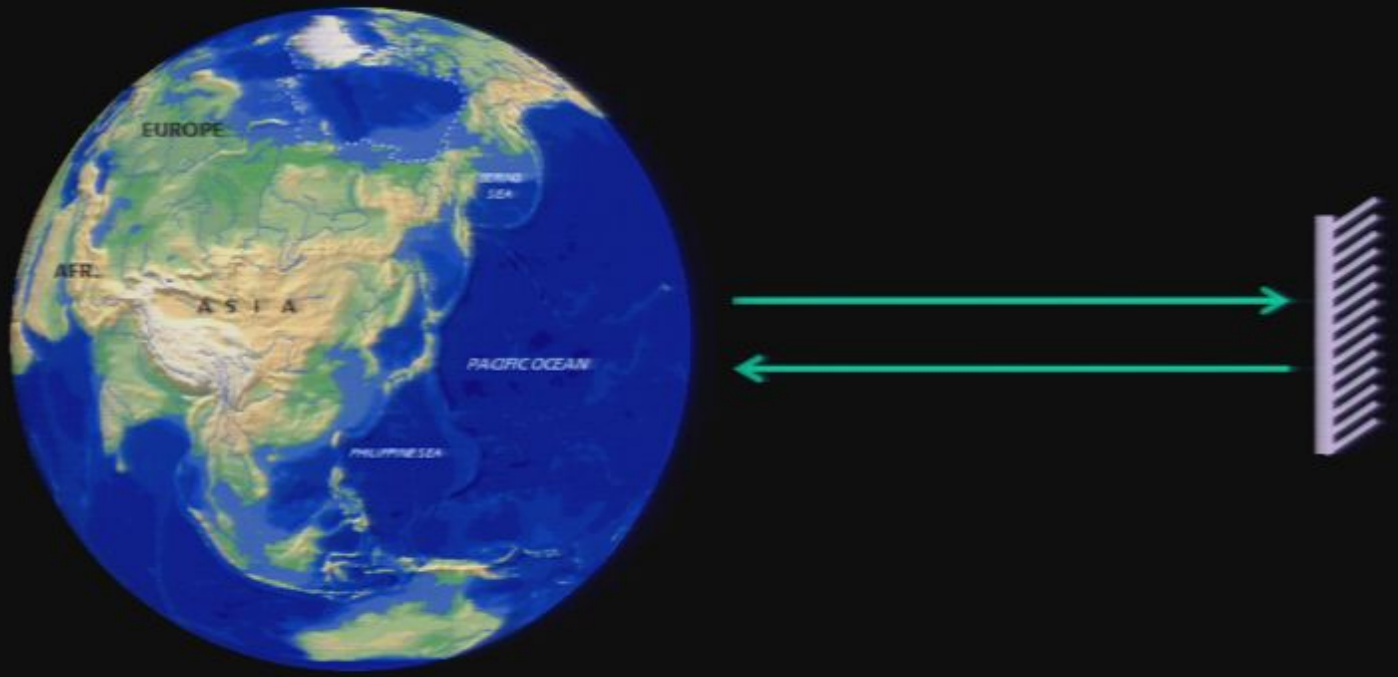
Probably not, due to randomizing effect of dynamics: recovering a minority share of the output of a known random permutation (or known random unitary transformation) reveals almost nothing about a minority share of its input.

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.

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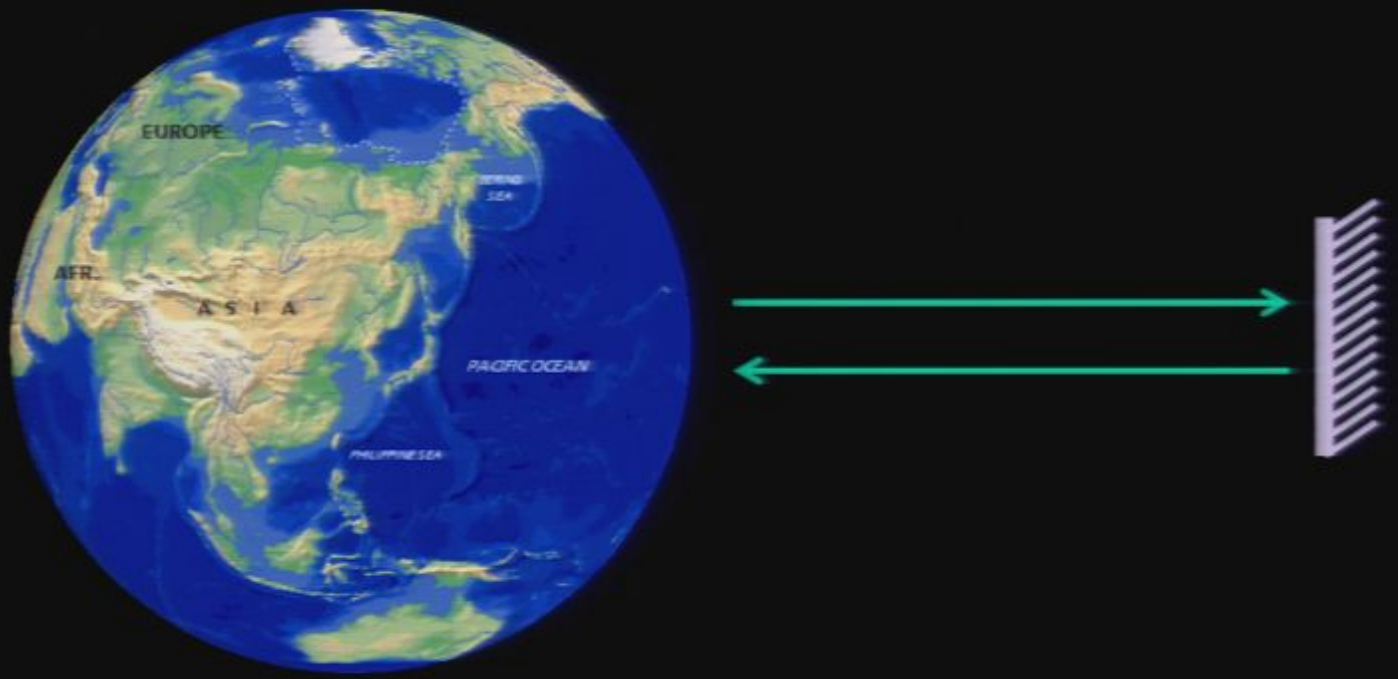

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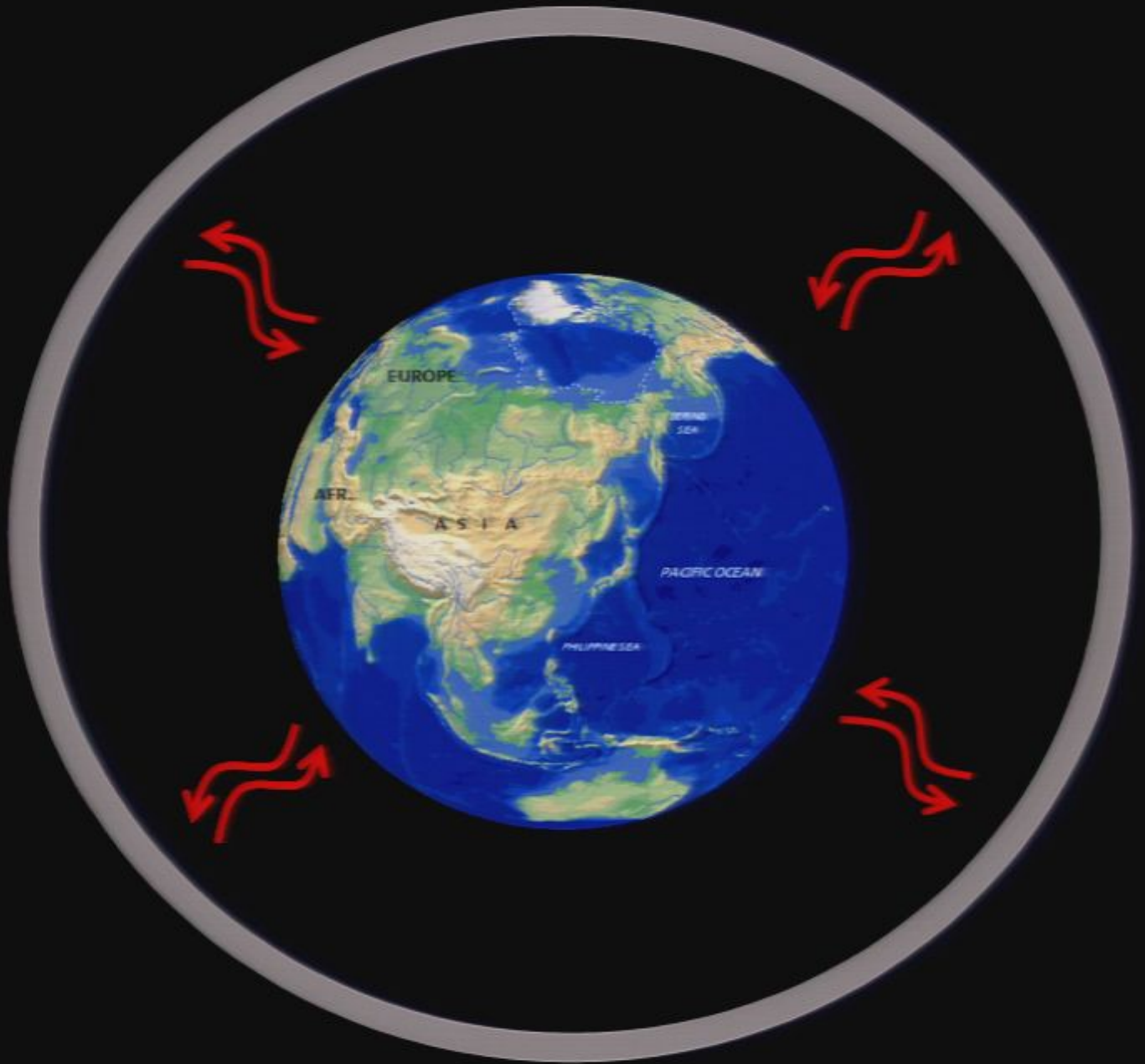
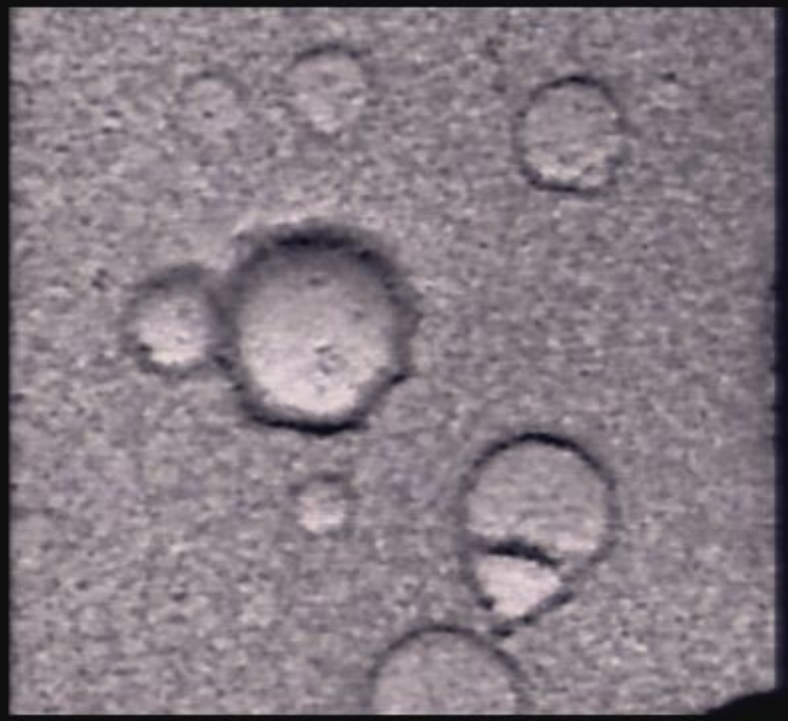


But for fully thermalized radiation, we would have to catch and reflect back so much of it, to reconstruct any particular item of interest, that the earth to would suffer a serious greenhouse problem.

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, fulfilling the classicality criterion of quantum Darwinism. 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.

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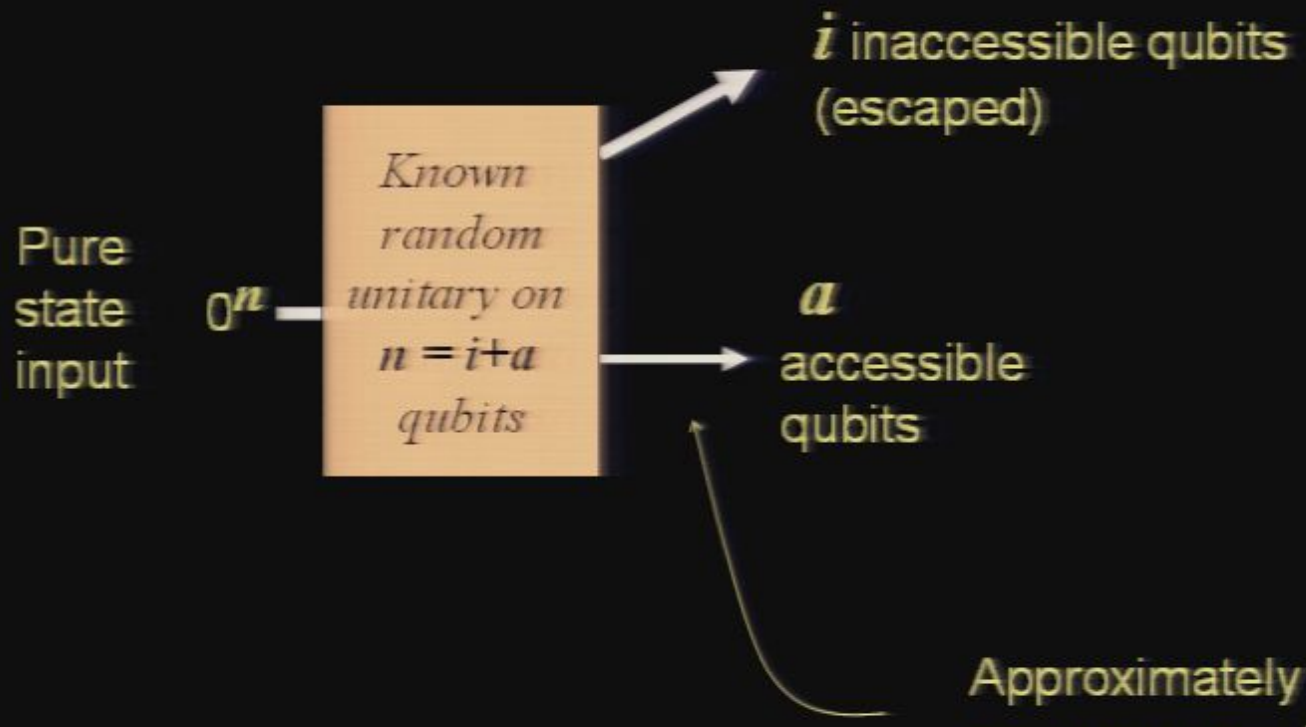
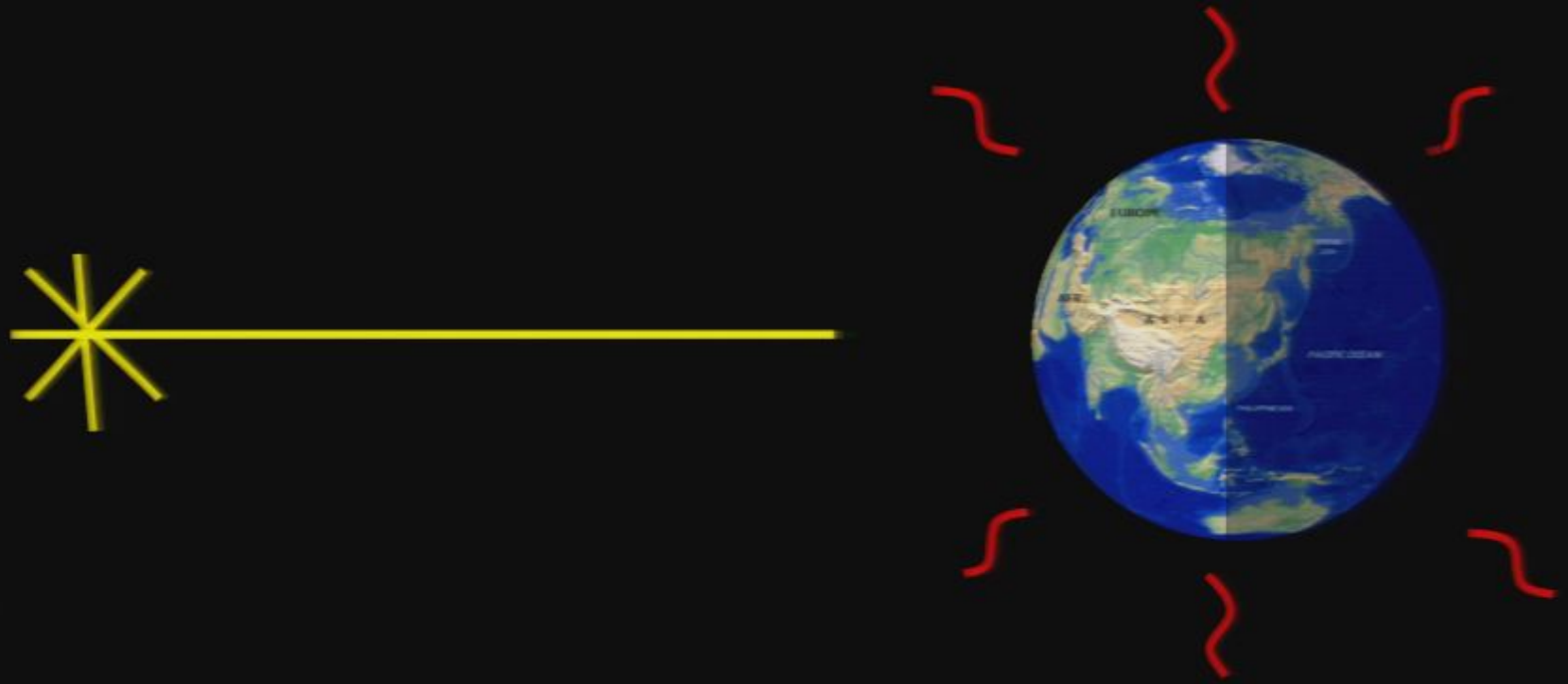
IN 1832 ON
THIS SPOT
NOTHING
HAPPENED

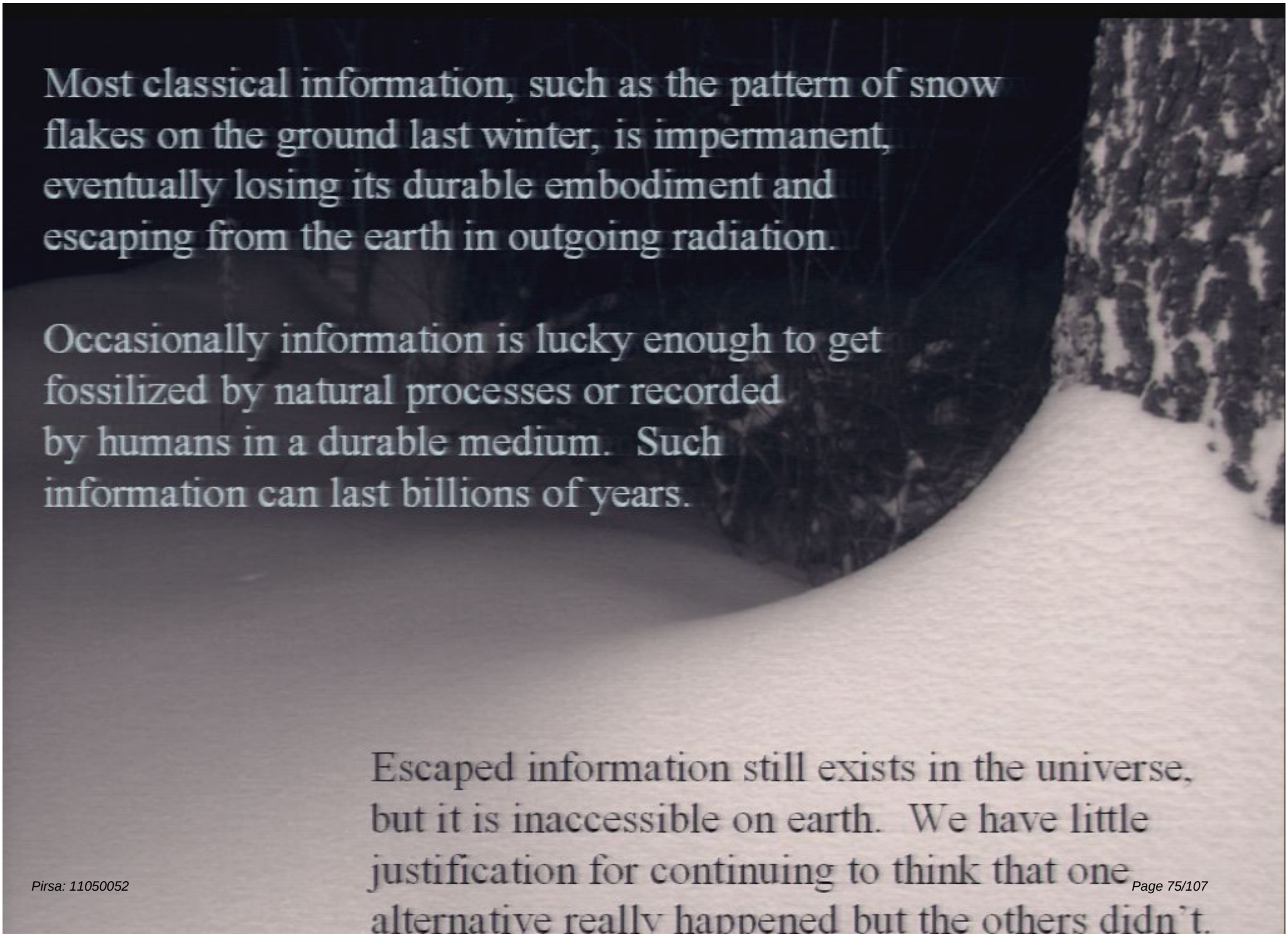
Is random input (eg radiation from the sun) necessary to wash information out of the Earth?

No. Unlike a classical system, a deterministically evolving quantum system can be randomized simply by allowing information to escape from it.





If the earth's solar input were replaced by a laser beam of equal power, the input entropy would be zero while its apparent output entropy rate would be about the same. Thus at a steady state the output entropy rate would also be zero, because of entanglement among the output modes. The earth would be functioning as a giant down-converter. Unlike an ordinary down-converter, the correlations would be exceedingly computationally complex and


Most classical information, such as the pattern of snow flakes on the ground last winter, is impermanent, eventually losing its durable embodiment and escaping from the earth in outgoing radiation.
Occasionally information is lucky enough to get fossilized by natural processes or recorded by humans in a durable medium. Such information can last billions of years.
Escaped information still exists in the universe, but it is inaccessible on earth. We have little justification for continuing to think that one alternative really happened but the others didn't.

Note that even though I have argued that escaped information no longer has a preferred value, it still has a preferred *basis*, according to quantum Darwinism.

One form of the Copenhagen interpretation (presuming a unitarily evolving Earth but an irreversible measurement process somewhere in the sky) says that escaped information does has a definite value, which we are ignorant of. If we find an extraterrestrial fossil, it will "agree" with the value we once knew but have forgotten.

Ruediger Schack says he'd rather believe that Sappho's lost poems are real than that the wave function of the universe is real.

I lean the other way, but it is only a matter of taste.

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?

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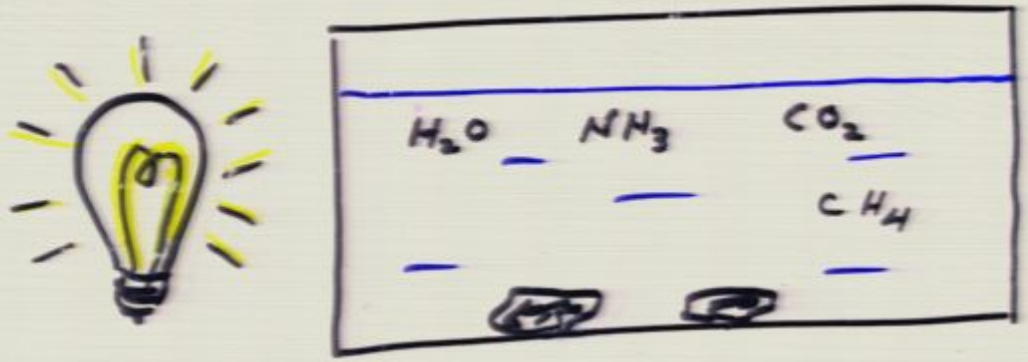
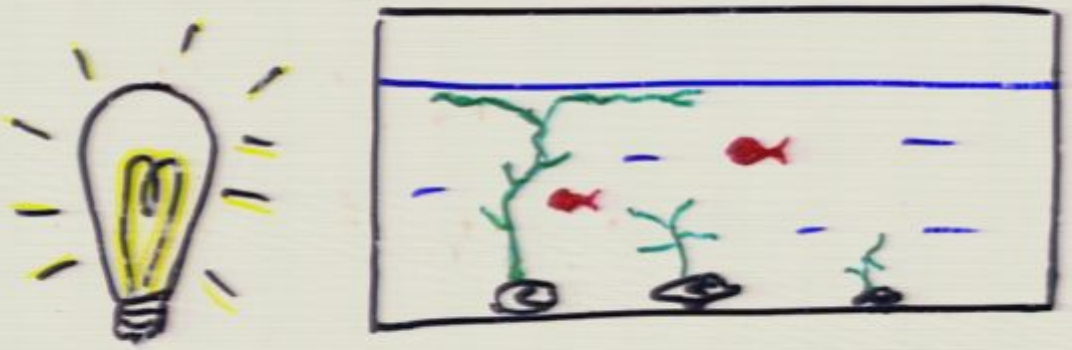
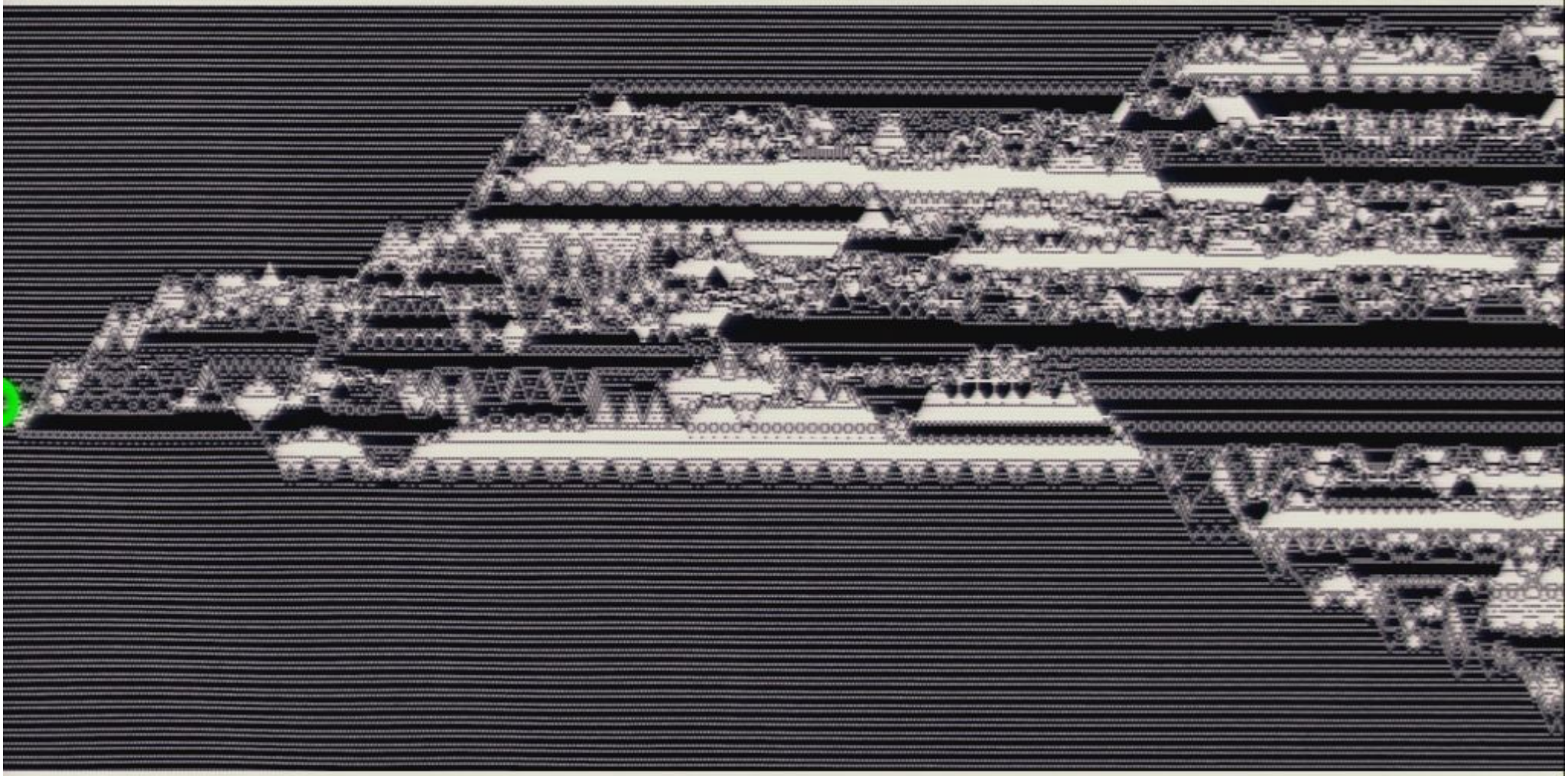
A simple cause can have a complicated effect, but not right away.



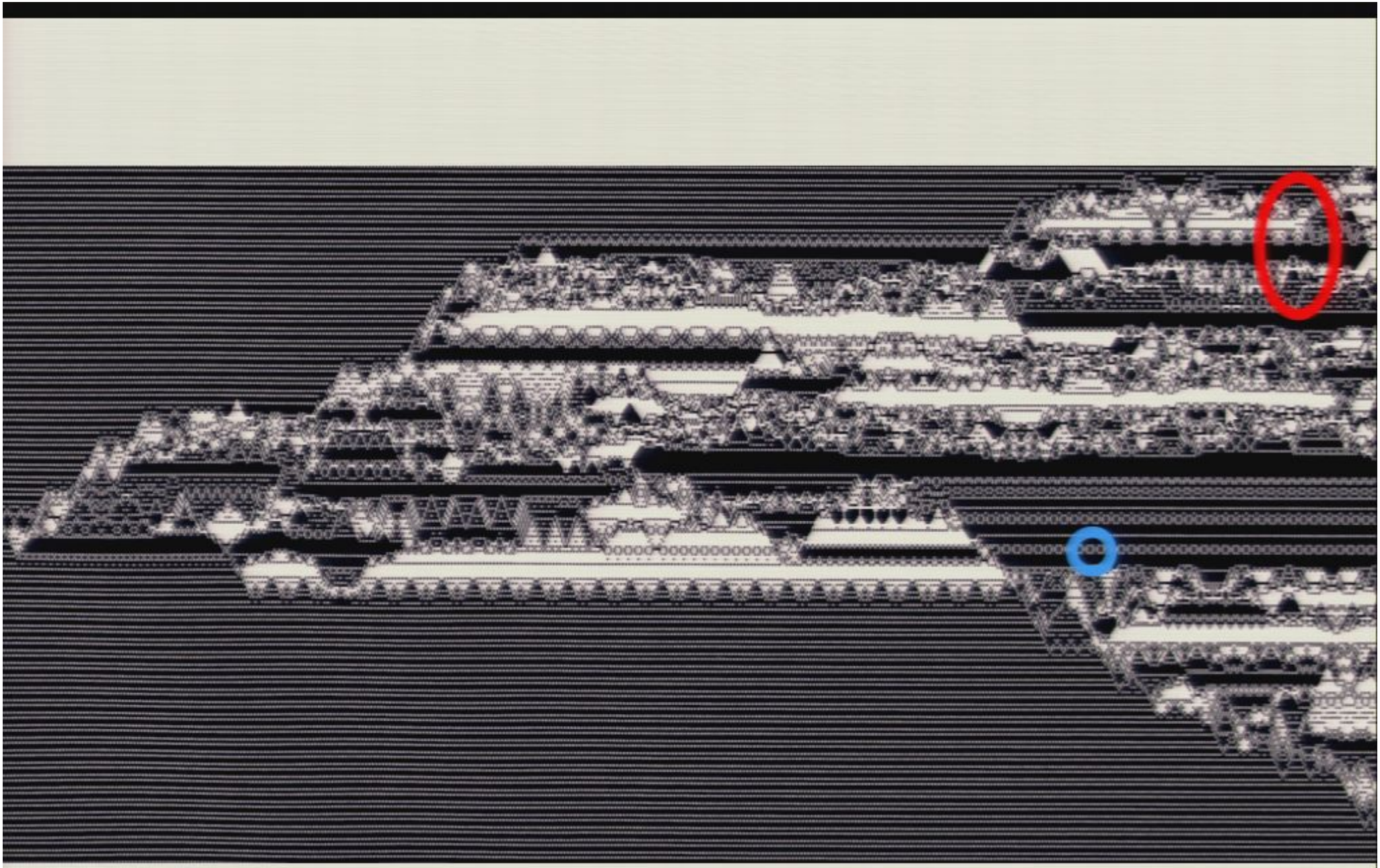
Much later



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

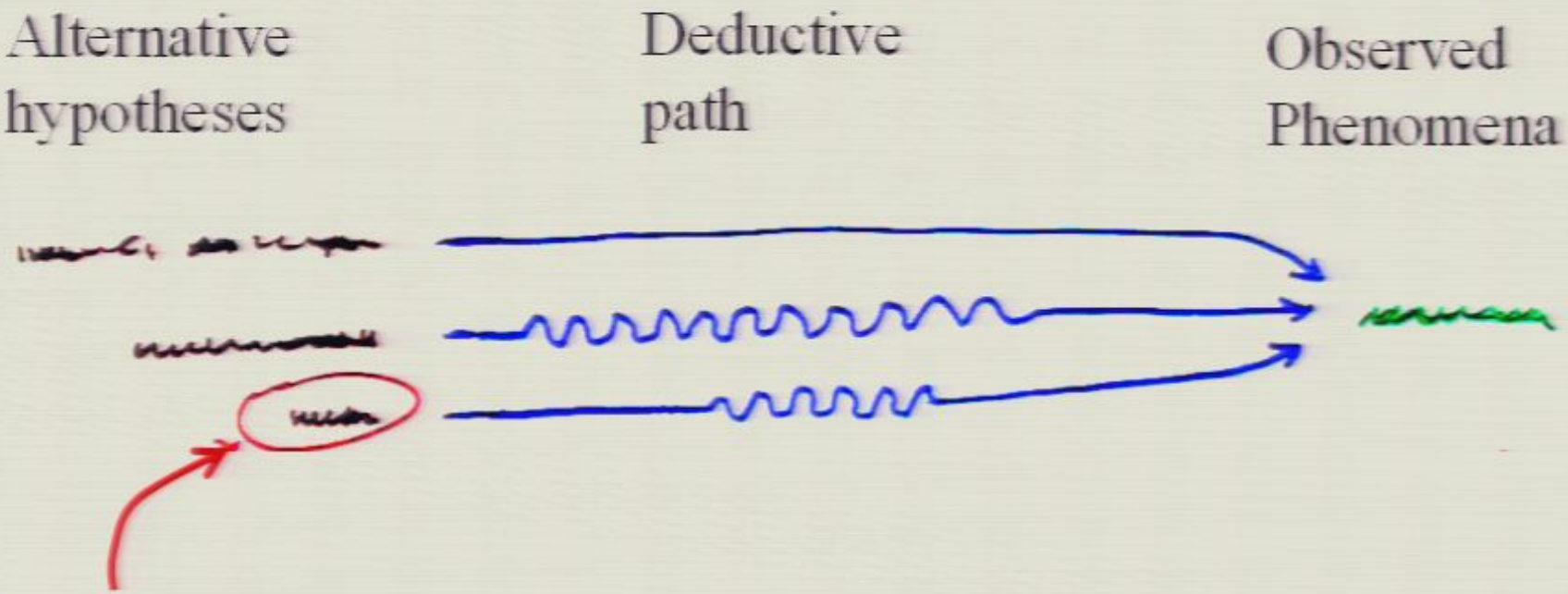


Small irregularity (green) in initial pattern produces a complex deterministic "wake" spreading out behind it.



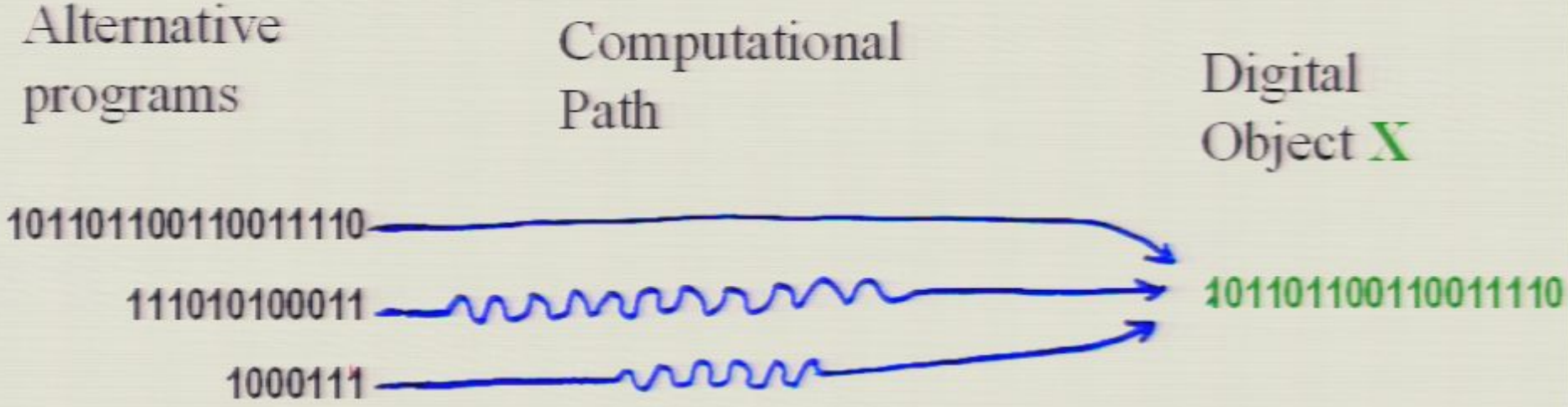
A sufficiently big piece of the wake (red) contains enough evidence to infer the whole history. A smaller pieces (blue) does not

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.



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.



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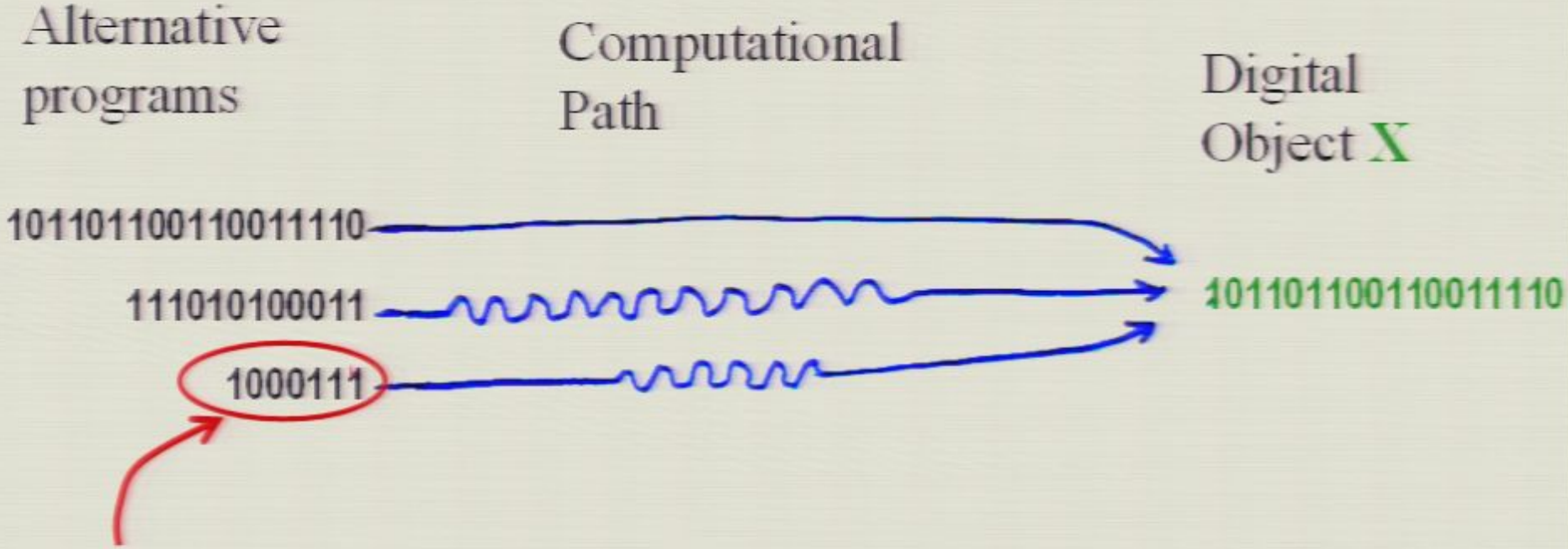

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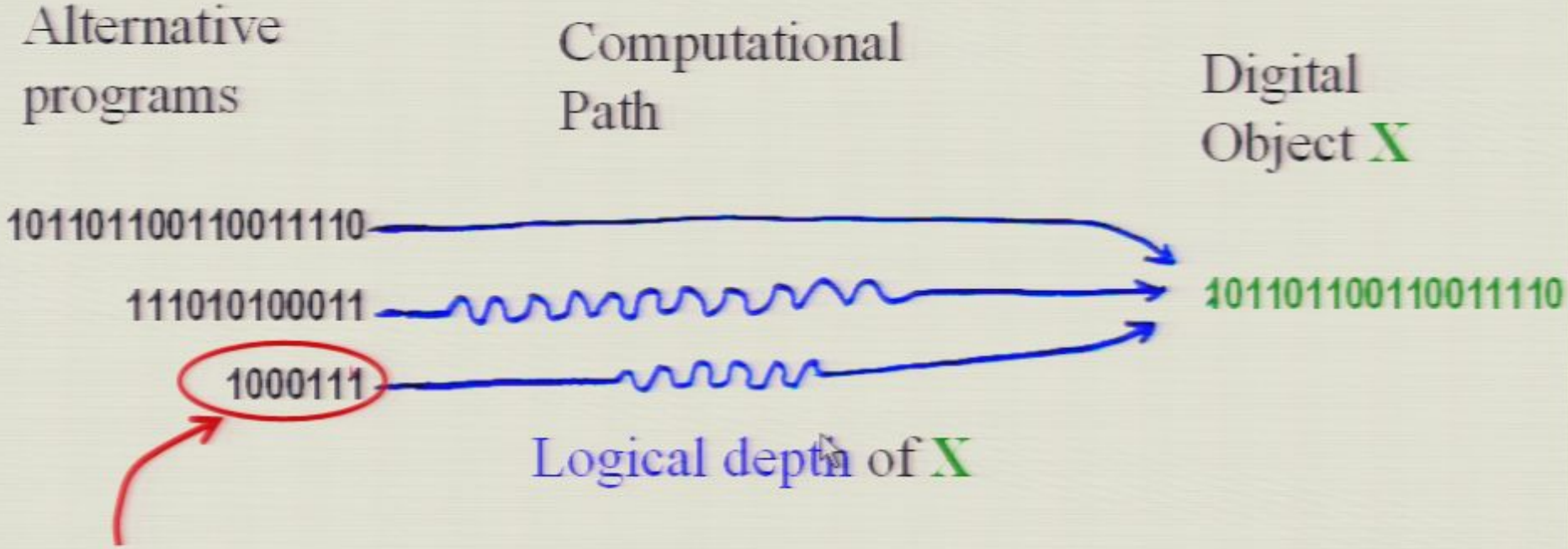

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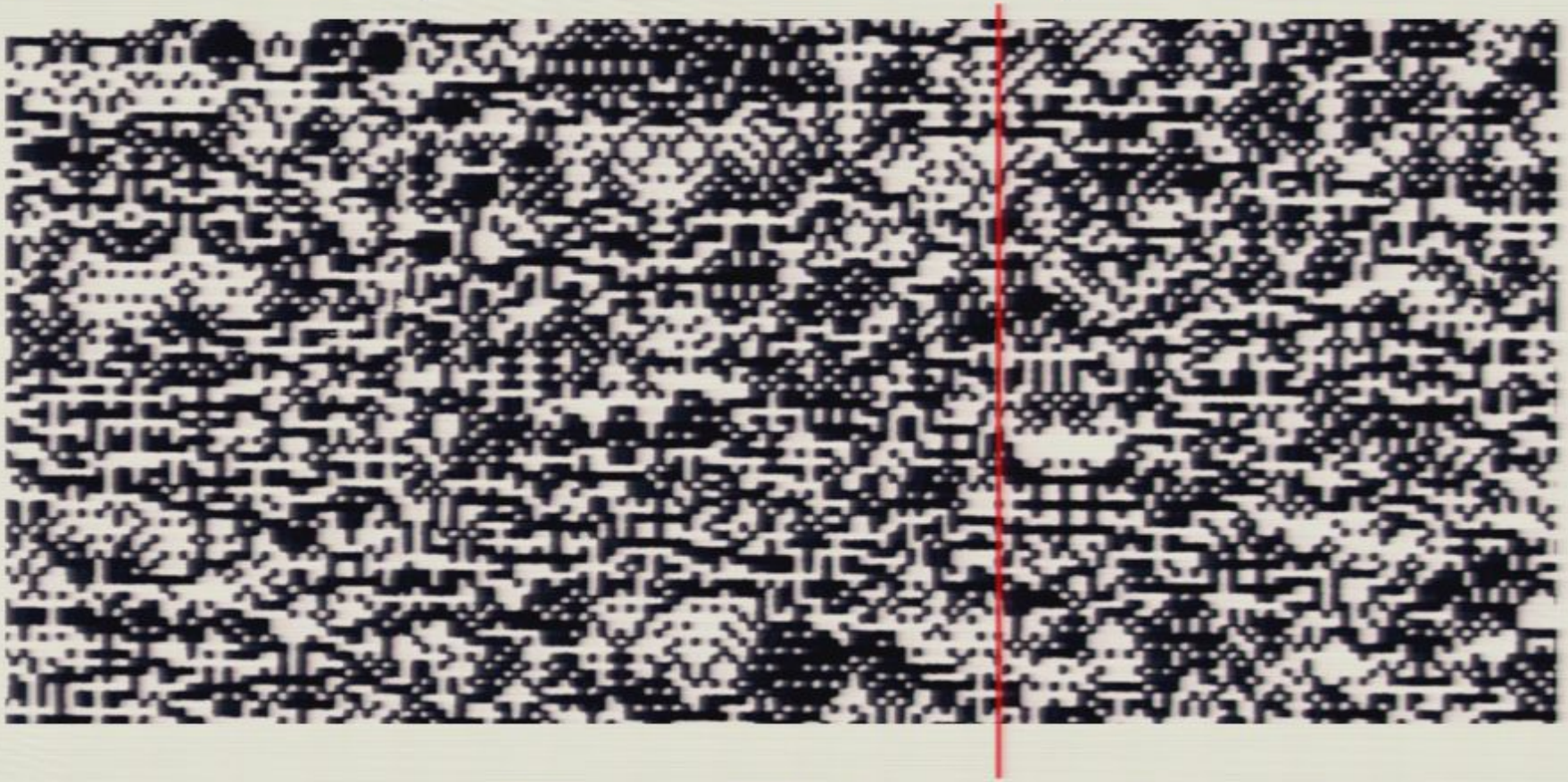
A trivially orderly sequence like 111111… is logically shallow because it can be computed rapidly from a short description.

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.

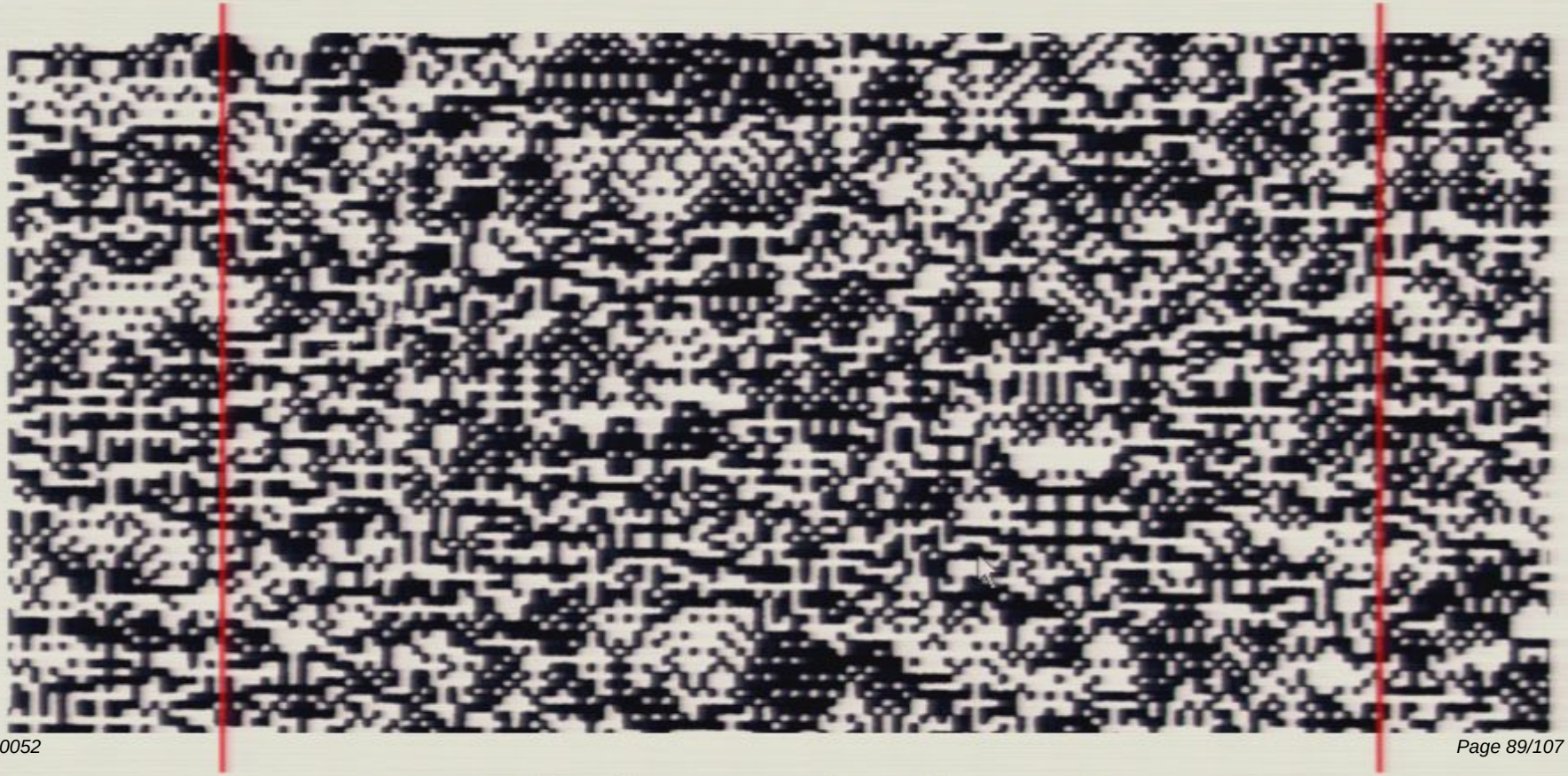
If a reversible local dynamics (e.g. the 1d system considered earlier) is allowed to run long enough in a closed system, comparable to the Poincaré recurrence time, the state becomes trivial and random.

Our world is complex because it is 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.)



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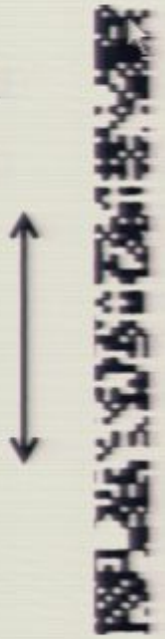
Equilibrium correlations mediated through present only



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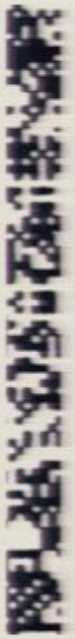
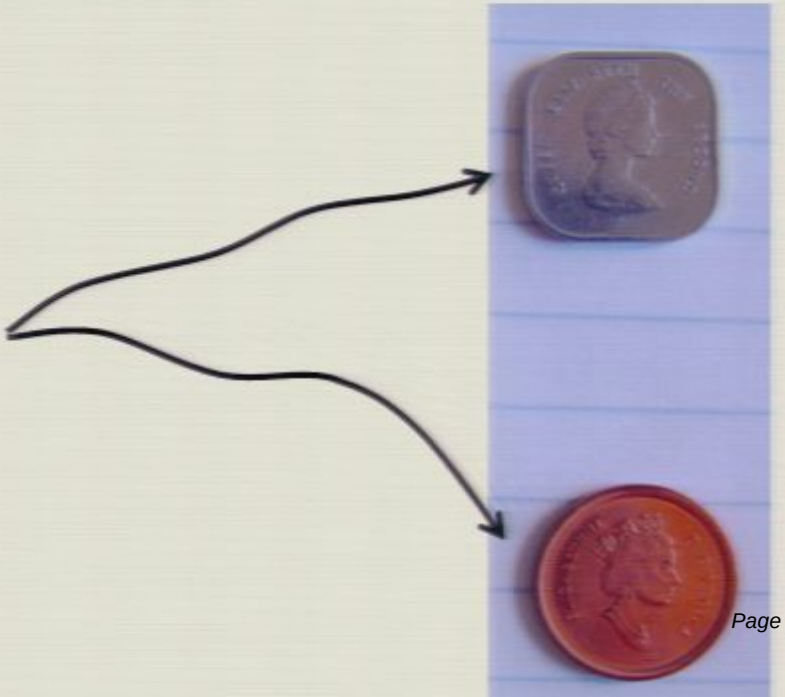


By contrast, in a non-equilibrium world, local dynamics can generically give rise to long range correlations, mediated not through the present but through a V-shaped path in space-time representing a common history.

time ⟶



Grenada 1999

Canada 2002

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The cellular automaton is a classical toy model, but quantum dynamics behaves similarly.

If the Earth were put in a large box and allowed to relax for a time comparable to its Poincaré recurrence time, its state would no longer be phenomenologically classical.

The radiation field in the box would no longer contain redundant optical replicas of details on the Earth's surface. Rather the radiation field would be thermal, its photons having been absorbed and reemitted from the Earth many times. The entire state in the box would be a microcanonical superposition of near-degenerate energy eigenststates of the closed Earth+cavity system. Such states are typically highly entangled and contain only short-range correlations.

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 terrestrial past nearly as ambiguous as the future.

- Thermal disequilibrium enables both complexity and classicality.

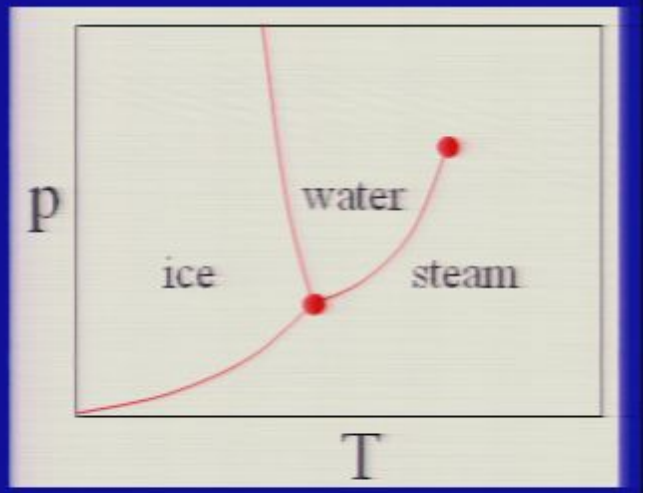
How strong is the connection between disequilibrium and complexity, in the sense of logical depth?

Are thermal equilibrium states generically shallow? Yes.

- Gibbs phase rule: for generic parameter values, a locally interacting classical system, of finite spatial dimensionality and at finite temperature, undergoes nucleation and growth of a unique Gibbs state of lowest bulk free energy.

  => no long term memory

  => as N, $t \to \infty$, depth remains bounded

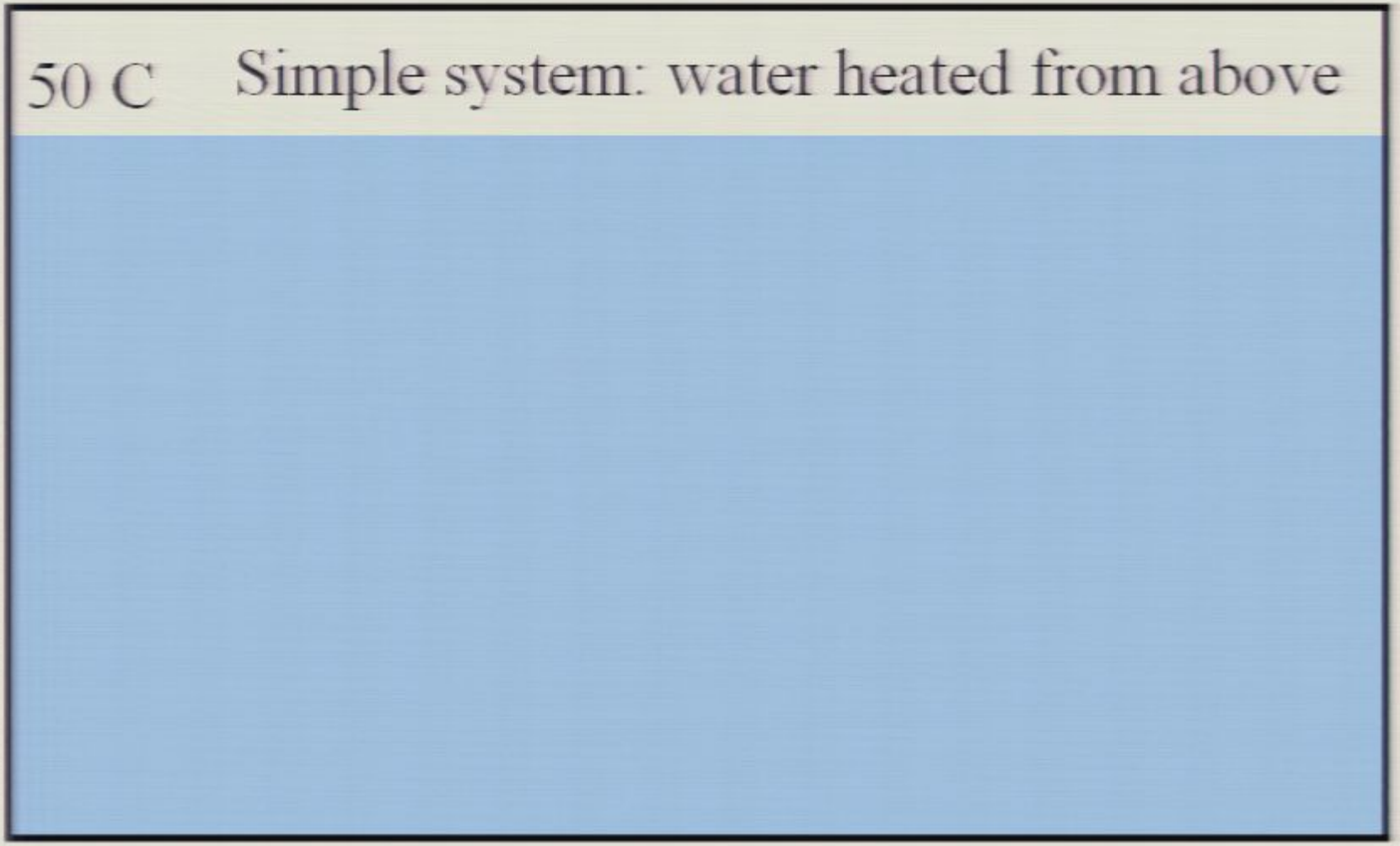


Quantum exception, in 3 or more dimensions.

[Bravyi et al 0907.2807, Alicki et al 0811.0033…]

Conversely, what else is required, besides disequilibrium, for a system to generate unbounded depth in the limit of unbounded time and spatial extent?

Dissipation without Complexity



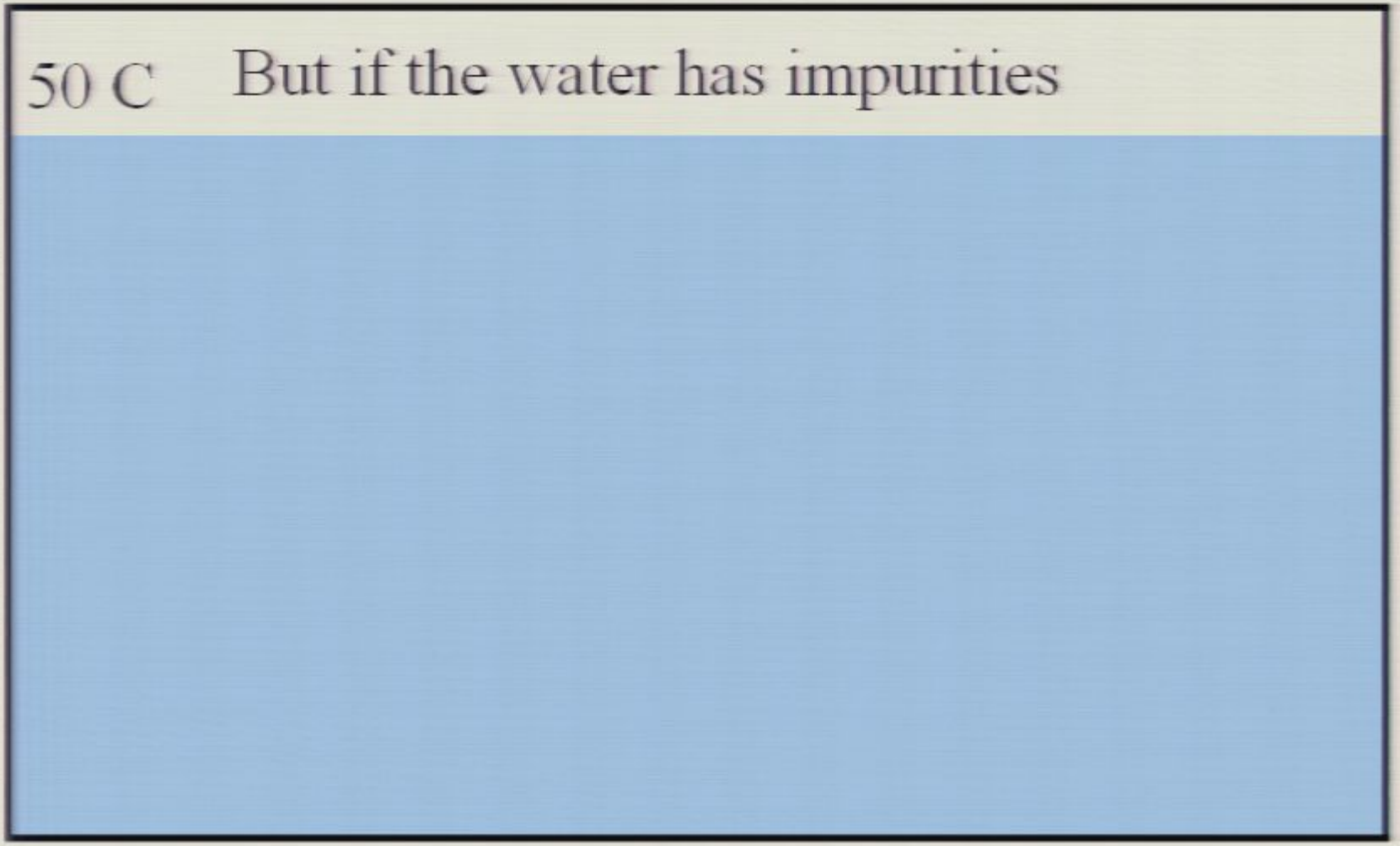
Dissipation without Complexity

50 C Simple system: water heated from above

Temperature gradient is in the wrong direction for convection. Thus we get static dissipation without any sort of computational complexity, beyond an analog solution of the Laplace equation.

10 C

50 C But if the water has impurities



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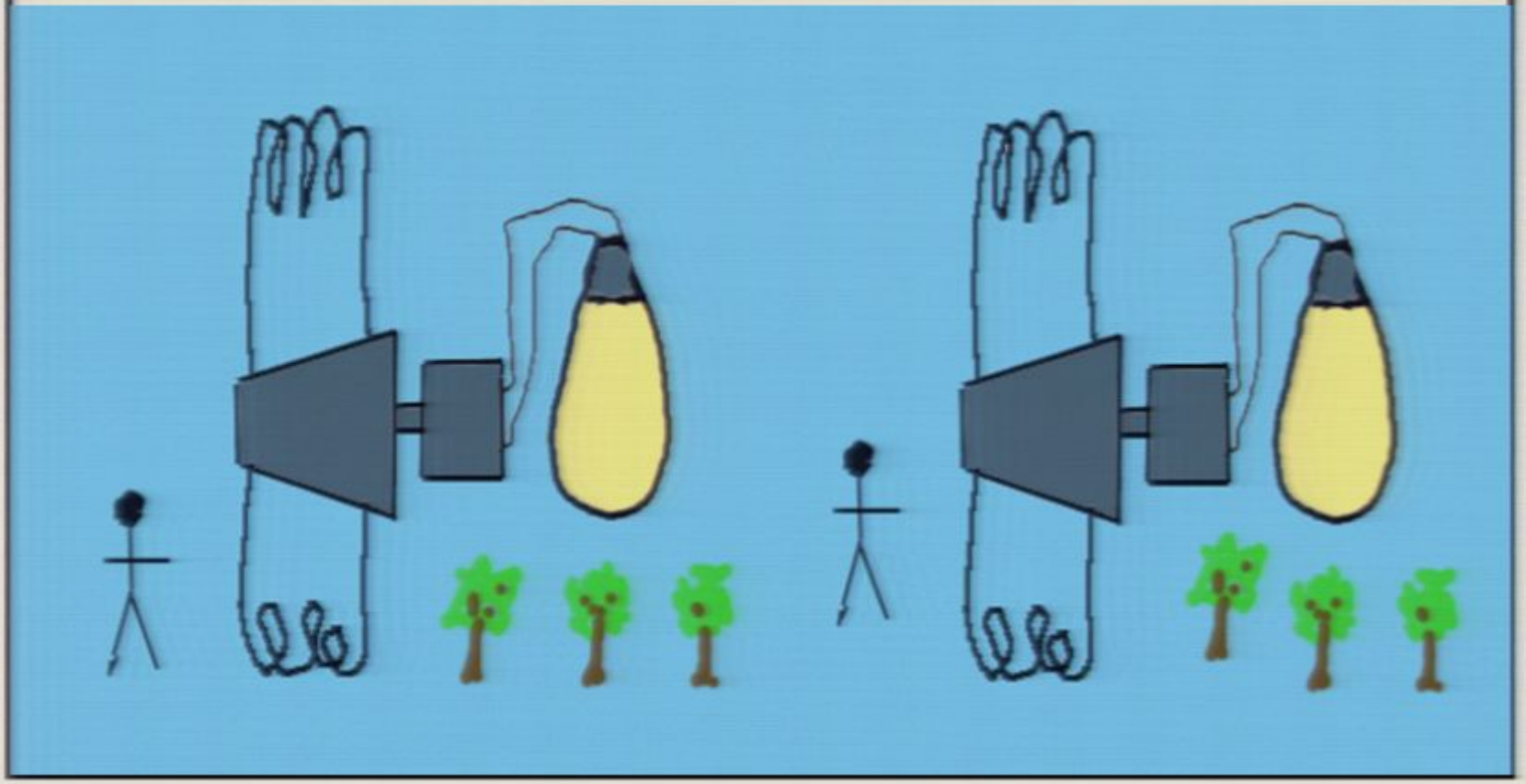

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Problem: But can complexity ever really be destroyed? Even after a destructive event like the Second World War, all the preexisting information, along with its logical depth, is still present in the Universe, though maybe escaped from the Earth. Indeed the complex transformations leading to its escape may have made the Universe even deeper than before, though the Earth may be shallower. If depth can't decrease, it would appear a rather vacuous measure of complexity.

Answer: The decrease in the *Earth's* depth comports with our feeling that something valuable was lost. But inquiring how the *Universe's* depth changes with time is too impatient a way of thinking. From God's viewpoint there is no time, nothing ever happens, and Universe's complexity doesn't increase or decrease.

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