Quantum Information, the Ambiguity of the Past, and the Birth and Death of Complexity

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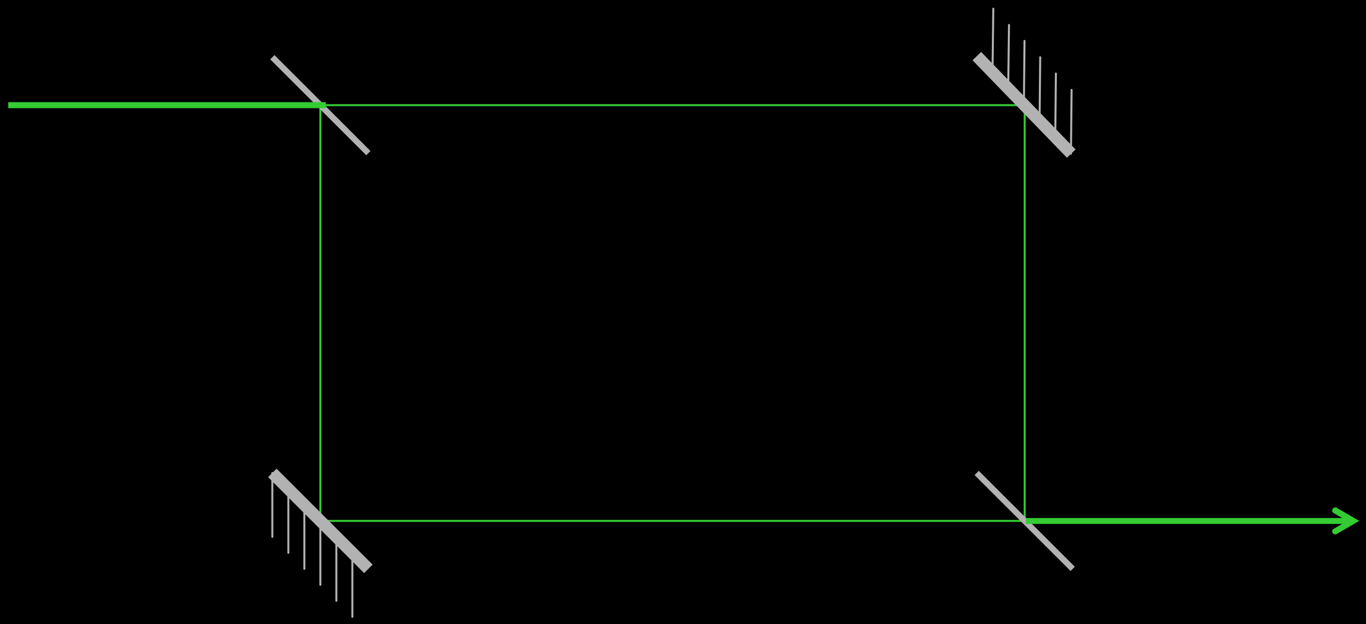
Reasoning from classical mechanics, Laplace thought the future and past were fully determined by the present, but attributed the perceived ambiguity of the future to our imperfect knowledge of the present, and/or our lack of sufficient computing power to predict the future. An omniscient God would know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

But past macroscopic classical information is 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 in the same way as future quantum outcomes.



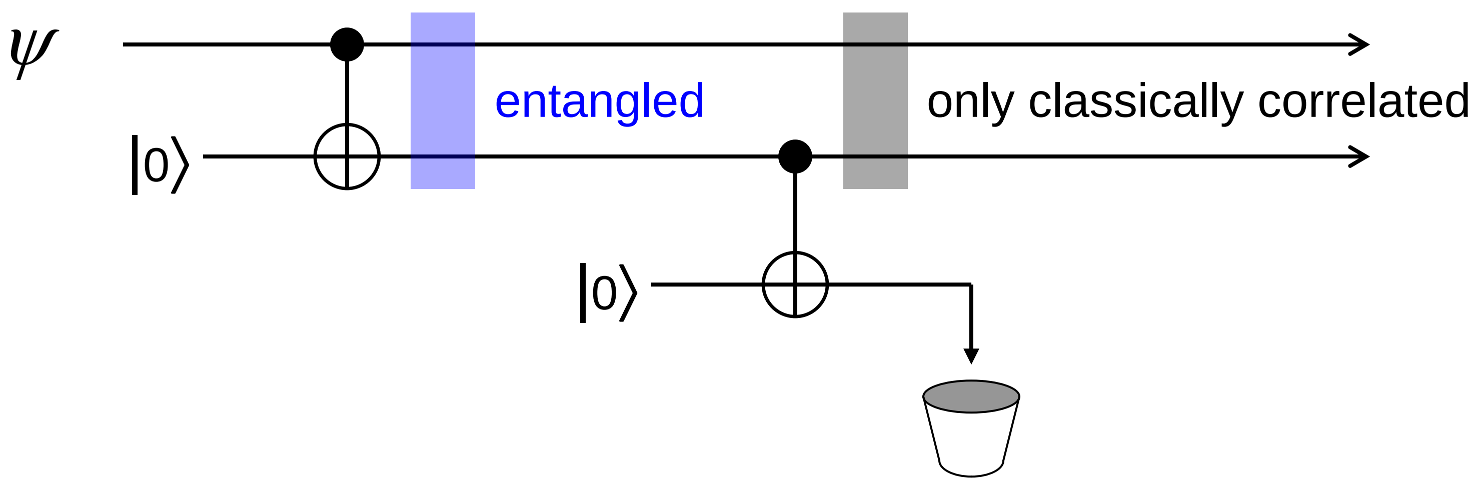
After the experiment is over, even God doesn’t remember which path the particle followed.

Monogamy of Entanglement

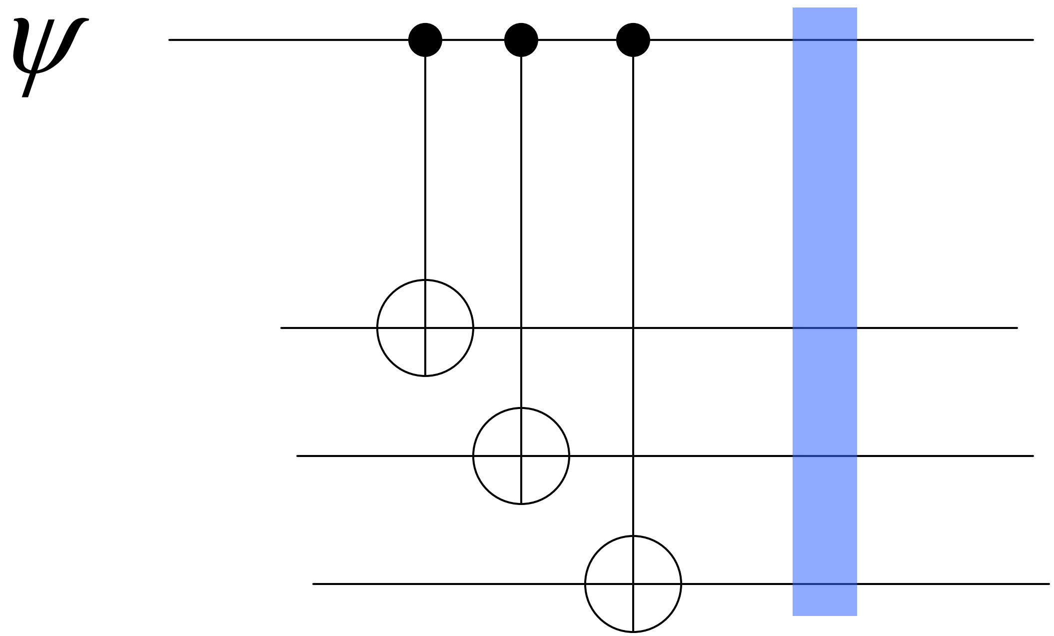
• If A and B are perfectly entangled with each other, they cannot be even classically correlated with anyone else.

• 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".



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



System

Environment:

Measured in 0/1 basis, it yields many redundant copies of the system's information. In other bases it does not.

Information becomes classical by being replicated redundantly throughout the environment. *"Quantum Darwinism"*
Blume-Kohout, Zurek quant-ph/0505031 etc.

*(This typically happens when the environment is **not** at thermal equilibrium, and when it contains many subsystems that interact more strongly with the system than with each other and… The earth's environment is like that.)*

In the practical tradeoff between Publicity and Privacy, digital technology has created a problem and an opportunity

Cheap, easy-to-use video cameras and cheap data storage leads 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 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.

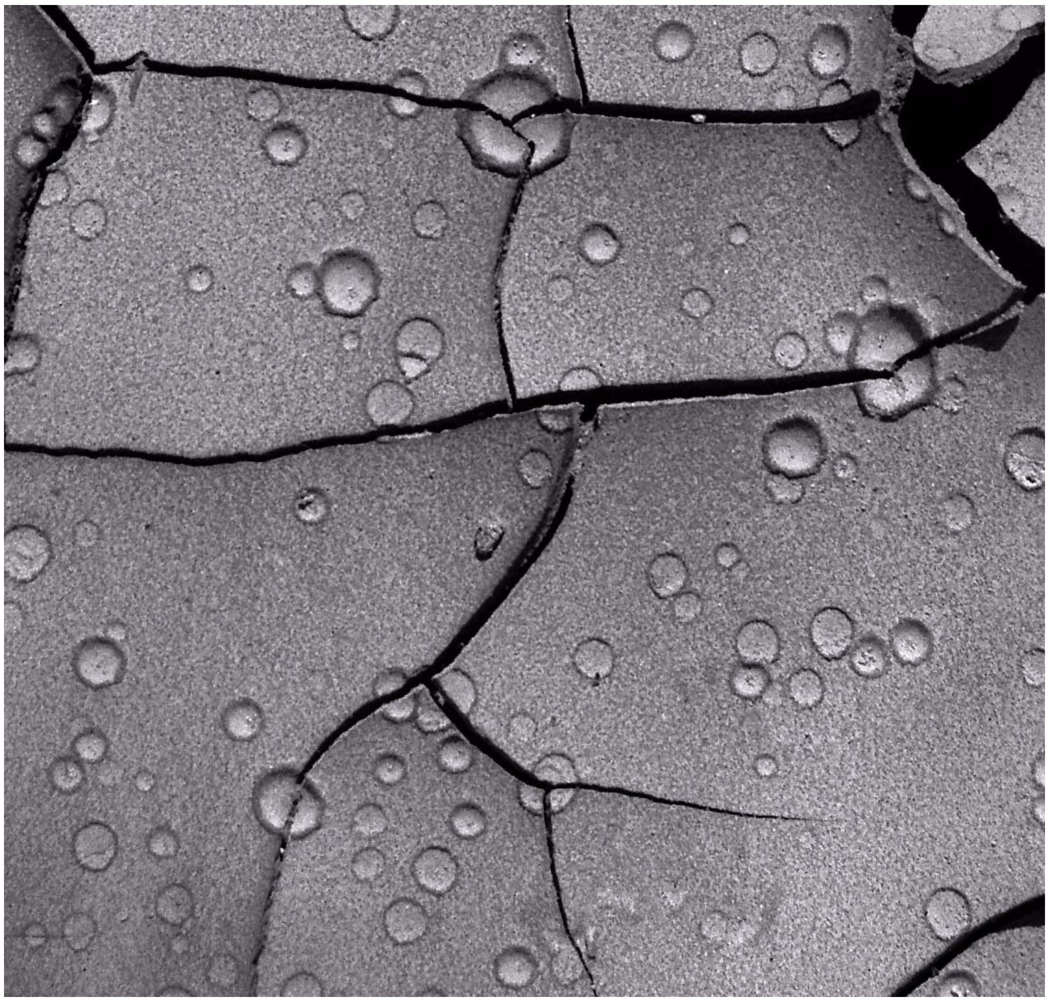
Ancient Greek poet Sappho, ca 620-525 BC, as depicted by Gustav Klimt ca 1900.

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, in India, after surviving nearly 2000 years, 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.

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.



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 the physicist Ettore Majorana 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.

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.

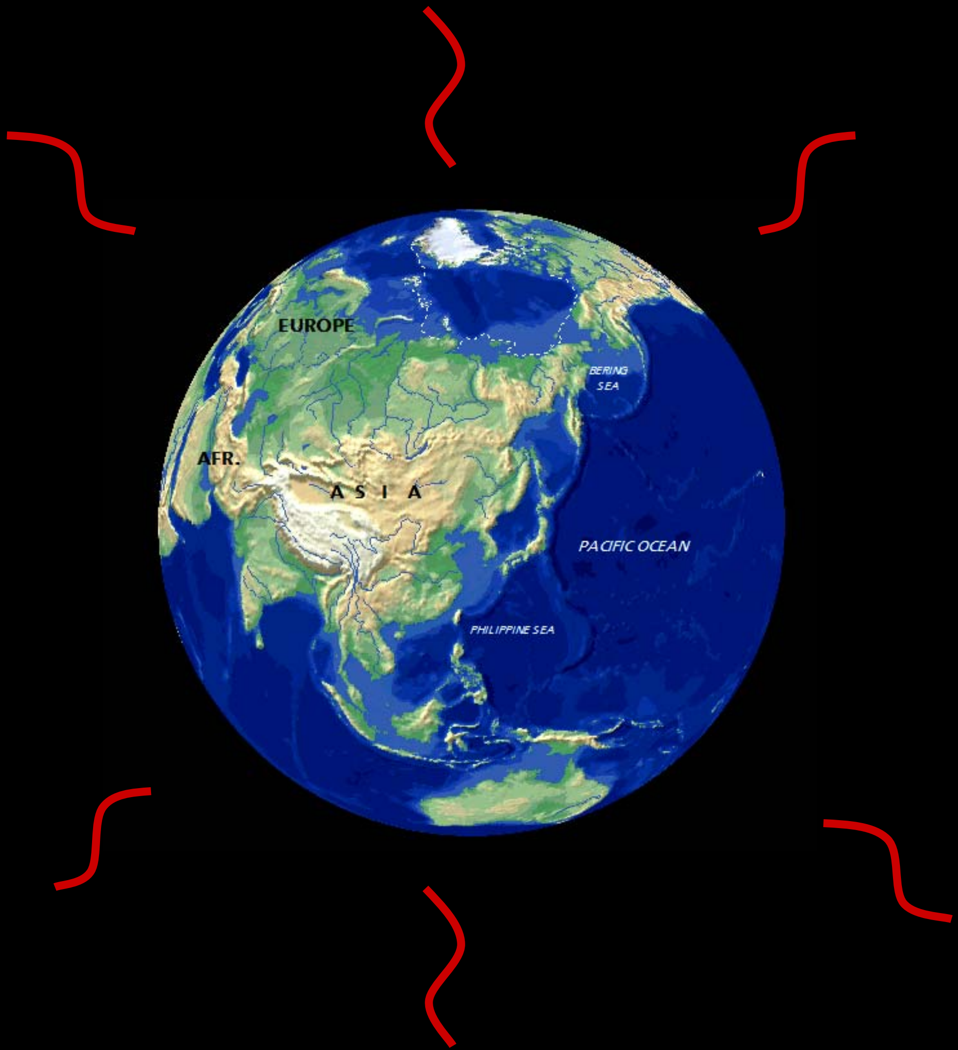
The Earth has finite information storage capacity, but it exports a lot of randomness (generates a lot of entanglement with its environment, in the quantum way of speaking) in the form of thermal radiation into the sky.

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

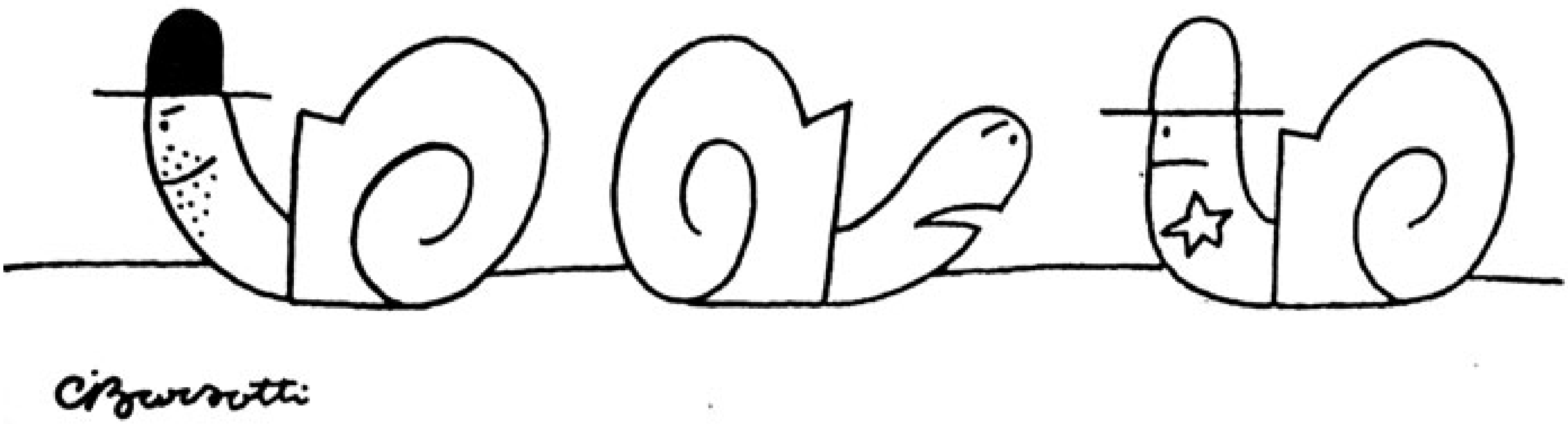
Geological information capture rate in "hard" degrees of freedom, stable for geological times against thermal motion (e.g. atomic substitutional disorder and crystal lattice defects in solid rock of earth's crust) = crust thickness ($\approx$10 km) $\times$ rock information density ($\approx$1 bit/cubic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

Human digital information capture rate 100GB/person x 10^9 people who are heavy information users $\approx 10^{21}$ 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.



"He's long gone, sheriff—you'll never catch him."

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 sushi.

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.

What can we do to make a particular chosen body of information long-lasting (say until the sun turns into a red giant)?

Why would we want to?

- To preserve important works of literature
- To preserve evidence of a crime until it is safe to publicize, thereby discouraging crime even in times of despotism and corruption
- Because we hate postmodernism and want to make even unimportant details of the past uncontestable.

Record the information in a durable digital medium, and bury many copies in geologically stable rock formations in various parts of the world, as if it were nuclear waste.

But suppose we wanted to store not all or most, but a lot of information, say a real-time video surveillance of entire earth surface at millimeter-millisecond resolution.

This works out to about 10^{16} bits/sq m year, well within geological capture rate.

Is this scary thing perhaps happening already, automatically, without deliberate human effort, just because frozen accidents in newly formed rock in a sense provide a hash of the current state of the earth?

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

Some further Questions

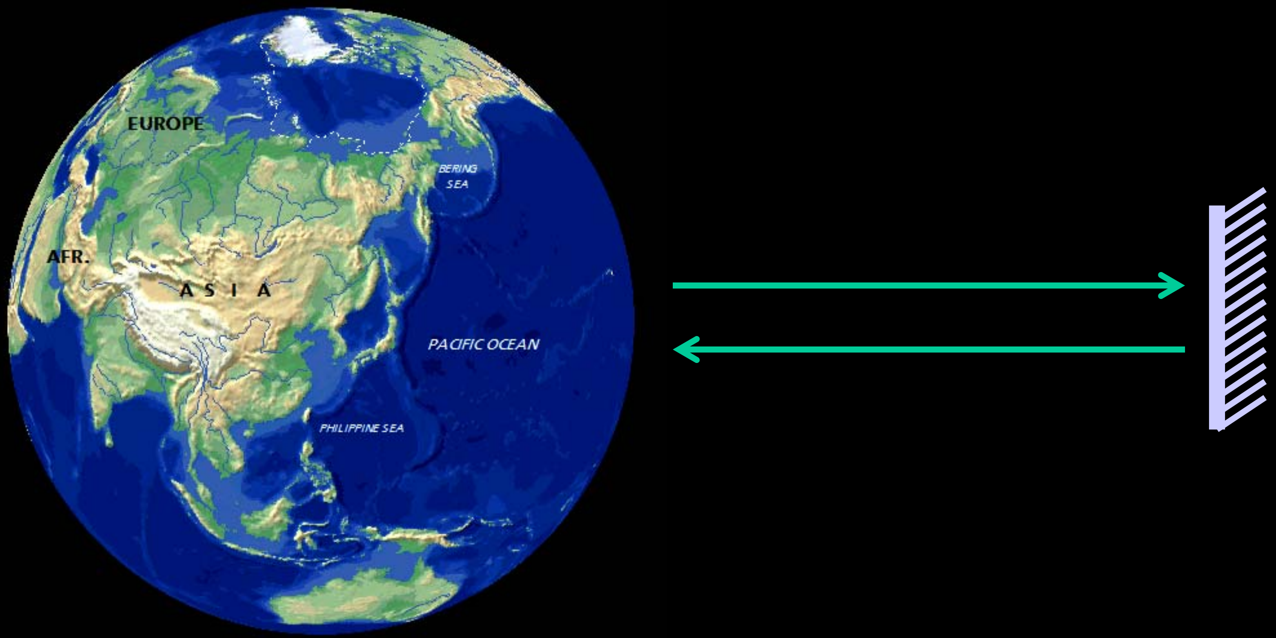
- Is it really impossible to recapture the escaped radiation?

- What is the ontological status of escaped information? Does the universe remember where the raindrops fell, even after all terrestrial evidence is gone?

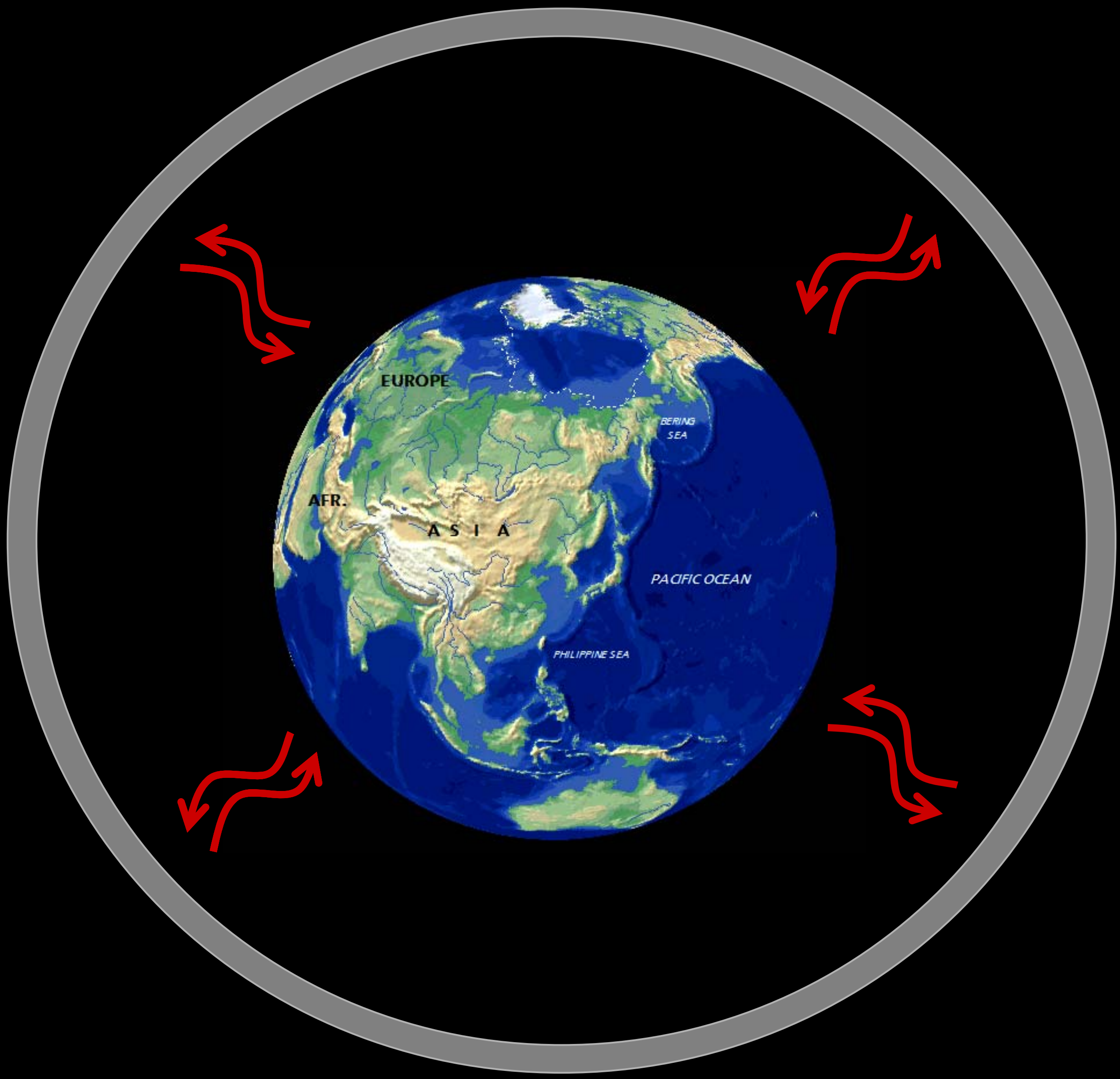
- Is random input (e.g. entropy of incoming solar radiation) necessary to make the earth forget things?

- Even after classical information is lost from “hard” geological storage, might it still be retained in the earth’s far more numerous “soft” degrees of freedom such as phonons in the earth’s core and mantle?

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

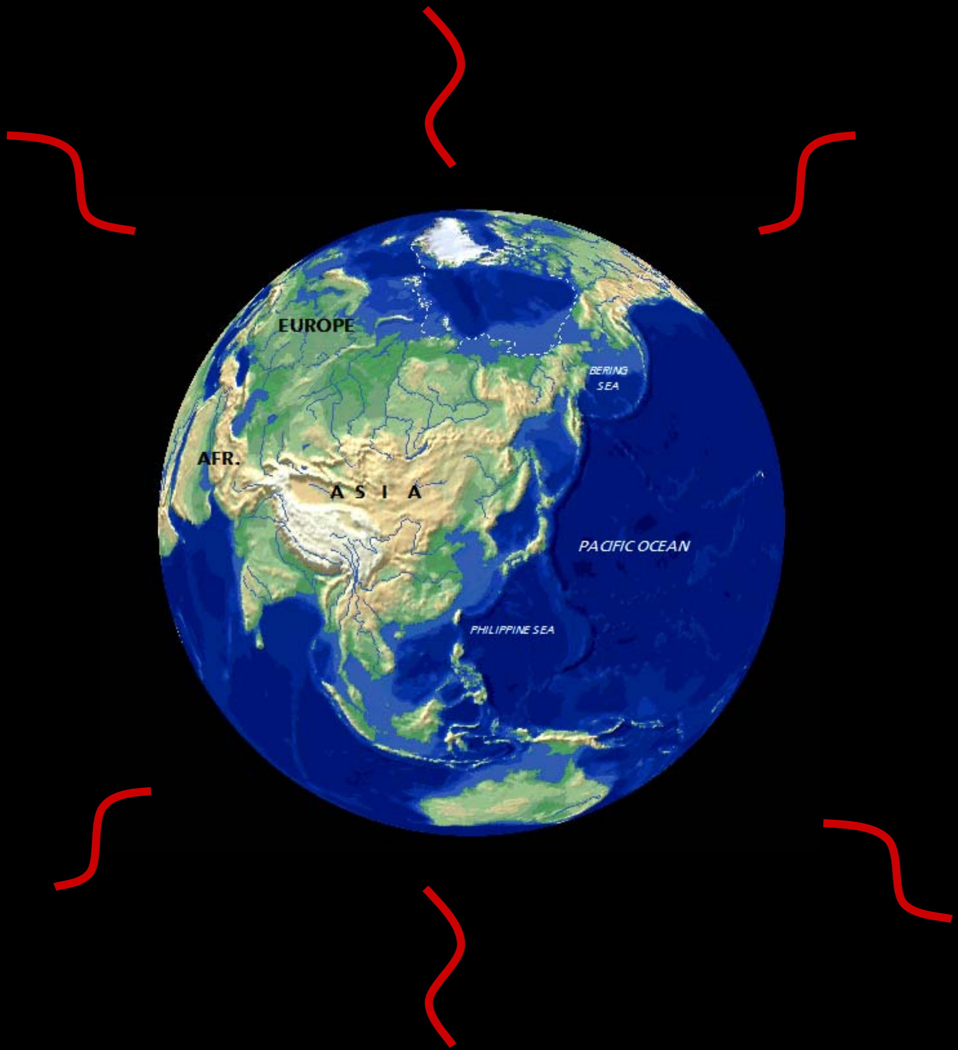


Yes. For specific items of non-thermalized outgoing radiation (e.g. optical earth views, old TV broadcasts) , this could be arranged, with advance planning, or it might happen accidentally. Such information could be called extraterrestrial fossils.



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 badly overheat.

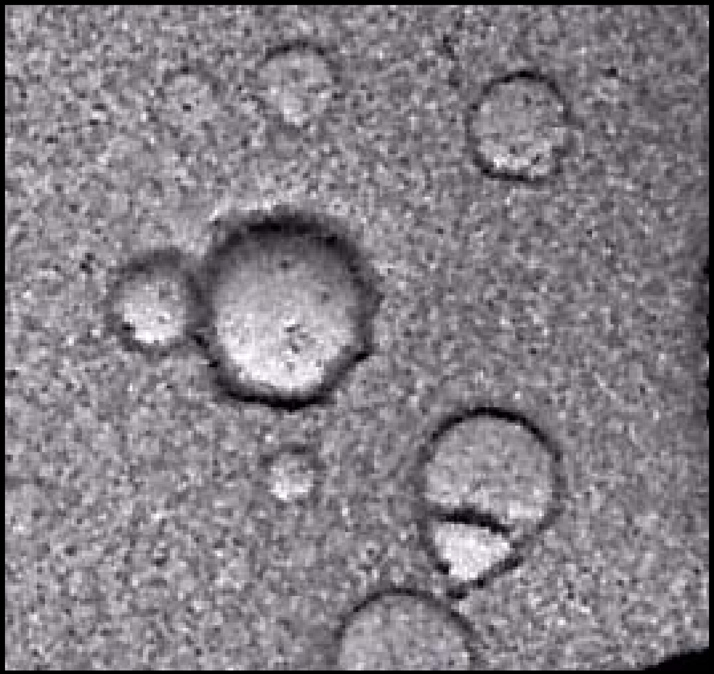
• Can we outrun the radiation?



For example, one might hope to outrun the thermal radiation, because the refractive index of interstellar space is slightly >1.

But this hope is probably dashed by the accelerating expansion of the universe (a.k.a. cosmological constant, dark energy) which causes remote objects now visible (e.g. other galaxies) to eventually become inaccessible.

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.

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**) /√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** /√2 Drop begins to evaporate, emitting further radiative replicas.

(**LLLLL**+**RRRRR** /√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

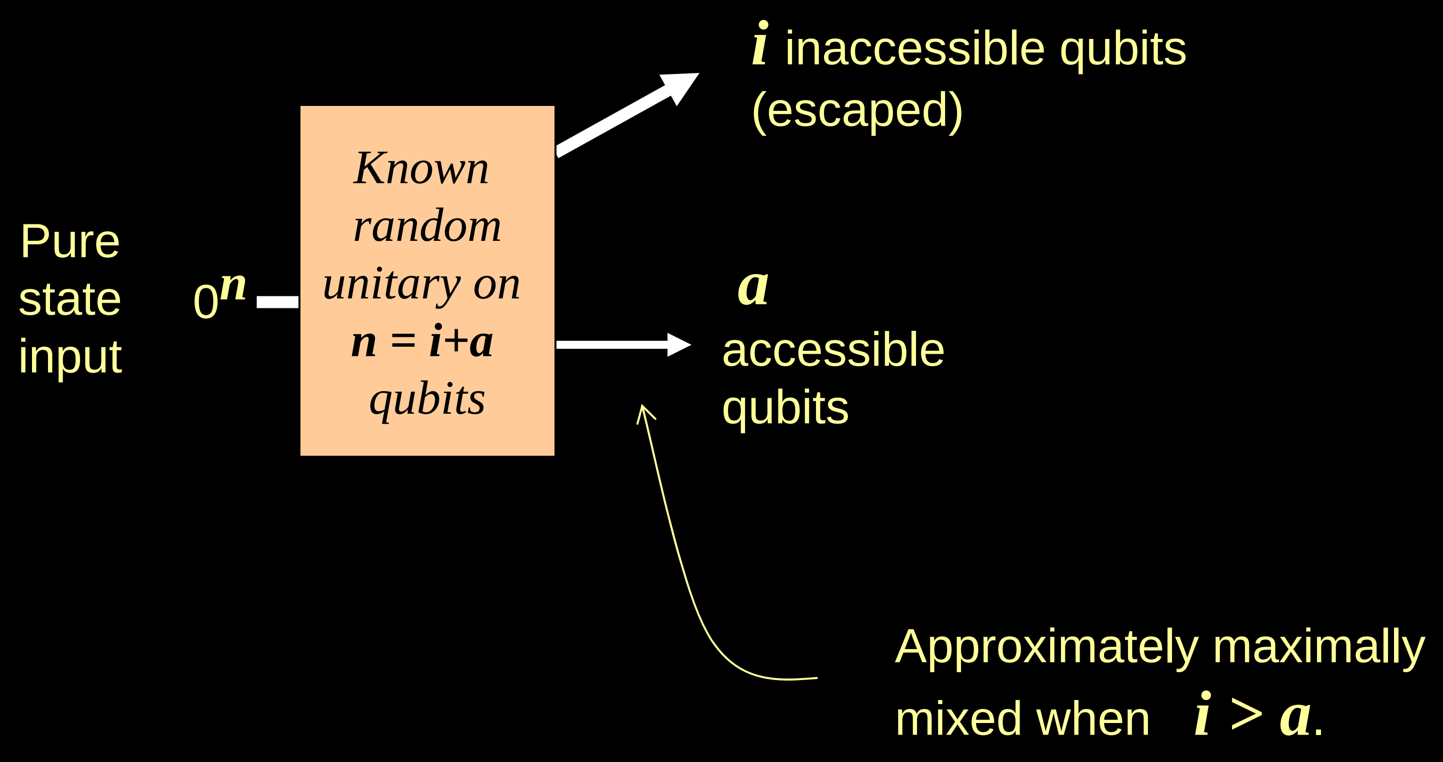
Escaped information as a kind of spontaneous quantum erasure:

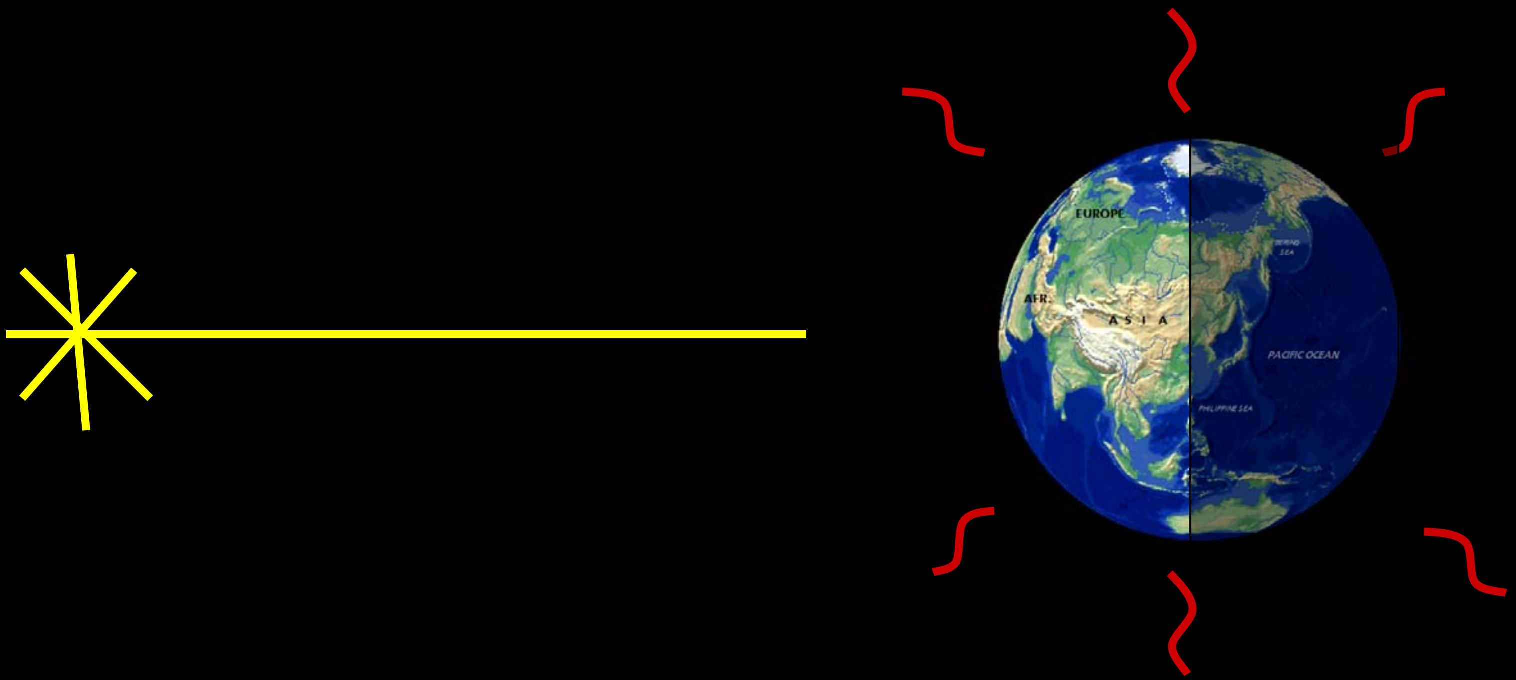
- Quantum erasure restores product state by undoing a measurement.
- Random unitary radiation gradually restores a near-product state
- A trivial form of quantum erasure would be to measure which path, generating an entangled state between, say, a photon's path and a monitoring atom, then to discard both the photon and the monitoring atom into the environment.

A form of information especially susceptible to escape is "which atom" information associated with thermal motion and chemical reactions, during which in many cases the atoms follow sufficiently classical trajectories that one can know, with high fidelity, which of several identical atoms in an initial configuration corresponds to a particular atom of that species in a later configuration. For example, one can say that during fermentation the #2 carbon of glucose ends up in the alcohol, rather than the carbon dioxide. Normally this is taken to mean that if that carbon were isotopically substituted, it will end up in the alcohol; but it can also be taken to mean that without isotopic substitution the environment in principle eavesdrops on the trajectories sufficiently well that it could attest the continuity of an atom's path from sugar to alcohol. I suspect that this kind of which-path information escapes in a time one could estimate in the same way as one does the information encoded in soft degrees of freedom in the earth.

Is random input (eg radiation from the sun) necessary to achieve randomization?

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 unobservable in practice.

Up to now, I have considered only geologically stable “hard” degrees of freedom in the crust, and neglected the far more numerous “soft” degrees of freedom (e.g. phonons and photons) in not only the crust but the whole body of the earth. These degrees of freedom have entropy about a million times *greater* than the annual radiant entropy flux leaving the earth. Could it be that, if Jimmy Hoffa had been were cremated in a way that efficiently coupled to soft degrees of freedom in the earth (deep underground, for example), this soft evidence would persist for about half a million years, even after the hard evidence was gone?

Probably not, because the entangled reference systems purifying these soft degrees of freedom are largely escaped, neutralizing their usefulness in recovering what happened to Hoffa. (This is similar to the argument given earlier that newly solidified crustal rock is not automatically recording a hash from which a low-resolution surveillance video of the earth’s surface can be recovered.)

A final question about information loss:

Blackbody radiation contains no information about the objects it illuminates. Does that mean it does not decohere them?

Thermal state in
ρ

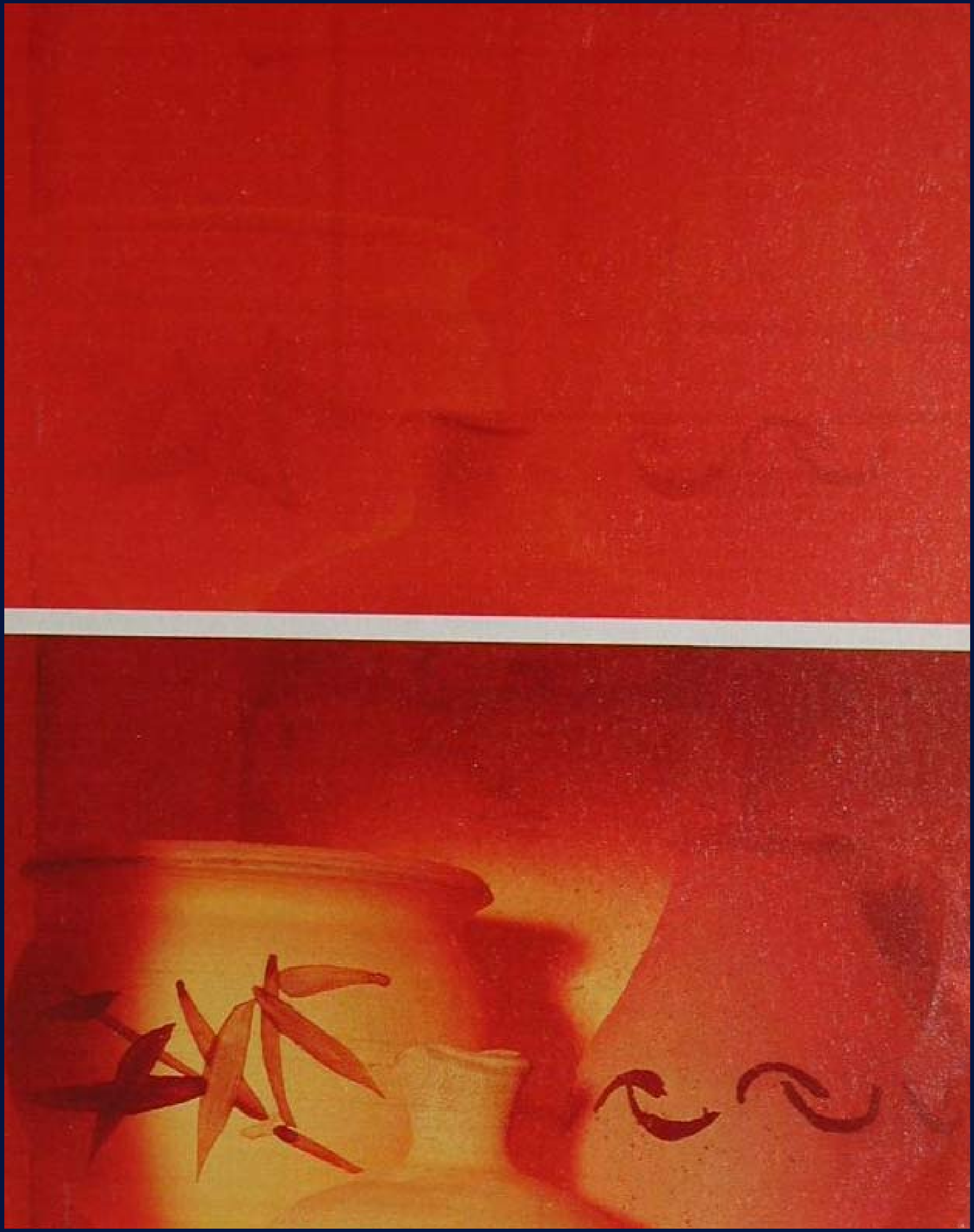
Thermal state out
ρ

No information

Looking inside a pottery kiln

by its own glow

by external light



Entangled Purification of Thermal input

Ψ_ρ

Different Purification out

Ψ'_ρ

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. Humans have little justification for continuing to think that one alternative actually 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.

R. Schack prefers that Sappho's lost poems be real instead of the wave function of the universe being real.

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

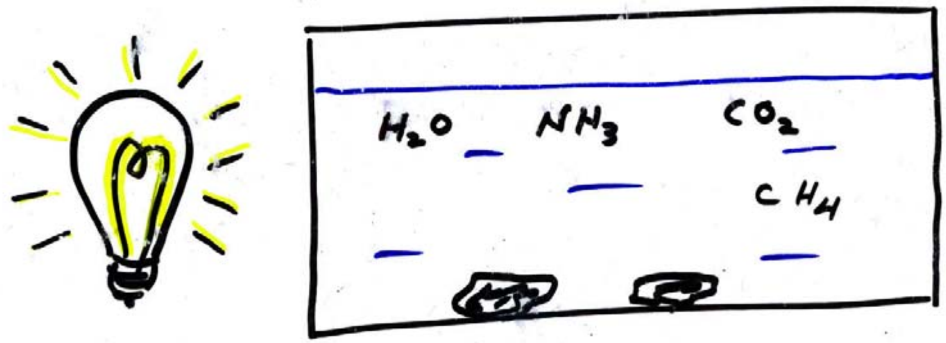
Enough about information & remembering and forgetting.

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

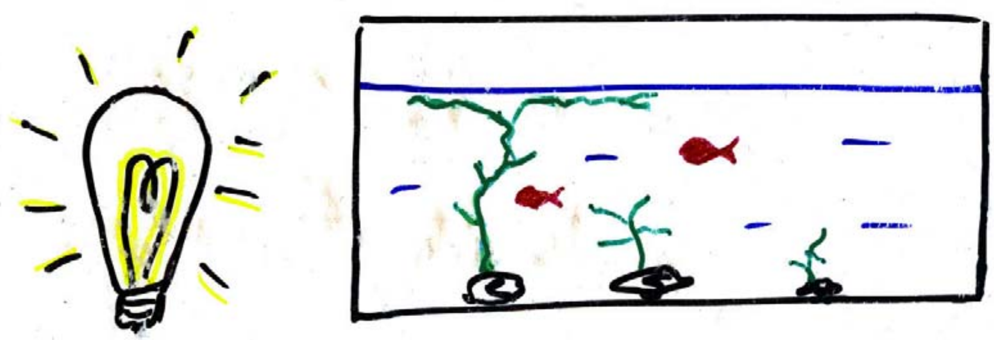
How should *complexity* be defined?

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

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

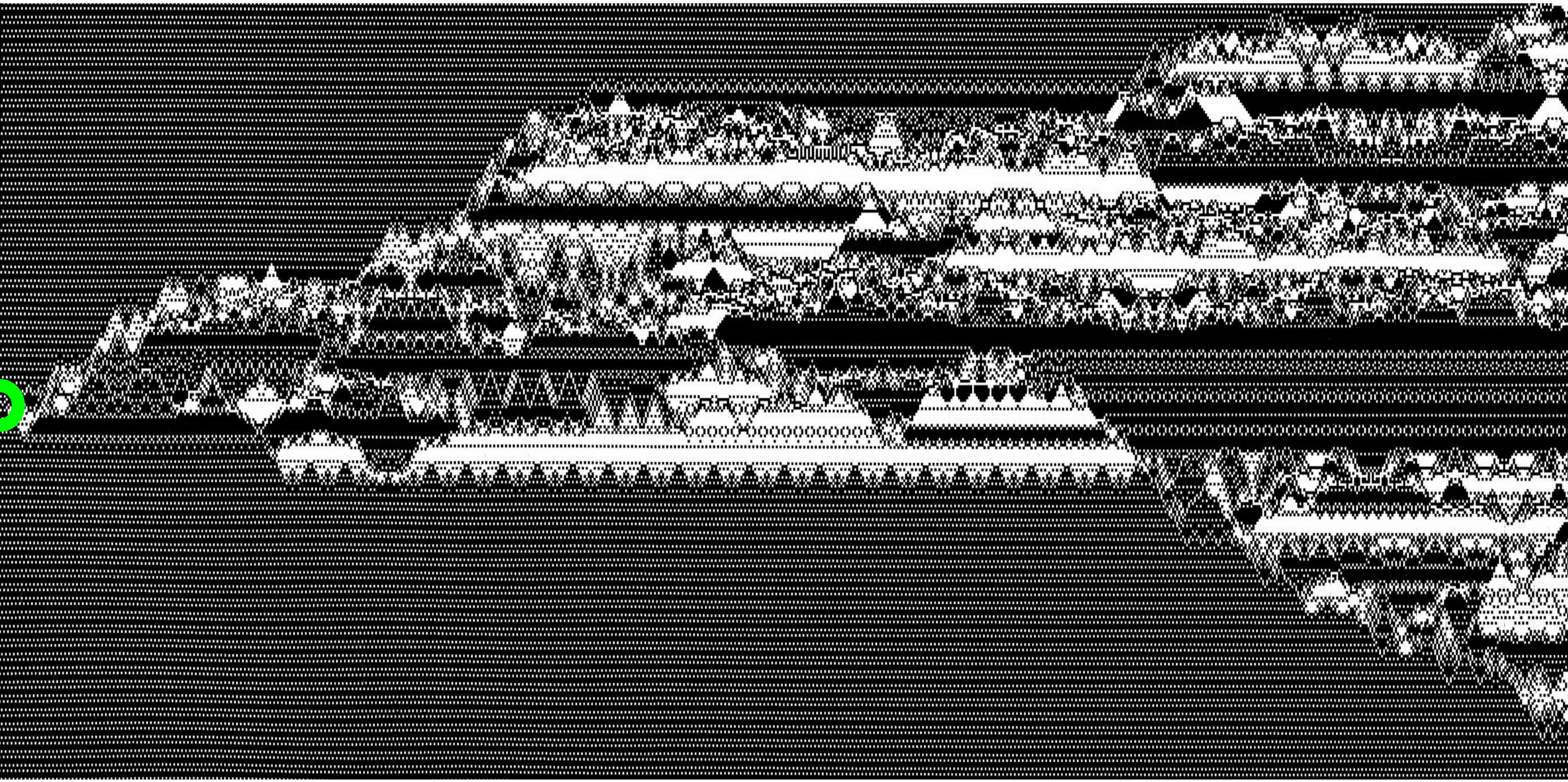


Much later

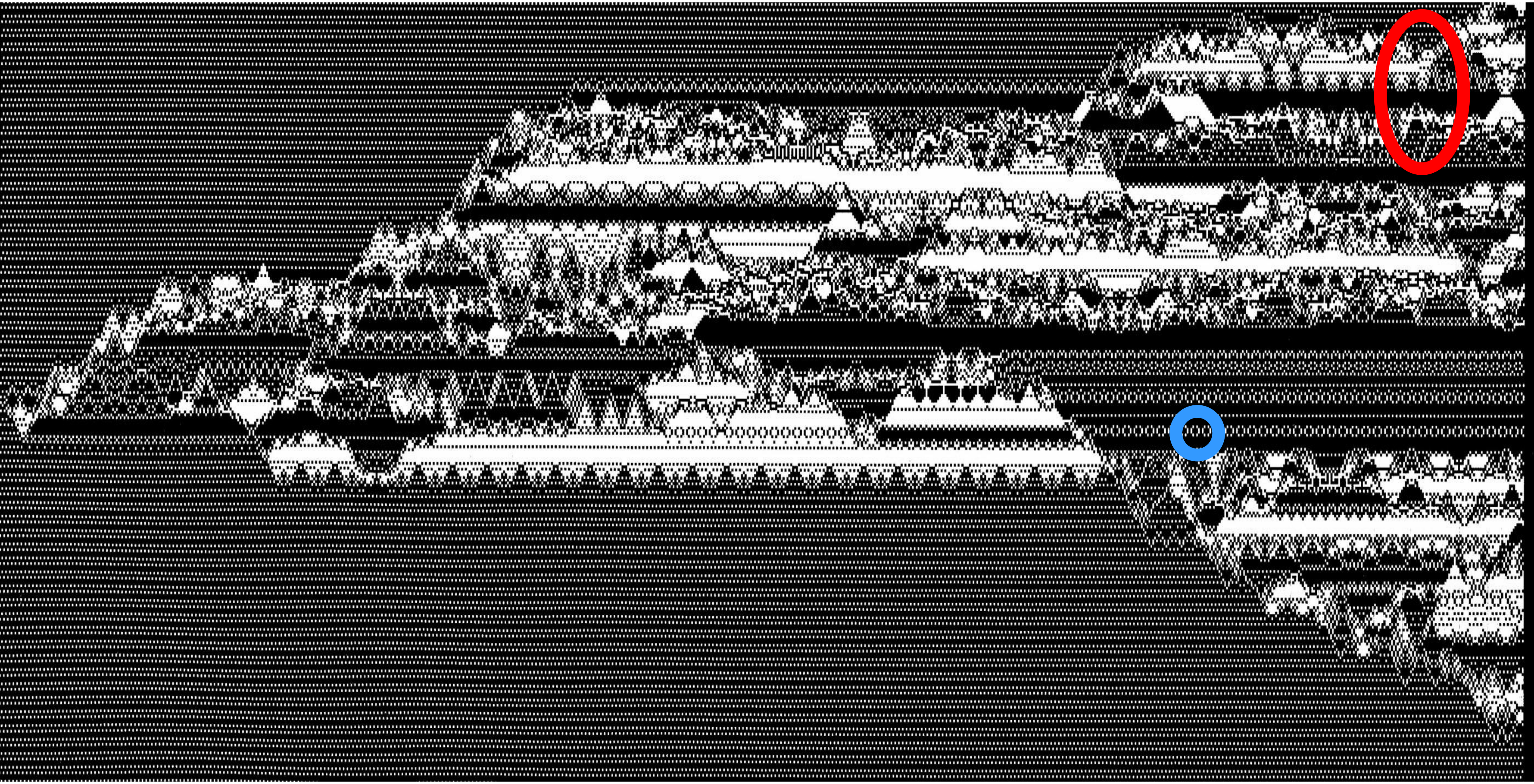


Self-organization, the spontaneous increase of complexity: A simple dynamics (a reversible deterministic cellular automaton) can produce a complicated effect from a simple cause.

time ⟶

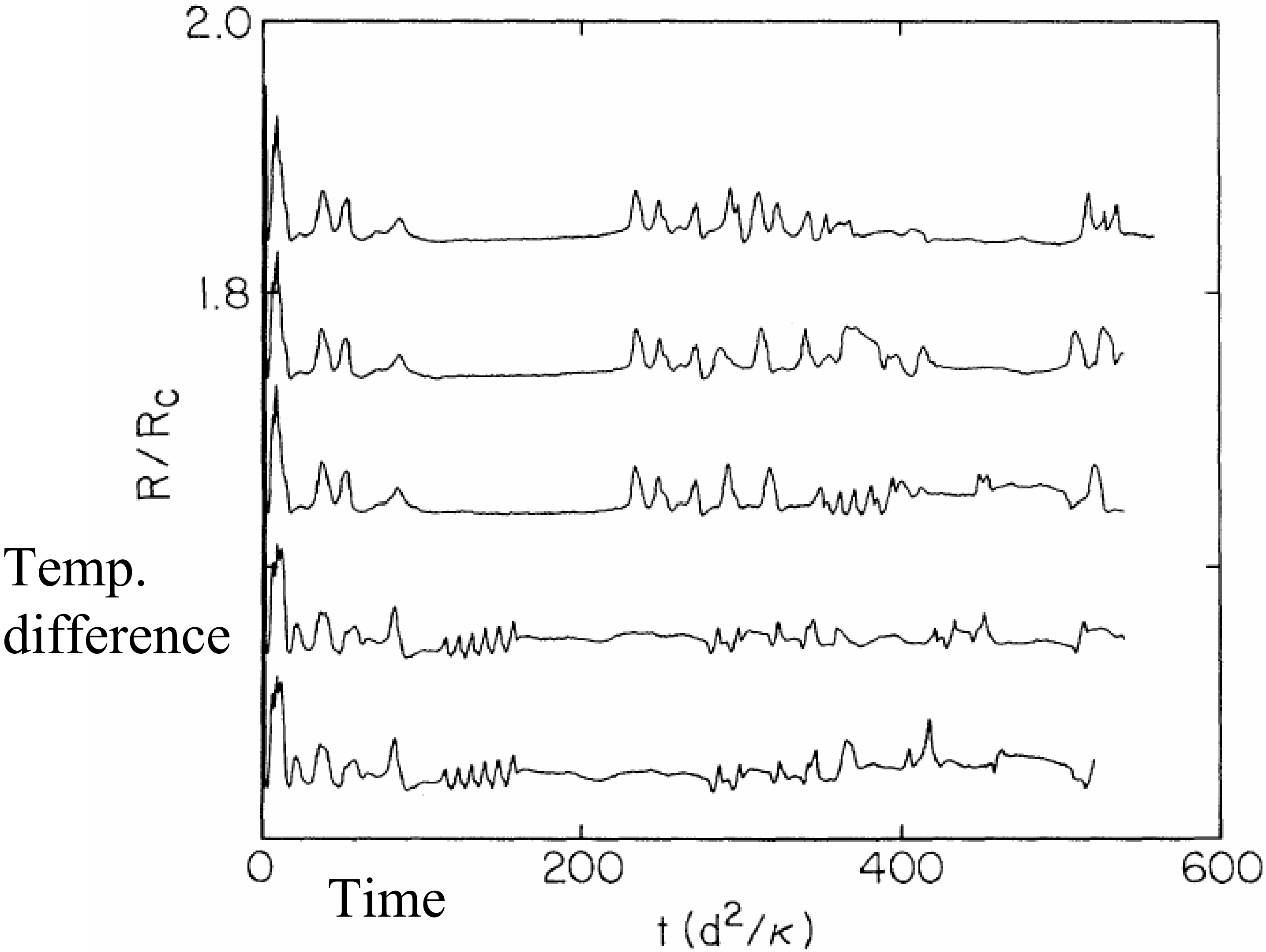


Small irregularity (green) in initial pattern produces a complex deterministic “wake” spreading out behind it.



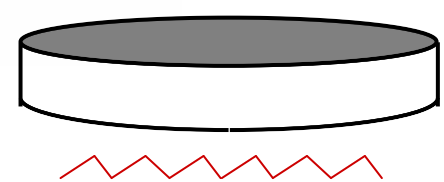
A sufficiently big piece of the wake (red) contains enough evidence to infer the whole history. A smaller pieces (blue) does not.


Wake behind Stepping Stone (Kamo River, Kyoto)
Does its present state record a lot about its past history?
(c) C.H. Bennett

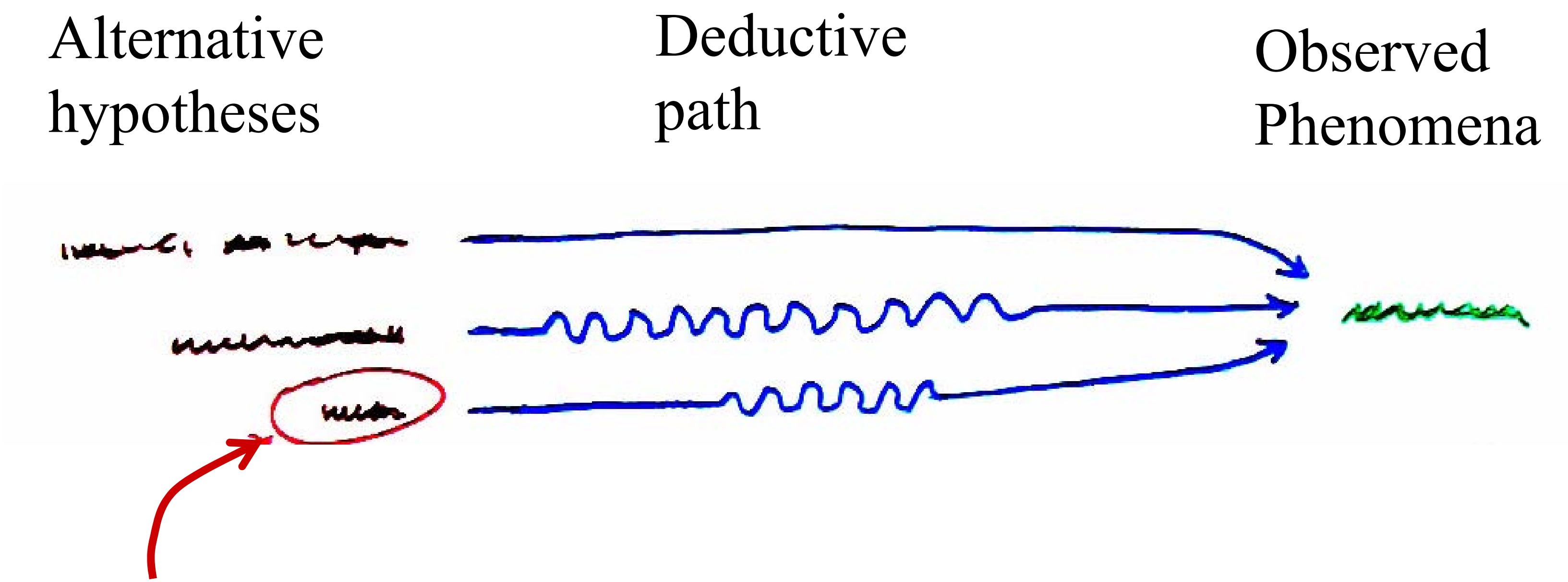


G. Ahlers & R.W. Walden PRL 1980

Rayleigh-Benard Convection in (normal) liquid helium in a flat cylindrical chamber heated from below

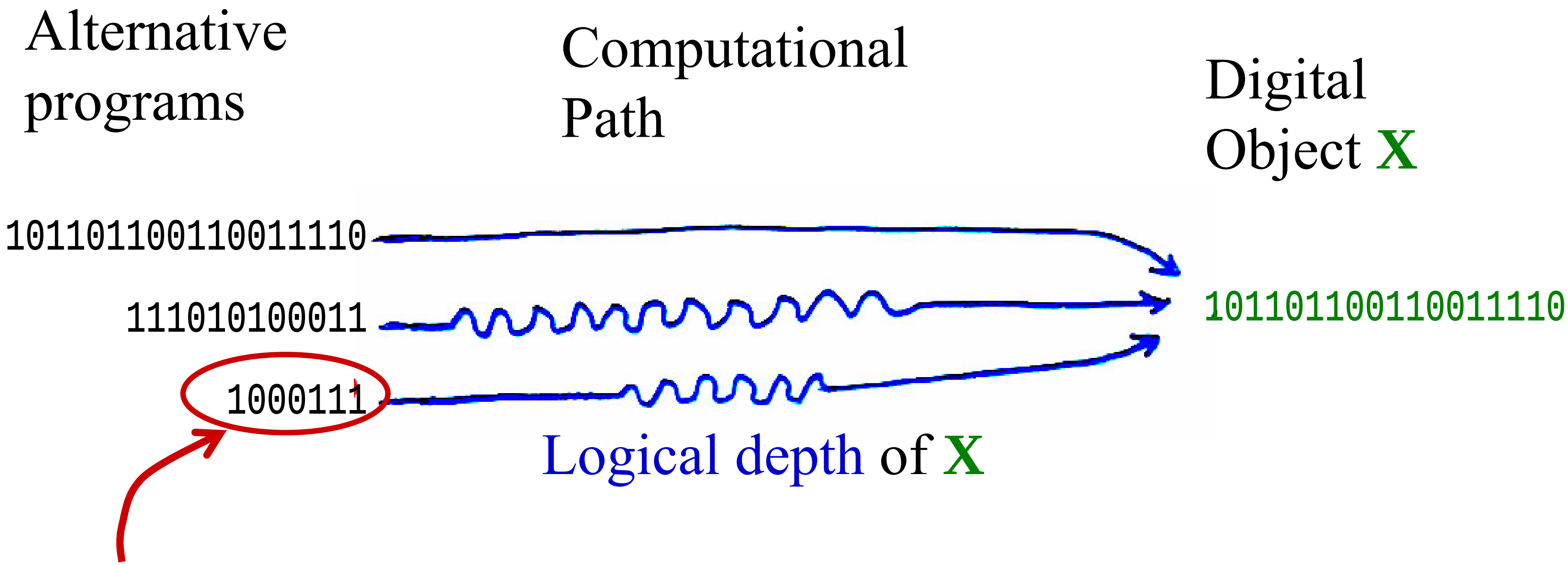


In the philosophy of science, the principle of Occam's Razor directs us to favor the most economical set of assumptions able to explain a given body of observational data.



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**.



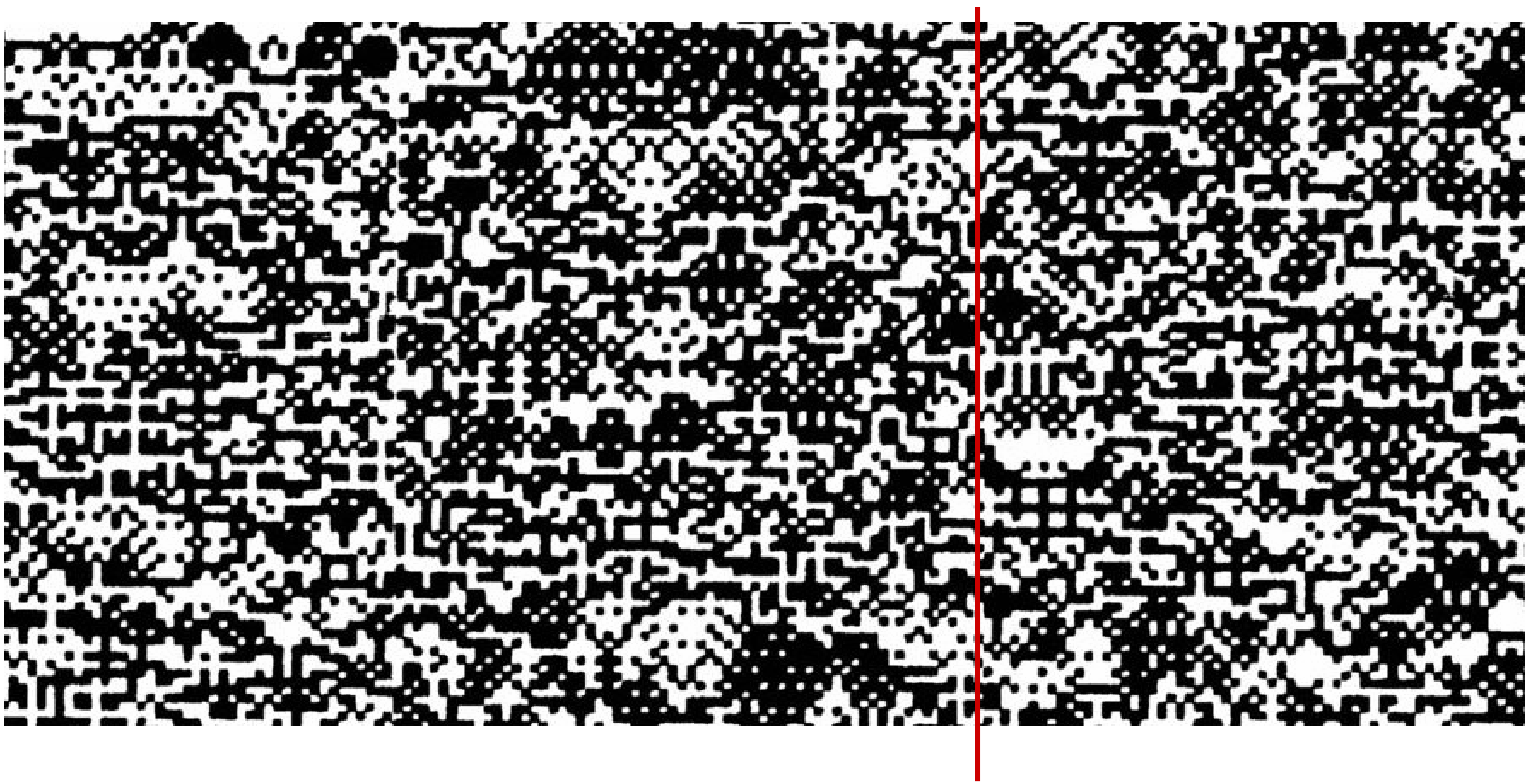
The shortest program is most plausible, so its *run time* measures the object's logical depth, or plausible amount of computational work required to create the object.

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.

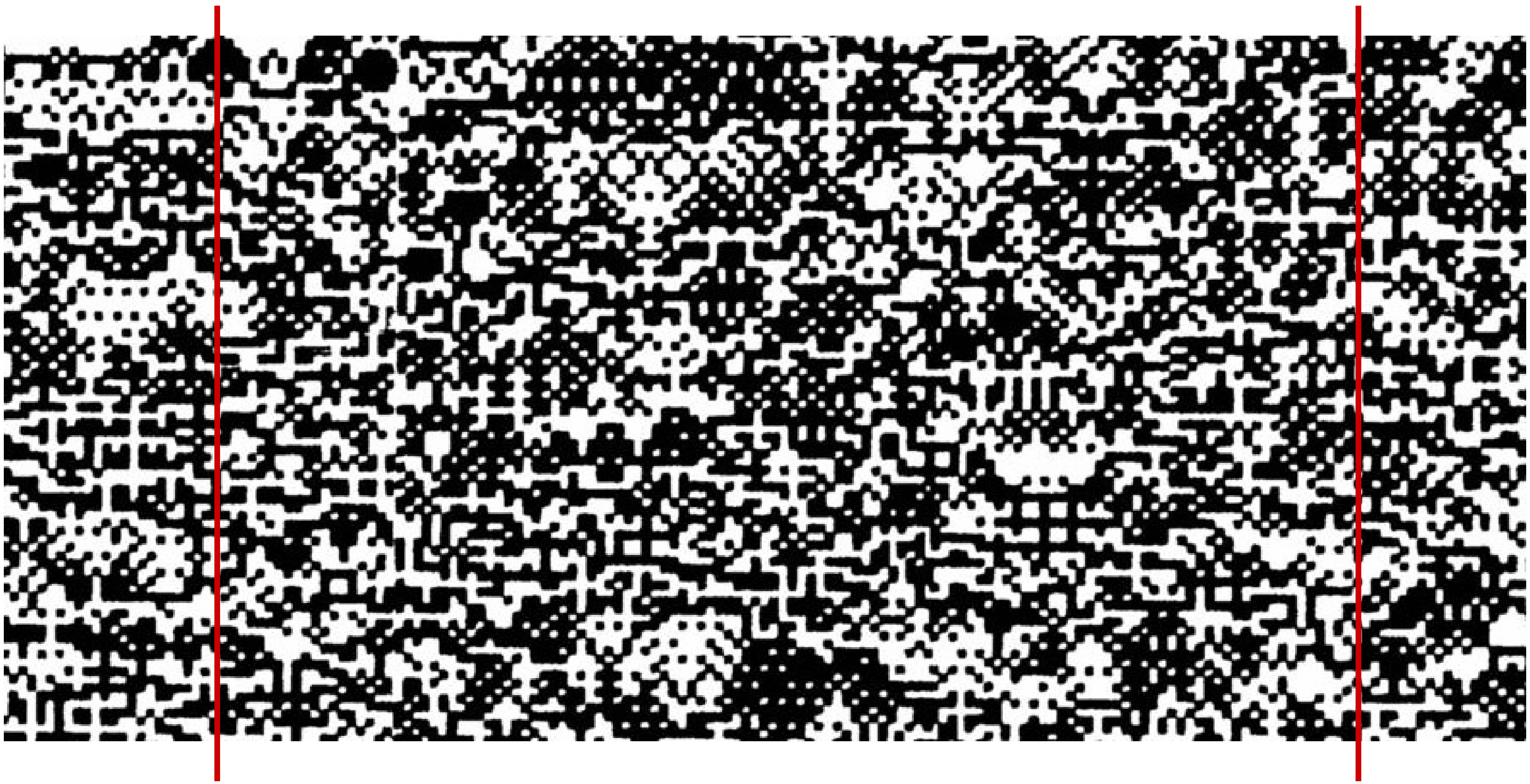
If a reversible local dynamics (e.g. the 1d system considered earlier) is allowed to run long enough in a closed system, comparable to the Poincaré recurrence time, the state becomes trivial and random.

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.)



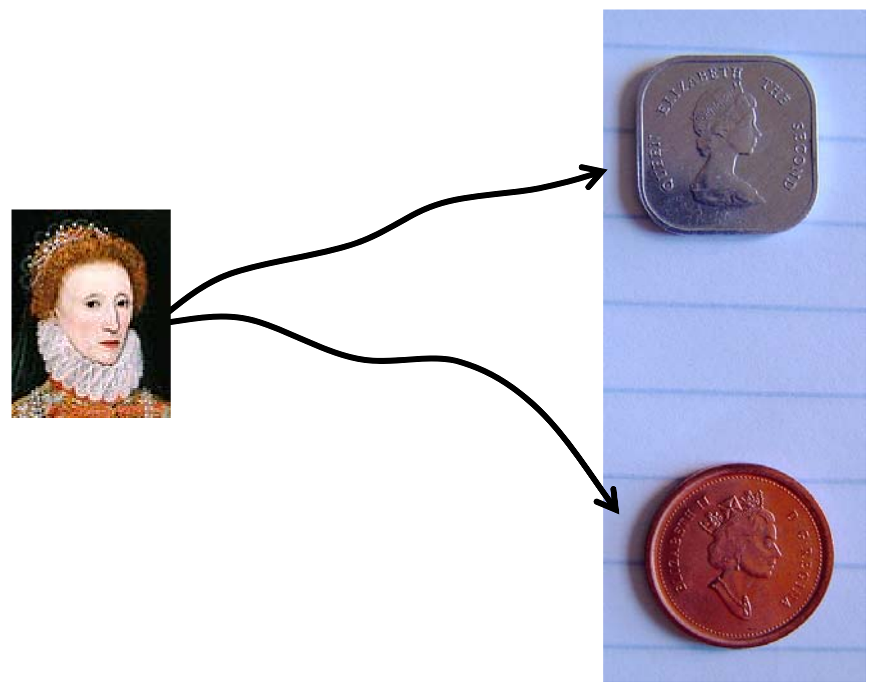
complex intervening dynamics

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.



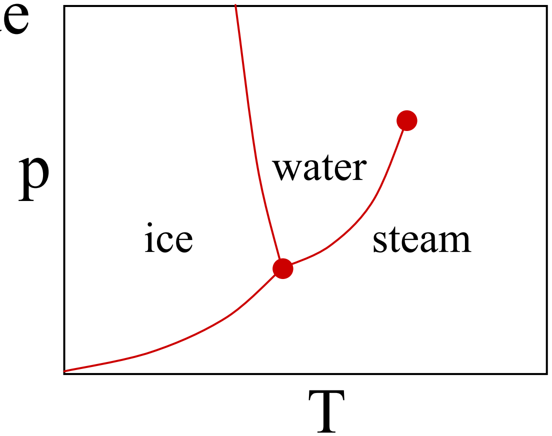
Grenada 1999

Canada 2002

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

Are thermal equilibrium states generically shallow? Yes.

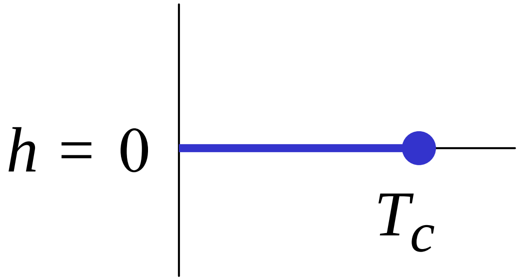
- Gibbs phase rule: for generic parameter values, a locally interacting classical system, of finite spatial dimensionality and at finite temperature, relaxes to a unique Gibbs state of lowest bulk free energy.



=> no long term memory
=> as N, $t \rightarrow \infty$, depth remains bounded

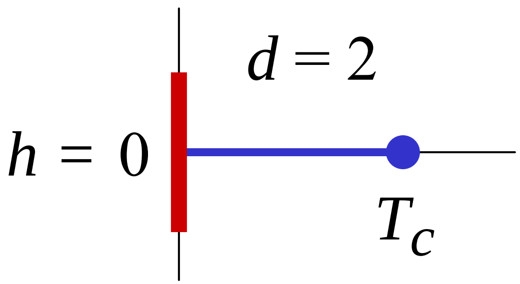
- Quantum exception, in 3 or more dimensions.

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

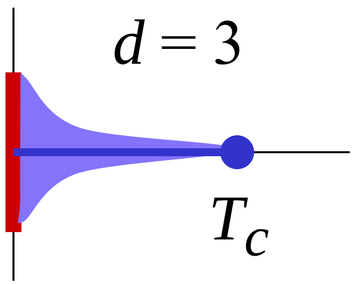


Phase Diagram of Classical Ising model in $d > 1$ dimension. Stores a classical bit reliably when h=0 and $T<T_c$

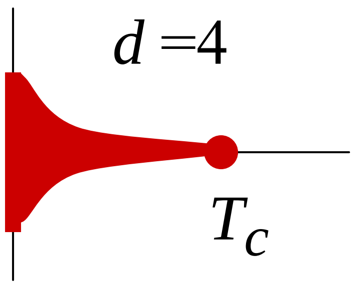
Phase diagrams for local quantum models (Toric codes)*



Degenerate ground state stores a qubit reliably at T=0, even for nonzero h. For T>0, stores a bit reliably only at h=0



Stores a qubit at T=0. For T>0, stores a quantum-encoded classical bit, probably even when h is nonzero



Stores a quantum-encoded qubit even at nonzero T and h.

*Bravyi et al 0907.2807, Alicki et al 0811.0033…

Dissipation without Complexity

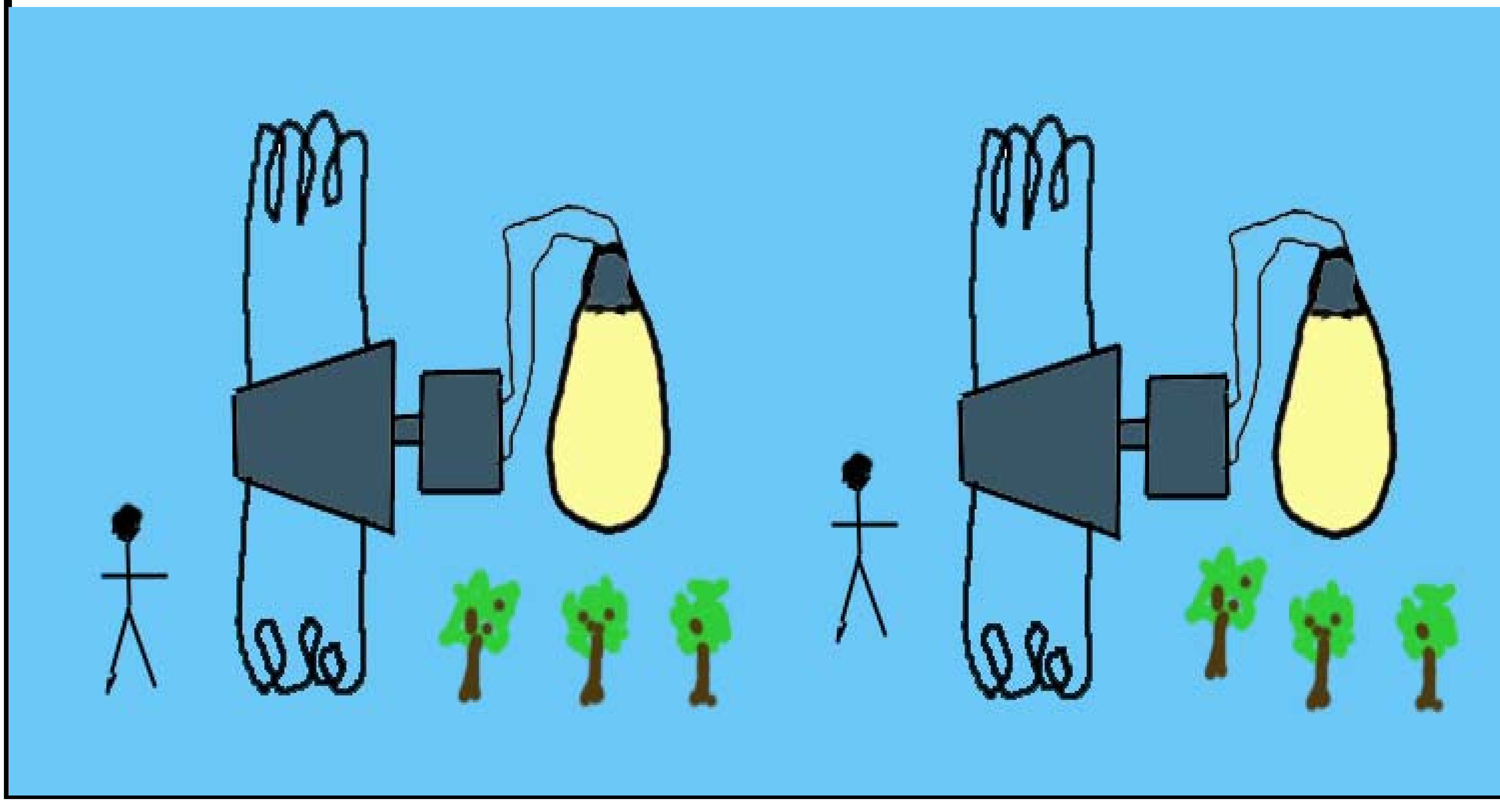
50 C

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

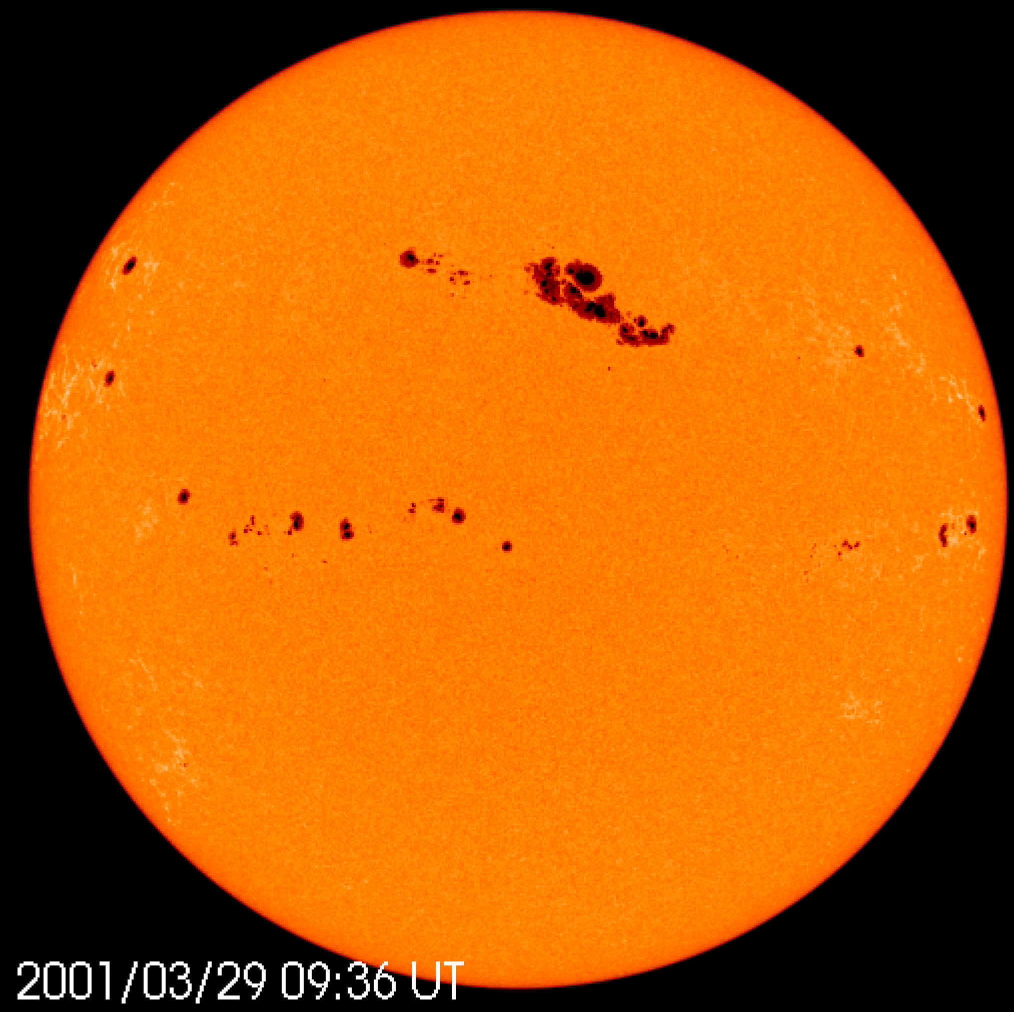
50 C But if the water has impurities



10 C Turbine civilization can maintain and repair itself, do universal computation even, apparently, in 1 unbounded spatial dimension.

Are some dissipative environments so hot, so rapidly mixing, as to preclude long term memory? Hard to say.

Are some dissipative environments capable of supporting long term memory, but not depth?



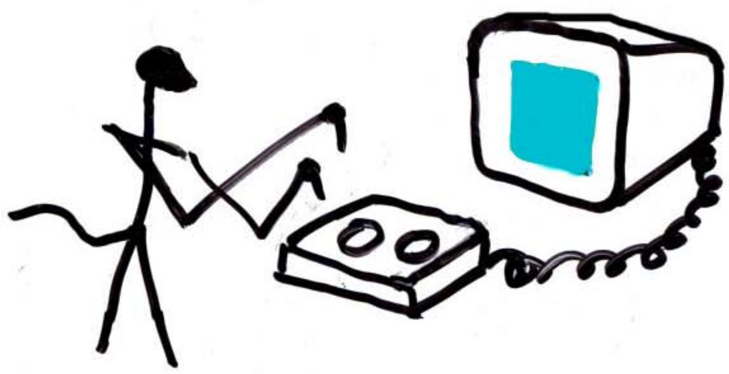
Biologically, are there environments where complexity confers no selective advantage and which therefore support only simple life, without niche ecology or the opportunity for preadaptation?

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 value of information.

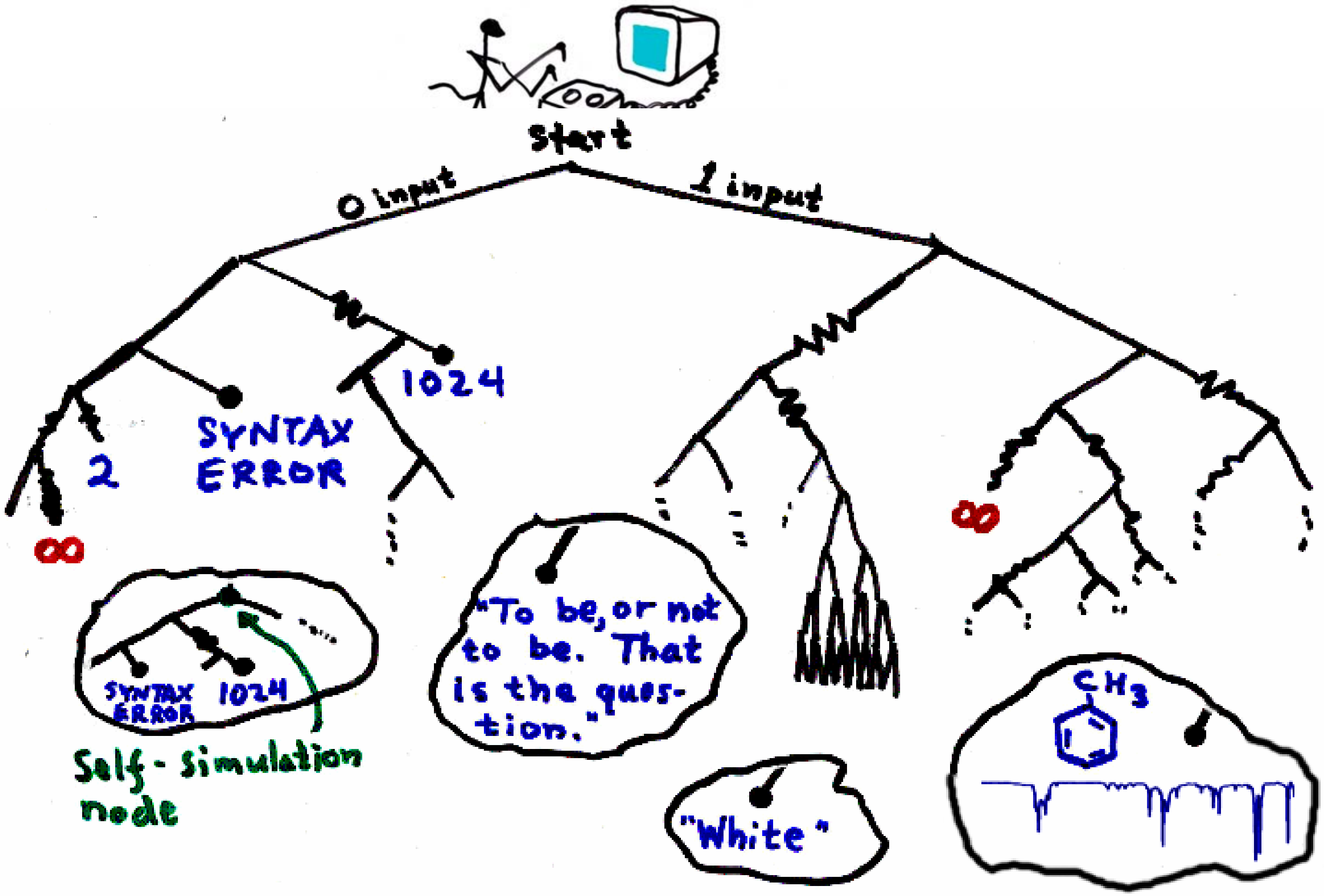
Answer: The decrease in the *Earth's* depth comports with our feeling that something valuable was lost. But inquiring how the *Universe's* depth changes with time is too impatient a way of thinking. From God's viewpoint there is no time, nothing ever happens, and Universe's complexity doesn't increase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

Extra Slides

Defining complexity: use a computerized version of the old idea of a monkey at a typewriter eventually typing the works of Shakespeare. Of course a modern monkey uses a computer instead of a typewriter.



A monkey randomly typing 0s and 1s into a universal binary computer has some chance of getting it to do any computation, produce any output (Chaitin 1975)



The input/output graph of this or any other universal computer is a microcosm of all cause/effect relations that can be demonstrated by deductive reasoning or numerical simulation.

Complexity (logical depth) as a measure of value.

Advantage: Nicely attributes value to literature, cultural artifacts, evolved genomes, ecosystems, species, and complex thoughts and emotions (treated in an utterly materialist way, as patterns of atoms in people's brains). Destroying the last copy of a good book, or the last individual of a species or human culture, is especially bad, because it destroys complex information not available elsewhere.

In many cases such losses are prevented by biological and cultural replicative processes. Even a major asteroid impact would probably not destroy all copies of Shakespeare's works, of the human genome, or all Model-T Fords.

Problem: scaling with number: we would like to believe that many people's happiness is not like many copies of a good book, scarcely more valuable than one copy.

Possible answer: People's experiences are so different that they hardly overlap. An adolescent, on falling in love for the first time, thinks "I am the first person ever to feel this". We elders smile. But for other kinds of experience it probably really is true. For example I find that my friends are all different, enriching and complicating my life in ways that overlap only slightly from one friend to another.

Jerusalem Talmud, Sanhedrin 4:1 (22a)

כל המאבד נפש אחת - מעלה עליו הכתוב כאילו קיים עולם
מלא, וכל המקיים נפש אחת - מעלה עליו הכתוב כאילו איבד
עולם מלא

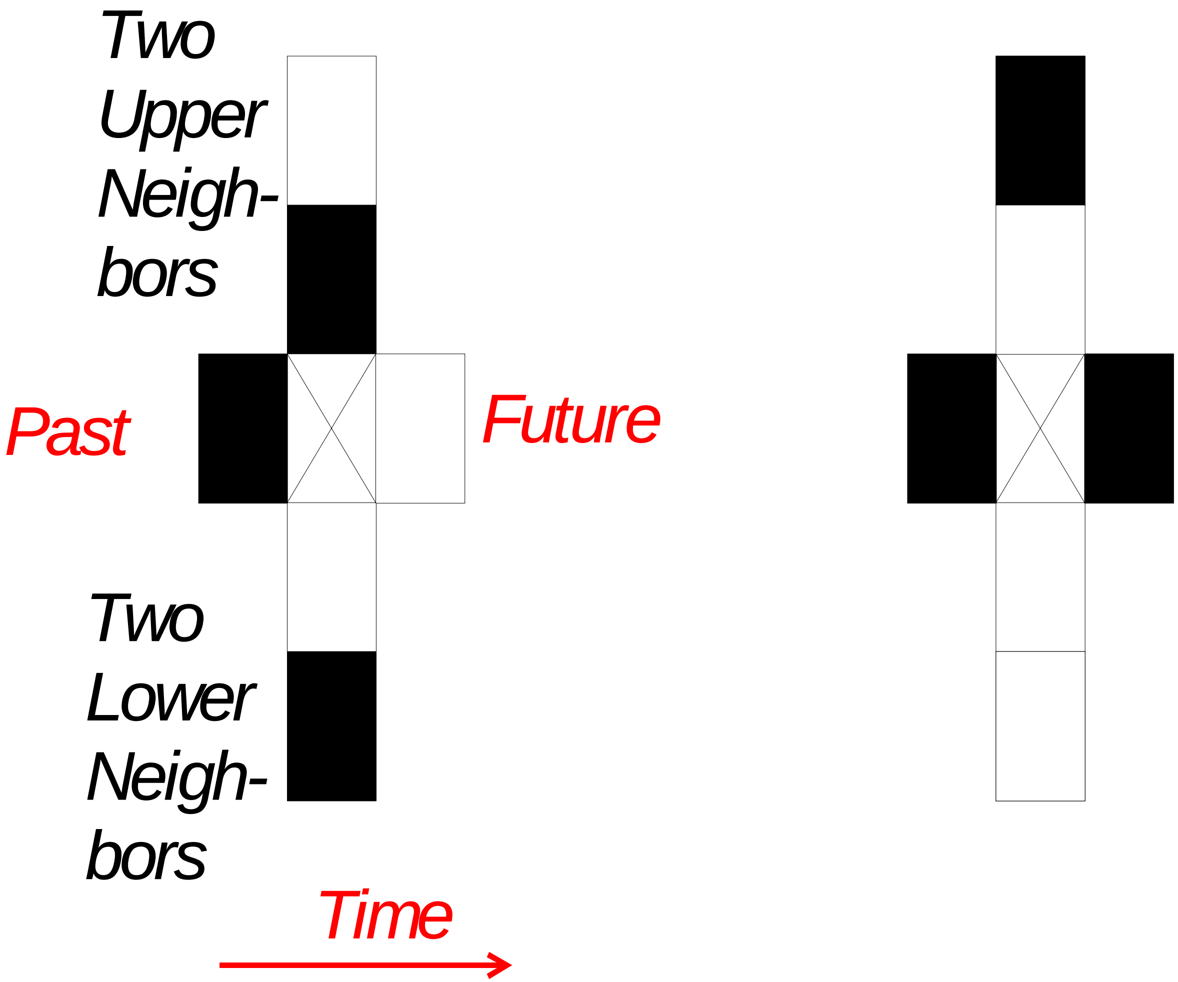
"Whoever destroys a soul, it is considered as if he destroyed an entire world. And whoever saves a life, it is considered as if he saved an entire world."

Radiation from a deterministically evolving system with zero input entropy

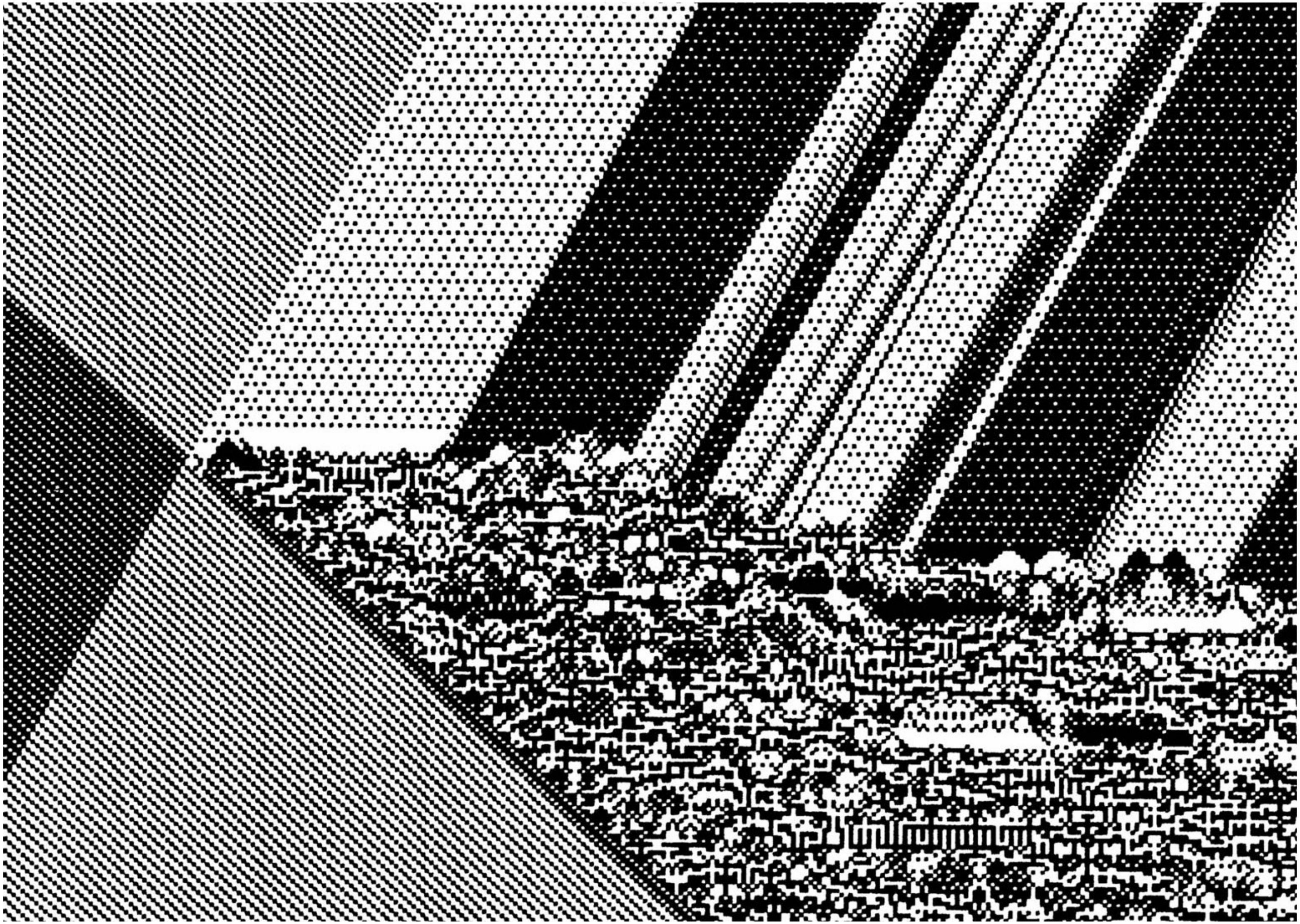
Discrete Classical (e.g. reversible cellular automaton):
  Pseudorandom radiation, pseudorandom residual system

Continuous Classical (chaotic)
  Random radiation, random residual system (both from mining the infinite-precision generic initial condition. If initial condition were special (computable), both residual system and radiation would be merely pseudorandom)

Discrete Quantum:
  Random residual system, random-looking radiation, entangled with itself and with residual system

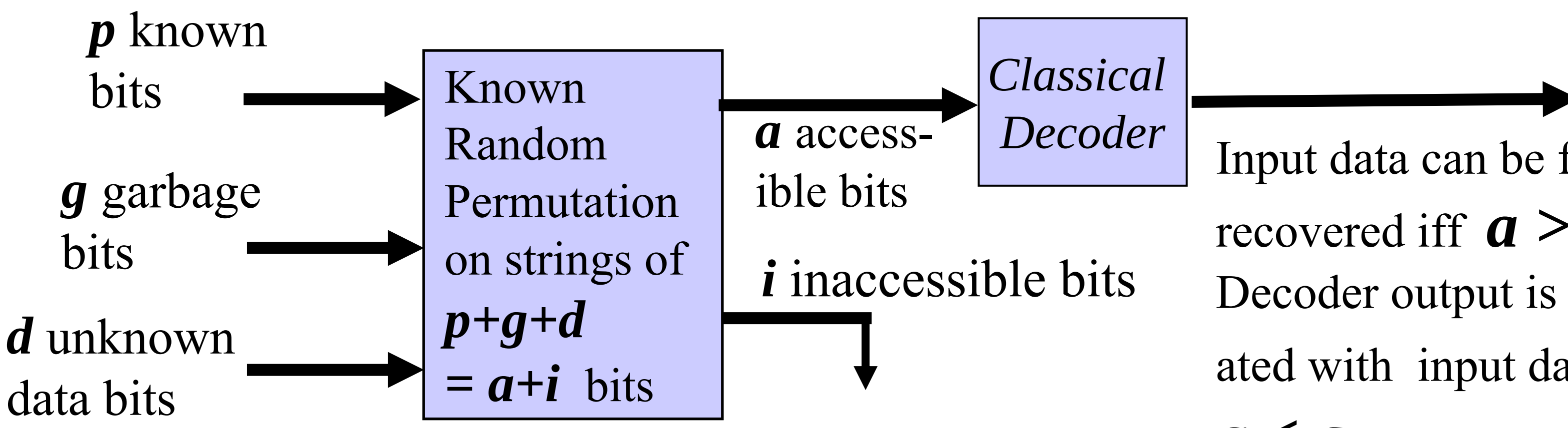


Range-2, deterministic, 1-dimensional Ising rule. Future differs from past if exactly two of the four nearest upper and lower neighbors are black and two are white at the present time.

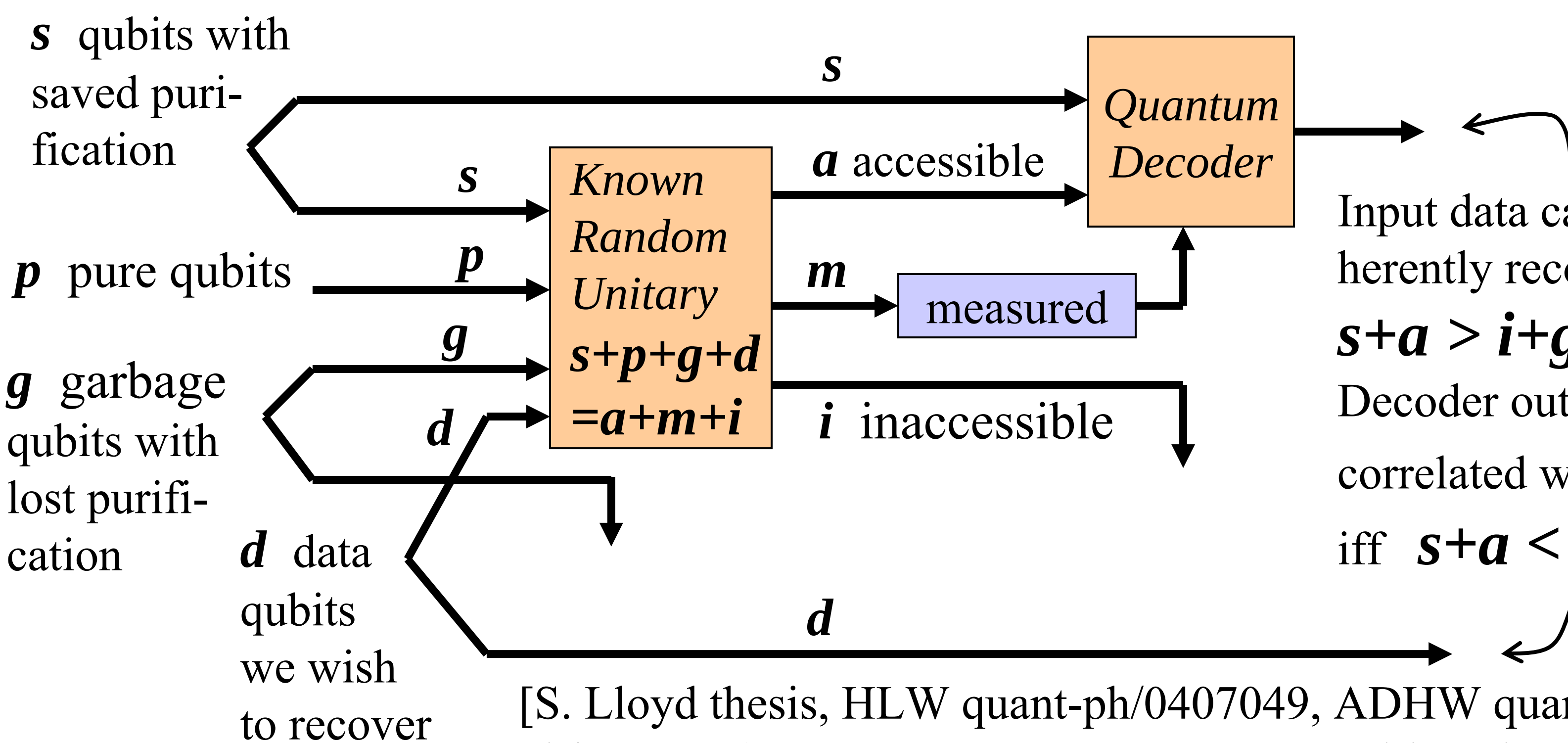


“Radiation” from a hot pseudorandom state formed by collision of two domain edges in simple initial condition in range-2 reversible deterministic 1d Ising cellular automaton

Information budget for random permutations and unitaries



Input data can be faithfully recovered iff $a > g+d$. Decoder output is uncorrel-ated with input data iff $a < g$.



Input data can be co-herently recovered iff $s+a > i+g+d$. Decoder output is un-correlated with data iff $s+a < i+g$.

[S. Lloyd thesis, HLW quant-ph/0407049, ADHW quant-ph/0606225), HP 0708.4025,…, Graeme Smith and CHB in prep.]