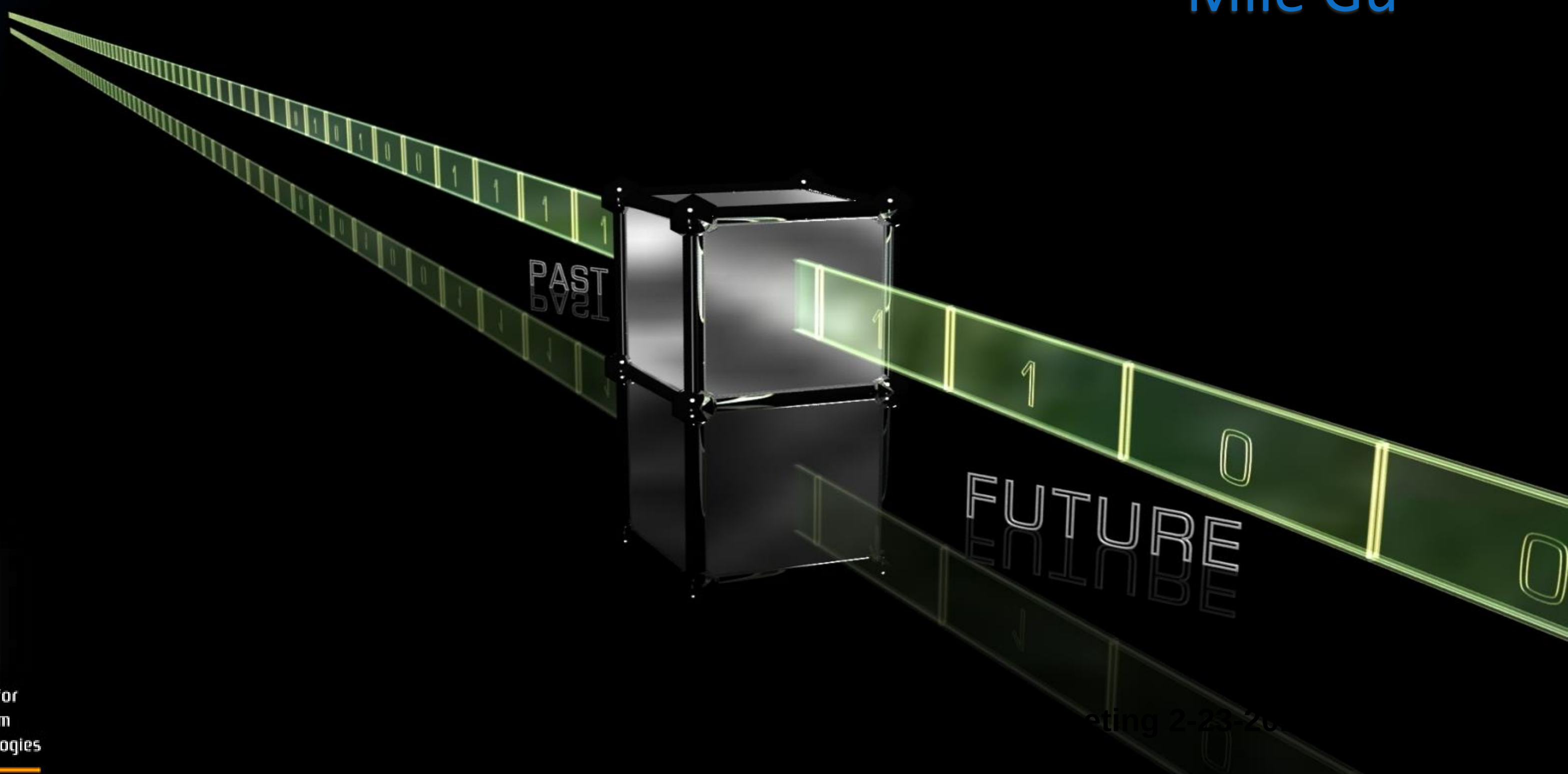
Quantum Simplicity

Can Quantum Theory Better Isolate the Causes of natural things?

Mile Gu



NANYANG TECHNOLOGICAL UNIVERSITY
Complexity Institute

John Templeton Foundation

Centre for Quantum Technologies
National University of Singapore

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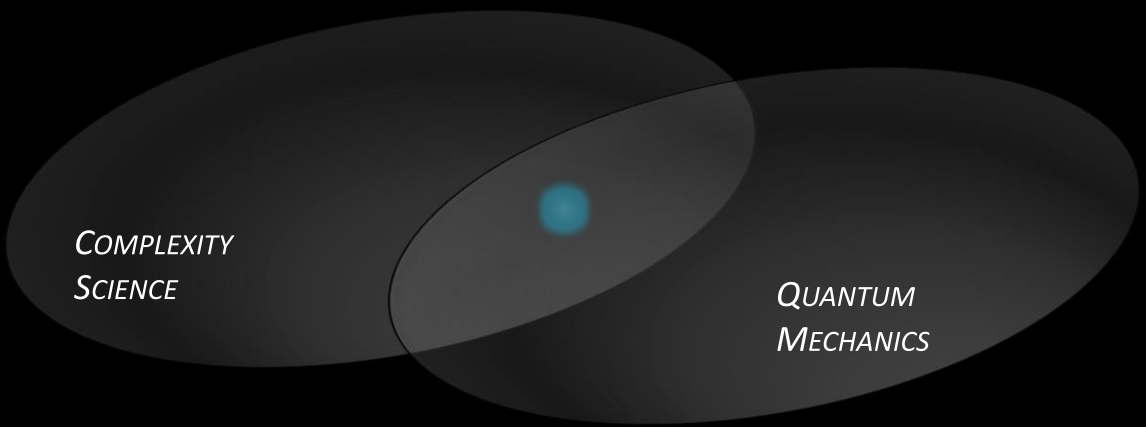
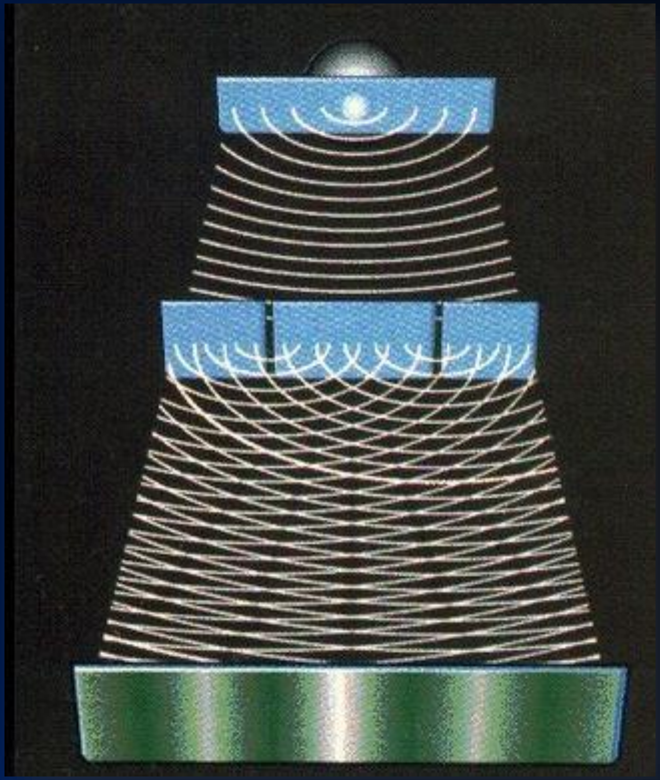
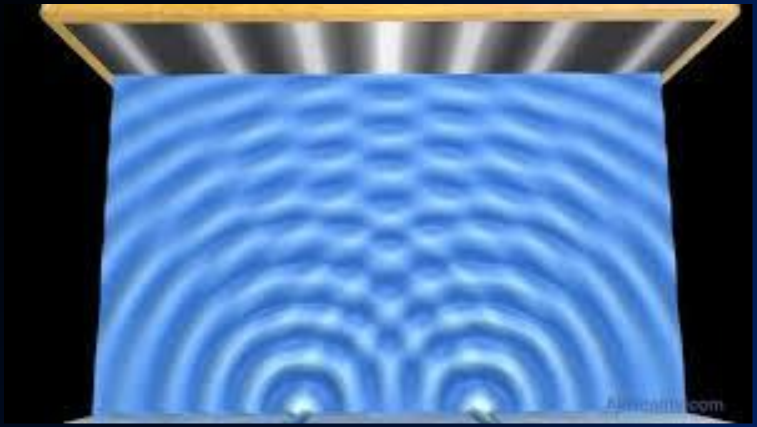


The Double Slit Experiment…





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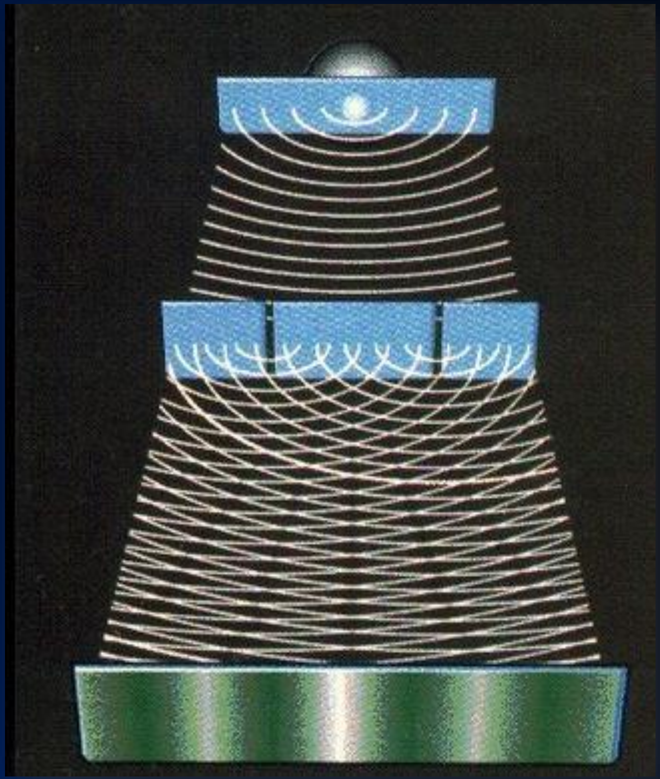

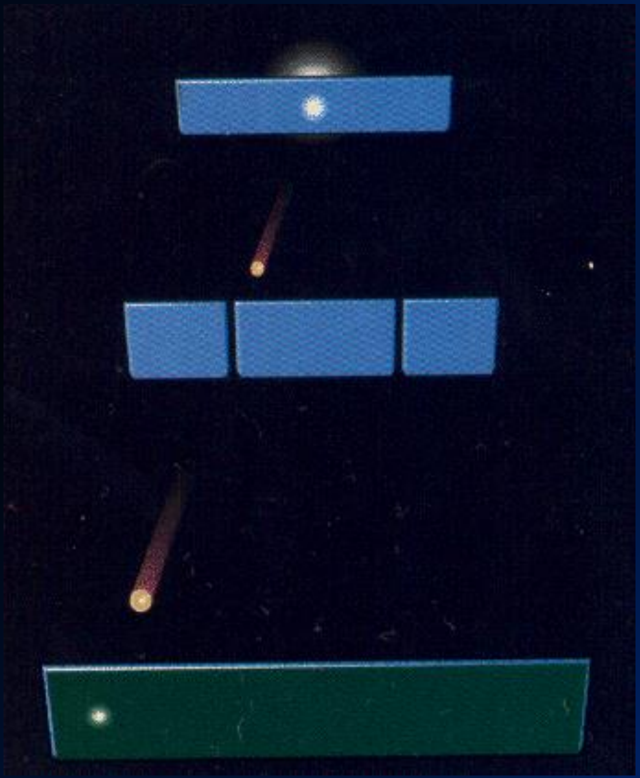

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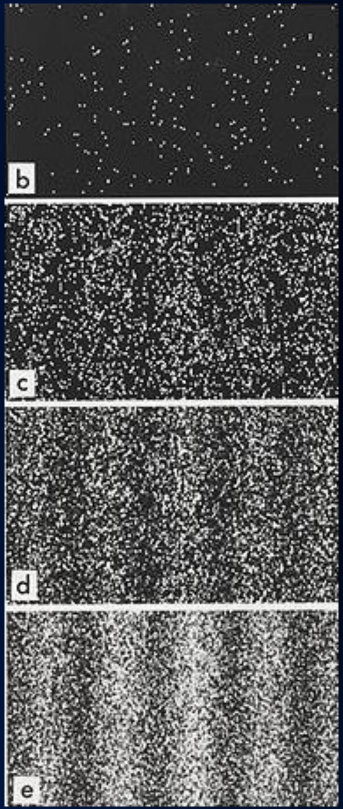
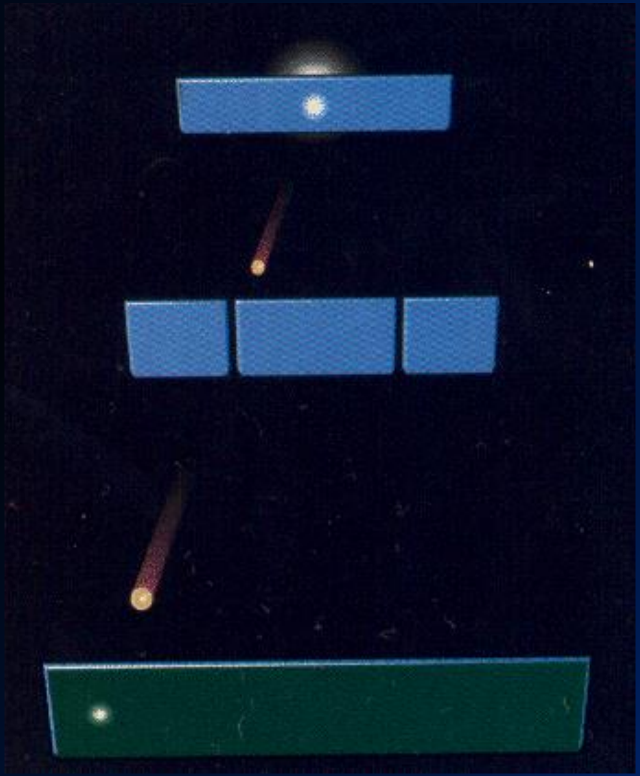
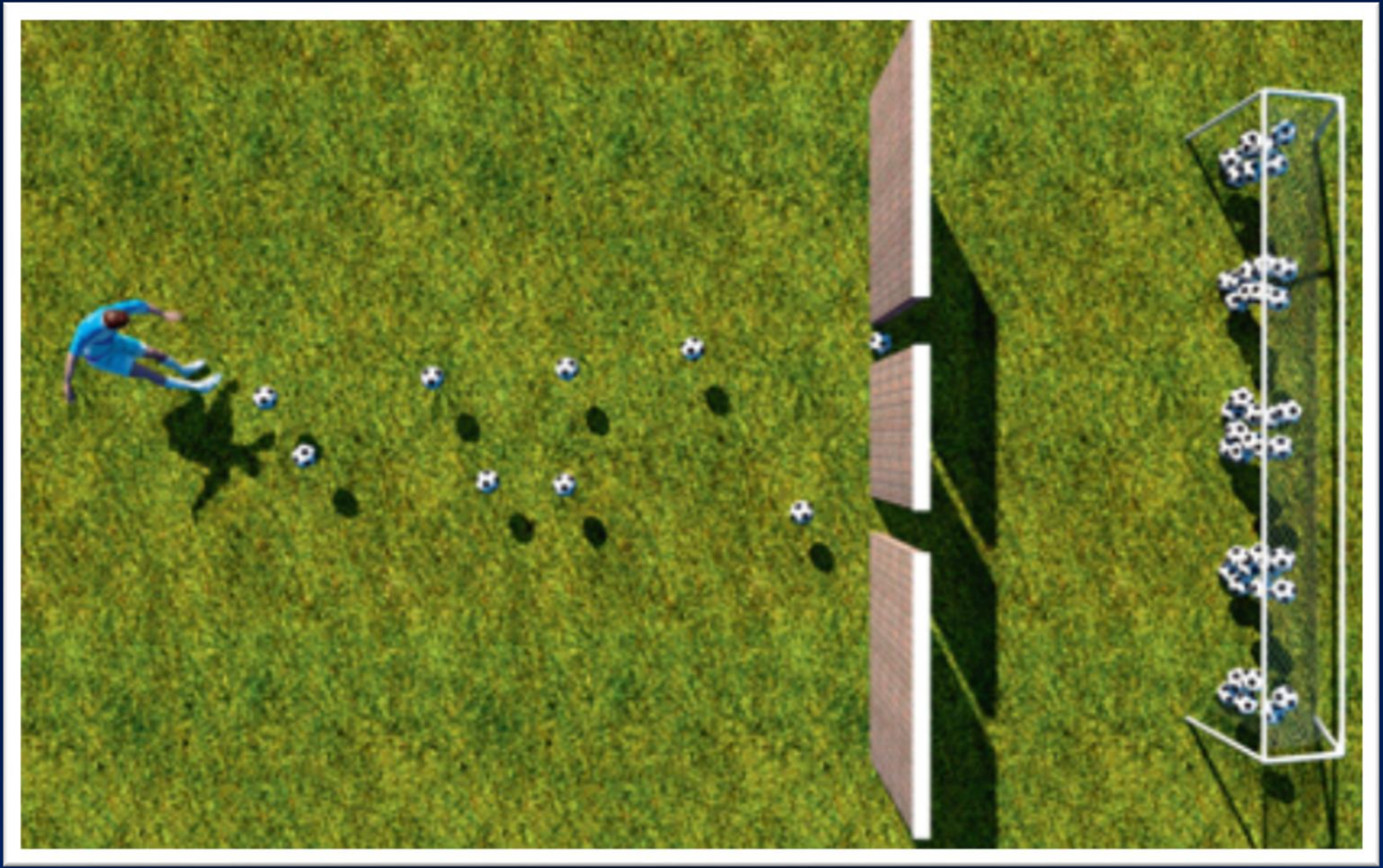




The Double Slit Experiment...



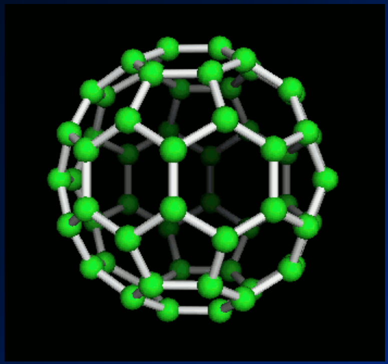
In Quantum Science…

Volume 87, Number 16 PHYSICAL REVIEW LETTERS 15 October 2001

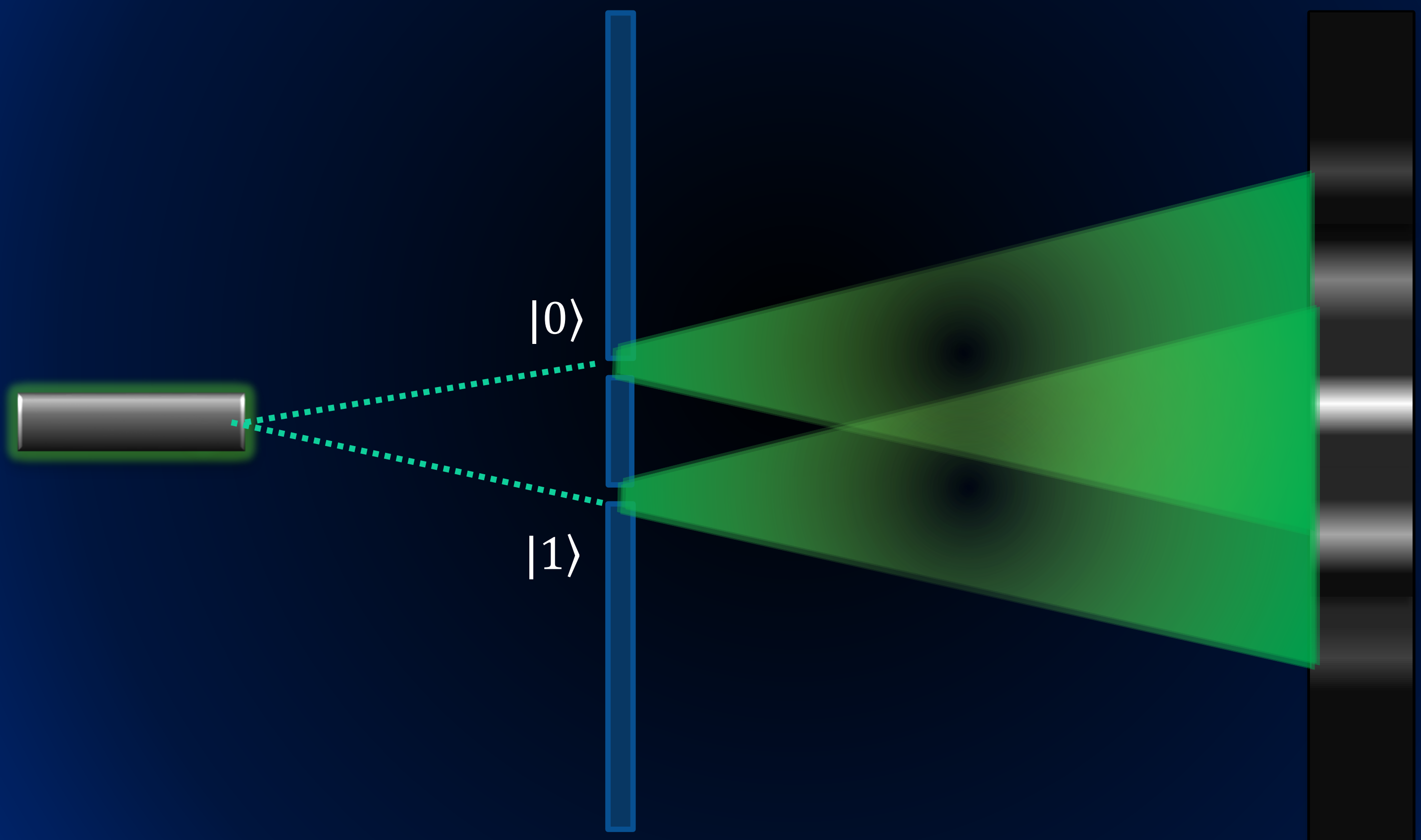
Diffraction of Complex Molecules by Structures Made of Light

Olaf Nairz, Björn Brezger, Markus Arndt, and Anton Zeilinger
Universität Wien, Institut für Experimentalphysik, Boltzmanngasse 5, A-1090 Wien, Austria
(Received 1 June 2001; published 26 September 2001)

We demonstrate that structures made of light can be used to coherently control the motion of complex molecules. In particular, we show diffraction of the fullerenes C_{60} and C_{70} at a thin grating based on a standing light wave. We prove experimentally that the principles of this effect, well known from atom optics, can be successfully extended to massive and large molecules which are internally in a thermodynamic mixed state and which do not exhibit narrow optical resonances. Our results will be important for the observation of quantum interference with even larger and more complex objects.



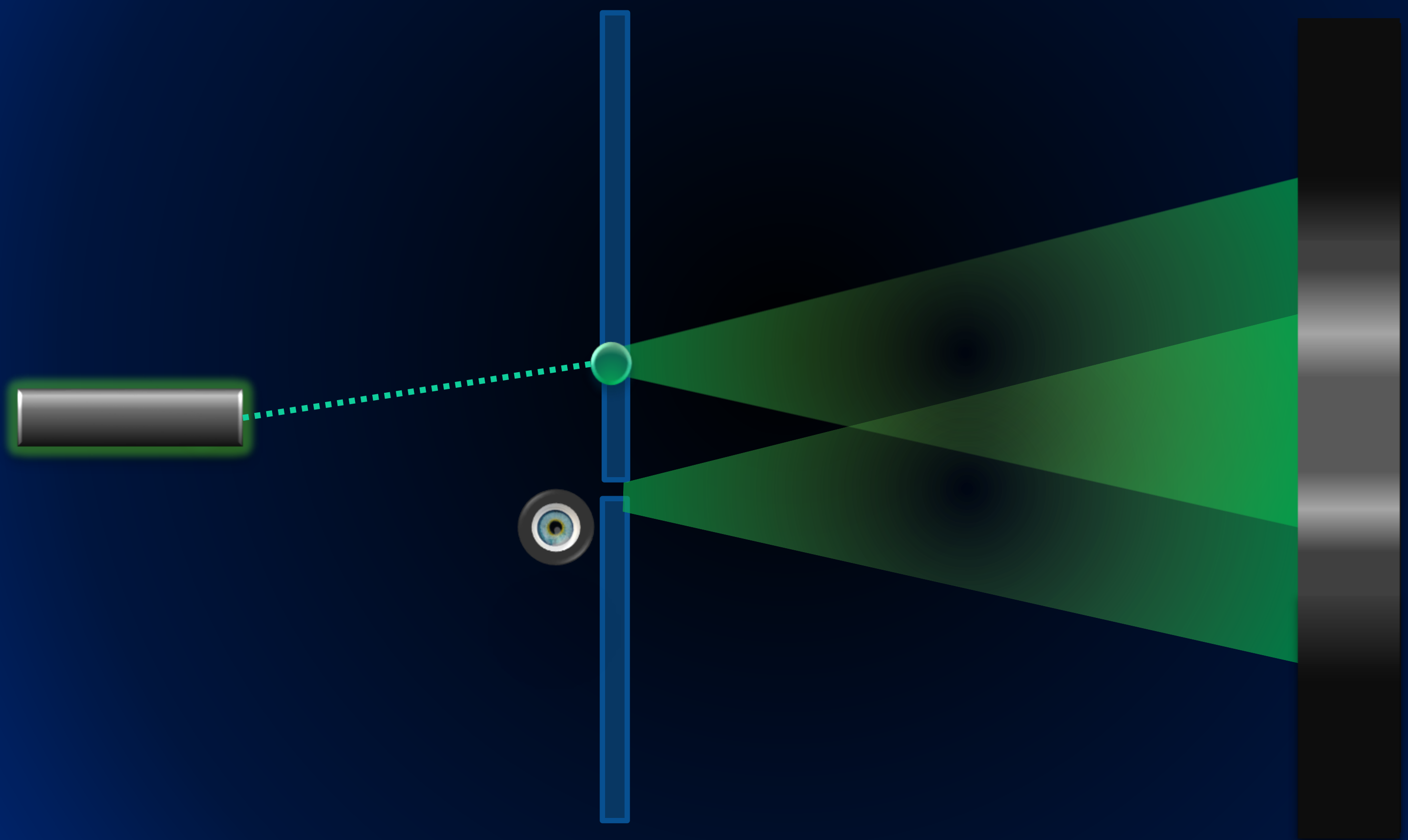
IN QUANTUM SCIENCE…



$|\varphi\rangle = |0\rangle + |1\rangle$

A particle can go through a superposition of both slits!

In Quantum Science…

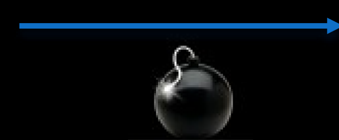


Measuring the particle position causes
Its quantum state to collapse

$$|0\rangle + |1\rangle \rightarrow |0\rangle$$

We have a stockpile of Single-Photon activated bombs – but some of them are duds.

Good Bombs have photo-detectors that, when seeing a photon, explodes.

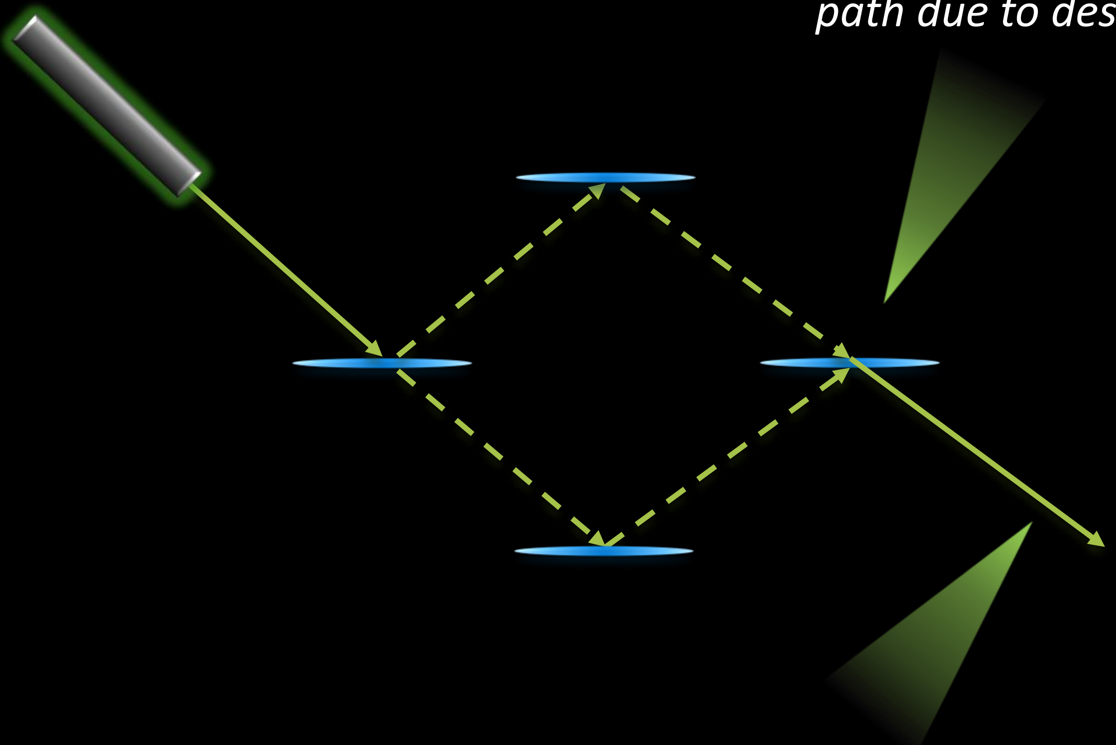


Bad bombs do not interact with photons

We have a stockpile of Single-Photon activated bombs – but some of them are duds.

How do we make sure every bomb works without blowing all of them in the process?

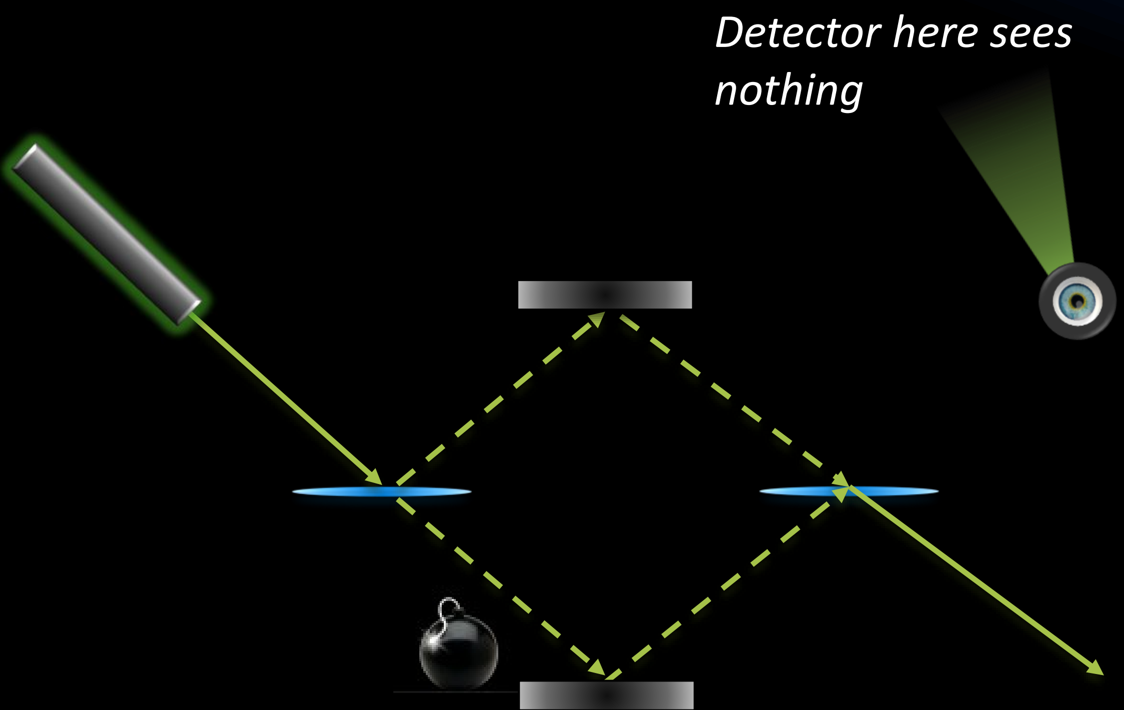
Quantum Bomb Detector:



Photons cannot emerge on the top path due to destructive interference

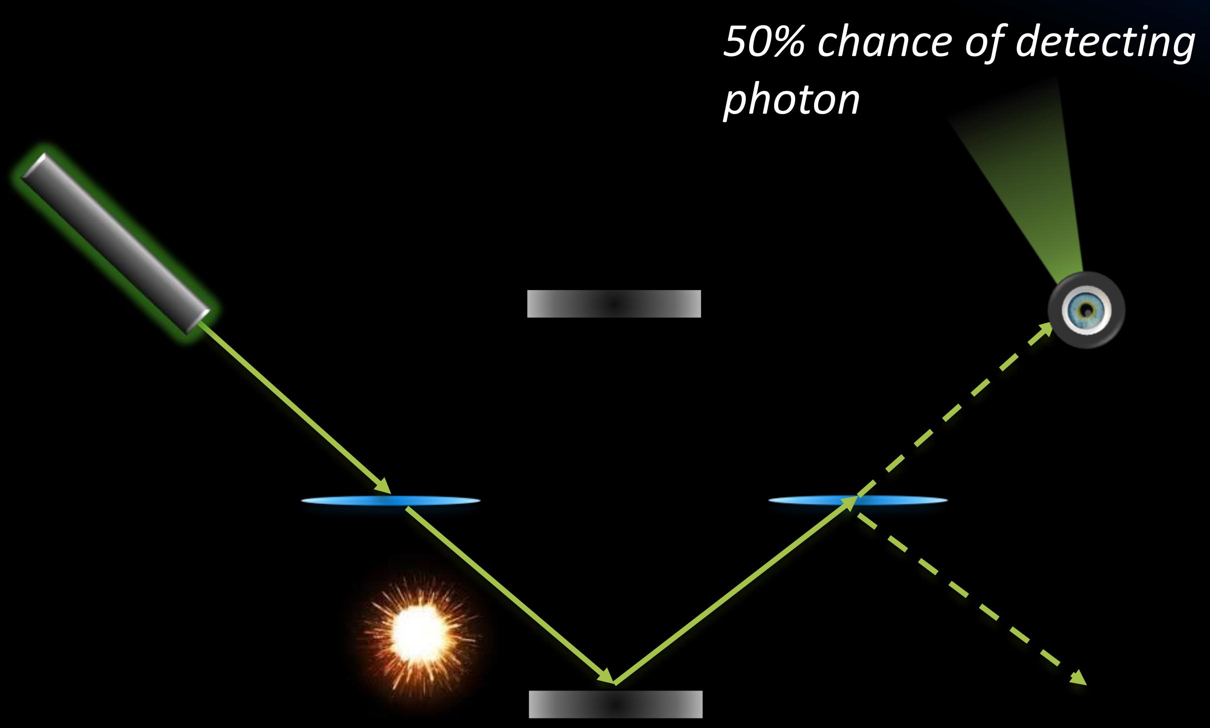
Interference forces photon emerge from lower path

Quantum Bomb Detector:



A Dud will not affect this interference.

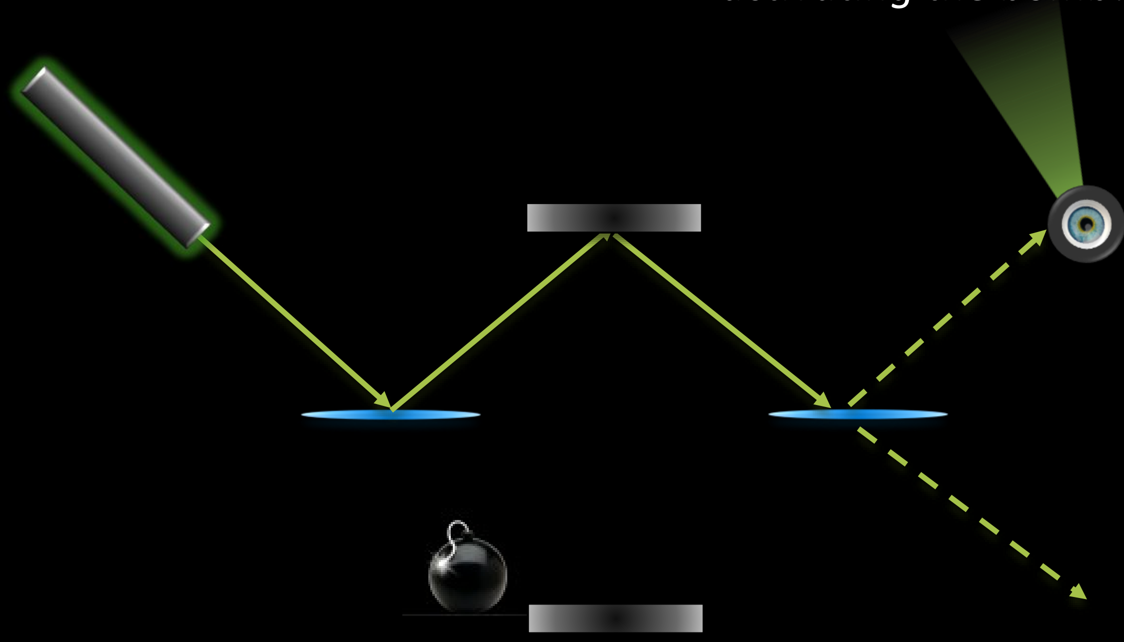
Quantum Bomb Detector:



A real bomb can detect photons, and thus destroys the interference pattern.

QUANTUM BOMB DETECTOR:

Detecting a photon here will allow us to verify a Bomb works, without activating the bomb!



Seeing without Looking: *This interference pattern is still destroyed, even when the Bomb never interacts with the photon! (experimentally verified 1994)*

ABANDONING LOCAL REALITY…

“Everything we call real is made of things that cannot be regarded as real. If quantum mechanics hasn’t profoundly shocked you, you haven’t understood it yet.”

- *Niels Bohr*

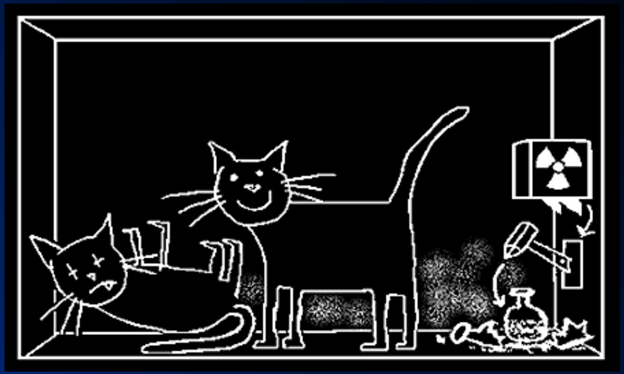
Quantum theory is not locally realistic

A system can exist in a superposition of different configurations.

Abandoning Local Reality…

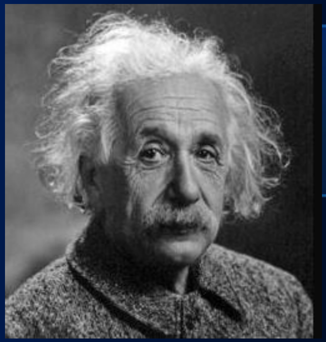
"Everything we call real is made of things that cannot be regarded as real. If quantum mechanics hasn't profoundly shocked you, you haven't understood it yet."

- Niels Bohr



Schrodinger's Cat $|\boldsymbol{Dead}\rangle + |\boldsymbol{Alive}\rangle$

Abandoning Local Reality…

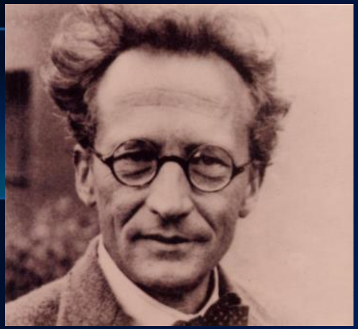


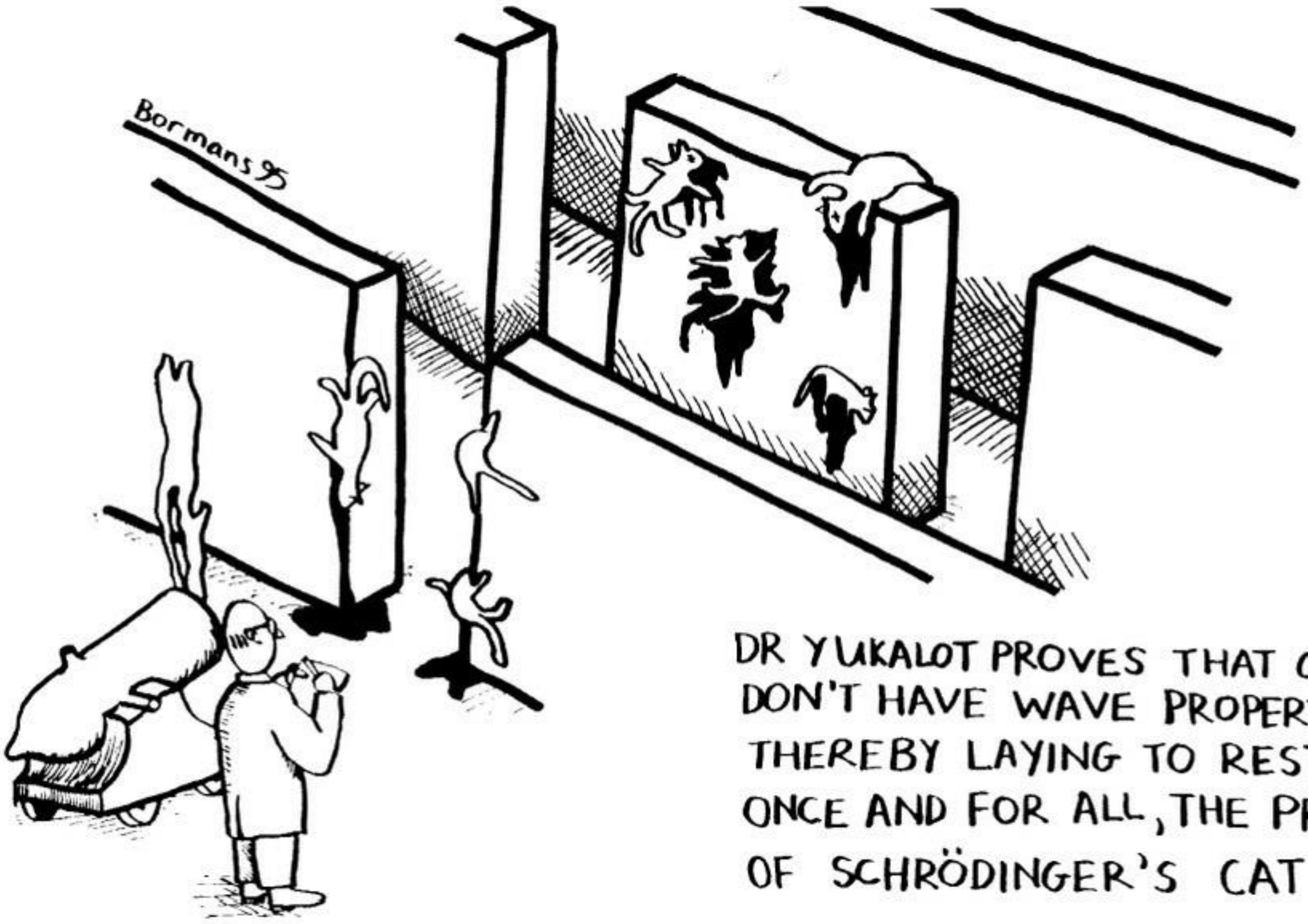
"God does not play dice with the universe."

- ***Einstein***

"I don't like it, and I'm sorry I had anything to do with it."

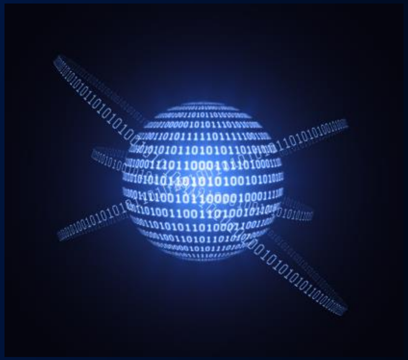
- ***Schrodinger***



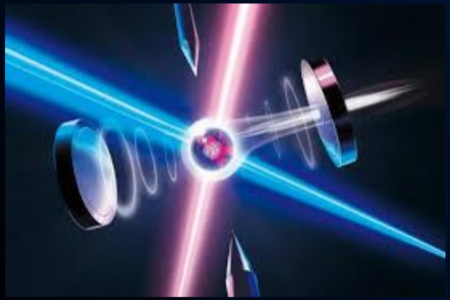


DR YUKALOT PROVES THAT CATS DON'T HAVE WAVE PROPERTIES, THEREBY LAYING TO REST, ONCE AND FOR ALL, THE PROBLEM OF SCHRÖDINGER'S CAT.

THE 2ND QUANTUM REVOLUTION (1980 – PRESENT)

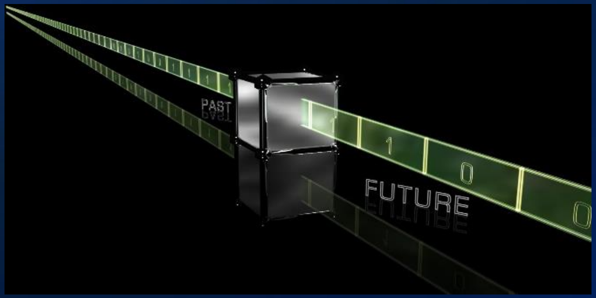


Quantum Computing



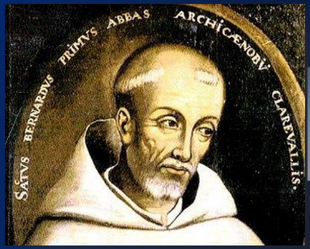
Quantum Metrology

Quantum Cryptography



Quantum Causal Modelling

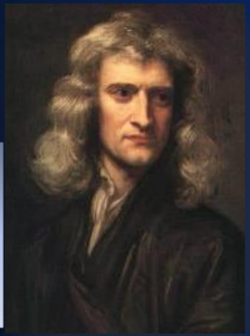
Occam's Razor



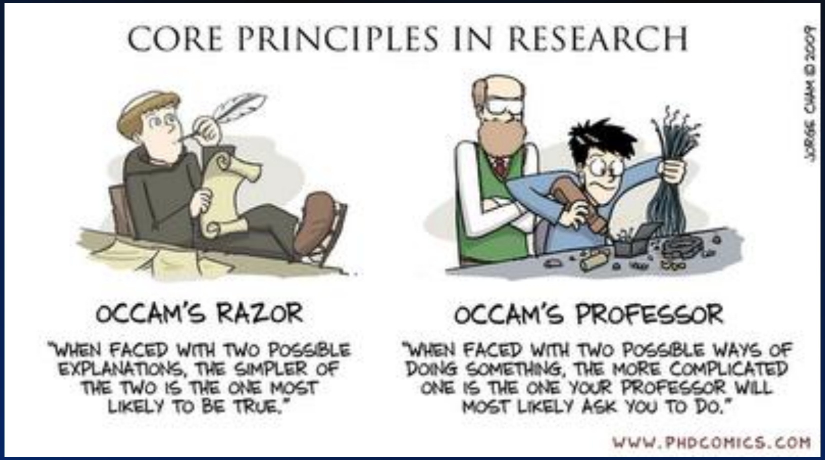
"Plurality is not to be posited without necessity."

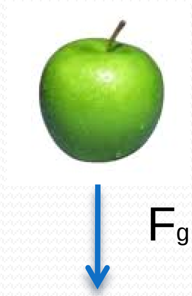
William of Ockham

"We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances."



Isaac Newton





Initial Position

Initial Velocity

Model

$$\frac{d^2y}{dt^2} = -g$$

Observed Behavior

$$y(t)$$

F_g

Initial Position

Initial Velocity

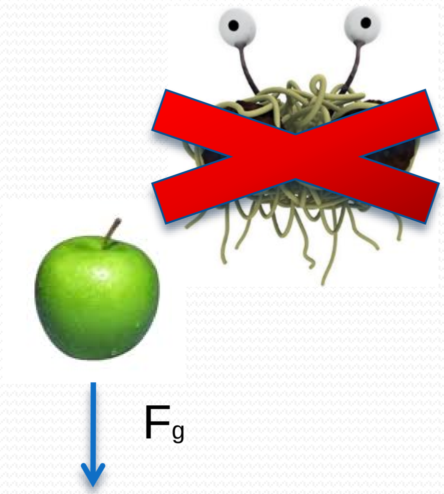
Entire Past History

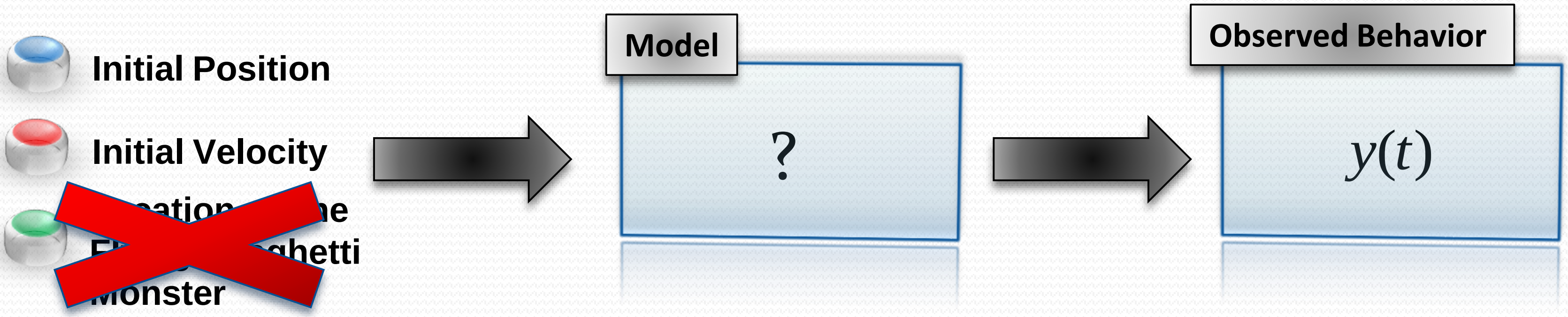
Model

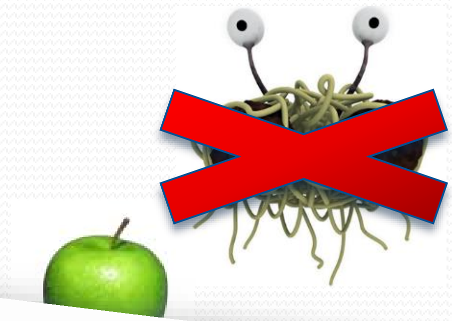
$$\frac{d^2y}{dt^2} = -g$$

Observed Behavior

$$y(t)$$

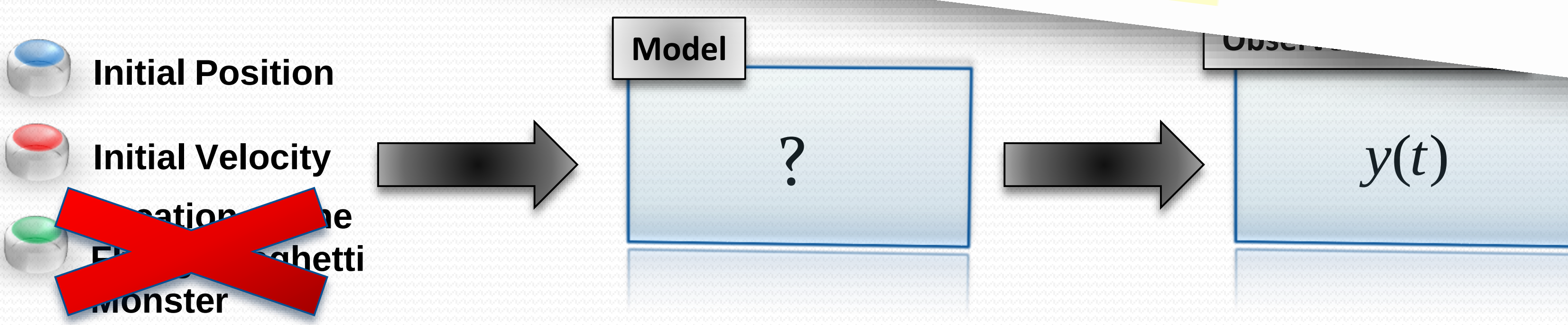

Fg


Initial Position
Initial Velocity
Model
?
Observed Behavior
y(t)

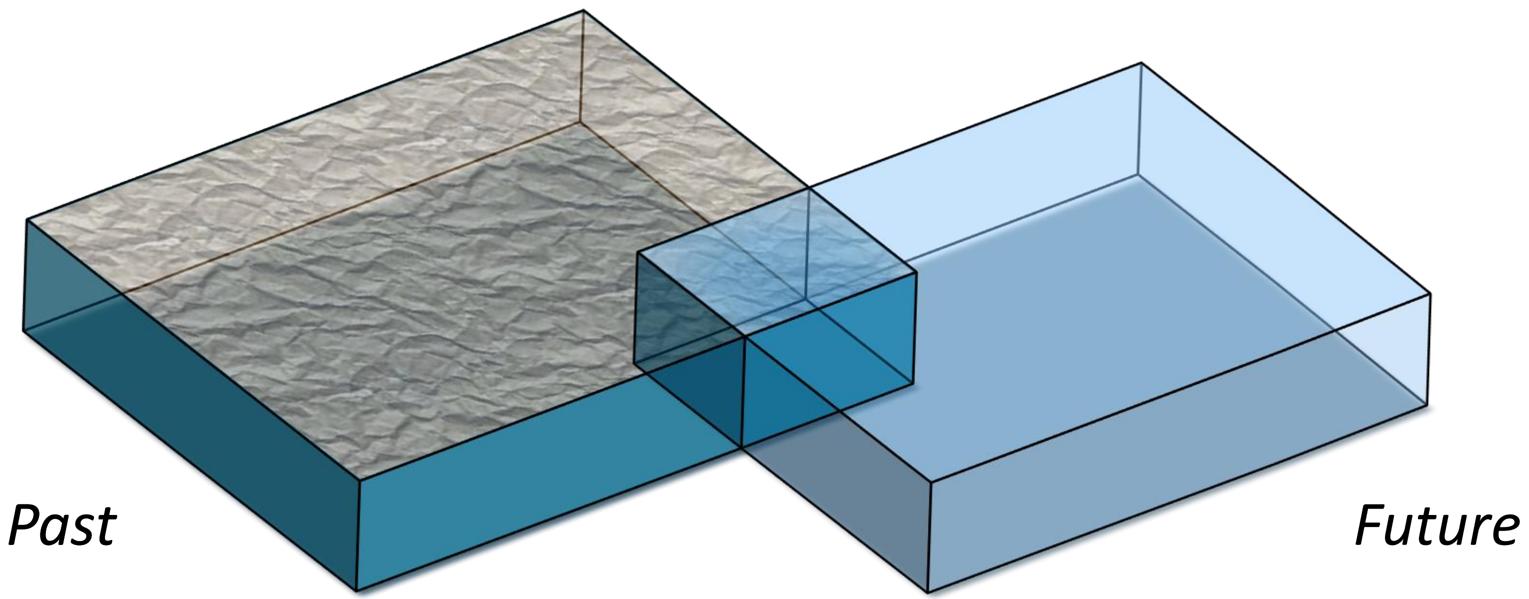


IN ADDITION, there are a number of lesser ways in which the manuscript should be improved;

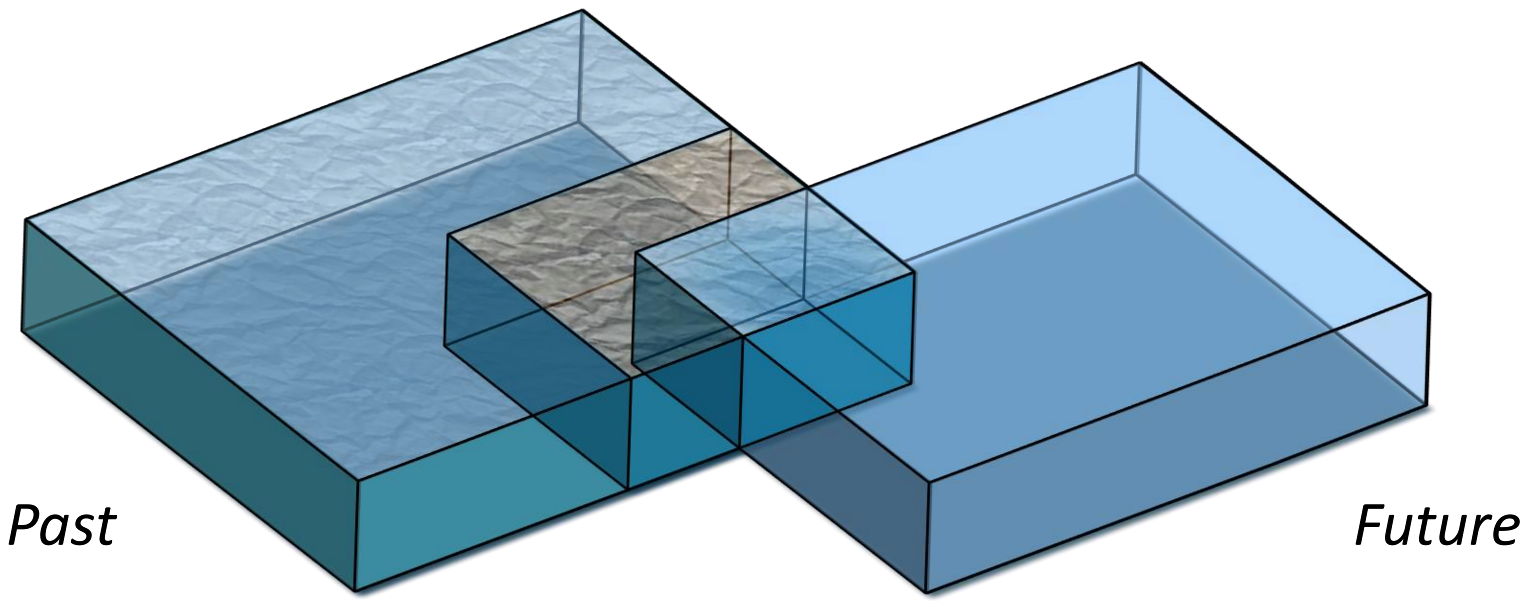
1. The authors should show due respect by referring to "The Flying Spaghetti Monster" rather than "a flying spaghetti monster".

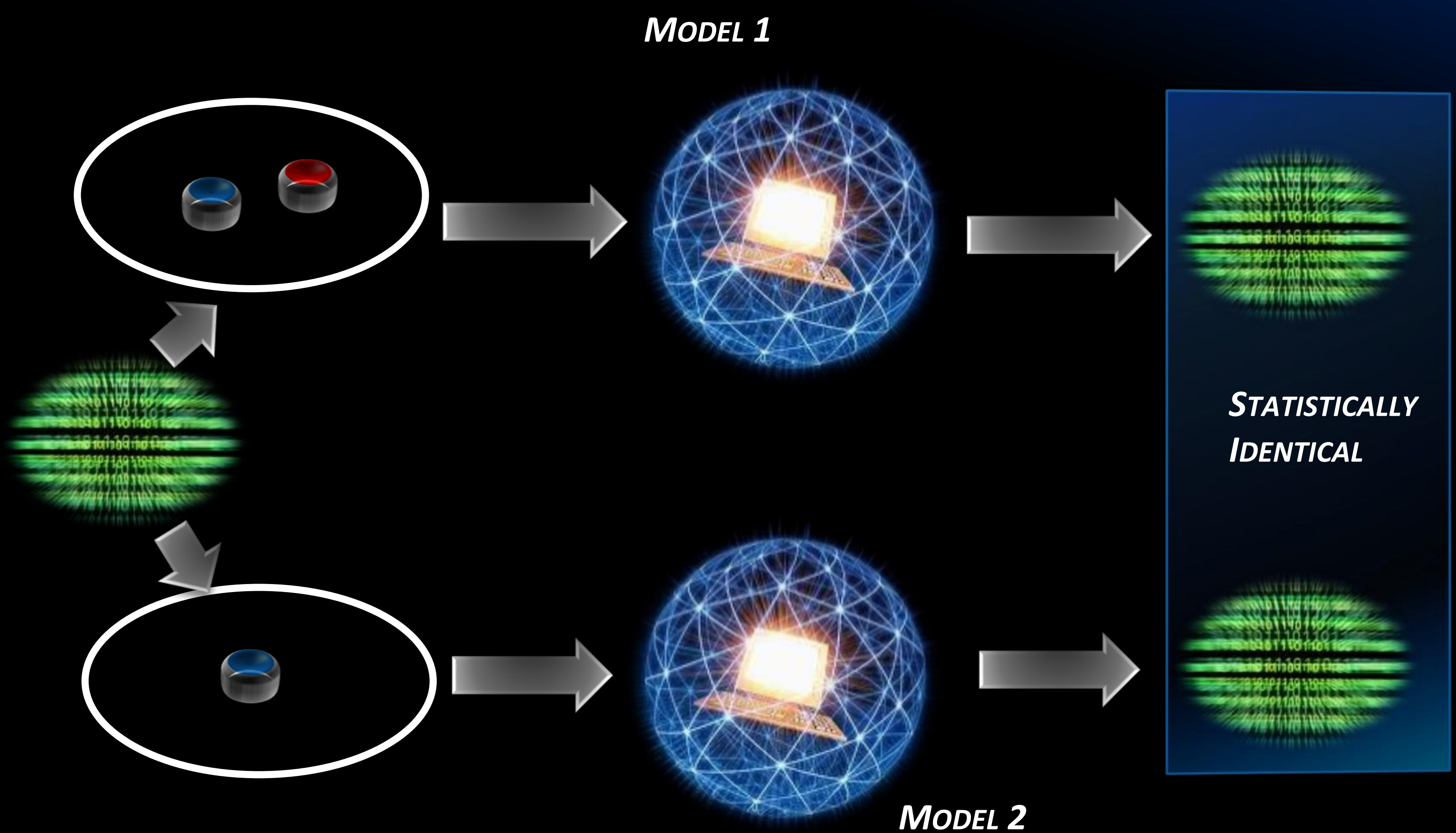


Without any understanding, every possible past is a potential cause of future events.

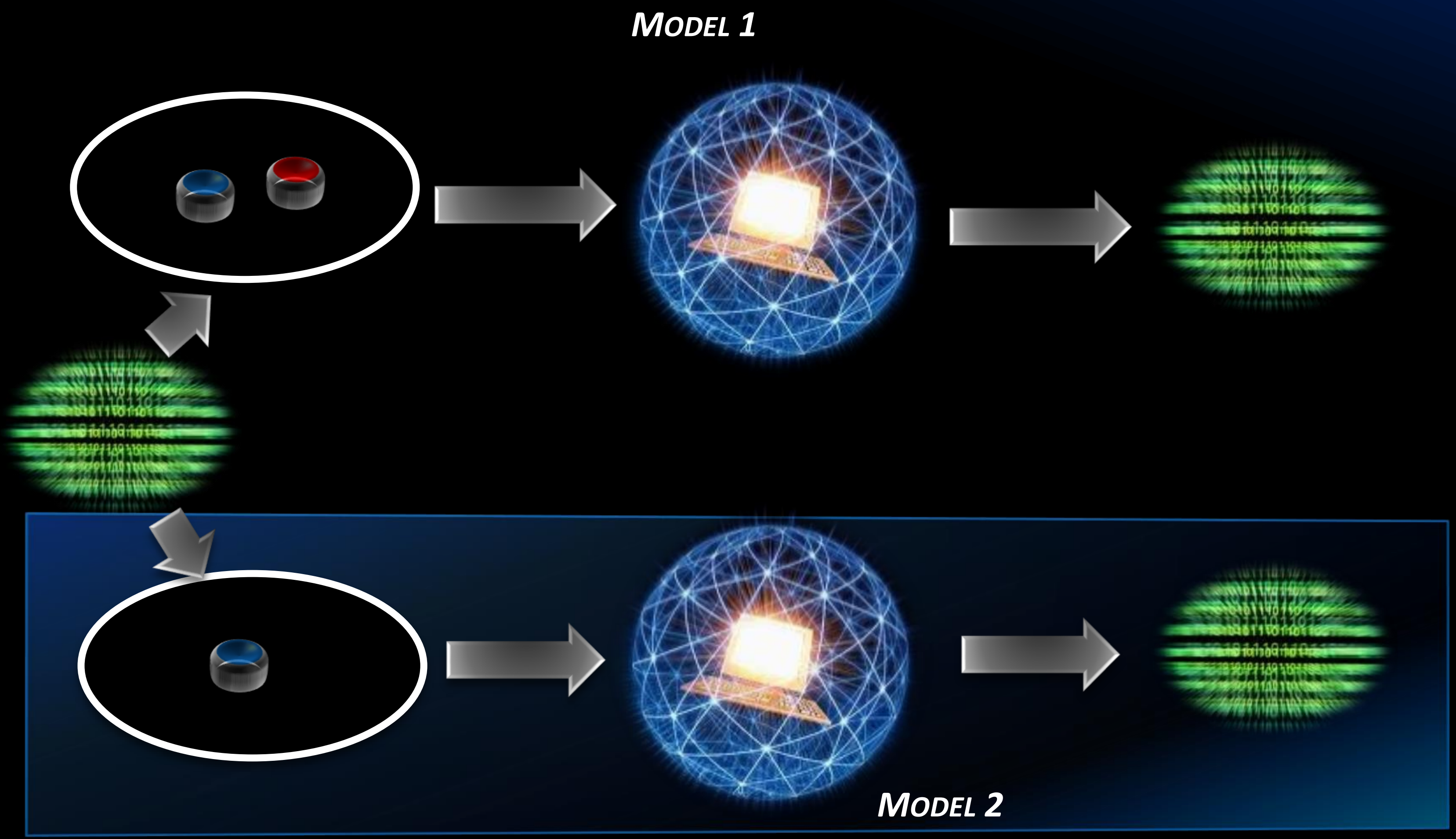


The better we can isolate the causes of natural things, the greater our understanding.



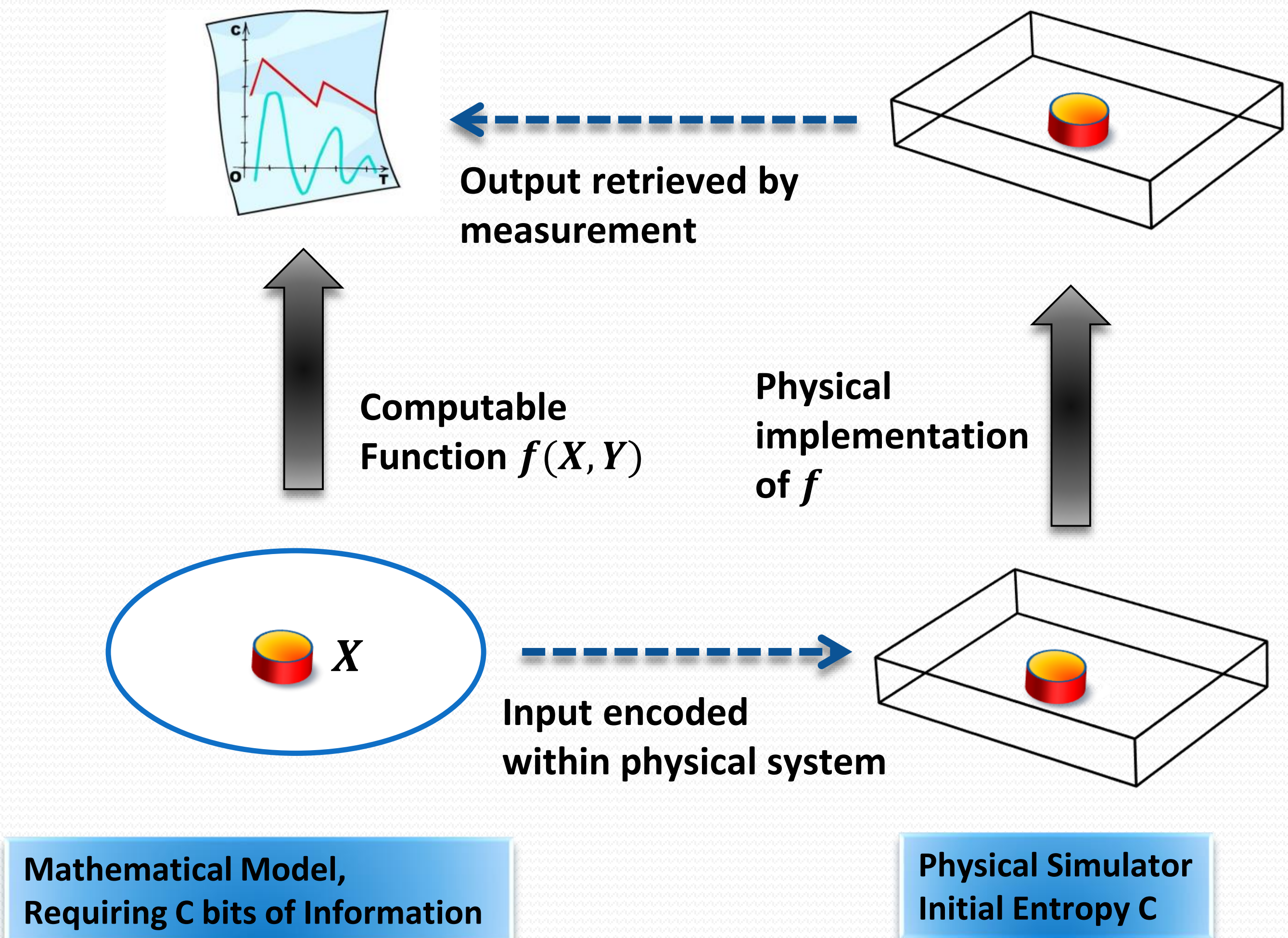


MODEL 1
STATISTICALLY IDENTICAL
MODEL 2



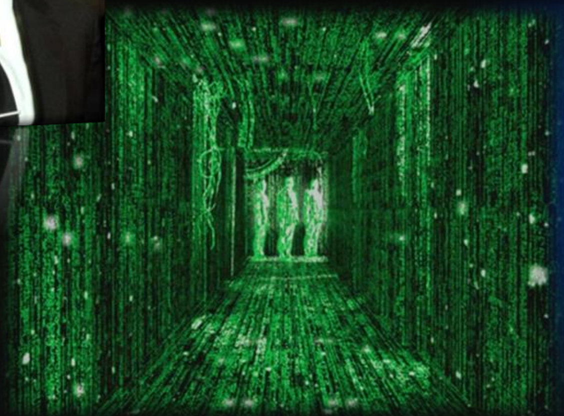
The Model the Requires the Least Input Information is preferred.
(as Quantified by Information Entropy)

Operational Implications



If understanding the dynamics of a phenomena requires knowledge of x, then any system that simulates the phenomena must store x.

Programming the Matrix

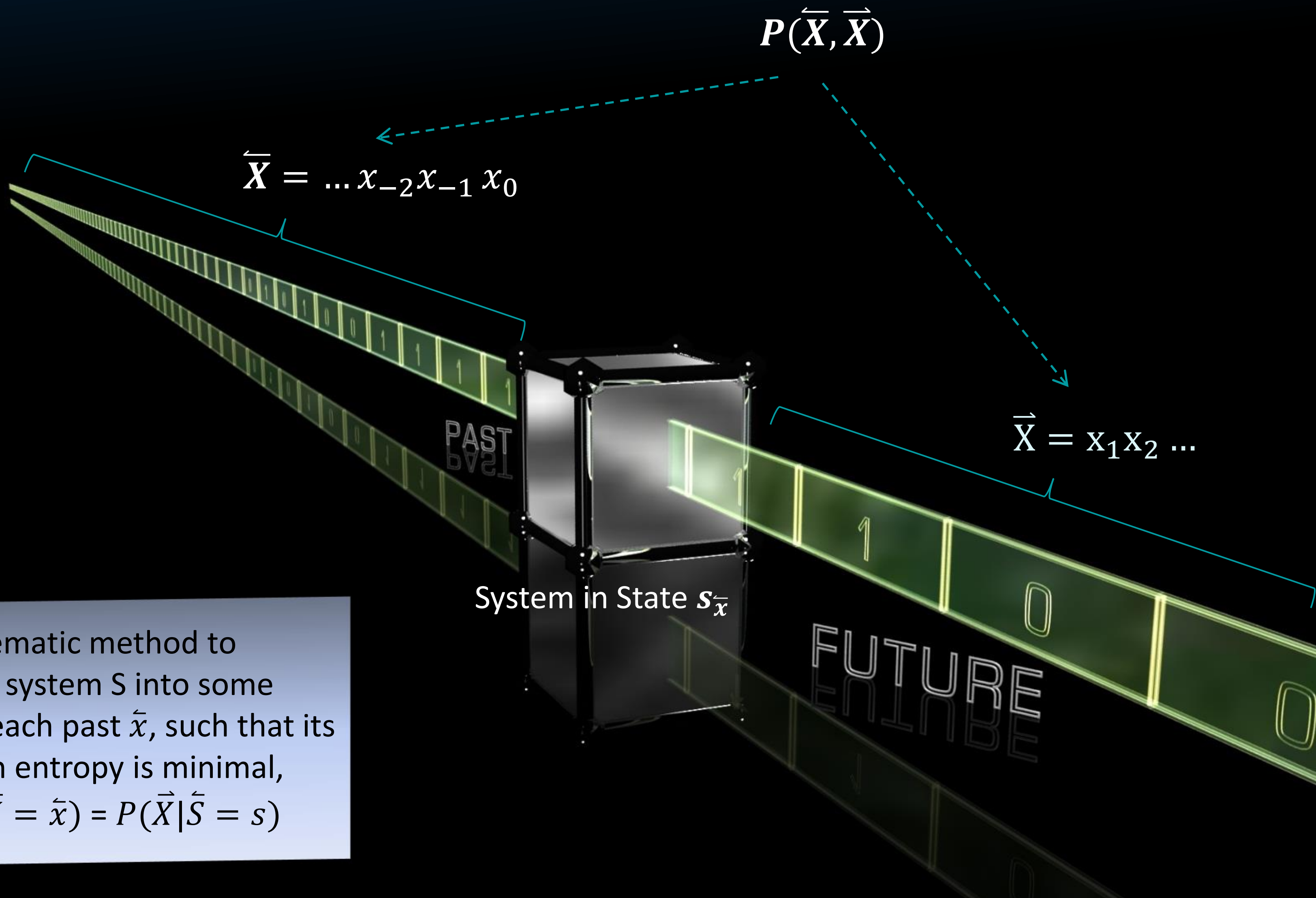


Suppose you're a programmer for the matrix

You are tasked to program an object to replicate a particular desired behaviour.

What is the least amount of past information you need to store?

Stochastic Processes



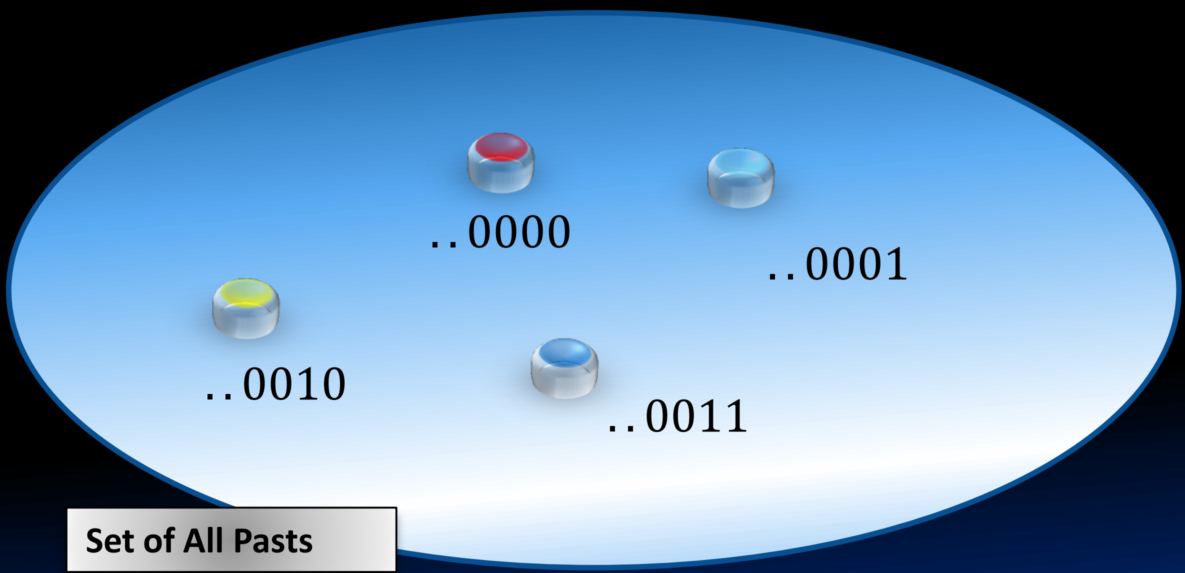
Task:

Find a systematic method to configure a system S into some state s for each past $\overleftarrow{x}$, such that its information entropy is minimal, and $P(\overrightarrow{X}|\overleftarrow{X} = \overleftarrow{x})$ = $P(\overrightarrow{X}|\overleftarrow{S} = s)$

Brute Force Approach..

$$S_{\overleftarrow{x}} = \overleftarrow{x}$$

Construct a system that stores each possible past in a separate configuration.



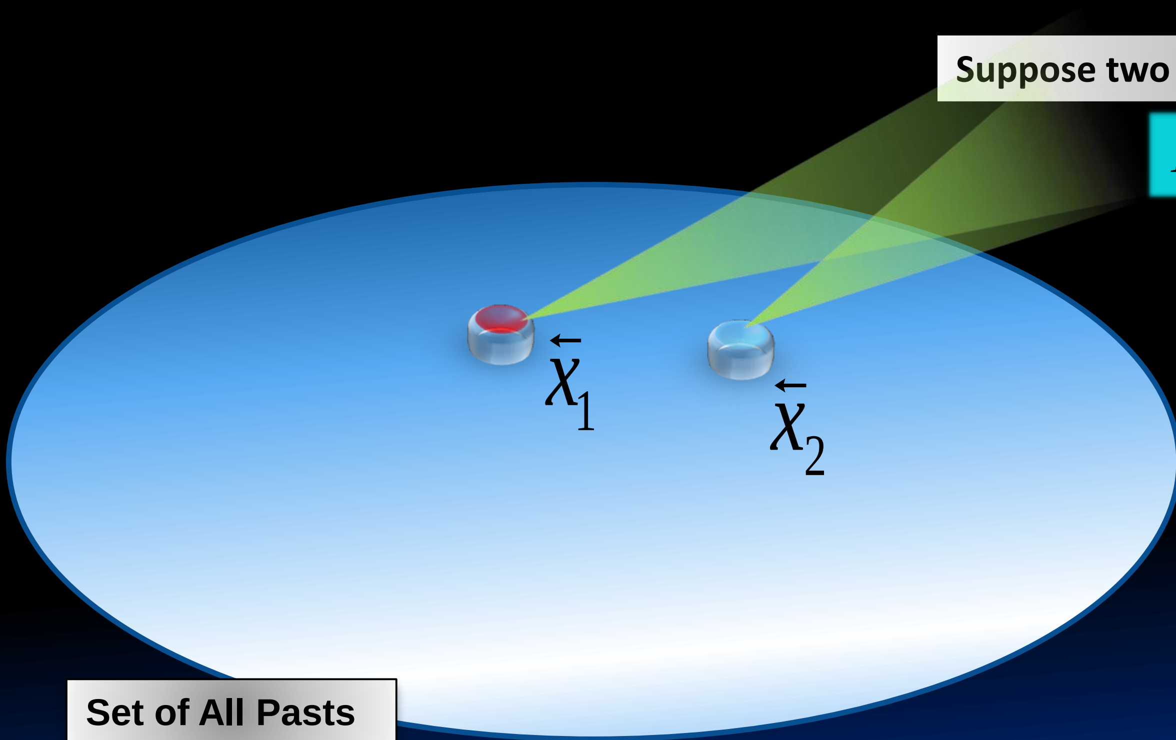
Random Processes would require infinite memory!

A More Refined Method

Suppose two pasts have statistically identical futures

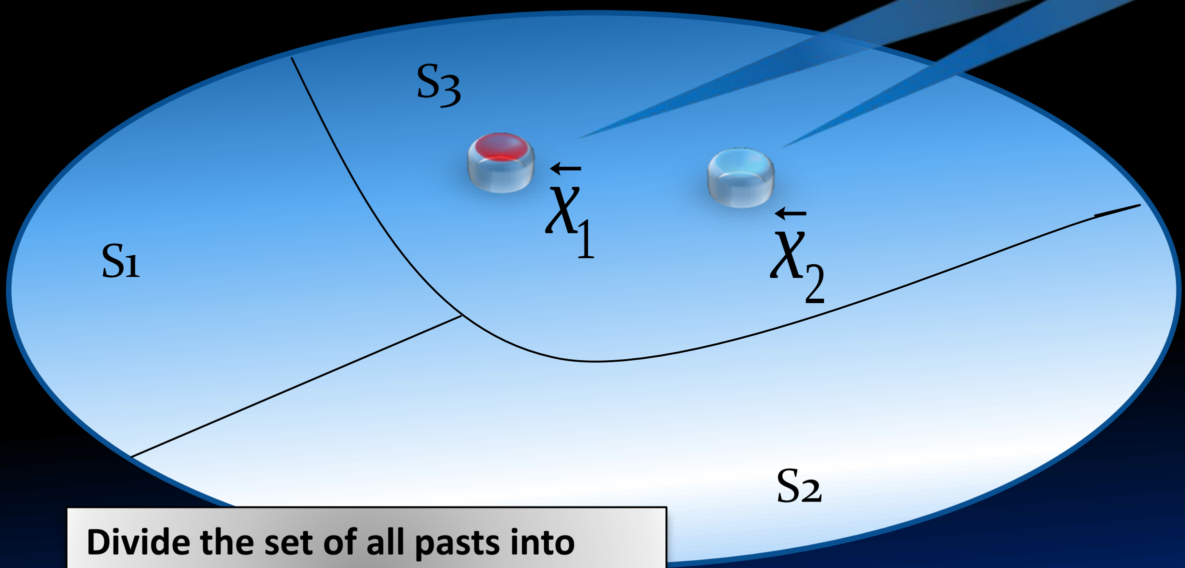
$$P(\overrightarrow{X} \mid \overleftarrow{X} = \overleftarrow{x}_1) = P(\overrightarrow{X} \mid \overleftarrow{X} = \overleftarrow{x}_2)$$

The information needed to distinguish the two is irrelevant to the future of the process and can thus be discarded.



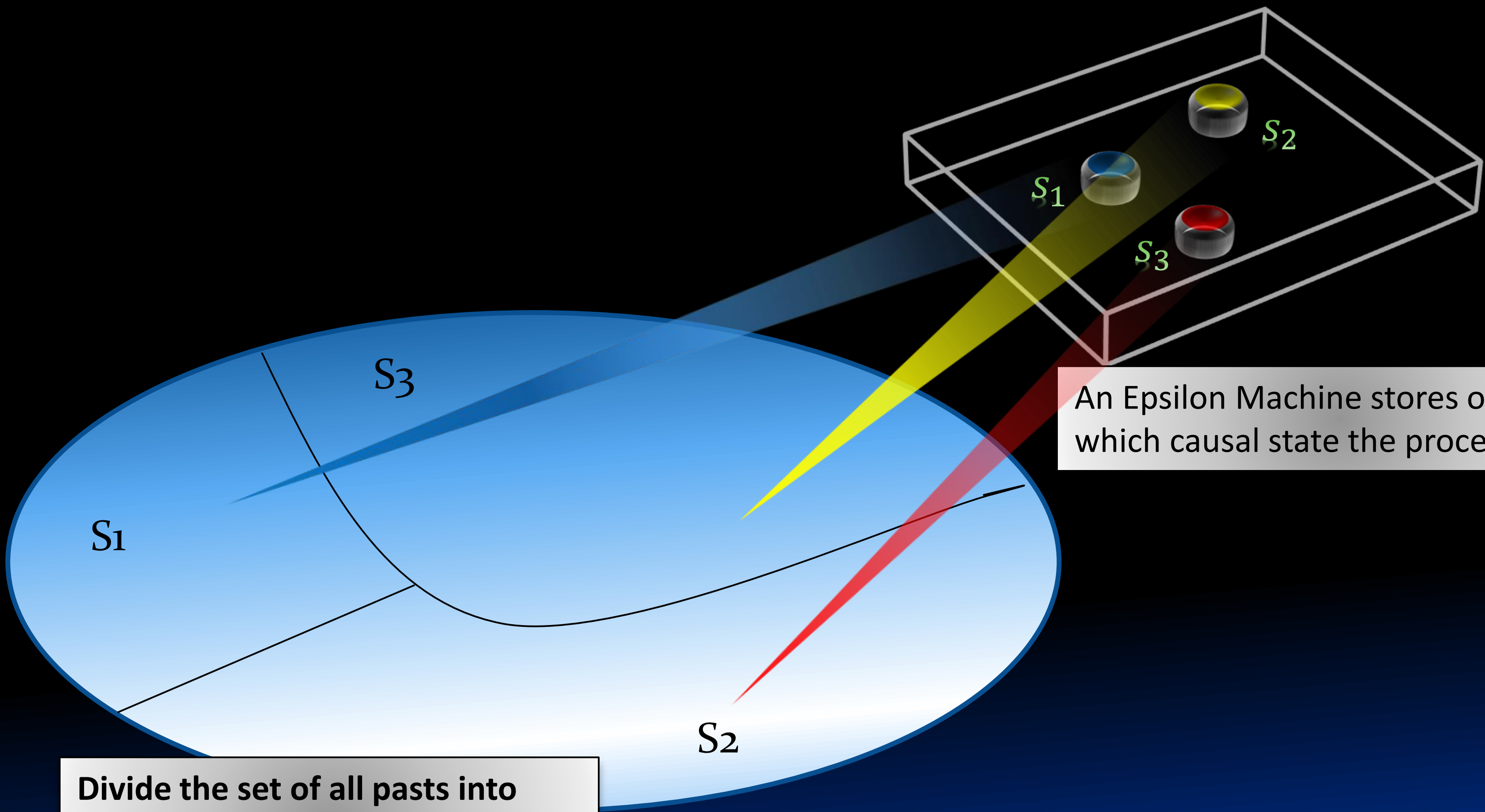
A More Refined Method

Two different possible pasts belong to the same group if they have coinciding futures.



Divide the set of all pasts into groups (subsets), referred to as Causal states.

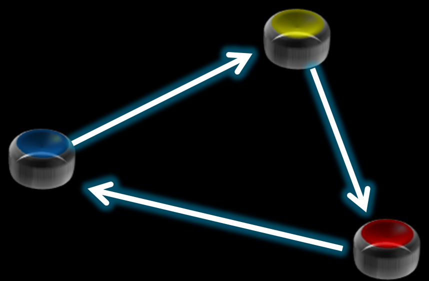
A More Refined Method

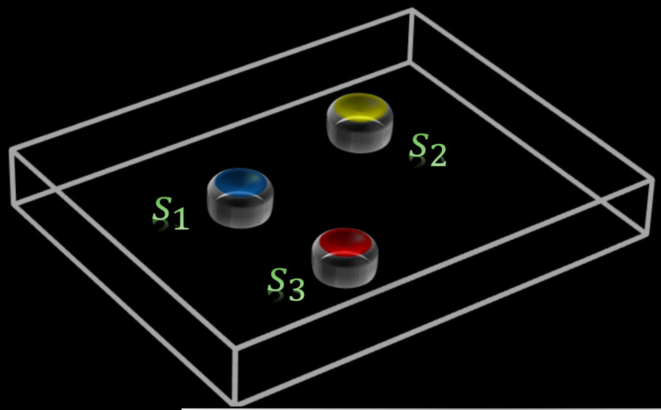


An Epsilon Machine stores only which causal state the process is in.

Divide the set of all pasts into groups (subsets), referred to as Causal states.

The Simplest Model… Epsilon Machines





An Epsilon Machine stores only which causal state the process is in.

The Stochastic Process can then be completely defined by transition probabilities on the causal states.

$$T^r{}_{j,k}$$

Probability a Stochastic process in Causal state S_j will emit output `r' and transition to S_k

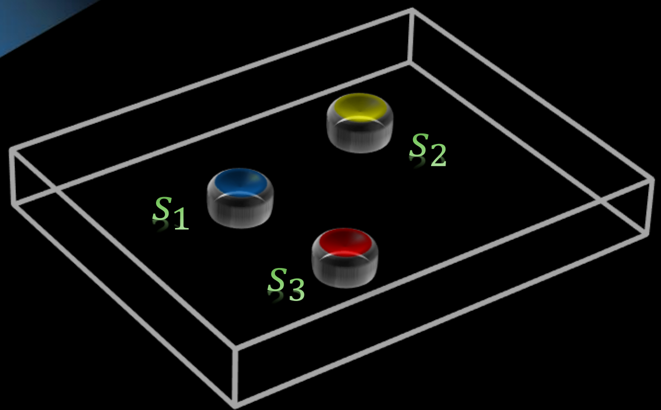
The Simplest Model...

Probability the process is in Causal State S_i

Internal Entropy

$$C_\mu = -\sum p_i \log p_i$$

(Amount of information needed to dtinsguish the causal states)



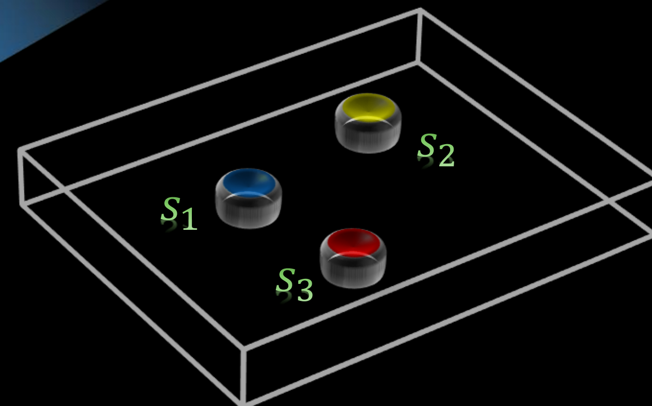
To simulate a sequence of random coin flips....

We have a process with exactly 1 Causal State

No Information about the Past is required!

Statistical Complexity

Probability the process is in Causal State S_i



Internal Entropy

$$C_\mu = -\sum p_i \log p_i$$

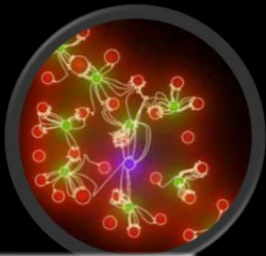
(Amount of information needed to communicate the causal state)

ε-machines are the provably simplest classical models

C_μ Is a **intrinsic** property of a stochastic process that is a signature of complexity and structure.

Crutchfield, Young, Phys. Rev. Lett. 63, 105–108 (1989)

STATISTICAL COMPLEXITY

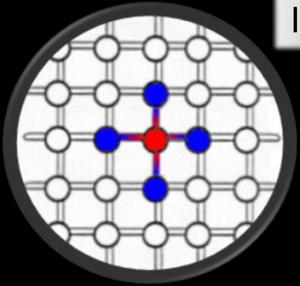


Neural Networks

Dripping Faucets

Applied to wide range of systems.

Pseudo-random
Number generators.



Ising Models

ε-machines are the provably simplest classical models

Crutchfield, Young, Phys. Rev. Lett. 63, 105–108 (1989)

C_μ Is a **intrinsic** property of a stochastic process that is a signature of complexity and structure.

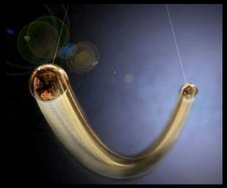
HIGH COMPLEXITY!

ORDERED

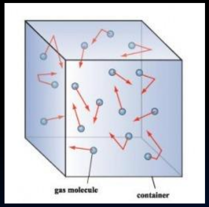
LOW COMPLEXITY

RANDOM

LOW COMPLEXITY

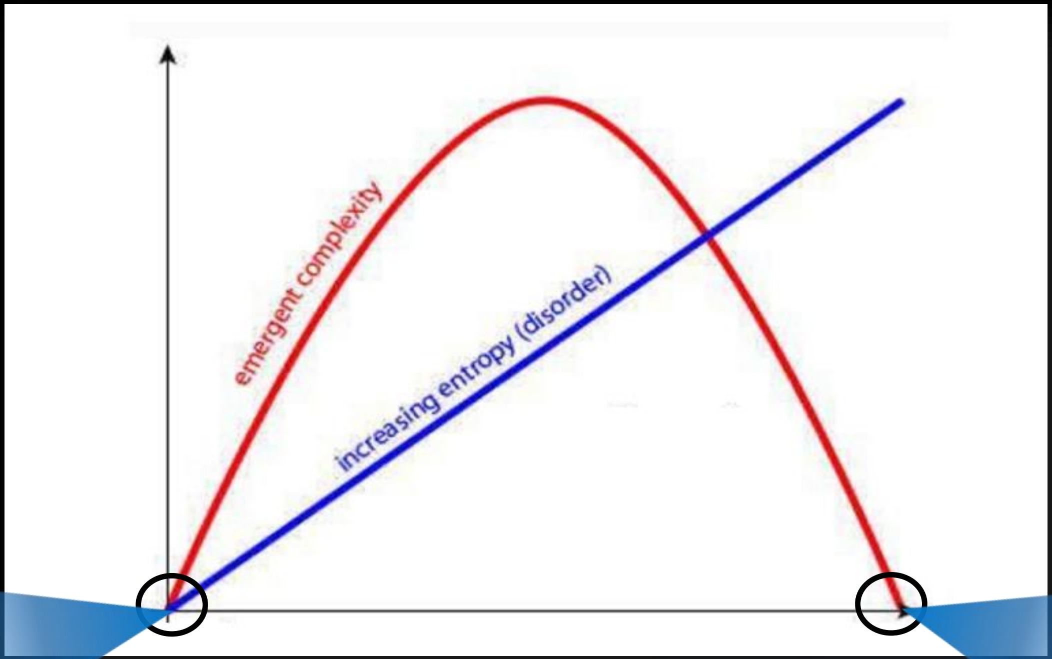


PENDULUMS



IDEAL GASES

Statistical Complexity

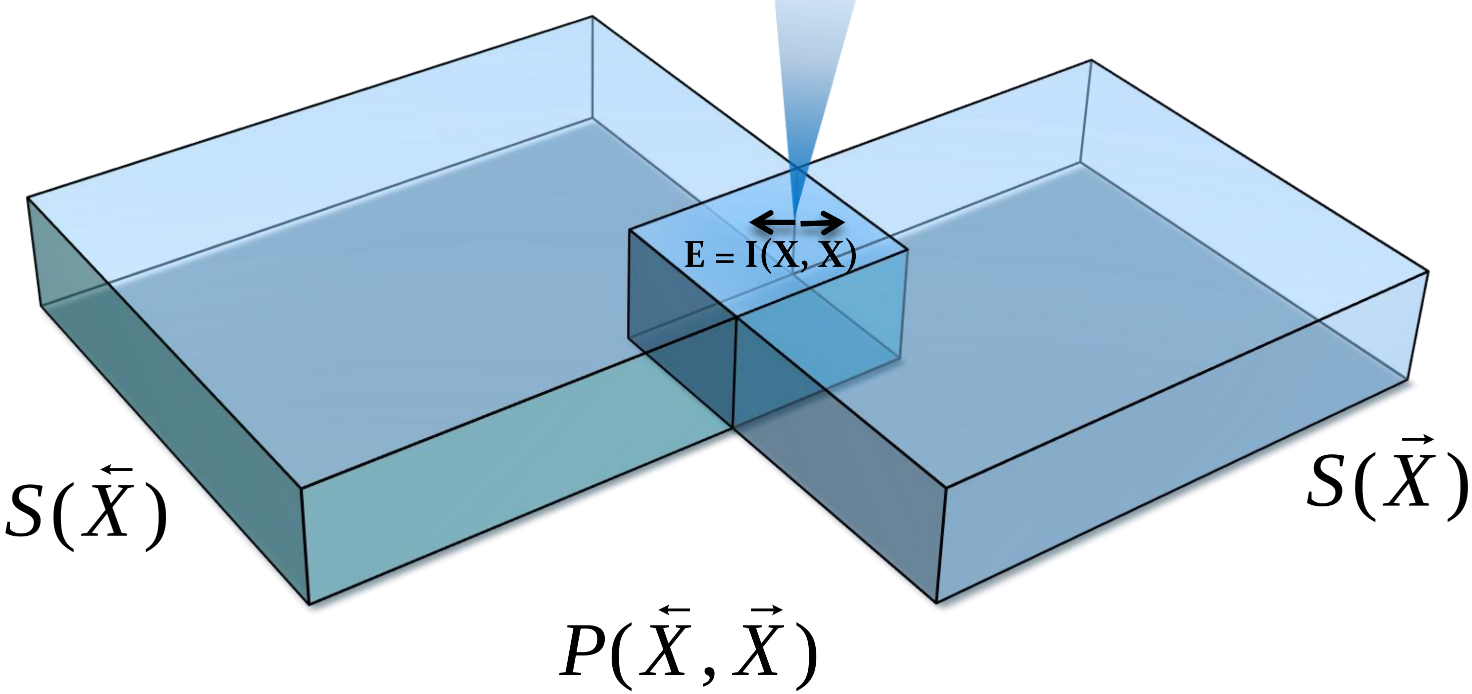


Statistical Complexity = 0 For uniform process

Statistical Complexity = 0 for random sequence.

Unavoidable Inefficiency

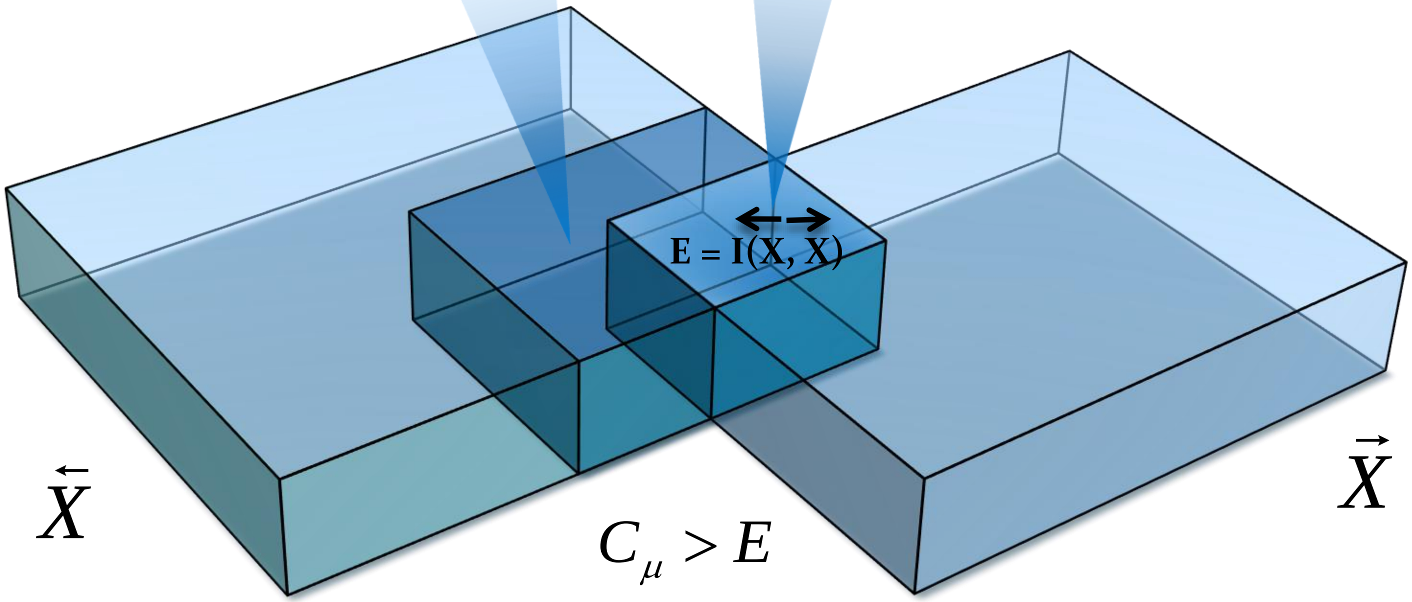
Amount of information past contains about the future (mutual information between past and future)



Unavoidable Inefficiency

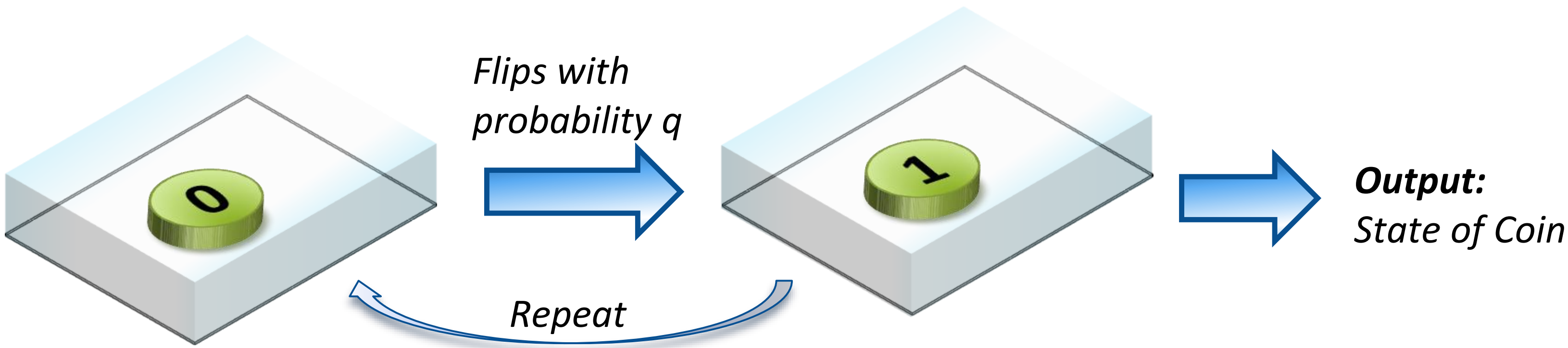
The optimal model generally require Input of entropy $C_\mu > E$!

Amount of information past contains about the future.

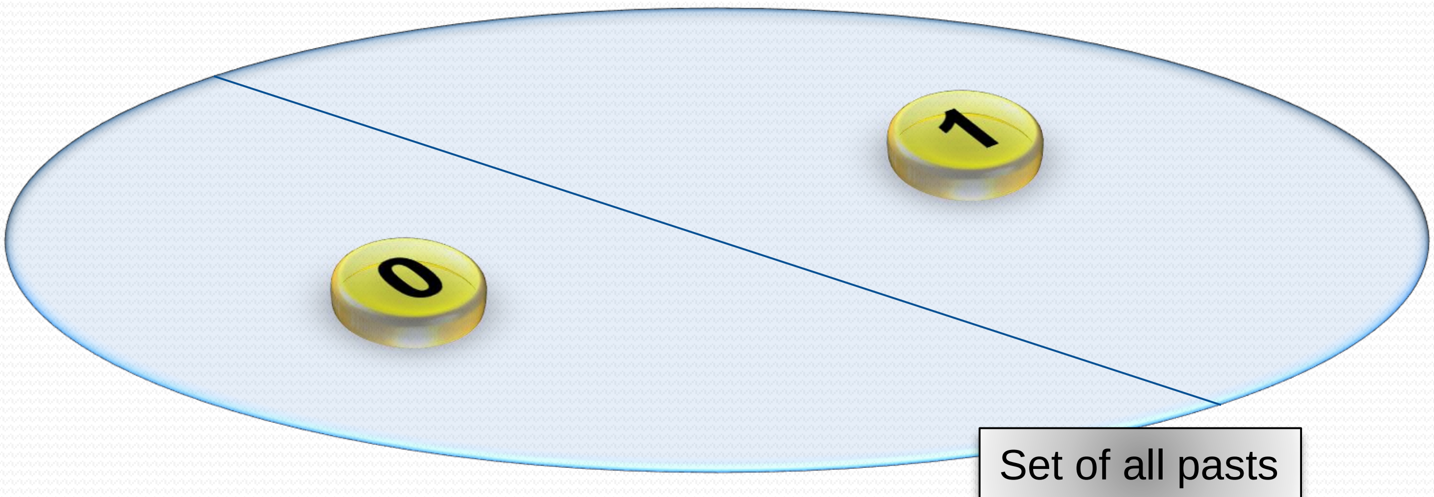


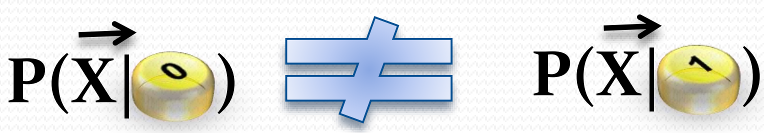
J. Crutchfield, C. Ellison, and J. Mahoney, *'Time's Barbed Arrow: Irreversibility, Crypticity, and Stored Information'* Phys. Rev. Lett 103, 094101, (2009)

Case Study: The Perturbed Coin



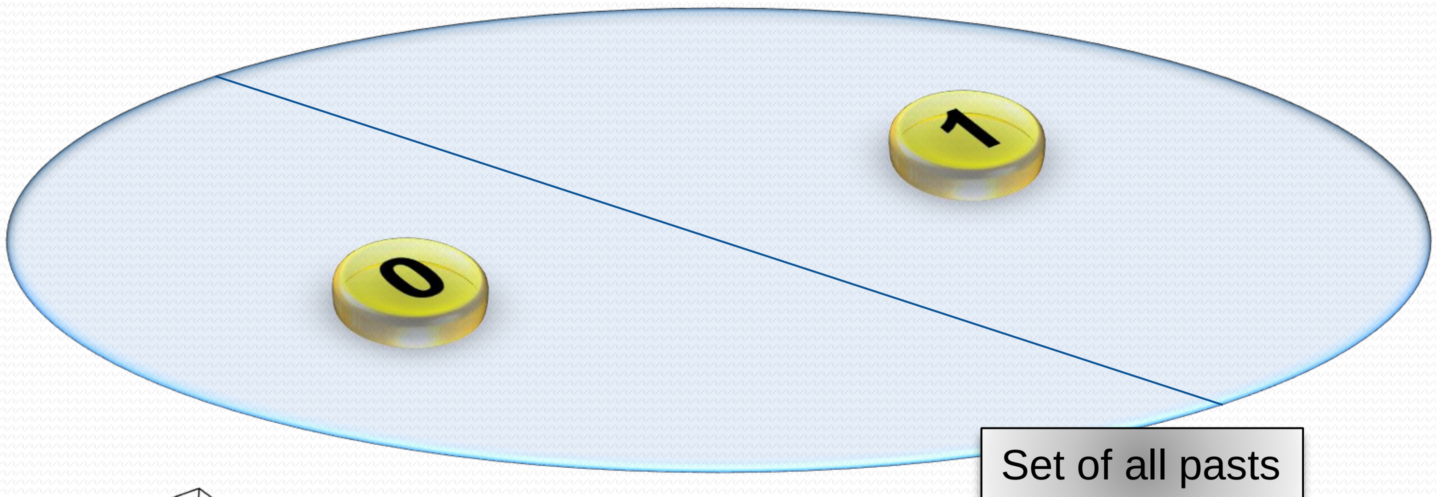
Case Study: The Perturbed Coin

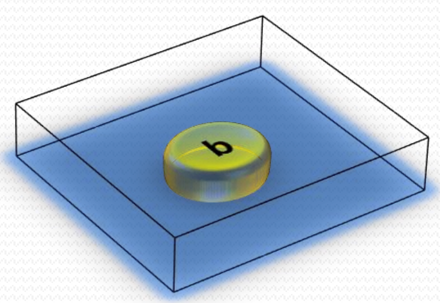




We cannot discard information about the state of the coin.

Case Study: The Perturbed Coin

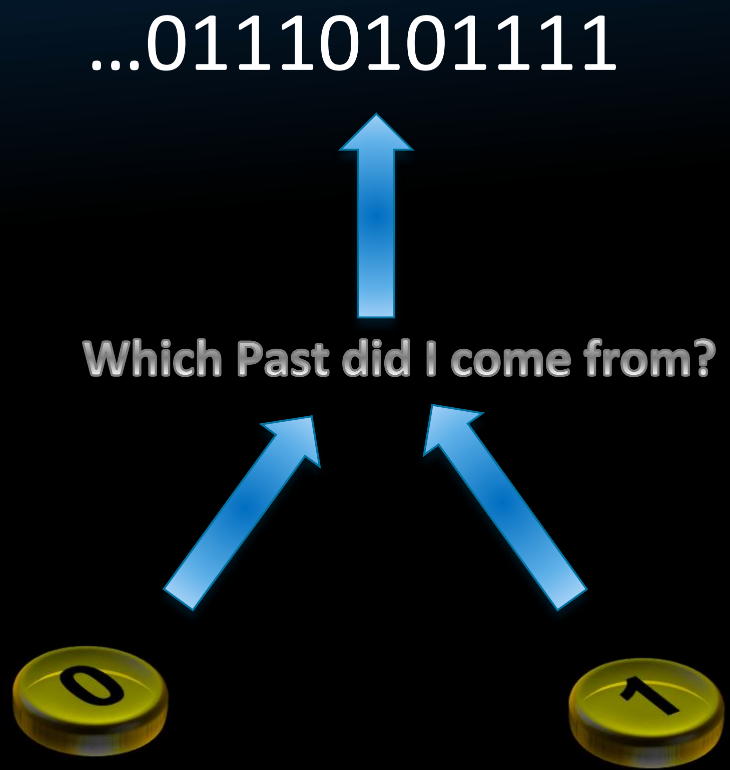




Optimal classical system for generating $\mathbf{P}(\overleftarrow{\mathbf{X}}, \overrightarrow{\mathbf{X}})$

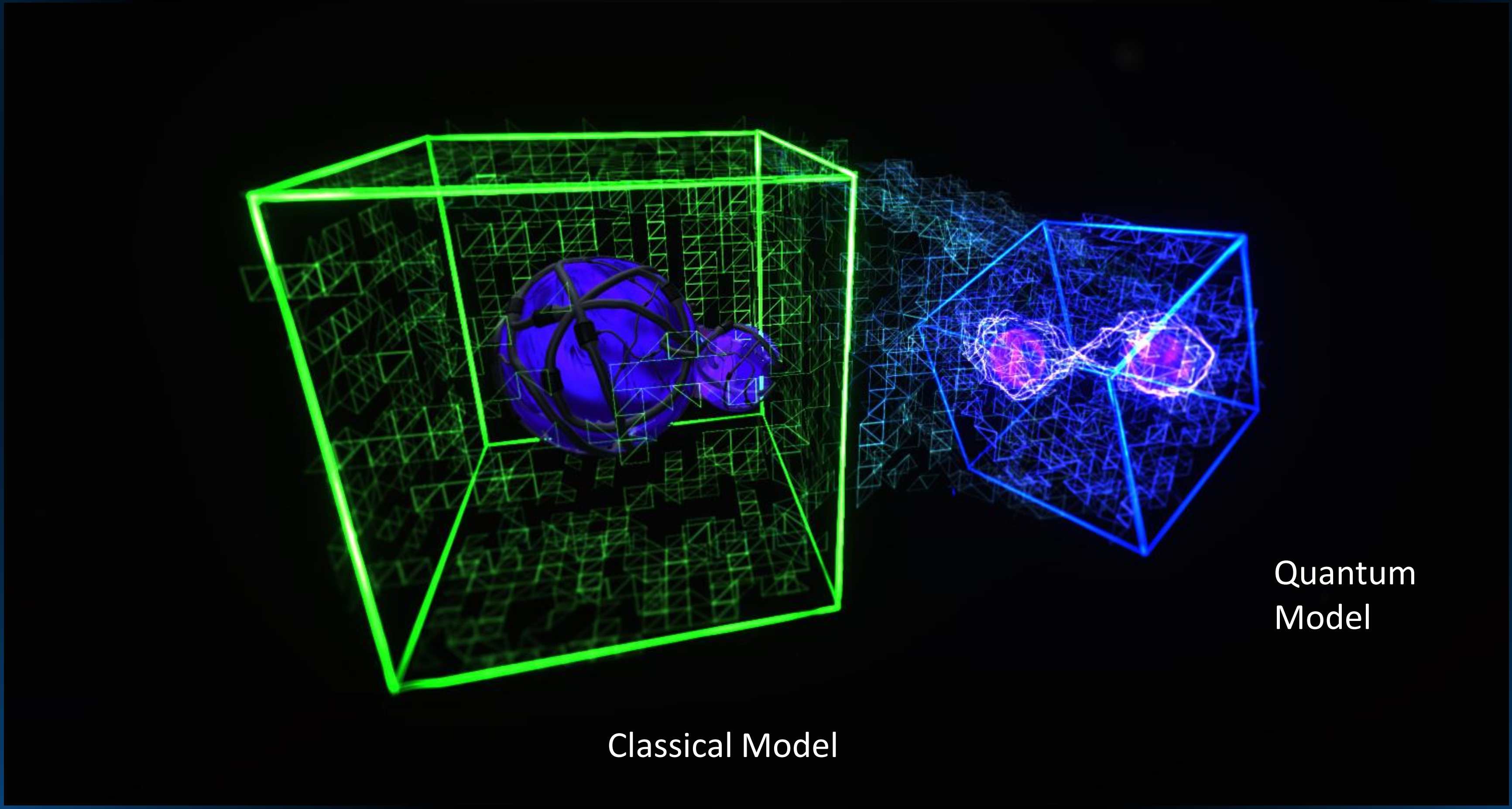
has information entropy of 1, for any q ≠ 0.5

But as q→ 0.5, the process tends towards a completely random sequence!

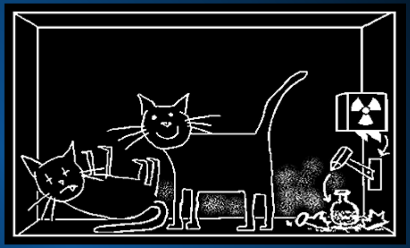


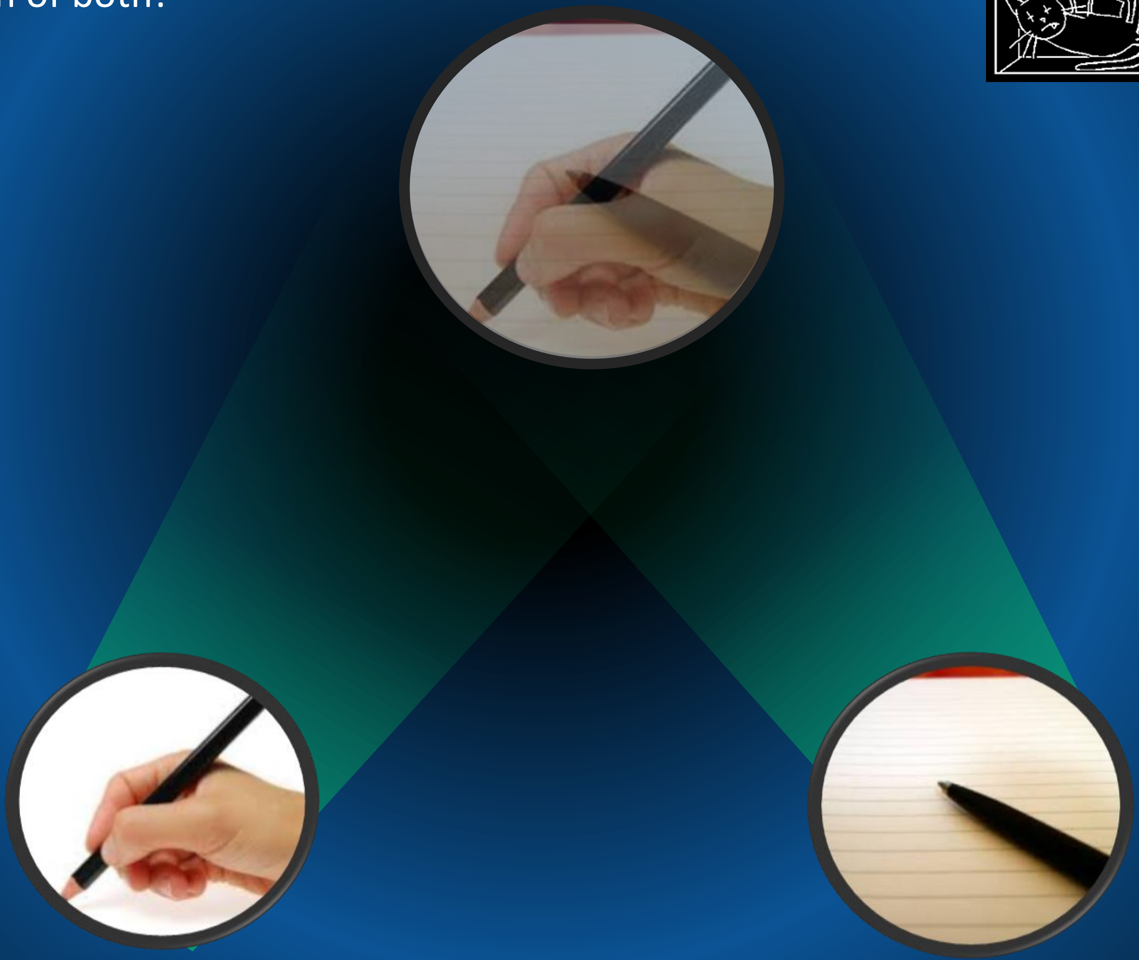
This model still stores unnecessary information!

Can Quantum Do Better?

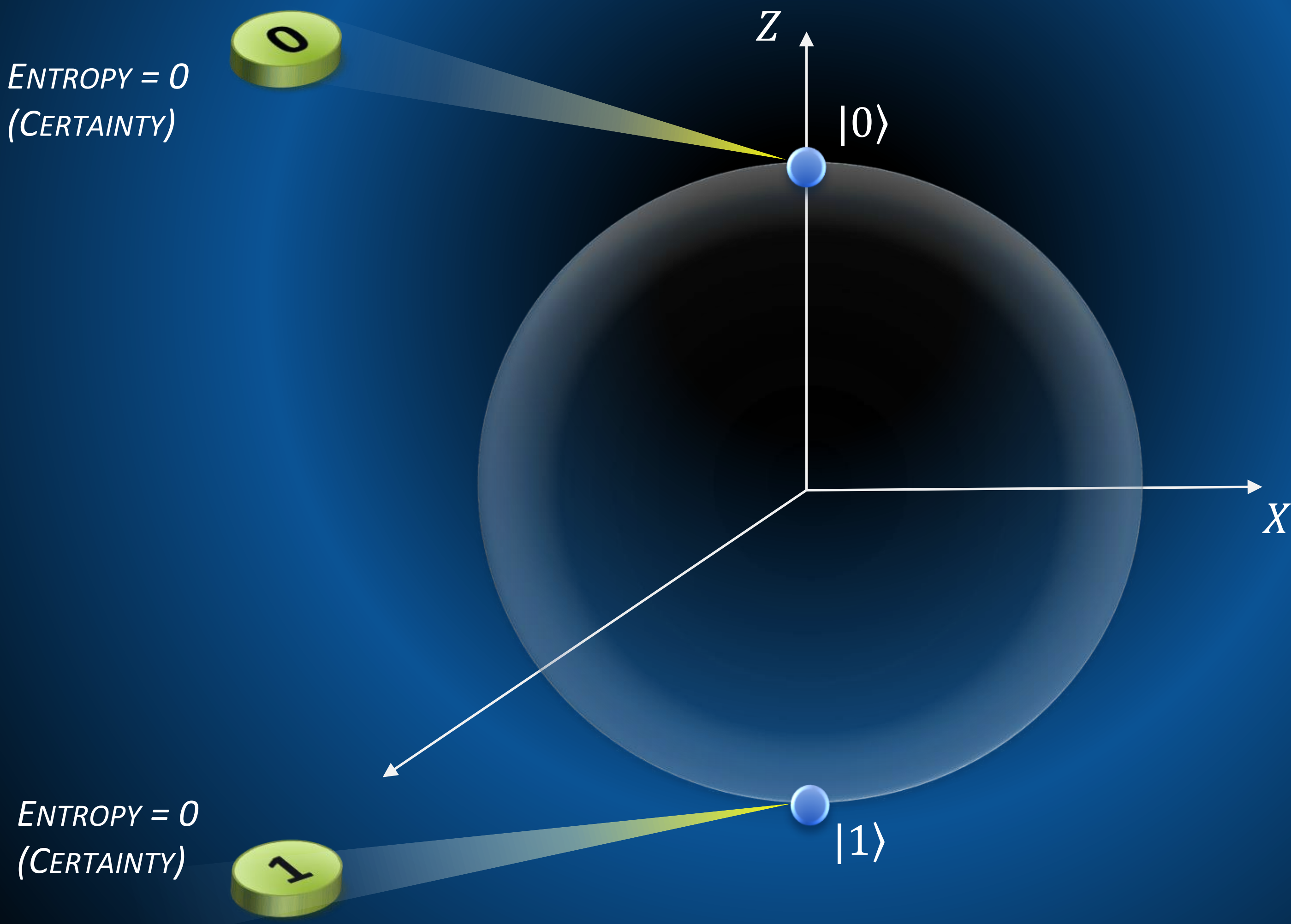



A quantum model can perform superposition of both!





From Bits to Qubits...



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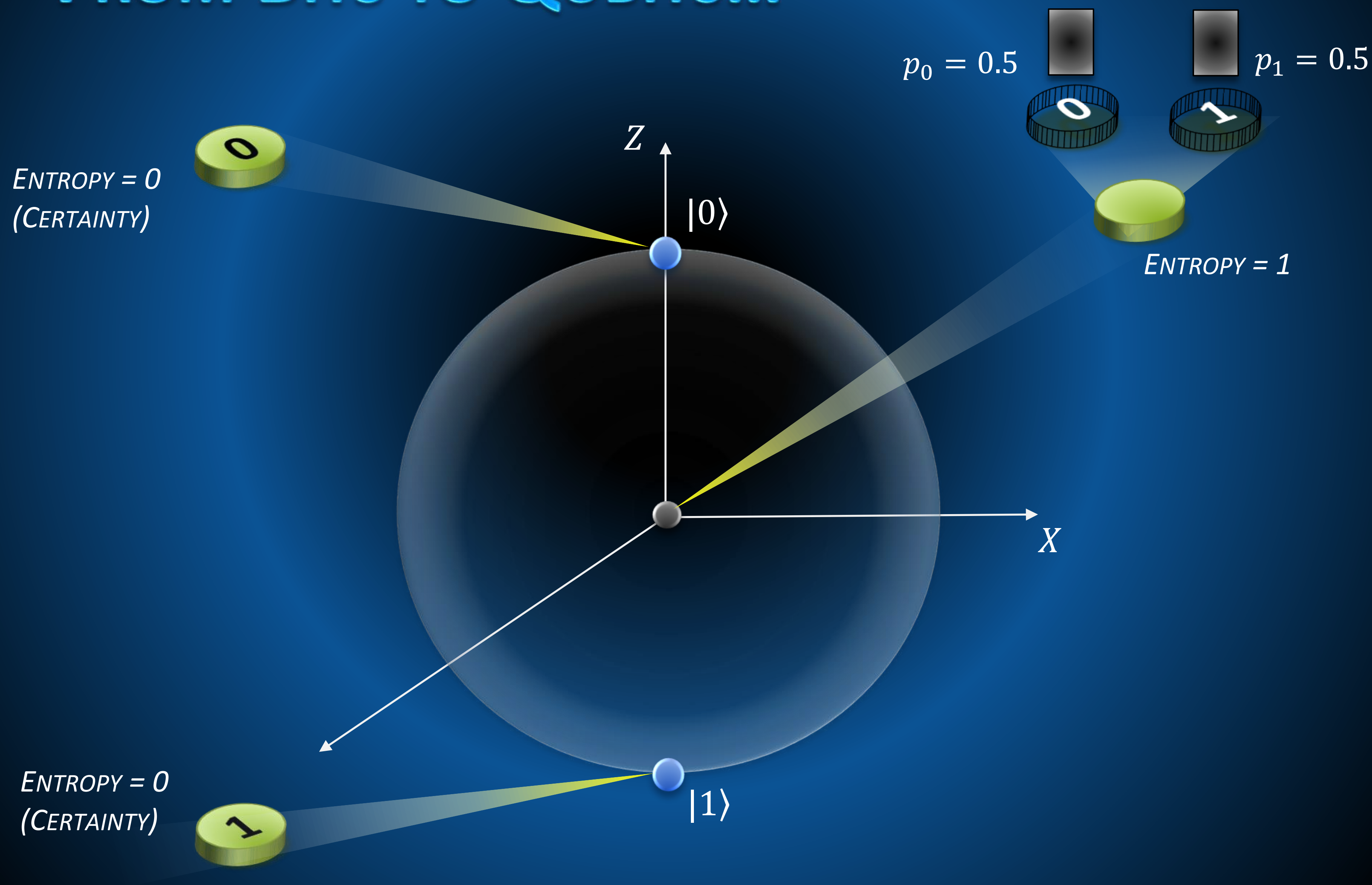

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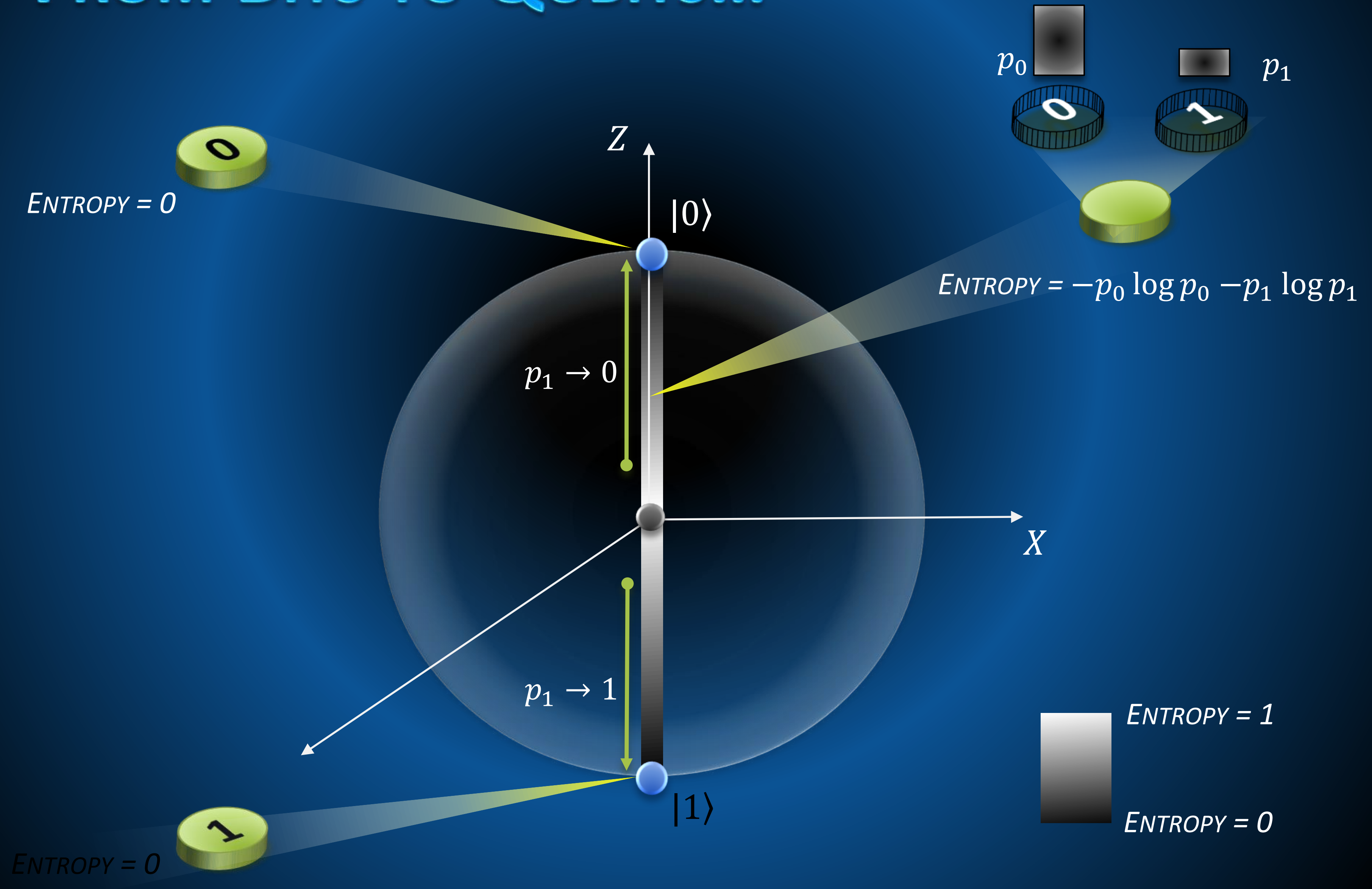

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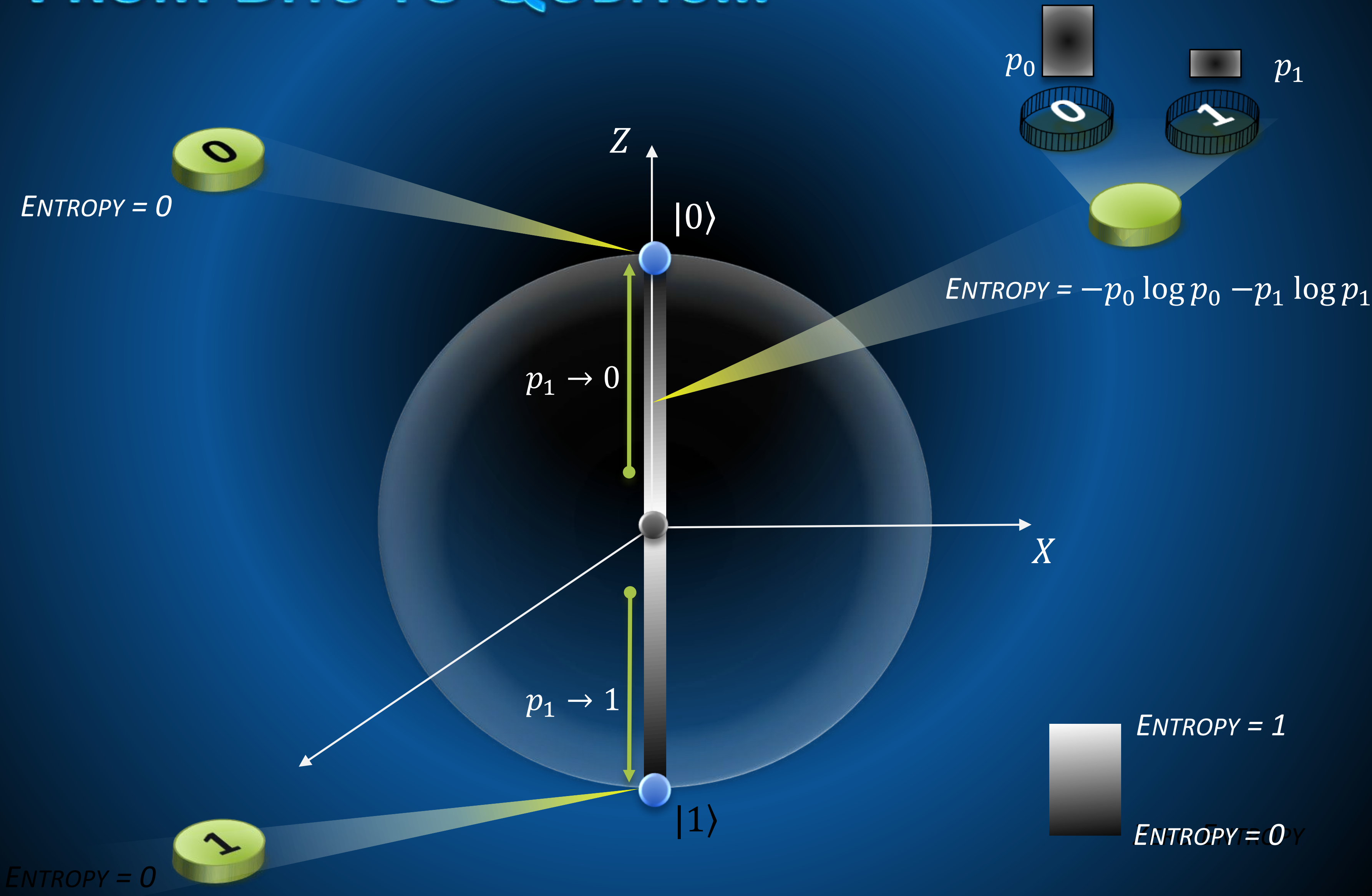

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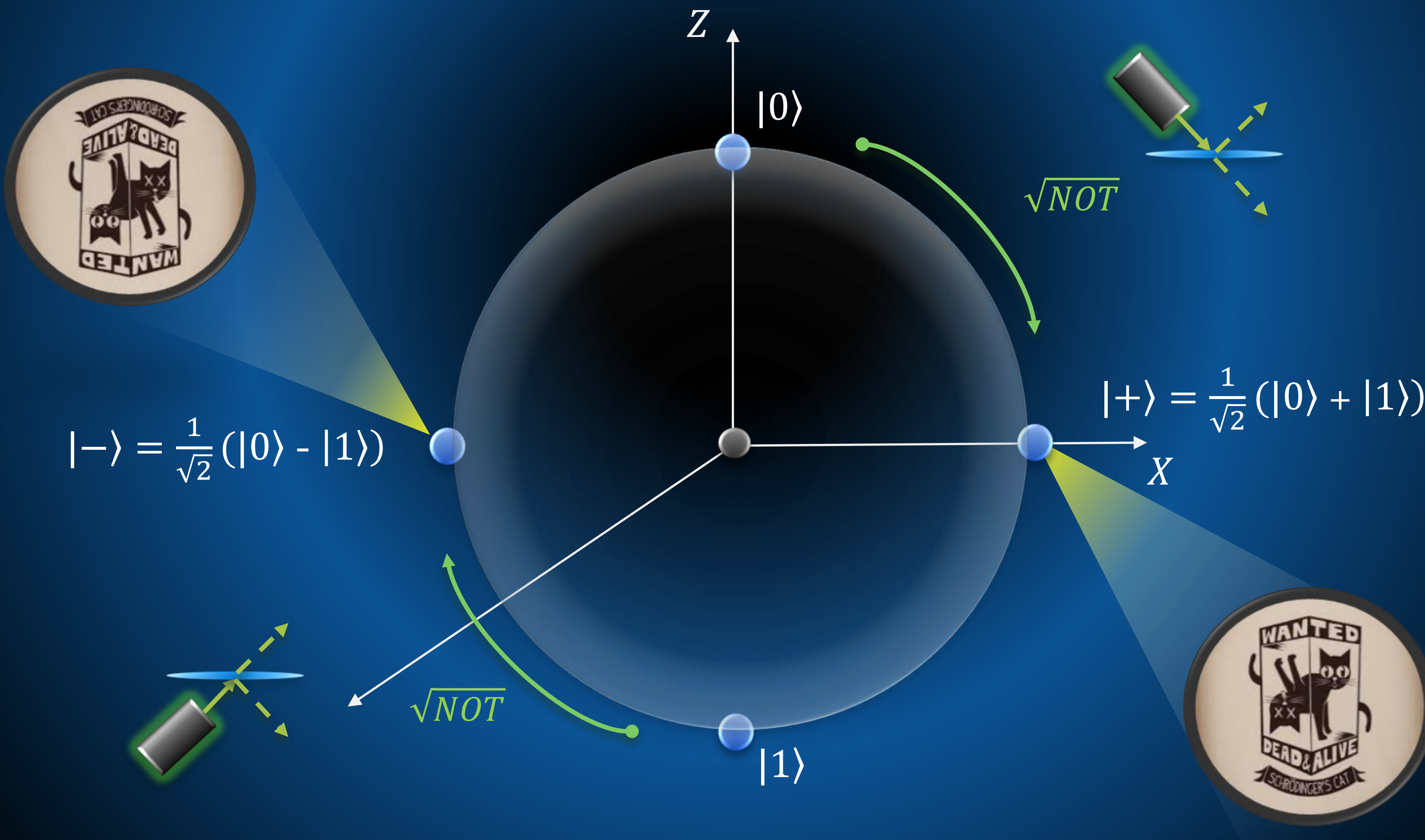
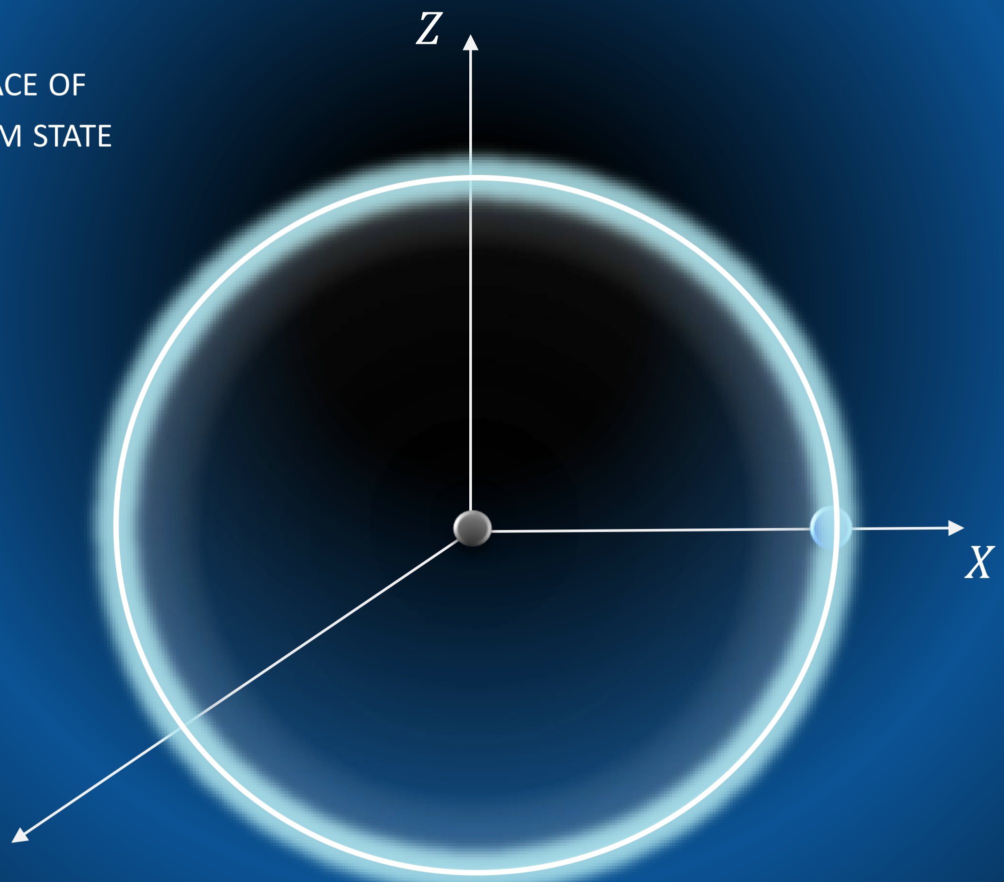


From Bits to Qubits...

Any point on surface of sphere is a quantum state with zero entropy.



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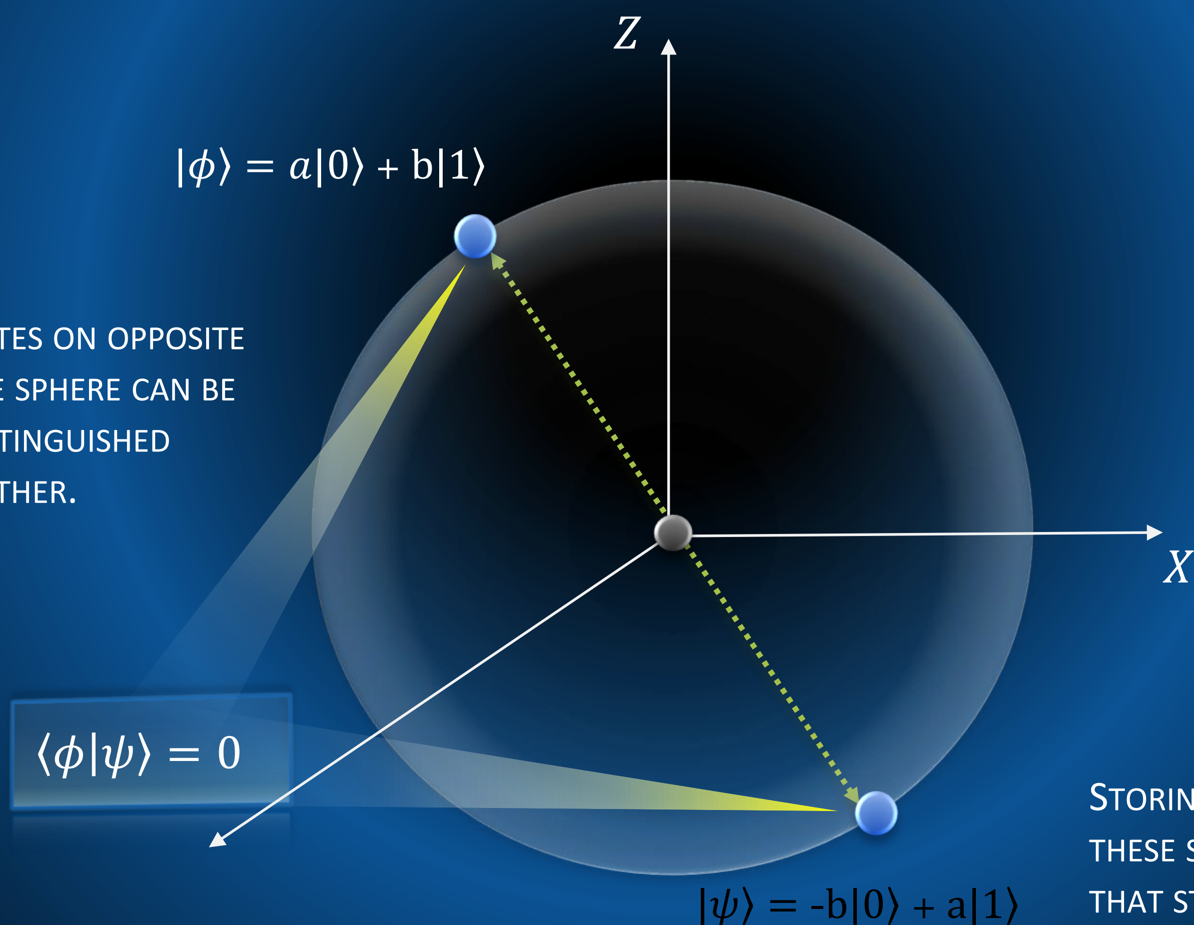
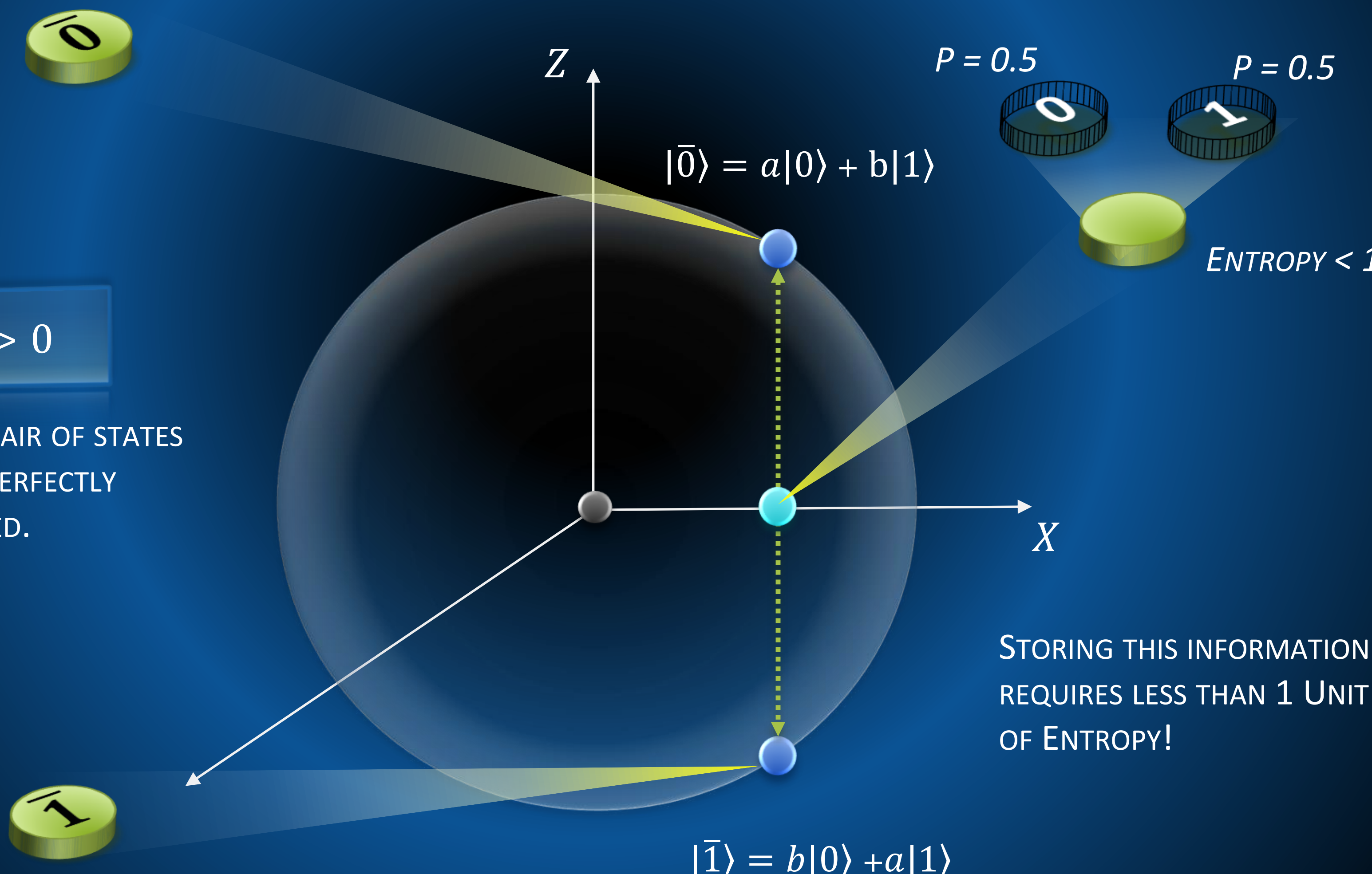


Any two states on opposite points of the sphere can be perfectly distinguished from each other.

Storing an equal mix of these states allows a Code that stores 1 bit of Information

From Bits to Qubits...

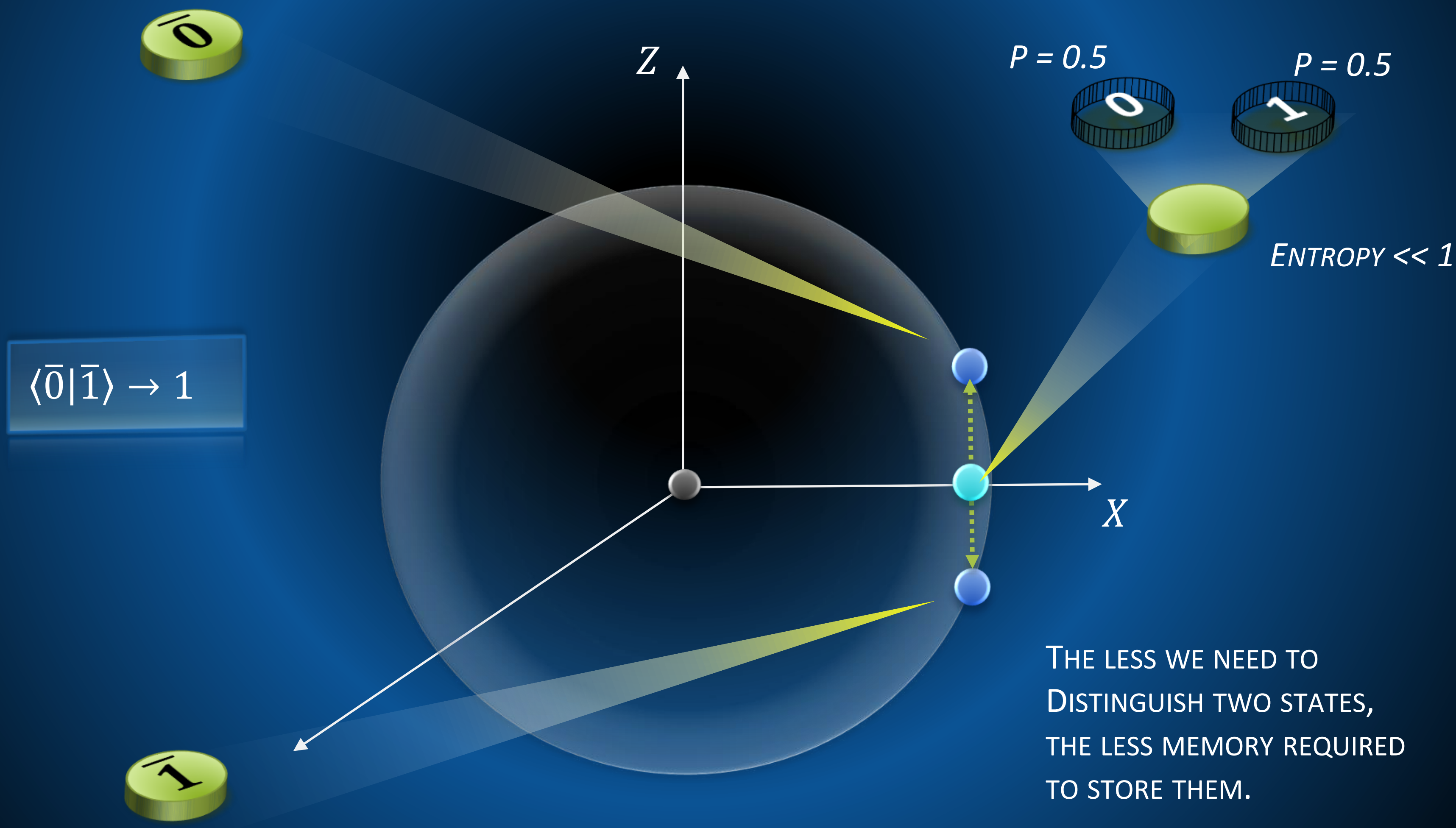


$\langle\bar{0}|\bar{1}\rangle > 0$

Any other pair of states cannot be perfectly distinguished.

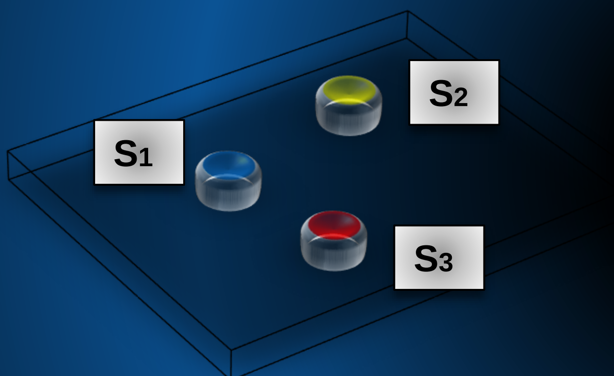
Storing this information requires less than 1 Unit of Entropy!

From Bits to Qubits...



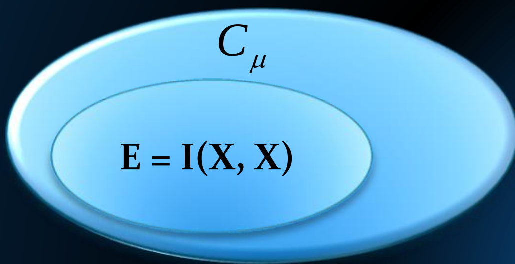
The less we need to distinguish two states, the less memory required to store them.

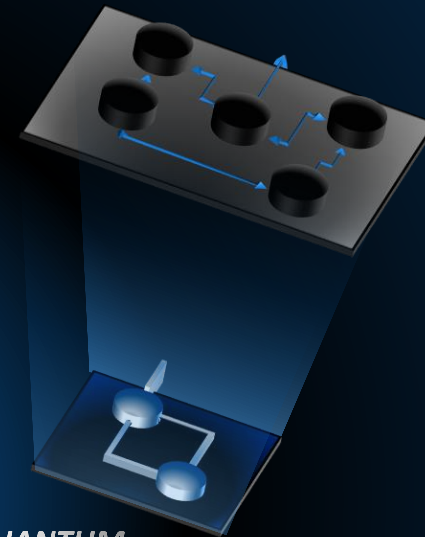
The Power of Non-Reality



Classical models must allocate enough storage to distinguish every causal state

Quantum systems can exploit the lack of reality to distinguish causal states only to the degree that they affect the future.



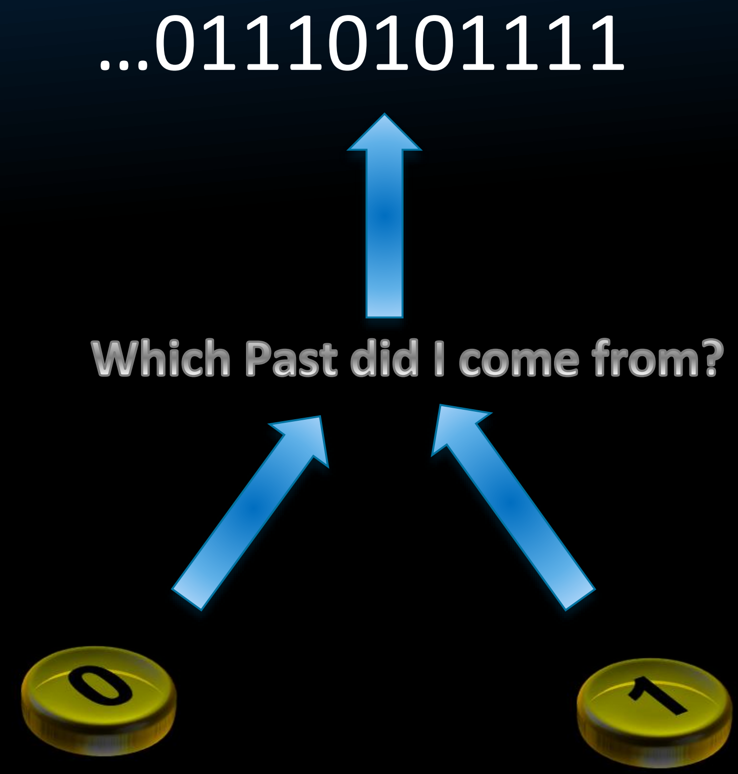


QUANTUM IS SIMPLER!

THEOREM

Provided the best classical model for a stochastic process stores some unnecessary information, there exists a simpler quantum model

M.Gu, K.Wiesner, E.Rieper, V.Vedral, Nature Communications, 3, 762

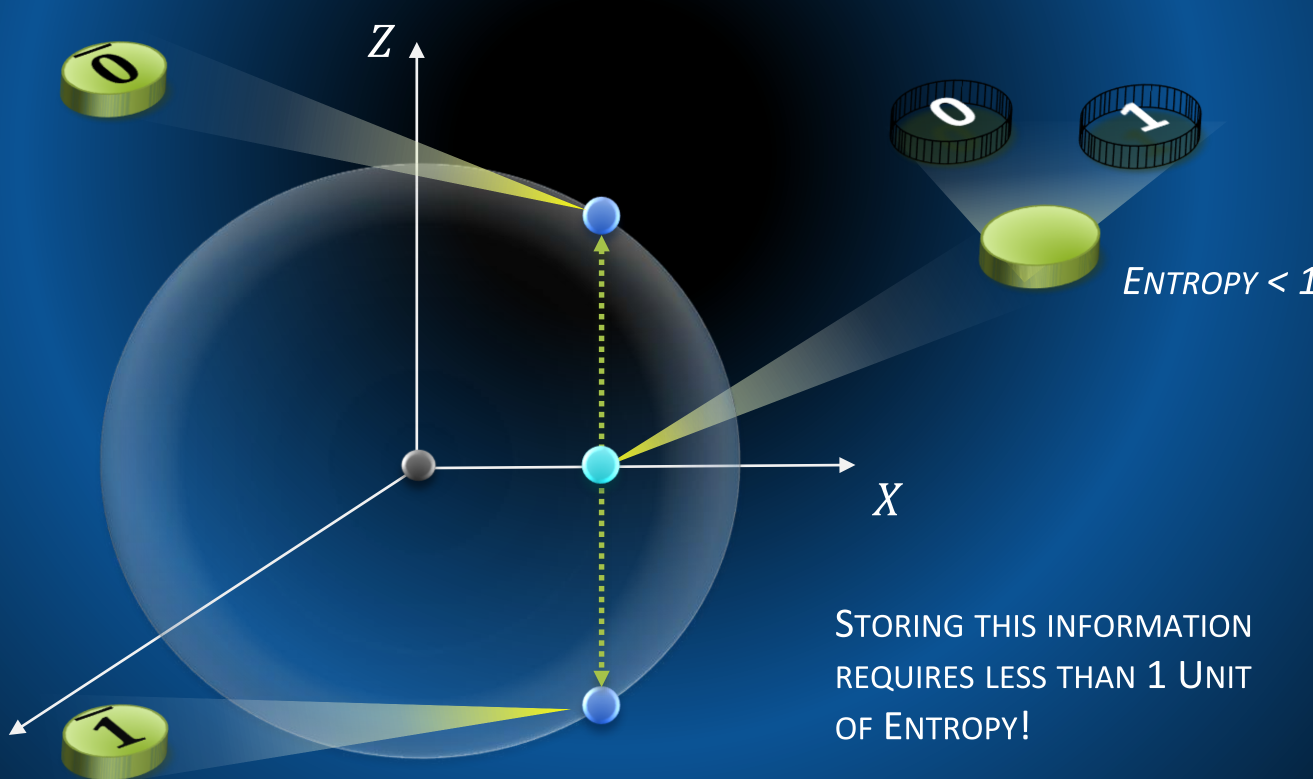


This model still stores unnecessary information!

Simplifying with Quantum

Encode 0 as $|\bar{0}\rangle = \sqrt{q}|0\rangle + \sqrt{1-q}|1\rangle$

Encode 1 as $|\bar{1}\rangle = \sqrt{1-q}|0\rangle + \sqrt{q}|1\rangle$



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Simplifying with Quantum

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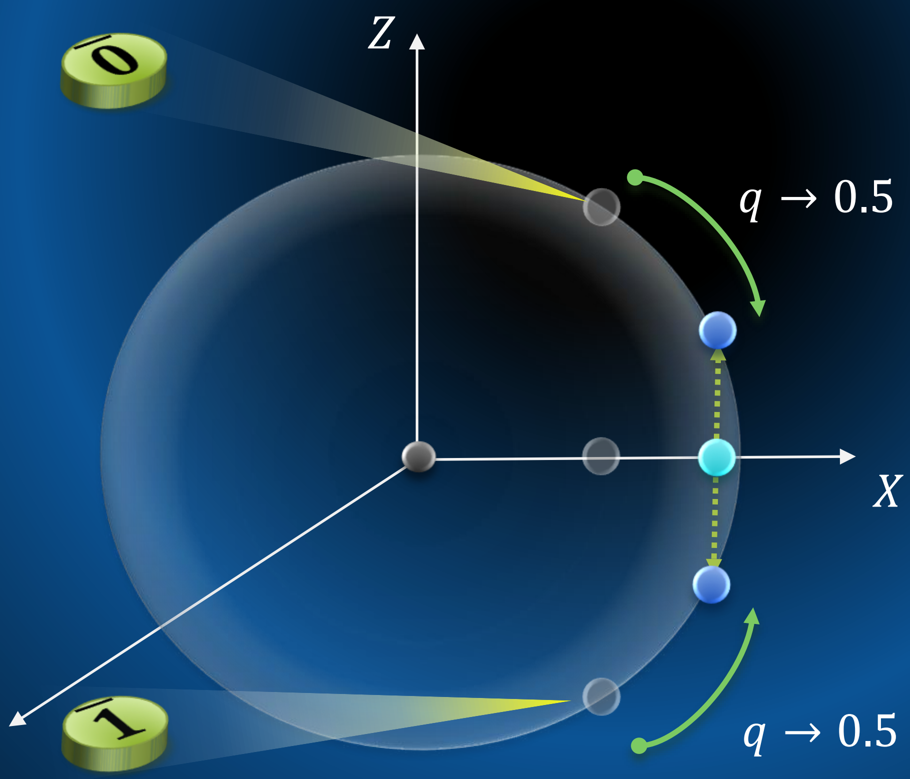
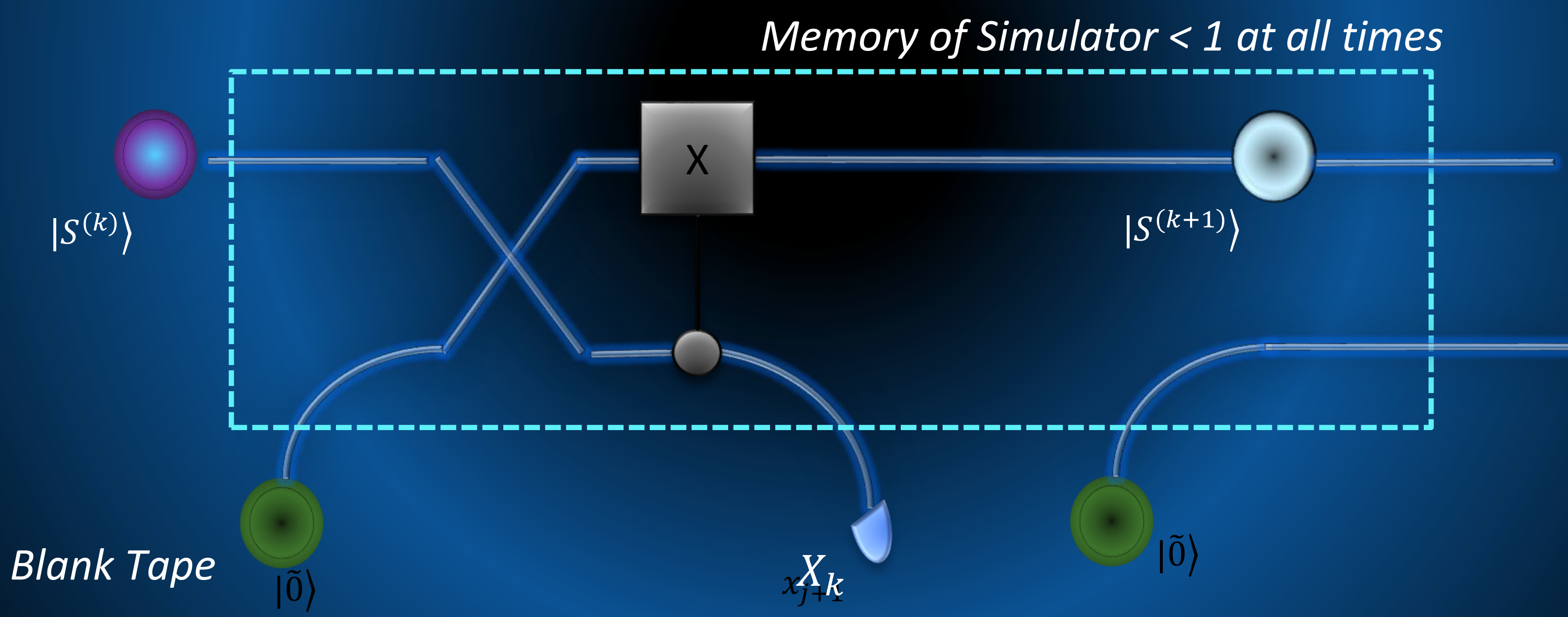


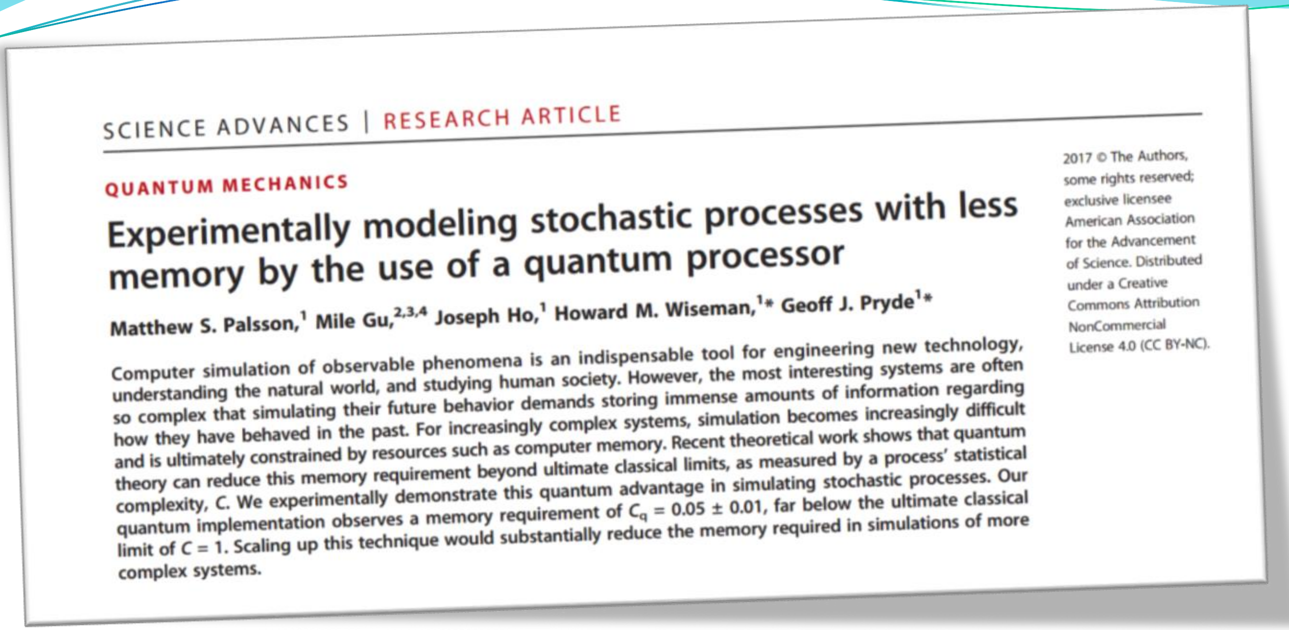
As $q \rightarrow 0.5$, the quantum model takes asymptotically no memory.

Simplifying with Quantum

Encode 0 as $|\bar{0}\rangle = \sqrt{q}|0\rangle + \sqrt{1-q}|1\rangle$

Encode 1 as $|\bar{1}\rangle = \sqrt{1-q}|0\rangle + \sqrt{q}|1\rangle$





SCIENCE ADVANCES | RESEARCH ARTICLE

QUANTUM MECHANICS

Experimentally modeling stochastic processes with less memory by the use of a quantum processor

Matthew S. Palsson,[1] Mile Gu,[2,3,4] Joseph Ho,[1] Howard M. Wiseman,[1]* Geoff J. Pryde[1]*

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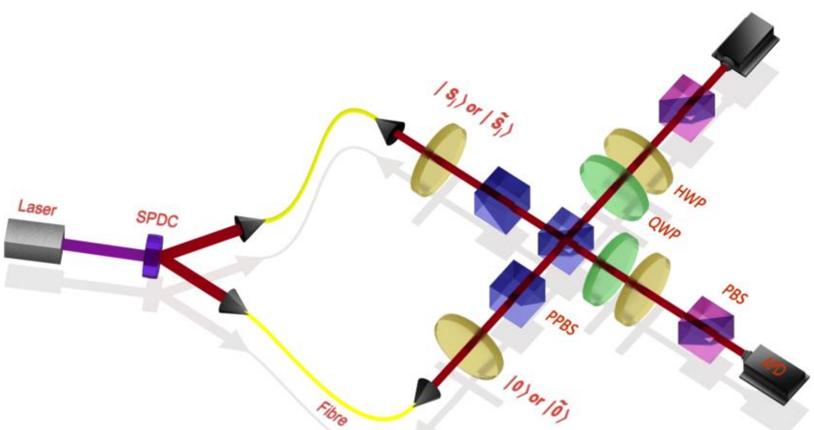
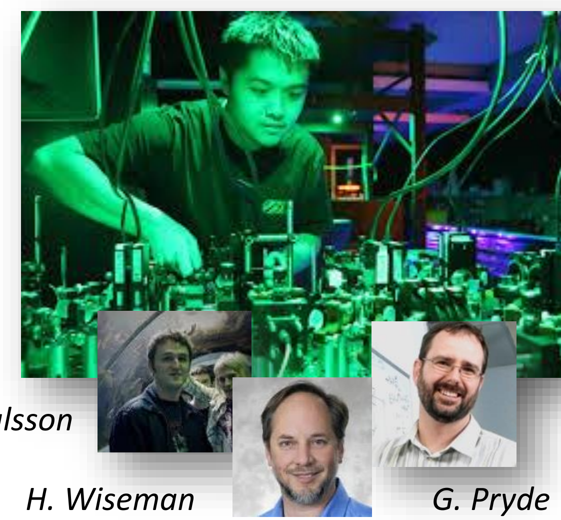
Science Advances
03 Feb 2017: Vol. 3, no. 2, e1601302



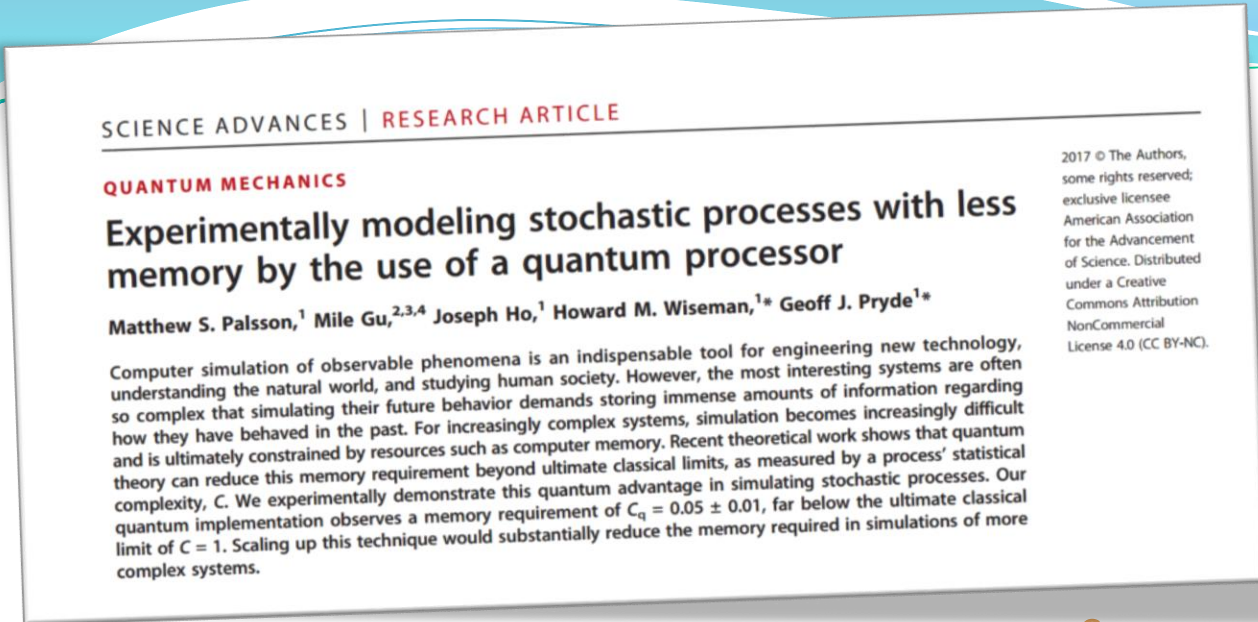


J. Ho

M. Palsson

H. Wiseman

G. Pryde



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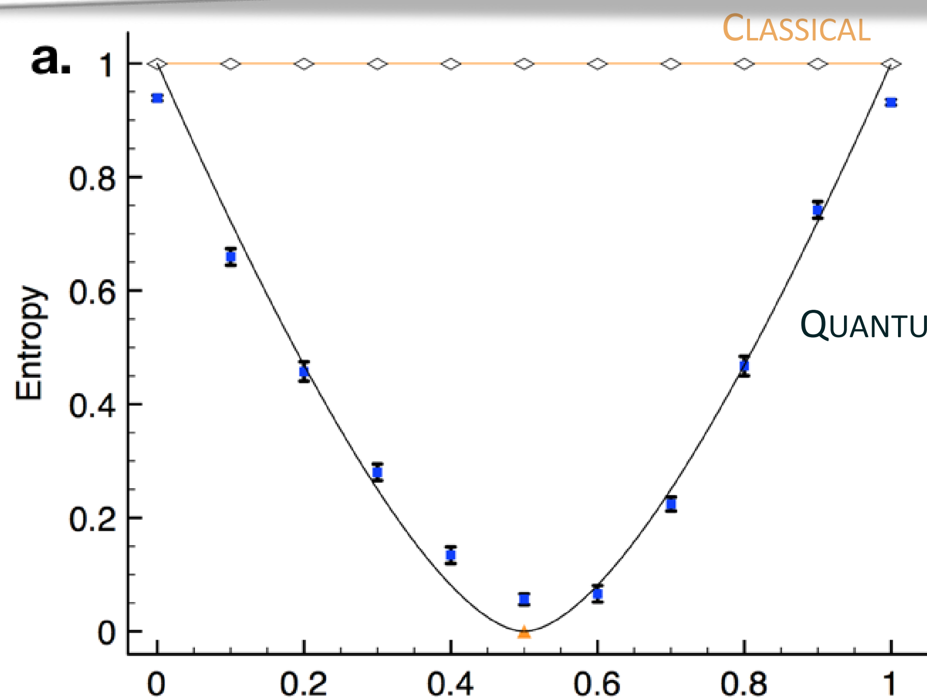
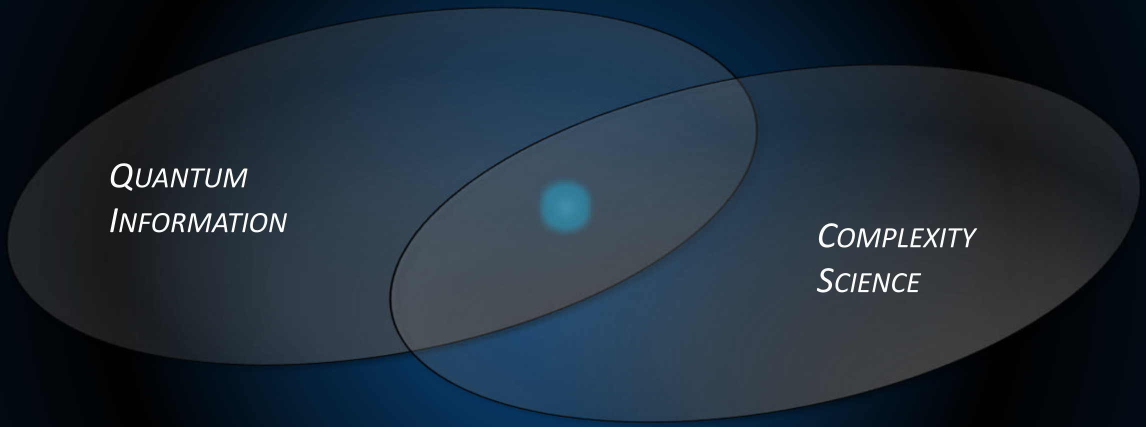
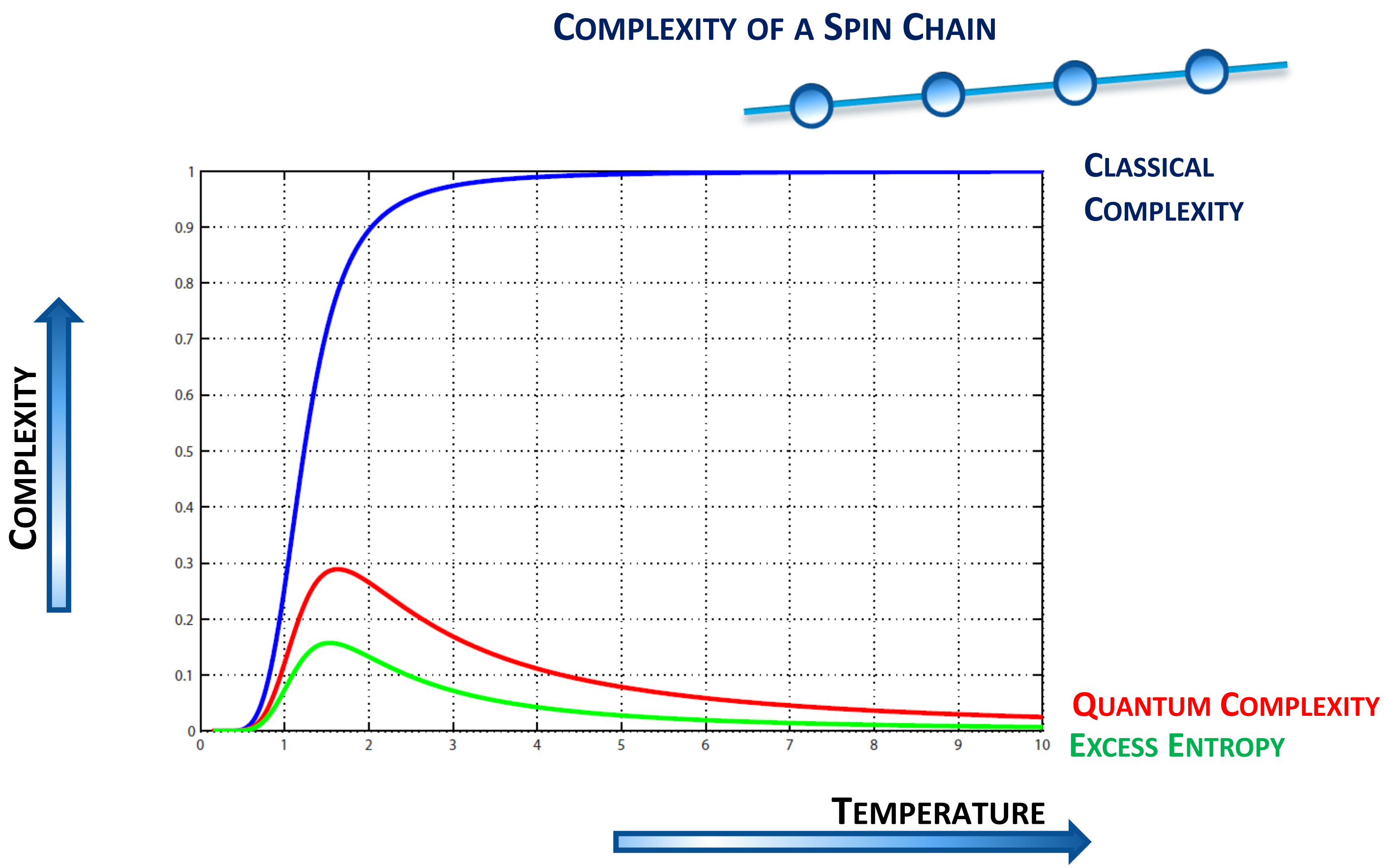




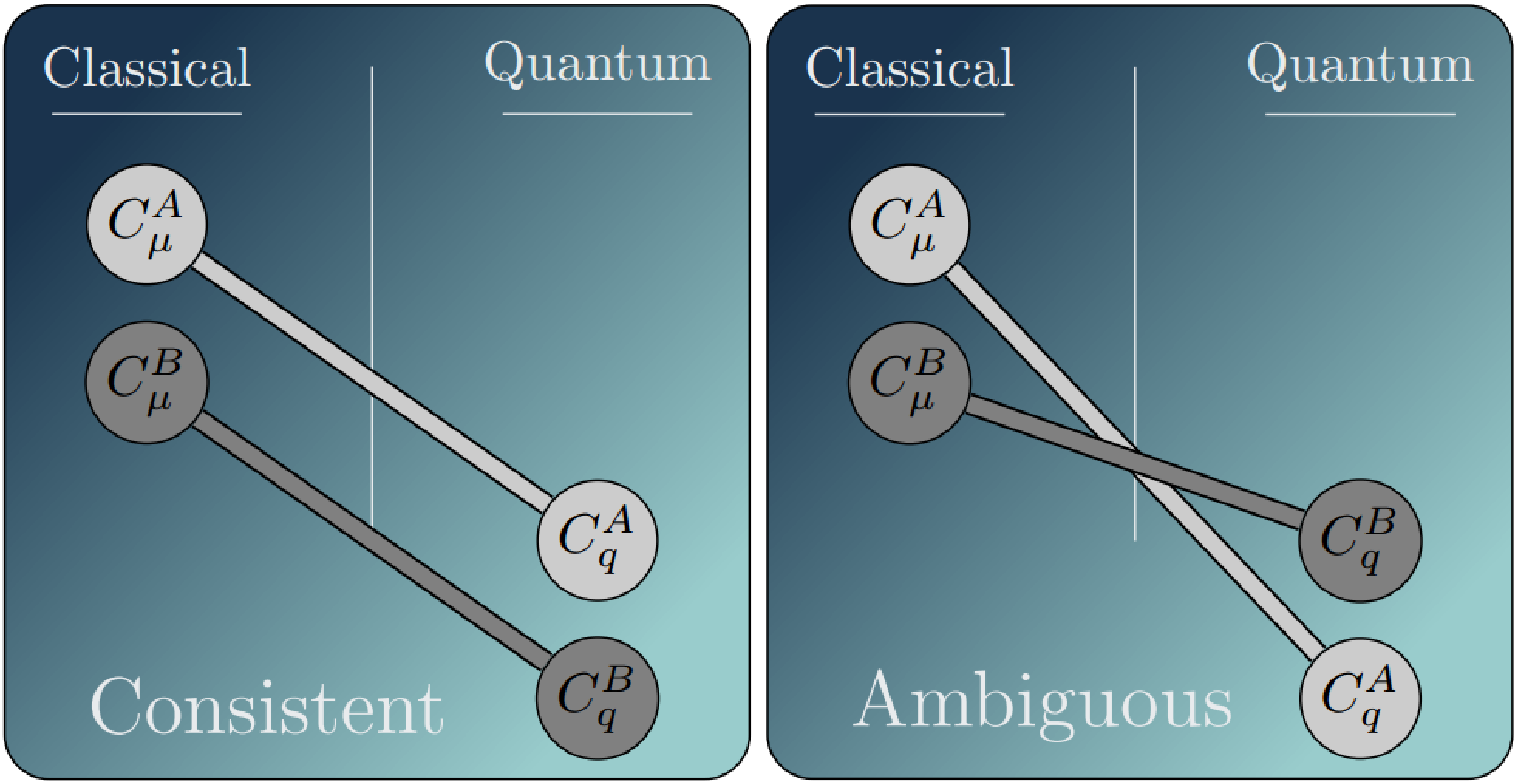
WHAT APPEARS COMPLEX CAN DEPEND FUNDAMENTALLY ON WHAT SORT OF INFORMATION THEORY WE USE!

Outlook – Qualitative Divergences



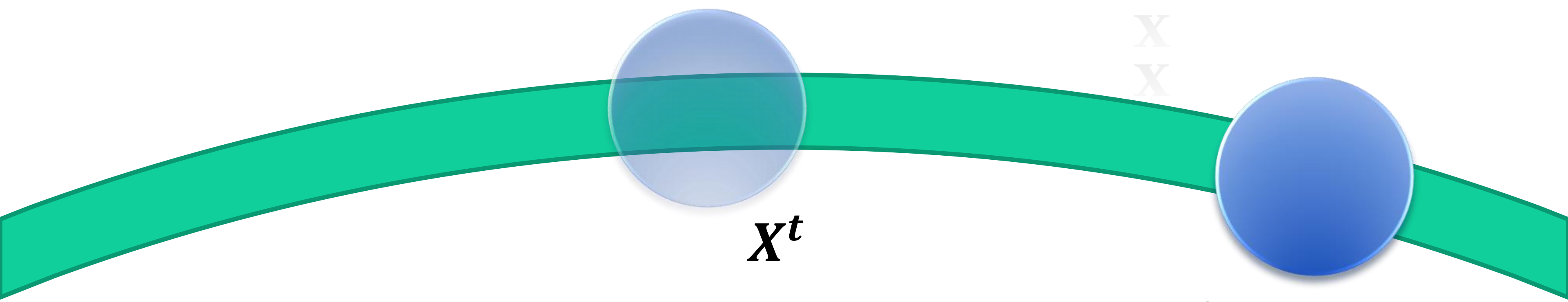
Suen, Whei Yeap, et al. "The classical-quantum divergence of complexity in the Ising spin chain." arXiv:1511.05738 (2015).

Outlook– Qualitative Divergences

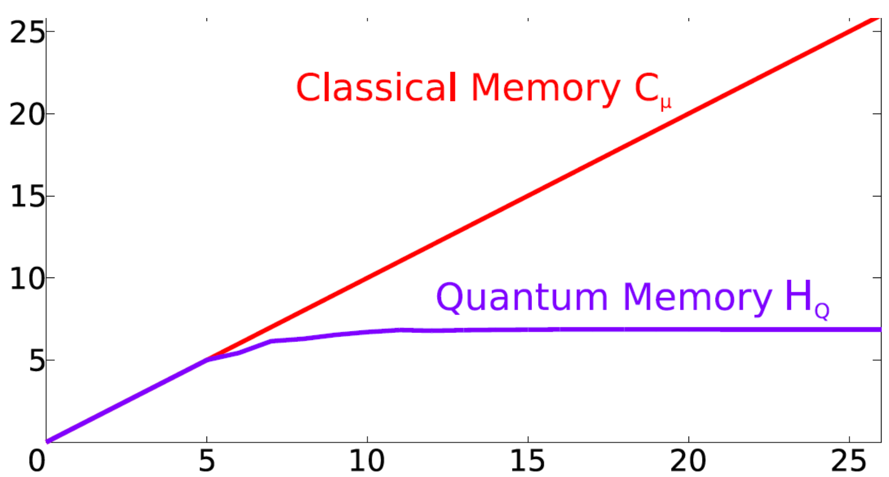


Aghamohammadi, C., Mahoney, J. R., & Crutchfield, J. P. *The Ambiguity of Simplicity.* arXiv:1602.08646.

Outlook – Qualitative Divergences



$$X^{t+1} = X^t + Y$$



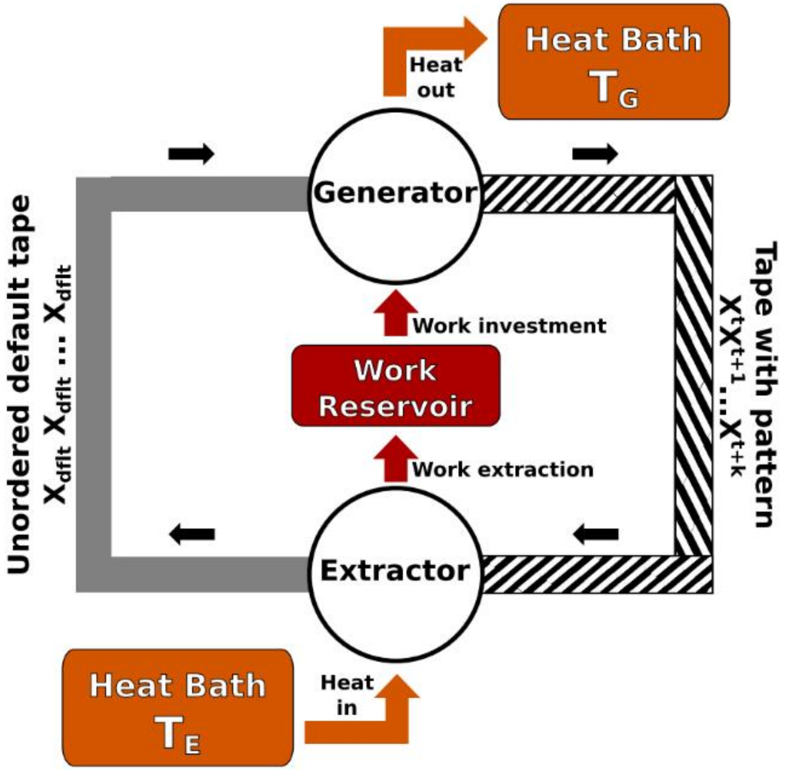
Growing Classical Complexity

Bounded Quantum Complexity

'Unbounded memory advantage of Stochastic Simulation', arXiv:1609.04408

Outlook - Thermodynamics

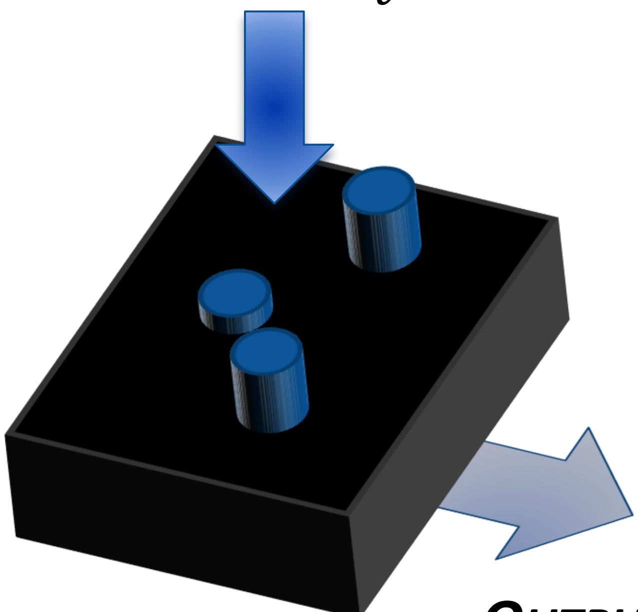
Maxwell's Demon



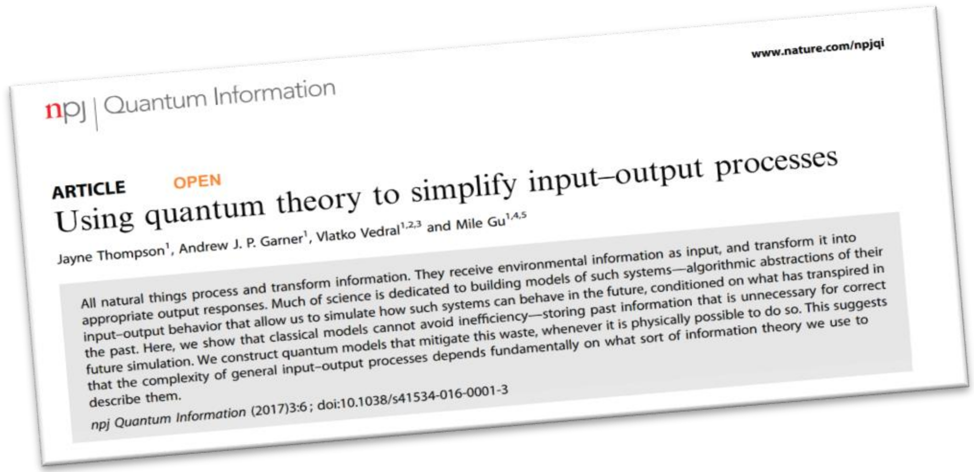
Andrew J. P. Garner, Jayne Thompson, Vlatko Vedral, and Mile Gu *The thermodynamics of complexity and pattern manipulation, arXiv:1510.00010*

Outlook – Interactive Systems

Input X_t



Output Y_t



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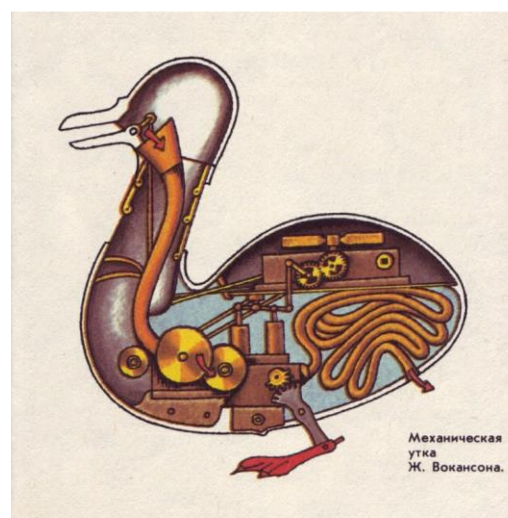
ARTICLE OPEN

Using quantum theory to simplify input–output processes

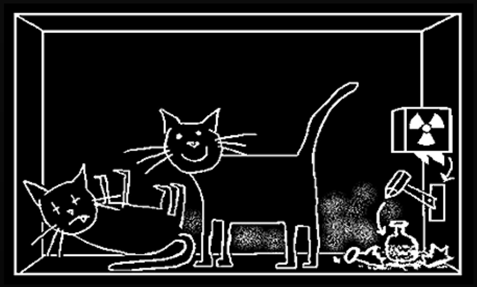
Jayne Thompson[1], Andrew J. P. Garner[1], Vlatko Vedral[1,2,3] and Mile Gu[1,4,5]

All natural things process and transform information. They receive environmental information as input, and transform it into appropriate output responses. Much of science is dedicated to building models of such systems—algorithmic abstractions of their input–output behavior that allow us to simulate how such systems can behave in the future, conditioned on what has transpired in the past. Here, we show that classical models cannot avoid inefficiency—storing past information that is unnecessary for correct future simulation. We construct quantum models that mitigate this waste, whenever it is physically possible to do so. This suggests that the complexity of general input–output processes depends fundamentally on what sort of information theory we use to describe them.

npj Quantum Information (2017)3:6 ; doi:10.1038/s41534-016-0001-3

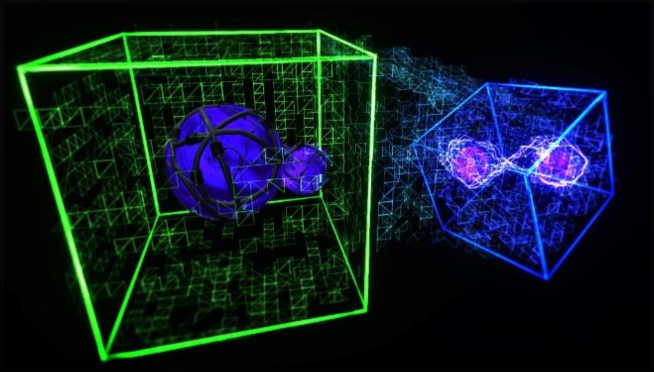


Summary



Quantum Systems are not Locally Realistic

A quantum system can be simultaneously in two different states at the same time.

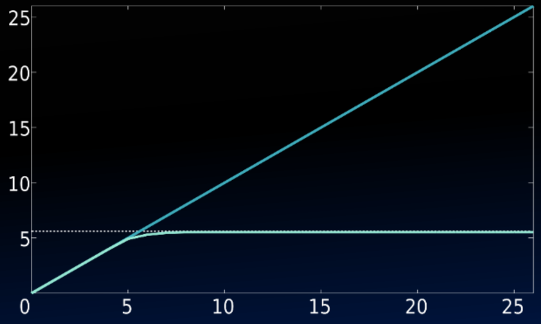


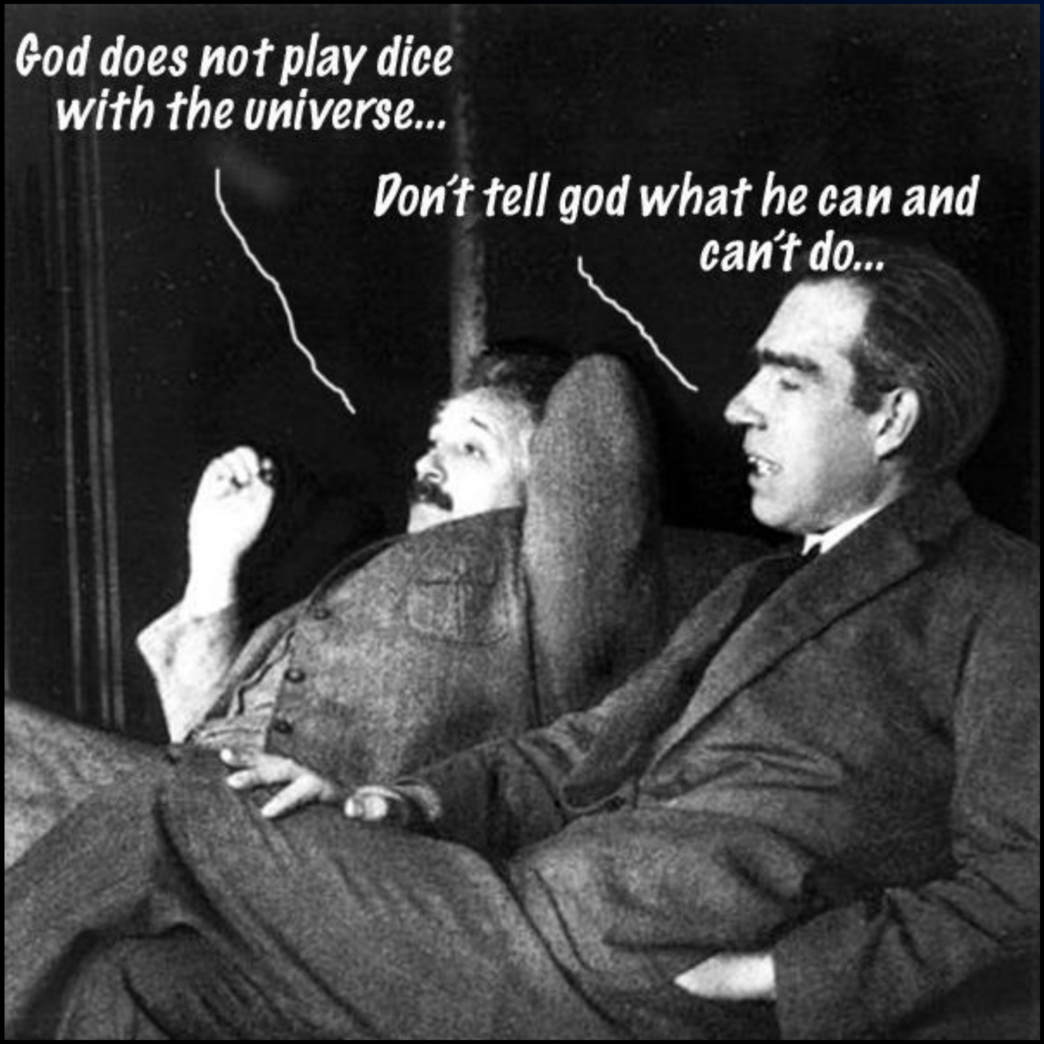
This allows them to Better isolate causes of natural things

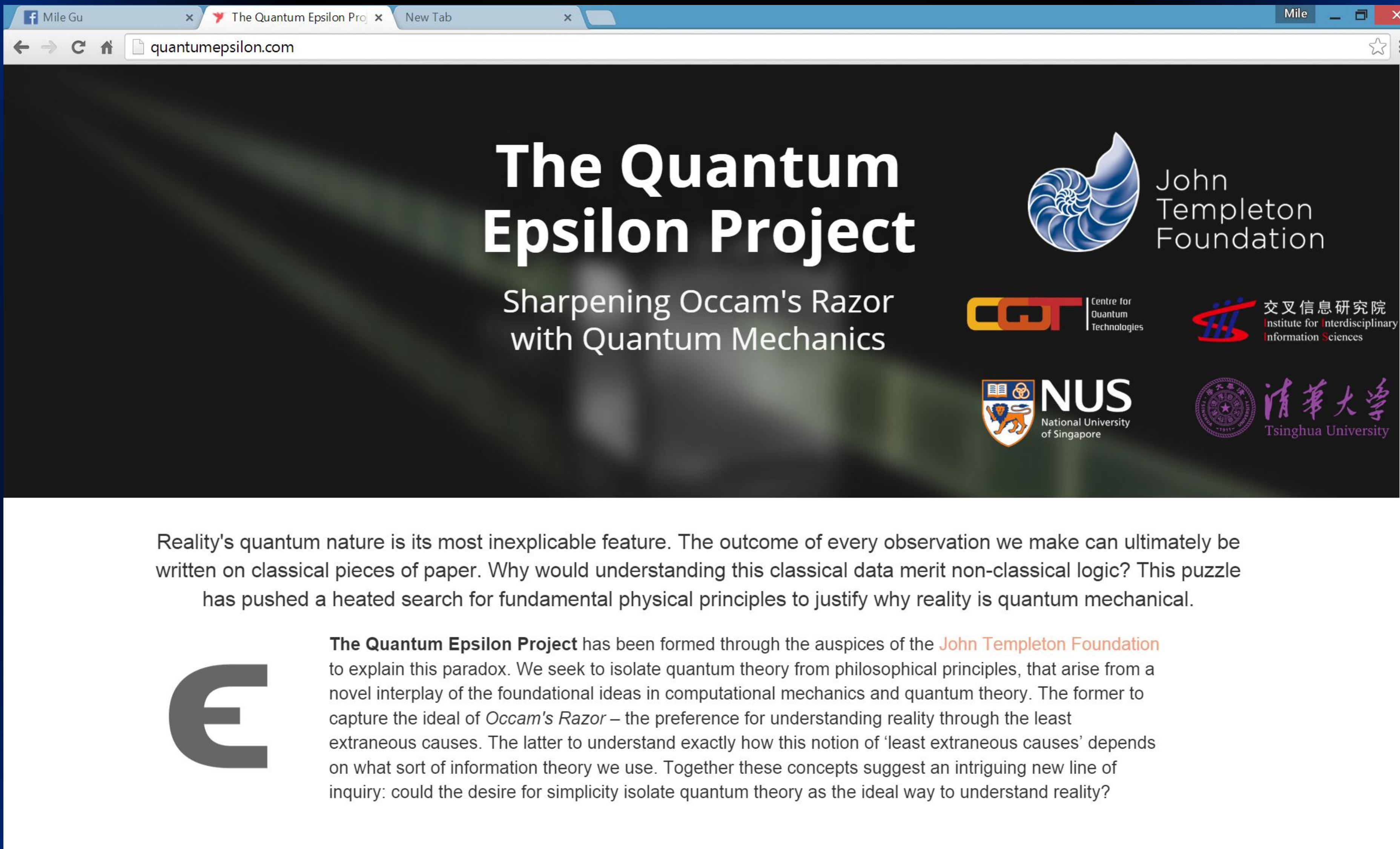
Quantum models can generate a future prediction using less past information than classical possible

Quantum Simplicity:

Many systems may look at simpler, if we can model or simulate them quantum mechanically




God does not play dice with the universe...
Don't tell god what he can and can't do...


Mile Gu | The Quantum Epsilon Pro | New Tab

quantumepsilon.com

The Quantum Epsilon Project

Sharpening Occam's Razor with Quantum Mechanics

John Templeton Foundation

Centre for Quantum Technologies

交叉信息研究院 Institute for Interdisciplinary Information Sciences

NUS National University of Singapore

清華大学 Tsinghua University

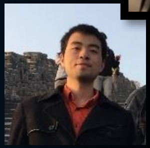
Reality's quantum nature is its most inexplicable feature. The outcome of every observation we make can ultimately be written on classical pieces of paper. Why would understanding this classical data merit non-classical logic? This puzzle has pushed a heated search for fundamental physical principles to justify why reality is quantum mechanical.

The Quantum Epsilon Project has been formed through the auspices of the John Templeton Foundation to explain this paradox. We seek to isolate quantum theory from philosophical principles, that arise from a novel interplay of the foundational ideas in computational mechanics and quantum theory. The former to capture the ideal of *Occam's Razor* – the preference for understanding reality through the least extraneous causes. The latter to understand exactly how this notion of 'least extraneous causes' depends on what sort of information theory we use. Together these concepts suggest an intriguing new line of inquiry: could the desire for simplicity isolate quantum theory as the ideal way to understand reality?

WWW.QUANTUMEPSILON.COM

The Quantum and Complexity Sciences Initiative at Singapore

Jayne Thompson



Yang Chengran

NANYANG TECHNOLOGICAL UNIVERSITY
Complexity Institute

CQT Centre for Quantum Technologies
National University of Singapore

Felix Binder *Varun Narasimhachar* *Sun Whei Yeap* *Liu Qing* *Andrew Garner* *Carlo Di Franco* *Mile Gu*

PhD Scholarships Available

www.quantumcomplexity.org

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K. Wiesner

V. Vedral

E. Rieper

nature COMMUNICATIONS

ARTICLE

Received 11 Jan 2012 | Accepted 28 Feb 2012 | Published 27 Mar 2012 DOI: 10.1038/ncomms1761

Quantum mechanics can reduce the complexity of classical models

Mile Gu[1], Karoline Wiesner[2], Elisabeth Rieper[1] & Vlatko Vedral[1,3,4]

Nature Communications, 3, 762

SCIENCE ADVANCES | RESEARCH ARTICLE

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Jayne Thompson

A. Garner

V. Vedral

OPINION THE BIG IDEA

Zen and the art of quantum complexity

Being two things at once may simplify reality say physicists Mile Gu and Vlatko Vedral

New Scientist, 15/11/2014, pg 28-29