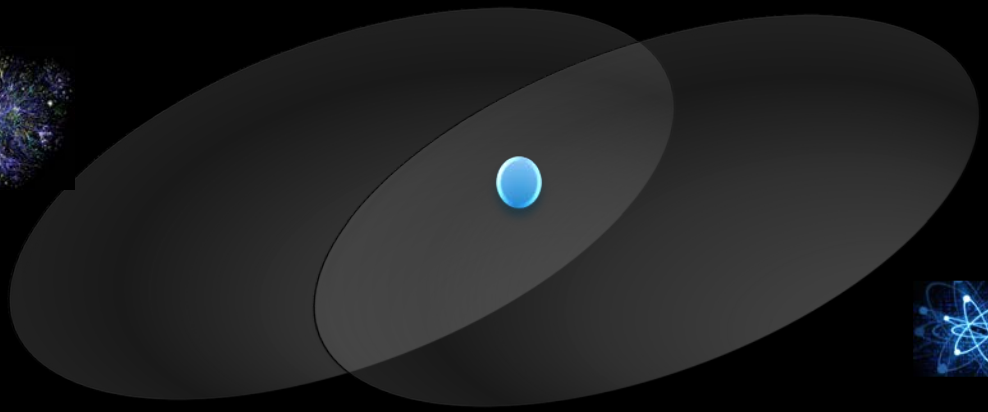
Complexity Science in the Presence of Quantum Observers and Agents

Mile Gu

Complexity Science



Quantum Information

FQXi Foundational Questions Institute
Complexity Institute NTU Singapore
Centre for Quantum Technologies National University of Singapore

FQXi meeting on the Physics of Intelligence and Agency

The Quantum and Complexity Science Initiative

Thomas Elliott

Alec Boyd

Complexity Institute, NTU

Centre for Quantum Technologies. NUS

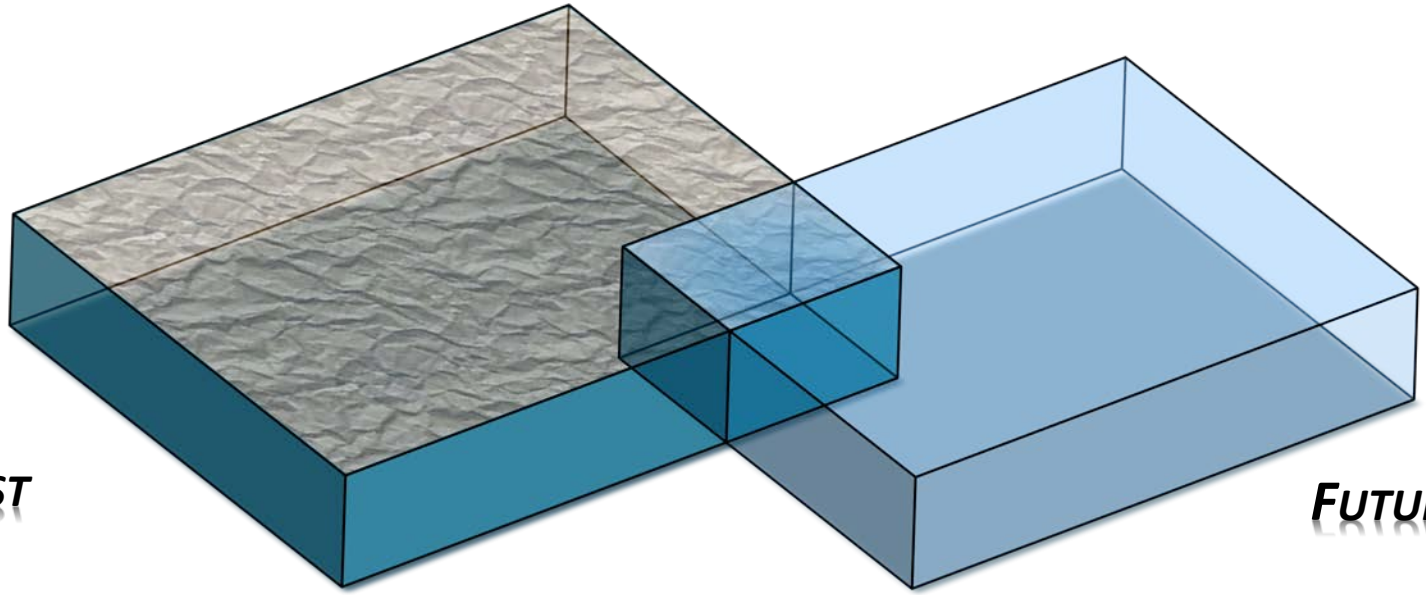
Sylvia Gu

WWW.QUANTUMCOMPLEXITY.ORG

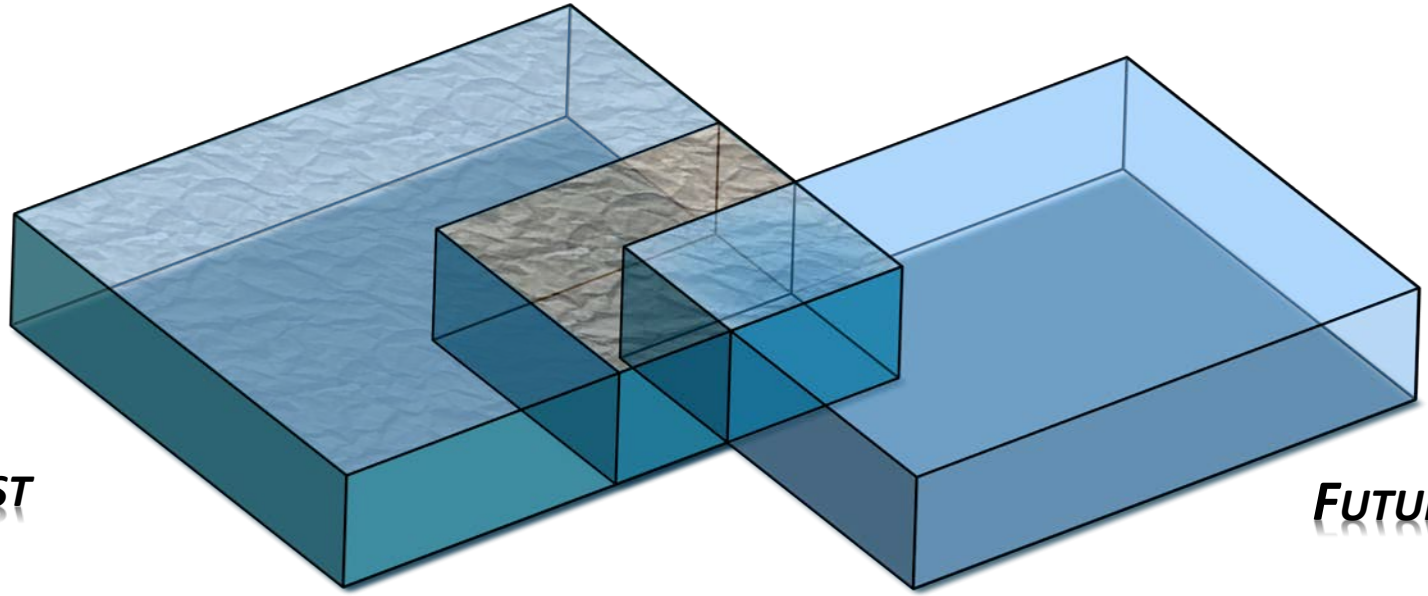
What is Complex?

PAST ...01100001110 11101011101... FUTURE

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



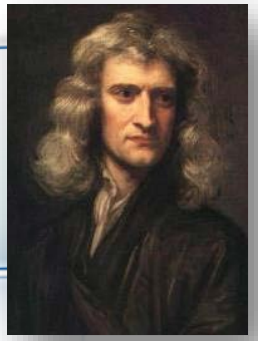
The better we can isolate the causes of natural things, the greater our understanding.

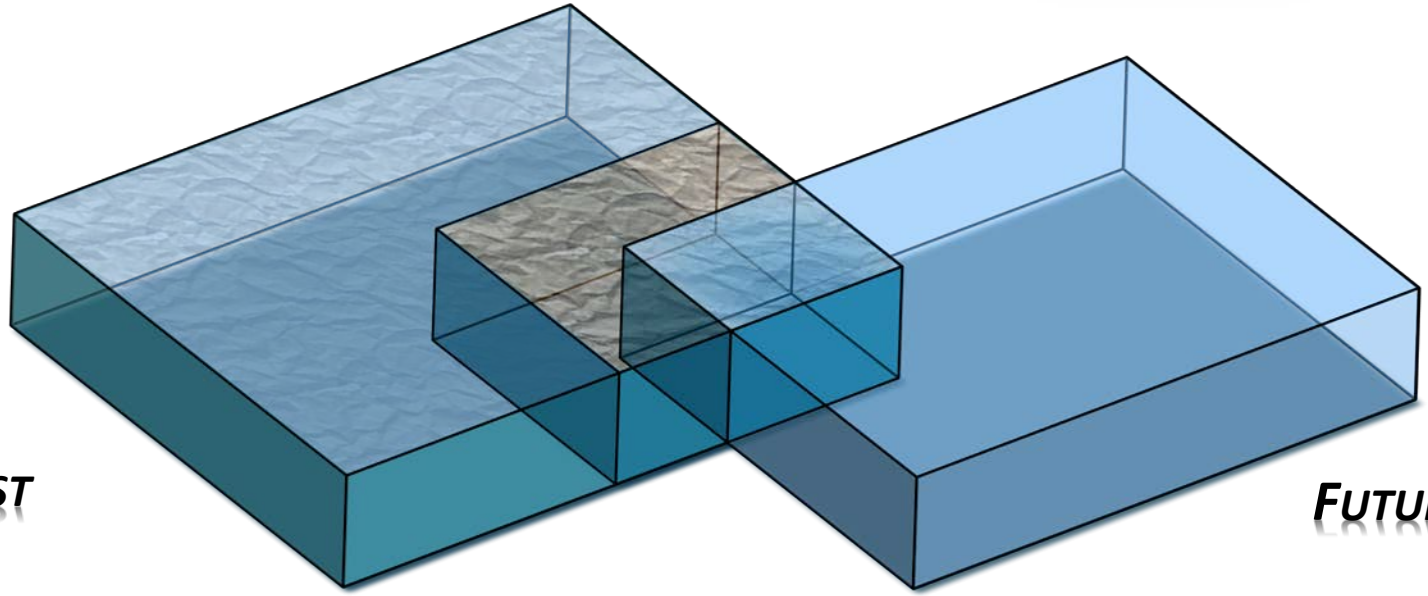


PAST

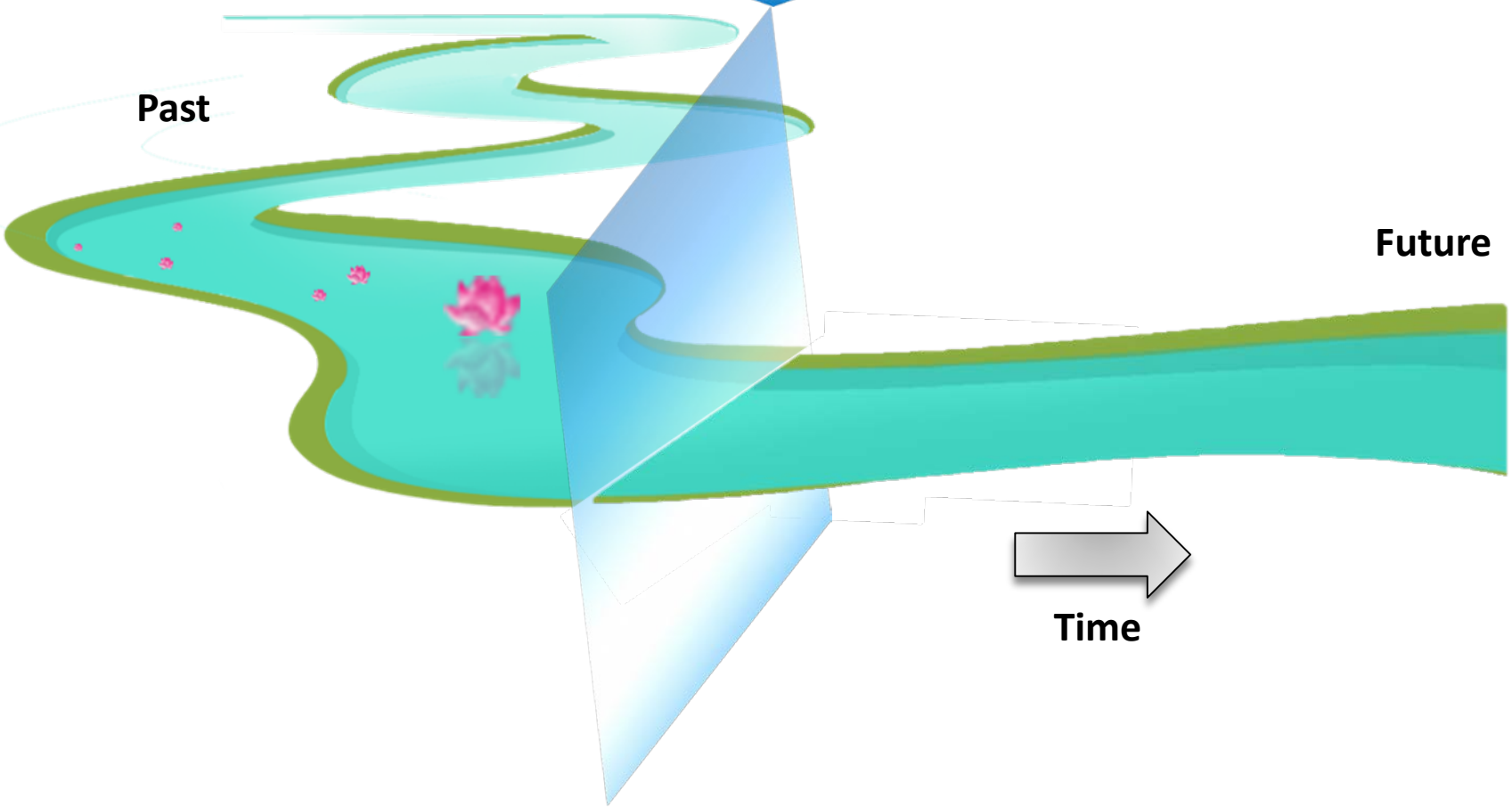
FUTURE

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

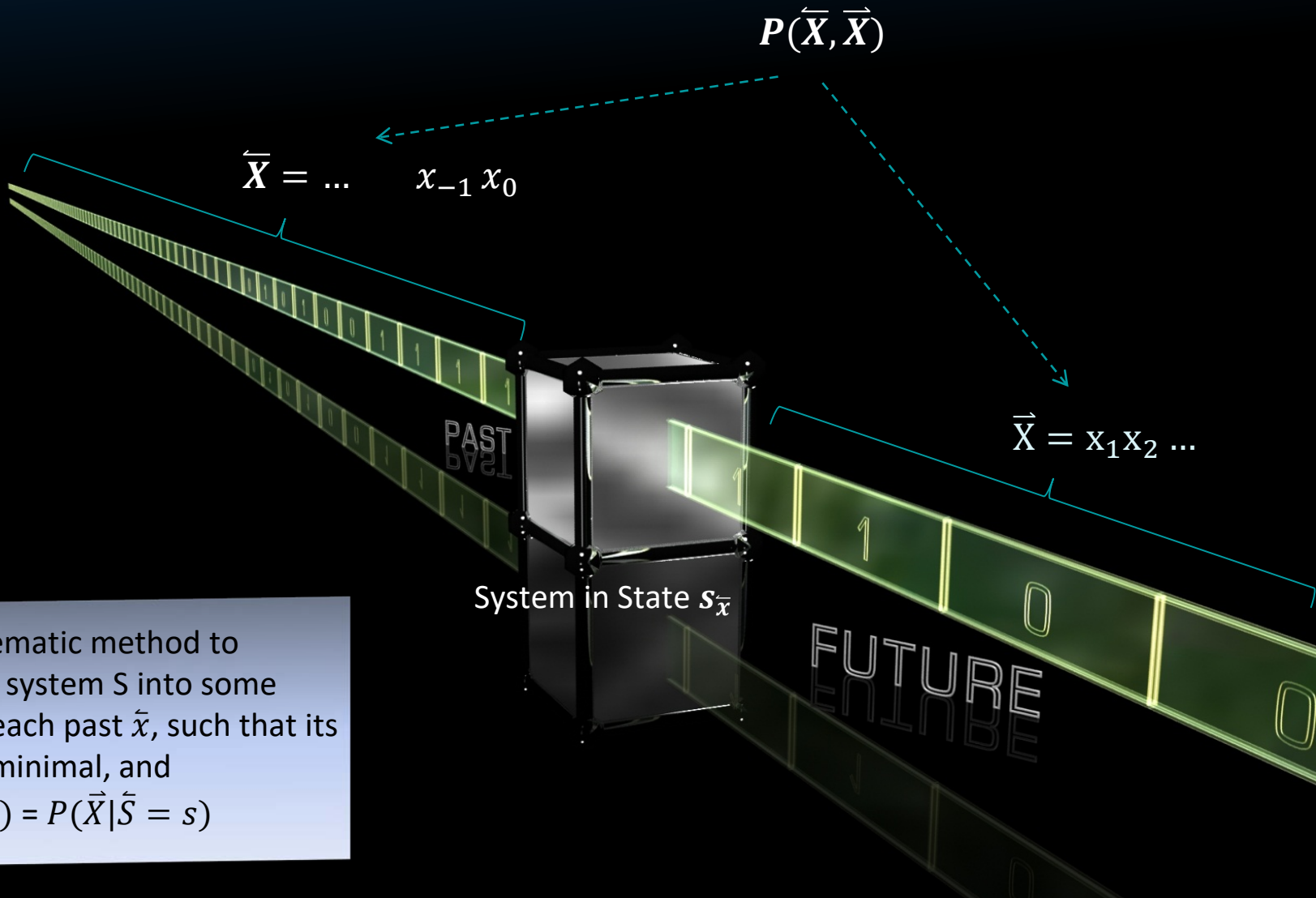




How much information passes through the present?



Special Case: Passive Processes



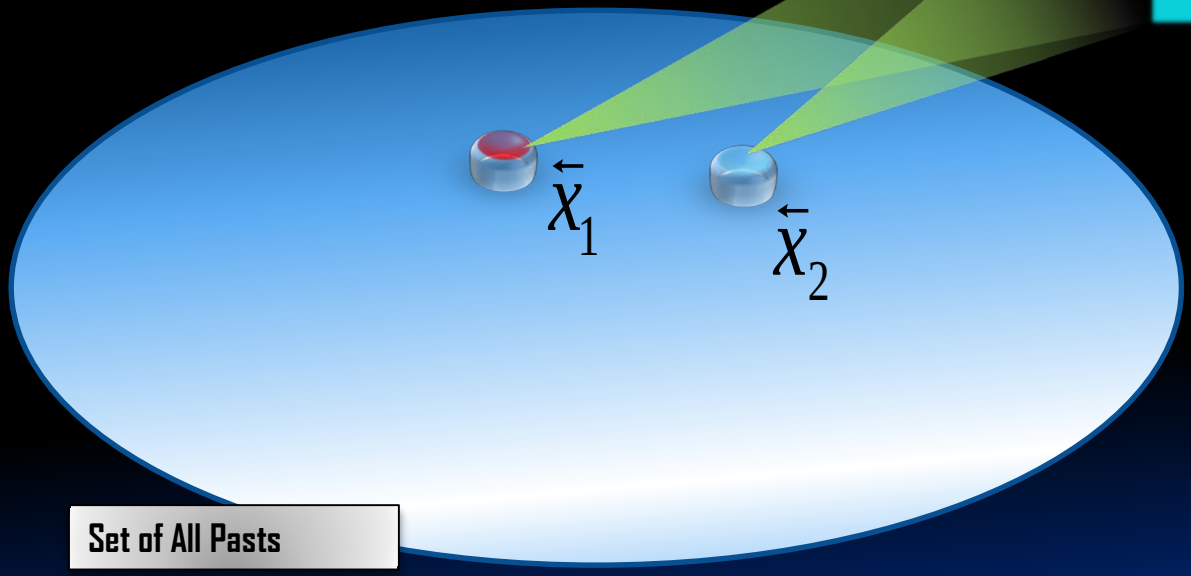
Task:

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

Special Case: Passive Processes

Suppose two pasts have statistically identical futures

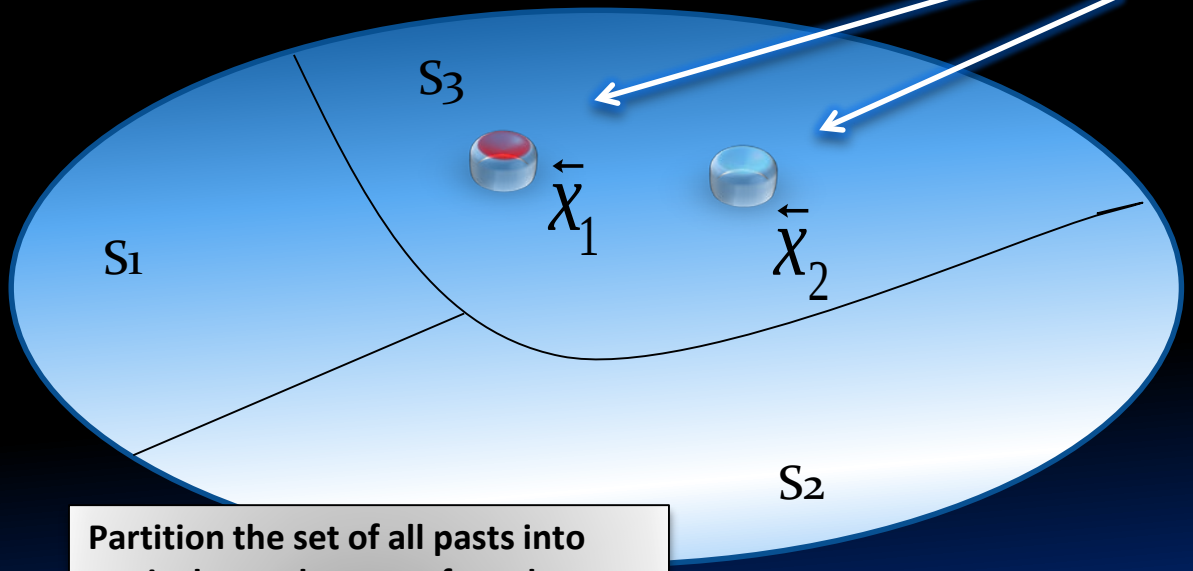
$$P(\vec{X} \mid \overleftarrow{X} = \overleftarrow{x}_1) = P(\vec{X} \mid \overleftarrow{X} = \overleftarrow{x}_2)$$



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

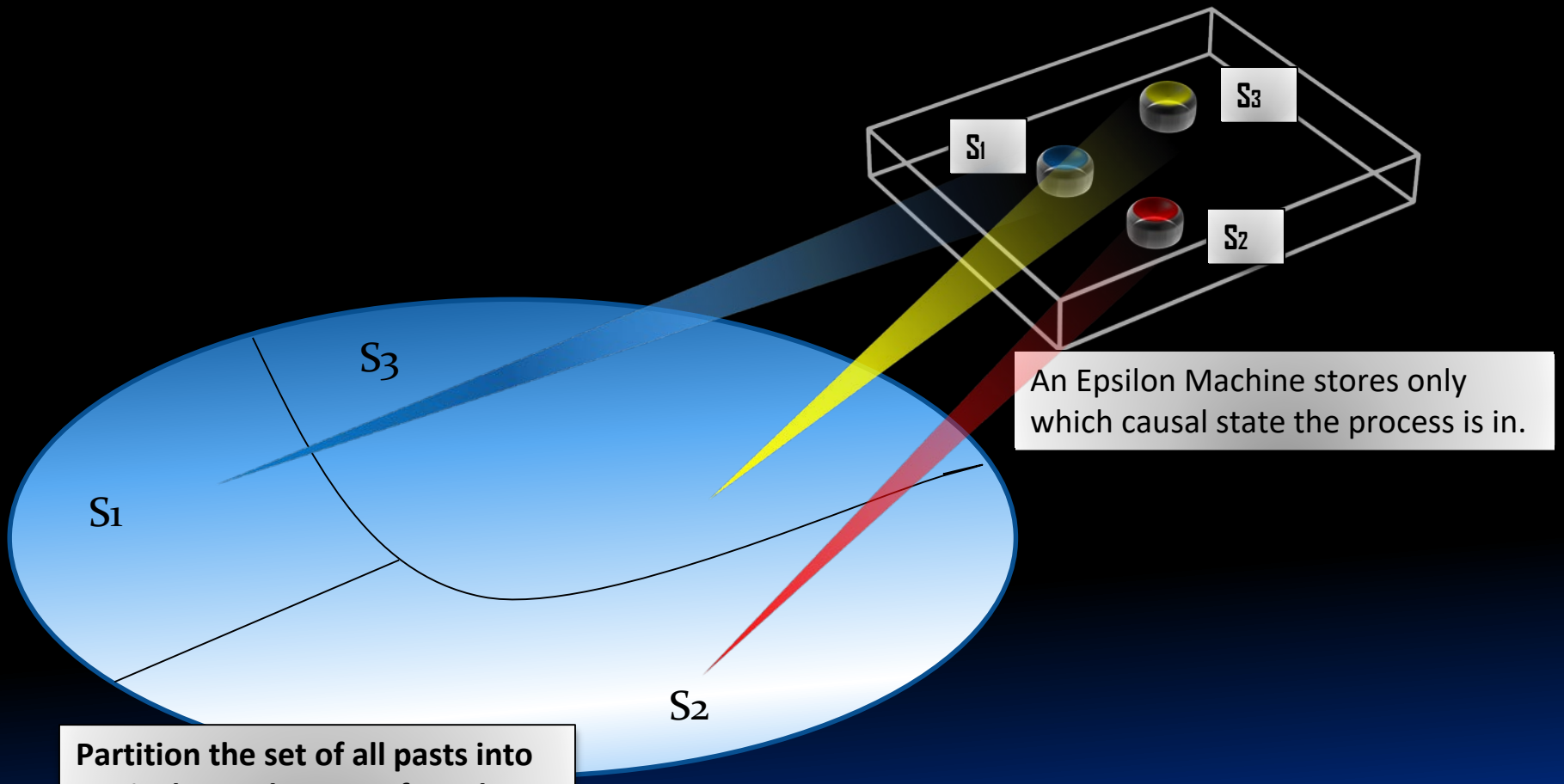
Special Case: Passive Processes

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



Partition the set of all pasts into equivalence classes, referred to as Causal states.

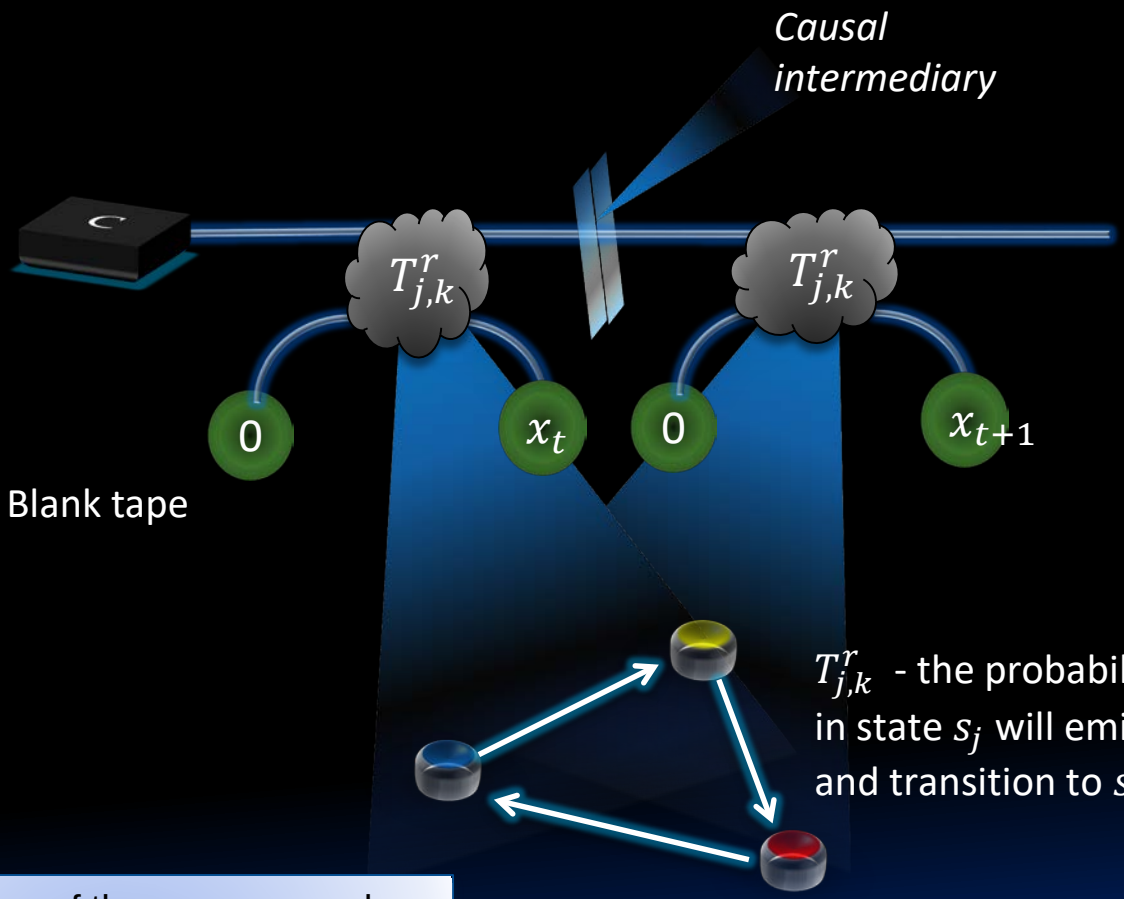
Special Case: Passive Processes



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

Partition the set of all pasts into equivalence classes, referred to as Causal states.

Epsilon Machines

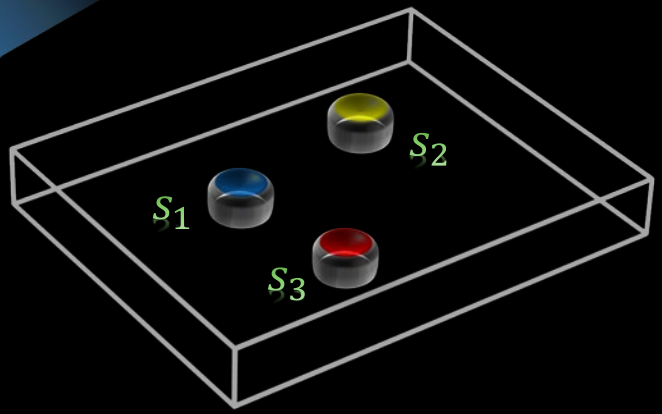


$T^r_{j,k}$ - the probability a machine in state s_j will emit output `r' and transition to s_k

The dynamics of the process can be reproduced by transitions on the set of causal states.

Epsilon Machines

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)

To simulate a sequence of random coin flips….

We have a process with exactly 1 Causal State

No Information about the Past is required!

High Complexity!

*

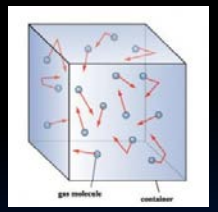
Ordered

Low Complexity

Random

Low Complexity

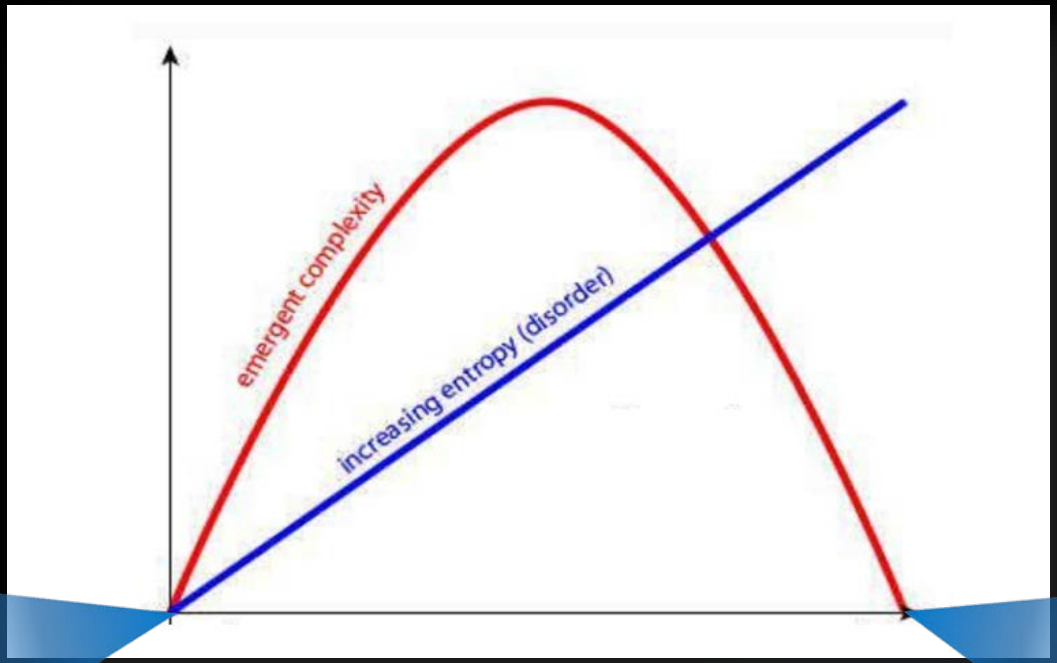
Pendulum



Ideal GAs

* Shamelessly Ripped from Sean Carroll's Slides

LOW COMPLEXITY HIGH COMPLEXITY LOW COMPLEXITY

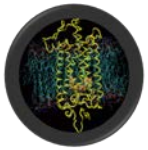


LOW DISORDER

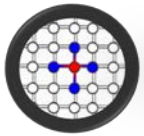
HIGH DISORDER

Statistical Complexity

Statistical Complexity



Molecular Dynamics



Condensed Matter

Neural Networks

Atmospherics

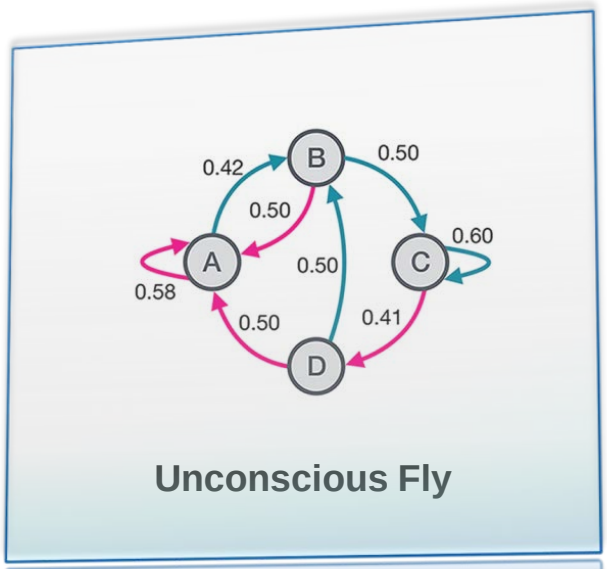
Financial Data

C_μ Is a **intrinsic** property of a stochastic process that quantifies its complexity and structure

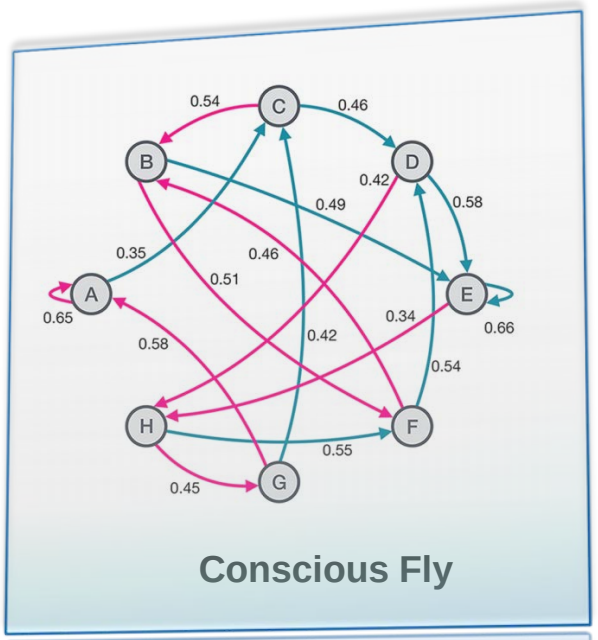
Crutchfield, Young, Phys. Rev. Lett. 63, 105–108 (1989)

Statistical Complexity

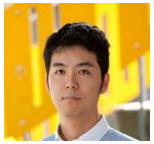
Used recently to detect consciousness.



Unconscious Fly



Conscious Fly

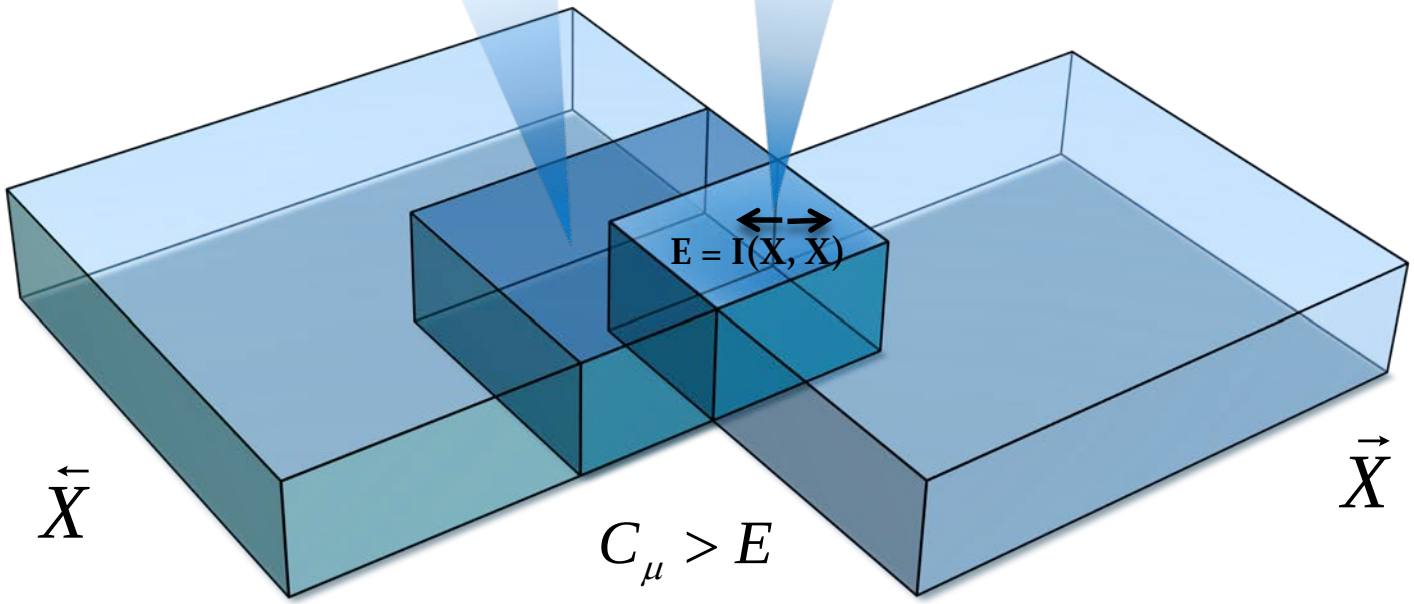


Distinguishing states of conscious arousal using statistical complexity. *arXiv preprint arXiv:1905.13173 (To be presented by Naotsugu Tsuchiys tomorrow)*

Causal Waste

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

Amount of information past contains about the future.

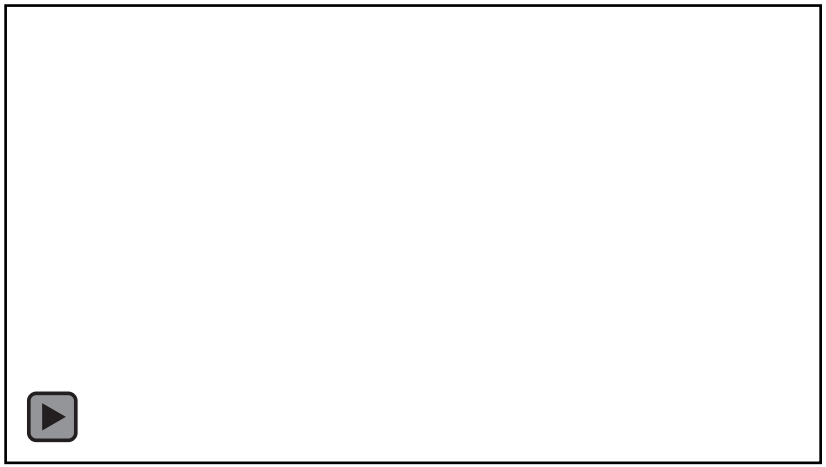


'Time's Barbed Arrow: Irreversibility, Crypticity, and Stored Information' Phys. Rev. Lett 103, 094101, (2009)

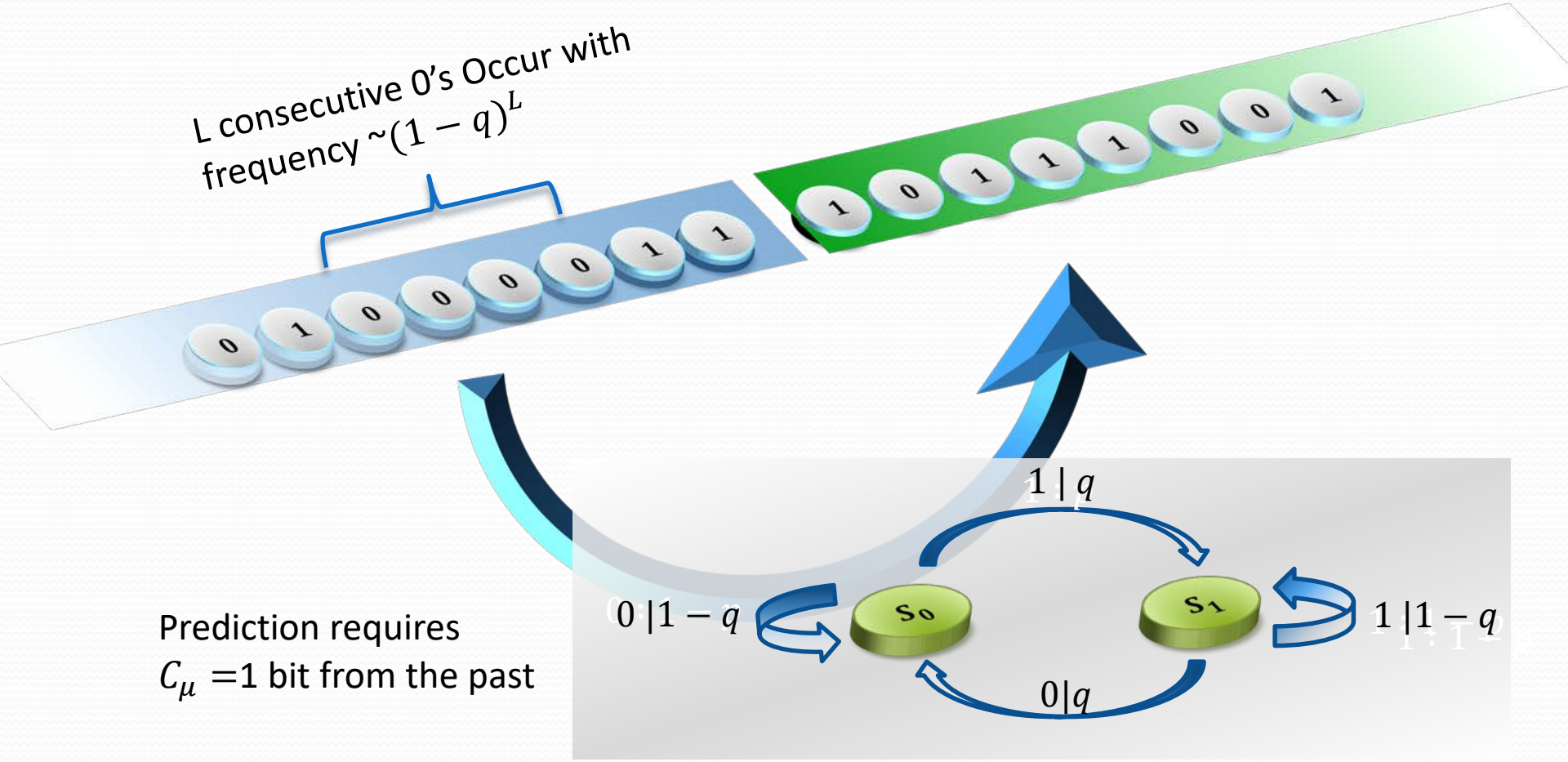
Case Study: The Perturbed Coin

L repeated symbols occurs with frequency $\sim(1-q)^L$

Output:
State of Coin

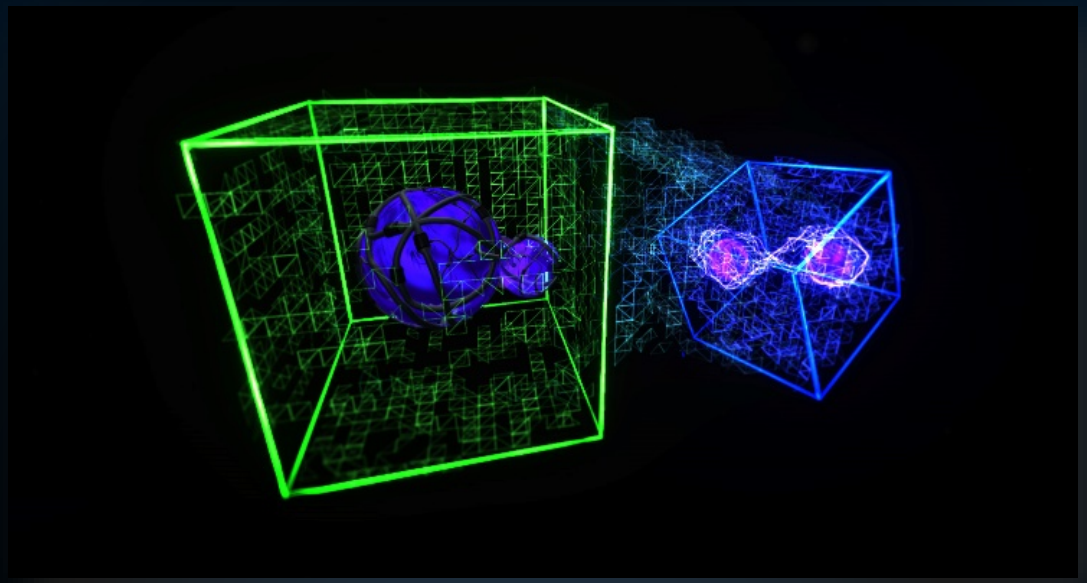


Case Study: The Perturbed Coin



Prediction requires
C_μ =1 bit from the past

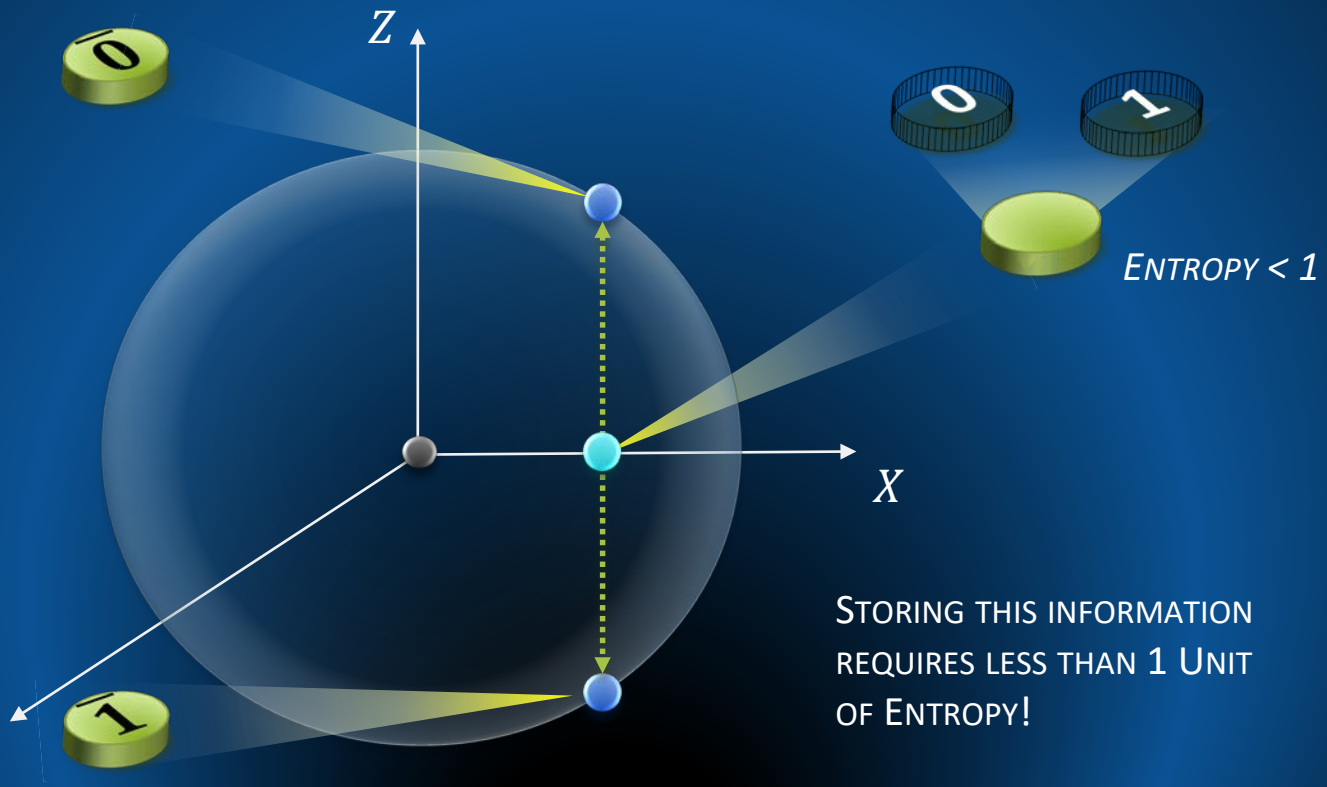
What about quantum?



Simplifying with Quantum

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

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



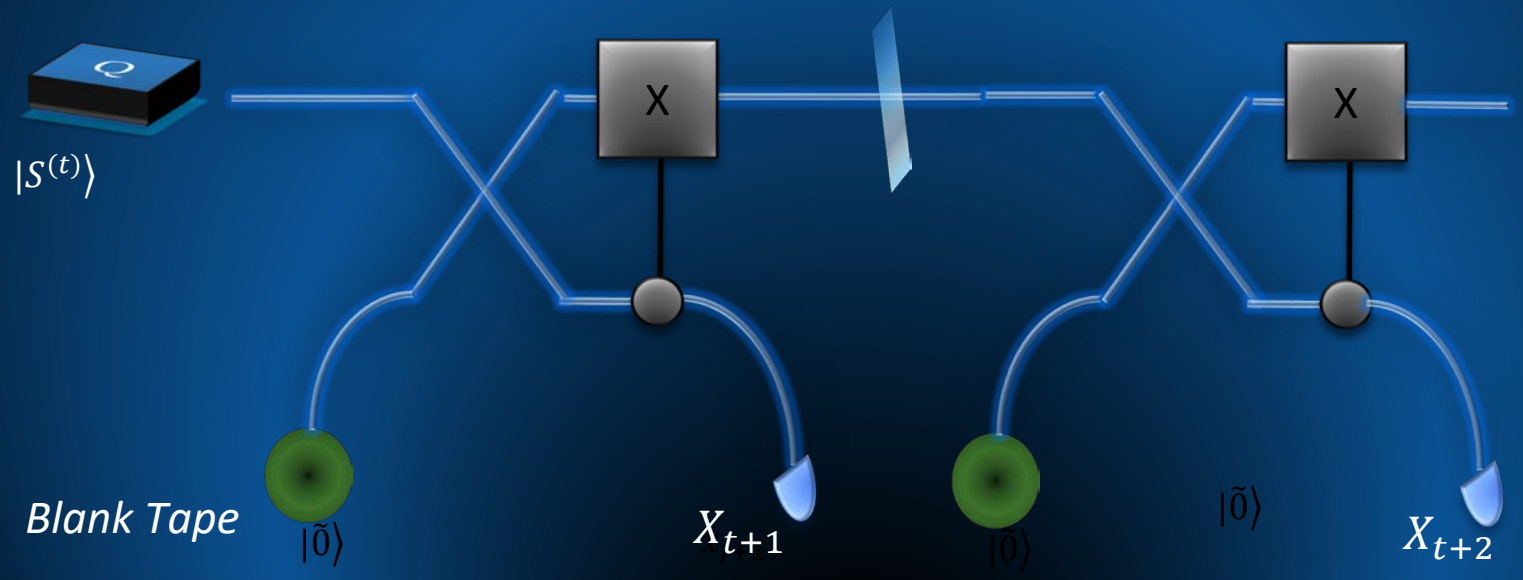
Entropy < 1

Storing this information requires less than 1 Unit of Entropy!

Simplifying with Quantum

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

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



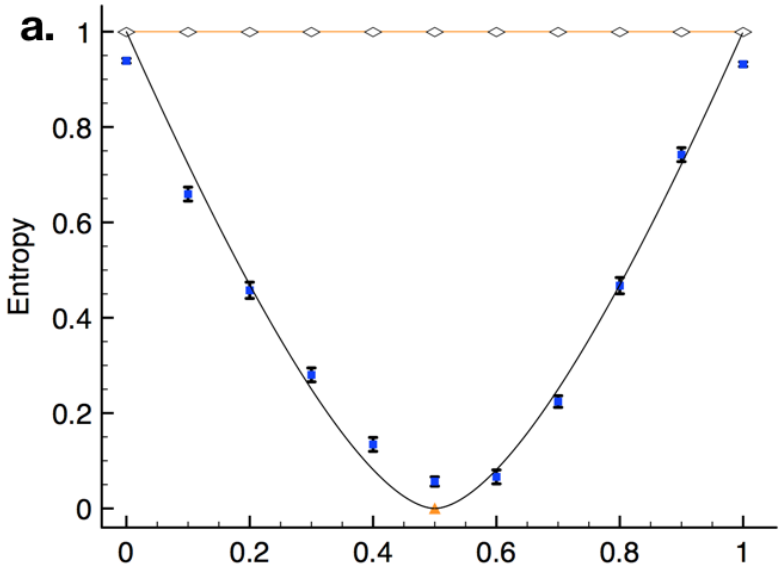
M.Palsson, M.Gu, J.Ho, H. Wiseman, G. Pryde. Science Advances , 3, 2, e1601302, 2017

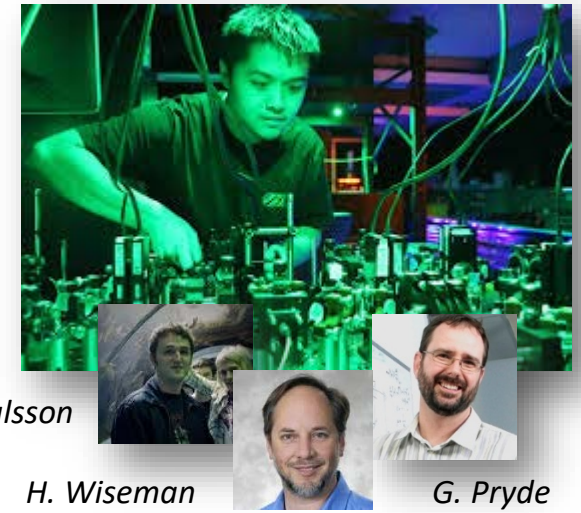
SCIENCE ADVANCES | RESEARCH ARTICLE

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]*





J. Ho

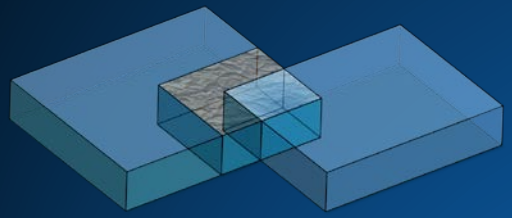
M. Palsson

H. Wiseman

G. Pryde

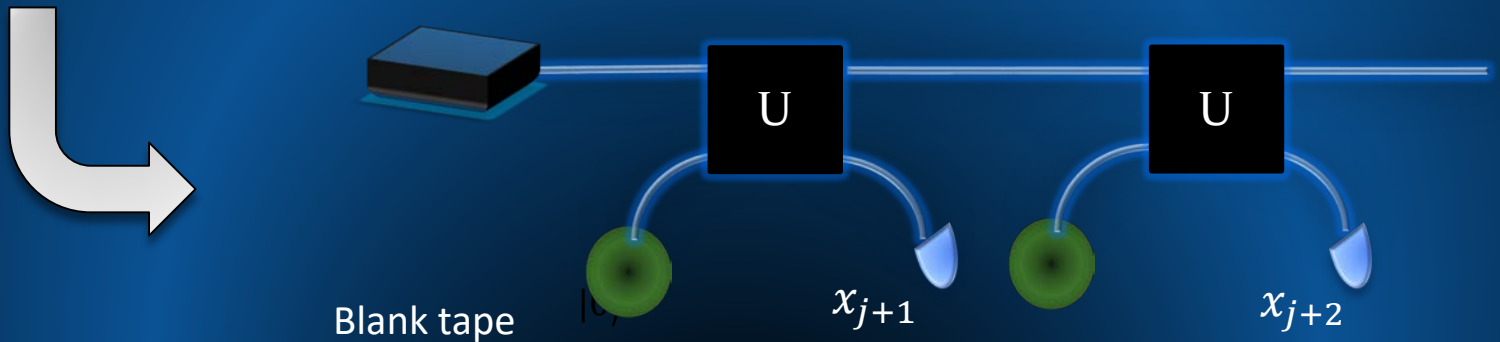
Science Advances , 03 Feb 2017: Vol. 3, no. 2, e1601302

GENERALITY



NON-ZERO CAUSAL WASTE $C_\mu > E$

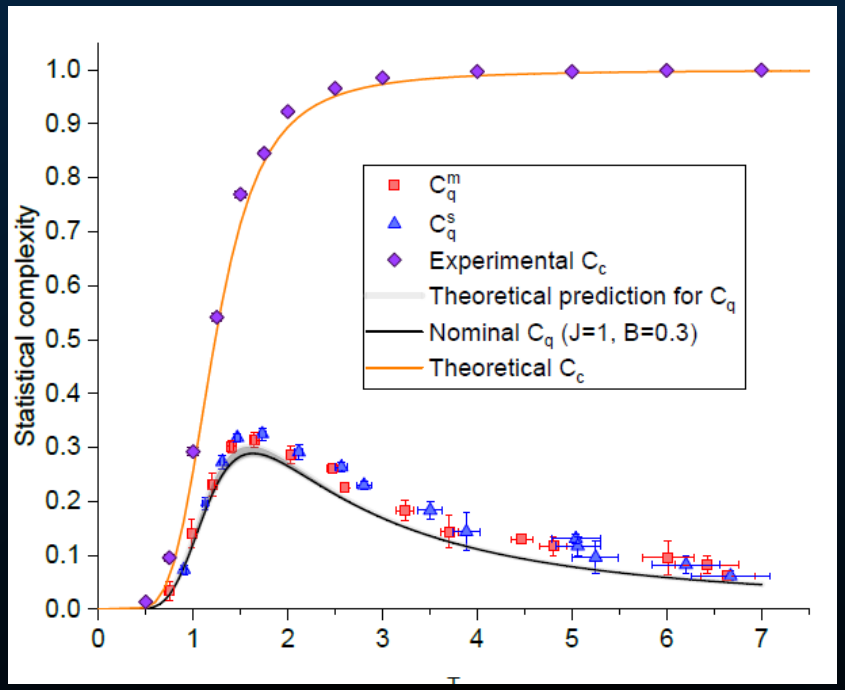
Systematic simpler quantum model whenever $C_\mu < E$



Gu, Mile, et al. "Quantum mechanics can reduce the complexity of classical models." Nat. Comm. 3, 762, 2012

Binder et. al. "Practical unitary simulator for non-markovian complex processes." Phys. Rev. Lett. 120.24, 240502, 2018

WHAT IS COMPLEX CAN DEPEND FUNDAMENTALLY ON THE NATURE OF THE OBSERVER



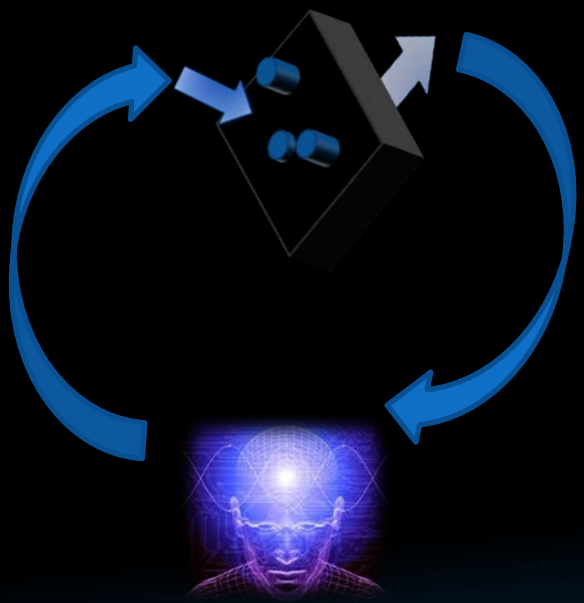
Complexity Science

Quantum Information

W.Y.Suen, et al. "The classical-quantum divergence of complexity in the Ising spin chain.“ Quantum 1 25 (2017)
F. Ghafari et.al. "Observing the ambiguity of simplicity via quantum simulations of an Ising spin chain." (2017)

General Adaptive Processes

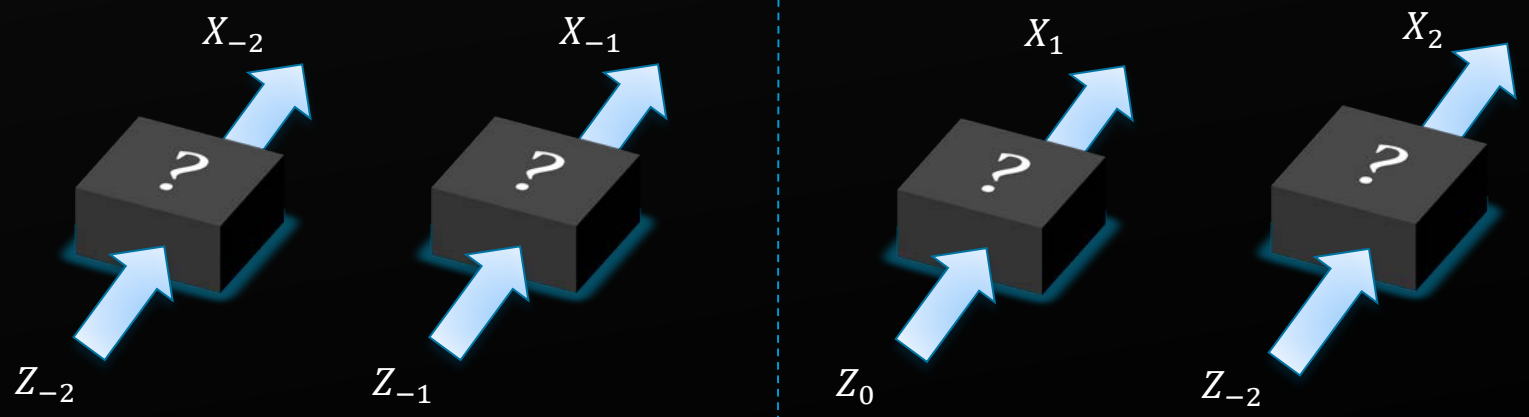
Input



Reaction?

Information Transducers

Past | Present | Future



$\overleftarrow{Z}_t = \ldots Z_1 Z_0$

$\overleftarrow{X}_t = \ldots X_1 X_0$

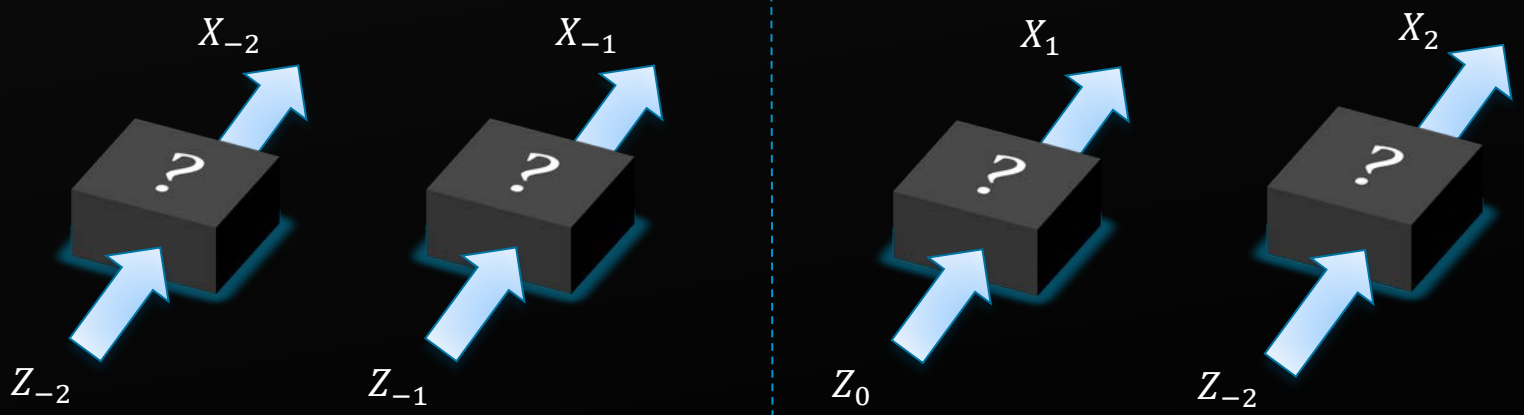
$\vec{Z} = Z_1 Z_2 \ldots$

$\vec{X} = X_1 X_2 \ldots$

Formally described by a family of stochastic processes.

$$\left\{ P\left(\overleftarrow{X}, \vec{X}\right)\Big|_{\overleftarrow{Z},\vec{Z}} \right\}$$

Information Transducers



$\overleftarrow{Z}_t = \ldots Z_1 Z_0$

$\overleftarrow{X}_t = \ldots X_1 X_0$

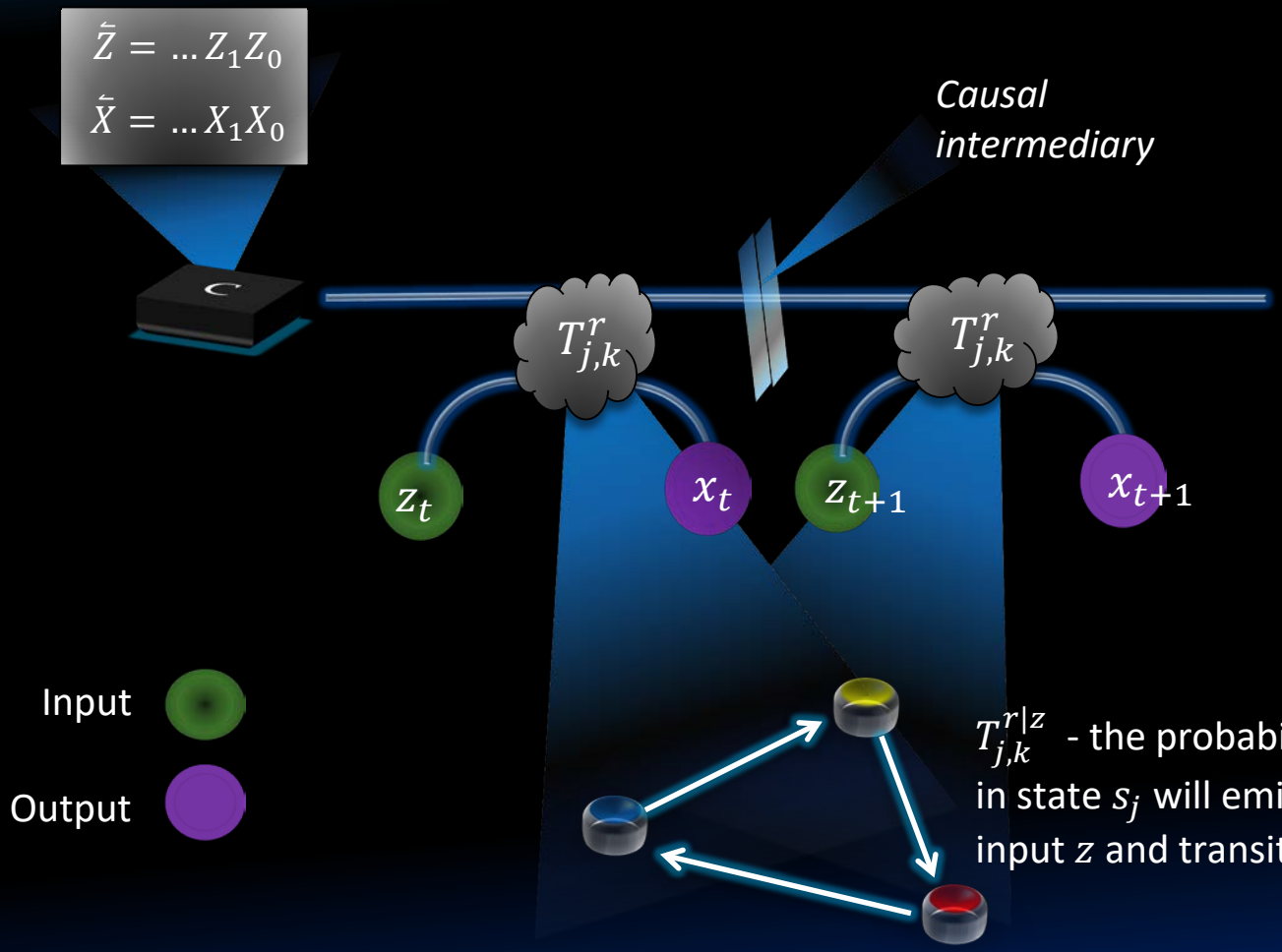
Past Information

$\vec{X} = X_1 X_2 \ldots$

Statistically correct future predictions

Future Input: $\vec{Z} = Z_1 Z_2 \ldots$

Information Transducers



$T^{r|z}_{j,k}$ - the probability a machine in state s_j will emit output `r' on input z and transition to s_k

Example

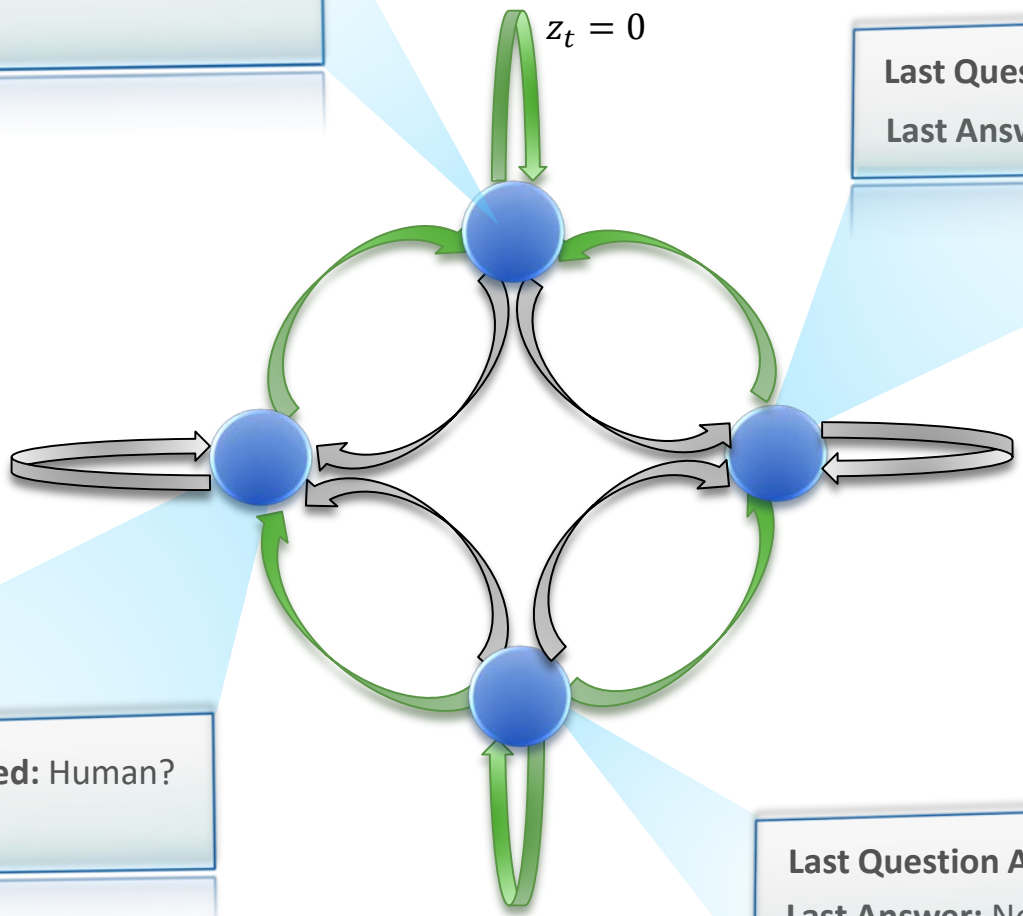
$Z_t = 0$: Do you like electric sheep?

$Z_t = 1$: Are you Human?

Observed Behaviour:

1. Answers must agree when asked the same question twice.
2. Otherwise, must answer randomly.

Last Question Asked: Electric Sheep?
Last Answer: Yes



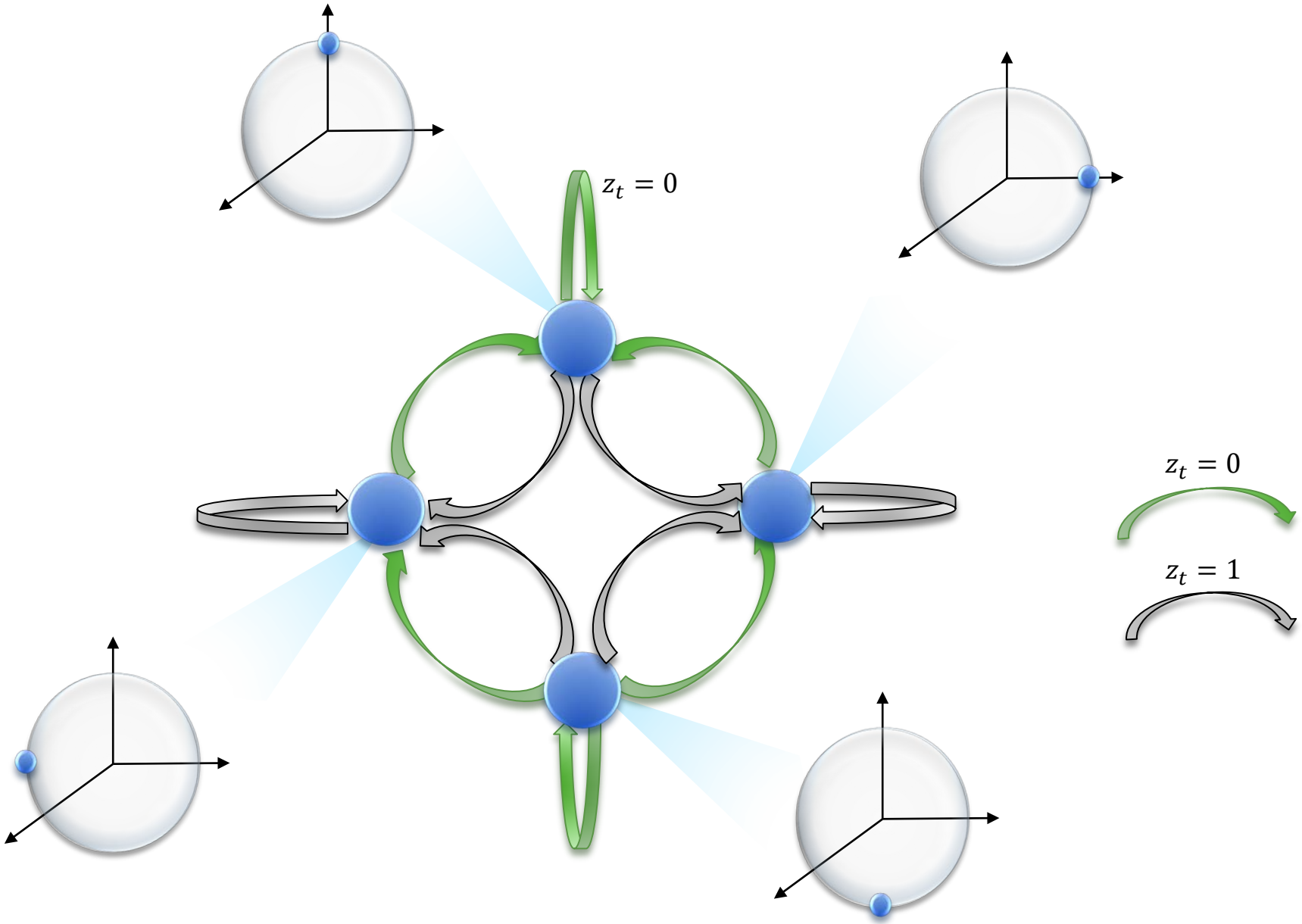
Last Question Asked: Human?
Last Answer: Yes

$z_t = 0$

$z_t = 1$

Last Question Asked: Human?
Last Answer: No

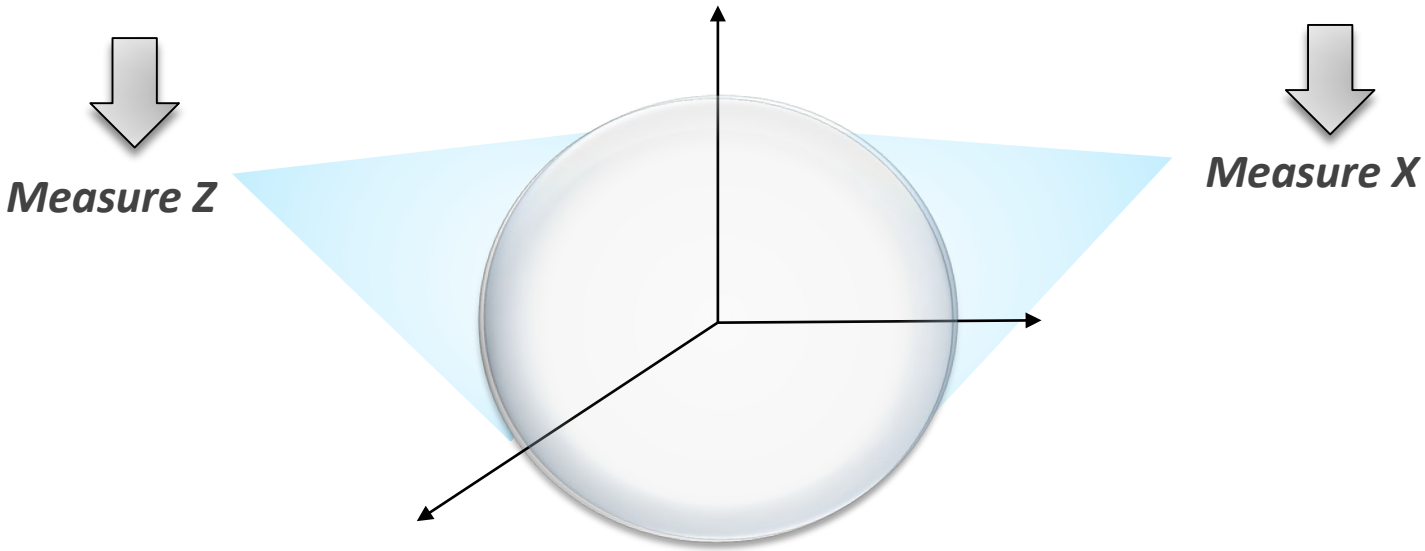
Last Question Asked: Human?
Last Answer: No


$z_t = 0$
$z_t = 0$
$z_t = 1$

Quantum Replicants

Q1: Do you like electric sheep?

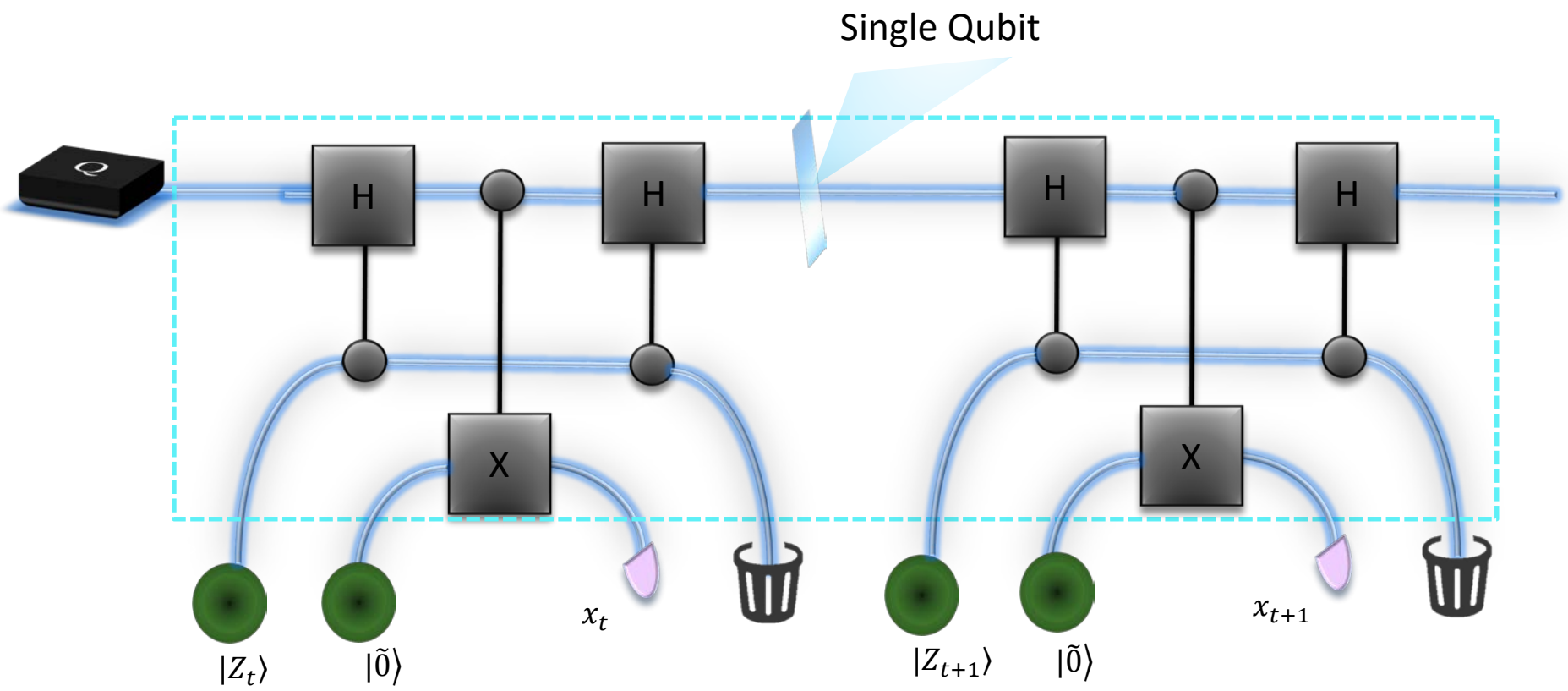
Q2: Are you Human?



***Required Behaviour*:**

1. Answers must agree with asked the same question twice.
2. Otherwise, must answer randomly.

Quantum Transducer



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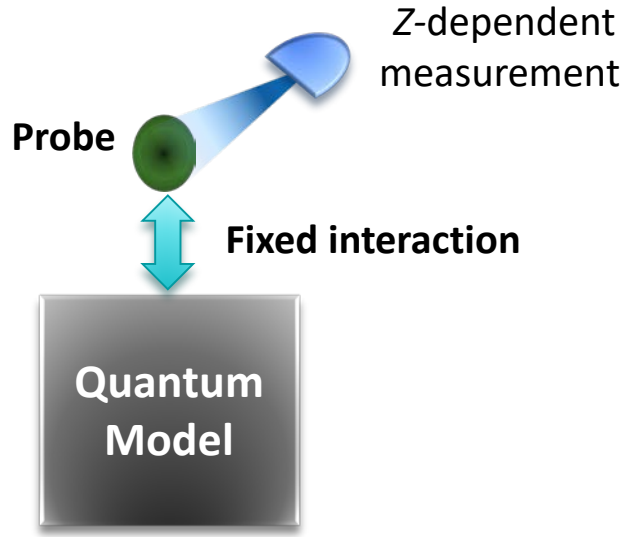
www.nature.com/npjqi

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]

Whenever improving upon classical models does not violate the information processing inequality, it is possible to do so with a quantum model.

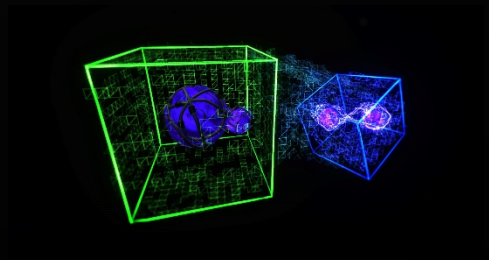


For scaling Results, see Thomas Elliot's Lightning Talk Tomorrow

Conclusions

- ***Statistical Complexity*** – aims to quantify structure by asking what the minimal past information an agents needs about a process to make statistically correct future predictions.

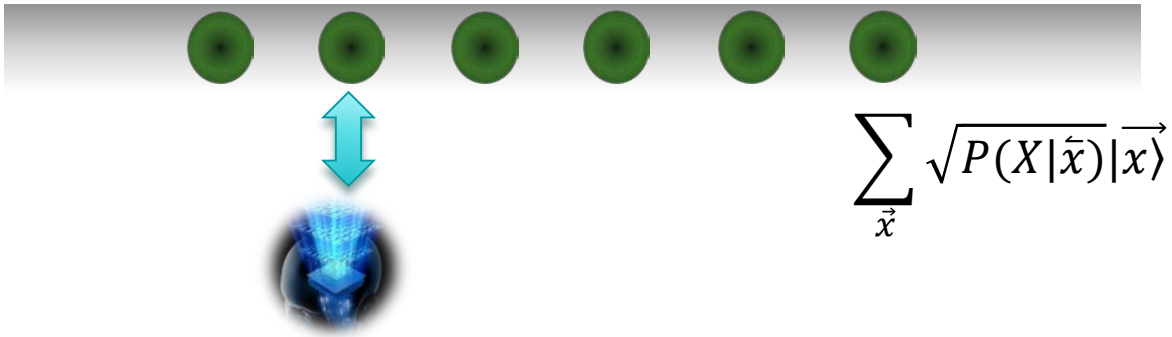
- ***Quantum Transducers –*** *environments may look simpler to quantum versus classical agents.*



- ***Qualitative Divergences*** *– qualitative behaviours in complexity may depend fundamentally on whether the observer processes classical or quantum information.*

Outlook: Quantum Superpositions?

Agents can generate quantum superpositions of futures



- Does this have operational advantage?
- Can this allow us to build a theory of complexity on quantum patterns?

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-019-08951-2 OPEN

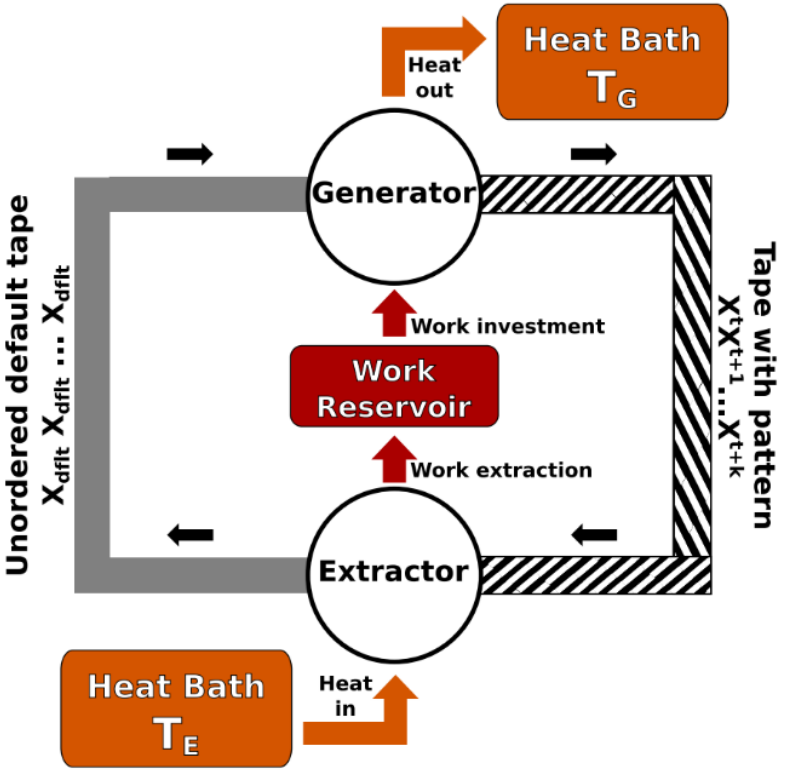
Interfering trajectories in experimental quantum-enhanced stochastic simulation

Farzad Ghafari[1], Nora Tischler[1], Carlo Di Franco[2,3], Jayne Thompson[4], Mile Gu[2,3,4] & Geoff J. Pryde[1]

Outlook: Thermodynamic Consequences?

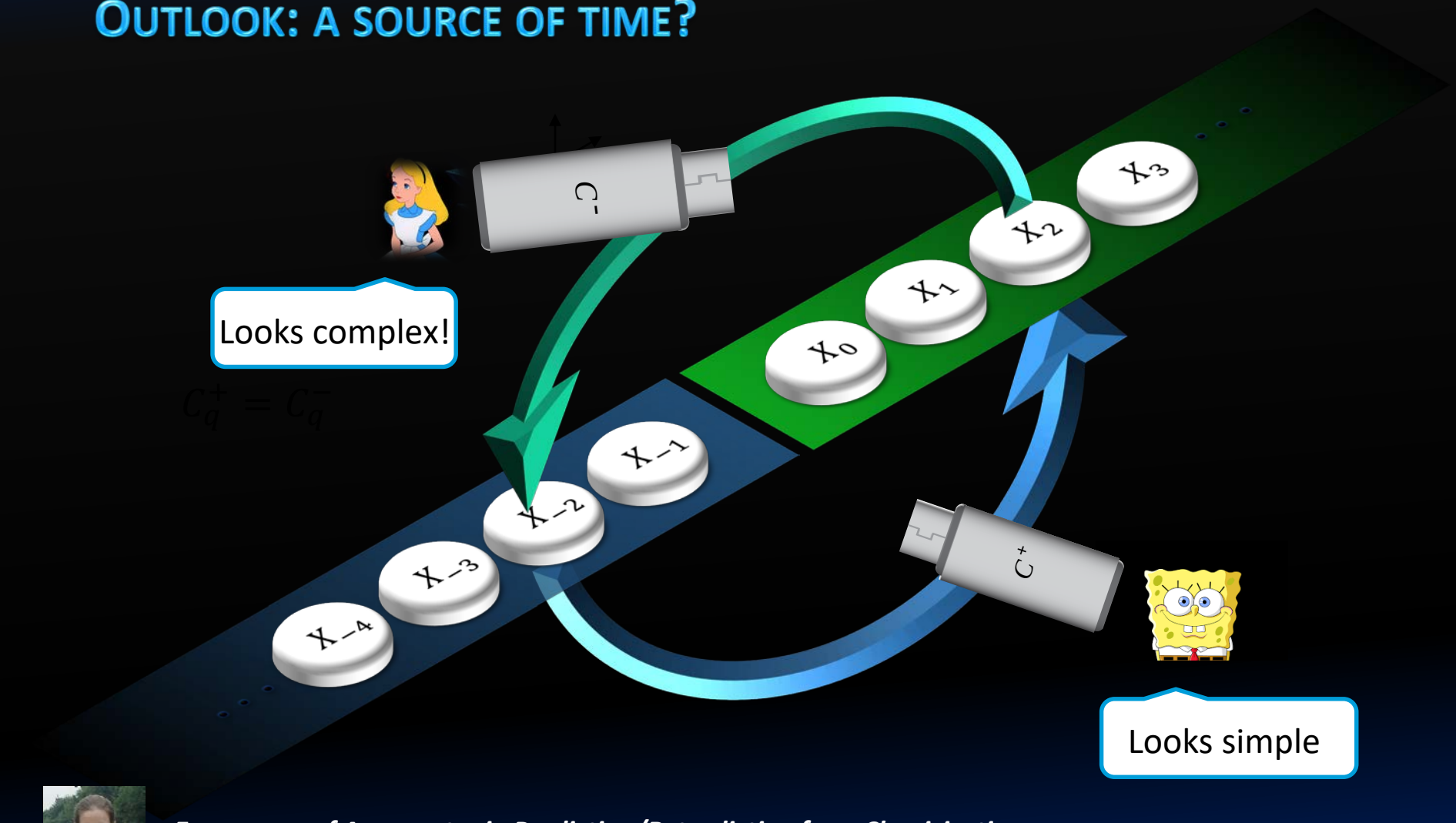
Maxwell's Demon

Optimal causal machine dissipates heat of at least $C_\mu - I(\overleftarrow{X}, \overrightarrow{X})$ *beyond Landaur's bound*



The thermodynamics of complexity and pattern manipulation, *Phys Rev E 95, 042140*
Thermodynamics of Modularity: Structural Costs Beyond the Landauer Bound, *Phys. Rev. X 8, 031036*

Outlook: a source of time?



Emergence of Asymmetry in Prediction/Retrodiction from Classicization (Talk Sunday 9:30am), Physical Review X, 8(3), 031013.

Two Relevant Satellite Workshops:

- ***Information Processing in Complex Systems***
  www.quantumcomplexity.org/information-processing-in-complex-systems

- ***Nonequilibrium Thermodynamics of Complex Agents***
  www.quantumcomplexity.org/thermolife

FQXi Conference on Agency at the Interface of Quantum and Complexity Science

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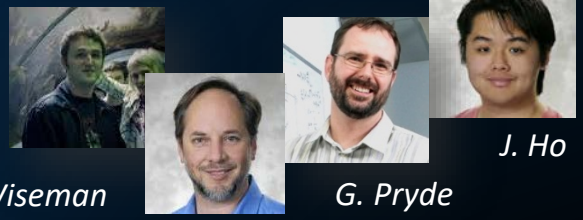
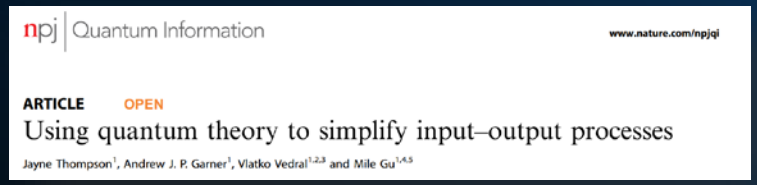
References

- ***Quantum Mechanics and reduce the complexity of classical models***
  - *Nature Communications, 3, 762*



M. Palsson *H. Wiseman* *G. Pryde* *J. Ho*



Experimental Quantum Processing Enhancement in modelling stochastic processes
- *Science Advances 3.2, e1601302, 2017*

- ***Using quantum theory to simplify input–output processes.*** *npj Quantum Information 3.1, 6, 2017*
- ***Unbounded memory advantage in stochastic simulation using quantum mechanics."*** *New Journal of Physics 19 (10), 103009, 2017*
- ***Superior Memory Efficiency of quantum devices for the simulation of continuous time processes.*** *npj: quantum information, 4 , 18 2018*
- **A practical, unitary simulator for non-Markovian complex processes**, Phys. Rev. Lett. 120, 240502, 2018
- **Causal asymmetry in a quantum world.** *Physical Review X, 8(3), 031013*.

Liu Qing *F. Binder* *A. Garner* *S. W. Yeap* *V. Vedral* *J. Thompson* *V. Narasimhacha* *T. Elliot* *C. Yang*