Title: Quantum and classical causal agents

Speakers: Sally Shrapnel

Series: Quantum Foundations

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Abstract: Agency accounts of causation are often criticised as being unacceptably subjective: if there were no human agents there would be no causal relations, or, at the very least, if humans had been different then so too would causal relations. Here we describe a model of a causal agent that is not human, allowing us to explore the latter claim.

Our causal agent is special kind of open, dissipative physical system, maintained far from equilibrium by a low entropy source of energy, with accurate sensors and actuators. It has a memory to record sensor measurements and actuator operations, and a learning system that can access the sensor and actuator records to learn and represent the causal relations. We claim that causal relations are relations between the internal sensor and actuator records and the causal concept inherent in these correlations is then inscribed in the physical dynamics of the internal learning machine. We use this model to examine the relationships between three familiar asymmetries aligned with causal asymmetry: time's arrow, the thermodynamic arrow and the arrow of deliberation and action. We consider both classical and quantum agent models and illustrate some differences between the two.

Quantum causal agents

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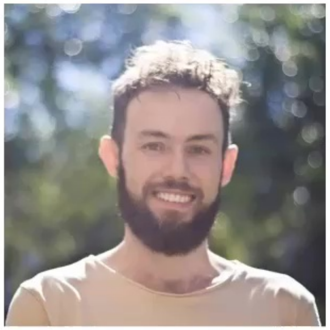

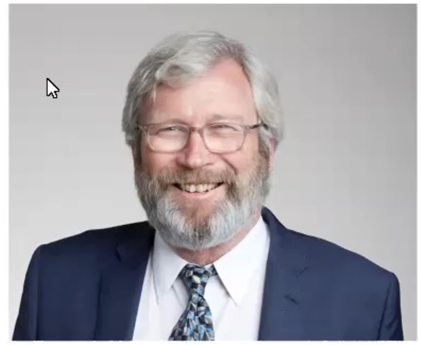

Minimal Causal Agents

arXiv: 1809.03191 GJ Milburn and SS, 2018, *Classical and quantum interventions*
arXiv: 1910.08985, M Kewming, SS, GJ Milburn, 2020, *Quantum Correlations in the Kerr Ising Model*
arXiv: 2009.04121 GJ Milburn and SS, 2020, *Physical grounds for causal perspectivalism*
arXiv: 2007.04426 M Kewming, SS, GJ Milburn, 2020, *Designing a physical quantum agent*
arXiv: 2007.02217 GJ Milburn, 2020, *The Thermodynamics of Clocks*
In preparation P Evans, GJ Milburn and SS, 2021, *Thermodynamic asymmetries and causal perspectivalism*

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Goal

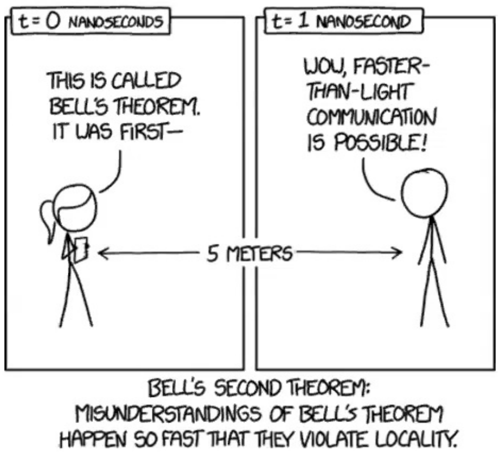
To describe the physics of simple autonomous agents that have the capacity to learn cause-effect relationships.

When such an agent has learned these causal relations, it can bring about certain ends by intervening in a specific manner.

Of particular interest for us is how such agents would differ if they had access to quantum resources in addition to classical resources.

Motivation

What can quantum theory teach us about causation?



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Motivation

Automated classical causal discovery/inference

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What about deep learning?

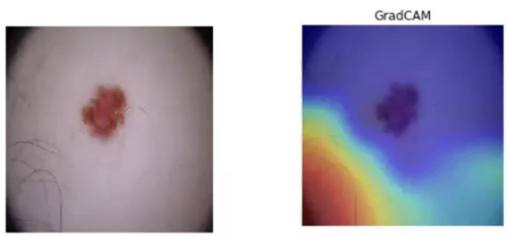
Spurious correlations

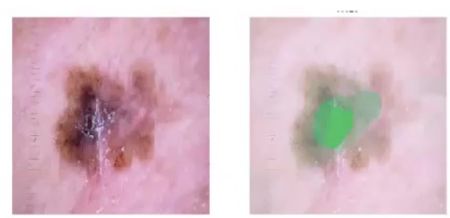
Adversarial examples

Domain shift

Interventional robustness

Spurious correlations





0.996 naevus

0.998 melanoma

"Deep neural network or dermatologist?" K Young, G Booth, Becks Simpson, R Dutton, S Shrapnel
arXiv: 1908.06612

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Models are not invariant to contextual interventions

It's a naevus

Now it is a melanoma!

Identifying *quantum* causes?

Quantum analogues of Markov, Faithfulness…[1]

- Very abstract,
- Device dependent
- Discovery techniques don't scale well
- Role of agent is abstracted away

Use classical machine learning?[2,3]

1. arXiv 1512.0710, Costa and SS, *Quantum Causal Modelling,* 2016
2. arXiv 1901.05158 SS, Costa, Milburn, *Quantum Markovianity as a supervised learning task* 2018
3. arXiv 2102.01327 Goswami, Giarmatzi, Monterola, SS, Romero, Costa, *Experimental characterisation of a non-Markovian quantum process* 2021

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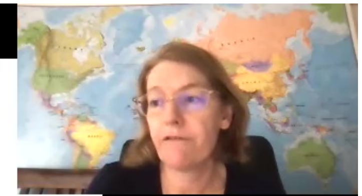
What about understanding causation from the perspective of an agent?



Physics of learning agent?

Humans are very messy, complex to model

Minimal Causal Agent?

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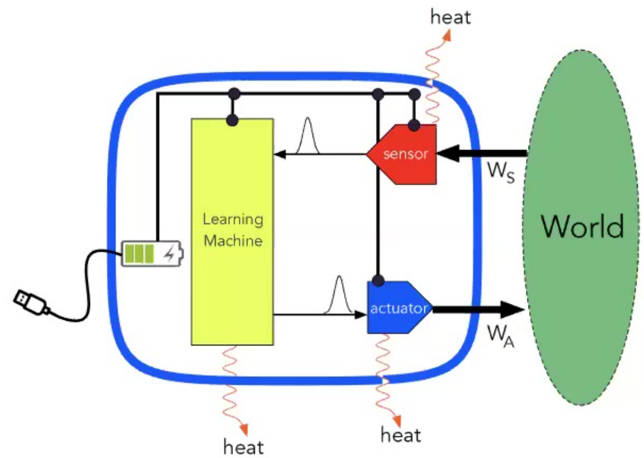
Desiderata

Finite,
Open,
Maintained in FFE steady state,
Stabilised by low S source of energy,
Special subsystems:
- actuators
- sensors
- memory
- learning process

Quantum vs classical



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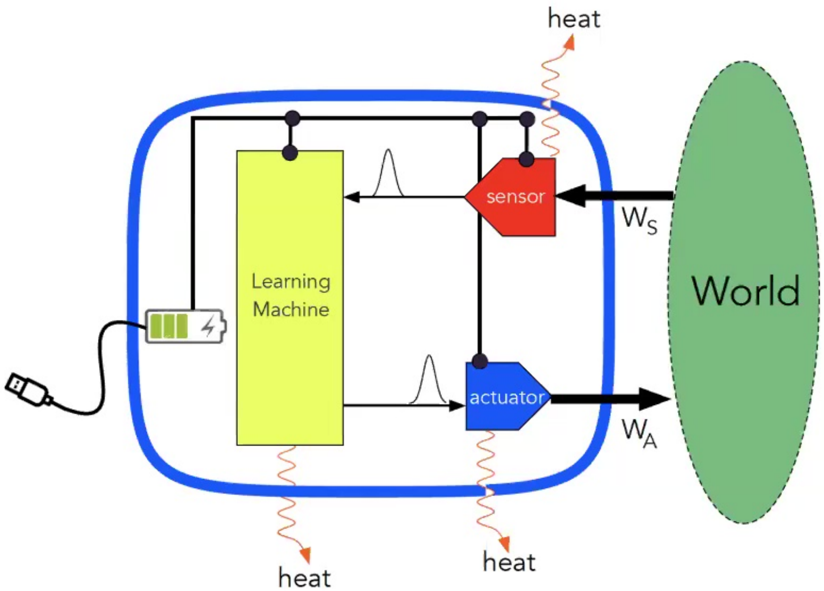
Actuators and sensors



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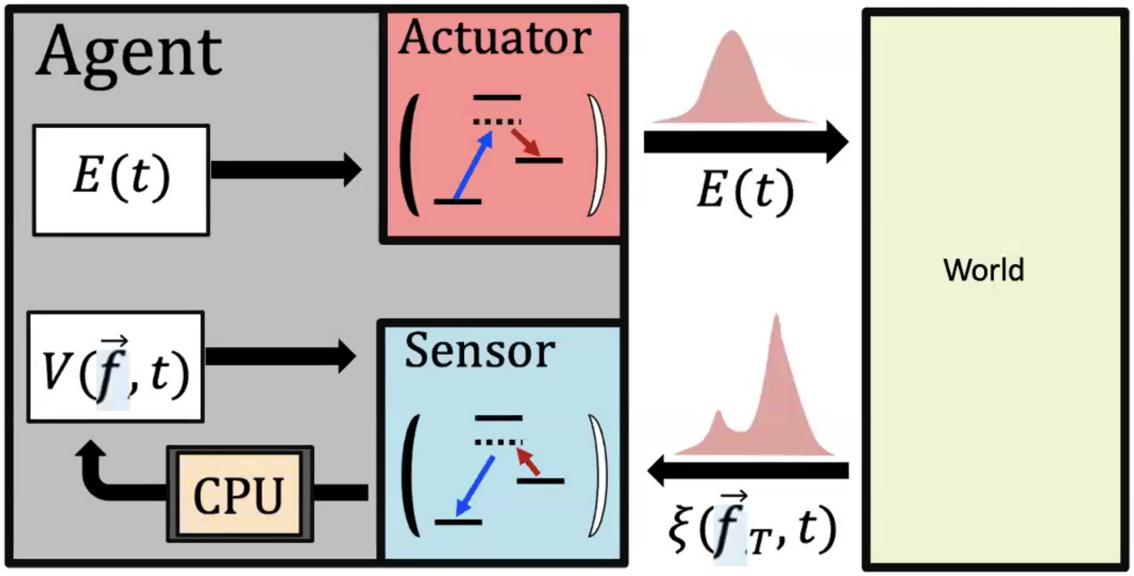
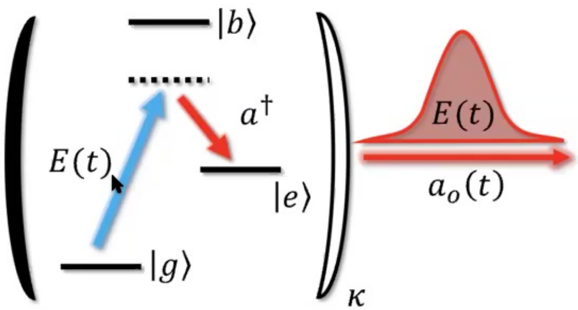
An all-optical agent: quantum vs classical



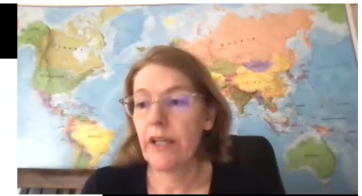
Slides thanks to Michael Kewming

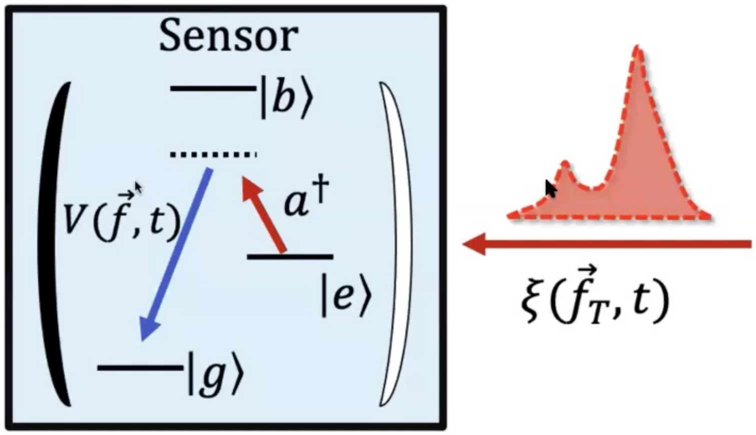
Actuator = single photon source



Quantum = Single photon Fock state

Classical = weak coherent state





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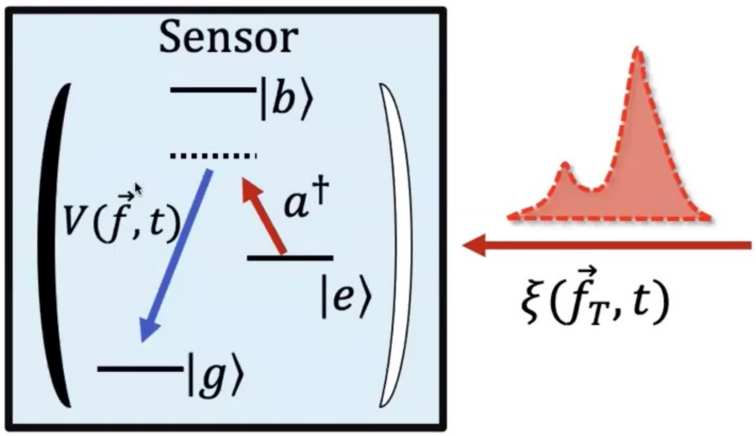

$$\Gamma = \left| \int_0^t V^*(\vec{f},t)\xi(\vec{f}_T,t) \right|^2$$

$$P_g(\mathrm{t}) = \frac{4\eta\Gamma}{\kappa}\tanh\left(\frac{\mu}{2}\right)$$ Quantum

$$P_g(\mathrm{t}) = \frac{4\eta\Gamma}{\kappa}\mathrm{e}^{-\frac{4\eta\Gamma}{\kappa}}\tanh\left(\frac{\mu}{2}\right)$$

Classical

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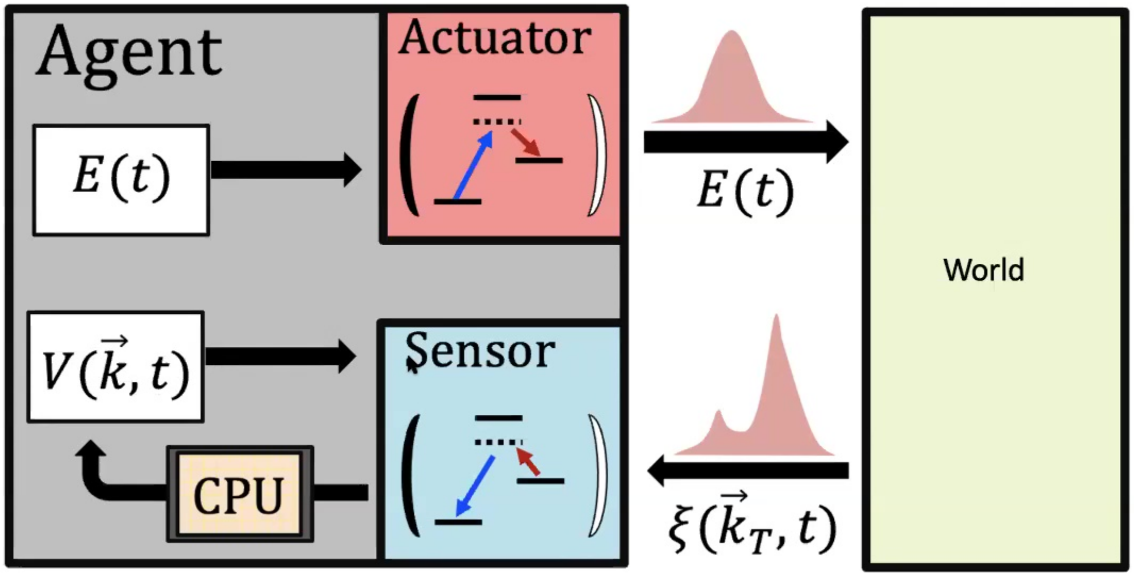
learning



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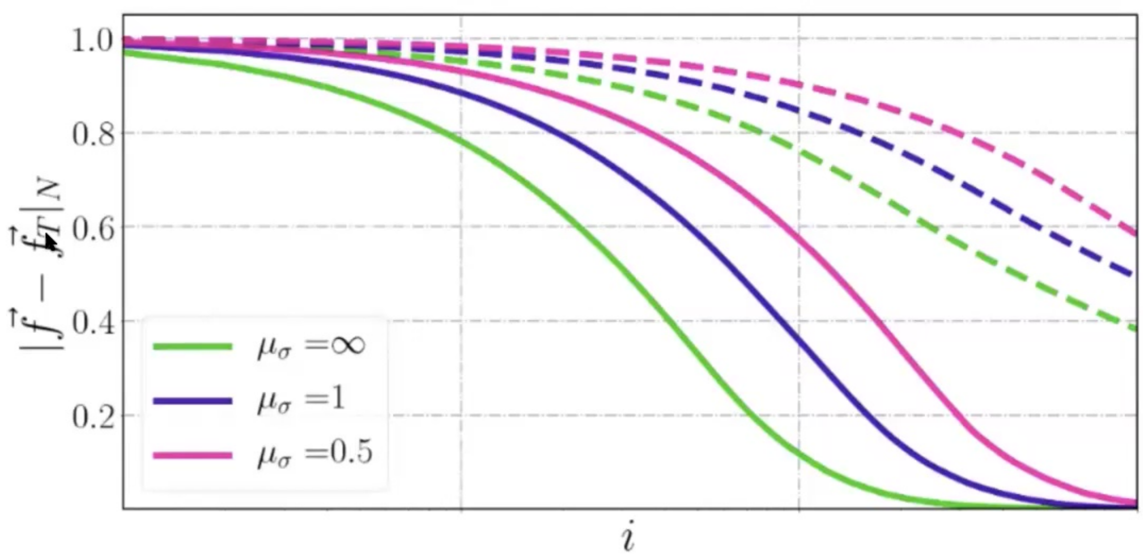
Minimise errors

$$I(t) = \frac{dP_e(\vec{f},t)}{dt} = \frac{d\vec{f}}{dt} \cdot \vec{\nabla}_{\vec{f}} P_e$$



Quantum: solid line
Classical: dashed line

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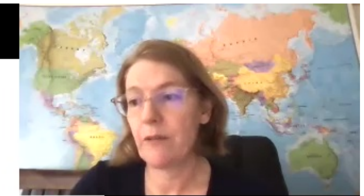


Thermodynamics

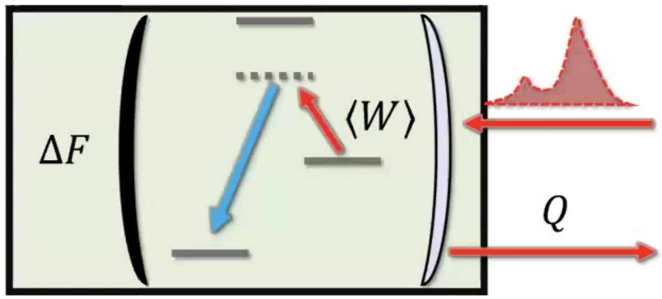


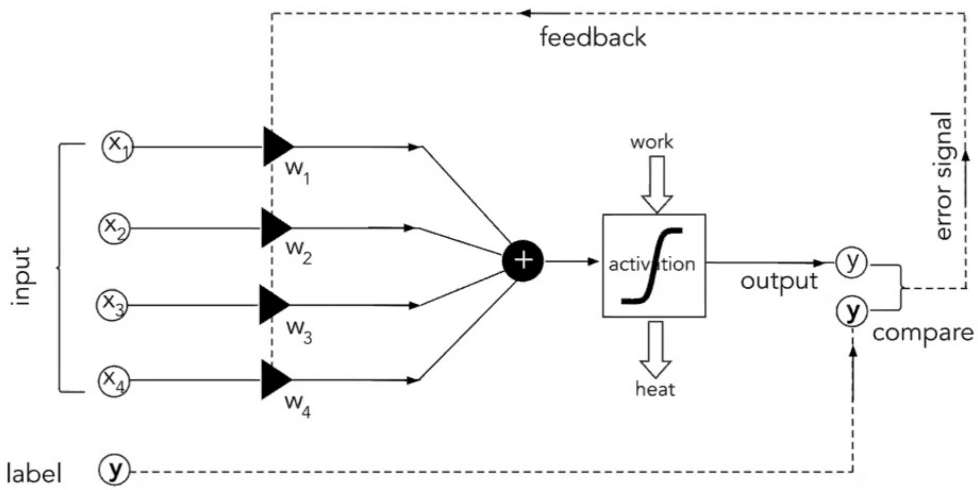
Figure 3. The free energy ΔF of the detector increases if the photon does work $\langle W \rangle$ on the atom by stimulating a transition. If the photon is not absorbed, it is reflected back into the environment as heat Q.

arXiv: 2007.04426 Kewming, SS, Milburn, 2020 “Designing a physical quantum agent”

arXiv:2006.15416 A B Boyd, JP Crutchfield, M Gu, 2020,”Thermodynamic learning through maximum work production”,

Learning machine

Thermodynamics of neural networks



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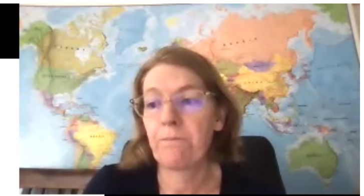
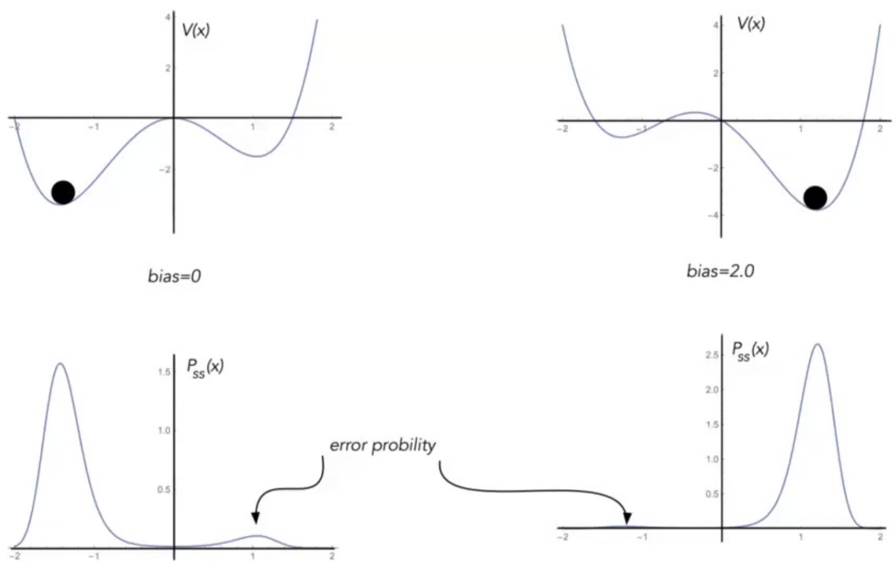


Activation function



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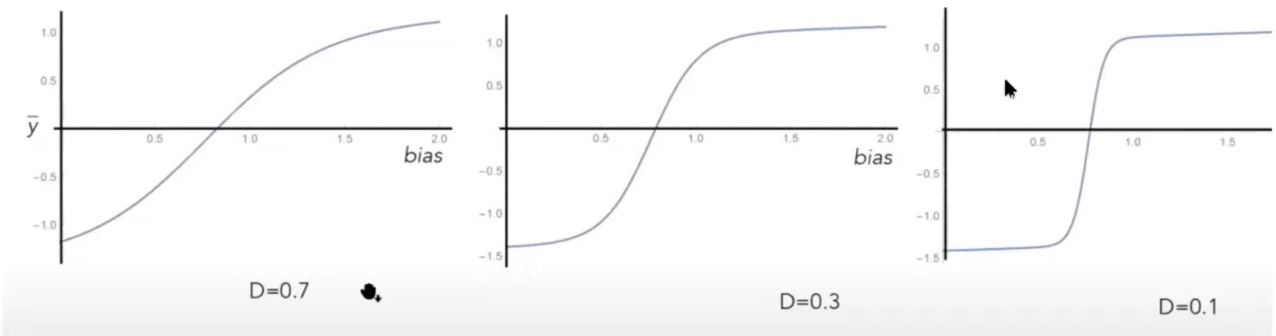

Decreasing noise

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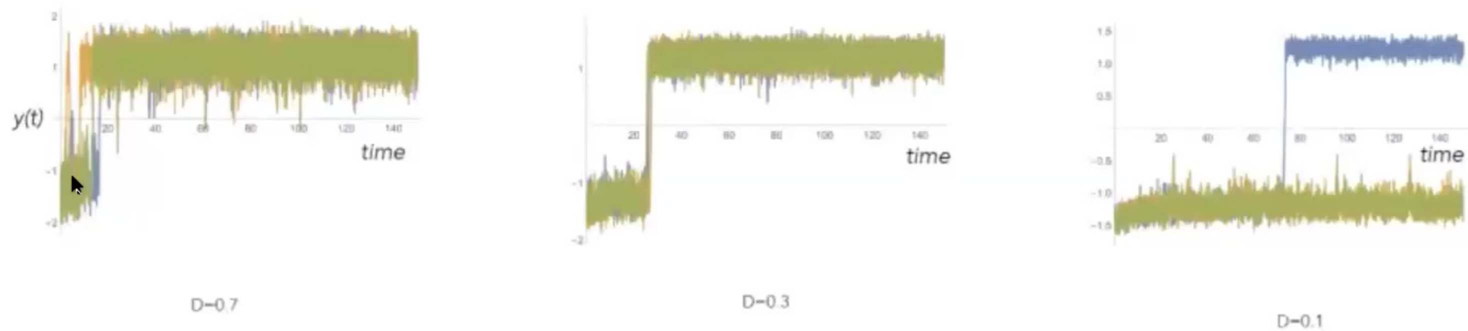

Decreasing noise

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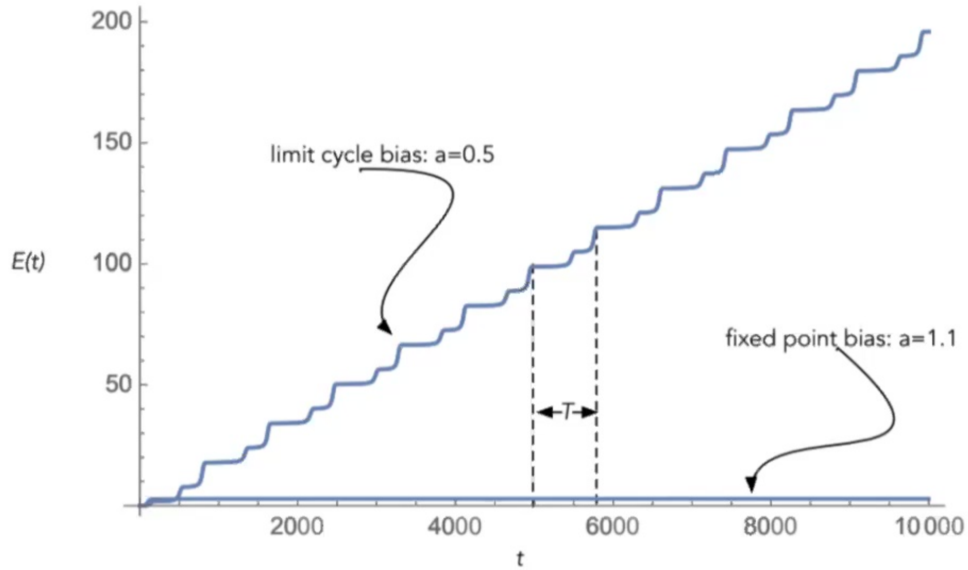
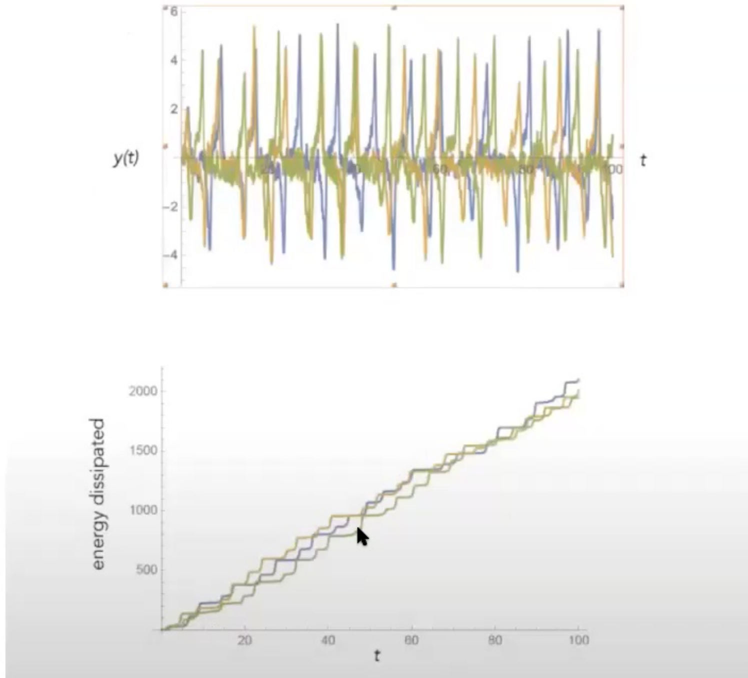
Limit cycles and perceptron learning



G. Milburn, 2020, The Thermodynamics of Clocks, arXiv:2007.02217

momentum



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Quantum learning via limit cycles

At zero temperature limit no longer thermal noise and classical learning will stop

Only noise is this kind of phase noise: origin is purely quantum phenomena like tunnelling or spontaneous emission (operate at optical frequencies).

Opportunity to build networks of perceptrons from quantum nano-clocks that run at very low power.

Summary

Accuracy of sensors and actuators is *limited* by noise:

➢quantum case improvements due to metrological advantages

However, the ability to learn *requires* noise:

➢quantum case improvements due to zero-temp learning (can operate at low power)

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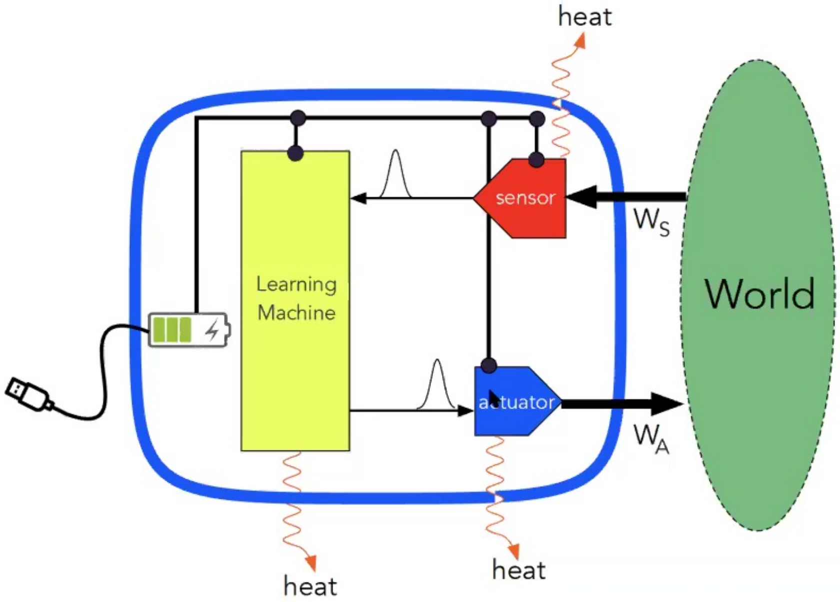
Arrow of causation



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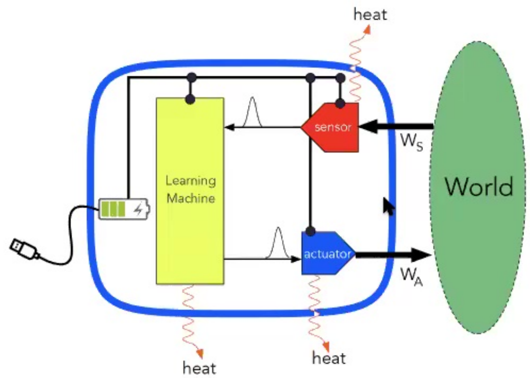
Thermodynamic arrow



Agents at thermodynamic equilibrium can't learn

Agents that learn will necessarily increase the entropy of their environment.

A universe in which agents can learn will *always appear to those agents* to be increasing in entropy.

But reverse the thermodynamics gradient of the learning machine it will no longer learn…learning *JUST IS* lowering of entropy

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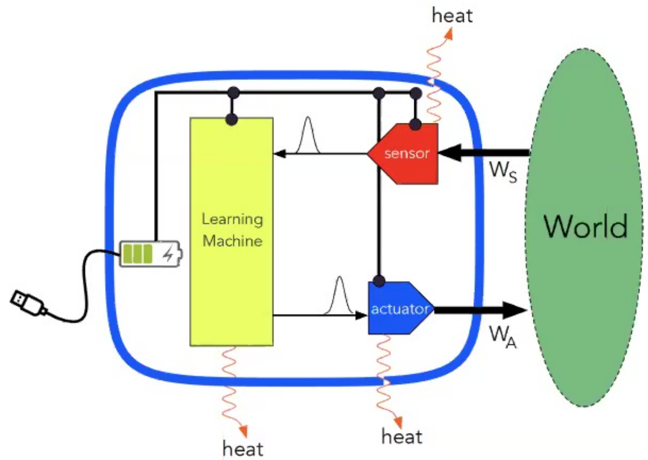
Temporal arrow



Where is time for this agent?

Let's just think of rates of learning.

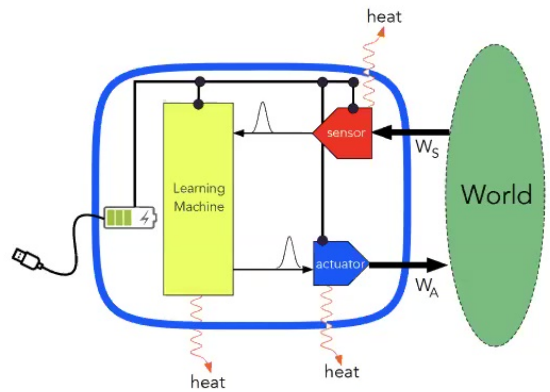
Refractory period of sensors and actuators.

Rate at which the learning machine converges is another rate limiting feature of this model

We have imagined a static environment for most of what I have said so far.
We can of course imagine an environment that is changing, the rate at which the learning system settles into a steady state must exceed the rate at which the environment is changing.

Does the agent need an internal time?

Arrow of intervention/action



Intervention comes first?

To know how to intervene you need to measure a system first

Deliberation?

Summary

Sketch of minimal causal agent

Can’t be in thermal equilibrium with their environment

FFE implies dissipation/fluctuations and constrained by thermodynamics

Time can be relational and local to agent