Exploratory AI horizons and Active Inference;

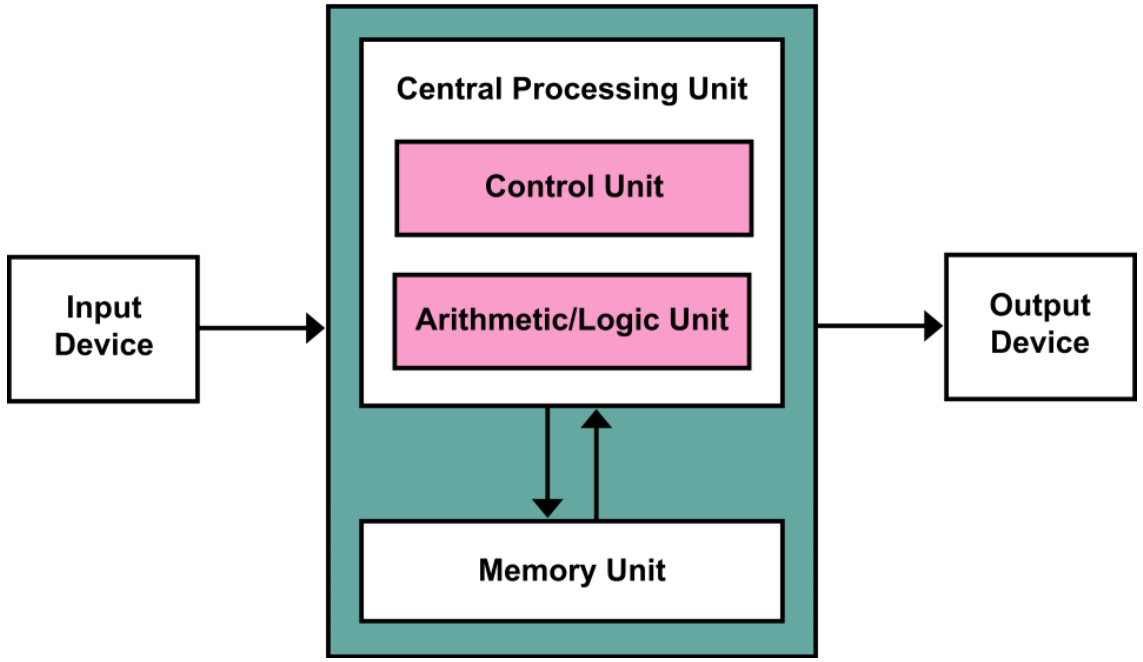
Discussing state-of-the-art and next-gen AI

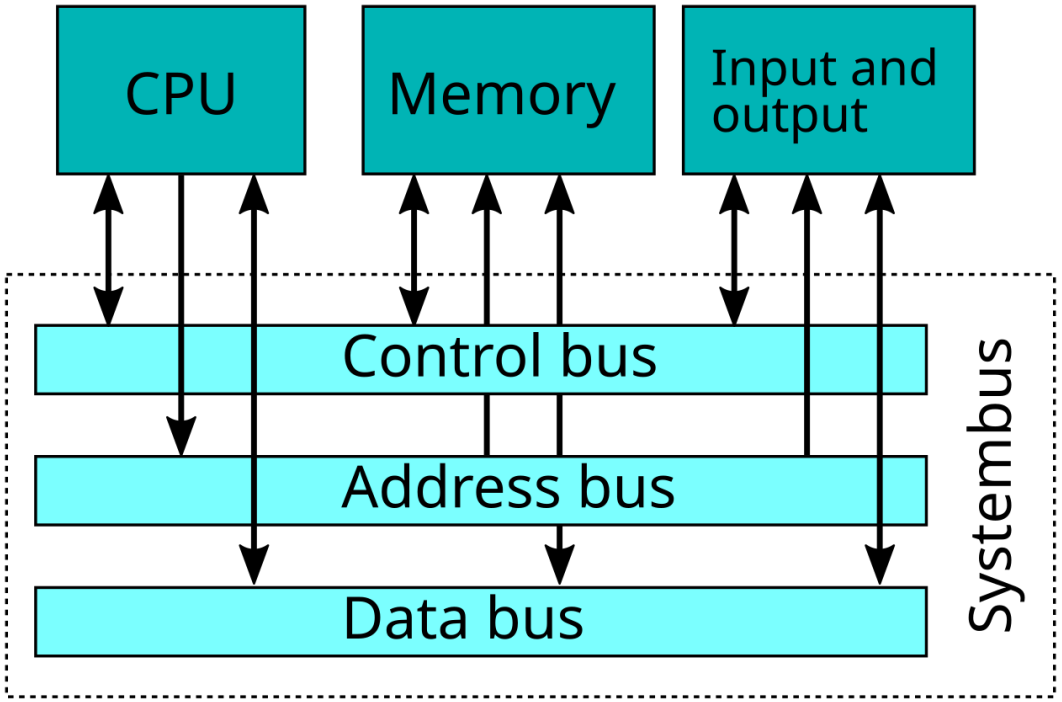
- Novel, *Non* von Neumann Embodiments of Computation
  - Reservoir Computing
  - Neuromorphic Architectures and Spiking neural networks (SNNs)
  - Quantum Computing and information security implications and NIST post-quantum contest
- Active Inference
  - The Free Energy Principle
  - Bayes Theorem and Markov Blankets
  - Modeling the Active Inference process

Exploratory AI horizons and Active Inference;

Discussing state-of-the-art and next-gen AI

von Neumann Architecture





Reservoir Computing

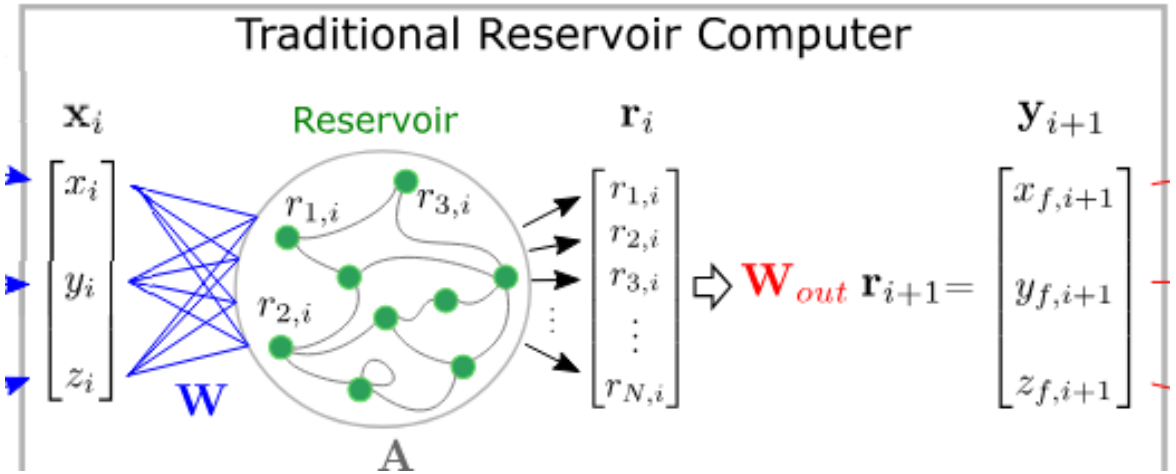
- The core idea of RC is that a significant portion of the computing task is performed not by a trained network, but by a very high-dimensional system (reservoir) that is essentially treated as a black box and whose output is fed into a single readout layer, which is the only component of the network that is trained.
- What is exploited here is the high dimensionality of the reservoir. The information that we are interested in is in principle encoded in the input signal, but it is mixed up, nonlinearly, with a huge amount of other stuff that we are not interested in. The projection onto a higher-dimensional space allows for separability.
- Also, it is often considered advantageous to operate the reservoir computer in a parameter range close to an instability (for example, in the vicinity of a transition to chaos), since there its behavior is particularly complex and therefore has a very high computational complexity.

Physical reservoir computing - (electronic, photonic, spintronic, mechanical, biological, chemical) - *"Input data was mechanically fed into a bucket of water, recordings of the water's surface then could be used for classification tasks."*

Recurrent Neural Network…

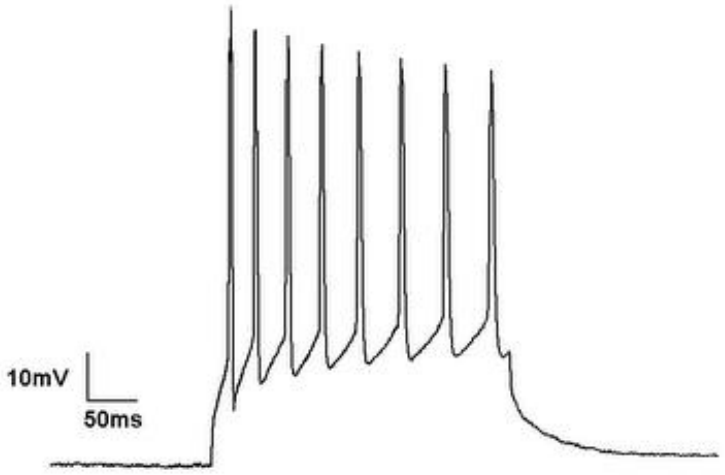
and Echo State Network Renderings of RC

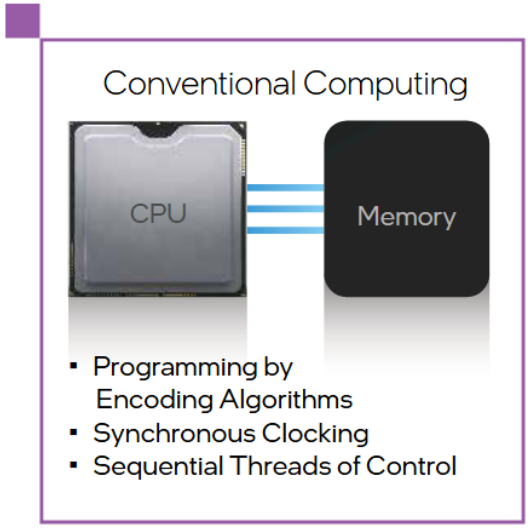
In RNN, information can also "move backwards" - allows system to have memory. Produces the complex dynamical system properties achieved in physical RC

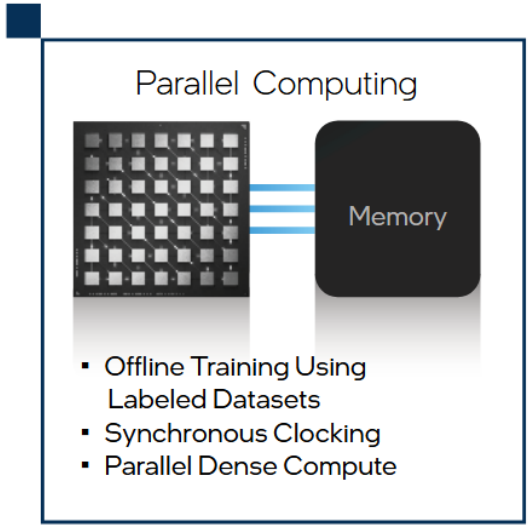


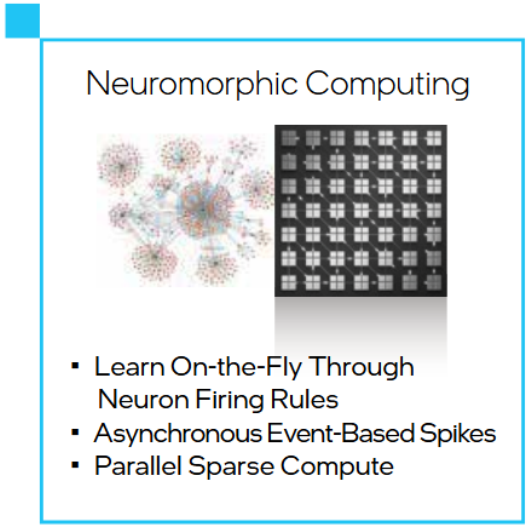
Neuromorphic Architectures and Spiking neural networks (SNNs)

Present day Neural Network Architectures … "*come at a very high price in computational power and pre-collected data. Many emerging AI applications—especially those that must operate in unpredictable real-world environments with power, latency, and data constraints—require fundamentally new approaches*….
Neuromorphic computing represents a fundamental rethinking of computer architecture at the transistor level, *inspired by the form and function of the brain's biological neural networks*.









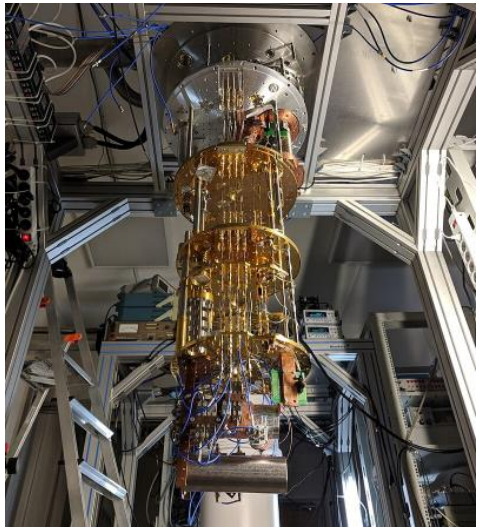
Exploratory AI horizons and Active Inference;

Discussing state-of-the-art and next-gen AI

Quantum Computing

- 2025 is international year of Quantum - *https://quantum2025.org/*
  - *"**No individual, society, country, institution, or discipline can claim ownership of the past or future of quantum science; it is knowledge that should be free to all**."*
- Employs Quantum Physics to produce non-classical "bits" – not just 0s and 1s, but (quantum) probabilistic superposition of these and intermediate states.
- "$106 Billion potential quantum technology market size by 2040"
- Some anticipate that older encryption methods will be broken by quantum computers within a decade – still require higher Qbits counts and improved methods for "noise reduction" in Quantum systems and circuits
- **NIST recently selected Post-quantum cryptography standards** through international competitive process - https://csrc.nist.gov/projects/post-quantum-cryptography

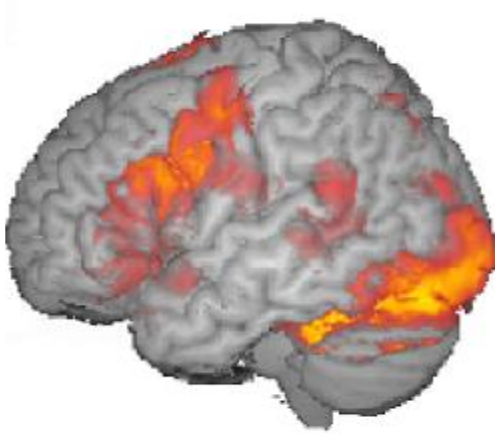
Noisy-intermediate scale quantum (NISQ) hardware.



"In early 2024, quantum computers are real and in regular use, and quantum runtime is offered as-a-service by many companies, via the internet / cloud"

Active Inference

- Inspired by study of predictive processing in Neuroscience – in particular the work and theory-building of Karl Friston who was tasked with determining how to animate the colouring of brain imagery for Functional Nuclear Magnetic Resonance Imaging systems (fNMRI) - a specialized type of MRI that measures brain activity by detecting changes in blood flow, allowing scientists to visualize which brain areas are active during specific tasks or at rest.



- Based on "The Free Energy Principle" – which generalizes and applied concepts of "Action" from the physical sciences and translating them into statistical analogies
  - Describes how the balance of kinetic versus potential energy of a physical system changes with trajectory.
- Also derived from implication of Bayesian statistics in an agential framework where the agent can sense and act on its environment so as to update it's generative model of the world – refine its predictions of adaptive behaviours – reusing its "surprise".
- A method for achieving a dynamic balance of exploration and exploitation
- A theory of all "things" (that "persist" – in the sense of retaining their pattern against the backdrop of their environment)

Active Inference

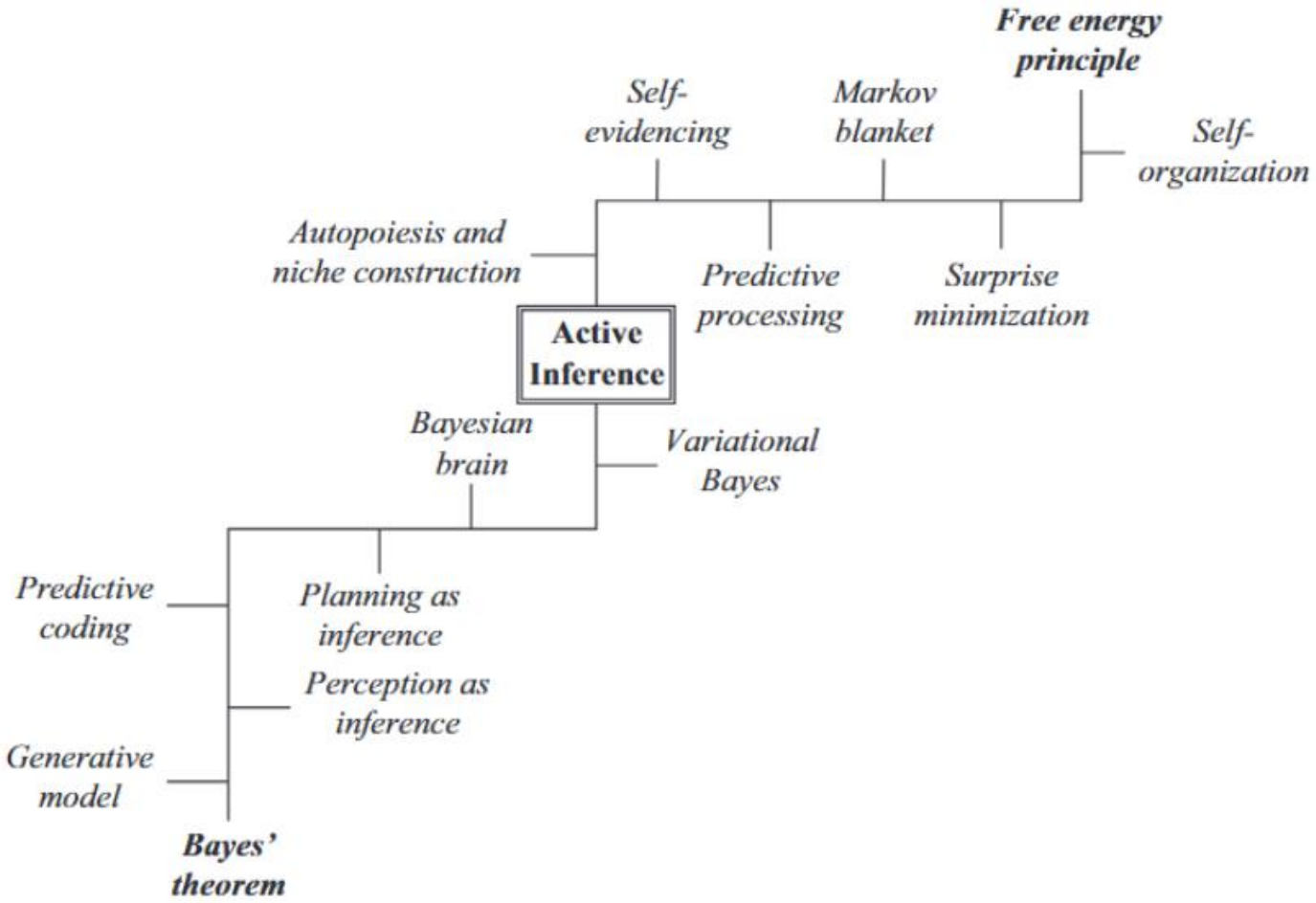


Figure 1.2
Two roads to Active Inference: the high road (starting from top-right) and the low road (starting from bottom-left).

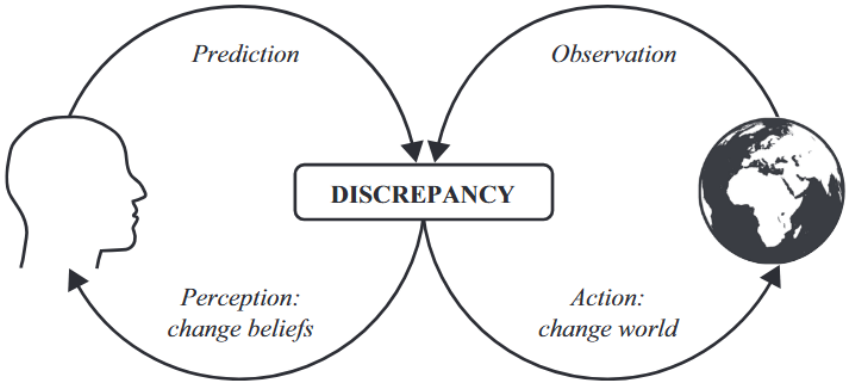


Figure 2.3
Both perception and action minimize discrepancy between model and world.

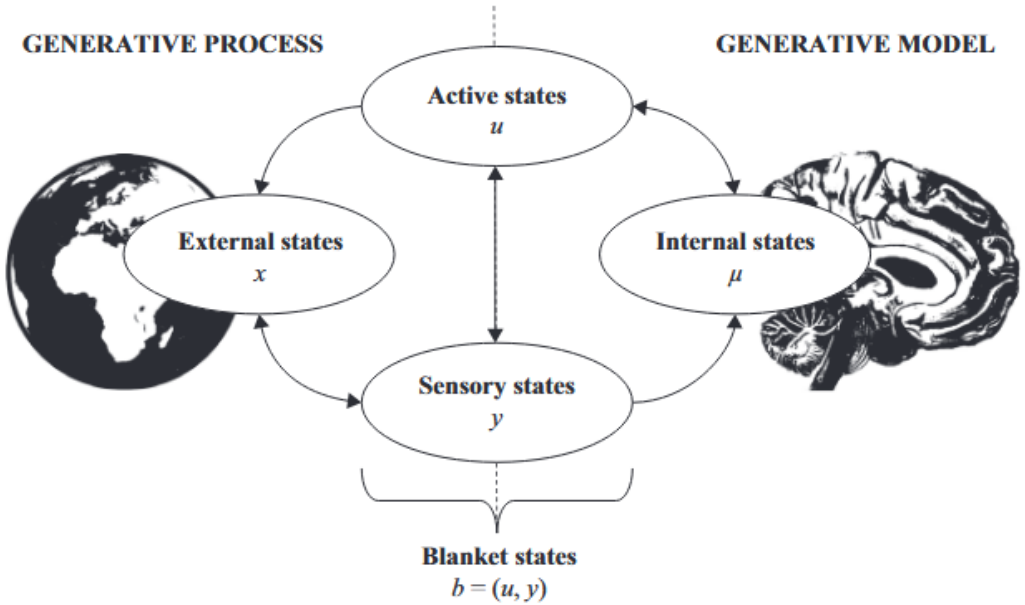


Figure 6.1

Active Inference

Bayes' theorem

$$P(A \mid B) = \frac{P(B \mid A) \cdot P(A)}{P(B)}$$

A, B	= events
$P(A\|B)$	= probability of A given B is true
$P(B\|A)$	= probability of B given A is true
$P(A), P(B)$	= the independent probabilities of A and B

Markov blanket:

- a formalization of the statistical separation between the organism's internal states and the world's external states…
- ..Crucially, internal and external states can only influence each other vicariously via intermediate (active
- and sensory) variables, called blanket states…
- This statistical separation— mediated by the Markov blanket—is crucial to endowing an organism with some degree of autonomy from the external world.

References

- https://en.wikipedia.org/wiki/Von_Neumann_architecture
- https://en.wikipedia.org/wiki/Reservoir_computing
- 2024, An introduction to reservoir computing https://arxiv.org/html/2412.13212v1
- 2018, Reservoir Computing Universality With Stochastic Inputs, https://arxiv.org/pdf/1807.02621
- 2021, Next generation reservoir computing https://www.nature.com/articles/s41467-021-25801-2
- 2024, Backpropagation Algorithms and Reservoir Computing in Recurrent Neural Networks for the Forecasting of Complex Spatiotemporal Dynamics https://arxiv.org/pdf/1910.05266
- https://en.wikipedia.org/wiki/Spiking_neural_network
- https://en.wikipedia.org/wiki/Quantum_neural_network
- Technology Brief, Intel Labs' Loihi 2 Neuromorphic Research Chip, ~2021 https://www.intel.com/content/www/us/en/research/neuromorphic-community.html
- 2024, World Economic Forum, Economy Blueprint Insight Report
- https://www.qureca.com/overview-of-quantum-initiatives-worldwide-2023/
- Natural Language, AI, and Quantum Computing in 2024 Research Ingredients and Directions in QNLP, https://arxiv.org/abs/2403.19758
- Quantum Self-Attention Neural Networks for Text Classification, https://arxiv.org/pdf/2205.05625
- https://en.wikipedia.org/wiki/Unconventional_computing
- 2022, Active Inference: The Free Energy Principle in Mind, Brain, and Behavior, https://direct.mit.edu/books/oa-monograph/5299/Active-InferenceThe-Free-Energy-Principle-in-Mind
- https://en.wikipedia.org/wiki/Action_(physics)
- Kullback–Leibler divergence