Quantum, Cognition and Computer Systems

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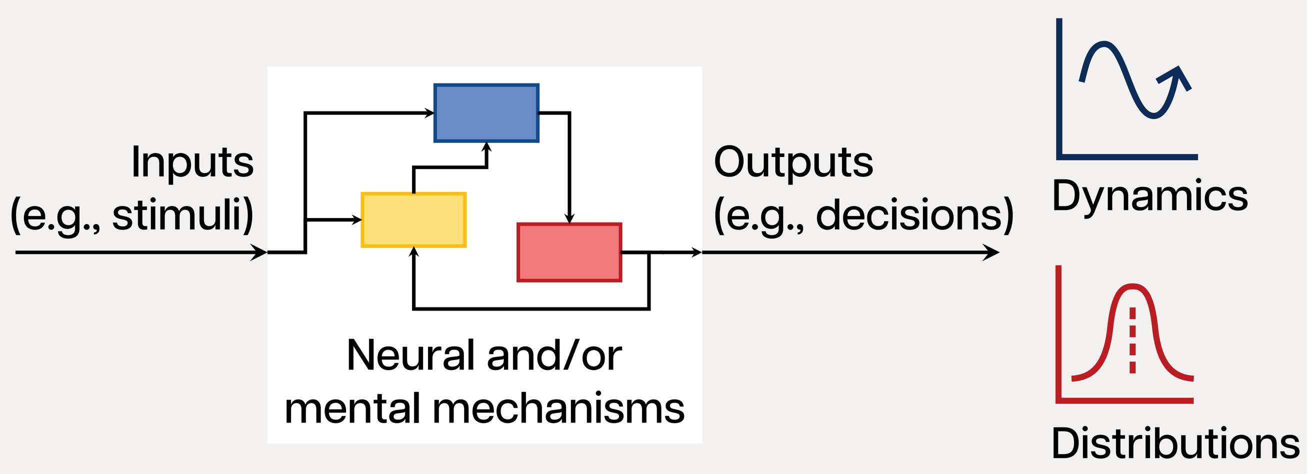
Cognitive Models



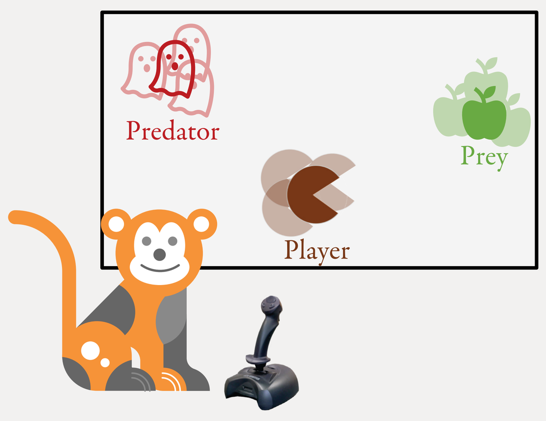
Key role in brain and behavioral sciences

Great influence on Artificial Intelligence

Computational Challenges

Modeling human-level cognition is complex

E.g., Predator-Prey task model (attention allocation)



Need to scale this to N entities and k attention levels

The emerging field of quantum cognition

- Use quantum probability (not physics) for modeling
- E.g., quantum walks to model decision-making
- New perspective:
  - intrinsic vs external uncertainty
  - response-affected decisions vs response read-out
- Coherent principles with better experimental coverage

Exploring frontiers of cognitive modeling requires computational acceleration, now more than ever

Idea: Use Quantum Systems

Can speedup certain tasks, in principle

Search, optimization, non-linear dynamics

Natural fit for quantum cognitive models

Goals

Demonstrate mapping of representative cognitive models to quantum computers

Study the impact of various design decisions on accuracy, performance and resource use

Investigate opportunities for hardware, application and algorithm improvements in the existing quantum stack

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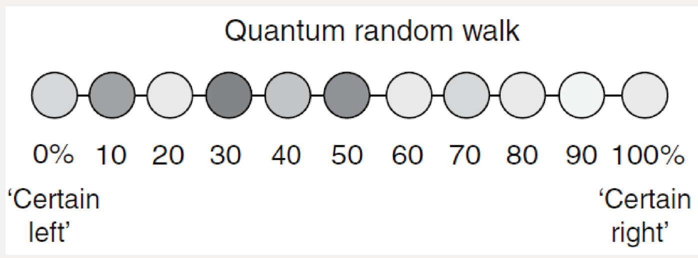
Cognitive Models and our Mapping to Quantum Systems

Two-alternative decision-making (quantum walks)



Hamiltonian, H

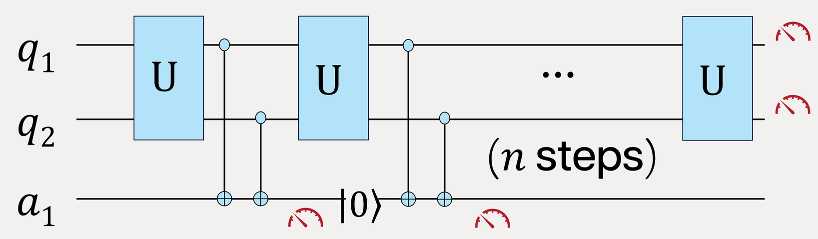
$$\begin{bmatrix} \mu_0 & \sigma & 0 & 0 & 0 \\ \sigma & \mu_{10} & \sigma & 0 & 0 \\ 0 & \sigma & \ddots & \sigma & 0 \\ 0 & 0 & \sigma & \mu_{90} & \sigma \\ 0 & 0 & 0 & \sigma & \mu_{100} \end{bmatrix}$$

$U = e^{-iH}$, P_d and P_{nd} are the projectors onto the decision and non-decision states

Reflecting: $P_d U^n \psi_0$

Absorbing: $P_d (P_{nd} U)^{n-1} \psi_0$

Absorbing boundaries walk

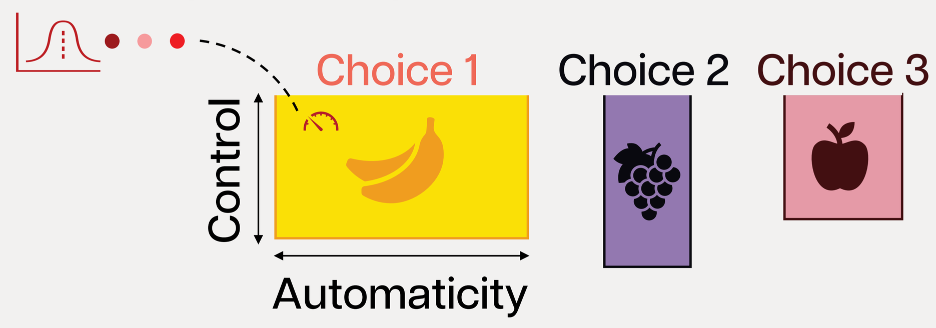


Tradeoff
width vs depth

Reflecting boundaries don't need ancilla qubits and intermediate measurements

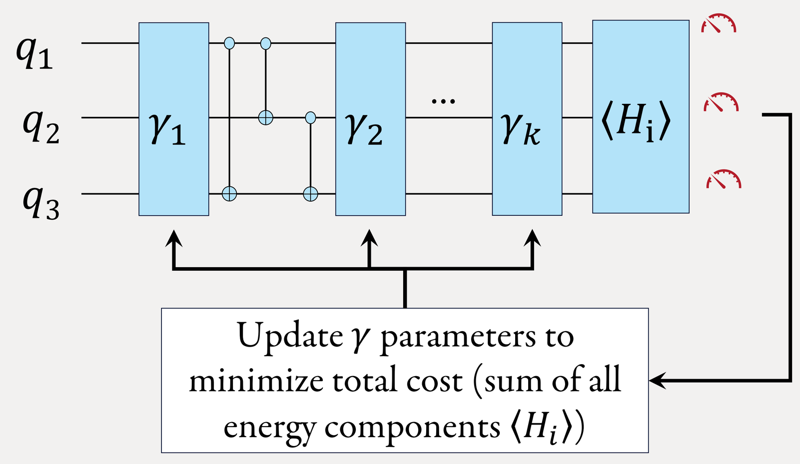
Multi-alternative decision making (potential wells)

Particles (excitation)



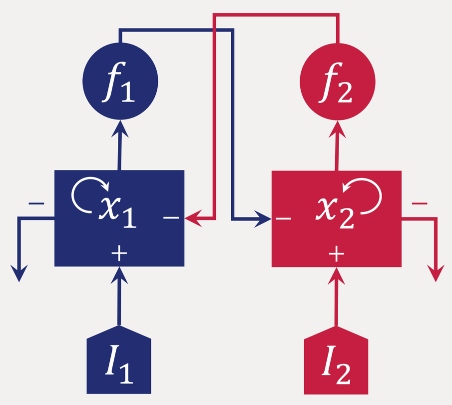
Eigenstates determine evidence accumulation

Variational quantum eigensolver (VQE)



Tradeoffs
Pauli decomposition vs momentum to calculate energy
Deflation vs subspace methods for excited states

Leaky competing accumulator for control/decision-making (nonlinear dynamics)



$$x_1(t) = x_1(t-1) + \big(I_1 - \lambda x_1(t-1) - \beta f_2(t-1)\big)\Delta t$$

$$f_1(t) = \frac{1}{1 + e^{-g x_1(t)}}$$

Quantum simulation with entanglement

Quantum annealing

Tradeoffs
f linearization, time expansion, Feynman's clock

Predator-Prey task model on cognitive control (optimization)

Quantum annealing (Boltzmann machine)

QAOA (Quantum approximate optimization algorithm)

Two-alternative decision-making variant (open system walk)

Preliminary Results

Quantum and classical implementations have the same result for some models (quantum walks, eigenstates) and are close for the rest

Execution times vary with algorithm and implementation choices, which is of practical and theoretical interest to cognitive modelers and quantum architects

E.g., Quantum Boltzmann machine is an order of magnitude faster than the classical

Our implementations reveal many limitations of the quantum systems stack

Limitations in hardware (projections), circuit choices (VQE), little support for parameter selection (circuits for walks, annealing properties), low programmability and high entry barrier

Significance of This Work

For cognitive scientists	**First demonstration of mapping cognitive models to quantum computers – enables new research and complex models**
For quantum architects and theorists	**A new benchmark suite to guide quantum hardware, architecture and software, and stimulate new algorithms, complementing existing ones** Existing quantum stack is heavily guided by only a few applications (e.g., physics, chemistry, machine learning)