CIFellows 2020-2021

Computing Innovation Fellows

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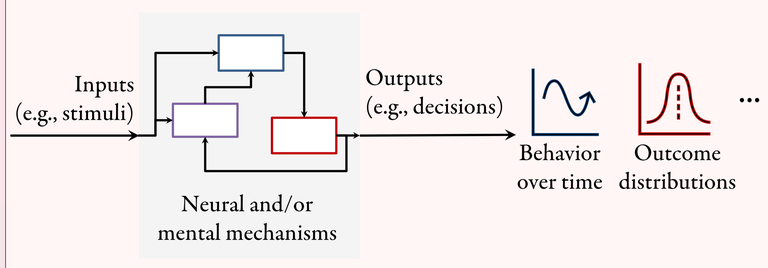
Connecting Cognitive Modeling with Quantum Systems

1 Cognitive Models

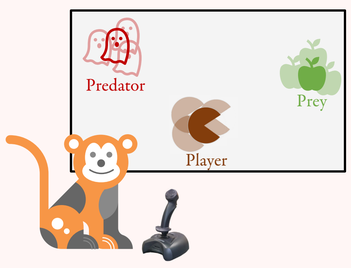


Cognitive modeling has been key in advancing not only the brain and behavioral sciences but also Machine Learning and Artificial Intelligence

2 Models are Computationally Intensive

Realistic models are computationally challenging

Example: Predator-Prey task model (attention allocation)



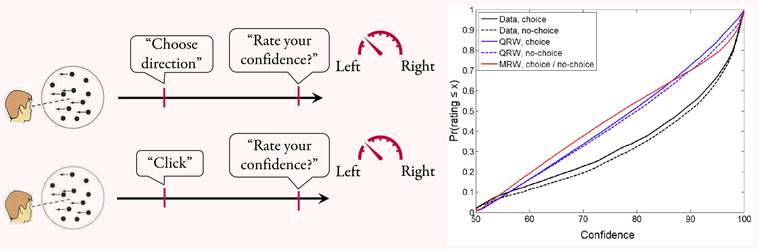
For N entities and k attention levels, N^k possible allocations to choose the best one!

Quantum cognition

- Quantum probability (not physics) to model cognition
- Ease of modeling and better coverage of experimental data

Example: Interference effect of choice on confidence

Kvam et al., "Interference effects of choice on confidence: Quantum characteristics of evidence accumulation" PNAS 2015



A Markov Random Walk (MRW) model produces identical responses in both scenarios while a Quantum Random Walk (QRW) model clearly shows the interference effect

Modeling human cognition can get even more complex

Need new infrastructure to advance the frontiers of cognitive modeling!

3 Proposal: Use Quantum Computing to Accelerate Cognitive Models

- Quantum systems can speedup certain computations, and are a natural fit to run quantum cognitive models

Challenges

- No known quantum implementations of cognitive models
- Not known if existing quantum computers can efficiently run cognitive models, when ported

4 Quantum Computing to Accelerate Cognitive Models

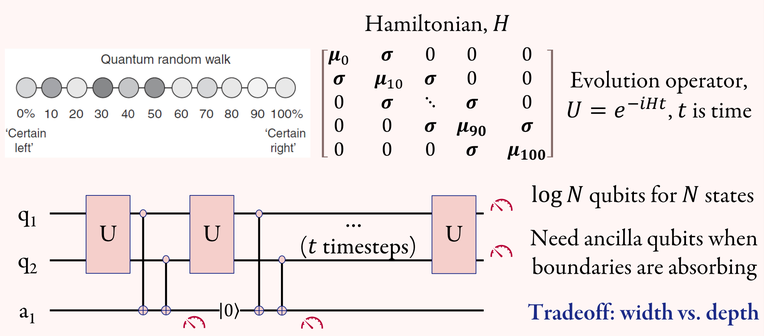
Proposed goals and contributions

- Develop quantum implementations of a suite of cognitive models
  - First demonstration of porting cognitive models to quantum computers
  - First quantum benchmark suite from the cognitive sciences
- Analysis of limitations in the quantum computing stack encountered when developing and running these models

Simultaneously advance cognitive modeling efforts and quantum systems engineering!

5a Cognitive Models and Quantum Mappings

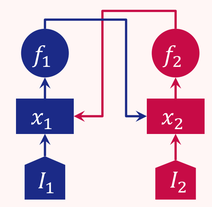
Quantum walks (Two alternative decision-making)



Open quantum walk (Two alternative decision-making)

- Evolution under quantum and Markov effects
- Use a quantum annealer to simulate noise and run the walk

Leaky Competing Accumulator (Cognitive control)



$$x_1(t) = \big(I_1 + (1-\lambda)x_1(t-1) - \beta f_1(t-1)\big)\Delta t$$

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

Linearize f_1, f_2, and expand the time dependency of x_1, x_2

Hamiltonian, $H_{prob} = \sum_i h_i \sigma_z^i + \sum_{i>j} h_{ij}\sigma_z^i\sigma_z^j$

Use quantum annealing (QA) with, $H_{anneal} = \alpha H_{initial} + \beta H_{prob}$

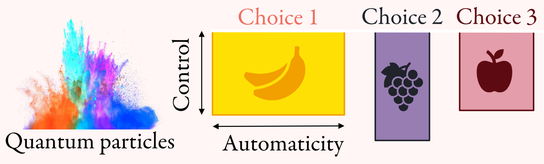
- Alternative algorithms can use entanglement to simulate interaction

Predator-Prey Task (Optimization and Control)

- Solve optimization through two methods: QA and Quantum approximate optimization algorithm (QAOA)
- Quantum annealing: formulate attention allocation and movement generation as a Boltzmann machine
- In QAOA, the system alternatively evolves under $H_{initial}$ and H_{prob}, and the optimal durations for each evolution are obtained classically similar to variational algorithms

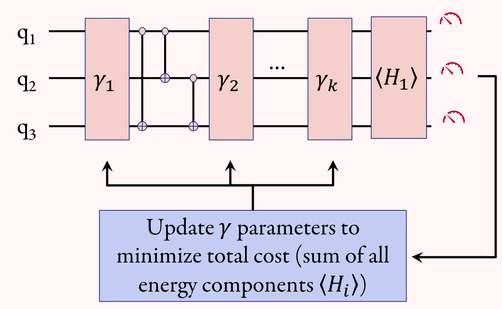
5b Cognitive Models and Quantum Mappings

Potential wells (Multi-alternative decision-making)



The probability of finding a particle in a well depends on the landscape's eigenvalues

- Variational Quantum Eigensolvers (VQE)



An alternative ansatz
Use qubits to represent the discretized position, and use a Quantum Fourier Transform block to find momentum and energy directly, without the separate components

6 Status and Preliminary Findings

- Developed prototype implementations of all the models, and performed (a limited) design space exploration with alternative mappings and algorithms
- ***Key finding 1:*** Existing quantum stack requires changes to fully accelerate cognitive models: special circuit designs (e.g., ansatz for VQE), algorithms (e.g., for LCA), and software support (e.g., for annealing, and easier programmability)
- ***Key finding 2:*** There are significant practical benefits to understanding and documenting the tradeoffs between equivalent alternative mappings and algorithms
- ***Key finding 3:*** The suite of cognitive models can be a complementary benchmark set in designing the quantum computing stack

7 Summary

This work ***(i) advances cognitive science*** by demonstrating the mapping of cognitive models to quantum computers, ***(ii) advances quantum systems*** by creating a new benchmark suite and identifying limitations in the existing quantum stack, and ***(iii) uncovers new opportunities to explore fundamental research questions:*** e.g., can quantum systems simulate classical dynamics (LCA) faster than a classical system?

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Current and Past Students: Gunnar Epping, Connor Hann, Lena Rosendahl, Yasmina Abukhadra, Nathan Ahn, Yu Jun Shen, Alejandro Simon, Bernardo Trevisan, Michael Tu, Mudi Yang, Jean Wang

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