Quantum, Cognition and Computer Systems

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**Cognitive Models**

- **Inputs (e.g., stimuli)**
- **Outputs (e.g., decisions)**
- **Distributions**
- **Dynamics**
- **Neural and/or mental mechanisms**

**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)

**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

**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

**Cognitive Models and our Mapping to Quantum Systems**

**Two-alternative decision-making (quantum walks)**

- Hamiltonian, $H$
- $U = e^{-iHt}$, $P_{\text{choice}}$ and $P_{\text{reflect}}$ are the projectors onto the decision and non-decision states
- Reflecting: $P_{\text{reflect}}U^n\psi_0$
- Absorbing: $P_{\text{choice}}(U_{\text{final}})^n\psi_0$

**Multi-alternative decision making (potential wells)**

- Particles (excitation)
- Projectors onto the decision and non-decision states
- Eigenstates determine evidence accumulation

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

- Quantum simulation with entanglement
- Quantum annealing

**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

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