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Title: Quantum Resources for Information Processing

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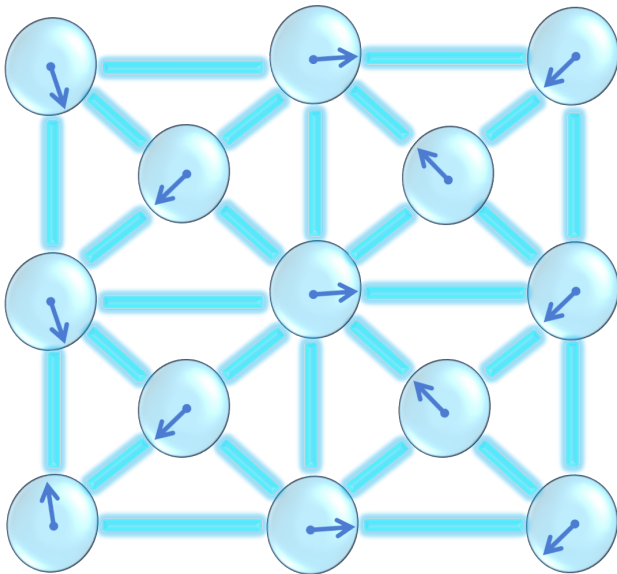
Quantum Resources for Information Processing

Davide Girolami

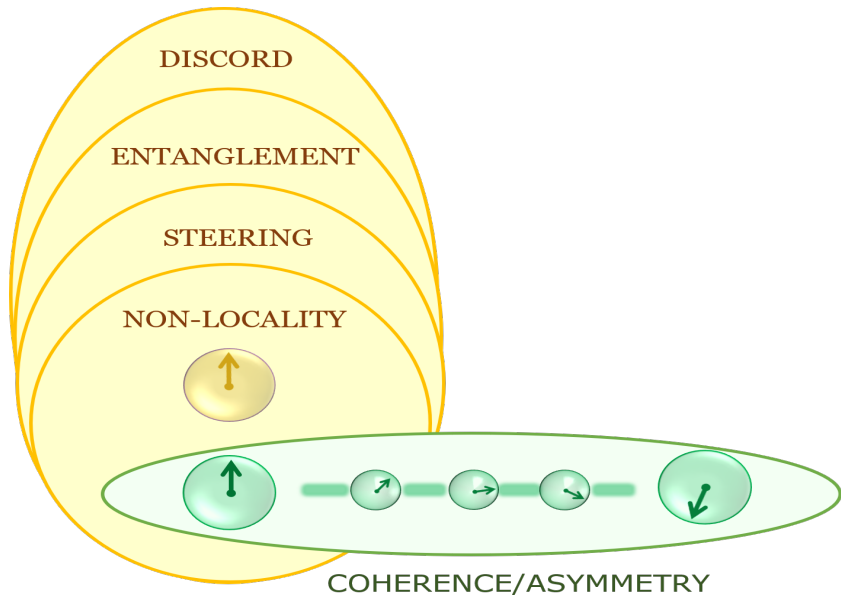
Mountain View, 9 January 2019



How quantum differs from classical?



Quantum Resources



Goal: Characterizing Quantum Resources

? Theoretical Quantification: $f_R(\rho)$ being monotone under free operations

? Demonstration of supraclassical performance: $f_R(\rho)$ is figure of merit in a task

? Experimental Detection:

$$f_R(\rho) = \langle O_{\text{exp}} \rangle, O_{\text{exp}} = O_{\text{exp}}^\dagger$$

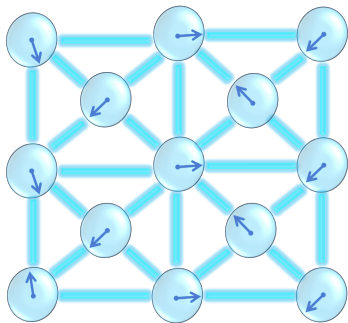
(Some) Technical Objectives

I Evaluating the power of quantum devices (Th)

II Evaluating the power of quantum devices (Exp)

III (Future) Quantum Resources for Artificial Intelligence

I Evaluating the power of quantum devices (Th)



- System $\mathcal{S}$, described by ρ_N
- How to quantify correlations of order $2 \leq k \leq N$ in an N particle system ?

Covariances? No thanks

$$\langle X_1 X_2 \dots X_N \rangle_{\rho_N} - \prod_i \langle X_i \rangle_{\rho_N}$$

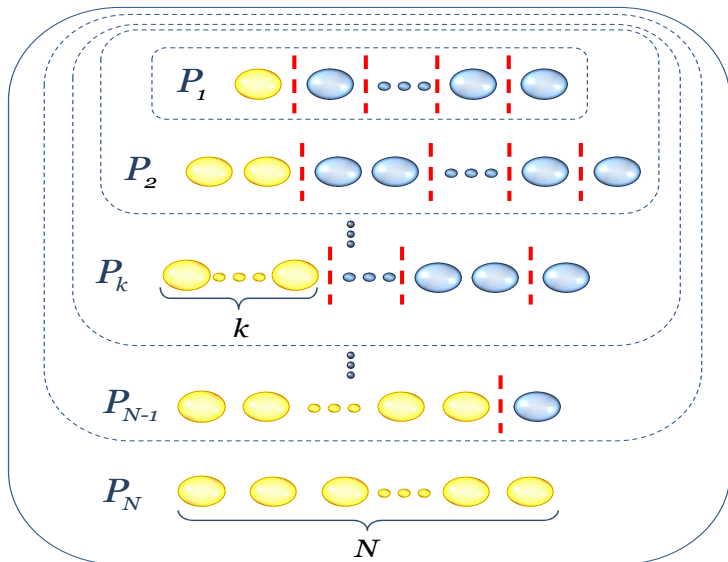
Don't detect **classical** correlations **X**

Can be created by local operations **X**

Can be created by fine graining **X**

D. Kaszlikowski, A. Sen, U. Sen, V. Vedral, and A. Winter, PRL 101, 070502 (2008); Z. Walczak, Comment; D. Kaszlikowski, *et al.*, Reply. Z. Walczak, PLA 374, 3999 (2010), C. H. Bennett, *et al.*, PRA 83, 012312 (2011)

Correlation hierarchy



Relative entropy of genuine multipartite correlations

- Correlations higher than k : distance to P_k

$$S^{k \rightarrow N}(\rho_N) := \min_{\sigma \in P_k} S(\rho_N || \sigma)$$

- Genuine k -partite correlations:

$$S^k(\rho_N) := S^{k-1 \rightarrow N}(\rho_N) - S^{k \rightarrow N}(\rho_N)$$

A Complexity measure

- ! Equally correlated states can have very different structure
- ? Single index classifying multipartite classical and quantum states

Weaving := weighted sum of genuine multipartite correlations

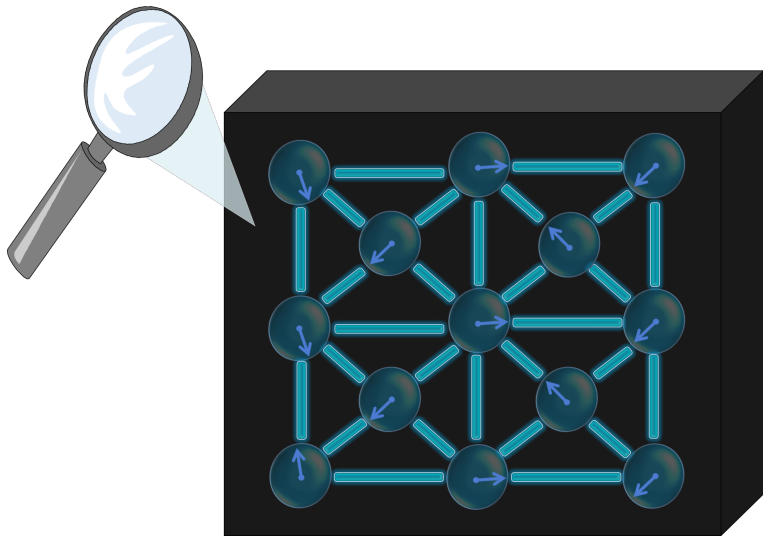
$$W_S(\rho_N) = \sum_{k=2}^N \omega_k S^k(\rho_N)$$

D. Girolami, T. Tufarelli, and C. Susa, Phys. Rev. Lett. 119, 140505 (2017)

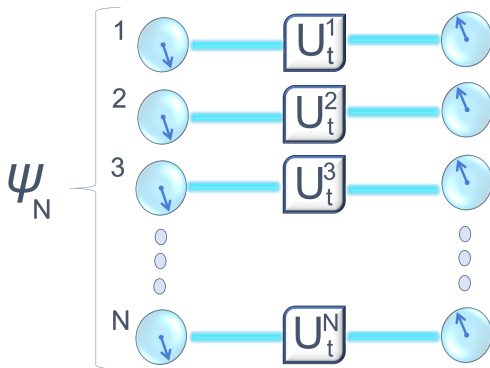
Test, $\omega_k = k - 1$

State	$\mathbf{W}_S$
$[(00\rangle\langle 00 + 11\rangle\langle 11)/2]^{\otimes N/2}$	$N/2$
$[\frac{(00\rangle+ 11\rangle)}{\sqrt{2}}]^{\otimes N/2}$	N
$(\sum_{i=1}^d ii\rangle / \sqrt{d})^{\otimes N/2}$	$N \log d$
$(0\rangle^{\otimes N} + 1\rangle^{\otimes N})/\sqrt{2}$	$\sim N \log N$
$\sum_i \mathcal{P}_i(0\rangle^{\otimes N/2} \otimes 1\rangle^{\otimes N/2})/\sqrt{\binom{N}{N/2}}$	$\sim N^2$

II Evaluating the power of quantum devices (Exp)

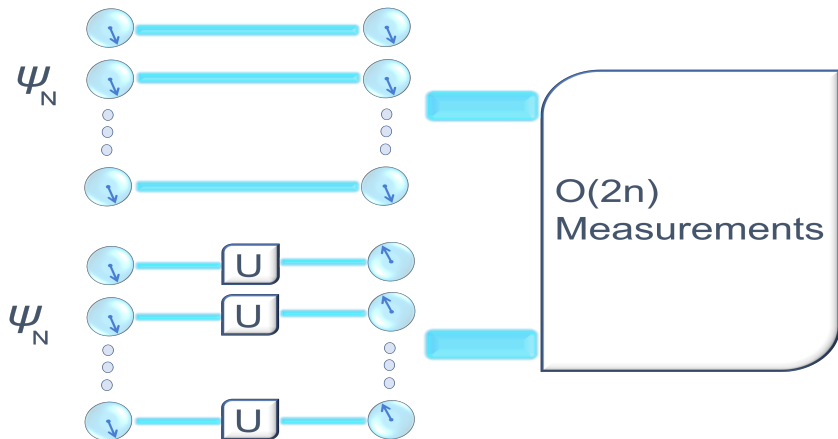


Usefulness = Superlinear Speed



- ★ $\text{Speed}(\Pi_i U_t^i \psi_N U_t^{i\dagger}) \geq f_{\text{linear}}(N) \Rightarrow \psi_N$ is entangled
- ★ $O(4^N)$ measurements required to reconstruct system state

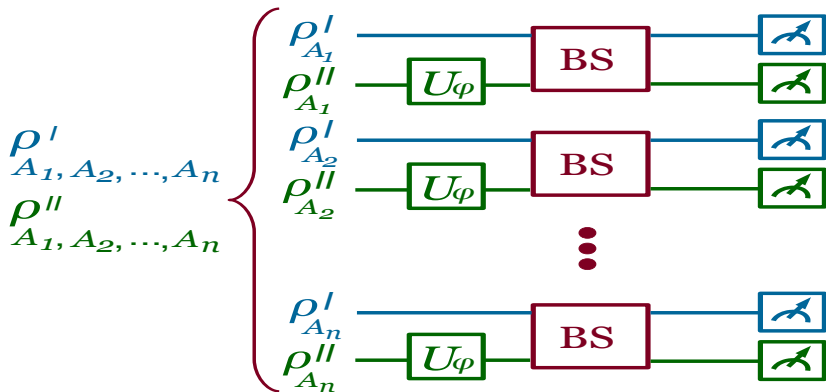
Evaluating Speed with limited resources



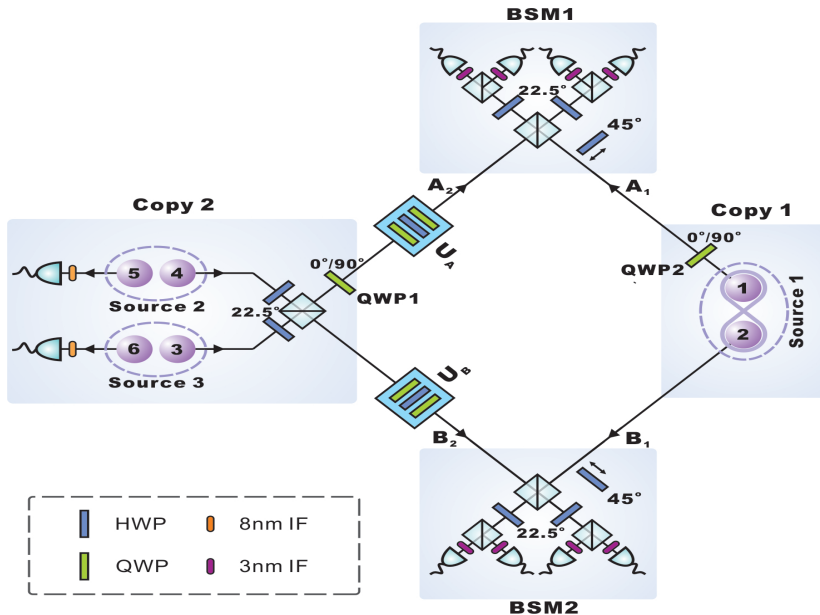
- ★ Two system copies and $O(3^n)$ measurements are sufficient to evaluate the speed function, even if system state and dynamics are unknown

EXP scheme for n-qubit systems

$$V_{1,2,\dots,n} = \bigotimes_i V_i, \quad V_i = I_2 - 2 |\phi_-^i\rangle \langle \phi_-^i|$$



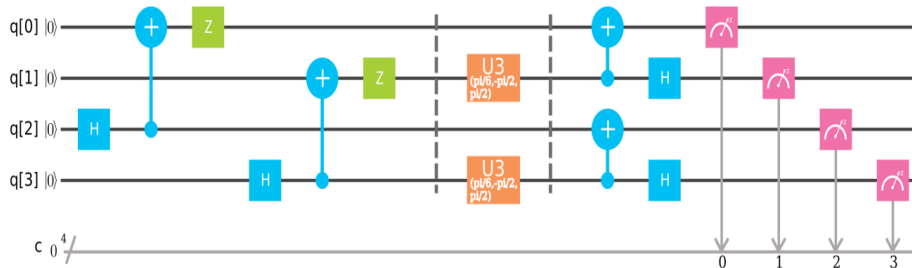
C. M. Alves and D. Jaksch, PRL 93, 110501 (2004), H. Jeong *et al.*, J. Opt. Soc. Am. B 31, 3057 (2014)



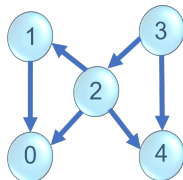
Devices: IBM Q

- <https://www.research.ibm.com/ibm-q/>
- 5-qubit, 16-qubit machines
- Superconducting qubits initialized in ground state at 15ml K, gate error= 10^{-3}
- remote access via Composer and Qiskit

Entanglement detection in ibmqx4

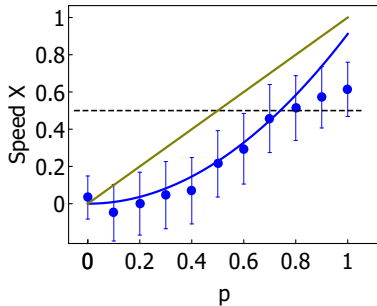
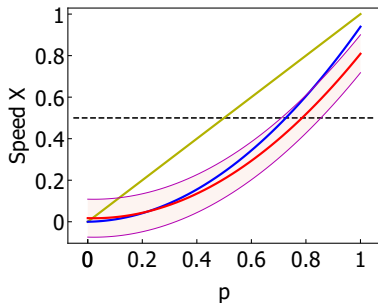


BUT constraints... split into two experiments



A comparison

$$\star \rho = p |\phi^+\rangle \langle \phi^+| + (1-p) |\phi^-\rangle \langle \phi^-|, p \in [0, 1], U_t = e^{-i\sigma_x t}, t = \pi/6$$



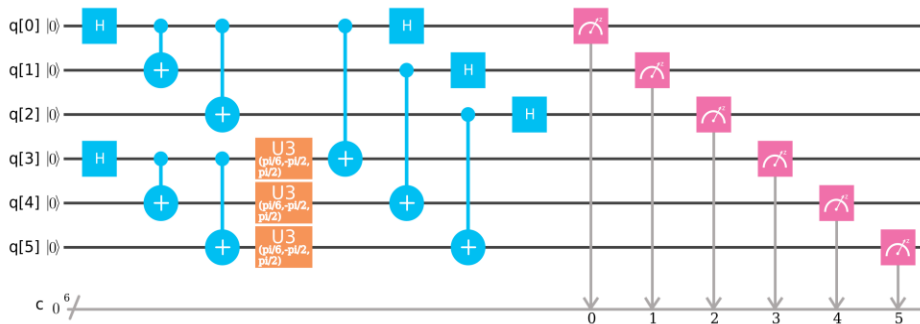
Left: ibmqx4; Right: optical setup, C. Zhang et al. PRA 96, 042327 (2017)

Original Scheme: D. Girolami, PRL 113, 170401 (2014)

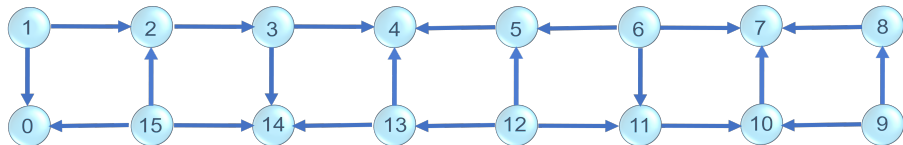
Multipartite Entanglement detection

- ★ A state ψ_N is k -partite entangled iff it is not a tensor product of states describing $\leq k$ -subsystems
- ★ E.g. $\psi_3 \neq \psi_2 \otimes \psi_1 \Rightarrow \psi_3$ displays 3-partite entanglement
- ★ $\text{Speed}(\sum_i U_t^i \psi_N U_t^{i\dagger}) \geq ([N/k]k + (N - [N/k]k)^2)/4$,
 $k \geq 2 \Rightarrow \psi_N$ is at least k -partite entangled

Multipartite Entanglement detection



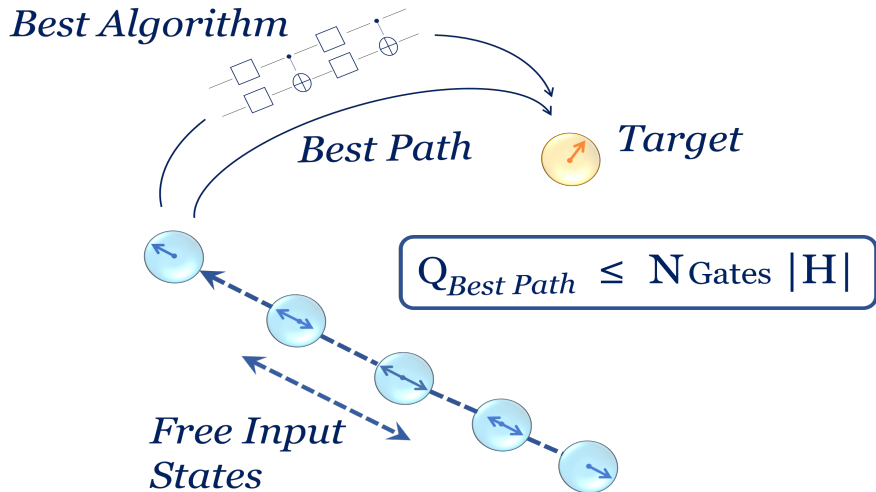
BUT constraints... split into three experiments



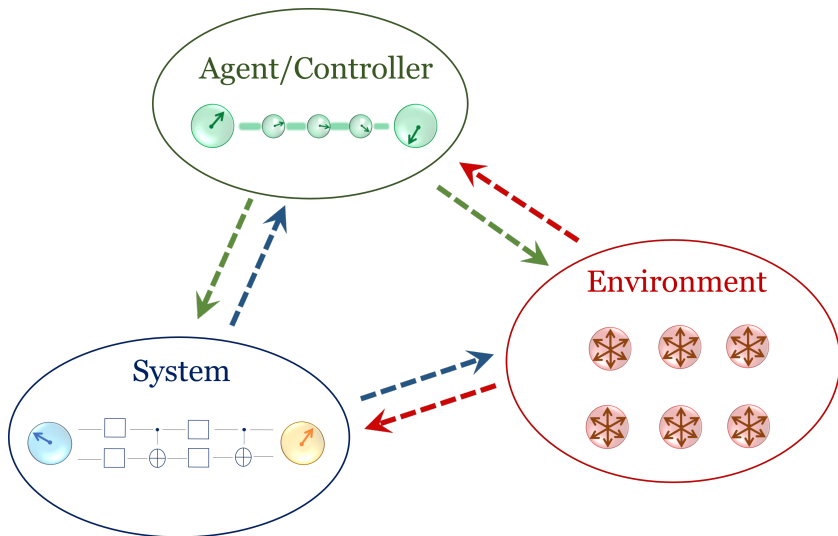
Detection of speed-up due to tripartite and bipartite Entanglement

- ★ $|GHZ\rangle = 1/\sqrt{2}(|000\rangle + |111\rangle)$, $U_t = e^{-i\sigma_x t}, e^{-i\sigma_z t}$, $t = \pi/6$
- ★ $\text{Speed}() \geq .75$ certifies bipartite entanglement, $\text{Speed}() \geq 1.25$ certifies tripartite entanglement
- ★ $\text{SpeedX}(\Pi_i U_t^i |GHZ\rangle) = 0.61 \pm 0.16$ **X**
- ★ $\text{SpeedZ}(\Pi_i U_t^i |GHZ\rangle) = 1.89 \pm 0.20$. **V**

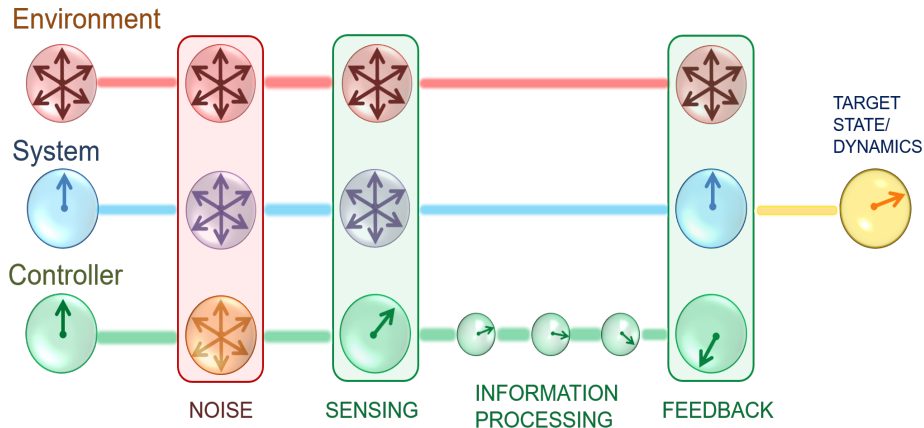
Bonus: Bound to state engineering



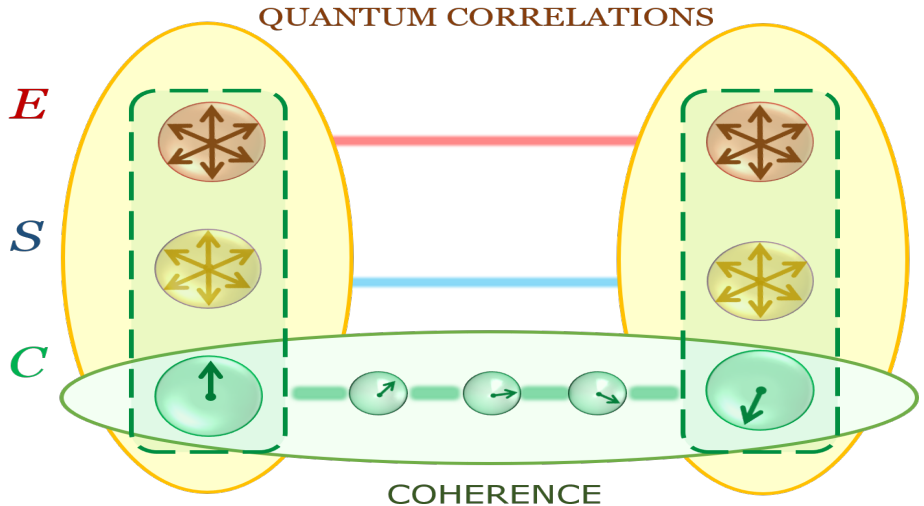
III Quantum Resources for AI



How quantum systems think?



How quantum systems think?



Quantum Decision Making

- Quantize classical strategies (Markov decision processes, dynamic programming)
- Attack by quantizing the Bellman equation(s) and performance comparing
- Deliberation as a quantum walk, faster decision (smarter?)
- Testable in today quantum machines, e.g. IBM chips (D-Wave?)

Summary

- Quantum Information Processing as clever use of quantum resources
- Foundational and practical value
- A great record of successes, but also future applications

The End

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