LA-UR-19-20054
Approved for public release; distribution is unlimited.

Title: Quantum Resources for Information Processing

Author(s): Girolami, Davide

Intended for: Talk for research visit at Purdue Univ.

Issued: 2019-01-08

Quantum Resources for Information Processing

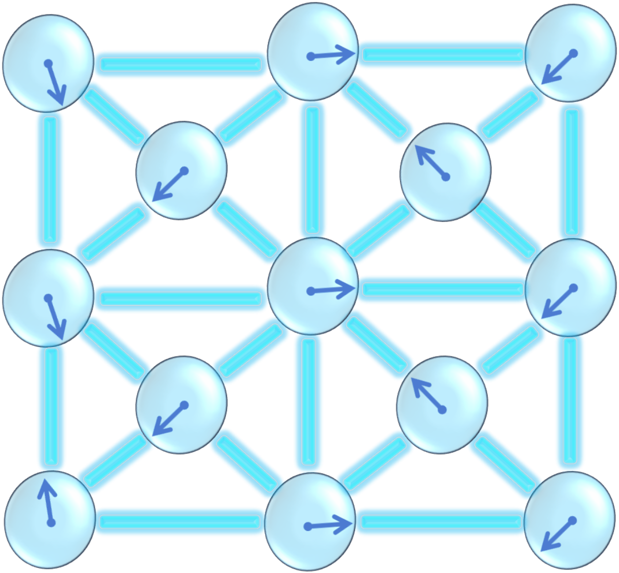
Davide Girolami

West Lafayette, 17 January 2019

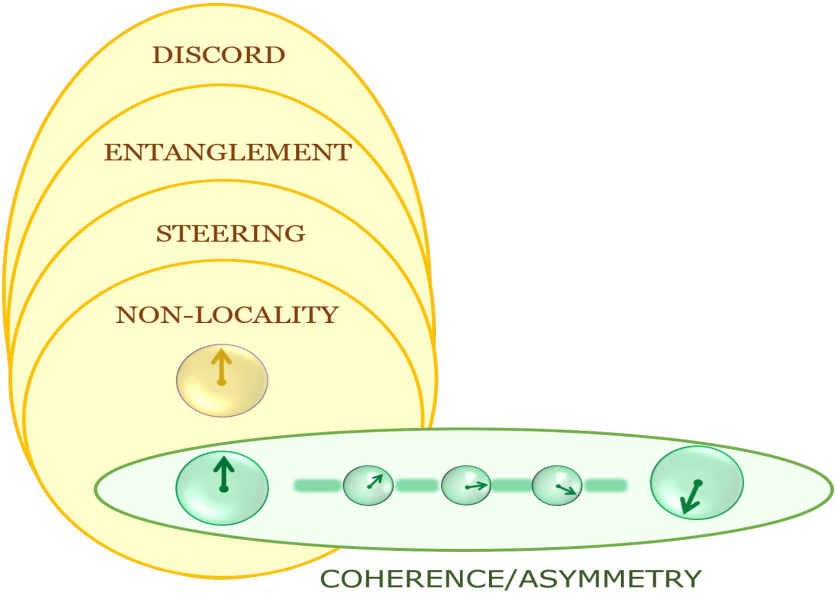
National Nuclear Security Administration

Los Alamos
NATIONAL LABORATORY
EST. 1943

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:

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

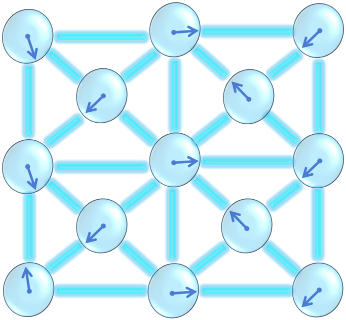
(Some) Technical Objectives

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

$$\langle X_1 X_2 \ldots X_N \rangle_{\rho_N} - \Pi_i \langle X_i \rangle_{\rho_N}$$

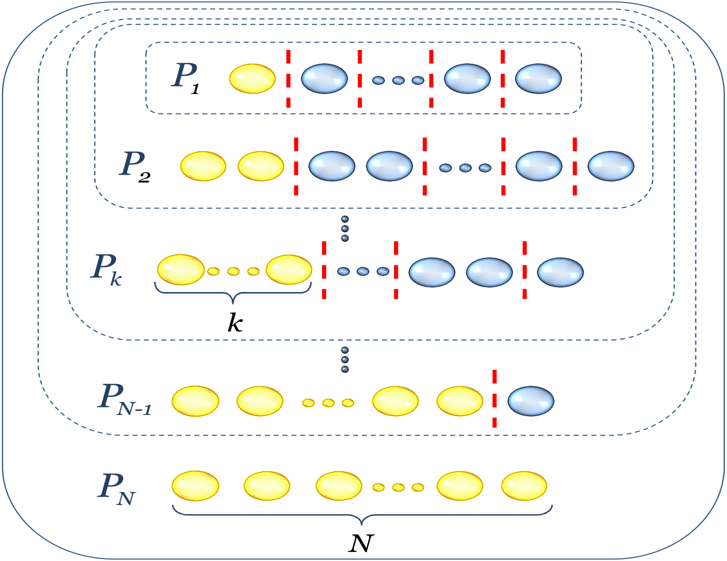
Don't detect **classical** correlations **X**

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

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

- Genuine k-partite correlations:

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

A Complexity measure

! Equally correlated states can have very different structure

? Single index classifying multiparti- te classical and quantum states

Weaving := weighted sum of genuine multipartite correlations

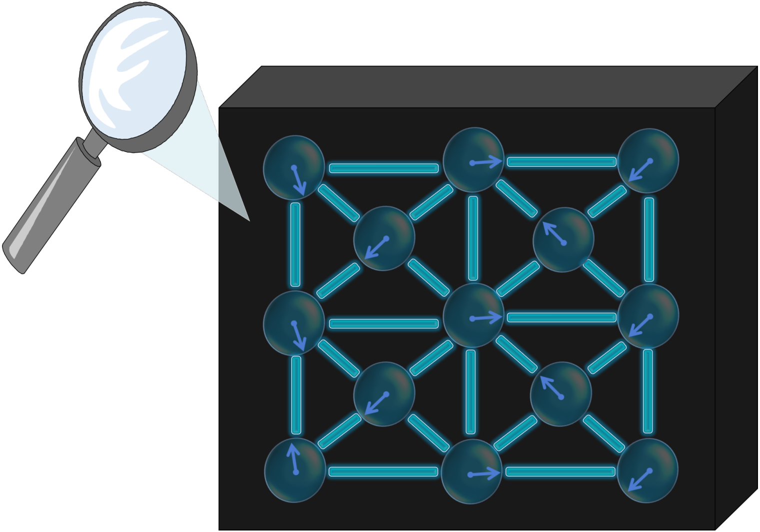
$$W_S(\rho_N) = \sum_{k=2}^{N} \omega_k S^k(\rho_N)$$

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

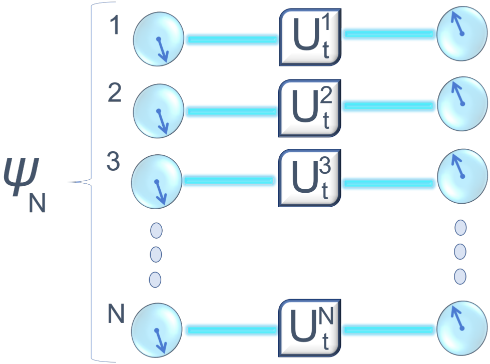
Test, $\omega_k = k - 1$

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

II Evaluating the power of quantum devices (Exp)

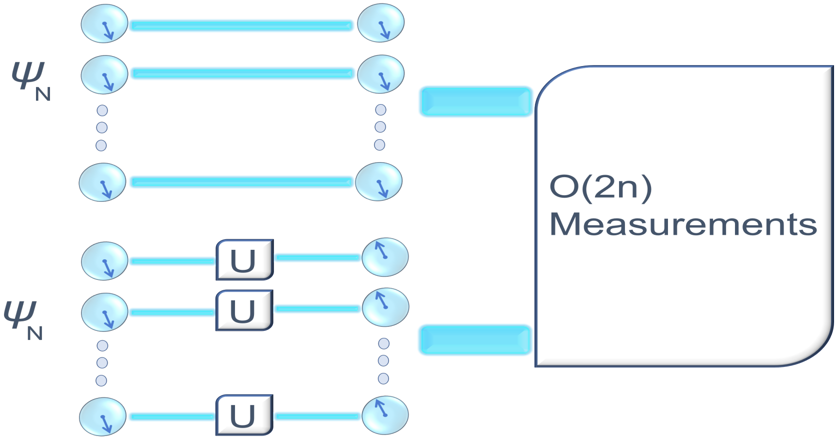


Usefulness = Superlinear Speed



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

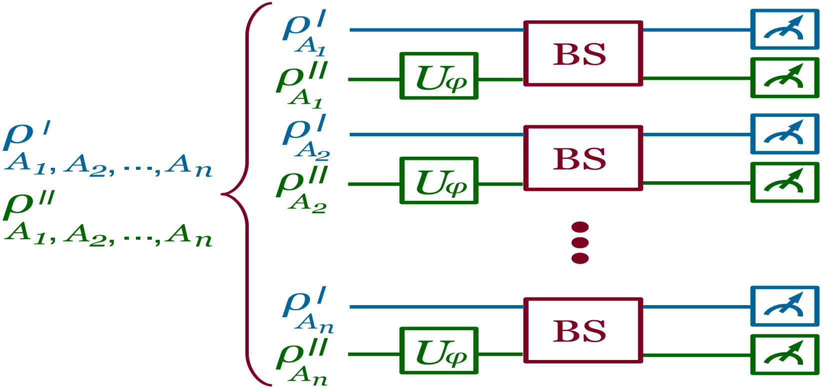
Evaluating Speed with limited resources



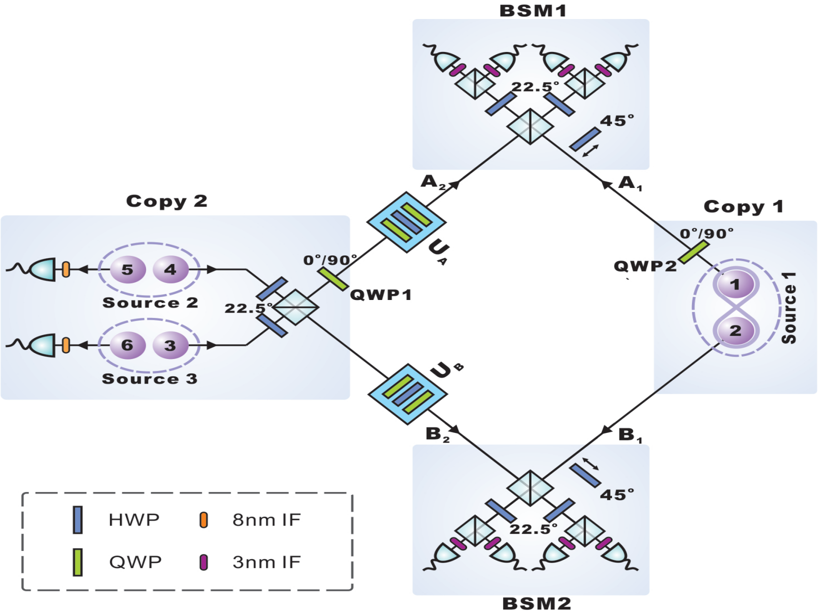
⋆ Two system copies and $O(3^n)$ measurements are sufficient to evaluate the speed function, even if system state and dynamics are unknown

EXP scheme for n-qubit systems

$$V_{1,2,\ldots,n} = \otimes_i V_i, \quad V_i = I_2 - 2\left|\phi_-^i\right\rangle\left\langle\phi_-^i\right|$$



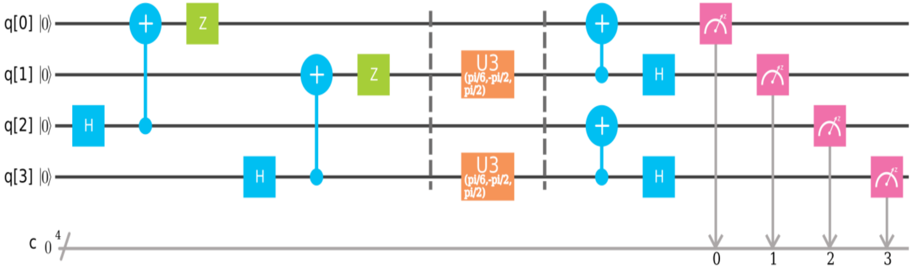
C. M. Alves and D. Jaksch, PRL 93, 110501 (2004), H. Jeong *et al.*, J. Opt. Soc. Am. B 31, 3057 (2014)


BSM1
22.5°
45°
A_2
A_1
Copy 2
Copy 1
0°/90°
U_A
QWP2
QWP1
5
4
1
Source 2
22.5°
Source 1
2
6
3
Source 3
U_B
B_2
B_1
45°
22.5°
HWP
8nm IF
QWP
3nm IF
BSM2

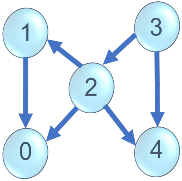
Devices: IBM Q

- `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

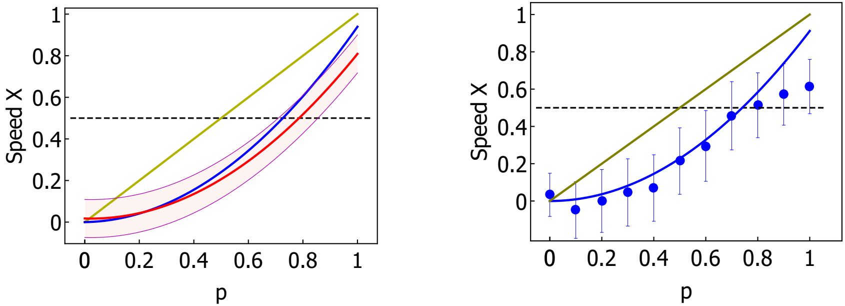


BUT constraints... split into two experiments



A comparison

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



Left: ibmqx4; Right: optical setup, C. Zhang et al. PRA 96, 042327 (2017)
Original Scheme: D. Girolami, PRL 113, 170401 (2014)

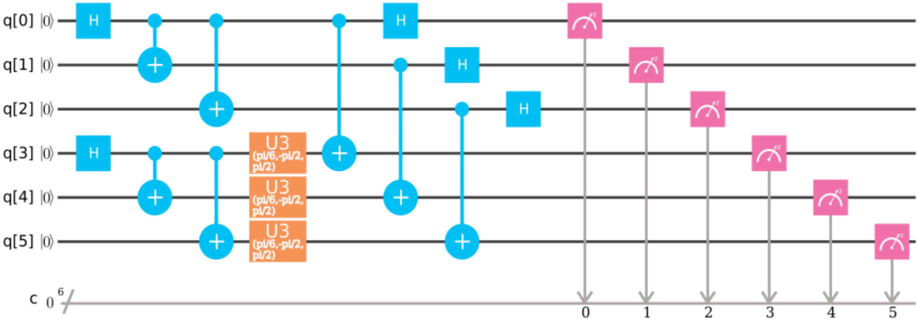
Multipartite Entanglement detection

- $\star$ A state Ψ_N is k-partite entangled iff it is not a tensor product of states describing $\leq k$-subsystems

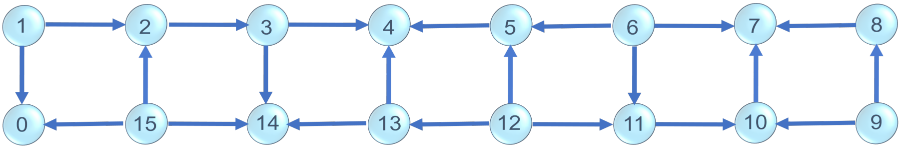
- $\star$ E.g. $\Psi_3 \neq \Psi_2 \otimes \Psi_1 \Rightarrow \Psi_3$ displays 3-partite entanglement

- $\star$ Speed$(\sum_i U_t^i \Psi_N U_t^{i\dagger}) \geq (\lfloor N/k \rfloor k + (N - \lfloor N/k \rfloor k)^2)/4$, $k \geq 2 \Rightarrow \Psi_N$ is at least k-partite entangled

Multipartite Entanglement detection



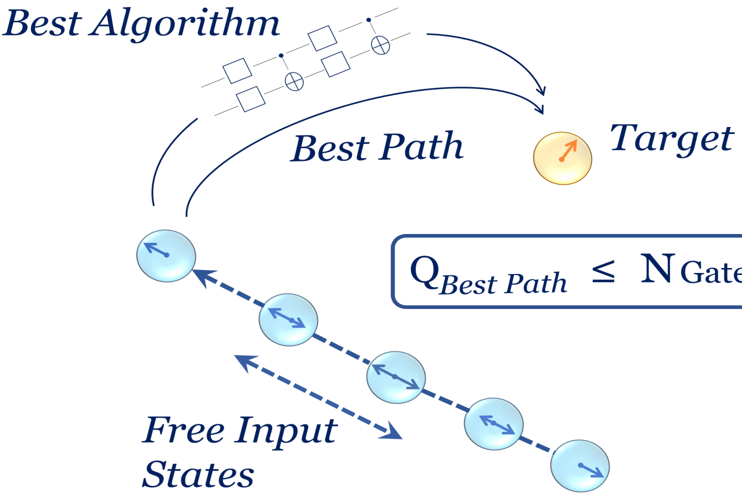
BUT constraints... split into three experiments



Detection of speed-up due to tripartite and bipartite Entanglement

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

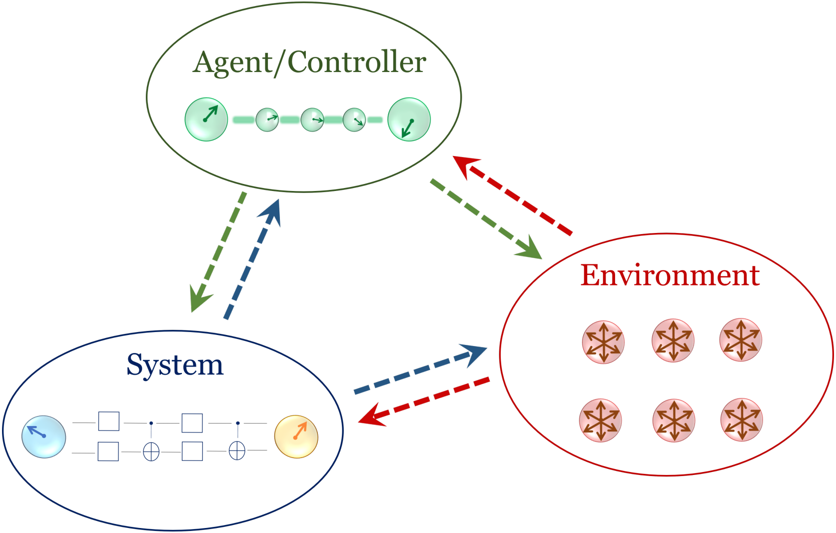
Bonus: Bound to state engineering



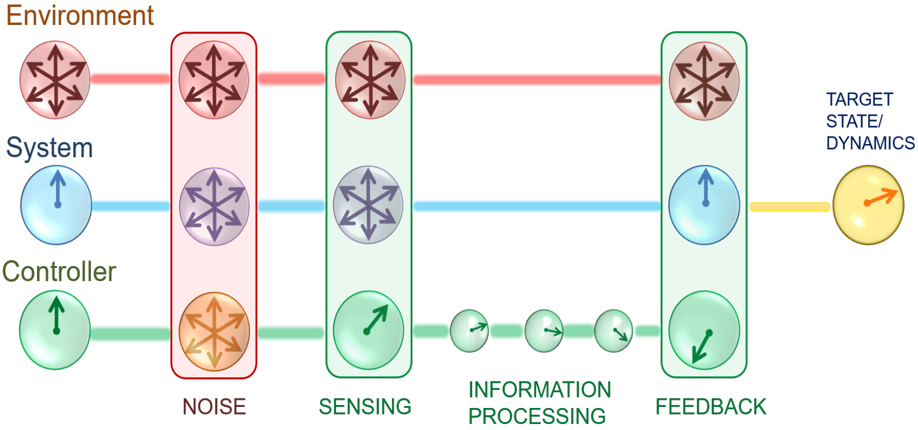
$$\boxed{Q_{\mathit{Best\ Path}} \leq N_{\mathrm{Gates}}\,|H|}$$

D. Girolami, Phys. Rev. Lett. (in press), arXiv:1808.01649

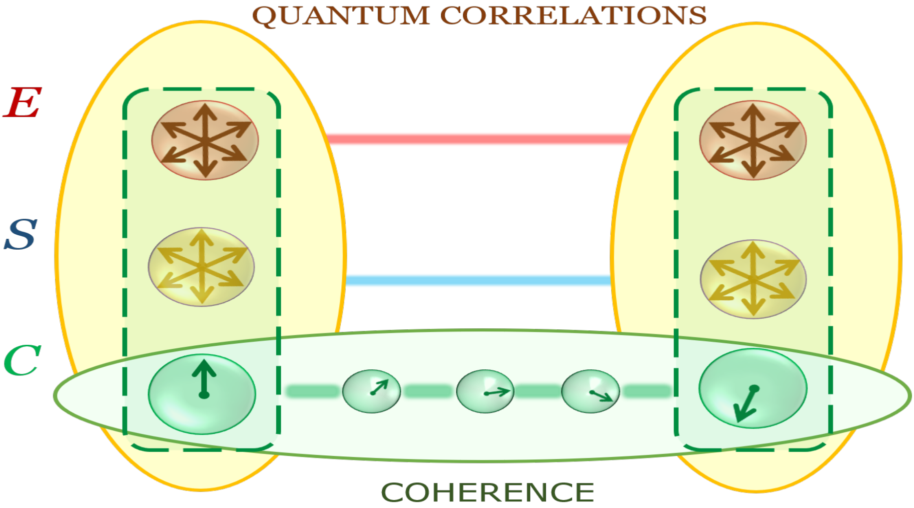
III Quantum Resources for AI



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

Email: davegirolami@gmail.com

Website: https://sites.google.com/site/davegirolami/