Entanglement catalysis for quantum states and noisy channels

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Republic of Poland
FNP Foundation for Polish Science
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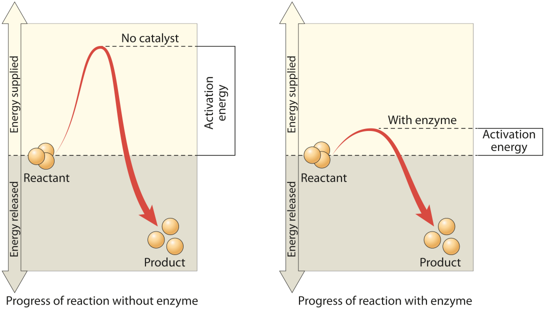
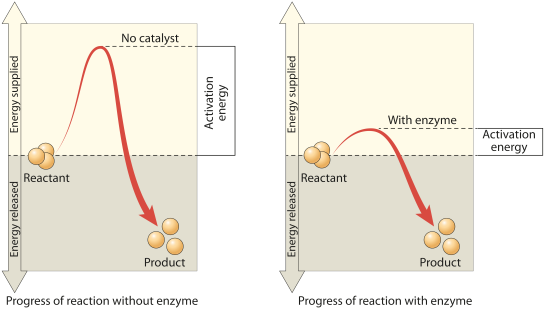
Entangled state conversion and catalysis[a]



- **Catalysis in chemistry:** process for increasing the rate of a chemical reaction

[a]Jonathan and Plenio, Phys. Rev. Lett. **83**, 3566 (1999)

Entangled state conversion and catalysis[a]



- **Catalysis in chemistry:** process for increasing the rate of a chemical reaction
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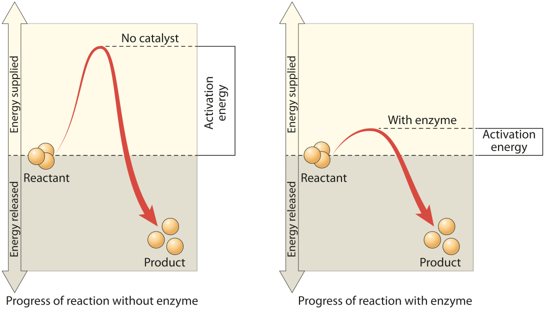

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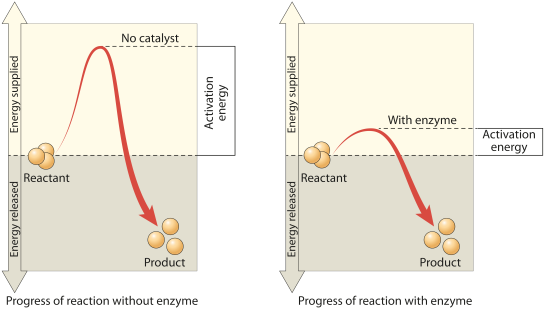

- **Entanglement catalysis:** process achieving entangled state transformations which are not possible without it
- **Quantum catalyst** remains unchanged in the procedure

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Outline

1. Exact entanglement catalysis
2. Approximate entanglement catalysis
3. Entanglement distribution with catalysis

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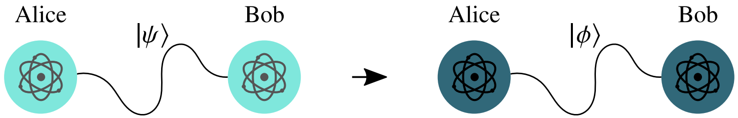
Entangled state conversion and catalysis



- Setup: Alice and Bob share an entangled state $|\psi\rangle$

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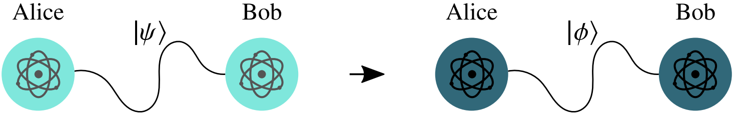

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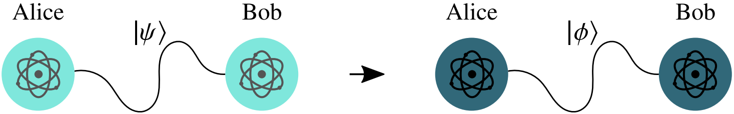

- **Question:** When is a conversion $|\psi\rangle \to |\phi\rangle$ possible?

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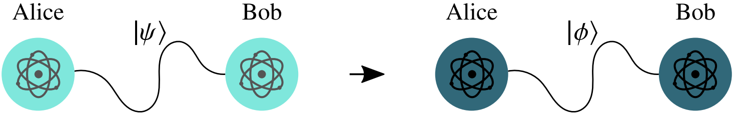

- **Question:** When is a conversion $|\psi\rangle \rightarrow |\phi\rangle$ possible?
- **Solution**[a]**:** Conversion possible if and only if

$$\sum_{i=1}^{k} \lambda_i \leq \sum_{i=1}^{k} \lambda_i' \tag{1}$$

for all $1 \leq k \leq d$

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Entangled state conversion and catalysis

- Transformation $|\psi\rangle \to |\phi\rangle$ not possible if $\sum_{i=1}^{k} \lambda_i > \sum_{i=1}^{k} \lambda'_i$

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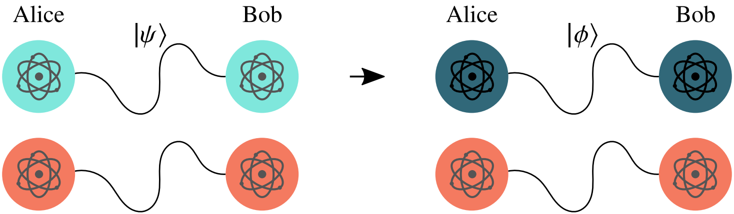

- Transformation $|\psi\rangle \to |\phi\rangle$ not possible if $\sum_{i=1}^{k} \lambda_i > \sum_{i=1}^{k} \lambda_i'$
- Catalytic transformation $|\psi\rangle \otimes |\mu\rangle \to |\phi\rangle \otimes |\mu\rangle$ possible[b]

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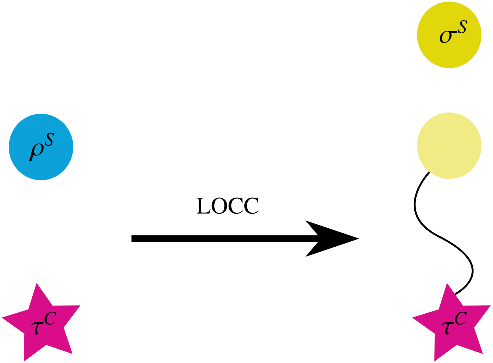
Approximate catalysis[a,b,c,d]



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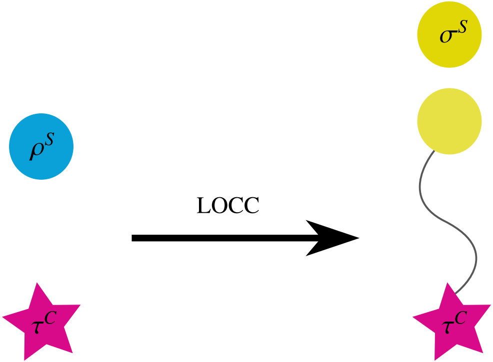

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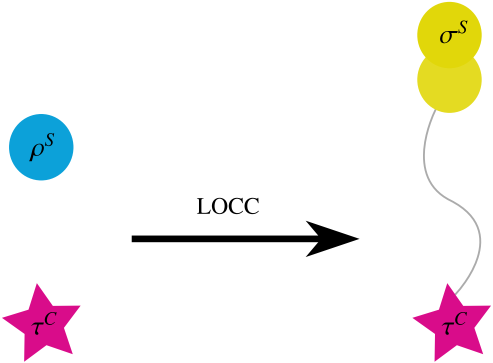

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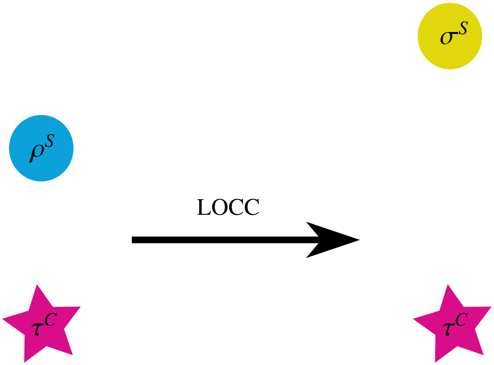

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Approximate catalysis[a][b][c][d]

- Conversion $\rho \to \sigma$ via LOCC with approximate catalysis possible if for any $\varepsilon > 0$ there is Λ and τ such that

$$\left\| \Lambda[\rho^{AB} \otimes \tau^{A'B'}] - \sigma^{AB} \otimes \tau^{A'B'} \right\|_1 < \varepsilon \tag{2}$$

$$\mathrm{Tr}_{AB}\left(\Lambda[\rho^{AB} \otimes \tau^{A'B'}]\right) = \tau^{A'B'} \tag{3}$$

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- Equivalent formulation: For any $\varepsilon > 0$ and any $\delta > 0$ there is Λ and τ such that

$$\left\|\mathrm{Tr}_{A'B'}\left(\Lambda[\rho^{AB} \otimes \tau^{A'B'}]\right) - \sigma^{AB}\right\|_1 \leq \varepsilon \tag{4}$$

$$\mathrm{Tr}_{AB}\left[\Lambda[\rho^{AB} \otimes \tau^{A'B'}]\right] = \tau^{A'B'} \tag{5}$$

$$I^{AB:A'B'}\left(\Lambda[\rho^{AB} \otimes \tau^{A'B'}]\right) \leq \delta \tag{6}$$

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Approximate catalysis

Theorem[a]**:** For two bipartite quantum states $|\psi\rangle^{AB}$ and $|\phi\rangle^{AB}$ approximate catalytic transformation $|\psi\rangle^{AB} \rightarrow |\phi\rangle^{AB}$ is possible if and only if

$$S(\psi^A) \geq S(\phi^A). \qquad (7)$$

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Idea of the proof:

- Catalyst state achieving the transition can be constructed using results from asymptotic entanglement theory and recent results on catalysis in quantum thermodynamics[b]

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- Optimality is proven by showing that squashed entanglement[c]is monotonic under catalytic LOCC

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Approximate catalysis[a][b][c][d][e]

Construction of the catalyst for $S(\psi^A) > S(\phi^A)$

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Approximate catalysis[a][b][c][d][e]

Construction of the catalyst for $S(\psi^A) > S(\phi^A)$

- Take n, $\varepsilon > 0$, and LOCC protocol Λ such that $\left\|\Gamma - \phi^{\otimes n}\right\|_1 < \varepsilon$ with $\Gamma = \Lambda\left(\psi^{\otimes n}\right)$

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- Define catalyst state

$$\tau = \frac{1}{n}\sum_{k=1}^{n} \psi^{\otimes k-1} \otimes \Gamma_{n-k} \otimes |k\rangle\langle k| \tag{8}$$

where Γ_i is the reduced state of Γ

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- Total system-catalyst state:

$$\psi \otimes \tau = \frac{1}{n}\sum_{k=1}^{n} \psi^{\otimes k} \otimes \Gamma_{n-k} \otimes |k\rangle\langle k| \tag{9}$$

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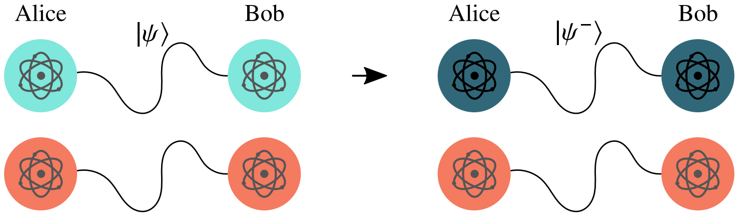

Applications in all singlet-based quantum information protocols:

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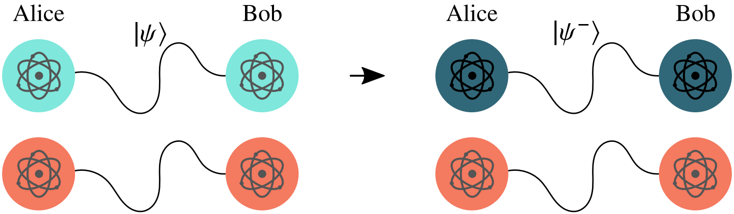

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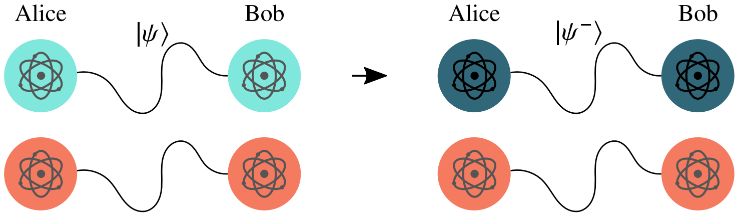

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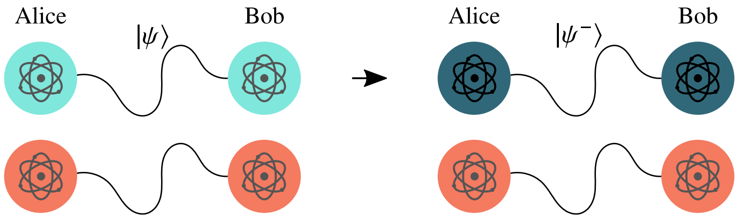

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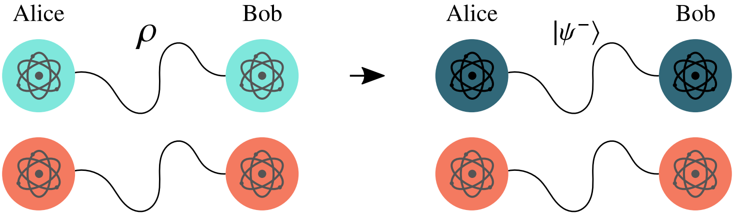

Applications in all singlet-based quantum information protocols:

- $|\psi\rangle$ can be converted into a singlet whenever $S(\psi^A) \geq 1$
- Quantum teleportation[b]
- Quantum key distribution
- Methods allow for **noisy initial states**

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Universal catalysis

- For a catalytic transition $|\psi\rangle^{AB} \to |\phi\rangle^{AB}$ the catalyst states depend on the initial and the final state

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- Question: does there exist a **universal catalyst**, enabling catalytic transition for all bipartite pure states?

Theorem[a]**:** For every $\varepsilon > 0$ there exists a universal catalyst state τ_ε such that for every pair of pure states $|\psi\rangle^{AB}$ and $|\phi\rangle^{AB}$ with $S(\psi^A) \geq S(\phi^A)$ there is an LOCC protocol Λ for which

$$\left\|\Lambda\left(\psi^{AB} \otimes \tau_\varepsilon^{A'B'}\right) - \phi^{AB} \otimes \tau_\varepsilon^{A'B'}\right\|_1 < \varepsilon \tag{10}$$

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Catalysis in settings beyond iid

- Asymptotic iid setting: Alice and Bob have access to *n* copies of a bipartite state $|\psi\rangle$

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Theorem[a]**:** Given fidelity $f > \frac{1}{2}$ and any $\varepsilon > 0$, there is a sequence of two-qubit states $\{|\psi_i\rangle\}$ such that for any n the probability of converting the state $\otimes_{i=1}^{n} |\psi_i\rangle$ into a singlet, via LOCC with fidelity f, is smaller than ε. At the same time, an unbounded number of singlets can be extracted from $\otimes_{i=1}^{n} |\psi_i\rangle$ with the help of catalysis, as $n \to \infty$.

[a] Datta, Kondra, Miller, Streltsov, arXiv:2202.05228

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1. Exact entanglement catalysis
2. Approximate entanglement catalysis
3. Entanglement distribution with catalysis

Entanglement distribution with catalysis[a]

- **Setup:** Alice and Bob have access to the quantum channel

$$\Lambda_l[\rho] = e^{-\alpha l}\rho + (1 - e^{-\alpha l})\frac{\mathbb{1}}{2} \tag{12}$$

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- **Setup:** Alice and Bob have access to the quantum channel

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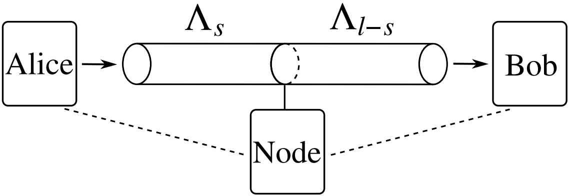
- **Goal:** Distribute entanglement through the channel
- Entanglement distribution possible for $l < \ln 3/\alpha$
- Can the length be increased with an intermediate repeater station+catalysis?



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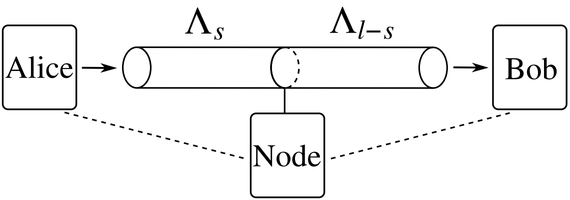
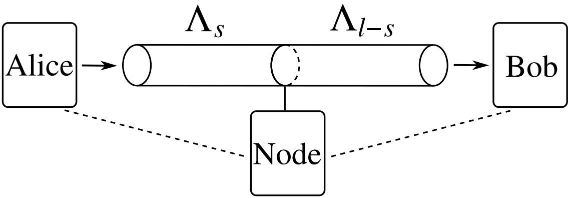


- **Repeater without catalysis:** no improvement, entanglement distribution possible for $l < \ln 3/\alpha$

[a]Datta, Kondra, Miller, Streltsov, arXiv:2202.05228

Entanglement distribution with catalysis[a]



- **Repeater without catalysis:** no improvement, entanglement distribution possible for $l < \ln 3/\alpha$
- **Catalysis without repeater:** no improvement, entanglement distribution possible for $l < \ln 3/\alpha$

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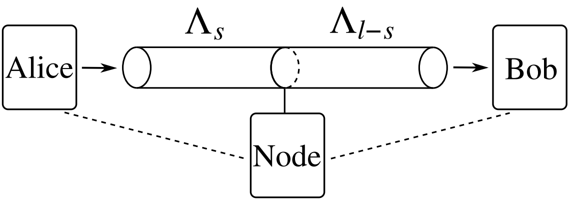

- **Repeater without catalysis:** no improvement, entanglement distribution possible for $l < \ln 3/\alpha$
- **Catalysis without repeater:** no improvement, entanglement distribution possible for $l < \ln 3/\alpha$
- **Repeater+catalysis:** entanglement distribution possible for $l < 2\ln 3/\alpha$

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Summary

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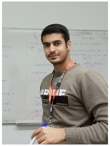
Team



For more details see
T. V. Kondra, C. Datta, and A. Streltsov,
Catalytic Transformations of Pure Entangled States,
Phys. Rev. Lett. **127**, 150503 (2021)

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Entanglement catalysis for quantum states and noisy channels,
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Catalysis of entanglement and other quantum resources,
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