Bengalis at Quantum Optics Group at ICFO

Aditi Sen De, Ujjwal Sen

Omjyoti Dutta

Manab Bera, Swapan Rana, Mohit Bera

Titas Chandra, Debraj Rakshit, Anindita Bera (?)

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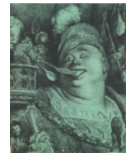

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ICFO – Quantum Optics Theory
Teoretyczna Optyka Kwantowa

Bengalis at Quantum Optics Group at ICFO

Maciej Lewenstein

ICFO – Institute of Photonic Sciences, 08860 Castelldefels, Spain

In my talk I will focus on recent results obtained in my group by the Indian researchers: Manab Bera, Swapan Rana, Debraj Rakshit, Titas Chandra and more. I will start talking about quantum thermodynamics, and derivation of quantum thermodynamics “without temperature”. I will continue to talk about general properties and limitations of quantum batteries. Finally, I will talk about coherence theory and, in particular, coherence as resource.

[1] Thermodynamics from information, Manabendra Nath Bera, Andreas Winter, Maciej Lewenstein, in print in “Quantum Thermodynamics”, a book by Springer, arXiv:1805.10282.
[2] Thermodynamics as a Consequence of Information Conservation, Manabendra Nath Bera, Arnau Riera, Maciej Lewenstein, Zahra Baghali Khanian, Andreas Winter, in print in Quantum, arXiv:1612.04779.
[3] Generalized Laws of Thermodynamics in the Presence of Correlations, Manabendra Nath Bera, Arnau Riera, Maciej Lewenstein, Andreas Winter, Nature Comm. **8**, 2180 (2017), arXiv:1612.04779.
[4] Bounds on Capacity and Power of Quantum Batteries, Sergi Julia-Farre, Tymoteusz Salamon, Arnau Riera, Manabendra N. Bera, Maciej Lewenstein, arXiv:1811.04005.
[5] Logarithmic coherence: Operational interpretation of ℓ_1-norm coherence, Swapan Rana, Preeti Parashar, Andreas Winter, Maciej Lewenstein, Phys. Rev. A 96, 052336 (2017).
[6] Entanglement and coherence in quantum state merging, A. Streltsov, E. Chitambar, S. Rana, M. N. Bera, A. Winter, M. Lewenstein, Phys. Rev. Lett. 116, 240405 (2016).
[7] Trace-distance measure of coherence, Swapan Rana, Preeti Parashar, Maciej Lewenstein, Phys. Rev. A 93, 012110 (2016).
[8] Towards resource theory of coherence in distributed scenarios, A. Streltsov, S. Rana, M. Bera, and M. Lewenstein, Phys. Rev. X 7, 011024 (2017).
[9] Assisted distillation of quantum coherence, E. Chitambar, A. Streltsov, S. Rana, M. N. Bera, G. Adesso, and M. Lewenstein, Phys. Rev. Lett. 116, 070402 (2016).
[10] Self-bound Bose-Fermi liquids in lower dimensions, Debraj Rakshit, Tomasz Karpiuk, Mirosław Brewczyk, Maciej Lewenstein, and Mariusz Gajda, arXiv:1808.04793.

Quantum thermodynamics (QTD)

Classical thermodynamics:

- *incoherent states: no superposition in different energy eigenstates*
- *number of particles* ⟶ *infinity*
- *bath-size* ⟶ *large*

QTD:

- *states with superpositions in different energy eigenstates*
- *inter-system correlations (even system-bath entanglement)*
- *number of particles* ⟶ *arbitrary*
- *bath-size* ⟶ *arbitrary*

QTD requires information theoretic approach:

- *Resource theory of QTD (bath-size* ⟶ *large)*
- *QTD from information conservation, for finite-bath (arXiv:1707.01750)*

Work and heat:

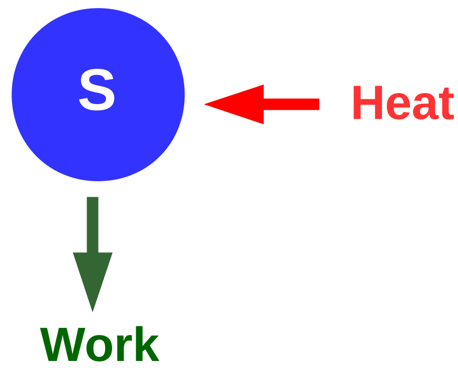
for small system and large bath

$\Delta E_S = -W - Q$ *Heat and work, path-dependent quantities*

WORK, done by system: $W \leqslant F_{fin} - F_{in}$

Helmholtz free energy: $F = E - T\,\mathcal{S}$

Entropy: $\mathcal{S} = -\sum_i p_i \ln p_i$



HEAT: the amount of energy flowing from one body to another, spontaneously due to their temperature difference, or by any means other than through work.

For a thermal bath, in Gibbsian form, minimizes free energy: $\gamma_B = \frac{e^{-H_B/T}}{Z}; \qquad Z = \mathrm{Tr}\, e^{-H_B/T}$

Temperature: T

Heat flow from the bath, to the system: $-Q = -\Delta E_B$

Work and heat

for small systems and baths

Entropy preserving (EP) operations

$$\rho \to \sigma \quad : \quad S(\rho) = S(\sigma)$$

There exists unitary and ancilla of dim $O(\sqrt{n \log n})$

$$\lim_{n\to\infty} \|\mathrm{Tr}_{\,\mathrm{anc}}\left(U\rho^{\otimes n} \otimes \eta U^{\dagger}\right) - \sigma^{\otimes n}\|_1 = 0$$

Min-energy principle: *for a state with fixed Hamiltonian H,*

$$\gamma(\rho) := \underset{\sigma \,:\, S(\sigma)=S(\rho)}{\arg\min} \; E(\sigma)$$

For a given entropy every state has intrinsic temperature,

$$\gamma(\rho) = \frac{e^{-\beta(\rho)H}}{\mathrm{Tr}\,(e^{-\beta(\rho)H})}$$

Bound (inaccessible) energy:

$$B(\rho) := \min_{\sigma \,:\, S(\sigma)=S(\rho)} E(\sigma) = E(\gamma(\rho))$$

Free (accessible) energy: $F(\rho) := E(\rho) - B(\rho)$

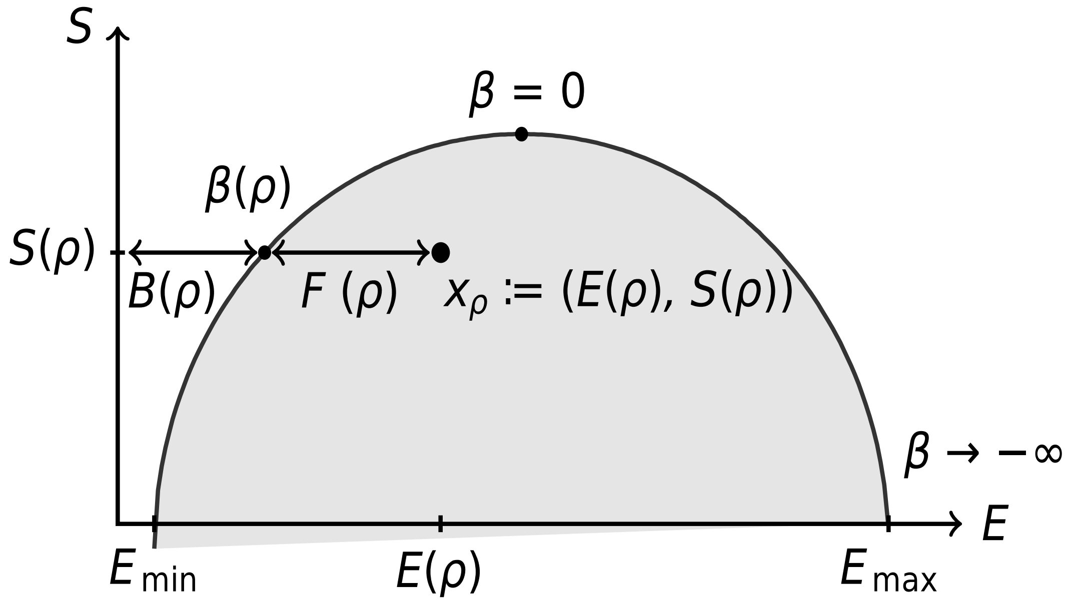
Heat: *for system A and its environment B, heat dissipated by A, in the process* $\rho_{AB} \xrightarrow{\Lambda^{ep}} \rho'_{AB}$

$$\Delta Q := B(\rho'_B) - B(\rho_B)$$

Work: $\Delta W_A := W - \Delta F_B$

where $W = \Delta E_A + \Delta E_B$ *and* $\Delta F_B = F(\rho'_B) - F(\rho_B)$

Energy-entropy diagram



Any quantum state ρ *is represented in the diagram as a point with coordinates* $x_\rho := (E(\rho), S(\rho))$. *The free energy* $F(\rho)$ *is the distance in the horizontal direction from the thermal boundary. The bound energy* $B(\rho)$ *is the distance in the horizontal direction between the thermal boundary and the energy reference.*

Zeroth and first laws

Zeroth law: *Given a collection of systems* $A_1, \ldots, A_n$ *with non-interacting Hamiltonians* $H_1, \ldots H_n$ *in a joint state,* $\rho_{A_1 \ldots A_n}$*, we call them to be mutually at equilibrium if and only if they "jointly" minimize the free energy, i.e.,*

$$F(\rho_{A_1 \ldots A_n}) = 0$$

First law: *For an arbitrary entropy preserving transformation involving a system A and its environment B,* $\rho_{AB} \to \rho'_{AB}$*, with fixed non-interacting Hamiltonians* H_A *and* H_B*,*

$$\Delta E_A = \Delta W_A - \Delta Q \,,$$

where heat $\Delta Q = B(\rho'_B) - B(\rho_B)$*, and work* $\Delta W_A = W - \Delta F_B$*.*

Second laws

Work extraction: For an arbitrary composite system ρ, the extractable work by any entropy preserving process $\rho \to \rho'$, $W = E(\rho) - E(\rho')$ is upper-bounded by the free energy

$$W \leq F(\rho)$$

where the equality is saturated if and only if $\rho' = \gamma(\rho)$.

Clausius statement: Any iso-informatic process involving two bodies A and B in an arbitrary state with intrinsic temperatures T_A and T_B respectively fulfills the following inequality

$$(T_B - T_A)\Delta S_A \geqslant \Delta F_A + \Delta F_B + T_B \Delta I(A:B) - W\,,$$

where $\Delta F_{A/B}$ is the change in the free energy of the bodyA/B, $\Delta I(A:B)$ is the change of mutual information and $W = \Delta E_A + \Delta E_B$ is the amount of external work performed on the global setting.

Second laws

Kelvin-Planck statement: *Any iso-informatic process involving two bodies A and B in an arbitrary state satisfies the following energy balance*

$$\Delta Q_B + \Delta Q_A = -(\Delta F_A + \Delta F_B) + W,$$

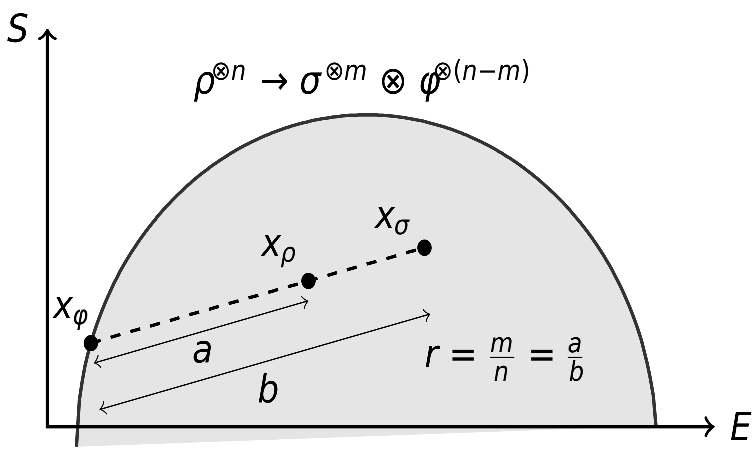
where $\Delta F_{A/B}$ *is the change in the free energy of the body* A/B, $\Delta Q_{A/B}$ *the heat dissipated by the body* A/B, *and* $W = \Delta E_A + \Delta E_B$ *is the amount of external work performed on the global setting.*

Carnot statement: *For an engine working with two initially uncorrelated environments* $\gamma_A \otimes \gamma_B$ *each in a local equilibrium state with intrinsic temperatures* $T_B > T_A$, *the efficiency of work extraction is bounded by*

$$\eta \leqslant 1 - \frac{\Delta B_A}{-\Delta B_B},$$

where ΔB_A *and* ΔB_B *are the change in bound energies of the systems A and B respectively.*

Resource theory



$$\Lambda(\rho^{\otimes n}) = \sigma^{\otimes m} \otimes \phi^{\otimes n-m},$$

where the number of copies n and m have to fulfill the energy and entropy conservation constraints

$$E(\rho^{\otimes n}) = E(\sigma^{\otimes m} \otimes \phi^{\otimes n-m})$$
$$S(\rho^{\otimes n}) = S(\sigma^{\otimes m} \otimes \phi^{\otimes n-m}).$$

The above conditions can be easily written as a geometric equation of the points $x_\psi = (E(\psi), S(\psi))$ with $\psi \in \{\rho, \sigma, \phi\}$ in the energy-entropy diagram

$$x_\rho = r\, x_\sigma + (1-r)\, x_\phi\,,$$

where

$$r := m/n$$

is the conversion rate, and we have only used the extensivity of both entropy and energy in the number of copies, e.g. $E(\rho^{\otimes n}) = nE(\rho)$.

Remarks

Thermodynamics from information conservation:

Temperature independent TD: also applicable for small baths.

Heat and work: in terms of bound and free energies.

Zeroth law: consequence of information conservation.

First and second laws: Energy and information conservation.

Resource theory: using simple geometric approach.

Extension to QTD with multiple conserved quantities:

Commuting: addressed in arXiv:1707.01750.

Non-commuting: under preparation.

Quantum batteries

Bounds on Capacity and Power of Quantum Batteries

Sergi Julià-Farré,[1,*] Tymoteusz Salamon,[1,2] Arnau Riera,[1,3] Manabendra N. Bera,[1,3,†] and Maciej Lewenstein[1,4]

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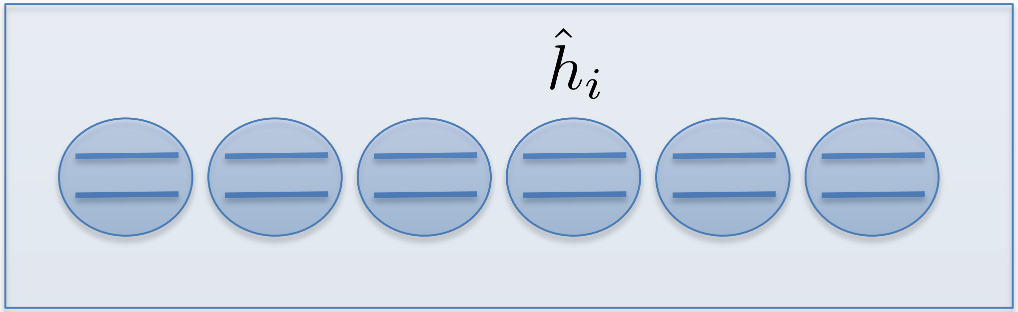
Quantum batteries, composed of quantum-cells, are expected to outperform their classical analogs. The origin of such advantages lies in the role of quantum correlations, which may arise during the charging and discharging processes performed on the battery. In this work, we introduce a systematic characterization of the relevant quantities of quantum batteries, i.e., *capacity* and *power*, in relation to such correlations. For these quantities, we derive tighter bounds for batteries that are a collection of non-interacting quantum-cells with fixed Hamiltonians. The bound on capacity is derived with the help of the energy-entropy diagram, and this bound is respected as long as the charging and discharging processes are entropy preserving. While studying power, we consider a geometric approach for the evolution of the battery state in the energy eigenspace of the battery Hamiltonian. Then, a tighter bound on power is derived for arbitrary charging process, in terms of the *Fisher information* and the *energy fluctuation* of the battery. The former quantifies the speed of evolution, and the latter encodes non-local character of the battery state. We discuss paradigmatic models for batteries that saturate the bounds both for the capacity and the power. Several physically realizable batteries, based on integrable spin chains, Lipkin-Meshkov-Glick model and Dicke model, are also studied in the light of these newly introduced bounds.

arXiv:1811.04005

Quantum batteries



$$\hat{H}_B = \sum_{i=1}^{N} \hat{h}_i$$

$$\text{Charging}: \ \hat{\rho}_B(t) \to \hat{U}(t)\hat{\rho}_B(0)\hat{U}^\dagger(t), \quad E(t) = \mathrm{Tr}[\hat{H}_B\hat{\rho}_B(t)]$$

$$\text{Capacity} := \max_t E\left(\hat{\rho}(t)\right) - \min_t E\left(\hat{\rho}(t)\right).$$

$$\text{Power} := \frac{\mathrm{d}}{\mathrm{dt}} E\left(\hat{\rho}(t)\right)$$

arXiv:1811.04005

Bound on the power

Battery energy eigenspace:

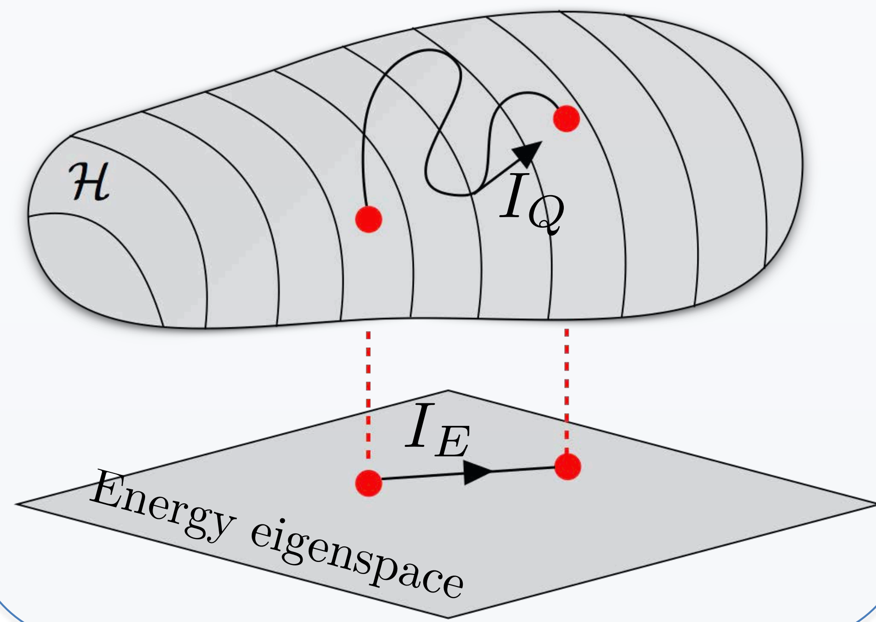
$$\hat{H}_B = \sum_k E_k \hat{P}_k$$

$$\rightarrow p_k(t) := Tr(\hat{\rho}(t)\hat{P}_k)$$

$$P(t) \leqslant \sqrt{\Delta \hat{H}_B(t)^2 \cdot I_E(t)}$$

$$I_E := \sum_k \frac{\dot{p}_k^2}{p_k}$$

Quantum speed of evol. projected in energy eigenspace



For pure states:

$$(\Delta \hat{H}_B)^2 = (\Delta^{Loc} \hat{H}_B)^2 + (\Delta^{Ent} \hat{H}_B)^2$$

arXiv:1811.04005

Parallel vs interacting charging

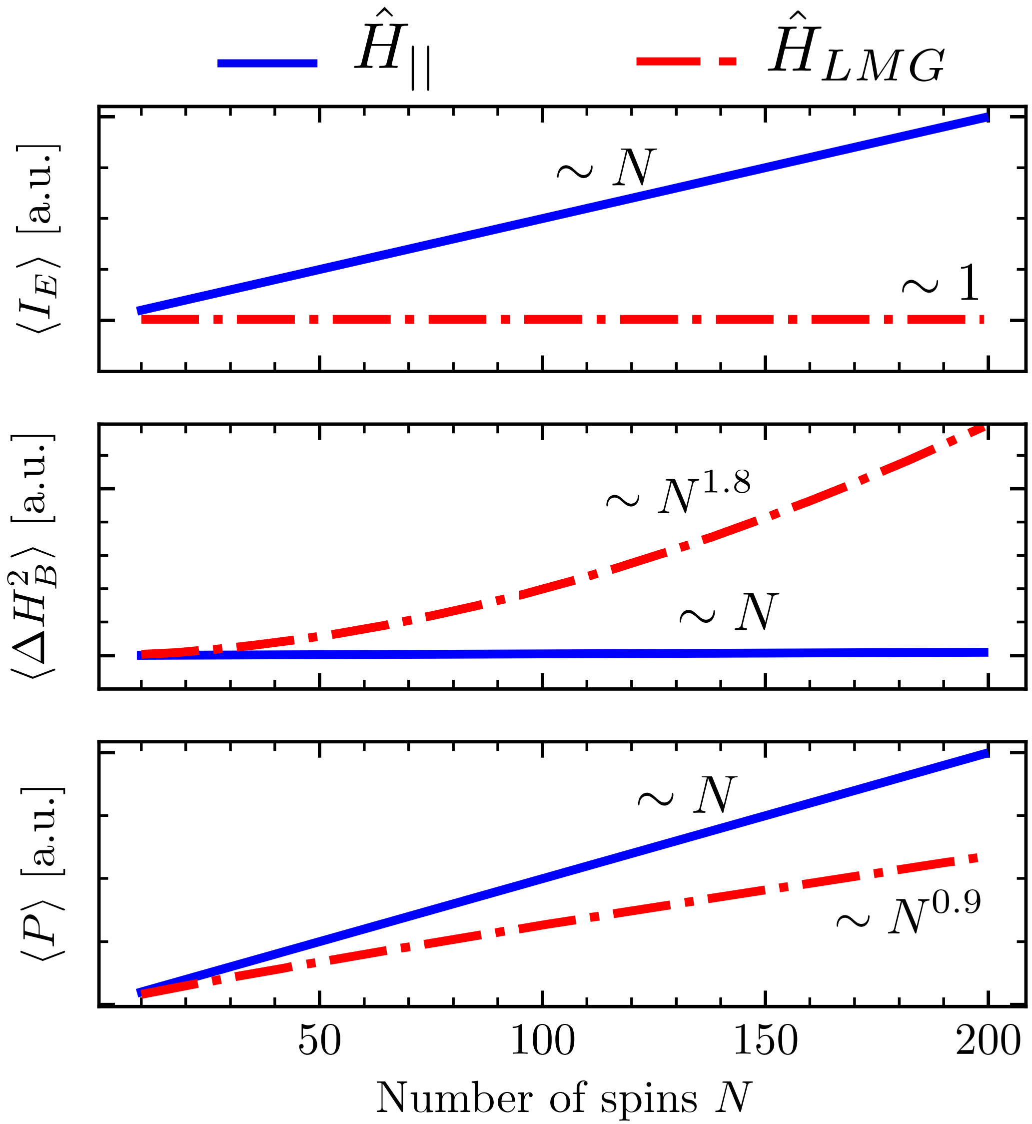
$$\hat{H}_B = \frac{1}{2}\sum_i \hat{\sigma}_z^i,$$

$$\hat{H}_{||} = \lambda \sum_i \hat{\sigma}_x^i,$$

$$\hat{H}_{LMG} = \frac{1}{2}\sum_i \hat{\sigma}_z^i +$$

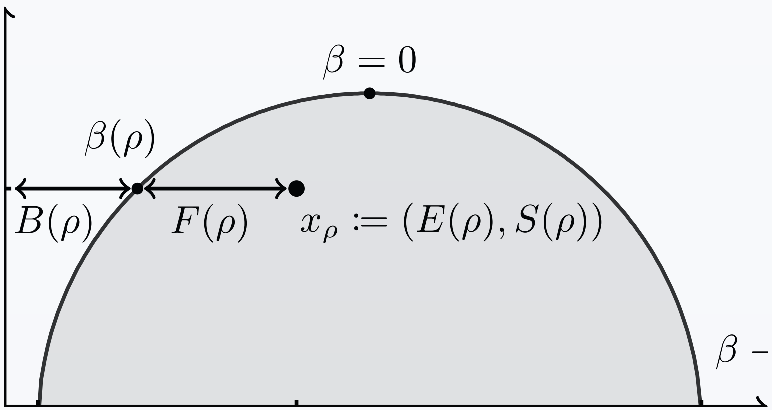
$$+ \frac{\lambda}{N}\sum_{i<j}(\hat{\sigma}_x^i\hat{\sigma}_x^j + \gamma\hat{\sigma}_y^i\hat{\sigma}_y^j)$$

$$(\gamma = -1, \quad \lambda = 5)$$



arXiv:1811.04005

Bound on the capacity



arXiv:1811.04005

Resource Theory of Coherence

- Contributing Bengalis: Swapan Rana, Manabendra Nath Bera
- Contributions from QOT: 1 PRX, 4 PRL, 2 PRA, 1 Mathematics
- Coherence team: Alexander Streltsov, SR, MNB, ML

Coherence at a glance

Many models of coherence theory [Streltsov *et al.*, Rev. Mod. Phys. (2017)]

IO: incoherent operation

Model	Reference
Maximally IO	Åberg, 2006
IO	Baumgratz *et al.*(2014); Winter & Yang (2016)
Strictly IO	Winter & Yang (2016) Yadin *et al.*(2016)
Translationally invariant operations	Marvian & Spekkens (2016)
Physical IO	Chitambar & Gour (2016)
Dephasing-covariant IO	Marvian & Spekkens (2016); Chitambar & Gour (2016)
Genuinely IO	de Vicente & Streltsov (2017)
Fully IO	de Vicente & Streltsov (2017)

Resource Theory of Quantum Coherence

IO theory of coherence [Baumgratz *et al.*, PRL (2014)]

- Free (incoherent) states: Diagonal states $\delta = \sum \delta_i |i\rangle\langle i|$, for a preferred/chosen o.n.b. $\{|i\rangle\}$. This is not a shortcoming!
- Free (incoherent) operations: Λ is incoherent iff there is a Kraus decomposition $\Lambda = \{K_n\}$ such that $K_n \delta K_n^\dagger$ is diagonal for all n and for all diagonal states δ.
- Maximally coherent state: $|\Phi_d\rangle = \frac{1}{\sqrt{d}} \sum |i\rangle$.
  - Any $\rho \in \mathscr{B}(\mathscr{H}^d)$ can be created from $|\Phi_d\rangle$:

$$|\Phi_d\rangle \xrightarrow[\text{with certainty}]{\text{only } \Lambda \in \mathscr{I}} \rho.$$

  - $|\Phi_d\rangle$ allows to implement arbitrary unitary $U \in SU(d)$.
  - Existence of $|\Phi_d\rangle$ allows all kind of concepts related to manipulation of resource e.g., formation, cost, distillation etc.

Operational Structure of RTQC [Winter & Yang, PRL (2016)]

- Distillable coherence (C_d):

$$C_d(\rho) = \sup R, \text{ s.t. } \rho^{\otimes n} \xrightarrow{\text{IC}} \stackrel{1-\epsilon}{\approx} \Phi_2^{\otimes nR} \text{ as } n \to \infty, \ \epsilon \to 0.$$

- Coherence of formation (C_f):

$$C_f(\rho) = \min \sum_i p_i S(\Delta(\psi_i)) \text{ s.t. } \rho = \sum_i p_i |\psi_i\rangle\langle\psi_i|.$$

- Coherence cost (C_c):

$$C_c(\rho) = \inf R, \text{ s.t. } \Phi_2^{\otimes nR} \xrightarrow{\text{IC}} \stackrel{1-\epsilon}{\approx} \rho^{\otimes n} \text{ as } n \to \infty, \ \epsilon \to 0.$$

- $C_d(\rho) = C_r(\rho)$ & $C_c(\rho) = C_f(\rho) \quad \forall \rho$.
- Additivity: $C_f(\rho \otimes \sigma) = C_f(\rho) + C_f(\sigma)$,
  $C_r(\rho \otimes \sigma) = C_r(\rho) + C_r(\sigma)$.

- Single copy transformation of pure states: followed by standard majorization criteria. Thus allows catalytic-, stochastic transformation, trumping etc.
- Asymptotic transformation of pure states: For ψ, φ, a rate $R \geq 0$, and any $\Lambda \in \mathscr{I}$

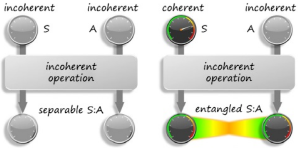
$$\psi^{\otimes n} \overset{\Lambda \in \mathscr{I}}{\longmapsto} \overset{1-\epsilon}{\approx} \varphi^{\otimes nR} \text{ as } n \to \infty,\ \epsilon \to 0,$$

  is possible if $R < \frac{C_r(\psi)}{C_r(\varphi)}$ and impossible if $R > \frac{C_r(\psi)}{C_r(\varphi)}$.
- Irreversability: $C_d(\rho) \leq C_c(\rho)$.
  Equality for all pure states, but for mixed ρ iff its eigenvectors are supported on the orthogonal subspaces spanned by a partition of the incoherent basis.

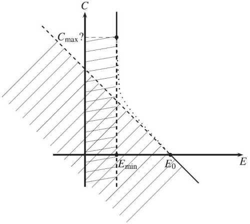
However, there is no bound coherence! $C_d = 0 \Longleftrightarrow C_c = 0$

Our contributions to RTQC

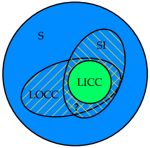
- Showing equivalence of coherence and entanglement at monotone level: Given a measure of one, it is possible to construct a measure of the other (with nice properties by inheritance)



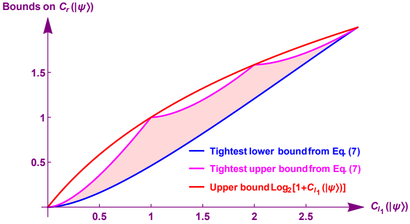
- Finding trade-off between coherence and entanglement in the elementary protocols of quantum information: Teleportation, assisted distillation, state merging etc.



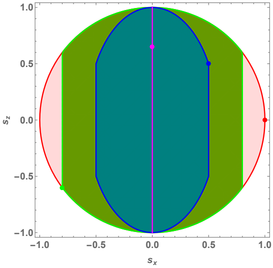
- Extending QRTC to multi-partite setting: Introducing new classes of multiparty operations and their hierarchies and applications.



- Constructing (and rejecting many functions to be) coherence measures: Their properties, operational interpretations, interrelations, similarities with entanglement etc.



- Structure of IOs: Minimum number of Kraus operators to describe IOs (and free operations of other coherence models) and relevance.



Exact number for qubit IO is **four**

- A canonical form for any qubit IO is given by

$$\left\{\begin{pmatrix} a_1 & b_1 \\ 0 & \end{pmatrix}, \begin{pmatrix} 0 & 0 \\ a_2 & b_2 \end{pmatrix}, \begin{pmatrix} a_3 & 0 \\ 0 & b_3 \end{pmatrix}, \begin{pmatrix} 0 & b_4 \\ a_4 & 0 \end{pmatrix}\right\},$$

where $a_i \geq 0$ and $\sum_{i=1}^{4} a_i^2 = \sum_{j=1}^{4} |b_j|^2 = 1$.

Exact number for qubit SIO is **four**

- A canonical form for any qubit SIO is given by

$$\left\{\begin{pmatrix} a_1 & 0 \\ 0 & b_1 \end{pmatrix}, \begin{pmatrix} 0 & b_2 \\ a_2 & 0 \end{pmatrix}, \begin{pmatrix} a_3 & 0 \\ 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 \\ a_4 & 0 \end{pmatrix}\right\},$$

where $a_i \geq 0$ and $\sum_{i=1}^4 a_i^2 = \sum_{j=1}^2 |b_j|^2 = 1$.

Bound for higher (d-) dimensional channels

- IO: # $\leq d(d^d - 1)/(d-1)$. Better than $d^4 + 1$ only for $d \leq 3$.
- SIO: # $\leq \sum_{k=1}^d d!/(k-1)!$. Better than $d^4 + 1$ only for $d \leq 5$.
- (S)IO: # $\geq d^2$ as the set of standard matrix units are linearly independent and forms an (S)IO.

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Conclusions: Quantum Narcissism