Quantum Conditional Relative Entropy and Quasi-factorization of the Relative Entropy

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1. Introduction

- $\mathcal{H}_{AB} = \mathcal{H}_A \otimes \mathcal{H}_B$ (or $\mathcal{H}_{ABC} = \mathcal{H}_A \otimes \mathcal{H}_B \otimes \mathcal{H}_C$).
- $\mathcal{B}_\Lambda := \mathcal{B}(\mathcal{H}_\Lambda)$, set of bounded linear operators.
- $\mathcal{A}_\Lambda \subseteq \mathcal{B}_\Lambda$, set of Hermitian operators.
- $\mathcal{S}_\Lambda := \{ f \in \mathcal{A}_\Lambda \, : \, f \geq 0$ and $\operatorname{tr}[f] = 1\}$.
- $f \in \mathcal{B}_\Lambda$ has support on $A \subseteq \Lambda$ if $f = f_A \otimes \mathbb{1}_B$ for certain $f_A \in \mathcal{B}_A$.
- Modified partial trace: $\operatorname{tr}_A : f \mapsto \operatorname{tr}_A[f] \otimes \mathbb{1}_A$, where $\operatorname{tr}_A[f]$ has support in B.
- We denote by f_B the observable $\operatorname{tr}_A[f]$ with support in B.

2. Motivation

Motivation

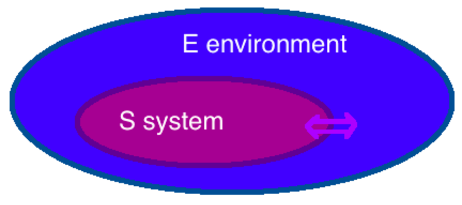

Figura: An open quantum many-body system.

- Interesting for information processing ⇒ Open (unavoidable interactions).
- Dynamics of S is dissipative!
- The continuous-time evolution of a state on S is given by a **quantum Markov semigroup**.

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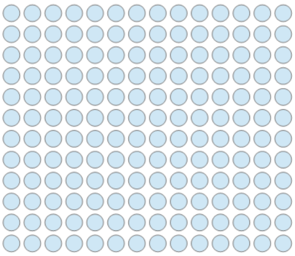

Figura: A quantum spin lattice system.

- Lattice $\Lambda \subset\subset \mathbb{Z}^d$.
- For every site x, $\mathcal{H}_x$ $(= \mathbb{C}^D)$.
- The global Hilbert space associated to Λ is $\mathcal{H}_\Lambda = \bigotimes_{x \in \Lambda} \mathcal{H}_x$.

Dissipative quantum system

Dissipative quantum systems

A **dissipative quantum system** is a 1-parameter continuous semigroup $\{\mathcal{T}_t^*\}_{t\geq 0}$ of completely positive, trace preserving (CPTP) maps (a.k.a. quantum channels) in $\mathcal{S}_\Lambda$.

- *Positive:* Maps positive operators to positive operators.
- *Completely positive:* $\mathcal{T}_t^* \otimes \mathbb{1} : \mathcal{S}_\Lambda \otimes \mathcal{M}_n \to \mathcal{S}_\Lambda \otimes \mathcal{M}_n$ is positive $\forall n \in \mathbb{N}, \forall t \geq 0$.
- *Trace preserving:* $\operatorname{tr}[\mathcal{T}_t^*(\rho_\Lambda)] = \operatorname{tr}[\rho_\Lambda] \ \forall \rho_\Lambda \in \mathcal{S}_\Lambda, \forall t \geq 0$.

Semigroup:

- $\mathcal{T}_t^* \circ \mathcal{T}_s^* = \mathcal{T}_{t+s}^*$.
- $\mathcal{T}_0^* = \mathbb{1}$.

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$$\frac{d}{dt}\mathcal{T}_t^* = \mathcal{T}_t^* \circ \mathcal{L}_\Lambda^* = \mathcal{L}_\Lambda^* \circ \mathcal{T}_t^* .$$

QMS generator

The infinitesimal generator $\mathcal{L}_\Lambda^*$ of the previous semigroup of quantum channels is called **Liouvillian**, or **Lindbladian**.

$$\mathcal{T}_t^* = e^{t\mathcal{L}_\Lambda^*} \Leftrightarrow \mathcal{L}_\Lambda^* = \frac{d}{dt}\mathcal{T}_t^* \mid_{t=0} .$$

Notation

We will denote, for every state ρ_Λ,

$$\rho_t := \mathcal{T}_t^*(\rho_\Lambda).$$

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Primitive QMS

We assume that $\{\mathcal{T}_t^*\}_{t\geq 0}$ has a unique full-rank invariant state, which we denote by σ_Λ.

Reversibility

We also assume that the quantum Markov proccess studied is **reversible**, i.e., satisfies the **detailed balance condition**:

$$\langle \rho_\Lambda, \mathcal{L}_\Lambda^*(\eta_\Lambda)\rangle_{\sigma_\Lambda} = \langle \mathcal{L}_\Lambda^*(\rho_\Lambda), \eta_\Lambda\rangle_{\sigma_\Lambda}$$

for every $\rho_\Lambda, \eta_\Lambda \in \mathcal{S}_\Lambda$.

$$\rho_\Lambda \xrightarrow{t} \rho_t := \mathcal{T}_t^*(\rho_\Lambda) = e^{t\mathcal{L}_\Lambda^*}(\rho_\Lambda) \xrightarrow{t\to\infty} \sigma_\Lambda$$

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Mixing time

We define the **mixing time** of $\mathcal{T}_t^*$ by

$$\tau(\varepsilon) = \min\left\{ t > 0 : \sup_{\rho_\Lambda \in \mathcal{S}_\Lambda} \left\| \mathcal{T}_t^*(\rho_\Lambda) - \mathcal{T}_\infty^*(\rho_\Lambda) \right\|_1 \leq \varepsilon \right\}.$$

Rapid mixing

We say that $\mathcal{L}_\Lambda^*$ satisfies **rapid mixing** if

$$\sup_{\rho \in \mathcal{S}_\Lambda} \left\| \rho_t - \sigma_\Lambda \right\|_1 \leq \text{poly}(|\Lambda|) e^{-\gamma t}.$$

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Find bounds for the mixing time!

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Log-Sobolev inequality (MLSI)

Let σ_Λ be the stationary state of a semigroup generated by the quantum dynamical master equation

$$\partial_t \rho_t = \mathcal{L}_\Lambda^*(\rho_t), \tag{1}$$

where $\mathcal{L}_\Lambda$ is the Liouvillian in the Heisenberg picture.

We define the **relative entropy** of ρ_t and σ_Λ by:

$$D(\rho_t||\sigma_\Lambda) = \operatorname{tr}[\rho_t(\log \rho_t - \log \sigma_\Lambda)]. \tag{2}$$

Therefore, since ρ_t evolves according to $\mathcal{L}_\Lambda^*$, the derivate of $D(\rho_t||\sigma_\Lambda)$ is given by

$$\partial_t D(\rho_t||\sigma_\Lambda) = \operatorname{tr}[\mathcal{L}_\Lambda^*(\rho_t)(\log \rho_t - \log \sigma_\Lambda)], \tag{3}$$

and we want to find a lower bound for the derivative of $D(\rho_t||\sigma_\Lambda)$ in terms of itself:

$$2\alpha D(\rho_t||\sigma_\Lambda) \leq -\operatorname{tr}[\mathcal{L}_\Lambda^*(\rho_t)(\log \rho_t - \log \sigma_\Lambda)]. \tag{4}$$

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Log-Sobolev constant

Let $\mathcal{L} : \mathcal{S}_\Lambda \to \mathcal{S}_\Lambda$ be a primitive reversible Lindbladian with stationary state σ_Λ. We define the **log-Sobolev constant** (MLSI constant) of $\mathcal{L}^*_\Lambda$ by

$$\alpha(\mathcal{L}^*_\Lambda) := \inf_{\rho_\Lambda \in \mathcal{S}_\Lambda} \frac{-\operatorname{tr}[\mathcal{L}^*_\Lambda(\rho_\Lambda)(\log \rho_\Lambda - \log \sigma_\Lambda)]}{2D(\rho_\Lambda || \sigma_\Lambda)}$$

Integrating, we have:

$$D(\rho_t || \sigma_\Lambda) \leq D(\rho_\Lambda || \sigma_\Lambda) e^{-2\,\alpha(\mathcal{L}^*_\Lambda)\,t}, \quad (5)$$

and putting this together with **Pinsker's inequality**, we have:

$$\|\rho_t - \sigma_\Lambda\|_1 \leq \sqrt{2D(\rho_\Lambda || \sigma_\Lambda)}\, e^{-\alpha(\mathcal{L}^*_\Lambda)\,t} \leq \sqrt{2\log(1/\sigma_{\text{min}})}\, e^{-\alpha(\mathcal{L}^*_\Lambda)\,t}. \quad (6)$$

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Result

If $\alpha(\mathcal{L}_\Lambda^*) > 0$,

$$\|\rho_t - \sigma_\Lambda\|_1 \leq \sqrt{2\log(1/\sigma_{\mathsf{min}})}\, e^{-\alpha(\mathcal{L}_\Lambda^*)t}.$$

Log-Sobolev constant $\Rightarrow$ Rapid mixing.

Problem

Find positive log-Sobolev constants!

Result

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3. Classical case

Classical entropy and conditional entropy

Consider a probability space $(\Omega, \mathcal{F}, \mu)$ and define, for every $f > 0$, the **entropy** of f by

$$\text{Ent}_\mu(f) = \mu(f \log f) - \mu(f) \log \mu(f).$$

Given a σ-algebra $\mathcal{G} \subseteq \mathcal{F}$, we define the **conditional entropy** of f in $\mathcal{G}$ by

$$\text{Ent}_\mu(f \mid \mathcal{G}) = \mu(f \log f \mid \mathcal{G}) - \mu(f \mid \mathcal{G}) \log \mu(f \mid \mathcal{G}).$$

With these definitions, the following lemma is proven:

Lemma, Dai Pra et al. '02

Let $(\Omega, \mathcal{F}, \mu)$ be a probability space, and $\mathcal{F}_1, \mathcal{F}_2$ sub-σ-algebras of $\mathcal{F}$. Suppose that there exists a probability measure $\bar{\mu}$ that makes $\mathcal{F}_1$ and $\mathcal{F}_2$ independent, $\mu \ll \bar{\mu}$ and $\mu \mid \mathcal{F}_i = \bar{\mu} \mid \mathcal{F}_i$ for $i = 1, 2$. Then, for every $f \geq 0$ such that $f \log f \in L^1(\mu)$ and $\mu(f) = 1$,

$$\mathrm{Ent}_\mu(f) \leq \frac{1}{1 - 4\|h - 1\|_\infty} \, \mu \left[\mathrm{Ent}_\mu(f \mid \mathcal{F}_1) + \mathrm{Ent}_\mu(f \mid \mathcal{F}_2)\right],$$

where $h = \dfrac{d\mu}{d\bar{\mu}}$.

Problem

Let $\mathcal{H}_{ABC} = \mathcal{H}_A \otimes \mathcal{H}_B \otimes \mathcal{H}_C$ and $\rho_{ABC}, \sigma_{ABC} \in S_{ABC}$. Can we prove something like

$$D(\rho_{ABC}||\sigma_{ABC}) \leq$$
$$\xi(\sigma_{AB}) \left[D_{AB}(\rho_{ABC}||\sigma_{ABC}) + D_{BC}(\rho_{ABC}||\sigma_{ABC}) \right] \ ?$$

Yes! (We will see how later)

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4. Conditional relative entropy

Quantum relative entropy

Let $f, g \in \mathcal{A}_\Lambda$, f verifying $\operatorname{tr}[f] \neq 0$. The **quantum relative entropy** of f and g is defined by:

$$D(f||g) = \frac{1}{\operatorname{tr}[f]} \operatorname{tr}\left[f(\log f - \log g)\right]. \tag{7}$$

Remark

In this talk, we only consider density matrices (with trace 1). In this case, the **quantum relative entropy** is given by:

$$D(\rho||\sigma) = \operatorname{tr}\left[\rho(\log \rho - \log \sigma)\right]. \tag{8}$$

Properties of the relative entropy

Let $\mathcal{H}_{AB} = \mathcal{H}_A \otimes \mathcal{H}_B$ and $\rho_{AB}, \sigma_{AB} \in \mathcal{S}_{AB}$. The following properties hold:

1. **Continuity.** $\rho_{AB} \mapsto D(\rho_{AB}||\sigma_{AB})$ is continuous.
2. **Additivity.** $D(\rho_A \otimes \rho_B||\sigma_A \otimes \sigma_B) = D(\rho_A||\sigma_A) + D(\rho_B||\sigma_B)$.
3. **Superadditivity.** $D(\rho_{AB}||\sigma_A \otimes \sigma_B) \geq D(\rho_A||\sigma_A) + D(\rho_B||\sigma_B)$.
4. **Monotonicity.** $D(\rho_{AB}||\sigma_{AB}) \geq D(T(\rho_{AB})||T(\sigma_{AB}))$ for every quantum channel T.

Characterization of the relative entropy, Wilming et al. '17, Matsumoto '10

If $f : \mathcal{S}_{AB} \times \mathcal{S}_{AB} \to \mathbb{R}_0^+$ satisfies $1 - 4$, then f is the relative entropy.

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Conditional relative entropy

Conditional relative entropy

Let $\mathcal{H}_{AB} = \mathcal{H}_A \otimes \mathcal{H}_B$. We define a **conditional relative entropy** in A as a function

$$D_A(\cdot||\cdot) : \mathcal{S}_{AB} \times \mathcal{S}_{AB} \to \mathbb{R}_0^+$$

verifying the following properties for every $\rho_{AB}, \sigma_{AB} \in \mathcal{S}_{AB}$:

1. **Continuity:** The map $\rho_{AB} \mapsto D_A(\rho_{AB}||\sigma_{AB})$ is continuous.
2. **Non-negativity:** $D_A(\rho_{AB}||\sigma_{AB}) \geq 0$ and
   (2.1) $D_A(\rho_{AB}||\sigma_{AB}){=}0$ iff $\rho_{AB} = \sigma_{AB}^{1/2}\sigma_B^{-1/2}\rho_B\sigma_B^{-1/2}\sigma_{AB}^{1/2}$.
3. **Semi-superadditivity:** $D_A(\rho_{AB}||\sigma_A \otimes \sigma_B) \geq D(\rho_A||\sigma_A)$ and
   (3.1) **Semi-additivity:** if $\rho_{AB} = \rho_A \otimes \rho_B$,
   $D_A(\rho_A \otimes \rho_B||\sigma_A \otimes \sigma_B) = D(\rho_A||\sigma_A)$.
4. **Semi-motonicity:** For every quantum channel $\mathcal{T}$,
   $$D_A(\mathcal{T}(\rho_{AB})||\mathcal{T}(\sigma_{AB})) + D_B((\operatorname{tr}_A \circ \mathcal{T})(\rho_{AB})||(\operatorname{tr}_A \circ \mathcal{T})(\sigma_{AB})) \leq D_A(\rho_{AB}||\sigma_{AB}) + D_B(\operatorname{tr}_A(\rho_{AB})||\operatorname{tr}_A(\sigma_{AB})).$$

Remark

Consider for every $\rho_{AB}, \sigma_{AB} \in \mathcal{S}_{AB}$

$$D^+_{A,B}(\rho_{AB}||\sigma_{AB}) = D_A(\rho_{AB}||\sigma_{AB}) + D_B(\rho_{AB}||\sigma_{AB}).$$

Then, $D^+_{A,B}$ verifies the following properties:

1. **Continuity:** $\rho_{AB} \mapsto D^+_{A,B}(\rho_{AB}||\sigma_{AB})$ is continuous.
2. **Additivity:**
   $D^+_{A,B}(\rho_A \otimes \rho_B||\sigma_A \otimes \sigma_B) = D(\rho_A||\sigma_A) + D(\rho_B||\sigma_B)$.
3. **Superadditivity:**
   $D^+_{A,B}(\rho_{AB}||\sigma_A \otimes \sigma_B) \geq D(\rho_A||\sigma_A) + D(\rho_B||\sigma_B)$.

However, it does not satisfy the property of monotonicity.

Axiomatic characterization of the conditional relative entropy

The only possible conditional relative entropy is given by:

$$D_A(\rho_{AB}||\sigma_{AB}) = D(\rho_{AB}||\sigma_{AB}) - D(\rho_B||\sigma_B)$$

for every $\rho_{AB}, \sigma_{AB} \in \mathcal{S}_{AB}$.

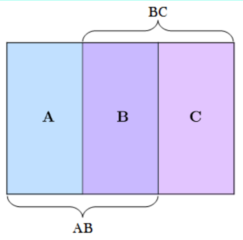

Figura: Choice of indices in $\mathcal{H}_{ABC} = \mathcal{H}_A \otimes \mathcal{H}_B \otimes \mathcal{H}_C$.

Result of **quasi-factorization** of the relative entropy, for every $\rho_{ABC}, \sigma_{ABC} \in \mathcal{S}_{ABC}$:

$$D(\rho_{ABC}||\sigma_{ABC}) \leq \xi(\sigma_{ABC}) \left[D_{AB}(\rho_{ABC}||\sigma_{ABC}) + D_{BC}(\rho_{ABC}||\sigma_{ABC}) \right],$$

where $\xi(\sigma_{ABC})$ depends only on σ_{ABC} and measures how far σ_{AC} is from $\sigma_A \otimes \sigma_C$.

Quasi-factorization for the CRE

Let $\mathcal{H}_{ABC} = \mathcal{H}_A \otimes \mathcal{H}_B \otimes \mathcal{H}_C$ and $\rho_{ABC}, \sigma_{ABC} \in \mathcal{S}_{ABC}$. Then, the following inequality holds

$$(1 - 2\|H(\sigma_{AC})\|_\infty) D(\rho_{ABC}||\sigma_{ABC}) \leq D_{AB}(\rho_{ABC}||\sigma_{ABC}) + D_{BC}(\rho_{ABC}||\sigma_{ABC}),$$

where

$$H(\sigma_{AC}) = \sigma_A^{-1/2} \otimes \sigma_C^{-1/2} \sigma_{AC} \, \sigma_A^{-1/2} \otimes \sigma_C^{-1/2} - \mathbb{1}_{AC}.$$

Note that $H(\sigma_{AC}) = 0$ if $\sigma_{AC} = \sigma_A \otimes \sigma_C$.

Classical case

$$\text{Ent}_\mu(f) \leq \frac{1}{1 - 4\|h-1\|_\infty} \mu \left[\text{Ent}_\mu(f \mid \mathcal{F}_1) + \text{Ent}_\mu(f \mid \mathcal{F}_2)\right],$$

where $h = \frac{d\mu}{d\bar{\mu}}$.

Quasi-factorization for the CRE

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$$(1 - 2\|H(\sigma_{AC})\|_\infty) D(\rho_{ABC}||\sigma_{ABC}) \leq D_{AB}(\rho_{ABC}||\sigma_{ABC}) + D_{BC}(\rho_{ABC}||\sigma_{ABC}) = 2D(\rho_{ABC}||\sigma_{ABC}) - D(\rho_C||\sigma_C) - D(\rho_A||\sigma_A).$$

$$\Leftrightarrow$$

$$(1 + 2\|H(\sigma_{AC})\|_\infty) D(\rho_{ABC}||\sigma_{ABC}) \geq D(\rho_A||\sigma_A) + D(\rho_C||\sigma_C).$$

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Recall:

- **Superadditivity.**
  $D(\rho_{AB}||\sigma_A \otimes \sigma_B) \geq D(\rho_A||\sigma_A) + D(\rho_B||\sigma_B)$.

Due to:

- **Monotonicity.** $D(\rho_{AB}||\sigma_{AB}) \geq D(T(\rho_{AB})||T(\sigma_{AB}))$ for every quantum channel T.

we have

$$2D(\rho_{AB}||\sigma_{AB}) \geq D(\rho_A||\sigma_A) + D(\rho_B||\sigma_B)$$

Our result:

$$\boxed{(1 + 2\|H(\sigma_{AB})\|_\infty)D(\rho_{AB}||\sigma_{AB}) \geq D(\rho_A||\sigma_A) + D(\rho_B||\sigma_B)}.$$

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5. Conditional relative entropy by expectations

WEAK CONDITIONAL RELATIVE ENTROPY

Let $\mathcal{H}_{AB} = \mathcal{H}_A \otimes \mathcal{H}_B$. We define a **weak conditional relative entropy** in A as a function

$$D_A(\cdot||\cdot) : \mathcal{S}_{AB} \times \mathcal{S}_{AB} \to \mathbb{R}_0^+$$

verifying the following properties for every $\rho_{AB}, \sigma_{AB} \in \mathcal{S}_{AB}$:

1. **Continuity:** The map $\rho_{AB} \mapsto D_A(\rho_{AB}||\sigma_{AB})$ is continuous.
2. **Non-negativity:** $D_A(\rho_{AB}||\sigma_{AB}) \geq 0$ and
   (2.1) $D_A(\rho_{AB}||\sigma_{AB})=0$ if, and only if, $\rho_{AB} = \mathbb{E}_A^*(\rho_{AB})$.
3. **Semi-superadditivity:** $D_A(\rho_{AB}||\sigma_A \otimes \sigma_B) \geq D(\rho_A||\sigma_A)$ and
   (3.1) **Semi-additivity:** if $\rho_{AB} = \rho_A \otimes \rho_B$,
   $D_A(\rho_A \otimes \rho_B||\sigma_A \otimes \sigma_B) = D(\rho_A||\sigma_A)$.

Minimal conditional expectation

Let $\mathcal{H}_{AB} = \mathcal{H}_A \otimes \mathcal{H}_B$ and $\sigma_{AB} \in \mathcal{S}_{AB}$, $f_{AB} \in \mathcal{A}_{AB}$. We define the **minimal conditional expectation** of σ_{AB} on A by

$$\mathbb{E}_A^{\sigma}(f_{AB}) := \operatorname{tr}_A[\eta_A^{\sigma} \, f_{AB} \, \eta_A^{\sigma\dagger}], \tag{9}$$

where $\eta_A^{\sigma} := (\operatorname{tr}_A[\sigma_{AB}])^{-1/2} \sigma_{AB}^{1/2}$.

For $\rho_{AB} \in \mathcal{S}_{AB}$, $(\mathbb{E}_A^{\sigma})^*$ (hereafter denoted by $\mathbb{E}_A^*$) is given by

$$\mathbb{E}_A^*(\rho_{AB}) := \sigma_{AB}^{1/2} \, \sigma_B^{-1/2} \, \rho_B \, \sigma_B^{-1/2} \, \sigma_{AB}^{1/2}. \tag{10}$$

It coincides with the Petz recovery map for the partial trace.

Conditional relative entropy by expectations

Conditional relative entropy by expectations

Let $\mathcal{H}_{AB} = \mathcal{H}_A \otimes \mathcal{H}_B$ and $\rho_{AB}, \sigma_{AB} \in S_{AB}$. Let $\mathbb{E}_A^*$ be defined as above. We define the **conditional relative entropy by expectations** of ρ_{AB} and σ_{AB} in A by:

$$D_A^E(\rho_{AB}||\sigma_{AB}) = D(\rho_{AB}||\mathbb{E}_A^*(\rho_{AB})).$$

Property

$D_A^E(\rho_{AB}||\sigma_{AB})$ is a weak conditional relative entropy.

Conditional relative entropy by expectations

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Property

$D_A^E(\rho_{AB}||\sigma_{AB})$ is a weak conditional relative entropy.

Problem

Under which conditions holds

$$D_A(\rho_{AB}||\sigma_{AB}) = D_A^E(\rho_{AB}||\sigma_{AB})?$$

Examples

1. If $[\rho_B, \sigma_{AB}] = [\rho_B, \sigma_B] = [\sigma_B, \sigma_{AB}] = 0$,
$$D_A(\rho_{AB}||\sigma_{AB}) = D_A^E(\rho_{AB}||\sigma_{AB}).$$
2. If $\sigma = \sigma_A \otimes \sigma_B$, then
$$D_A(\rho_{AB}||\sigma_{AB}) = D_A^E(\rho_{AB}||\sigma_{AB}).$$
3. $D_A(\rho_{AB}||\sigma_{AB}) = 0 \Leftrightarrow D_A^E(\rho_{AB}||\sigma_{AB}) = 0.$

In general, it is an open question.

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In general, it is an open question.

Relation with the classical case

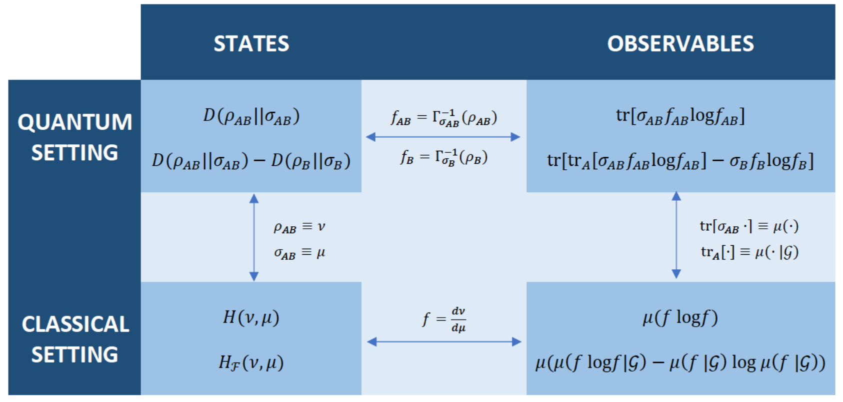

Figura: Identification between classical and quantum quantities when the states considered are classical.

Quasi-factorization CRE by expectations

Let $\mathcal{H}_{AB} = \mathcal{H}_A \otimes \mathcal{H}_B$ and $\rho_{AB}, \sigma_{AB} \in \mathcal{S}_{AB}$. The following inequality holds

$$(1 - \xi(\sigma_{AB})) D(\rho_{AB} || \sigma_{AB}) \leq D_A^E(\rho_{AB} || \sigma_{AB}) + D_B^E(\rho_{AB} || \sigma_{AB}), \quad (11)$$

where

$$\xi(\sigma_{ABC}) = 2\left(E_1(t) + E_2(t)\right),$$

and

$$E_1(t) = \int_{-\infty}^{+\infty} dt \beta_0(t) \left\| \sigma_B^{\frac{-1+it}{2}} \sigma_{AB}^{\frac{1-it}{2}} \sigma_A^{\frac{-1+it}{2}} - \mathbb{1}_{AB} \right\|_\infty \left\| \sigma_A^{-1/2} \sigma_{AB}^{\frac{1+it}{2}} \sigma_B^{-1/2} \right\|_\infty$$

$$E_2(t) = \int_{-\infty}^{+\infty} dt\, \beta_0(t) \left\| \sigma_B^{\frac{-1-it}{2}} \sigma_{AB}^{\frac{1+it}{2}} \sigma_A^{\frac{-1-it}{2}} - \mathbb{1}_{AB} \right\|_\infty,$$

with $\beta_0(t) = \dfrac{\pi}{2}(\cosh(\pi t) + 1)^{-1}$.

Note that $\xi(\sigma_{AB}) = 0$ if σ_{AB} is a tensor product between A and B.

6. Quantum spin lattices

QUANTUM SPIN LATTICES

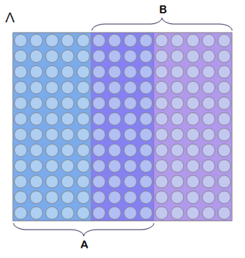

Figura: A quantum spin lattice system Λ and $A, B \subseteq \Lambda$ such that $A \cup B = \Lambda$.

PROBLEM

For a certain $\mathcal{L}_\Lambda^*$, can we prove $\alpha(\mathcal{L}_\Lambda^*) > 0$ using the result of quasi-factorization of the relative entropy?

Quasi-factorization of the relative entropy.

+

Recursive geometric argument.
Lower bound for the log-Sobolev constant in terms of a conditional log-Sobolev constant.

+

Positive (and size-independent) conditional log-Sobolev constant.

$\Downarrow$

Positive log-Sobolev constant.

Quasi-factorization of the relative entropy.

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Positive log-Sobolev constant.

General quasi-factorization for σ a tensor product

Let $\mathcal{H}_\Lambda = \bigotimes_{x\in\Lambda} \mathcal{H}_x$ and $\rho_\Lambda, \sigma_\Lambda \in \mathcal{S}_\Lambda$ such that $\sigma_\Lambda = \bigotimes_{x\in\Lambda} \sigma_x$. The following inequality holds:

$$D(\rho_\Lambda || \sigma_\Lambda) \leq \sum_{x\in\Lambda} D_x(\rho_\Lambda || \sigma_\Lambda). \tag{12}$$

Proof based on **strong subadditivity**.

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Proof based on **strong subadditivity**.

The **heat-bath dynamics**, with product fixed point, has a positive log-Sobolev constant.

Consider the local Lindbladian

$$\mathcal{L}_x^* := \mathbb{E}_x^* - \mathbb{1}_\Lambda,$$

and the global Lindbladian

$$\mathcal{L}_\Lambda^* = \sum_{x \in \Lambda} \mathcal{L}_x^*.$$

Since

$$\mathbb{E}_x^*(\rho_\Lambda) = \sigma_\Lambda^{1/2} \sigma_{x^c}^{-1/2} \rho_{x^c} \sigma_{x^c}^{-1/2} \sigma_\Lambda^{1/2} = \sigma_x \otimes \rho_{x^c}$$

for every $\rho_\Lambda \in \mathcal{S}_\Lambda$, we have

$$\mathcal{L}_\Lambda^*(\rho_\Lambda) = \sum_{x \in \Lambda} (\sigma_x \otimes \rho_{x^c} - \rho_\Lambda).$$

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Conditional log-Sobolev constant

For $A \subset \Lambda$, we define the **conditional log-Sobolev constant** of $\mathcal{L}_\Lambda^*$ in A by

$$\alpha_\Lambda(\mathcal{L}_A^*) := \inf_{\rho_\Lambda \in \mathcal{S}_\Lambda} \frac{-\operatorname{tr}[\mathcal{L}_A^*(\rho_\Lambda)(\log \rho_\Lambda - \log \sigma_\Lambda)]}{2 D_A(\rho_\Lambda || \sigma_\Lambda)},$$

where σ_Λ is the fixed point of the evolution, and $D_A(\rho_\Lambda||\sigma_\Lambda)$ is the conditional relative entropy.

Lemma

$$\alpha_\Lambda(\mathcal{L}_x^*) \geq \frac{1}{2}.$$

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Positive log-Sobolev constant

$$\alpha(\mathcal{L}_\Lambda^*) \geq \frac{1}{2}.$$

$$\begin{aligned} D(\rho_\Lambda || \sigma_\Lambda) &\leq \sum_{x\in\Lambda} D_x(\rho_\Lambda||\sigma_\Lambda) \\ &\leq \sum_{x\in\Lambda} \frac{-\operatorname{tr}[\mathcal{L}_x^*(\rho_\Lambda)(\log\rho_\Lambda - \log\sigma_\Lambda)]}{2\alpha_\Lambda(\mathcal{L}_x^*)} \\ &\leq \frac{1}{2\inf\limits_{x\in\Lambda}\alpha_\Lambda(\mathcal{L}_x^*)} \sum_{x\in\Lambda} -\operatorname{tr}[\mathcal{L}_x^*(\rho_\Lambda)(\log\rho_\Lambda - \log\sigma_\Lambda)] \\ &= \frac{1}{2\inf\limits_{x\in\Lambda}\alpha_\Lambda(\mathcal{L}_x^*)} \left(-\operatorname{tr}[\mathcal{L}_\Lambda^*(\rho_\Lambda)(\log\rho_\Lambda - \log\sigma_\Lambda)]\right) \\ &\leq \left(-\operatorname{tr}[\mathcal{L}_\Lambda^*(\rho_\Lambda)(\log\rho_\Lambda - \log\sigma_\Lambda)]\right). \end{aligned}$$

Positive log-Sobolev constant

$$\alpha(\mathcal{L}_\Lambda^*) \geq \frac{1}{2}.$$

$$\begin{aligned}
D(\rho_\Lambda || \sigma_\Lambda) &\leq \sum_{x\in\Lambda} D_x(\rho_\Lambda || \sigma_\Lambda) \\
&\leq \sum_{x\in\Lambda} \frac{-\operatorname{tr}[\mathcal{L}_x^*(\rho_\Lambda)(\log\rho_\Lambda - \log\sigma_\Lambda)]}{2\alpha_\Lambda(\mathcal{L}_x^*)} \\
&\leq \frac{1}{2\inf\limits_{x\in\Lambda} \alpha_\Lambda(\mathcal{L}_x^*)} \sum_{x\in\Lambda} -\operatorname{tr}[\mathcal{L}_x^*(\rho_\Lambda)(\log\rho_\Lambda - \log\sigma_\Lambda)] \\
&= \frac{1}{2\inf\limits_{x\in\Lambda} \alpha_\Lambda(\mathcal{L}_x^*)} \left(-\operatorname{tr}[\mathcal{L}_\Lambda^*(\rho_\Lambda)(\log\rho_\Lambda - \log\sigma_\Lambda)]\right) \\
&\leq \left(-\operatorname{tr}[\mathcal{L}_\Lambda^*(\rho_\Lambda)(\log\rho_\Lambda - \log\sigma_\Lambda)]\right).
\end{aligned}$$

Open problems

Problem 1

Can we use any of the quasi-factorization results to prove log-Sobolev constants in a more general setting?

(Kastoryano-Brandao, '15) The heat-bath dynamics, with σ_Λ the Gibbs state of a commuting Hamiltonian, has positive spectral gap. $\Rightarrow$ Log-Sobolev constant?

Problem 2

Is there a better definition for conditional relative entropy?

Problem 3

When do $D_A(\rho_{AB}||\sigma_{AB})$ and $D_A^E(\rho_{AB}||\sigma_{AB})$ coincide?

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7. Proof of quasi-factorization for the CRE

Quasi-factorization for the CRE

Let $\mathcal{H}_{ABC} = \mathcal{H}_A \otimes \mathcal{H}_B \otimes \mathcal{H}_C$ and $\rho_{ABC}, \sigma_{ABC} \in \mathcal{S}_{ABC}$. Then, the following inequality holds

$$(1 - 2\|H(\sigma_{AC})\|_\infty) D(\rho_{ABC}||\sigma_{ABC}) \leq D_{AB}(\rho_{ABC}||\sigma_{ABC}) + D_{BC}(\rho_{ABC}||\sigma_{ABC}),$$

where

$$H(\sigma_{AC}) = \sigma_A^{-1/2} \otimes \sigma_C^{-1/2} \sigma_{AC} \, \sigma_A^{-1/2} \otimes \sigma_C^{-1/2} - \mathbb{1}_{AC}.$$

Note that $H(\sigma_{AC}) = 0$ if σ_{AC} is a tensor product between A and C.

$$(1 + 2\|H(\sigma_{AB})\|_\infty) D(\rho_{AB}||\sigma_{AB}) \geq D(\rho_A||\sigma_A) + D(\rho_B||\sigma_B)$$

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Note that $H(\sigma_{AC}) = 0$ if σ_{AC} is a tensor product between A and C.

$$\boxed{(1 + 2\|H(\sigma_{AB})\|_\infty) D(\rho_{AB}||\sigma_{AB}) \geq D(\rho_A||\sigma_A) + D(\rho_B||\sigma_B)}$$

Step 1

$$D(\rho_{AB}||\sigma_{AB}) \geq D(\rho_A||\sigma_A) + D(\rho_B||\sigma_B) - \log \operatorname{tr} M, \tag{13}$$

where $M = \exp\left[\log \sigma_{AB} - \log \sigma_A \otimes \sigma_B + \log \rho_A \otimes \rho_B\right]$.

It holds that:

$$D(\rho_{AB}||\sigma_{AB}) - [D(\rho_A||\sigma_A) + D(\rho_B||\sigma_B)] =$$

$$= \operatorname{tr}\left[\rho_{AB}\left(\log \rho_{AB} - \underbrace{\left(\log \sigma_{AB} - \log \sigma_A \otimes \sigma_B + \log \rho_A \otimes \rho_B\right)}_{\log M}\right)\right]$$

$$= D(\rho_{AB}||M) \geq -\log \operatorname{tr} M.$$

Step 1

$$D(\rho_{AB}||\sigma_{AB}) \geq D(\rho_A||\sigma_A) + D(\rho_B||\sigma_B) - \log \operatorname{tr} M, \qquad (13)$$

where $M = \exp\left[\log \sigma_{AB} - \log \sigma_A \otimes \sigma_B + \log \rho_A \otimes \rho_B\right]$.

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Step 2

$$\log \operatorname{tr} M \leq \operatorname{tr}[L(\sigma_{AB})\,(\rho_A - \sigma_A) \otimes (\rho_B - \sigma_B)], \tag{14}$$

where

$$L(\sigma_{AB}) = \mathcal{T}_{\sigma_A \otimes \sigma_B}(\sigma_{AB}) - \mathbb{1}_{AB}.$$

Theorem (Lieb)

Let g a positive operator, and define

$$\mathcal{T}_g(f) = \int_0^\infty \mathrm{d}t\,(g+t)^{-1} f (g+t)^{-1}.$$

$\mathcal{T}_g$ is positive-semidefinite if g is. We have that

$$\operatorname{tr}[\exp(-f+g+h)] \leq \operatorname{tr}\left[e^h \mathcal{T}_{e^f}(e^g)\right].$$

We apply Lieb's theorem to the previous equation :

$$\begin{aligned} \operatorname{tr} M &\leq \operatorname{tr}[\rho_A \otimes \rho_B \mathcal{T}_{\sigma_A \otimes \sigma_B}(\sigma_{AB})] \\ &= \operatorname{tr}\left[\rho_A \otimes \rho_B \underbrace{\left(\mathcal{T}_{\sigma_A \otimes \sigma_B}(\sigma_{AB}) - \mathbb{1}_{AB}\right)}_{L(\sigma_{AB})}\right] + \underbrace{\operatorname{tr}[\rho_A \otimes \rho_B]}_{1}. \end{aligned}$$

By using the fact $\log(x) \leq x - 1$, we conclude

$$\log \operatorname{tr} M \leq \operatorname{tr} M - 1 \leq \operatorname{tr}[L(\sigma_{AB})\,\rho_A \otimes \rho_B].$$

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Lemma (Sutter et al.)

For $f \in \mathcal{S}_{AB}$ and $g \in \mathcal{A}_{AB}$ the following holds:

$$\mathcal{T}_g(f) = \int_{-\infty}^{\infty} dt \, \beta_0(t) \, g^{\frac{-1-it}{2}} \, f \, g^{\frac{-1+it}{2}} ,$$

with

$$\beta_0(t) = \frac{\pi}{2}(\cosh(\pi t) + 1)^{-1}.$$

Lemma

For every operator $O_A \in \mathcal{B}_A$ and $O_B \in \mathcal{B}_B$ the following holds:

$$\operatorname{tr}[L(\sigma_{AB}) \, \sigma_A \otimes O_B] = \operatorname{tr}[L(\sigma_{AB}) \, O_A \otimes \sigma_B] = 0.$$

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Step 3

$$\operatorname{tr}[L(\sigma_{AB})\,(\rho_A - \sigma_A) \otimes (\rho_B - \sigma_B)] \leq 2\|L(\sigma_{AB})\|_\infty D(\rho_{AB}\|\sigma_{AB}). \tag{15}$$

In virtue of Hölder's inequality and tensorization of Schatten norms,

$$\begin{aligned}\operatorname{tr}[L(\sigma_{AB})\,(\rho_A - \sigma_A) \otimes (\rho_B - \sigma_B)] \leq \\ \|L(\sigma_{AB})\|_\infty \|(\rho_A - \sigma_A) \otimes (\rho_B - \sigma_B)\|_1 \\ = \|L(\sigma_{AB})\|_\infty \|\rho_A - \sigma_A\|_1 \|\rho_B - \sigma_B\|_1.\end{aligned}$$

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Theorem (Pinsker)

For ρ_{AB} and σ_{AB} density matrices, it holds that

$$\|\rho_{AB} - \sigma_{AB}\|_1^2 \leq 2D(\rho_{AB}||\sigma_{AB}).$$

Using Pinsker's theorem and the data-processing inequality, we can conclude:

$$\operatorname{tr}[L(\sigma_{AB})(\rho_A - \sigma_A) \otimes (\rho_B - \sigma_B)] \leq 2\|L(\sigma_{AB})\|_\infty D(\rho_{AB}||\sigma_{AB}).$$

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Using Pinsker's theorem and the data-processing inequality, we can conclude:

$$\operatorname{tr}[L(\sigma_{AB})\,(\rho_A - \sigma_A) \otimes (\rho_B - \sigma_B)] \leq 2\left\| L(\sigma_{AB}) \right\|_\infty D(\rho_{AB}||\sigma_{AB}).$$

Step 4

$$\left\| L(\sigma_{AB}) \right\|_\infty \leq \left\| \sigma_A^{-1/2} \otimes \sigma_B^{-1/2} \, \sigma_{AB} \, \sigma_A^{-1/2} \otimes \sigma_B^{-1/2} - \mathbb{1}_{AB} \right\|_\infty . \quad (16)$$

For further knowledge, Arxiv: 1705.03521 and 1804.09525