Universal recoverability in quantum information theory

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Main message

- Entropy inequalities established in the 1970s are a mathematical consequence of the postulates of quantum physics
- They are helpful in determining the ultimate limits on many physical processes (communication, thermodynamics, uncertainty relations)
- Many of these entropy inequalities are equivalent to each other, so we can say that together they constitute a fundamental law of quantum information theory
- There has been recent interest in refining these inequalities, trying to understand how well one can attempt to reverse an irreversible physical process
- We discuss progress in this direction

Background — entropies

Umegaki relative entropy [Ume62]

The quantum relative entropy is a measure of dissimilarity between two quantum states. Defined for state ρ and positive semi-definite σ as

$$D(\rho\|\sigma) \equiv \text{Tr}\{\rho[\log \rho - \log \sigma]\}$$

whenever $\text{supp}(\rho) \subseteq \text{supp}(\sigma)$ and $+\infty$ otherwise

Physical interpretation with quantum Stein's lemma [HP91, NO00]

Given are n quantum systems, all of which are prepared in either the state ρ or σ. With a constraint of $\varepsilon \in (0, 1)$ on the Type I error of misidentifying ρ, then the optimal error exponent for the Type II error of misidentifying σ is $D(\rho\|\sigma)$.

Background — entropies

Relative entropy as "mother" entropy

Many important entropies can be written in terms of relative entropy:

- $H(A)_\rho \equiv -D(\rho_A \| I_A)$ (entropy)
- $H(A|B)_\rho \equiv -D(\rho_{AB} \| I_A \otimes \rho_B)$ (conditional entropy)
- $I(A;B)_\rho \equiv D(\rho_{AB} \| \rho_A \otimes \rho_B)$ (mutual information)
- $I(A;B|C)_\rho \equiv D(\rho_{ABC} \| \exp\{\log \rho_{AC} + \log \rho_{BC} - \log \rho_C\})$ (cond. MI)

Equivalences

- $H(A|B)_\rho = H(AB)_\rho - H(B)_\rho$
- $I(A;B)_\rho = H(A)_\rho + H(B)_\rho - H(AB)_\rho$
- $I(A;B)_\rho = H(B)_\rho - H(B|A)_\rho$
- $I(A;B|C)_\rho = H(AC)_\rho + H(BC)_\rho - H(ABC)_\rho - H(C)_\rho$
- $I(A;B|C)_\rho = H(B|C)_\rho - H(B|AC)_\rho$

Fundamental law of quantum information theory

Monotonicity of quantum relative entropy [Lin75, Uhl77]

Let ρ be a state, let σ be positive semi-definite, and let $\mathcal{N}$ be a quantum channel. Then

$$D(\rho\|\sigma) \geq D(\mathcal{N}(\rho)\|\mathcal{N}(\sigma))$$

"Distinguishability does not increase under a physical process"
Characterizes a fundamental irreversibility in any physical process

Proof approaches

- Lieb concavity theorem [L73]
- relative modular operator method (see, e.g., [NP04])
- quantum Stein's lemma [BS03]

Strong subadditivity

Strong subadditivity [LR73]

Let ρ_{ABC} be a tripartite quantum state. Then

$$I(A;B|C)_\rho \geq 0$$

Equivalent statements (by definition)

- Entropy sum of two individual systems is larger than entropy sum of their union and intersection:

$$H(AC)_\rho + H(BC)_\rho \geq H(ABC)_\rho + H(C)_\rho$$

- Conditional entropy does not decrease under the loss of system A:

$$H(B|C)_\rho \geq H(B|AC)_\rho$$

Equality conditions [Pet86, Pet88]

When does equality in monotonicity of relative entropy hold?

- $D(\rho\|\sigma) = D(\mathcal{N}(\rho)\|\mathcal{N}(\sigma))$ iff $\exists$ a recovery map $\mathcal{P}_{\sigma,\mathcal{N}}$ such that

$$\rho = (\mathcal{P}_{\sigma,\mathcal{N}} \circ \mathcal{N})(\rho), \qquad \sigma = (\mathcal{P}_{\sigma,\mathcal{N}} \circ \mathcal{N})(\sigma)$$

- This "Petz" recovery map has the following explicit form [HJPW04]:

$$\mathcal{P}_{\sigma,\mathcal{N}}(\omega) \equiv \sigma^{1/2}\mathcal{N}^{\dagger}\left((\mathcal{N}(\sigma))^{-1/2}\omega(\mathcal{N}(\sigma))^{-1/2}\right)\sigma^{1/2}$$

- Classical case: Distributions p_X and q_X and a channel $\mathcal{N}(y|x)$. Then the Petz recovery map $\mathcal{P}(x|y)$ is given by the Bayes theorem:

$$\mathcal{P}(x|y)q_Y(y) = \mathcal{N}(y|x)q_X(x)$$

where $q_Y(y) \equiv \sum_x \mathcal{N}(y|x)q_X(x)$

More on Petz recovery map

- Linear, completely positive by inspection and trace non-increasing because

$$\begin{aligned}\operatorname{Tr}\{\mathcal{P}_{\sigma,\mathcal{N}}(\omega)\} &= \operatorname{Tr}\{\sigma^{1/2}\mathcal{N}^\dagger\left((\mathcal{N}(\sigma))^{-1/2}\omega(\mathcal{N}(\sigma))^{-1/2}\right)\sigma^{1/2}\} \\ &= \operatorname{Tr}\{\sigma\mathcal{N}^\dagger\left((\mathcal{N}(\sigma))^{-1/2}\omega(\mathcal{N}(\sigma))^{-1/2}\right)\} \\ &= \operatorname{Tr}\{\mathcal{N}(\sigma)(\mathcal{N}(\sigma))^{-1/2}\omega(\mathcal{N}(\sigma))^{-1/2}\} \\ &\leq \operatorname{Tr}\{\omega\}\end{aligned}$$

- The Petz recovery map perfectly recovers σ from $\mathcal{N}(\sigma)$:

$$\begin{aligned}\mathcal{P}_{\sigma,\mathcal{N}}(\mathcal{N}(\sigma)) &= \sigma^{1/2}\mathcal{N}^\dagger\left((\mathcal{N}(\sigma))^{-1/2}\mathcal{N}(\sigma)(\mathcal{N}(\sigma))^{-1/2}\right)\sigma^{1/2} \\ &= \sigma^{1/2}\mathcal{N}^\dagger(I)\,\sigma^{1/2} \\ &= \sigma\end{aligned}$$

Petz recovery map for strong subadditivity

- Strong subadditivity is a special case of monotonicity of relative entropy with $\rho = \omega_{ABC}$, $\sigma = \omega_{AC} \otimes I_B$, and $\mathcal{N} = \mathrm{Tr}_A$
- Then $\mathcal{N}^\dagger(\cdot) = (\cdot) \otimes I_A$ and Petz recovery map is

$$\mathcal{P}_{C\to AC}(\tau_C) = \omega_{AC}^{1/2}\left(\omega_C^{-1/2}\tau_C\omega_C^{-1/2} \otimes I_A\right)\omega_{AC}^{1/2}$$

- Interpretation: If system A is lost but $H(B|C)_\omega = H(B|AC)_\omega$, then one can recover the full state on ABC by performing the Petz recovery map on system C of ω_{BC}, i.e.,

$$\omega_{ABC} = \mathcal{P}_{C\to AC}(\omega_{BC})$$

Approximate case

Approximate case would be useful for applications

Approximate case for monotonicity of relative entropy

- What can we say when $D(\rho\|\sigma) - D(\mathcal{N}(\rho)\|\mathcal{N}(\sigma)) = \varepsilon$?
- Does there exist a CPTP map $\mathcal{R}$ that recovers σ perfectly from $\mathcal{N}(\sigma)$ while recovering ρ from $\mathcal{N}(\rho)$ approximately? [WL12]

Approximate case for strong subadditivity

- What can we say when $H(B|C)_\omega - H(B|AC)_\omega = \varepsilon$?
- Is ω_{ABC} approximately recoverable from ω_{BC} by performing a recovery map on system C alone? [WL12]

Other measures of similarity for quantum states

Trace distance

Trace distance between ρ and σ is $\|\rho - \sigma\|_1$ where $\|A\|_1 = \text{Tr}\{\sqrt{A^\dagger A}\}$. Has a one-shot operational interpretation as the bias in success probability when distinguishing ρ and σ with an optimal quantum measurement.

Fidelity [Uhl76]

Fidelity between ρ and σ is $F(\rho, \sigma) \equiv \|\sqrt{\rho}\sqrt{\sigma}\|_1^2$. Has a one-shot operational interpretation as the probability with which a purification of ρ could pass a test for being a purification of σ.

Breakthrough result of [FR14]

Remainder term for strong subadditivity [FR14]

$\exists$ unitary channels $\mathcal{U}_C$ and $\mathcal{V}_{AC}$ such that

$$H(B|C)_\omega - H(B|AC)_\omega \geq -\log F(\omega_{ABC}, (\mathcal{V}_{AC} \circ \mathcal{P}_{C \to AC} \circ \mathcal{U}_C)(\omega_{BC}))$$

Nothing known from [FR14] about these unitaries! However, can conclude that $I(A;B|C)$ is small iff ω_{ABC} is approximately recoverable from system C alone after the loss of system A.

Remainder term for monotonicity of relative entropy [BLW14]

$\exists$ unitary channels $\mathcal{U}$ and $\mathcal{V}$ such that

$$D(\rho\|\sigma) - D(\mathcal{N}(\rho)\|\mathcal{N}(\sigma)) \geq -\log F(\rho, (\mathcal{V} \circ \mathcal{P}_{\sigma,\mathcal{N}} \circ \mathcal{U})(\mathcal{N}(\rho)))$$

Again, nothing known from [BLW14] about $\mathcal{U}$ and $\mathcal{V}$.

New result of [Wil15, JSRWW15]

Recoverability Theorem

Let ρ and σ satisfy $\text{supp}(\rho) \subseteq \text{supp}(\sigma)$ and let $\mathcal{N}$ be a channel. Then

$$D(\rho\|\sigma) - D(\mathcal{N}(\rho)\|\mathcal{N}(\sigma)) \geq -\int_{-\infty}^{\infty} dt\, p(t) \log\left[F\left(\rho, \mathcal{P}_{\sigma,\mathcal{N}}^{t/2}(\mathcal{N}(\rho))\right)\right],$$

where $p(t)$ is a distribution and $\mathcal{P}_{\sigma,\mathcal{N}}^{t}$ is a rotated Petz recovery map:

$$\mathcal{P}_{\sigma,\mathcal{N}}^{t}(\cdot) \equiv \left(\mathcal{U}_{\sigma,t} \circ \mathcal{P}_{\sigma,\mathcal{N}} \circ \mathcal{U}_{\mathcal{N}(\sigma),-t}\right)(\cdot),$$

$\mathcal{P}_{\sigma,\mathcal{N}}$ is the Petz recovery map, and $\mathcal{U}_{\sigma,t}$ and $\mathcal{U}_{\mathcal{N}(\sigma),-t}$ are defined from $\mathcal{U}_{\omega,t}(\cdot) \equiv \omega^{it}(\cdot)\,\omega^{-it}$, with ω a positive semi-definite operator.

Two tools for proof

Rényi generalization of a relative entropy difference and the Stein–Hirschman operator interpolation theorem

Universal Recovery

Universal Recoverability Corollary

Let ρ and σ satisfy $\text{supp}(\rho) \subseteq \text{supp}(\sigma)$ and let $\mathcal{N}$ be a channel. Then

$$D(\rho\|\sigma) - D(\mathcal{N}(\rho)\|\mathcal{N}(\sigma)) \geq -\log F\left(\rho, \mathcal{R}_{\sigma,\mathcal{N}}\left(\mathcal{N}(\rho)\right)\right),$$

where

$$\mathcal{R}_{\sigma,\mathcal{N}} \equiv \int_{-\infty}^{\infty} dt\, p(t)\, \mathcal{P}_{\sigma,\mathcal{N}}^{t/2}$$

(follows from concavity of logarithm and fidelity)

Universal Distribution

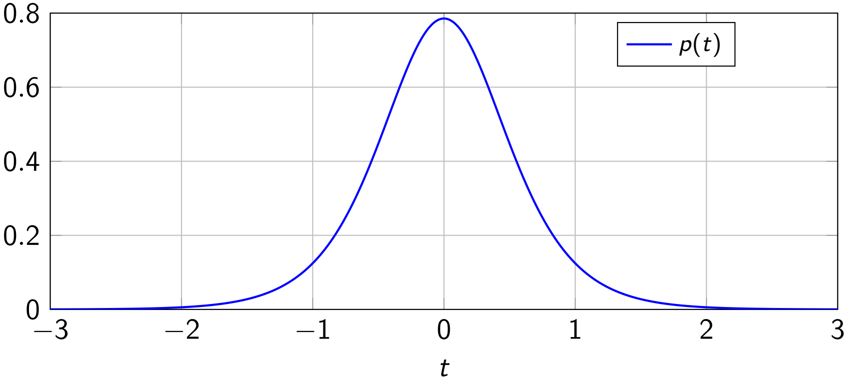

Figure: This plot depicts the probability density $p(t) := \frac{\pi}{2}\left(\cosh(\pi t) + 1\right)^{-1}$ as a function of $t \in \mathbb{R}$. We see that it is peaked around $t = 0$ which corresponds to the Petz recovery map.

Rényi generalizations of a relative entropy difference

Definition from [BSW14, SBW14]

$$\widetilde{\Delta}_\alpha(\rho,\sigma,\mathcal{N}) \equiv \frac{2}{\alpha'} \log \left\| \left(\mathcal{N}(\rho)^{-\alpha'/2} \mathcal{N}(\sigma)^{\alpha'/2} \otimes I_E \right) U \sigma^{-\alpha'/2} \rho^{1/2} \right\|_{2\alpha},$$

where $\alpha \in (0,1) \cup (1,\infty)$, $\alpha' \equiv (\alpha-1)/\alpha$, and $U_{S\to BE}$ is an isometric extension of $\mathcal{N}$.

Important properties

$$\lim_{\alpha\to 1} \widetilde{\Delta}_\alpha(\rho,\sigma,\mathcal{N}) = D(\rho\|\sigma) - D(\mathcal{N}(\rho)\|\mathcal{N}(\sigma)).$$

$$\widetilde{\Delta}_{1/2}(\rho,\sigma,\mathcal{N}) = -\log F\left(\rho, \mathcal{P}_{\sigma,\mathcal{N}}\left(\mathcal{N}(\rho)\right)\right).$$

Stein–Hirschman operator interpolation theorem (setup)

Let $S \equiv \{z \in \mathbb{C} : 0 < \operatorname{Re}\{z\} < 1\}$, and let $L(\mathcal{H})$ be the space of bounded linear operators acting on $\mathcal{H}$. Let $G : \overline{S} \to L(\mathcal{H})$ be an operator-valued function bounded on $\overline{S}$, holomorphic on S, and continuous on the boundary $\partial\overline{S}$. Let $\theta \in (0,1)$ and define p_θ by

$$\frac{1}{p_\theta} = \frac{1-\theta}{p_0} + \frac{\theta}{p_1} \ ,$$

where $p_0, p_1 \in [1, \infty]$.

Stein–Hirschman operator interpolation theorem (statement)

Then the following bound holds

$$\log \|G(\theta)\|_{p_\theta} \leq \int_{-\infty}^{\infty} dt \ \left(\alpha_\theta(t) \log\left[\|G(it)\|_{p_0}^{1-\theta}\right] + \beta_\theta(t) \log\left[\|G(1+it)\|_{p_1}^{\theta}\right]\right) ,$$

$$\text{where } \alpha_\theta(t) \equiv \frac{\sin(\pi\theta)}{2(1-\theta)\left[\cosh(\pi t) - \cos(\pi\theta)\right]},$$

$$\beta_\theta(t) \equiv \frac{\sin(\pi\theta)}{2\theta\left[\cosh(\pi t) + \cos(\pi\theta)\right]},$$

$$\lim_{\theta \searrow 0} \beta_\theta(t) = p(t).$$

Proof of Recoverability Theorem

Tune parameters

$$\text{Pick } G(z) \equiv \left([\mathcal{N}(\rho)]^{z/2} [\mathcal{N}(\sigma)]^{-z/2} \otimes I_E \right) U \sigma^{z/2} \rho^{1/2},$$

$$p_0 = 2, \;\; p_1 = 1, \;\; \theta \in (0,1) \;\; \Rightarrow p_\theta = \frac{2}{1+\theta}$$

Evaluate norms

$$\|G(it)\|_2 = \left\| \left(\mathcal{N}(\rho)^{it/2} \mathcal{N}(\sigma)^{-it/2} \otimes I_E \right) U \sigma^{it/2} \rho^{1/2} \right\|_2 \leq \left\| \rho^{1/2} \right\|_2 = 1,$$

$$\|G(1+it)\|_1 = \left[F\left(\rho, \mathcal{P}^{t/2}_{\sigma,\mathcal{N}}(\mathcal{N}(\rho)) \right) \right]^{1/2}.$$

Proof of Recoverability Theorem (ctd.)

Apply the Stein–Hirschman theorem

$$\log \left\| \left([\mathcal{N}(\rho)]^{\theta/2} [\mathcal{N}(\sigma)]^{-\theta/2} \otimes I_E \right) U \sigma^{\theta/2} \rho^{1/2} \right\|_{2/(1+\theta)} \leq \int_{-\infty}^{\infty} dt \; \beta_\theta(t) \log \left[F\left(\rho, (\mathcal{P}_{\sigma,\mathcal{N}}^{t/2} \circ \mathcal{N})(\rho) \right)^{\theta/2} \right].$$

Final step

Apply a minus sign, multiply both sides by $2/\theta$, and take the limit as $\theta \searrow 0$ to conclude.

SSA refinement as a special case

Let ρ_{ABC} be a density operator acting on a finite-dimensional Hilbert space $\mathcal{H}_A \otimes \mathcal{H}_B \otimes \mathcal{H}_C$. Then the following inequality holds

$$I(A;B|C)_\rho \geq -\int_{-\infty}^{\infty} dt\, p(t) \log \left[F(\rho_{ABC}, \mathcal{P}^{t/2}_{C\to AC}(\rho_{BC})) \right],$$

where $\mathcal{P}^t_{C\to AC}$ is the following rotated Petz recovery map:

$$\mathcal{P}^t_{C\to AC}(\cdot) \equiv (\mathcal{U}_{\rho_{AC},t} \circ \mathcal{P}_{C\to AC} \circ \mathcal{U}_{\rho_C,-t})(\cdot),$$

the Petz recovery map $\mathcal{P}_{C\to AC}$ is defined as

$$\mathcal{P}_{C\to AC}(\cdot) \equiv \rho_{AC}^{1/2} \left[\rho_C^{-1/2} (\cdot) \rho_C^{-1/2} \otimes I_A \right] \rho_{AC}^{1/2},$$

and the partial isometric maps $\mathcal{U}_{\rho_{AC},t}$ and $\mathcal{U}_{\rho_C,-t}$ are defined as before.

Conclusions

- The result of [FR14] already had a number of important implications in quantum information theory.
- The new result in [Wil15, JSRWW15] applies to relative entropy differences, has a brief proof, and yields a universal recovery map (depending only on σ and $\mathcal{N}$).
- It is still conjectured that the recovery map can be the Petz recovery map alone (not a rotated Petz map).

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