Continuity bounds on quantum entropies and applications to quantum communication

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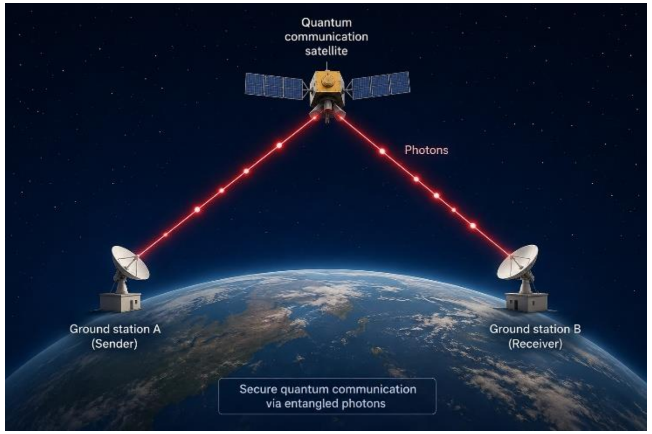
ICE seminar – June 2026

Outline

1. Quantum communication in a nutshell
2. Continuity bounds for entropies
3. Applications of continuity bounds for communication
4. Perspectives

1. Quantum communication in a nutshell

Quantum communication: motivation

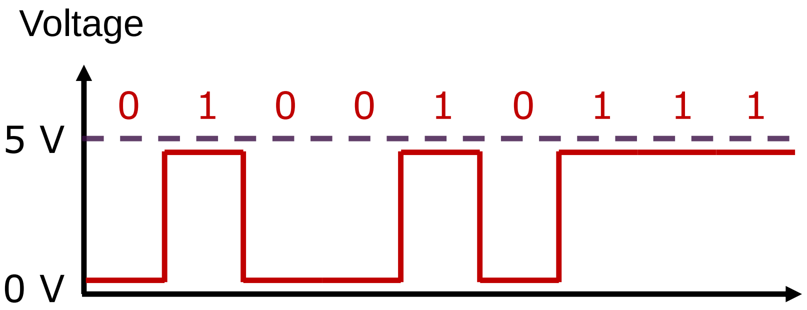


- Promise: future fast, long-distance and secure communications
- Hope: part of a future global *quantum internet*
- Investments: US, UK, and French government spent between **1 and 3 billions euros** in the last 5 years [1,2,3]
- Example: Fibre-based and satellite-to-ground *quantum key distribution* performed over **800 km** in low-loss optical fibres [4] and **2000 km** in free space [5]

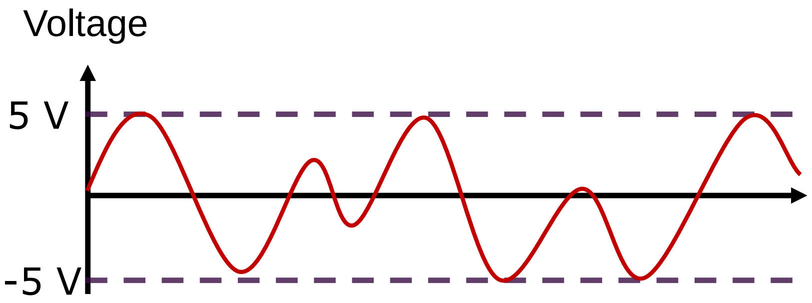
[1] C. S. Smith, *Forbes*, 2023.
[2] UK National Quantum Technology Program, 2024. https://uknqt.ukri.org/
[3] M. Swayne, *The Quantum Insider*, 2024.
[4] S. Wang *et al*., *Nature Photonics,* vol. 16, p. 154, 2022.
[5] Y. A. Chen *et al*., *Nature,* vol. 589, p. 214, 2021.

Encoding information: classical vs quantum

	Discrete encoding	Continuous encoding
Classical	**Digital** signal	**Analogical** signal



Digital signal



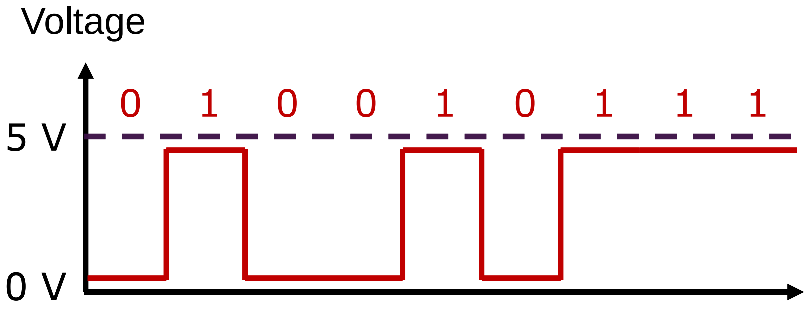
Analogical signal

Encoding information: classical vs quantum

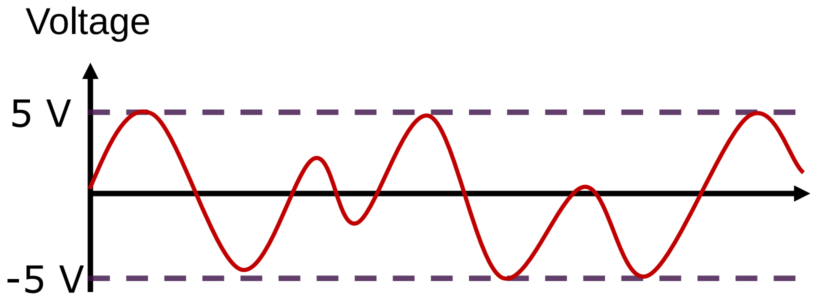
Discrete encoding

Continuous encoding

Classical

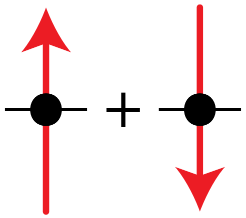


Digital signal



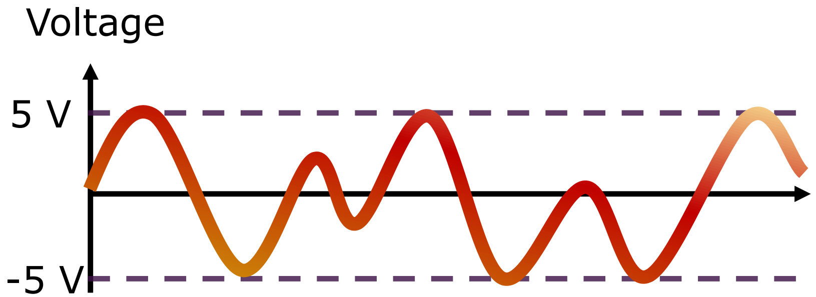
Analogical signal

Quantum



electron

⇒ **Finite**-dimensional system



⇒ **Infinite**-dimensional system

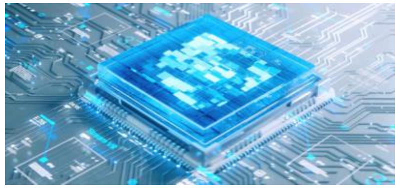
Encoding information: classical vs quantum

Discrete encoding

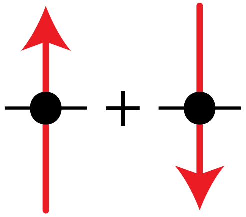
Continuous encoding

Bosonic systems, for instance integrated photonic platforms

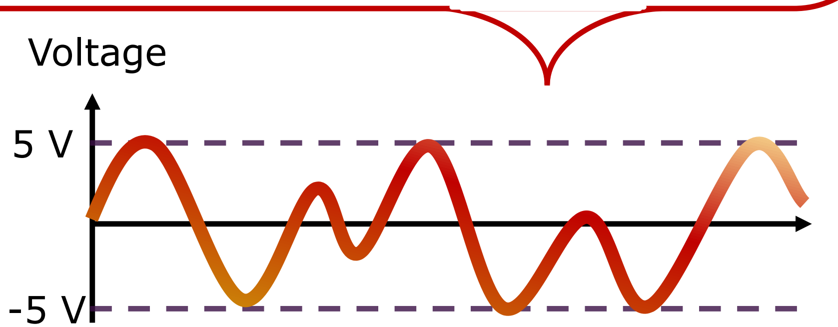
- Better **bandwidths**
- Greater number of **entangled quantum states**
- Powerful **theoretical** tools



Quantum



electron



$\Rightarrow$ **Finite**-dimensional system

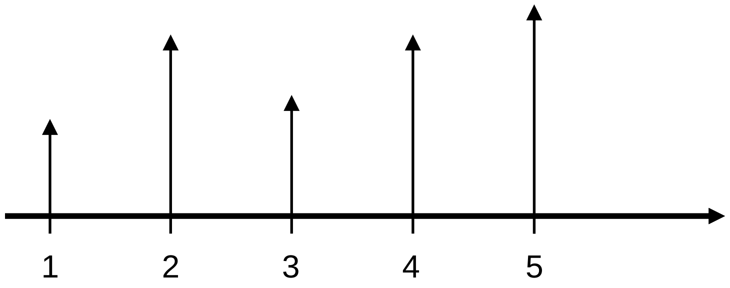
$\Rightarrow$ **Infinite**-dimensional system

States and information content

Classical: Finite set $\mathcal{X} := \{1, 2, \cdots, |\mathcal{X}|\}$

States: $p_X = \{p_X(x)\}_{x\in\mathcal{X}}$

$$p_X(x) \geq 0 \, \forall x, \quad \sum_{x\in\mathcal{X}} p_X(x) = 1$$



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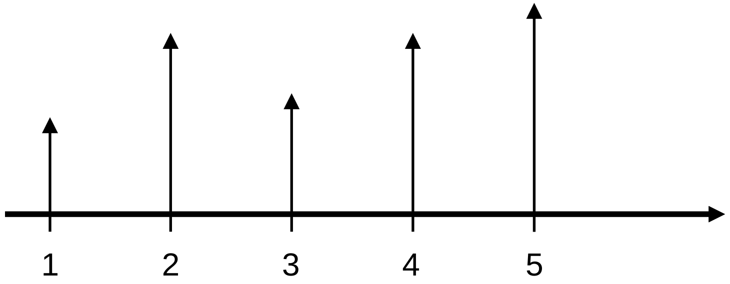

Quantum: Complex Hilbert space $\mathcal{H}$

States: ρ matrix on $\mathcal{H}$

$$\rho = \rho^\dagger, \quad \rho \geq 0, \quad \mathrm{Tr}(\rho) = 1$$

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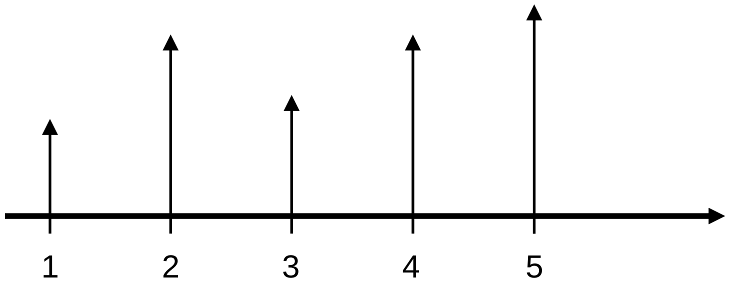


Quantum: Complex Hilbert space $\mathcal{H}$

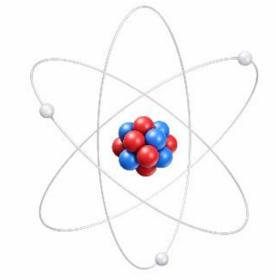
States: ρ matrix on $\mathcal{H}$

$$\rho = \rho^\dagger, \quad \rho \geq 0, \quad \mathrm{Tr}(\rho) = 1$$

$$\rho = \sum_{x \in \mathcal{X}} \overbrace{p_X(x)}^{} \overbrace{|\psi_x\rangle\langle\psi_x|}^{\text{Matrix}}$$

Column vector

Row vector



Information encoded in both: $\{p_X(x)\}, \{|\psi_x\rangle\}$

Obtaining information: quantum measurements

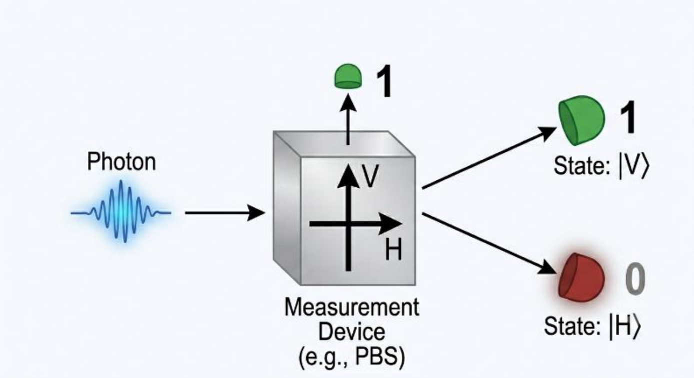
Positive operator-valued measurement (POVM): $\{E_m\}, \quad E_m \geq 0 \quad \forall m, \quad \sum_m E_m = I$

$$\rho \longrightarrow \boxed{\text{POVM}} \longrightarrow \quad q_m = \mathrm{Tr}(\rho E_m)$$

Probability distribution

m represents an outcome

Example: measuring polarization of a photon



Information content: Shannon vs von Neumann entropy

Classical: $p_X = \{p_X(x)\}_{x\in\mathcal{X}}$

Shannon entropy:

$$H(X) = -\sum_{x\in\mathcal{X}} p_X(x)\log p_X(x)$$

$\Rightarrow$ Limit on how much we can **compress** information

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$\Rightarrow$ Limit on how much we can **compress** information

Quantum: $\rho = \sum_{x\in\mathcal{X}} p_X(x)|\psi_x\rangle\langle\psi_x|$

von Neumann entropy:

$$\begin{aligned} S(\rho) &= -\mathrm{Tr}(\rho\log\rho) \\ &= H(X) \end{aligned}$$

$\Rightarrow$ Measure of uncertainty of the quantum system

$\Rightarrow$ Limit on how much we can **compress** quantum information

Noisy channels

Classical: $p_X = \{p_X(x)\}_{x \in \mathcal{X}}$

Classical channel: conditional probability

$$p_Y(y) = \sum_{x \in \mathcal{X}} p_{Y|X}(y|x)\, p_X(x)$$

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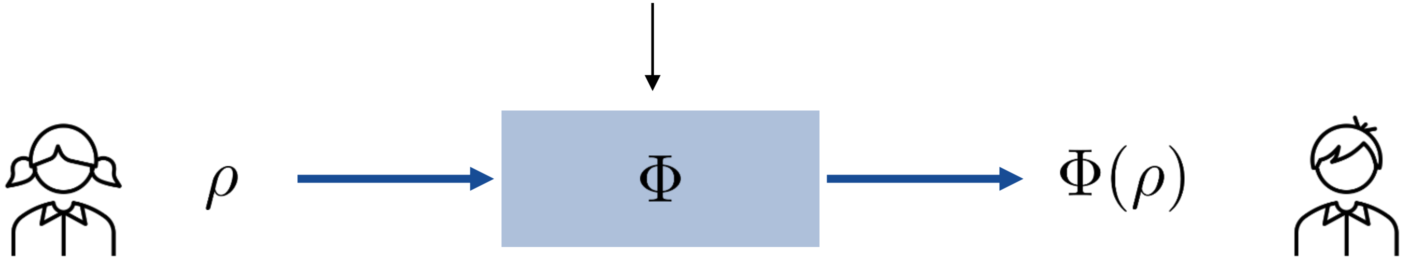
Quantum channel: completely-positive trace-preserving (CPTP) map

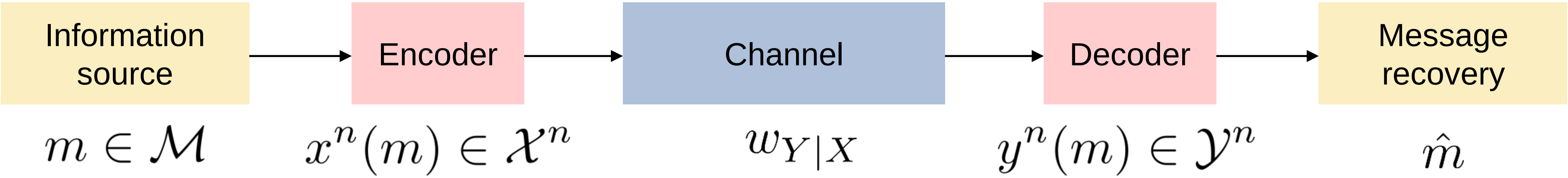


ρ density matrix $\Rightarrow$ $\Phi(\rho)$ density matrix

Examples: optical fibers, free-space, … very well modelled by Gaussian bosonic channels

Communication through noisy channels

Typical classical communication scenario:



Information source → Encoder → Channel → Decoder → Message recovery

$m \in \mathcal{M}$ $x^n(m) \in \mathcal{X}^n$ $w_{Y|X}$ $y^n(m) \in \mathcal{Y}^n$ $\hat{m}$

Communication through noisy channels

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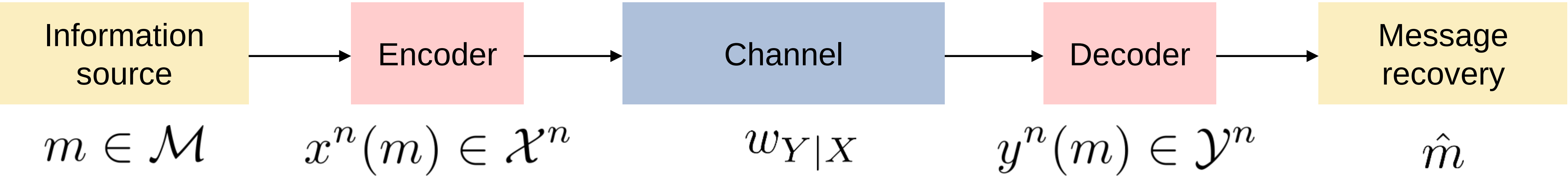

Information source

Encoder

Channel

Decoder

Message recovery

$m \in \mathcal{M}$ $x^n(m) \in \mathcal{X}^n$ $w_{Y|X}$ $y^n(m) \in \mathcal{Y}^n$ $\hat{m}$

- Channel **capacity**: highest achievable rate at which the channel **reliably** transmits information
- One of the most fundamental problems in information theory
- Often leads to some of the most complex problems in information theory
- Importance: orients the design of explicit information coding strategies and sets benchmarks for testing practical communication schemes

Communication through noisy channels

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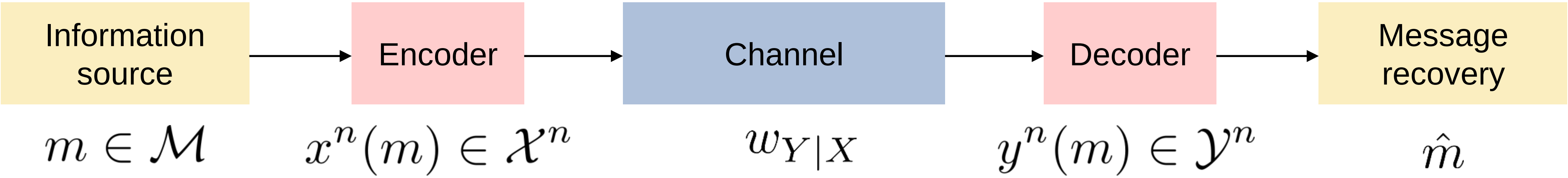

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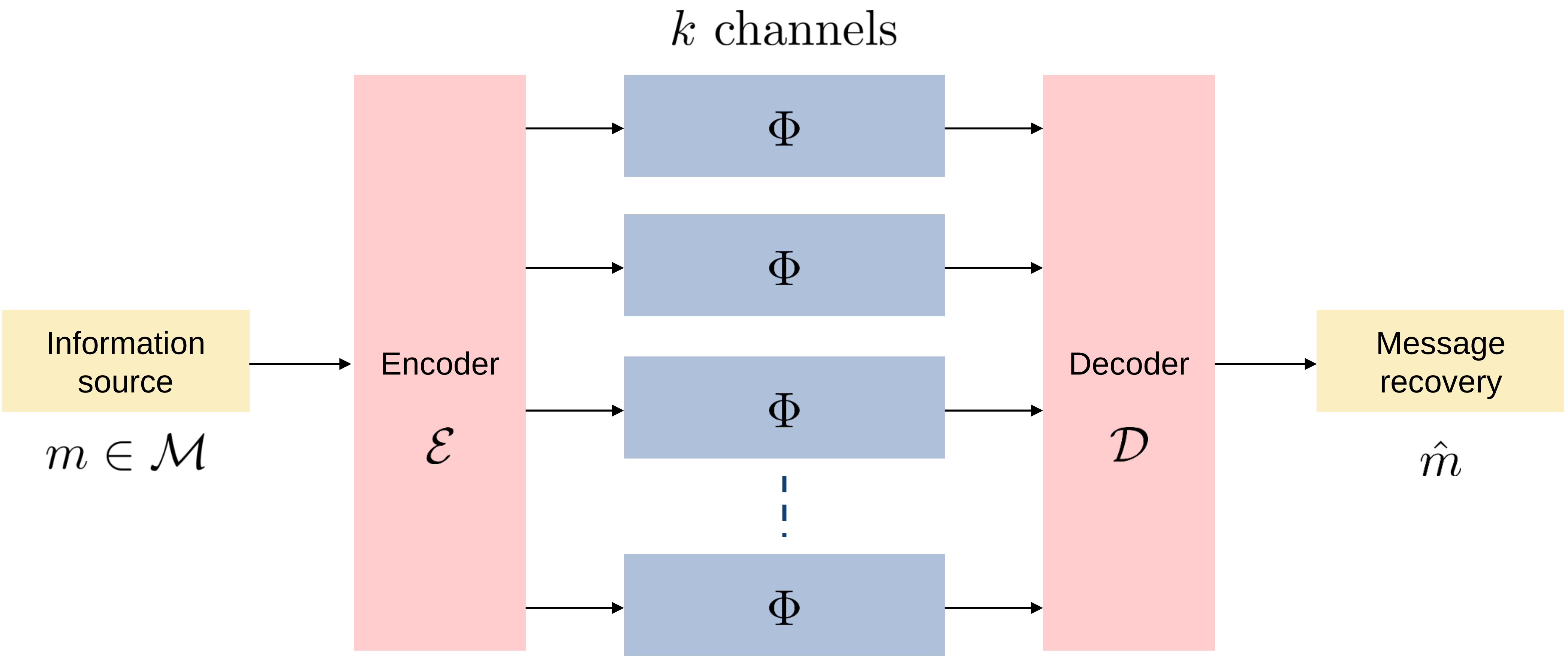
Shannon’s formula tells us (for a memoryless channel):

$$C(w) = \max_{p_X} I(X;Y)$$

$\Longrightarrow$ single-letter formula

Quantum communication

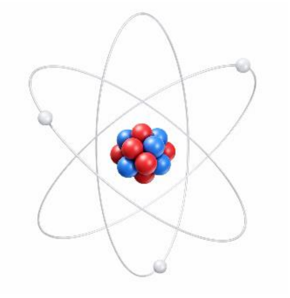
Typical quantum communication scenario:



Quantum state

Quantum measurement

Quantum communication

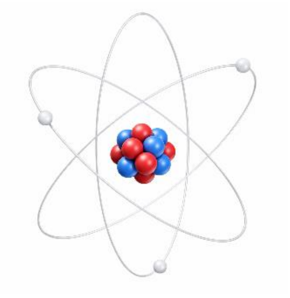


In the quantum case, various notions of capacities:

- **Classical** capacity of a **quantum** channel
- **Entanglement-assisted classical** capacity of a **quantum** channel
- **Quantum** capacity of a **quantum** channel
- …

Some of the most complex problems in quantum information theory: we know very little of capacities!

Quantum communication



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Typically, capacities are of the form:

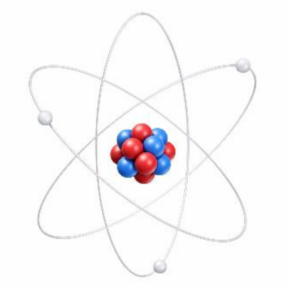
Single-letter

$$Q(\Phi) = \lim_{k\to\infty} \frac{1}{k} Q^{(1)}(\Phi^{\otimes k})$$

Regularisation

k applications of the channel

Quantum communication



In general:

$$Q(\Phi) = \lim_{k\to\infty} \frac{1}{k} Q^{(1)}(\Phi^{\otimes k}) \quad \neq \quad Q^{(1)}(\Phi)$$

Indeed,

$$Q^{(1)}(\Phi \otimes \Phi) > Q^{(1)}(\Phi) + Q^{(1)}(\Phi)$$

$$\uparrow$$

strict inequality

Main difficulty: $Q^{(1)}$ is often a difference of entropies, difficult to deal with.

To circumvent this problem: **continuity bounds for entropies**.

Main idea: can we compute distances rather than entropy differences?

2. Continuity bounds for entropies

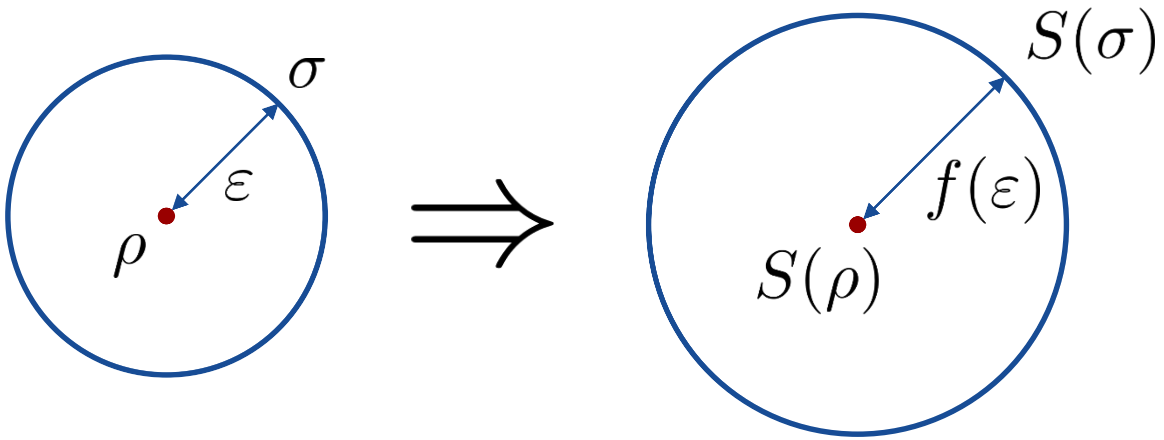
Main idea

If two states are close in some distance, how close are their entropies?

For example, for the von Neumann entropy, can we find a function f such that

$$\mathrm{d}(\rho,\sigma) \leq \varepsilon \quad \Rightarrow \quad |S(\rho) - S(\sigma)| \leq f(\varepsilon) \quad \text{with} \quad f(\varepsilon) \xrightarrow{\varepsilon \to 0} 0 \qquad ?$$

distance

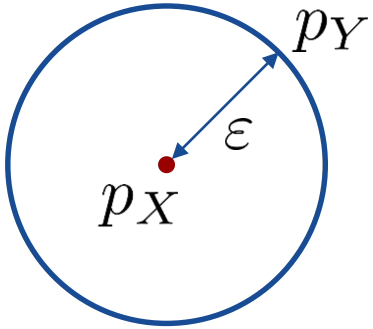


- **(i) Tight**: can be achieved for some states
- **(ii) Uniform**: does not depend on the specifics of ρ and σ

Distances

- **Classical:** Total variation distance

$$\mathrm{d}(X,Y) = \mathrm{TV}(X,Y) = \frac{1}{2}\sum_{i\in\mathcal{X}} |p_X(x) - p_Y(x)|$$



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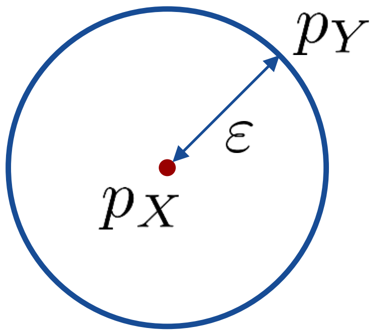

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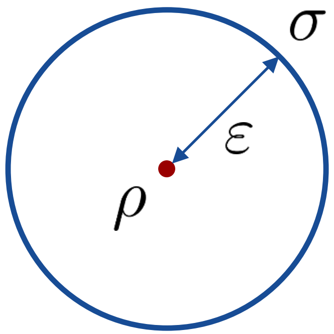
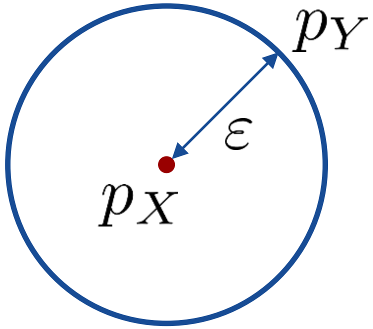


- **Quantum:** Trace distance

$$\mathrm{d}(\rho,\sigma) = \frac{1}{2}||\rho - \sigma||_1, \quad ||A||_1 = \mathrm{Tr}\sqrt{A^\dagger A}$$

Distances



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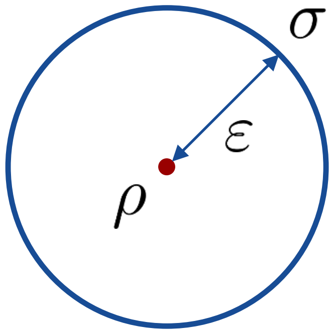


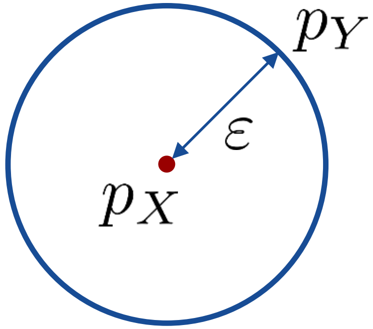
- **Quantum:** Trace distance

$$\mathrm{d}(\rho,\sigma) = \frac{1}{2}||\rho - \sigma||_1, \quad \|A\|_1 = \mathrm{Tr}\sqrt{A^\dagger A}$$

If ρ and σ commute, i.e., $$\rho = \sum_{x\in\mathcal{X}} p_X(x)|\psi_x\rangle\langle\psi_x|, \quad \sigma = \sum_{x\in\mathcal{X}} p_Y(x)|\psi_x\rangle\langle\psi_x|$$

then $$\frac{1}{2}||\rho - \sigma||_1 = \mathrm{TV}(X,Y)$$

Continuity bound for the Shannon entropy



$$\mathrm{d}(X,Y) = \mathrm{TV}(X,Y) = \frac{1}{2}\sum_{i\in\mathcal{X}} |p_X(x) - p_Y(x)|$$

Theorem. *[Csiszár]*
If $\mathrm{d}(X,Y) \leq \varepsilon$, *then*

$$|H(X) - H(Y)| \leq \varepsilon \log(|\mathcal{X}| - 1) + h(\varepsilon),$$

where $h(\varepsilon) = -\varepsilon \log \varepsilon - (1-\varepsilon)\log(1-\varepsilon)$.

saturated for: $p_X = \left\{1-\varepsilon, \frac{\varepsilon}{d-1}, \dots, \frac{\varepsilon}{d-1}\right\}, \quad p_Y = \{1, 0, \dots, 0\}$

Proof based on Fano’s inequality and maximal coupling [Sason]

- **Fano’s** inequality:

$$\boxed{H(X|Y) \leq h(\nu) + \nu \log(|\mathcal{X}| - 1) \quad \text{where} \quad \nu = \mathbb{P}(X \neq Y)}$$

- **Coupling**: a coupling of (X, Y) is a pair $(\hat{X}, \hat{Y})$ with the same marginal distributions as of (X, Y)

- **Maximal coupling**: $\mathbb{P}(\hat{X} = \hat{Y})$ is maximal

- Property: If $(\hat{X}, \hat{Y})$ is a maximal coupling, then $\boxed{\mathbb{P}(\hat{X} \neq \hat{Y}) = \mathrm{TV}(X, Y)}$

Proof based on Fano’s inequality and maximal coupling [Sason]

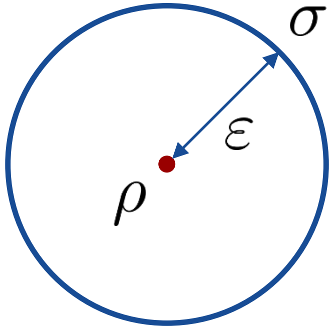
Fano’s inequality: $X(\hat{X}|\hat{Y}) \leq h(\nu) + \nu \log(|\mathcal{X}| - 1)$ $\nu = \mathbb{P}(\hat{X} \neq \hat{Y}) = \mathrm{TV}(X, Y)$

Continuity bound [6]:

$$\begin{aligned}
|H(X) - H(Y)| &= |H(\hat{X}) - H(\hat{Y})| \\
&= |H(\hat{X}|\hat{Y}) - H(\hat{Y}|\hat{X})| \\
&\leq \max\{H(\hat{X}|\hat{Y}), H(\hat{Y}|\hat{X})\} \\
&\leq h(\nu) + \nu \log(|\mathcal{X}| - 1) \\
&\leq h(\varepsilon) + \varepsilon \log(|\mathcal{X}| - 1)
\end{aligned}$$

[6] I. Sason, *IEEE Trans. Inf. Theory,* vol. 59, p. 7118, 2013.

Continuity bound for the von Neumann entropy



$$\mathrm{d}(\rho,\sigma) = \frac{1}{2}||\rho - \sigma||_1, \quad \|A\|_1 = \mathrm{Tr}\sqrt{A^\dagger A}$$

Theorem. *[Audenaert, Fannes, Petz]*
If $\mathrm{d}(\rho,\sigma) \le \varepsilon$, *then*

dimension of the quantum system

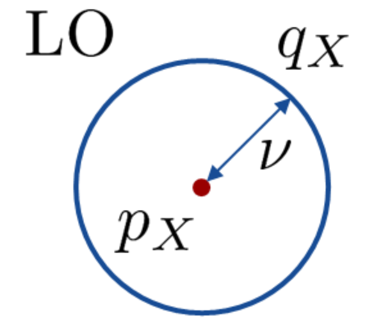
$$|S(\rho) - S(\sigma)| \le \varepsilon \log(d-1) + h(\varepsilon),$$

where $h(\varepsilon) = -\varepsilon \log \varepsilon - (1-\varepsilon)\log(1-\varepsilon)$.

Implied by Csiszár's bound

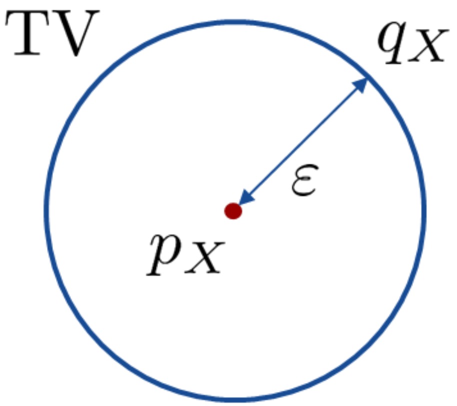
… can we do better? Classical case

Other distance: Local distance



$$\nu = \mathrm{LO}(p_X, q_X) := \sup_{x\in\mathcal{X}} |p_X(x) - q_X(x)|$$

$$\varepsilon = \mathrm{TV}(p_X, q_X) := \frac{1}{2}\sum_{x\in\mathcal{X}} |p_X(x) - q_X(x)|$$



$$\boxed{\sum_{x\in\mathcal{X}} p_X(x) = \sum_{x\in\mathcal{X}} q_X(x) = 1 \quad \Rightarrow \quad \nu \le \varepsilon}$$

Improved continuity bound for classical

$$f_d(\varepsilon,\nu) \coloneqq h(\varepsilon) + d_+\,\nu\log\nu + \mu\log\mu + \varepsilon\log d_- - \varepsilon\log\varepsilon \qquad |\mathcal{X}| = d$$

Division of ε by ν → $\varepsilon = d_+\nu + \mu,$

quotient

remainder

$$d_- \coloneqq \begin{cases} d - d_+, & \text{if } \mu = 0, \\ d - d_+ - 1, & \text{else.} \end{cases}$$

ν Local distance

ε TV distance

Theorem. [7]

$$|H(X)_p - H(X)_q| \leq f_d(\varepsilon,\nu)$$

Also saturated.

We recover classical Audenaert-Fannes-Petz when $\varepsilon = \nu$

[6] I. Sason, *IEEE Trans. Inf. Theory,* vol. 59, p. 7118, 2013.

[7] M. G. Jabbour and N. Datta, *IEEE Journal on Selected Areas in Information Theory*, vol. 59, p. 645 (2024).

Improved continuity bound for classical

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Division of ε by ν → $\varepsilon = d_+\nu + \mu,$

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ν Local distance

ε TV distance

Theorem. [7]

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We recover classical Audenaert-Fannes-Petz when $\varepsilon = \nu$

Also quantum!

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What about conditional entropies?

$$H(Y|X) = H(X,Y) - H(X) = \sum_{x\in\mathcal{X}} p_X(x) H(Y|X=x)$$

Distance between **joint** distributions

Using the **2$^{\text{nd}}$ identity**, one can show that [8]

$$\mathrm{TV}(p_{XY}, p_{X'Y'}) \leq \varepsilon$$

$$|H(X|Y) - H(X'|Y')| \leq \varepsilon \log(|\mathcal{X}| - 1) + h(\varepsilon)$$

Same bound as for usual Shannon entropy!   (worst case scenario when X is “trivial”)

[8] M. A. Alhejji and G. Smith, 2020 *IEEE International Symposium on Information Theory (ISIT)*.

What about conditional entropies?

$$H(Y|X) = H(X,Y) - H(X) = \sum_{x \in \mathcal{X}} p_X(x) H(Y|X = x)$$

Distance between **joint** distributions

Using the **2nd identity**, one can show that [8]

$$\mathrm{TV}(p_{XY}, p_{X'Y'}) \leq \varepsilon$$

$$|H(X|Y) - H(X'|Y')| \leq \varepsilon \log(|\mathcal{X}| - 1) + h(\varepsilon)$$

Same bound as for usual Shannon entropy! (worst case scenario when Y is “trivial”)

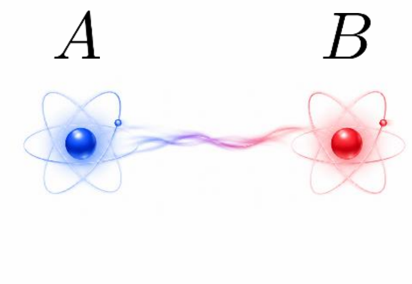
What about the quantum conditional entropy?

[8] M. A. Alhejji and G. Smith, 2020 *IEEE International Symposium on Information Theory (ISIT)*.

What about quantum conditional entropies?

$$H(Y|X) = H(X,Y) - H(X) = \underbrace{\sum_{x\in\mathcal{X}} p_X(x)H(Y|X=x)}_{\text{Only valid when conditioning on a \textbf{classical} system!}}$$

For two **correlated** quantum systems A and B



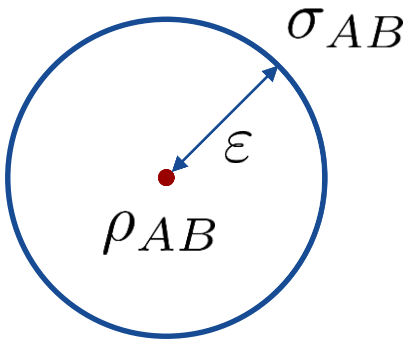
$$S(B|A)_{\rho_{AB}} = S(\rho_{AB}) - S(\rho_A)$$

where $\rho_A = \mathrm{Tr}_B\left(\rho_{AB}\right)$ (partial trace of system B, i.e., we discard system B)

Things become difficult when the conditioning is done on a **quantum** system A !

Continuity bound for quantum conditional entropy

$$\mathrm{d}(\rho_{AB},\sigma_{AB}) = \frac{1}{2}||\rho_{AB}-\sigma_{AB}||_1$$



Theorem. *[Alicki, Fannes, Winter][9,10]*
If $\mathrm{d}(\rho_{AB},\sigma_{AB}) \leq \varepsilon$, *then*

$$|S(B|A)_{\rho_{AB}} - S(B|A)_{\sigma_{AB}}| \leq \varepsilon\log(d_B) + (1+\varepsilon)h\left(\frac{\varepsilon}{1+\varepsilon}\right),$$

where $h(\varepsilon) = -\varepsilon\log\varepsilon - (1-\varepsilon)\log(1-\varepsilon)$.

Not tight, we know a better bound exists (conjectured).

[9] R. Alicki and M. Fannes, *J. Phys. A: Math. Gen.,* vol. 37, p. L55, 2004.
[10] A. Winter, *Commun. Math. Phys.,* vol. 347, p. 291, 2016.

A fundamental entropic inequality

Trace distance: $$\mathrm{d}(\rho,\sigma)=\frac{1}{2}||\rho-\sigma||_1, \quad \|A\|_1=\mathrm{Tr}\sqrt{A^\dagger A}$$

If we diagonalise $\rho-\sigma=\Delta_+-\Delta_-$ where $\Delta_+\geq 0, \quad \Delta_-\geq 0, \quad \Delta_+\perp\Delta_-$

A fundamental entropic inequality

Trace distance: $\mathrm{d}(\rho,\sigma) = \frac{1}{2}||\rho - \sigma||_1, \quad \|A\|_1 = \mathrm{Tr}\sqrt{A^\dagger A}$

If we diagonalise $\rho - \sigma = \Delta_+ - \Delta_-$ where $\Delta_+ \geq 0, \quad \Delta_- \geq 0, \quad \Delta_+ \perp \Delta_-$

We prove [11], if $\mathrm{d}(\rho,\sigma) = \varepsilon$

$$\boxed{S(\rho) - S(\sigma) \leq \varepsilon S(\rho_+) - \varepsilon S(\sigma_-) + h(\varepsilon)}$$

where $\Delta_+ = \varepsilon\rho_+, \quad \Delta_- = \varepsilon\sigma_-$

Quantum states (semidefinite positive, trace 1)

[11] K. Audenaert, B. Bergh, N. Datta, M. G. Jabbour, Á. Capel and P. Gondolf, *IEEE Trans. Inf. Theory,* vol. 71, p. 7029, 2025.

… directly implies the continuity bound for von Neumann

$$\boxed{S(\rho) - S(\sigma) \leq \varepsilon S(\rho_+) - \varepsilon S(\sigma_-) + h(\varepsilon)} \qquad \rho_+ \perp \sigma_-$$

(i) $S(\sigma_-) \geq 0$

(ii) ρ_+ supported by subspace of dimension less than d

$$\Rightarrow \quad S(\rho_+) \leq \log(d-1)$$

$$\Rightarrow \quad S(\rho) - S(\sigma) \leq \varepsilon \log(d-1) + h(\varepsilon)$$

… directly implies the continuity bound for von Neumann

$$\boxed{S(\rho) - S(\sigma) \leq \varepsilon S(\rho_+) - \varepsilon S(\sigma_-) + h(\varepsilon)} \qquad \rho_+ \perp \sigma_-$$

$(i) \quad S(\sigma_-) \geq 0$

$(ii) \quad \rho_+$ supported by subspace of dimension less than d

$$\Rightarrow \quad S(\rho_+) \leq \log(d-1)$$

$$\Rightarrow \quad S(\rho) - S(\sigma) \leq \varepsilon \log(d-1) + h(\varepsilon)$$

Also allows us to improve the continuity bound for the **quantum conditional entropy**!

Continuity bounds for other entropies / in other contexts

- Continuity bound for the **Arimoto-Rényi conditional entropy** [12]
- Continuity bound for the **quantum relative entropy** (Kullback-Leibler divergence) [11]
- **Fano inequality** for the conditional entropy of **infinite-dimensional systems** [13,14]
- Continuity bound for the von Neumann entropy and quantum Rényi entropy of **infinite-dimensional systems** (with applications to bosonic system, e.g., photonic systems) [11,13,14,15]

[11] K. Audenaert, B. Bergh, N. Datta, M. G. Jabbour, Á. Capel and P. Gondolf, *IEEE Trans. Inf. Theory,* vol. 71, p. 7029, 2025.

[12] M. G. Jabbour and N. Datta, *IEEE Trans. Inf. Theory,* vol. 68, p. 2169, 2022.

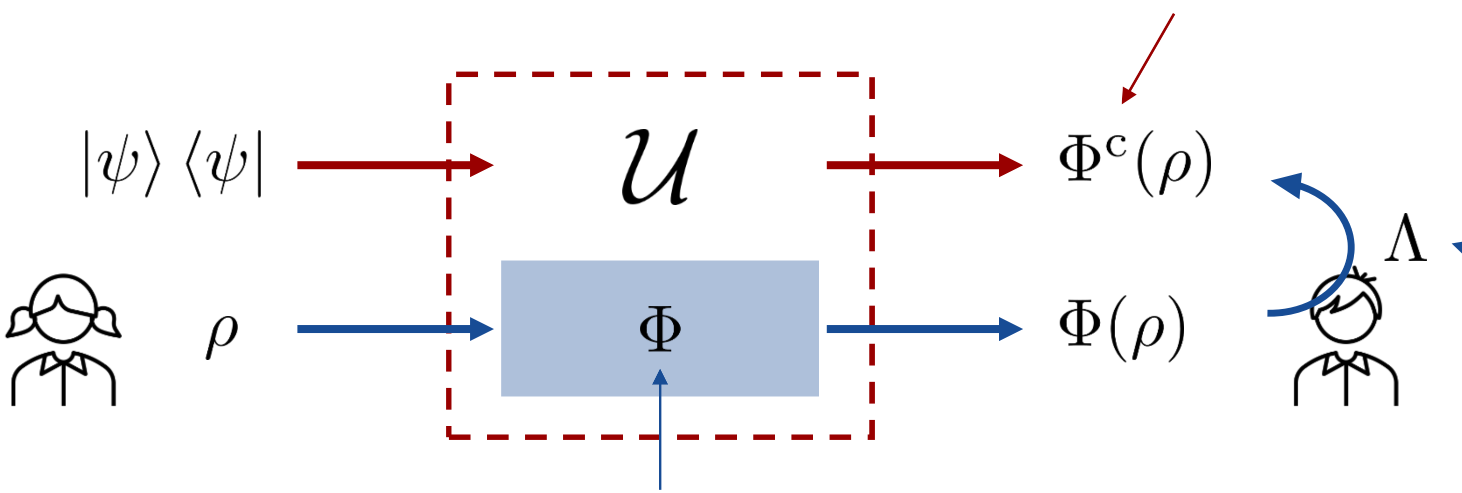
[13] S. Becker, N. Datta and M. G. Jabbour, *IEEE Trans. Inf. Theory,* vol. 69, p. 4128, 2023.

[14] S. Becker, N. Datta, M. G. Jabbour and M. Shirokov, *arXiv:2410.02686[quant-ph]*, 2024.

[15] J. Schindler, P. Strasberg, N. Galke, A. Winter and M. G. Jabbour, *arXiv:2503.15612[quant-ph]*, 2025.

3. Applying continuity bounds to quantum communication

Quantum communication



Environment

Degrading channel

Completely positive and trace preserving map

$$\boxed{\Phi^c = \Lambda \circ \Phi}$$

Quantum capacity:

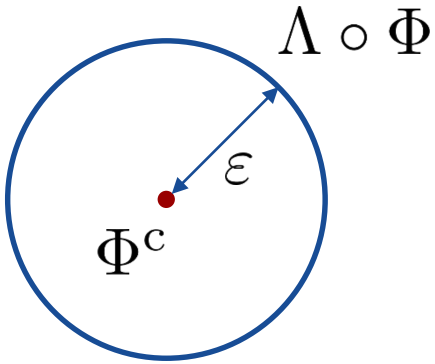
$$Q(\Phi) = \lim_{k\to\infty} \frac{1}{k} Q^{(1)}(\Phi^{\otimes k})$$

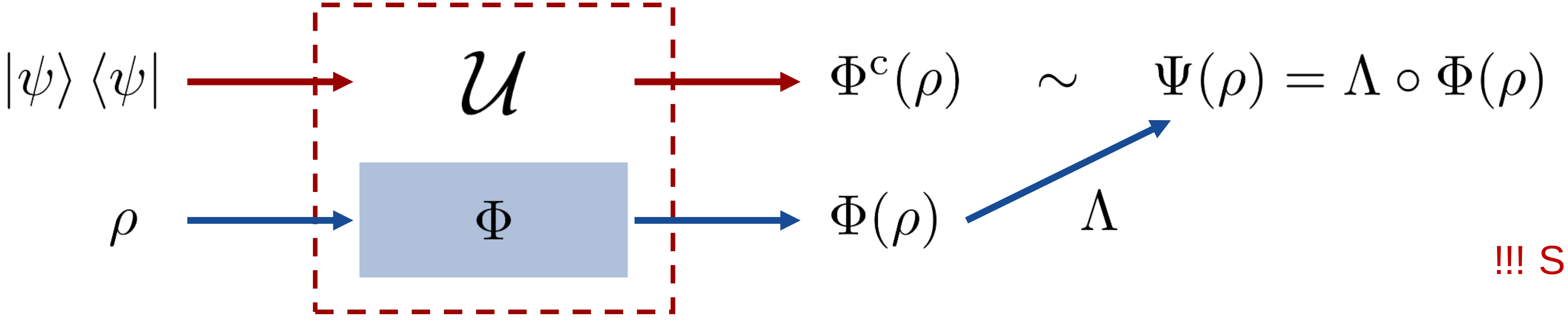
$\Rightarrow Q^{(1)}(\Phi)$ additive

Can be computed!

$$Q^{(1)}(\Phi) = \max_{\rho} \left(S(\Phi(\rho)) - S(\Phi^c(\rho)) \right)$$

ε-degradable channels





!!! Simplified reasoning !!!

Diamond norm: $\varepsilon = \left\|\Phi^c - \Lambda \circ \Phi\right\|_\diamond = \max_{||\rho||_1 \leq 1} ||([\Phi^c - \Lambda \circ \Phi] \otimes \mathrm{id})(\rho)||_1$

We find Λ by minimising ε, using well-known semidefinite programs for the diamond norm.

$$\Rightarrow Q^{(1)}(\Phi) = \max_{\rho} \left(S(\Phi(\rho)) - S(\Lambda \circ \Phi(\rho))\right) \leq \varepsilon \log(d-1) + h(\varepsilon)$$

We can obtain very good upper bounds on capacities with this method!

A note on some more applications

Continuity bounds on quantum entropies are used in the proofs of:

- The quantum Shannon source compression theorem
- The quantum Shannon channel coding theorem

4. Perspectives

Perspectives

- The “holy grail” of continuity bounds for quantum entropies: a **tight** (i.e., the best possible) **uniform continuity bound for the quantum conditional entropy**
- Improving continuity bounds by means of the **majorization lattice** (upcoming paper with a student)
- Some interesting applications in **classical information theory** you can think of?

**[I will start looking for a PhD student and a postdoc (2 years) (ANR JCJC funding)
Subject: quantum analogue of Shannon’s Entropy Power Inequality (EPI)]**

Thank you!