Randomization theorems for quantum channels

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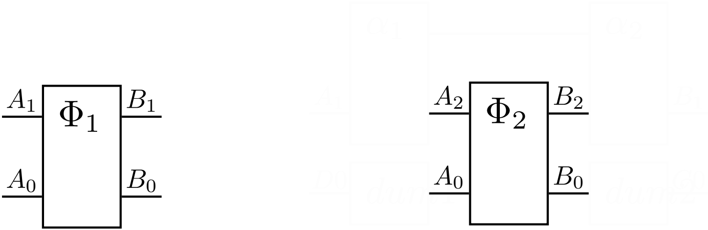
The problem

Given two channels



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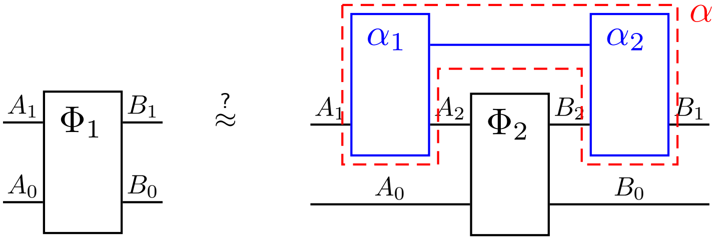

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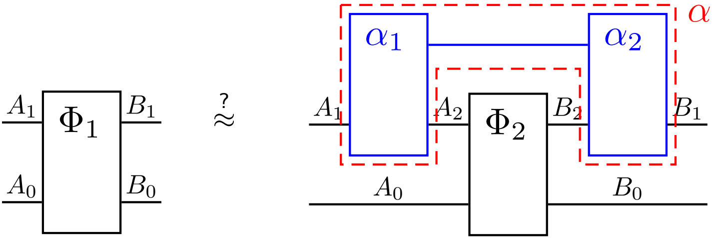

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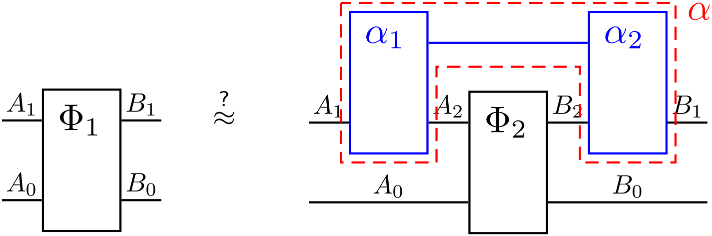

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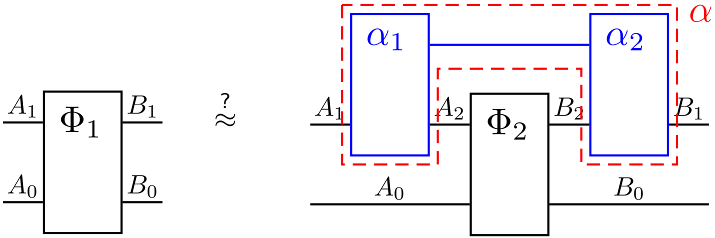

- α is a superchannel
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- all superchannels or some restrictions on α

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  - comparison of classical experiments: (Blackwell 1953, Torgersen 1970)
  - more general comparison of classical channels: (Shannon 1958)

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Deficiency

Let us return to the general case:

- we define the deficiency as

$$\delta_{\mathcal{T}}(\Phi_1 \| \Phi_2) := \min_{\alpha \in \mathcal{T}} \|\Phi_1 - \alpha(\Phi_2)\|_{\diamond}$$

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- equivalence relation:

$$\Phi_1 \sim_{\mathcal{T}} \Phi_2 \iff \Delta_{\mathcal{T}}(\Phi_1, \Phi_2) = 0$$

Deficiency

- These are extensions of Le Cam deficiency/distance for classical statistical experiments: $\mathcal{F}_1 = \{p_\theta, \theta \in \Theta\}$, $\mathcal{F}_2 = \{q_\theta, \theta \in \Theta\}$

$$\delta(\mathcal{F}_1 \| \mathcal{F}_2) = \min_{\alpha} \sup_{\theta} \|p_\theta - \alpha(q_\theta)\|_1$$

- Randomization theorem (Le Cam 1964): deficiency is characterized by comparing risks in decision problems: informativity

Randomization theorem for classical channels

Φ_1, Φ_2 - classical channels with equal input spaces: $A_1 = A_2 = A$,
$\mathcal{T} = post$:= set of post-processings

Theorem

Let $\epsilon \geq 0$, Then $\delta_{post}(\Phi_1 \| \Phi_2) \leq \epsilon$ if and only if:
for any ensemble $\mathcal{E} = \{\lambda_x, p_x\}$ of classical states $p_x \in \mathcal{S}(A)$,

$$P_{succ}(\Phi_1(\mathcal{E})) \leq P_{succ}(\Phi_2(\mathcal{E})) + \frac{\epsilon}{2} P_{succ}(\mathcal{E}),$$

here $\Phi_i(\mathcal{E}) = \{\lambda_x, \Phi_i(p_x)\}$.

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for any ensemble on $AR \iff$
for any $\rho \in \mathcal{S}(AR)$:

$$2^{-H_{min}(R|B_1)_{\rho_1}} \leq 2^{-H_{min}(R|B_2)_{\rho_2}} + \frac{\epsilon}{2} 2^{-H_{min}(R|A)_\rho}$$

$\rho_i = (\Phi_i \otimes id_R)(\rho)$, H_{min} - conditional min-entropy

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- properties (monotonicity) of conditional min-entropy
- minimax theorem (Le Cam)

Choi isomorphism

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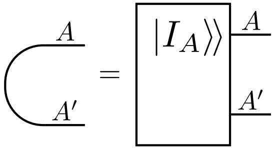

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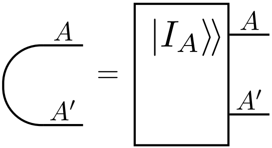

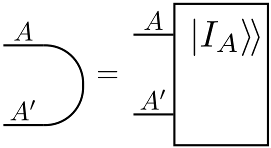

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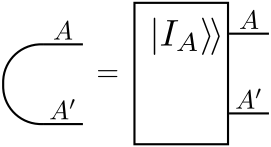

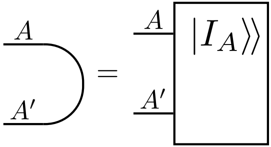

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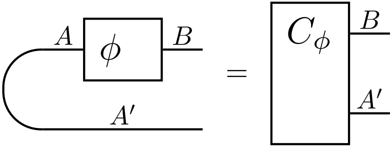

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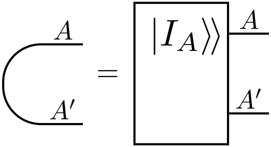
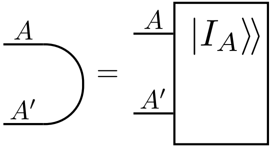
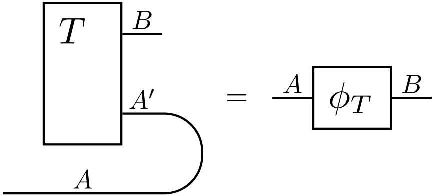




the inverse:



Ordered spaces of hermitian maps

- $\mathcal{L} = \mathcal{L}(A \to B) \equiv$ the space of hermitian-preserving maps

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- Choi isomorphism:

$$(\mathcal{L}, \mathcal{L}^+) \simeq (\mathcal{B}_h(BA'), \mathcal{B}(BA')^+)$$

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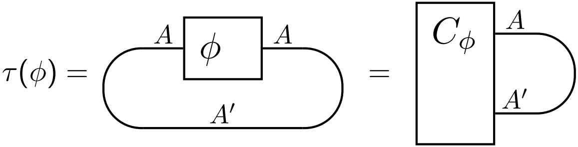

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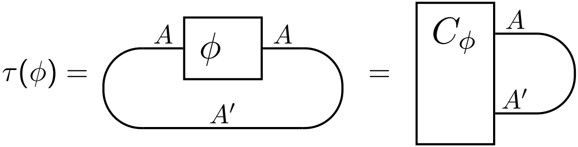

the trace of ϕ as a linear map

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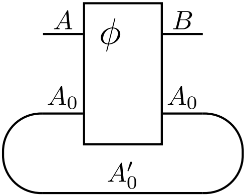

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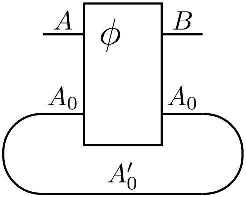
$\tau_{A_0}(\phi) \;=$ 

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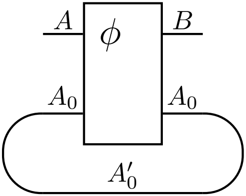

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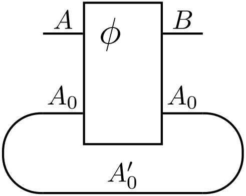

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- $\tau(\phi \circ (\alpha \otimes id)) = \tau(\tau_{A_0}(\phi) \circ \alpha)$

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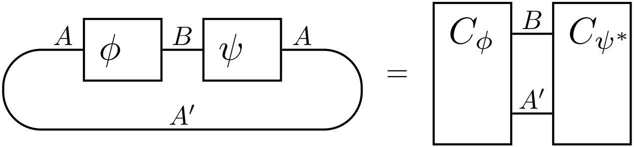

Diamond norm and conditional min-entropy

For $\phi \in \mathcal{L} = \mathcal{L}(A \to B)$, the diamond norm is defined as

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- distinguishability norm for channels $\mathcal{B}(A) \to \mathcal{B}(B)$
- constructed from the convex structure of the set of channels

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Dual expressions:

$$\begin{aligned} \|\phi\|_\diamond &= \min_{\alpha \in \mathcal{C}} \min\{\lambda > 0, -\lambda\alpha \leq \phi \leq \lambda\alpha\} \\ &= \max_{\gamma \in \tilde{\mathcal{C}}} \max_{-\gamma \leq \eta \leq \gamma} \langle \eta, \phi \rangle \end{aligned}$$

Diamond norm and conditional min-entropy

The dual norm: for $\psi \in \mathcal{L}^*$,

$$\begin{aligned}\|\psi\|^\diamond &= \min_{\gamma \in \tilde{\mathcal{C}}} \min\{\lambda > 0, -\lambda\gamma \leq \psi \leq \lambda\gamma\} \\ &= \max_{\alpha \in \mathcal{C}} \max_{-\alpha \leq \xi \leq \alpha} \langle \psi, \xi \rangle\end{aligned}$$

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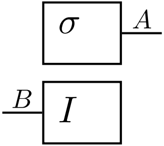
Diamond norm and conditional min-entropy

- maps in $\tilde{\mathcal{C}}$:



$\sigma \in \mathcal{S}(A)$

Diamond norm and conditional min-entropy

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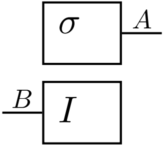

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Diamond norm and conditional min-entropy

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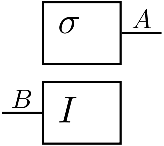

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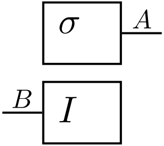

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- conditional min-entropy: $H_{min}(B|A)_\rho$

Diamond norm and conditional min-entropy

Dual expression:

$$\|\psi\|^{\diamond} = \max_{\alpha \in \mathcal{C}} \langle\, \psi, \alpha \,\rangle = \max_{\alpha \in \mathcal{C}} \langle\!\langle\, I_B | (\alpha \otimes id)(\rho) | I_B \rangle\!\rangle$$

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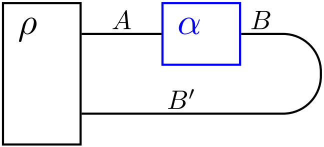

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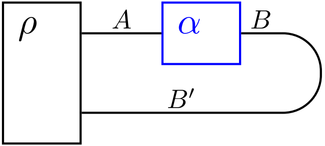
$= \max\limits_{\alpha\in\mathcal{C}}$ 

operational interpretation of $H_{min}(B|A)_\rho$ (König et al., 2009):

(up to d_B) the largest fidelity with maximally entangled state, that can be obtained by applying a channel on A

The 2-diamond norm and conditional 2-min-entropy

Let now

- $\mathcal{L} = \mathcal{L}(A_1 A_2 \to B_1 B_2)$

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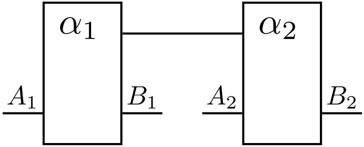
$\alpha \;=$



$= \; \alpha_1 * \alpha_2$

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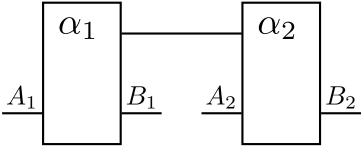
$\alpha =$  $= \alpha_1 * \alpha_2$

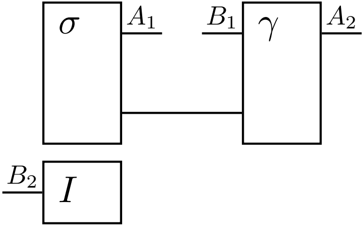
- $\mathcal{C}_2$ is an affine section of $\mathcal{L}^+$

The 2-diamond norm and conditional 2-min-entropy

The dual section $\tilde{\mathcal{C}}_2$: set of superchannels

The 2-diamond norm and conditional 2-min-entropy

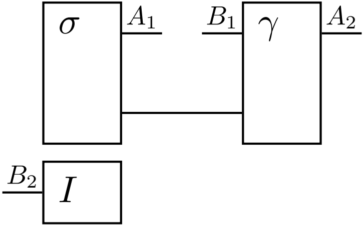
The dual section $\tilde{\mathcal{C}}_2$: set of superchannels



$$= \gamma * \sigma \otimes \mathrm{Tr}_{B_2}$$

The 2-diamond norm and conditional 2-min-entropy

The dual section $\tilde{\mathcal{C}}_2$: set of superchannels



$$= \gamma * \sigma \otimes \mathrm{Tr}_{B_2}$$

σ is a state, γ a channel

The 2-diamond norm and conditional 2-min-entropy

- we can define a pair of dual norms in $\mathcal{L}$, $\mathcal{L}^*$ as before:

$$
\begin{aligned}
\|\phi\|_{2\diamond} &= \min_{\alpha \in \mathcal{C}_2} \min\{\lambda > 0, -\lambda\alpha \leq \phi \leq \lambda\alpha\} \\
&= \max_{\gamma \in \tilde{\mathcal{C}}_2} \max_{-\gamma \leq \eta \leq \gamma} \langle \eta, \phi \rangle \\
\|\psi\|^{2\diamond} &= \min_{\gamma \in \tilde{\mathcal{C}}_2} \min\{\lambda > 0, -\lambda\gamma \leq \psi \leq \lambda\gamma\} \\
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- $\|\cdot\|_{2\diamond}$ is a distinguishability norm for superchannels

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- $\|\cdot\|_{2\diamond}$ is a distinguishability norm for superchannels
- from $\|\cdot\|^{2\diamond}$, we obtain the conditional 2-min-entropy

The 2-diamond norm and conditional 2-min-entropy

For $\psi \in (\mathcal{L}^+)^*$, $\rho = C_\psi$:

$$\|\psi\|^{2\diamond} = \min_{\sigma,\gamma} \min\{\lambda > 0,\ \psi \leq \lambda\sigma * \gamma \otimes \mathrm{Tr}_{B_2}\} = 2^{-H^{(2)}_{min}(B|A)_\rho}$$

$$= \max_{\alpha \in \mathcal{C}_2} \langle \alpha, \psi \rangle = \max_{\alpha \in \mathcal{C}_2} \langle\langle I_{B_1 B_2} | (\alpha \otimes id)(\rho) | I_{B_1 B_2} \rangle\rangle$$

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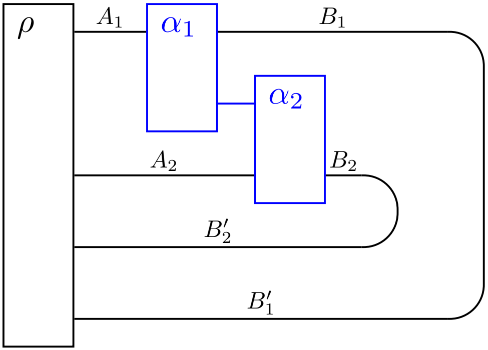
$\max\limits_{\alpha_1,\alpha_2}$ 

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Useful properties of $H^{(2)}_{min}$: (Gour, 2018)

- monotonicity for any superchannel $\Theta \in \mathcal{C}_2(B_3 \to B_1, A_1 \to A_3)$:
$$\|\phi\|^{2\diamond} \geq \|\Theta(\phi)\|^{2\diamond}$$
- additivity
$$\|\phi \otimes \psi\|^{2\diamond} = \|\phi\|^{2\diamond} \|\psi\|^{2\diamond}$$

Comparison of bipartite channels

We compute the deficiency $\delta_{sc}(\Phi_1 \| \Phi_2)$:

$$\min_{\alpha \in \mathcal{C}_2} \|\Phi_1 - \alpha(\Phi_2)\|_\diamond =$$

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$$(\text{minimax thm.}) = 2 \max_{\gamma} \min_{\alpha} \langle\, \gamma, \Phi_1 - \alpha(\Phi_2)\, \rangle$$

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\text{(minimax thm.)} &= 2 \max_\gamma \min_\alpha \langle\, \gamma, \Phi_1 - \alpha(\Phi_2)\, \rangle \\
&\leq 2 \max_\gamma \left(\langle\, \gamma, \Phi_1\, \rangle - \max_{\alpha \in \mathcal{C}_2} \langle\, \gamma, \alpha(\Phi_2)\, \rangle \right)
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(\text{minimax thm.}) &= 2 \max_{\gamma} \min_{\alpha} \langle\, \gamma, \Phi_1 - \alpha(\Phi_2)\, \rangle \\
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&\le 2\max_{\gamma}\left(\max_{\beta\in\mathcal{C}_2}\langle\,\gamma,\beta(\Phi_1)\,\rangle-\max_{\alpha\in\mathcal{C}_2}\langle\,\gamma,\alpha(\Phi_2)\,\rangle\right)\\
&\le \epsilon\,?
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$$\max_{\alpha \in \mathcal{C}_2} \langle \gamma, \alpha(\Phi_i) \rangle = ?$$

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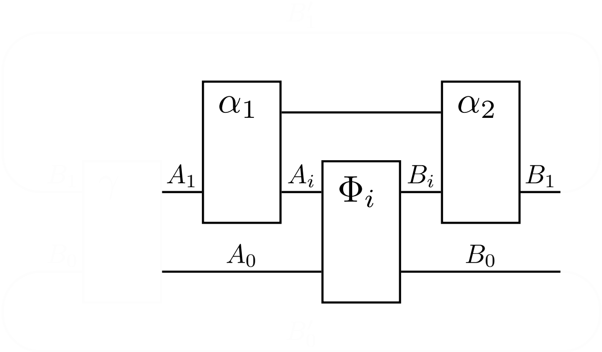

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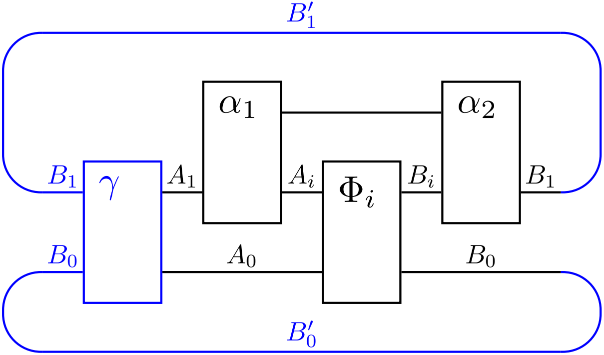

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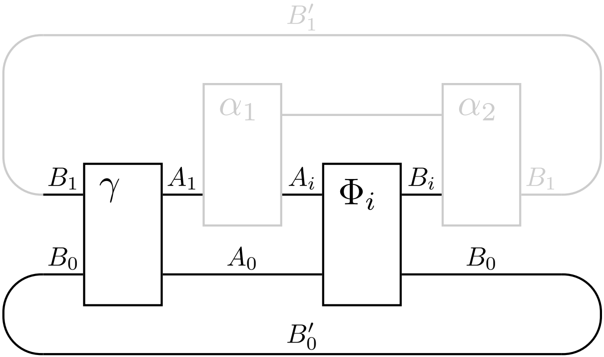

$$= \tau_{B_0}(\gamma * \Phi_i)$$

Comparison of bipartite channels

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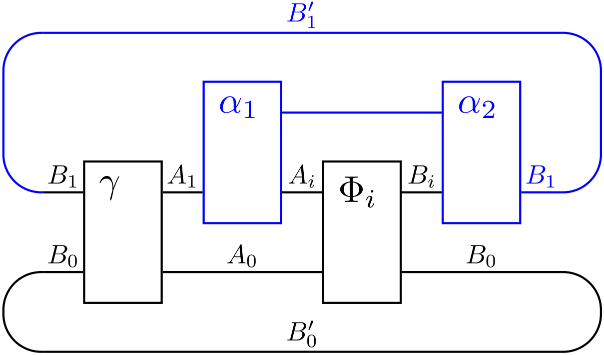
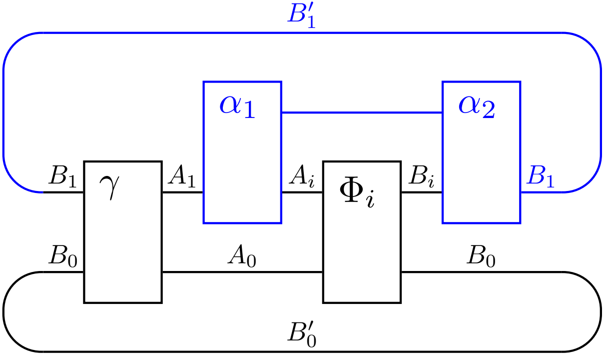


Comparison of bipartite channels

$$\max_{\alpha\in\mathcal{C}_2}\langle\,\gamma,\alpha(\Phi_i)\,\rangle = \max_{\alpha\in\mathcal{C}_2}\langle\,\tau_{B_0}(\gamma*\Phi_i),\alpha\,\rangle = \|\tau_{B_0}(\gamma*\Phi_i)\|^{2\diamond}$$



Comparison of bipartite channels

Theorem

Let $\epsilon \geq 0$. Then $\delta_{sc}(\Phi_1 \| \Phi_2) \leq \epsilon$ if and only if for all systems A_3, B_3 and all $\gamma \in \mathcal{L}^+(B_3 B_0 \to A_3 A_0)$ we have

$$\|\tau_{B_0}(\gamma * \Phi_1)\|^{2\diamond} \leq \|\tau_{B_0}(\gamma * \Phi_2)\|^{2\diamond} + \frac{\epsilon}{2}\|\gamma\|^{\diamond}.$$

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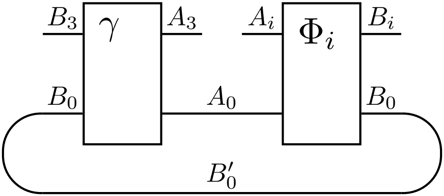

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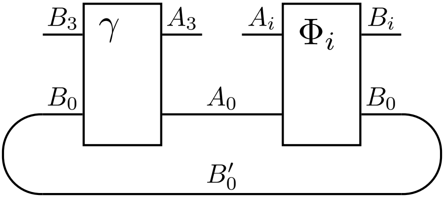

We can restrict to $A_3 \simeq A_1$ and $B_3 \simeq B_1$.

Conditional min-entropy and guessing probabilities

For an ensemble $\mathcal{E} = \{\lambda_x, \rho_x\}$, $\rho_x \in \mathcal{S}(A)$, let

$$\phi_{\mathcal{E}} \in \mathcal{L}^+(B \to A), \quad C_{\phi_{\mathcal{E}}} = \rho_{\mathcal{E}} := \sum_x |x\rangle\langle x| \otimes \lambda_x \rho_x$$

$$\phi_{\mathcal{E}} = \overset{x}{\text{———}}\boxed{\lambda_x \rho_x}\overset{A}{\text{———}}$$

-classical-to-quantum map

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-classical-to-quantum map

Optimal success probability (König et al. 2009)

$$P_{succ}(\mathcal{E}) = \max_M \sum_x \lambda_x \mathrm{Tr}\left[\rho_x M_x\right] = \|\phi_{\mathcal{E}}\|^{\diamond} = 2^{-H_{min}(X|A)_{\rho_{\mathcal{E}}}}$$

Conditional min-entropy and guessing probabilities

Let $\gamma \in \mathcal{L}^+(R \to A)$, $\rho = C_\gamma \in \mathcal{S}(AR)$. We produce an ensemble

$$\mathcal{E}_\rho = \{\frac{1}{d_R^2}, \rho_x\}, \quad \rho_x = (id_A \otimes \mathcal{U}_x^R)(\rho) \in \mathcal{S}(AR),$$

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where

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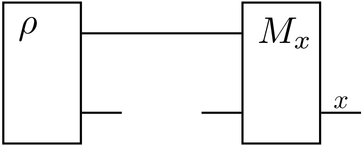
Then we have

$$P_{succ}(\mathcal{E}_\rho) = \frac{1}{d_R}\|\gamma\|^\diamond = \frac{1}{d_R} 2^{-H_{min}(R|A)_\rho}$$

Conditional min-entropy and guessing probabilities

Channel discrimination problem:

- an ensemble of channels $\mathcal{E}_R = \{\frac{1}{d_R^2}, \mathcal{U}_x^R\}$
- testers (PPOVMs) with input state ρ:



- success probability:

$$P_{succ}(\mathcal{E}_R, \rho) := \max_M \sum_x \mathrm{Tr}\left[(id \otimes \mathcal{U}_x^R)(\rho) M_x\right] = \frac{1}{d_R} 2^{-H_{min}(R|A)_\rho}$$

Conditional min-entropy and guessing probabilities

For any ensemble $\mathcal{E} = \{\frac{1}{d_R^2}, \Psi_x\}_{x=1}^{d_R^2}$ of unital channels:

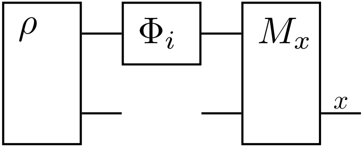
$$P_{succ}(\mathcal{E}, \rho) \leq \frac{1}{d_R} 2^{-H_{min}(R|A)_\rho}$$

Conditional min-entropy and guessing probabilities

For any ensemble $\mathcal{E} = \{\frac{1}{d_R^2}, \Psi_x\}_{x=1}^{d_R^2}$ of unital channels:

$$P_{succ}(\mathcal{E}, \rho) \leq \frac{1}{d_R} 2^{-H_{min}(R|A)_\rho}$$

For a pair of quantum channels $\Phi_i : A \to B_i$, $\delta_{post}(\Phi_1 \| \Phi_2)$ can be characterized by comparing testers of the form



for this type of tasks, for any $\rho \in \mathcal{S}(AR)$.

Comparison of bipartite channels by guessing probabilities

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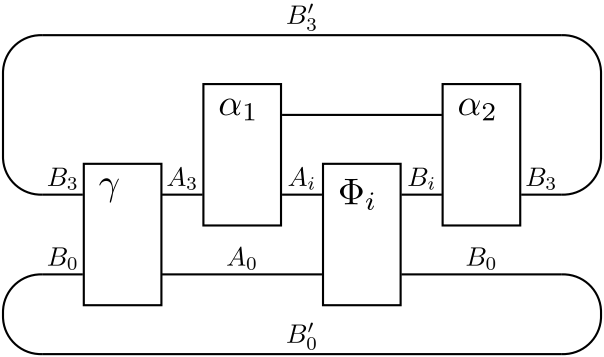

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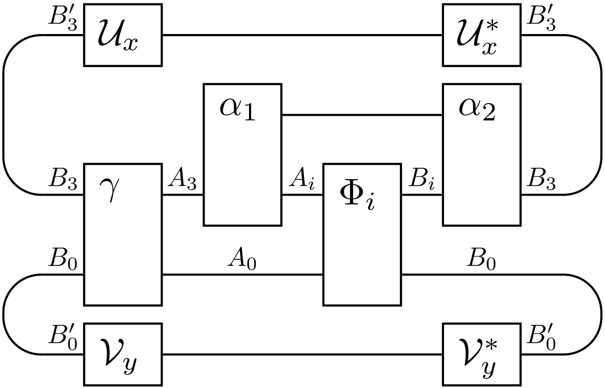

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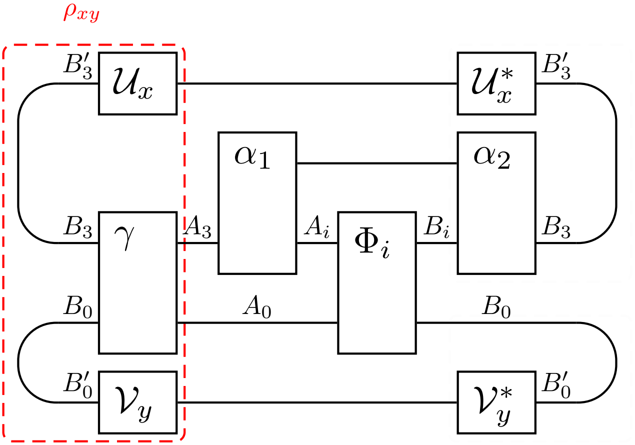

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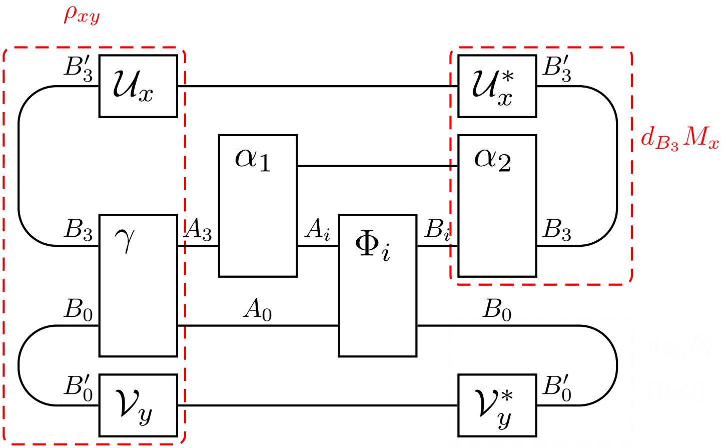

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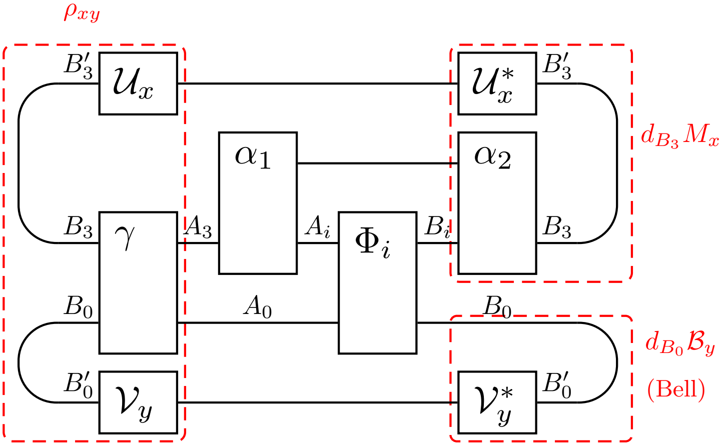

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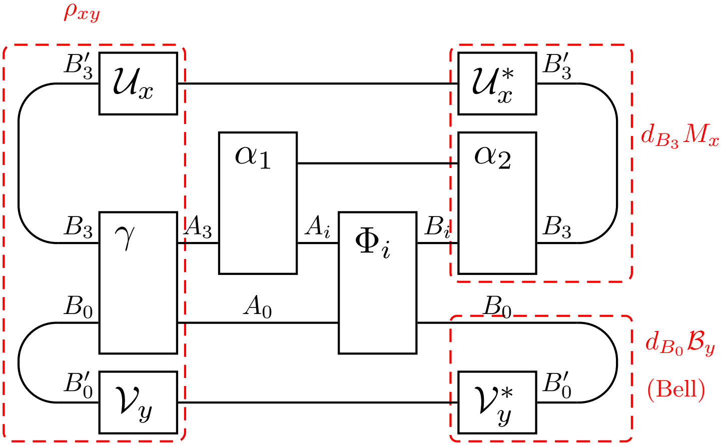

$$= \frac{1}{d_{B_3} d_{B_0}} \sum_{x,y} \mathrm{Tr}\left[\rho_{xy}(\alpha_1 * \Phi_i)^*(M_x \otimes \mathcal{B}_y)\right]$$

Comparison of bipartite channels by guessing probabilities

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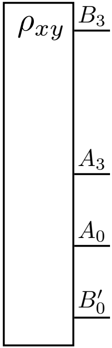

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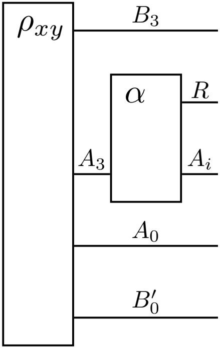

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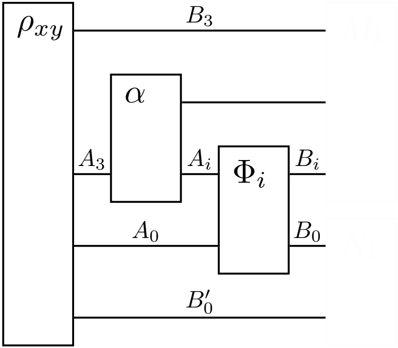

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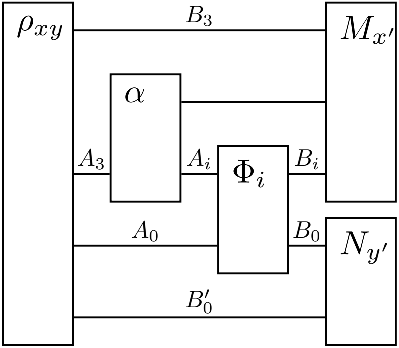

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The optimal success probability is

$$P_{succ}(\mathcal{E}, \Phi_i, N) := \max_{\alpha, M} P_{succ}(\mathcal{E}, (\Phi_i * \alpha)^*(M \otimes N))$$

Comparison of bipartite channels: guessing probabilities

Theorem

$\delta_{sc}(\Phi_1\|\Phi_2) \le \epsilon$ if and only if for any A_3, B_3, any POVM N on B_0B_0' and any ensemble $\mathcal{E} = \{\lambda_{xy}, \rho_{xy}\}$, on $B_3A_3A_0B_0'$, we have

$$P_{succ}(\mathcal{E}, \Phi_1, N) \le P_{succ}(\mathcal{E}, \Phi_2, N) + \frac{\epsilon}{2} P_{succ}(\mathcal{E})$$

We may restrict to $A_3 \simeq A_1$, $B_3 \simeq B_1$ and $N = \mathcal{B}$ the Bell measurement.

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For characterization by guessing probabilities: restrictions on allowed pairs (α, M) of pre-processing and measurement.