Separation of quantum, spatial quantum, and approximate quantum correlations

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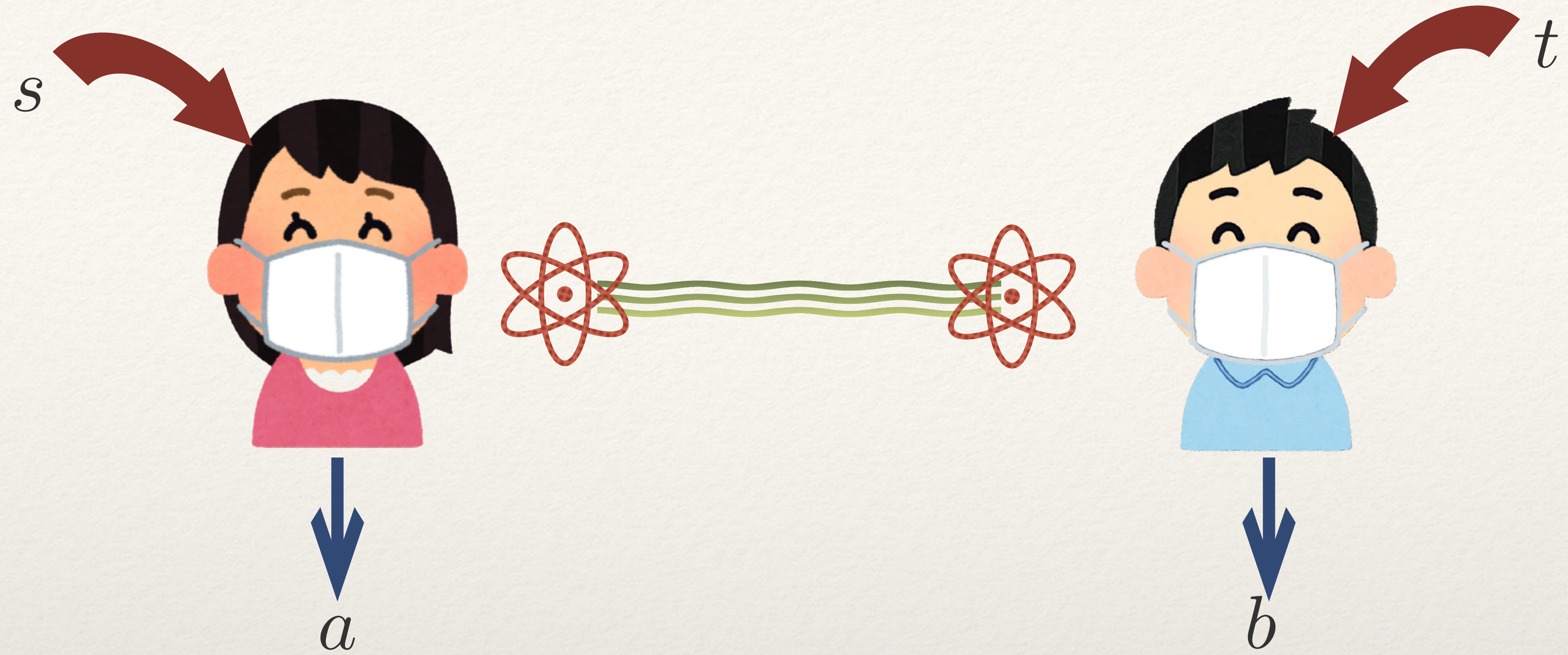
Two-player one-round games

- Cooperative game
- Alice and Bob win if $(a, b, s, t) \in V$

- CHSH game: $a, b, s, t \in \{0, 1\}$. Winning condition: $a \oplus b = s.t$

Two-player one-round games



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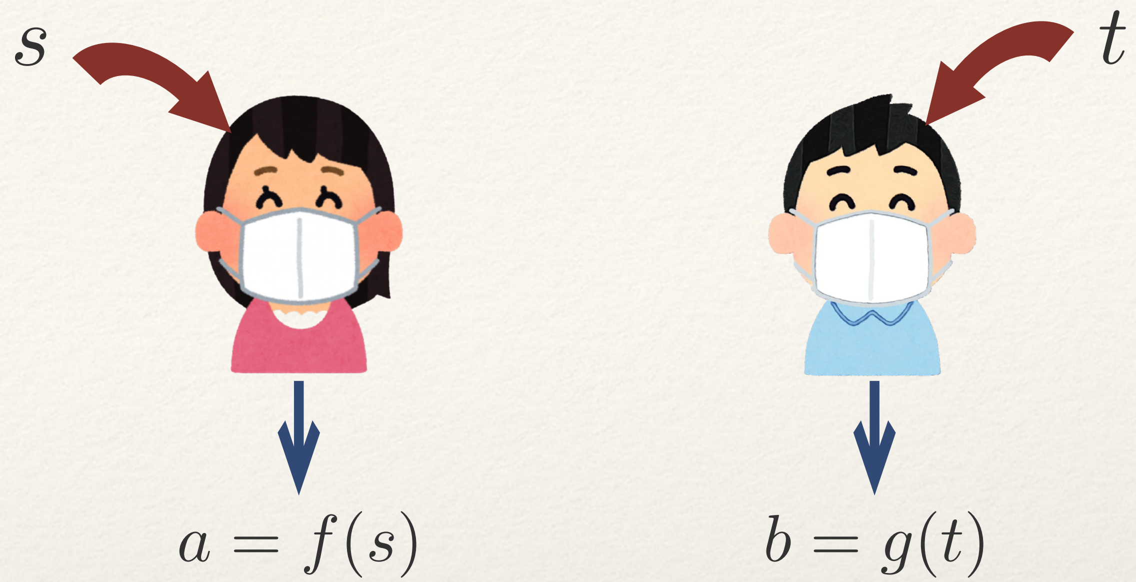
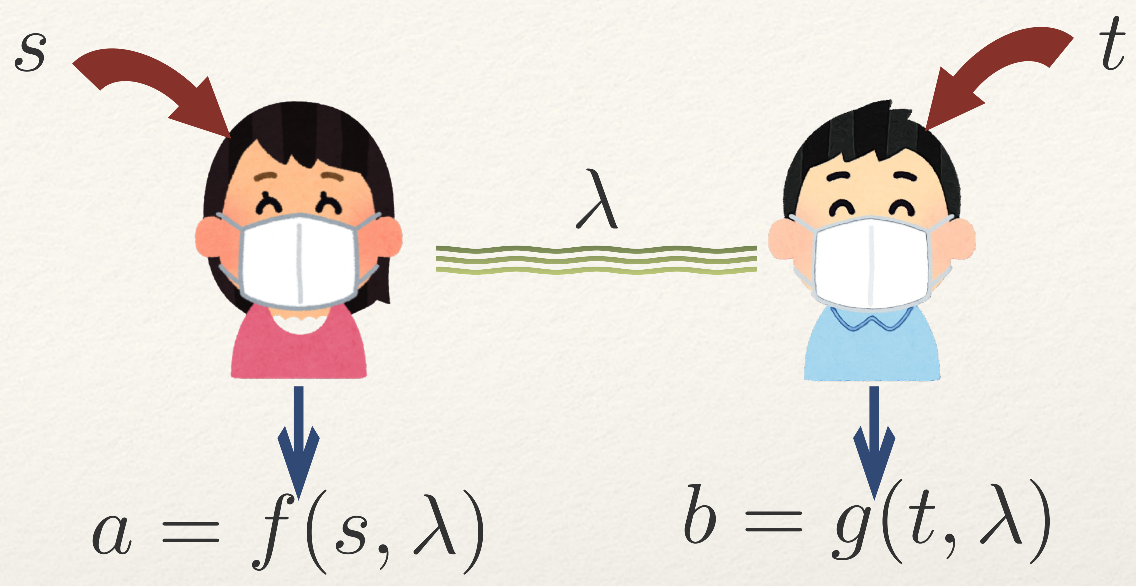
Classical Strategies

- Alice and Bob apply functions f and g on their inputs to produce $a = f(s)$ and $b = g(t)$



Classical Strategies

- Alice and Bob apply functions f and g on their inputs to produce $a = f(s)$ and $b = g(t)$
- If they share randomness λ then they compute $a = f(s, \lambda)$ and $b = g(t, \lambda)$

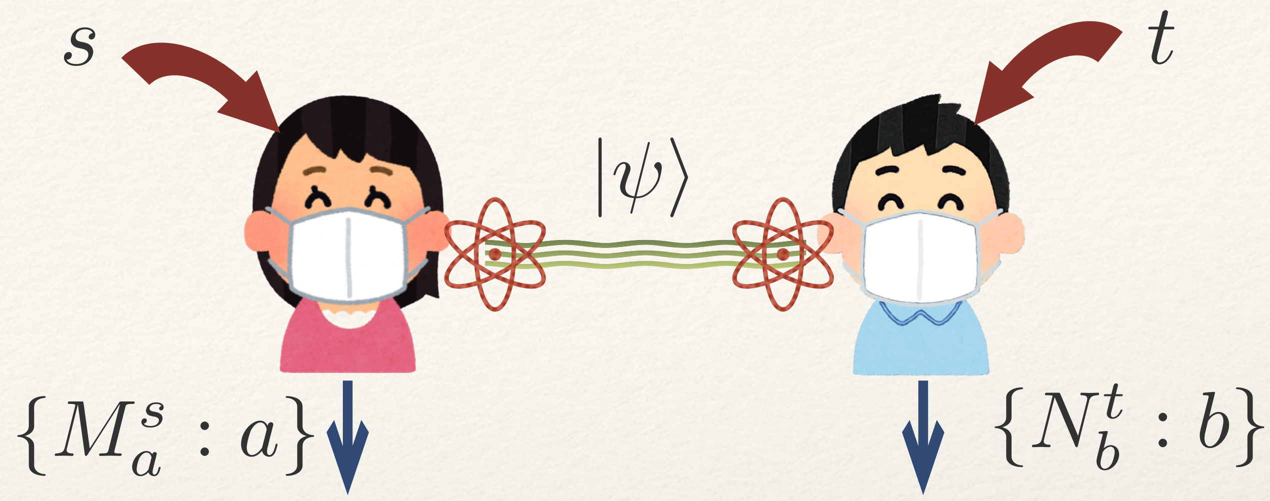


$p(a, b|s, t)$ = probability of outputs a and b, when the inputs are s and t

$$p(a, b|s, t) = \sum_\lambda p(\lambda)\, p(a|s, \lambda)\, p(b|t, \lambda)$$

Quantum Strategies

- Alice and Bob share quantum state $|\psi\rangle$
- They apply measurements $\{M_a^s : a\}$ and $\{N_b^t : b\}$



$$p(a, b|s, t) = \langle\psi|M_a^s \otimes N_b^t|\psi\rangle$$

Vector in $\mathcal{H} \otimes \mathcal{H}$

Positive semidefinite Operators acting on a Hilbert space $\mathcal{H}$

$$\textstyle\sum_a M_a^s = I_{\mathcal{H}} \quad \forall s, \qquad \sum_b N_b^t = I_{\mathcal{H}} \quad \forall t.$$

Example: CHSH game

$a, b, s, t \in \{0, 1\}$ Winning condition: $a \oplus b = s.t$

Classical Strategy

- Alice and Bob always output $a=0$ and $b=0$.
- With probability $3/4$ we have $s.t=0$
- Thus with probability $3/4$ Alice and Bob win
- Maximum probability of winning is 3/4

Example: CHSH game

$a, b, s, t \in \{0,1\}$ Winning condition: $a \oplus b = s.t$

Classical Strategy

- Alice and Bob always output *a*=*0* and *b*=*0*.
- With probability *3/4* we have *s.t*=*0*
- Thus with probability *3/4* Alice and Bob win
- Maximum probability of winning is 3/4

Quantum Strategy

- $|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

$M_0^0 - M_1^0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ $M_0^1 - M_1^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$

$N_0^0 - N_1^0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$ $N_0^1 - N_1^1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & -1 \\ -1 & -1 \end{pmatrix}$

- For all *s, t, a, b* with $a \oplus b = s.t$:

$$\langle\psi|M_a^s \otimes N_b^t|\psi\rangle = \frac{1+\sqrt{2}}{2\sqrt{2}}$$

- Wining probability is

$$\frac{1+\sqrt{2}}{2\sqrt{2}} > 3/4$$

Bell's Nonlocality

Hierarchy of Quantum Correlations

$$p(a,b|s,t) = \langle\psi|M_a^s \otimes N_b^t|\psi\rangle = \langle\psi, M_a^s \otimes N_b^y \psi\rangle$$

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- Quantum correlations $\mathcal{C}_q$: finite dimensional H

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$$\mathcal{C}_{qa} = \overline{\mathcal{C}_q} = \overline{\mathcal{C}_{qs}}$$

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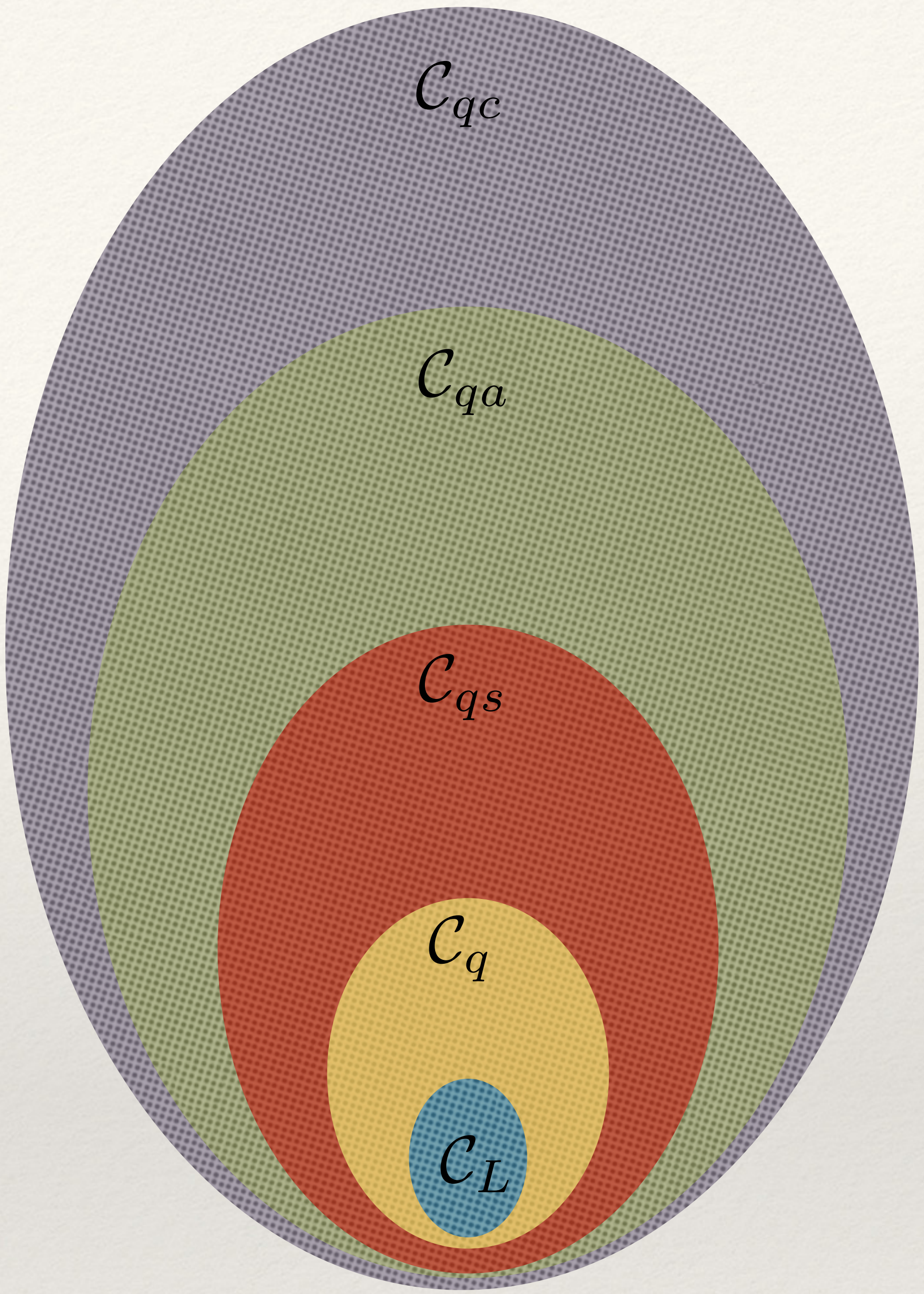
Question?

Hierarchy of Quantum Correlations

$$\mathcal{C}_L \subseteq \mathcal{C}_q \subseteq \mathcal{C}_{qs} \subseteq \mathcal{C}_{qa} \subseteq \mathcal{C}_{qc}$$

- Bell (1964): $\mathcal{C}_L \neq \mathcal{C}_q$



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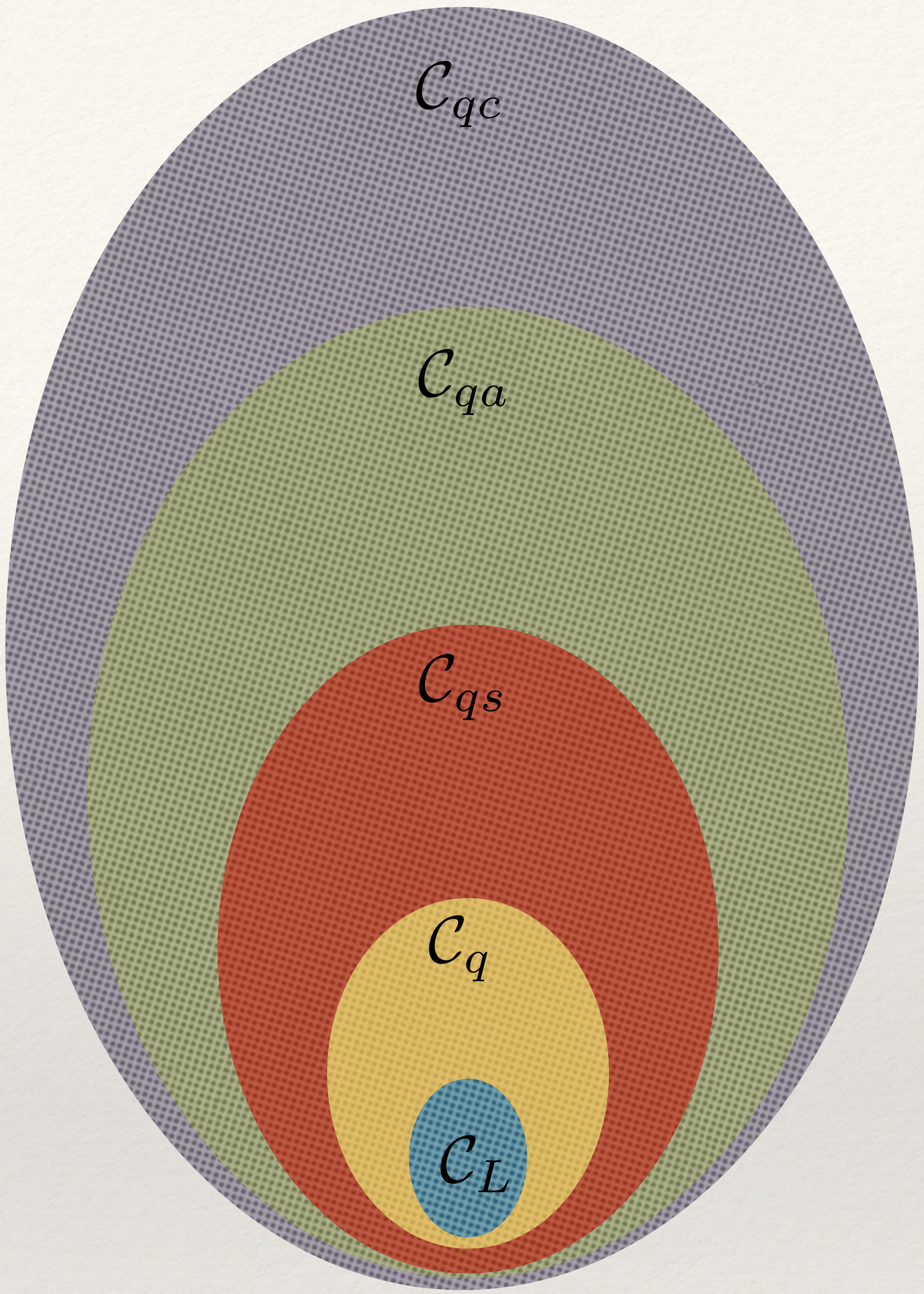

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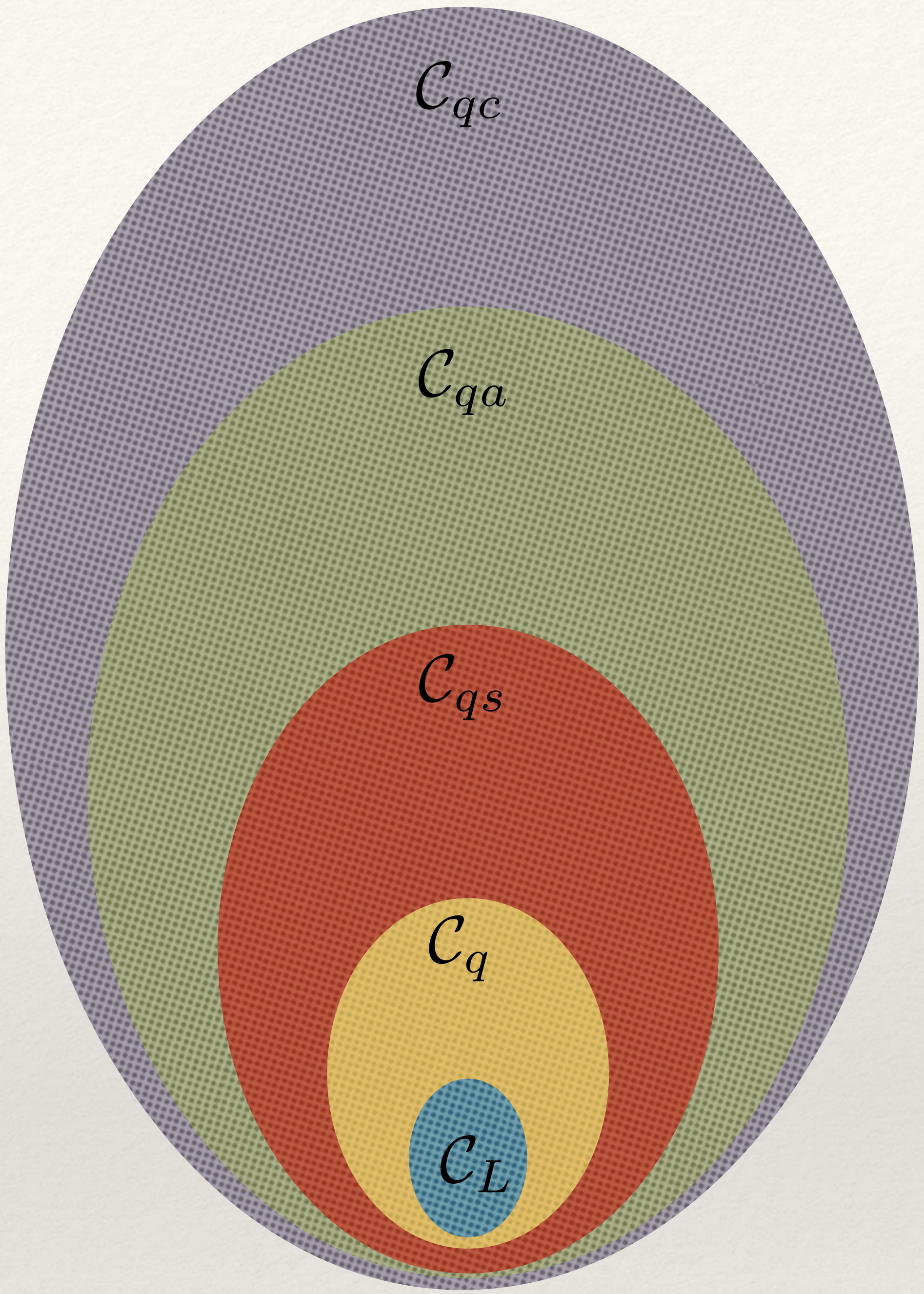

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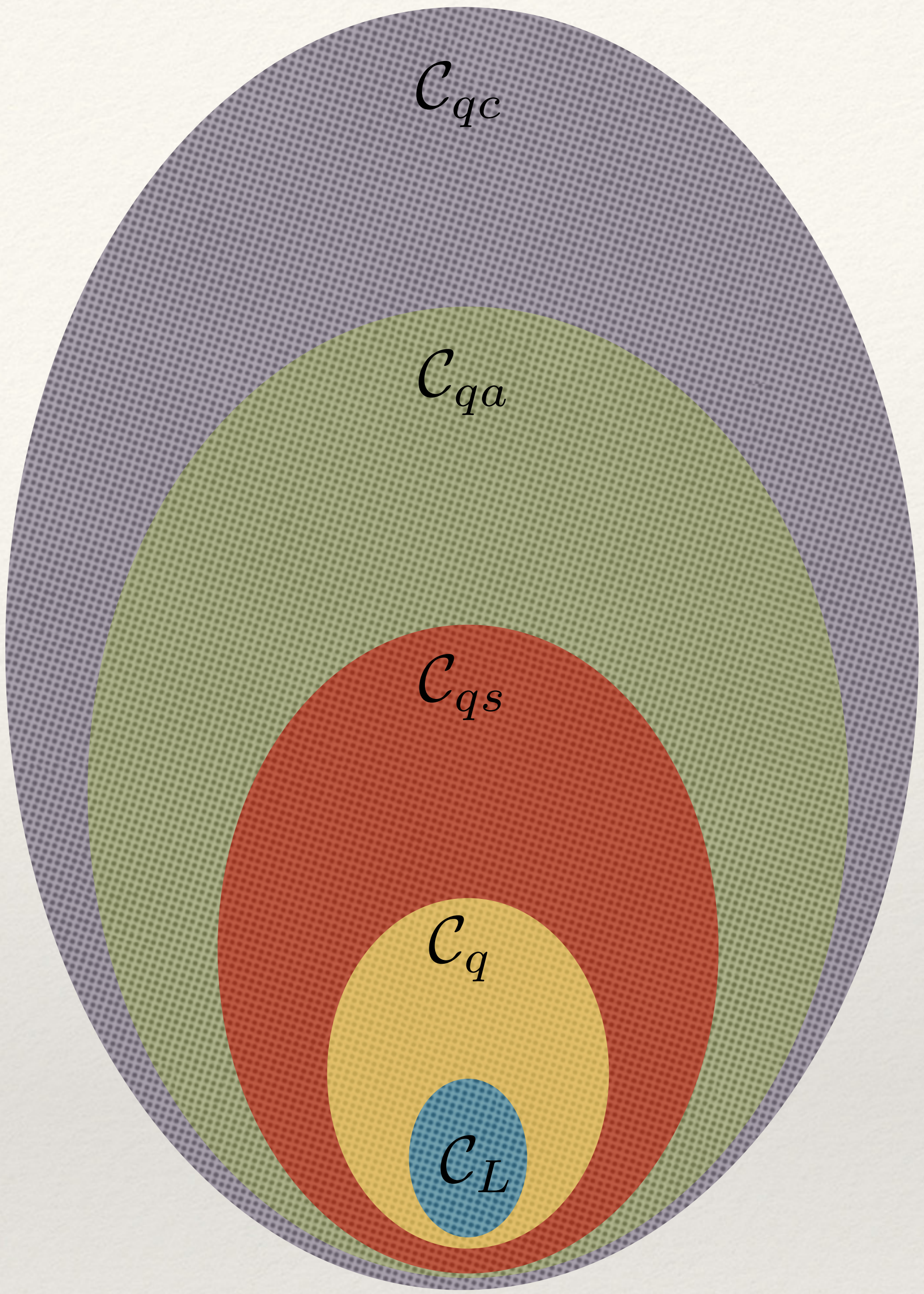
They indeed prove MIP*=RE
And refuted Connes' embedding conjecture



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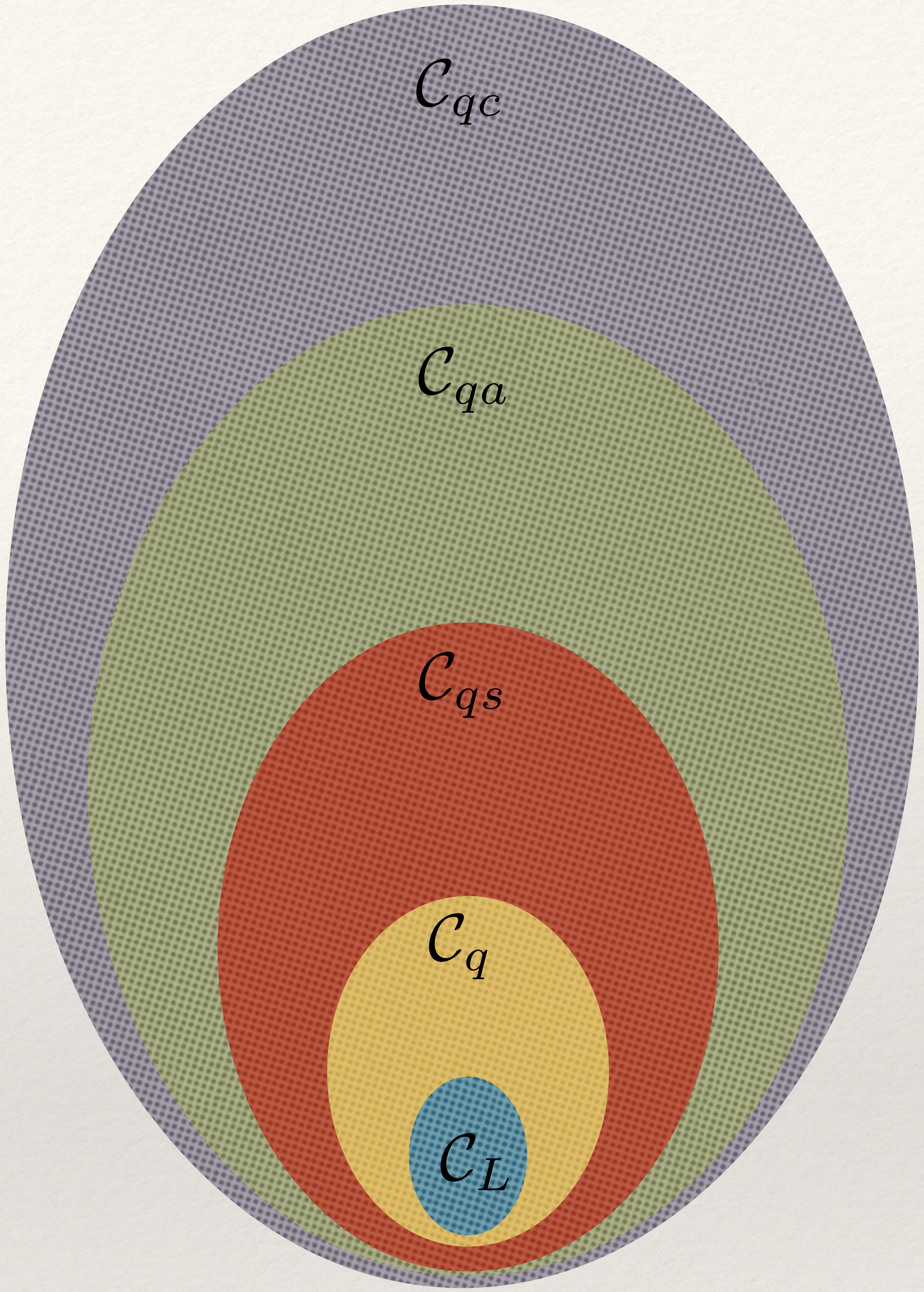

All inclusions are strict

Our results: Improvements in $\mathcal{C}_q \neq \mathcal{C}_{qs}$ and $\mathcal{C}_{qa} \neq \mathcal{C}_{qs}$

Main results:

$\mathcal{C}_*^{(n_A,n_B,m_A,m_B)}$: set of correlations with $s \in [n_A], t \in [n_B]$
and $a \in [m_A], b \in [m_B]$

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Theorem: $\mathcal{C}_q \neq \mathcal{C}_{qs}$ for *(4, 4, 2, 2)*

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Proof ideas (I): self-testing

The quantum strategy for winning the CHSH game with probability $\frac{1+\sqrt{2}}{2\sqrt{2}}$ is essentially unique.

If

$$\frac{1}{4} \sum_{\substack{a,b,s,t: \\ a \oplus b = s.t}} \langle \psi | M_a^s \otimes N_b^t | \psi \rangle = \frac{1+\sqrt{2}}{2\sqrt{2}}$$

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$$|\psi\rangle = \frac{1}{\sqrt{C}}\Big(\cdots + \alpha^3|-3,-3\rangle + \alpha^2|-2,-2\rangle + \alpha|-1,-1\rangle + |0,0\rangle + \alpha|1,1\rangle + \alpha^2|2,2\rangle + \alpha^3|3,3\rangle + \cdots\Big)$$

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$\sim |00\rangle + \alpha|11\rangle$ $\quad\sim |00\rangle + \alpha|11\rangle$ $\quad\sim |00\rangle + \alpha|11\rangle$

$$\Rightarrow\quad |\psi\rangle \sim \frac{1}{\sqrt{1+\alpha^2}}(|00\rangle + \alpha|11\rangle)\otimes|\psi'\rangle$$

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$|\psi\rangle \sim \frac{1}{\sqrt{1+\alpha^2}}(|00\rangle + \alpha|11\rangle)\otimes|\psi''\rangle$

Given $|\psi\rangle$ the tilted-CHSH game can be played in two different ways!

Proof ideas (II): entanglement embezzlement

There is $|\Phi_n\rangle$ such that up to local isometries

$$|\Phi_n\rangle \approx^{\epsilon_n} \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \otimes |\Phi_n\rangle \qquad \epsilon_n = \frac{\ln 2}{\ln n}$$

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$$|\Phi_n\rangle = \frac{1}{\sqrt{C_n}} \sum_{j=1}^{n} \frac{1}{\sqrt{j}} |j, j\rangle \qquad C_n = \sum_{j=1}^{n} \frac{1}{j}$$

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$$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \otimes |\Phi_n\rangle = \frac{1}{\sqrt{C_n}} = \sum_{j=1}^{n} \frac{1}{\sqrt{2j}}(|0j, 0j\rangle + |1j, 1j\rangle)$$

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Isometry: $\begin{cases} 0j \mapsto 2j-1 \\ 1j \mapsto 2j \end{cases}$

$$\text{Inner product: } \geq \frac{1}{C_n}\left(\frac{1}{2} + \frac{1}{2} + \frac{1}{4} + \frac{1}{4} + \cdots + \frac{1}{n} + \frac{1}{n}\right)$$

$$\geq \frac{\ln(n/2)}{\ln n} = 1 - \frac{\ln 2}{\ln n}$$

Proof ideas

[Van Dam & Hayden, arXiv:quant-ph/0201041]

- Embezzling vector:

$$|\Phi_n\rangle = \frac{1}{\sqrt{C_n}} \sum_{j=1}^{n} \frac{1}{\sqrt{j}} |j, j\rangle$$

Harmonic number

$$C_n = \sum_{j=1}^{n} \frac{1}{j}$$

- Target vector:

$$|v\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

$$|\Phi_n\rangle : \frac{1}{\sqrt{C_n}}\begin{pmatrix} \frac{1}{\sqrt{1}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{3}} & \cdots \frac{1}{\sqrt{n}} \end{pmatrix}$$

$$|v\rangle \otimes |\Phi_n\rangle : \frac{1}{\sqrt{C_n}}\begin{pmatrix} \frac{1}{\sqrt{2\cdot 1}} & \frac{1}{\sqrt{2\cdot 2}} & \frac{1}{\sqrt{2\cdot 3}} & \cdots \frac{1}{\sqrt{2\cdot n}} \\ \frac{1}{\sqrt{2\cdot 1}} & \frac{1}{\sqrt{2\cdot 2}} & \frac{1}{\sqrt{2\cdot 3}} & \cdots \frac{1}{\sqrt{2\cdot n}} \end{pmatrix}$$

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$$|v\rangle \otimes |\Phi_n\rangle : \frac{1}{\sqrt{C_n}}\left(\frac{1}{\sqrt{2}} \quad \frac{1}{\sqrt{2}} \quad \frac{1}{\sqrt{4}} \quad \frac{1}{\sqrt{4}} \quad \cdots\cdots \quad \frac{1}{\sqrt{2n}} \quad \frac{1}{\sqrt{2n}}\right)$$

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$$\approx \frac{\ln(n/2)}{\ln n} = 1 - \frac{\ln 2}{\ln n}$$

Summary

- Introduced the hierarchy of correlations

$$\mathcal{C}_L \subseteq \mathcal{C}_q \subseteq \mathcal{C}_{qs} \subseteq \mathcal{C}_{qa} \subseteq \mathcal{C}_{qc}$$

- We now know that all the inclusions are strict.
- Problem: find the smallest parameters (n_A, n_B, m_A, m_B) for which the separations work.
- We showed $\mathcal{C}_q \neq \mathcal{C}_{qs}$ for (4, 4, 2, 2).
- Conjecture: $\mathcal{C}_q \neq \mathcal{C}_{qs}$ for (3, 3, 2, 2).
- Question: can we use other features in infinite dimensions to prove separations?

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THANK YOU