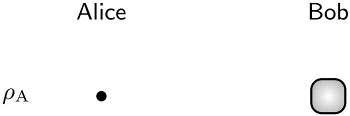
Postquantum steering

Ana Belén Sainz, Nicolas Brunner, Daniel Cavalcanti
Paul Skrzypczyk and Tamás Vértesi

Phys. Rev. Lett. 115, 190403 (2015)

Steering



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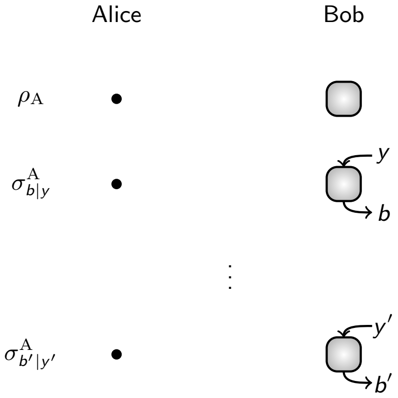
Alice
Bob
ρ_{A}
$\sigma^{\mathrm{A}}_{b|y}$
y
b
$\sigma^{\mathrm{A}}_{b'|y'}$
y'
b'

Steering

Fix y $\longrightarrow$ ensemble: $\{\sigma^{\mathrm{A}}_{b|y}\}_b\,,$ $\longrightarrow$ $\rho_{\mathrm{A}} = \sum_b \sigma^{\mathrm{A}}_{b|y}$

Assemblage: $\{\sigma^{\mathrm{A}}_{b|y}\}_{b,y}$. $p(b|y) = \mathrm{tr}\left(\sigma^{\mathrm{A}}_{b|y}\right)$.

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Given an assemblage, **could it have a classical explanation?**

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Set of "classical" assemblages

Steering Inequality:
$\mathrm{tr} \sum_{by} F_{by}\, \sigma^{\mathrm{A}}_{b|y} \leq \beta_{\mathrm{US}}$

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Given an assemblage, **could it have a quantum explanation?**

Bipartite steering

$$\text{Given } \{\sigma^{\mathrm{A}}_{b|y}\}_{b,y}, \quad \rho_{\mathrm{A}} = \sum_b \sigma^{\mathrm{A}}_{b|y}, \quad \mathrm{tr}\,(\rho_{\mathrm{A}}) = 1$$

$$\exists\, \rho_{\mathrm{AB}}, \quad \{M_{b|y}\}_{b,y} \quad \text{st} \quad \sigma^{\mathrm{A}}_{b|y} = \mathrm{tr}_{\mathrm{B}}\left(\mathbb{1}_{\mathrm{A}} \otimes M_{b|y}\, \rho_{\mathrm{AB}}\right)$$

[1] N. Gisin, Helvetica Physica Acta 62, 363 (1989).
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- Alice and Bob: **Yes !** GHJW theorem[1]
- **Multipartite scenarios?**

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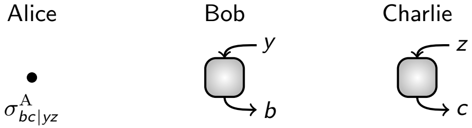
Steering: multipartite scenarios



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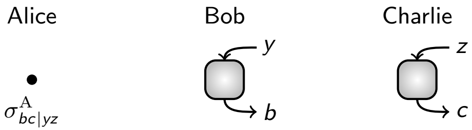

Fix $y, z \quad \longrightarrow \quad$ ensemble: $\quad \{\sigma^{\mathrm{A}}_{bc|yz}\}_{b,c}\,, \quad \longrightarrow \quad \rho_{\mathrm{A}} = \sum_{b,c} \sigma^{\mathrm{A}}_{bc|yz}$

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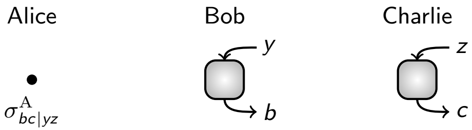

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No Signalling: $\sum_b \sigma^{\mathrm{A}}_{bc|yz} = \sum_b \sigma^{\mathrm{A}}_{bc|y'z}$, $\quad \sum_c \sigma^{\mathrm{A}}_{bc|yz} = \sum_c \sigma^{\mathrm{A}}_{bc|yz'}$

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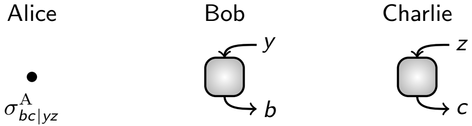

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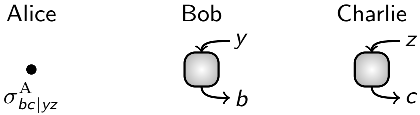
$\exists\, \rho_{\mathrm{ABC}}, \quad \{M_{b|y}\}_{b,y}, \quad \{M_{c|z}\}_{c,z}$ **st** $\quad \sigma^{\mathrm{A}}_{bc|yz} = \mathrm{tr}_{\mathrm{B}}\left(\mathbb{1}_{\mathrm{A}} \otimes M_{b|y} \otimes M_{c|z}\, \rho_{\mathrm{ABC}}\right)$

Postquantum steering: example



$$b, c, y, z \in \{0, 1\}$$

$$\rho_{\mathrm{A}} = \frac{\mathbb{1}}{2}\,.$$

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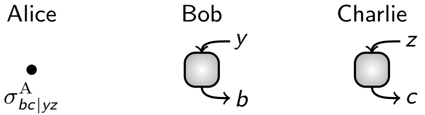

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- $(y, z) = (0, 0), (0, 1), (1, 0)$:

$$\sigma^{\mathrm{A}}_{bc|yz} = \begin{cases} \frac{\mathbb{1}}{4}, & \text{if } b = c\,, \\ 0\,, & \text{if } b \neq c\,, \end{cases}$$

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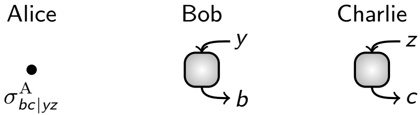

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$$p(bc|yz) = \mathrm{tr}\left(\sigma^{\mathrm{A}}_{bc|yz}\right) \overset{quantum}{=} \mathrm{tr}_{\mathrm{BC}}\left(M_{b|y} \otimes M_{c|z}\, \rho_{\mathrm{BC}}\right)$$

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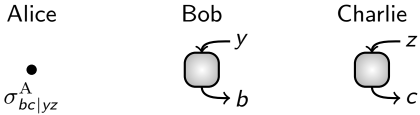

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$$\begin{aligned} p(bc|yz) &= \mathrm{tr}\left(\sigma^{\mathrm{A}}_{bc|yz}\right) \\ &\overset{quantum}{=} \mathrm{tr}_{\mathrm{BC}}\left(M_{b|y} \otimes M_{c|z}\,\rho_{\mathrm{BC}}\right) \end{aligned}$$

$$p(bc|yz) = \begin{cases} \frac{1}{2}\,, & \text{if } b \oplus c = yz\,, \\ 0\,, & \text{otherwise}\,. \end{cases}$$

No quantum realisation for the assemblage

Postquantum steering: example without postquantum nonlocality

(1) Postquantum assemblage $\left\{\sigma^{\mathrm{A}}_{bc|yz}\right\}_{b,y,c,z}$

(2) Quantum correlations for every measurement by Alice:

$p(abc|xyz) = \mathrm{tr}\left(M_{a|x} \otimes \sigma^{\mathrm{A}}_{bc|yz}\right)$

(1) Postquantum assemblage $\sigma^{\mathrm{A}}_{bc|yz}$

Steering inequality: F_{bcyz}

$$\mathrm{tr} \sum_{bcyz} F_{bcyz}\, \sigma^{\mathrm{A}}_{bc|yz}$$

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Almost quantum assemblages: $\widetilde{\mathrm{Q}} \supset \mathrm{Q}$

$$\beta_{\widetilde{\mathrm{Q}}} \geq \beta_{\mathrm{Q}}$$

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Almost quantum assemblages: $\widetilde{\mathrm{Q}} \supset \mathrm{Q}$

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$\mathrm{tr} \sum_{bcyz} F_{bcyz}\, \sigma^{\mathrm{A}}_{bc|yz} > \beta_{\widetilde{\mathrm{Q}}} \quad \Rightarrow \quad \sigma^{\mathrm{A}}_{bc|yz}$ **is postquantum**

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(2) Quantum correlations $p(abc|xyz)$

(i) $p(abc|xyz)$ is local

(ii) Real qubit assemblage, local for all projective measurements

(iii) Qutrit assemblage, local for all POVMs[2].

[2] F. Hirsch, M. T. Quintino, J. Bowles and N. Brunner, Phys. Rev. Lett, 111, 160402 (2013).

(ii) Qubit assemblage, local for all PVM

$$\Pi_{a|x}(\mu) = \mu\,\Pi_{a|x} + (1-\mu)\,\mathbb{1}/2, \quad \sigma^{\mathrm{A}}_{bc|yz}(\mu) = \mu\,\sigma^{\mathrm{A}}_{bc|yz} + (1-\mu)\,\mathrm{tr}\left(\sigma^{\mathrm{A}}_{bc|yz}\right)\mathbb{1}/2$$

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- $p(abc|xyz) = \mathrm{tr}_{\mathrm{A}}\left(\Pi_{a|x}(\mu)\,\sigma^{\mathrm{A}}_{bc|yz}\right) = \mathrm{tr}_{\mathrm{A}}\left(\Pi_{a|x}\,\sigma^{\mathrm{A}}_{bc|yz}(\mu)\right)$
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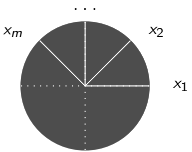

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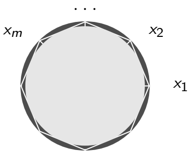

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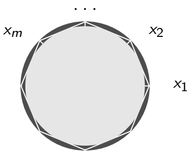

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$\Leftrightarrow$ $\sigma^{\mathrm{A}}_{bc|yz}(\mu)$ **local** $\forall\,\Pi_{a|x}$

Postquantum steering: example without postquantum nonlocality

- Four dichotomic measurements (X, Z)
- Search:

Fix $F_{bc|yz}$:

- Compute $\beta_{\widetilde{\mathrm{Q}}}$ (SDP).
- Find max violation of the inequality by the 'local' assemblages (SDP).
  $\longrightarrow \quad \sigma^{\mathrm{A}}_{bc|yz}$
- Compute $\beta^* = \mathrm{tr} \sum_{bcyz} F_{bcyz} \, \sigma^*_{bc|yz}$, $\sigma^*_{bc|yz} := \sigma^{\mathrm{A}}_{bc|yz}(\mu = \cos(\frac{\pi}{8}))$

  If $\beta^* > \beta_{\widetilde{\mathrm{Q}}}$: done! , otherwise, change $F_{bc|yz}$, start over.

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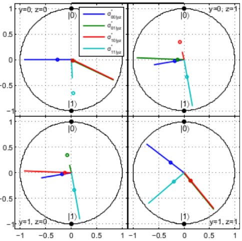

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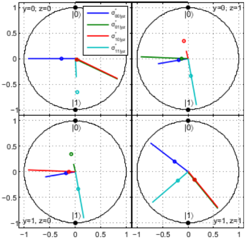

Summary and open questions

- Steering beyond quantum theory $\rightarrow$ multipartite scenarios
- Genuinely new effect
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- Fundamental difference between bipartite and multipartite scenarios

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- Genuinely new effect
  $\rightarrow$ postquantum steering $\not\Rightarrow$ postquantum nonlocality
- Fundamental difference between bipartite and multipartite scenarios

- Insight on the characterisation of quantum phenomena
- General framework for non-signalling assemblages
  $\rightarrow$ quantify postquantumness
- Information-theoretic applications of postquantum steering

Thanks !!!

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