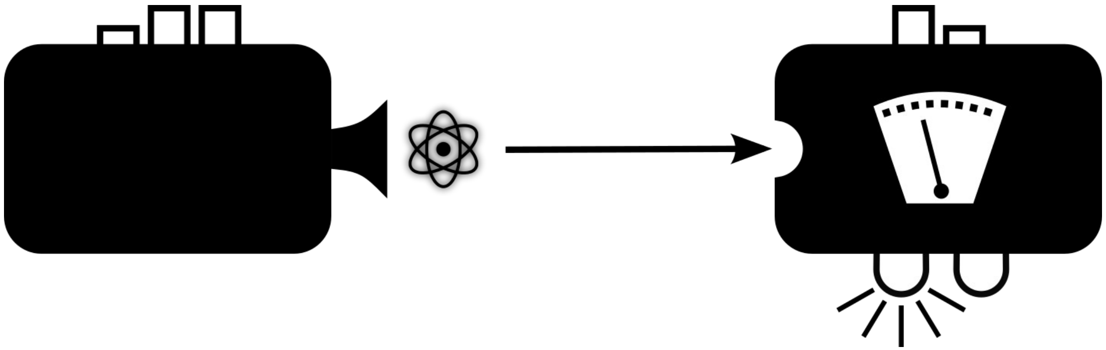
QUANTUM CORRELATIONS UNDER RESTRICTED TRANSFER OF INFORMATION



Jonatan Bohr Brask
DTU Physics

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DANMARKS FRIE FORSKNINGSFOND
INDEPENDENT RESEARCH FUND DENMARK

Causality in the Quantum World, Capri, September 2019

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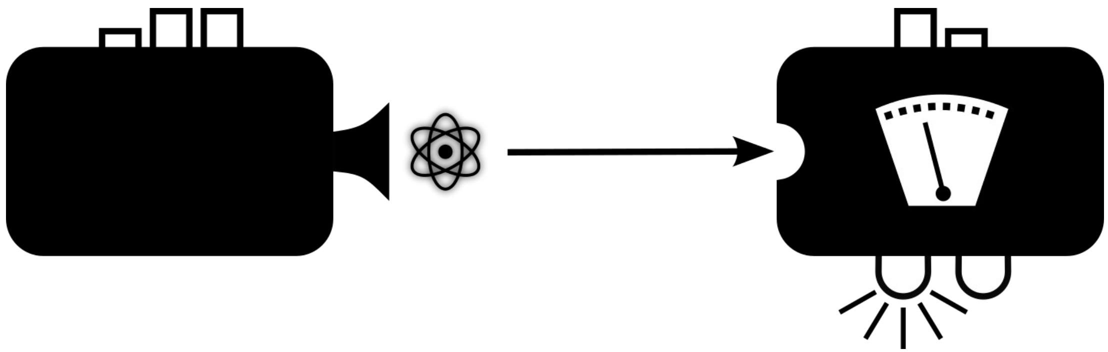

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A. Tavakoli, E. Zambrini Cruzeiro,
JBB, N. Gisin, N. Brunner

arXiv:1909.05656

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Correlations...

In any physical theory with a notion of distinct observables, we can look at correlations....

$$p(A, B)$$

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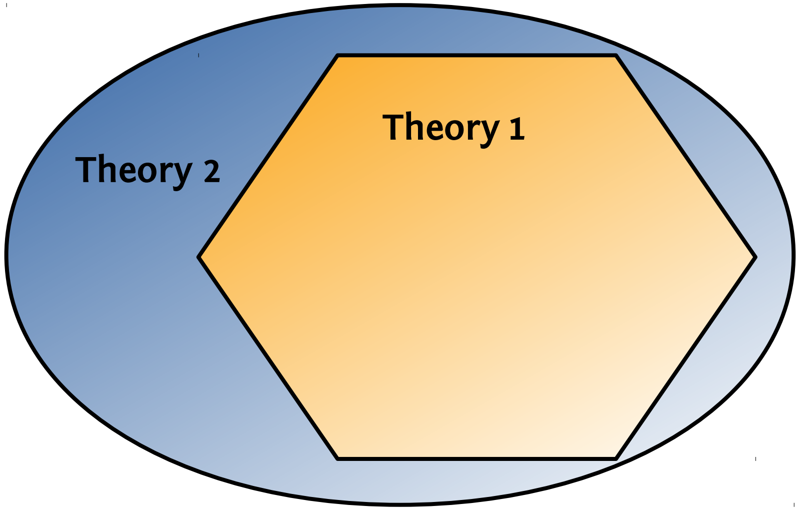
A B

Use correlations to distinguish and classify physical theories.



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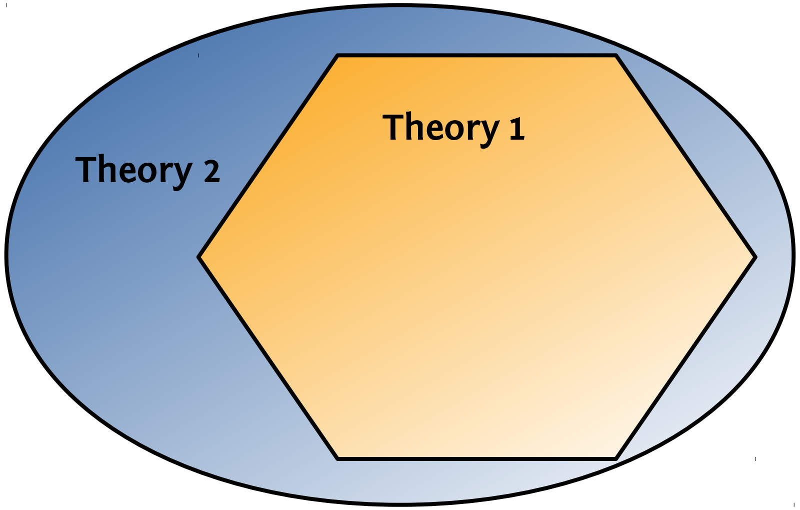

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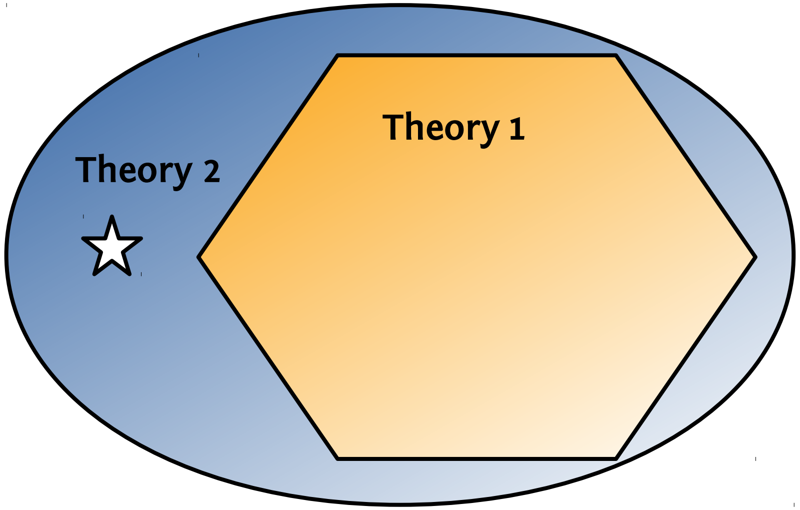

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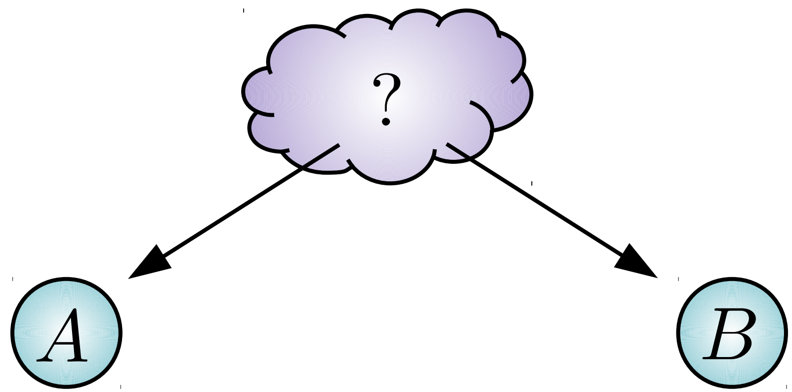

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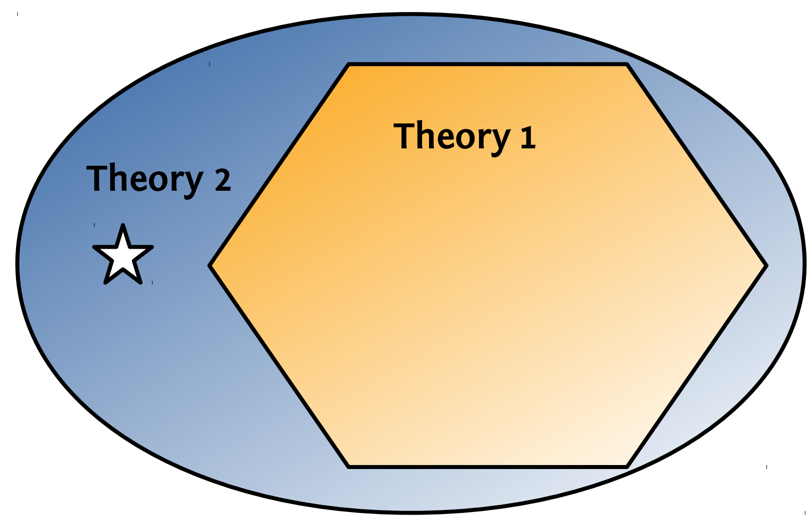

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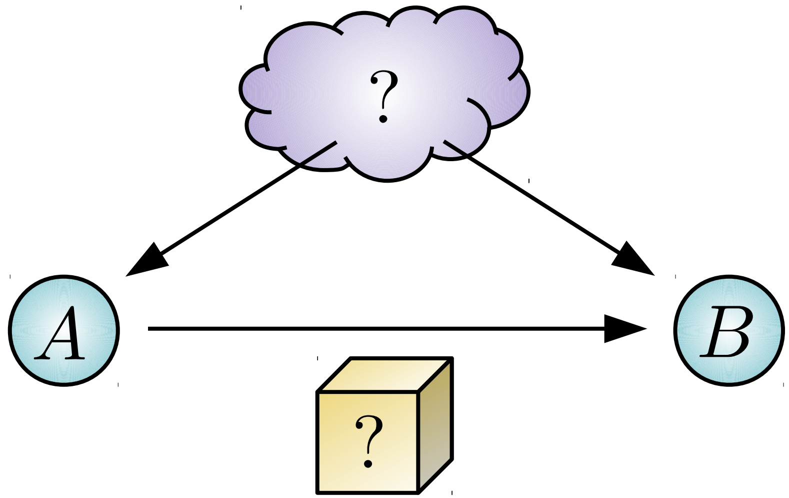

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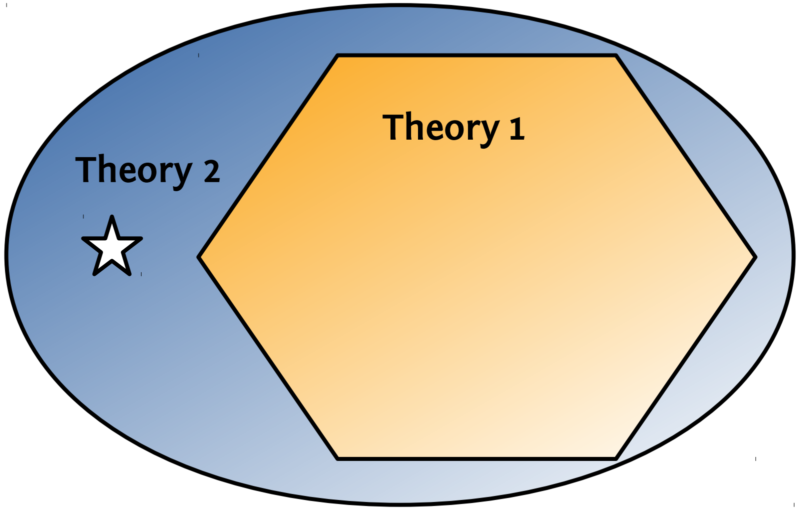

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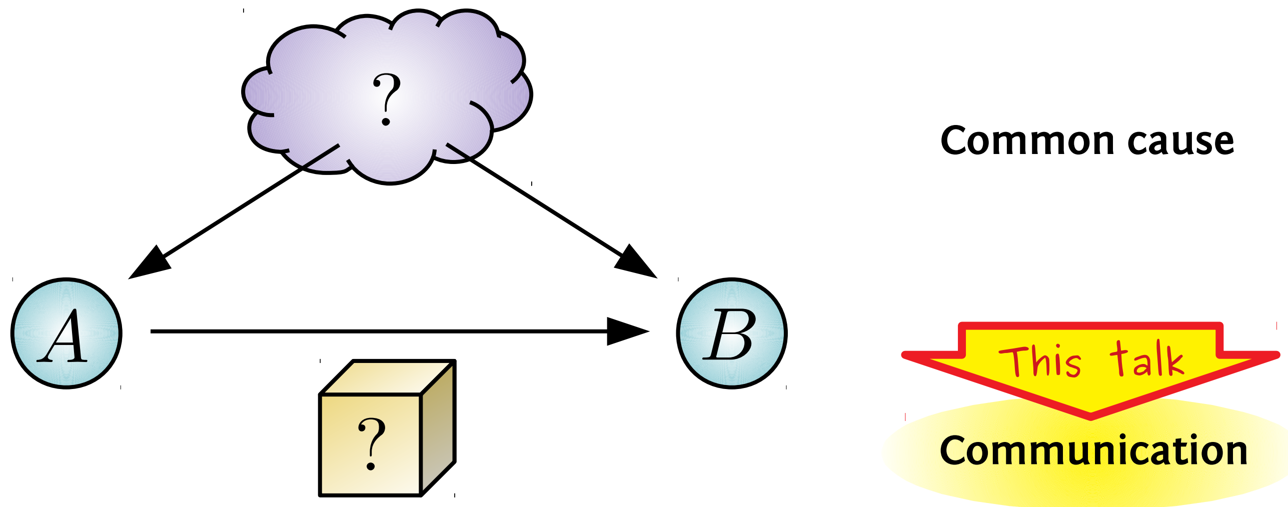

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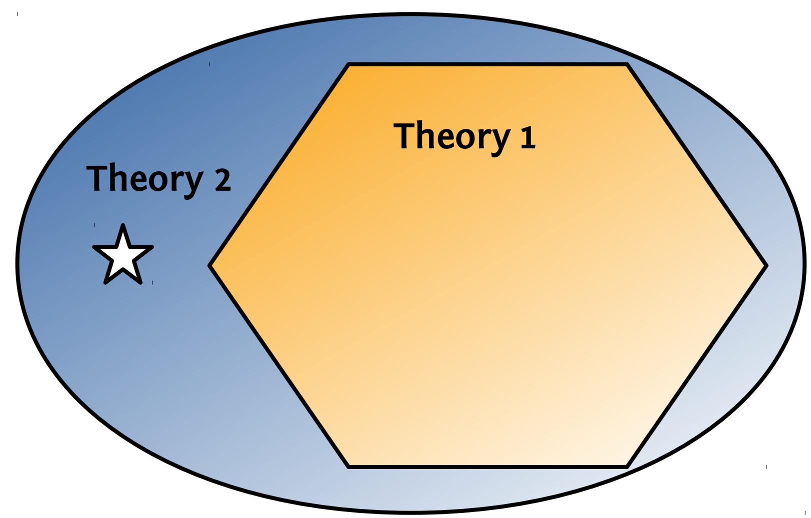

Communication and correlations – prepare-and-measure scenarios

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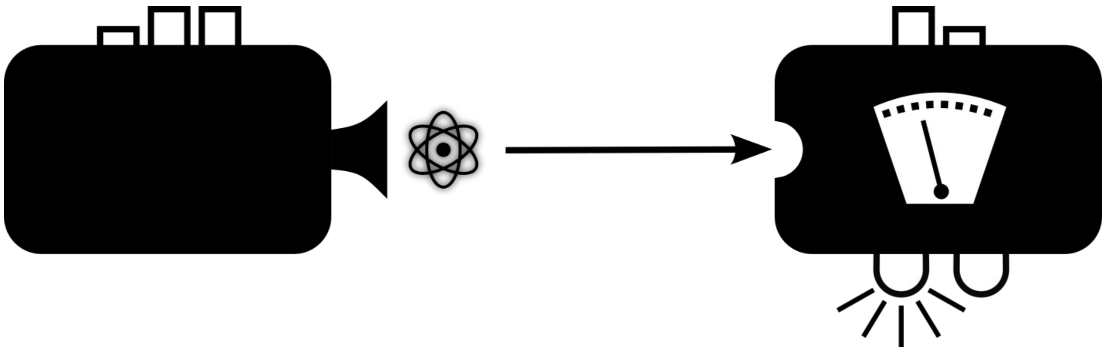

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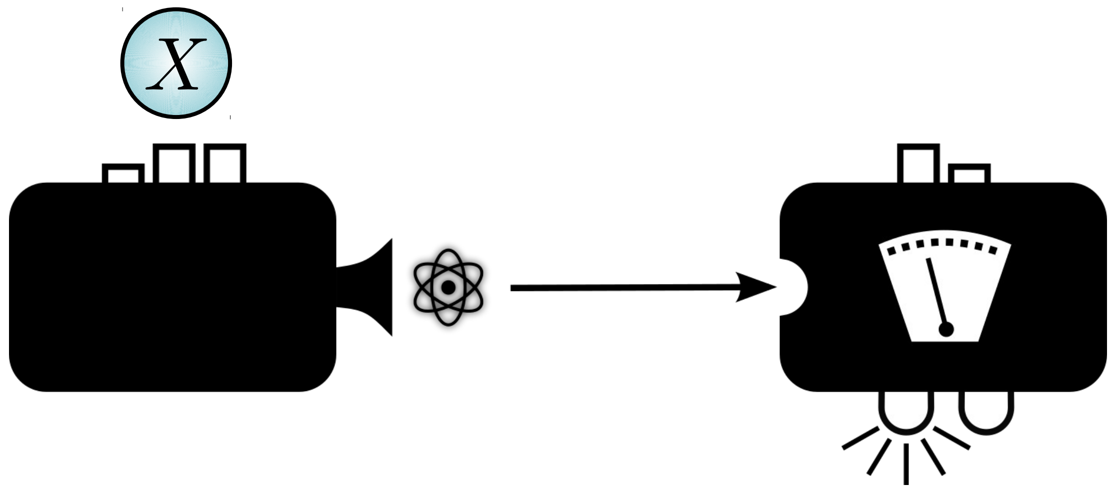

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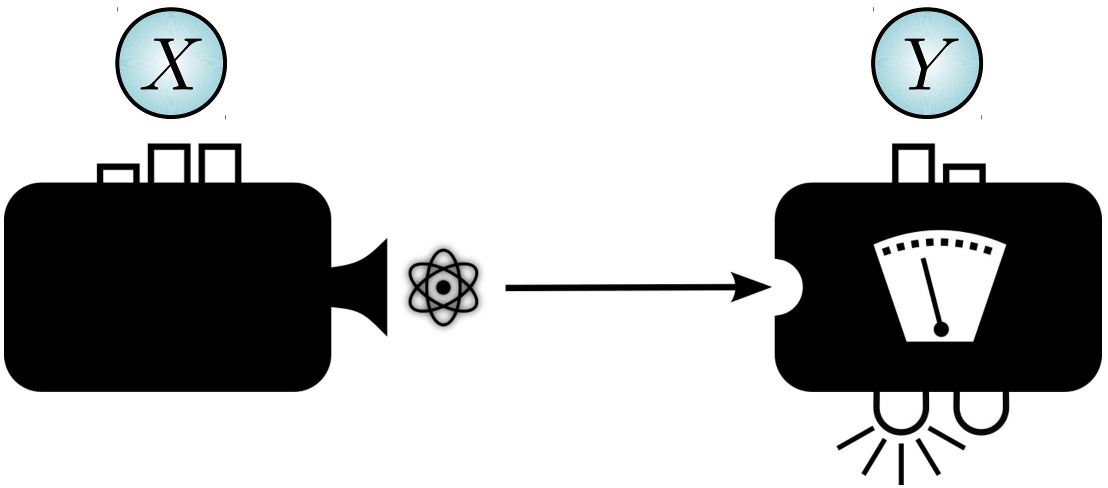

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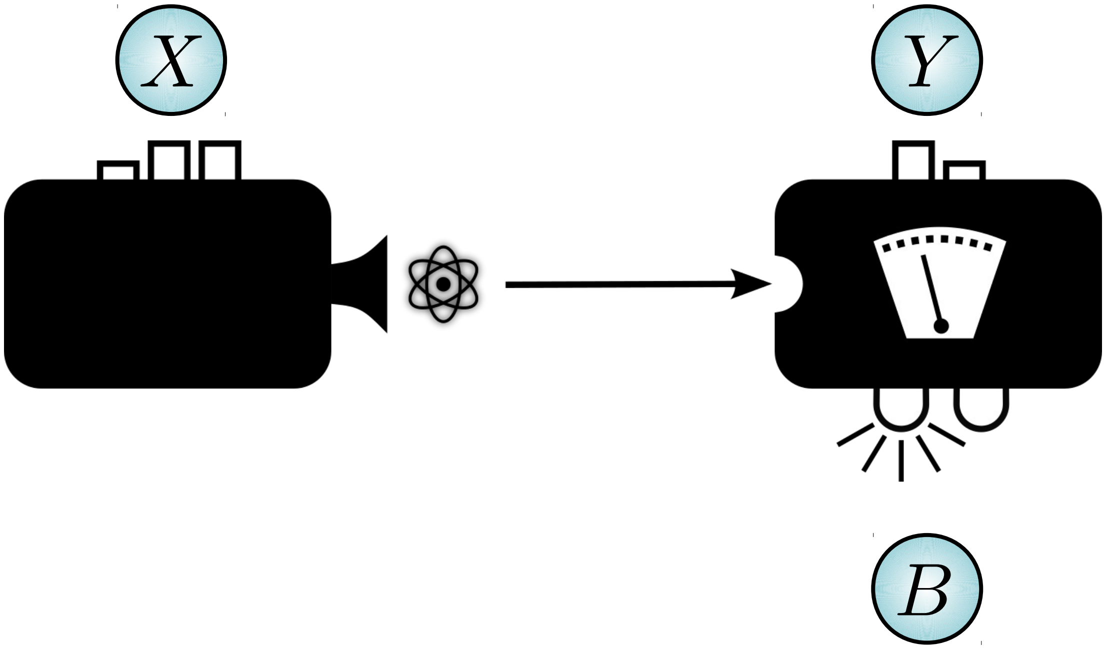

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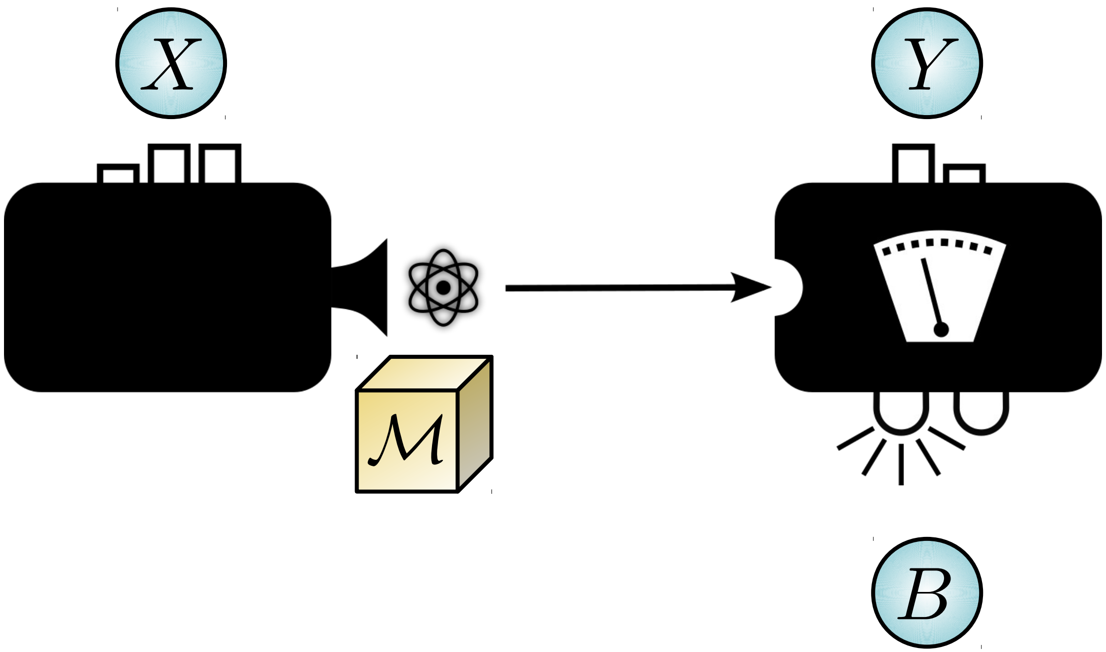

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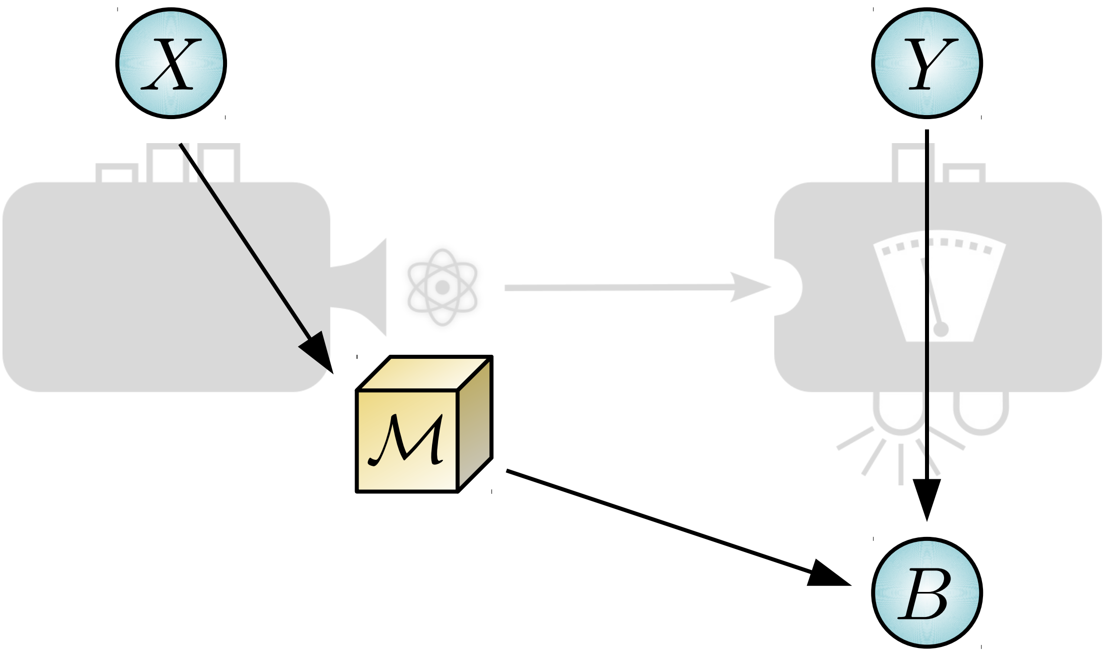

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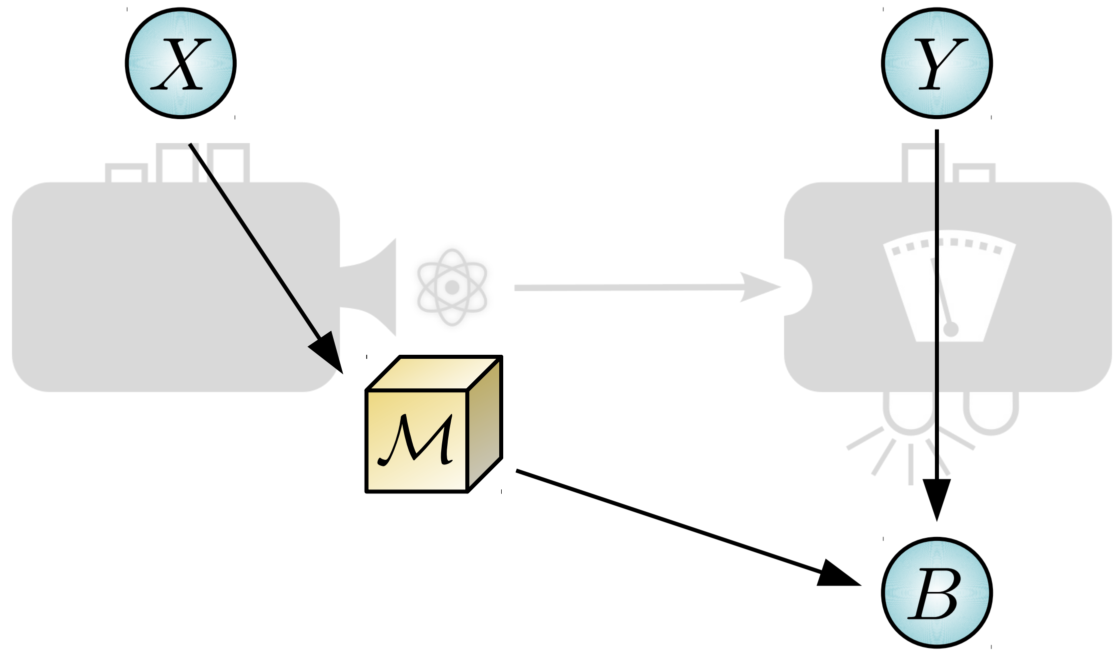

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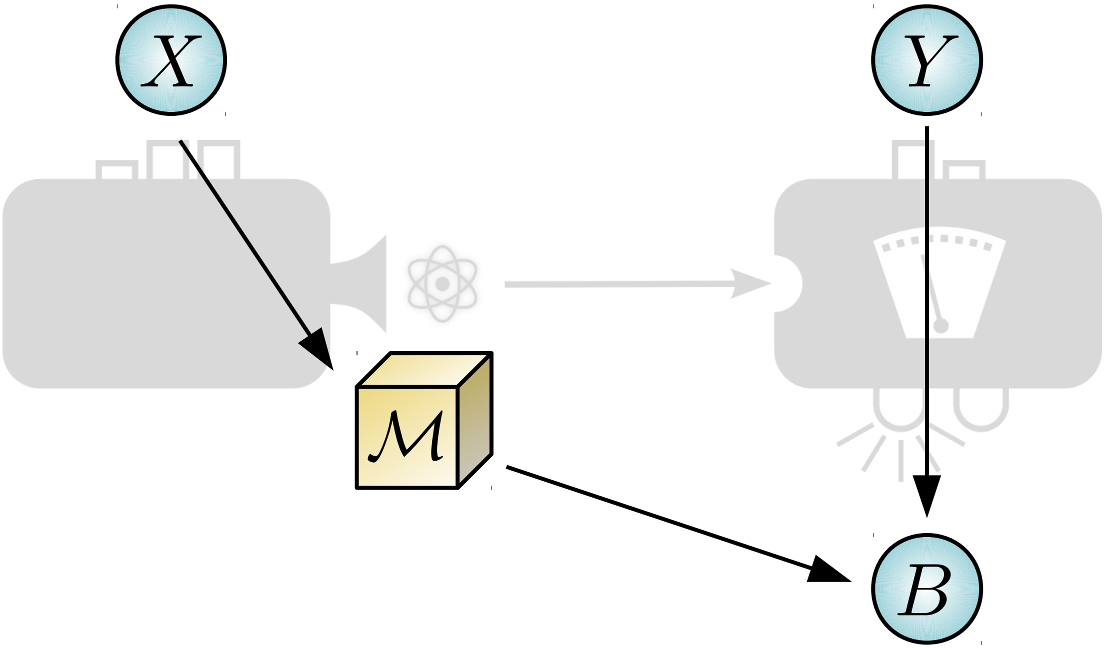

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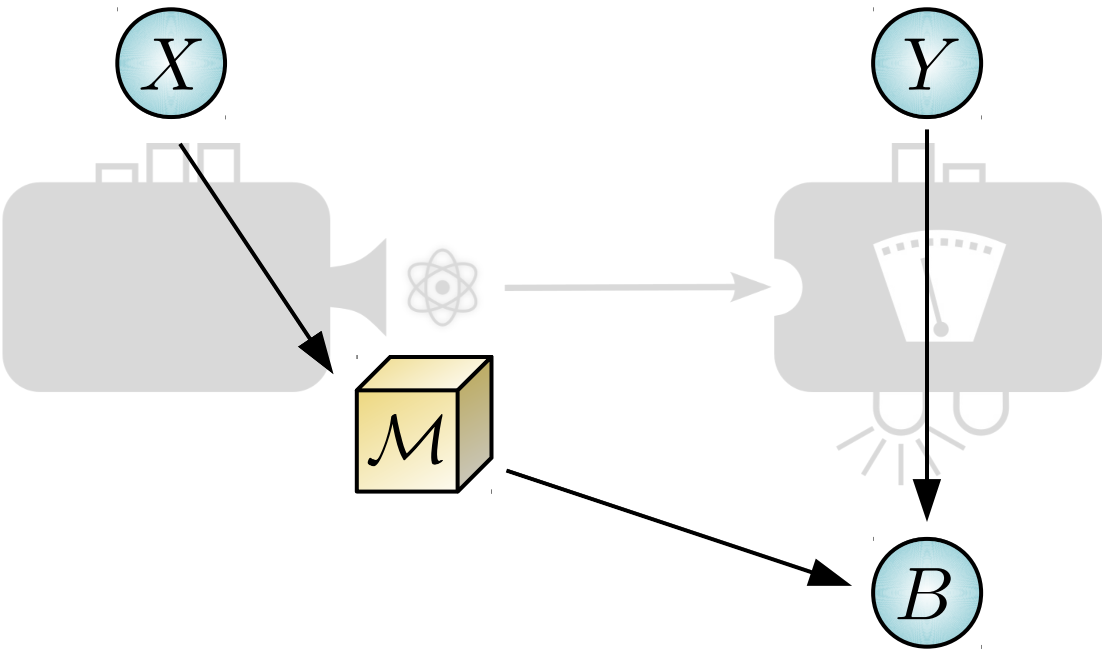

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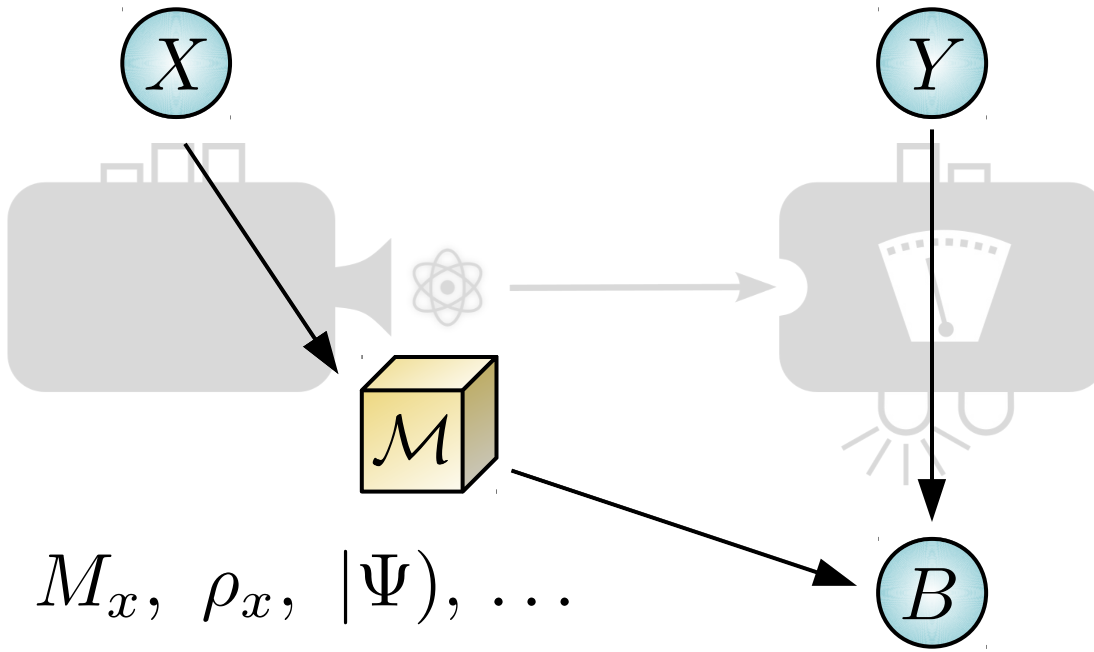

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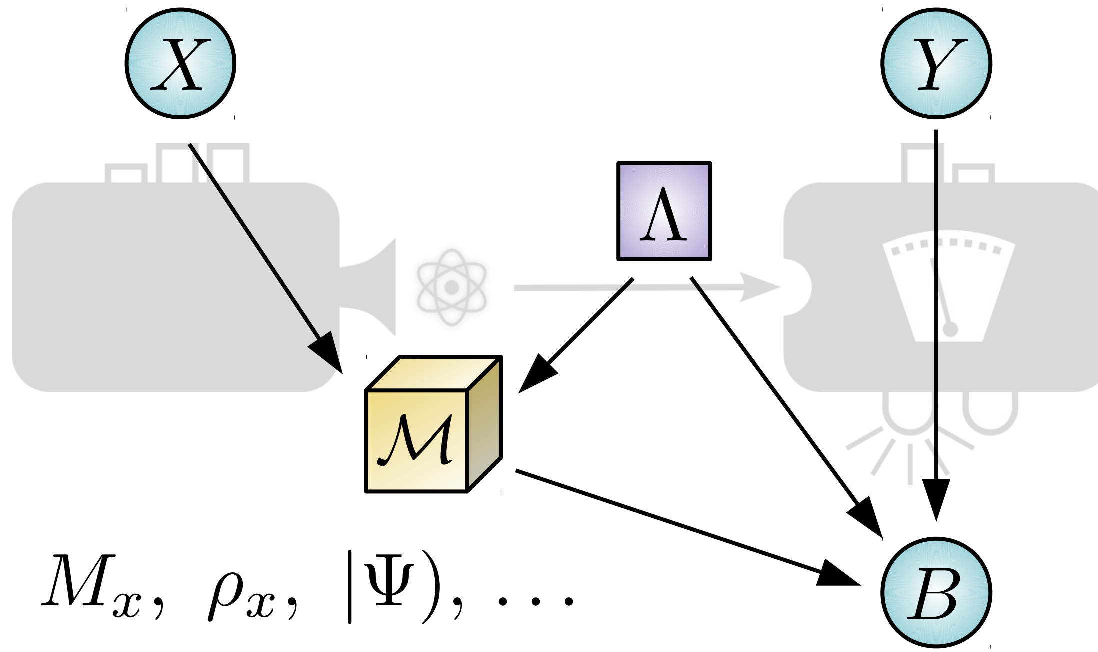

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Approaches to limiting communication

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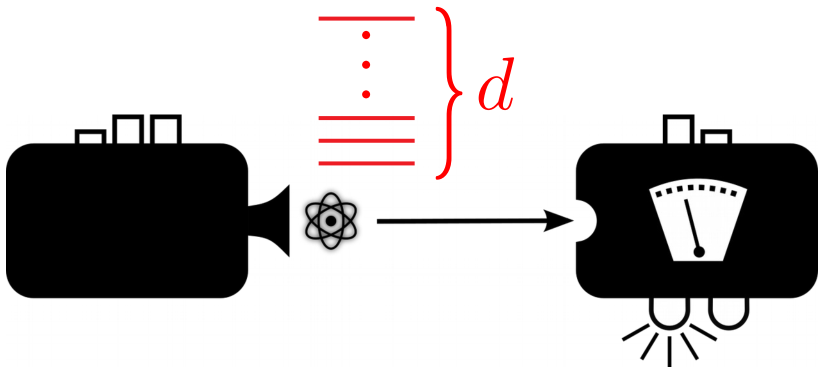
Bounded message dimension.

- Limit number of distinguishable states.



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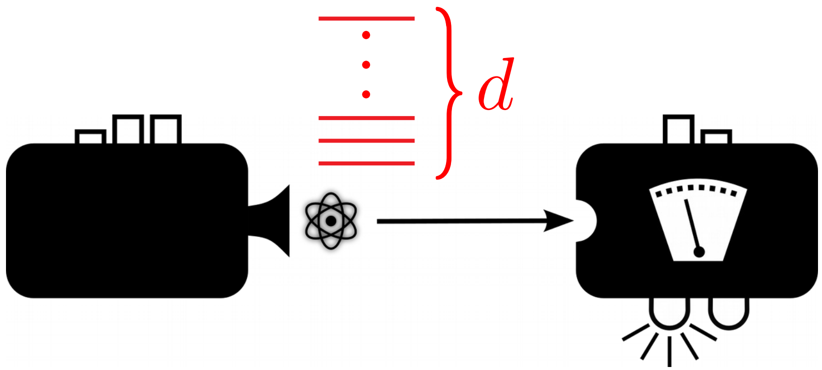

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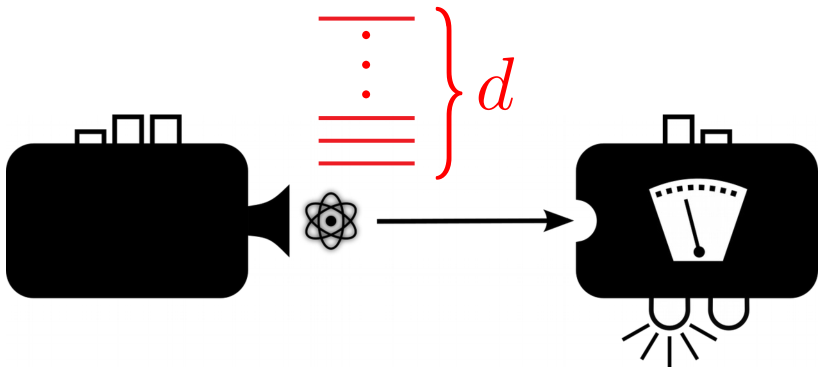

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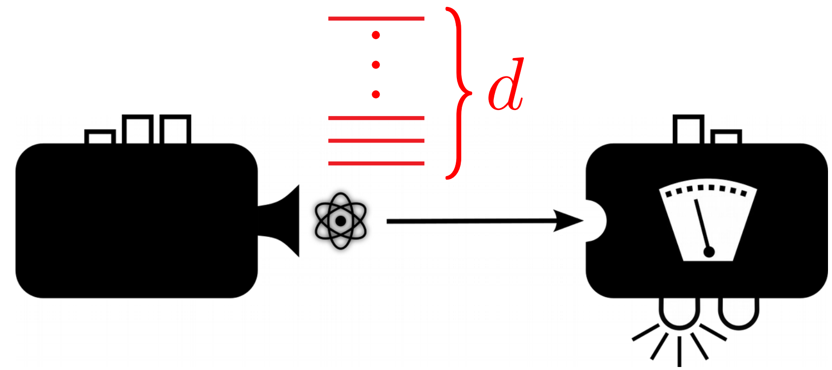
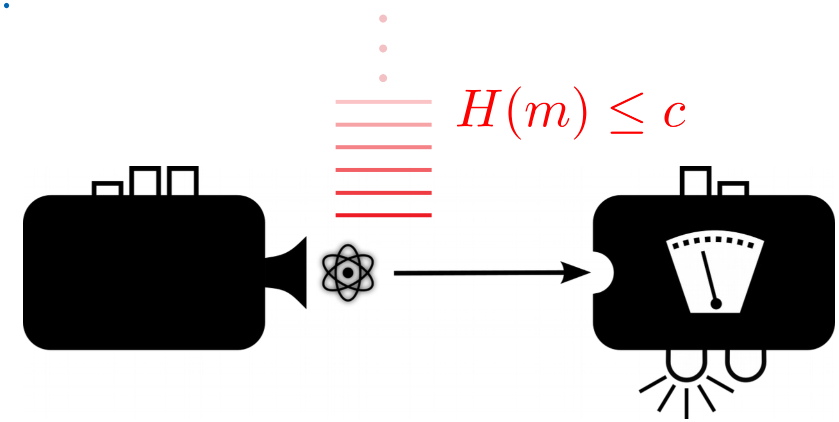


Bounded entropy of message distribution.

- Limit information content w/o restricting size.

Chaves *et al.* (2015), Zhu (2016)



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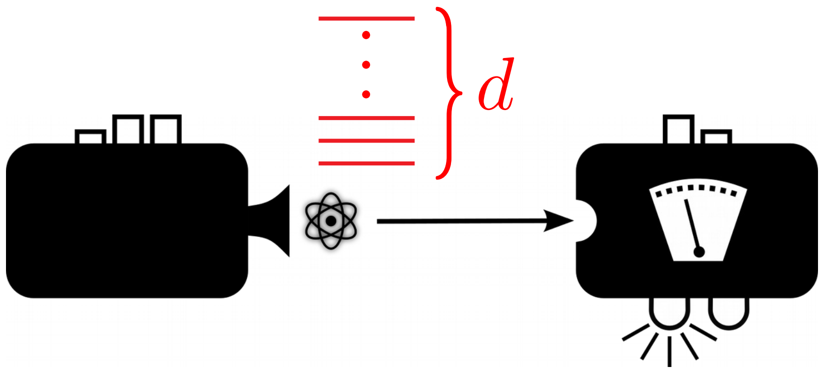

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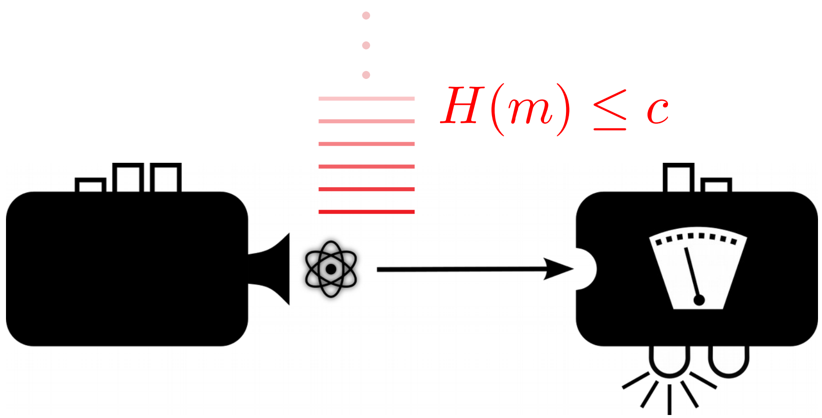

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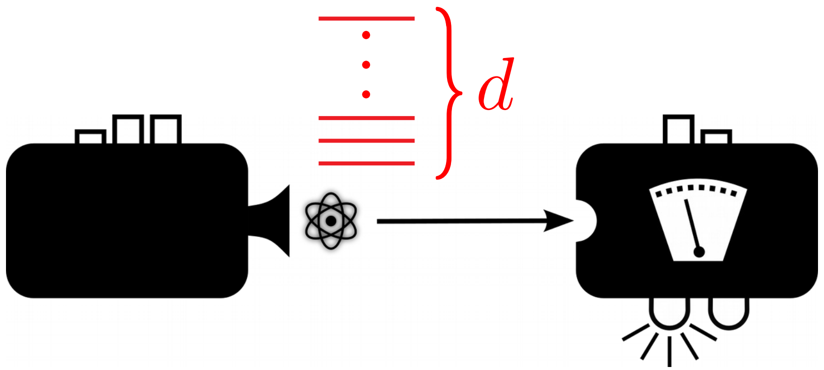

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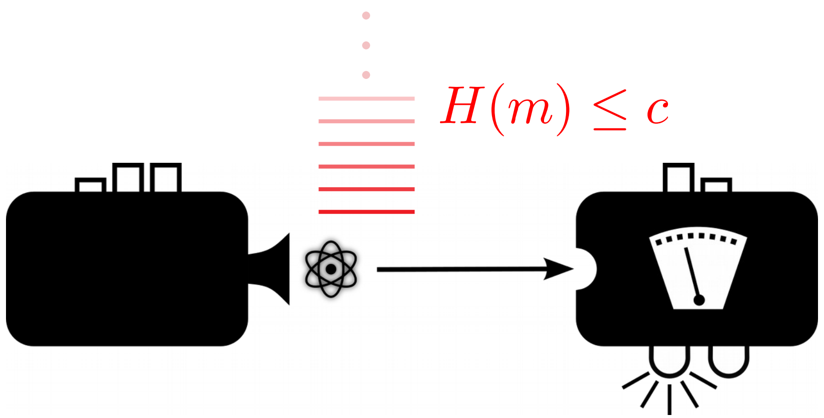

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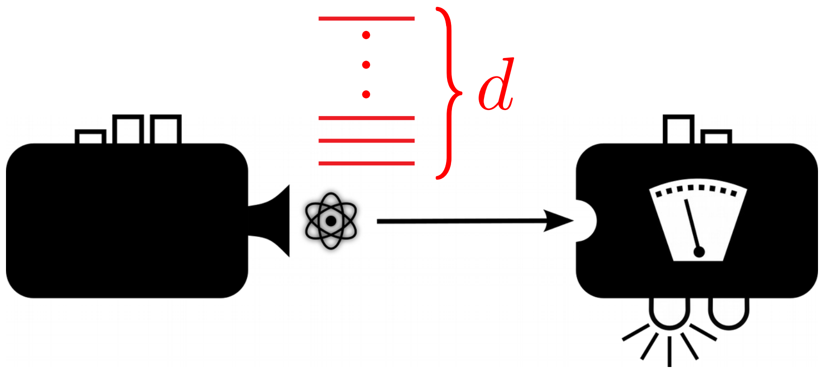

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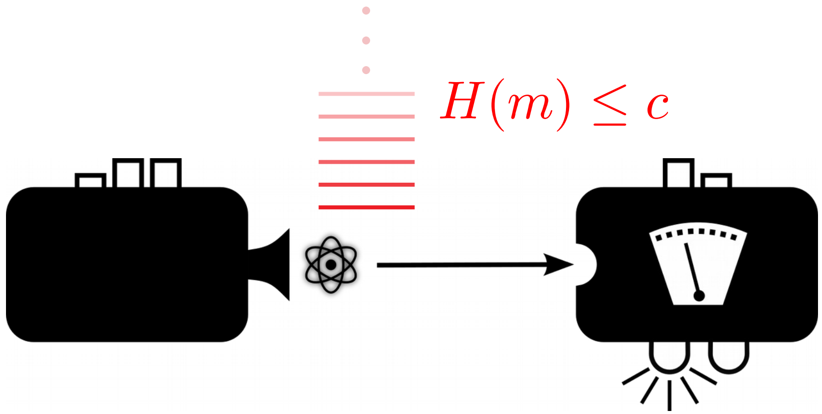

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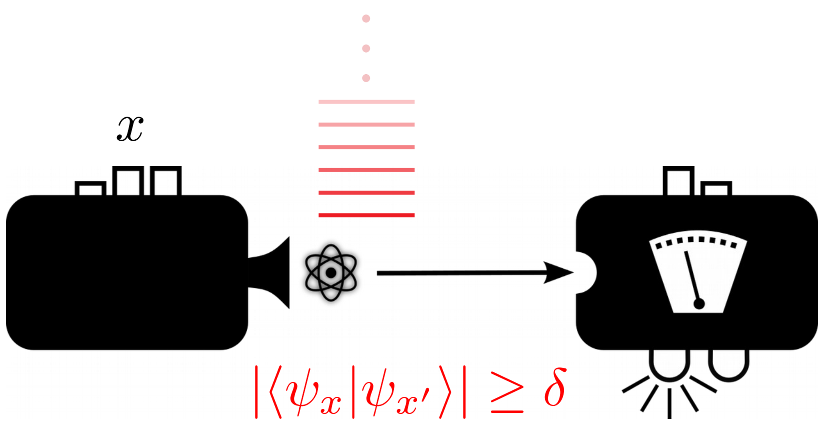
Bounded state overlap / Bounded message energy



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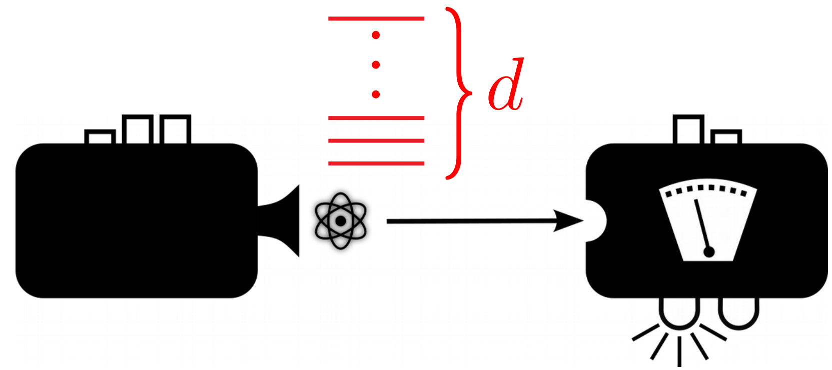

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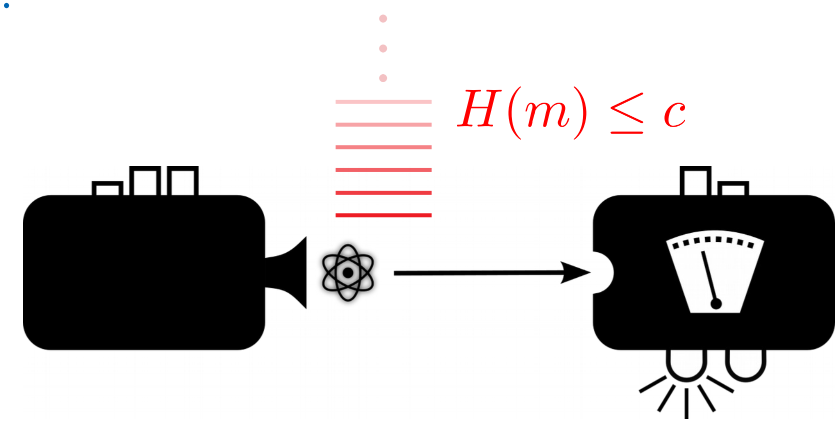

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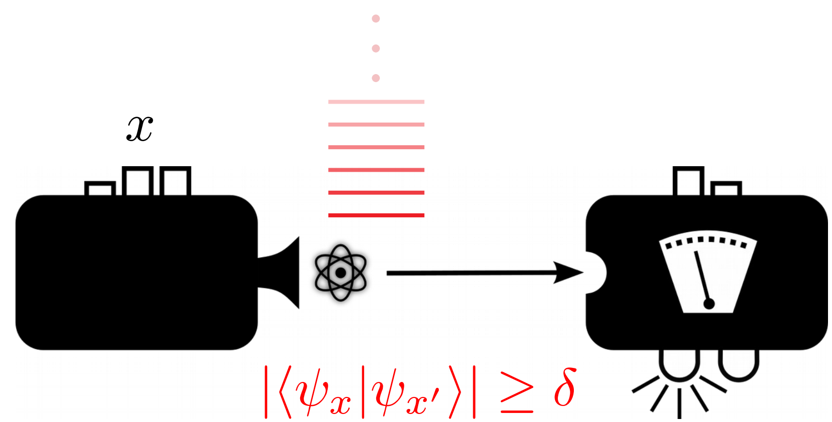

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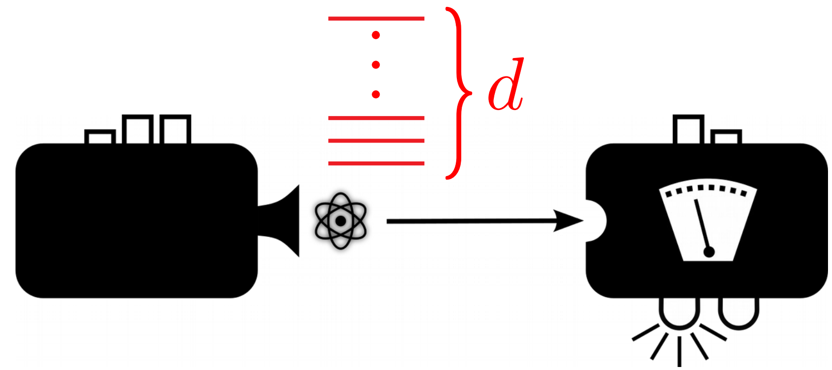

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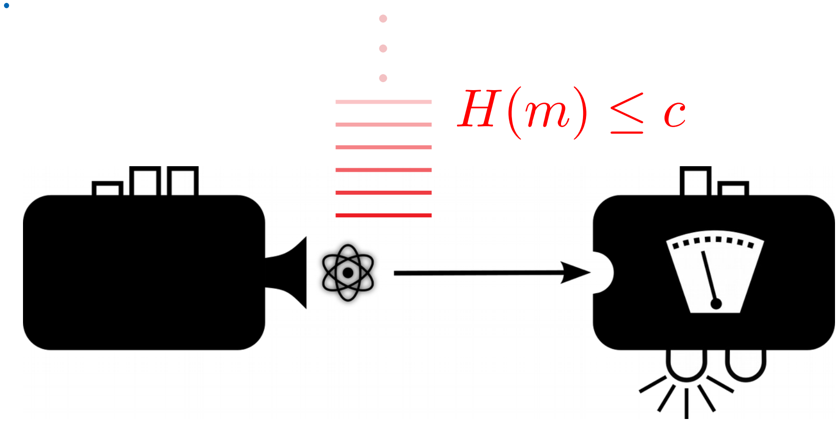

Bounded state overlap / Bounded message energy

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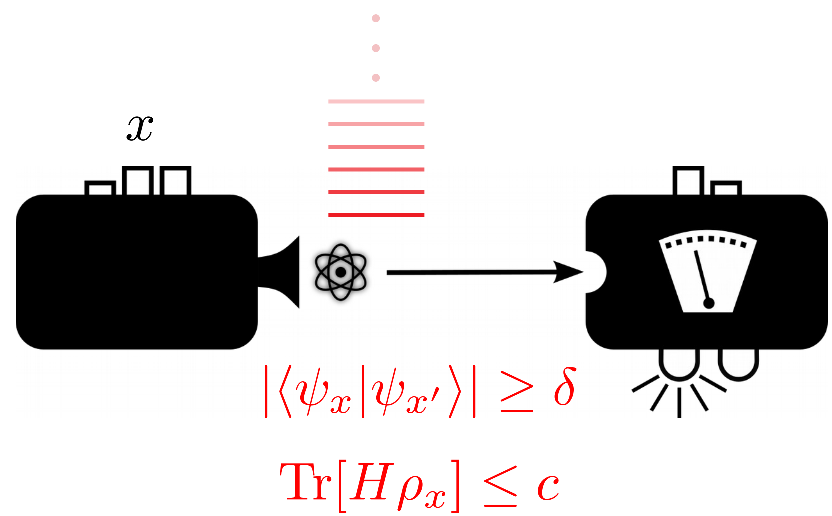

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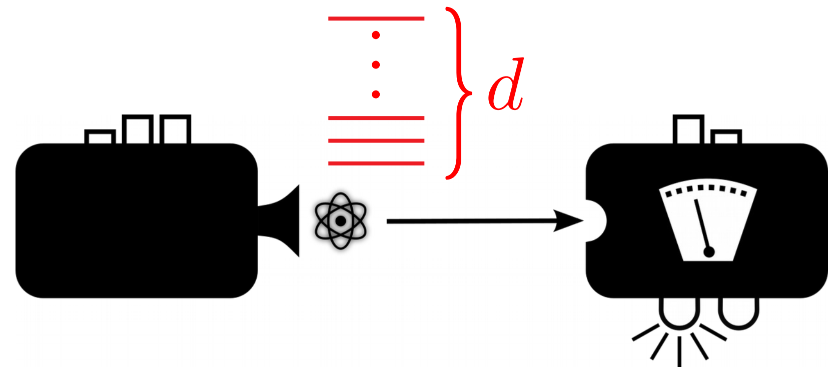

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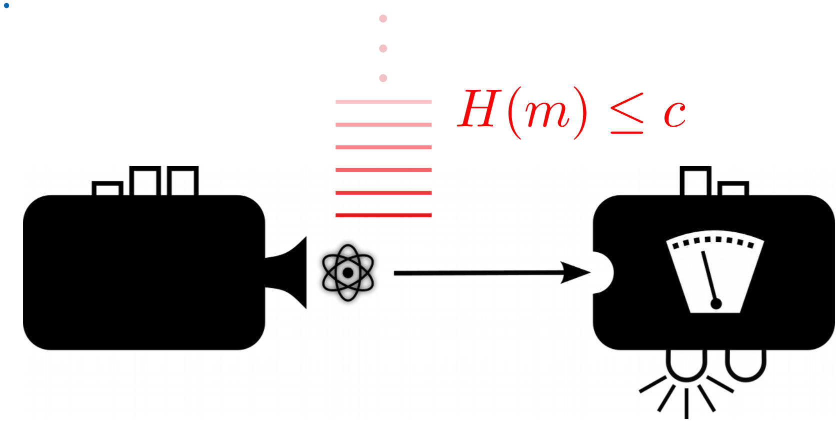

Bounded state overlap / Bounded message energy

- Target quantum / classical separation.
- Advantageous for optical implementations of "grey-box" (semi-device-independent) QIP applications (e.g. QRNG).

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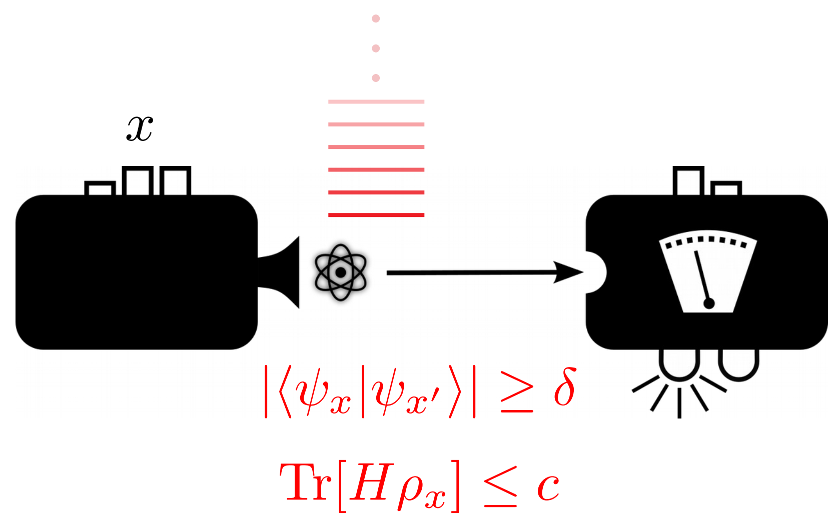

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Idea:
Directly limit information about input which can be recovered from message.

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Quantify information as change in uncertainty

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$$P_g(X) = \max_x \, p_X(x)$$

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Uncertainty w/o message

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Uncertainty w. message

$$H_{min}(X|\mathcal{E}) = -\log_2[P_g(X|\mathcal{E})]$$

The *information* is the difference

$$\mathcal{I}_X(\mathcal{E}) = H_{min}(X) - H_{min}(X|\mathcal{E})$$

Here: Limit the accessible information

Idea:
Directly limit information about input which can be recovered from message.

Quantify information as change in uncertainty

ensemble of messages

particular message

Prob. to guess input w/o message

$$P_g(X) = \max_x p_X(x)$$

Prob. to guess input w. message

$$P_g(X|\mathcal{E}) = \max_{guess.\,strat.} \sum_x p_X(x) p(x_{guess} = x|e_x)$$

$$= \max_{N_x} \sum_x p_X(x) \mathrm{Tr}[\rho_x N_x]$$

Uncertainty w/o message

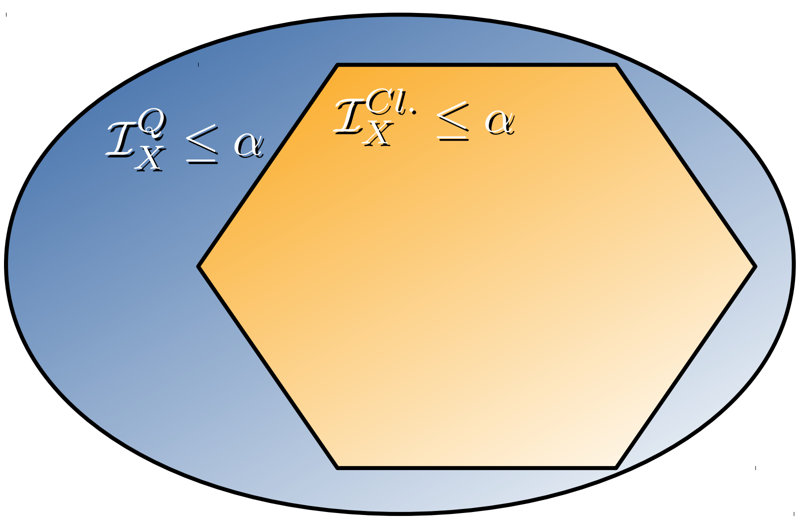
$$H_{min}(X) = -\log_2[P_g(X)]$$

Uncertainty w. message

$$H_{min}(X|\mathcal{E}) = -\log_2[P_g(X|\mathcal{E})]$$

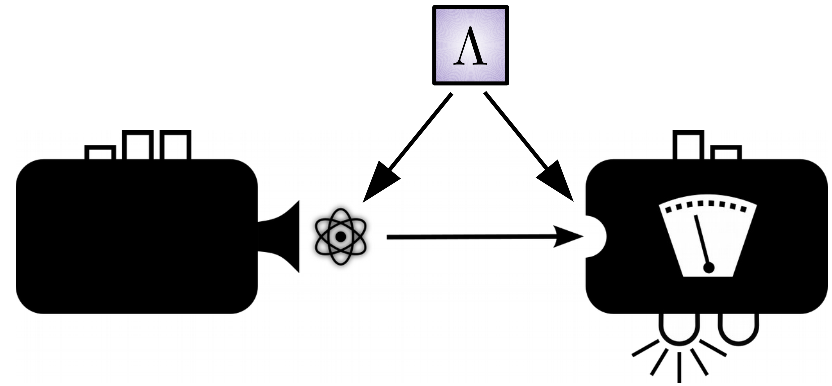
The *information* is the difference

$$\mathcal{I}_X(\mathcal{E}) = H_{min}(X) - H_{min}(X|\mathcal{E})$$



We allow for shared randomness.

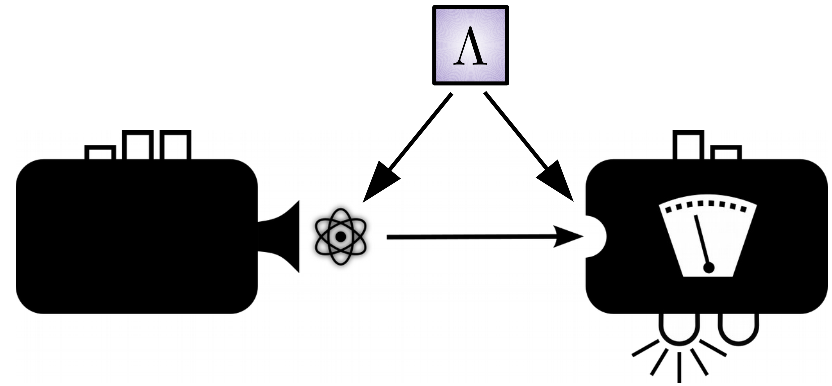
$$P_g(X|\mathcal{E}) = \sum_\lambda P_g(X|\mathcal{E}_\lambda)$$



We allow for shared randomness.

$$P_g(X|\mathcal{E}) = \sum_\lambda P_g(X|\mathcal{E}_\lambda)$$

$$E.g.\ :\ \ P_g(X|\mathcal{E}_\lambda) = \max_{N_x^\lambda} \sum_x p_X(x)[N_x^\lambda \rho_x^\lambda]$$



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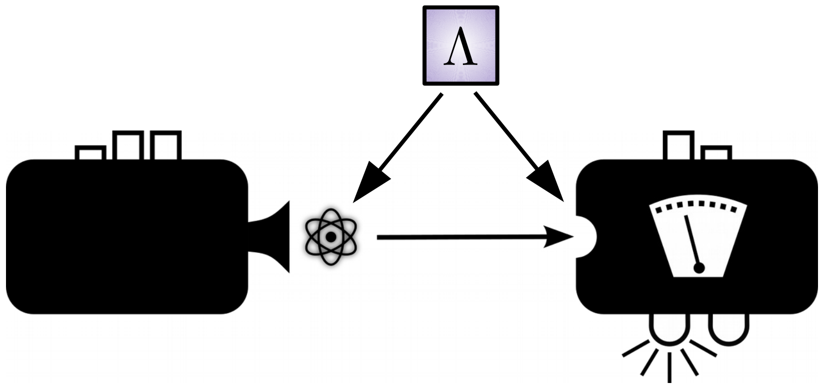

Classical correlations under restricted information

We allow for shared randomness.

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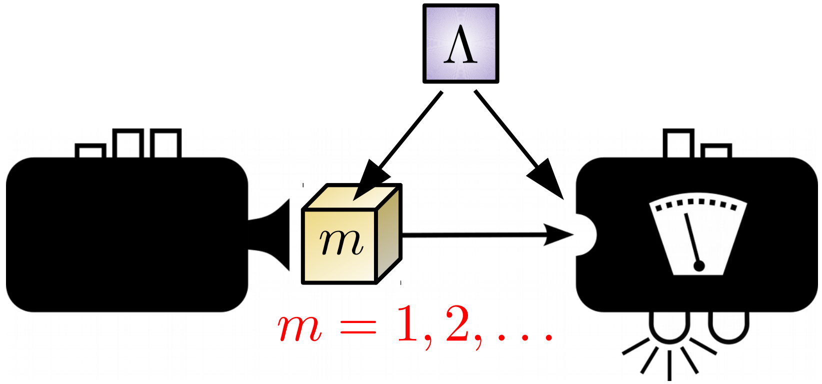

Classical correlations under restricted information

$$p(b|x,y) = \sum_\lambda p(\lambda) \sum_{m=1}^{d} p_A(m|x,\lambda) p_B(b|m,y,\lambda)$$

We allow for shared randomness.

$$P_g(X|\mathcal{E}) = \sum_\lambda P_g(X|\mathcal{E}_\lambda)$$

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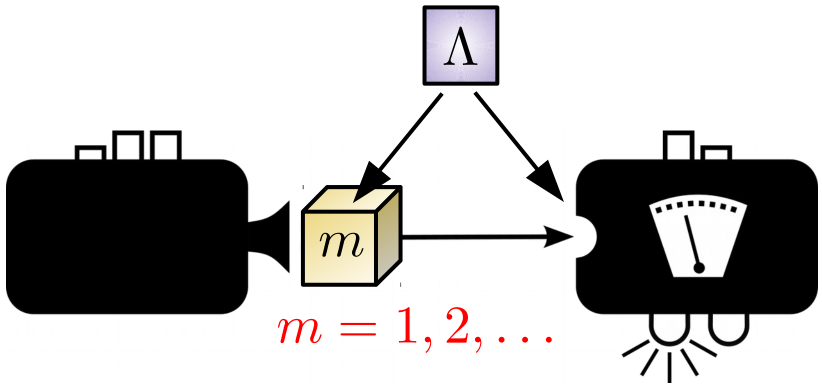

Classical correlations under restricted information

can restrict to *d = # inputs*

can take these deterministic

$$p(b|x,y) = \sum_\lambda p(\lambda) \sum_{m=1}^{d} p_A(m|x,\lambda) p_B(b|m,y,\lambda)$$

We allow for shared randomness.

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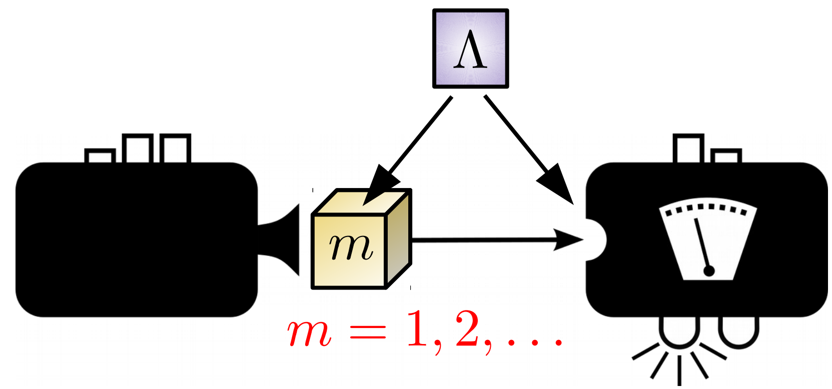

Classical correlations under restricted information

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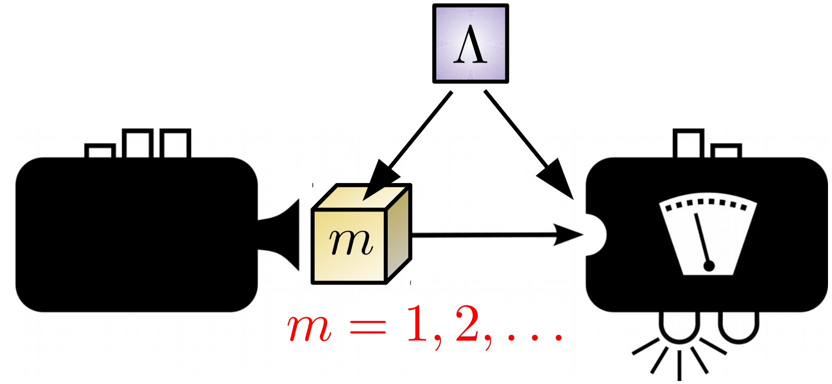
$$p(b|x,y) = \sum_\lambda p(\lambda) \sum_{m=1}^{d} p_A(m|x,\lambda) p_B(b|m,y,\lambda)$$

$$\mathcal{I}_X \leq \alpha \quad \rightarrow \quad \sum_\lambda p(\lambda) P_g^\lambda \leq 2^{\alpha - H_{min}(X)}$$

We allow for shared randomness.

$$P_g(X|\mathcal{E}) = \sum_\lambda P_g(X|\mathcal{E}_\lambda)$$

$$E.g.\ :\ P_g(X|\mathcal{E}_\lambda) = \max_{N_x^\lambda} \sum_x p_X(x)[N_x^\lambda \rho_x^\lambda]$$



Classical correlations under restricted information

can restrict to d = # *inputs*

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linear in dist. over λ

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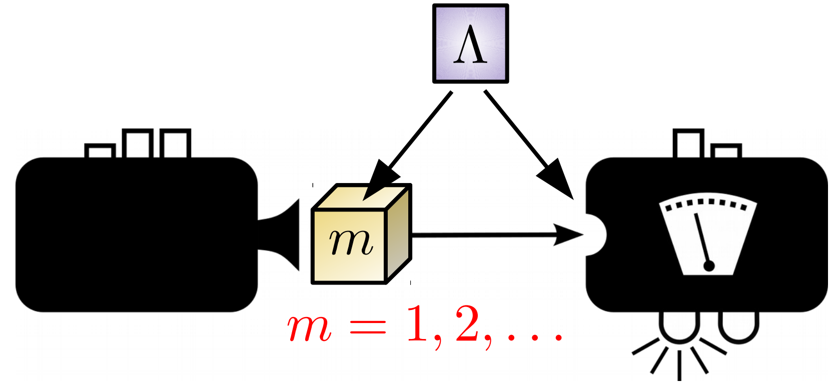

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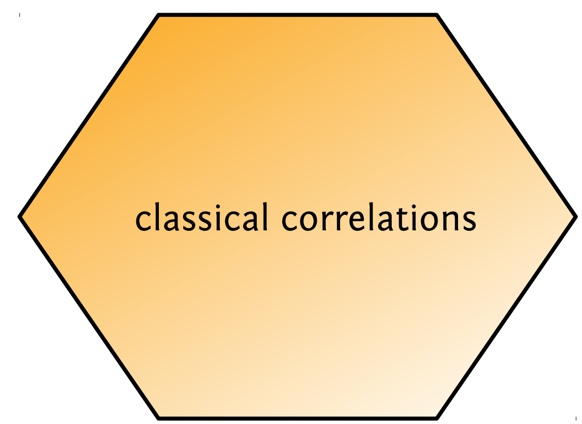
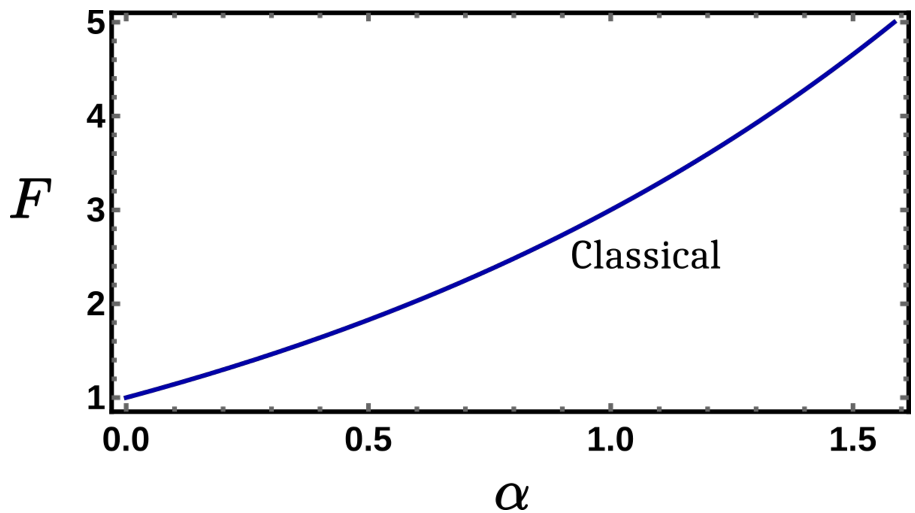
linear in dist. over λ

Classical set is a convex polytope



Facet inequality / "information witness" - for 3 inputs (Alice), 2 inputs, 2 outputs (Bob)

$$F = -(E_{11} + E_{12} + E_{21}) + (E_{22} + E_{31}) \leq 2^{\alpha+1} - 1 \qquad E_{xy} = p(0|xy) - p(1|xy)$$



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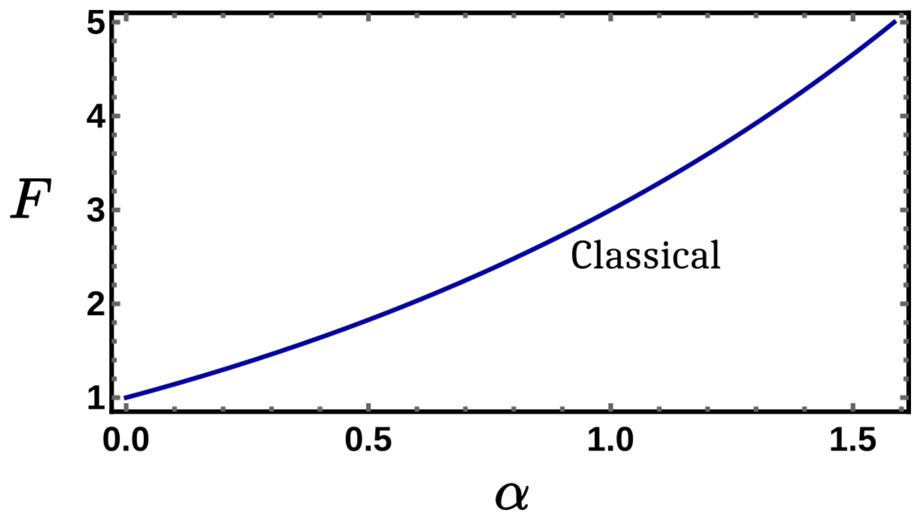
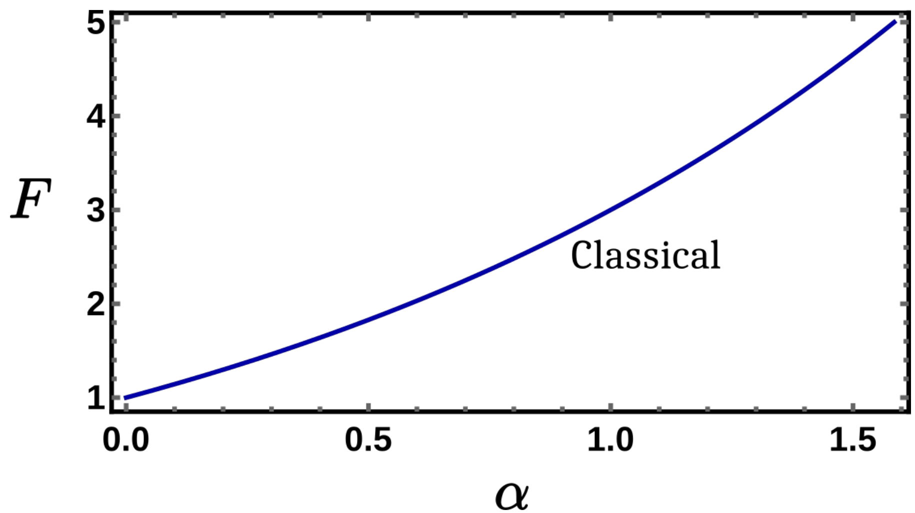


Quantum violation

Facet inequality / "information witness" - for 3 inputs (Alice), 2 inputs, 2 outputs (Bob)

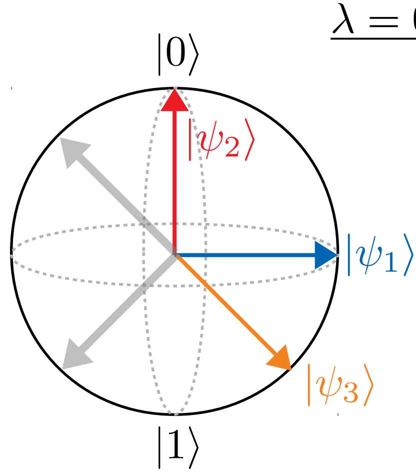
$$F = -(E_{11} + E_{12} + E_{21}) + (E_{22} + E_{31}) \leq 2^{\alpha+1} - 1 \qquad E_{xy} = p(0|xy) - p(1|xy)$$



Quantum violation

$p(\lambda = 0) = q$

$\underline{\lambda = 0}$



$$\{p_X(x) = \frac{1}{3}, |\psi_x\rangle\}$$

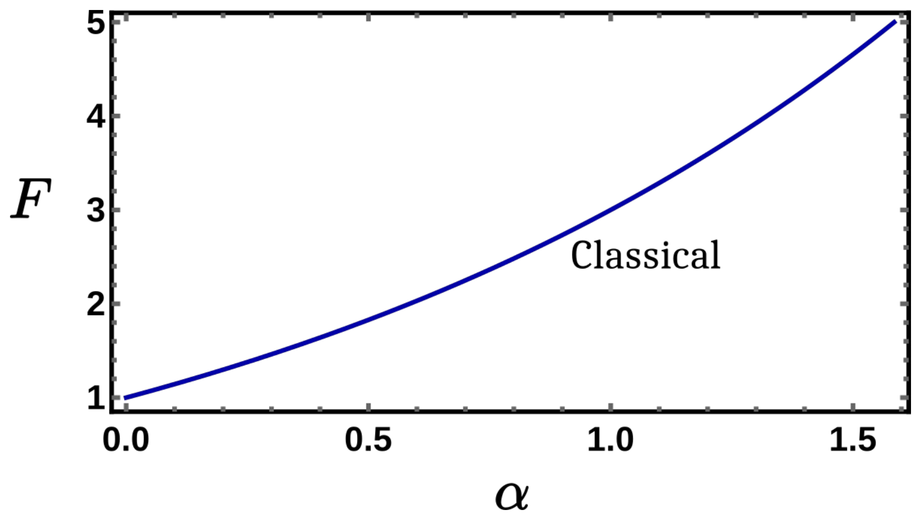
$\underline{\lambda = 1}$

No communication.

$b = 1$ always

Facet inequality / "information witness" - for 3 inputs (Alice), 2 inputs, 2 outputs (Bob)

$$F = -(E_{11} + E_{12} + E_{21}) + (E_{22} + E_{31}) \leq 2^{\alpha+1} - 1 \qquad E_{xy} = p(0|xy) - p(1|xy)$$



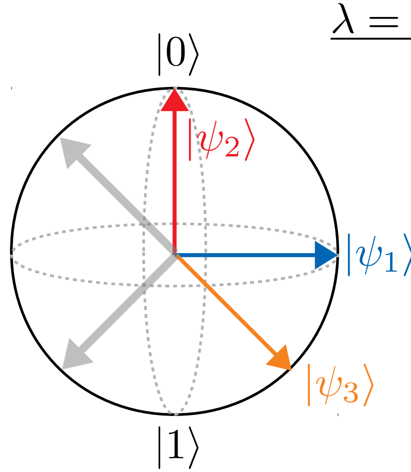
Quantum violation

<u>$\lambda = 0$</u>

<u>$\lambda = 1$</u>

$p(\lambda = 0) = q$

$\mathcal{I}_X = \log_2(1+q)$



$\{p_X(x) = \frac{1}{3}, |\psi_x\rangle\}$

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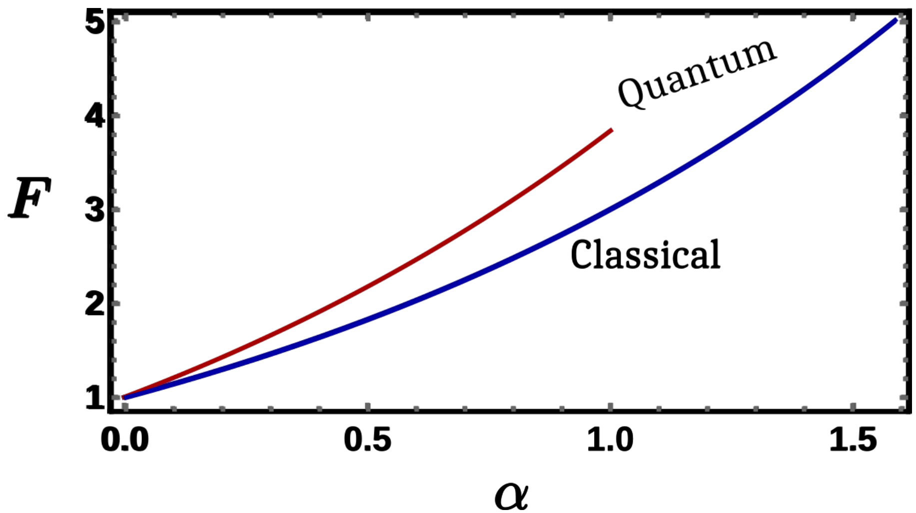


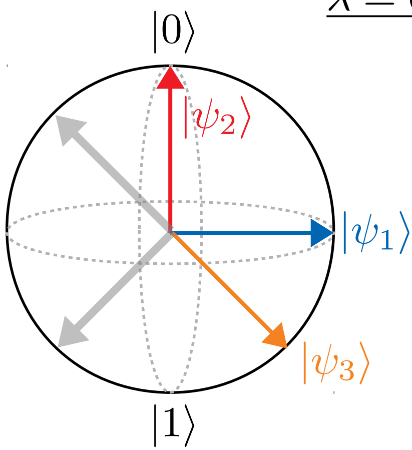
$$\underbrace{\hspace{5em}}_{1+2\sqrt{2}q}$$

Quantum violation

$p(\lambda = 0) = q$

$\mathcal{I}_X = \log_2(1+q)$

$\underline{\lambda = 0}$



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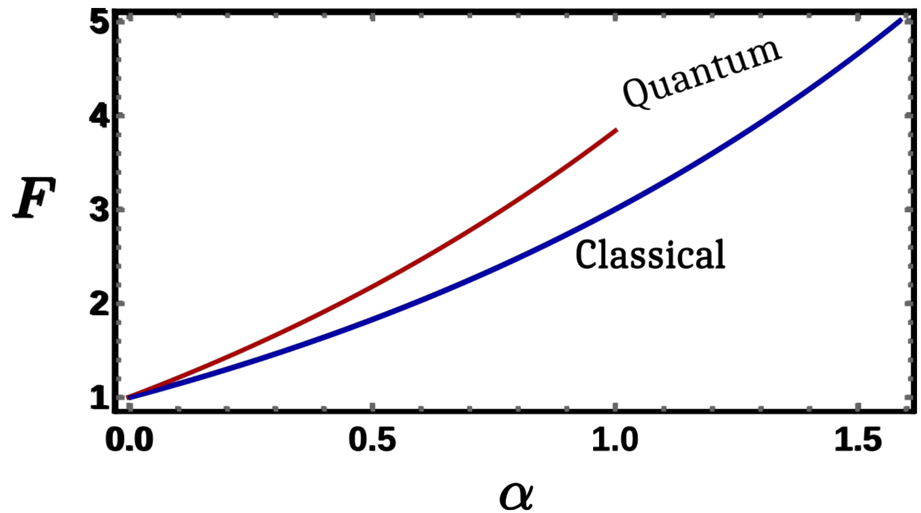

$1 + 2\sqrt{2}q$

Quantum violation

$\underline{\lambda = 0}$ $\underline{\lambda = 1}$

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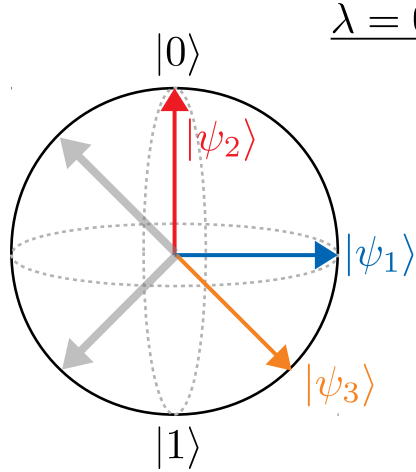
$\mathcal{I}_X = \log_2(1 + q)$



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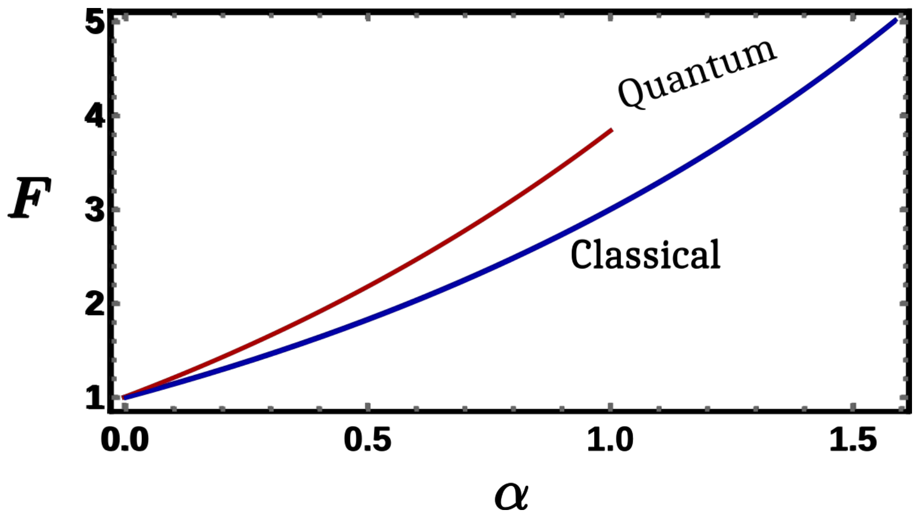

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Quantum violation

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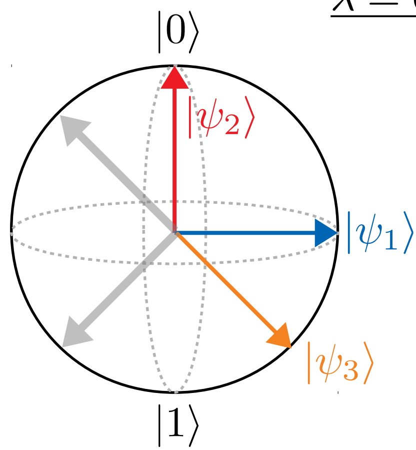

$$\{p_X(x) = \frac{1}{3}, |\psi_x\rangle\}$$

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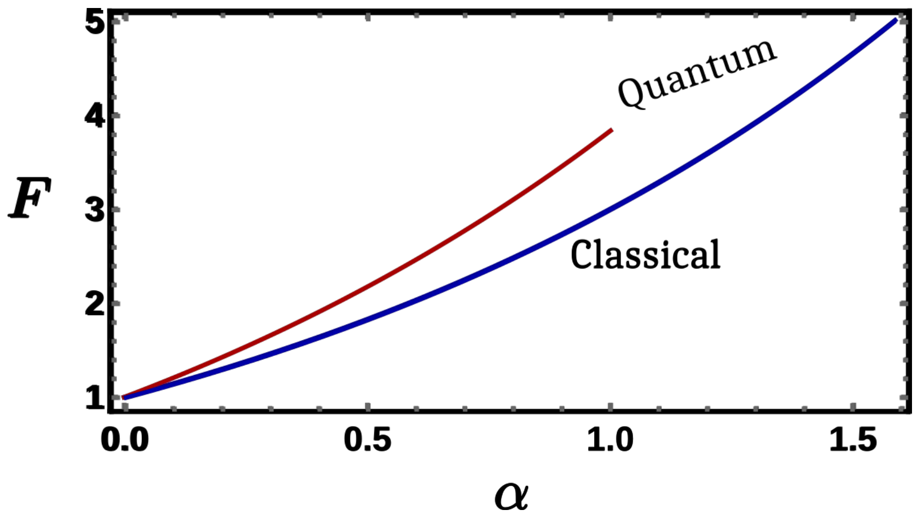
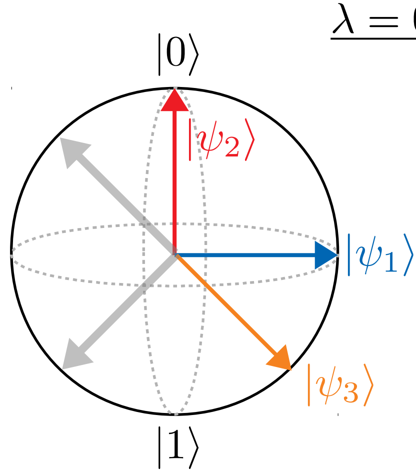


$$1 + 2\sqrt{2}q$$

Quantum violation

$p(\lambda = 0) = q$

$\underline{\lambda = 0}$



$$\{p_X(x) = \frac{1}{3}, |\psi_x\rangle\}$$

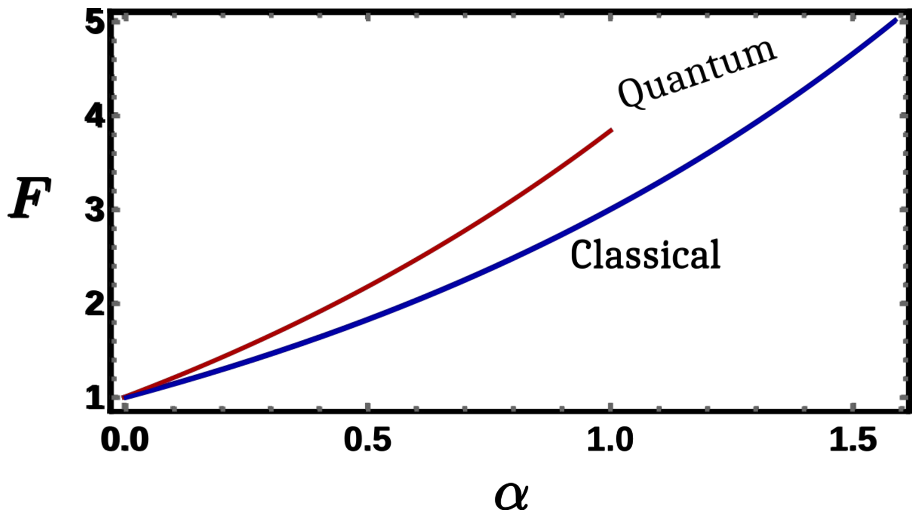
$\underline{\lambda = 1}$

Send input

$F = 5$

Facet inequality / "information witness" - for 3 inputs (Alice), 2 inputs, 2 outputs (Bob)

$$F = -(E_{11} + E_{12} + E_{21}) + (E_{22} + E_{31}) \leq 2^{\alpha+1} - 1 \qquad E_{xy} = p(0|xy) - p(1|xy)$$



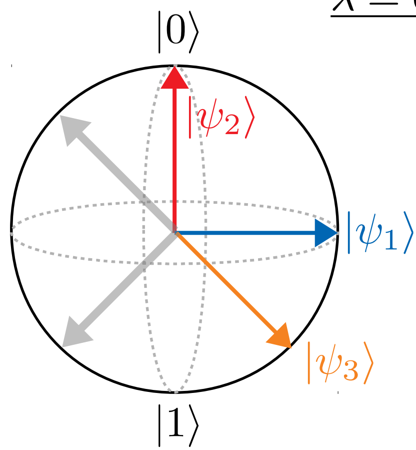
$1 + 2\sqrt{2}q$

Quantum violation

$\underline{\lambda = 0}$

$p(\lambda = 0) = q$

$\mathcal{I}_X = \log_2(3 - q)$



$\{p_X(x) = \frac{1}{3}, |\psi_x\rangle\}$

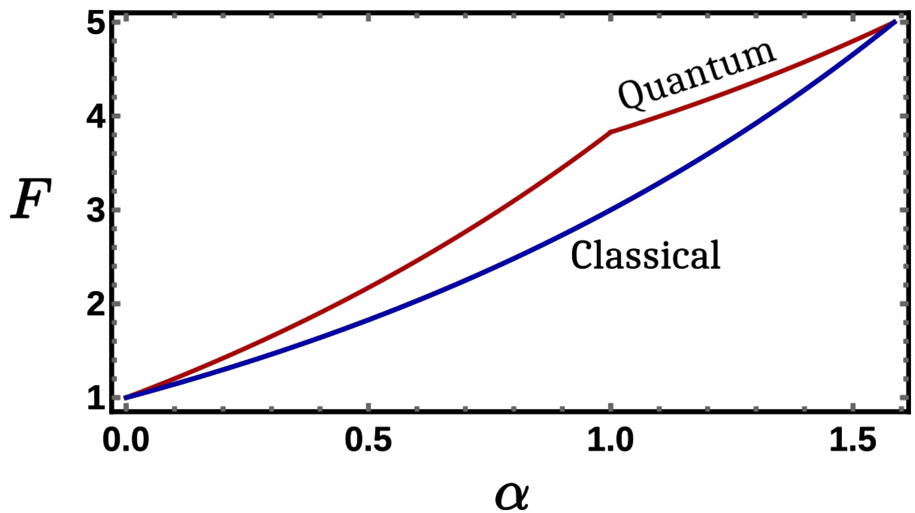
$\underline{\lambda = 1}$

Send input

$F = 5$

Facet inequality / "information witness" - for 3 inputs (Alice), 2 inputs, 2 outputs (Bob)

$$F = -(E_{11} + E_{12} + E_{21}) + (E_{22} + E_{31}) \leq 2^{\alpha+1} - 1 \qquad E_{xy} = p(0|xy) - p(1|xy)$$



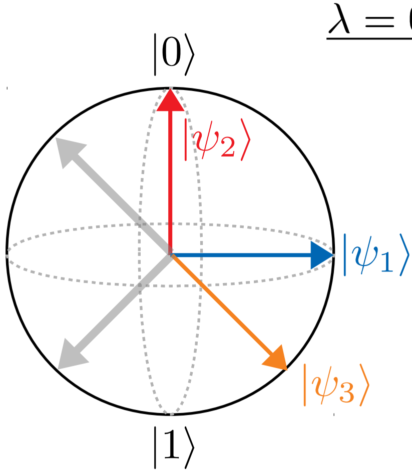
$1 + 2\sqrt{2}q$ $\qquad$ $1 + 2\sqrt{2}q + 5(1-q)$

Quantum violation

$\underline{\lambda = 0}$ $\qquad$ $\underline{\lambda = 1}$

$p(\lambda = 0) = q$

$\mathcal{I}_X = \log_2(3-q)$



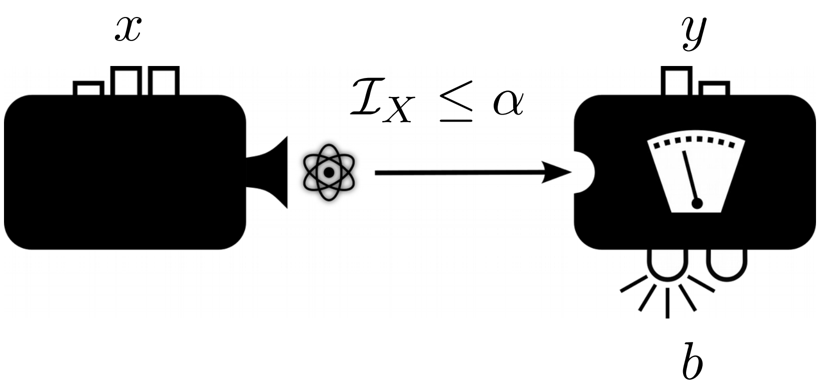
$\{p_X(x) = \frac{1}{3}, |\psi_x\rangle\}$

Send input

$F = 5$

Theory-independent bound

Post-processing of output → lower bound on information given observed data



Theory-independent bound

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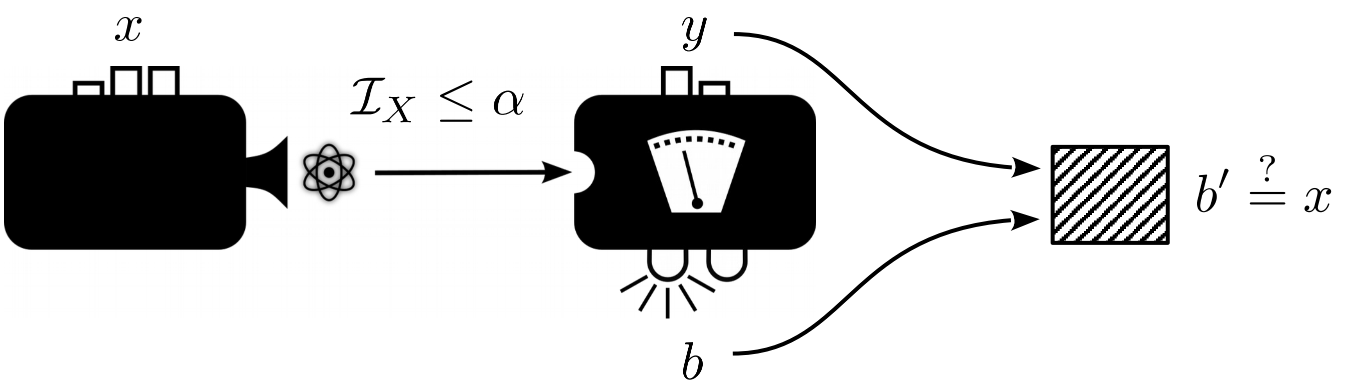

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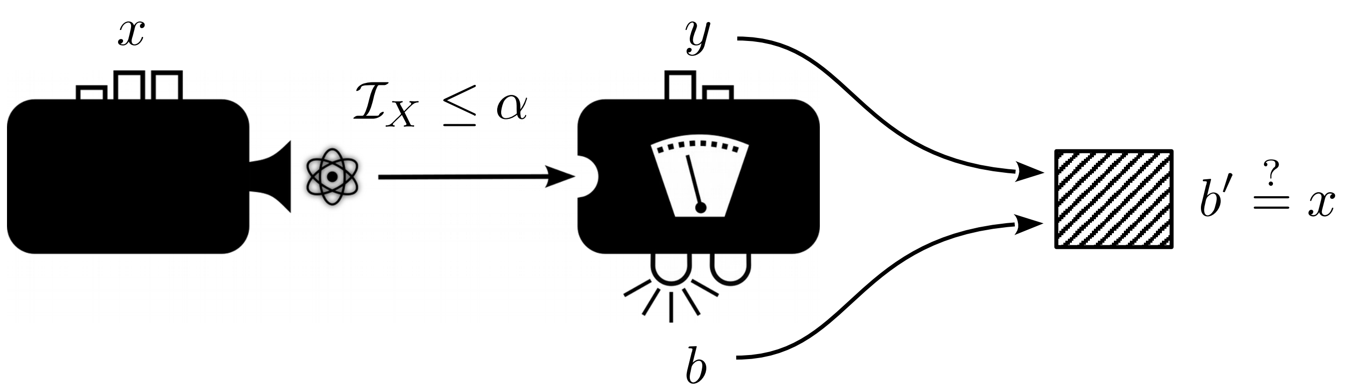
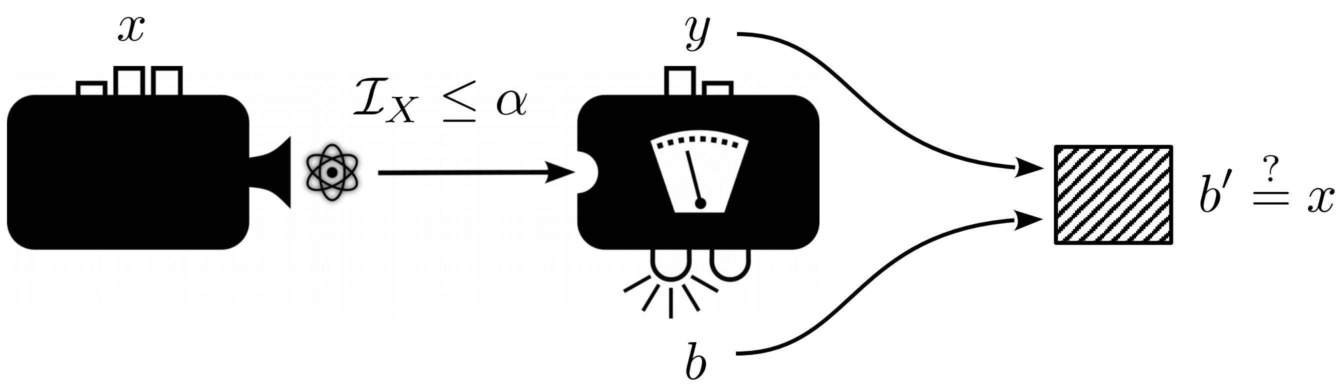


How well can we recover the input given the data?

$$p(b|xy)$$

Theory-independent bound

Post-processing of output → lower bound on information given observed data



How well can we recover the input given the data?

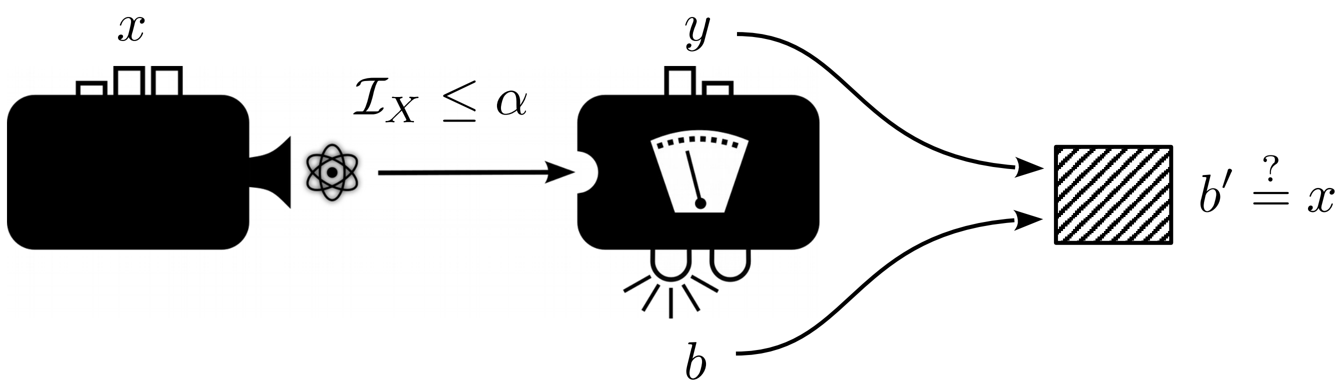
$p(b|xy)$

For any input for Bob and any (classical) post-processing

$$\sum_{x,b} p_X(x) p(b|xy) p(b' = x|y,b) \leq 2^{\alpha - H_{min}(X)}$$

Theory-independent bound

Post-processing of output → lower bound on information given observed data



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For any input for Bob and any (classical) post-processing

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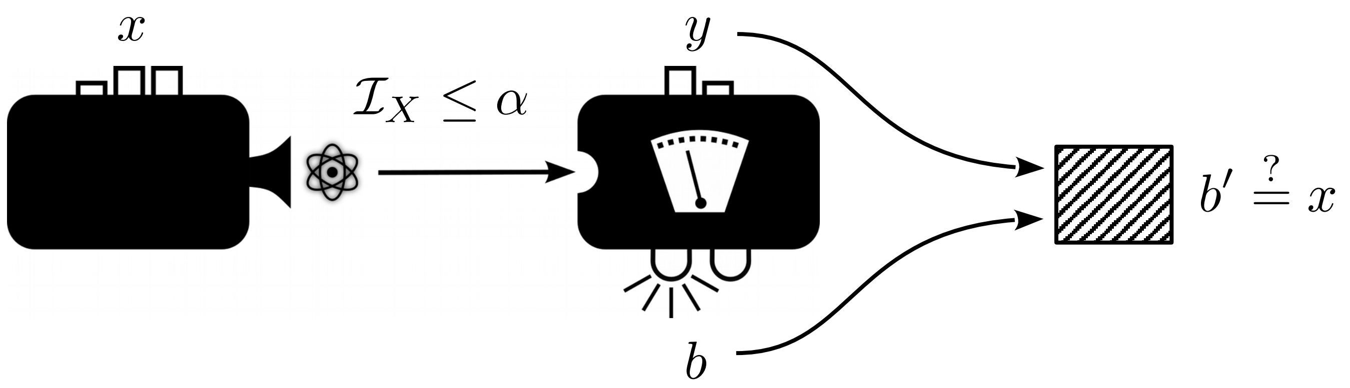
Theory-independent bound

Post-processing of output → lower bound on information given observed data



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$p(b|xy)$

For any input for Bob and any (classical) post-processing

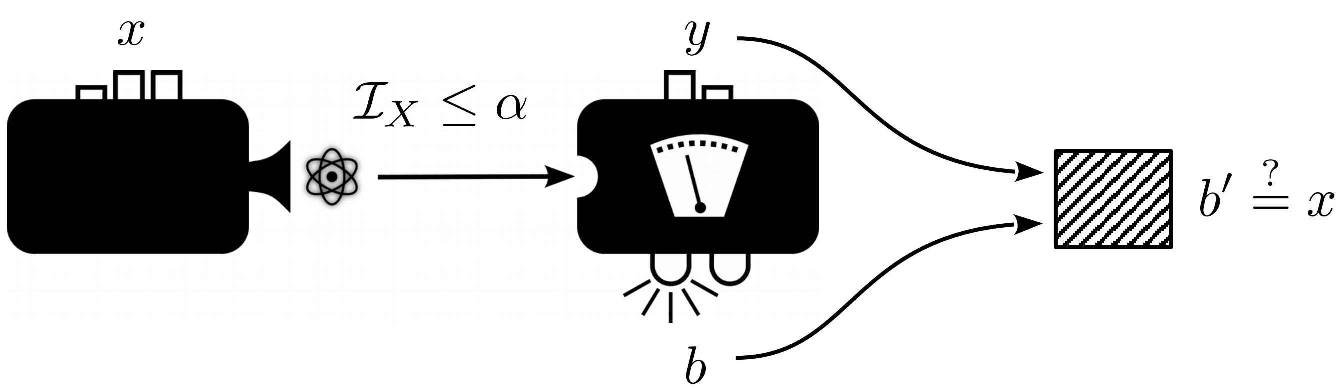
observed data

$$\sum_{x,b} p_X(x)p(b|xy)p(b' = x|y,b) \leq 2^{\alpha - H_{min}(X)}$$

post-processing

Theory-independent bound

Post-processing of output → lower bound on information given observed data



How well can we recover the input given the data?

$p(b|xy)$

For any input for Bob and any (classical) post-processing

observed data

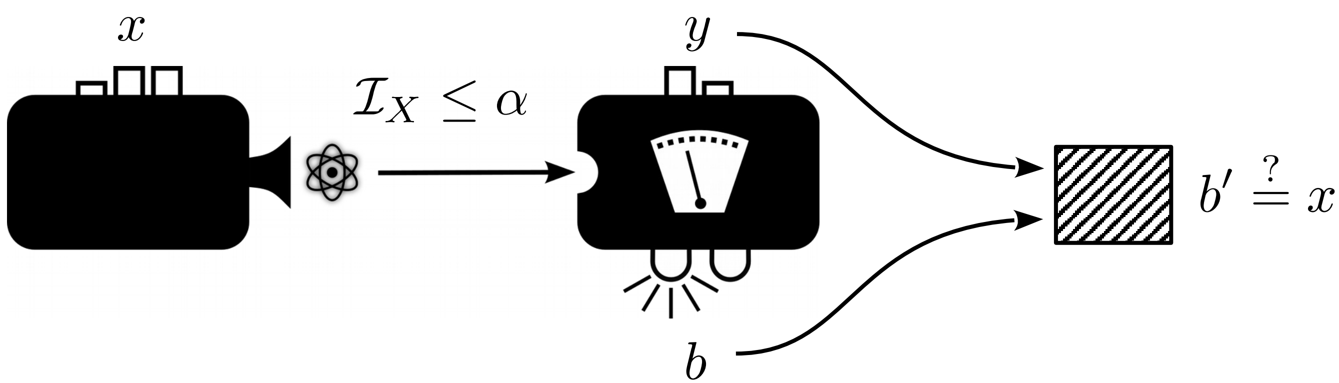
information in message

$$\sum_{x,b} p_X(x) p(b|xy) p(b' = x|y,b) \leq 2^{\alpha - H_{min}(X)}$$

post-processing

Theory-independent bound

Post-processing of output → lower bound on information given observed data



How well can we recover the input given the data?

$p(b|xy)$

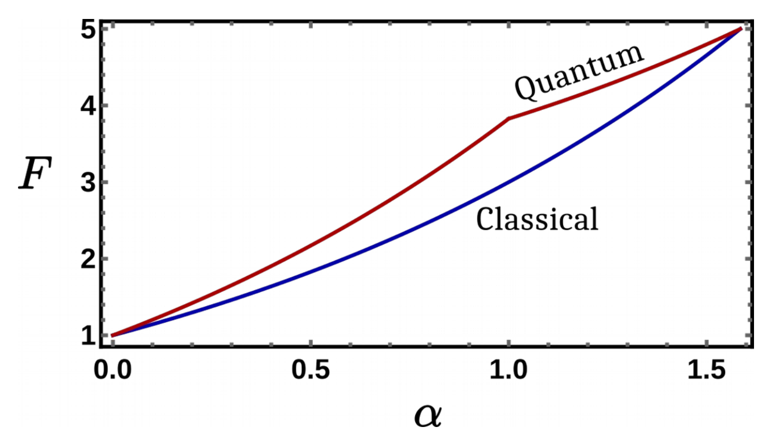
For any input for Bob and any (classical) post-processing

observed data

information in message

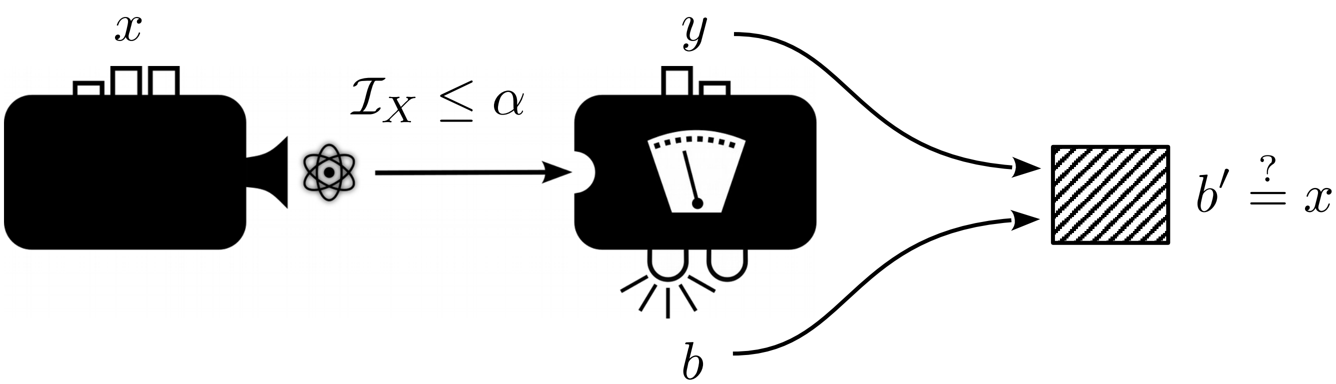
$$\sum_{x,b} p_X(x)p(b|xy)p(b'=x|y,b) \leq 2^{\alpha - H_{min}(X)}$$

post-processing



Theory-independent bound

Post-processing of output → lower bound on information given observed data



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observed data

information in message

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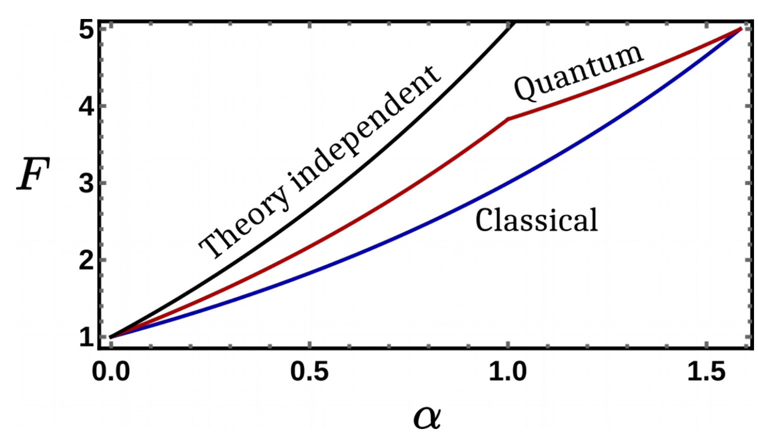
post-processing



Information vs. dimension

Correlation achievable with qudits (dim. *d*) $\Longrightarrow$ Achievable with $\mathcal{I}_X \leq \log_2(d)$

Information vs. dimension

Correlation achievable with qudits (dim. *d*) Achievable with $\mathcal{I}_X \leq \log_2(d)$

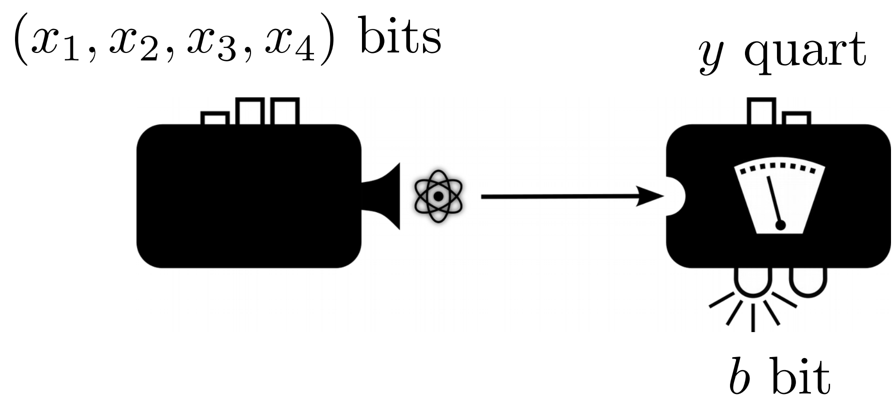
Information vs. dimension

Correlation achievable with qudits (dim. *d*) $\Rightarrow$ $\not\Leftarrow$ Achievable with $\mathcal{I}_X \leq \log_2(d)$

Information vs. dimension

Correlation achievable with qudits (dim. *d*) $\underset{\not\Leftarrow}{\Rightarrow}$ Achievable with $\mathcal{I}_X \leq \log_2(d)$

Example : random access code



Information vs. dimension

Correlation achievable with qudits (dim. *d*) $\Longrightarrow$ / $\not\Longleftarrow$ Achievable with $\mathcal{I}_X \leq \log_2(d)$

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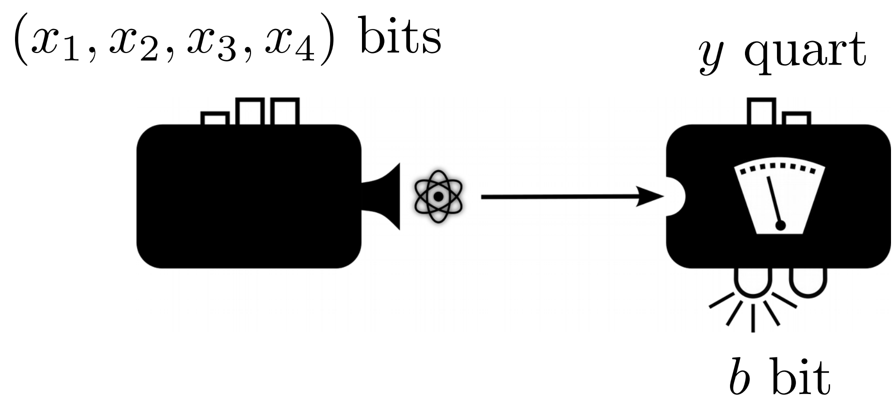
$$F_{RAC} = \frac{1}{64}\sum_{x,y} p(b = x_y | x, y)$$



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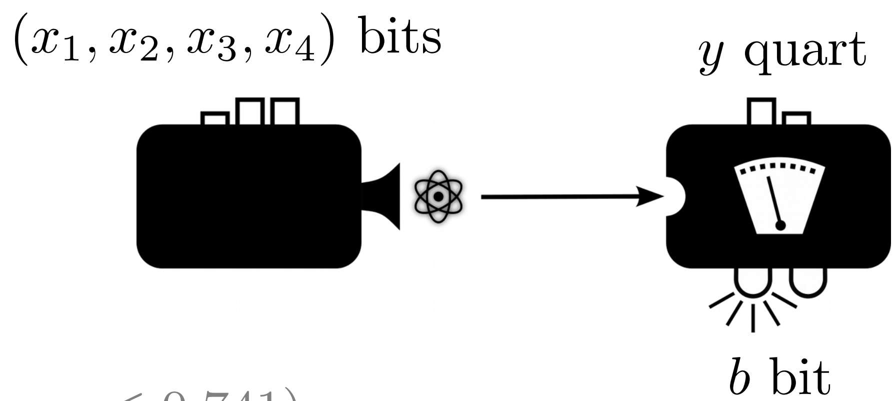

For qubits: $F_{RAC} < 3/4$ (and probably $F_{RAC} \leq 0.741$)

Tavakoli *et al.*, *PRA*, 98, 062307 (2018), Ambainis *et al.*, *arXiv:0810.2937* (2008).

Information vs. dimension

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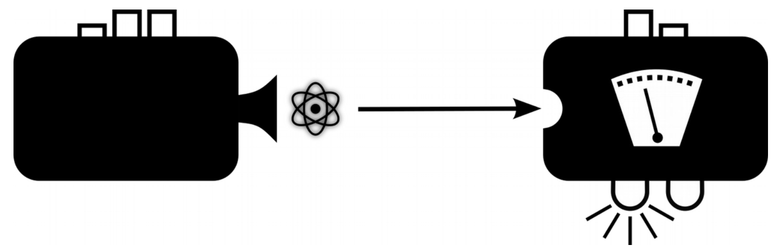

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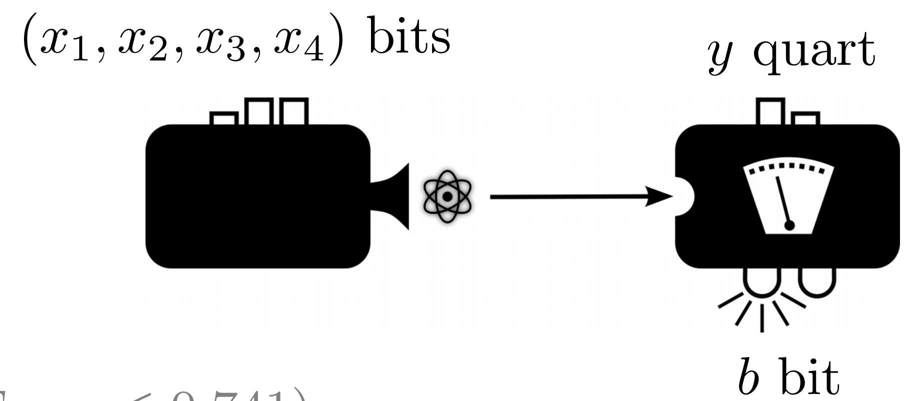

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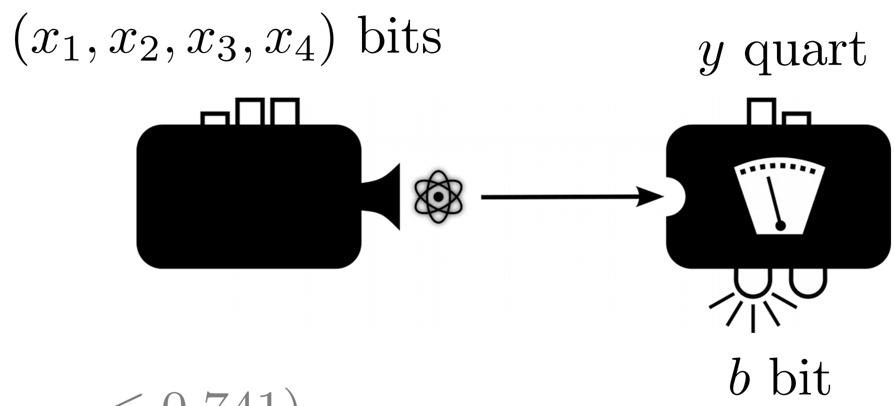

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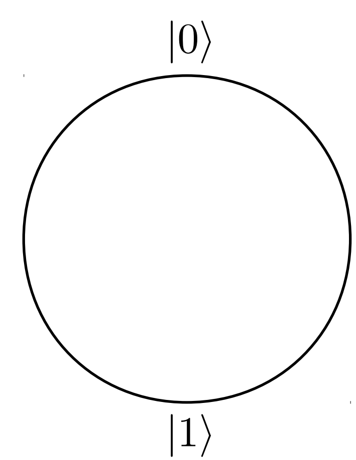

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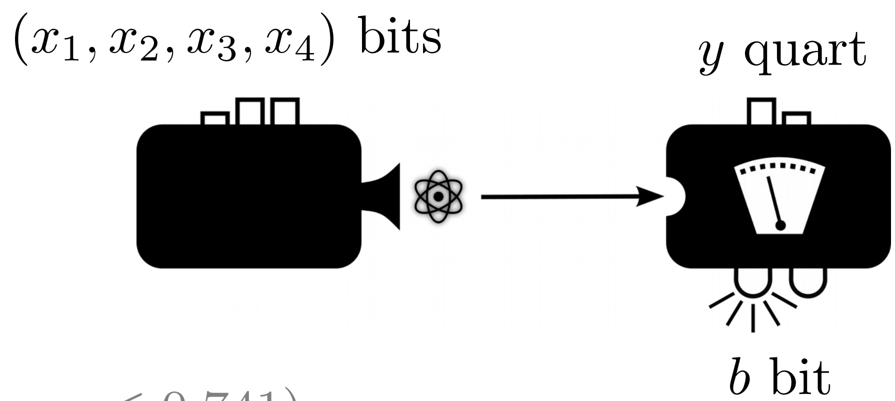

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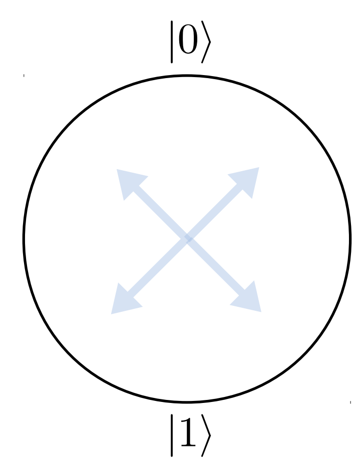

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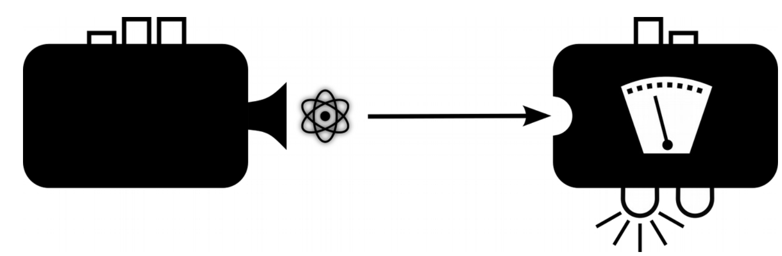

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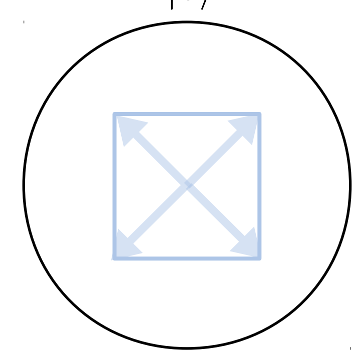

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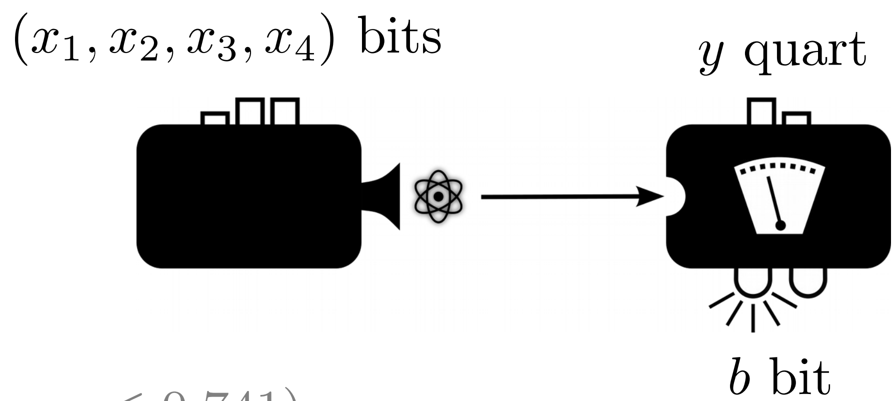

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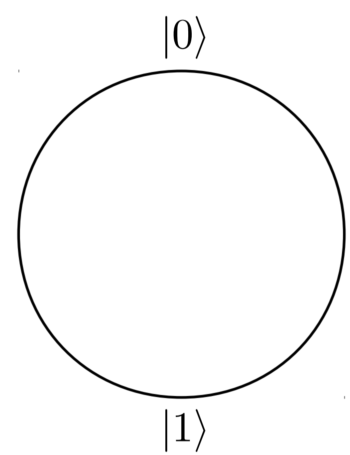

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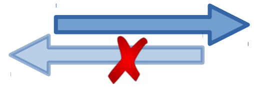
Correlation achievable with qudits (dim. *d*)  Achievable with $\mathcal{I}_X \leq \log_2(d)$

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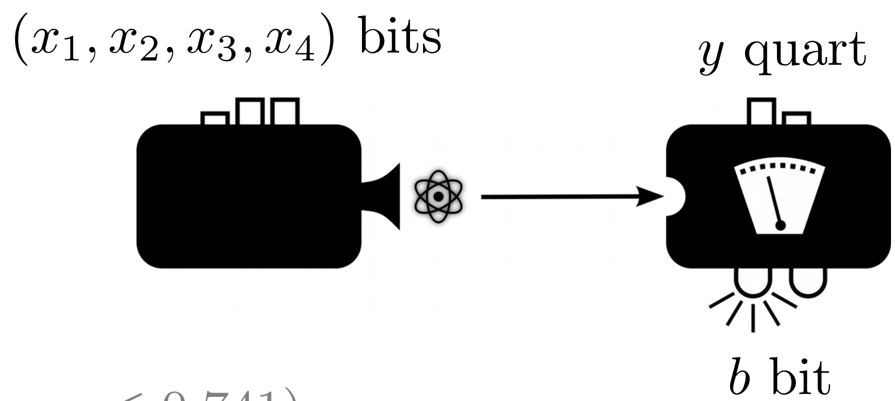

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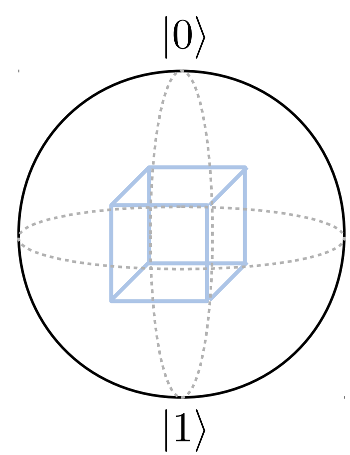

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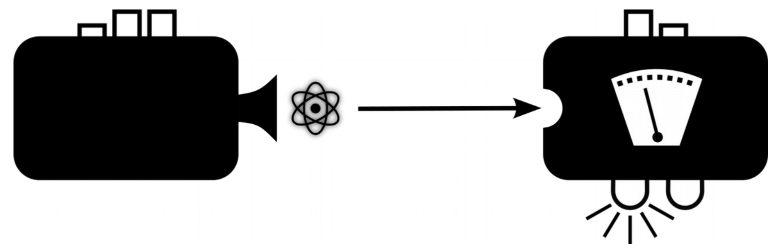

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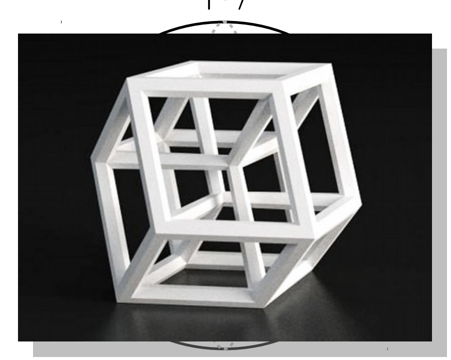

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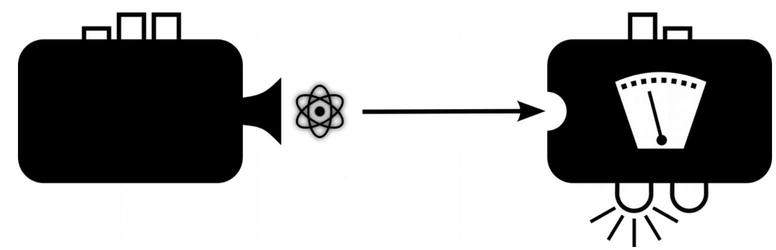

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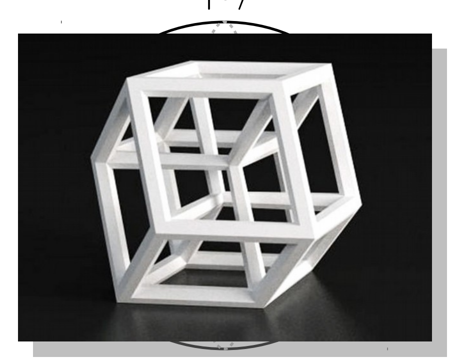

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<u>Measurements</u>

$\sigma_x\otimes\sigma_x \quad \sigma_z\otimes\sigma_x$

$\sigma_y\otimes\sigma_x \quad \mathbb{1}\otimes\sigma_y$

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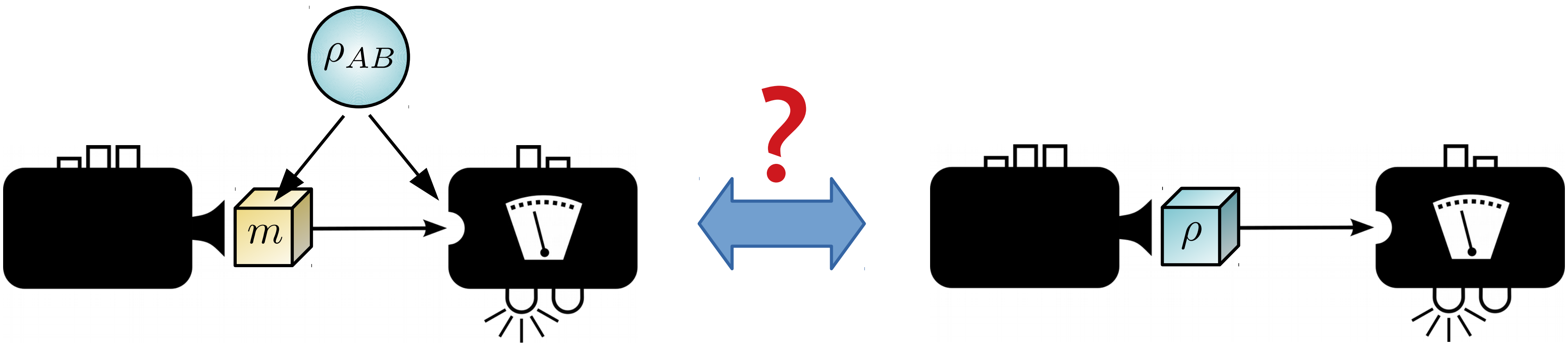
Entanglement-assisted classical Comm. vs. quantum comm.



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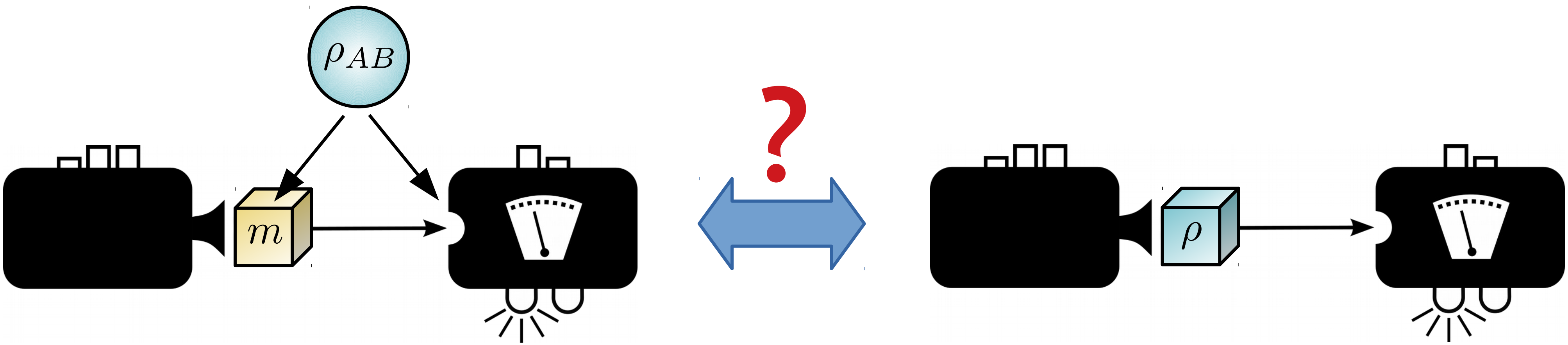

Bounding dimension → no general hierarchy

For different RAC tasks, one approach outperforms the other and vice versa

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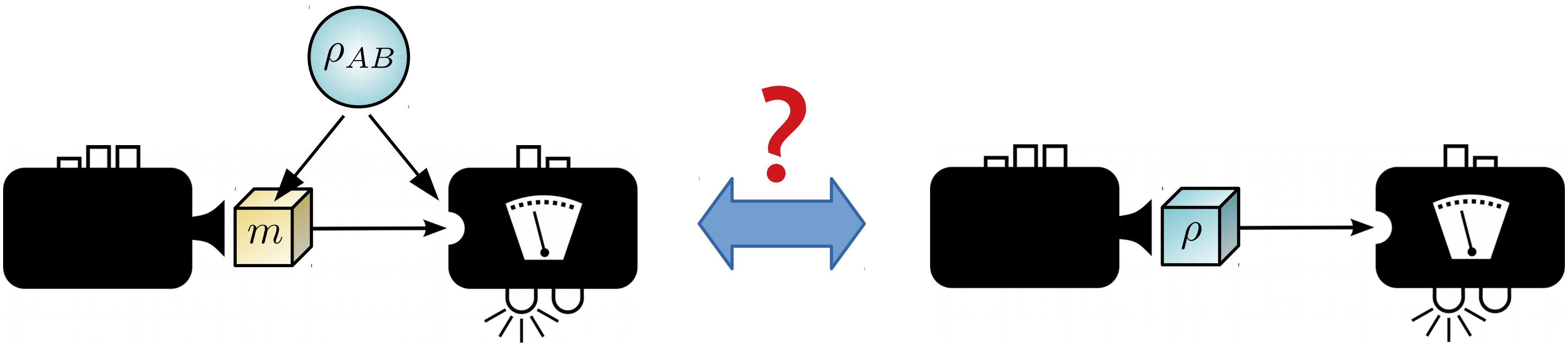

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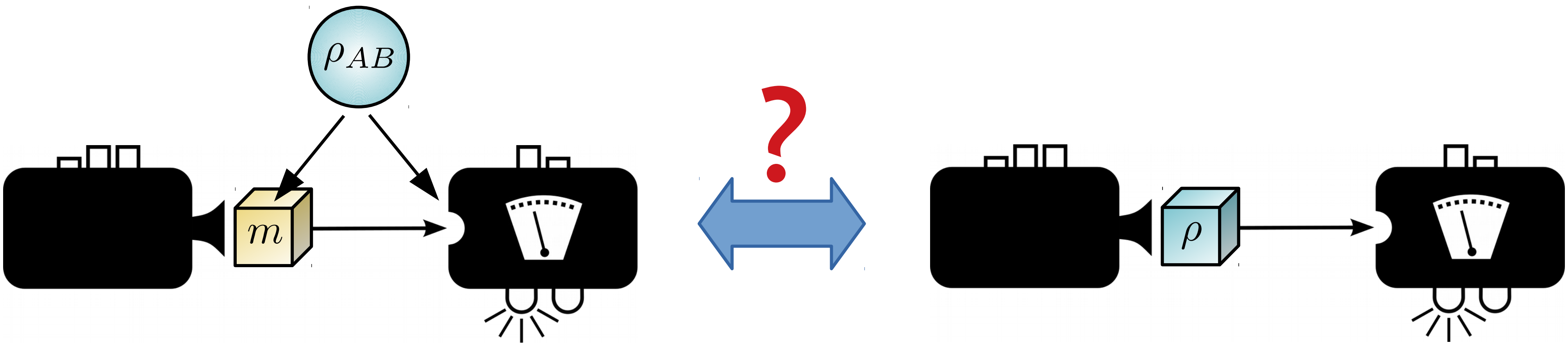

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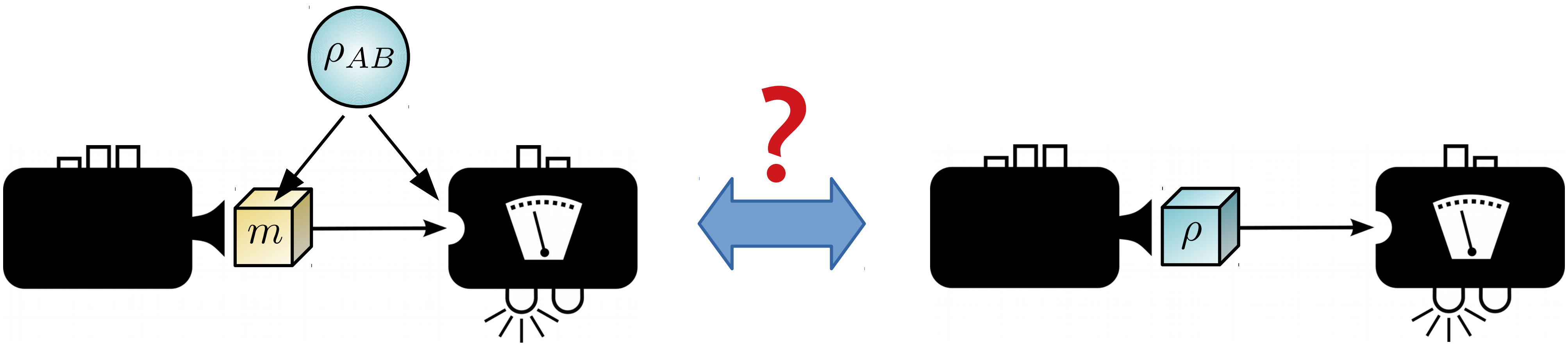

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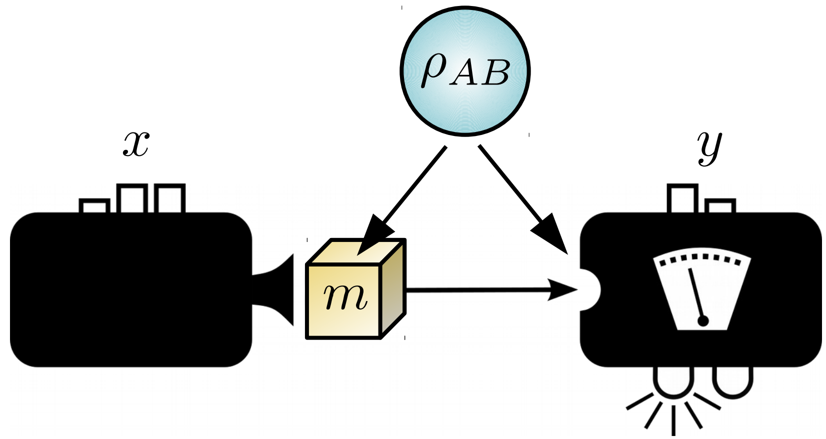
Bounding information → quantum communication is *always* more powerful

Entanglement-assisted classical communication



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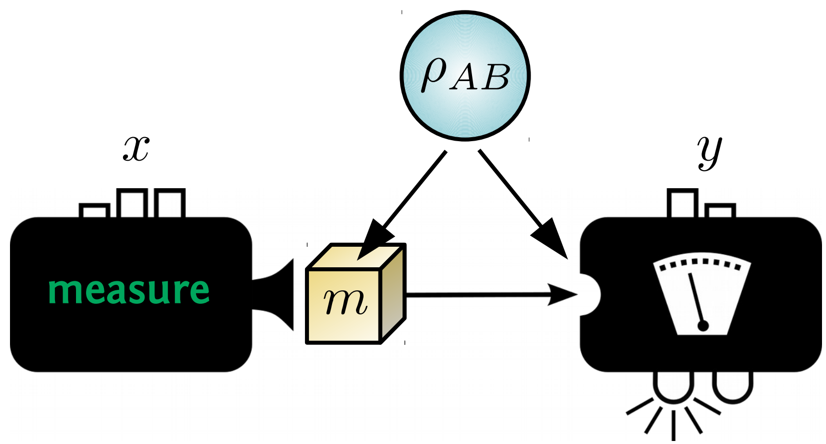

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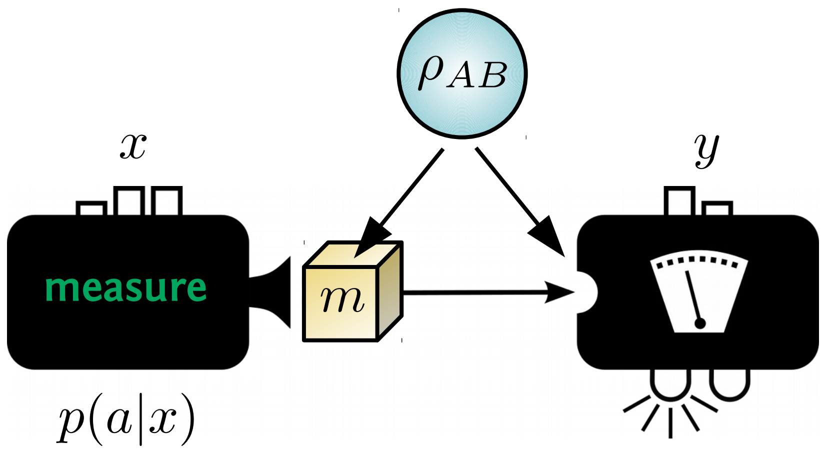

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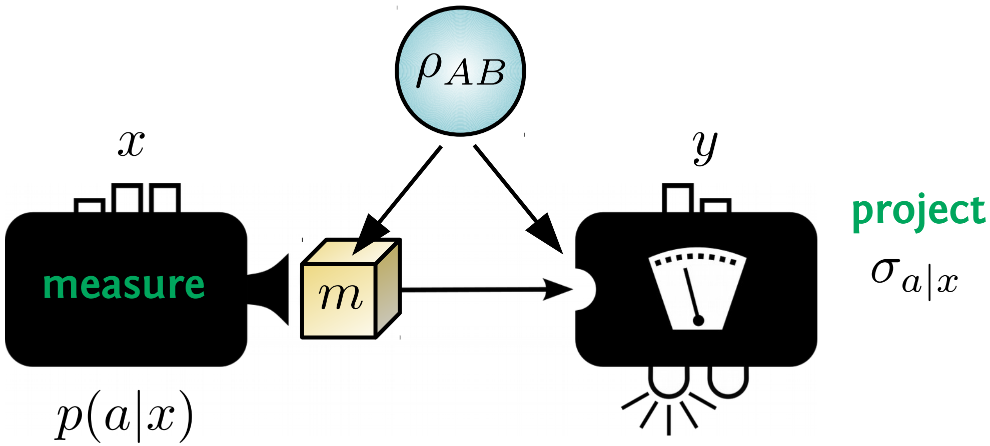

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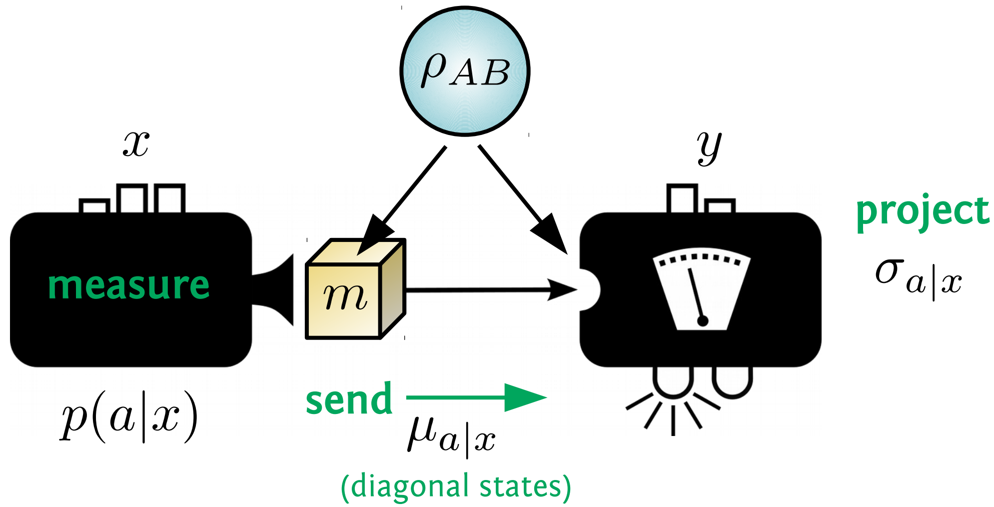

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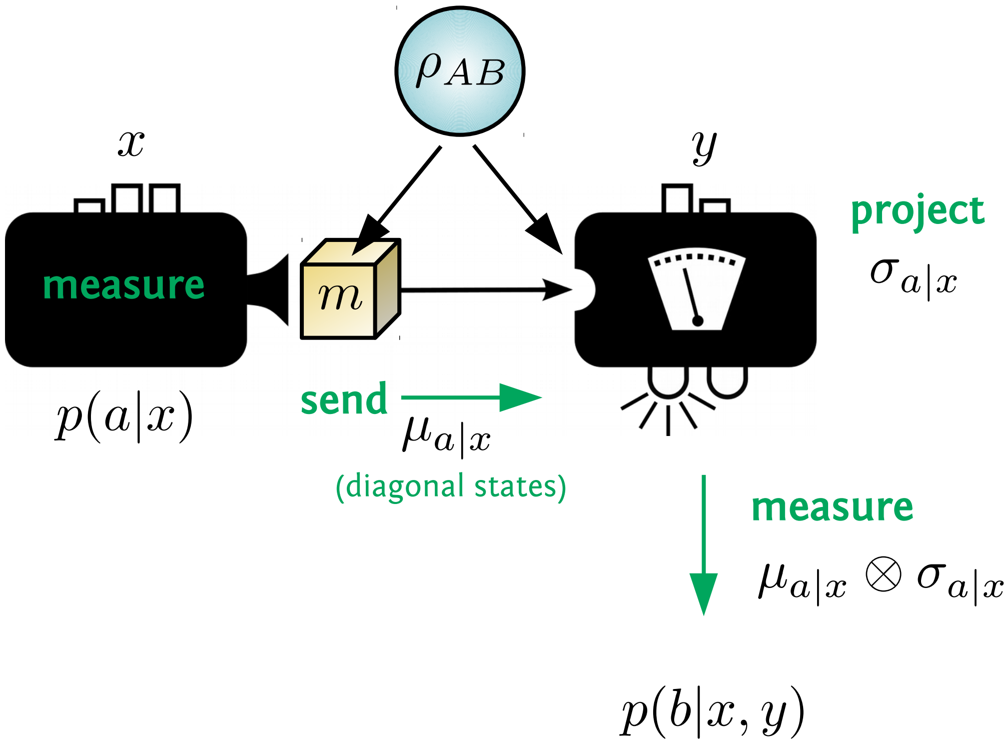

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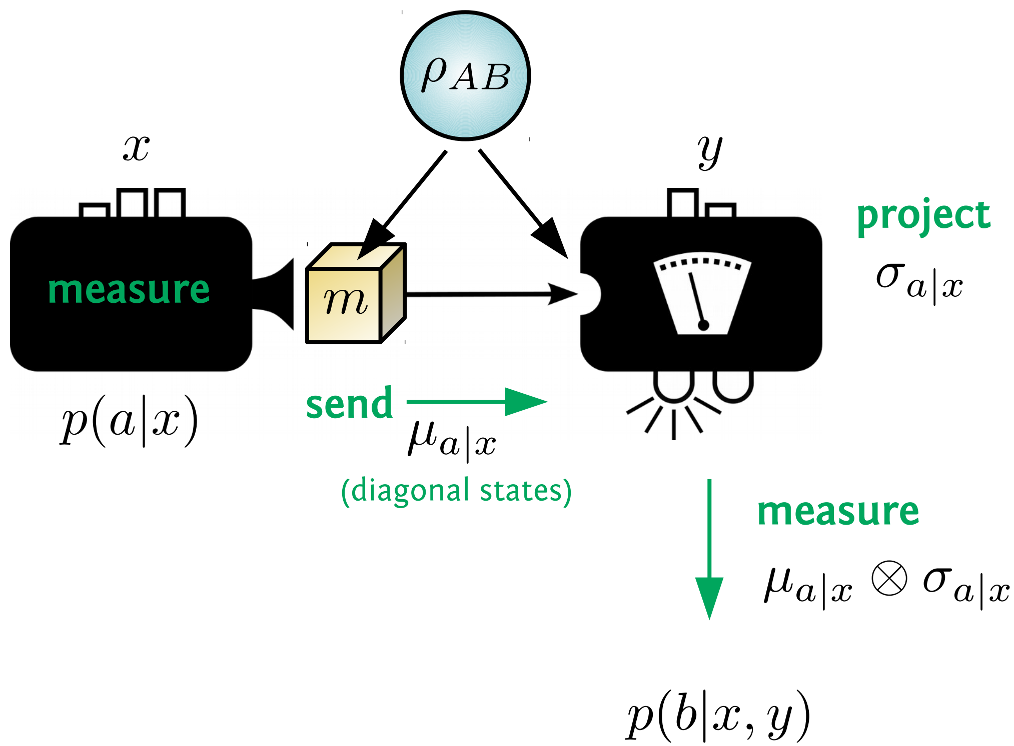

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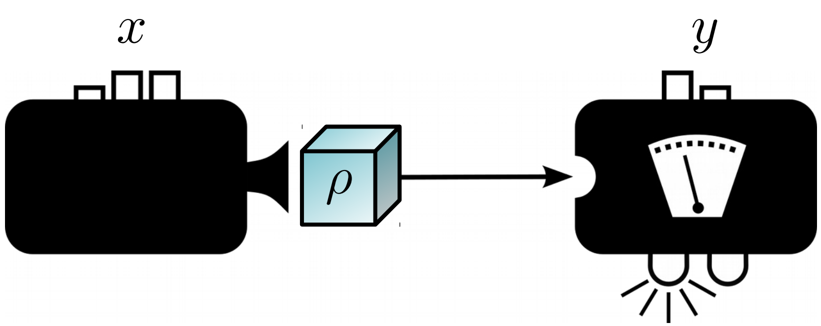
Quantum communication



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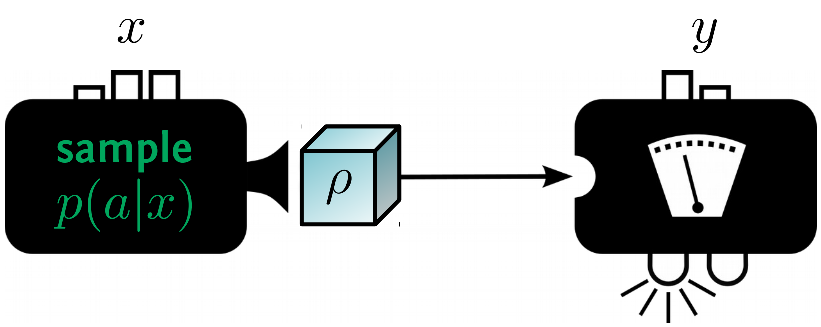

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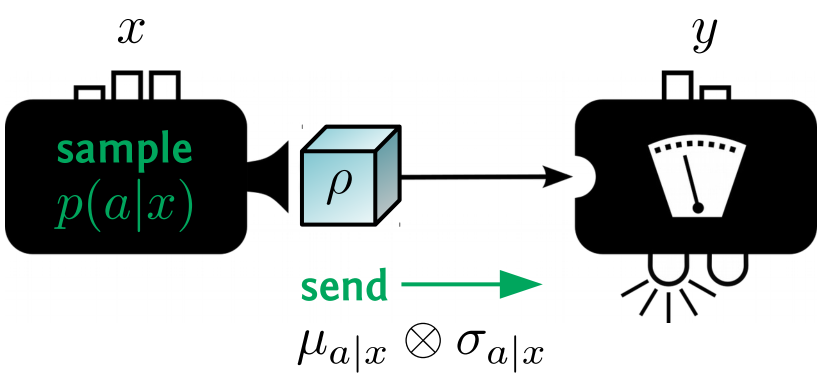

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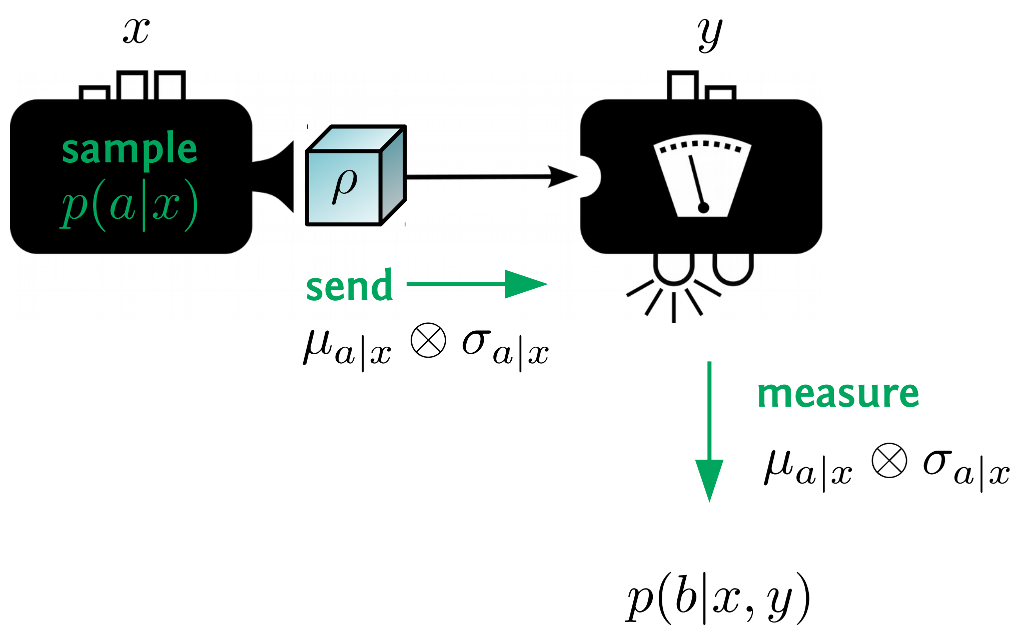

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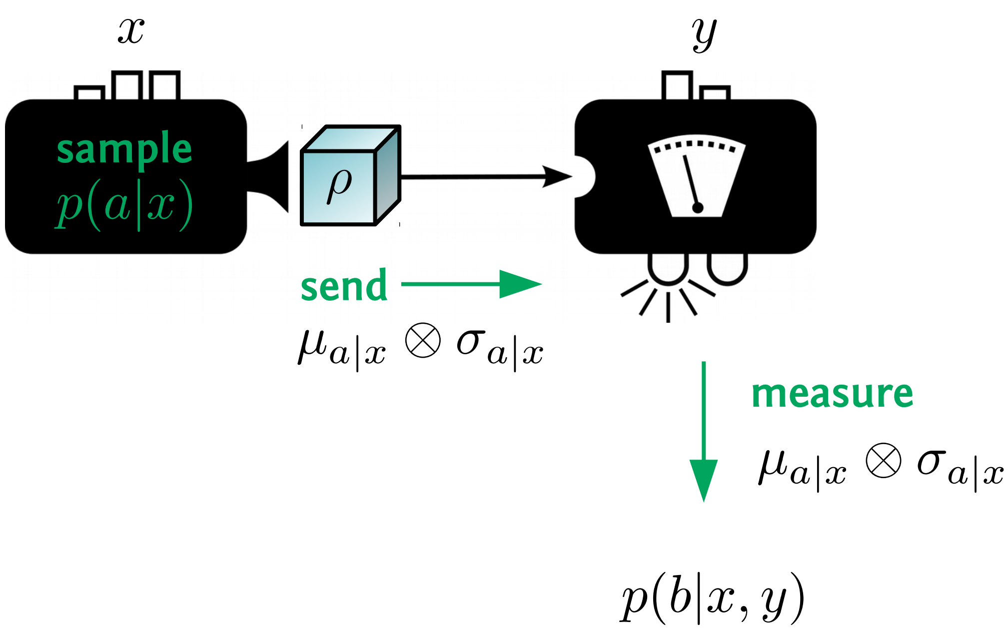

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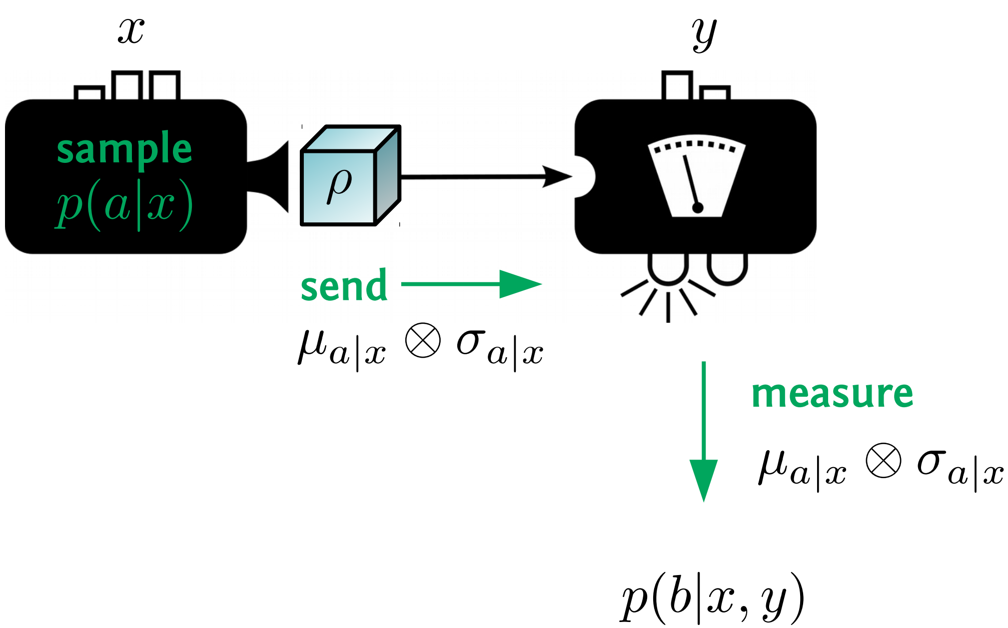

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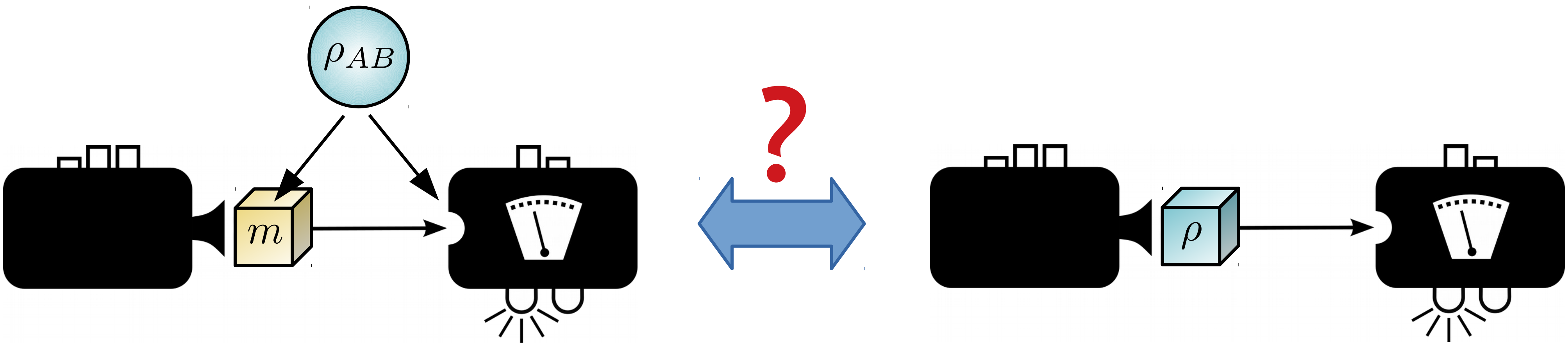

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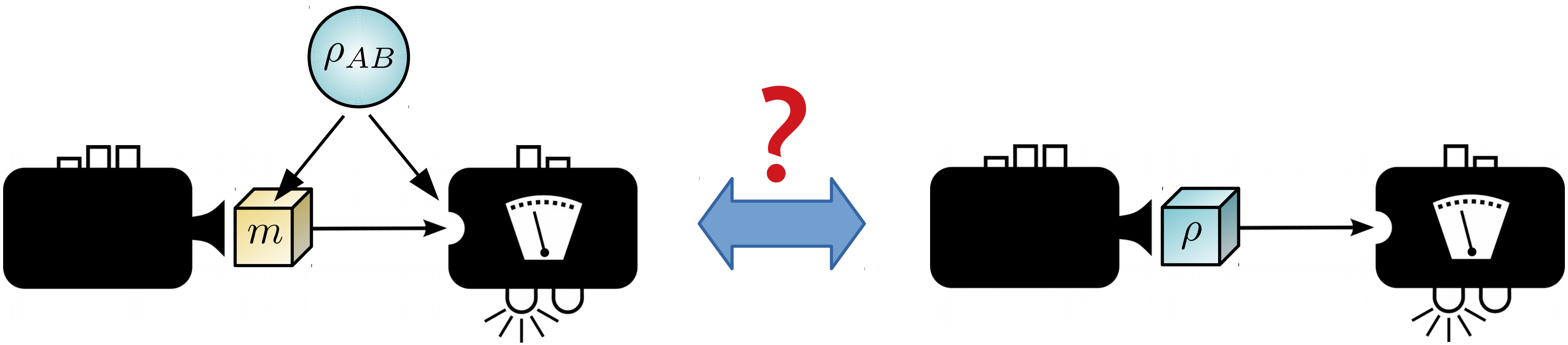

Bounding dimension → no general hierarchy

For different communication tasks (e.g. RACs), one approach outperforms the other and vice versa

› Hameedi *et al.*, *PRA*, 95, 052345 (2017).
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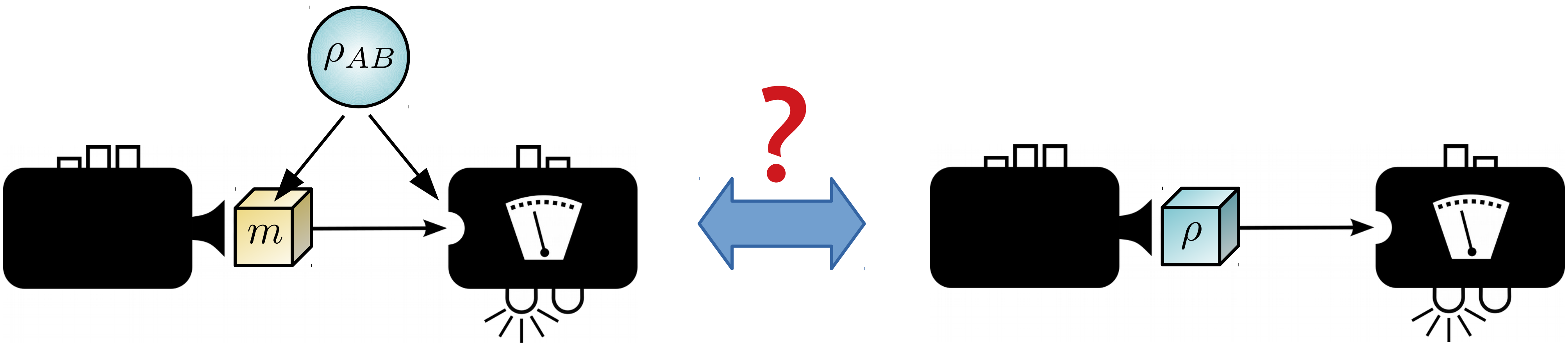

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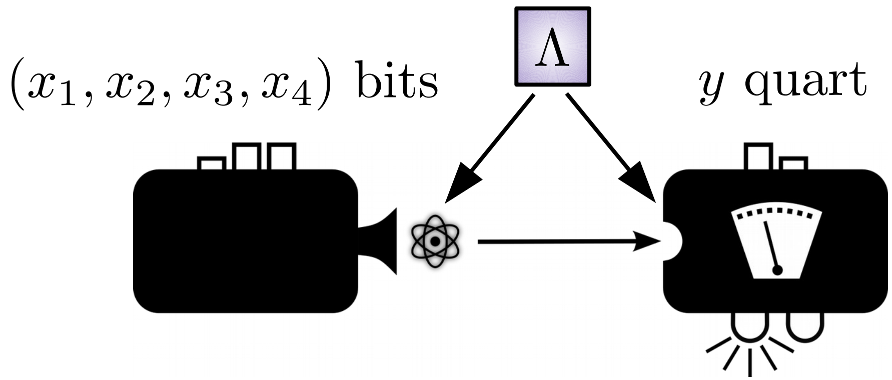
because $\mathrm{Tr}[(\mu_{a|x} \otimes \sigma_{a|x}) N_x] \leq \mathrm{Tr}[\mu_{a|x} \mathrm{Tr}_B[N_x]]$

Information vs. dimension revisited

For qubits: $F_{RAC} < 3/4$ (and probably $F_{RAC} \leq 0.741$)

For bounded information: $F_{RAC} = 3/4$ with $\mathcal{I}_X = 1$

Can we have a larger separation?



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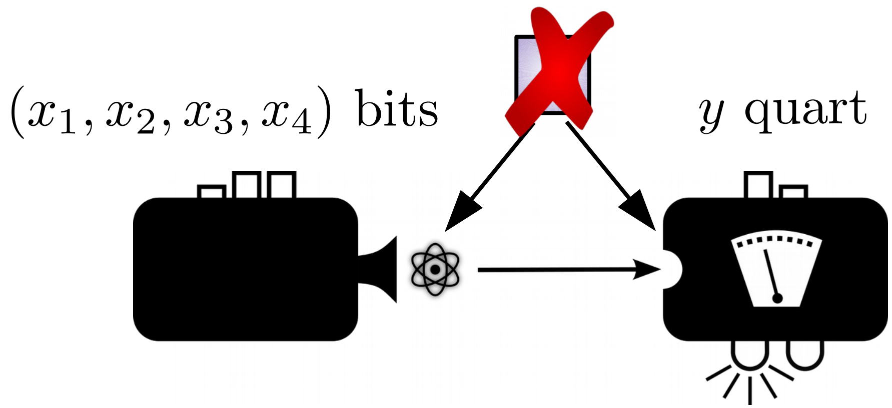

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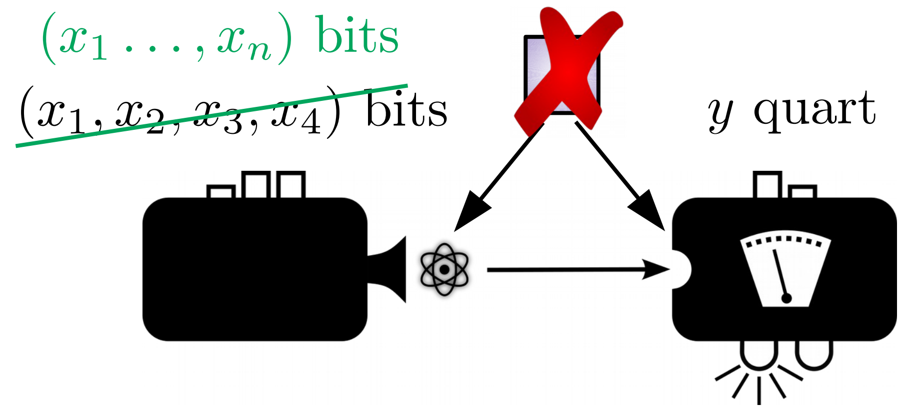

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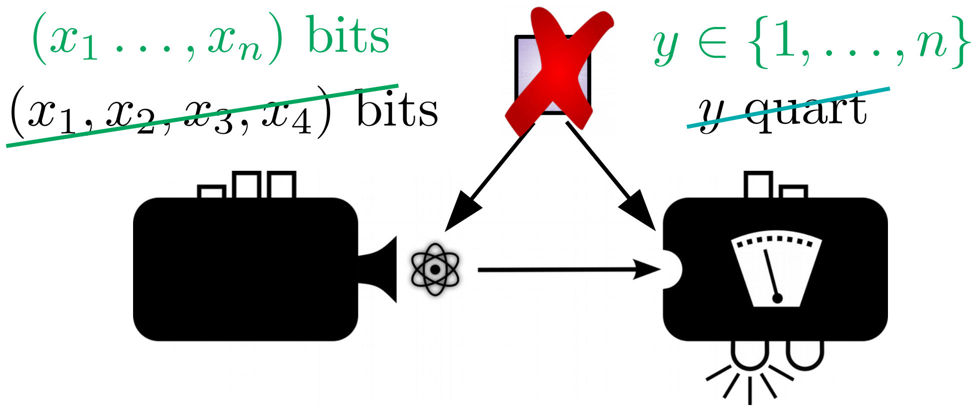

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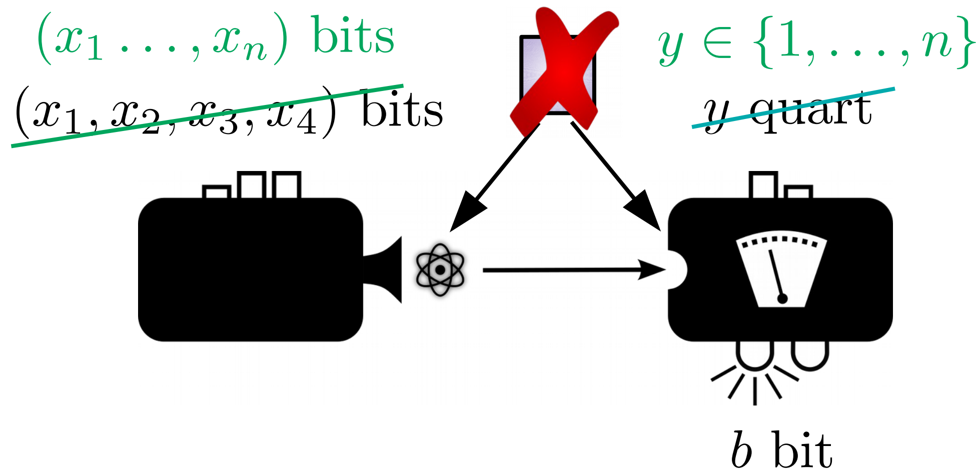

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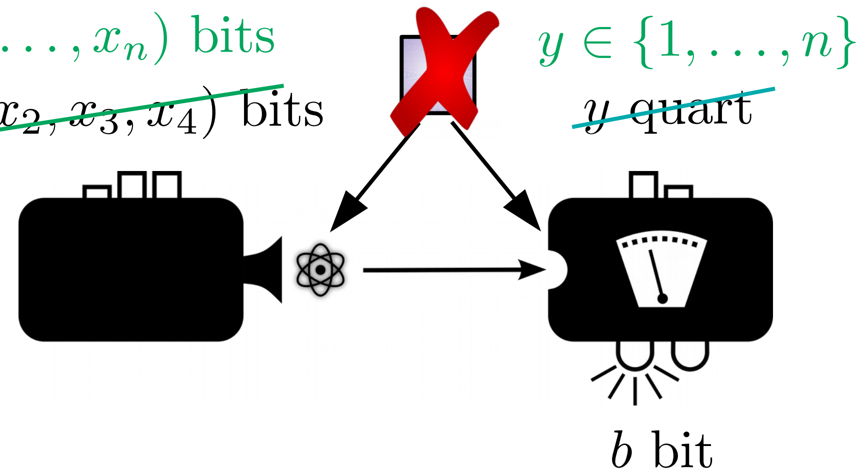

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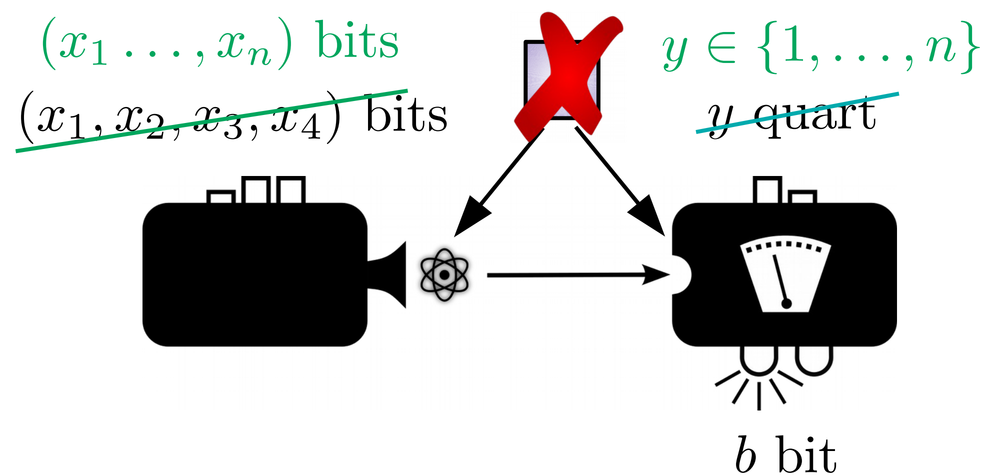

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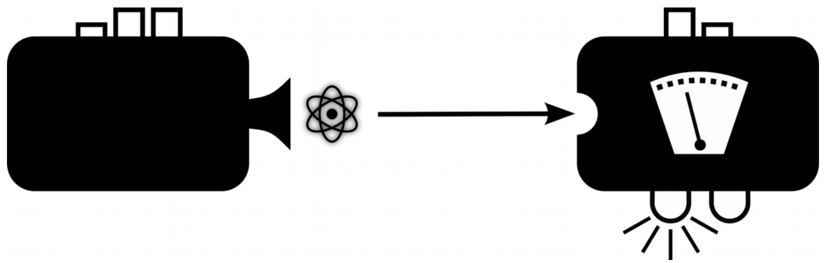
Unbounded separation

Summary

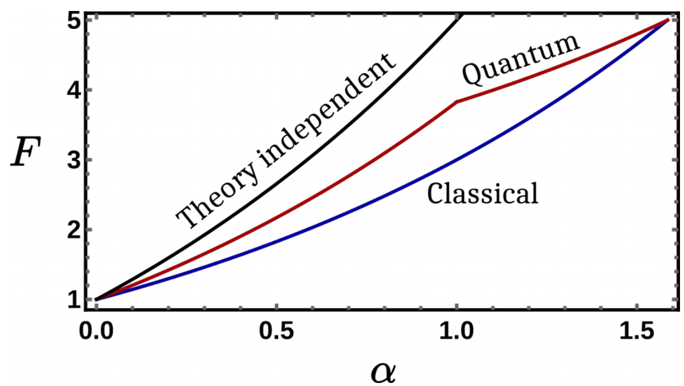
arXiv:1909.05656

Bounding information – ability to guess the input from the message.

Alternative to bounding dimension, entropy, overlap, energy,...



- **Separate classical from quantum correlations.**
- **Device-independent bound on the information.**



- **Stronger correlations with same/less information as dimension-bounded schemes.**
- **Restore hierarchy of quantum communication vs. entanglement-assisted classical communication.**