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# Device-Independent Quantification of Quantum Resources



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## Motivation and Goals

- Quantum resources (states, measurements, channels, ...) provide advantages that can be operationally quantified
- Quantifying a given resource typically requires well characterised states and/or measurements to probe the resource
- What resources can be characterised in a **device independent** way?
- Goal:** use techniques from self-testing to **certify and quantify any resourceful object** in a black-box setting

## Quantum Resources

We consider resources with convex free sets:

- States:** entanglement, steerability, non-Gaussianity, magic, ...
- Measurements:** incompatibility, non-projective-simulability, ...
- Channels:** non-entanglement-breaking and non-incompatibility-breaking channels, thermal operations, ...

We focus on **channel resources**

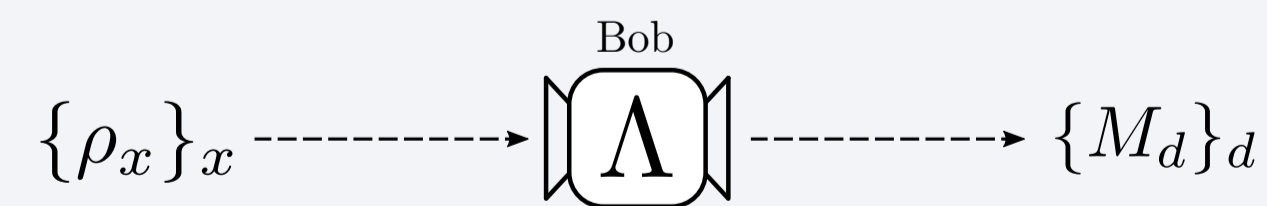
- The resourcefulness of  $\Lambda$  w.r.t. a free set  $F$  can be quantified with the **generalised robustness**:

$$R_F(\Lambda) = \min_{\tilde{\Lambda}} \left\{ t \geq 0 \mid \frac{\Lambda + t\tilde{\Lambda}}{1+t} \in F \right\}$$

## Resource Quantification with Input-Output Games [2]

- $R_F(\Lambda)$  related to operational advantage in an input-output game  $\mathcal{G} = (\mathcal{E}, \mathcal{M}, \Omega)$ :

$$\begin{aligned} \mathcal{E} &= \{p(x)\rho_x\}_x && \text{(input state ensemble)} \\ \mathcal{M} &= \{M_d\}_d && \text{(a POVM)} \\ \Omega &= \{w_{x,d}\}_{x,d} && \text{(score)} \end{aligned}$$



$$P(\Lambda, \mathcal{G}) = \sum_{x,d} p(x) \omega_{x,d} \text{tr}[\Lambda(\rho_x)M_d] \quad \text{(payout)}$$

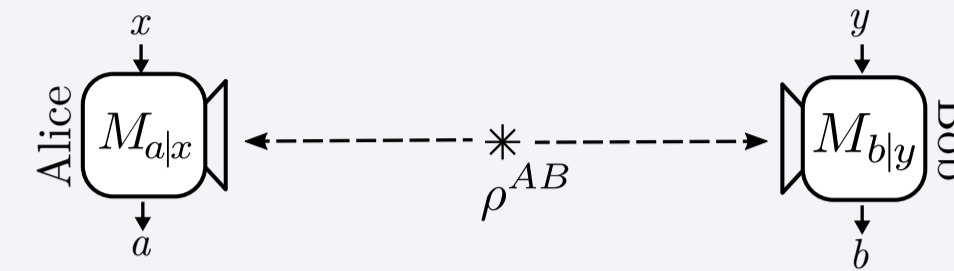
- For well-normalised input-output games, payout a resource can give is directly related to its robustness:

$$1 + \mathcal{R}_F(\Lambda) = \max_{\mathcal{G}} P(\Lambda, \mathcal{G})$$

- Device dependent: Must trust  $\mathcal{E}$  and  $\mathcal{M}$ !**

## Self-testing [3]

Certify exact form of a state and measurements from correlations  $p(a, b|x, y)$

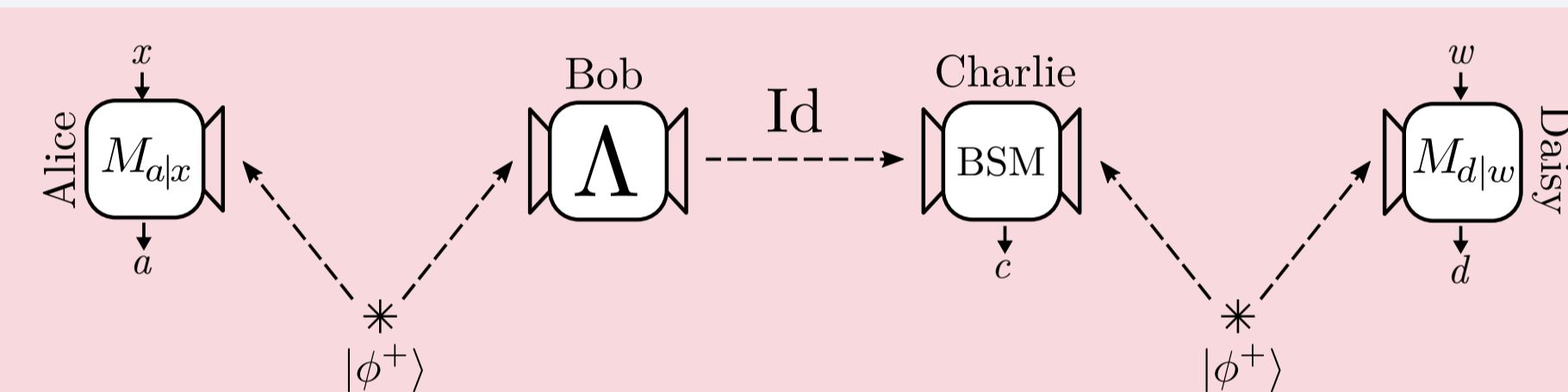


- E.g.: maximal violation of a Bell inequality can certify:
  - $\rho \simeq |\phi^+\rangle\langle\phi^+|$ , Alice and Bob measure Pauli  $X, Y, Z$
- Certification up to local isometries and complex conjugate

## Reference Scenario & Protocol

Use self-testing to characterise, device-independently:

- remote preparation of pure states  $\{\rho_x\}_x$
- arbitrary measurement  $\{M_d\}_d$



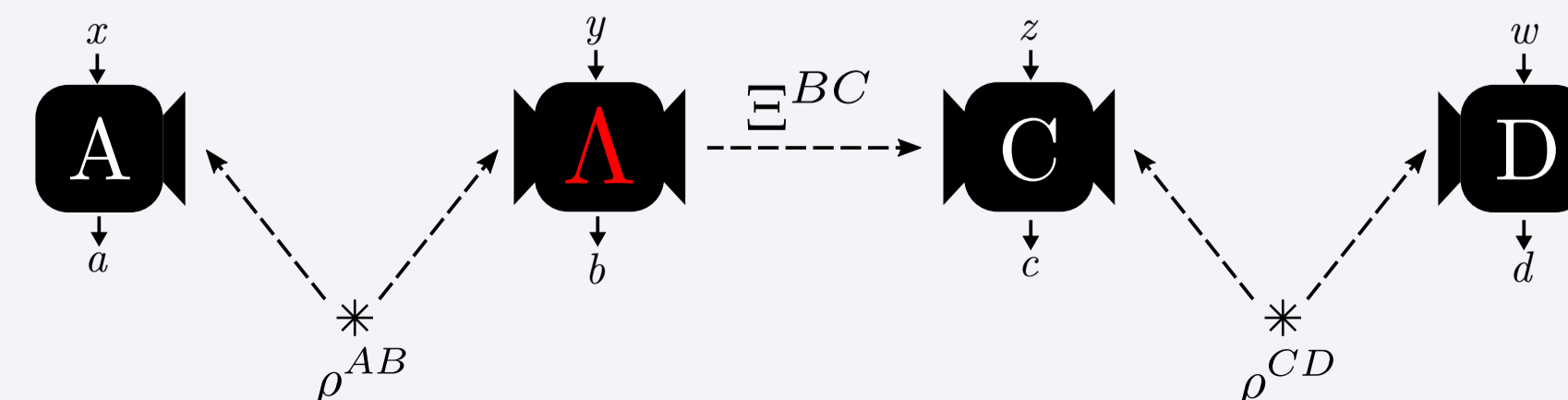
- On input  $x$ , Alice remotely prepares  $\rho_x$  for Bob by performing a suitable measurement on her share of  $|\phi^+\rangle^{AB}$ .
- Bob applies  $\Lambda$  to  $\rho_x$  and sends  $\Lambda(\rho_x)$  to Charlie via the identity channel  $\text{Id}$ .
- Charlie performs a Bell-state measurement (BSM) on  $\Lambda(\rho_x)$  and his share of  $|\phi^+\rangle^{CD}$ , teleporting to Daisy the state  $\sigma_c \Lambda(\rho_x) \sigma_c^\dagger$ .
- Daisy measures  $\{M_d|w\}_d = \{\sigma_w M_d \sigma_w^\dagger\}_d$  on the teleported state; for  $w = c$  this is equivalent to measuring  $\{M_d\}_d$  on  $\Lambda(\rho_x)$ .

$$P(\Lambda, \mathcal{G}) = \sum_{x,d} p(x) \omega_{x,d} \sum_{c,w} \frac{1}{p(0|x)} p(0, c, d|x, w) \delta_{c,w}$$

## Device-independent Quantification Protocol

Add extra inputs to self-test (up to local isometries):

- Maximally entangled states  $\rho^{AB}$  and  $\rho^{CD}$
- Pauli  $X, Y, Z$  measurements for Alice and Daisy
- Identity channel  $\Xi^{BC}$
- Bell-state measurement for Charlie



## Quantification Statement

- The statistics on “quantification rounds” give the payoff  $P(\Lambda^{\text{ext}}, \mathcal{G})$  of an **effective (extractable) channel**

$$\Lambda^{\text{ext}} = h_{00}\Lambda_{00}^{\text{ext}} + h_{11}\tilde{\Lambda}_{11}^{\text{ext}}$$

- $\tilde{\Lambda}_{11}^{\text{ext}}(\rho) = \Lambda_{11}^{\text{ext}}(\rho^*)^*$  (conjugate channel)
- $\Lambda_{ii}^{\text{ext}}$  can be extracted with local isometries from the physical effective channel  $\mathcal{T}^{C \rightarrow D} \circ \Xi^{BC} \circ \Lambda$  from Bob to Daisy and takes into account “junk states”  $\xi_{ii}$  arising during extraction
- $\Lambda_{00}$  and  $\Lambda_{11}$  differ in junk states arising from self-testing (indistinguishability of correlated Alice-Daisy conjugation)
- DI certification that we can extract a channel with payout  $P(\Lambda^{\text{ext}}, \mathcal{G})$  on  $\mathcal{G}$

## Relation to Physical Channel

For “well-behaved” resources:

- Resource certification:** If  $\Lambda$  is resourceless, so is  $\Lambda^{\text{ext}}$
- Quantification bound:**  $P(\Lambda^{\text{ext}}, \mathcal{G}) \leq \max_{\mathcal{G}'} P(\Lambda, \mathcal{G}')$ 
  - i.e.,  $R_F(\Lambda^{\text{ext}}) \leq R_F(\Lambda)$

Resource must satisfy certain preconditions:

- Can't be increased by local unitaries
- Insensitive to channel conjugation
- Unaffected by attaching extra DOFs that measurements are trivial on

## Examples

- Non-entanglement-breaking and non-incompatibility-breaking channels are faithfully quantified in this way
- Can be significantly simplified for state or measurement resources
  - E.g., input-output games  $\rightarrow$  state-discrimination games
  - Complements known DI certification of all entangled states [4]
- We likewise obtain a fully black-box certification of any sets of incompatible measurements

## Conclusions and Open Questions

- DI **certification** of any\* resourceful channel
- Correlations **quantify** the resourcefulness of implemented channel
- Causal network structure of protocol important to its success
- Full characterisation of which resources can be quantified in this way?

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