Bound entangled states with secret key and their classical counterpart

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A brief summary

Main result

A new construction of *bound entangled states with secret key*

Steps involved

1. Understand what is the classical analogue of this
2. Construct a probability distribution P_{ABE} that has the desired properties
3. Set $|\psi\rangle_{ABE} = \sqrt{P_{ABE}}$

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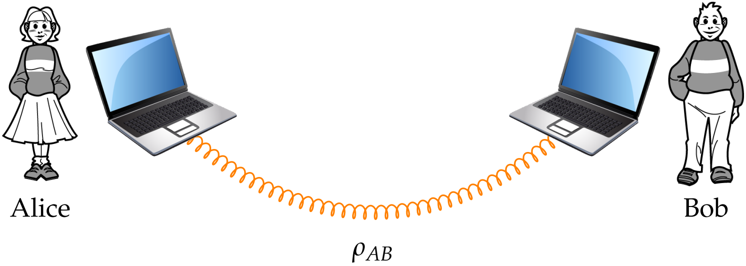
The significance of trash in cryptography

Shared entanglement and randomness

- Cryptographic and computational resource



Shared entanglement and randomness

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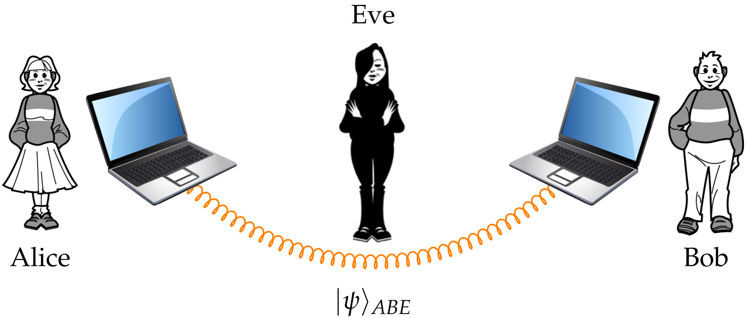
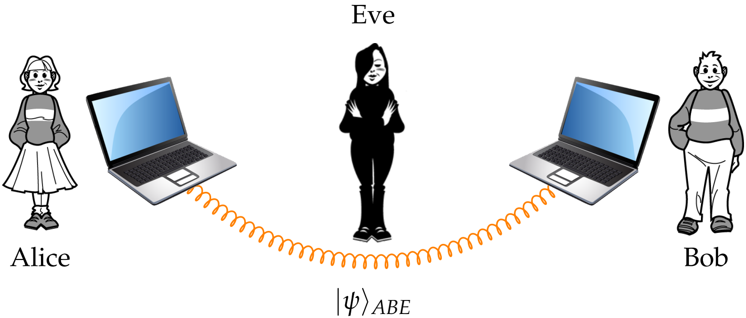
- Joint state: $|\psi\rangle_{ABE}$ or P_{ABE}



Shared entanglement and randomness

- Cryptographic and computational resource
- Joint state: $|\psi\rangle_{ABE}$ or P_{ABE}
- When is such resource useful?



Perfect resources

When is P_{ABE} a perfect resource?

1. Identical for A and B
2. Uniformly random
3. Private from E

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$$P_{ABE} = \mathrm{KEY}_{AB} \otimes \mathrm{TRASH}_E$$
$$\mathrm{KEY}_{AB} = \begin{cases} 0_A 0_B & \text{w.p. } 1/2 \\ 1_A 1_B & \text{w.p. } 1/2 \end{cases}$$

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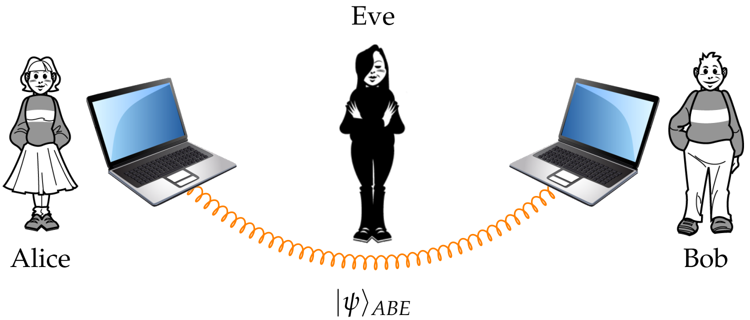
$$|\psi\rangle_{ABE} = |\mathrm{KEY}\rangle_{AB} \otimes |\mathrm{TRASH}\rangle_E$$
$$|\mathrm{KEY}\rangle_{AB} = \frac{1}{\sqrt{2}}(|00\rangle_{AB} + |11\rangle_{AB})$$

Distillation



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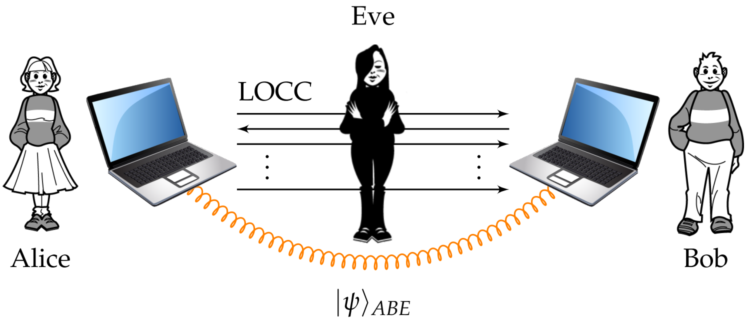

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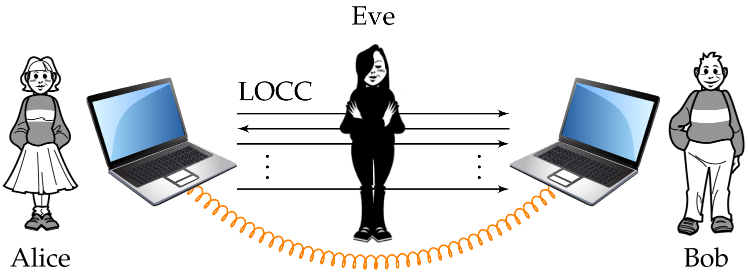

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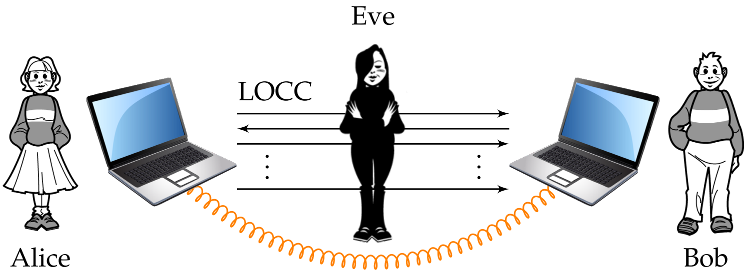


$$|\mathrm{KEY}\rangle_{AB}^{\otimes k} \otimes |\mathrm{TRASH}\rangle_E$$

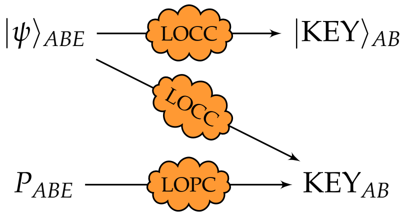
Entanglement distillation rate

$$D(|\psi\rangle_{ABE}) := \lim_{n\to\infty} \frac{1}{n}\Big(\#\text{ of } |\mathrm{KEY}\rangle_{AB} \text{ from } |\psi\rangle_{ABE}^{\otimes n} \text{ via LOCC}\Big)$$

More distillation rates

- $D(|\psi\rangle_{ABE})$ – entanglement distillation rate
- $K(P_{ABE})$ – key distillation rate

More distillation rates



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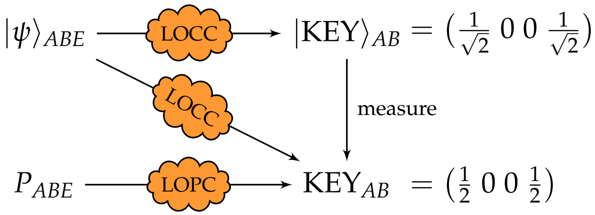

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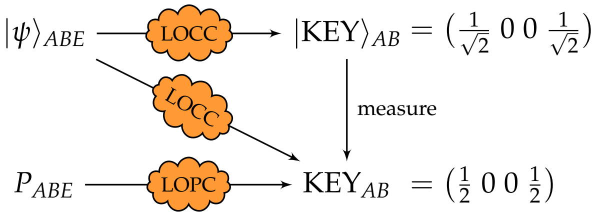

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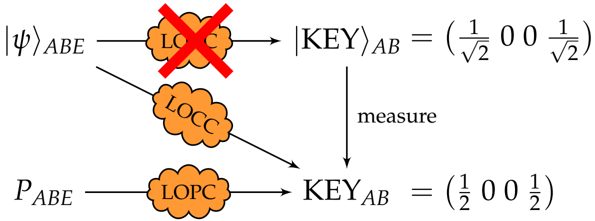

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Bound entanglement

$|\psi\rangle_{ABE}$ is entangled
but $D(|\psi\rangle_{ABE}) = 0$

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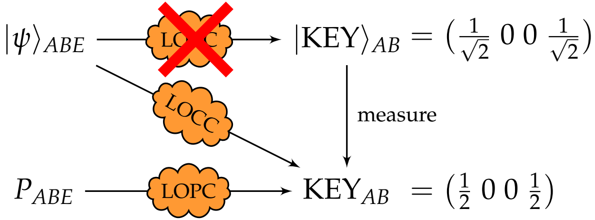

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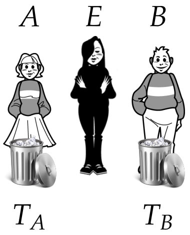
Bound entanglement
$|\psi\rangle_{ABE}$ is entangled
but $D(|\psi\rangle_{ABE}) = 0$

Private bound entanglement
$|\psi\rangle_{ABE}$ is bound entangled
but $K(|\psi\rangle_{ABE}) > 0$ [HHHO05]

Entanglement vs classical key



Compare

$$|\Psi_1\rangle := \frac{1}{\sqrt{2}}\Big(|00\rangle_{AB} + |11\rangle_{AB}\Big) \otimes |\varphi\rangle_{T_A T_B} \otimes |\phi\rangle_E$$

$$|\Psi_2\rangle := \frac{1}{\sqrt{2}}\Big(|00\rangle_{AB}|\varphi\rangle_{T_A T_B} + |11\rangle_{AB}|\varphi^{\perp}\rangle_{T_A T_B}\Big) \otimes |\phi\rangle_E$$

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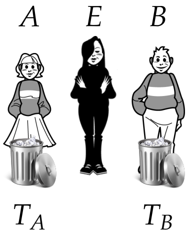

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- If T_A and T_B are discarded, $|\Psi_1\rangle$ contains a quantum $|\text{KEY}\rangle$ whereas $|\Psi_2\rangle$ contains only a classical KEY

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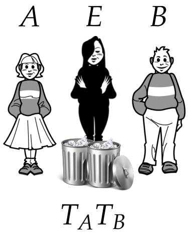

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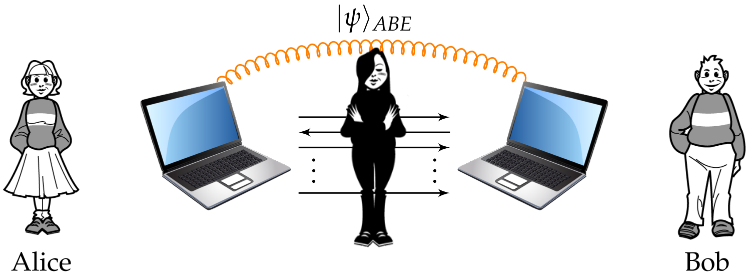
Observe

- If T_A and T_B are discarded, $|\Psi_1\rangle$ contains a quantum $|\text{KEY}\rangle$ whereas $|\Psi_2\rangle$ contains only a classical KEY
- Quantum $|\text{KEY}\rangle$ is immune against Eve accessing T_A and T_B (due to monogamy of entanglement)

Distillation with remanent devices



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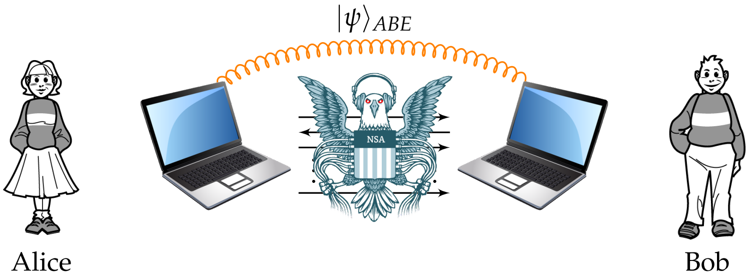

Extra assumption

- At the end of the protocol Eve confiscates both devices; she can recover all information that was erased
- Alice and Bob can keep *only* the key

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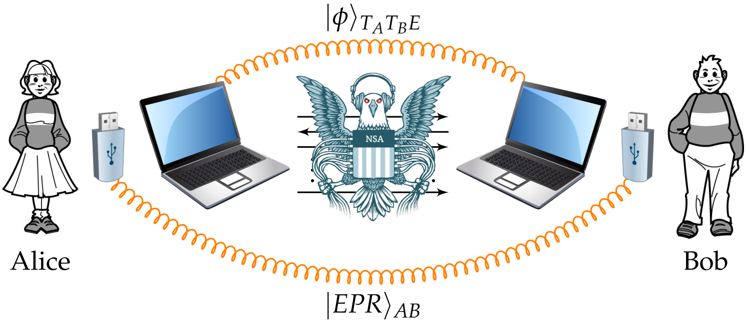

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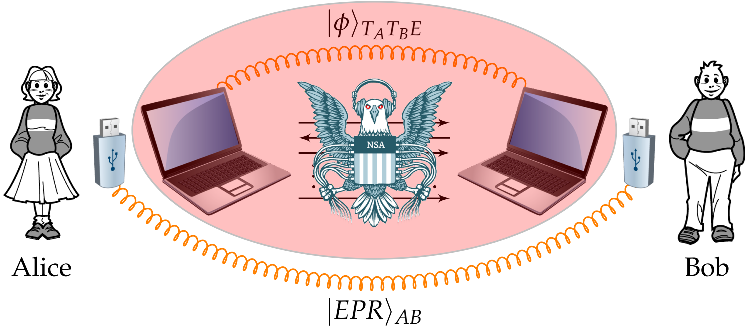

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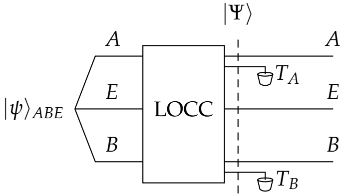

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entangled key

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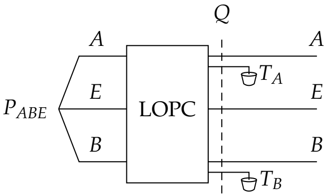
classical key

Classical distillation



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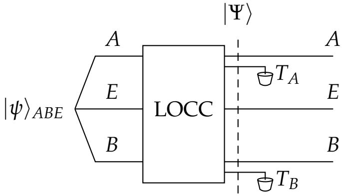

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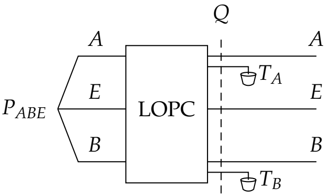

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Private randomness

- There are two types of private randomness!

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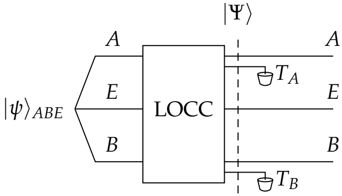

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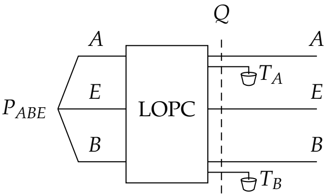

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- Classical analog of entanglement [CP02] is private randomness that is distilled on remanent devices

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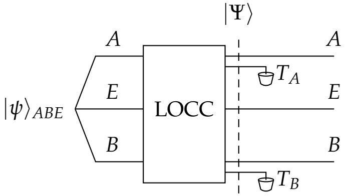

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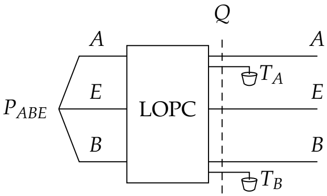

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classical key?

Private randomness

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- Classical analog of entanglement [CP02] is private randomness that is distilled on remanent devices
- This resource needs a new name…

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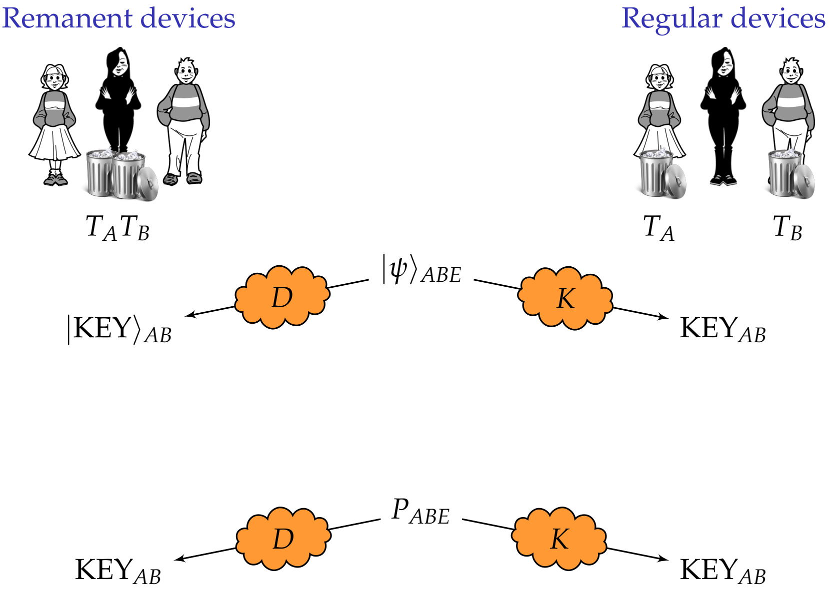
enclanglement


Remanent devices
Regular devices
$T_A T_B$
T_A
T_B
$|\psi\rangle_{ABE}$
D
K
$|\mathrm{KEY}\rangle_{AB}$
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P_{ABE}
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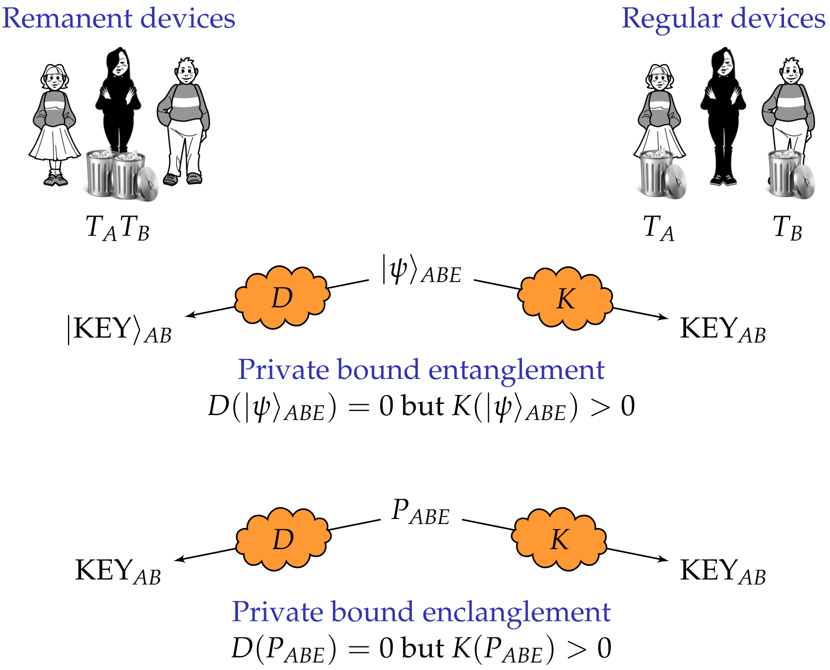
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Main results

Theorem 1

If $|\psi\rangle_{ABE} = \sqrt{P_{ABE}}$ is quantical then

- $D(\psi_{ABE}) \geq D(P_{ABE})$ and
- $K(\psi_{ABE}) \geq K(P_{ABE})$

Theorem 2

There exist quantical distributions P_{ABE} with $D(P_{ABE}) = 0$ and $K(P_{ABE}) > 0$

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Corollaries

1. New construction of private bound entanglement
2. Noise helps in one-way classical key distillation

quant[um]

+

[class]*ical*

=

quantical

Quantical distributions / states

P_{ABE} is *quantical* if any single party's state can be unambiguously determined by the rest of the parties:*

$$\forall b, e : |\{a : p(a,b,e) \neq 0\}| \leq 1$$
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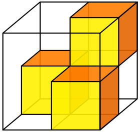

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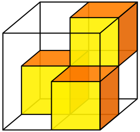

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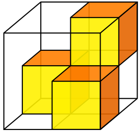

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Dual nature

- Quantical P_{ABE} and $|\psi\rangle_{ABE}$ describe the same entity
- Entropic quantities for P_{ABE} and $|\psi\rangle_{ABE}$ agree
- Quantical P_{ABE} has a "classical Schmidt decomposition" w.r.t. any bipartition

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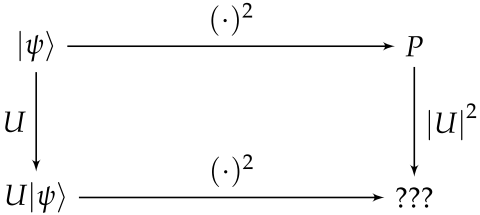
Proof idea

1. Classical protocol can be promoted to a quantum one



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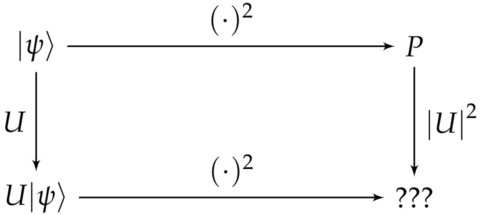

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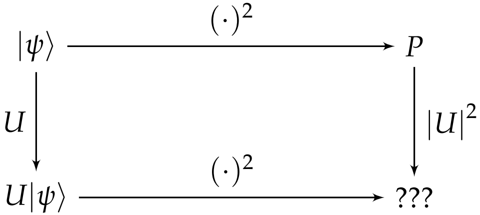


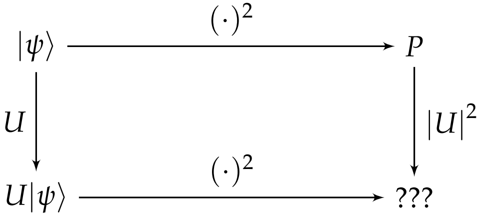
Theorem 1

If $|\psi\rangle_{ABE} = \sqrt{P_{ABE}}$ is quantical then

- $D(\psi_{ABE}) \geq D(P_{ABE})$ and
- $K(\psi_{ABE}) \geq K(P_{ABE})$

Proof idea

1. Classical protocol can be promoted to a quantum one
2. P_{ABE} remains quantical throughout the protocol
3. Entropic quantities for P_{ABE} and $|\psi\rangle_{ABE}$ agree
4. Promoted protocol achieves the same rate



Theorem 2

There exist quantical distributions P_{ABE} with $D(P_{ABE}) = 0$ and $K(P_{ABE}) > 0$

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$$K(P_{ABE}) \geq \max_{A \to X} \big[I(X;B) - I(X;E)\big]$$

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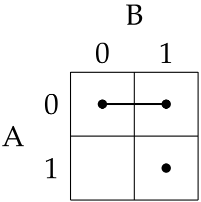
- Choose $|X| = 2$ and do numerics

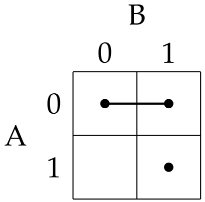
Recipe for quanticality and PT-invariance



$$\left(a|00\rangle_{AB} + b|01\rangle_{AB}\right)|x\rangle_E$$

$$+\, c|11\rangle_{AB} \;\; |y\rangle_E$$

Recipe for quanticality and PT-invariance



$$\big(a|00\rangle_{AB} + b|01\rangle_{AB}\big)\,|x\rangle_E$$
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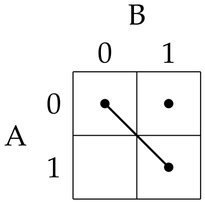
Quantical

- Union of disjoint cliques
- Each clique is “diagonal” (no repeated rows or columns)

Recipe for quanticality and PT-invariance



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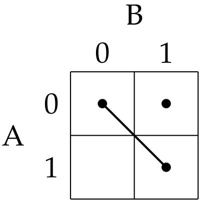

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- Union of crosses
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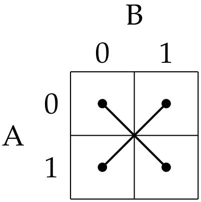
Recipe for quanticality and PT-invariance



$$\big(a|00\rangle_{AB} + b|11\rangle_{AB}\big)\,|x\rangle_E$$
$$+\,\big(c|01\rangle_{AB} + d|10\rangle_{AB}\big)\,|y\rangle_E$$

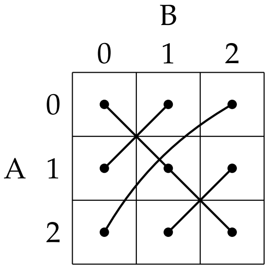
Quantical

- Union of disjoint cliques
- Each clique is “diagonal” (no repeated rows or columns)

PT-invariant

- Union of crosses
- Each cross has zero determinant

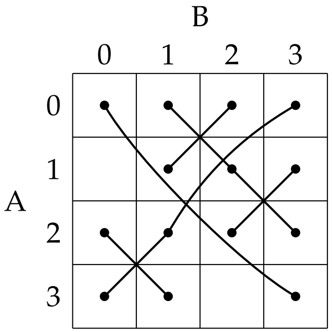
Example in 3×3



$$P_{AB} = \begin{pmatrix} 0.167184 & 0.171529 & 0.001243 \\ 0.089041 & 0.091355 & 0.017492 \\ 0.441714 & 0.017157 & 0.003285 \end{pmatrix}$$

$$D(P_{ABE}) = 0 \quad \text{but} \quad K(P_{ABE}) \geq 0.0057852$$

Example in 4×4

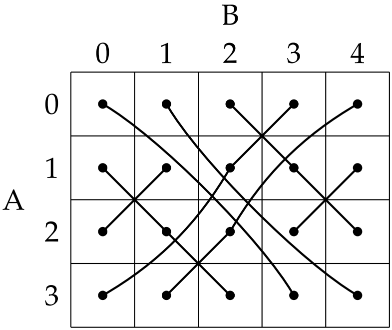


$$K(P_{ABE}) \geq 0.0293914$$

Better than [HPHH08]

$$K(P_{ABE}) \geq 0.0213399$$

Example in 4×5



$$K(P_{ABE}) \geq 0.0480494$$

Conclusions

Results

- New construction of private bound entanglement
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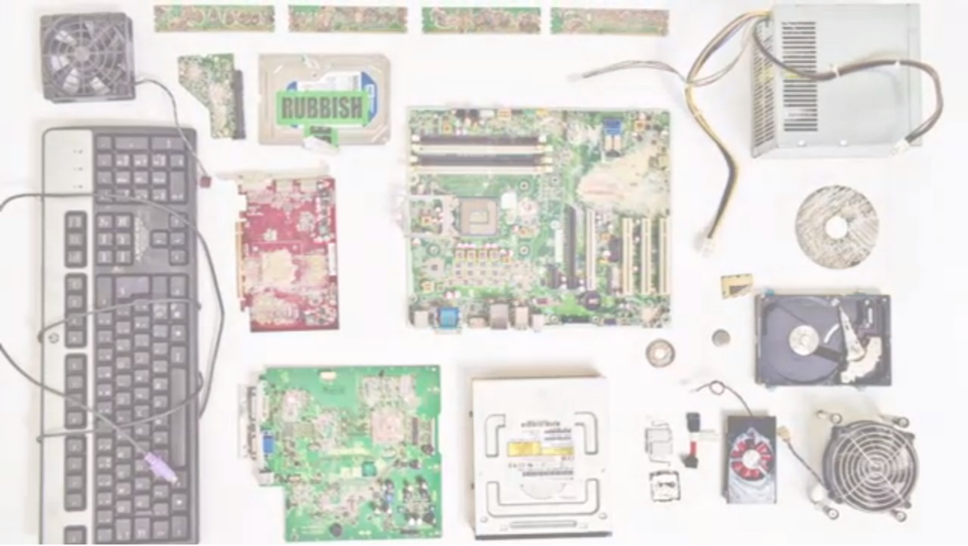
Work in progress…

- Quantical mechanics and a classical analogue of superactivation (of the quantical capacity)



That’s it!

Image: destroyed Guardian computer with Snowden files

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