Device-independent protocols from computational assumptions

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Joint work with

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(UC Berkeley)

Yfke Dulek
(CWI & QuSoft)

Thomas Vidick
(Caltech)

Self-testing of a single quantum device under computational assumptions, arXiv:2001.09161.

Device-independent quantum key distribution from computational assumptions, arXiv:2010.04175.

Outline

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1. Setting for “standard” DIQKD

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security based on Bell inequality violation

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2. Setting for “computational” DIQKD ← can’t base security on Bell inequality violation
3. Main technical tool: computational self-testing

replaces Bell inequality violation

Device-independent QKD

Ekert, Quantum cryptography based on Bell's theorem, PRL 67, 661 (1991).
Mayers & Yao, Quantum cryptography with imperfect apparatus, FOCS 1998.

Device-independent QKD

Eve

Alice

Bob

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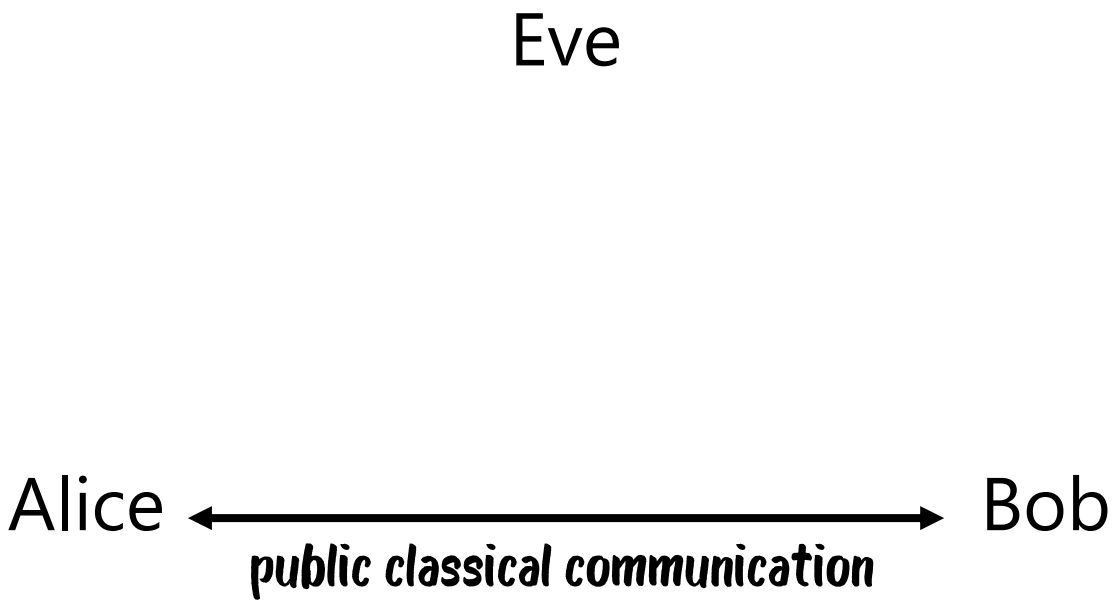
Device-independent QKD



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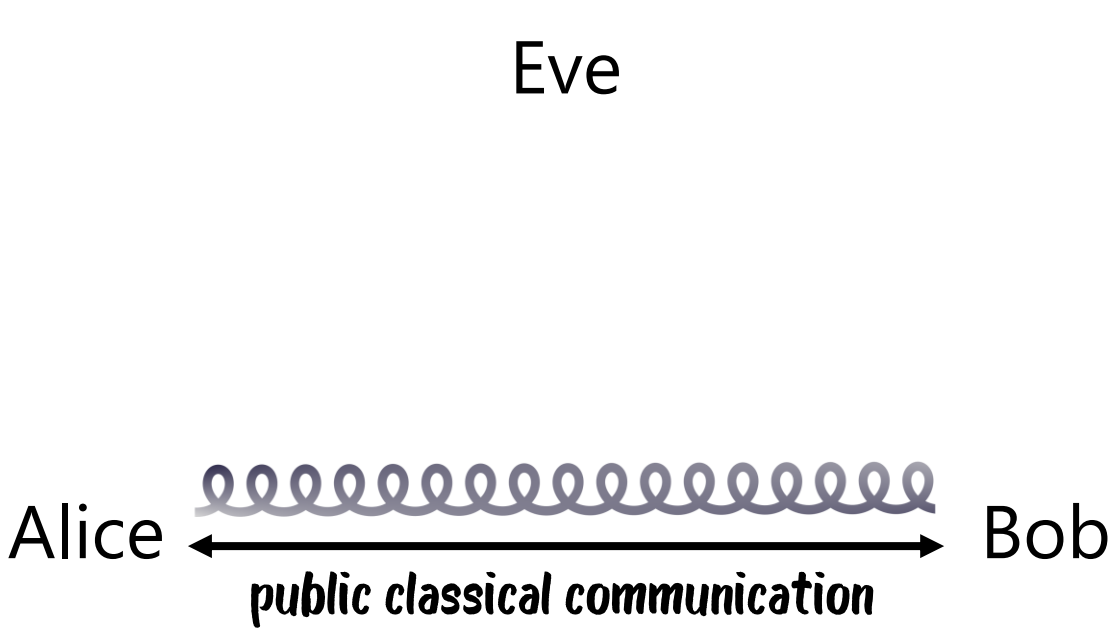

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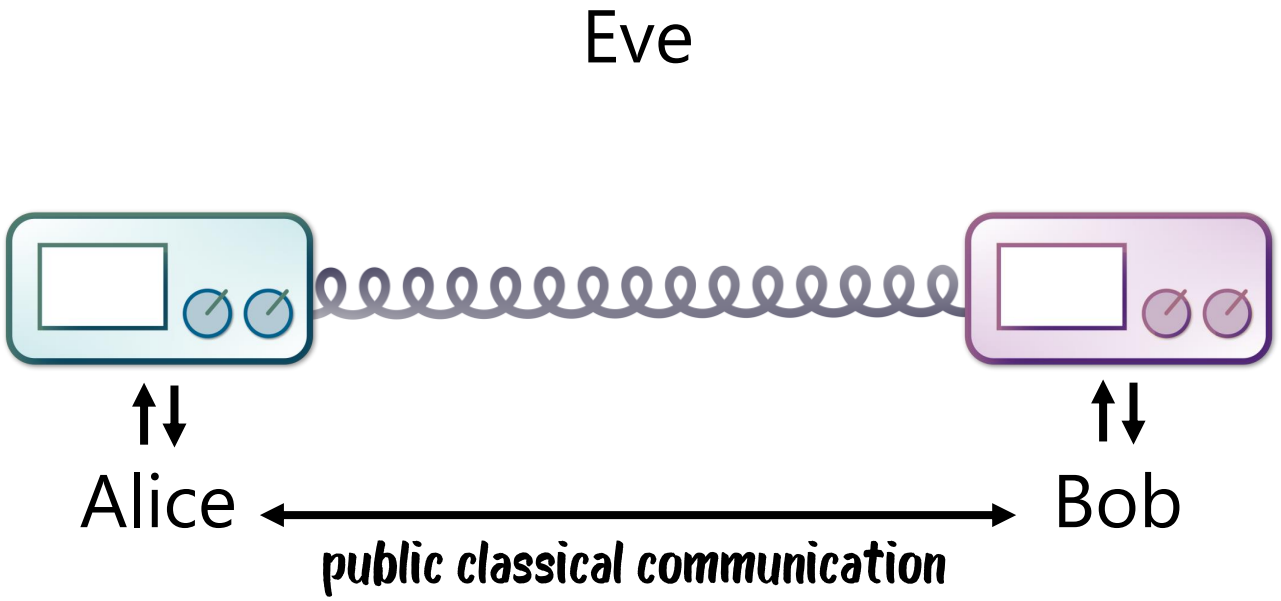

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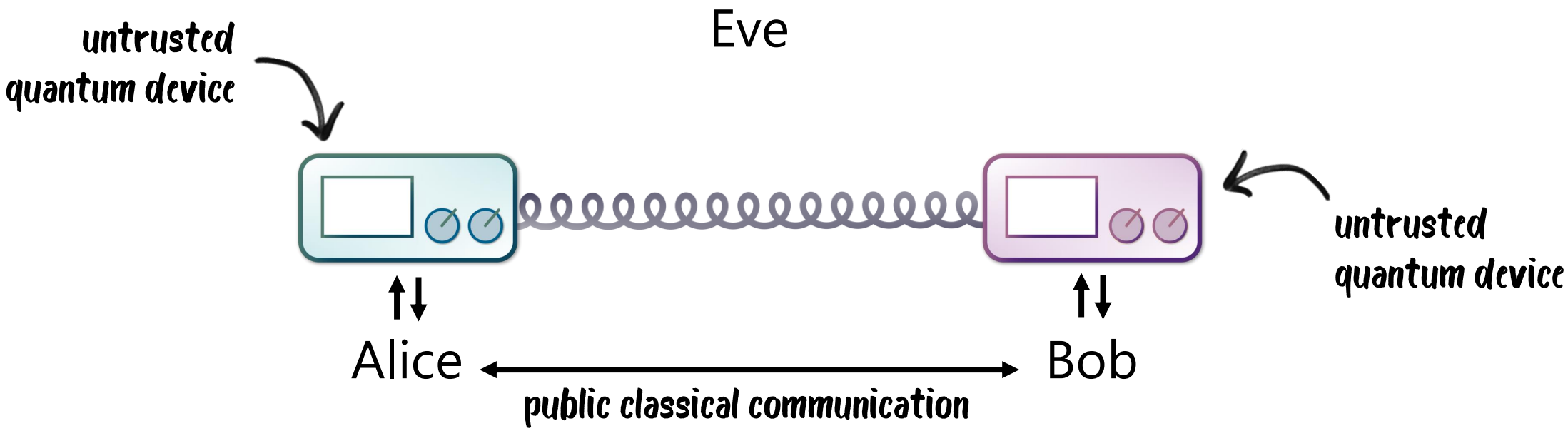

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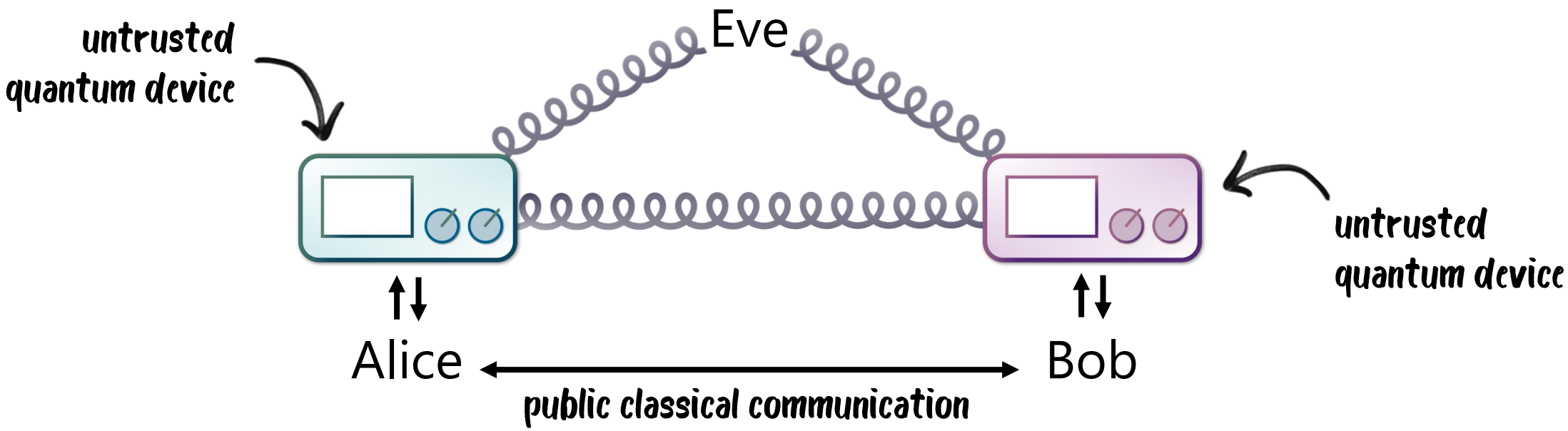

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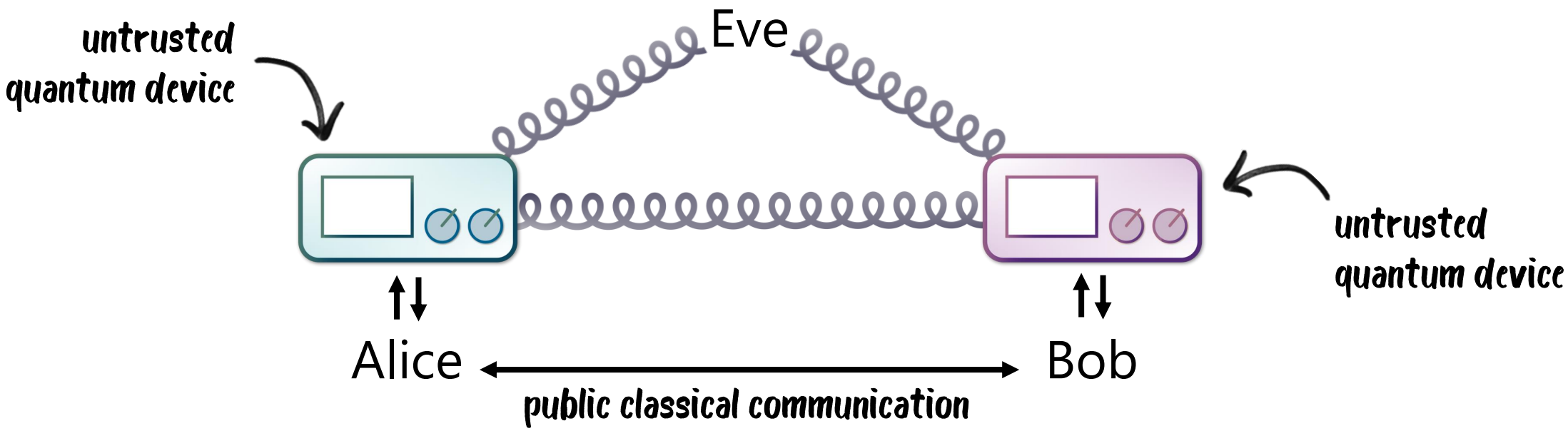

Bell inequality
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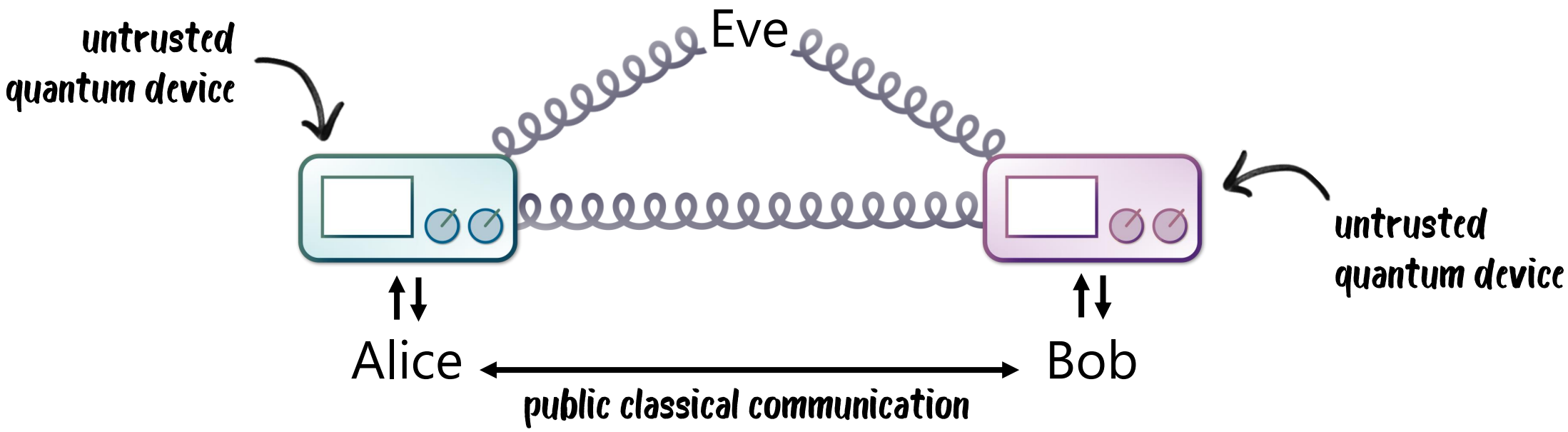

Bell inequality violation → Statement about devices' states and measurements

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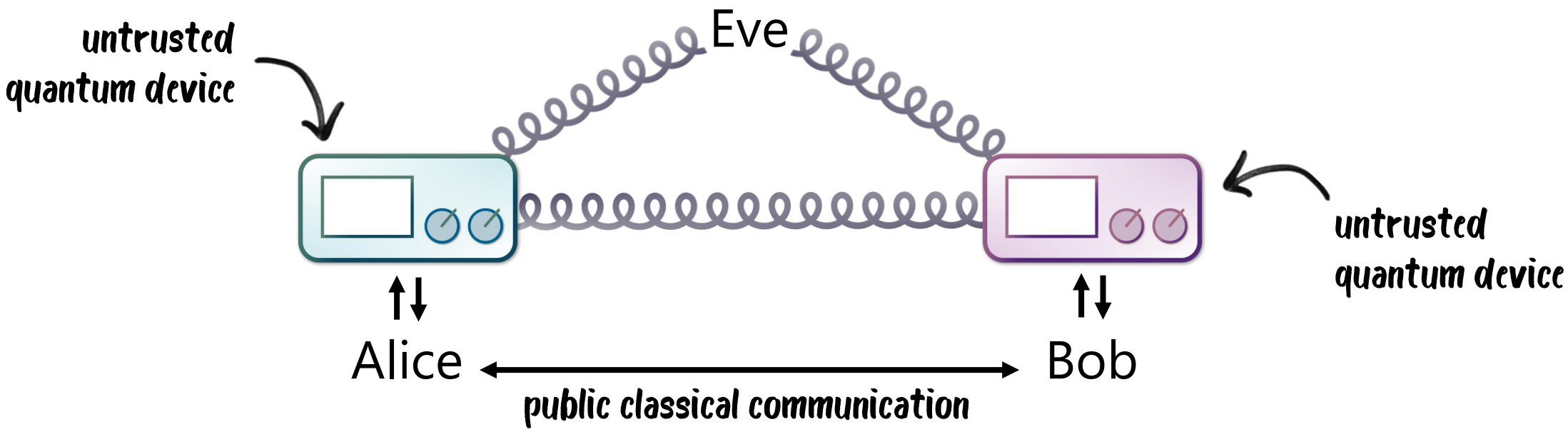

Bell inequality violation → Statement about devices' states and measurements → **Information-theoretic security** of final key

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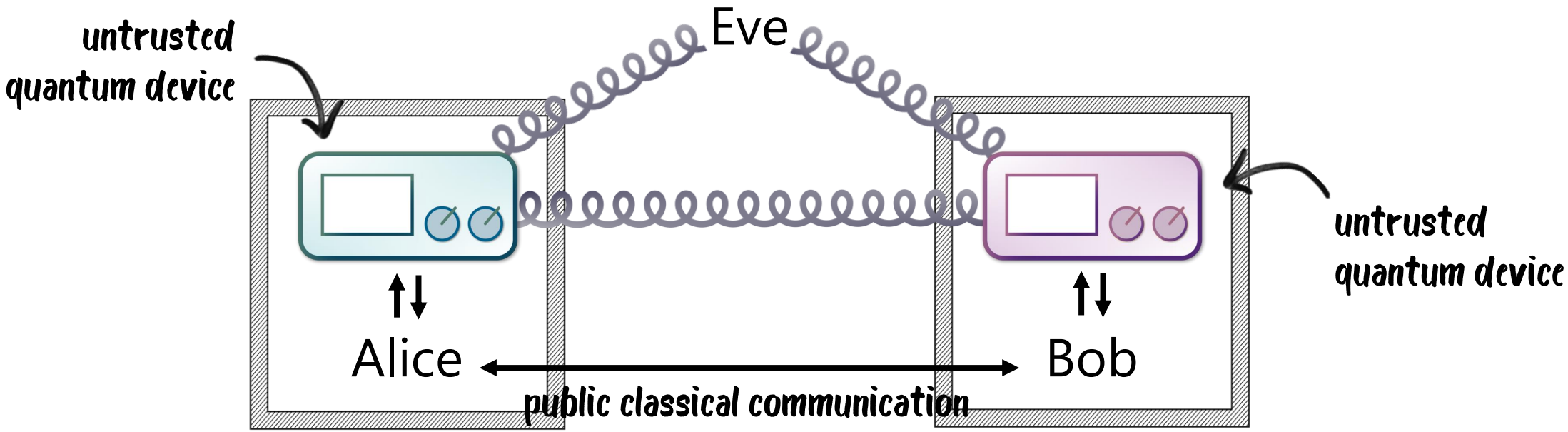

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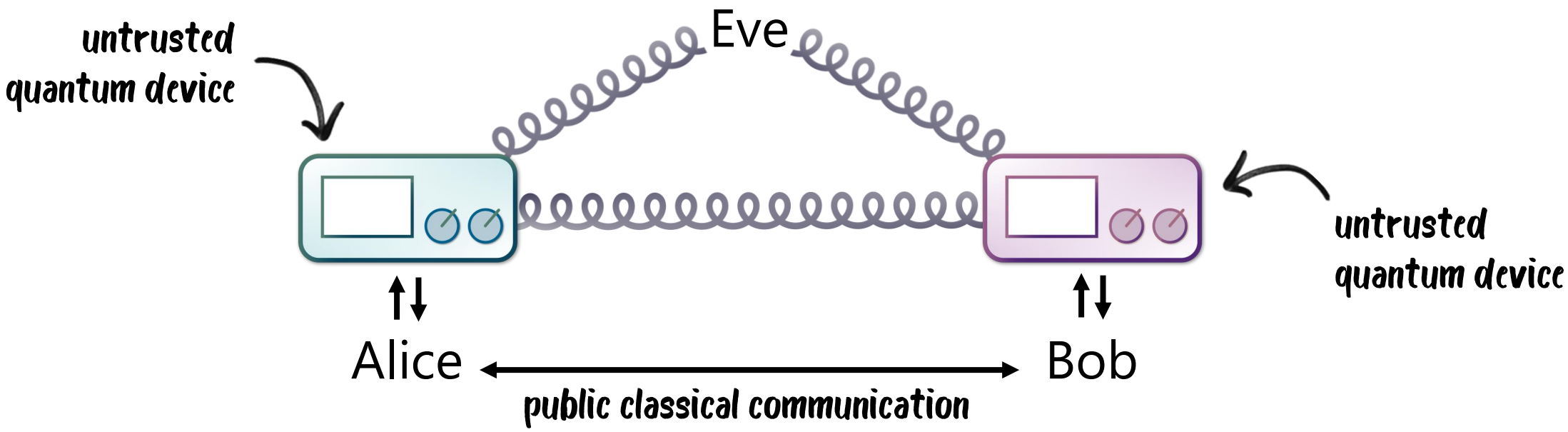

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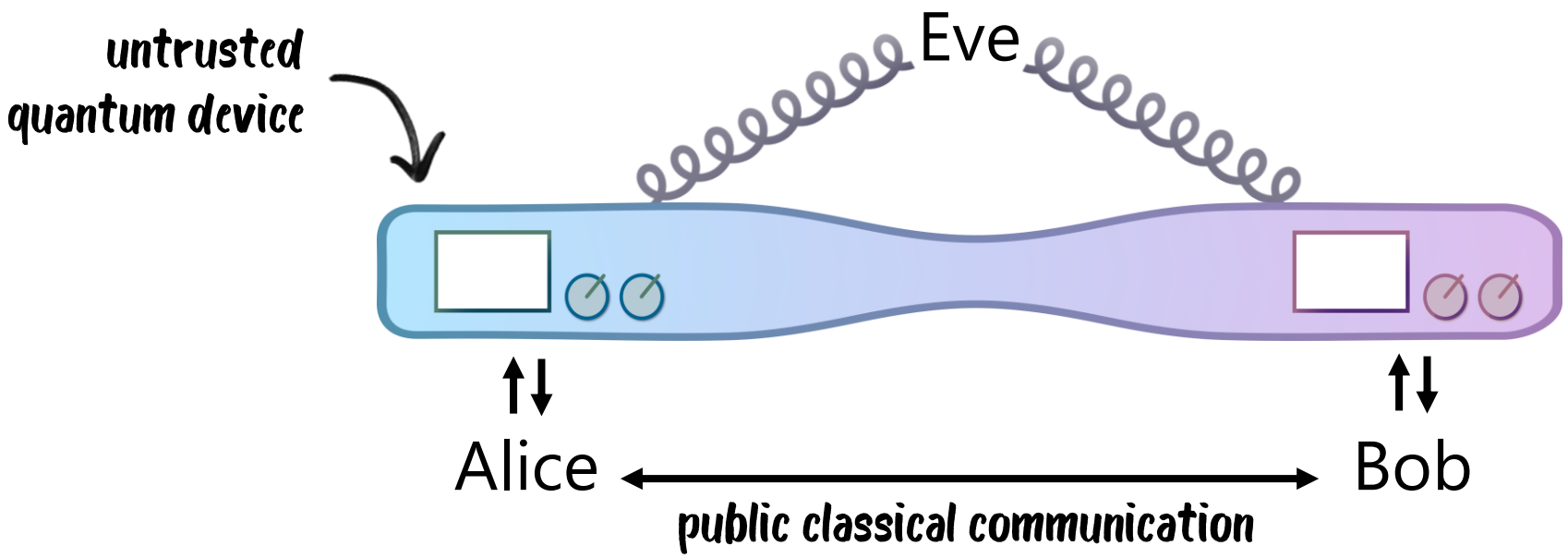

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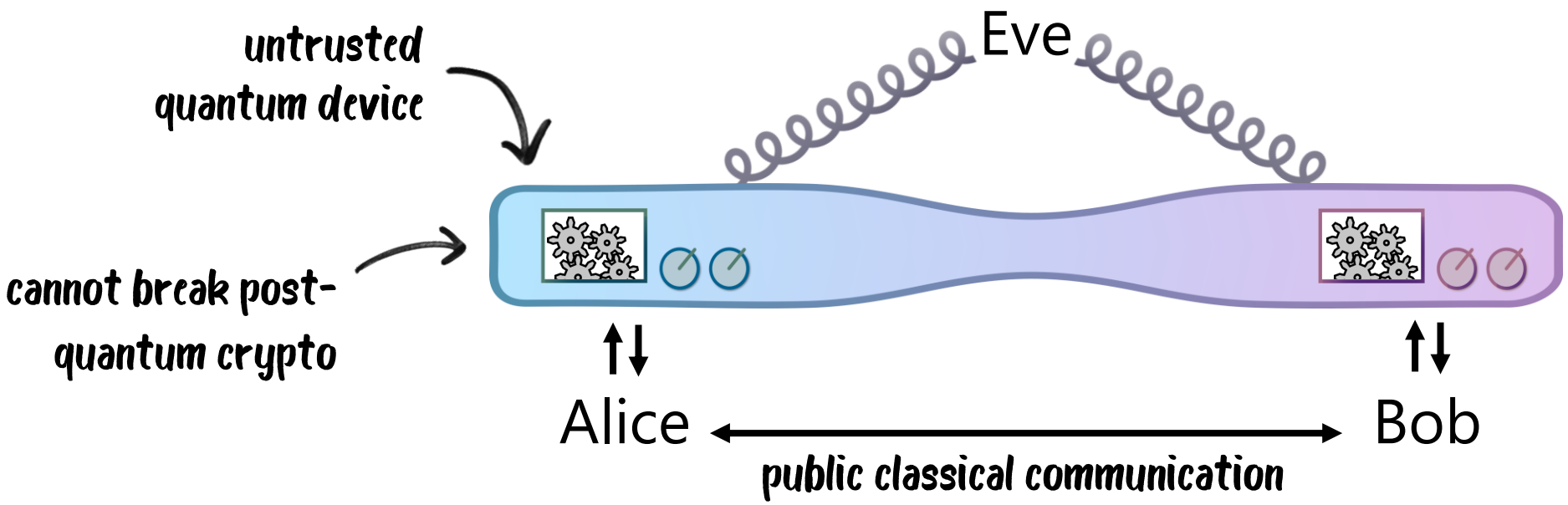
Computational DIQKD setting



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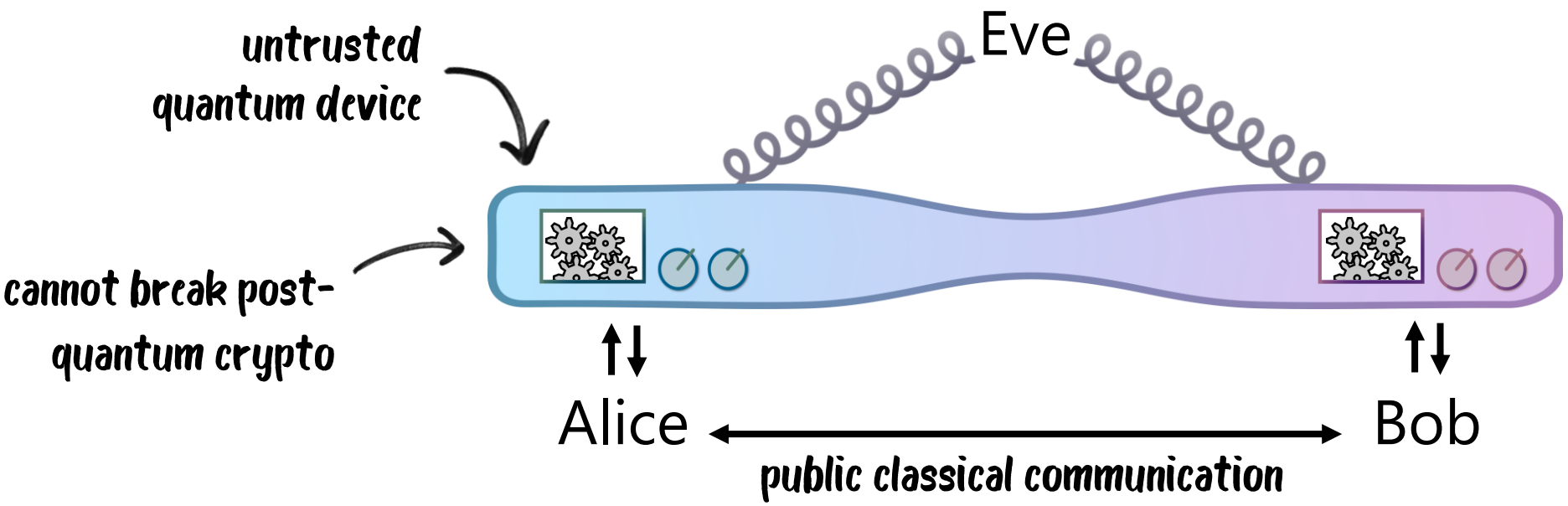

Interactive protocol with **computational assumption** → Statement about devices' states and measurements → **Information-theoretic security** of final key

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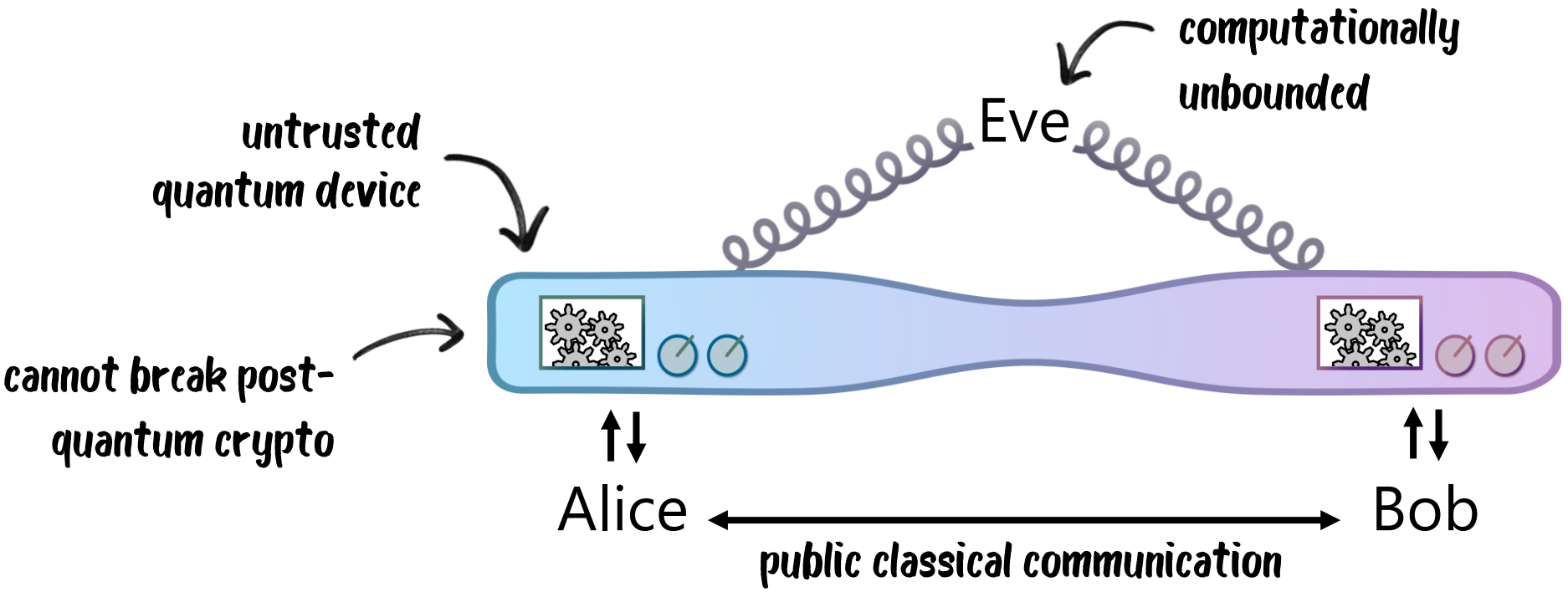

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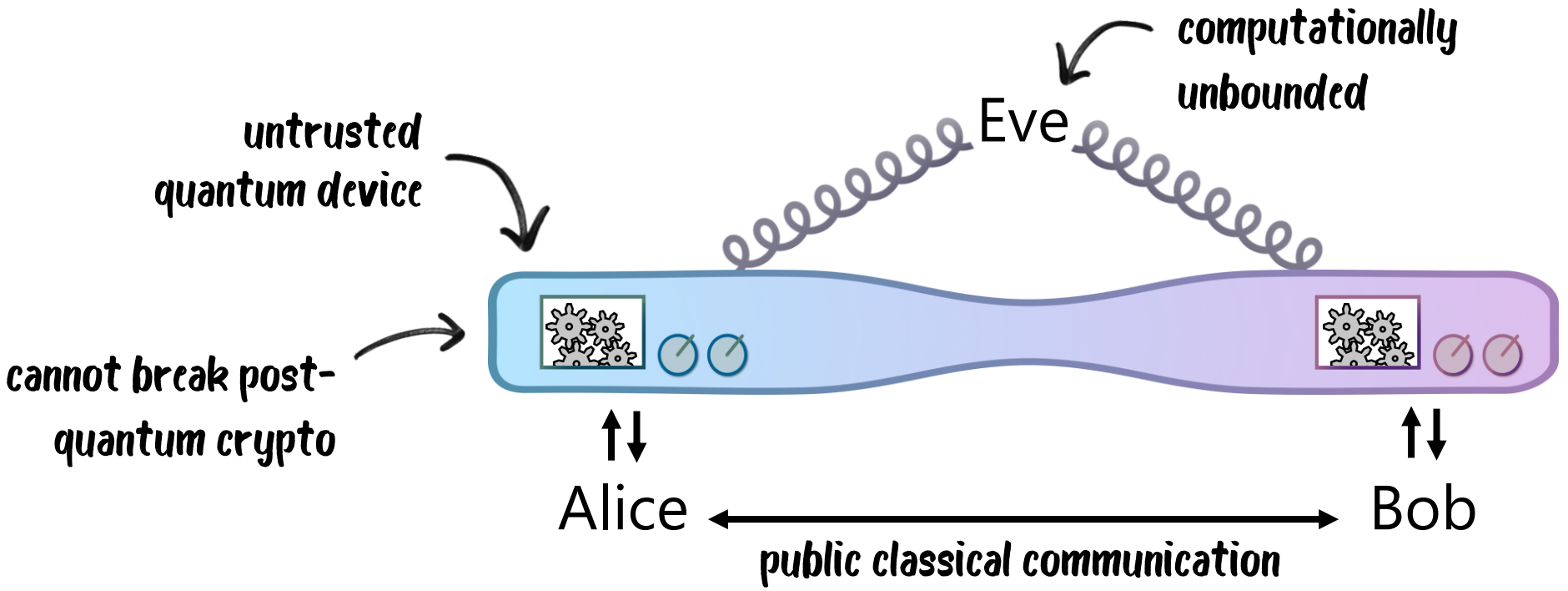

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required only for duration of the protocol

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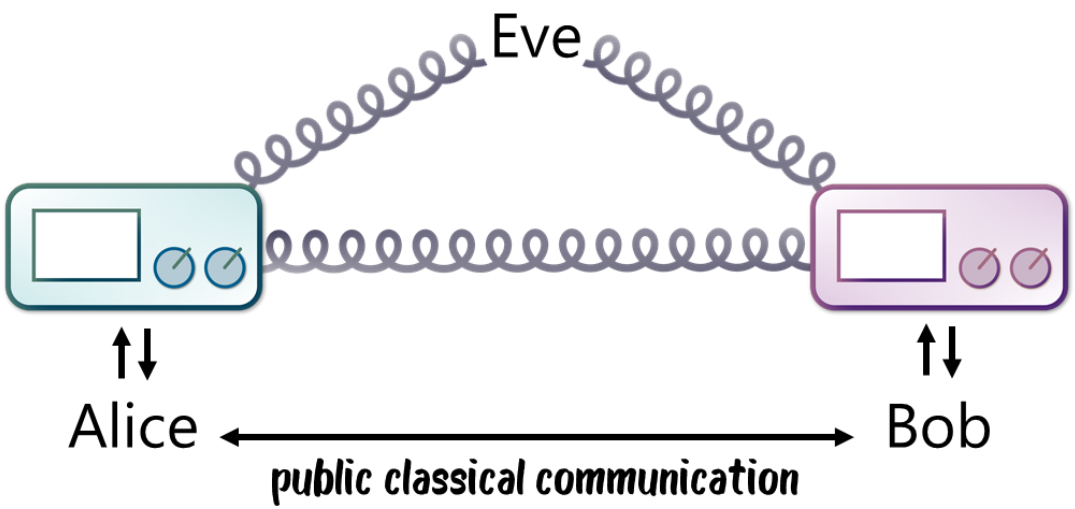
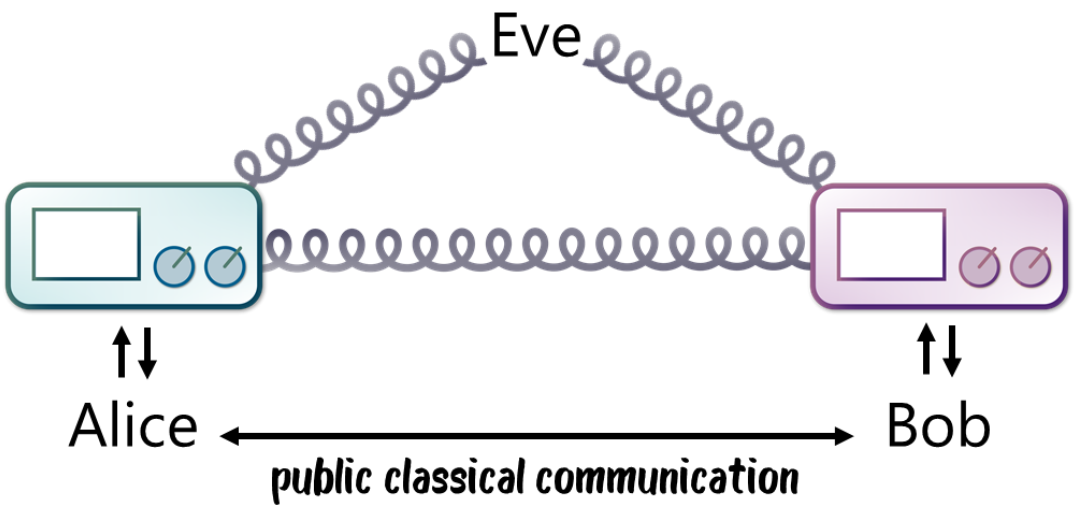

Eve
Alice
Bob
public classical communication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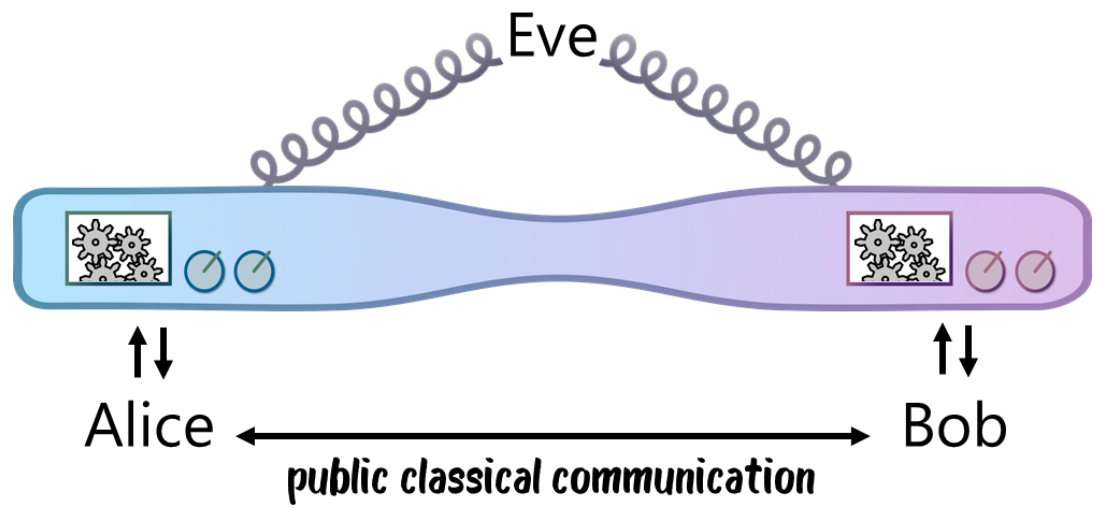
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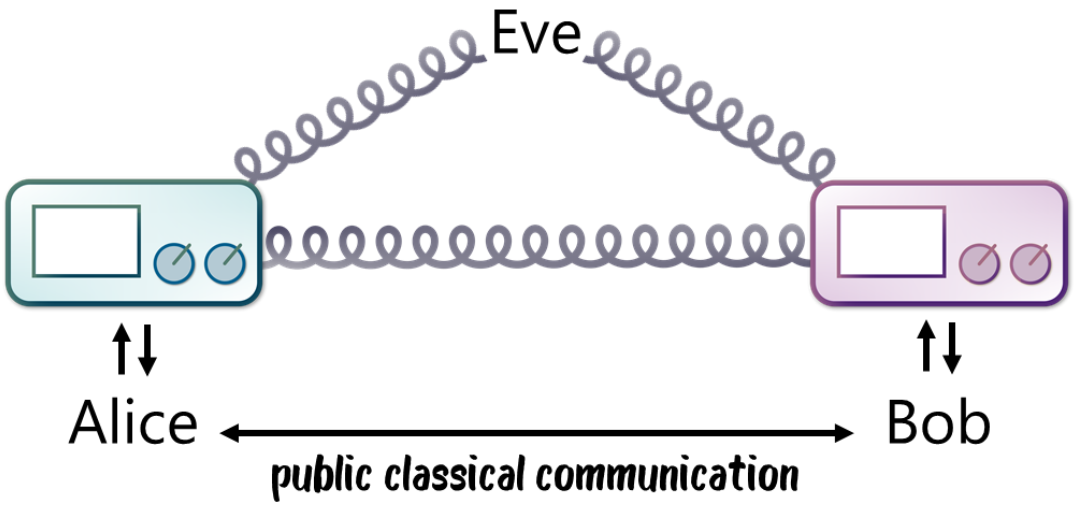
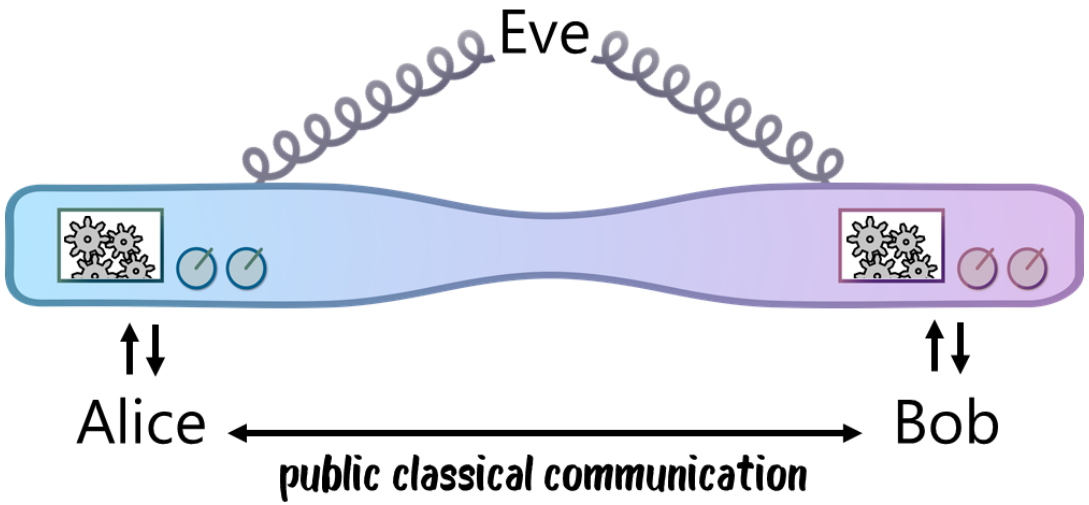




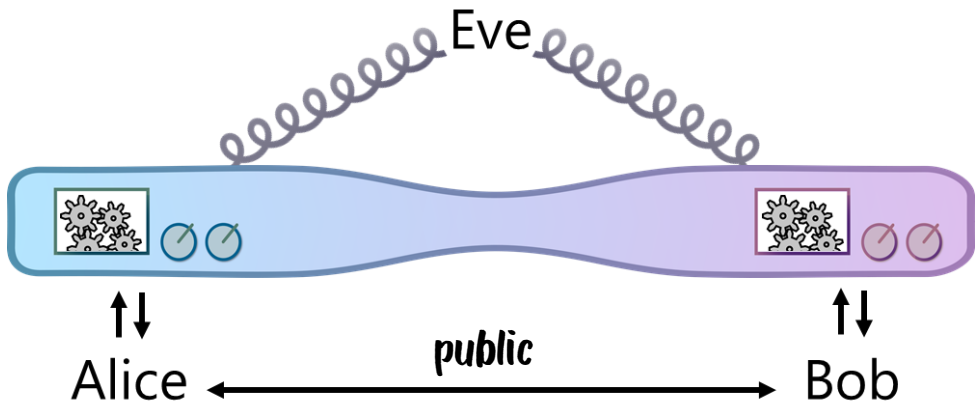
Extra requirement: **honest** devices should be able to succeed in the protocol with pre-shared EPR pairs and local operations

Computational self-testing protocol

Computational self-testing

Classical **interactive protocol** run by Alice and Bob

Device can win or lose



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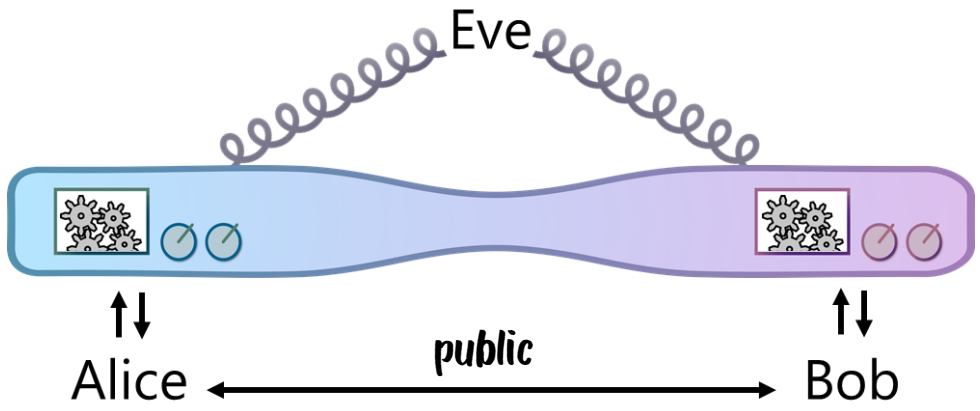

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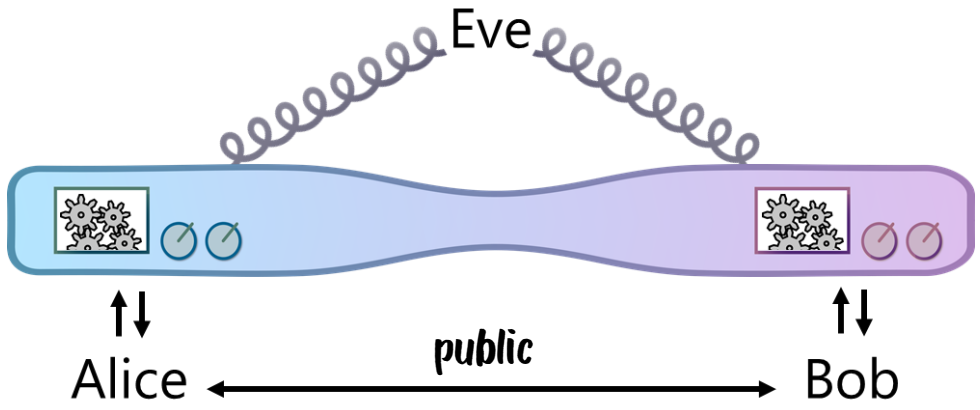

If a **computationally bounded device** wins with probability (close to) 1:

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Computational self-testing

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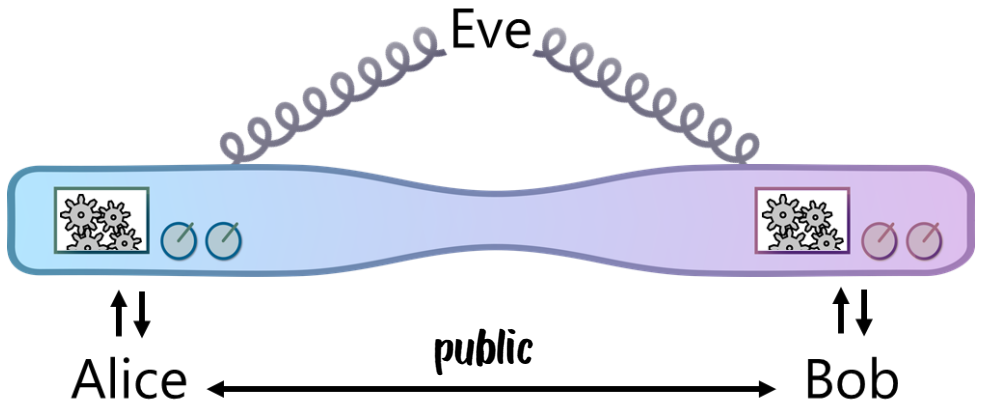

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Computational self-testing

Classical **interactive protocol** run by

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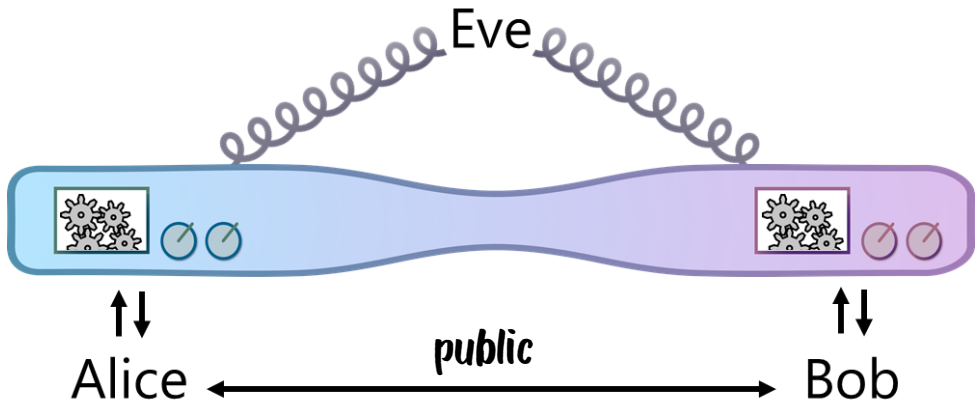
Device can win or lose



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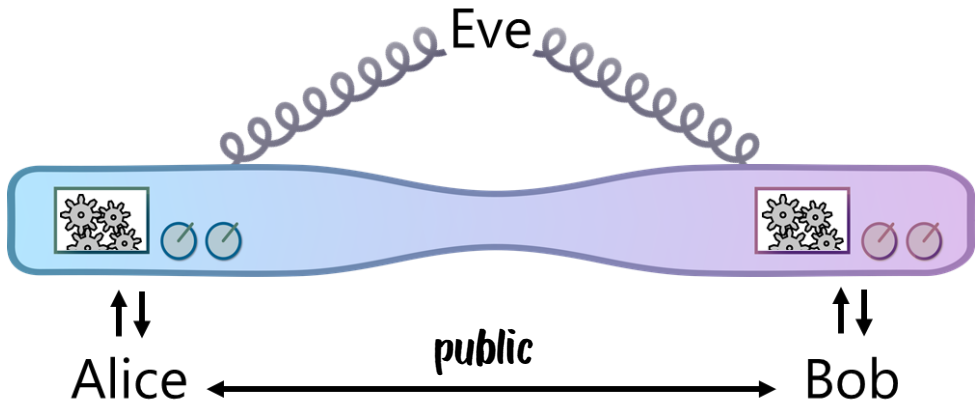

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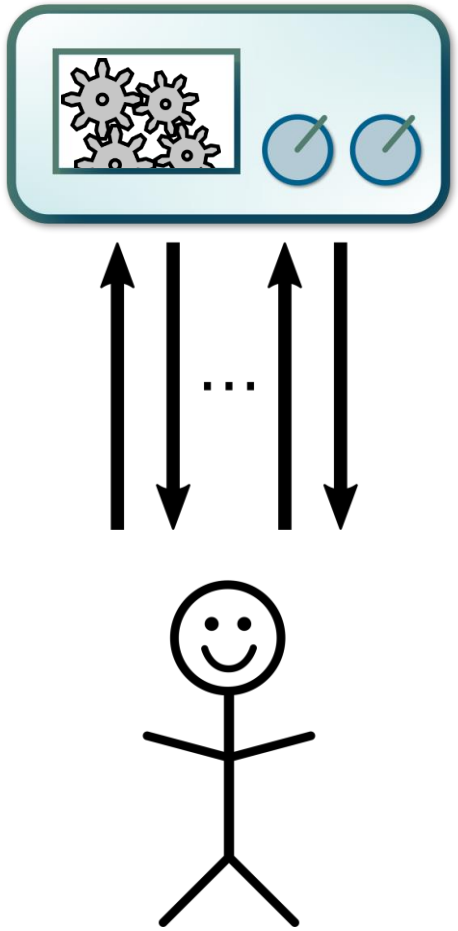
Previous work



- Certifiable information-theoretic randomness expansion (Brakerski et al. 2018)

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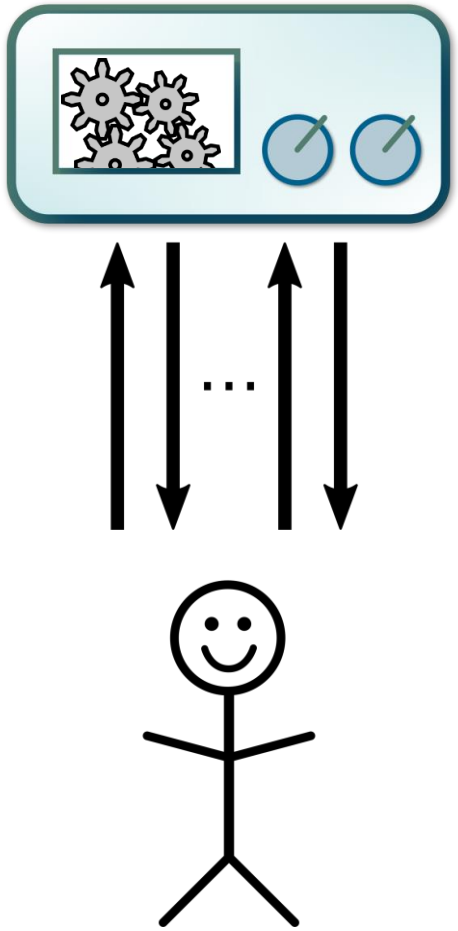

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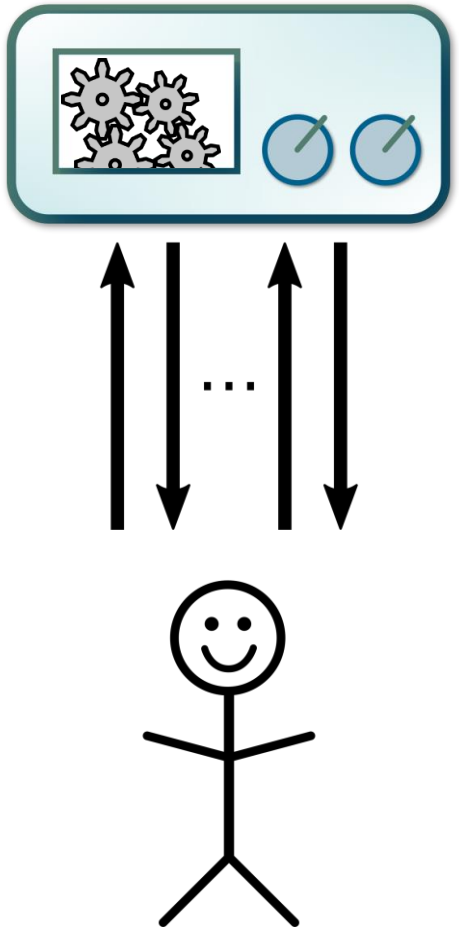

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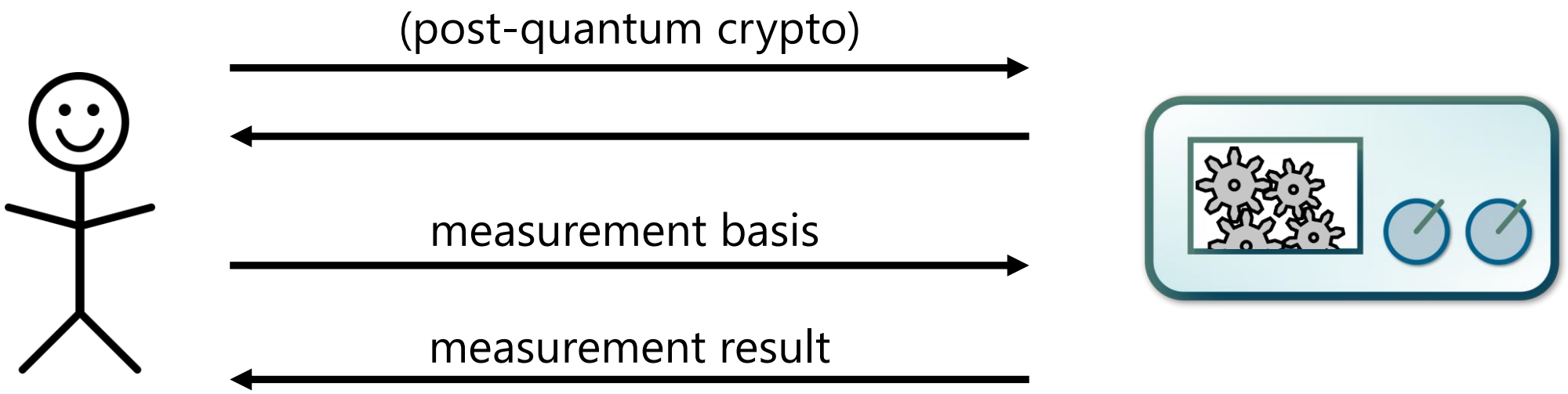
Remote state preparation [GV'19]

Given: set of **single-qubit** states $\{|\psi_i\rangle\} = \{|0\rangle, |1\rangle, |+\rangle, |-\rangle\}$



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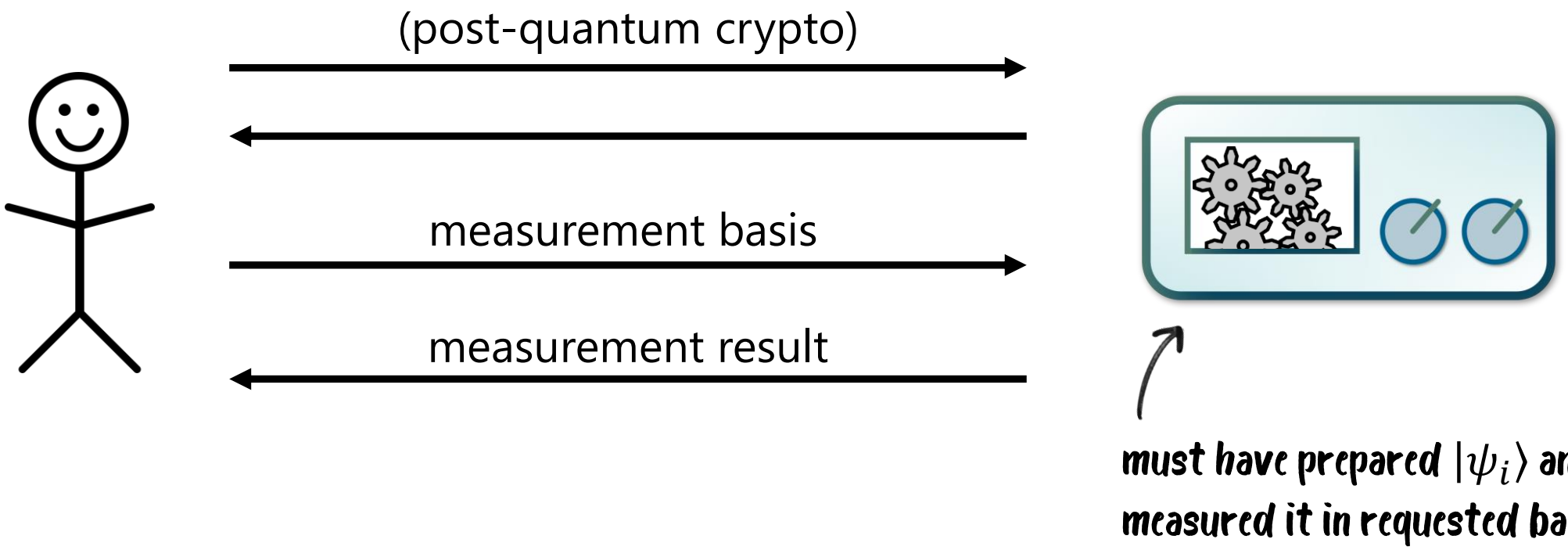

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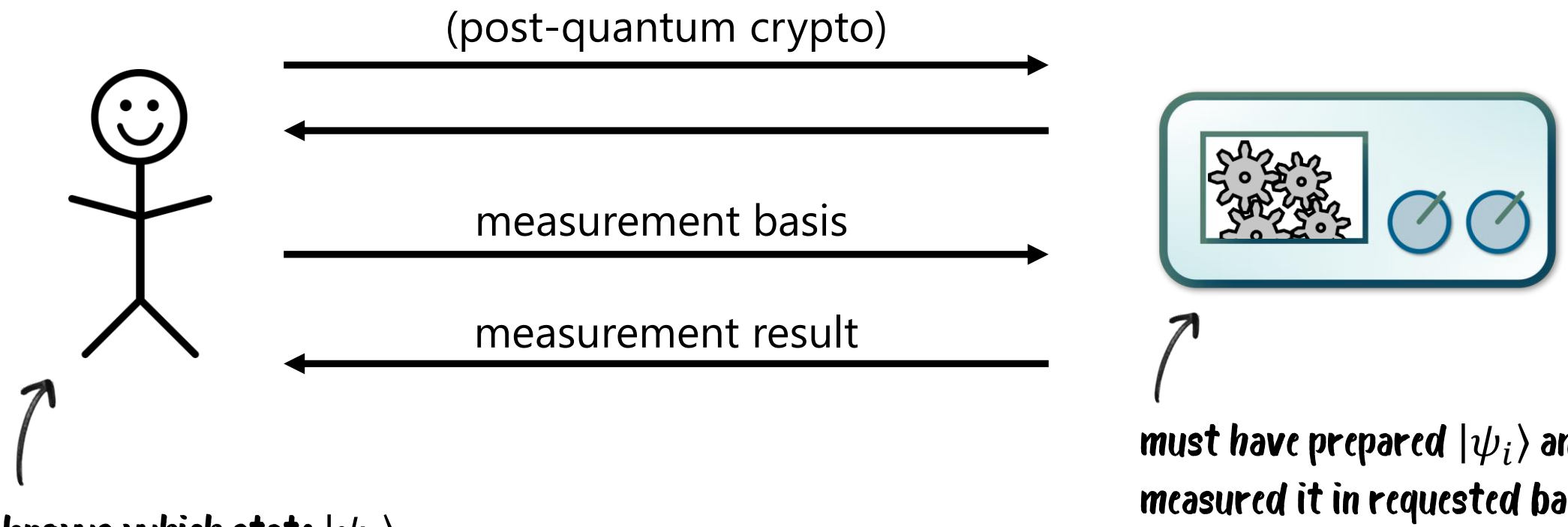

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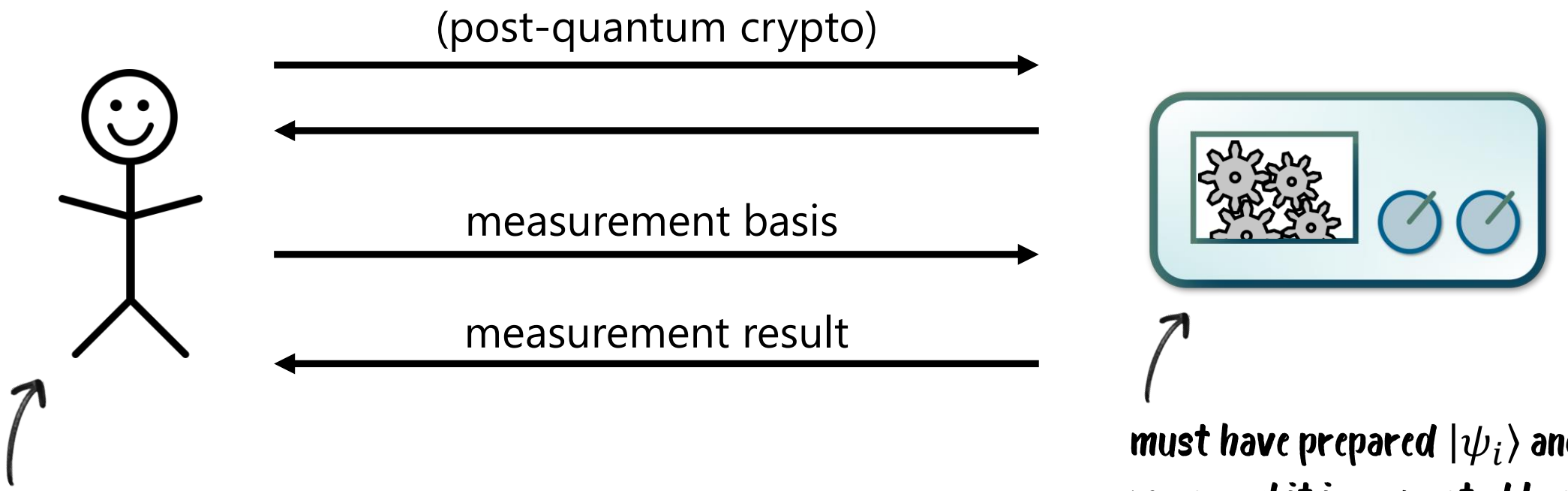

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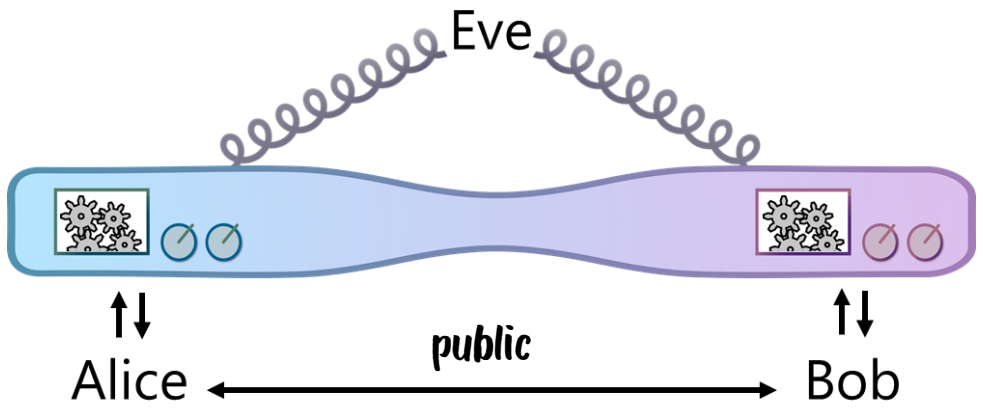
Main challenges for self-testing EPR states

- Device should prepare two qubits and perform single-qubit measurements
  → Alice and Bob need to enforce **tensor product structure** on device's global space



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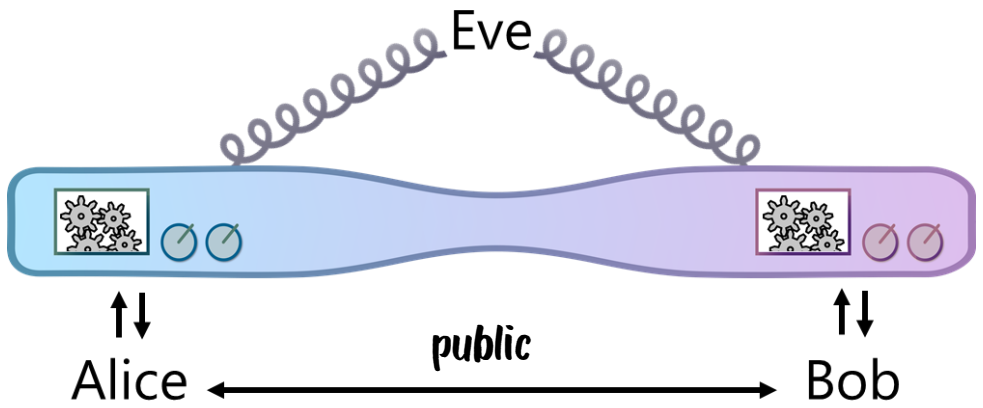

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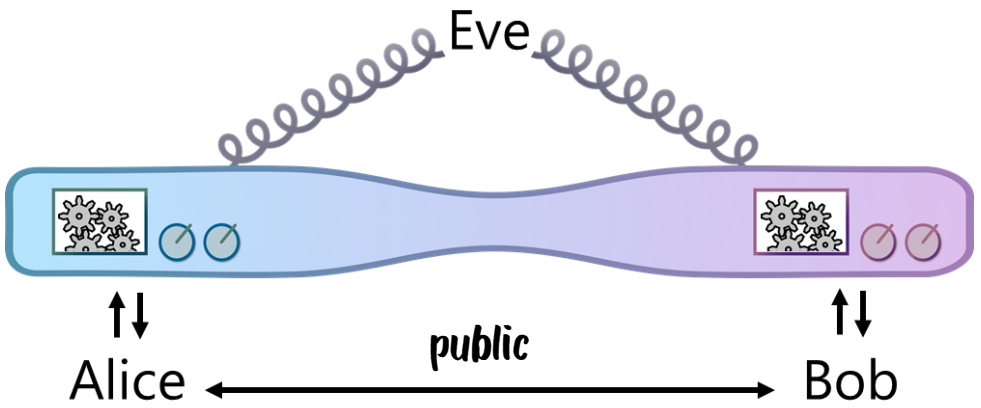
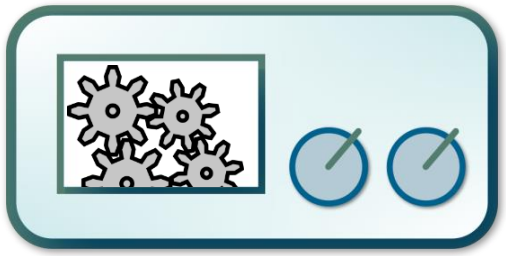


- Device should **entangle** qubits with respect to this tensor product structure
- **Honest** device should only have to use **local operations** and pre-shared EPR pairs

Remote state preparation with two isolated devices

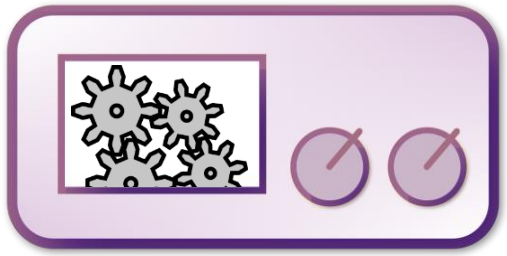
$\{|0\rangle, |1\rangle, |+\rangle, |-\rangle\}$



RSP

Alice

$\{|0\rangle, |1\rangle, |+\rangle, |-\rangle\}$



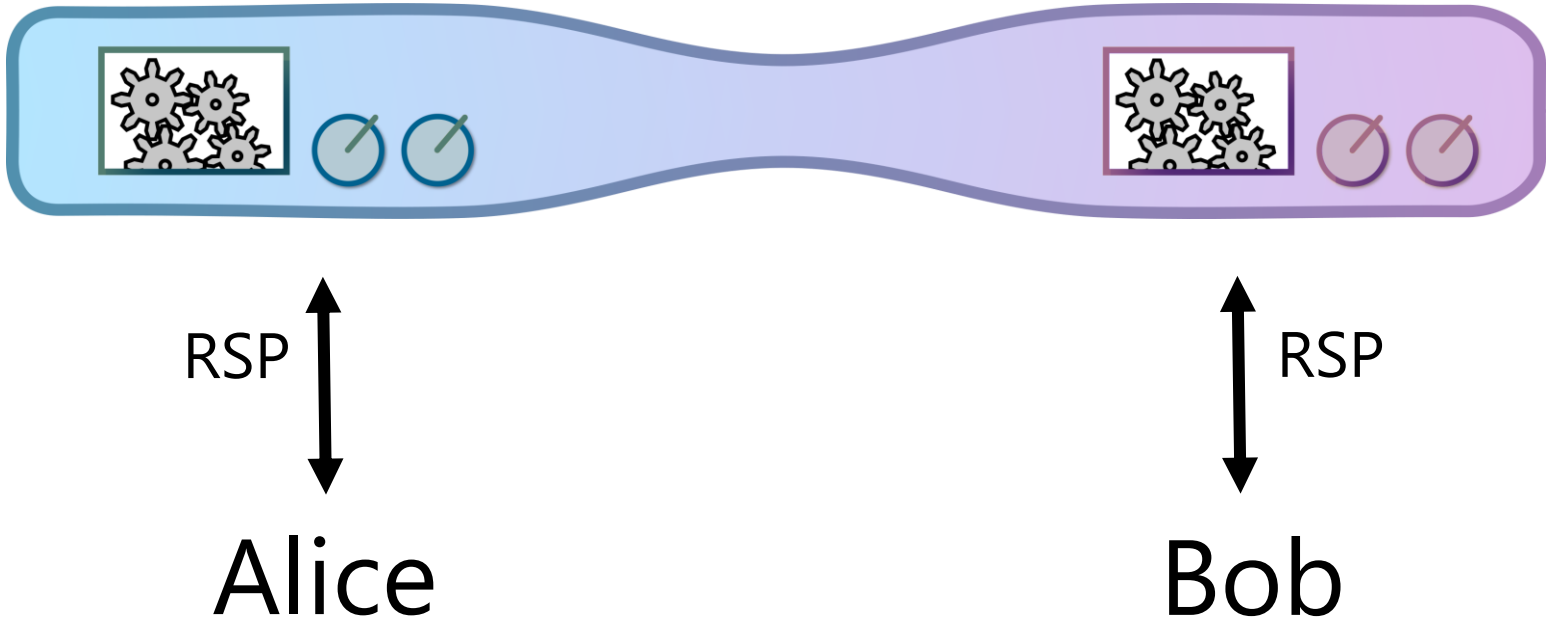
RSP

Bob

Remote State Preparation [GV'19]

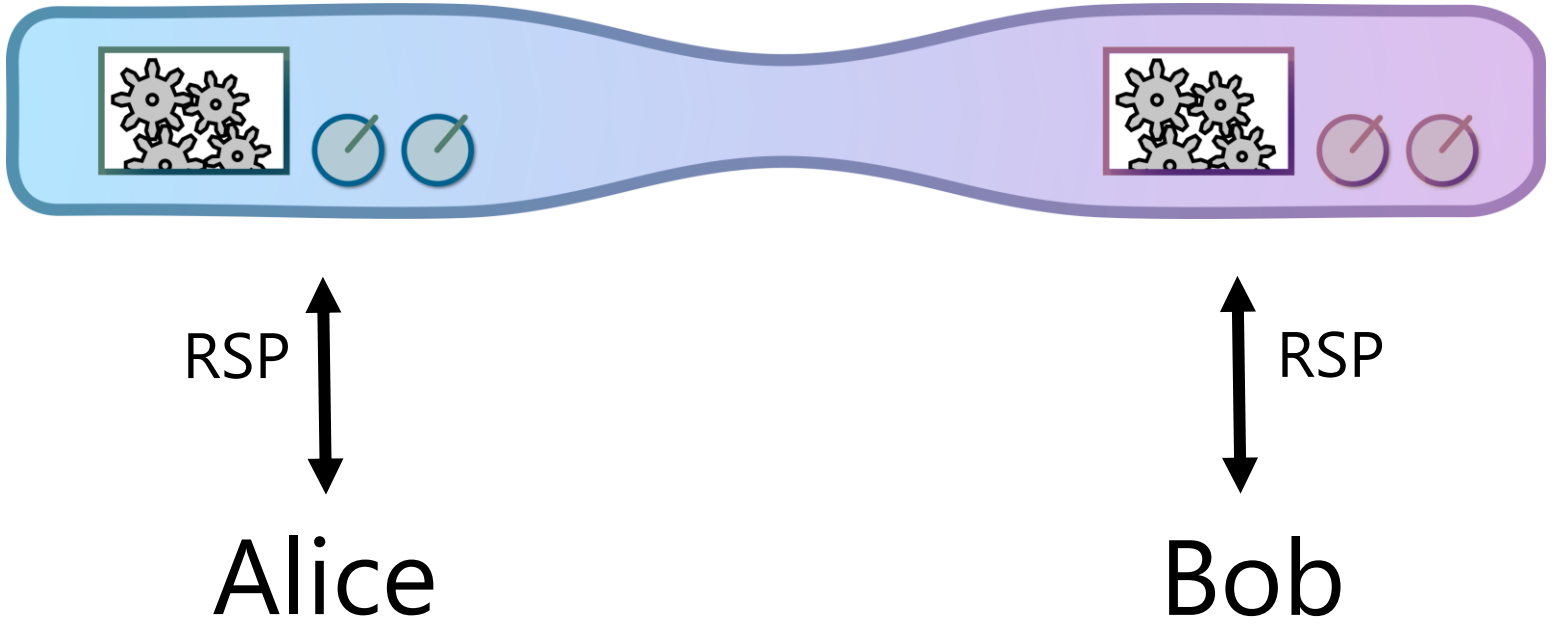
Parallel implementation with single device

$$\{|0\rangle, |1\rangle, |+\rangle, |-\rangle\} \times \{|0\rangle, |1\rangle, |+\rangle, |-\rangle\}$$



$|0/1\rangle|0/1\rangle$
$|0/1\rangle|\pm\rangle$
$|\pm\rangle|\pm\rangle$

$|\pm\rangle|0/1\rangle$



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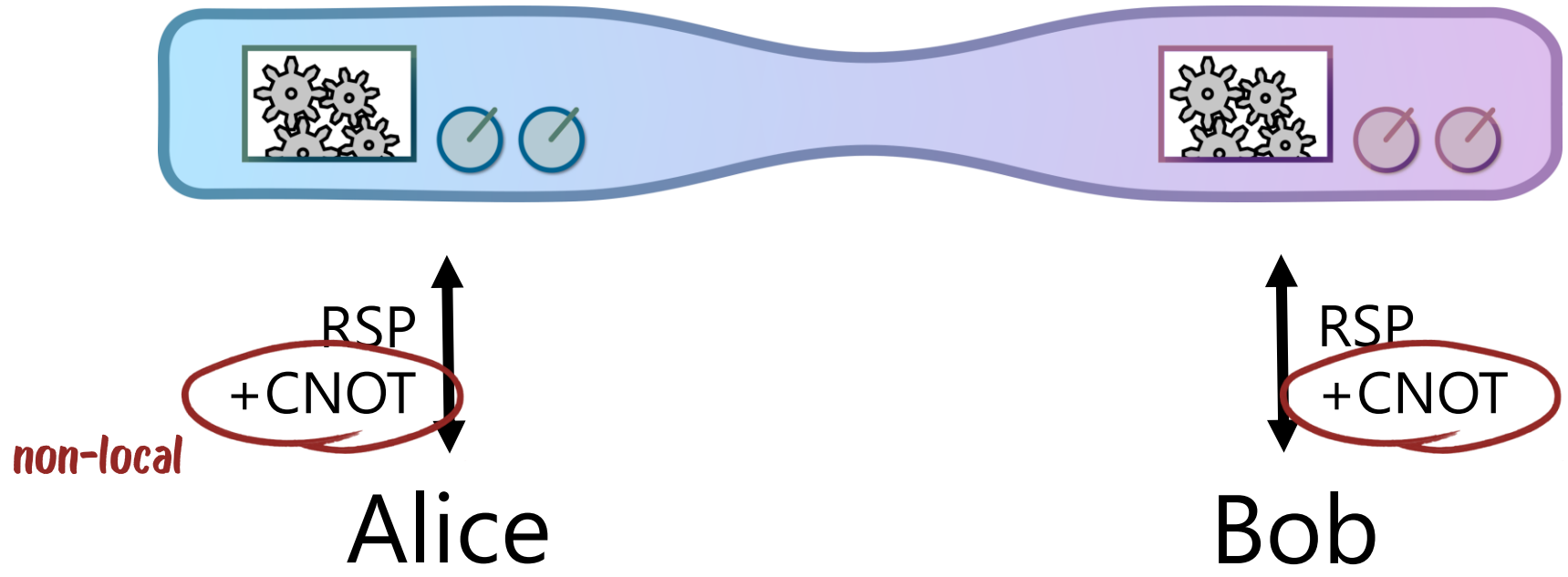
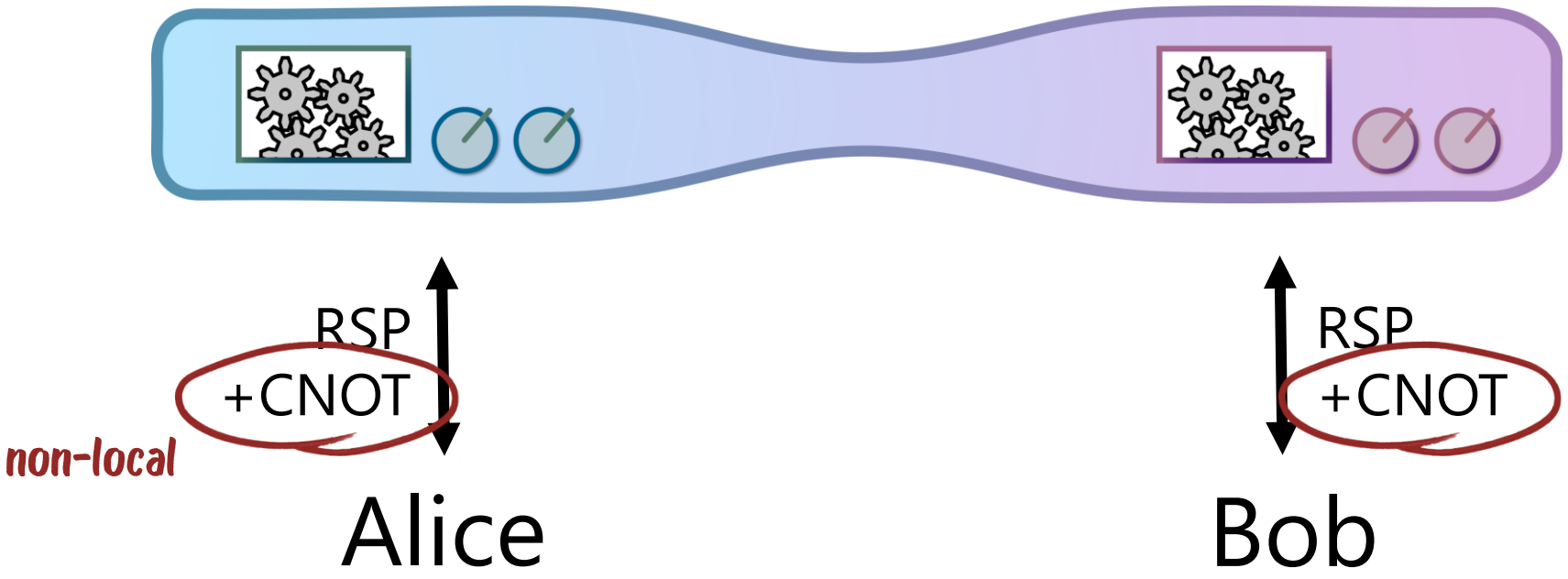


$|0/1\rangle|0/1\rangle$
$|0/1\rangle|\pm\rangle$
$|\pm\rangle|\pm\rangle$

CNOT

$|\pm\rangle|0/1\rangle$



$|0/1\rangle|0/1\rangle$
$|0/1\rangle|\pm\rangle$
$|\pm\rangle|\pm\rangle$

$|\pm\rangle|0/1\rangle$

CNOT

$|0/1\rangle|0/1\rangle$
$|0/1\rangle|\pm\rangle$
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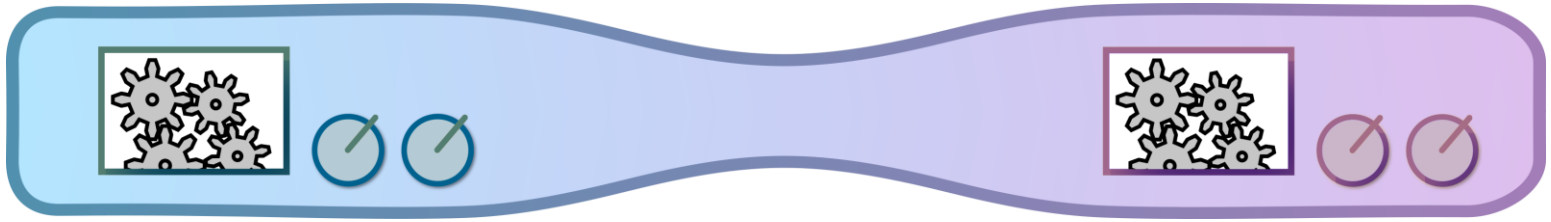


RSP
+CNOT

non-local

RSP
+CNOT

Alice

Bob

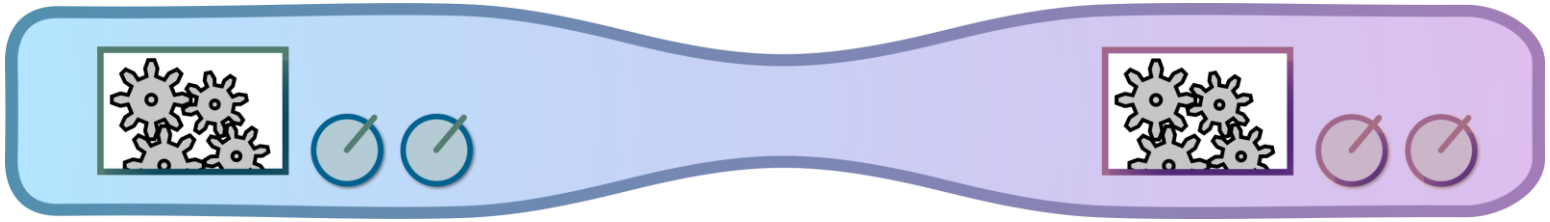
$|0/1\rangle|0/1\rangle$
$|0/1\rangle|\pm\rangle$
$|\pm\rangle|\pm\rangle$

CNOT

$|0/1\rangle|0/1\rangle$
$|0/1\rangle|\pm\rangle$
$|\pm\rangle|\pm\rangle$

$|\pm\rangle|0/1\rangle$

$|00\rangle \pm |11\rangle, |01\rangle \pm |10\rangle$



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$|0/1\rangle|0/1\rangle$
$|0/1\rangle|\pm\rangle$
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CNOT ⟼

$|0/1\rangle|0/1\rangle$
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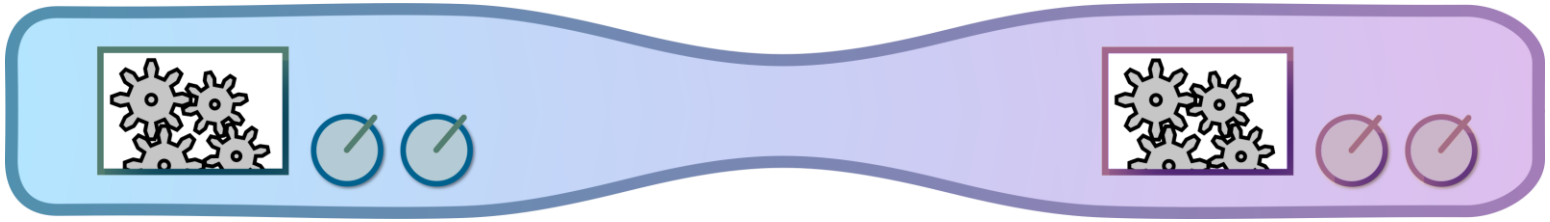

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$|0/1\rangle|0/1\rangle$
$|0/1\rangle|\pm\rangle$
$|\pm\rangle|\pm\rangle$

CNOT

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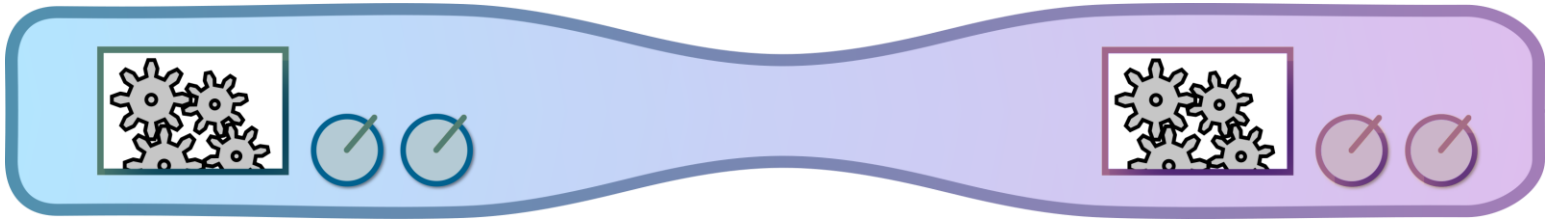
$|0/1\rangle|\pm\rangle$
$|\pm\rangle|\pm\rangle$

Certify **single-qubit** measurements

$|\pm\rangle|0/1\rangle$

$|00\rangle \pm |11\rangle, |01\rangle \pm |10\rangle$



RSP
+CNOT

non-local

RSP
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Alice

Bob

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$|0/1\rangle|\pm\rangle$
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CNOT

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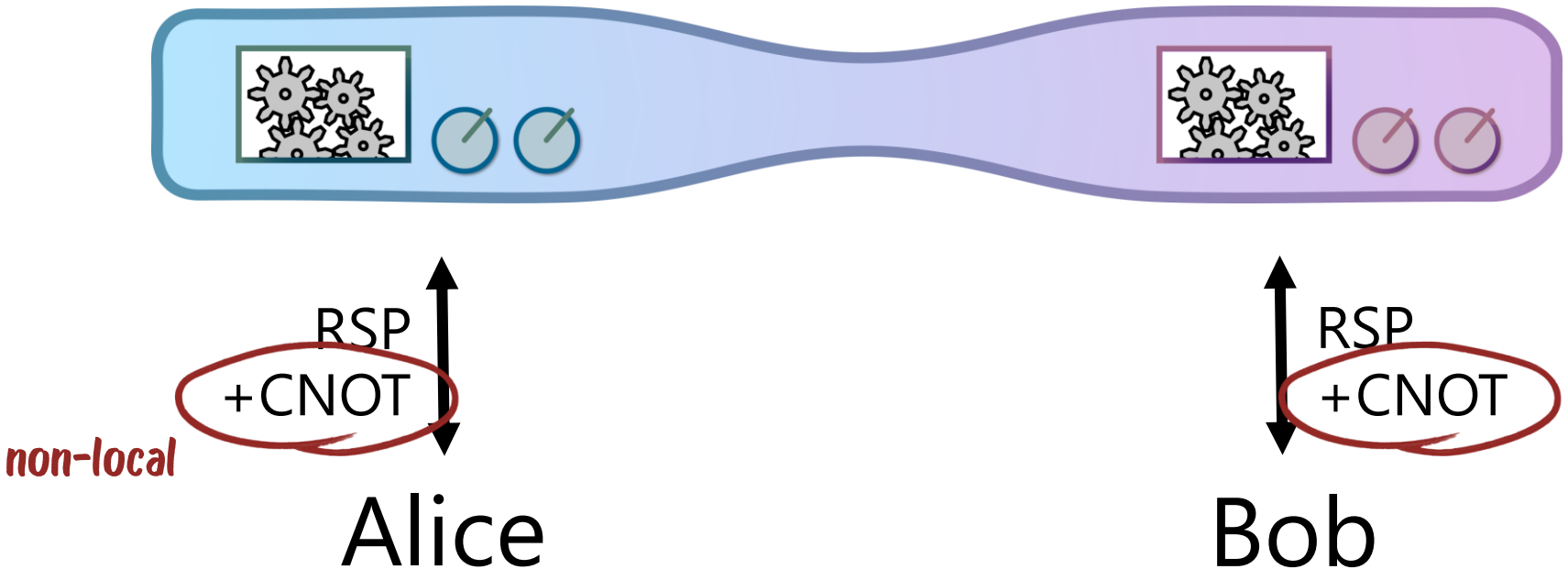
Certify **Bell**-like correlations



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$|\pm\rangle|\pm\rangle$

CNOT

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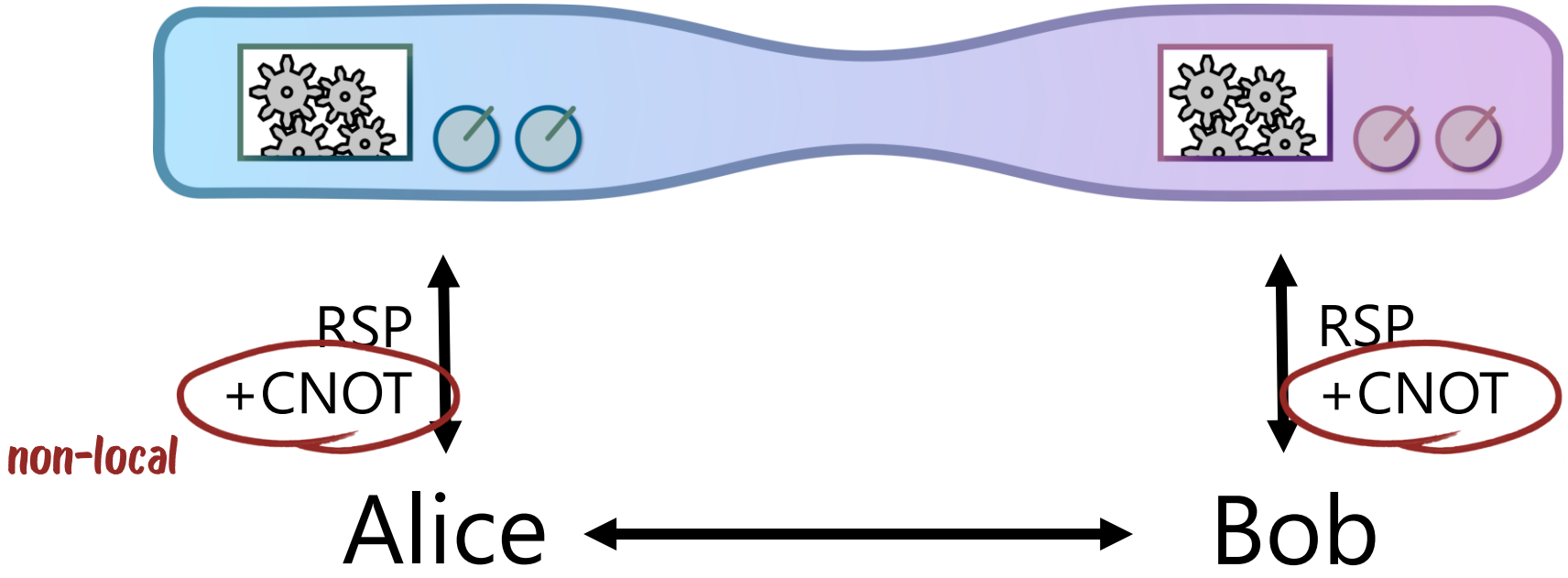

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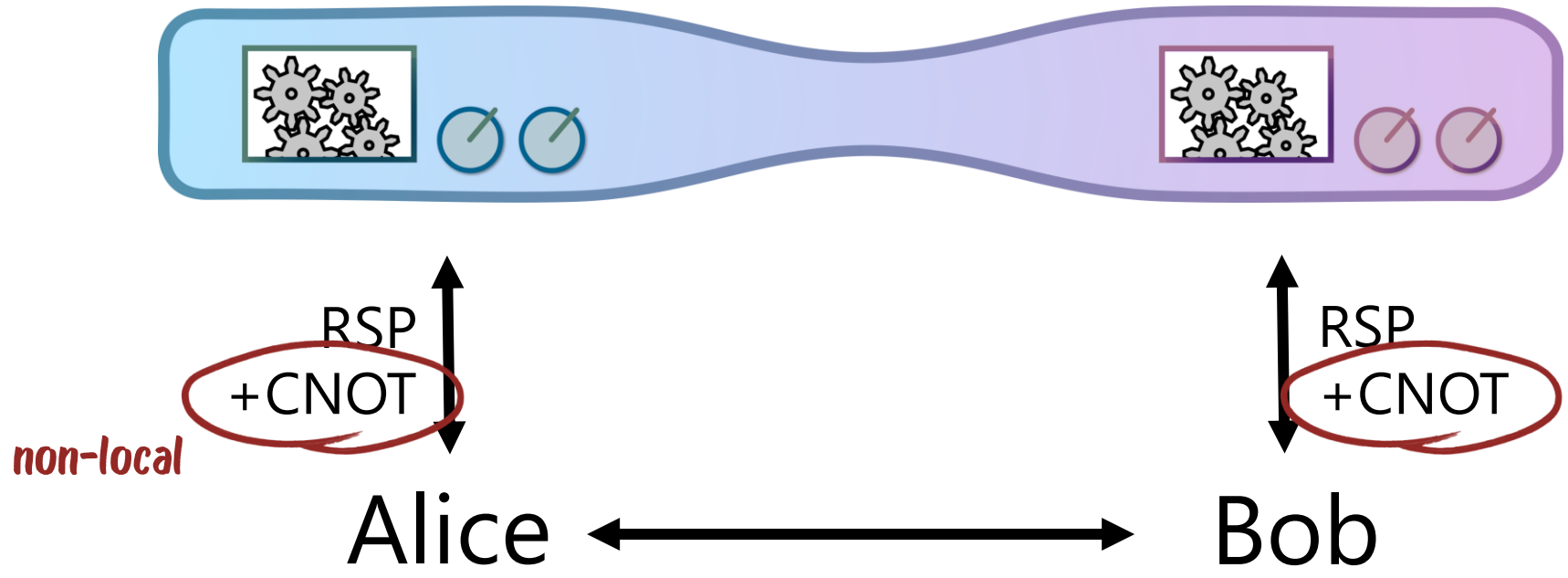

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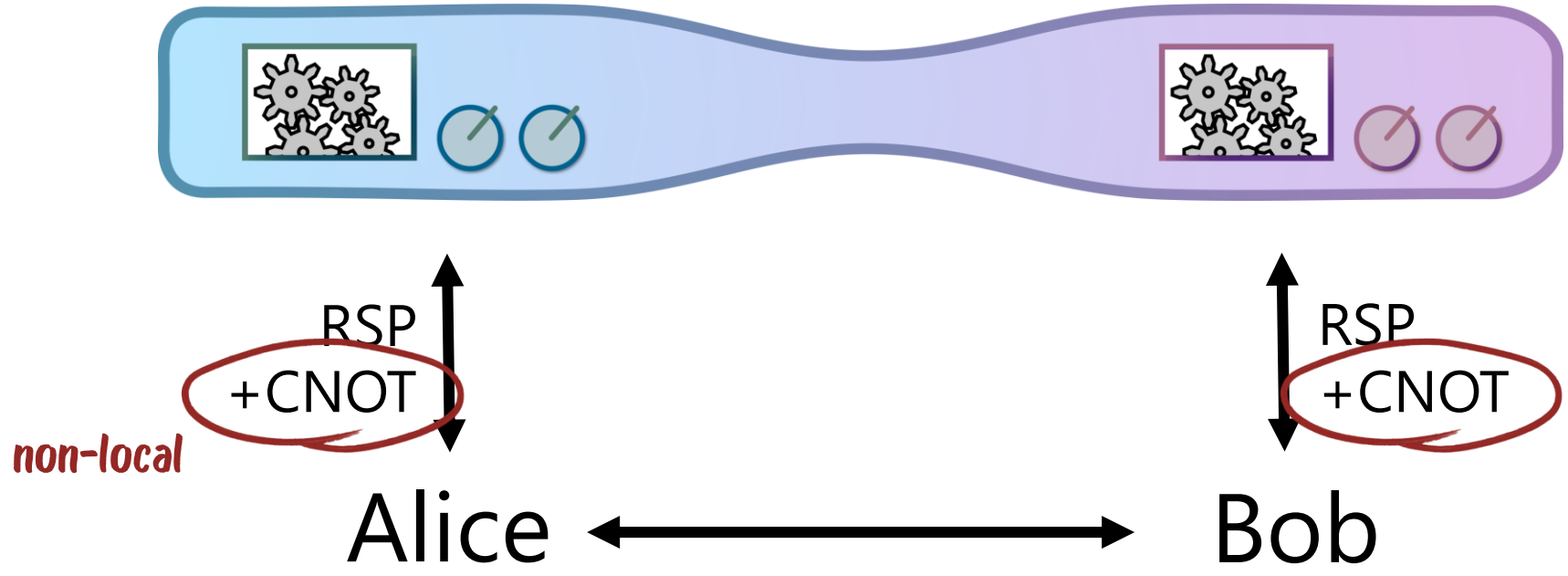
Certify **single-qubit** measurements

Certify **Bell**-like correlations

$\Rightarrow$ Blindness

Certify **single-qubit measurements** on **Bell state**



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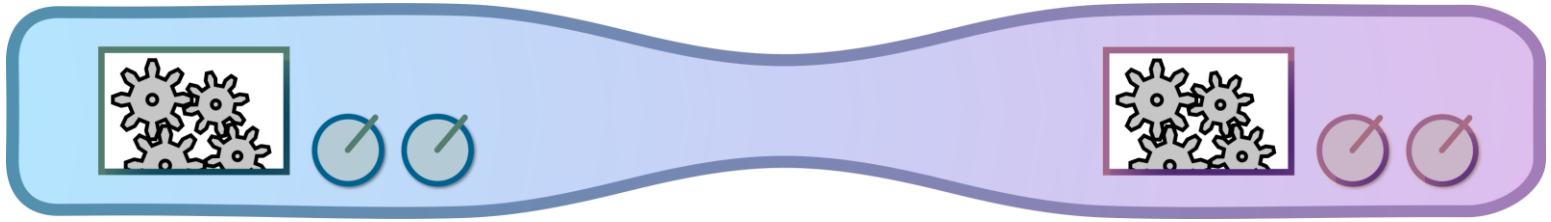

RSP
+gate teleportation

RSP
+gate teleportation

Alice $\longleftrightarrow$ Bob

Honest **local** strategy with pre-shared EPR pairs

- Goal:

$$CNOT|\phi\rangle_{Alice}|\psi\rangle_{Bob}$$

non-local gate

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- With local operations and pre-shared EPR pairs: use gate teleportation

Gottesman & Chuang, Quantum Teleportation is a Universal Computational Primitive. Nature. 402: 390–393

Honest **local** strategy with pre-shared EPR pairs

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non-local gate

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$$|\phi\rangle_{Alice}|\psi\rangle_{Bob}|EPR\rangle_{AB}$$

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↓ Local measurements with measurement results $a, b \in \{0,1\}$

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Local measurements with measurement results $a, b \in \{0,1\}$

$$(\sigma_Z^a \sigma_X^b \otimes \sigma_Z^b \sigma_X^a) CNOT|\phi\rangle_{Alice}|\psi\rangle_{Bob}$$

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Local measurements with measurement results $a, b \in \{0,1\}$

send a to Alice, b to Bob

Alice and Bob adapt checks to account for correction operator

$$(\sigma_Z^a \sigma_X^b \otimes \sigma_Z^b \sigma_X^a) CNOT|\phi\rangle_{Alice}|\psi\rangle_{Bob}$$

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Summary

T. Metger and T. Vidick, Self-testing of a single quantum device under computational assumptions, arXiv:2001.09161
T. Metger, Y. Dulek, A. Coladangelo, and R. Arnon-Friedman, Device-independent quantum key distribution from computational assumptions, arXiv:2010.04175

Summary

- Main result: self-testing and DIQKD protocols that don't rely on Bell inequalities
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Future work

- Self-test arbitrary states
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- Computational DIQKD without self-testing
- Other applications of cryptographic leash

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