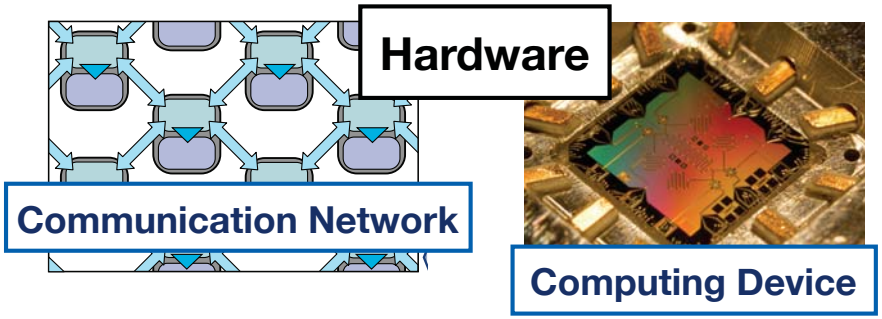
Verification of Quantum Computing

Elham Kashefi

University of Edinburgh
Oxford Quantum Technology Hub
Paris Centre for Quantum Computing
Laboratoire traitement et communication de l'information

Our Vision of Quantum Technology

Our Vision of Quantum Technology



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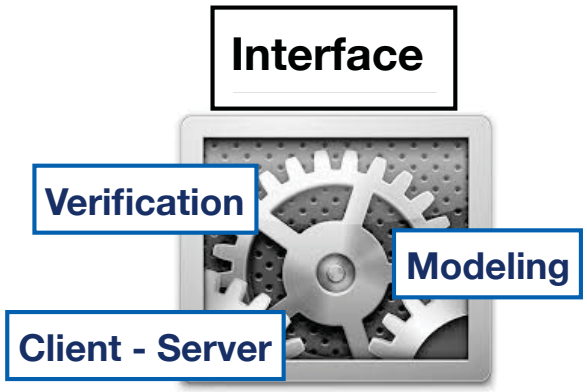

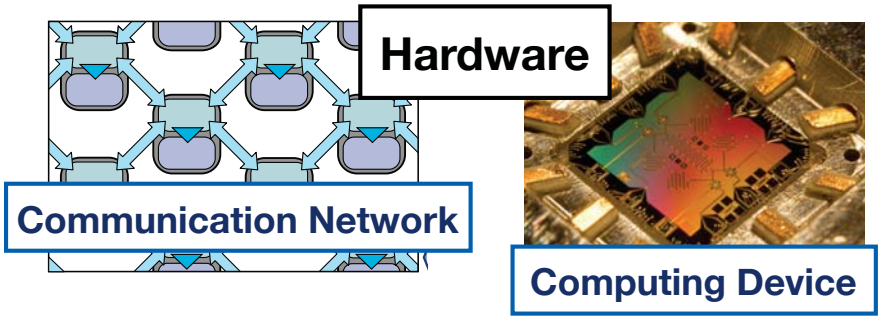

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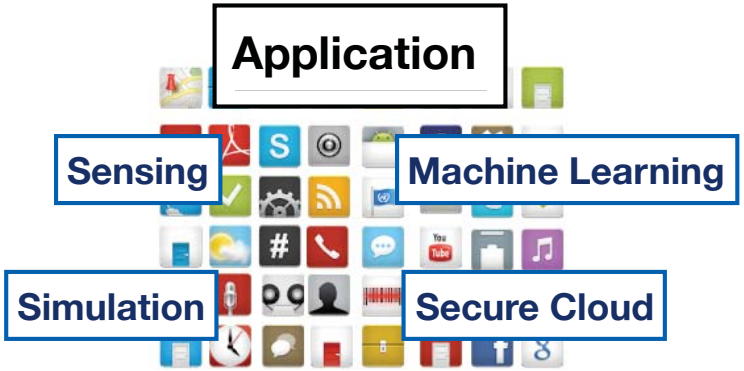

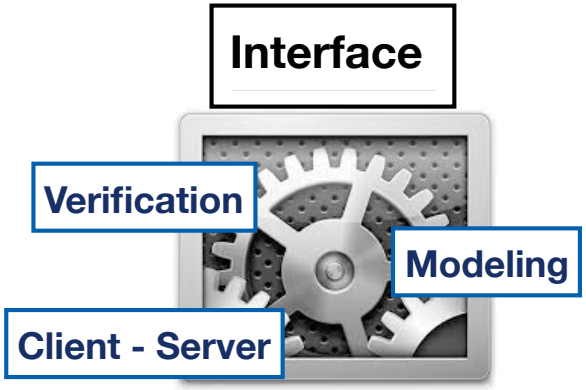

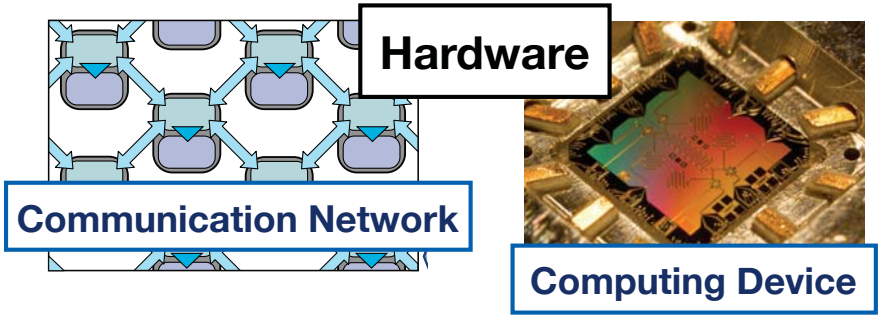

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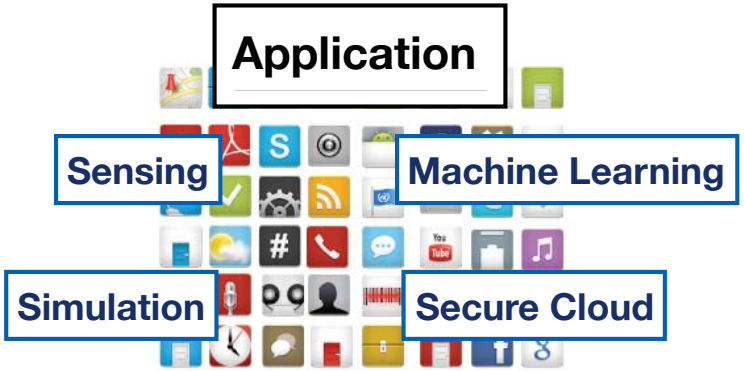

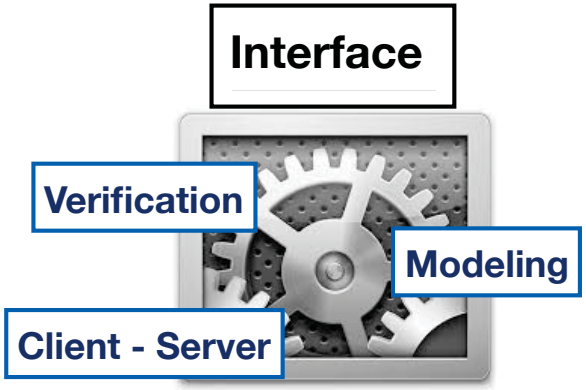

EK *et.al.* *Measurement Calculus*
ICALP 2006, J. ACM 2007
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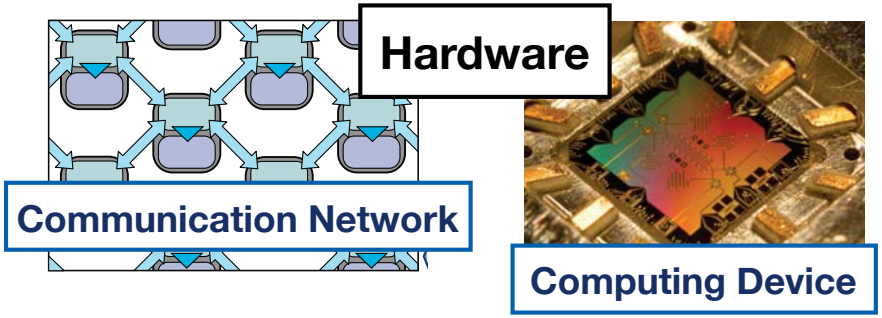

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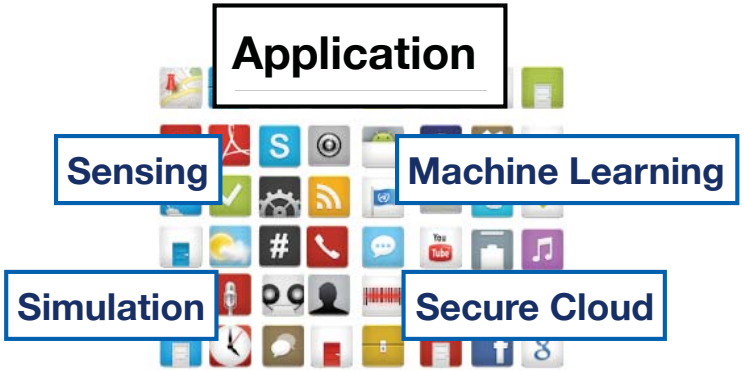

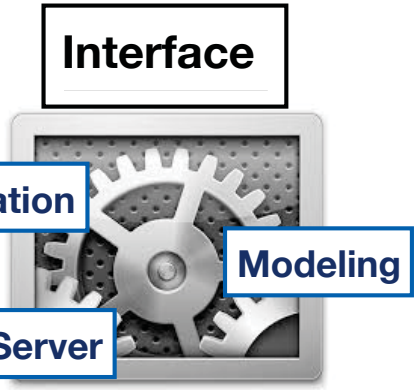

***EK** et.al. Verification*
New J. Phys. 2015, Qcrypt, 2015

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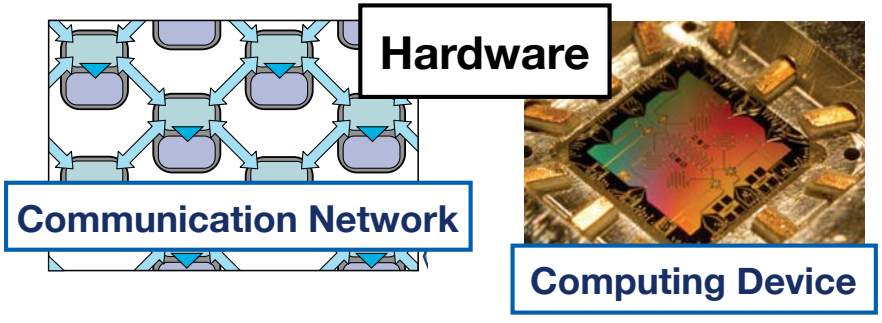
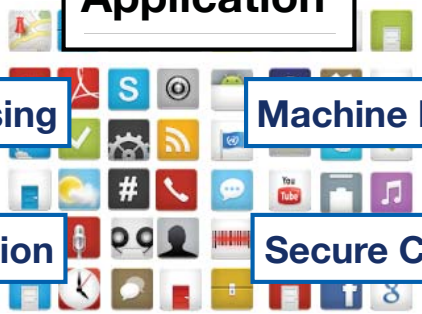


Our Vision of Quantum Technology

Application



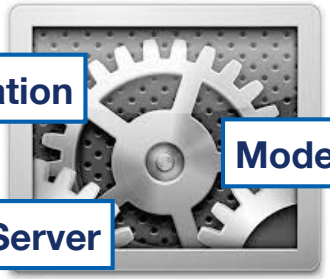
Sensing

Machine Learning

Simulation

Secure Cloud

Interface



Verification

Modeling

Client - Server

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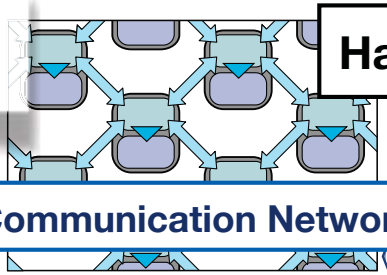
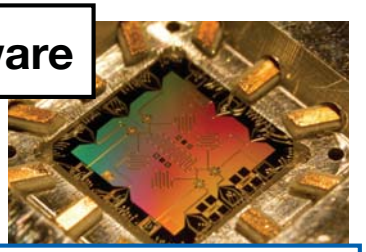
Hardware



Communication Network



Computing Device

***EK** et.al. Verification Experiment*
Nature Physics 13

***EK** et.al. Blind QC Experiment*
Science 12

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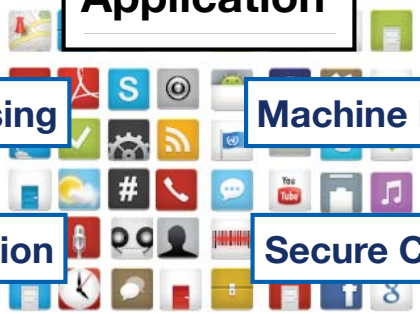

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***EK** et.al. Quantum-enhanced Cloud*
J. QIC 2015, Phys. Rev. A 2016, Patent

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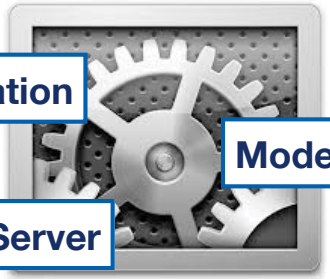

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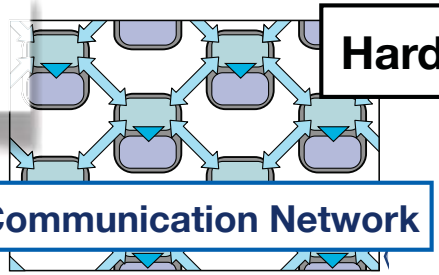

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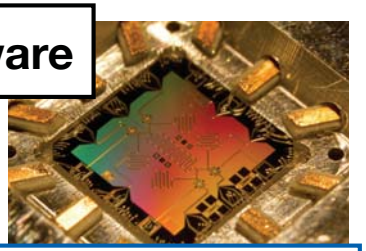

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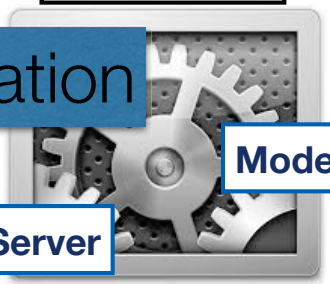

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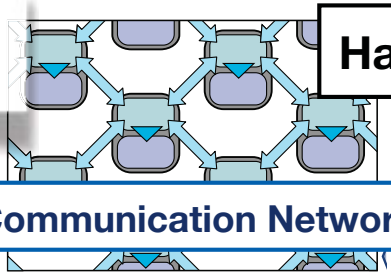

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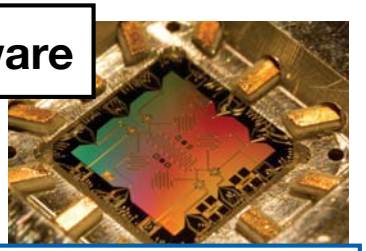


Computing Device

EK et.al. Blind QC Experiment
Science 12

Quantum Era

National Investments

Europe 1bn€
UK 270M £
Netherlands 80M $
US, Singapore,Canada

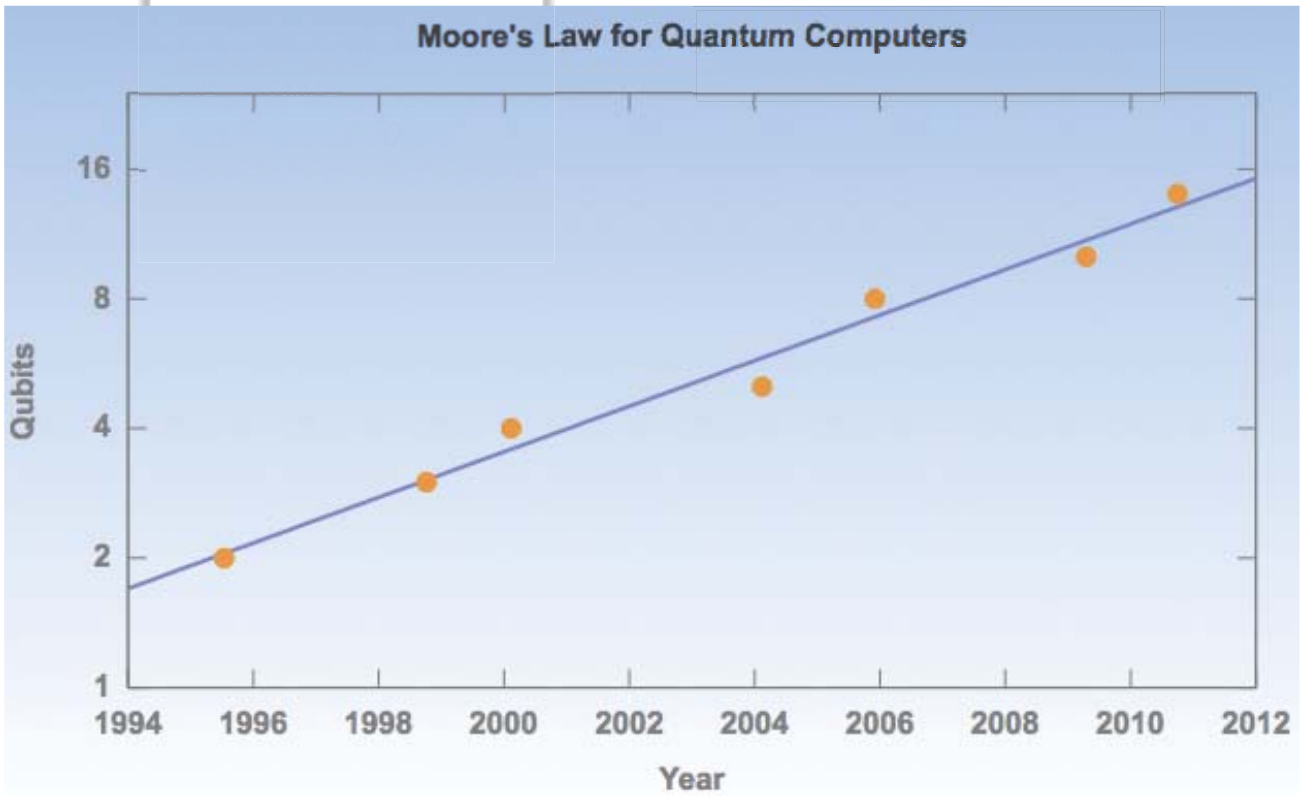
Quantum Machines

Private Investments

Google, IBM, Intel
Big VC founds
Startups Companies: D-Wave

Quantum Era

National Investments



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Quantum Era

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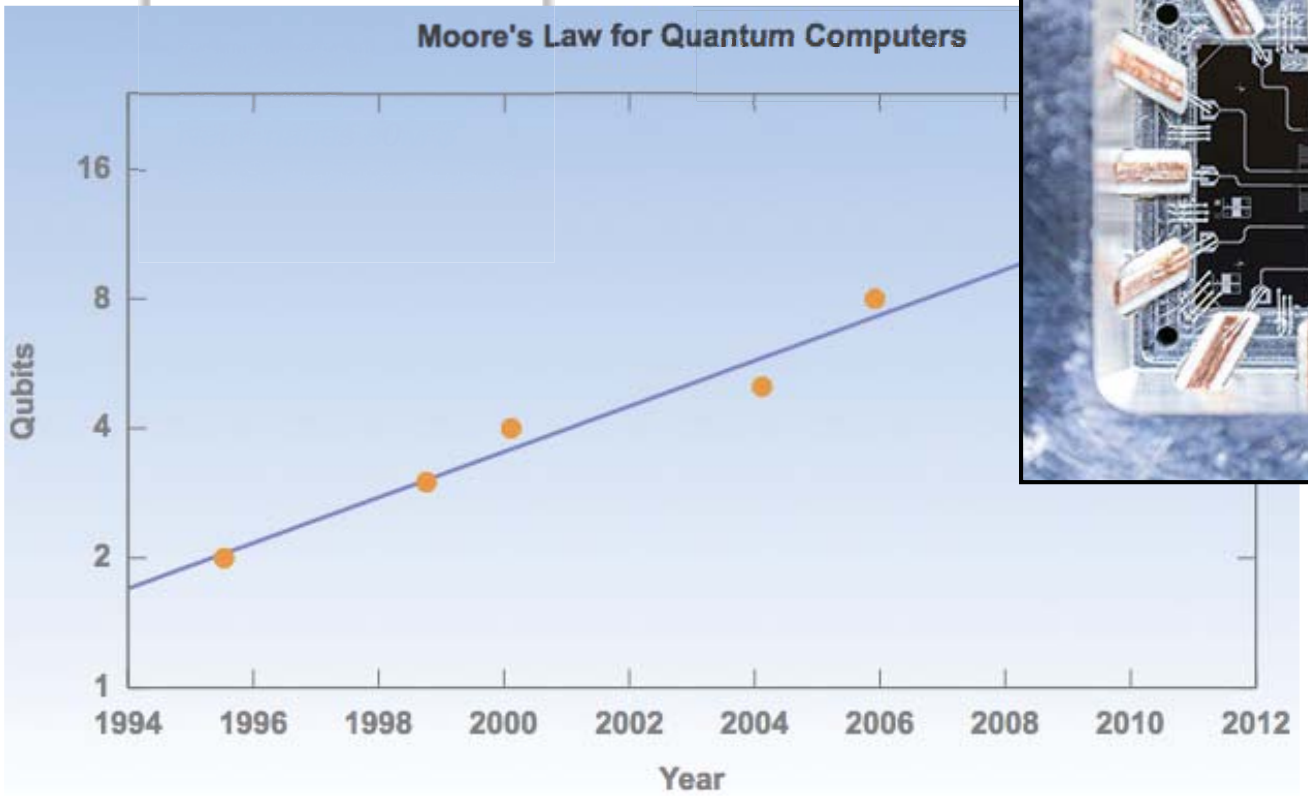
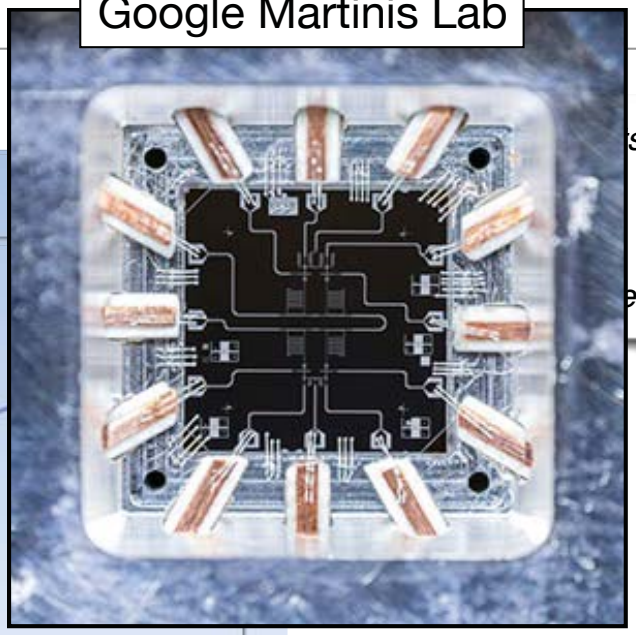


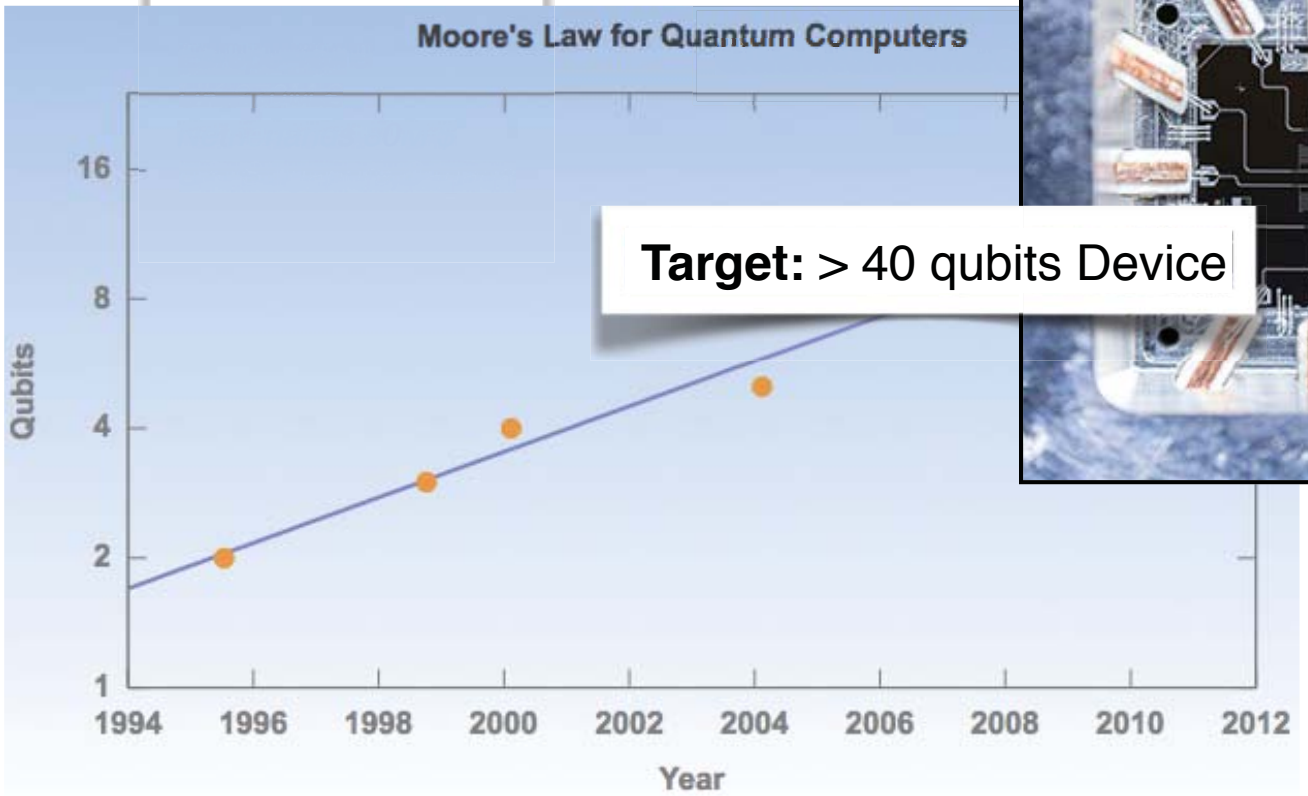
Google Martinis Lab



es: D-Wave

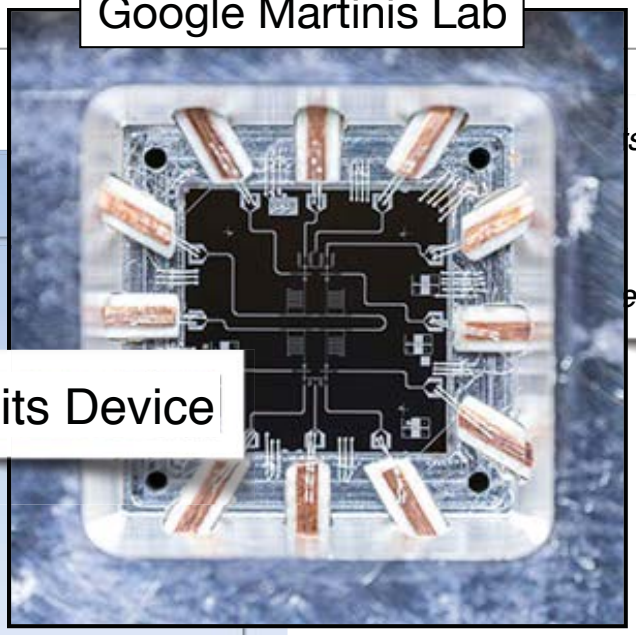
Quantum Era

National Investments



Target: > 40 qubits Device

Google Martinis Lab



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Quantum Era

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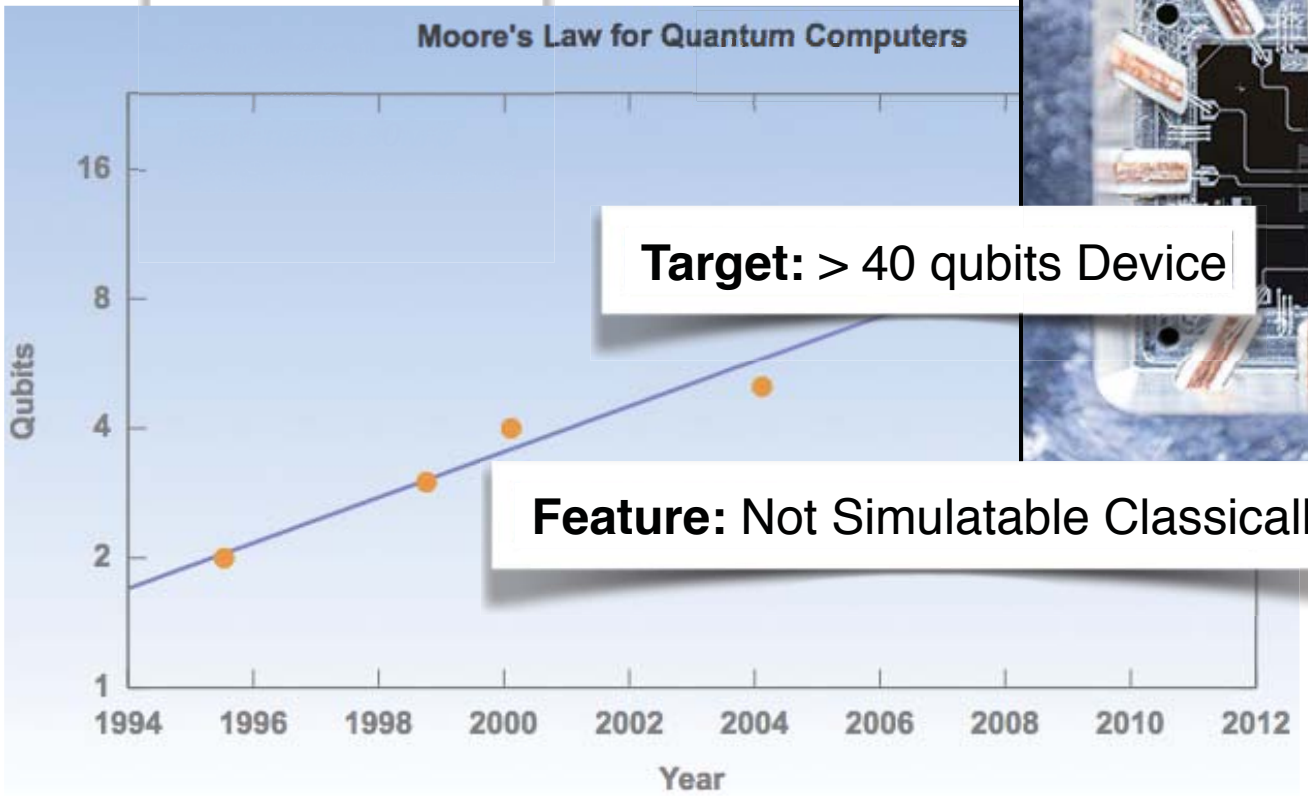

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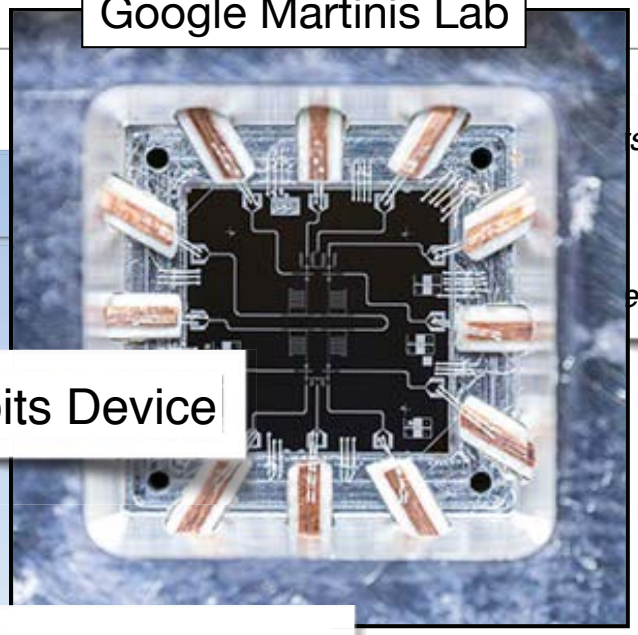


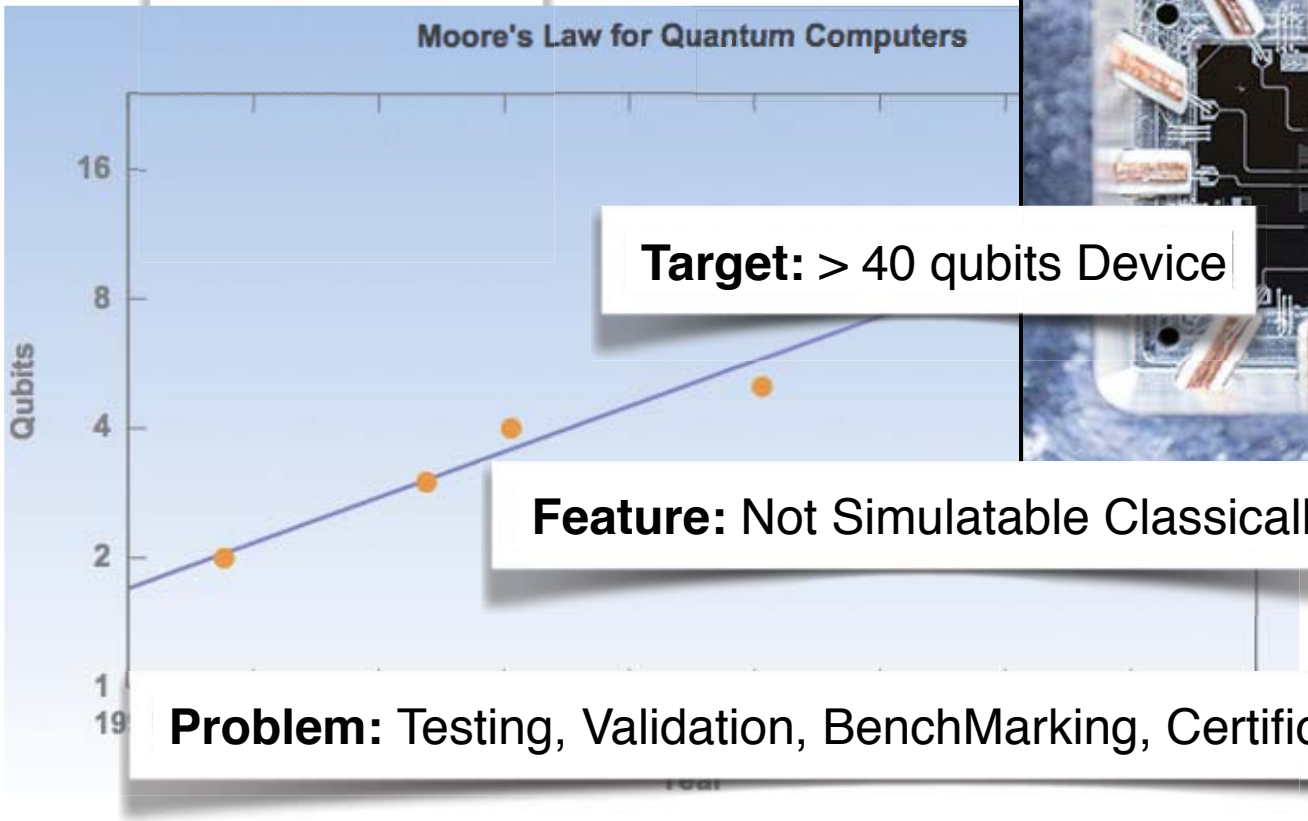
es: D-Wave

Target: > 40 qubits Device

Feature: Not Simulatable Classically

Quantum Era

National Investments



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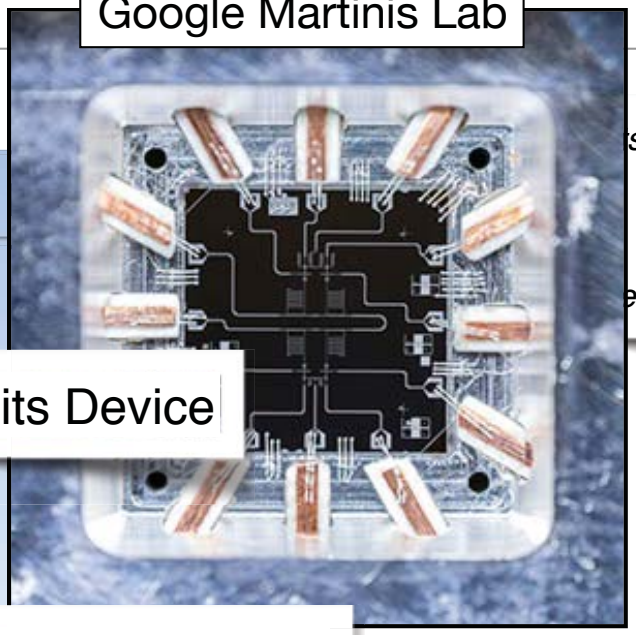

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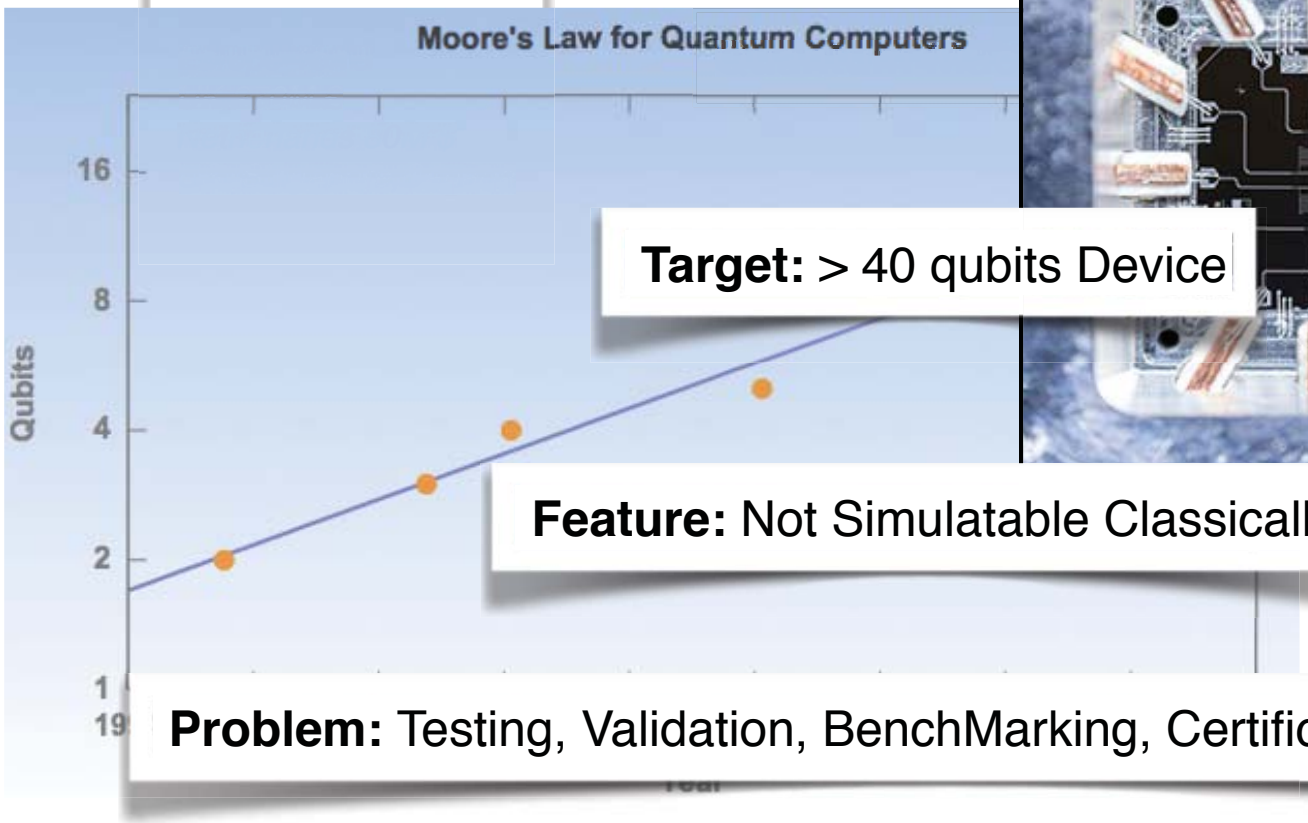
Problem: Testing, Validation, BenchMarking, Certification, Verification …

Quantum Era

National Investments



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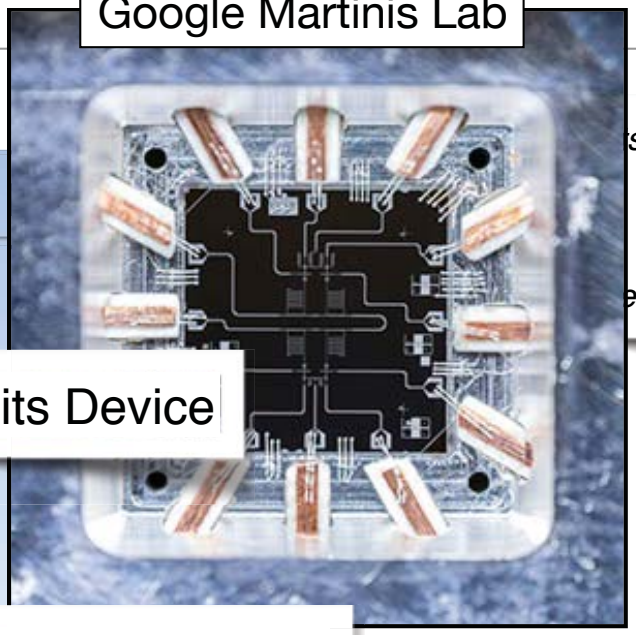

es: D-Wave

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Feature: Not Simulatable Classically

Problem: Testing, Validation, BenchMarking, Certification, Verification …

Do we need another quantum computer to testing a quantum computer or
can we bootstrap a mini quantum device to test a bigger one

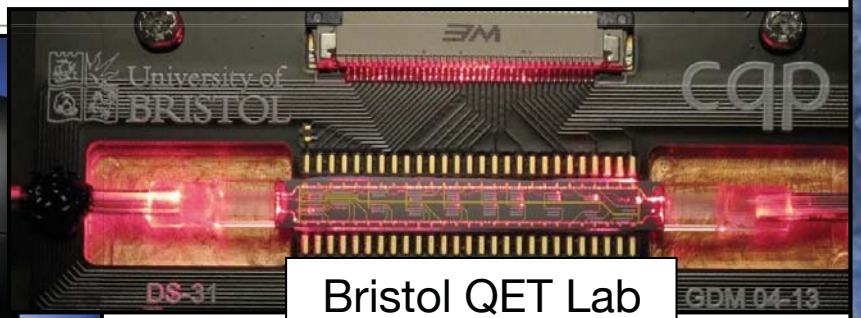
Question

Quantum Machines Era

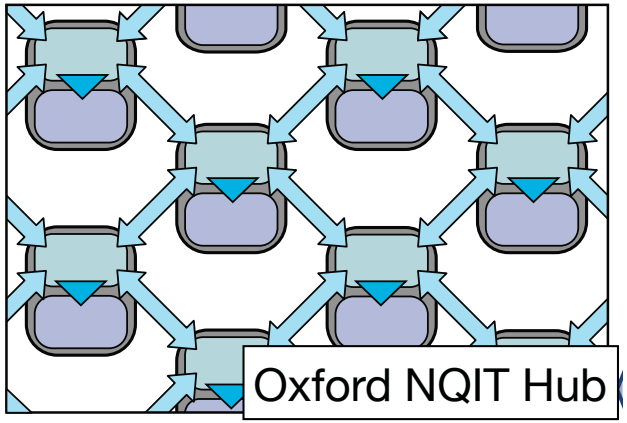
Question

Question

Lockheed Martin/NASA/Google
Artificial Intelligence lab



Bristol QET Lab



Oxford NQIT Hub

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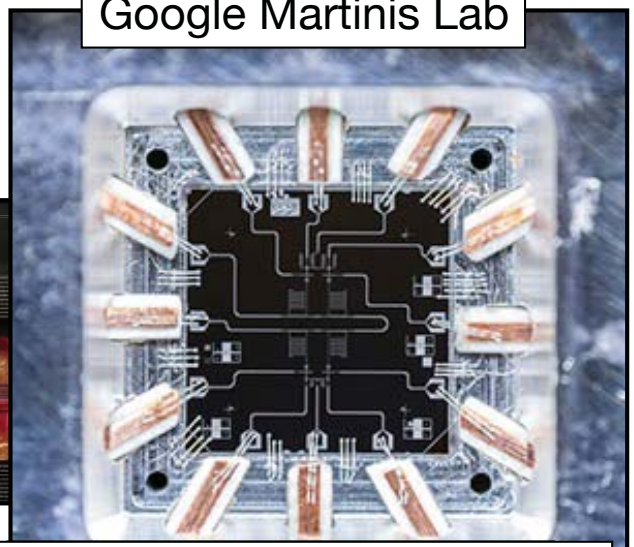

TU Delft Quantum Tech Lab

Question

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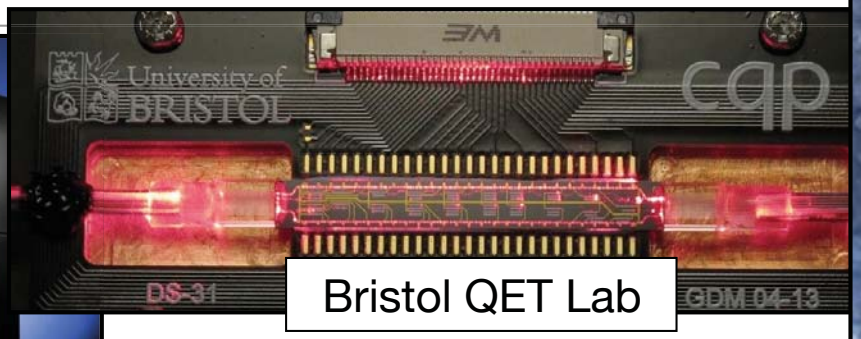

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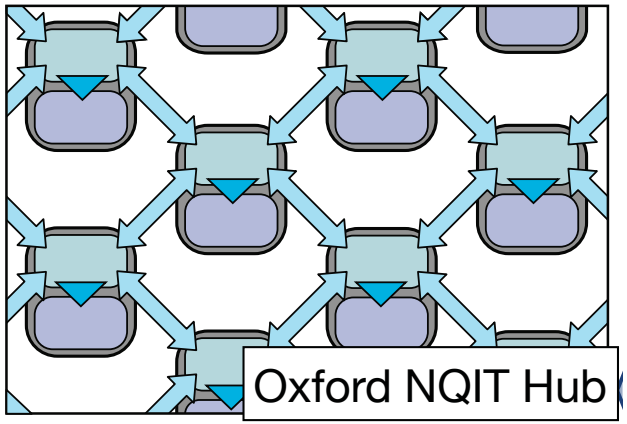

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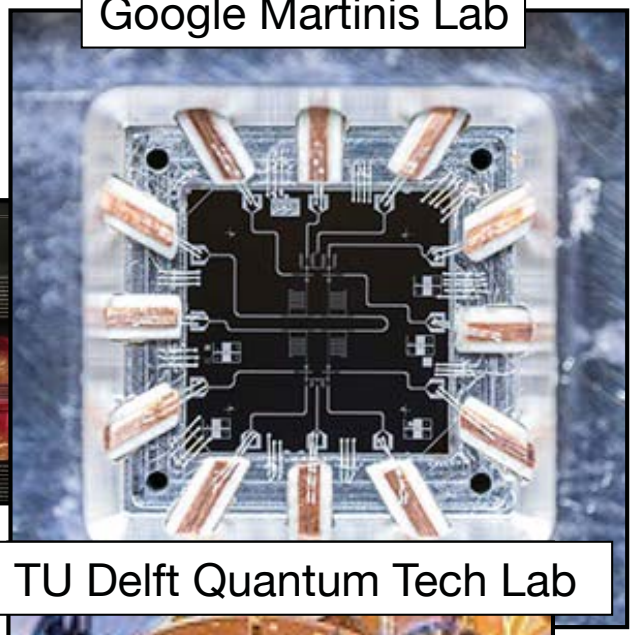

Google Martinis Lab

TU Delft Quantum Tech Lab

These devices become **relevant** at the moment they are no longer classically simulatable

Question

Lockheed Martin/NASA/Google
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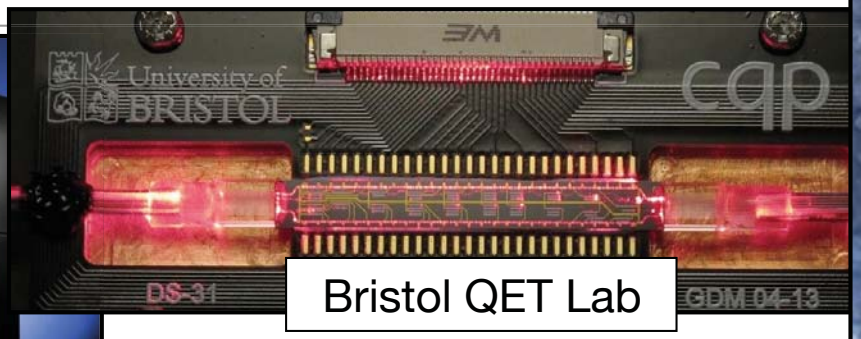

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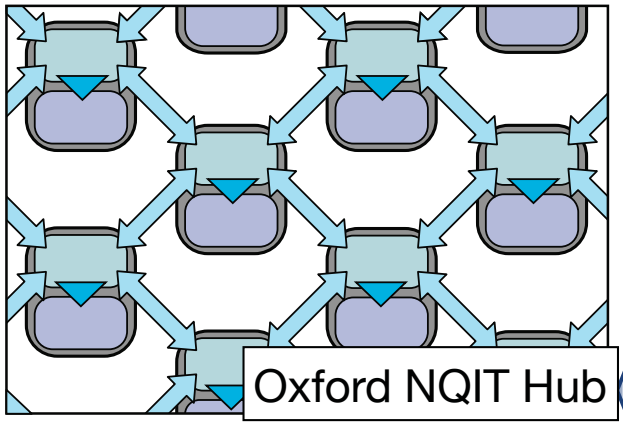

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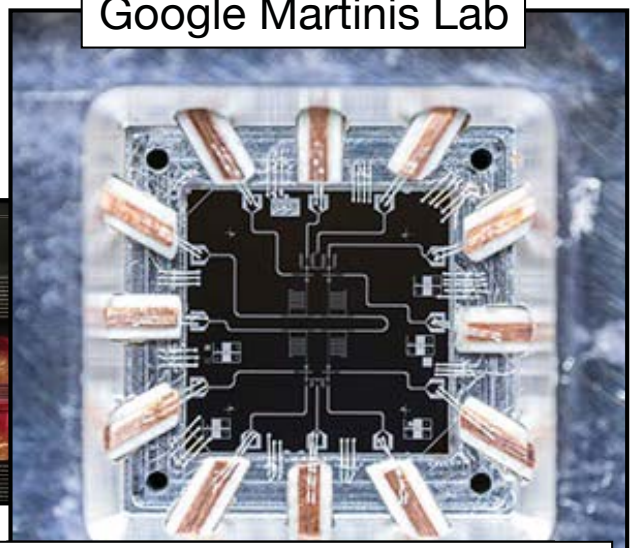


TU Delft Quantum Tech Lab

These devices become **relevant** at the moment they are no longer classically simulatable

Existing methods of Testing/Validation/Simulation/Monitoring/Tomography ... all become **IRRELEVANT**

Target

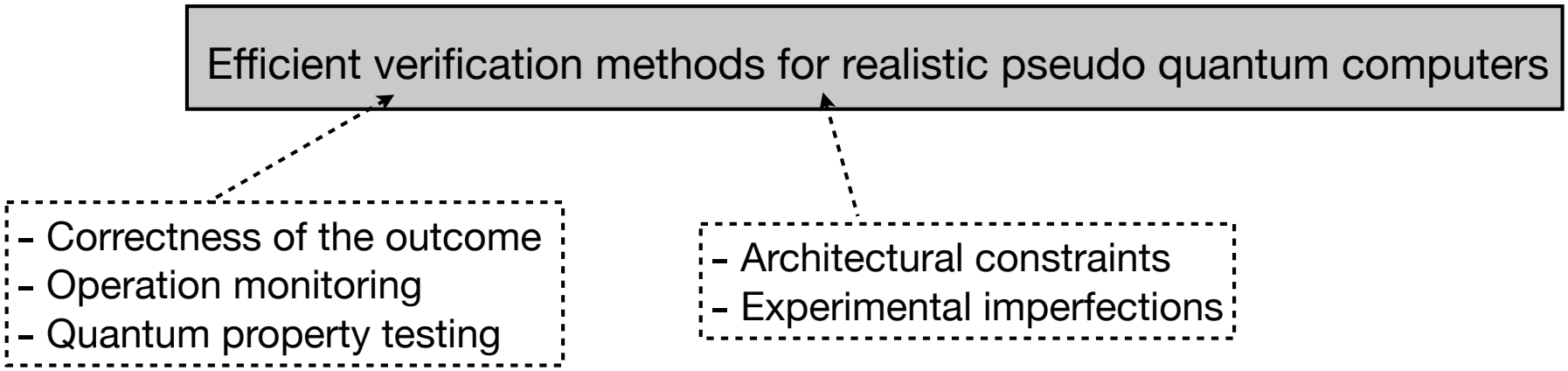
Efficient verification methods for realistic pseudo quantum computers

Target

Efficient verification methods for realistic pseudo quantum computers

- Correctness of the outcome
- Operation monitoring
- Quantum property testing

Target


Efficient verification methods for realistic pseudo quantum computers
- Correctness of the outcome
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- Architectural constraints
- Experimental imperfections

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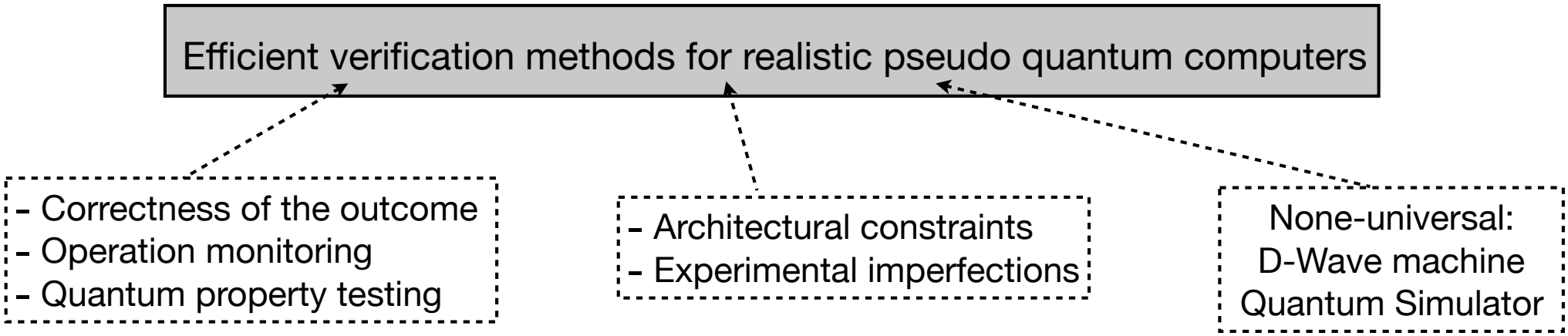
Efficient verification methods for realistic pseudo quantum computers
- Correctness of the outcome
- Operation monitoring
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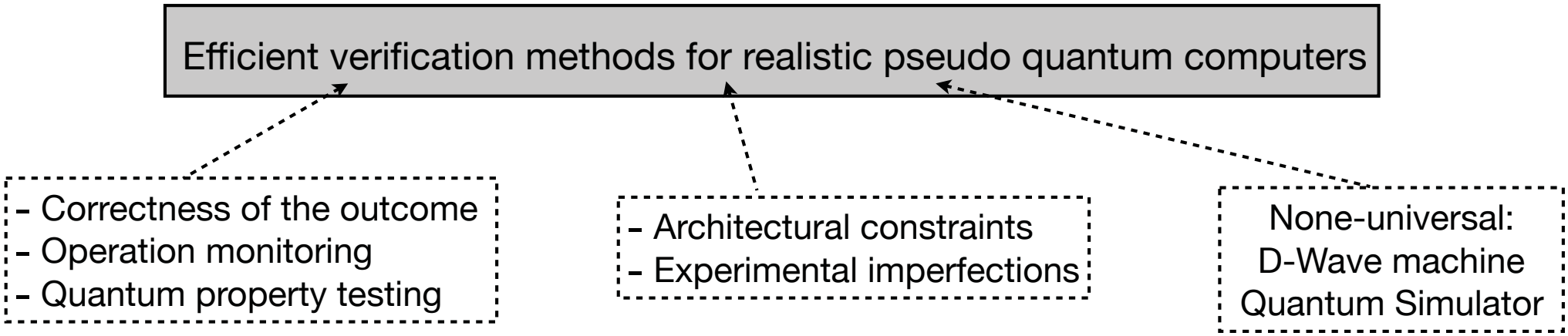
- Architectural constraints
- Experimental imperfections
None-universal:
D-Wave machine
Quantum Simulator

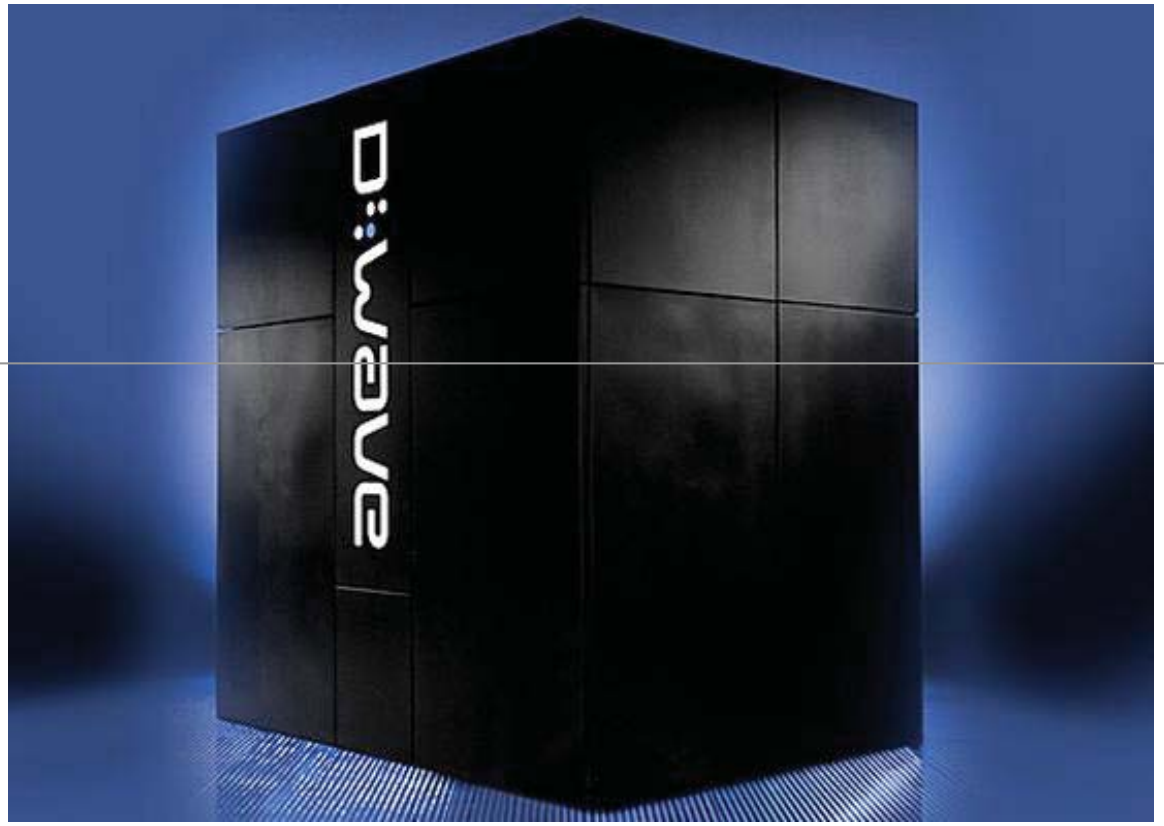
Target



Goal

Over the next decades, as quantum technology matures globally
we will provide **testing criteria** for industry adaptation

Should we pay $10000000 for a quantum computer



Should we pay $10000000 for a quantum computer

Simple test: We ask the box to factor a big number

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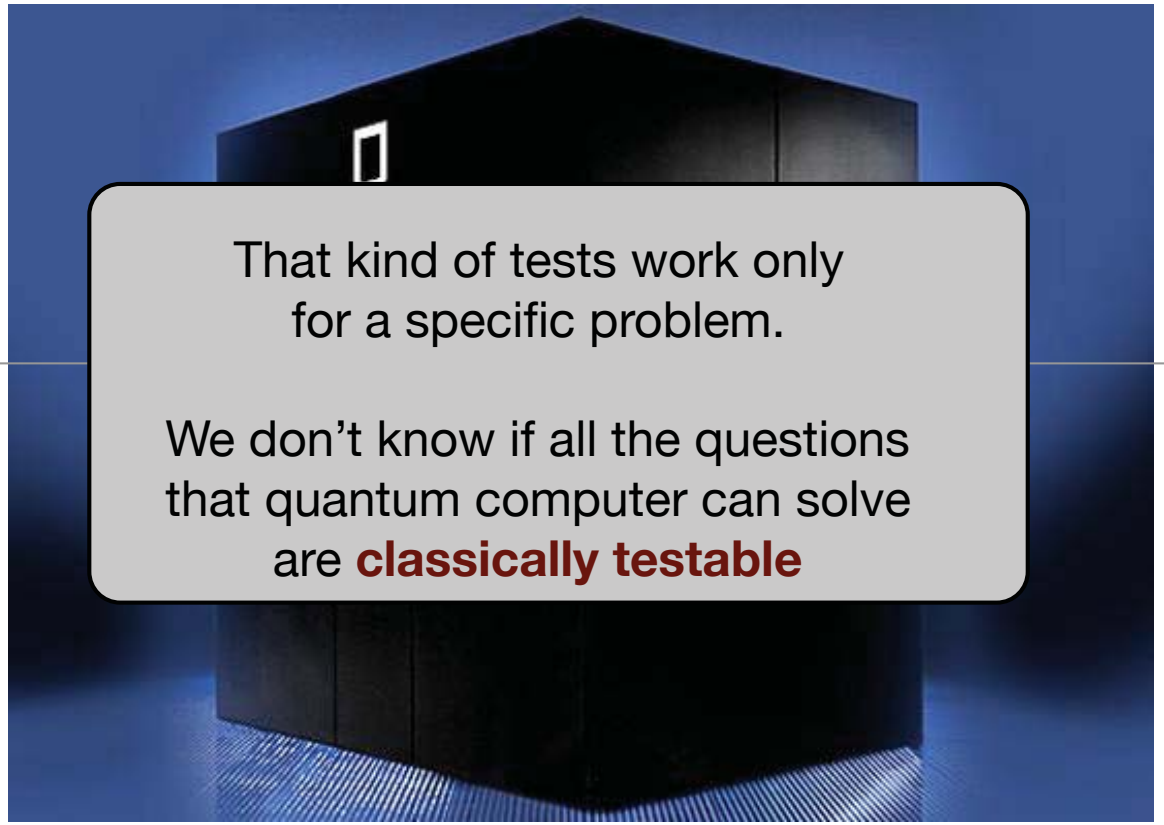

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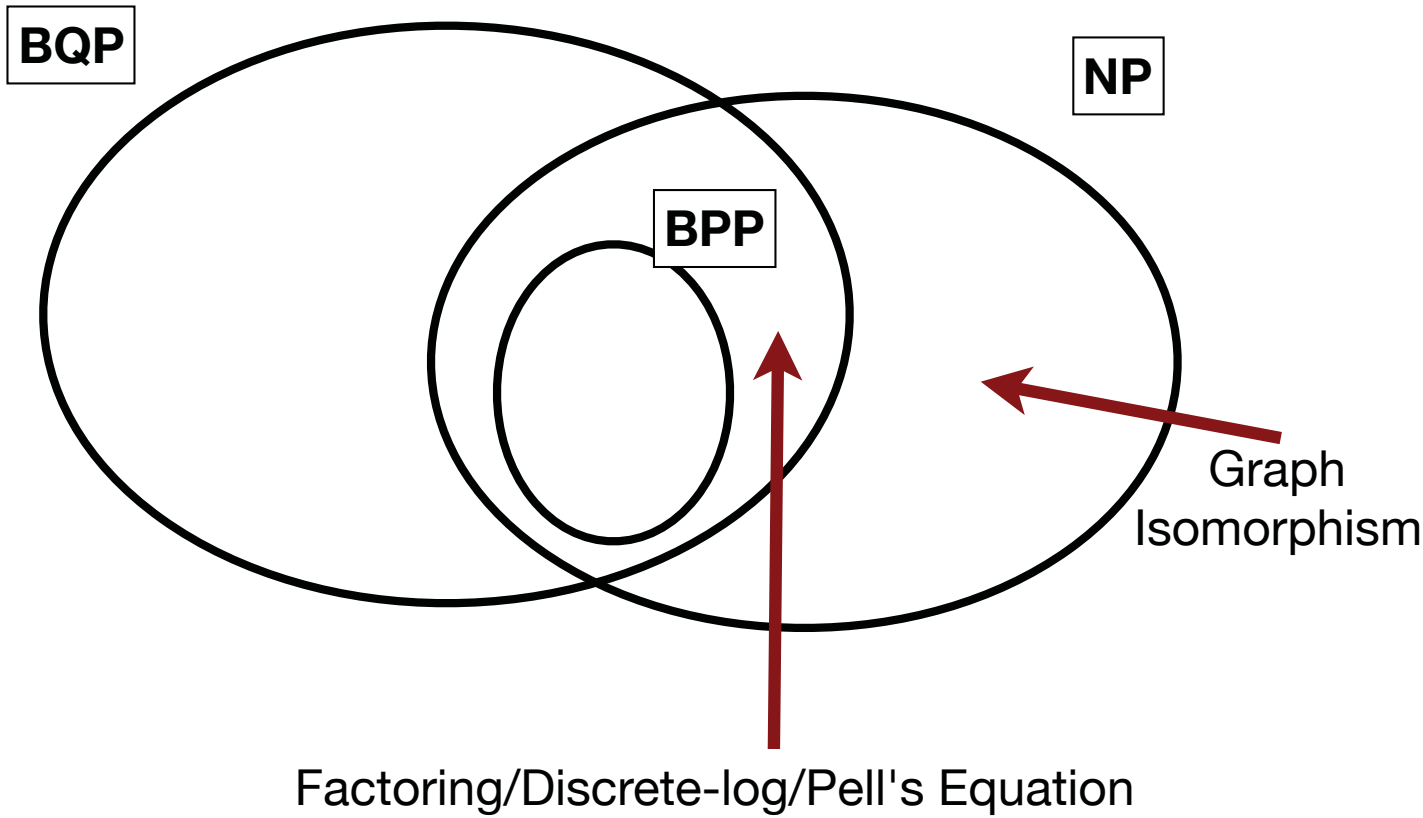
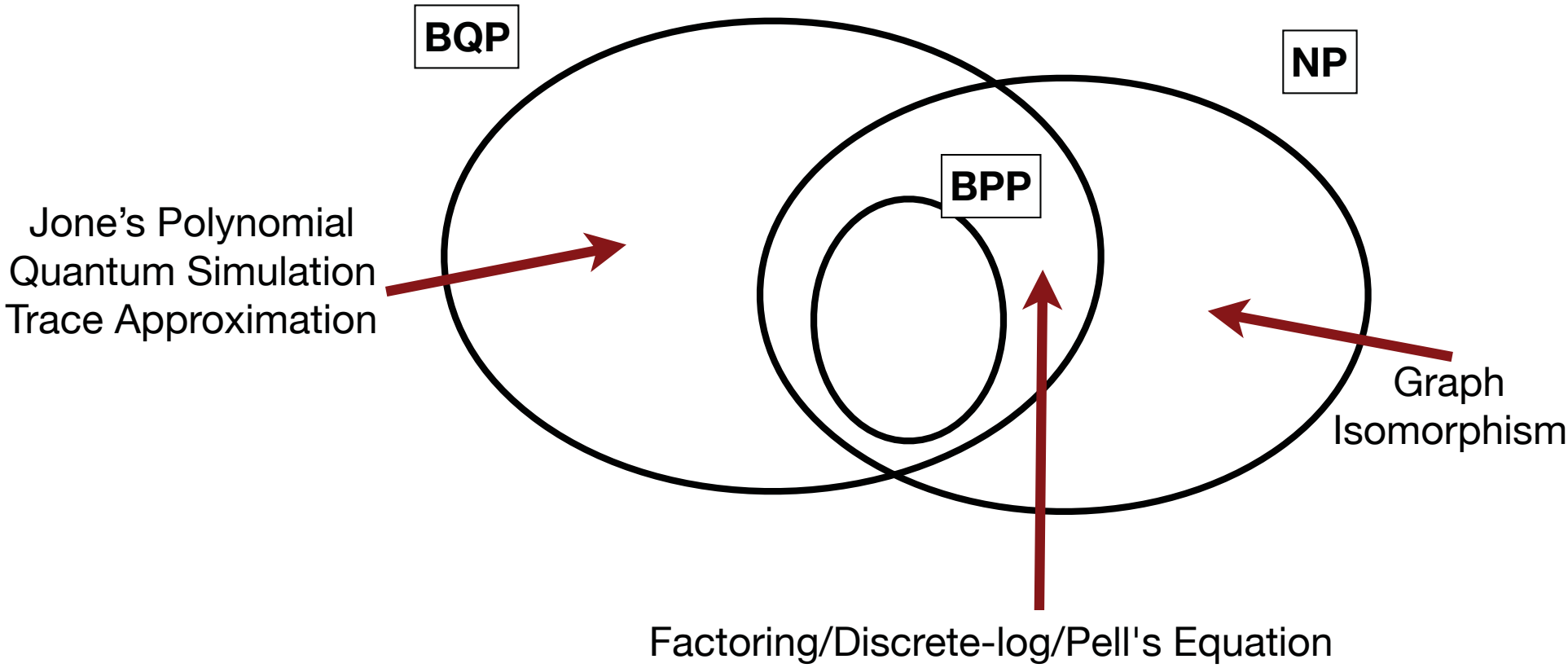
Complexity Picture



Complexity Picture



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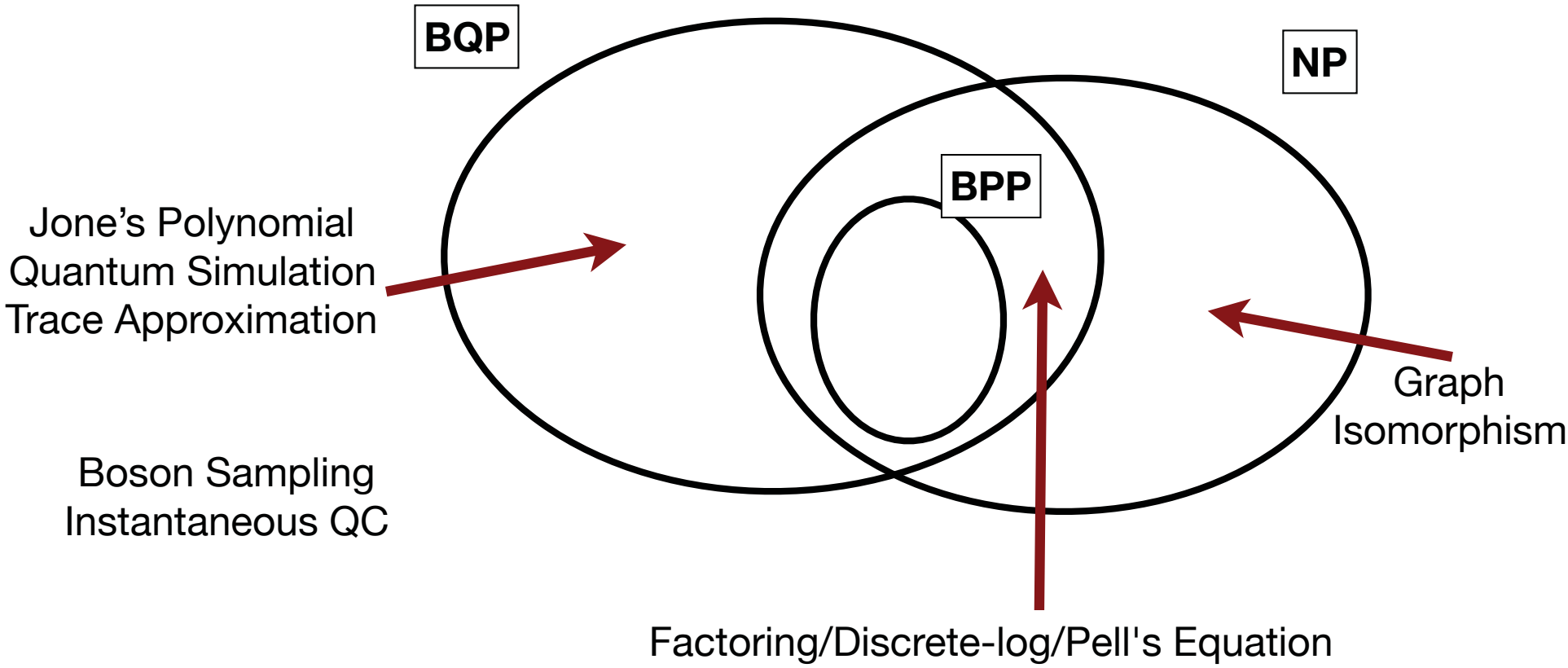

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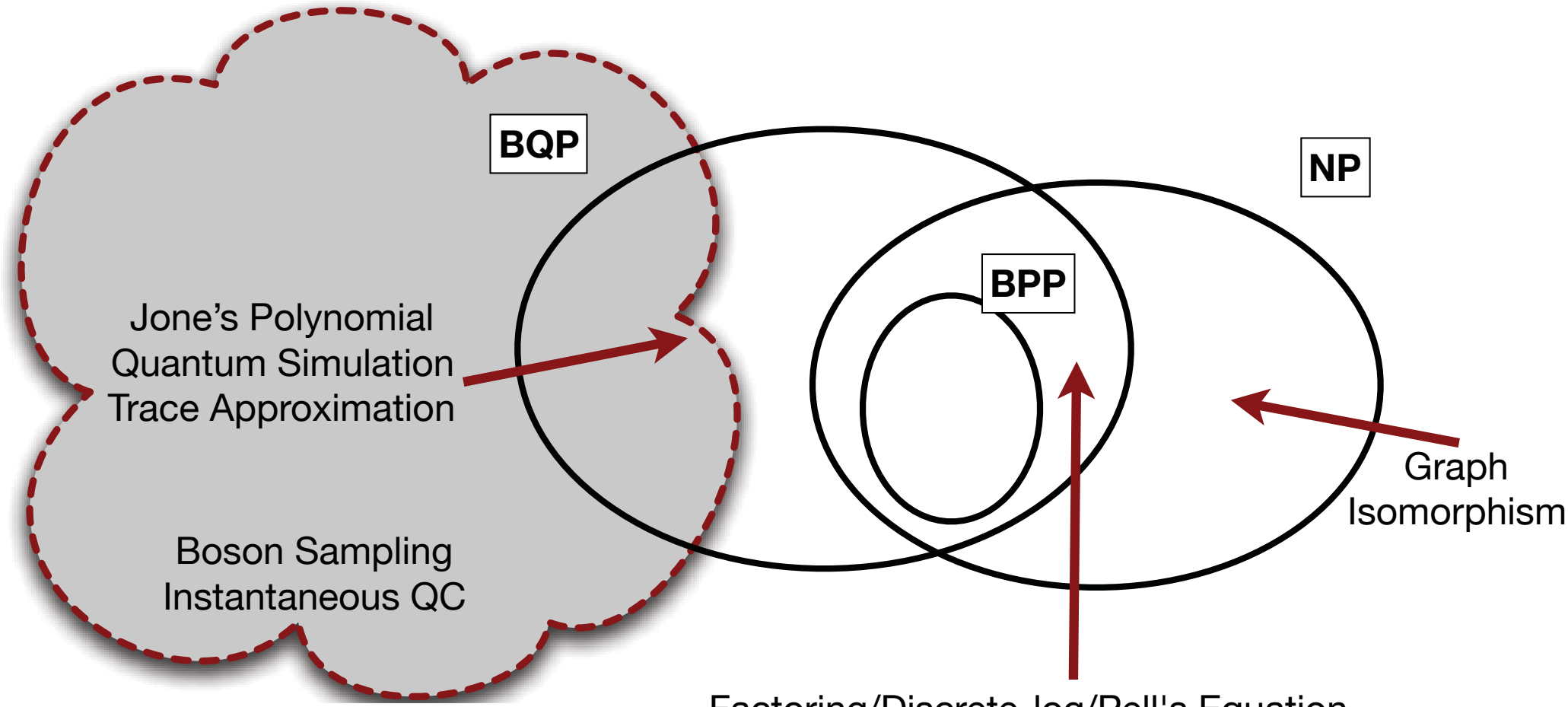
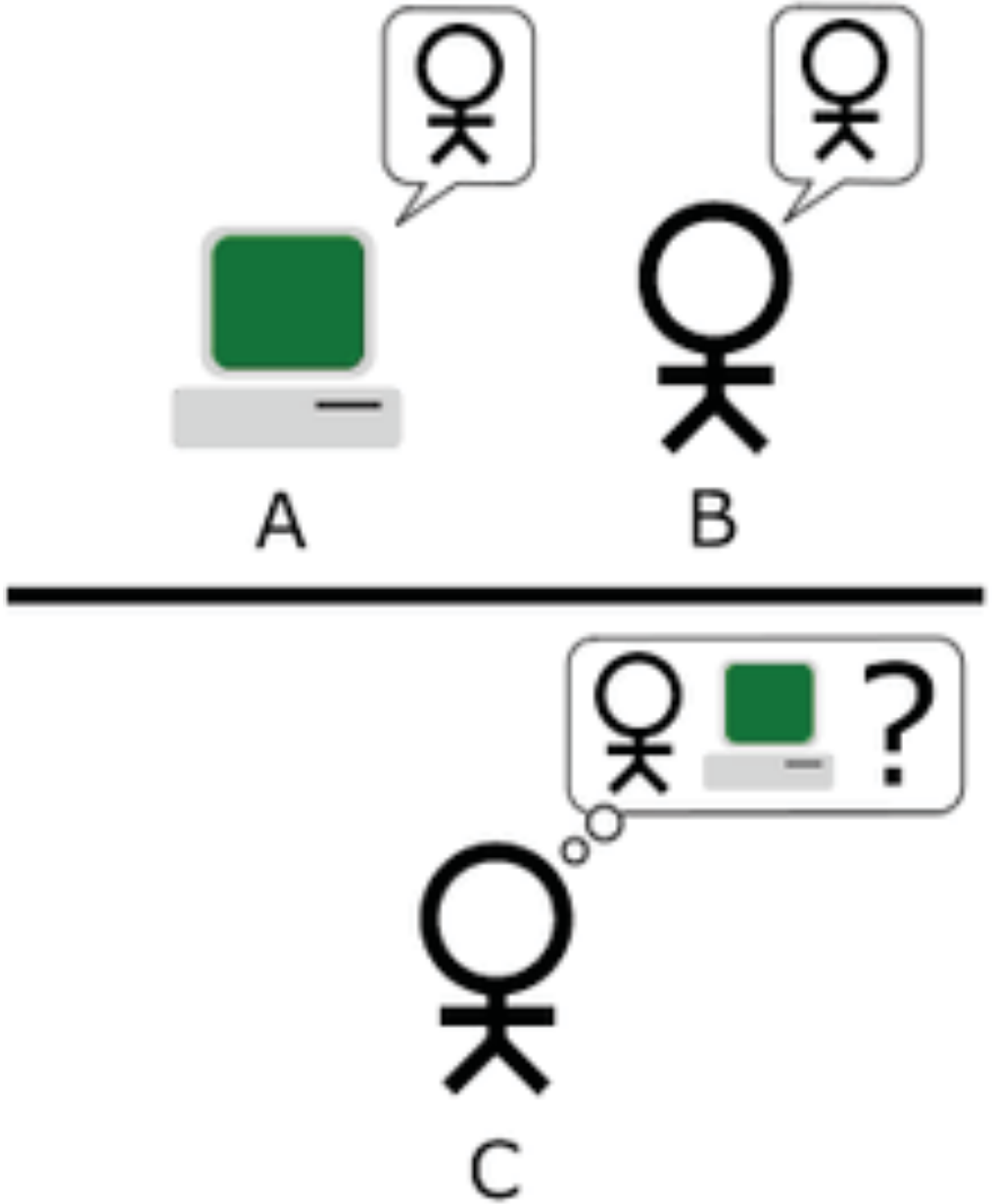


Testing outcome correctness ?

Quantum Turing Test



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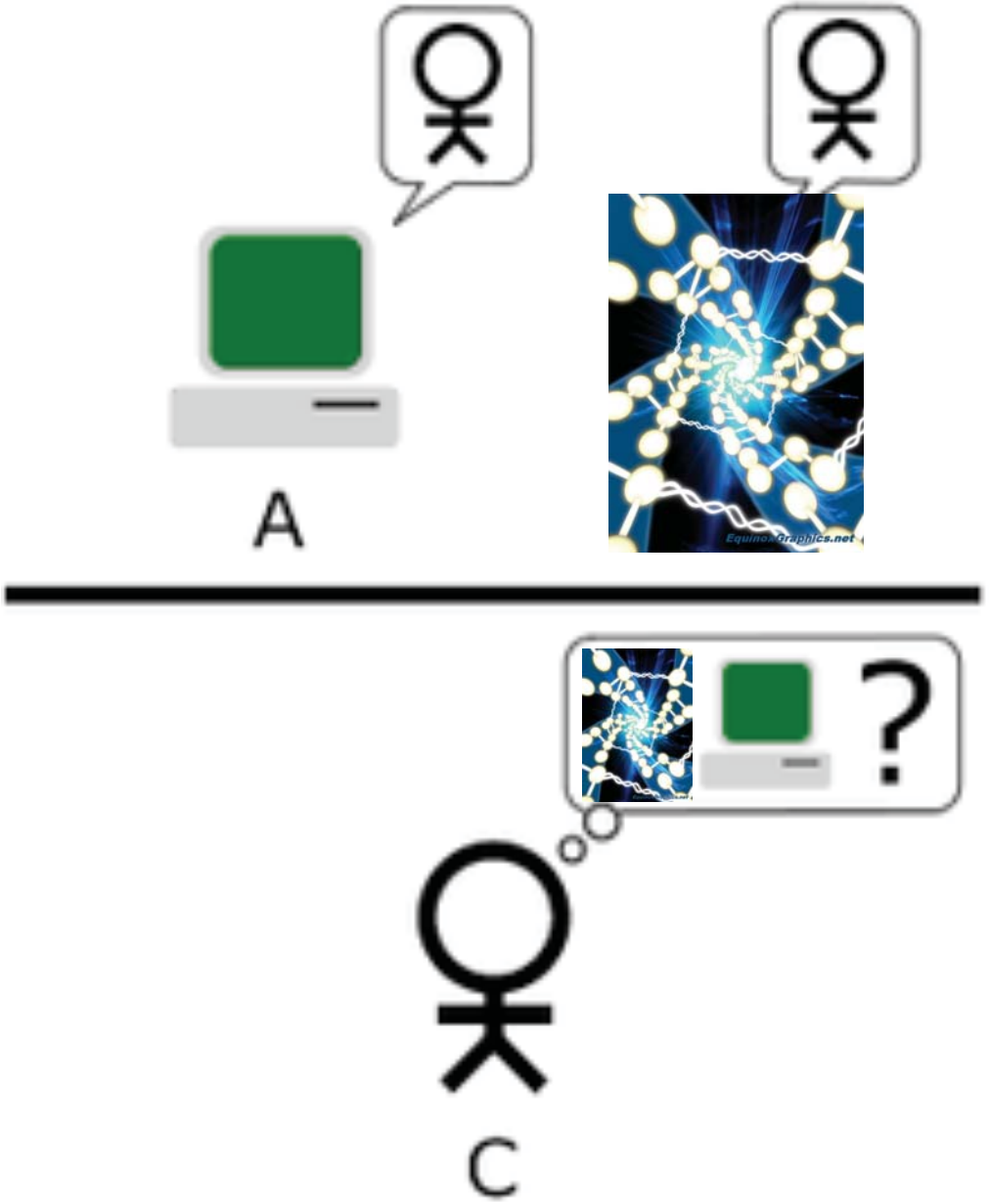

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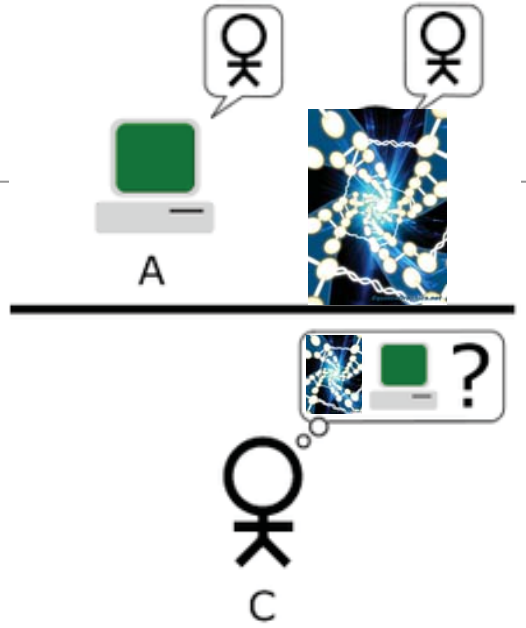
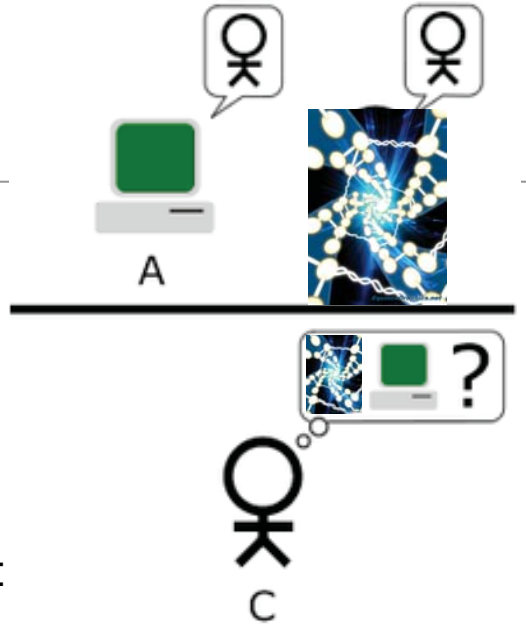


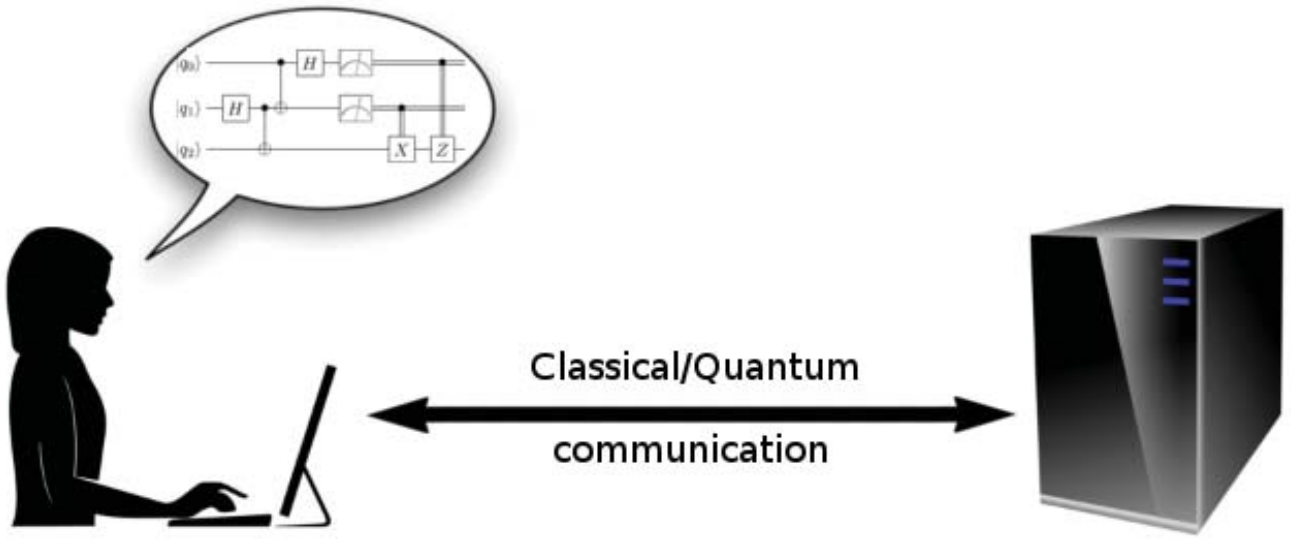
Quantum Turing test



- Can we classically communicate or do we need a bit of **quantumness** to test quantum computer

- Can we do the test **efficiently** or do we need super powerful computer to test quantum computer

Quantum Verification



- Computationally limited verifier
- Powerful quantum server(s)
- Certify the correctness of the computation

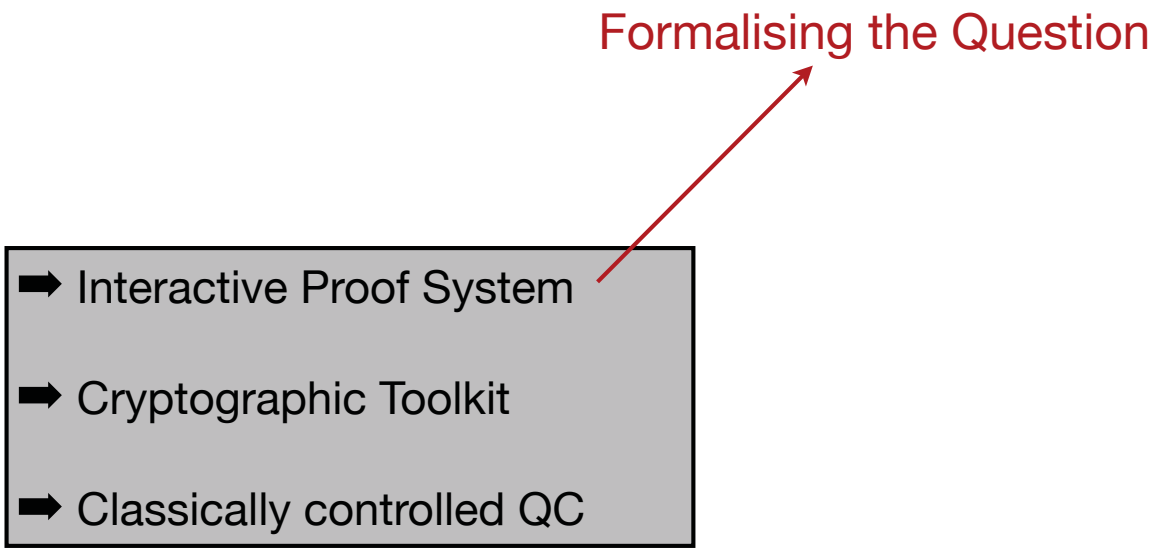
General Approaches

- State authentication-Based protocols
- Trapification based
- Measuring entanglement correlation protocols

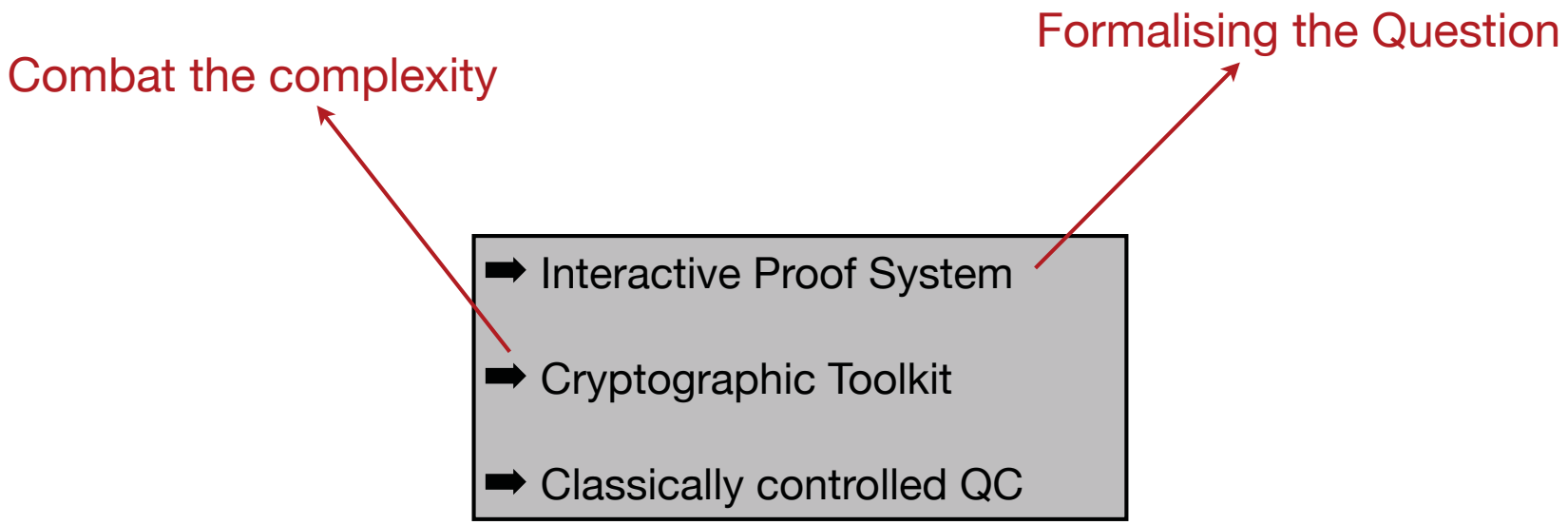
How do we do it

- ➡ Interactive Proof System
- ➡ Cryptographic Toolkit
- ➡ Classically controlled QC

How do we do it



How do we do it



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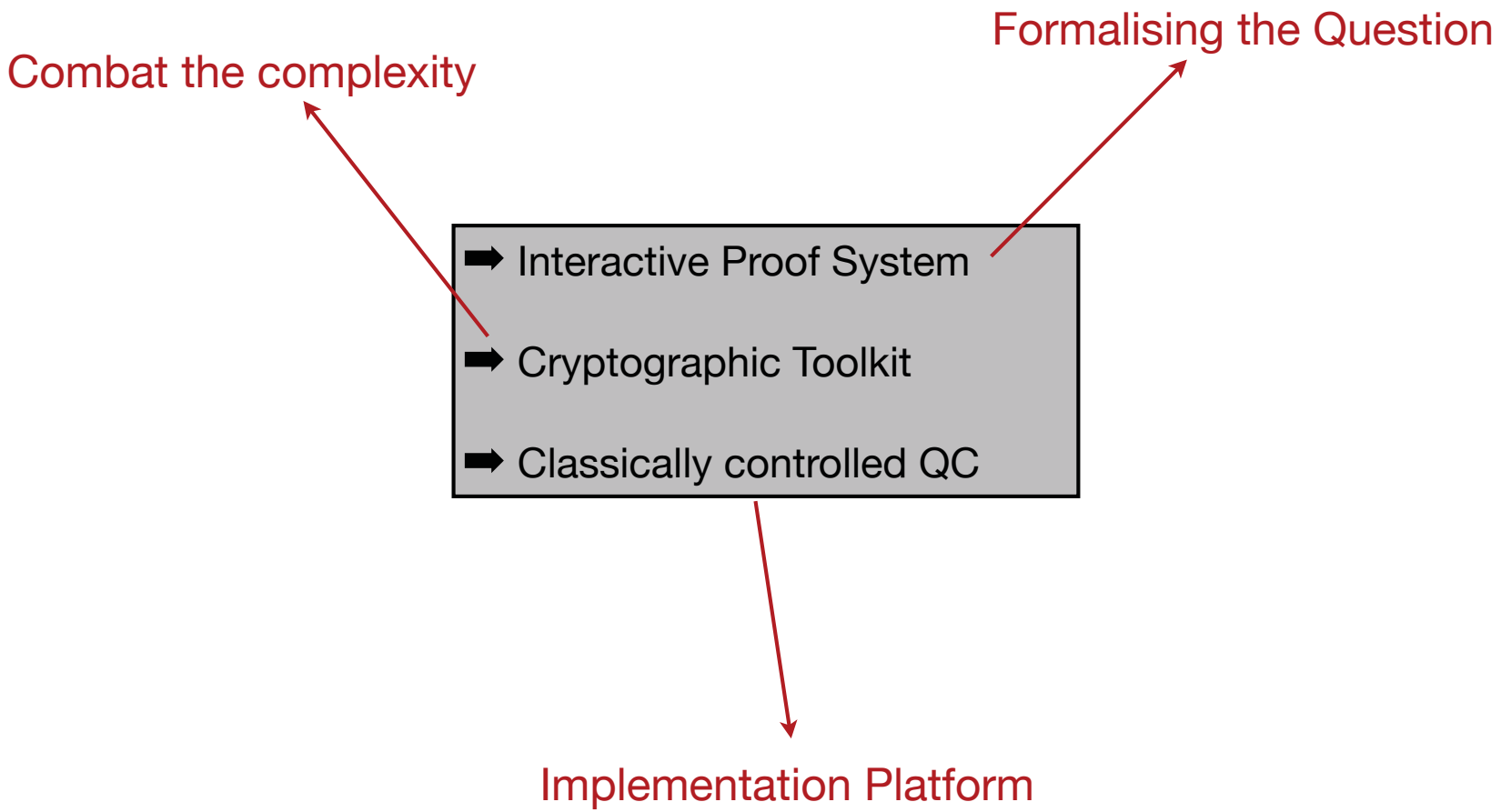
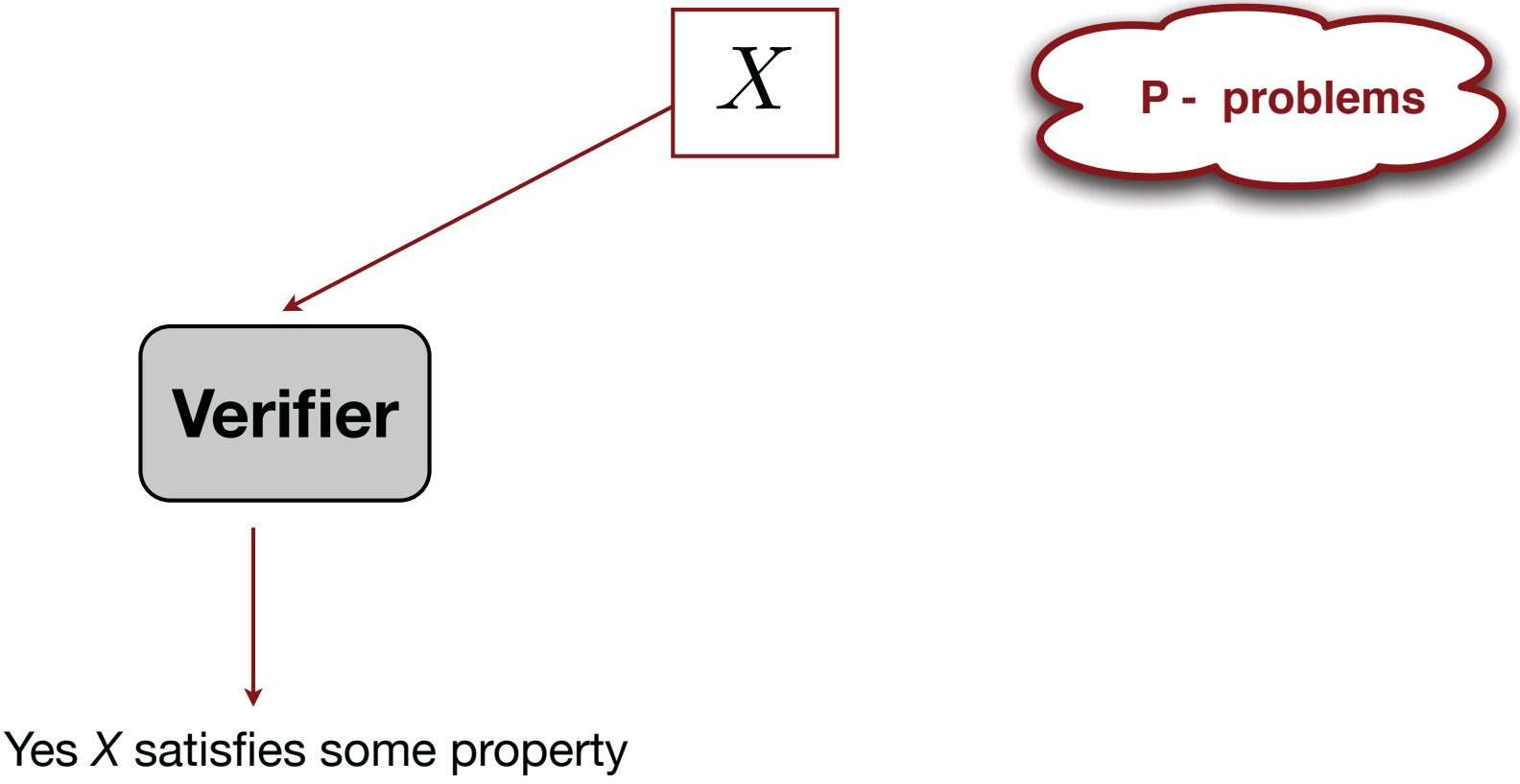


Complexity as Proof System



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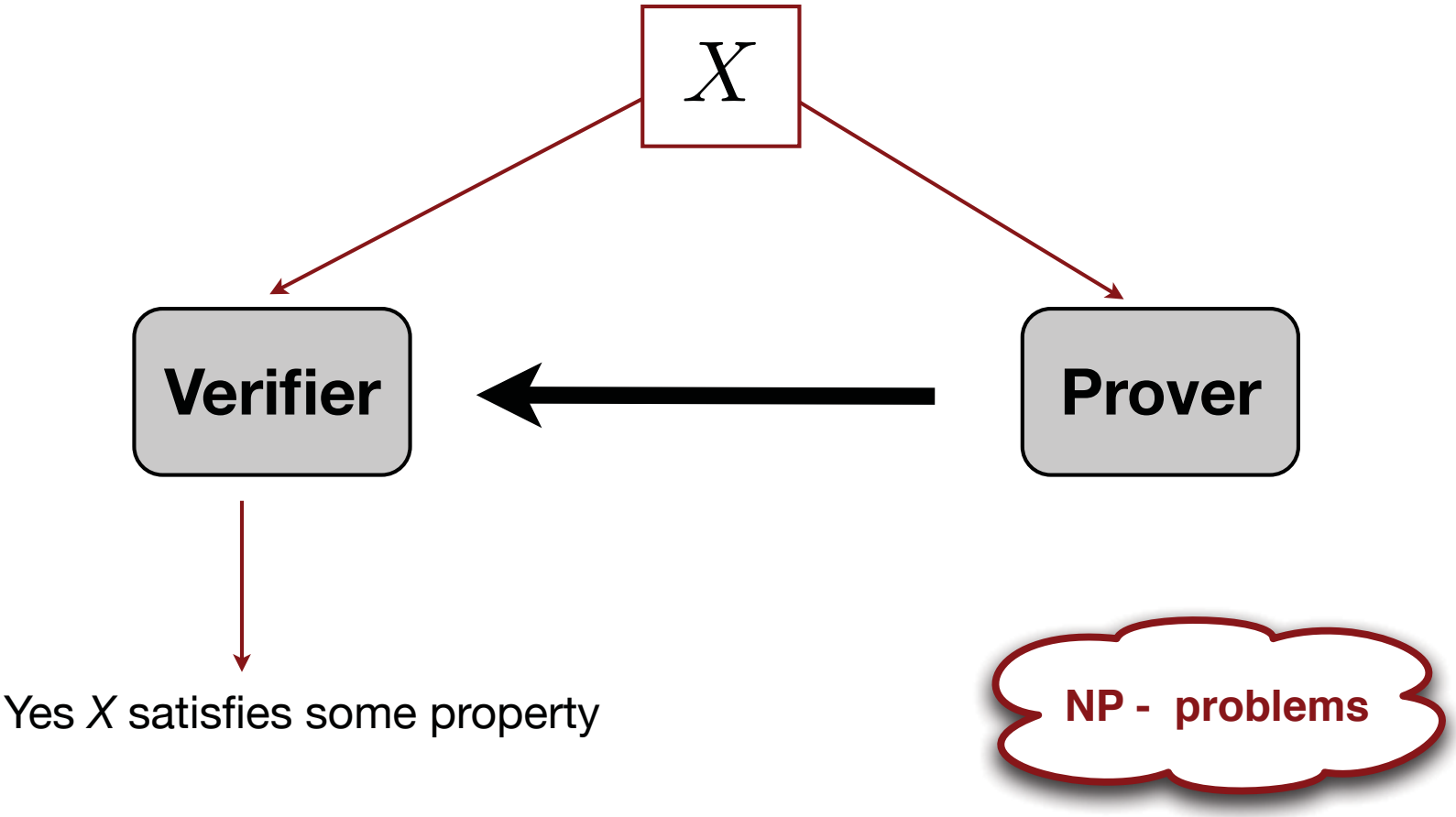

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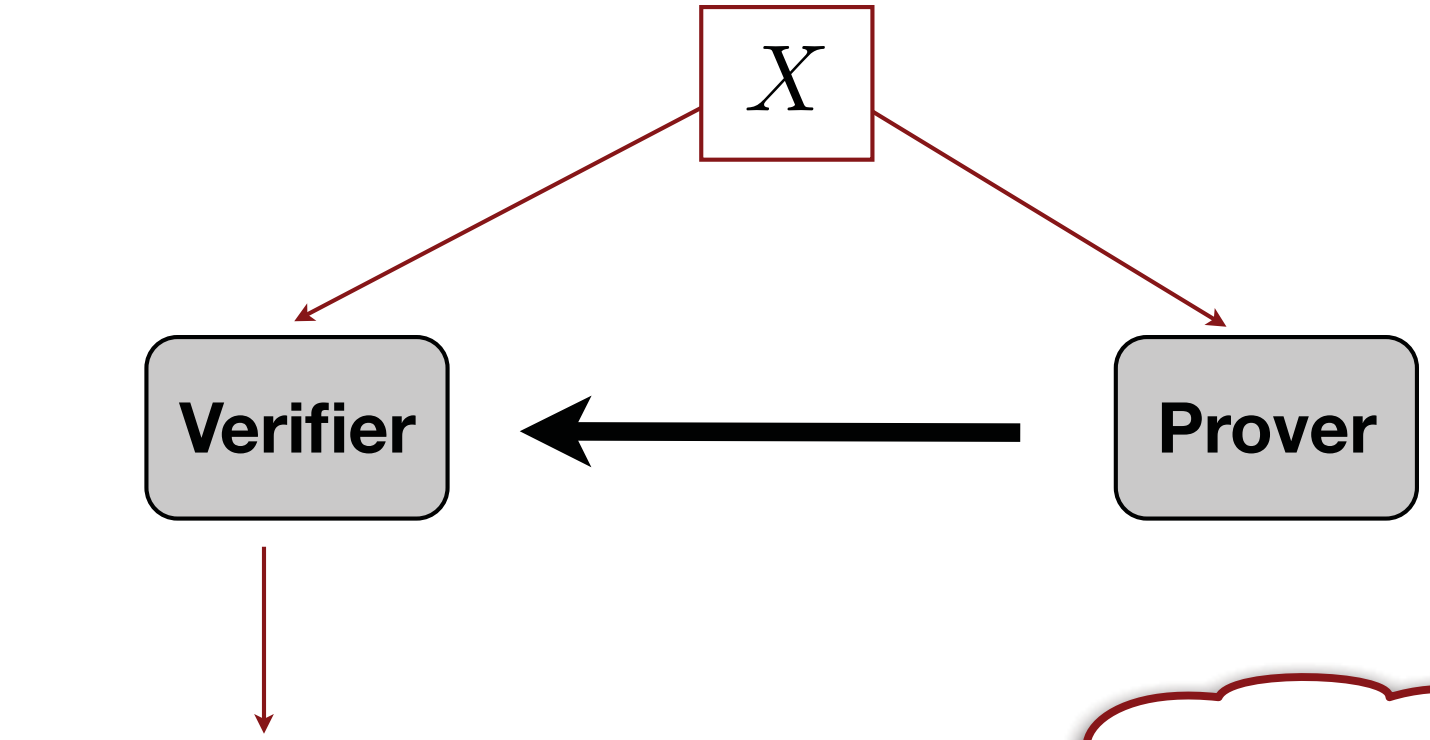
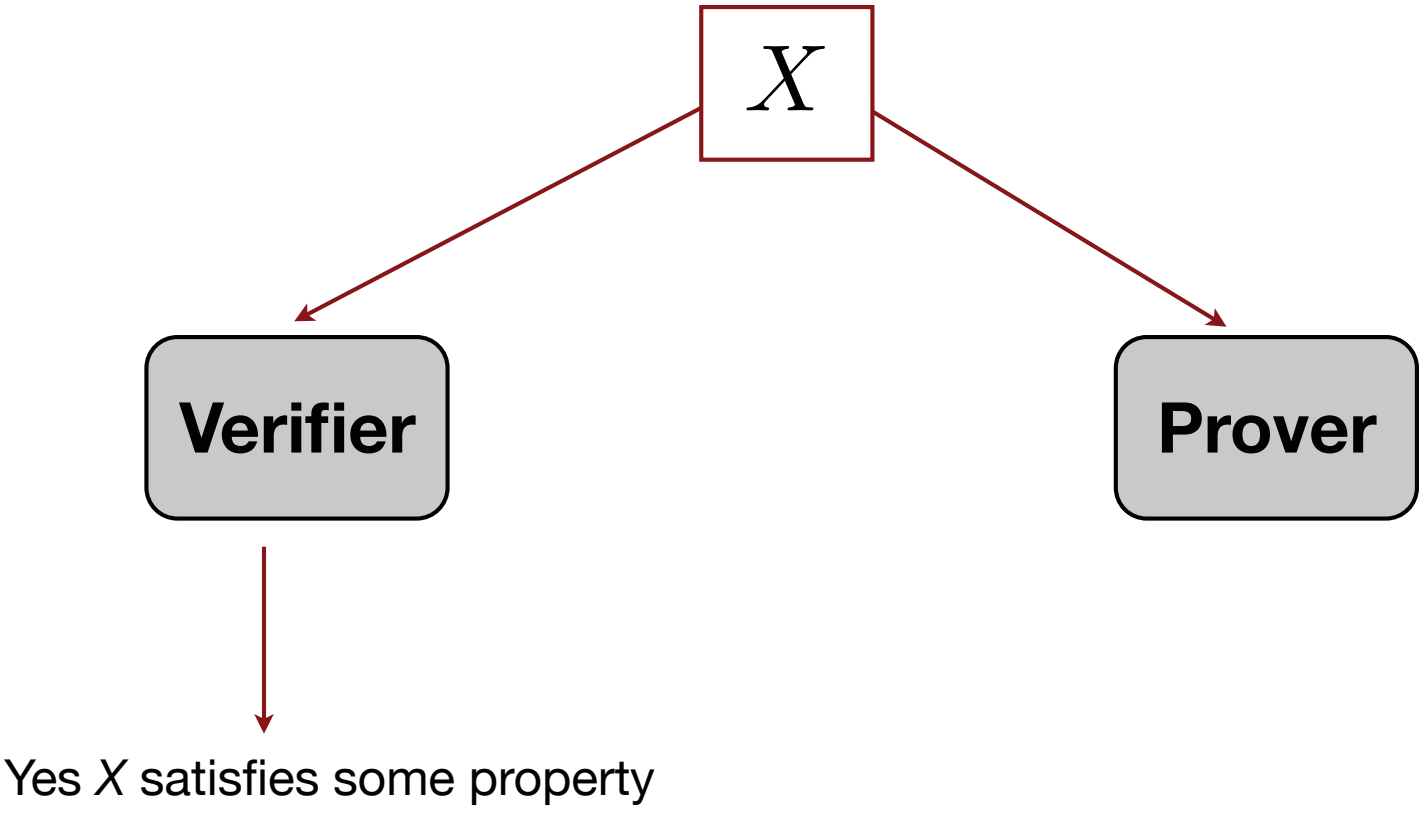


Generalisation: Interactive Proofs



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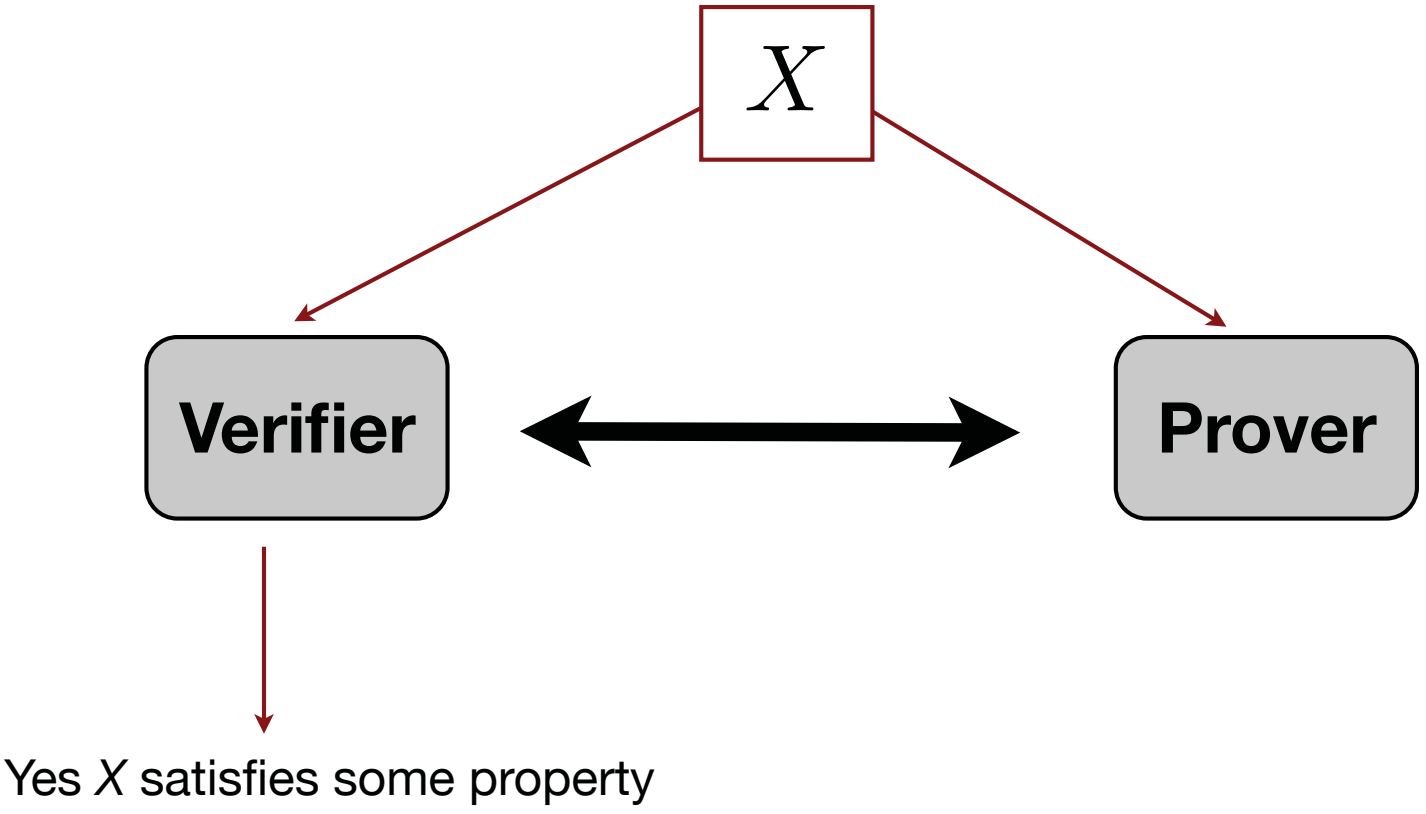

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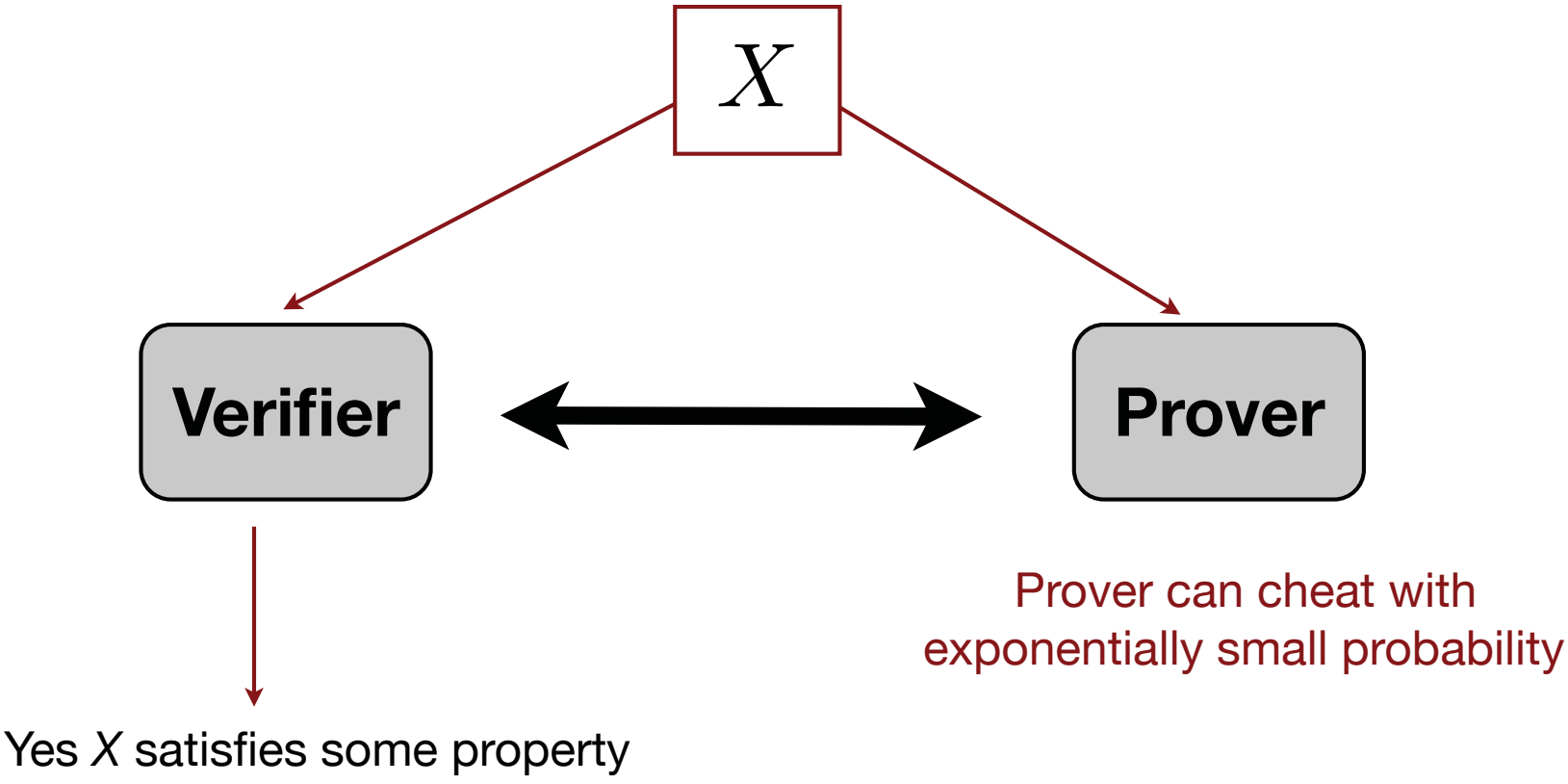

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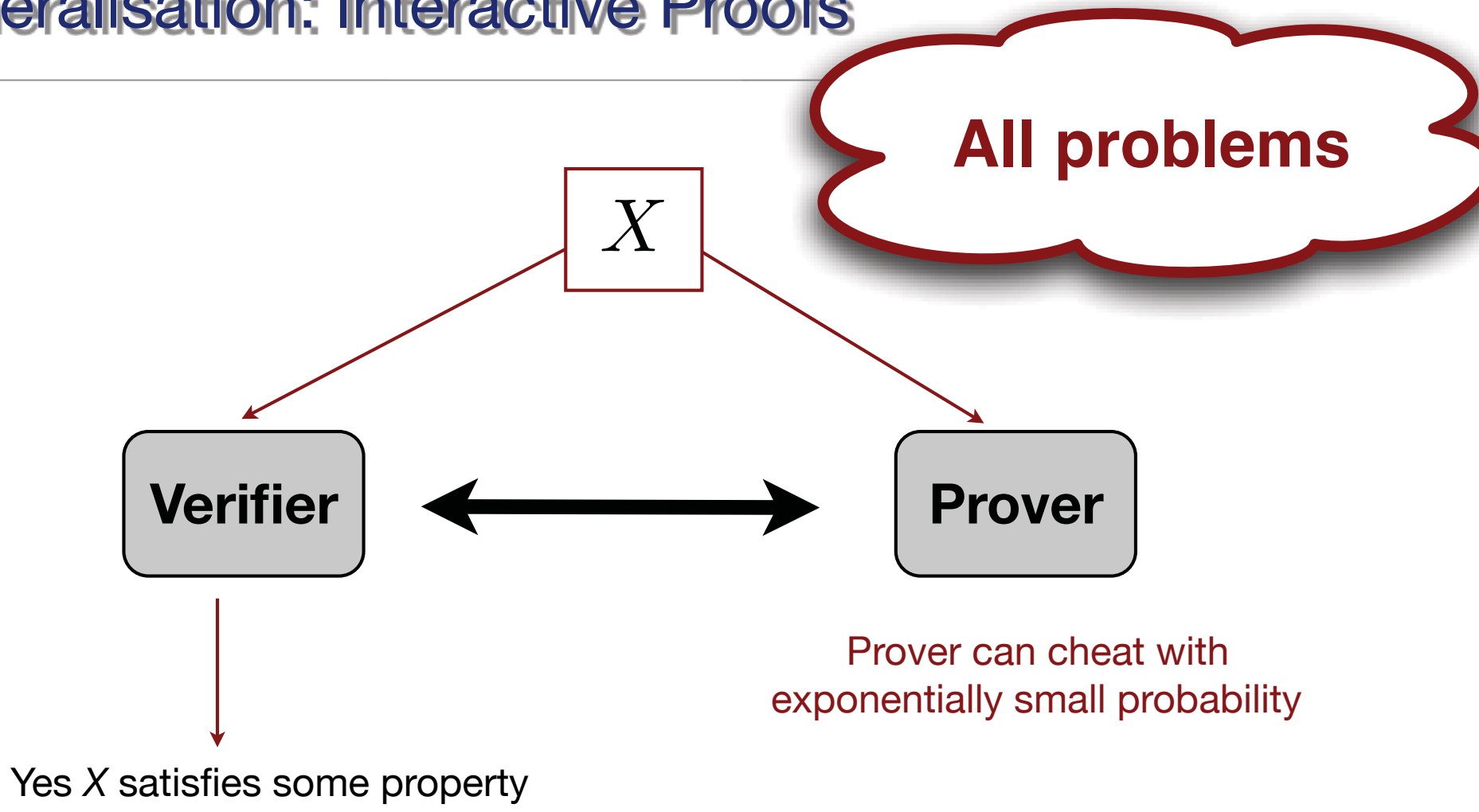

Interactive Proofs

A **PROTOCOL** between a

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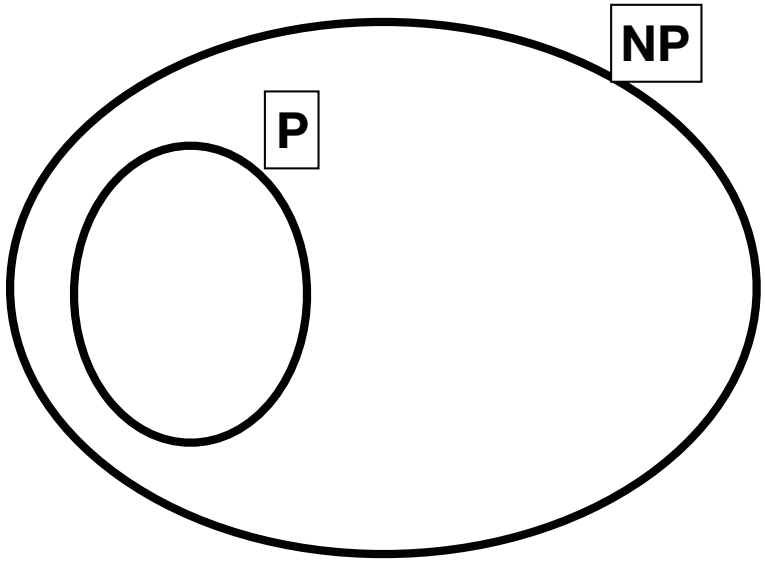
Soundness: $(\forall x \notin L)(\forall P')\ \Pr\left[(V \leftrightarrow P')(x)\ accepts\right] \leq \frac{1}{2}$

Interactive Proofs



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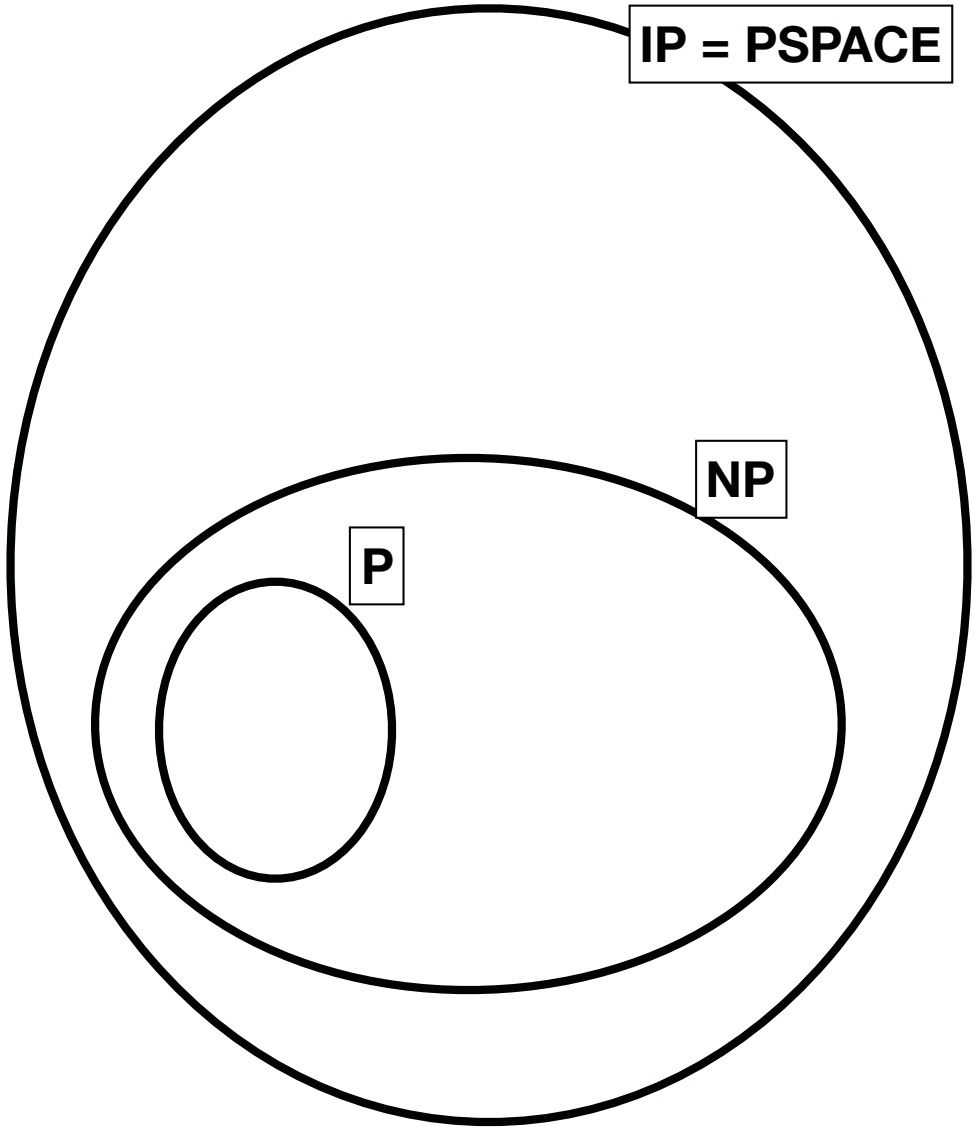

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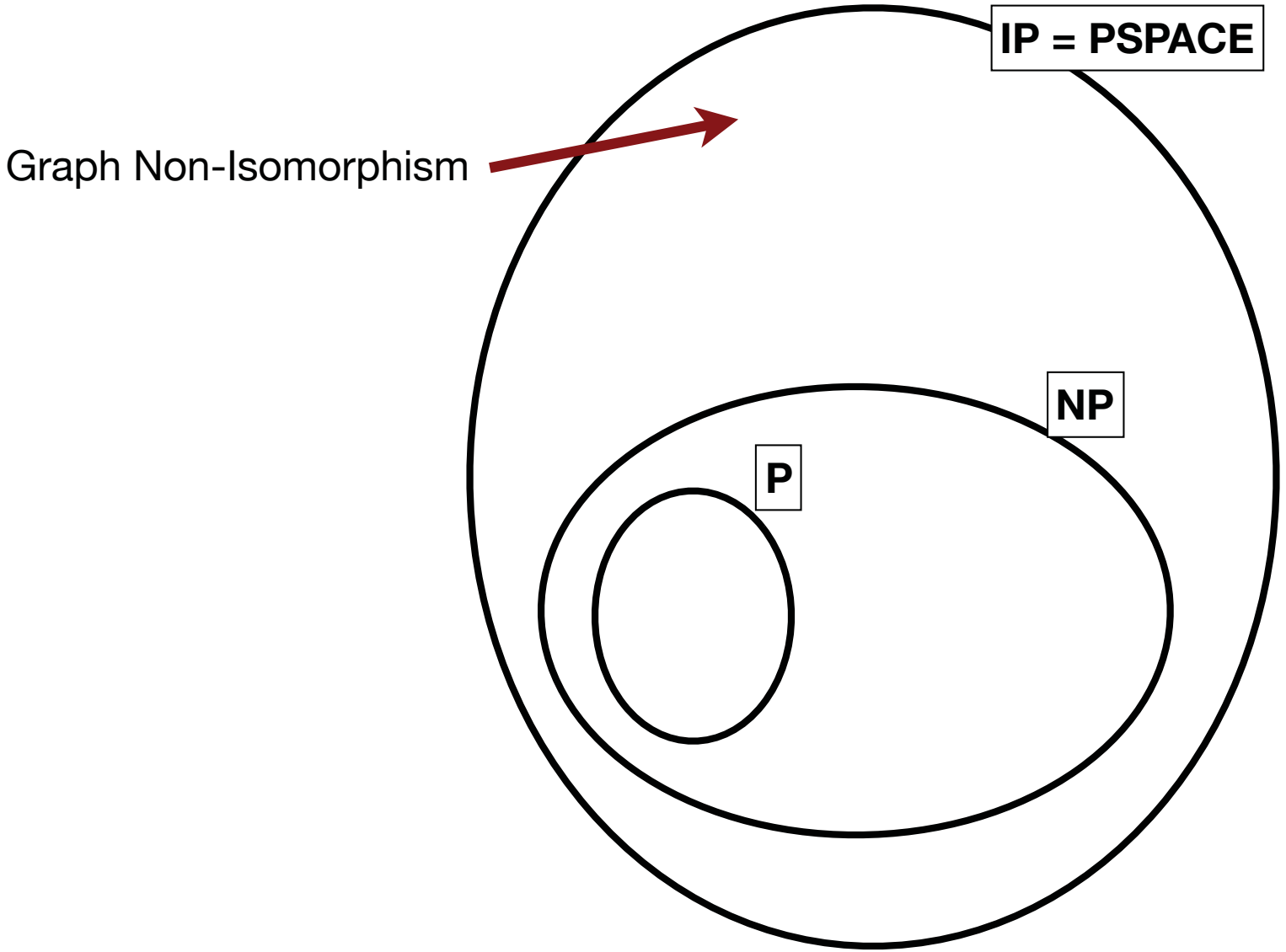
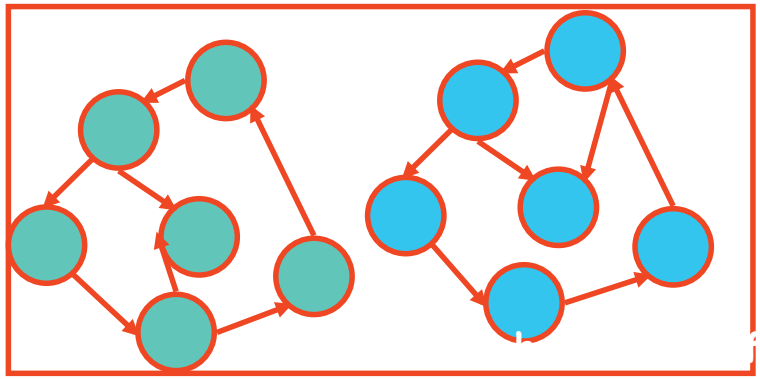
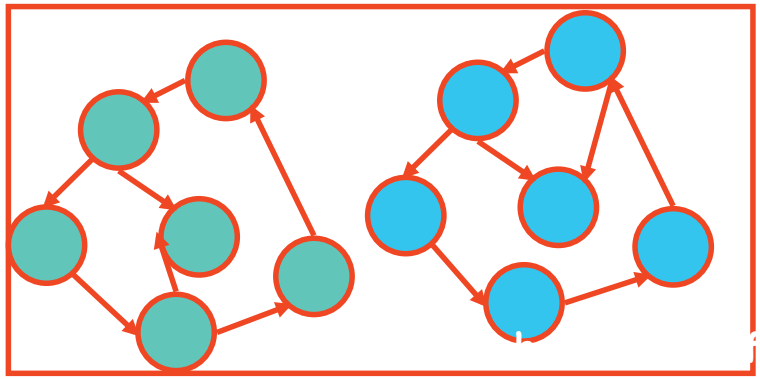


Graph Non-Isomorphism



The common input

Graph Non-Isomorphism



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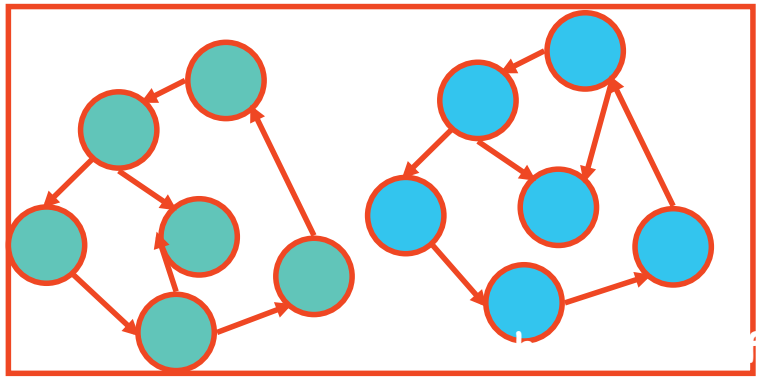

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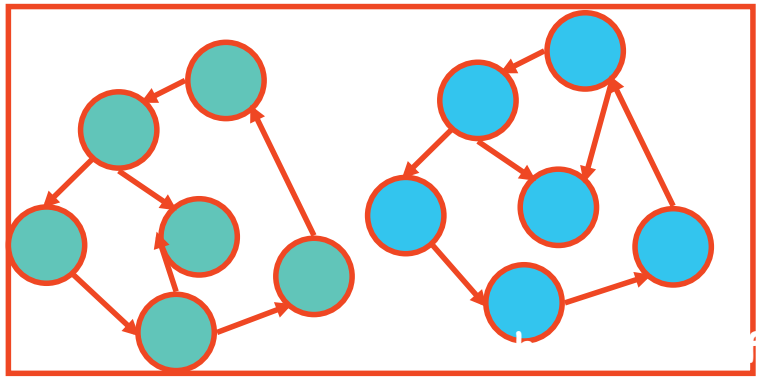

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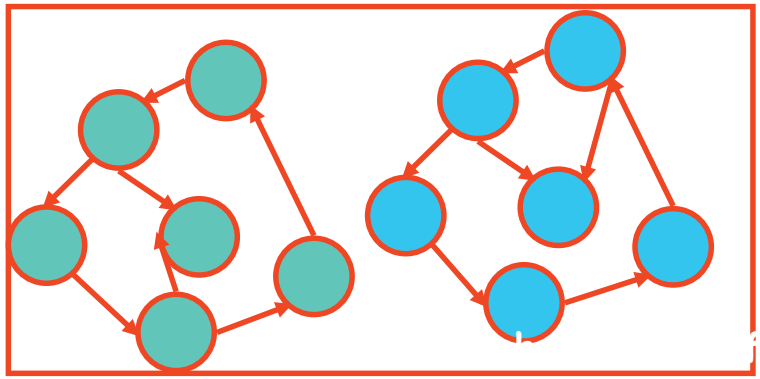

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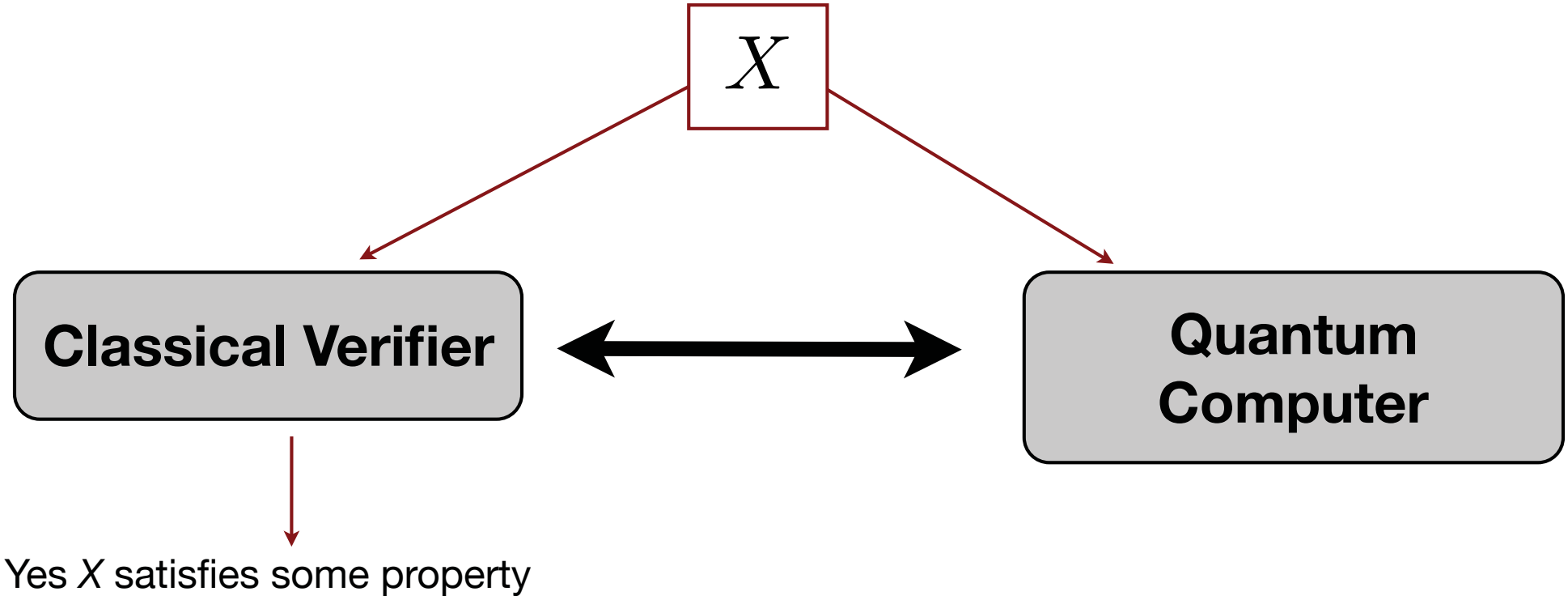
The verifier can check the answer easily

IP for Quantum Computing



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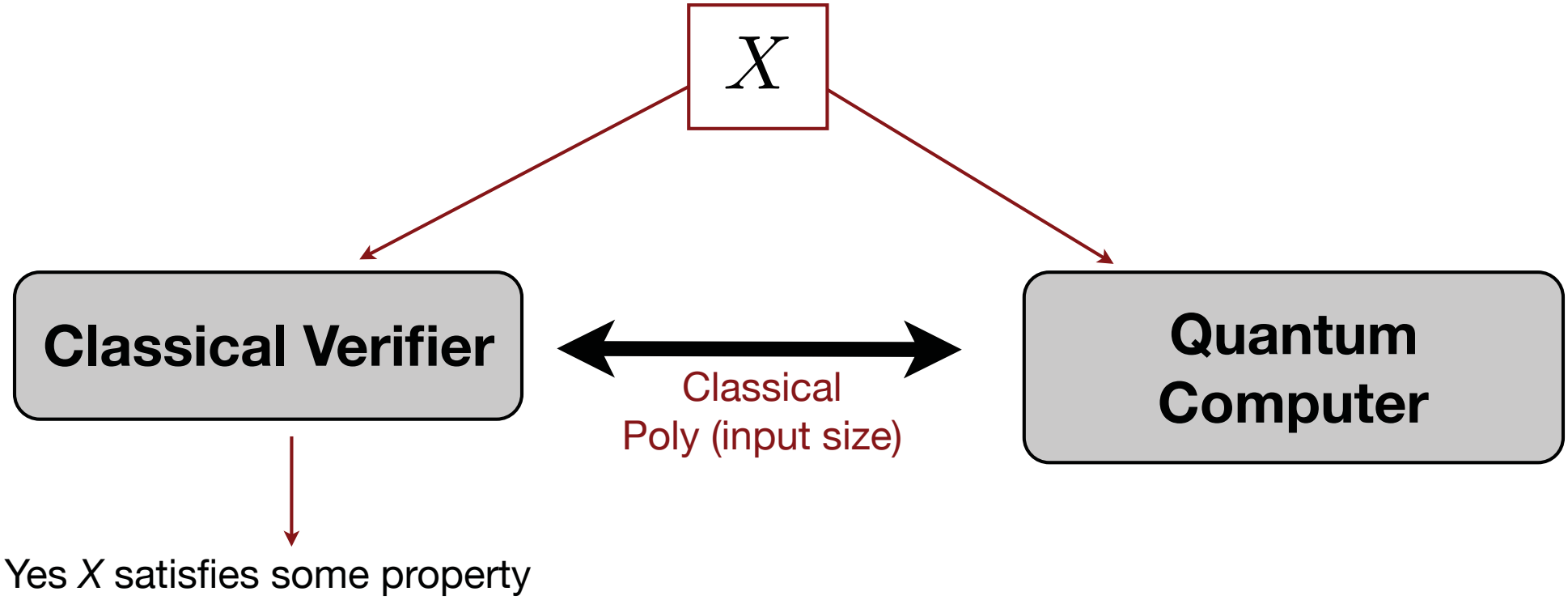

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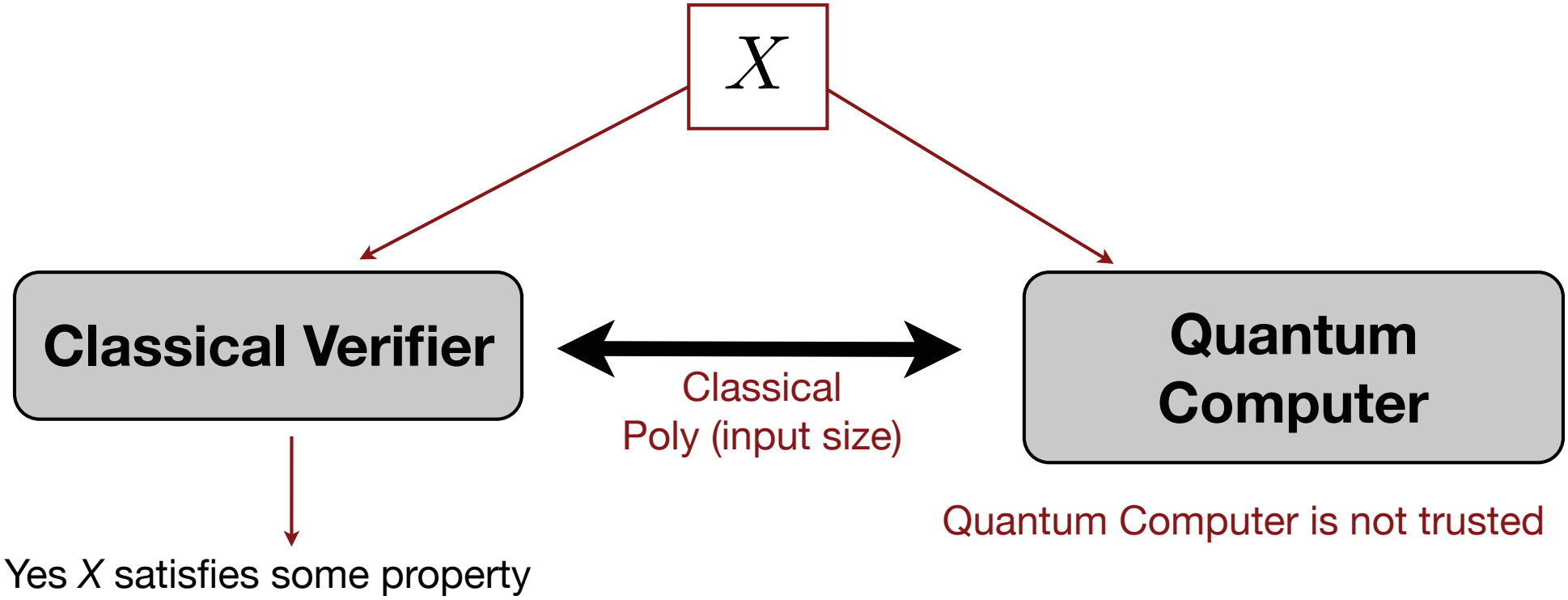

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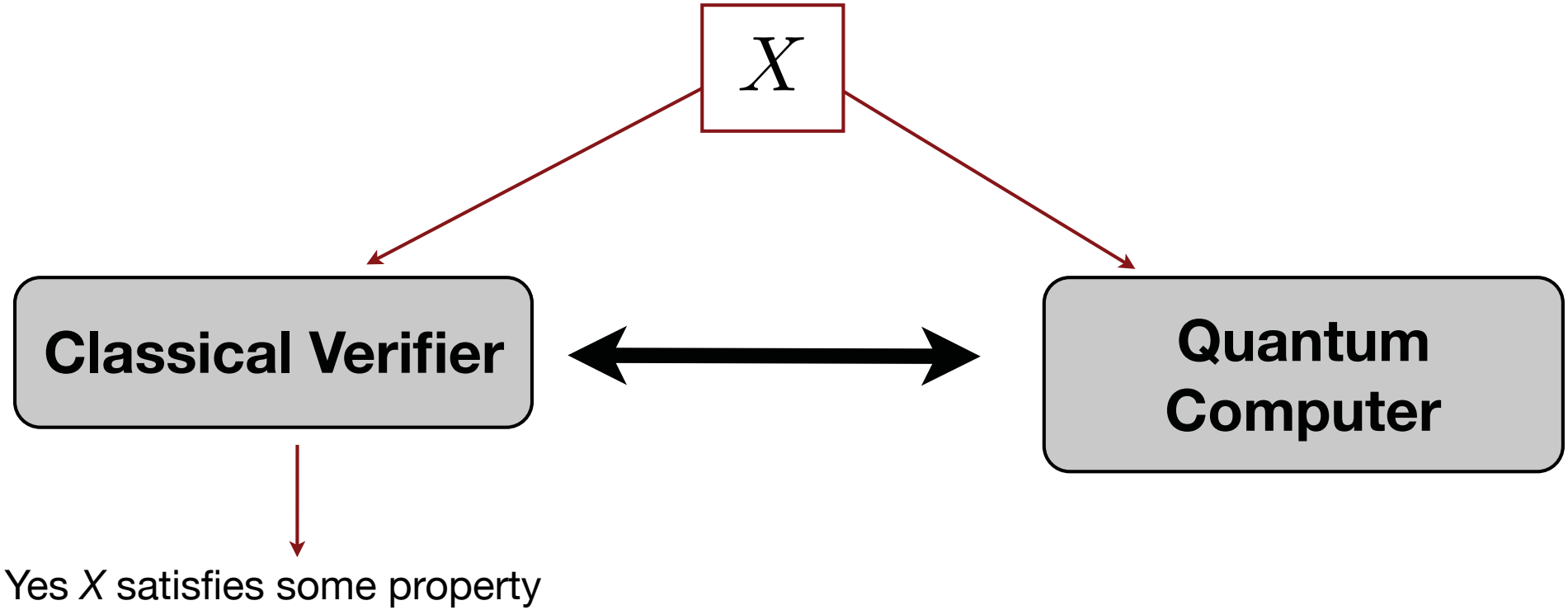

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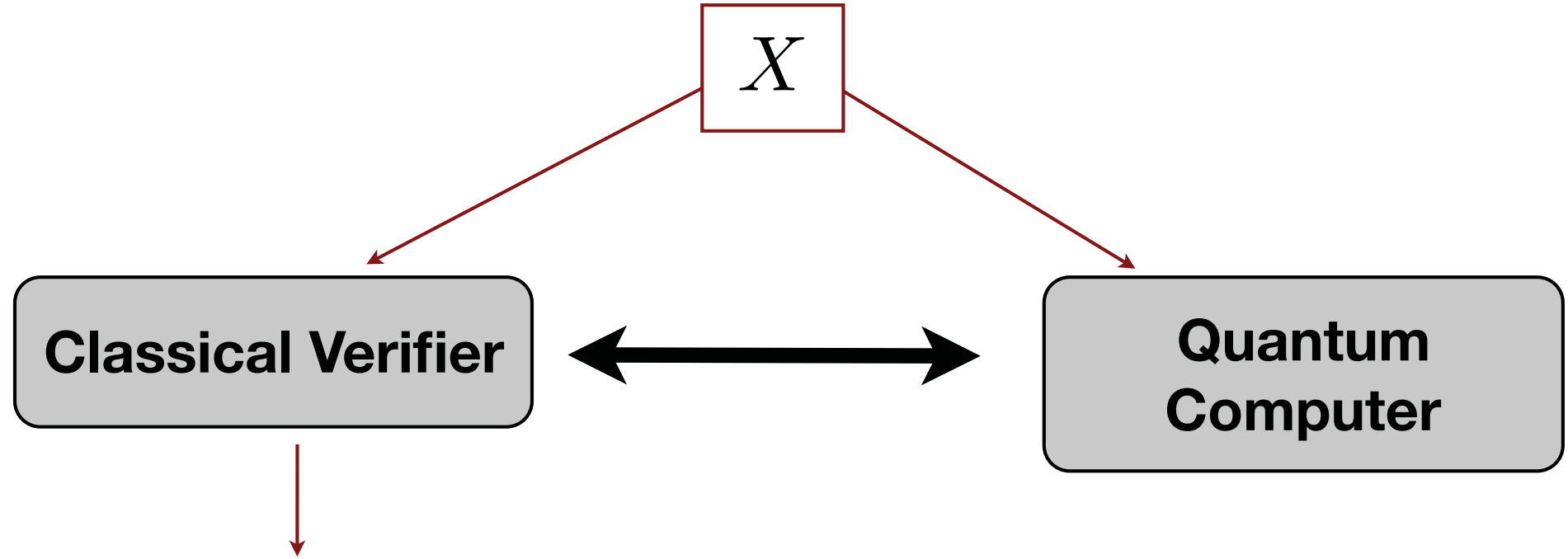
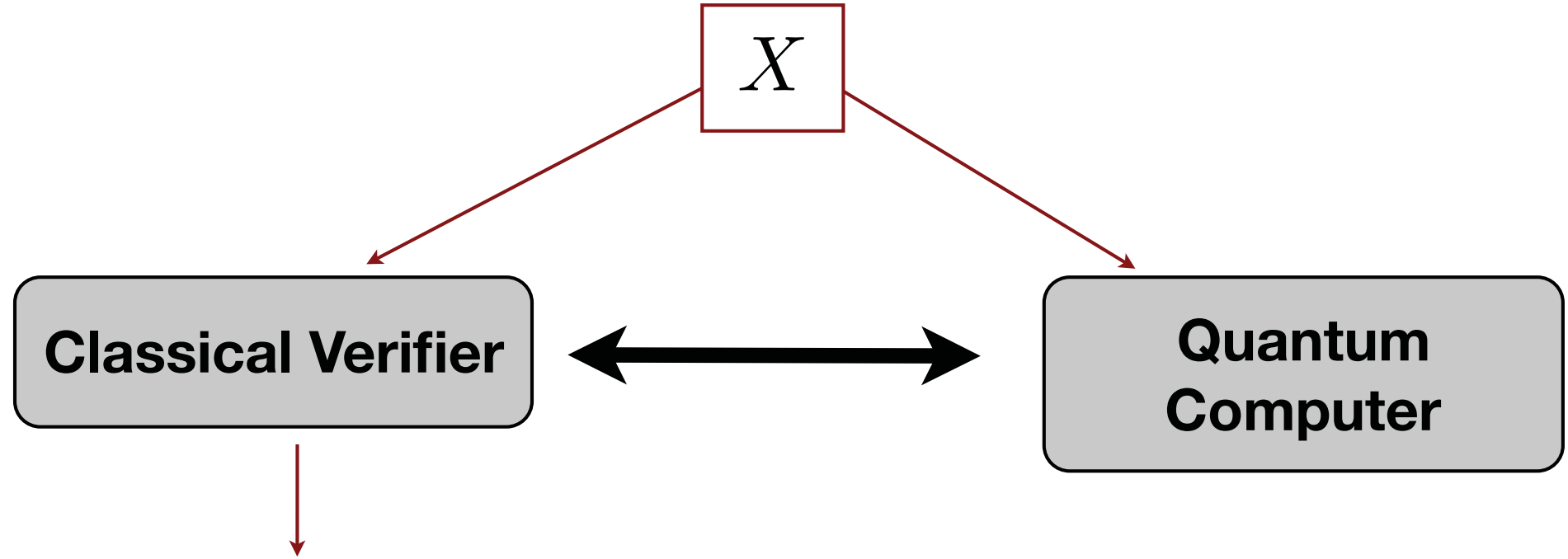


Gottesman (04) - Vazirani (07)- Aaronson **$25** *Challenge (07)*

Does BQP admit an interactive protocol

where the prover is in BQP and the verifier is in BPP?

IP for Quantum Computing



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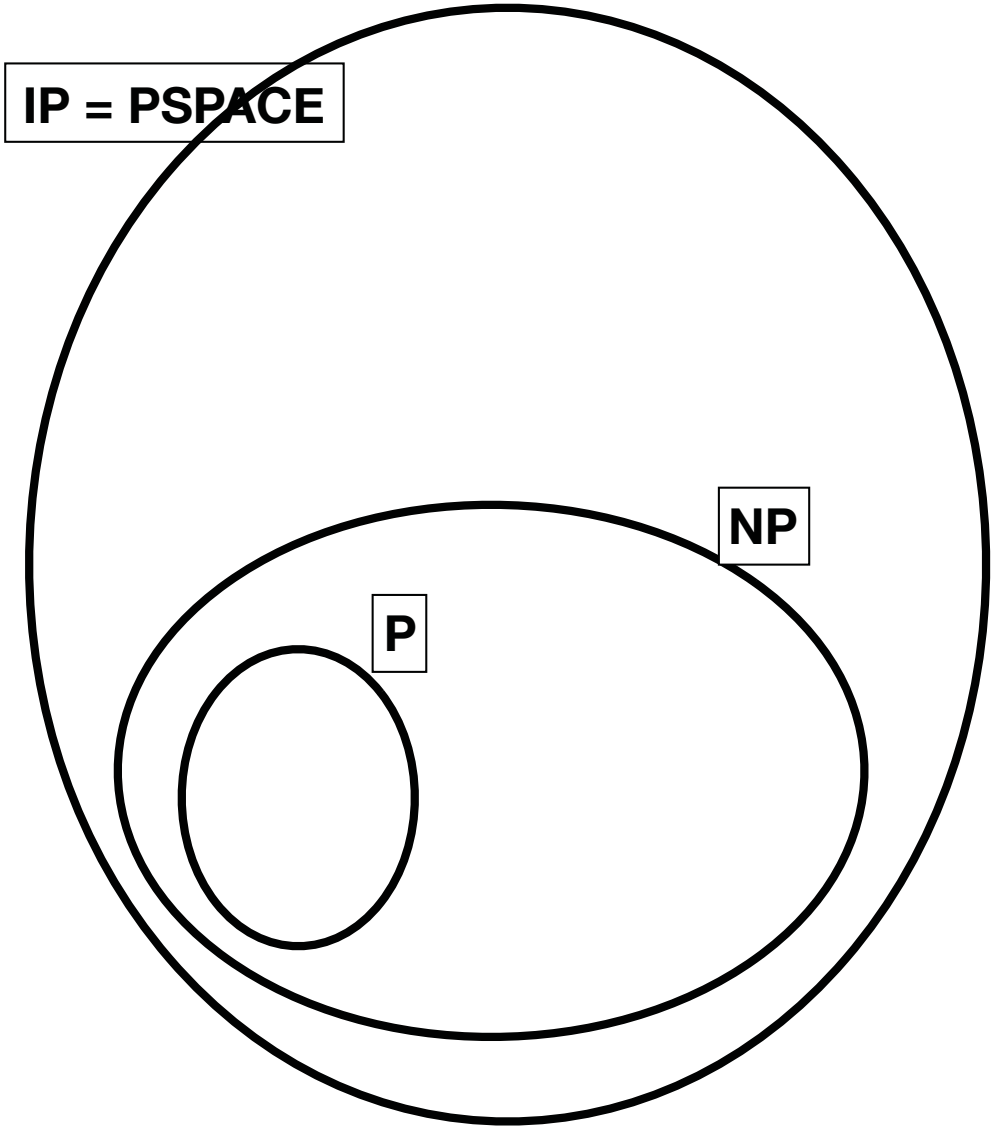
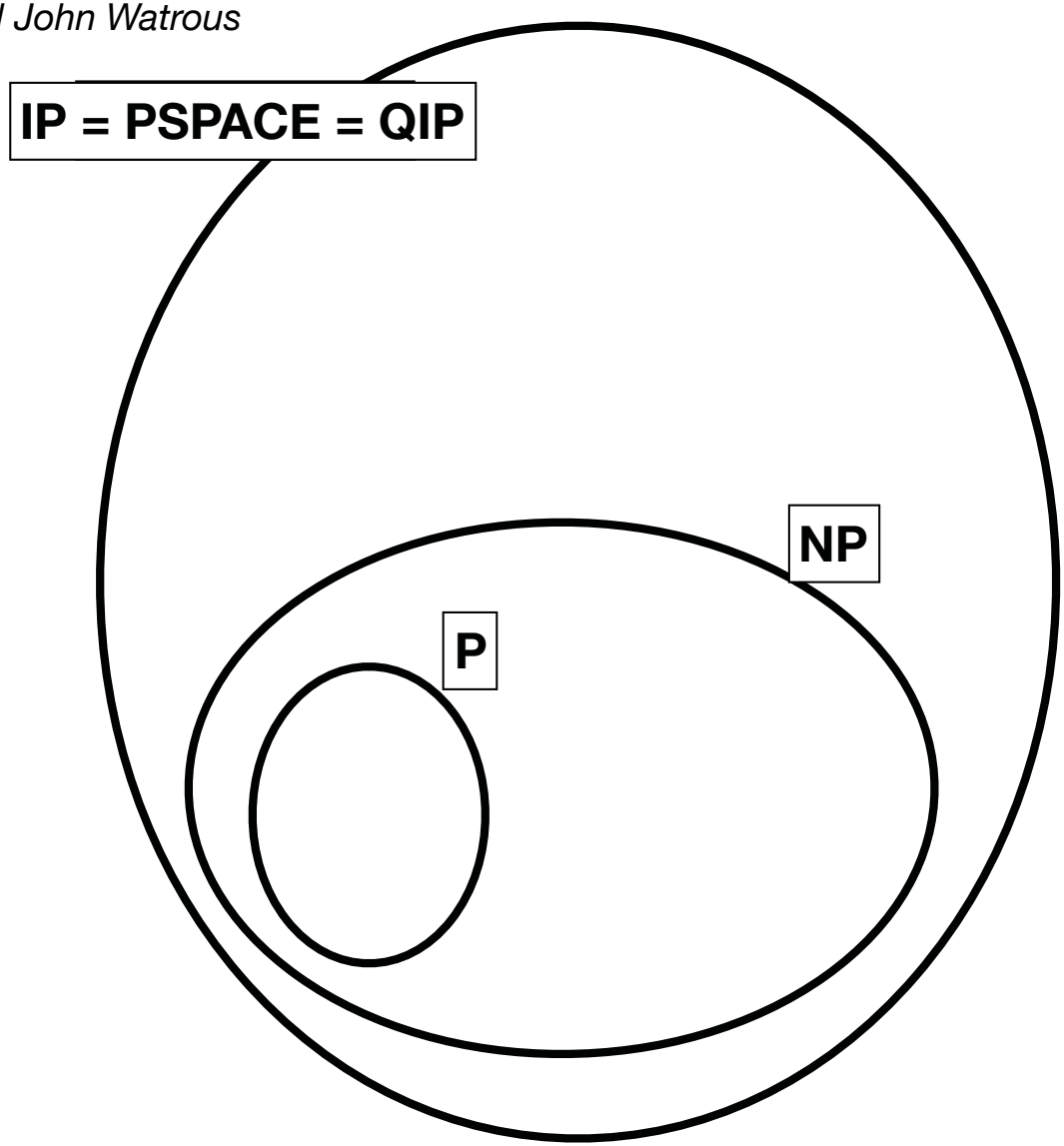
D. Aharonov and U. Vazirani, arXiv:1206.3686 (2012).

IP for Quantum Computing



IP for Quantum Computing

Rahul Jain, Zhengfeng Ji, Sarvagya Upadhyay, and John Watrous



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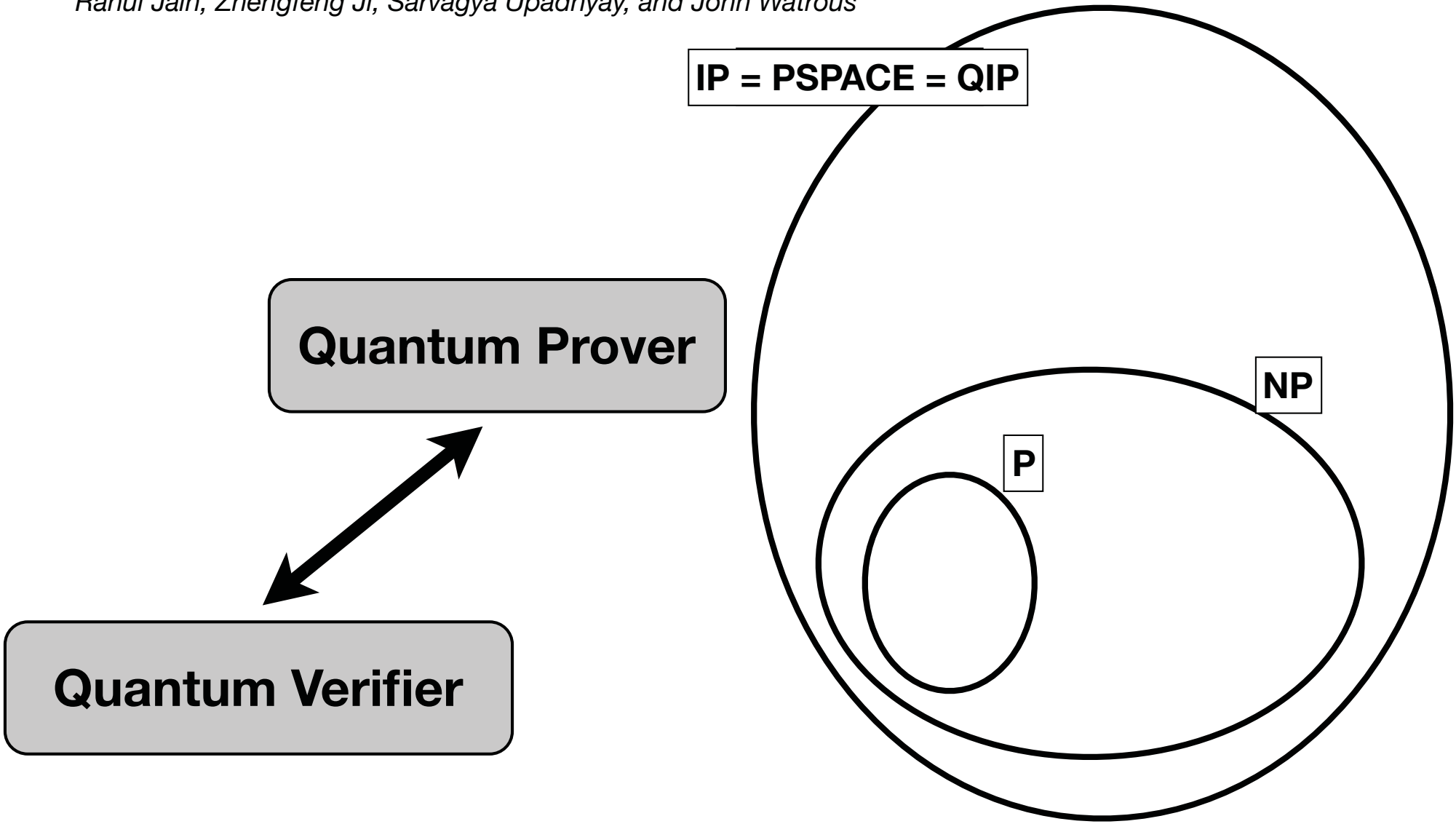

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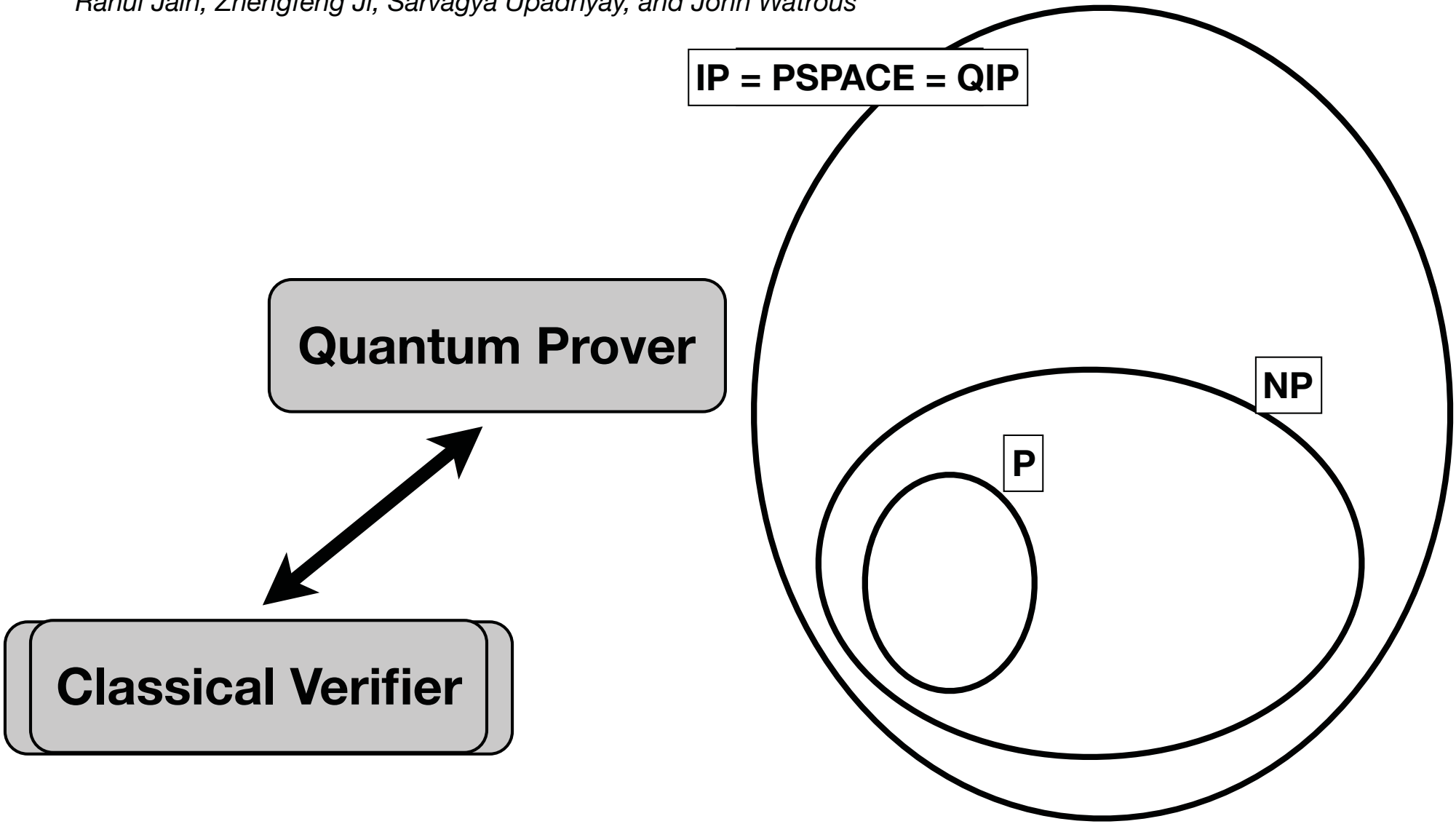

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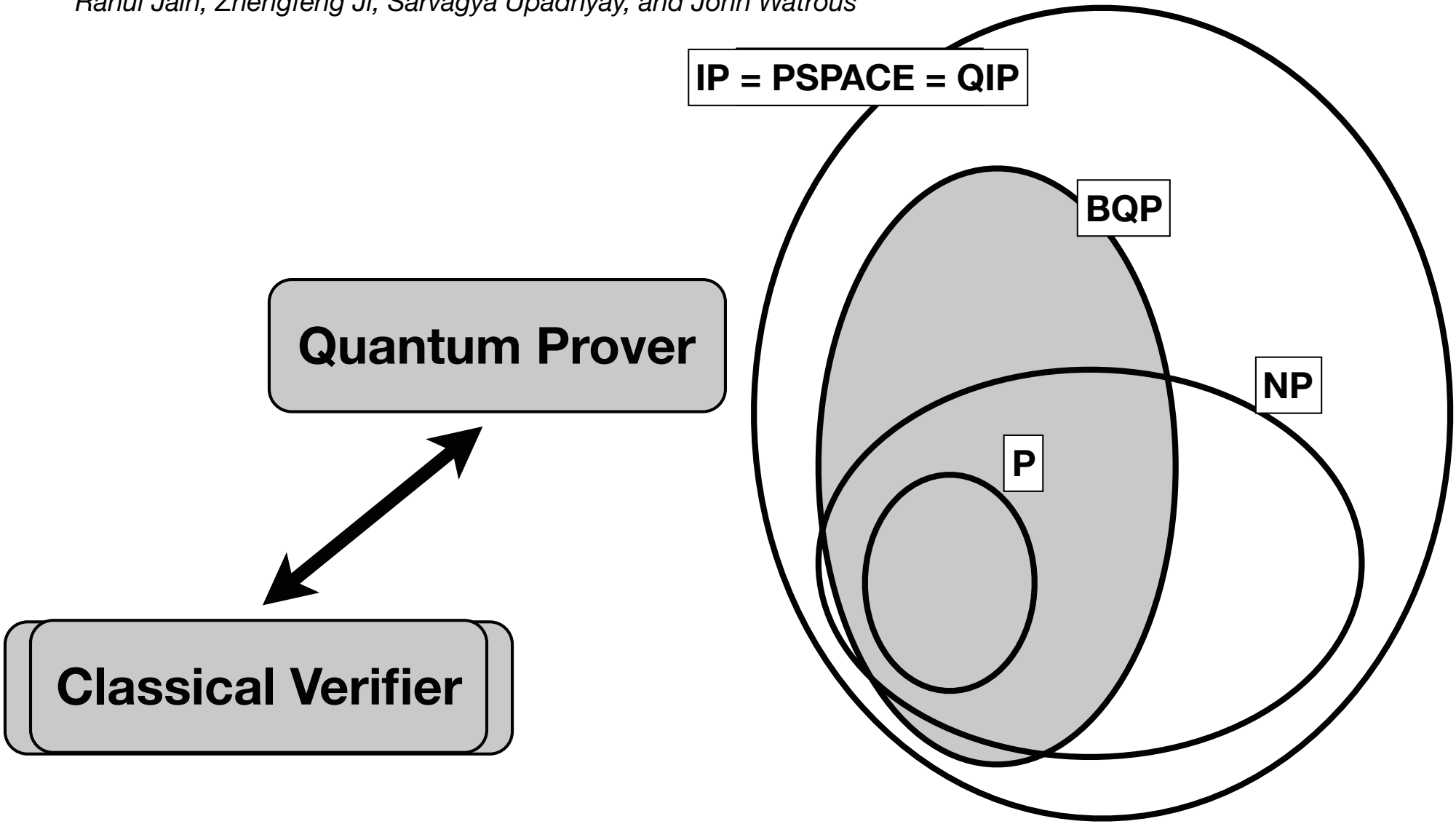

Hiding Complexity

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Encryption

Enables Secure Communication

Access to data is all or nothing

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Encryption

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Access to data is all or nothing

Modern Encryption

Enables arbitrary computation on encrypted data ***without decrypting***

Holy Grail of Cryptography since 1987

Rivest, Adleman and Dertouzos

Can we process encrypted data without decrypting it

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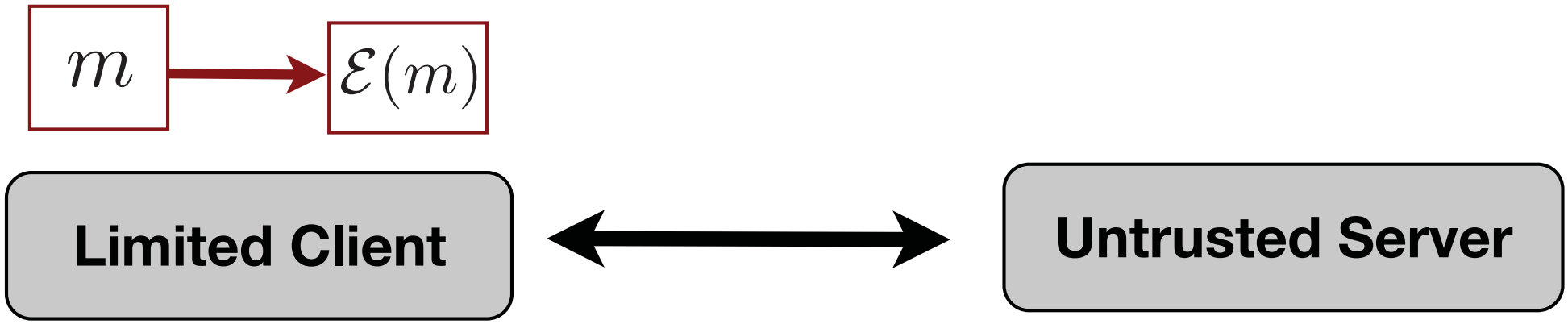

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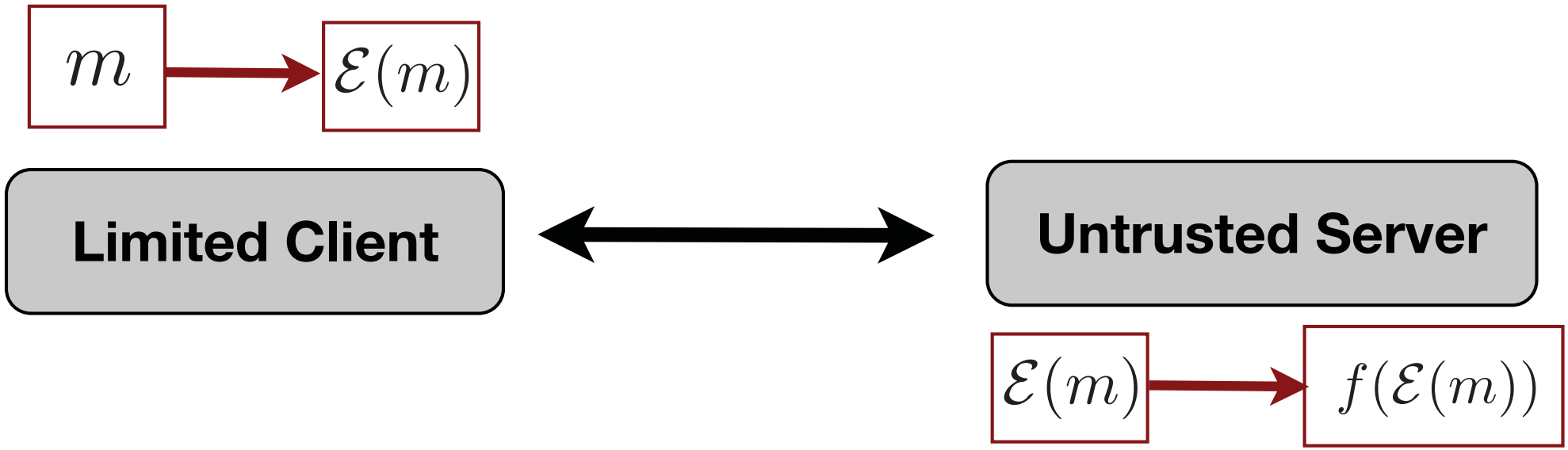

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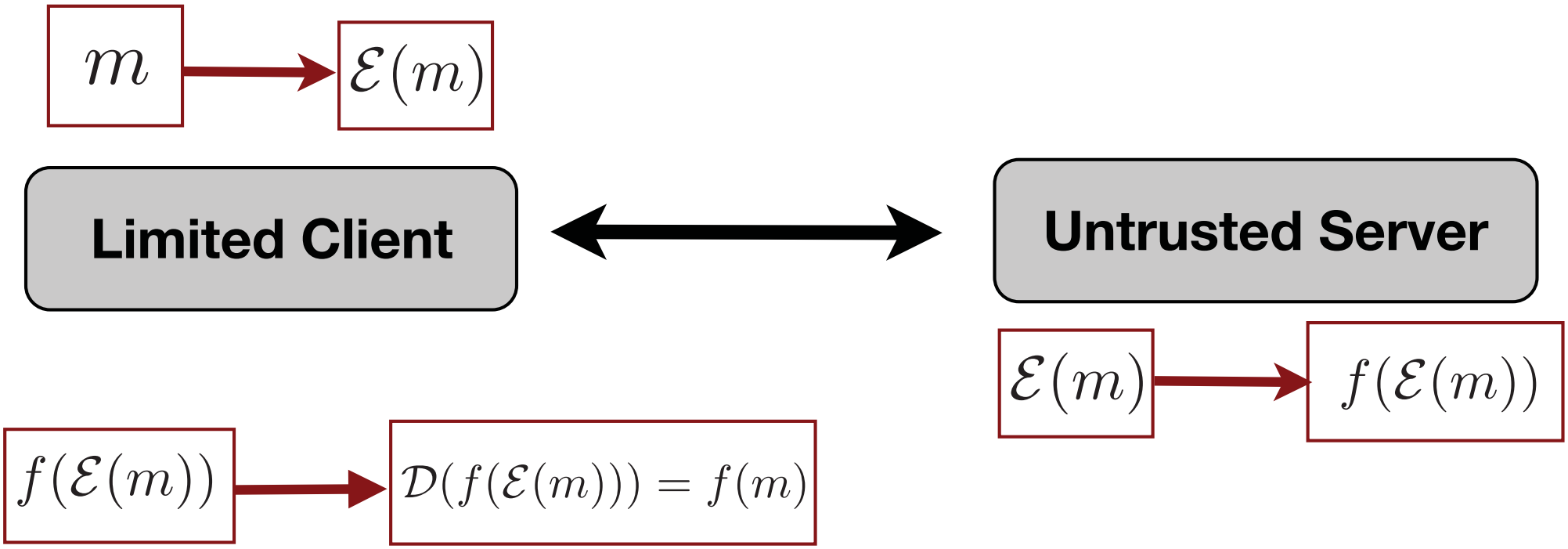

Fully Homomorphic Encryption (FHE)

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Gentry 09: A Lattice-based cryptosystem that is fully homomorphic

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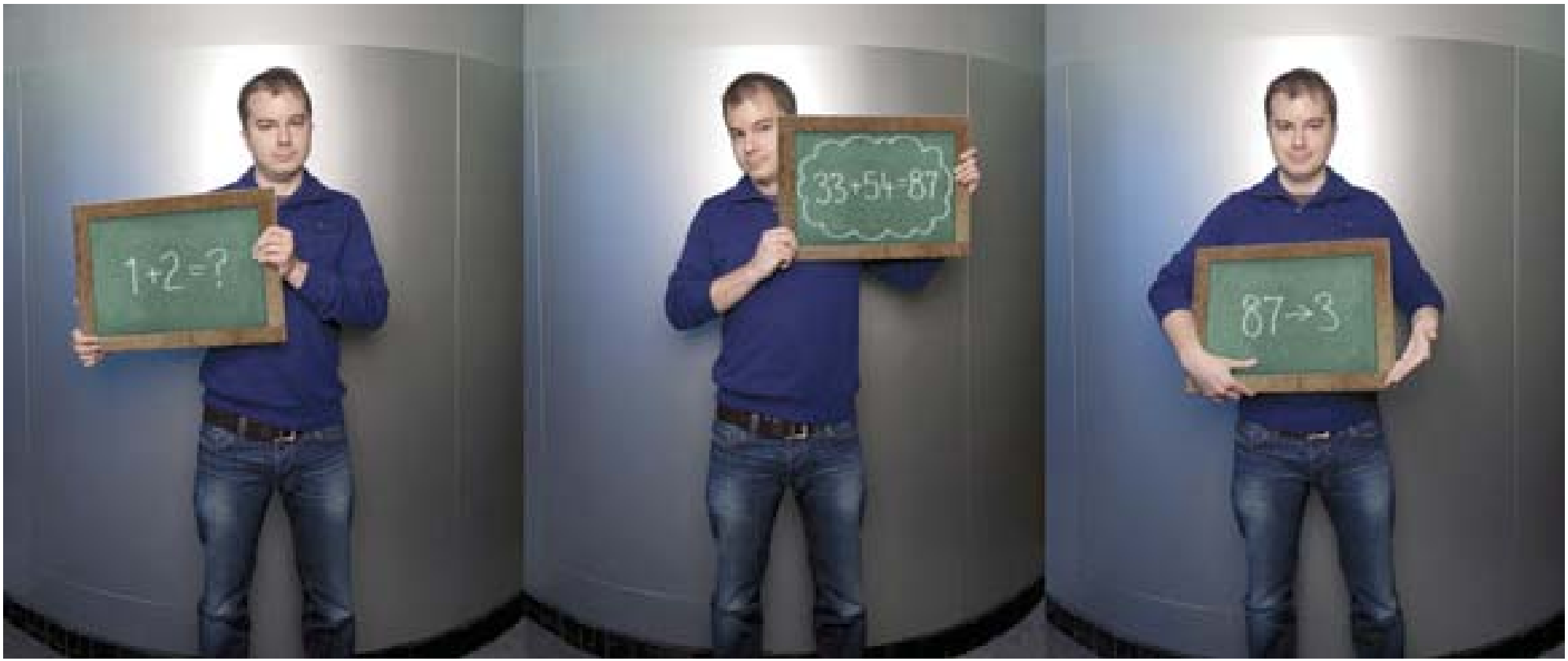

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3278764873692384398479478394739487234997938798370947005983095830958094850349850498487 9ut9875937493

+ %^&&£££$%

590094867-3498674-0967590674589764597 65-9067459685489765498765468978745943580487568760876508457095

Fully Homomorphic Encryption (FHE)

Gentry 09: A Lattice-based cryptosystem that is fully homomorphic

Long Key
Complicated Server Operations
Computational Security

Applications

Secure Cloud

Remote File Storage

Secure Multi Party Computation

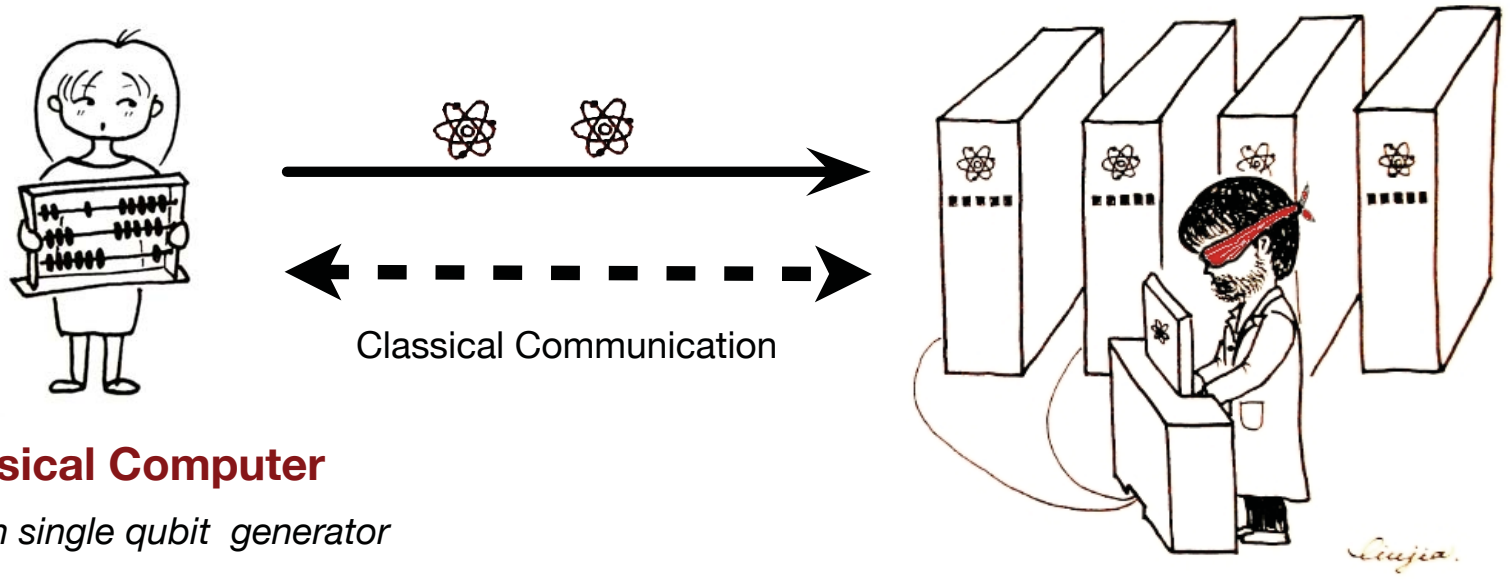
Verification of Outsourced Computation

Short Proof of Knowledge

....

Universal Blind Quantum Computing (UBQC)

Broadbent, Fitzsimons and Kashefi 09: Quantum Key Distribution + Quantum Teleportation



Classical Computer

random single qubit generator

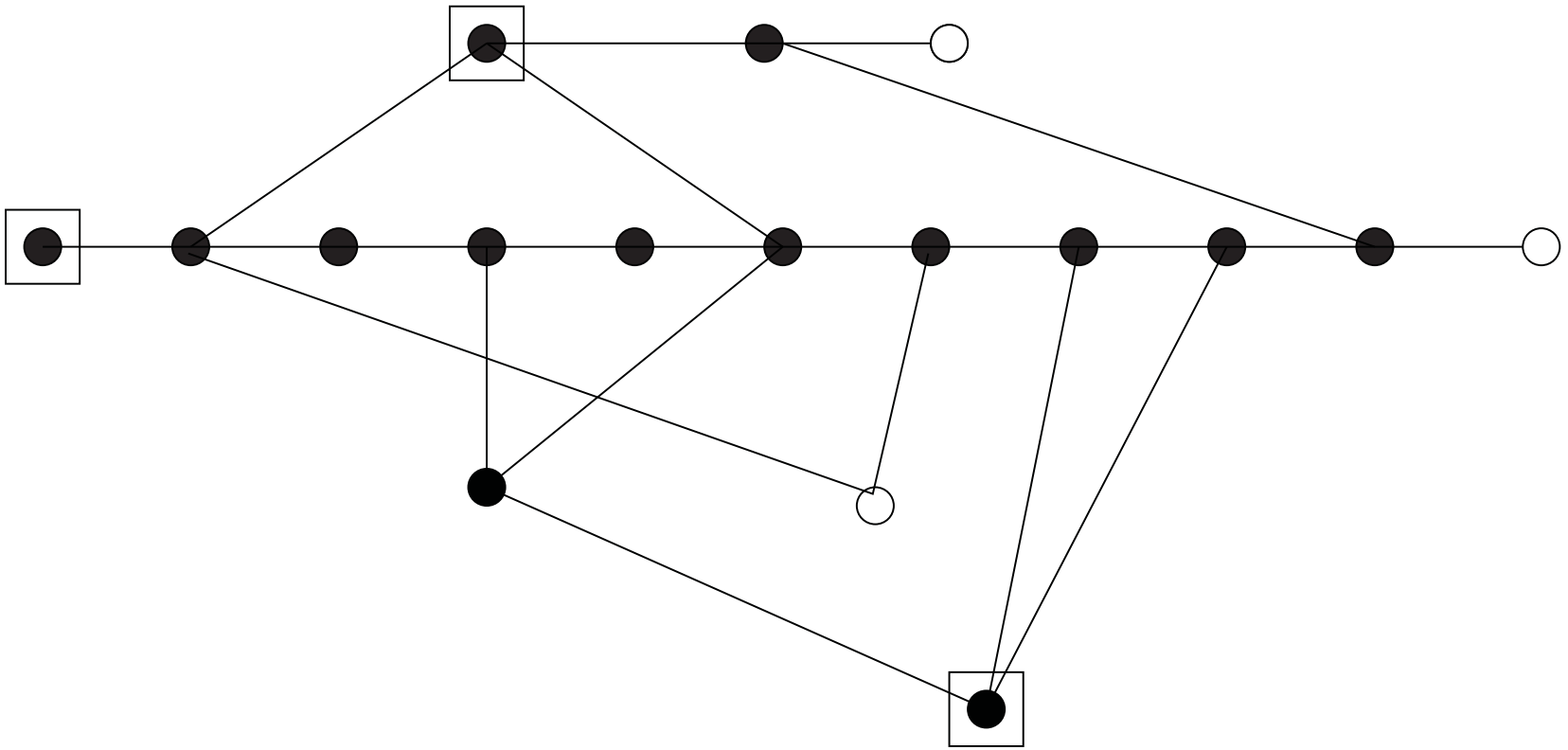
Unconditional Perfect Privacy

Server learns nothing about client's input/output/computation

Measurement-based QC

- New qubits, to prepare the auxiliary qubits: N
- Entanglements, to build the quantum channel: E
- Measurements, to propagate (manipulate) qubits: M
- Corrections, to make the computation deterministic: C

Quantum Pacman



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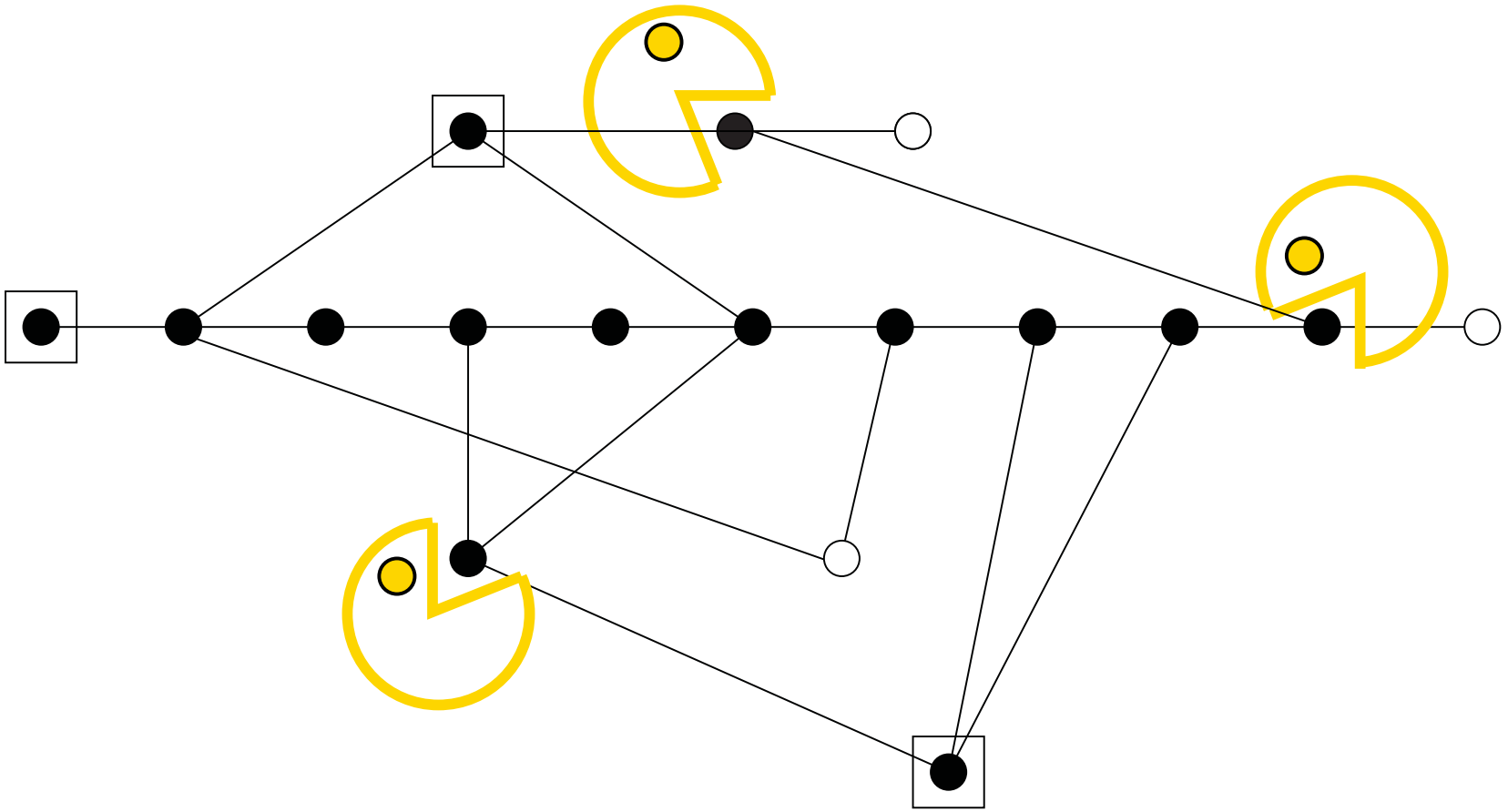

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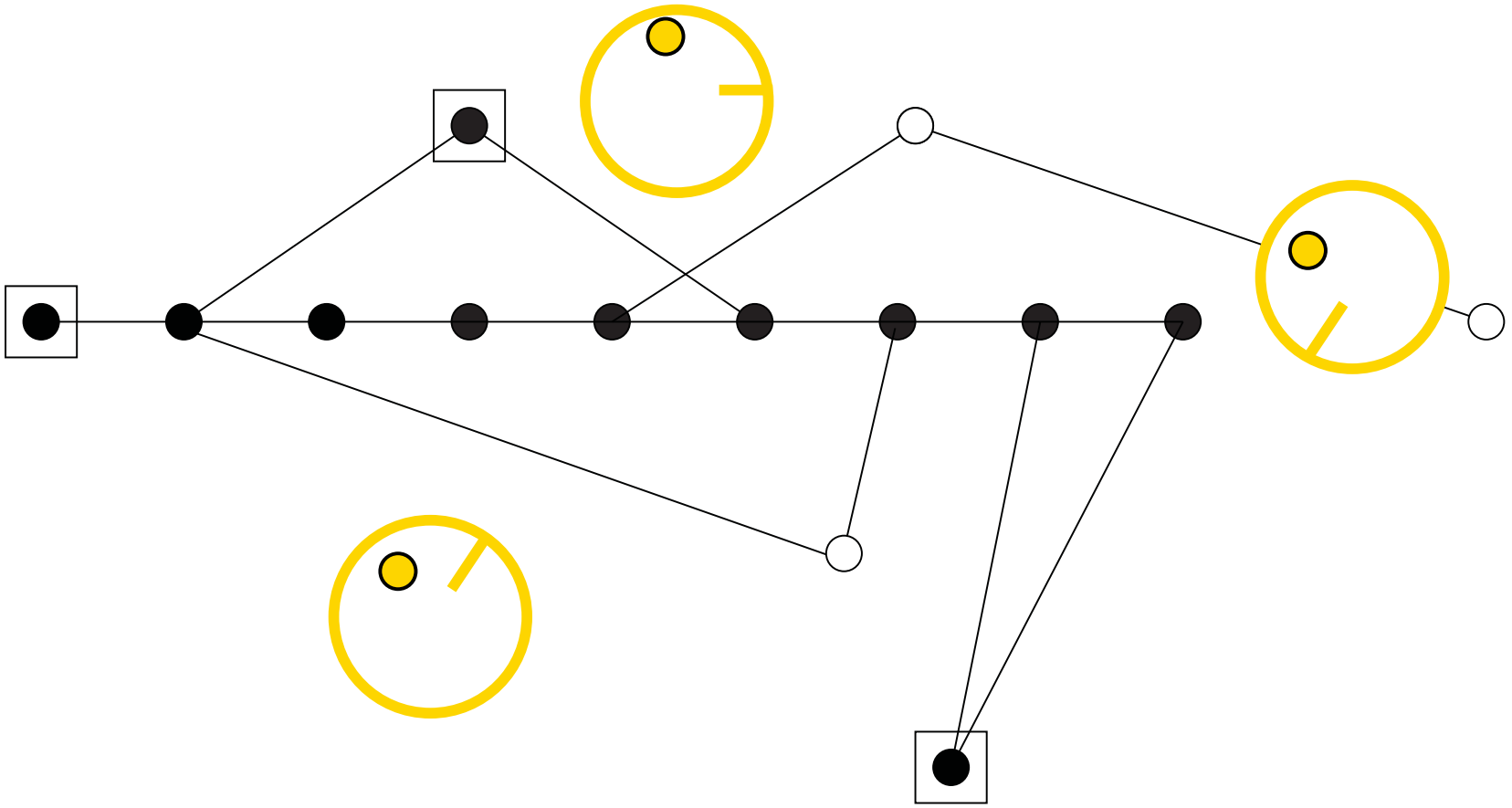

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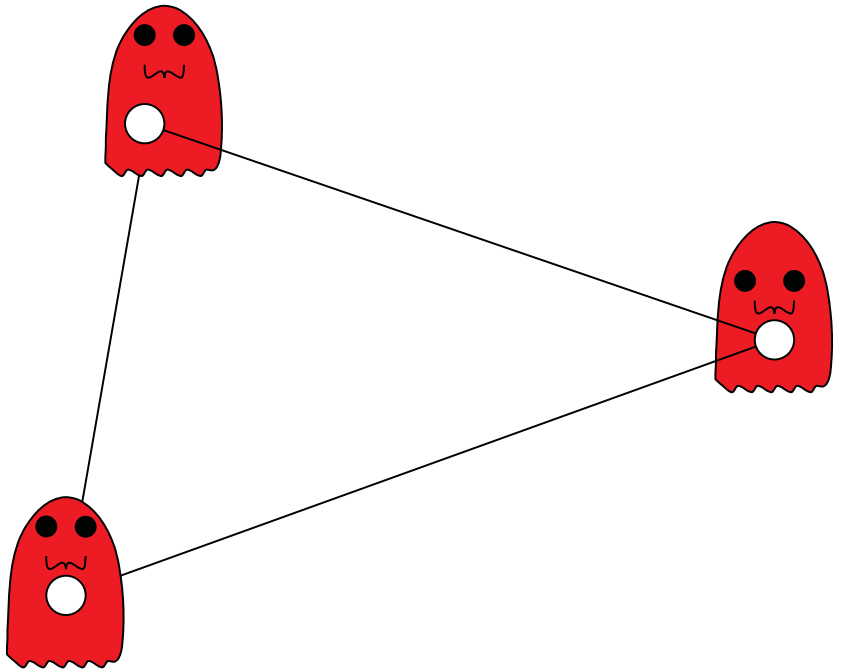
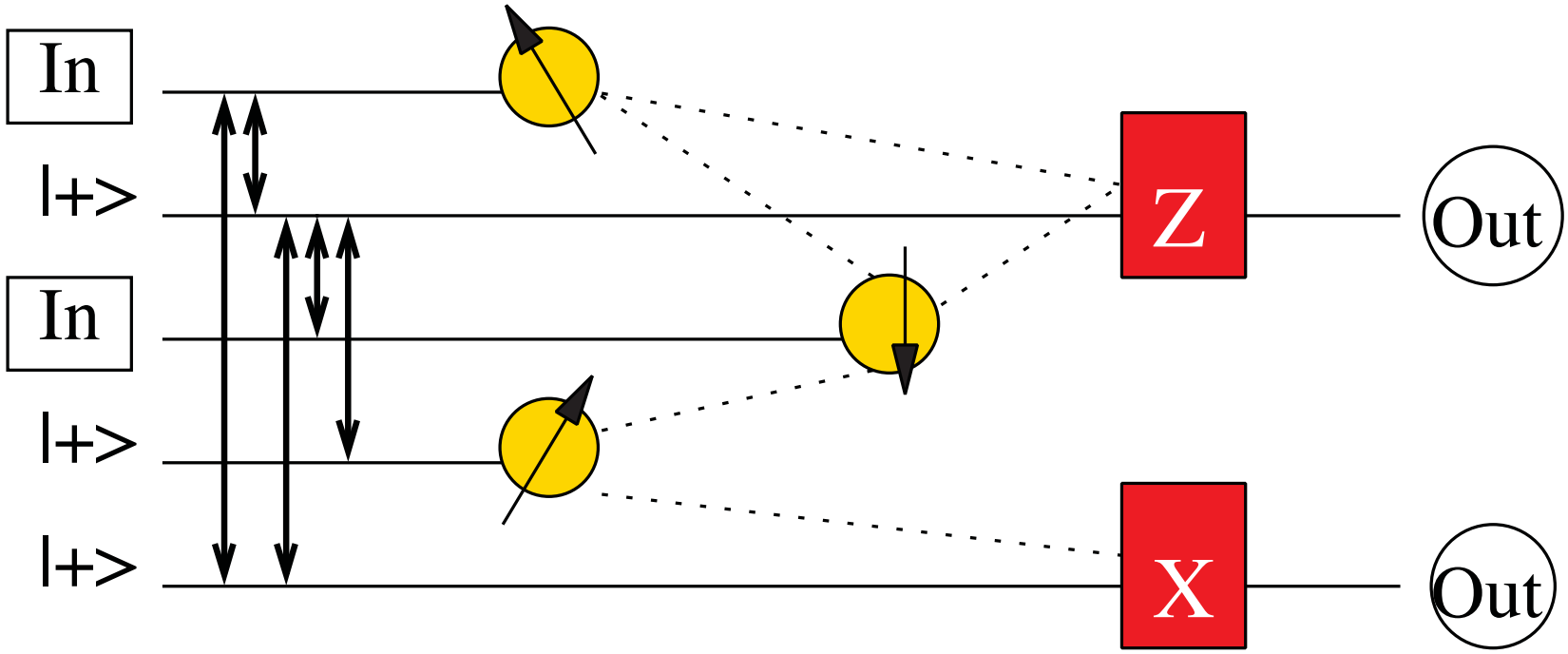
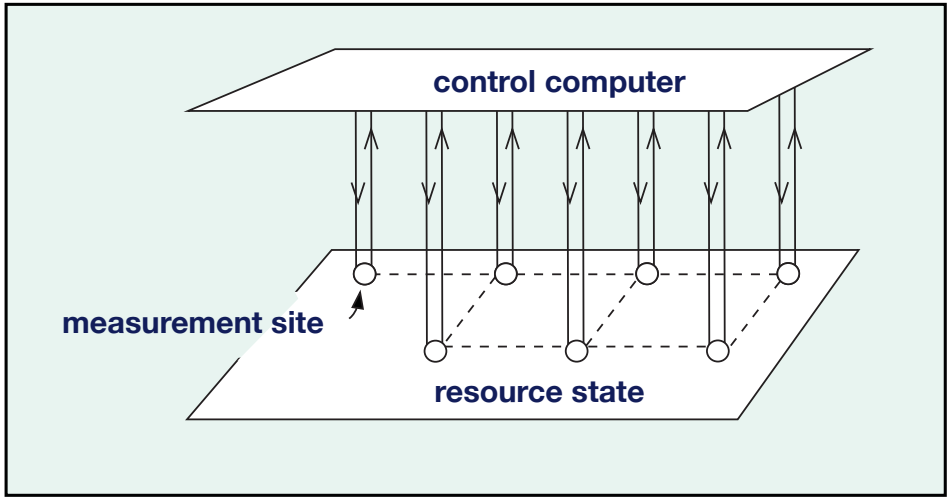


Circuit Picture



Formal Calculus

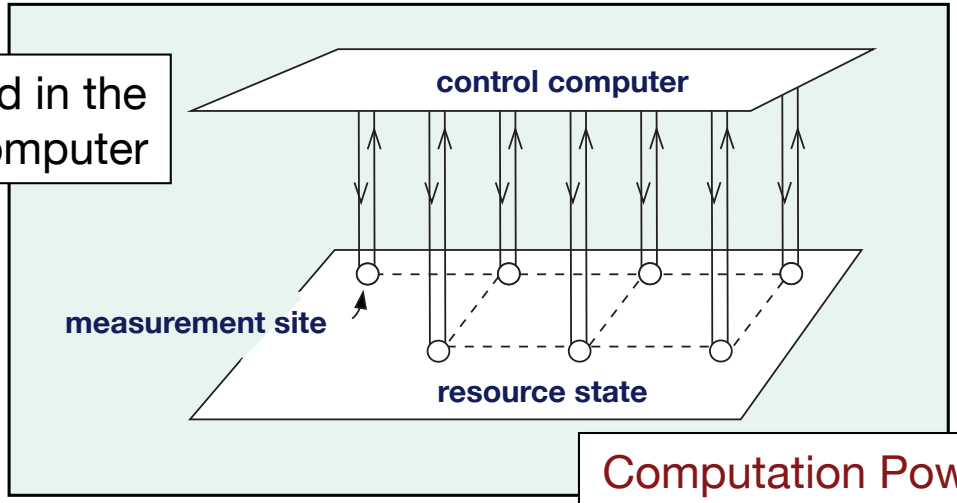
Kashefi et.al. Measurement Calculus JACM 2007



Formal Calculus

Kashefi et.al. Measurement Calculus JACM 2007

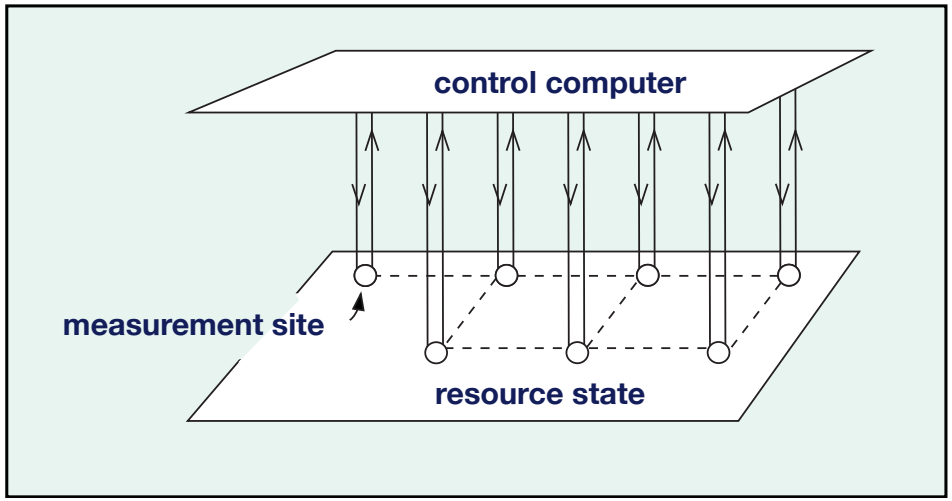
Program is encoded in the classical control computer



Computation Power is encoded in the quantum entanglement

Hiding in MBQC

Program is encoded in the classical control computer
Computation Power is encoded in the entanglement

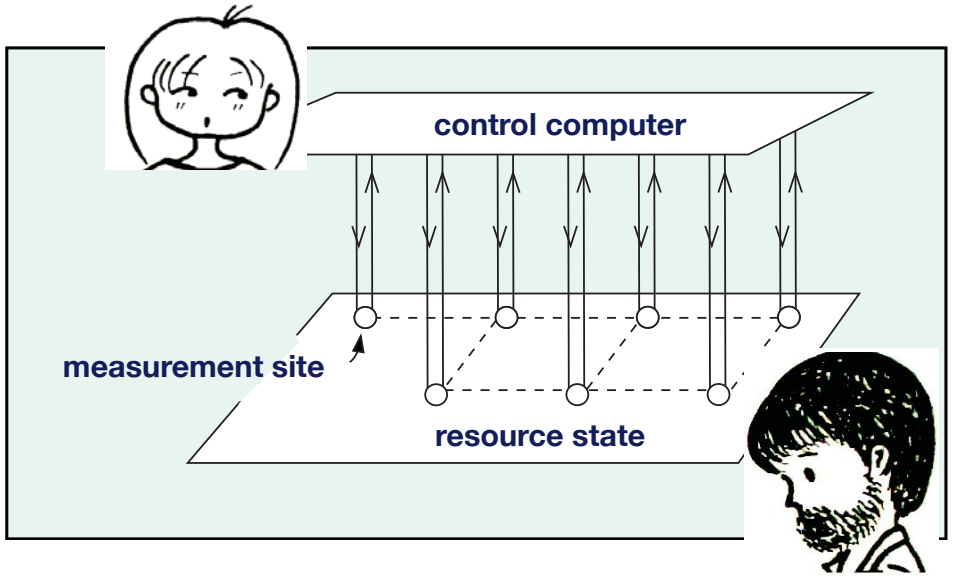


Raussendorf and Briegel, PRL, 2001

Danos, Panangaden, Kashefi, JACM, 2009

Hiding in MBQC

Program is encoded in the classical control computer
Computation Power is encoded in the entanglement



Raussendorf and Briegel, PRL, 2001

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Hiding in MBQC

$$J(\alpha) \;:=\; \tfrac{1}{\sqrt{2}} \begin{pmatrix} 1 & e^{i\alpha} \\ 1 & -e^{i\alpha} \end{pmatrix}$$

Hiding in MBQC

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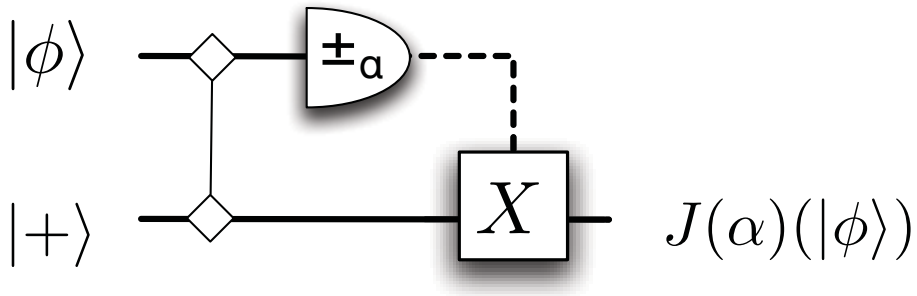
gate teleportation



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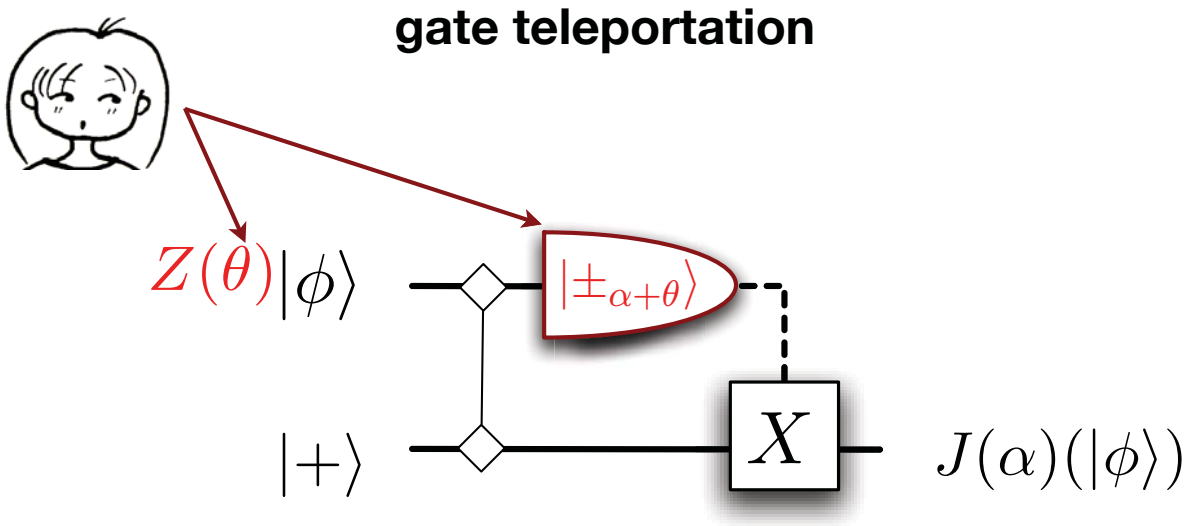

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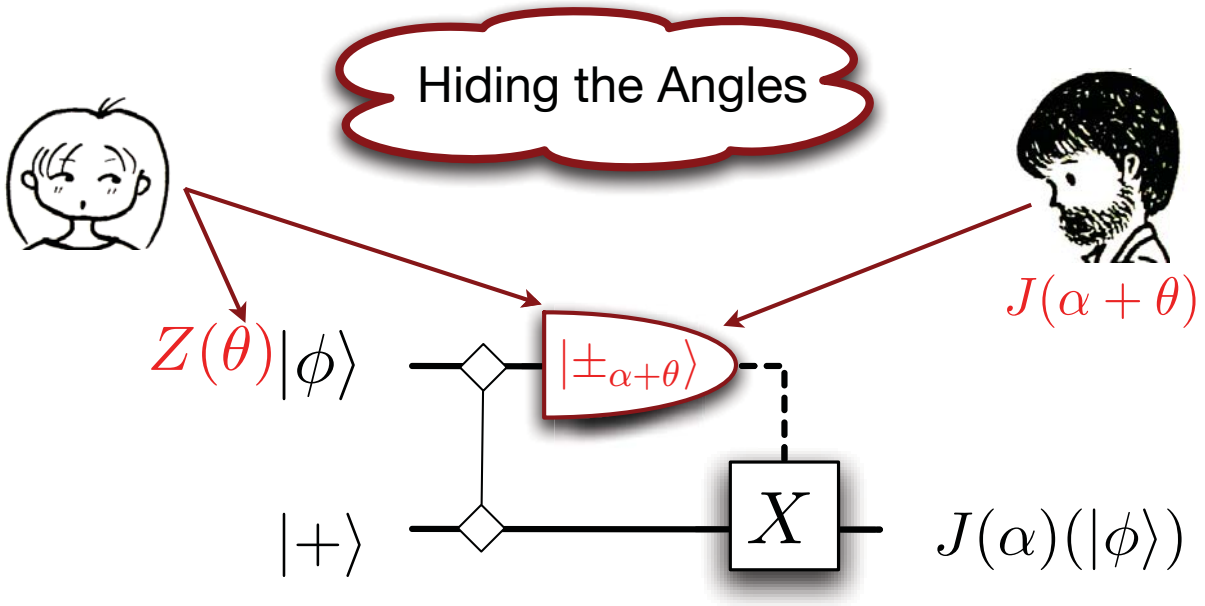
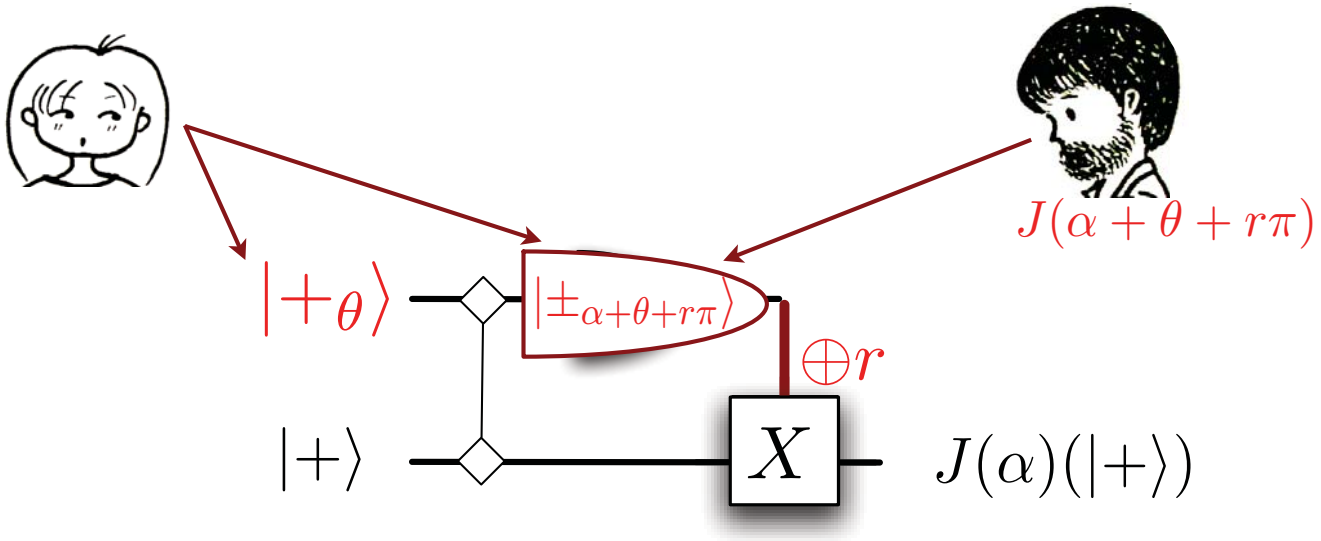


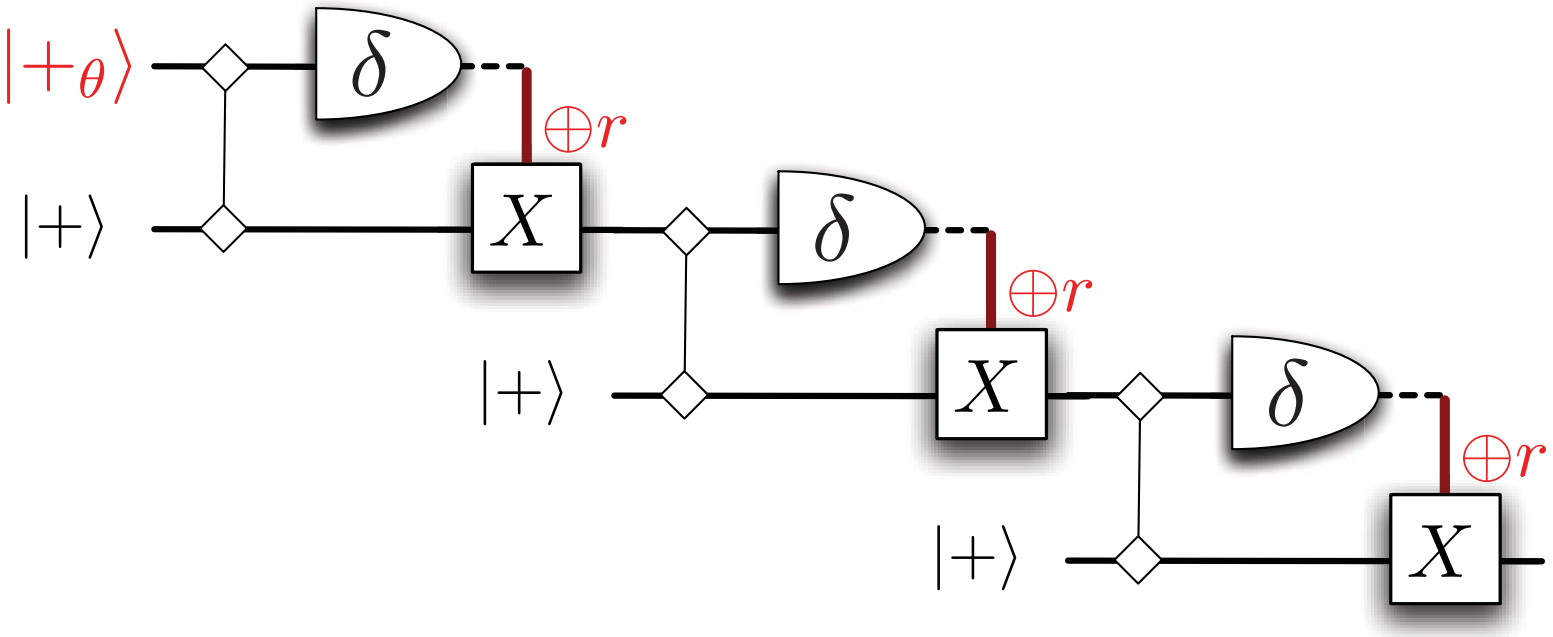
Thinking inside the box

$$J(\alpha) := \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & e^{i\alpha} \\ 1 & -e^{i\alpha} \end{pmatrix}$$



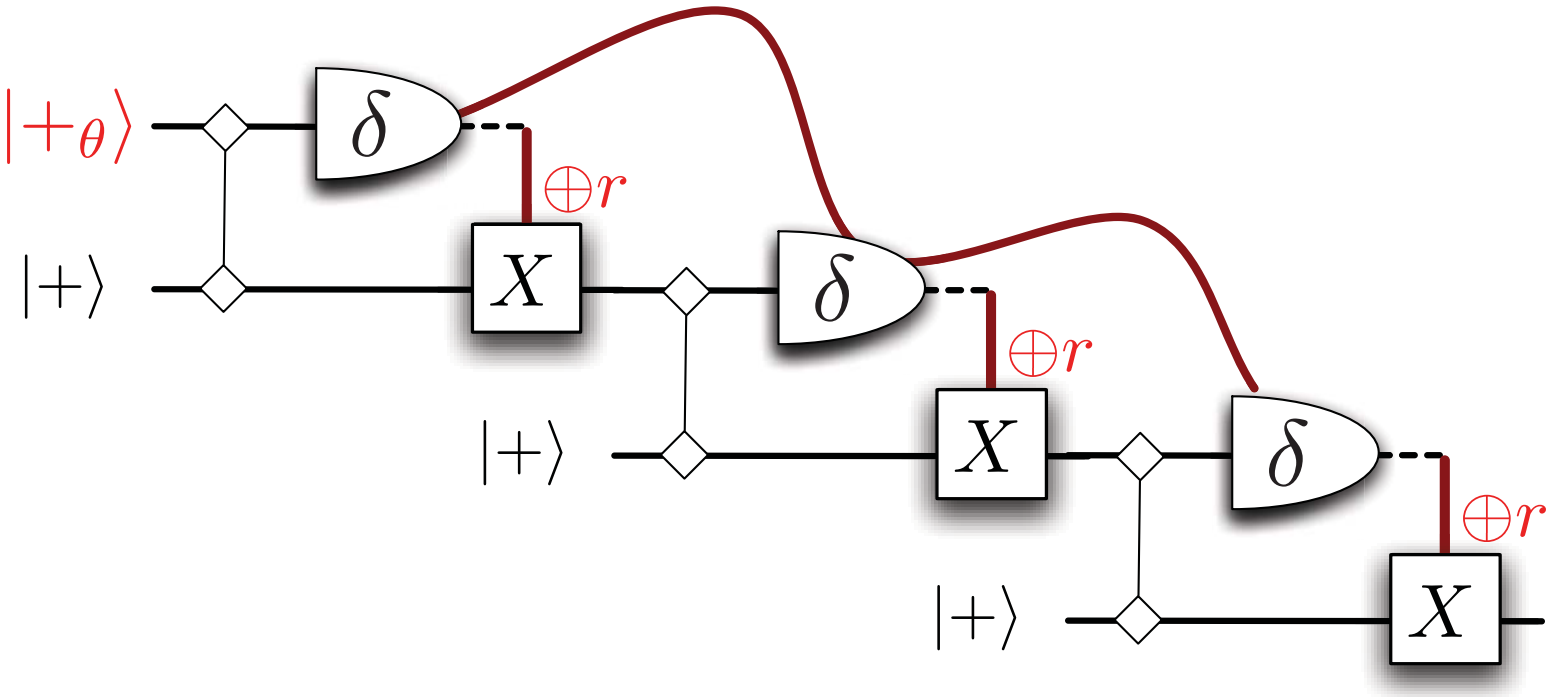
Hiding the measurement result

Gates Composition



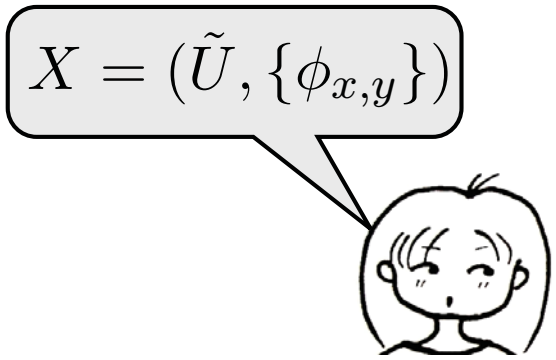
Client-Server interactions

Gates Composition



Client-Server interactions

Universal Blind Quantum Computing



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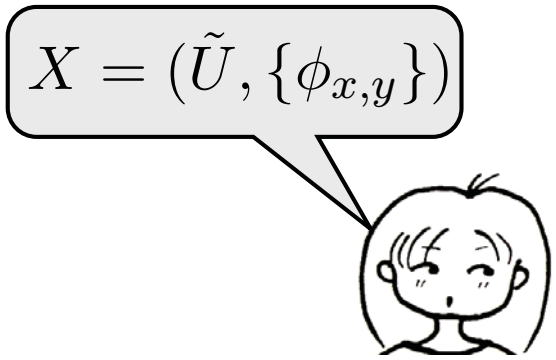
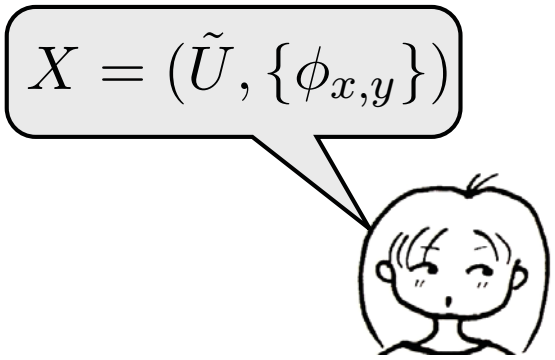


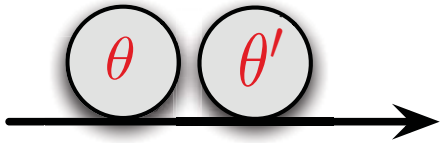
random single qubit generator

$$1/\sqrt{2}\left(|0\rangle + e^{i\theta}\,|1\rangle\right)$$

$$\theta = 0, \pi/4, 2\pi/4, \ldots, 7\pi/4$$

Universal Blind Quantum Computing





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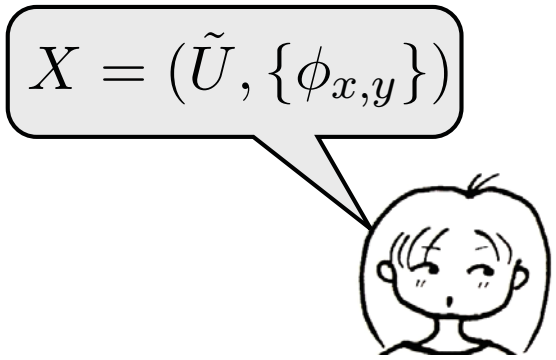

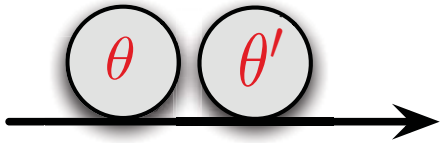

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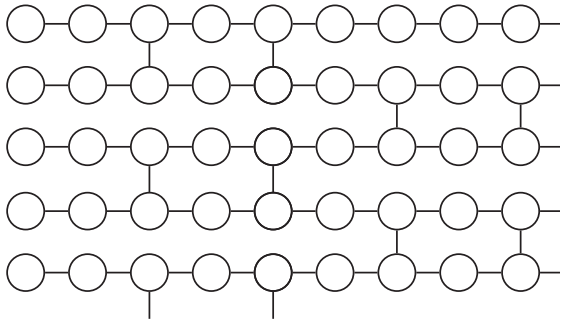

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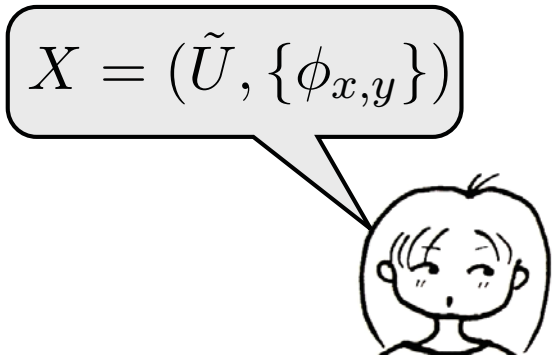

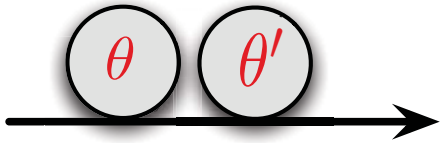

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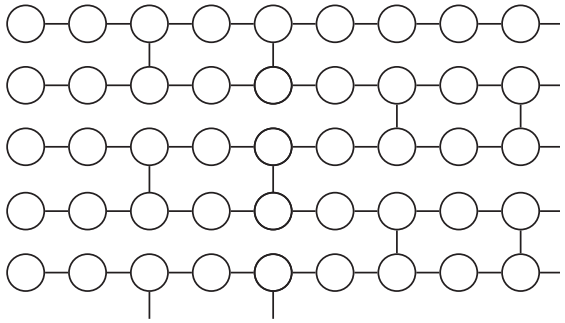
$$r_{x,y} \in_R \{0,1\}$$

$$\delta_{x,y} = \phi'_{x,y} + \theta_{x,y} + \pi r_{x,y}$$



Universal Blind Quantum Computing

$X = (\tilde{U}, \{\phi_{x,y}\})$

random single qubit generator

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θ θ'

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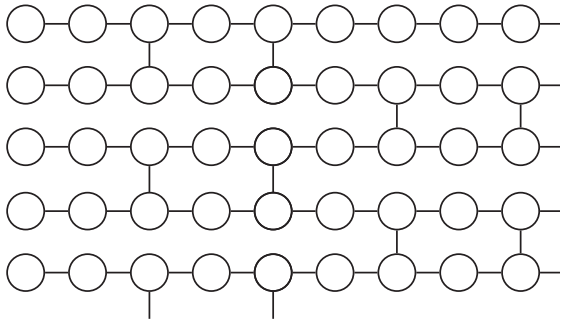

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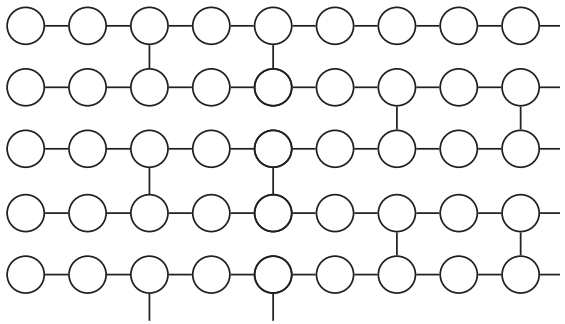

$$\left\{\left|+\delta_{x,y}\right\rangle, \left|-\delta_{x,y}\right\rangle\right\}$$

Universal Blind Quantum Computing

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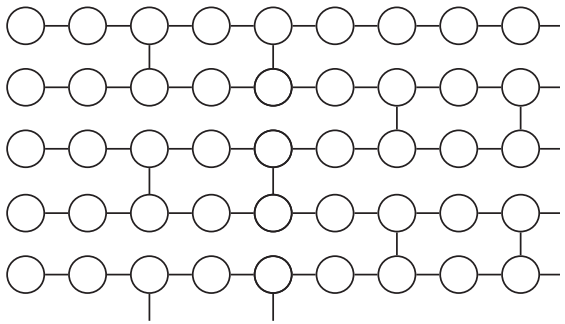

$s_{x,y} \in \{0,1\}$

$\{|+_{\delta_{x,y}}\rangle, |-_{\delta_{x,y}}\rangle\}$

Universal Blind Quantum Computing

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random single qubit generator

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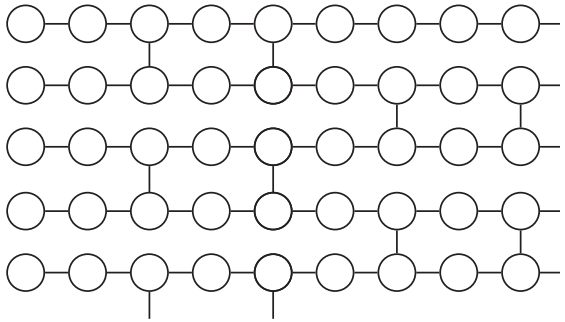


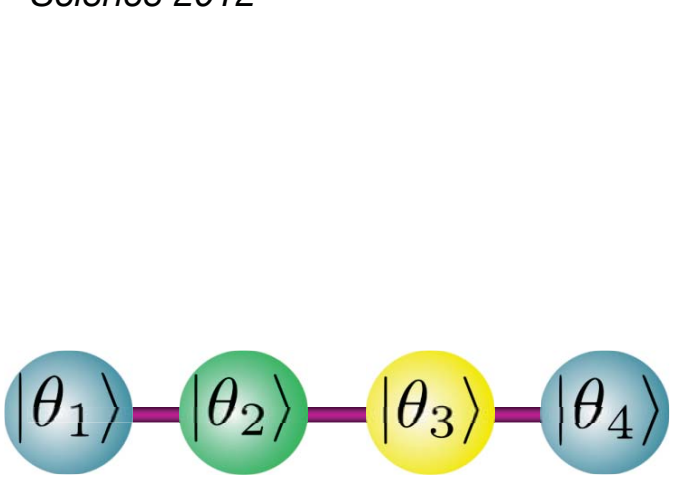
$\{|+_{\delta_{x,y}}\rangle, |-_{\delta_{x,y}}\rangle\}$

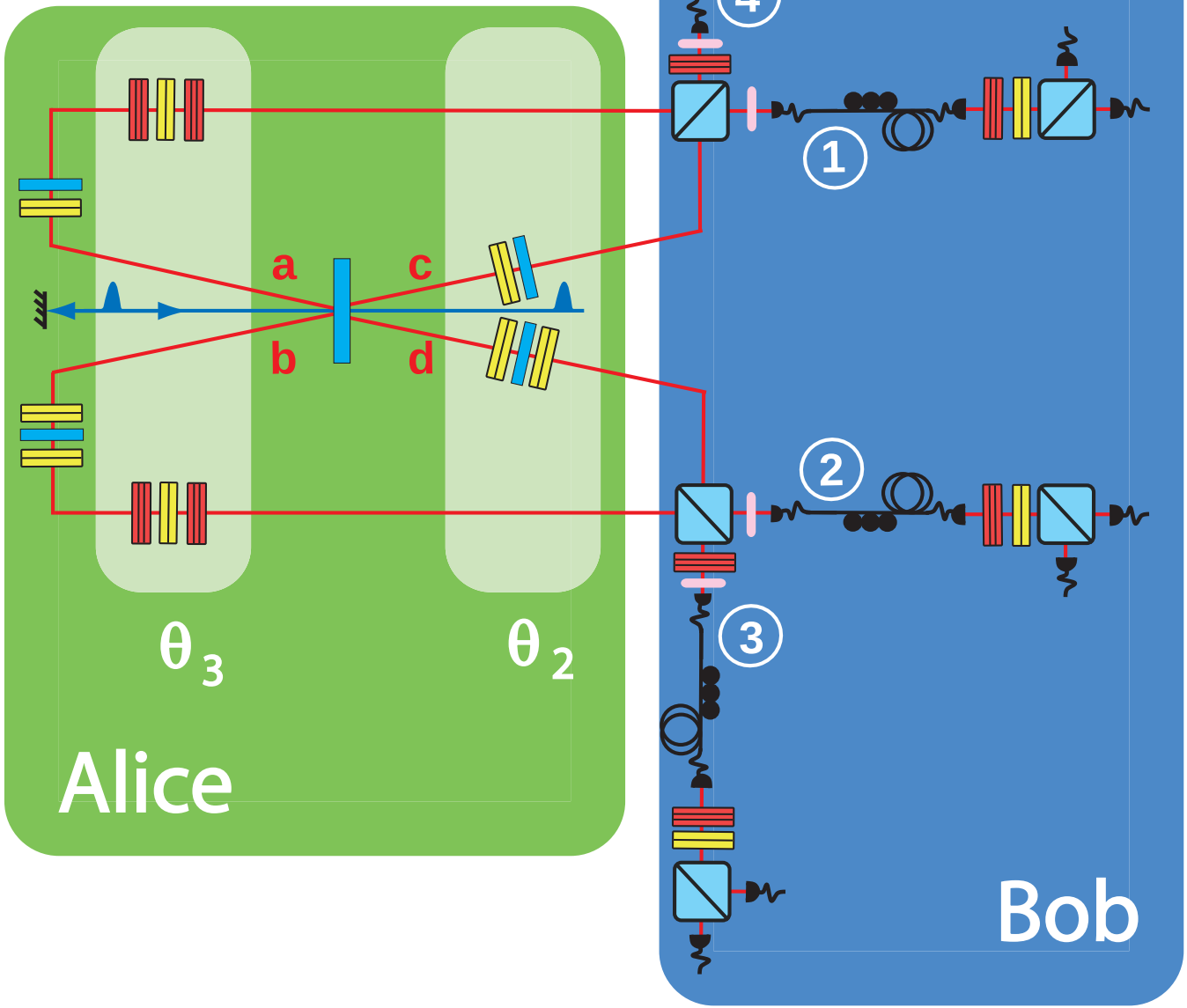
$s_{x,y} \in \{0,1\}$

$s_{x,y} := s_{x,y} + r_{x,y}$

Experimental Implementation

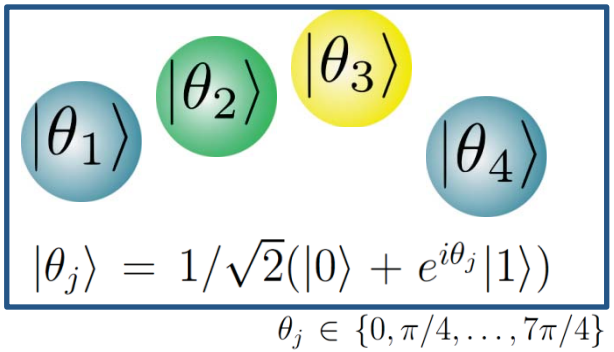
S. Barz, E. Kashefi, A. Broadbent, J. Fitzsimons, A. Zeilinger, P. Walther, Science 2012





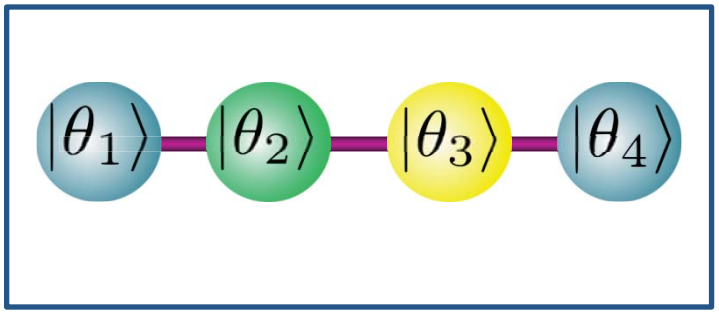
Experimental Implementation

Client:
limited computational power



Prepares random qubits

Quantum server:
full power of Quantum Computation



Entangles qubits

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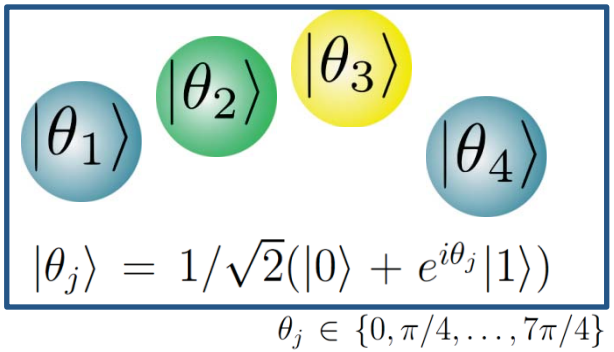

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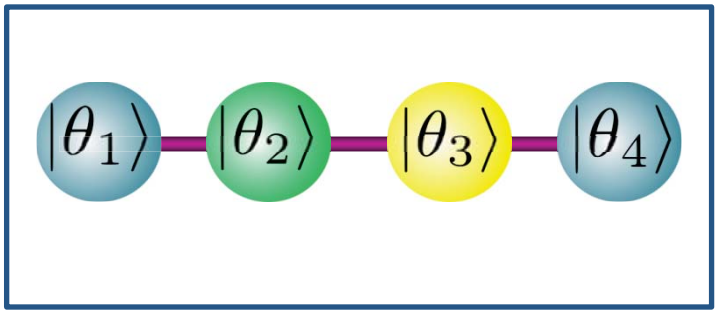


Entangles qubits

$$\delta_j = \theta_j + \phi_j + \pi r_j$$

Computes measurement angles

- Measurement instruction for server
- Initial rotation of the qubit
- Target rotation
- Random bit flip

Verification

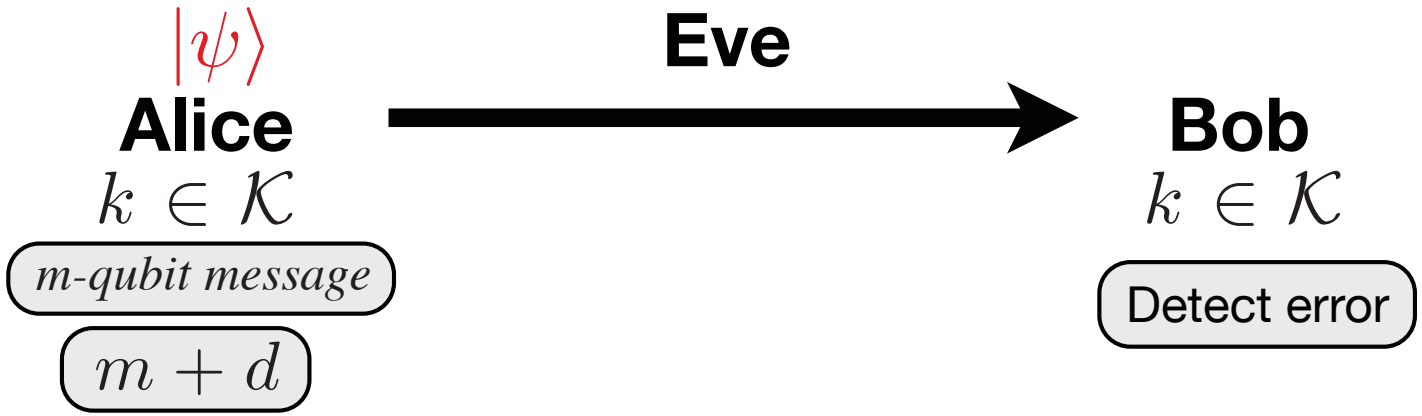
Verification

- Correctness: in the absence of any interference, client accepts and the output is correct

- Soundness: Verifier rejects an incorrect output, except with probability at most exponentially small in the security parameter

Fitzsimons and Kashefi, arXiv:1203.5217, 2012

Verification vs Authentication



Barnum, Crepeau, Gottesman, Smith and Tapp, FOCS02

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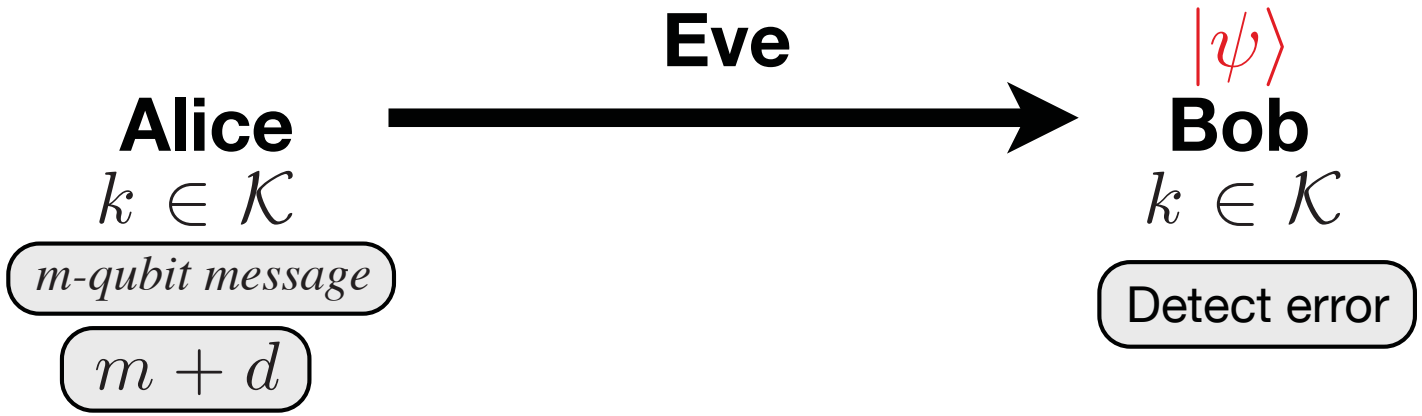

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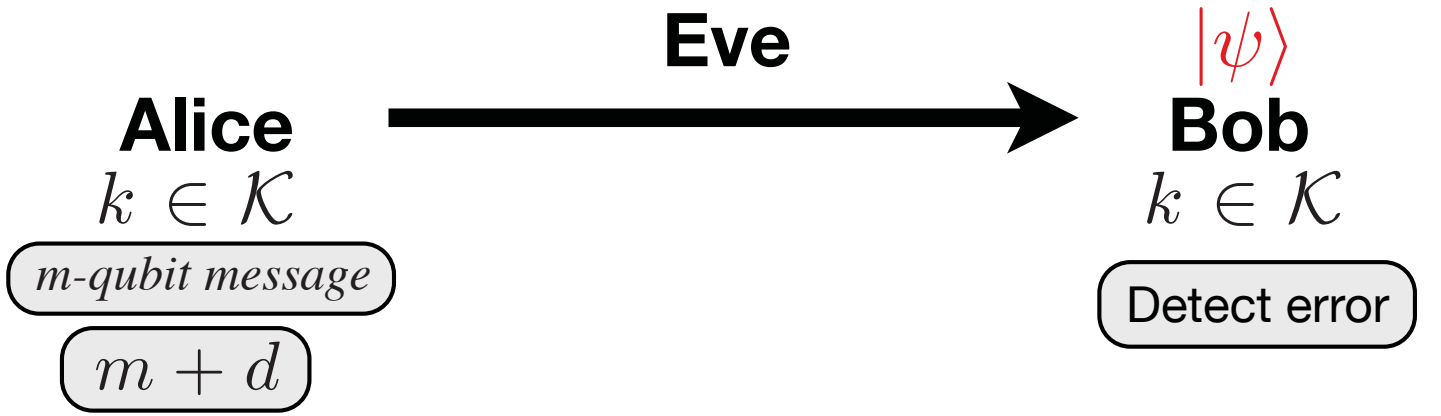

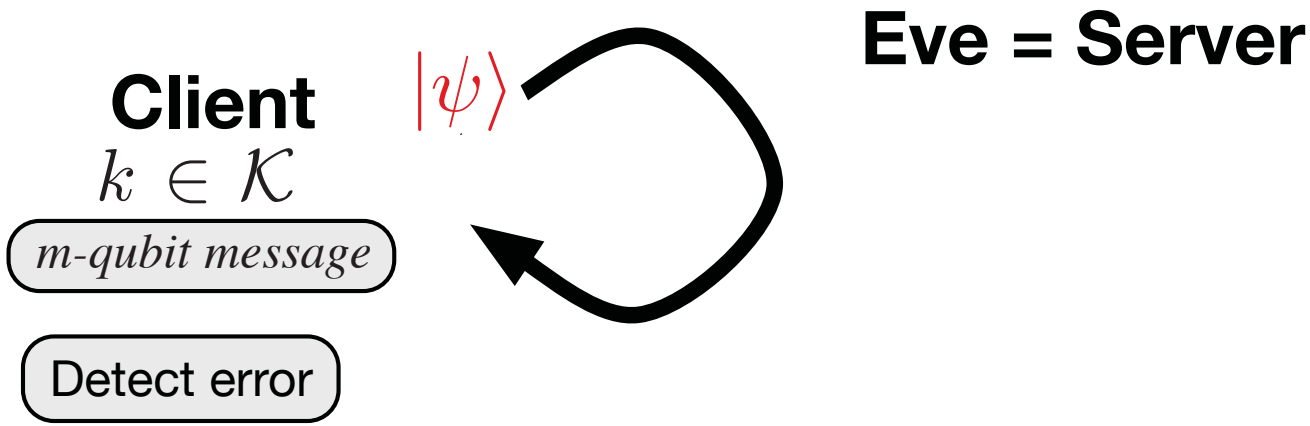

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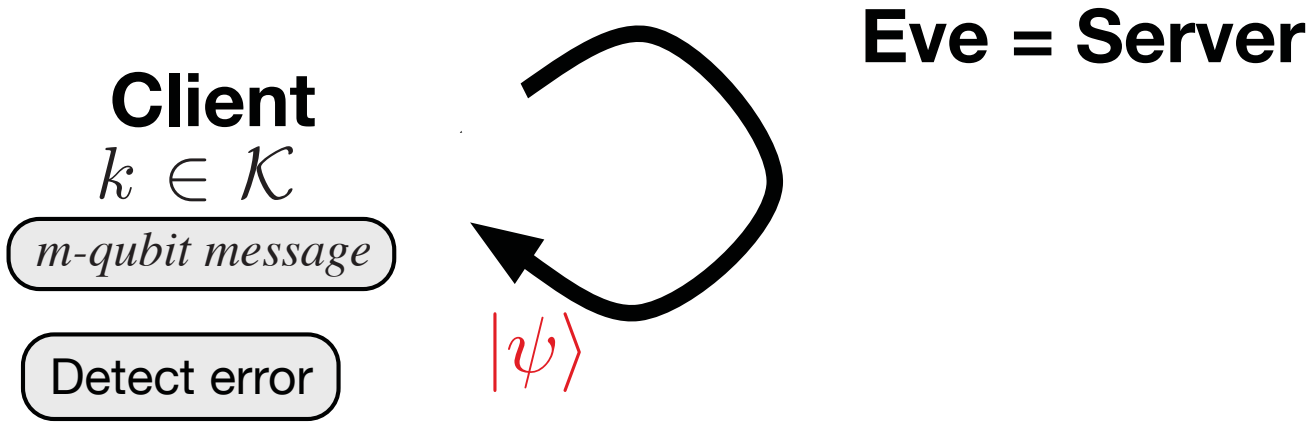

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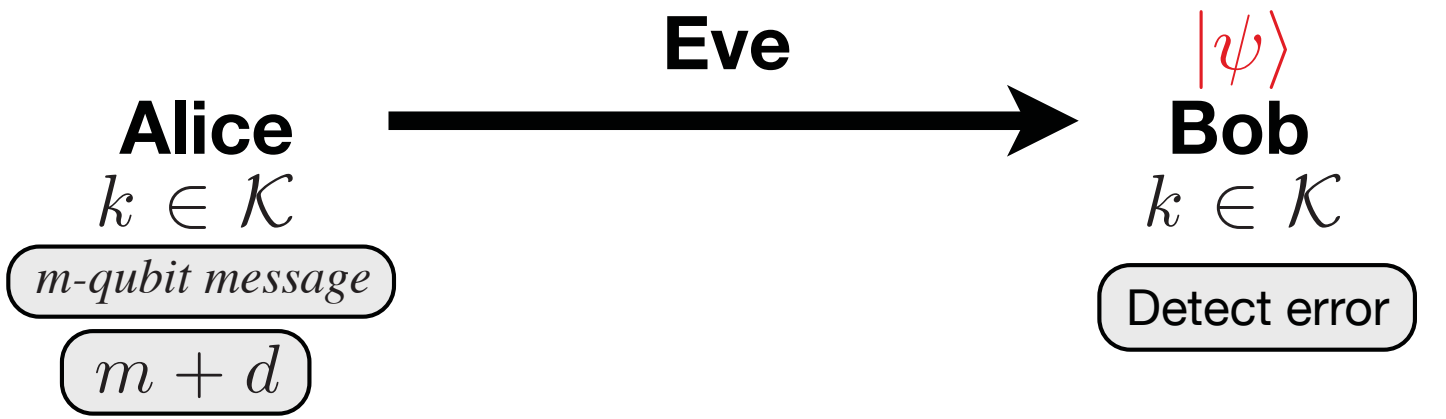

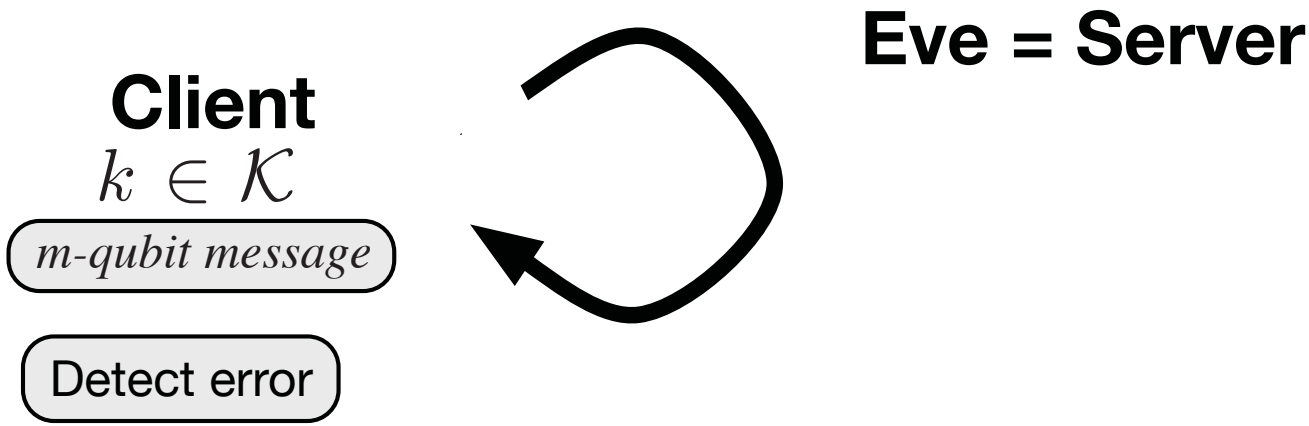

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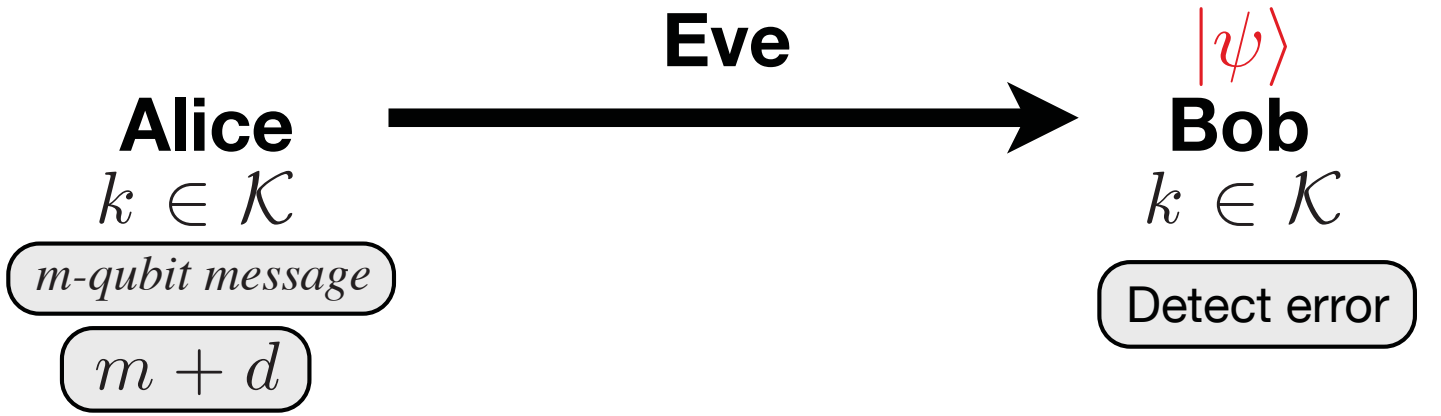
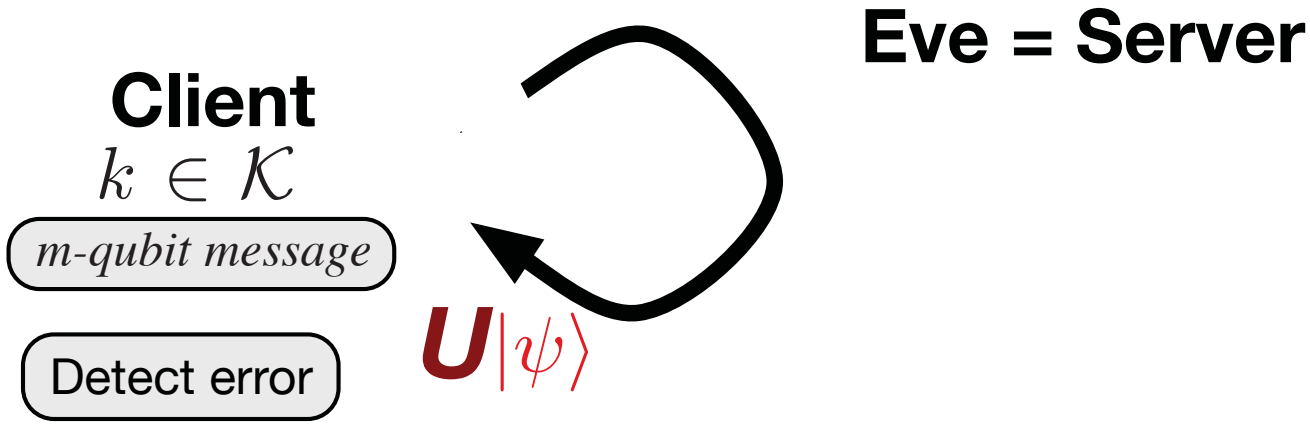




ε-Verification

Alice

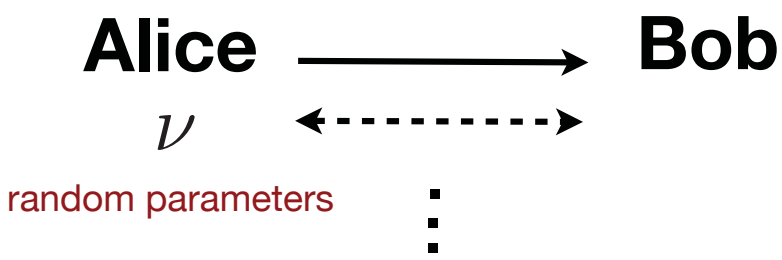
ν

random parameters

Bob

ε-Verification

ε-Verification



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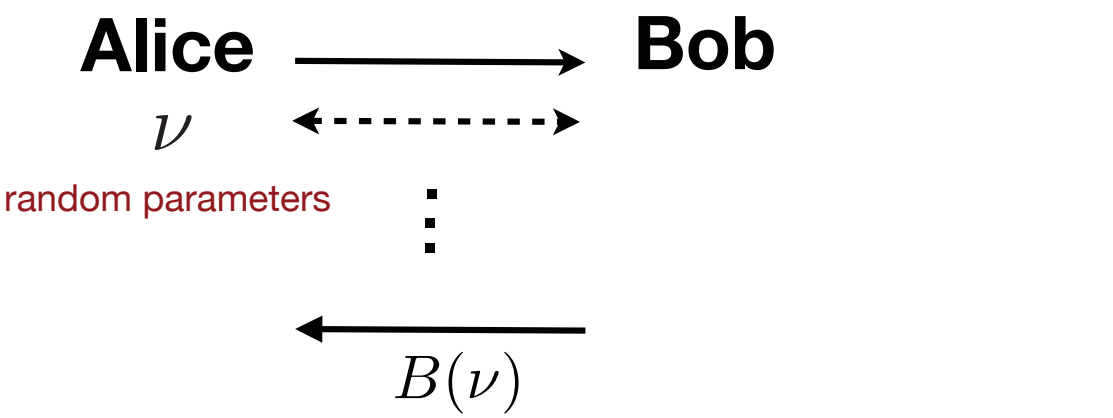

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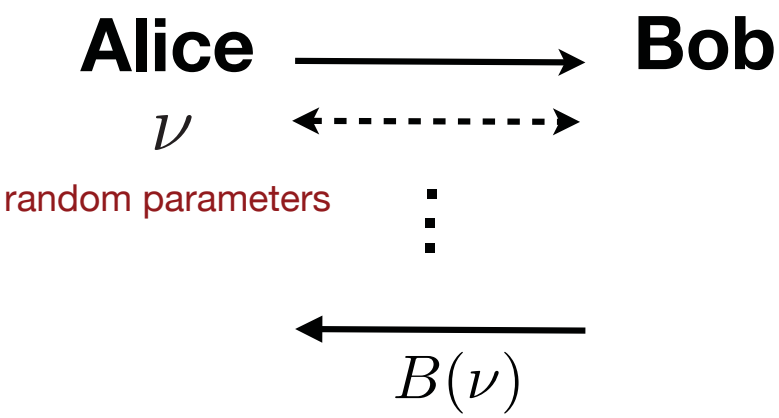
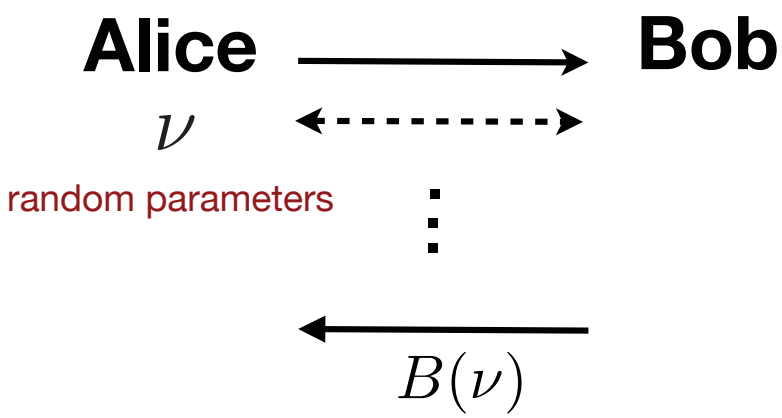


For any server's strategy the probability of client accepting an incorrect outcome density operator is bounded by ε:

ε-Verification



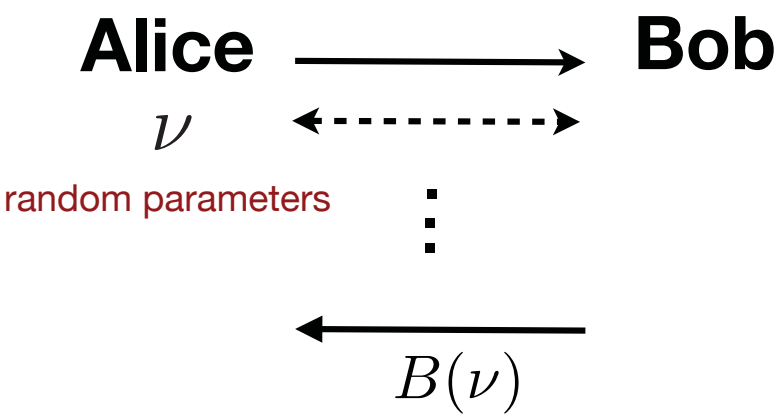
density operator of classical and quantum output

For any server's strategy the probability of client accepting an incorrect outcome density operator is bounded by ε:

$$P^{\nu}_{incorrect} = (\mathbb{I} - |\Psi^{\nu}_{ideal}\rangle\langle\Psi^{\nu}_{ideal}|) \otimes |r^{\nu}_{t}\rangle\langle r^{\nu}_{t}|$$

Accept Key

ε-Verification



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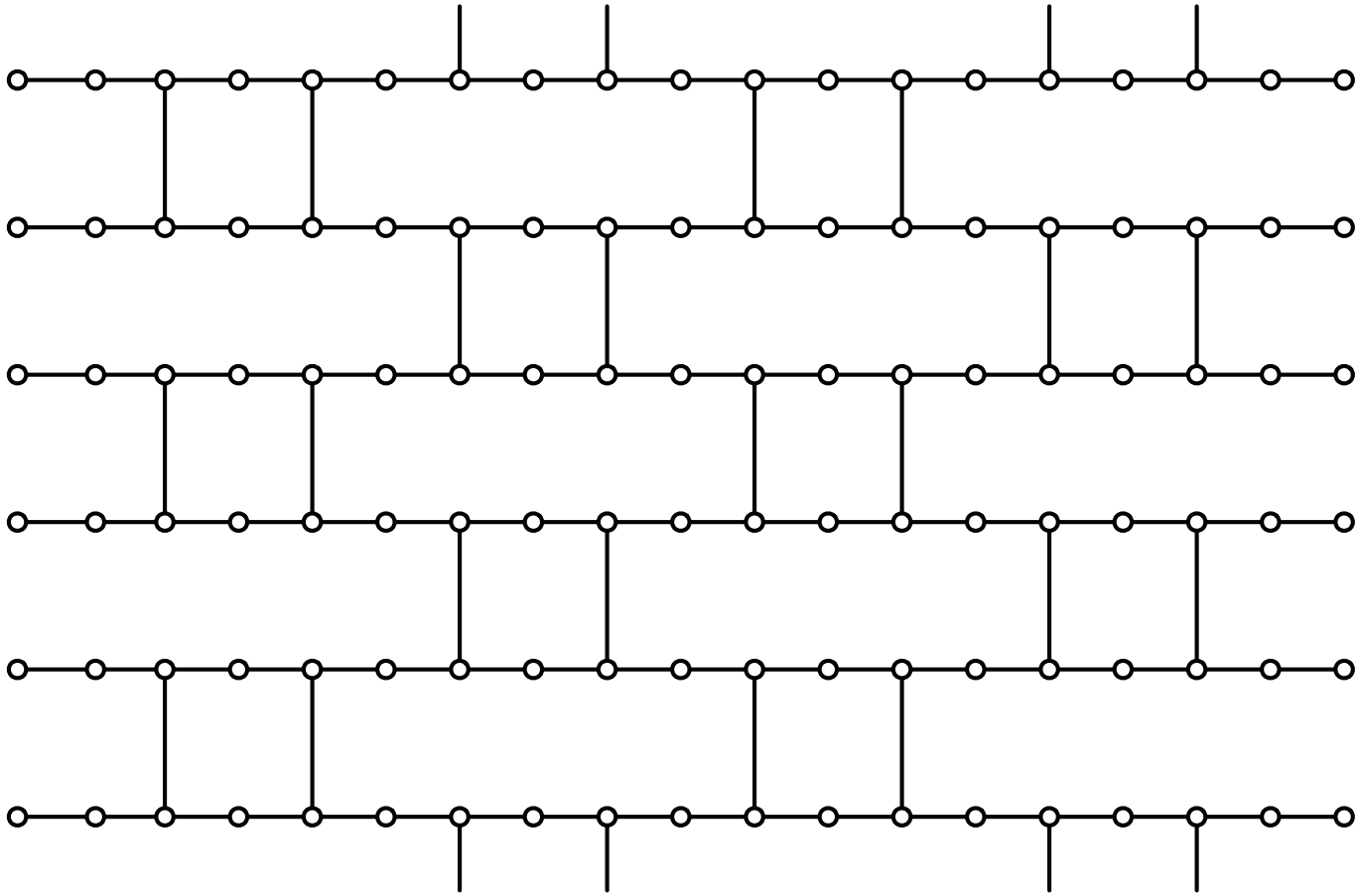
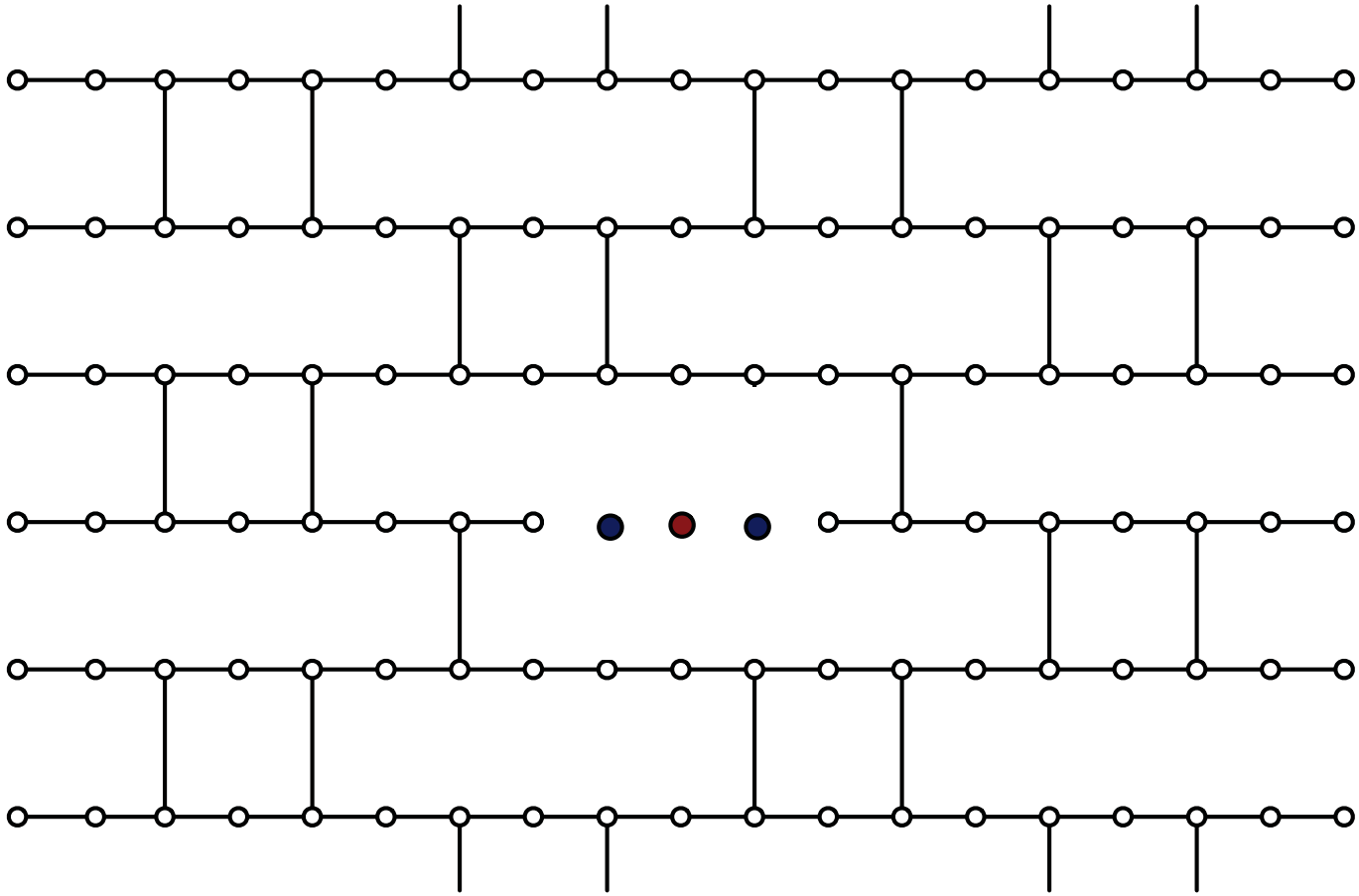
Accept Key

$$\sum_{\nu} \; p(\nu) \; Tr\left(P^{\nu}_{incorrect} \; B(\nu)\right) \leq \epsilon$$

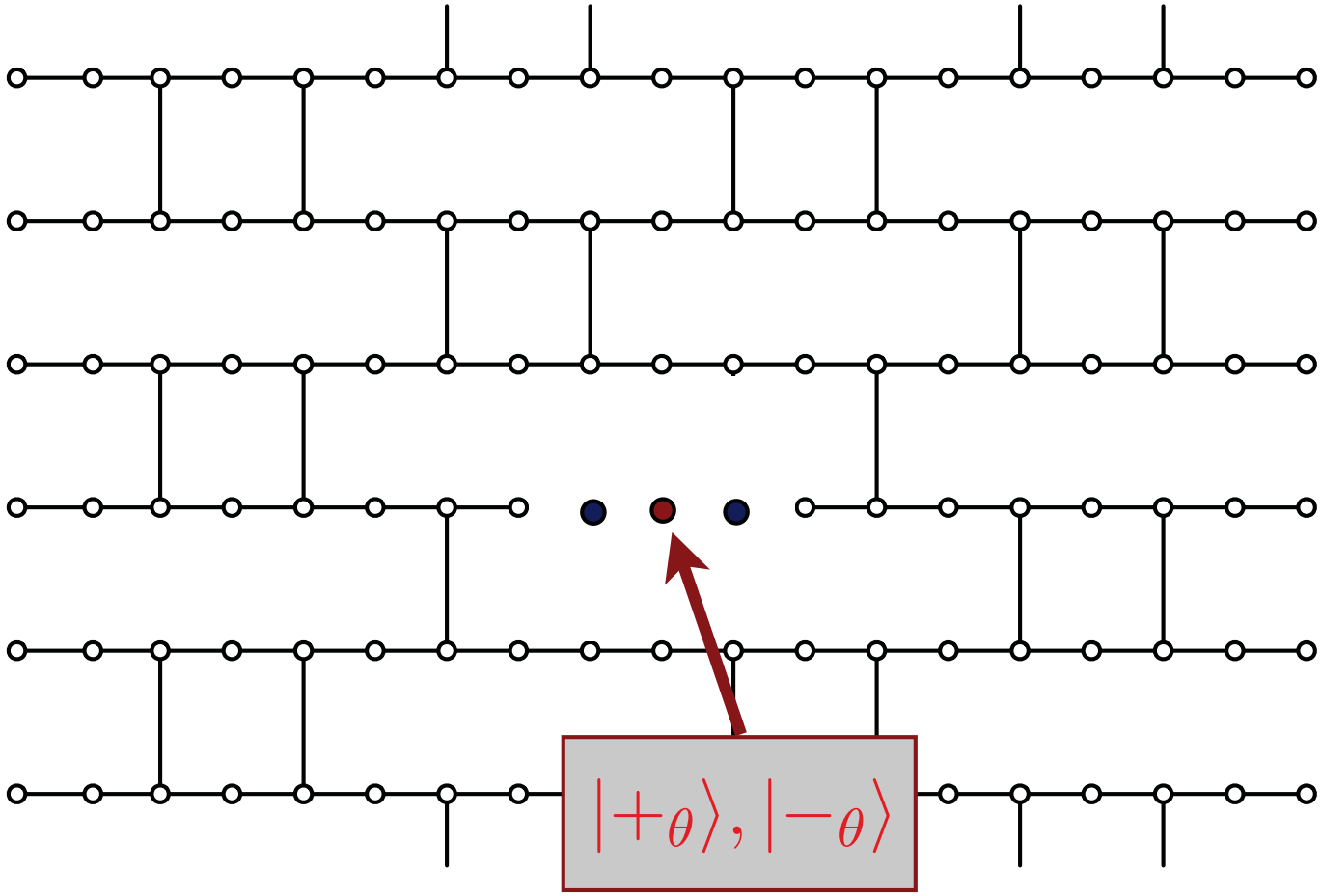
Adding Traps



Adding Traps



Adding Traps



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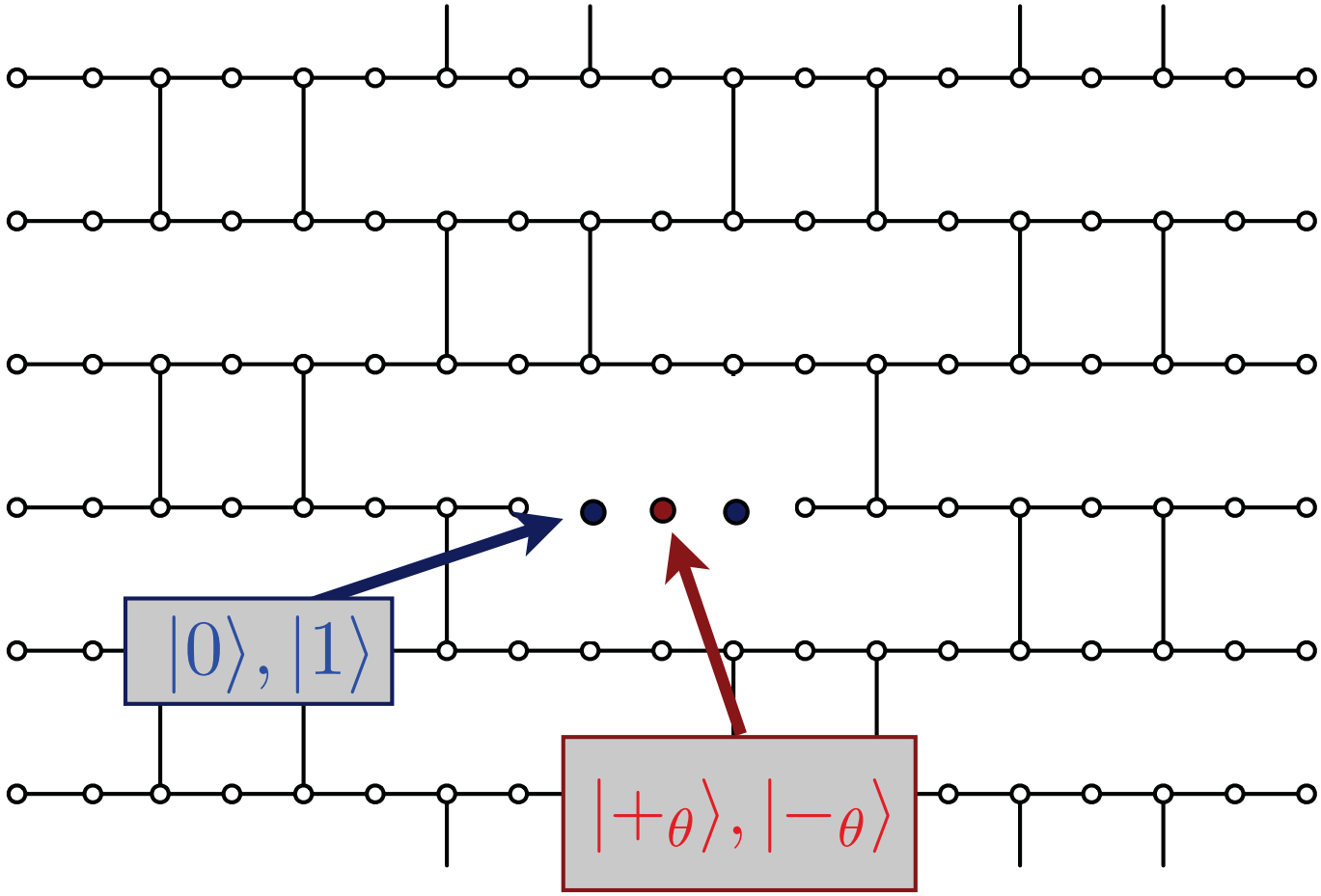

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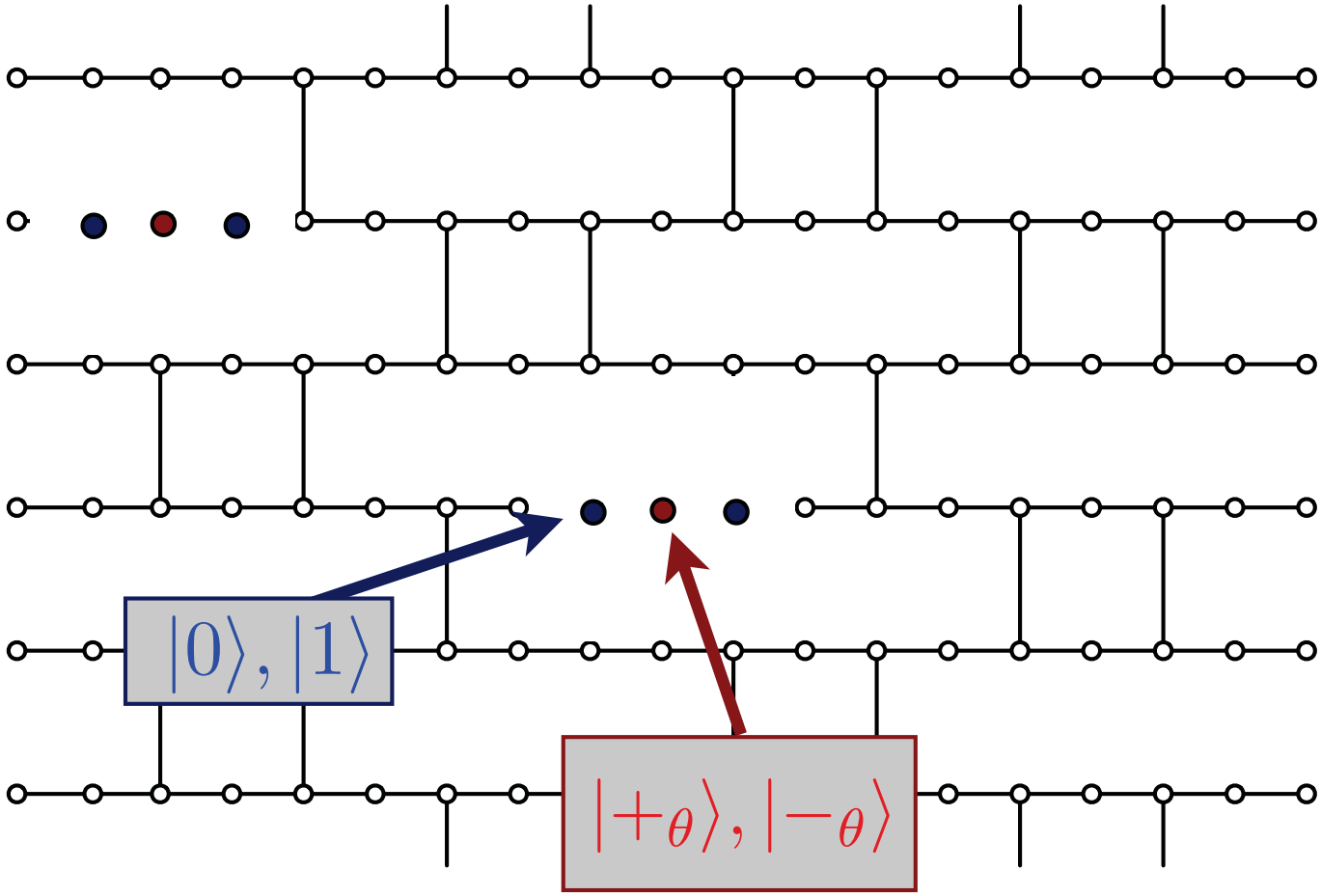
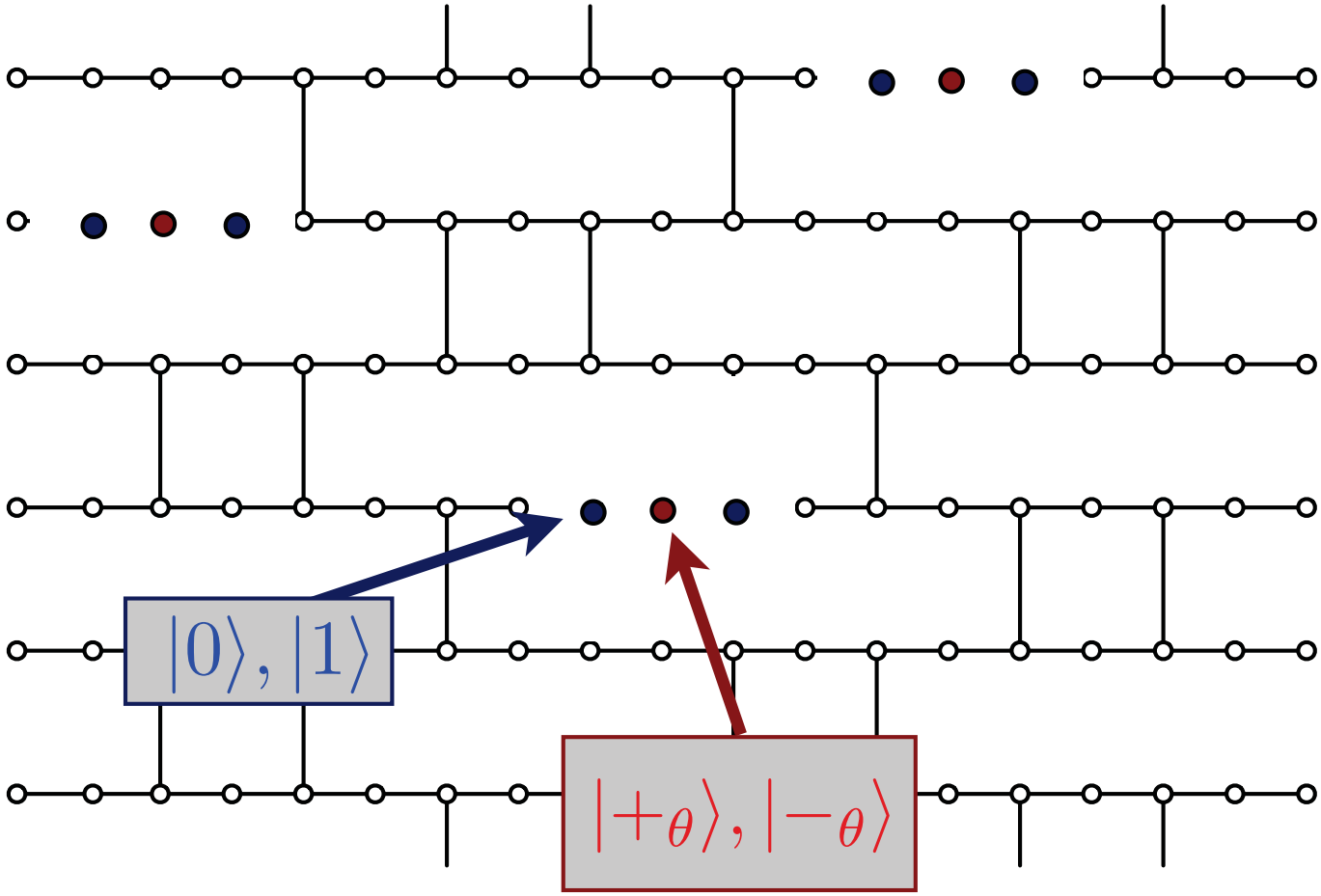


Adding Traps



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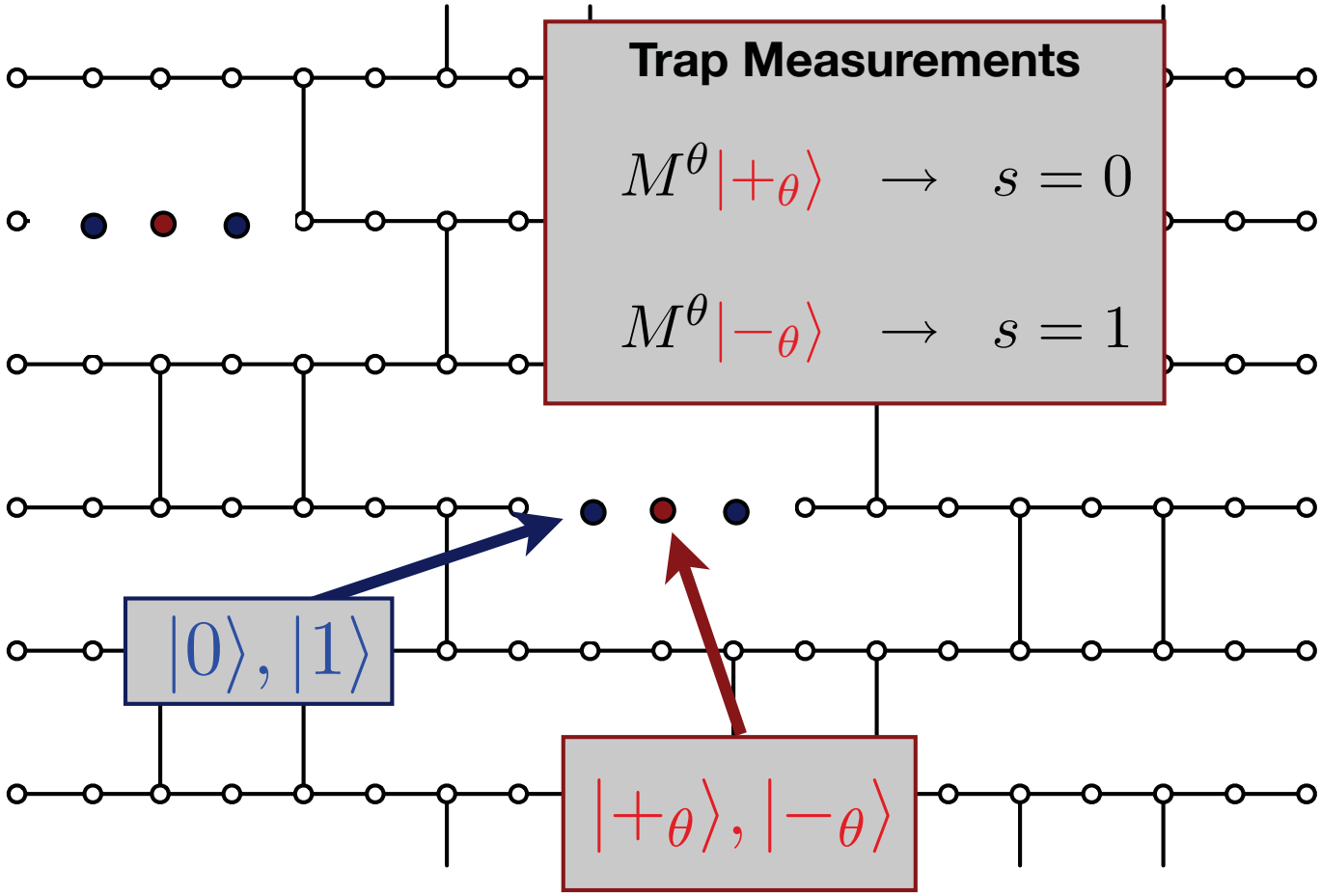
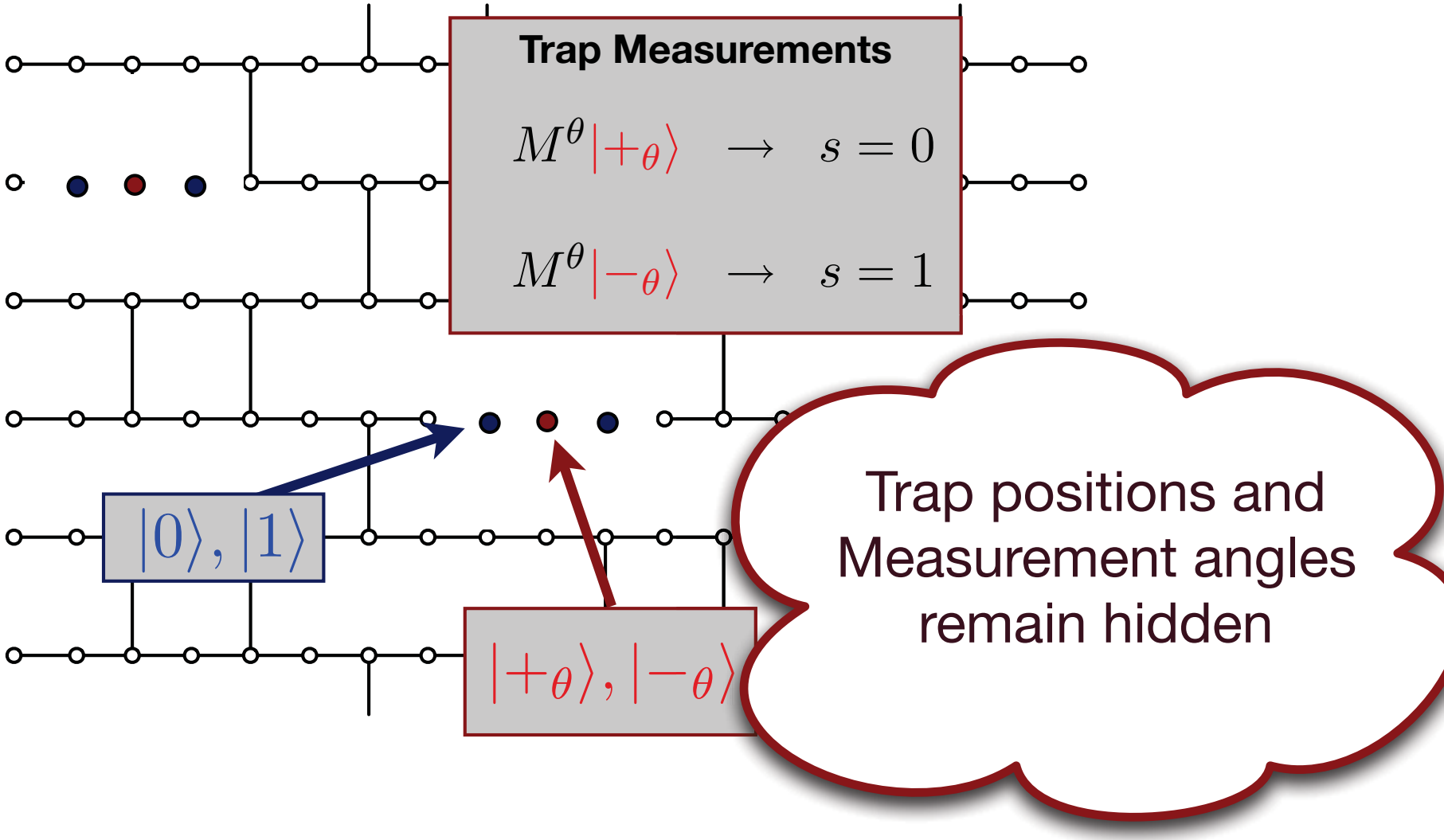


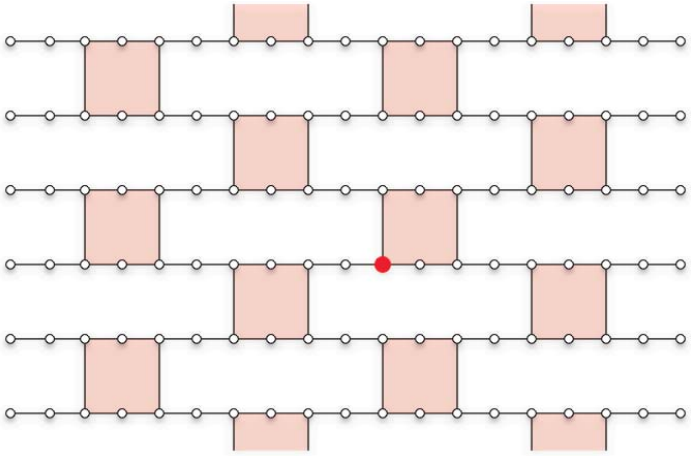
Adding Traps



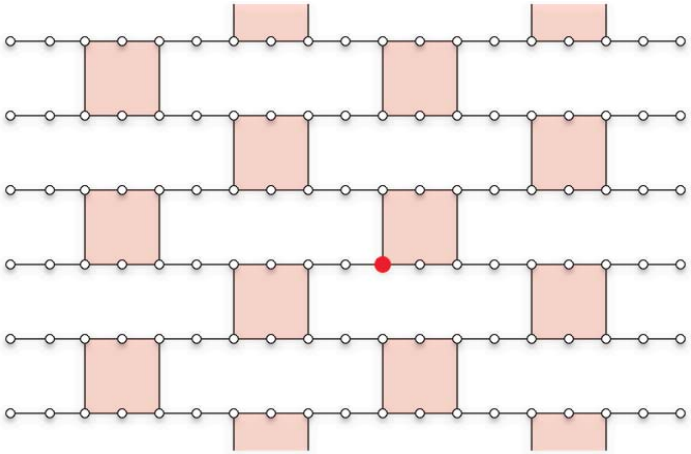
Verification with single trap

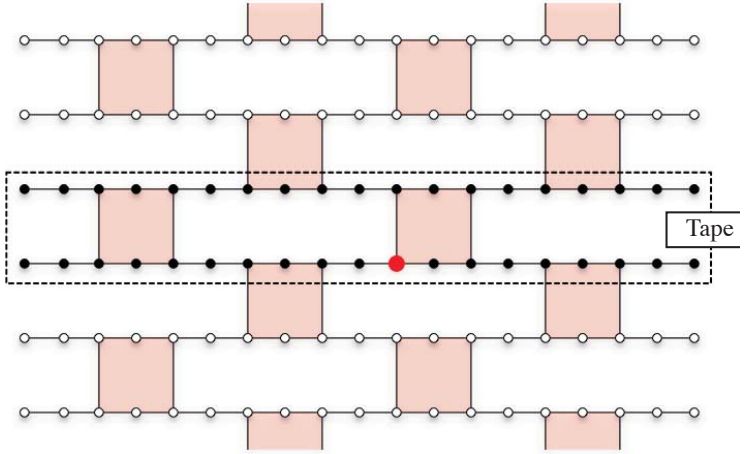
Theorem. Protocol is $(1 - 1/2N)$-verifiable in general, and in the case of purely classical output it is $(1 - 1/N)$-verifiable, where N is the total number of qubits in the protocol.

Verification

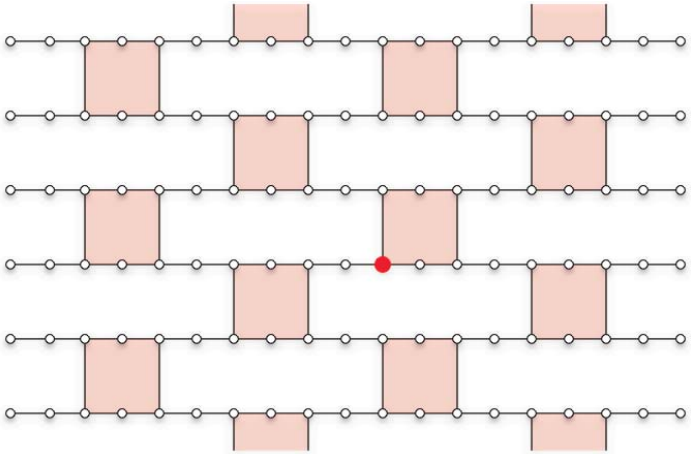


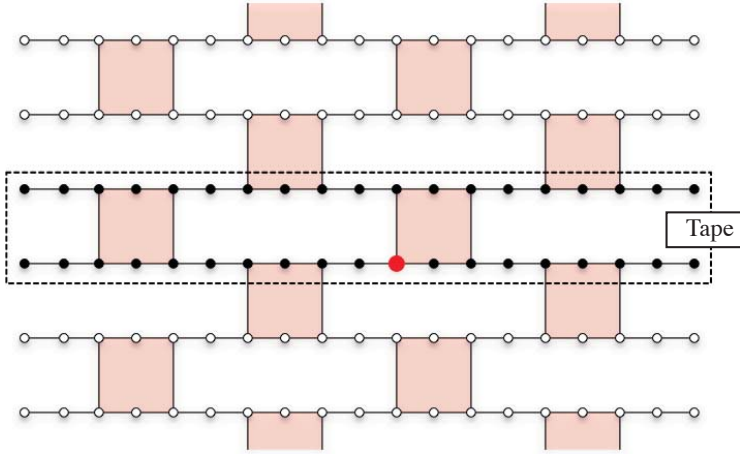
Verification

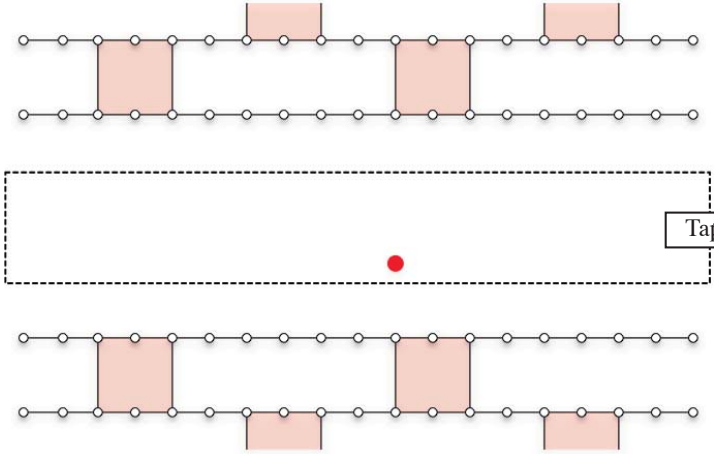




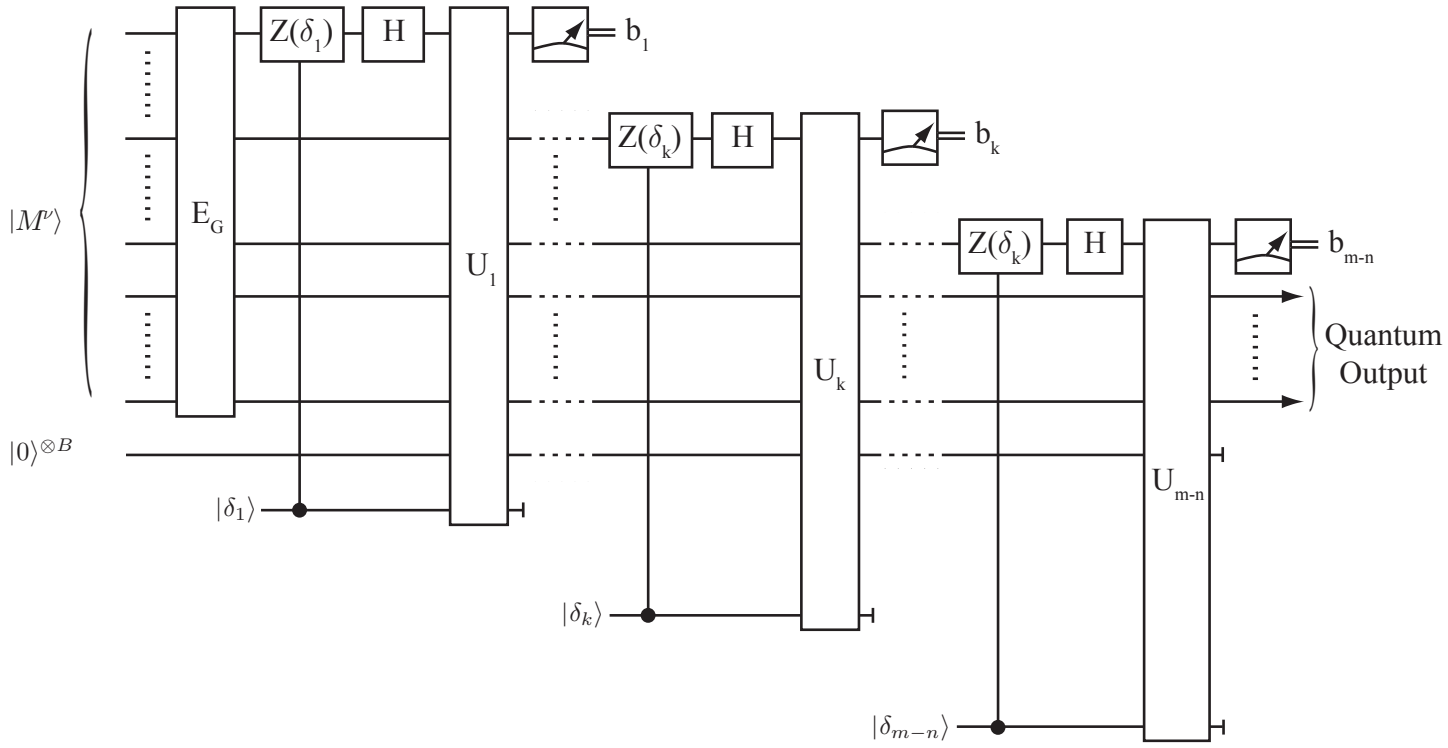
Verification





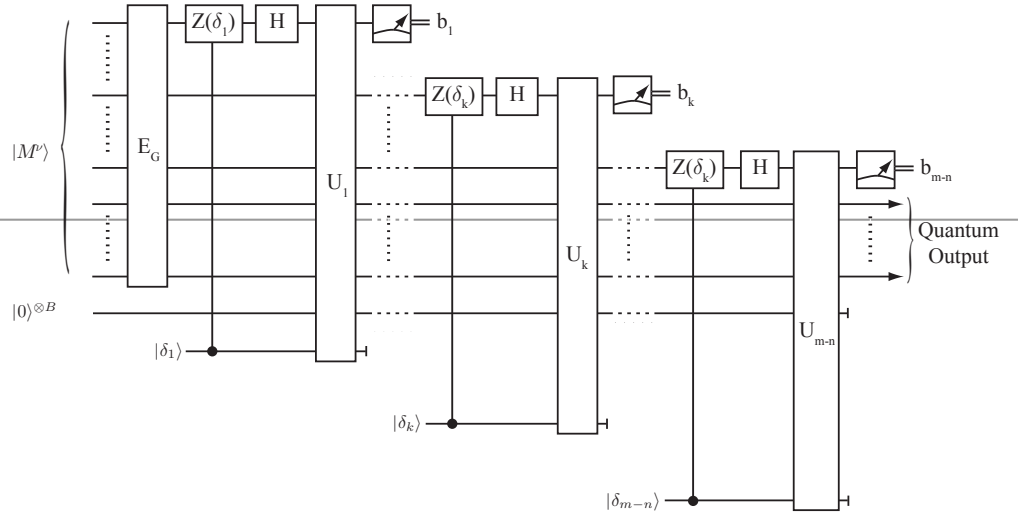


ε-Verification



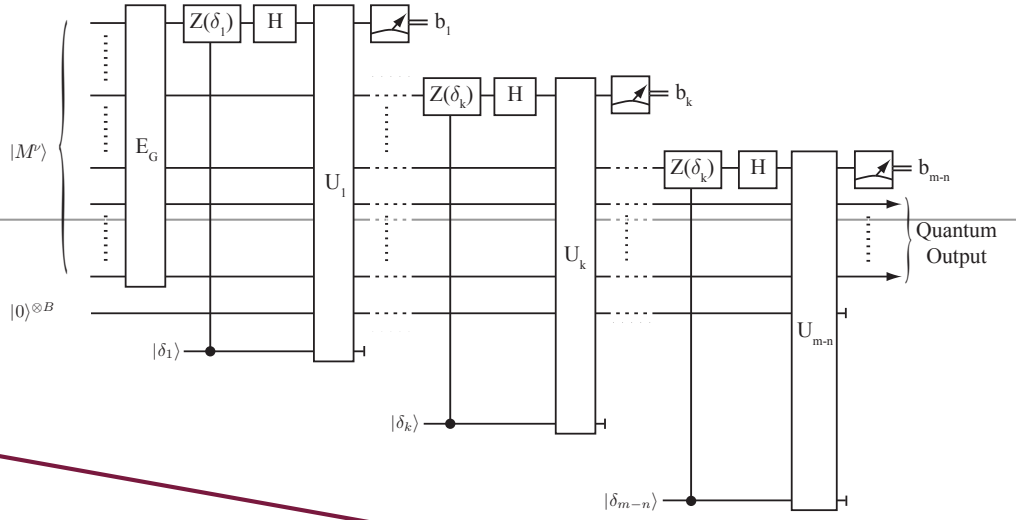
$$B_j(\nu) = \mathrm{Tr}_B \left(\sum_b |b + c_r\rangle \langle b| \, C_{\nu_C,b} \Omega \mathcal{P}((\otimes^B |0\rangle \langle 0|) \otimes \left|\Psi^{\nu,b}\right\rangle \left\langle \Psi^{\nu,b}\right|) \mathcal{P}^\dagger \Omega^\dagger C^\dagger_{\nu_C,b} |b\rangle \langle b + c_r| \right)$$

ε-Verification



$$p_{\text{incorrect}} \leq \sum_{k,\nu_T} \sum_{i \in E_i} \alpha_{ik} \alpha_{ik}^{*} p(\nu_T) \text{Tr}\left(\langle \eta_t^{\nu_T} | \, \sigma_i \left(|\eta_t^{\nu_T}\rangle \langle \eta_t^{\nu_T}| \otimes |\delta_t\rangle \langle \delta_t| \otimes \frac{I}{\text{Tr}(I)} \right) \sigma_i \, |\eta_t^{\nu_T}\rangle \right)$$

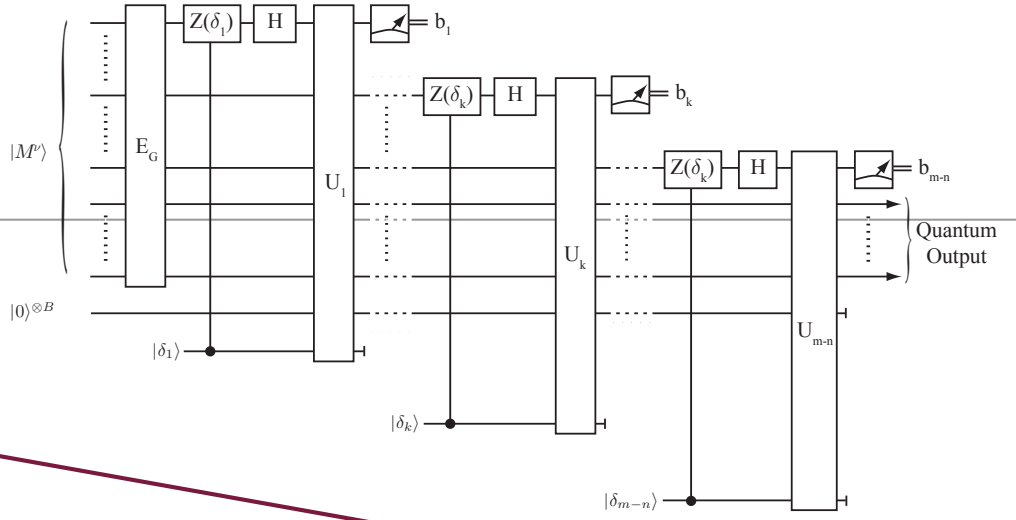
ε-Verification



Blindness

$$p_{\text{incorrect}} \leq \sum_{k,\nu_T} \sum_{i \in E_i} \alpha_{ik} \alpha_{ik}^{*} p(\nu_T) \text{Tr}\left(\langle \eta_t^{\nu_T} | \sigma_i \left(|\eta_t^{\nu_T}\rangle \langle \eta_t^{\nu_T}| \otimes |\delta_t\rangle \langle \delta_t| \otimes \frac{I}{\text{Tr}(I)} \right) \sigma_i |\eta_t^{\nu_T}\rangle \right)$$

ε-Verification



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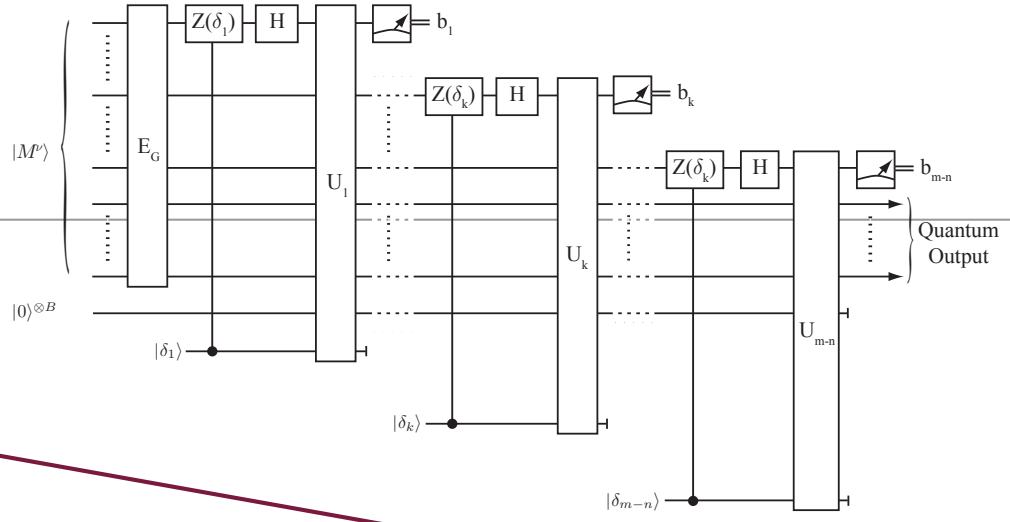
$$\vdots$$

$$= \frac{1}{16m} \sum_{k} \sum_{i \in E_i} |\alpha_{ki}|^2 \sum_{t, r_t, \theta_t} \left(\langle \eta_t^{\nu_T} | \sigma_{i|t} |\eta_t^{\nu_T}\rangle \right)^2$$

ε-Verification



Blindness

$$p_{\text{incorrect}} \leq \sum_{k,\nu_T} \sum_{i \in E_i} \alpha_{ik} \alpha_{ik}^* p(\nu_T) \text{Tr}\left(\langle \eta_t^{\nu_T} | \sigma_i \left(|\eta_t^{\nu_T}\rangle \langle \eta_t^{\nu_T}| \otimes |\delta_t\rangle \langle \delta_t| \otimes \frac{I}{\text{Tr}(I)} \right) \sigma_i |\eta_t^{\nu_T}\rangle \right)$$

$$\vdots$$

$$= \frac{1}{16m} \sum_k \sum_{i \in E_i} |\alpha_{ki}|^2 \sum_{t, r_t, \theta_t} \left(\langle \eta_t^{\nu_T} | \sigma_{i|t} |\eta_t^{\nu_T}\rangle \right)^2$$

$$\vdots$$

$$\leq 1 - \frac{1}{2m}$$

Probability Amplification

To increase the probability of any local error being detected

O(N) many traps in random locations

Probability Amplification

To increase the probability of any local error being detected

O(N) many traps in random locations

To increase the minimum weight of any operator which leads to an incorrect outcome

Fault-Tolerance

Probability Amplification

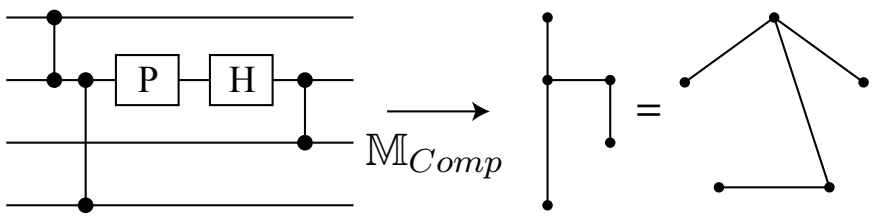
Probability Amplification

Challenge: Traps break the graph

Probability Amplification

Challenge: Traps break the graph

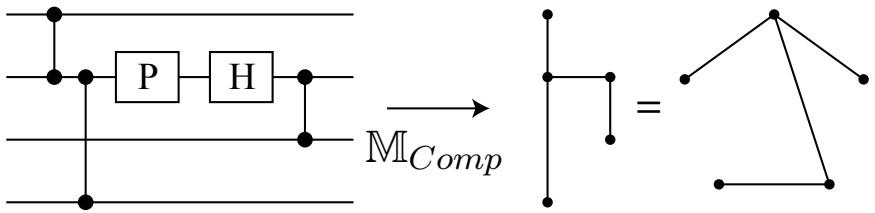
1.



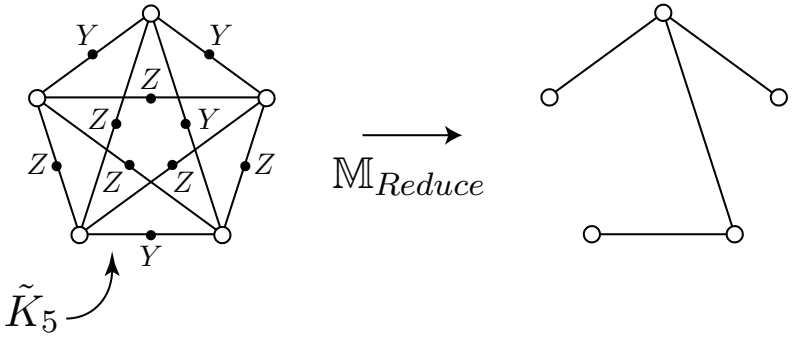
Probability Amplification

Challenge: Traps break the graph

1.



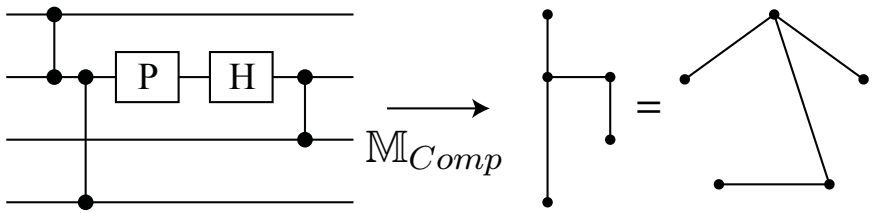
2.



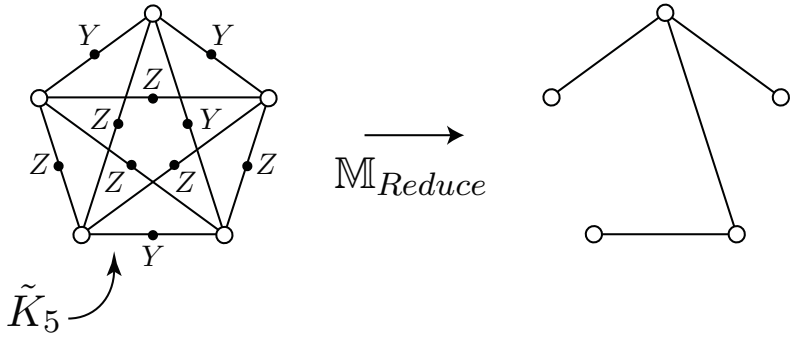
Probability Amplification

Challenge: Traps break the graph

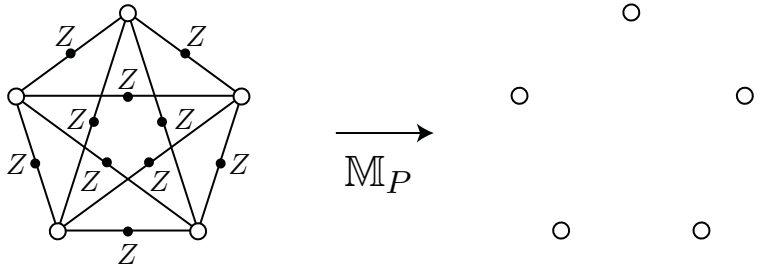
1.



2.



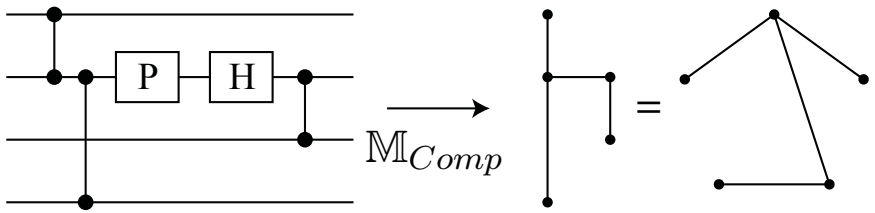
3.



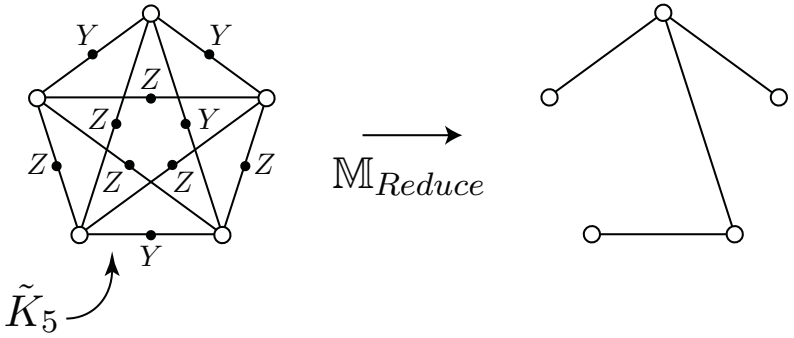
Probability Amplification

Challenge: Traps break the graph

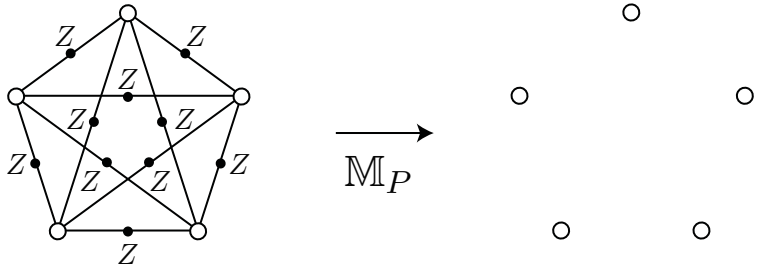
1.



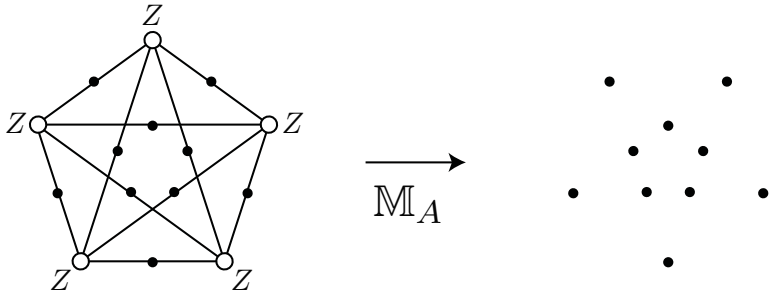
2.



3.



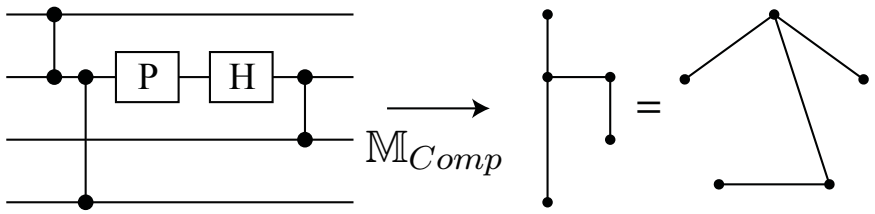
4.



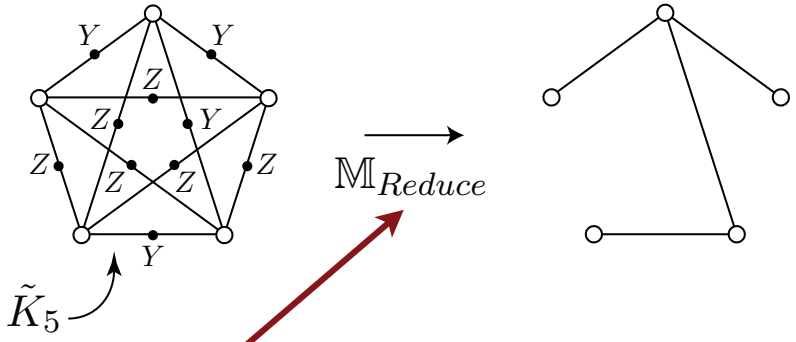
Probability Amplification

Challenge: Traps break the graph

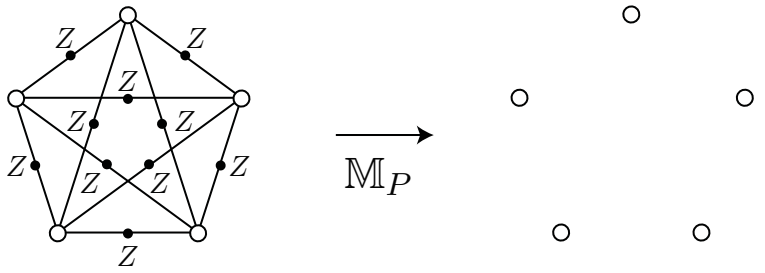
1.



2.

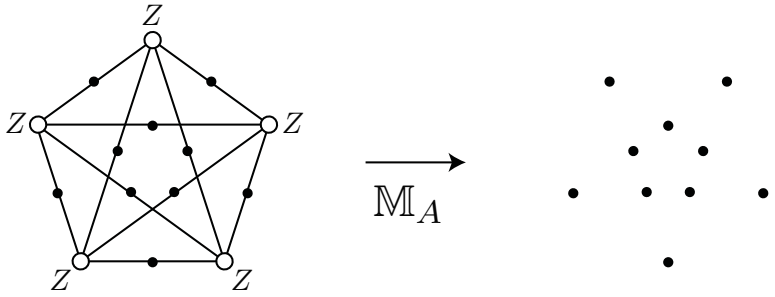


3.



Required 3D lattice for Raussendorf, Harrington and Goyal Topological error-correcting code with defect thickness *d*

4.

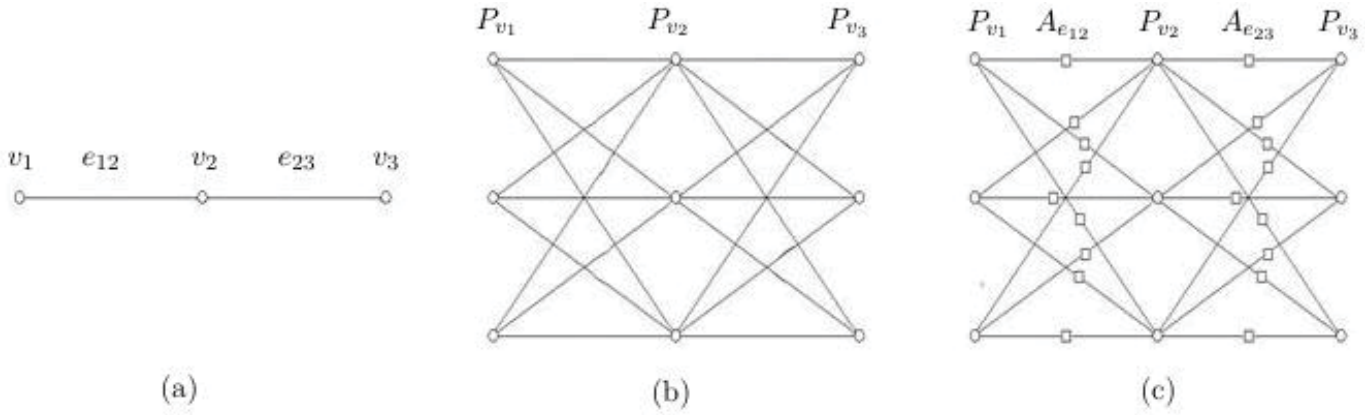


Efficient Verifiable UBQC

[Kashefi-Wallden 16]

Dotted triple-graph construction ⟶ O(N) overheads for VUBQC

generic resource state, that one can insert multiple independent traps without revealing anything or disrupting the computation



Efficient Verifiable UBQC

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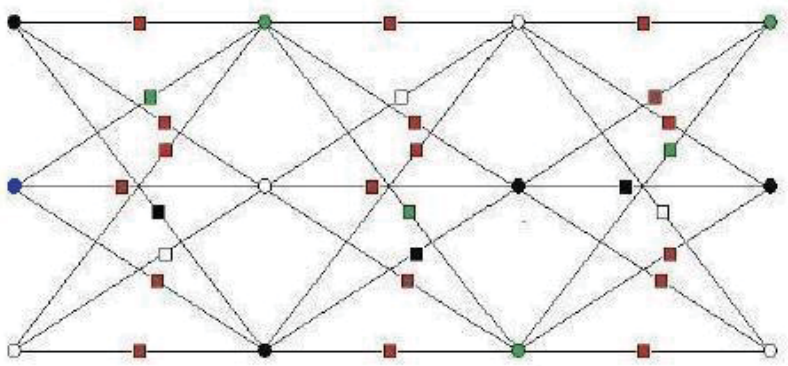
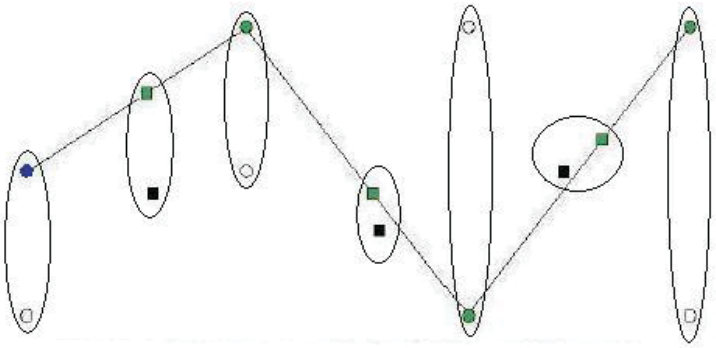
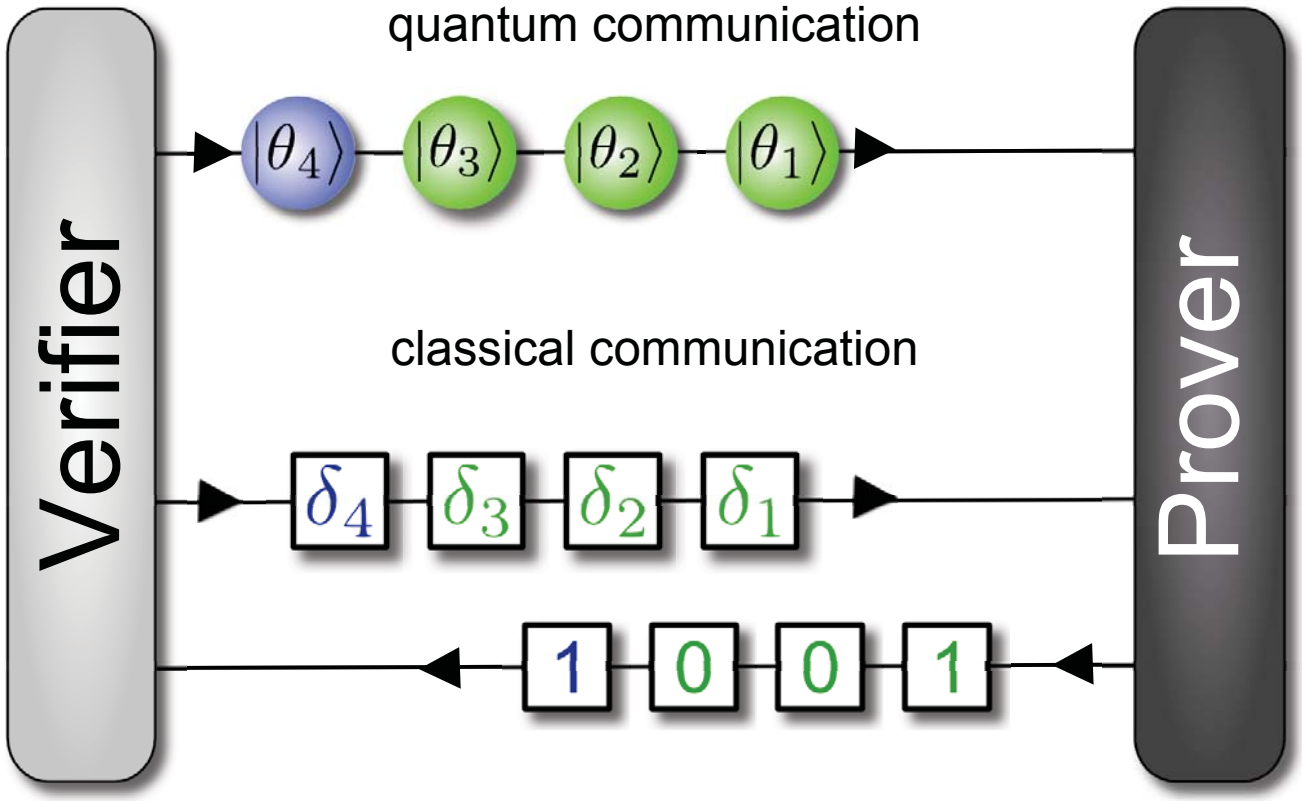


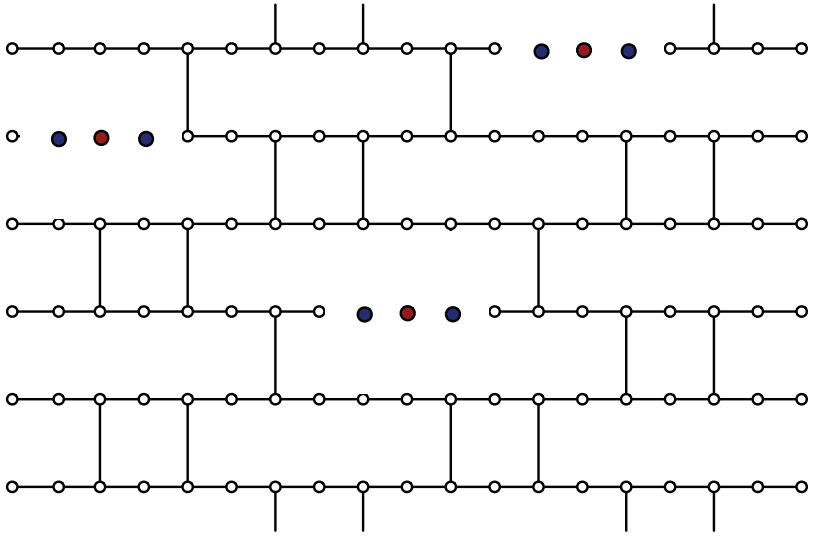
(a) Trap-colouring



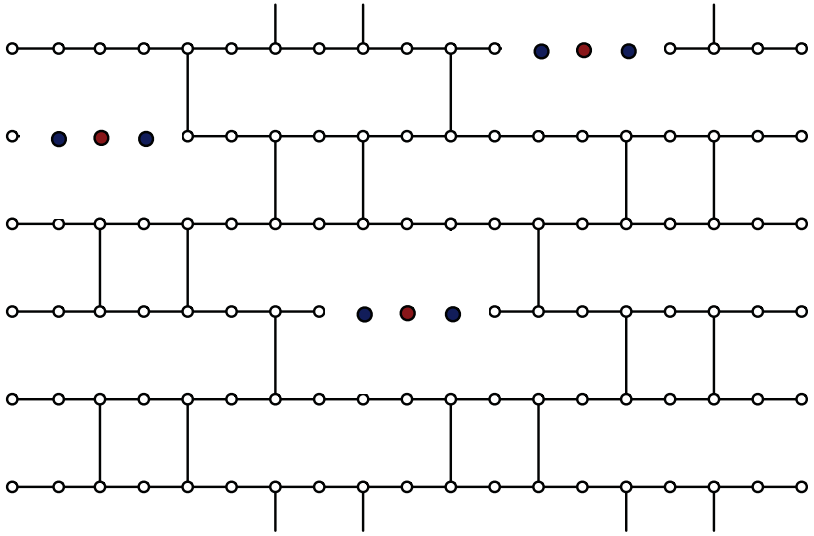
What can we do with 4-qubits

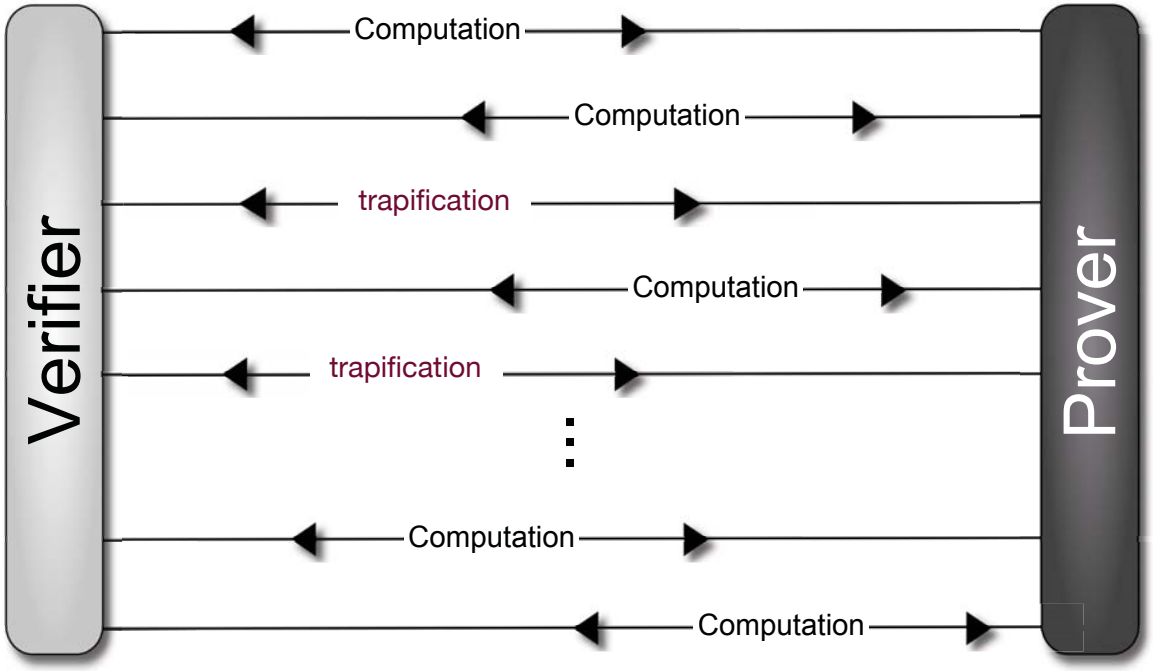


Restricting to Classical Input and Output



Restricting to Classical Input and Output





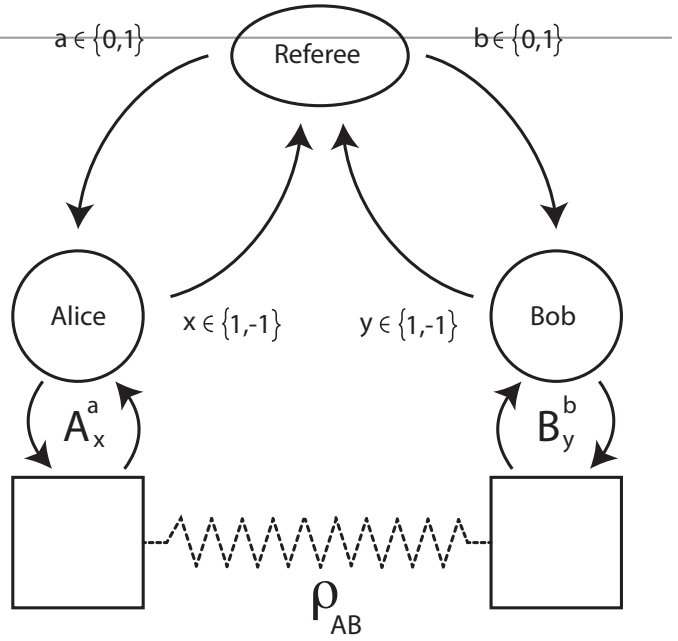
A Complete new proof of verification was required

Pauli (σ_i)	Trap Stabilizer Measurement			Overall
	$X \otimes \mathbb{I} \otimes Y \otimes Y$	$Y \otimes X \otimes X \otimes Y$	$Y \otimes Y \otimes \mathbb{I} \otimes X$	
$C \otimes C \otimes C \otimes C$	✓	✓	✓	✓
$C \otimes C \otimes C \otimes A$	✗	✗	✗	✗
$C \otimes C \otimes A \otimes C$	✗	✗	✓	✗
$C \otimes C \otimes A \otimes A$	✓	✓	✗	✗
$C \otimes A \otimes C \otimes C$	✓	✗	✗	✗
$C \otimes A \otimes C \otimes A$	✗	✓	✓	✗
$C \otimes A \otimes A \otimes C$	✗	✓	✗	✗
$C \otimes A \otimes A \otimes A$	✓	✗	✓	✗
$A \otimes C \otimes C \otimes C$	✗	✗	✗	✗
$A \otimes C \otimes C \otimes A$	✓	✓	✓	✓
$A \otimes C \otimes A \otimes C$	✓	✓	✗	✗
$A \otimes C \otimes A \otimes A$	✗	✗	✓	✗
$A \otimes A \otimes C \otimes C$	✗	✓	✓	✗
$A \otimes A \otimes C \otimes A$	✓	✗	✗	✗
$A \otimes A \otimes A \otimes C$	✓	✗	✓	✗
$A \otimes A \otimes A \otimes A$	✗	✓	✗	✗

A Complete new proof of verification was required

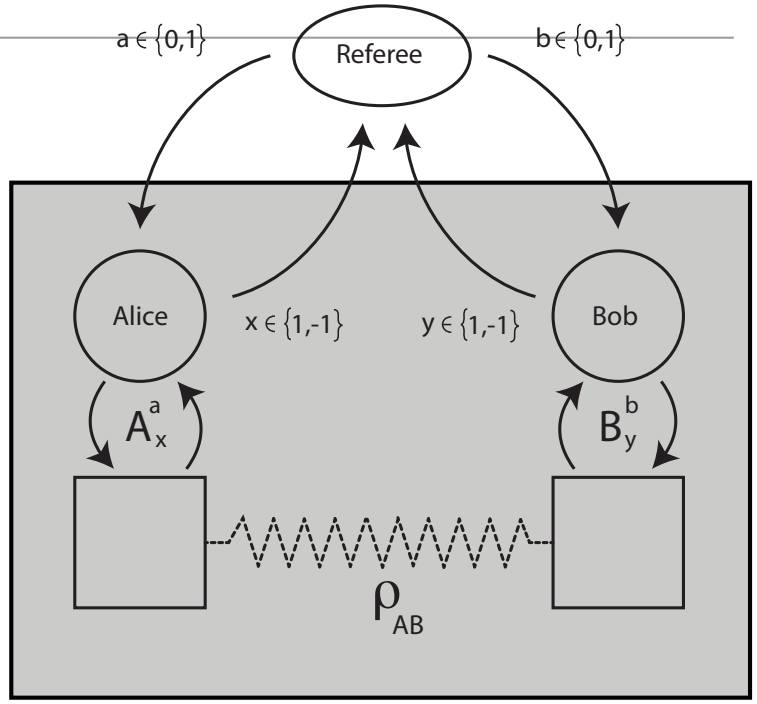
Pauli (σ_i)	Trap Stabilizer Measurement			Overall
	$X \otimes \mathbb{I} \otimes Y \otimes Y$	$Y \otimes X \otimes X \otimes Y$	$Y \otimes Y \otimes \mathbb{I} \otimes X$	
$C \otimes C \otimes C \otimes C$	✓	✓	✓	✓
$C \otimes C \otimes C \otimes A$	✗	✗	✗	✗
$C \otimes C \otimes A \otimes C$	✗	✗	✓	✗
$C \otimes C \otimes A \otimes A$	✓	✓	✗	✗
$C \otimes A \otimes C \otimes C$	✓	✗	✗	✗
$C \otimes A \otimes C \otimes A$	✗	✓	✓	✗
$C \otimes A \otimes A \otimes C$	✗	✓	✗	✗
$C \otimes A \otimes A \otimes A$	✓	✗	✓	✗
$A \otimes C \otimes C \otimes C$	✗	✗	✗	✗
$A \otimes C \otimes C \otimes A$	✓	✓	✓	✓
$A \otimes C \otimes A \otimes C$	✓	✓	✗	✗
$A \otimes C \otimes A \otimes A$	✗	✗	✓	✗
$A \otimes A \otimes C \otimes C$	✗	✓	✓	✗
$A \otimes A \otimes C \otimes A$	✓	✗	✗	✗
$A \otimes A \otimes A \otimes C$	✓	✗	✓	✗
$A \otimes A \otimes A \otimes A$	✗	✓	✗	✗

Blind Verification of Entanglement



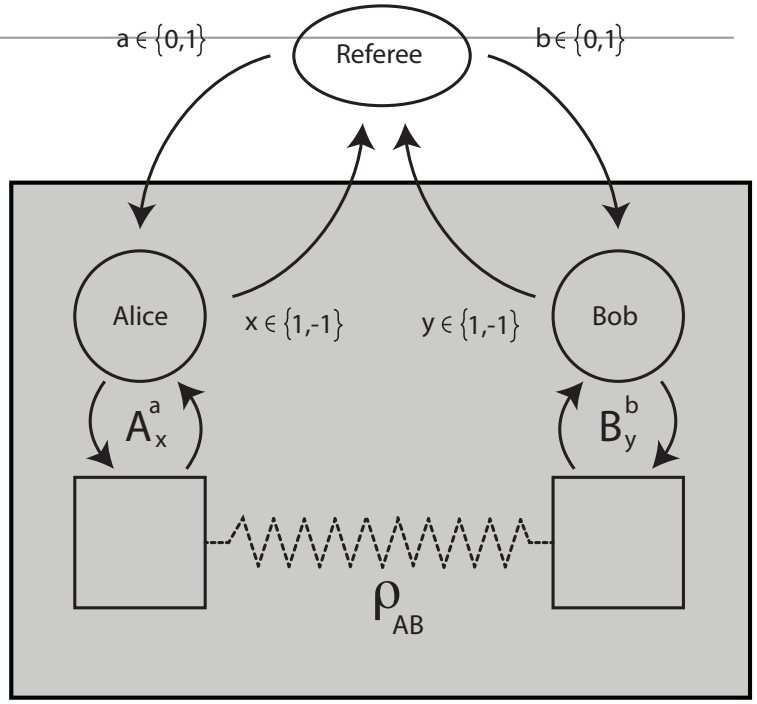
Blind Verification of Entanglement

Perform by an untrusted server



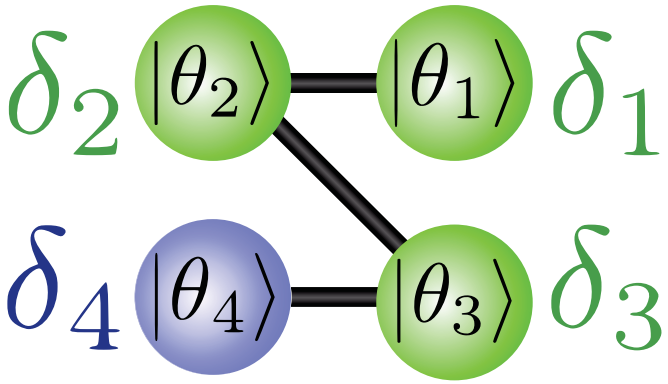
Blind Verification of Entanglement

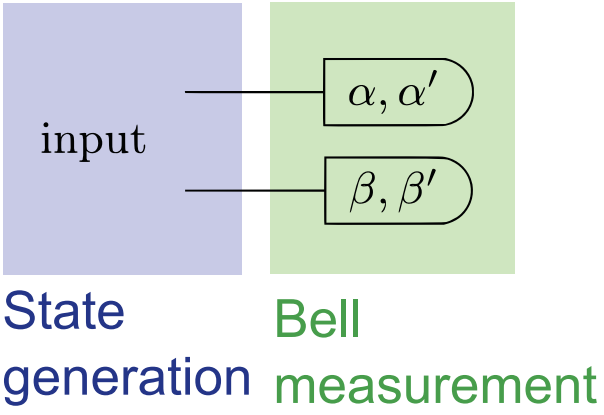
Perform by an untrusted server

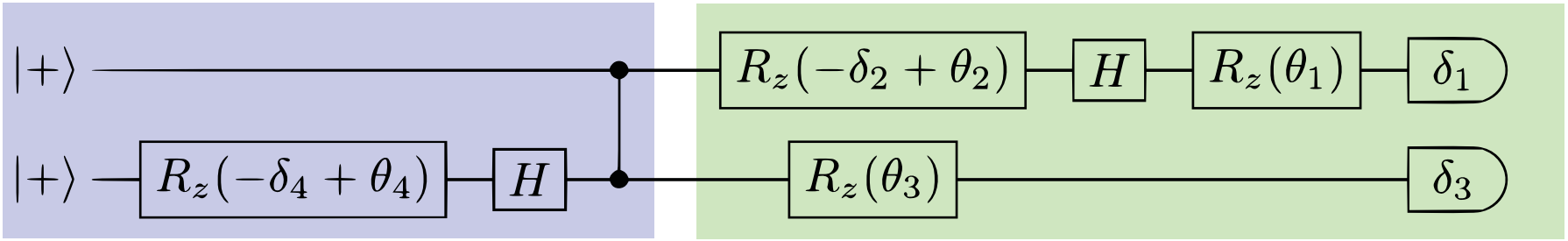


If server knows he is running Bell test,
he can create fake outcomes to violate the inequality,
the trapificaiton procedure in between prevents this to happen

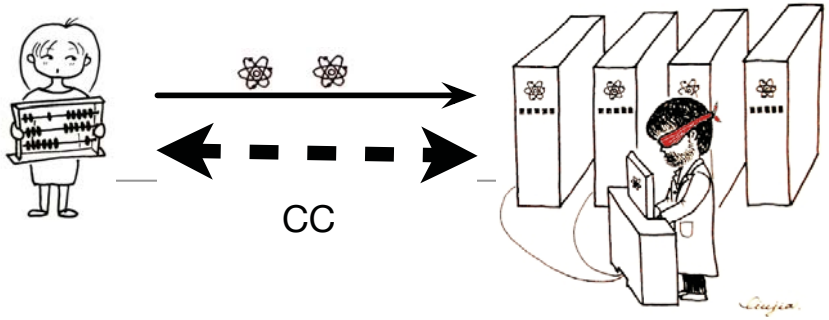
Blind Verification of Entanglement



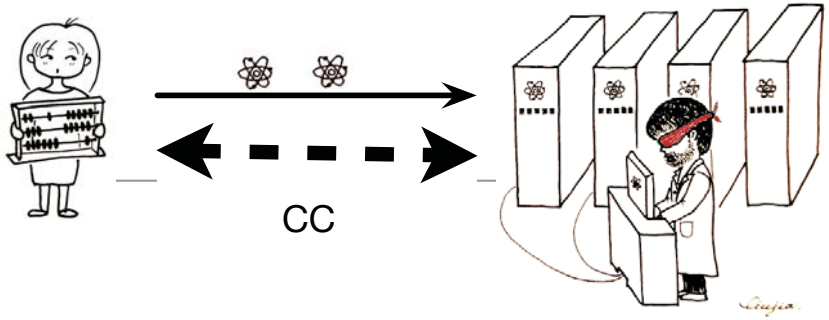




Quantum Property Testing



Quantum Property Testing



Non-classical Correlation

Contextuality

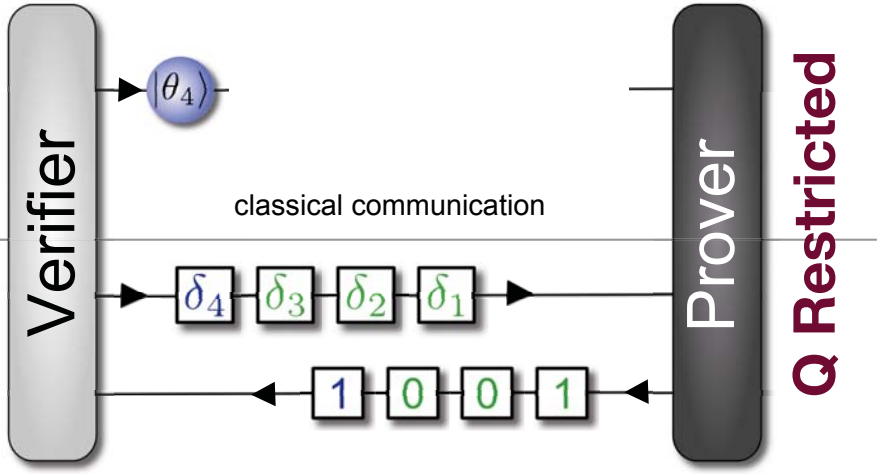
Dimentionality

Superposition

VUBQC extension

VUBQC extension

Verification of one-pure-qubit computation
Kapourniotis, Kashefi, Datta, TQC14



VUBQC extension

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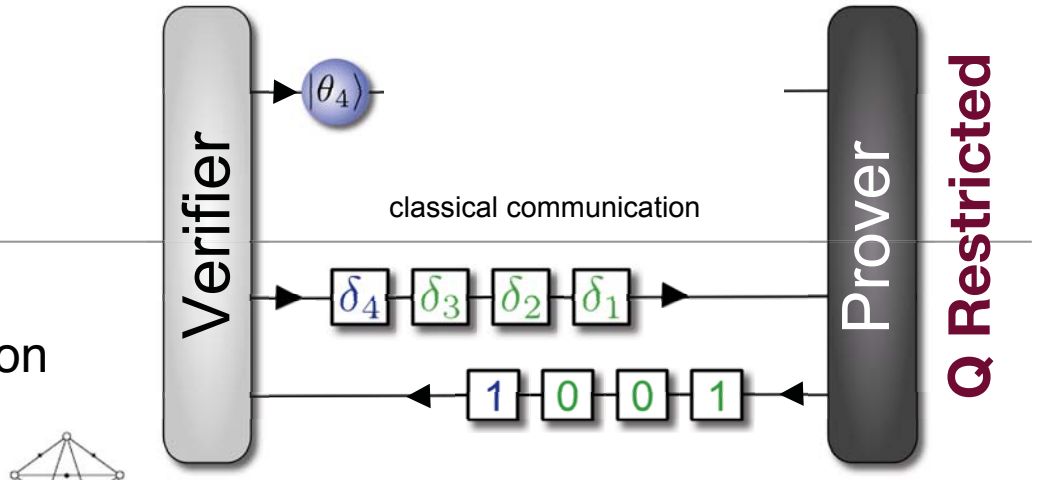

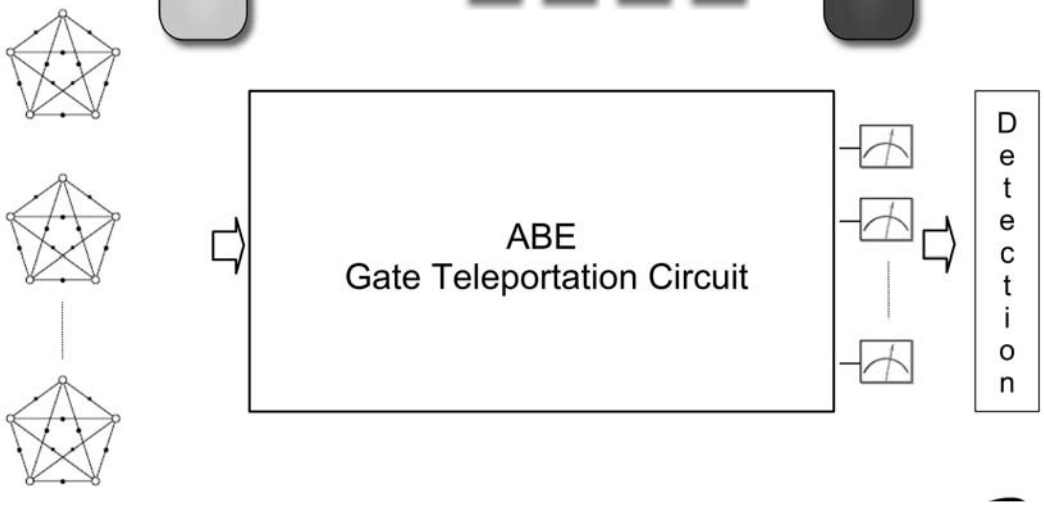

Verification with minimal communicatio
Kapourniotis, Dunjko, Kashefi ASQIC15

VUBQC extension

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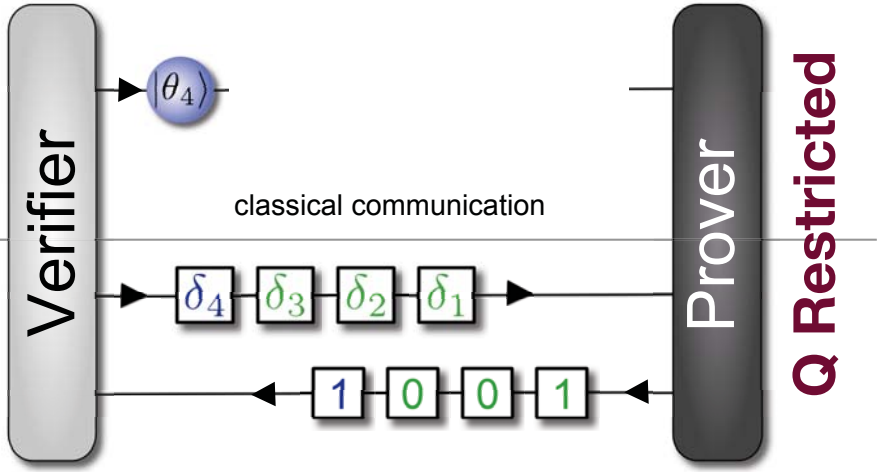
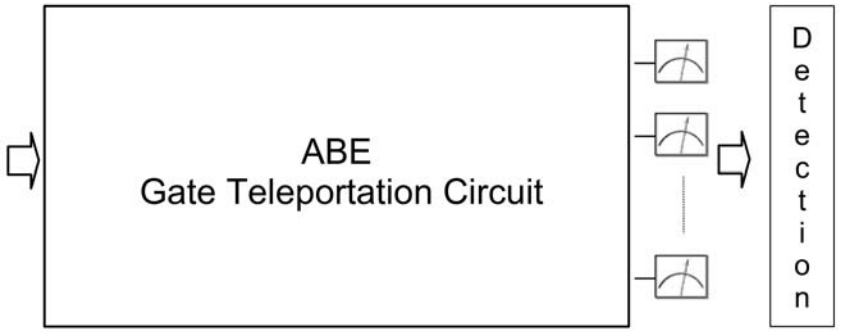
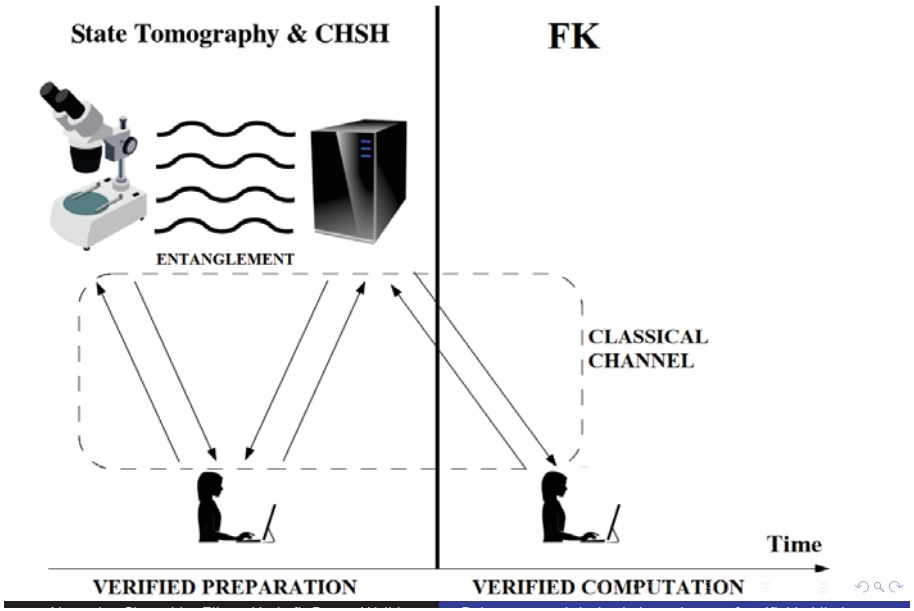


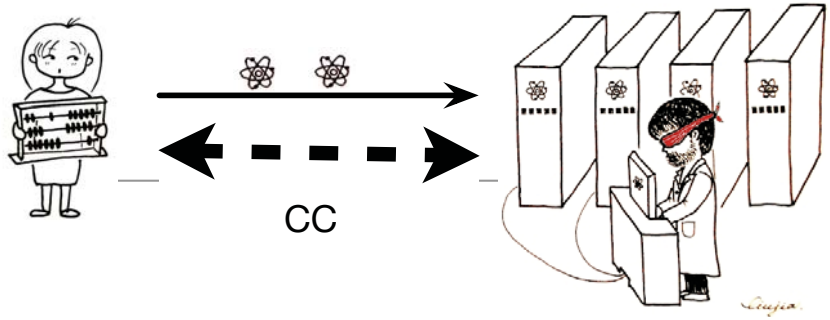


Verification with minimal communicatio
Kapourniotis, Dunjko, Kashefi ASQIC15

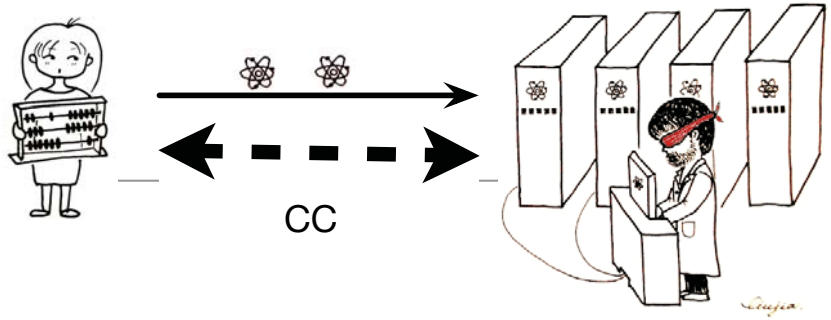
Robust and Device-independent Verification
Gheorghiu, Kashefi, Wallden NJP15



Model Dependent



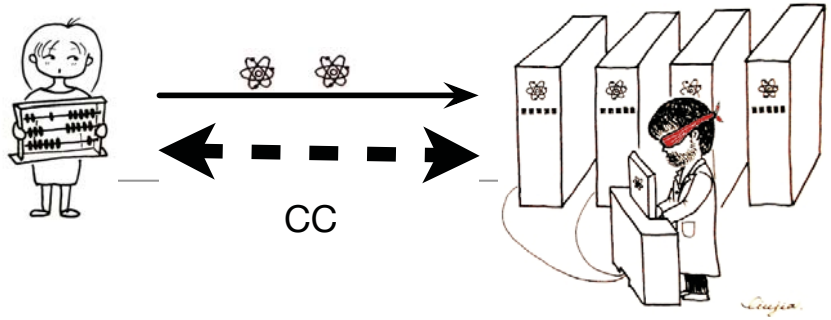
Model Dependent



Adaptation to Computational Capacity of Intermediate Models of QC

D-Wave
Boson Sampling
Instantaneous QC
Quantum Simulator

Model Dependent



Adaptation to Computational Capacity of Intermediate Models of QC

D-Wave
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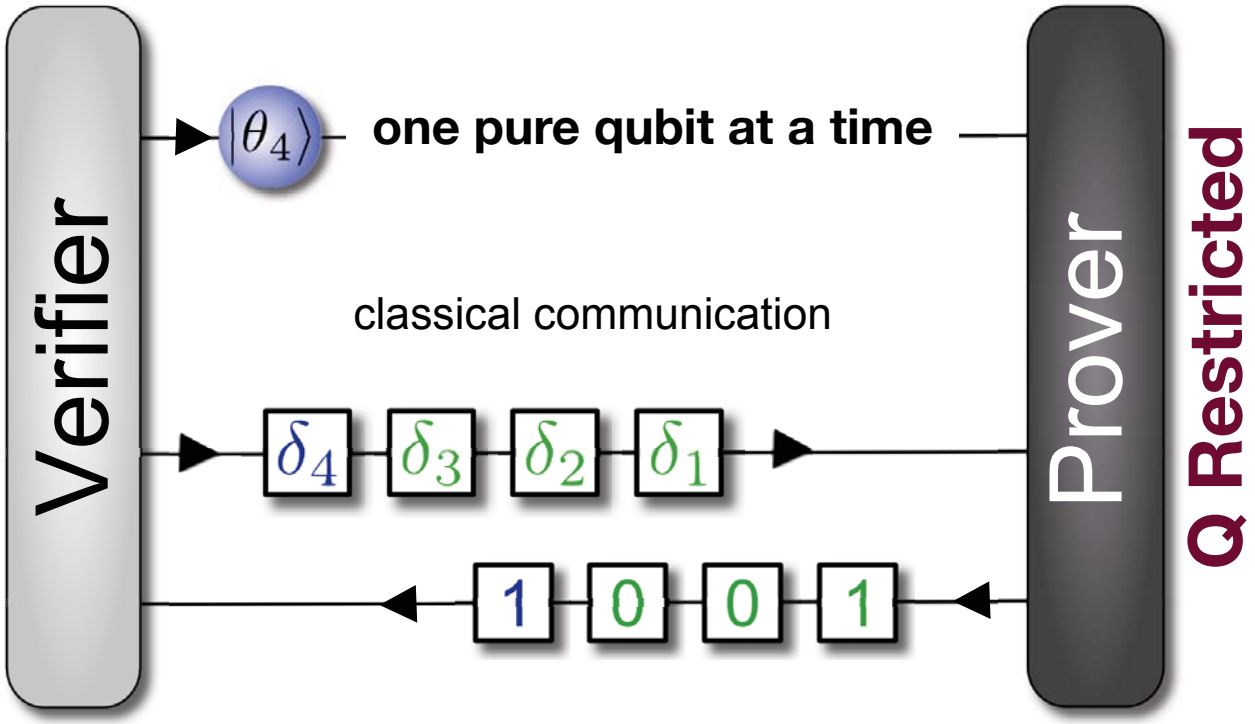
Quantum Simulator

Simplified Noise Model

Quantum Turing Test for One Pure Qubit



Kapourtionis, Kashefi, Datta, TQC, 2014

MBQC with One Pure Qubit

A runnable sequence of commands where for every elementary command the purity doesn't exceed

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$$\pi(\rho_i) < \pi(\rho_{in}) + c$$

Input state with constant many pure qubtis

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Constructive Def. An MBQC with surjective flow

$$P_{\boldsymbol{a}} = \prod_{i \in O} X_i^{S_i^x} Z_i^{S_i^z} \overrightarrow{\prod_{i \in O^c}} \left(S_i^z [M_i^{a_i}]^{S_i^x} \left(\prod_{\{k : k \sim i, k \succeq i\}} E_{i,k} \right) N_{f(i)}(|+\rangle) \right)$$

MBQC with One Pure Qubit

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Input sta
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UBQC comes for free in MBQC with pure qubit

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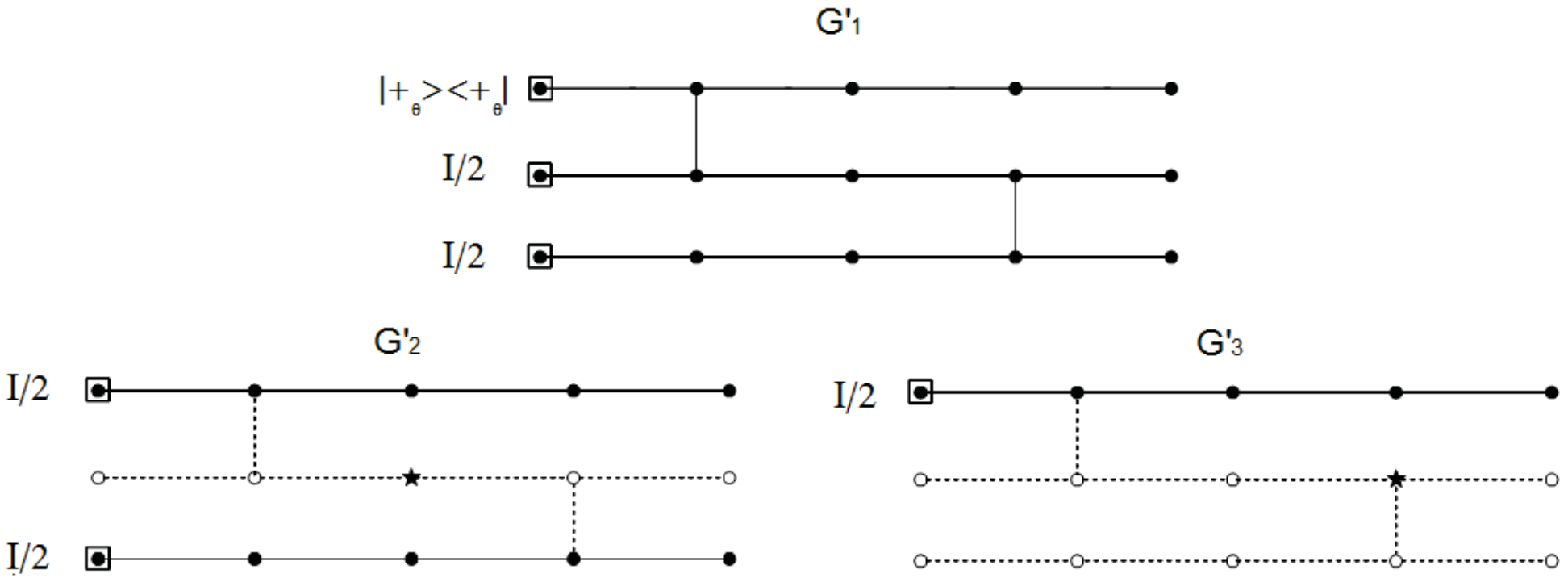
Verified Delegated QC with One Pure Qubit



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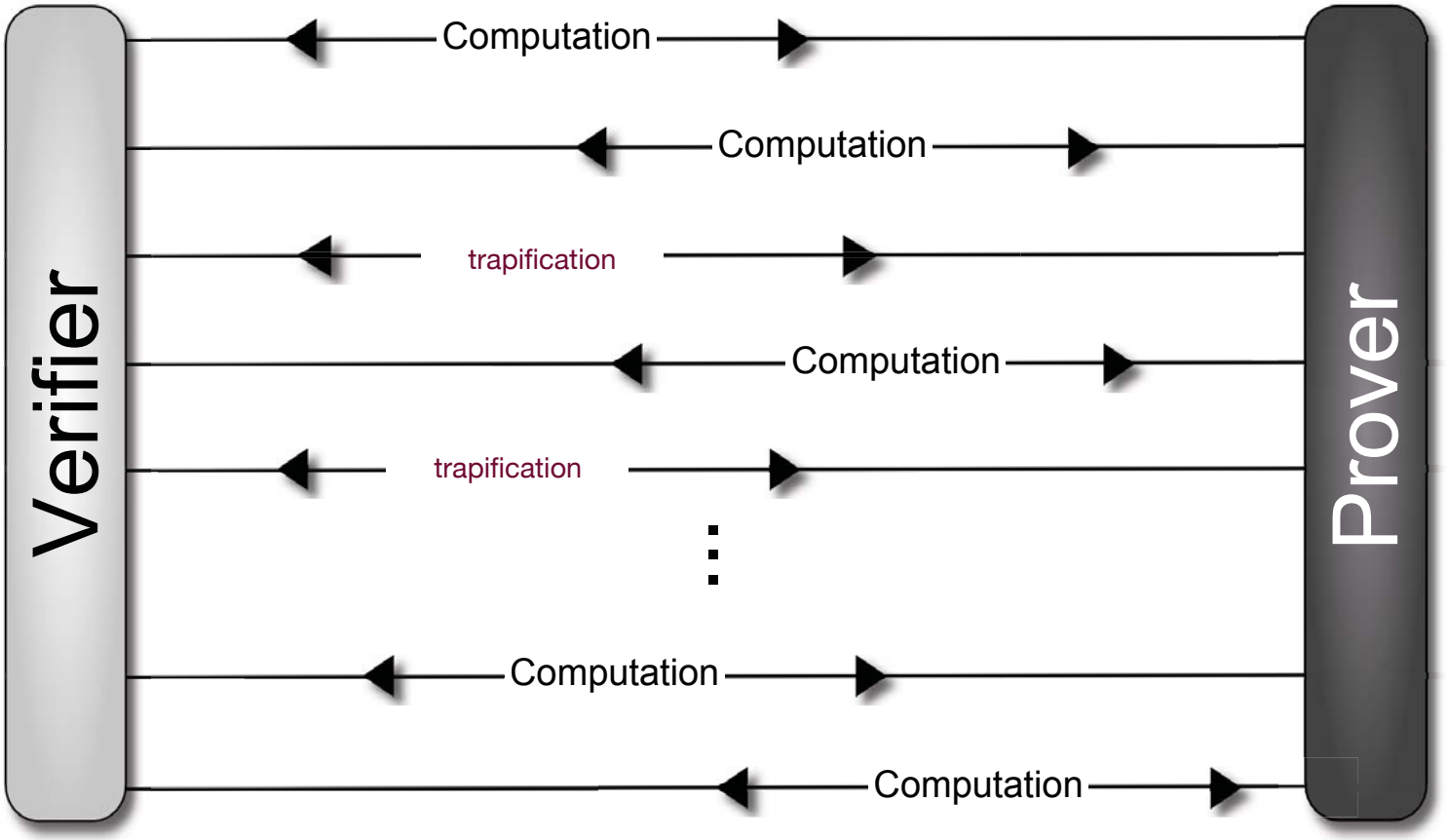
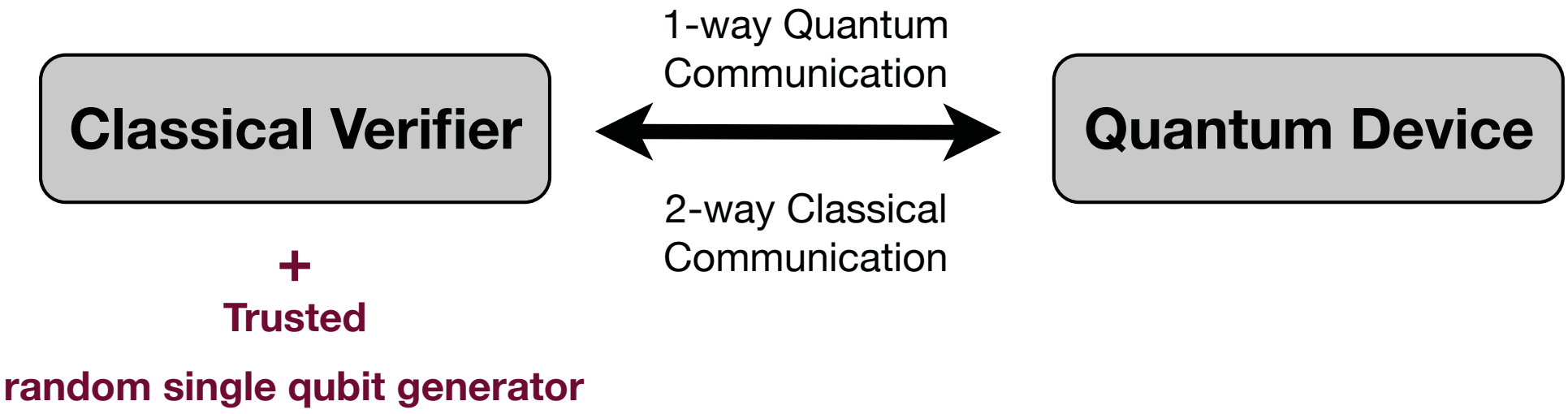


From QKD to verifiable quantum internet



Clients only requires (trusted) preparation of BB84 single qubits states (prepare-and-send).

[Dunjko-Kashefi 16]

From QKD to verifiable quantum internet

Classical Verifier

1-way Quantum Communication

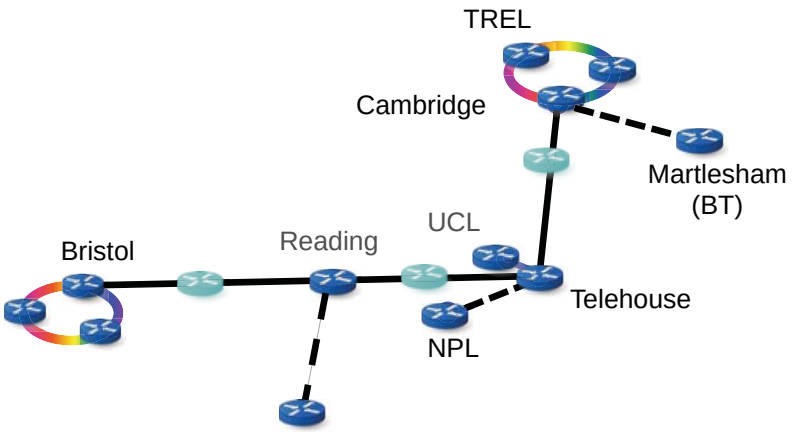
2-way Classical Communication

Quantum Device

+

Trusted

random single qubit generator



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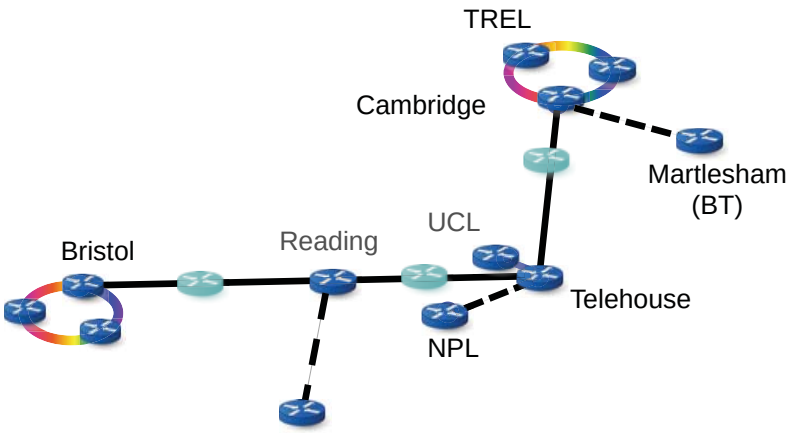

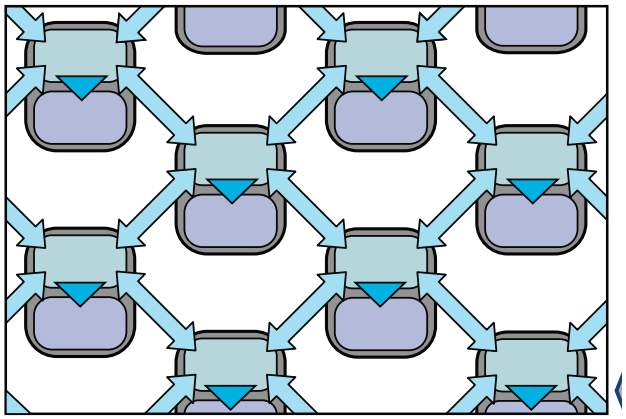

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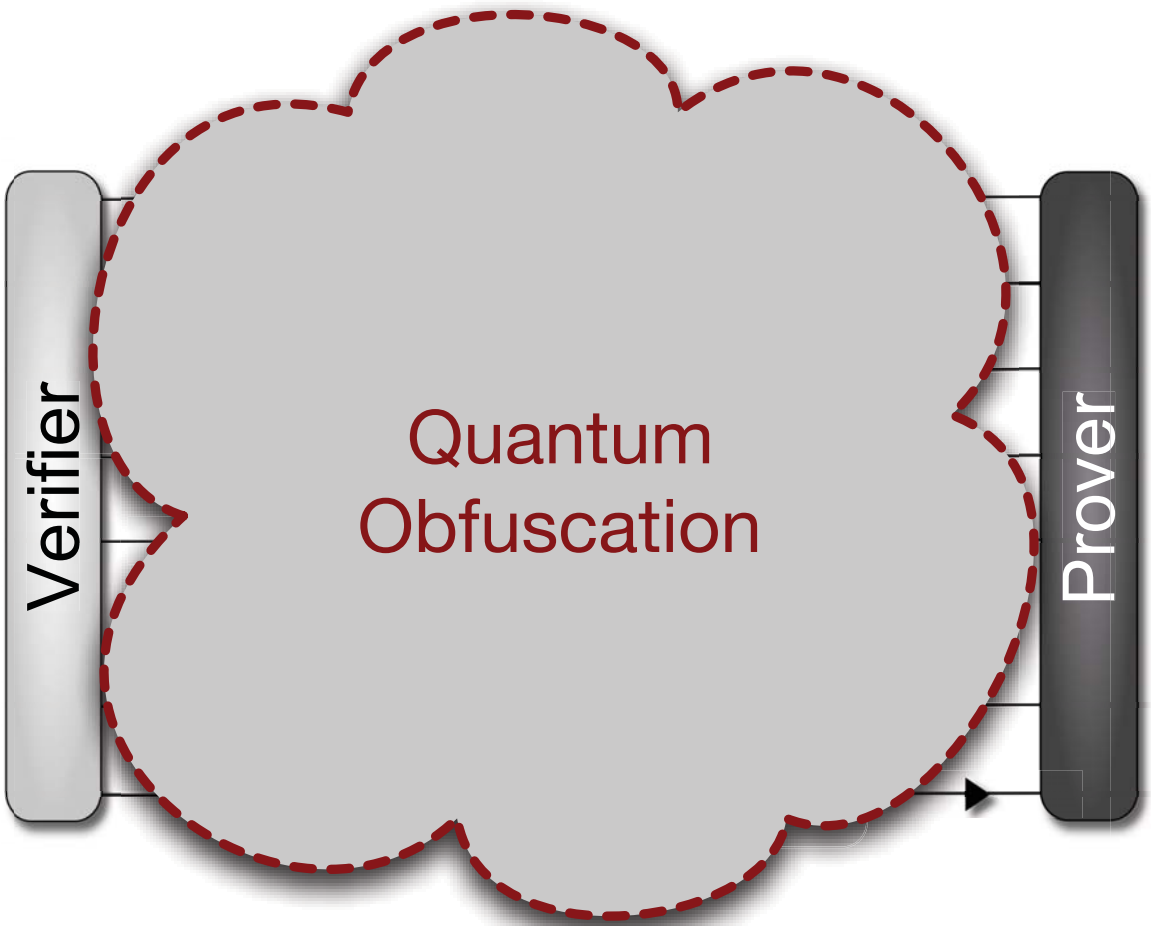
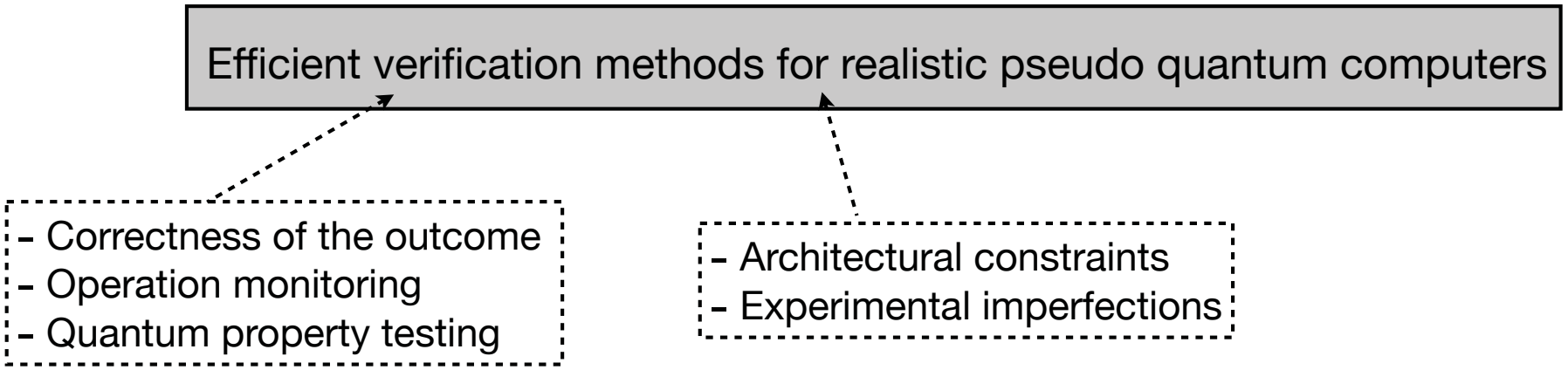
[Dunjko-Kashefi 16]

Can we get ride of qubit ?



Alagic, Fefferman, 2016

Perspective



Perspective

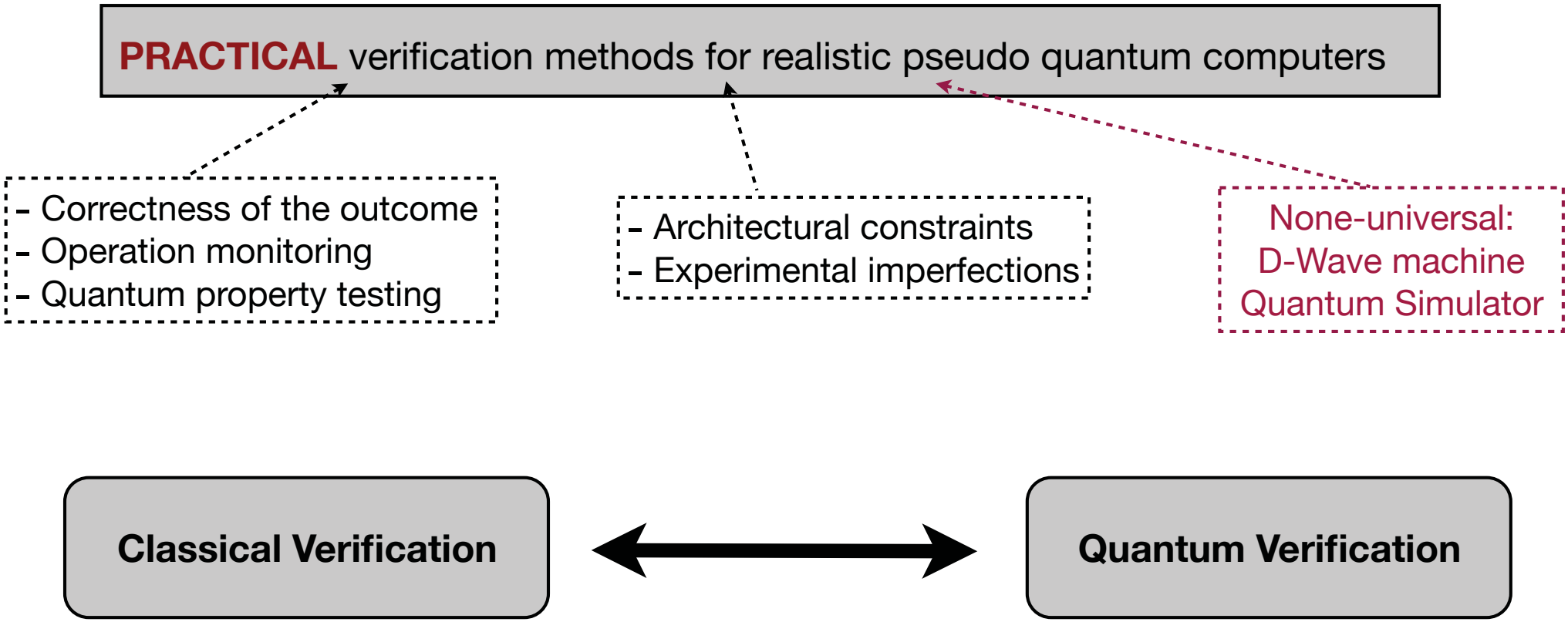
PRACTICAL verification methods for realistic pseudo quantum computers

- Correctness of the outcome
- Operation monitoring
- Quantum property testing

- Architectural constraints
- Experimental imperfections

None-universal:
D-Wave machine
Quantum Simulator

Perspective



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Classical Verification ⟷ **Quantum Verification**

Breakable Security

Server's Time

Perspective

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Classical Verification ⟷ **Quantum Verification**

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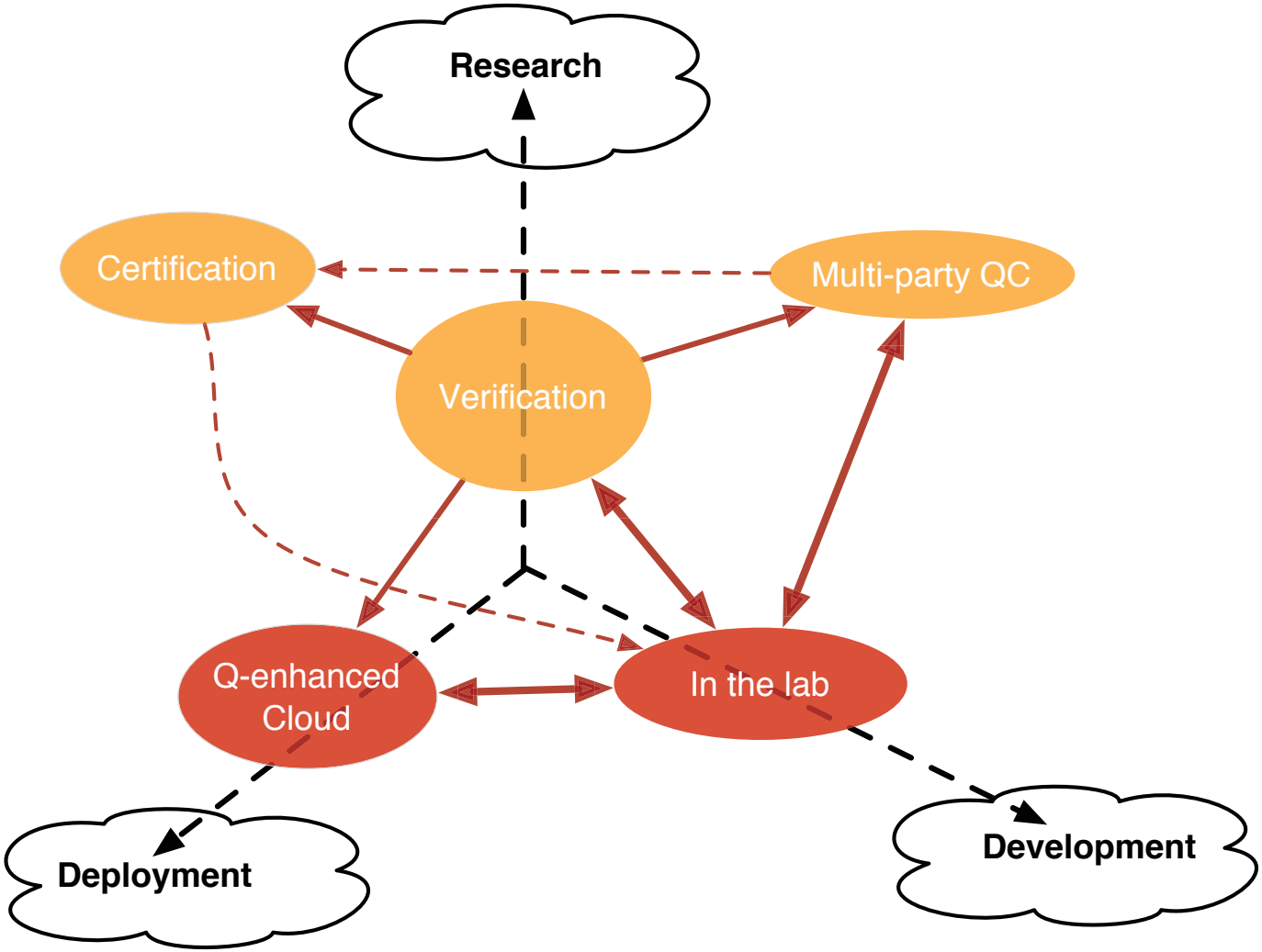
Universal Machine

Interaction

The Edinburgh-Paris Quantum Team



The Edinburgh-Paris Quantum Team