Fault-tolerant verification of quantum supremacy & Accreditation of NISQ devices

Animesh Datta

Department of Physics, University of Warwick, UK

Samuele Ferracin, Theodoros Kapourniotis

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Quantum Physics

Nonadaptive fault-tolerant verification of quantum supremacy with noise

Theodoros Kapourniotis, Animesh Datta

(Submitted on 28 Mar 2017 (v1), last revised 27 Feb 2019 (this version, v3))

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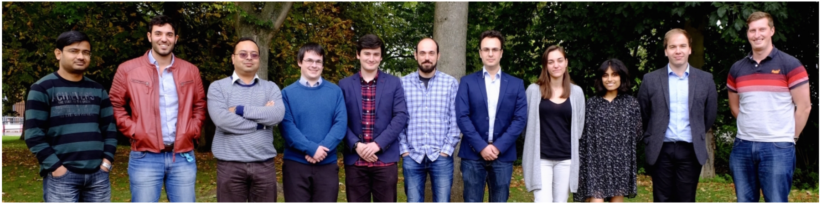
Quantum Physics

Accrediting outputs of noisy intermediate-scale quantum computing devices

Samuele Ferracin, Theodoros Kapourniotis, Animesh Datta

(Submitted on 23 Nov 2018 (v1), last revised 30 May 2019 (this version, v2))

Papers



- Dominic Branford
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Quantum supremacy

Quantum supremacy

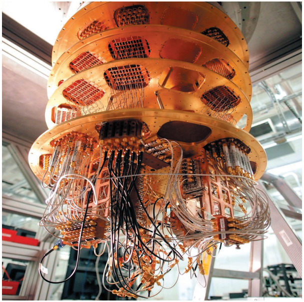
Why quantum supremacy? It used to be ...

1. quantum simulator — Manin/Feynman (1980/82)
2. quantum computer — Shor (1994)
3. quantum 'supreme' device — Aaronson/Arkhipov (2013)

It may look like the promise of quantum information is shrinking

The slide down from computation to supremacy is because

- Experiments are hard!
- All of DiVincenzo's criteria need fulfilling



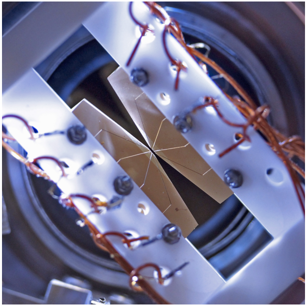


Figure: Experimental advances have been enormous (Google, UMD)

We still don't have a big enough system with low enough noise

If we had a universal QC, we wouldn't be talking about supremacy

Theoretical shortcomings

- Many examples of exponential improvement in QIP
- Simon's algorithm (oracle separation between BPP & BQP)
- Shor's algorithm (compared to best known classical algorithm)
- ✗ Hofstadter butterfly @ Google (provably polynomial)
- ...

No theoretical impossibility of classical polynomial algorithms

Tang, 1807.04271

No proof QC is exponentially stronger than classical

If we had a proven exponential gap of QC, we wouldn't be talking about supremacy

So, we've settled for

Quantum supremacy

- Theoretical proof of exponential gaps (with conjectures)
- Sub-universal (typically sampling) problems

- The idea has been around for a long time

  Knill/Laflamme, DQC1, 1998- | Terhal/DiVincenzo, Fermionic QC, 2002-

- Revived interest after complexity-theoretic hardness proofs (sampling problems with conjectures)

  Bremner/Jozsa/Shepherd/Montanaro, IQP, 2010- | Aaronson/Arkhipov, BosonSampling, 2013-

  Morimae/Fujii/Fitzsimons, $DQC1_k$ 2014- | Fefferman/Umans, FourierSampling, 2015-

  Farhi/Harrow, QAOA, 2016- | Google, RandomSampling, 2016-

  Gao/Wang/Duan, IsingSampling, 2016

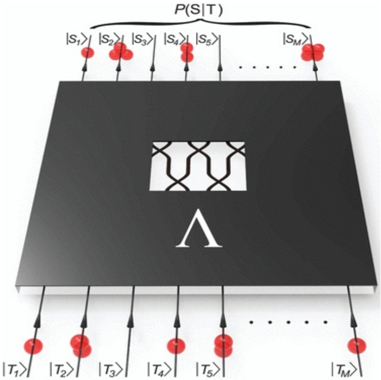
- Some performed/proposed experiments

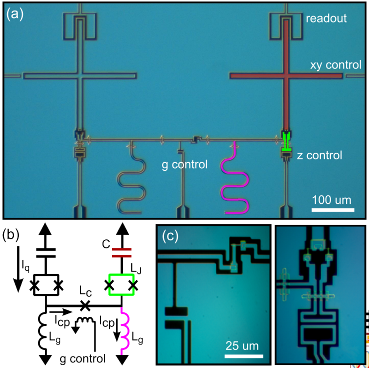
  Oxford, Vienna, Rome, Brisbane, Shanghai, Google, IBM, ...

Quantum supremacy experiments

What do quantum supremacy experiments prove?

Figure: Boson sampling (Oxford), Random sampling(Google)





Is quantum supremacy <u>really</u> easier than quantum computation?

All experiments are imperfect and noisy

- Can imperfect/noisy experiments ‘show’ quantum supremacy?

All experiments are imperfect and noisy

- Can imperfect/noisy experiments 'show' quantum supremacy?

- Physical system must be quantum (non-classical)

  Rahimi-Keshari/Ralph/Caves, PRX, **6**, 021039, (2016)

  [need low(er) noise/imperfection]

- Computational task must be supreme (super-classical)

  DWave | Neville *et al.* Nat. Phys. 13, 1153 (2017) | Google/IBM

  [need large(r) system]

All experiments are imperfect and noisy

- Can imperfect/noisy experiments 'show' quantum supremacy?
- But even with better and larger systems ...

Noise

- Is the problem still hard?
- Otherwise experiments useless (for quantum supremacy)

Imperfections

- Is the solution correct?
- Not solving decision problems

The two fundamental issues are

- Proofs of hardness of sampling (with noise)
- Verification of quantum supremacy (with imperfections)

Aaronson/Chen, 1612.05903

Harrow/Montanaro, Nature 549, 203 (2017)

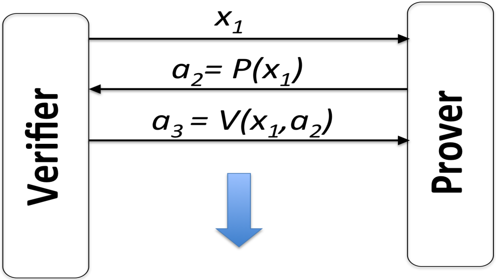
Why do we care?

- Is quantum supremacy easier than quantum simulation?
- Is quantum supremacy easier than quantum computation?
- If so, by how much?

Verification of quantum computation

I. Direct certification, benchmarking (Hardware solution)
   Certify a small system, hope it stills holds for a big one

II. Interactive proof system: verification (Software solution)



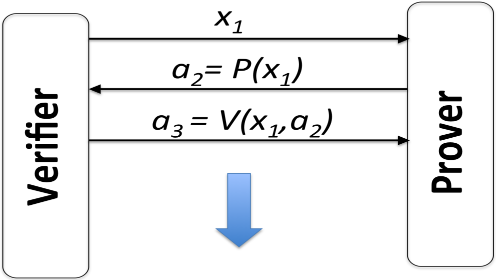
Aharonov, Ben-Or, Broadbent, Fitzsimmons, Hayashi, Kashefi, Morimae, Vazirani, Vidick, ...

To verify, must trust

Our work: 'Prepare-and-send' protocol

Verification of quantum computation

II. Interactive proof system: verification (Software solution)



- Hide easy 'trap' computations within hard computation
- Check the correctness of the 'traps'
- Bound the correctness of the overall computation
- Also useful in adverserial setting

Aharonov, Ben-Or, Broadbent, Fitzsimmons, Hayashi, Kashefi, Morimae, Vazirani, Vidick, ...

To verify, must trust

Our work: 'Prepare-and-send' protocol

Verification scheme for quantum supremacy

New definition of verifiability over i.i.d. repetitions based on

$$\text{var} \equiv \frac{1}{2} \sum_{\boldsymbol{x}} |q^{\text{exc}}(\boldsymbol{x}) - q^{\text{nsy}}(\boldsymbol{x})|,$$

Fitzsimmons/Kashefi, PRA 96, 012303 (2017)

(1) Takes as input a verification protocol, $M \in \mathbb{N}, l \in [0, 1]$

(2) Outputs a string and a bit.

(3) The bit determines if the string is accepted or rejected.

(4) After running M i.i.d repetitions of (1) it outputs one of the M output strings at random. Accept if at least a fraction l of the protocols accept and reject otherwise.

Verifiability

Definition (Verifiability)

A scheme is verifiable if its output is

- $(\delta', \delta)-$complete: For an honest prover having only bounded noise, the scheme accepts at least with probability δ', and

$$\mathrm{var} \leq 1 - \delta$$

  for the output string.
- $(\varepsilon', \varepsilon)-$sound: For any, including adversarial, prover if the scheme accepts then

$$\mathrm{var} \leq \varepsilon$$

  with confidence ε'.

Kapourniotis/AD, arXiv:1703.09568

Blindness is a necessary ingredient in our verification scheme

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Blindness is a necessary ingredient in our verification scheme

Our work: Trap-based verification of Ising sampling problem

Ising sampler

- Translationally-invariant, nonadaptive, Ising spin model

$$\mathcal{H} = -\sum_{\langle i,j \rangle} J Z_i Z_j + \sum_i B_i Z_i$$

- The probability $p_{\boldsymbol{x}}$ of measuring bit string $\boldsymbol{x}$ from partition function $\mathcal{Z}_{\boldsymbol{x}}$

$$p_{\boldsymbol{x}} = \frac{\left|\mathrm{Tr}\left(e^{-i(\mathcal{H}+\frac{\pi}{2}\sum_i x_i Z_i)}\right|^2}{2^{2mn}} \equiv \frac{|\mathcal{Z}_{\boldsymbol{x}}|^2}{2^{2mn}}$$

Gao/Wang/Duan, PRL, **118**, 40502 (2017)

- Partition function at imaginary temperatures insightful

Lee/Yang, Phys. Rev. **87**, 410 (1952)

Fujii/Morimae, NJP **19**, 033003 (2017)

Goldberg/Guo, Computational Complexity **26**, 765 (2017)

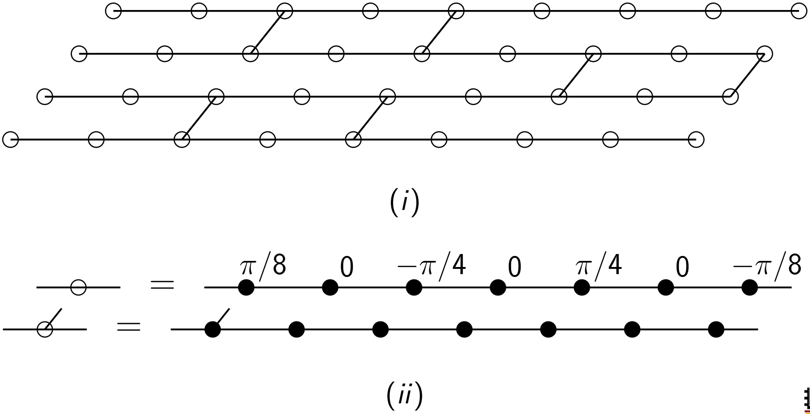


Figure: Avoids Multi-instanceness (unlike IQP, BS, RSC)

Gao/Wang/Duan, PRL, **118**, 40502 (2017)

Traps

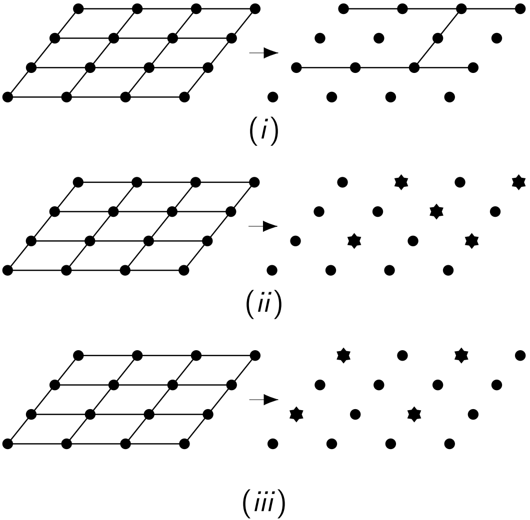


Figure: Verifier chooses a random ordering of $2\kappa + 1$ graph states. Single qubit traps.

Kapourniotis/AD, arXiv:1703.09568

Noise model

- 'Prepare-and-send' protocol
- Blindness (Quantum one-time pad)

$$\mathcal{N}_j = (1 - \epsilon_{V,P})\mathcal{I} + \mathcal{E}_j$$

where

- $\epsilon_V = ||\mathcal{E}_j||_\diamond$ for preparation noise [Verifier]
- $\epsilon_P = ||\mathcal{E}_j||_\diamond$ for entangling/measurement noise [Honest Prover]

Theorem (Non-fault tolerance verification scheme)

There exists a verification scheme with

$$M = \frac{\log(1/\beta)}{2\kappa^2 N^2(\epsilon_V + \epsilon_P)^2},$$

$$I = 1 - \kappa N(2\epsilon_V + 4\epsilon_P)$$

that is

$$\left(1-\beta, 1-\sqrt{N(\epsilon_V + 3\epsilon_P)}\right) - \textit{complete}$$

and

$$\left(1-\beta, \sqrt{\kappa N(3\epsilon_V + 5\epsilon_P) + \Delta_\kappa}\right) - \textit{sound},$$

where $\Delta_\kappa = \kappa!(\kappa+1)!/(2\kappa+1)! \sim 2^{-\kappa}$.

Kapourniotis/AD, arXiv:1703.09568

Recall

Definition (Verifiability)

A scheme is verifiable if its output is

- $(\delta', \delta)-$complete: For an honest prover having only bounded noise, the scheme accepts at least with probability δ', and
$$\text{var} \leq 1 - \delta$$
for the output string.
- $(\varepsilon', \varepsilon)-$sound: For any, including adversarial, prover if the scheme accepts then
$$\text{var} \leq \varepsilon$$
with confidence ε'.

Kapourniotis/AD, arXiv:1703.09568

Problem

For verifiable quantum supremacy, we need

$$N(\epsilon_V + 3\epsilon_P) \quad \text{const.}$$

and

$$\kappa N(3\epsilon_V + 5\epsilon_P) + \Delta_\kappa \qquad \downarrow$$

Impossible in large systems(N) with constant noise($\epsilon_{P,V}$)

Want to verify quantum supremacy for large N and constant $\epsilon_{P,V}$

Solution: Quantum fault tolerance

- Use FT (3D cluster state) encoding for universal QC

✗ RHG encoding require adaptive operations (gate distillation)

Raussendor/Harrington/Goyal, NJP 9, 199 (2007)

- On target computation, use free postselection due to Fujii

1610.03632

- Trap computation is Clifford, so nonadaptive

Solution: Quantum fault tolerance

✗ RHG encoding require adaptive operations (gate distillation)

Raussendor/Harrington/Goyal, NJP 9, 199 (2007)

- On target computation, use free postselection due to Fujii

1610.03632

- Trap computation is Clifford, so nonadaptive
- FT thresholds

RHG error-correction in traps

$$\epsilon_{\text{thres}} = 0.75\%$$

Less than $\epsilon_{\text{thres}} = 2.84\%$ for unverified quantum supremacy

1610.03632

RHG error-detection in traps

$$\epsilon_{\text{thres}} = 1.97\%$$

Extend Fujii 1610.03632 to additive errors

Kapourniotis/AD, arXiv:1703.09568

FT thresholds for verifiable quantum supremacy

Supremacy easier than universal QC

$$\epsilon_{\text{thres}} = 1.97\%$$

- Replace error correction with error detection
- Works as isolated trap qubits isolated can be retransmitted individually
- Same completeness & soundness with κ replaced by $M\kappa$

ϵ	$\epsilon_{\text{thres}}/20$	$\epsilon_{\text{thres}}/50$	$\epsilon_{\text{thres}}/100$
M	3×10^8	2863	54

✓ M independent of problem size

- Improved by judicious braiding or other topological code
- Larger ϵ_{thres} with simpler problem specific code

Kapourniotis/AD, arXiv:1703.09568

Blindness and fault tolerance

✗ Leaking logical measurement angles in magic state distillation

✗ For distillation, need to reveal information about state distilled

Ising Sampler and Trap Computations MBQC
(Logical layer)

Protected topology using defects

Blind 3D cluster-state MBQC
(Physical layer)

Kapourniotis/AD, arXiv:1703.09568

On target computation, use free postselection due to Fujii

$$\mathrm{var}^{\mathrm{Post}} \equiv \frac{1}{2}\sum_{\boldsymbol{x}} |q^{\mathrm{exc}}(\boldsymbol{x}|y=0) - q^{\mathrm{nsy}}(\boldsymbol{x}|y=0)|$$

Definition (Verifiability of a scheme for post-selected distribution)

A scheme is verifiable conditioned on the post-selection register being zero, if its output is

- $(\delta', \delta)-$complete: For an honest prover having only bounded noise, the scheme accepts at least with probability δ', and

$$\mathrm{var}^{\mathrm{Post}} \leq 1-\delta$$

  for the the output string.

- $(\varepsilon', \varepsilon)-$sound: For any, including adversarial, prover if the scheme accepts, then

$$\mathrm{var}^{\mathrm{Post}} \leq \varepsilon$$

  with confidence ε'.

Kapourniotis/AD, arXiv:1703.09568

Our results (Long term aim of experiments)

Theorem (Fault-tolerant verification scheme)

There exists a verification scheme with

$$M = \log(1/\beta)/(2\epsilon''^2)$$

and

$$l = (1 - 2\epsilon''),$$

that is

$$(1-\beta, 1-\sqrt{\epsilon''}) - \textit{complete}$$

and

$$(1-\beta, \sqrt{3\epsilon'' + \Delta_\kappa}) - \textit{sound}$$

where $\Delta_\kappa = \kappa!(\kappa+1)!/(2\kappa+1)!$.

- Milestone towards FT QC

Kapourniotis/AD, arXiv:1703.09568

Conjecture (Average-case hardness)

For $0 \leq \alpha_1, \beta_1 \leq 1$, *approximating the probability distribution of the Ising sampler by* $p^{\mathrm{apx}}(\boldsymbol{x}|y=0)$ *up to multiplicative error*

$$|p^{\mathrm{apx}}(\boldsymbol{x}|y=0) - q^{\mathrm{exc}}(\boldsymbol{x}|y=0)| \leq \alpha_1 q^{\mathrm{exc}}(\boldsymbol{x}|y=0)$$

in time poly$(|\boldsymbol{x}|, 1/\alpha_1, 1/\beta_1)$ *is* $\#P$*-hard for at least a fraction* β_1 *of* $\boldsymbol{x}$ *instances.*

Conjecture (Anti-concentration)

There exist some $0 \leq \alpha_2, \beta_2 \leq 1$, $1/\alpha_2 \in \mathrm{poly}(1/\beta_2)$ *such that for all* x

$$\mathrm{prob}\left(q^{\mathrm{exc}}(\boldsymbol{x}|y=0) \geq \frac{\alpha_2}{2^N}\right) \geq \beta_2$$

More general than Bremner/Montanaro/Shepherd, PRL 117, 080501 (2016)

Theorem (Fault-tolerant hardness)

Assume that the two Conjectures hold. Then sampling from the output distribution of the experimental Ising sampler $q^{\mathrm{nsy}}(\boldsymbol{x}, y)$ *with a classical machine, assuming a* $(\varepsilon', \varepsilon)$*-sound verification scheme accepts with*

$$\varepsilon \leq \frac{(\beta_1 + \beta_2 - 1 - 2^{-N})\alpha_1\alpha_2}{2},$$

implies, with confidence ε'*, a collapse in the polynomial hierarchy to the third level.*

Kapourniotis/AD, arXiv:1703.09568

First FT verification of quantum supremacy

FT supremacy verification milestone for FT QC

Kapourniotis/AD, arXiv:1703.09568

We still need

- bespoke FT thresholds for verifying specific supremacy models
- bespoke error correcting codes for specific supremacy models
- verification schemes for specific architectures
- to use verification schemes in experiments
  - short term (Thm 1)
  - long term (Thm 2/3)
  - But we want everything now. NISQ devices...

NISQ devices have a credibility problem

If/when a NISQ device solves a hard problem (not in NP), how do we know its done so correctly?

- ✗ NISQ devices are noisy and imperfect
- ✗ Cannot check efficiently on a classical computer

"Quantum Accreditation"

To build big (intermediate) systems, start with small ones

- State tomography
- Process tomography
- Measurement (Detector) tomography

Numerous references ...

Too many parameters for NISQ devices

Good gate fidelities are not enough

- Randomised benchmarking
- Gate set tomography

Knill *et. al.*, PRA 77, 012307 (2008)

Blume-Kohout *et. al.*, Nat. Comm. 8, 14485 (2017)

Makes unrealistic assumptions

Average fidelity ϵ is a poor bound

Sanders *et. al.*, NJP 18 012002 (2016)

$$1 - \epsilon \lesssim \epsilon_G = ||G - G^{\mathrm{ideal}}||_\diamond \lesssim \sqrt{1 - \epsilon}$$

Verification of quantum supremacy

PHYS: Statistical methods (e.g., cross entropy)

Inadequate | Bouland *et al.*, Nat. Phys. (2018)

TCS: Interactive proof system

Childs, Aharonov, Ben-Or, Broadbent, Eisert, Fitzsimmons, Hayashi, Kashefi, Mahajan

Morimae, Vazirani, Vidick, Zhu, Us ....

- Hide easy 'trap' computations within hard computation
- Check the correctness of the 'traps'
- Bound distance between ideal (p_{id}) and actual (p_{act}) output

Exorbitant overheads (due to MBQC)

- Even constant overheads are impractical

CS meets experiments: Scalable *vs* practical

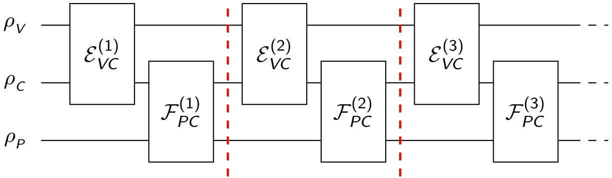
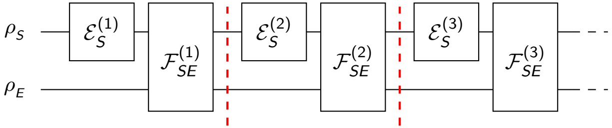


Figure: CS: Verifier, prover, and a shared register C.

Figure: Experiments: System and environment.



- In the circuit model

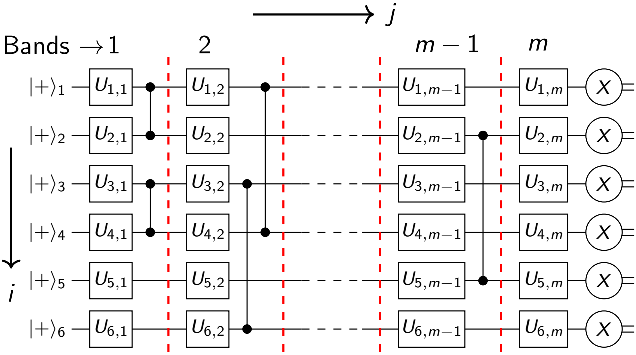


Figure: A six-qubit example of target circuit.

- Several ($v > 1$) trap circuits
- Traps designed to capture all noise
- Trap and target circuits of same size

Our work

Ferracin/Kapourniotis/AD, 1811.09709

- In the circuit model
- Different trust assumptions (noise model)

N1: Noise in state preparation, entangling gates, measurements is arbitrary CPTP map encompassing system & environment

$$\rho_{\text{out}} = \mathrm{Tr}_E \left[\circ_{p=1}^{q} \mathcal{N}_{SE}^{(p)} (\mathcal{E}_S^{(p)} \otimes \mathcal{I}_E)(\rho_S \otimes \rho_E) \right]$$

and is unbounded in diamond norm;

N2: Single qubit gates are trusted

Single qubit gates are the best component in leading architectures

Different from 'prepare & send' or 'receive & measure'

Accreditation Protocol - One run

$$\rho_{\text{out}} = \mathrm{Tr}_E\left[\,\circ_{p=1}^{q}\,\mathcal{N}_{SE}^{(p)}(\mathcal{E}_S^{(p)} \otimes \mathcal{I}_E)(\rho_S \otimes \rho_E)\right]$$

Protocol $\{\mathcal{E}_S^{(p)}\}_{p=1}^{q}$ accredits outputs in presence of $\{\mathcal{N}_{SE}^{(p)}\}_{p=1}^{q}$ if

$$\begin{aligned}\rho_{\text{out}} &= b\,\tau'^{\,\text{tar}}_{\text{out}} \otimes |\text{acc}\rangle\langle\text{acc}| \\ &+ (1-b)\left(l\,\sigma^{\text{tar}}_{\text{out}} \otimes |\text{acc}\rangle\langle\text{acc}| + (1-l)\tau^{\text{tar}}_{\text{out}} \otimes |\text{rej}\rangle\langle\text{rej}|\right),\end{aligned}$$

where
$\sigma^{\text{tar}}_{\text{out}}$ ($\tau'^{\,\text{tar}}_{\text{out}}$) is target circuit state after noiseless (noisy) protocol,
$\tau^{\text{tar}}_{\text{out}}$ is an arbitrary state for the target circuit,
$|\text{acc}\rangle$ is the state of the flag indicating acceptance,
$|\text{rej}\rangle = |\text{acc} \oplus 1\rangle$,
$0 \leq l \leq 1$, $0 \leq b \leq \varepsilon$ and $\varepsilon \in [0,1]$.

$1-\varepsilon$ is the *credibility* of the accreditation protocol.

Accreditation Protocol - One run

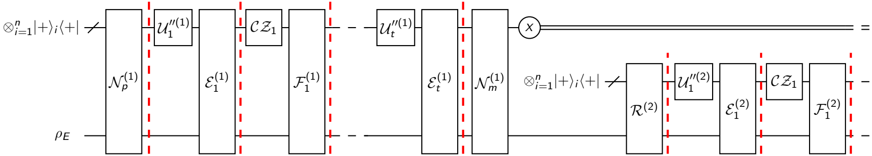


Figure: One target computation and v trap computations.

Correlated noise across all $v+1$ circuits - in space and time.

- Use $U'_{i,j} = X_i^{\alpha'_{i,j}} Z_i^{\alpha_{i,j}} U_{i,j}$, $\alpha_{i,j}, \alpha'_{i,j} \in \{0,1\}$ are random bits
- Pauli twirl decomposes noise into combination of local Paulis
- Traps designed to capture all local Pauli noise

Accreditation Protocol - Many runs

- After d protocol runs (with same target and v different traps),
- If all runs are affected by i.i.d. noise,
- then, with confidence $1 - e^{-2d\theta^2}$, $\theta \in (0, N_{\text{acc}}/d)$

$$\frac{1}{2} \sum_{\bar{s}} \left| p_{\text{noiseless}}(\bar{s}) - p_{\text{noisy}}(\bar{s}) \right| \leq \frac{\varepsilon}{N_{\text{acc}}/d - \theta} ,$$

for all $N_{\text{acc}} \in [0, d]$ protocol runs ending with $|\text{acc}\rangle$ flag bit.

Results

Theorem

Suppose that all single-qubit gates are <u>noiseless</u>.
For any number $v \geq 3$ of trap circuits, our protocol can accredit the outputs of a noisy quantum computer affected by noise of the form N1 with

$$\varepsilon = \frac{\kappa}{v+1} \; ,$$

where $\kappa = 3(3/4)^2 \approx 1.7$.

Ferracin/Kapourniotis/AD, 1811.09709

Noisy single qubit gates

- Different trust assumptions (noise model)

N1: Noise in state preparation, entangling gates, measurements is arbitrary CPTP map encompassing system & environment

$$\rho_{\text{out}} = \mathrm{Tr}_E\big[\circ_{p=1}^{q}\, \mathcal{N}_{SE}^{(p)}(\mathcal{E}_S^{(p)} \otimes \mathcal{I}_E)(\rho_S \otimes \rho_E)\big]$$

and is unbounded in diamond norm;

N2: Noise in single-qubit gates is arbitrary (inc. gate-dependent) CPTP map encompassing system & environment

$$\widetilde{\mathcal{U}}_j = \mathcal{N}_j^{(k)}(\mathcal{U}_j \otimes \mathcal{I}_E) \;\; \text{with} \;\; ||\mathcal{N}_j^{(k)} - \mathcal{I}_{SE}||_\diamond \leq r_j^{(k)}$$

and $0 \leq r_j^{(k)} < 1$ (bounded in diamond norm).

Results

Theorem

Our protocol with $v \geq 3$ of trap circuits can accredit the outputs of a noisy quantum computer affected by noise of the form N1 *and* N2 *with*

$$\varepsilon = g\frac{\kappa}{v+1} + \left(1 - g\right), \tag{1}$$

where $\kappa = 3(3/4)^2 \approx 1.7$ *and* $g = \prod_{j,k}(1 - r^{(k)}_{\text{max},\ j})$.

Ferracin/Kapourniotis/AD, 1811.09709

$$\frac{1}{2}\sum_{\bar{s}}\left|p_{\text{noiseless}}(\bar{s}) - p_{\text{noisy}}(\bar{s})\right| \le \frac{\varepsilon}{N_{\text{acc}}/d - \theta}\ ,$$

Since N_{acc}/d is an estimate of prob(acc) (and if prob(acc)$\geq \delta$.)

$$\frac{1}{2}\sum_{\bar{s}}\left|p_{\text{noiseless}}(\bar{s}) - p_{\text{noisy}}(\bar{s})\right| \le \frac{\varepsilon}{\mathrm{prob(acc)}} \le \frac{\varepsilon}{\delta}.$$

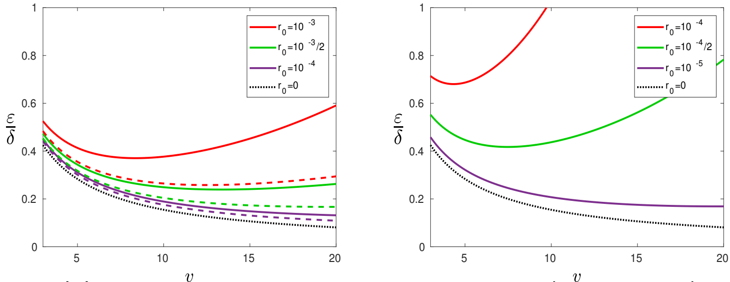


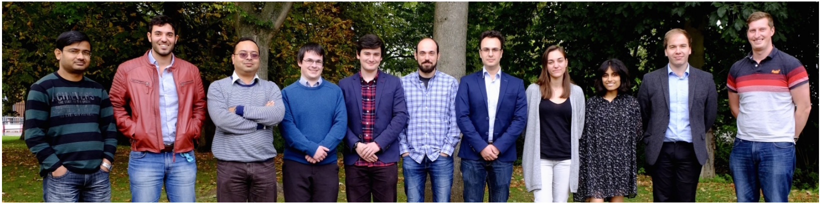
Figure: **(a)** Preparing GHZ states, with $n = m = 7$ (dashed lines) and $n = m = 10$ (solid lines). **(b)** Google RCS supremacy with $n = 62$ qubits and circuit depth $m = 34$.

So, Accreditation

- is practical (and scalable)
- is inspired by trap-based verification schemes
- is different from verification
- combines best features from physics & CS
- inspires new mesothetic (verifier-in-the-middle) verification scheme

Ferracin/Kapourniotis/AD, 1811.09709

Us



- Dominic Branford
- Samuele Ferracin
- Jamie Friel
- Evangelia Bisketzi
- Aiman Khan
- Andrew Jackson
- Theodoros Kapourniotis
- Max Marcus
- Francesco Albarelli

Thank you!

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