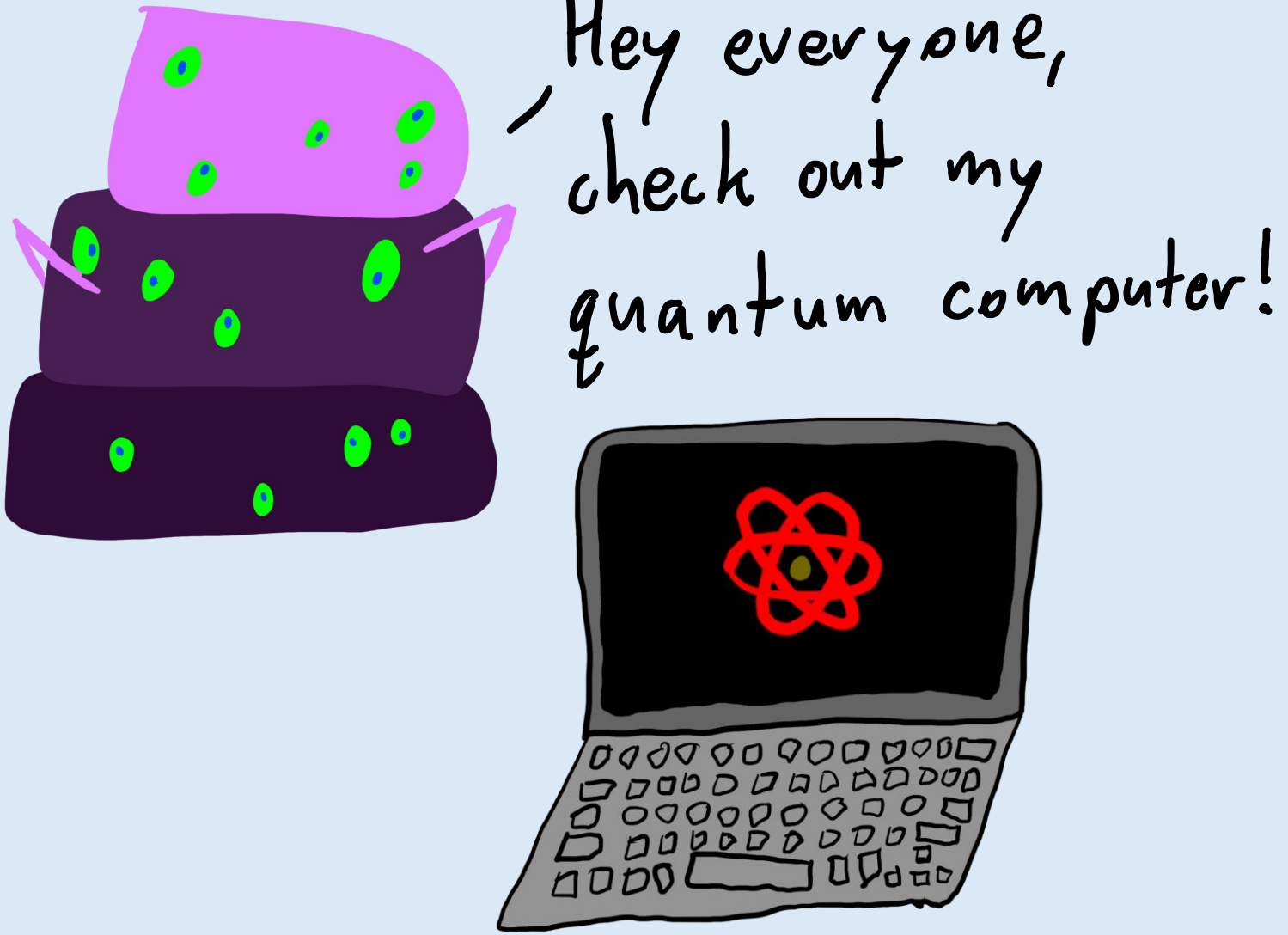
On Cryptography and Distribution Verification

with Applications to Quantum Advantage

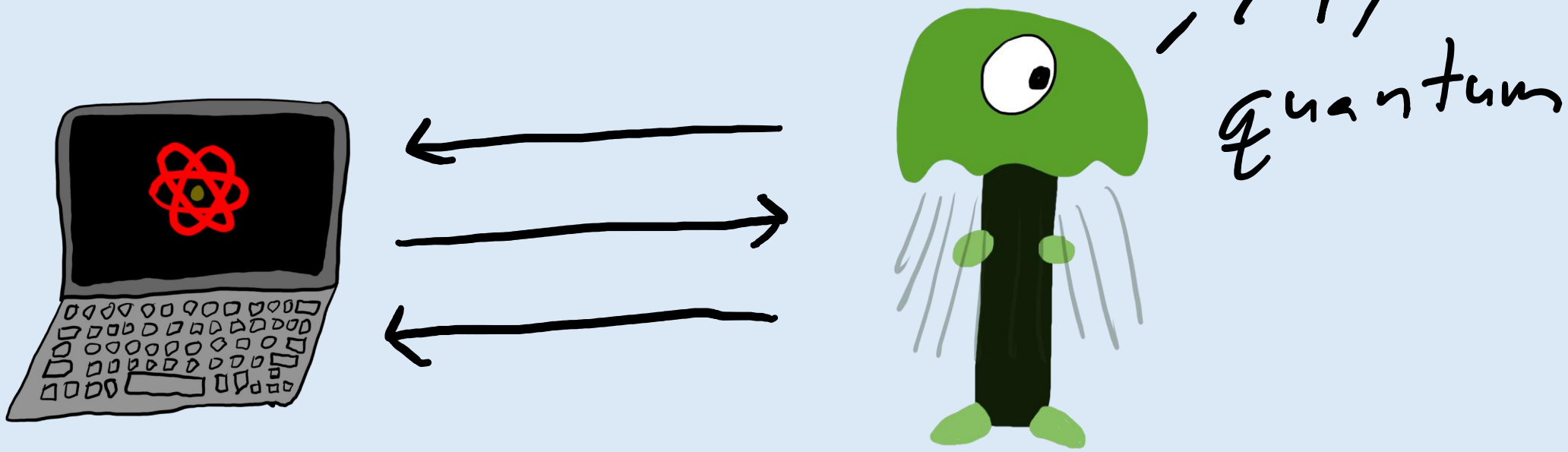
Bruno Cavalar, **Eli Goldin**, Matthew Gray, Taiga Hiroka, Tomoyuki Morimae

Quantum Advantage



Quantum Advantage

Proof of Quantumness



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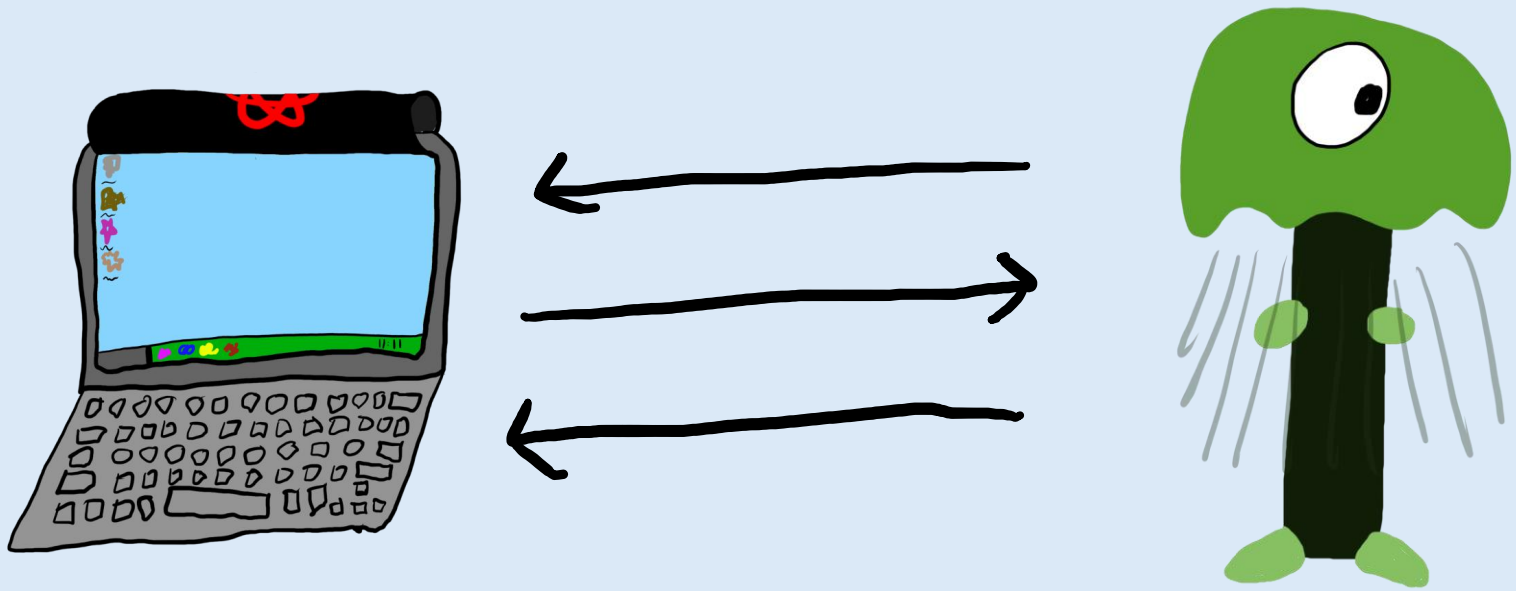
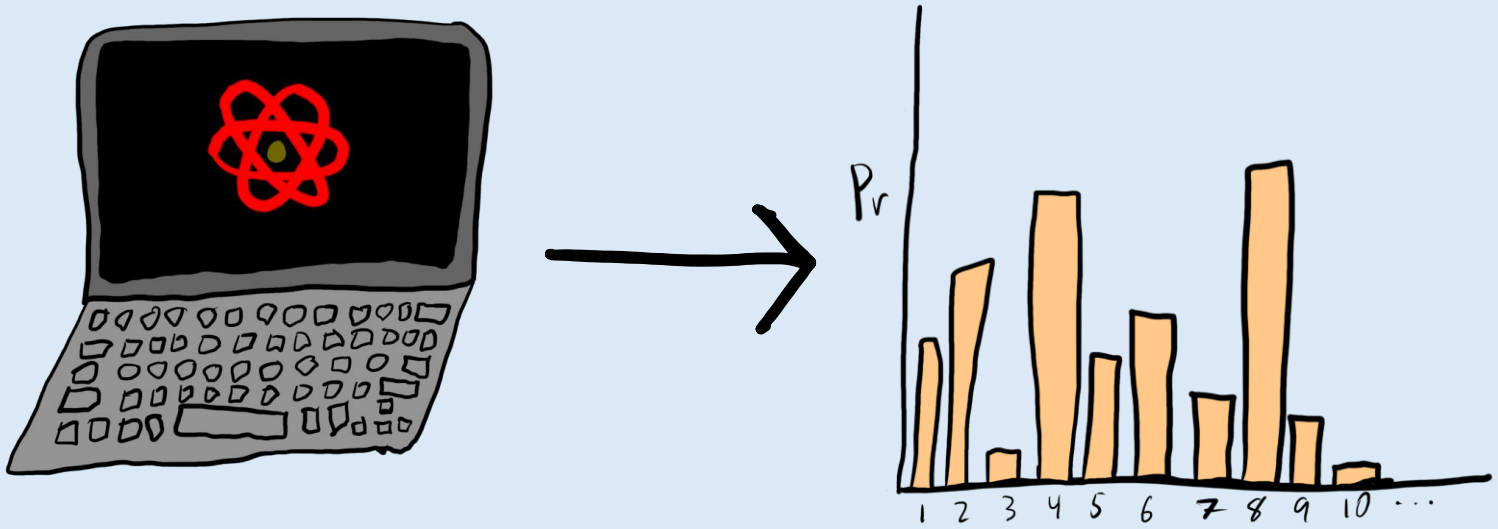


EXPENSIVE

[BCM+18, BKVV20, KMCVY21, MY22, YZ22, KLVY23, NZ23, BK

Quantum Advantage Samplers



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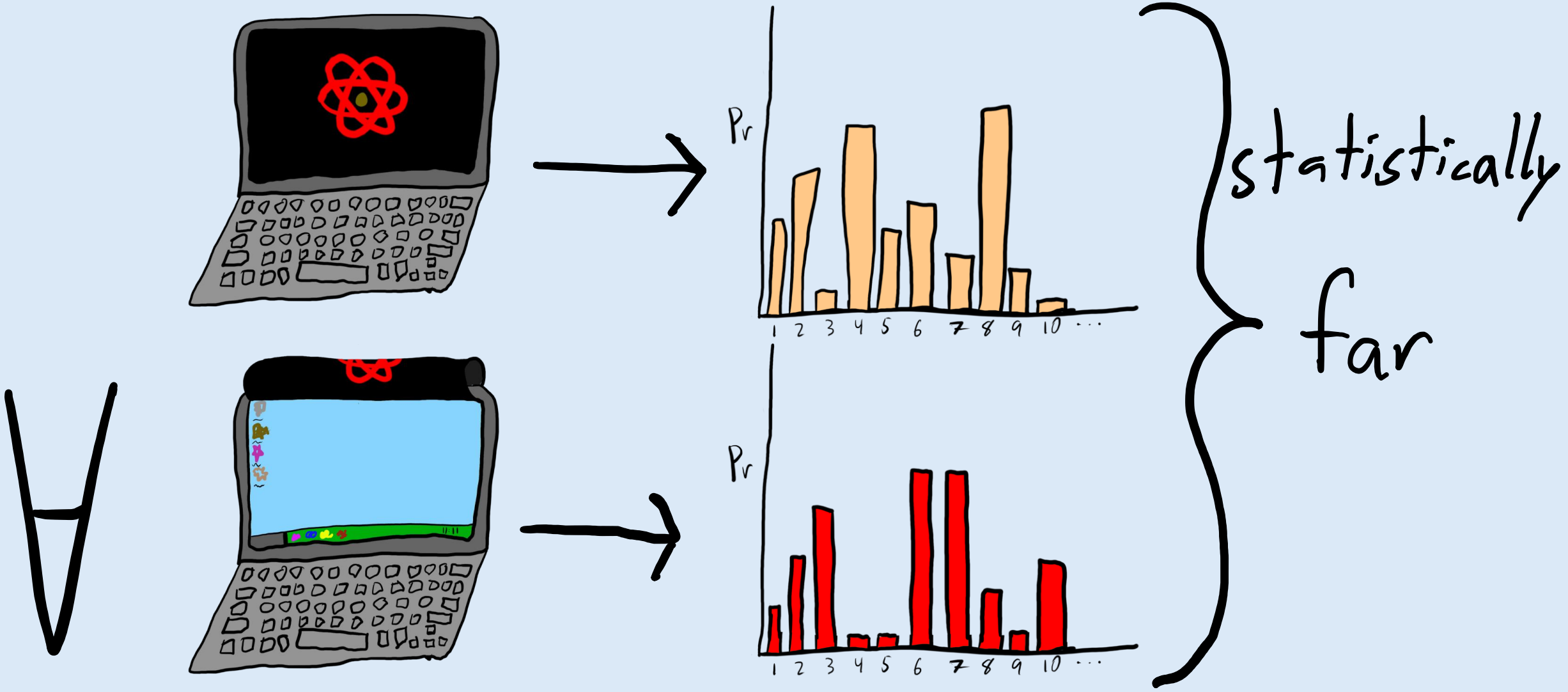
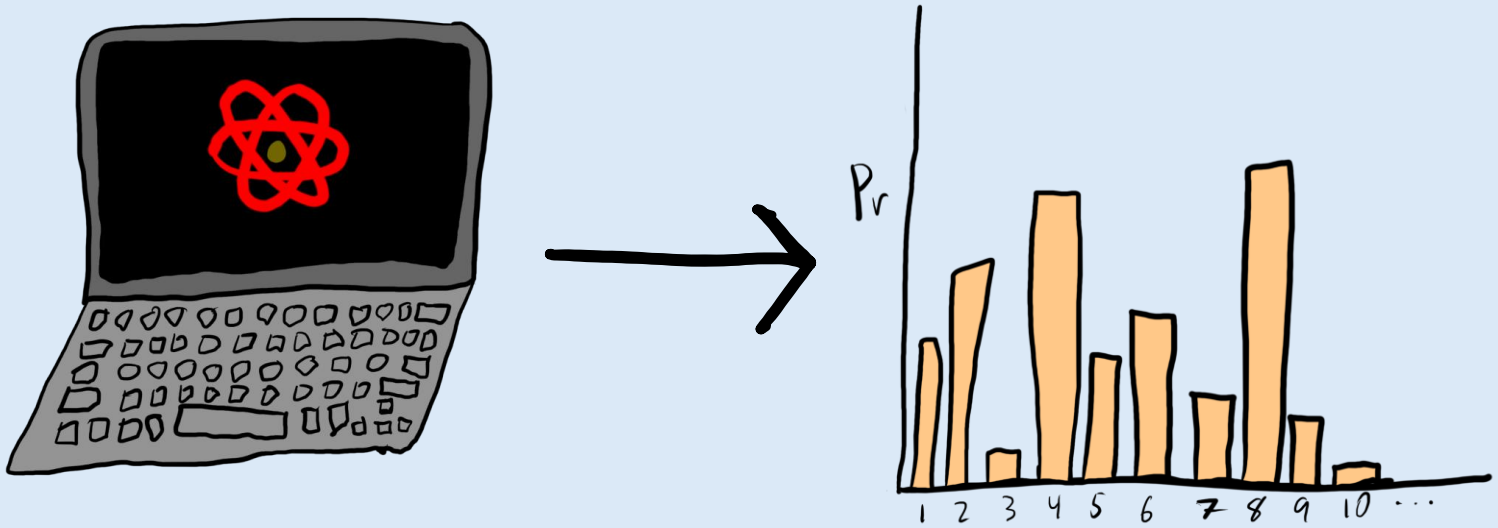


Quantum Advantage Samplers

Examples:

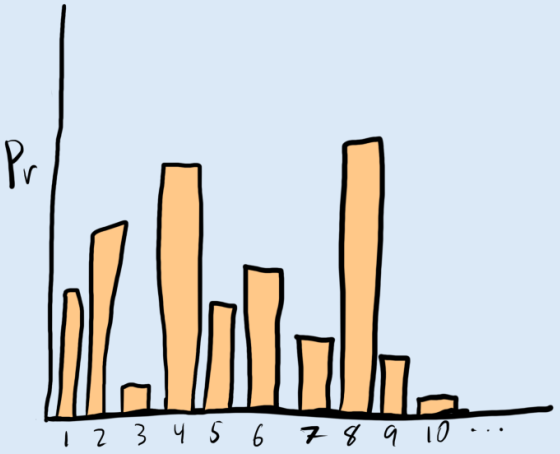
- Random circuit sampling [BFNV19]
- IQP circuits [BJS11]
- Boson sampling [AA11]

Quantum Advantage Samplers

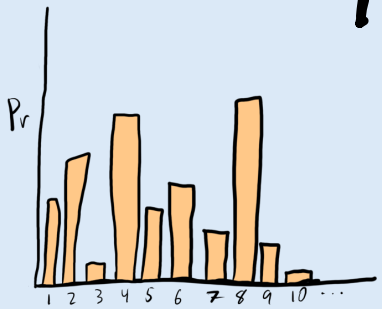


No verifier :(

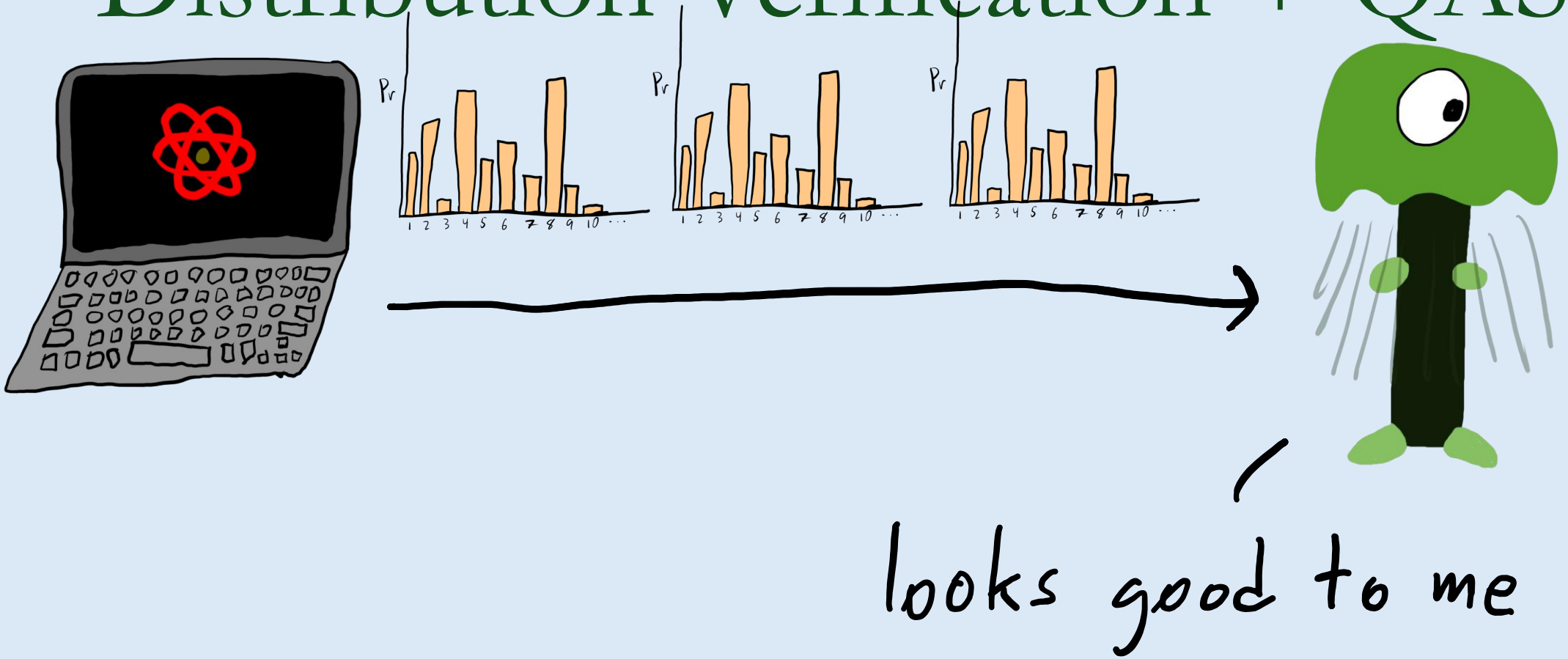
Distribution Verification

Input: 

, $x_1, \ldots, x_t$

Goal: Test if $x_1, \ldots, x_t$ came from 

Distribution Verification + QAS



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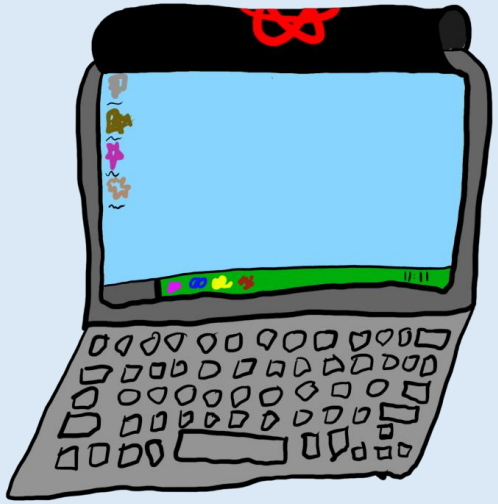

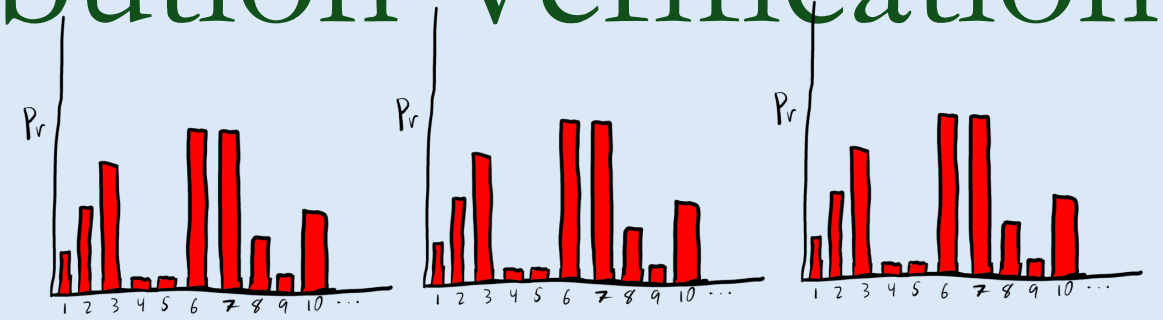

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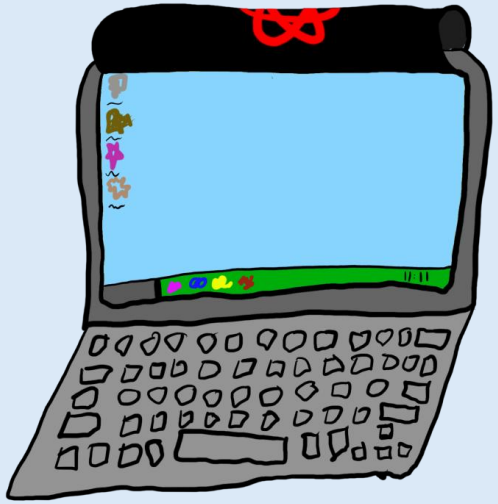

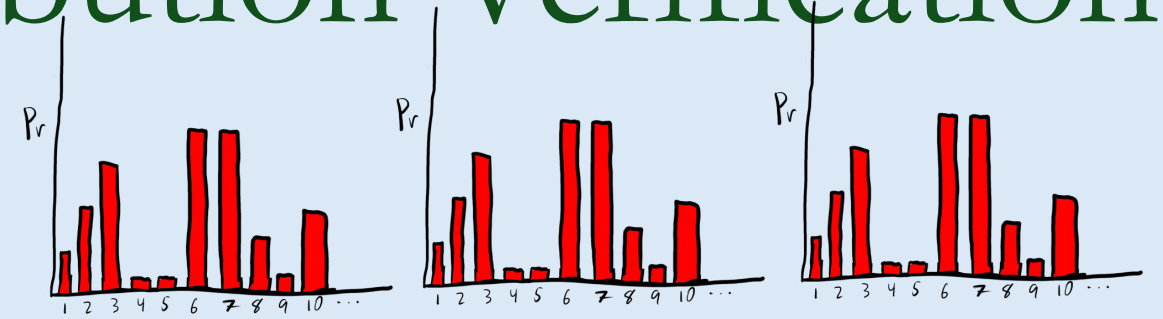

IMPOSTER

*uniform adversaries

Distribution Verification

Well studied in setting of property testing (identity test)

[BFR+00, BFR+01, DKN15, Pan08, VV17, ...]

Identity Testing

Identity test for D: Ver s.t.

- (Correctness): $\Pr_{D^+ \to x_1, \ldots, x_t} [\text{Ver}(x_1, \ldots, x_t) \to 1] \geq \text{high}$

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$$\Pr_{G^+ \to x'_1, \ldots, x'_t} [\text{Ver}(x'_1, \ldots, x'_t) \to 1] \leq \text{low}$$

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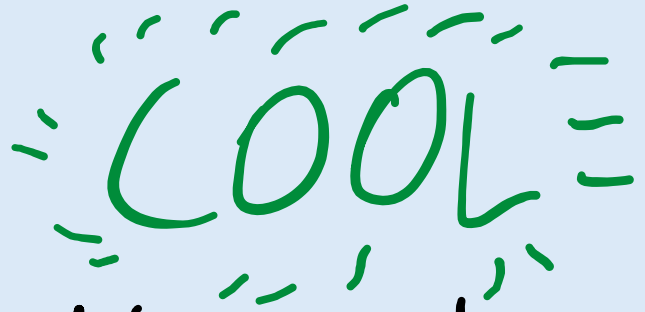

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Identity Testing

[BFF+01, Pan08, VV17]:

D over $\{0,1\}^n$

optimal sample complexity: $\Omega(2^{n/2})$

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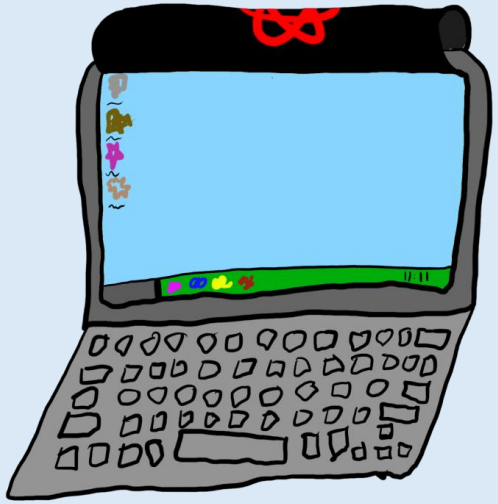
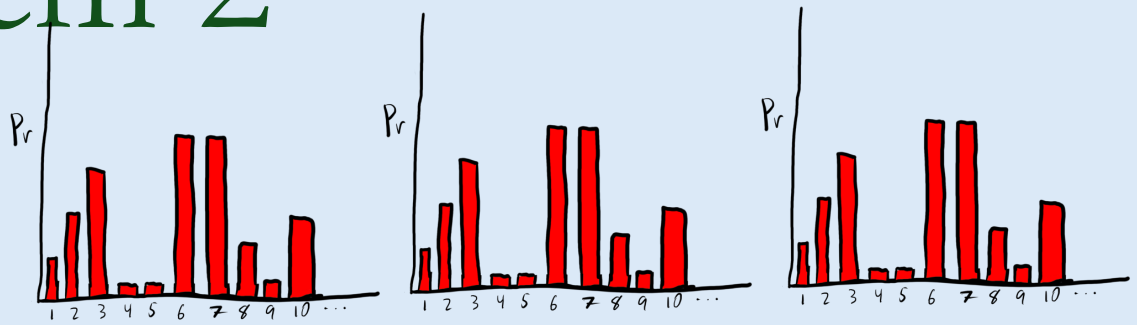
Problem 2





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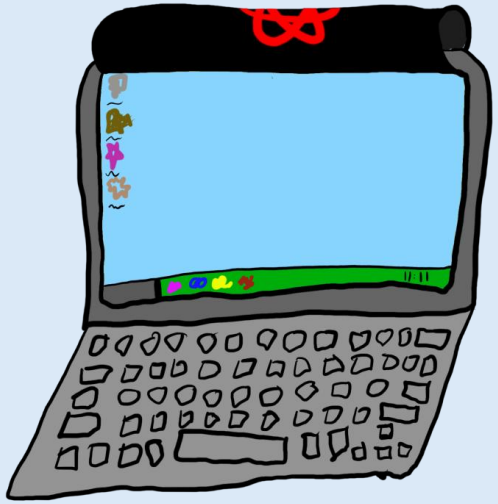

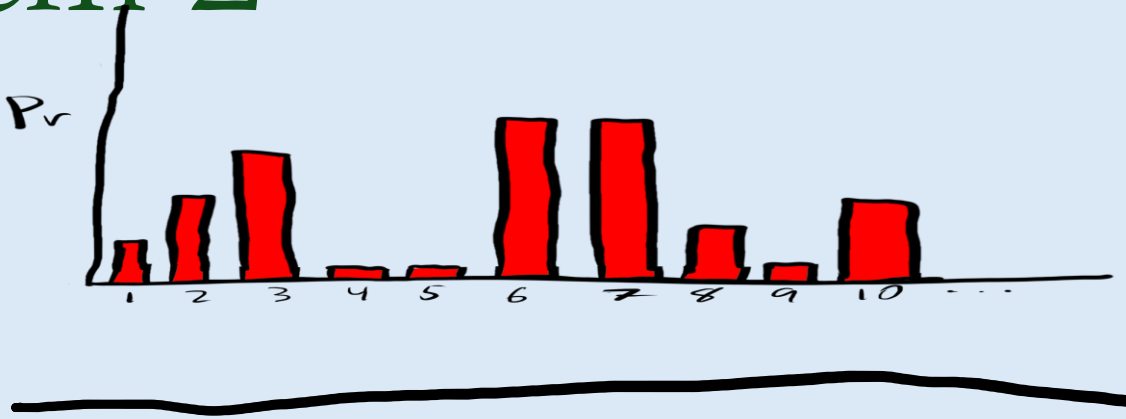

hmm, looks quantum to me...

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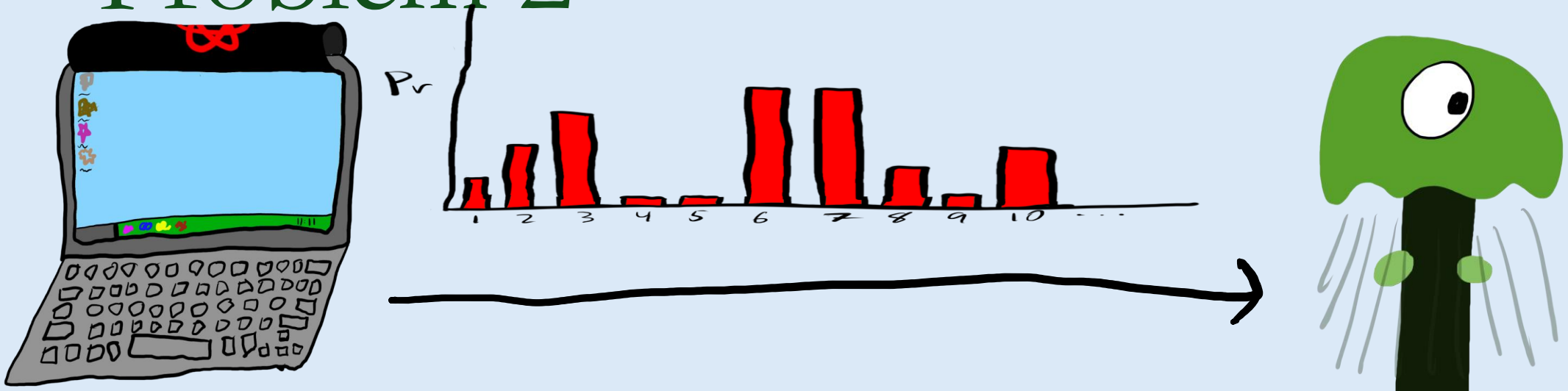

FOOLED YOU, AGAIN!

hmm, looks quantum to me...

Distribution Verification

D efficiently verifiable if $\exists$ eff. Ver st.

- (Correctness): $\Pr_{D^+ \to x_1, \ldots, x_t} [\mathrm{Ver}(x_1, \ldots, x_t) \to 1] \geq 1 - \frac{1}{n^c}$

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gets ε + runtime of G

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Main Question

When is a (classical/quantum) distribution efficiently verifiable?

Our Results

Classical Setting

- if OWFs exist, then every sufficiently random samplable dist. is NOT efficiently verifiable.

Classical Setting

$H_\infty \geq \omega(\log n)$

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Classical Setting

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- if OWFs exist, then every sufficiently random samplable dist. is NOT efficiently verifiable.

- if OWFs do not exist, then every samplable dist. IS efficiently verifiable. !!

Quantum Setting

- If one-way puzzles do not exist, then every quantum advantage sampler is efficiently verifiable with security against PPT machines

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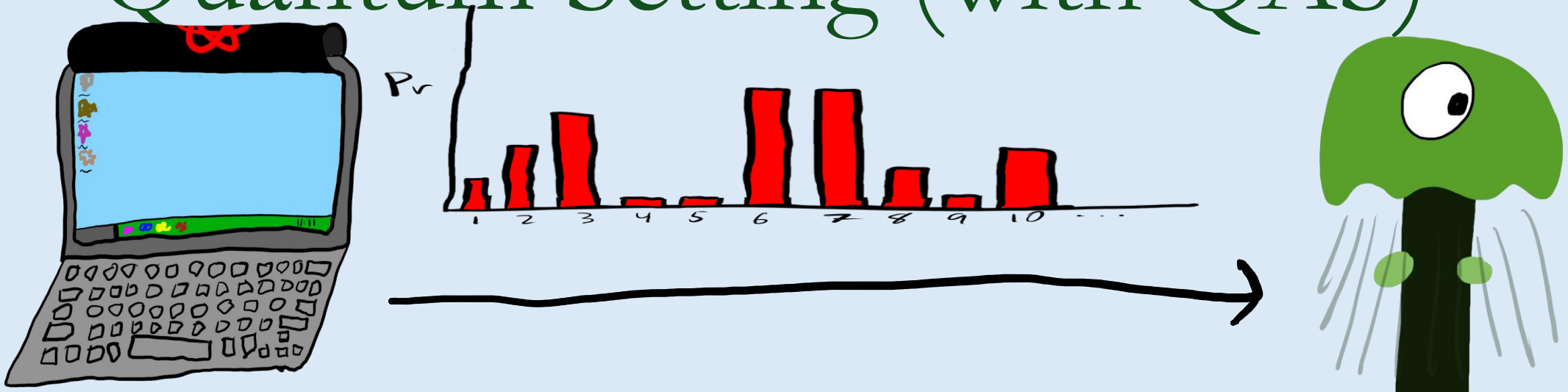
Note: Ver is quantum

Quantum Setting (with QAS)

GOOD ENOUGH

Quantum Setting (with QAS)



GOOD ENOUGH

Ha! Nice try.

Techniques

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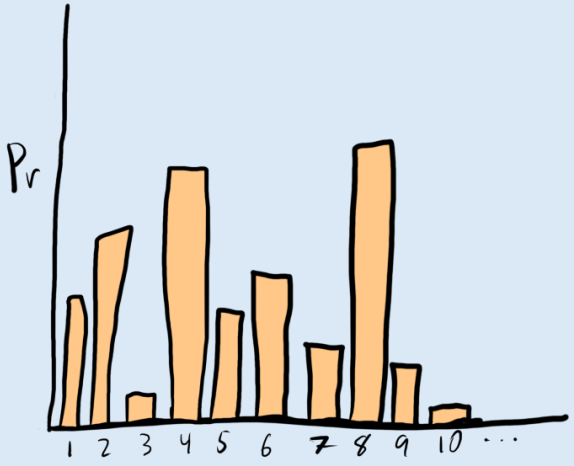
OWF Counterexample

$D(r) \rightarrow$



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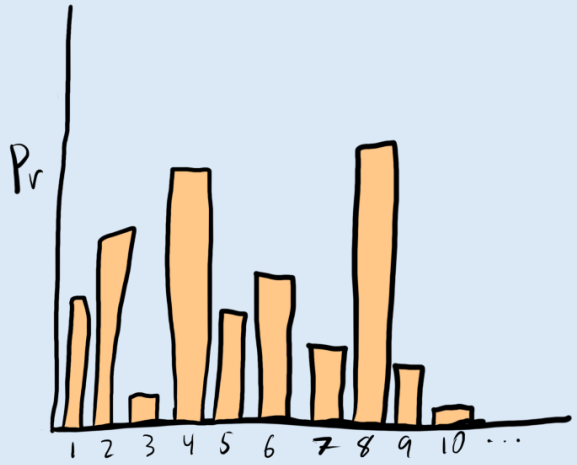
$D(r) \rightarrow$ 

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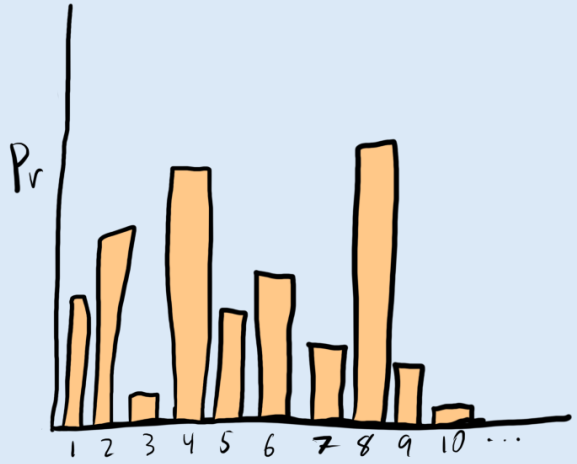

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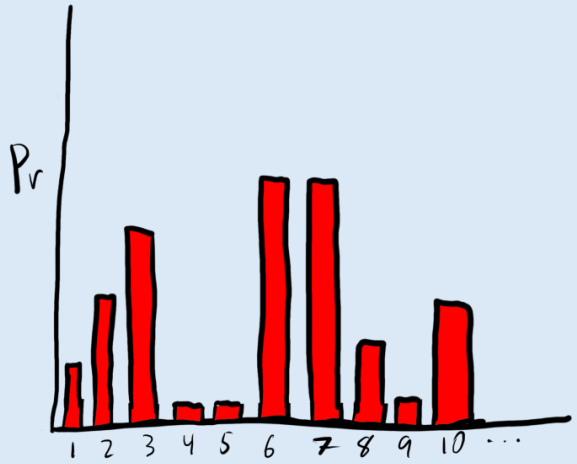
$D(G(r)) \rightarrow$



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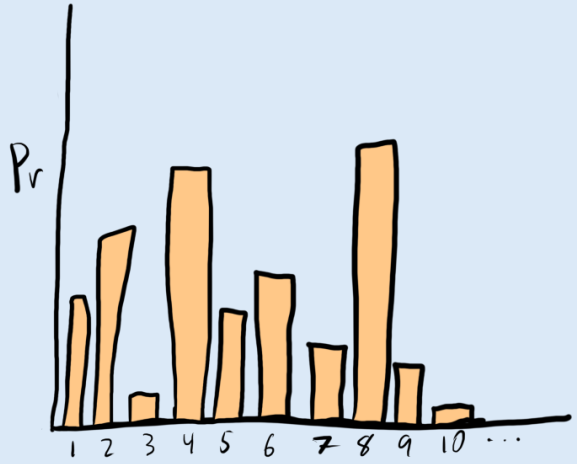

, G a PRG

Statistically far!

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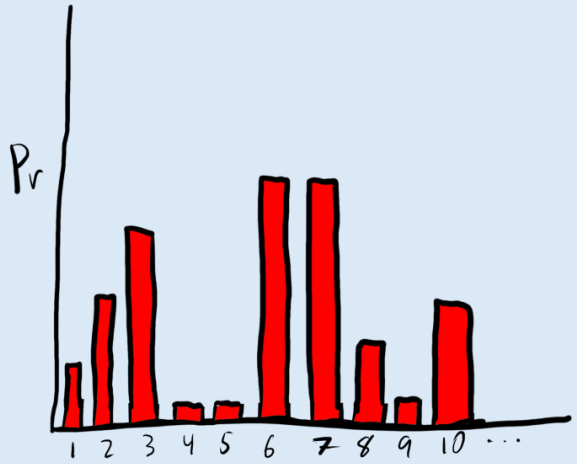

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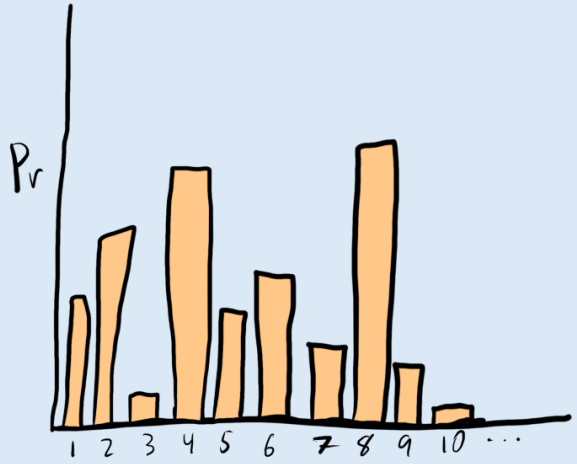

$\approx_S$

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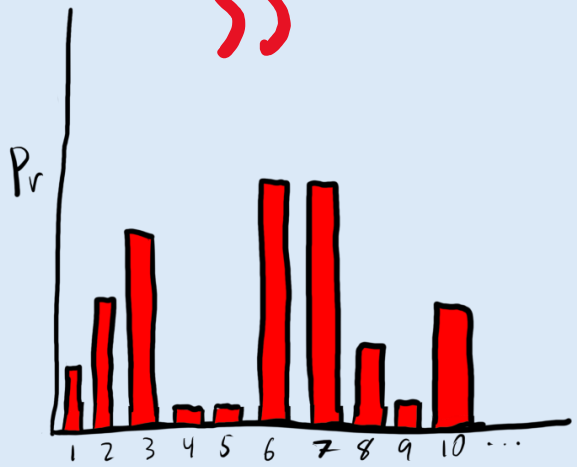

, G a PRG

Statistically far!

Indistinguishable!

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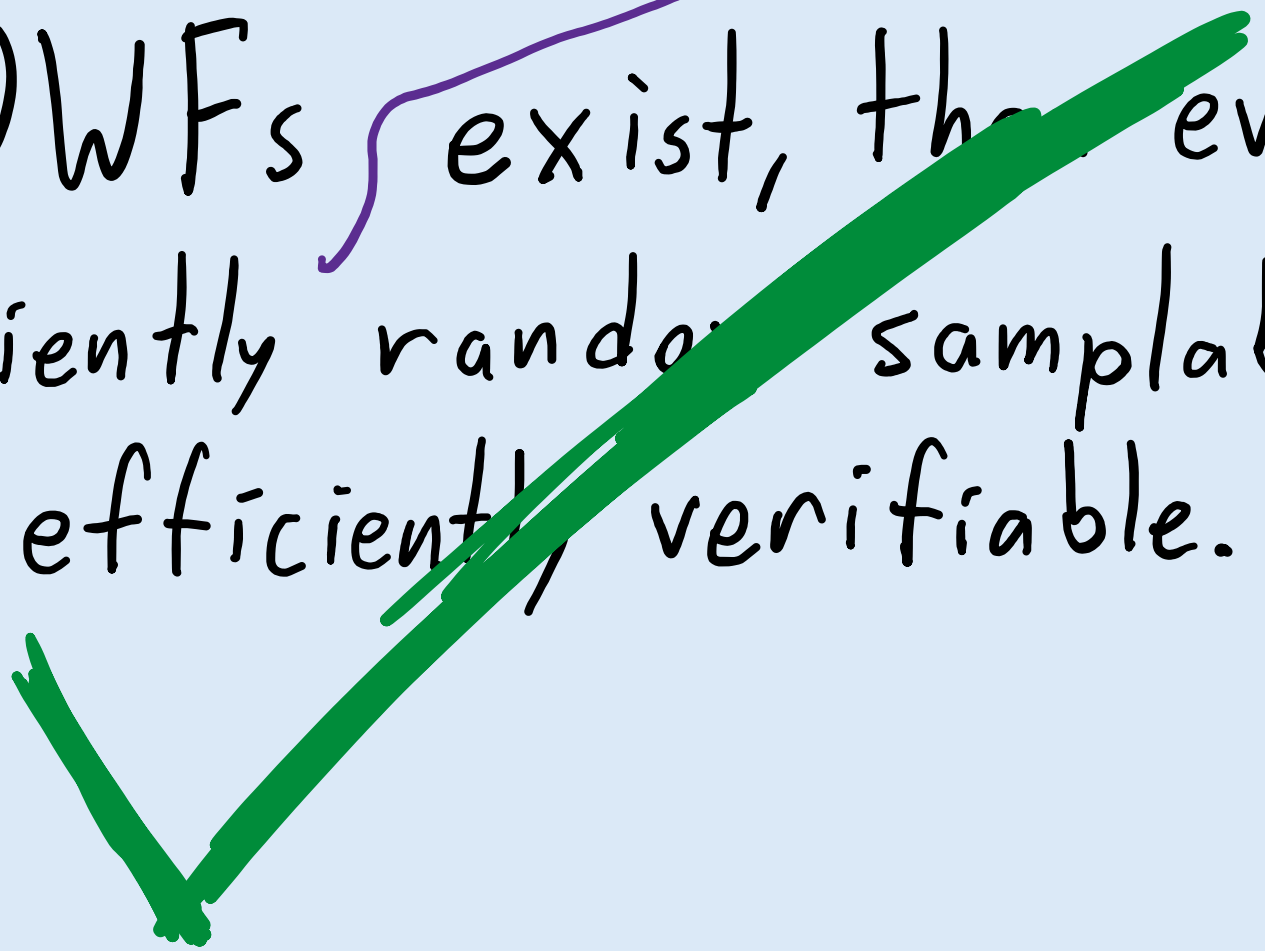

Classical Setting

- if OWFs do not exist, then every samplable dist. IS efficiently verifiable.

Classical Setting

Key Tool: Kolmogorov Complexity

- if OWFs do not exist, then every samplable dist. IS efficiently verifiable.

Kolmogorov Complexity

$K(x)$ = length of the shortest Turing machine outputting x.

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Kolmogorov Complexity

Fact: D samplable dist.,

w.h.p. $D \to x$, $K(x) \approx \log \frac{1}{\Pr[D \to x]}$

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[LOZ1] Coding Theorem

$\forall x$,

$K(x) \leq |D| + \log\left(\frac{1}{\Pr[D \to x]}\right) + c$

Kolmogorov Complexity

Fact: D samplable dist.,

w.h.p. $D \to x$, $K(x) \approx \log \frac{1}{\Pr[D \to x]}$

[LV93] Incompressability

w.h.p. over $D \to x$,

$$K(x) \geq \log\left(\frac{1}{\Pr[D \to x]}\right) - c$$

[Oz1] Coding Theorem

$\forall x$,

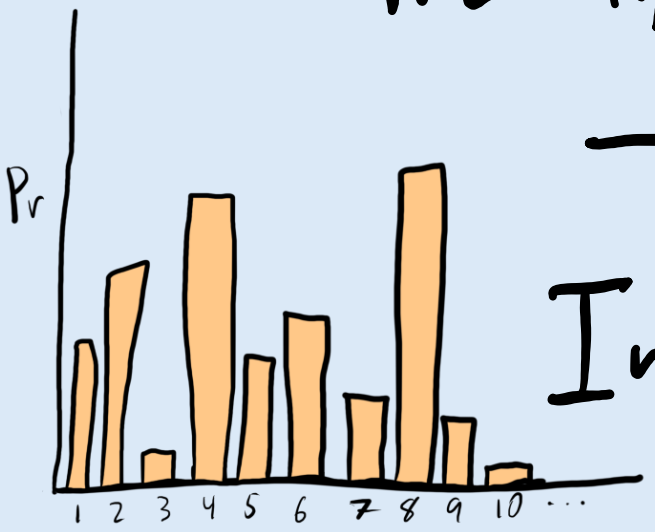
$$K(x) \leq |D| + \log\left(\frac{1}{\Pr[D \to x]}\right) + c$$

Inefficient Verifier [Aaronson14]

$$Ver(x_1, \ldots, x_t): \text{output } 1 \iff$$

$$\log \frac{1}{Pr[D \to x_1] \cdots Pr[D \to x_t]} \leq K(x_1, \ldots, x_t) + c$$

$$\longrightarrow x_1, \ldots, x_t$$



Incompressability: w.h.p. ✓

Inefficient Verifier [Aaronson14]

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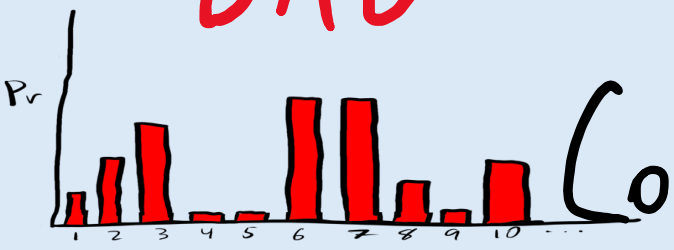

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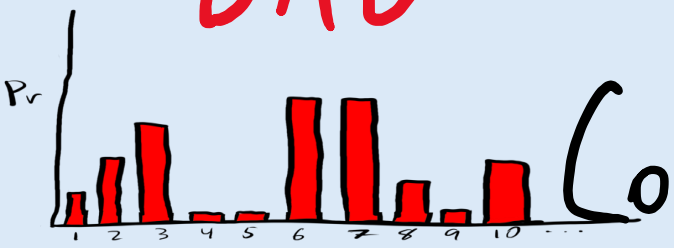

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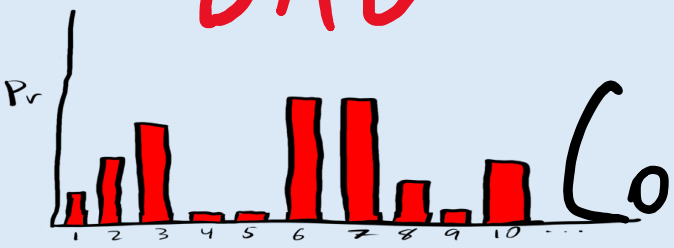

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Efficient Verifier

Idea: if OWFs don't exist, can estimate $\log \frac{1}{\Pr[D \to x_1] \cdots \Pr[D \to x_2]}$ (prob. estimation) [IL89]

Probability Estimation

[IL89]: For all dist. D, there exists Est s.t. w.h.p. $D \to x$,

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(1-sided error): $\forall x$, $Est(x) \geq -\log \Pr[D \to x]$

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Problem: $K(x_1, \ldots, x_t)$ uncomputable

Solution: Use different type of K-complexity

$uK^t(x)$

$uK^t(x) = -\log \Pr[\text{random TM outputs } x]$

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$$= -\log_{\pi \leftarrow \{0,1\}^t} \Pr\left[\left(UTM^t(\pi)\right) \to x\right]$$

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Coding theorem + incompressability still hold!

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Coding theorem + incompressability still hold!

$$Ver(x_1, \ldots, x_t) \to 1 \Leftrightarrow \log \frac{1}{\Pr[D \to x_1] \cdots \Pr[D \to x_t]} \leq uK^t(x) + c$$

works!

Estimating uK^t

Thm [HN23]: If OWFs do not exist, then there exists Est such that for ALL samplable D,

w.h.p. $x \leftarrow D$, $Est(x) \approx uK^t(x)$

Final Verifier

$$Ver(x_1, \ldots, x_t) \to 1 \Leftrightarrow \log \frac{1}{\Pr[D \to x_1] \cdots \Pr[D \to x_t]} \leq u K^t(x) + c$$

replace w/ approximations you get via no OWFs

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D good $\Rightarrow$ approximations right $\Rightarrow$ passes Ver

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So far

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So far $\Rightarrow$ right, lower bounded

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1-sided error critical!

Classical Setting

- if OWFs do not exist, then every samplable dist. IS efficiently verifiable.

Quantum Setting

- If one-way puzzles do not exist, then every quantum advantage sampler is efficiently verifiable with security against PPT machines

Quantum Setting

OWPuzz: quantum analogue of OWF

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$\text{Samp} \to (\overbrace{k}^{\text{classical}}, s)$

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Security: Given s, hard to sample from conditional dist. on k.

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Security: Given s, hard to sample from conditional dist. on k.

OWF $\Rightarrow$ OWPuzz $\Rightarrow$ quantum commitments

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$qK^t(x) = -\log \Pr[\text{random QTM} \to x]$

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[CGGH25, HM25, KTZ25]

No OWPuzz $\Rightarrow$ prob. est. for quantum samplable dists

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[CGGHZ5, HM25, KTZ5]

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$\Rightarrow$ estimator for qK^t

Problem: no 1-sided error!

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Key idea: If D is samplable quantumly but NOT classically,

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Key idea: If D is samplable quantumly but NOT classically, To verify, estimate both!

w.h.p. $D \to x$

$$qK^t(x) \ll uK^t(x)$$

Quantum Setting

D a QAS:

$\mathrm{Ver}(x_1, \ldots, x_t)$: estimate $q_u K^t(x_1, \ldots, x_t)$ and $u K^t(x_1, \ldots, x_t)$. Output 1

$\Leftrightarrow q_u K^t \ll u K^t$

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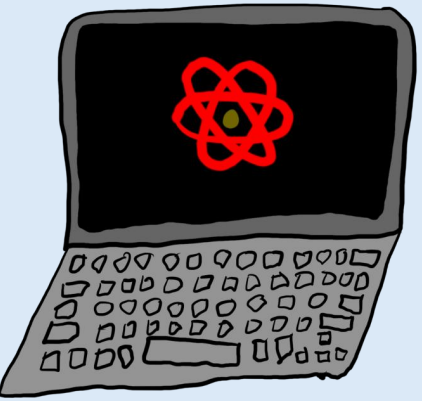

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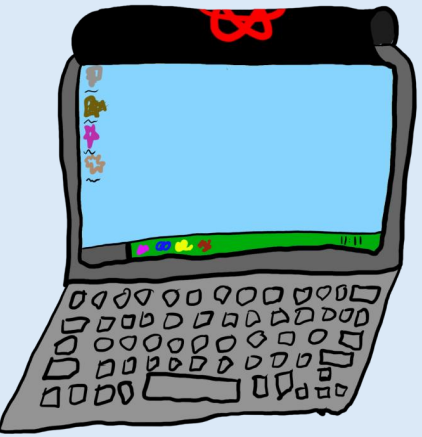

$\rightarrow qu K^t \approx u K^t$ ✗

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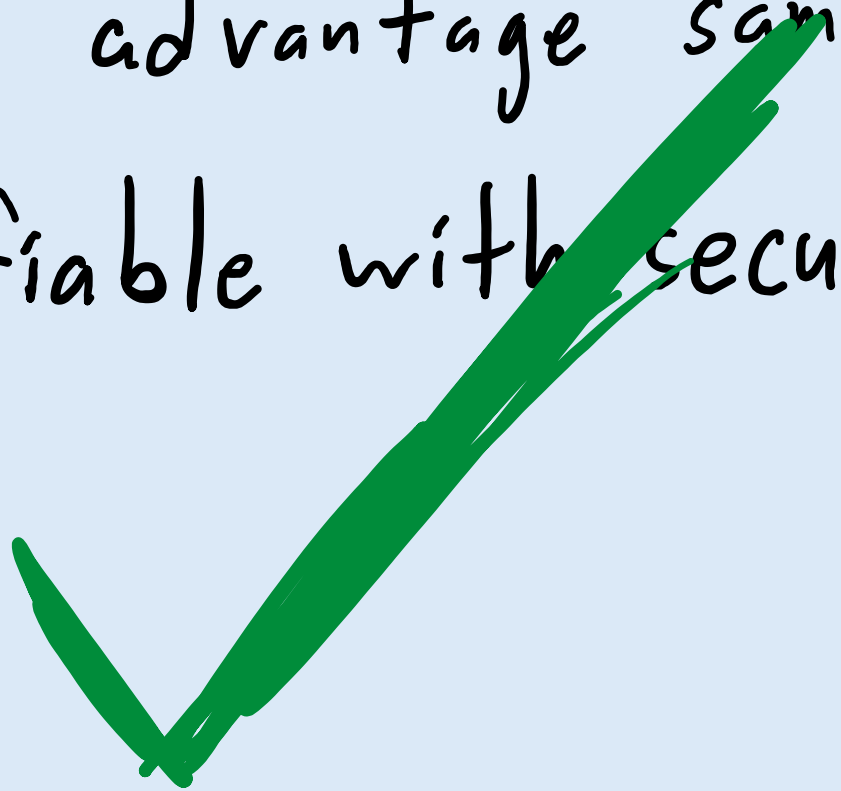

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- Lower complexity classes?

Thank You!