

QUANTUM COMPUTING

ADVANCED TOPICS IN ~~CYBERSECURITY~~ CRYPTOGRAPHY (7CCSMATC)

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OUTLINE

Qubits

Many Qubits

Grover's Algorithm

Shor's Algorithm

Commitment Schemes

Teach you just enough quantum computing to get a sense of how it affects cryptography.

REFERENCES

- Thomas Debris-Alazard. *Lecture 1: Introduction to Quantum Computing*. INF587 Quantum computer science and applications <https://tdalazard.io/S1.pdf>
- Noson S Yanofsky and Mirco A Mannucci. **Quantum Computing for Computer Scientists**. Cambridge University Press, 2008, esp. Chapters 1, 2, 3 and 6
- Fermi Ma's talk Quantum Secure Commitments and Collapsing Hash Functions delivered as part of the *Quantum Cryptography for Dummies* reading group at the *Lattices: Algorithms, Complexity, and Cryptography* special semester at the Simons Institute, 2020

QUBITS

$$b \in \{0, 1\}$$

PROBABILISTIC BIT

- Probabilistic bit: $\begin{pmatrix} p \\ q \end{pmatrix}$ where $p := \Pr(b = 0)$ and $q := \Pr(b = 1)$
- Computing on probabilistic bits

$$\begin{pmatrix} p \\ q \end{pmatrix} \rightarrow \begin{pmatrix} p' \\ q' \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \cdot \begin{pmatrix} p \\ q \end{pmatrix} \text{ where } \begin{cases} a + c = 1 \\ b + d = 1 \end{cases} \text{ and } a, b, c, d \geq 0$$

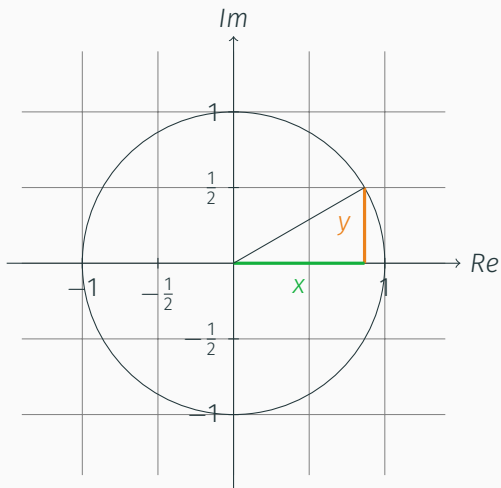
Example: $b \rightarrow b \oplus b$

$$\begin{pmatrix} p \\ q \end{pmatrix} \rightarrow \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} p \\ q \end{pmatrix}$$

Example: $b \rightarrow b \oplus 1$

$$\begin{pmatrix} p \\ q \end{pmatrix} \rightarrow \begin{pmatrix} q \\ p \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \cdot \begin{pmatrix} p \\ q \end{pmatrix}$$

COMPLEX NUMBERS



- $i := \sqrt{-1}$
- $z := x + iy$
- $Re(z) := x$
- $Im(z) := y$
- $|z| = \sqrt{x^2 + y^2}$

QUANTUM BIT (QUBIT): “PROBABILISTIC BITS WITH COMPLEX PROBABILITIES”

- A **qubit** $|\psi\rangle$ is an element of \mathbb{C}^2 with Euclidean norm 1:

$$|\psi\rangle = \alpha \cdot |0\rangle + \beta \cdot |1\rangle \text{ with } \alpha, \beta \in \mathbb{C} \text{ (called amplitude) and } |\alpha|^2 + |\beta|^2 = 1$$

- $|0\rangle, |1\rangle$ is an orthonormal basis of \mathbb{C}^2 . Usually defined as

$$|0\rangle := \begin{pmatrix} 1 \\ 0 \end{pmatrix} \text{ and } |1\rangle := \begin{pmatrix} 0 \\ 1 \end{pmatrix} \text{ which then implies } \alpha \cdot |0\rangle + \beta \cdot |1\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}.$$

- We call this a **superposition** of $|0\rangle$ and $|1\rangle$.

MEASUREMENTS

We cannot “see” qubits, we can only measure in their classical states.

Measurement: probabilistic orthogonal projection. Given $|0\rangle, |1\rangle \in \mathbb{C}^2$:

$$|\psi\rangle = \alpha \cdot |0\rangle + \beta \cdot |1\rangle \xrightarrow{\text{measure}} \begin{cases} |0\rangle & \text{with probability } |\alpha|^2 \\ |1\rangle & \text{with probability } |\beta|^2 \end{cases}$$

- A **unitary matrix in $\mathbb{C}^{2 \times 2}$** is any matrix such that $\mathbf{U} \cdot \mathbf{U}^\dagger = \mathbf{U}^\dagger \cdot \mathbf{U} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ where \mathbf{U}^\dagger is the conjugate transpose of \mathbf{U} :

$$\mathbf{U} = \begin{pmatrix} u_{00} + v_{00} \cdot i & u_{01} + v_{01} \cdot i \\ u_{10} + v_{10} \cdot i & u_{11} + v_{11} \cdot i \end{pmatrix}, \quad \mathbf{U}^\dagger := \begin{pmatrix} u_{00} - v_{00} \cdot i & u_{10} - v_{10} \cdot i \\ u_{01} - v_{01} \cdot i & u_{11} - v_{11} \cdot i \end{pmatrix}$$

- **Computation:** $|\psi\rangle \rightarrow \mathbf{U} \cdot |\psi\rangle$
 - All quantum computations are reversible:

$$|\psi\rangle \xrightarrow{\mathbf{U}} \mathbf{U} \cdot |\psi\rangle \xrightarrow{\mathbf{U}^\dagger} \mathbf{U}^\dagger \cdot \mathbf{U} \cdot |\psi\rangle = |\psi\rangle$$

- We call \mathbf{U} **quantum gates**

... are linear-algebra machines.

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*Mathematics is the art of reducing
any problem to linear algebra.*

— William Stein



EXAMPLES OF QUANTUM GATES

Example NOT-gate $b \rightarrow "b \oplus 1"$

$$|\psi\rangle = \alpha |0\rangle + \beta \cdot |1\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix} \longrightarrow \begin{pmatrix} \beta \\ \alpha \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \cdot |\psi\rangle$$

EXAMPLES OF QUANTUM GATES

Example NOT-gate $b \rightarrow "b \oplus 1"$

$$|\psi\rangle = \alpha |0\rangle + \beta \cdot |1\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix} \longrightarrow \begin{pmatrix} \beta \\ \alpha \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \cdot |\psi\rangle$$

Example $b \rightarrow b \oplus b$

Computation is not reversible!

HADAMARD-GATE H I

$$\mathbf{H} \cdot |\psi\rangle = \mathbf{H} \cdot (\alpha |0\rangle + \beta \cdot |1\rangle) = \mathbf{H} \cdot \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \cdot \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} \alpha + \beta \\ \alpha - \beta \end{pmatrix}$$

HADAMARD-GATE H I

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$$\cdot \mathbf{H} \cdot |0\rangle = \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} 1+0 \\ 1-0 \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{pmatrix}$$

- measure $|0\rangle$ or $|1\rangle$ with probability $1/2$!

HADAMARD-GATE H I

$$\mathbf{H} \cdot |\psi\rangle = \mathbf{H} \cdot (\alpha |0\rangle + \beta \cdot |1\rangle) = \mathbf{H} \cdot \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \cdot \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} \alpha + \beta \\ \alpha - \beta \end{pmatrix}$$

$$\cdot \mathbf{H} \cdot |0\rangle = \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} 1+0 \\ 1-0 \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{pmatrix}$$

• measure $|0\rangle$ or $|1\rangle$ with probability 1/2!

$$\cdot \mathbf{H} \cdot \begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{pmatrix} = \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} 1/\sqrt{2} + 1/\sqrt{2} \\ 1/\sqrt{2} - 1/\sqrt{2} \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} = |0\rangle$$

• and we're back!

HADAMARD-GATE H II

The outputs of the Hadamard gate applied to $|0\rangle$ and $|1\rangle$ are so important we give them names:

$$|+\rangle := \frac{1}{\sqrt{2}} \cdot (|0\rangle + |1\rangle) = \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$
$$|-\rangle := \frac{1}{\sqrt{2}} \cdot (|0\rangle - |1\rangle) = \frac{1}{\sqrt{2}} \cdot \begin{pmatrix} 1 \\ -1 \end{pmatrix}$$

We cannot achieve the Hadamard gate with probabilistic bits \Rightarrow quantum advantage

MANY QUBITS

TENSOR PRODUCTS

Let $\mathbf{v} \in \mathbb{C}^n$ and $\mathbf{w} \in \mathbb{C}^m$, their tensor product is $\mathbf{v} \otimes \mathbf{w} := (v_0 \cdot \mathbf{w}, \dots, v_{n-1} \cdot \mathbf{w})$

- This is the same as the rows of:

$$\begin{pmatrix} v_0 \\ v_1 \\ \vdots \\ v_{n-1} \end{pmatrix} \cdot \begin{pmatrix} w_0 & w_1 & \cdots & w_{m-1} \end{pmatrix} = \begin{pmatrix} v_0 \cdot w_0 & v_0 \cdot w_1 & \cdots & v_0 \cdot w_{m-1} \\ v_1 \cdot w_0 & v_1 \cdot w_1 & \cdots & v_1 \cdot w_{m-1} \\ \vdots & \vdots & \ddots & \vdots \\ v_{n-1} \cdot w_0 & v_{n-1} \cdot w_1 & \cdots & v_{n-1} \cdot w_{m-1} \end{pmatrix}$$

TENSOR PRODUCTS

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- For any scalar z , we have $z \cdot (\mathbf{v} \otimes \mathbf{w}) = (z \cdot \mathbf{v}) \otimes \mathbf{w} = \mathbf{v} \otimes (z \cdot \mathbf{w})$
- For any $\mathbf{v}_0, \mathbf{v}_1 \in \mathbb{C}^n$, we have $(\mathbf{v}_0 + \mathbf{v}_1) \otimes \mathbf{w} = \mathbf{v}_0 \otimes \mathbf{w} + \mathbf{v}_1 \otimes \mathbf{w}$
- For any $\mathbf{w}_0, \mathbf{w}_1 \in \mathbb{C}^m$, we have $\mathbf{v} \otimes (\mathbf{w}_0 + \mathbf{w}_1) = \mathbf{v} \otimes \mathbf{w}_0 + \mathbf{v} \otimes \mathbf{w}_1$

TENSOR PRODUCTS OF SPACES

Consider

- $\mathbb{C}^n = \text{Span}_{\mathbb{C}}(\mathbf{v}_0, \dots, \mathbf{v}_{n-1})$ where e.g. $\mathbf{v}_0 := (1, 0, \dots, 0)$ etc, or some other basis of \mathbb{C}^n
- $\mathbb{C}^m = \text{Span}_{\mathbb{C}}(\mathbf{w}_0, \dots, \mathbf{w}_{m-1})$ where e.g. $\mathbf{w}_0 := (1, 0, \dots, 0)$ etc, or some other basis of \mathbb{C}^m

We have:

- $\mathbb{C}^n \otimes \mathbb{C}^m := \text{Span}_{\mathbb{C}}(\mathbf{v}_i \otimes \mathbf{w}_j : 0 \leq i < n; 0 \leq j < m)$
- $\mathbb{C}^n \otimes \mathbb{C}^m$ has dimension $n \times m$
- $\mathbf{x} \in \mathbb{C}^n \otimes \mathbb{C}^m \iff \exists \alpha_{i,j} : \sum_{0 \leq i < n, 0 \leq j < m} \alpha_{i,j} \cdot \mathbf{v}_i \otimes \mathbf{w}_j$

TENSOR PRODUCTS OF MATRICES

$$A := \begin{pmatrix} a_{0,0} & \cdots & a_{0,n-1} \\ \vdots & \ddots & \vdots \\ a_{m-1,0} & \cdots & a_{m-1,n-1} \end{pmatrix}, \quad B := \begin{pmatrix} b_{0,0} & \cdots & b_{0,q-1} \\ \vdots & \ddots & \vdots \\ b_{p-1,0} & \cdots & b_{p-1,q-1} \end{pmatrix}$$
$$A \otimes B := \begin{pmatrix} a_{0,0} \cdot B & \cdots & a_{0,m-1} \cdot B \\ \vdots & \ddots & \vdots \\ a_{n-1,0} \cdot B & \cdots & a_{n-1,m-1} \cdot B \end{pmatrix} \in \mathbb{C}^{mp \times nq}$$

EXAMPLES

$$1. \begin{pmatrix} 1 \\ 2 \end{pmatrix} \otimes \begin{pmatrix} 2 \\ 3 \end{pmatrix} = \begin{pmatrix} 1 \cdot 2 \\ 1 \cdot 3 \\ 2 \cdot 2 \\ 2 \cdot 3 \end{pmatrix} = \begin{pmatrix} 2 \\ 3 \\ 4 \\ 6 \end{pmatrix}$$

$$2. \mathbf{X} \otimes \mathbf{H} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \otimes \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{pmatrix}$$

n QUBIT STATES

- Recall that a qubit $|\psi\rangle$ is an element in \mathbb{C}^2 with norm 1.

- A **register of n qubits** $|\psi\rangle$ is an element in $\underbrace{\mathbb{C}^2 \otimes \dots \otimes \mathbb{C}^2}_{n \text{ times}} = \mathbb{C}^{2^n}$.

- Let $|0\rangle, |1\rangle$ be an orthonormal basis of \mathbb{C}^2 , then

$$(|b_0\rangle \otimes |b_1\rangle \otimes \dots \otimes |b_{n-1}\rangle : b_0, \dots, b_{n-1} \in \{0, 1\})$$

is an orthonormal basis of $\underbrace{\mathbb{C}^2 \otimes \dots \otimes \mathbb{C}^2}_{n \text{ times}} = \mathbb{C}^{2^n}$.

```
ket0 = matrix(2, 1, [1,0])
ket1 = matrix(2, 1, [0,1])
ket0.tensor_product(ket0), \
ket0.tensor_product(ket1), \
ket1.tensor_product(ket0), \
ket1.tensor_product(ket1)
```

```
(
[1] [0] [0] [0]
[0] [1] [0] [0]
[-] [-] [-] [-]
[0] [0] [1] [0]
[0], [0], [0], [1]
)
```

NOTATION

- For $b_0, \dots, b_{n-1} \in \{0, 1\}$ we write

$$|b_0 b_1 \dots b_{n-1}\rangle := |b_0\rangle \otimes |b_1\rangle \otimes \dots \otimes |b_{n-1}\rangle$$

- For $|\psi_0\rangle, |\psi_1\rangle, \dots, |\psi_{n-1}\rangle \in \mathbb{C}^2$, we write

$$|\psi_0\rangle |\psi_1\rangle \dots |\psi_{n-1}\rangle := |\psi_0\rangle \otimes |\psi_1\rangle \otimes \dots \otimes |\psi_{n-1}\rangle$$

- Any $|\psi\rangle \in \mathbb{C}^{2^n}$ of n qubits can be written as

$$|\psi\rangle = \sum_{\mathbf{x} \in \{0,1\}^n} \alpha_{\mathbf{x}} |\mathbf{x}\rangle \quad \text{where } \alpha_{\mathbf{x}} \in \mathbb{C} \text{ (called amplitude) and } \sum_{\mathbf{x} \in \{0,1\}^n} |\alpha_{\mathbf{x}}|^2 = 1$$

SEPARABLE STATES

Definition

An n -qubit state $|\psi\rangle$ is called **separable** if it can be decomposed as $|\psi\rangle = |\psi_0\rangle \otimes |\psi_1\rangle$.

Examples

- $|00\rangle = |0\rangle \otimes |0\rangle$
- $\frac{1}{2} \cdot (|00\rangle + |01\rangle + |10\rangle + |11\rangle) = \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle) \otimes \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle)$

```
ket0 = matrix(2, 1, [1,0]); ket1 = matrix(2, 1, [0,1])  
(1/sqrt(2)*ket0 + 1/sqrt(2)*ket1).tensor_product(1/sqrt(2)*ket0 + 1/sqrt(2)*ket1)
```

```
[1/2]  
[1/2]  
[...]  
[1/2]  
[1/2]
```

ENTANGLED STATES

Definition

An n -qubit state $|\psi\rangle$ is called **entangled** if it cannot be decomposed as $|\psi\rangle = |\psi_0\rangle \otimes |\psi_1\rangle$.

Example

$$\frac{1}{\sqrt{2}} \cdot (|00\rangle + |11\rangle)$$

```
ket0 = matrix(2, 1, [1,0]); ket1 = matrix(2, 1, [0,1])  
(1/sqrt(2)) * (ket0.tensor_product(ket0) + ket1.tensor_product(ket1))
```

```
[1/2*sqrt(2)]  
[          0]  
[          0]  
[1/2*sqrt(2)]
```

MEASURING n QUBIT STATES

Measuring the state:

$$|\psi\rangle = \sum_{i_0, \dots, i_{n-1} \in \{0,1\}^n} \alpha_{i_0 \dots i_{n-1}} |e_{i_0} \dots e_{i_{n-1}}\rangle \xrightarrow{\text{measure}} |e_{j_0} \dots e_{j_{n-1}}\rangle \text{ with probability } |\alpha_{j_0 \dots j_{n-1}}|^2$$

Measuring the first register:

$$|\psi\rangle = \alpha_0 \cdot |e_0\rangle |\psi_0\rangle + \alpha_1 \cdot |e_1\rangle |\psi_1\rangle \xrightarrow{\text{measure}} \begin{cases} |e_0\rangle |\psi_0\rangle & \text{with prob. } |\alpha_0|^2 \\ |e_1\rangle |\psi_1\rangle & \text{with prob. } |\alpha_1|^2 \end{cases}$$

We necessarily have $|\alpha_0|^2 + |\alpha_1|^2 = 1$

- A unitary matrix $\mathbf{U} \in \mathbb{C}^{2^n \times 2^n}$, i.e. $\mathbf{U}^\dagger \cdot \mathbf{U} = \mathbf{I}_{2^n}$ is called a **quantum circuit**
- Any classical circuit f on n -bits can be written as a unitary \mathbf{U}_f on $2n$ -qubits

$$\mathbf{U}_f \cdot |\psi\rangle |0\rangle = |\psi\rangle |f(\psi)\rangle$$

MEASURING ENTANGLED REGISTERS

Consider $U_f \cdot |x, y\rangle = |x, f(x) \oplus y\rangle$ for some $f : \{0, 1\}^n \rightarrow \{0, 1\}$.

- Measure the last register $|f(x) \oplus y\rangle$ to obtain v
- The first register $|x\rangle$ **collapses** to those $x \in \{0, 1\}^n$ s.t. $f(x) \oplus y = v$.
- The first n registers hold a superposition of the preimages of v under f .
- Measurements must stay consistent. Turns out this is quite powerful!

NO-CLONING THEOREM

Cannot copy a quantum state

- We can “cut” and “paste” a quantum state, but we cannot “copy” and “paste”.
- “Move is possible. Copy is impossible.”

Proof Sketch:

- There is no linear map C from $|\psi\rangle \otimes |0\rangle$ to $|\psi\rangle \otimes |\psi\rangle$.
- It would need to map $\frac{|x\rangle+|y\rangle}{\sqrt{2}} \otimes |0\rangle$ to $\frac{|x\rangle+|y\rangle}{\sqrt{2}} \otimes \frac{|x\rangle+|y\rangle}{\sqrt{2}}$
- By linearity, we'd need: $C\left(\frac{|x\rangle+|y\rangle}{\sqrt{2}} \otimes |0\rangle\right) =$
 - $\frac{1}{\sqrt{2}} \cdot C((|x\rangle + |y\rangle) \otimes |0\rangle)$
 - $\frac{1}{\sqrt{2}} \cdot (C(|x\rangle \otimes |0\rangle) + C(|y\rangle \otimes |0\rangle))$
 - $\frac{1}{\sqrt{2}} \cdot (|x\rangle \otimes |x\rangle + |y\rangle \otimes |y\rangle)$
 - $\neq \frac{|x\rangle+|y\rangle}{\sqrt{2}} \otimes \frac{|x\rangle+|y\rangle}{\sqrt{2}}$

GROVER'S ALGORITHM

PROBLEM STATEMENT

Given some function $f : \{0, 1\}^n \rightarrow \{0, 1\}$, we want to find some special element x_0 .

- For example, given an plaintext-ciphertext pair (p, c) for AES, we might write $f : k \rightarrow \text{AES}(k, p) \stackrel{?}{=} c$.
- Classically, we'd need to call f about 2^n times to find x_0
- Grover's algorithm only needs $\sqrt{2^n} = 2^{n/2}$ queries

EXAMPLE

• $n = 2; x_0 = 10; \mathbf{U}_f \cdot |x, y\rangle = |x, f(x) \oplus y\rangle$

$$\mathbf{U}_f := \begin{array}{c} \begin{array}{cccccccc} & 00,0 & 00,1 & 01,0 & 01,1 & 10,0 & 10,1 & 11,0 & 11,1 \end{array} \\ \begin{array}{l} 00,0 \\ 00,1 \\ 01,0 \\ 01,1 \\ 10,0 \\ 10,1 \\ 11,0 \\ 11,1 \end{array} \left(\begin{array}{cccccccc} 1 & & & & & & & \\ & 1 & & & & & & \\ & & 1 & & & & & \\ & & & 1 & & & & \\ & & & & 1 & & & \\ & & & & & 1 & & \\ & & & & & & 1 & \\ & & & & & & & 1 & 1 \end{array} \right) \end{array}$$

FIRST ATTEMPT

Let's apply the Hadamard gate on the first n registers, apply U_f and measure

$$|\psi_0\rangle = |\mathbf{0}, 0\rangle$$

$$|\psi_1\rangle = (\mathbf{H}^{\oplus n} \otimes \mathbf{I}) \cdot |\mathbf{0}, 0\rangle = \left[\frac{\sum_{\mathbf{x} \in \{0,1\}^n} |\mathbf{x}\rangle}{\sqrt{2^n}} \right] |0\rangle$$

$$|\psi_2\rangle = U_f \cdot \left[\frac{\sum_{\mathbf{x} \in \{0,1\}^n} |\mathbf{x}\rangle}{\sqrt{2^n}} \right] |0\rangle = \frac{\sum_{\mathbf{x} \in \{0,1\}^n} |\mathbf{x}, f(\mathbf{x})\rangle}{\sqrt{2^n}}$$

Measuring the last qubit will produce 1 with probability $1/2^n$. **If that event happens, then measuring the first n qubits will output the correct answer x_0 .**

TRICK 1: PHASE INVERSION I

Apply the Hadamard gate on the **last** register and apply U_f

$$|\psi_0\rangle = |x, 1\rangle$$

$$|\psi_1\rangle = (I_n \otimes H) \cdot |x, 1\rangle = |x\rangle \left[\frac{|0\rangle - |1\rangle}{\sqrt{2}} \right] = \left[\frac{|x, 0\rangle - |x, 1\rangle}{\sqrt{2}} \right]$$

$$|\psi_2\rangle = U_f \cdot \left(|x\rangle \left[\frac{|0\rangle - |1\rangle}{\sqrt{2}} \right] \right) = |x\rangle \left[\frac{|f(x) \oplus 0\rangle - |f(x) \oplus 1\rangle}{\sqrt{2}} \right] = |x\rangle \left[\frac{|f(x)\rangle - |\overline{f(x)}\rangle}{\sqrt{2}} \right]$$

$$= (-1)^{f(x)} \cdot |x\rangle \left[\frac{|0\rangle - |1\rangle}{\sqrt{2}} \right] = \begin{cases} -1 |x\rangle \left[\frac{|0\rangle - |1\rangle}{\sqrt{2}} \right], & \text{if } x = x_0 \\ +1 |x\rangle \left[\frac{|0\rangle - |1\rangle}{\sqrt{2}} \right], & \text{if } x \neq x_0 \end{cases}$$

TRICK 1: PHASE INVERSION II

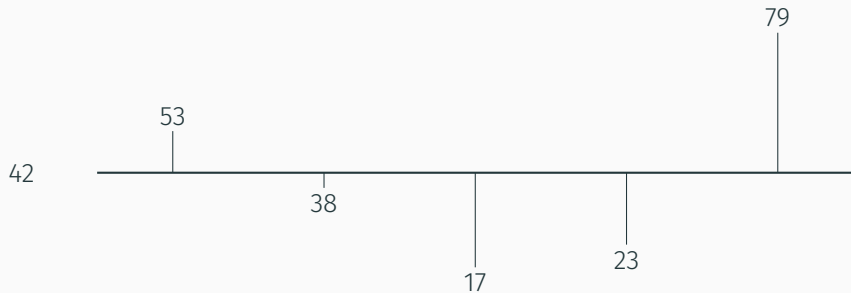
Applying:

$$\mathbf{U}_f \cdot (\mathbf{I}_n \otimes \mathbf{H}) \cdot \begin{pmatrix} 1/2 \\ 1/2 \\ 1/2 \\ 1/2 \end{pmatrix} = \begin{pmatrix} 1/2 \\ 1/2 \\ -1/2 \\ 1/2 \end{pmatrix}$$

Useless?

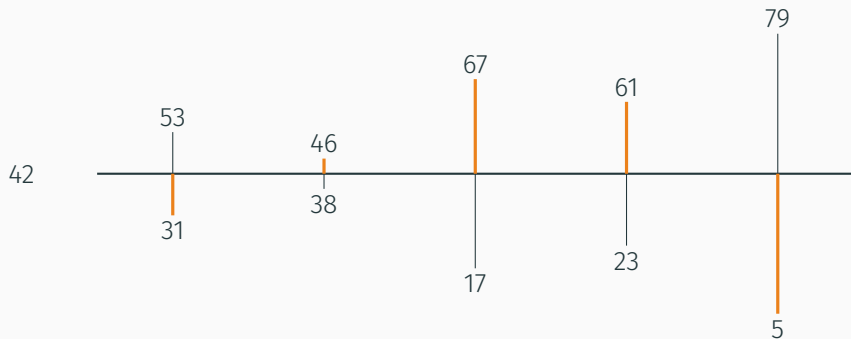
$$|(-1/2)|^2 = |1/2|^2$$

TRICK 2: INVERSION ABOUT THE MEAN (EXAMPLE)



$$y = \mu + (\mu - x) = -x + 2\mu$$

TRICK 2: INVERSION ABOUT THE MEAN (EXAMPLE)



$$y = \mu + (\mu - x) = -x + 2\mu$$

TRICK 2: INVERSION ABOUT THE MEAN I

Computing the mean:

$$M = \begin{pmatrix} 1/2^n & 1/2^n & \dots & 1/2^n & 1/2^n \\ 1/2^n & 1/2^n & \dots & 1/2^n & 1/2^n \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 1/2^n & 1/2^n & \dots & 1/2^n & 1/2^n \\ 1/2^n & 1/2^n & \dots & 1/2^n & 1/2^n \end{pmatrix}$$

$$M \cdot v = \begin{pmatrix} 1/2^n \cdot \sum_{i=0}^{2^n} v_i \\ 1/2^n \cdot \sum_{i=0}^{2^n} v_i \\ \vdots \\ 1/2^n \cdot \sum_{i=0}^{2^n} v_i \\ 1/2^n \cdot \sum_{i=0}^{2^n} v_i \end{pmatrix}$$

TRICK 2: INVERSION ABOUT THE MEAN II

Inversion about the mean:

$$-I + 2M = \begin{pmatrix} (-1 + 2/2^n) & 2/2^n & \dots & 2/2^n & 2/2^n \\ 2/2^n & (-1 + 2/2^n) & \dots & 2/2^n & 2/2^n \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 2/2^n & \dots & 2/2^n & (-1 + 2/2^n) & 2/2^n \\ 2/2^n & \dots & 2/2^n & 2/2^n & (-1 + 2/2^n) \end{pmatrix}$$
$$(-I + 2M) \cdot \mathbf{v} = \begin{pmatrix} v_0 + 2/2^n \cdot \sum_{i=0}^{2^n-1} v_i \\ v_1 + 2/2^n \cdot \sum_{i=0}^{2^n-1} v_i \\ \vdots \\ v_{2^n-2} + 2/2^n \cdot \sum_{i=0}^{2^n-1} v_i \\ v_{2^n-1} + 2/2^n \cdot \sum_{i=0}^{2^n-1} v_i \end{pmatrix}$$

TRICK 2: INVERSION ABOUT THE MEAN III

A straight-forward calculation shows that $-I + 2M$ is indeed unitary and thus a quantum circuit!

COMBINING THE TWO TRICKS

```
def phasef(v, i):  
    v = enumerate(v)  
    v = [v_ * (-1)**int(i==j) for j,v_ in v]  
    return vector(v)
```

```
phasef(vector(ZZ, 4, [1,1,1,1]), 2)
```

(1, 1, -1, 1)

```
def imeanf(v):  
    N = ZZ(len(v))  
    M = matrix(QQ, len(v), len(v), [1/N]*N**2)  
    I = identity_matrix(N)  
    return (-I + 2*M)*v
```

```
imeanf(vector(ZZ, 5, [53,38,17,23,79]))
```

(31, 46, 67, 61, 5)

COMBINING THE TWO TRICKS

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def phasef(v, i):  
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    return (-I + 2*M)*v
```

```
imeanf(vector(ZZ, 5, [53,38,17,23,79]))
```

(31, 46, 67, 61, 5)

```
v = vector(RealField(prec=12), 5, [10]*5)  
print(f" input: {v}")  
v = phasef(v, i=3); print(f"step 1a: {v}")  
v = imeanf(v); print(f"step 1b: {v}, Δ: {max(v)-min(v)}")  
v = phasef(v, i=3); print(f"step 2a: {v}")  
v = imeanf(v); print(f"step 2b: {v}, Δ: {max(v)-min(v)}")  
v = phasef(v, i=3); print(f"step 3a: {v}")  
v = imeanf(v); print(f"step 3b: {v}, Δ: {max(v)-min(v)}")
```

```
input: (10.0, 10.0, 10.0, 10.0, 10.0)  
step 1a: (10.0, 10.0, 10.0, -10.0, 10.0)  
step 1b: (2.00, 2.00, 2.00, 22.0, 2.00), Δ: 20.0  
step 2a: (2.00, 2.00, 2.00, -22.0, 2.00)  
step 2b: (-7.60, -7.60, -7.60, 16.4, -7.60), Δ: 24.0  
step 3a: (-7.60, -7.60, -7.60, -16.4, -7.60)  
step 3b: (-11.1, -11.1, -11.1, -2.33, -11.1), Δ: 8.80
```

COMBINING THE TWO TRICKS

```
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    v = enumerate(v)  
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```

```
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step 3b: (-11.1, -11.1, -11.1, -2.33, -11.1), Δ: 8.80
```

The optimal number of repetitions is $\sqrt{\dim(v)}$

GROVER'S ALGORITHM

1. Start with $|0\rangle$
2. Apply $H^{\otimes n}$
3. Repeat $\sqrt{2^n}$ times:
 - 3.1 Apply phase inversion $U_f \cdot (I \otimes H)$
 - 3.2 Apply inversion about the mean $-I + 2M$
4. Measure the qubits

RECAP: GROVER VS AES

Best known quantum algorithms for attacking symmetric cryptography are based on Grover's algorithm.

- Search key space of size 2^n in $2^{n/2}$ operations: AES-256 \rightarrow 128 “quantum bits of security”.
- Taking all costs into account: $> 2^{152}$ classical operations for AES-256.¹
- Assuming a max depth of 2^{96} for a quantum circuit: overall AES-256 cost is $\approx 2^{190}$.
- Does not parallelise: have to wait for 2^x steps, cannot buy 2^{32} quantum computers and wait $2^x/2^{32}$ steps.

¹Samuel Jaques, Michael Naehrig, Martin Roetteler, and Fernando Virdia. **Implementing Grover Oracles for Quantum Key Search on AES and LowMC**. In: *EUROCRYPT 2020, Part II*. ed. by Anne Canteaut and Yuval Ishai. Vol. 12106. LNCS. Springer, Cham, May 2020, pp. 280–310. DOI: 10.1007/978-3-030-45724-2_10.

SHOR'S ALGORITHM

TASK

Given $N = p \cdot q$ for p, q prime find p or q .

A MAGICAL NEW OPERATION

Consider a function $f_{a,N}(x)$ for any $0 < a < N$, which computes $f_{a,N}(x) := a^x \bmod N$

Example:

```
p, q = 13, 15
```

```
N = p*q
```

```
a = 2
```

```
def f(x):
```

```
    return power_mod(a, x, N)
```

```
f(13)
```

```
p, q = 3, 5
```

```
N = p*q
```

```
a = 2
```

```
[list(range(N)), None, [f(i) for i in range(N)]]
```

2

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	2	4	8	1	2	4	8	1	2	4	8	1	2	4

A MAGICAL NEW OPERATION

Theorem (Euler's Theorem)

For any modulus N and any coprime integer a , it holds that

$$a^{\phi(n)} \equiv 1 \pmod{N}$$

where $\phi(n)$, Euler's totient function, counts the integers up to n relatively prime to n .

- So $f_{a,N}(\cdot)$ should have some period r : $f_{a,N}(x) \equiv f_{a,N}(x + r)$.
- We can implement $f_{a,N}(\cdot)$ efficiently on classical and on quantum computers
- On a quantum computer, we can find this period efficiently but this assumed hard on classical computers.

A Magical New Operation

Let $\mathcal{P}(a, N)$ be an oracle that outputs r s.t. $f_{a,N}(x) \equiv f_{a,N}(x + r)$.

FACTORING WITH THAT MAGICAL NEW OPERATION

1. Pick a random $2 \leq a < N$.
2. If $\gcd(a, N) \neq 1$, output a as a factor of N .
3. Call $\mathcal{P}(a, N)$ and retrieve r .
4. If r is not even, start over.
5. We have $a^r \equiv 1 \pmod N$ and thus $N \mid (a^r - 1)$.
6. Write $a^r - 1 = (\sqrt{a^r} + 1) \cdot (\sqrt{a^r} - 1)$.²
7. So we get $N \mid (a^{r/2} - 1) \cdot (a^{r/2} + 1)$, i.e. any factor of N is a factor of $(a^{r/2} - 1)$, $(a^{r/2} + 1)$ or both
 - 7.1 It can't be that $N \mid a^{r/2} - 1$ because the period is r and not $r/2$
 - 7.2 It could be that $N \mid a^{r/2} + 1$ and then the algorithm fails
8. Compute $d := \gcd(N, a^{r/2} + 1)$

² $x^2 - y^2 = (x - y) \cdot (x + y)$

THE MAGICAL NEW OPERATION

1. We can implement $f_{a,N}(\cdot)$ as a quantum circuit $U_{f_{a,N}(\cdot)}$ acting on $m := \lceil \log N^2 \rceil$ qubits
2. We can apply Hadamard gates on the inputs before applying $U_{f_{a,N}(\cdot)}$
3. This gives us a state³

$$|\phi_2\rangle := \frac{\sum_{\mathbf{x} \in \{0,1\}^m} |\mathbf{x}, f_{a,N}(\mathbf{x})\rangle}{\sqrt{2^m}} = \frac{\sum_{\mathbf{x} \in \{0,1\}^m} |\mathbf{x}, a^{\mathbf{x}} \bmod N\rangle}{\sqrt{2^m}}.$$

4. The final ingredient is a **Quantum Fourier Transform** (QFT) which more or less extracts the period from such a state.⁴

³I'm identifying the binary representation \mathbf{x} of x with x here.

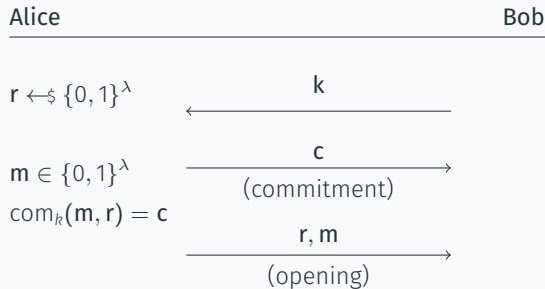
⁴I have yet to find a simple way of explaining it :(

RECAP: SHOR VS RSA, DH, ...



COMMITMENT SCHEMES

COMMITMENT SCHEMES



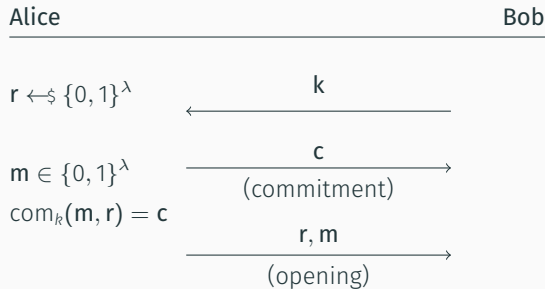
Statistically Hiding:

$$\Pr \left[b' = b \mid \begin{array}{l} (m_0, m_1) \leftarrow \mathcal{A}(k) \\ b \leftarrow \{0, 1\} \\ r \leftarrow \{0, 1\}^\lambda \\ c \leftarrow \text{com}_k(m_b, r) \\ b' \leftarrow \mathcal{A}(c) \end{array} \right] = \frac{1}{2}$$

for any \mathcal{A} .

Computationally Binding: “PPT adversary cannot change its mind after sending c ”

COMMITMENT SCHEMES



Statistically Hiding:

$$\Pr \left[b' = b \mid \begin{array}{l} (m_0, m_1) \leftarrow \mathcal{A}(k) \\ b \leftarrow \{0, 1\} \\ r \leftarrow \{0, 1\}^\lambda \\ c \leftarrow \text{com}_k(m_b, r) \\ b' \leftarrow \mathcal{A}(c) \end{array} \right] = \frac{1}{2}$$

for any \mathcal{A} .

Computationally Binding: “PPT adversary cannot change its mind after sending c ”

How should we formalise this?

CLASSICAL DEFINITION

“PPT adversary cannot change its mind after sending c ”

Classical Definition

PPT \mathcal{A} cannot find $(\mathbf{m}, r, \mathbf{m}', r')$ where $\mathbf{m} \neq \mathbf{m}'$ and

$$\text{com}_k(\mathbf{m}, r) = \text{com}_k(\mathbf{m}', r').$$

In particular, any collision-resistant hash function implies a binding commitment scheme.

- A commitment scheme cannot be statistically hiding and statistically binding at the same time
 - If it is statistically hiding this means that for any $\mathbf{c} = \text{com}_k(\mathbf{m}, \mathbf{r})$ there exists some \mathbf{r}' such that $\mathbf{c} = \text{com}_k(\mathbf{m}', \mathbf{r}')$ for any \mathbf{m}' .
 - If it is statistically binding this means that for any $\mathbf{c} = \text{com}_k(\mathbf{m}, \mathbf{r})$ there exists no \mathbf{r}' such that $\mathbf{c} = \text{com}_k(\mathbf{m}', \mathbf{r})$ for any $\mathbf{m}' \neq \mathbf{m}$.
- Any IND-CPA secure encryption scheme is a hiding commitment scheme
- Any perfectly-correct encryption scheme is a binding commitment scheme, otherwise decryption might fail

CLASSICAL DEFINITION

“PPT adversary cannot change its mind after sending c ”

Classical Definition

PPT \mathcal{A} cannot find $(\mathbf{m}, r, \mathbf{m}', r')$ where $\mathbf{m} \neq \mathbf{m}'$ and

$$\text{com}_k(\mathbf{m}, r) = \text{com}_k(\mathbf{m}', r').$$

In particular, any collision-resistant hash function implies a binding commitment scheme.

Punchline

This is not true if \mathcal{A} is a quantum adversary.

ATTACK ON CLASSICAL DEFINITION I

There exists a quantum-secure collision-resistant hash function H where \mathcal{A} can open $\text{com}_k(\mathbf{m}, \mathbf{r}) := H(\mathbf{m}, \mathbf{r})$ to any \mathbf{m} .⁵

- Quantum adversary cannot find two pairs $(\mathbf{m}, \mathbf{r}), (\mathbf{m}', \mathbf{r}')$ that agree on $\text{com}_k(\mathbf{m}, \mathbf{r}) = \text{com}_k(\mathbf{m}', \mathbf{r}')$
- But it can open to some message \mathbf{m} even if it learns it after sending \mathbf{c} .

Caveat

The attack depends on an oracle that we do not know how to build. But even with this oracle collision resistance holds.

⁵Andris Ambainis, Ansis Rosmanis, and Dominique Unruh. **Quantum Attacks on Classical Proof Systems: The Hardness of Quantum Rewinding**. In: *55th FOCS*. IEEE Computer Society Press, Oct. 2014, pp. 474–483. DOI: 10.1109/FOCS.2014.57; Dominique Unruh. **Computationally Binding Quantum Commitments**. In: *EUROCRYPT 2016, Part II*. ed. by Marc Fischlin and Jean-Sébastien Coron. Vol. 9666. LNCS. Springer, Berlin, Heidelberg, May 2016, pp. 497–527. DOI: 10.1007/978-3-662-49896-5_18.

ATTACK ON CLASSICAL DEFINITION II

1. Prepare a quantum state

$$|\phi\rangle := \left[\frac{\sum_{\mathbf{m}, \mathbf{r} \in \{0,1\}^\lambda \times \{0,1\}^\lambda} |\mathbf{m}\rangle |\mathbf{r}\rangle}{\sqrt{2^{2\lambda}}} \right] |0\rangle$$

2. Apply H on the first two registers and add result to the third

$$|\phi\rangle := \frac{\sum_{\mathbf{m}, \mathbf{r} \in \{0,1\}^\lambda \times \{0,1\}^\lambda} |\mathbf{m}\rangle |\mathbf{r}\rangle |H(\mathbf{m}, \mathbf{r})\rangle}{\sqrt{2^{2\lambda}}}$$

3. Measure the third register to obtain some value \mathbf{h}

$$|\phi\rangle := \frac{\sum_{(\mathbf{m}, \mathbf{r}) \mid \mathbf{h} = H(\mathbf{m}, \mathbf{r})} |\mathbf{m}\rangle |\mathbf{r}\rangle}{\sqrt{|\{(\mathbf{m}, \mathbf{r}) \mid \mathbf{h} = H(\mathbf{m}, \mathbf{r})\}|}} |\mathbf{h}\rangle$$

The first register now contains **all** preimages of \mathbf{h} .

4. Use the magic oracle⁶ to filter $\left\{ (m, r) \mid h = H(m, r) \right\}$ to

$$\left\{ (m, r) \mid h = H(m, r) \wedge m = m_0 \right\}$$

for any chosen m_0 .

5. Measure the first register to obtain (m_0, r) and submit as an opening.

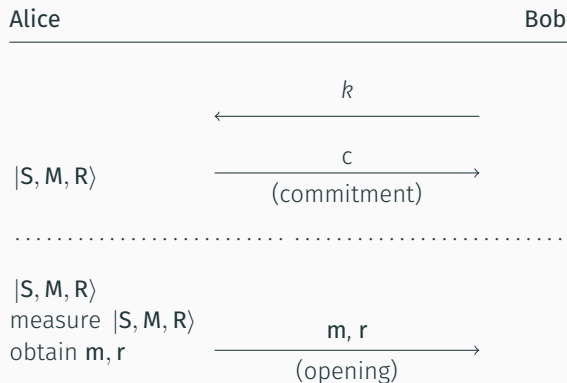
Collision Resistance

This does not violate collision resistance because we are “using up” our state, i.e. we can only measure once, still.

⁶This is a variant of Grover’s algorithm but we don’t know how to implement the required steps.

CORRECTED DEFINITION: FORMALISING THE ATTACKER

Can write down our attacker like this:



CORRECTED DEFINITION: WHAT DOES IDEAL LOOK LIKE?

Collapse-binding Commitment

```
1 :  $b \leftarrow_{\$} \{0, 1\}; k \leftarrow_{\$} \{0, 1\}^{\lambda}$ 
2 :  $c, |S, M, R\rangle \leftarrow \mathcal{A}(k)$ 
3 : compute  $|S, M, R, V_c(M, R)\rangle$  //  $V_c(M, R) = 1$  iff  $\text{com}_k(M, R) = c$ 
4 : measure  $|V_c(M, R)\rangle = v$ 
5 : // measurement has no effect if  $|M\rangle = |m\rangle$ , i.e. “collapsed”
6 : if  $v = 1 \wedge b = 0$  then measure  $|M\rangle$ 
7 :  $b' \leftarrow \mathcal{A}(|S, M, R, V_c(M, R)\rangle)$ 
8 : return  $b = b'$ 
```

Dominique Unruh.

Computationally Binding Quantum Commitments. In:
EUROCRYPT 2016, Part II. ed. by
Marc Fischlin and
Jean-Sébastien Coron.
Vol. 9666. LNCS. Springer,
Berlin, Heidelberg, May 2016,
pp. 497–527. DOI: 10.1007/978-
3-662-49896-5_18

COLLAPSING HASH FUNCTIONS

Collapsing Hash Function H

```
1:  $b \leftarrow \{0, 1\}$ 
2:  $|\psi\rangle_0 := |S\rangle \sum_x |x, 0\rangle \leftarrow \mathcal{A}(H)$ 
3:  $|\psi\rangle_1 := |S\rangle \sum_x |x, H(x)\rangle$ 
4: if  $b = 0$  then
5:   measure  $|x\rangle \in |\psi\rangle_1 \rightarrow |\psi\rangle_2$ 
6: else
7:   measure  $|H(x)\rangle \in |\psi\rangle_1 \rightarrow |\psi\rangle_2$ 
8:  $b' \leftarrow \mathcal{A}(|\psi\rangle_2)$ 
9: return  $b = b'$ 
```

Figure 1: Collapsing Hash Function

Game indeed differs:

- $b = 0$: collapses to a single input-output pair
- $b = 1$: collapses to all preimages of measured value $H(x)$

[Unr16]: This implies collapse-binding commitments.

A NEW CLASSICAL DEFINITION

Any **somewhere statistically binding** hash function is collapsing.

SOMEWHERE STATISTICALLY BINDING (SSB)

- Consider $H(\mathbf{x}_0 \mid \mathbf{x}_1 \mid \dots \mid \mathbf{x}_{\ell-1})$
 - There are “modes” $H^{(i)}(\mathbf{x}_0 \mid \mathbf{x}_1)$ that are **statistically binding** to block \mathbf{x}_i
 - We also have “index hiding”: $H \approx_c H^{(i)} \approx_c H^{(j)}$ for any i, j .
-
- Since $H()$ is compressing it it cannot be statistically binding to its input
 - But it can be statistically binding for one small block
 - If cannot tell which block it is statistically binding to, have an SSB hash function
 - Can build this from a perfectly correct fully-homomorphic encryption scheme

FIN

IF YOU TAKE NOTHING ELSE FROM THIS LECTURE: QUANTUM
COMPUTERS WON'T SOLVE HARD PROBLEMS INSTANTLY BY JUST
TRYING ALL SOLUTIONS IN PARALLEL.

CREDIT: <https://scottaaronson.blog/>

- [ARU14] Andris Ambainis, Ansis Rosmanis, and Dominique Unruh. **Quantum Attacks on Classical Proof Systems: The Hardness of Quantum Rewinding**. In: *55th FOCS*. IEEE Computer Society Press, Oct. 2014, pp. 474–483. DOI: 10.1109/FOCS.2014.57.
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- [Unr16] Dominique Unruh. **Computationally Binding Quantum Commitments**. In: *EUROCRYPT 2016, Part II*. Ed. by Marc Fischlin and Jean-Sébastien Coron. Vol. 9666. LNCS. Springer, Berlin, Heidelberg, May 2016, pp. 497–527. DOI: 10.1007/978-3-662-49896-5_18.

- [YM08] Noson S Yanofsky and Mirco A Mannucci. **Quantum Computing for Computer Scientists**. Cambridge University Press, 2008.