

CMPT 476 Lecture 18

Simon's algorithm

(Not actually
Simon, probably)



Hm I'm Simon.
This is my
algorithm.

So far the algorithms we've seen have been pretty trivial. On the one hand, it seems the "problems" were reverse-engineered based on the interference patterns generated from the hadamard transform. On the other hand, we didn't even really get a non-trivial advantage over classical algorithms on those problems.

Today we'll look at the first non-trivial quantum algorithm which gives an **exponential speed-up** in the black-box model over classical computations, albeit for another **synthetic** problem.

(Simon's algorithm)

While the Bernstein-Vazirani algorithm gives a **query complexity speed-up** compared to probabilistic algorithms, in the end it's only **linear** since we have an **$O(n)$ classical algorithm**

$$f(100\cdots 0) = s_1$$

$$f(010\cdots 0) = s_2$$

$$f(001\cdots 0) = s_3$$

:

$$f(000\cdots 1) = s_n$$

Moreover, BV itself takes **$O(n)$ total work** so it's not a "real" speed-up. In 1994, Simon set out to show that there could be no "real" speed-up and instead found the first "**truly exponential speed-up**".
not really...

Simon's Problem

Input: A function $f: \{0,1\}^n \rightarrow \{0,1\}^n$

Promise: $\exists s \in \{0,1\}^n$ such that $s \neq 0$ and $f(x) = f(y)$ if & only if $x = y \text{ or } x = y \oplus s$

Goal: Find s .

bitwise xor of Y and S

Simon's problem is **artificial** (like all problems we've seen so far), but it's closely related to and based on the hardness of finding **collisions**

x, y such that $f(x) = f(y)$

Cryptographic hash functions like SHA are based on the hardness of finding collisions too.

First: how do we solve Simon classically?

Ex.

Suppose we have $f: \{0,1\}^3 \rightarrow \{0,1\}^3$ with the truth table

Ask professor why $S = 111$

x	$f(x)$
000	101
001	011
010	111
011	010
100	011
101	111
110	011
111	101

Note - the values of f don't matter only
collisions

Should be 010

If we sample $f(001) = 011$ and $f(110) = 011$, then we've found $x = 001$ & $y = 110$ such that $f(x) = f(y)$. Since $f(x) = f(y)$ iff $x = y \oplus s$, then

$$s = x \oplus y = 001 \oplus 110 = 111$$

If however $f(x) \neq f(y)$, we've learned **nothing** about s . We know there are collisions since $s \neq 0$ so, the question is how many queries do we need to find one with **high probability**?

We need to use at least $\sqrt{2^n}$ queries to have 50% chance of finding s .

Fact

Any probabilistic algorithm solving Simon's problem with probability $\frac{1}{2}$ must use $\Omega(\sqrt{2^n})$ queries.
 f can be any function as long as it satisfies the conditions.

(at least)

This number comes from the **birthday paradox**:

The probability one pair out of **23** people share a birthday is **> 50%**

In general, to find a collision out of **N** uniformly distributed possibilities with **> 50% probability** you need

Simon created an algorithm to sample the orthogonal subspace of s

$\approx \sqrt{N}$ samples.

(A quantum algorithm)

Simon's algorithm is our first one which is meaningfully different from Deutsch's. It uses interference on collisions

$|x\rangle, |y=x \oplus s\rangle$ where $f(x) = f(y)$
to repeatedly sample vectors orthogonal to s .

We first recall some facts from linear algebra.
Note that $\{0, 1\}^n = \mathbb{Z}_2^n$ is a vector space.

(Orthogonal subspace)

Given a subspace S of a vector space V_n , denote by
 S^\perp the orthogonal complement of S in V .

$$S^\perp = \{v \in V \mid s \cdot v = 0 \ \forall s \in S\}$$

The orthogonal complement of S is a subspace of V_n and

$$\dim(V) = \dim(S) + \dim(S^\perp)$$

(Finding a complement)

Let $s \in \mathbb{Z}_2^n$. Then $S^\perp = (\text{span}\{s\})^\perp$. Suppose we can randomly sample from S^\perp — how could we find s ?

Idea:

Take many samples x_1, \dots, x_k and solve
the linear system for $s = s_1, \dots, s_n$

How does this help us find s ?

$$\begin{bmatrix} x_1^T \\ \vdots \\ x_k^T \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_n \end{bmatrix} = \begin{bmatrix} x_1 \cdot s \\ \vdots \\ x_k \cdot s \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 0 \end{bmatrix}$$

if s is in this space, do we not have a dimension of 2^n ?

How do we know that the dimension of $s_{\text{orthogonal}}$ is $n - 1$?

How many x 's do we need? Well if they're linearly independent then $n - 1$ since

$$\begin{aligned} \dim(S^\perp) &= \dim(\mathbb{Z}_2^n) - \dim(\text{span}\{s\}) \\ &= n - 1 \end{aligned}$$

Linear algebra in finite fields

Dot product in $\mathbb{Z}_{\{2\}}^{\{n\}}$ is (xor $x_1y_1 z_2y_2$

(Simon's algorithm, high-level)

At a high-level, Simon's algorithm works like this

1. Set $A = []$

2. While $\text{rank}(A) < n - 1$ do:

 3. Prepare a uniform superposition

$$\frac{1}{\sqrt{2^n}} \sum_{z \in \{0,1\}^n} |z\rangle$$

 4. Measure to get $z_i \in \{0,1\}^n$

 5. Append row z_i to A

6. Solve $As = 0$ for s

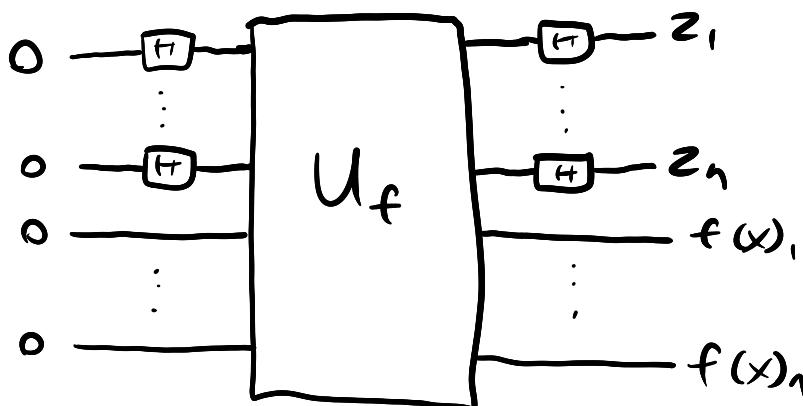
} quantum part

(The quantum part)

The genius of Simon's algorithm is in observing that interference can be used to prepare the state

$$\frac{1}{\sqrt{2^n}} \sum_{z \in \{0,1\}^n} |z\rangle$$

The idea is to generate a uniform superposition of $x \in \{0,1\}^n$, then pair up collisions with a call to f .



Here we use a **State oracle** $U_f |x\rangle |0\rangle = |x\rangle |f(x)\rangle$, so the state after U_f is

$$\frac{1}{\sqrt{2^n}} \sum_{x \in \{0,1\}^n} |x\rangle |f(x)\rangle$$

Now, suppose we measure the second register to get one particular value $w = f(x)$. The resulting state will be a (normalized) sum over all $y \in \{0,1\}^n$ such that $f(y) = w$. Observe that there are exactly two strings $x, x \oplus s$ such that $f(x) = f(y)$.

Why? suppose $\exists y, z \in \{0,1\}^n$ s.t. $f(x) = f(y) = f(z)$.

$$\text{Then } x = s \oplus y = s \oplus z \Rightarrow y \oplus z = 0 \Rightarrow y = z$$

Likewise, since $s \neq 0$, $x \oplus s \neq x$.

So after measuring $f(x)$ the state is

$$\frac{1}{\sqrt{2}} (|x\rangle + |x \oplus s\rangle) |f(x)\rangle, \quad x \in \{0,1\}^n$$

Now what is the effect of the Hadamard gates?

Since $H^{\otimes n}|x\rangle = \frac{1}{\sqrt{2^n}} \sum_{z \in \{0,1\}^n} (-1)^{x \cdot z} |z\rangle$, we have

$$\begin{aligned} & \left(H^{\otimes n} \frac{1}{\sqrt{2}} (|x\rangle + |x \oplus s\rangle) \right) |f(x)\rangle \\ &= \frac{1}{\sqrt{2}} \left(\frac{1}{\sqrt{2^n}} \sum_z (-1)^{x \cdot z} |z\rangle + \frac{1}{\sqrt{2^n}} \sum_z (-1)^{(x \oplus s) \cdot z} |z\rangle \right) |f(x)\rangle \\ &= \frac{1}{\sqrt{2^{n+1}}} \sum_z \left[(-1)^{x \cdot z} + (-1)^{(x \oplus s) \cdot z} \right] |z\rangle |f(x)\rangle \end{aligned}$$

Now which $|z\rangle$'s have non-zero amplitude? If $x \cdot z \neq (x \oplus s) \cdot z$, then

$$(-1)^{x \cdot z} + (-1)^{(x \oplus s) \cdot z} = 0$$

But $(x \oplus s) \cdot z = x \cdot z \oplus s \cdot z$, so $x \cdot z = (x \oplus s) \cdot z$ implies $s \cdot z = 0$, or $z \in S^\perp$!

So, if we measure the first register, we get some $z \in S^\perp$ as required. Or, in our original language the final quantum state from which we sample is

$$\frac{1}{\sqrt{2^{n+1}}} \sum_{z \in S^\perp} (-1)^{x \cdot z} |z\rangle |f(x)\rangle$$

(The role of measuring $|f(x)\rangle$)

One thing to note is that the measurement of $|f(x)\rangle$ is actually irrelevant — it only serves to simplify the analysis. If we don't measure $f(x)$, the only difference in the final state is that it is a superposition over all possible x 's:

$$N \sum_{x \in \{0,1\}^n} \sum_{z \in S^\perp} (-1)^{x \cdot z} |z\rangle |f(x)\rangle$$

Normalization factor

Measuring the first register still gives us some $z \in S^\perp$ since for any x, y where $f(x) = f(y)$,

$$|z\rangle |f(x)\rangle \text{ and } |z\rangle |f(y)\rangle$$

have the same phase, since $x \cdot z = (x \oplus y) \cdot z = y \cdot z$.

(Complexity analysis)

Since Simon's algorithm involves a loop where we repeatedly sample from S^\perp until we have a basis, we need to know how many times we need to repeat. This part makes it a probabilistic runtime because we could technically get the sequence of samples

$$z, z, z, z, z, \dots \quad (\text{i.e. same string each time})$$

In reality, each time we sample, we get something not in the span of the previous samples with high probability. To see why, think about the extremal cases: when we've seen 1 sample, or $n-2$ samples.

• 1 sample z : $|\text{span}\{z\}| = 1$,

$$|Z_2^n - \text{span}\{z\}| = 2^n - 1$$

• $n-2$ samples z_1, \dots, z_{n-2} : $|\text{span}\{z_i\}| \leq 2^{n-2}$

$$\begin{aligned} |Z - \text{span}\{z_i\}| &\geq 2^n - 2^{n-2} \\ &= 3 \cdot 2^{n-2} \end{aligned}$$

So even when we already have $n-2$ lin. ind. samples, we get the last one with $\frac{3}{4}$ probability!

Fact the expected number of samples needed is n

This gives Simon's algorithm an expected quantum query complexity of $O(n)$ with $O(n)$ additional classical work to solve the linear system.

Alternatively, we could just sample $m \in O(n)$ times and if we haven't found a basis yet just give up.

In practice, $m \approx n+1$ is enough to give a high probability of success. This is a common idea in probabilistic algorithms, where a deterministic algorithm with a probabilistic runtime can be turned into a probabilistic algorithm with a deterministic runtime.

(Recap of algorithms so far)

So far we've seen a series of algorithms with increasing separation between their **classical** and **quantum** query complexities. To summarize,

Problem	Classical query complexity	Probabilistic query complexity	Quantum query complexity
Deutsch	2	2	1
Deutsch-Jozsa	$O(2^n)$	2	1
Bernstein-Vazirani	$O(n)$	$O(n)$	1
Simon	$O(2^n)$	$O(2^n)$	$O(n)$

However, this is just the **query complexity** - we need to ask whether such a speed-up is **meaningful** in practice.

(Is query complexity meaningful?)

It depends — in particular on whether we can learn the property more efficiently by looking at the implementation of f . In polynomial interpolation, say we have a sub-routine in python which implements f . If this sub-routine is something like

```
def f(x):  
    return  $a_0 + a_1 * x + \dots + a_d * (x^{\underbrace{d}})$  power operator
```

then we can get the answer in $O(1)$ by opening up the black-box. On the other hand, f may be implemented by some other means — e.g. some financial algorithm — and we want to learn a property which is not apparent from the implementation.

Since we don't have true black boxes in quantum computation, the true complexity is relative to the implementation of the oracle, and to give a speed-up over classical computing it must give a speed-up over any classical algorithm given the same or a comparable implementation of f . That rules out a quantum speed-up for the algorithms we've seen over any implementation that explicitly uses the hidden string. Other options for the function in Simon's algorithm for example are

$$f(x) = Ax, \text{rank}(A) = n - 1$$

In this case, the best classical algorithm runs in time $O(n^3)$ by gaussian elimination, so there can be no (non-trivial) quantum speed-up.

Next we'll start to look at algorithms which offer true speed-ups, starting with an algorithm inspired by Simon's...

SHOR!