Quantum Computation

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0 Introduction

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—Lecture 2—

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Recall that we have an oracle U_f for $f : \mathbb{Z}_M \to \mathbb{Z}_\mathbb{N}$ periodic, with period r, $A = M/r$. We want to find r in $O(poly(m))$ time where $m = \log M$.

1.1 The quantum algorithm

Work on state space $\mathcal{H}_M \otimes \mathcal{N}$ with basis $\{|i\rangle|k\rangle\}_{i\in\mathbb{Z}_M, k\in\mathbb{Z}_N}$.
• Step 1. Make staet $\frac{1}{\sqrt{M}}\sum_{i=0}^{M-1}|i\rangle|0\rangle$.
• Step 2. Apply U_f to get $\frac{1}{\sqrt{M}}\sum_{i=0}^{M-1}|i\rangle|f(i)\rangle$.
• Step 3. Measure the 2nd register to get a result y. By Born rule, the first register collapses to all those i's (and only those) with $f(i)$ equal to the seen y, i.e. $i = x_0, x_0+r, ..., x_0+(A-1)r$, where $0 \le x_0 < r$ in 1st period has $f(m) = y$. Discard 2nd register to get $|per\rangle = \frac{1}{\sqrt{A}}\sum_{j=0}^{A-1}|x_0 + jr\rangle$.
Note: each of the r possible function values y occurs with same probability $1/r$, so $0 \le x_0 < r$ has been chosen uniformly at random.
If we now measure $|per\rangle$, we'd get a value $x_0 + jr$ for uniformly random j, i.e. random element (x_0^{th}) of a random period (j^{th}), i.e. random element of $\mathbb{Z}_m$, so we could get no information about r.
• Step 4. Apply quantum Fourier transform mod M (QFT) to $|per\rangle$. Recall the definition of QFT: $QFT : |x\rangle \to \sum_{y=0}^{M-1}\omega^{xy}|y\rangle$ for all $x \in \mathbb{Z}_M$ where $\omega = e^{2\pi i/M}$ is the Mth root of unity. The existing result is that QFT mod M can be implemented in $O(M^2)$ time.
Then we get

$$
\begin{aligned}
QFT|per\rangle &= \frac{1}{\sqrt{MA}}\sum_{j=0}^{A-1}\left(\sum_{y=0}^{M-1}\omega^{(x_0+jr)y}|y\rangle\right) \\
&= \frac{1}{\sqrt{MA}}\sum_{y=0}^{M-1}\omega^{x_0 y}\left[\sum_{j=0}^{A-1}\omega^{jry}\right]|y\rangle \ (*)
\end{aligned}
$$

where we group all the terms with the same $|y\rangle$ together. One good thing is that the sum inside the square bracket is a geometric series, with ratio $\alpha = \omega^{ry} = e^{2\pi i r y/M} = (e^{2\pi i/A})^y$.
Hence term inside bracket $= A$ if $\alpha = 1$, i.e. $y = kA = k\frac{M}{r}$, $k = 0, 1, ..., (r-1)$, and equals 0 otherwise when $\alpha \neq 1$. Now

$$
QFT|per\rangle = \sqrt{\frac{A}{M}}\sum_{k=0}^{r-1}\omega^{x_0 k\frac{M}{r}}|k\frac{M}{r}\rangle
$$

The random shift x_0 now appears only in phase, so measurement probabilities are now independent of x_0!

Measuring $QFT|per\rangle$ gives a value c, where $c = k_0\frac{M}{r}$ with $0 \leq k_0 \leq r-1$ chosen uniformly at random. Thus $\frac{k_0}{r} = \frac{c}{M}$, note that c, M are known, r is unknown (what we want), and k_0 is unknown but uniformly random.

So note that if we are lucky and get a k_0 that is coprime to r then we could just simplify $\frac{c}{M}$ to get r. Obviously we cannot be always lucky every time, but by theorem in number theory, the number of integers $< r$ coprime to r grows as $O(r/\log\log r)$ for large r, so we know probability of k_0 coprime to r is $O(\frac{1}{\log\log r})$.

Then by some probability calculation we know that $O(1/p)$ trials are enough to achieve $1-\varepsilon$ probability of success.

So afer Step 4, cancel c/M to the lowest terms a/b, giving r as denominator b (if k_0 is coprime to r). Check b value by computing $f(0)$ and $f(b)$, since $b = r$ iff $f(0) = f(b)$.

Repeating $K = O(\log\log r)$ times gives r with any desired probability.

Further insights into utility of QFT here:
Write $R = \{0, r, 2r, ..., (A-1)r\} \subseteq \mathbb{Z}_M$. $|R\rangle = \frac{1}{\sqrt{A}}\sum_{k=0}^{A-1}|kr\rangle$, and $|per\rangle = |x_0 + R\rangle = \frac{1}{\sqrt{A}}\sum_{k=0}^{A-1}|x_0 + br\rangle$ where x_0 is the random shift that caused problem previously.
For each $x_0 \in \mathbb{Z}_M$, consider mapping $k \to k + x_0$ (shift by x_0) on $\mathbb{Z}_M$, which is a 1-1 invertible map.

So linear map $U(x_0)$ on $\mathcal{H}_M$ defined by $U(x_0) : |k\rangle \to |k + x_0\rangle$ is unitary, and $|x_0 + R\rangle = U(x_0)|R\rangle$.

Since $(\mathbb{Z}_M, +)$ is abelian, $U(x_0)U(x_1) = U(x_0 + x_1) = U(x_1)U(x_0)$ i.e. all $U(x_0)$'s commute as operators on $\mathcal{H}_M$.
So we have orthonormal basis of common eigenvectors $|\chi_k\rangle\}_{k\in\mathbb{Z}_M}$, called *shift invariant states.*

$U(x_0)|\chi_k\rangle = \omega(x_0, k)|\chi_k\rangle$ for all $x_0, k \in \mathbb{Z}_M$ with $|\omega(x_0, k)| = 1$. Now consider $|R\rangle$ written in $|\chi\rangle$ basis,
$|R\rangle = \sum_{k=0}^{M-1} a_k|\chi_k\rangle$ where a_k's depending on r (not x_0).
Then $|per\rangle = U(x_0)|R\rangle = \sum_{k=0}^{M-1} a_k\omega(x_0, k)|\chi_k\rangle$, and measurement in the χ-basis has $prob(k) = |a_k\omega(x_0, k)|^2 = |a_k|^2$ which is independent of x_0, i.e. giving information about r!