

QUANTUM COMPUTATION AND QUANTUM INFORMATION: THE QUANTUM FOURIER TRANSFORM

1.

We consider the linear map in \mathbb{C}^N which acts on the computational basis as

$$|j\rangle \mapsto \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} e^{\frac{2i\pi jk}{N}} |k\rangle$$

Let A be the matrix of the transformation in the computational basis.

$$\forall (k, l) \in \llbracket 0, N-1 \rrbracket^2, \quad a_{kl} = \frac{1}{\sqrt{N}} e^{\frac{2i\pi kl}{N}}$$

The adjoint matrix A^\dagger is then

$$\begin{aligned} \forall (k, l) \in \llbracket 0, N-1 \rrbracket^2, \quad b_{kl} &= a_{lk}^* \\ &= \frac{1}{\sqrt{N}} e^{-\frac{2i\pi kl}{N}} \end{aligned}$$

We compute the coefficient k, l of the product AA^\dagger :

$$\begin{aligned} \forall (k, l) \in \llbracket 0, N-1 \rrbracket^2, \quad c_{kl} &= \sum_{j=0}^{N-1} a_{kj} b_{jl} \\ &= \frac{1}{N} \sum_{j=0}^{N-1} e^{\frac{2i\pi j}{N} (k-l)} \\ &= \frac{1}{N} \sum_{j=0}^{N-1} (e^{\frac{2i\pi}{N} (k-l)})^j \\ &= \begin{cases} \frac{1}{N} \frac{1 - (e^{\frac{2i\pi}{N} (k-l)})^N}{1 - e^{\frac{2i\pi}{N} (k-l)}} = 0 & \text{if } e^{\frac{2i\pi}{N} (k-l)} \neq 1, \\ 1 & \text{if } e^{\frac{2i\pi}{N} (k-l)} = 1. \end{cases} \\ &= \begin{cases} 0 & \text{if } k \neq l, \\ 1 & \text{if } k = l. \end{cases} \\ &= \delta_{kl} \end{aligned}$$

which shows that $AA^\dagger = A^\dagger A = I$ i.e. A is unitary.

2.

Here the dimension of the state space is $N = 2^n$. The Fourier transform of the n qubit state $|00 \dots 0\rangle$ is

$$A|0\rangle = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} |k\rangle$$

we can write k in binary $k_{n-1} \dots k_1 k_0$

$$A|0\rangle = \frac{1}{2^{n/2}} \sum_{k_0, k_1, \dots, k_{n-1}=0}^1 |k_{n-1} \dots k_1 k_0\rangle$$

or in product representation,

$$= \frac{1}{2^{n/2}} \underbrace{(|0\rangle + |1\rangle)(|0\rangle + |1\rangle) \dots (|0\rangle + |1\rangle)}_{n \text{ qubits}}$$

3.

Let $N = 2^n$ and $Y = (y_k)_{k \in \llbracket 0, N-1 \rrbracket}$ be the classical fourier transform of $X = (x_k)_{k \in \llbracket 0, N-1 \rrbracket}$.

$$\forall k \in \llbracket 0, N-1 \rrbracket, \quad y_k = \sum_{j=0}^{N-1} e^{\frac{2i\pi k j}{2^n}} x_j$$

The factor $\frac{1}{\sqrt{N}}$ is omitted for clarity. We can write j in binary $j_{n-1} \dots j_1 j_0$

$$\begin{aligned} y_k &= \sum_{j_0, j_1, \dots, j_{n-1}=0}^1 e^{\frac{2i\pi k(2^{n-1}j_{n-1} + \dots + 2j_1 + j_0)}{2^n}} x_j \\ &= \sum_{j_1, \dots, j_{n-1}=0}^1 e^{\frac{2i\pi k(2^{n-1}j_{n-1} + \dots + 2j_1)}{2^n}} x_{j_{n-1} \dots j_1 0} + \sum_{j_1, \dots, j_{n-1}=0}^1 e^{\frac{2i\pi k(2^{n-1}j_{n-1} + \dots + 2j_1 + 1)}{2^n}} x_{j_{n-1} \dots j_1 1} \\ &= \sum_{j_1, \dots, j_{n-1}=0}^1 e^{\frac{2i\pi k(2^{n-1}j_{n-1} + \dots + 2j_1)}{2^n}} x_{j_{n-1} \dots j_1 0} + e^{\frac{2i\pi k}{2^n}} \sum_{j_1, \dots, j_{n-1}=0}^1 e^{\frac{2i\pi k(2^{n-1}j_{n-1} + \dots + 2j_1)}{2^n}} x_{j_{n-1} \dots j_1 1} \\ &= \sum_{j_1, \dots, j_{n-1}=0}^1 e^{\frac{2i\pi k(2^{n-2}j_{n-1} + \dots + j_1)}{2^{n-1}}} x_{j_{n-1} \dots j_1 0} + e^{\frac{2i\pi k}{2^n}} \sum_{j_1, \dots, j_{n-1}=0}^1 e^{\frac{2i\pi k(2^{n-2}j_{n-1} + \dots + j_1)}{2^{n-1}}} x_{j_{n-1} \dots j_1 1} \end{aligned}$$

We see the first sum is the k^{th} coefficient of the FT of the sequence $(x_{2k})_{k \in \llbracket 0, N/2-1 \rrbracket}$ and the second is the k^{th} coefficient of the FT of $(x_{2k+1})_{k \in \llbracket 0, N/2-1 \rrbracket}$. This shows that to compute FT of sequence of length N , we have to compute 2 FT of sequence of length $\frac{N}{2}$ and do $2N$ complex additions/multiplications. The complexity of the operation $T(N)$ follows the recurrence:

$$T(N) = 2T\left(\frac{N}{2}\right) + 2N$$

We can use the Master theorem [1]:

Theorem. Let $a \geq 1$ and $b > 1$ be constants, let $f(n)$ be a function, and let $T(n)$ be defined on the non negative integers by the recurrence

$$T(n) = aT\left(\frac{n}{b}\right) + f(n)$$

where we interpret $\frac{n}{b}$ to mean either $\lfloor \frac{n}{b} \rfloor$ or $\lceil \frac{n}{b} \rceil$. Then $T(n)$ has the following asymptotic bounds:

- (1) If $f(n) = O(n^{\log_b a - \epsilon})$ for some constant $\epsilon > 0$, then $T(n) = \Theta(n^{\log_b a})$.
- (2) If $f(n) = \Theta(n^{\log_b a})$, then $T(n) = \Theta(n^{\log_b a} \log n)$.
- (3) If $f(n) = \Omega(n^{\log_b a + \epsilon})$ for some constant $\epsilon > 0$, and if $af(\frac{n}{b}) \leq cf(n)$ for some constant $c < 1$ and n sufficiently large, then $T(n) = \Theta(f(n))$.

Here we are in the second case of the theorem, so $T(N) = \Theta(N \log(N)) = \Theta(n 2^n)$.

Instead of \mathbb{C} , the Fourier transform may be used in any ring as soon as we are given a N th root of unity. The book *The design and analysis of computer algorithms* [2] provides an overview of the FFT, an algorithm using bits operations and application to fast integer multiplication.

5.

The inverse Fourier Transform

$$|j\rangle \mapsto \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} e^{-\frac{2i\pi j k}{N}} |k\rangle$$

is the adjoint of the Fourier Transform. The quantum circuit of figure 1 is obtained from the FT's circuit, replacing each R_k gate by its adjoint

$$R_k^\dagger = \begin{bmatrix} 1 & 0 \\ 0 & e^{-\frac{2i\pi}{2^k}} \end{bmatrix}$$



FIGURE 1. Quantum circuit for IFT.

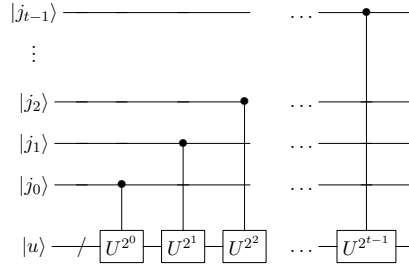


FIGURE 2. Sequence of controlled U.

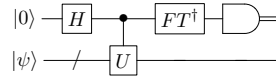
7.

In figure 2, the t qubits of the first register are prepared with $|j\rangle = |j_{t-1} \dots j_1 j_0\rangle$, the second register is prepared with some state $|u\rangle$. After the first controlled-U operation, the state is $|j\rangle |U^{j_0 2^0} u\rangle$. After the second controlled-U, the state is $|j\rangle |U^{j_1 2^1} U^{j_0 2^0} u\rangle = |j\rangle |U^{j_0 2^0 + j_1 2^1} u\rangle$ and so on. The final state is $|j\rangle |U^{j_0 2^0 + j_1 2^1 + \dots + j_{t-1} 2^{t-1}} u\rangle = |j\rangle |U^j u\rangle$.

8.

By linearity, the phase estimation algorithm takes input $|0\rangle |\Sigma_{u \in A} c_u |u\rangle\rangle$, where A is some orthonormal basis of eigenstates of U , to output $\sum_{u \in A} c_u |\widetilde{\varphi}_u\rangle |u\rangle$, where $\widetilde{\varphi}_u$ is an estimation of the phase of the eigenvalue associated with eigenstate u . If we fix $u_0 \in A$ beforehand, the probability to measure $\widetilde{\varphi}_{u_0}$ when measuring the first register in the computational basis is

$$\begin{aligned}
 & \left(\sum_{u \in A} c_u^* \langle \widetilde{\varphi}_u | \langle u | \right) P_{\widetilde{\varphi}_{u_0}} \otimes I \left(\sum_{u \in A} c_u |\widetilde{\varphi}_u\rangle |u\rangle \right) = \left(\sum_{u \in A} c_u^* \langle \widetilde{\varphi}_u | \langle u | \right) \left(\sum_{\substack{u \in A \\ \widetilde{\varphi}_u = \widetilde{\varphi}_{u_0}}} c_u |\widetilde{\varphi}_u\rangle |u\rangle \right) \\
 & = \left(\sum_{u \in A} c_u^* \langle \widetilde{\varphi}_u | \langle u | \right) \left(\sum_{\substack{u \in A \\ \widetilde{\varphi}_u = \widetilde{\varphi}_{u_0}}} c_u |\widetilde{\varphi}_{u_0}\rangle |u\rangle \right) \\
 & = \sum_{\substack{v \in A \\ u \in A \\ \widetilde{\varphi}_u = \widetilde{\varphi}_{u_0}}} c_v^* c_u \langle \widetilde{\varphi}_v | \widetilde{\varphi}_u \rangle \langle v | u \rangle \\
 & = \sum_{\substack{v \in A \\ u \in A \\ \widetilde{\varphi}_u = \widetilde{\varphi}_{u_0}}} c_v^* c_u \langle \widetilde{\varphi}_v | \widetilde{\varphi}_u \rangle \delta_{vu} \\
 & = \sum_{\substack{u \in A \\ \widetilde{\varphi}_u = \widetilde{\varphi}_{u_0}}} |c_u|^2 \\
 & \geq |c_{u_0}|^2
 \end{aligned}$$

FIGURE 3. Phase estimation circuit with $t = 1$.

I is the identity operator of whatever state space U operates on, while $P_{\widetilde{\varphi_{u_0}}}$ is the orthonormal projector onto the space generated by the vector $|\widetilde{\varphi_{u_0}}\rangle$ of the computational basis. Besides, following the analysis of the book, $\widetilde{\varphi_{u_0}}$ is an approximation to φ_{u_0} to an accuracy 2^{-n} with probability at least $1 - \epsilon$ if we make use of $t = n + \lceil \log(2 + \frac{1}{2\epsilon}) \rceil$ bits in the first register. We conclude we get the desired approximation of φ_{u_0} at the end of the phase estimation algorithm with probability at least $|c_{u_0}|^2(1 - \epsilon)$.

9.

U being unitary with eigenvalues -1 and $+1$, the state space is the direct sum of the two orthogonal eigenspaces $E_{-1} \oplus E_1$. Thus we can uniquely decompose any $|\psi\rangle = |\psi_{-1}\rangle + |\psi_{+1}\rangle$, with $|\psi_{-1}\rangle \in E_{-1}$ and $|\psi_{+1}\rangle \in E_1$. Then $-1 = e^{i\pi} = e^{2i\pi 0.1}$ and $1 = e^0 = e^{2i\pi 0.0}$ shows that it is sufficient to make use of $t = 1$ wire in the first register in the phase estimation procedure to read directly the phase of any eigenvector. If we use $|0\rangle |\psi\rangle$ as input in the circuit of figure 3, the output before the final measurement will be $|0\rangle |\psi_{+1}\rangle + |1\rangle |\psi_{-1}\rangle$.

When we measure the first register, we obtain 0 with probability

$$\begin{aligned} (\langle 0| \langle \psi_{+1}| + \langle 1| \langle \psi_{-1}|) P_0 \otimes I(|0\rangle |\psi_{+1}\rangle + |1\rangle |\psi_{-1}\rangle) &= (\langle 0| \langle \psi_{+1}| + \langle 1| \langle \psi_{-1}|)(|0\rangle |\psi_{+1}\rangle) \\ &= \langle 0|0\rangle \langle \psi_{+1}|\psi_{+1}\rangle \\ &= \langle \psi_{+1}|\psi_{+1}\rangle \end{aligned}$$

or 1 with probability

$$\begin{aligned} (\langle 0| \langle \psi_{+1}| + \langle 1| \langle \psi_{-1}|) P_1 \otimes I(|0\rangle |\psi_{+1}\rangle + |1\rangle |\psi_{-1}\rangle) &= (\langle 0| \langle \psi_{+1}| + \langle 1| \langle \psi_{-1}|)(|1\rangle |\psi_{-1}\rangle) \\ &= \langle 1|1\rangle \langle \psi_{-1}|\psi_{-1}\rangle \\ &= \langle \psi_{-1}|\psi_{-1}\rangle \end{aligned}$$

The state will collapse respectively into $\frac{1}{\sqrt{\langle \psi_{+1}|\psi_{+1}\rangle}} |0\rangle |\psi_{+1}\rangle$ or $\frac{1}{\sqrt{\langle \psi_{-1}|\psi_{-1}\rangle}} |1\rangle |\psi_{-1}\rangle$. Thus if we read 0 in the first register, that means that we have an eigenvector associated to eigenvalue $+1$ in the second register, and if we read 1 in the first register, that means that we have an eigenvector associated to eigenvalue -1 in the second register.

Once we have noticed that the FT in dimension $N = 2^1$ is just the Hadamard operator, we conclude the phase estimation circuit in this particular case is the just the same as the circuit of exercise 4.34.

10.

$$\begin{aligned} x^2 &= 25 = 4 \\ x^3 &= 20 = -1 \\ x^4 &= 4^2 = 16 \\ x^5 &= 16 \times 5 = 80 \\ &= 17 \\ x^6 &= (-1)^2 = 1 \end{aligned}$$

11.

Theorem (Euler). For $N \in \mathbb{N}^*$, let

$$\varphi(N) = \#\{m \in \llbracket 1, N \rrbracket, m \wedge N = 1\}$$

We have

$$\forall x \in \mathbb{N}^*, \quad x \wedge N = 1 \Rightarrow x^{\varphi(N)} = 1 \pmod{N}$$

Then by definition of the order r , $r \leq \varphi(N) \leq N$.

12.

Since $x \wedge N = 1$, from Bezout's Theorem $\exists(u, v) \in \mathbb{Z}^2$ such that $ux + vN = 1$ that is $\exists u$ such that $ux = 1 \pmod N$ which shows that x has a multiplicative inverse $x^{-1} = u$ in the ring $(\frac{\mathbb{Z}}{N\mathbb{Z}}, +, \times)$. We define the linear map U' on $(\mathbb{C}^2)^{\otimes L} \cong \mathbb{C}^{2^L}$ that acts on the computational basis as

$$\forall y \in \{0, 1\}^L, \quad U' |y\rangle = \begin{cases} |x^{-1}y \pmod N\rangle & \text{if } y < N, \\ y & \text{if } y \in \llbracket N, 2^L - 1 \rrbracket. \end{cases}$$

We have

$$\begin{aligned} \forall y_1, y_2 \in \{0, 1\}^L, \quad \langle y_1 | U(y_2) \rangle = 1 &\Leftrightarrow y_1 = y_2 \in \llbracket N, 2^L - 1 \rrbracket \text{ or } (y_1, y_2 < N \text{ and } xy_2 = y_1 \pmod N) \\ &\Leftrightarrow y_1 = y_2 \in \llbracket N, 2^L - 1 \rrbracket \text{ or } (y_1, y_2 < N \text{ and } \exists k \in \mathbb{Z}, xy_2 = y_1 + kN) \\ &\Leftrightarrow y_1 = y_2 \in \llbracket N, 2^L - 1 \rrbracket \text{ or } (y_1, y_2 < N \text{ and } \exists k \in \mathbb{Z}, y_2 = x^{-1}y_1 + x^{-1}kN) \\ &\Leftrightarrow y_1 = y_2 \in \llbracket N, 2^L - 1 \rrbracket \text{ or } (y_1, y_2 < N \text{ and } \exists k' \in \mathbb{Z}, y_2 = x^{-1}y_1 + k'N) \\ &\Leftrightarrow y_1 = y_2 \in \llbracket N, 2^L - 1 \rrbracket \text{ or } (y_1, y_2 < N \text{ and } x^{-1}y_1 = y_2 \pmod N) \\ &\Leftrightarrow \langle U'(y_1) | y_2 \rangle = 1 \end{aligned}$$

so, since $\langle U'(y_1) | y_2 \rangle, \langle y_1 | U(y_2) \rangle \in \{0, 1\}$,

$$\forall y_1, y_2 \in \{0, 1\}^L, \quad \langle y_1 | U(y_2) \rangle = \langle U'(y_1) | y_2 \rangle$$

This shows that $U' = U^\dagger$. since it is obvious that U is invertible and $U^\dagger = U^{-1}$, we have shown that U is unitary.

13.

$(|u_s\rangle)_{s \in \llbracket 0, r-1 \rrbracket}$ is defined to be the IFT of the sequence $(|x^k \pmod N\rangle)_{k \in \llbracket 0, r-1 \rrbracket}$:

$$\forall s \in \llbracket 0, r-1 \rrbracket, \quad |u_s\rangle = \frac{1}{\sqrt{r}} \sum_{k=0}^{r-1} e^{-\frac{2i\pi sk}{r}} |x^k \pmod N\rangle$$

Thus the equalities

$$\forall k \in \llbracket 0, r-1 \rrbracket, \quad |x^k \pmod N\rangle = \frac{1}{\sqrt{r}} \sum_{s=0}^{r-1} e^{\frac{2i\pi sk}{r}} |u_s\rangle$$

just state the fact that $(|x^k \pmod N\rangle)_{k \in \llbracket 0, r-1 \rrbracket}$ is the FT of the sequence $(|u_s\rangle)_{s \in \llbracket 0, r-1 \rrbracket}$. Let's check this. Let $k \in \llbracket 0, r-1 \rrbracket$,

$$\begin{aligned} \frac{1}{\sqrt{r}} \sum_{s=0}^{r-1} e^{\frac{2i\pi sk}{r}} |u_s\rangle &= \frac{1}{r} \sum_{s=0}^{r-1} e^{\frac{2i\pi sk}{r}} \sum_{j=0}^{r-1} e^{-\frac{2i\pi sj}{r}} |x^j \pmod N\rangle \\ &= \frac{1}{r} \sum_{j=0}^{r-1} \left(\sum_{s=0}^{r-1} (e^{\frac{2i\pi(k-j)}{r}})^s \right) |x^j \pmod N\rangle \\ &= \frac{1}{r} \sum_{j=0}^{r-1} r \delta_{jk} |x^j \pmod N\rangle \\ &= |x^k \pmod N\rangle \end{aligned}$$

For $k = 0$ we obtain

$$\frac{1}{\sqrt{r}} \sum_{s=0}^{r-1} |u_s\rangle = |1\rangle$$

15.

The easiest way is to think with the prime decomposition of the integers x and y . Let $d = x \wedge y$ and $m = x \vee y$. Let p_0, p_1, \dots, p_n be the prime numbers which appear in either prime decomposition. We can write

$$\begin{aligned} x &= p_0^{\alpha_0} p_1^{\alpha_1} \dots p_n^{\alpha_n} \\ y &= p_0^{\beta_0} p_1^{\beta_1} \dots p_n^{\beta_n} \end{aligned}$$

where $\alpha_i, \beta_i \in \mathbb{N}$. Then it is clear that

$$\begin{aligned} d &= p_0^{\gamma_0} p_1^{\gamma_1} \dots p_n^{\gamma_n} \\ m &= p_0^{\delta_0} p_1^{\delta_1} \dots p_n^{\delta_n} \end{aligned}$$

where $\gamma_i = \min(\alpha_i, \beta_i)$ and $\delta_i = \max(\alpha_i, \beta_i)$. We have $\alpha_i + \beta_i = \gamma_i + \delta_i$. Then,

$$\begin{aligned} md &= p_0^{\gamma_0} p_1^{\gamma_1} \dots p_n^{\gamma_n} p_0^{\delta_0} p_1^{\delta_1} \dots p_n^{\delta_n} \\ &= p_0^{\gamma_0 + \delta_0} p_1^{\gamma_1 + \delta_1} \dots p_n^{\gamma_n + \delta_n} \\ &= p_0^{\alpha_0 + \beta_0} p_1^{\alpha_1 + \beta_1} \dots p_n^{\alpha_n + \beta_n} \\ &= xy \end{aligned}$$

16.

Let $x \geq 2$.

$$\begin{aligned} \int_x^{x+1} \frac{1}{y^2} dy &= \frac{1}{x} - \frac{1}{x+1} \\ &= \frac{1}{x(x+1)} \end{aligned}$$

since

$$x+1 \leq \frac{3}{2}x \Leftrightarrow 2 \leq x$$

$$\int_x^{x+1} \frac{1}{y^2} dy = \frac{1}{x(x+1)} \geq \frac{2}{3x^2}$$

If we sum these inequalities

$$\sum_{q=2}^{+\infty} \frac{1}{q^2} \leq \frac{3}{2} \sum_{q=2}^{+\infty} \int_q^{q+1} \frac{1}{y^2} dy = \frac{3}{2} \int_2^{+\infty} \frac{1}{y^2} dy = \frac{3}{4}$$

and finally

$$\sum_{\substack{q \in \mathbb{N}^* \\ q \text{ is prime}}} \frac{1}{q^2} \leq \sum_{q=2}^{+\infty} \frac{1}{q^2} \leq \frac{3}{4}$$

17.

17.1. The assertion $N = a^b \Rightarrow b \leq L$ is obviously wrong if $N = a = 1$. Since we aim to prove an asymptotical result, we can assume that $N \geq 2$.

$$\begin{aligned} N = a^b &\Leftrightarrow \log N = b \log a \\ &\Leftrightarrow \frac{\log N}{\log a} = b & (N \geq 2 \Rightarrow a \geq 2 \Rightarrow \log a \geq 1 > 0) \\ &\Rightarrow b \leq \log N \\ &\Leftrightarrow b \leq \lfloor \log N \rfloor = L - 1 < L \quad (b \in \mathbb{N}) \end{aligned}$$

17.2. Let $N = 2^l + a_{l-1}2^{l-1} + \dots + a_12 + a_0$ with $l + 1 \leq L$ and $a_i \in \{0, 1\}$.

$$\begin{aligned} N &= 2^l(1 + a_{l-1}2^{-1} + \dots + a_12^{-l+1} + a_02^{-l}) \\ &= 2^l(1 + f) \end{aligned}$$

with $f \in [0, 1[$.

$$\begin{aligned} \log N &= l + \log(1 + a_{l-1}2^{-1} + \dots + a_12^{-l+1} + a_02^{-l}) \\ &= l + \log(1 + f) \end{aligned}$$

where \log is \log_2 . This shows that to compute an approximation to $\log N$, we just need an approximation of \log in range $[1, 2[$ or any interval of the form $[t, 2t[$ for instance $[\frac{3}{4}, \frac{1}{2}[$. Besides,

$$\begin{aligned} \forall x \in]-1, 1], \quad \ln(1+x) &= x - \frac{x^2}{2} + \frac{x^3}{3} - \dots + (-1)^{n+1} \frac{x^n}{n} + \dots \\ &= \sum_{k=1}^{+\infty} (-1)^{k+1} \frac{x^k}{k} \end{aligned}$$

Let's write it until order $L - 1$:

$$\forall x \in]-1, +\infty[, \quad \ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \dots + (-1)^{L+1} \frac{x^{L-1}}{L-1} + \sum_{k=L}^{+\infty} (-1)^{k+1} \frac{x^k}{k}$$

For $x \in [0, \frac{1}{2}[$, this is an alternating series and we can bound the rest by

$$\begin{aligned} \left| \sum_{k=L}^{+\infty} (-1)^{k+1} \frac{x^k}{k} \right| &\leq \left| (-1)^L \frac{x^L}{L} \right| \\ &\leq \frac{1}{2^L L} \end{aligned}$$

For $x \in [-\frac{1}{4}, 0[$, we can use Lagrange formula to bound the rest by

$$\begin{aligned} \exists \xi \in [-\frac{1}{4}, 0[, \quad \left| \sum_{k=L}^{+\infty} (-1)^{k+1} \frac{x^k}{k} \right| &= \left| \frac{\log^{(L)}(\xi)}{(L)!} x^L \right| \\ &= \frac{(L-1)!}{(1+\xi)^{L-1}} |x^L| \\ &= \frac{1}{(1+\xi)^{L-1}} |x^L| \\ &\leq \frac{1}{(1+\xi)^{L-1}} \frac{1}{4^{L-1}} \\ &\leq \frac{1}{(\frac{3}{4})^{L-1}} \frac{1}{4^{L-1}} \\ &= \frac{1}{3^{L-1}} \end{aligned}$$

This shows that we can use the Taylor series up to order $L - 1$ to approximate $\ln(x)$ with precision 2^{-L} on the range $[\frac{3}{4}, \frac{1}{2}[$. This is to simplify the complexity analysis. In actual implementation though better and faster approximation are used: See the book by Cheney [4] for mathematical foundations of the approximation of functions by polynomials including the Remez algorithm. See also this insightful post [3] which discusses tradeoffs between accuracy and speed in approximating this log function, taking into account error induced by floating-point representation of real numbers. Here [5] can be found an actual implementation of the C standard library.

In addition to the Taylor error, there is an error occuring when computing the polynomial using floating-point arithmetic. If we store the significand of the floating-point variables in binary on $L+1$ bits, and use

$O(L)$ bits to do arithmetic operations, each operation will incur a relative error of at most $\epsilon = 2^{-L-1}$, i.e.

$$\begin{aligned} x \oplus y &= (x + y)(1 + \xi) \\ x \ominus y &= (x - y)(1 + \xi) \\ x \otimes y &= (x \times y)(1 + \xi) \\ x \oslash y &= (x \div y)(1 + \xi) \end{aligned}$$

where $|\xi| \leq \epsilon$ and the values on the left are the value computed exactly and then rounded on $L + 1$ digits. For the details on floating point arithmetic see [6]. The previous polynomial can be rewritten as:

$$\begin{aligned} P(x) &= \sum_{k=1}^n (-1)^{k+1} \frac{1}{k} x^k \\ &= x \left(1 + x \left(-\frac{1}{2} + x \left(\frac{1}{3} + \dots + ((-1)^{n-1} \frac{1}{n-1} + (-1)^n \frac{1}{n} x) \dots \right) \right) \right) \end{aligned}$$

This shows that the evaluation costs n fused multiply-add operations. If one rounding error occurs for each of the multiply-add, we have the following bound on the error due to floating-point arithmetic (see [7] for a detailed analysis):

$$\begin{aligned} |\bar{P}(x) - \tilde{P}(x)| &= \left| \sum_{j=1}^{n-1} (\xi_j \sum_{i=j}^n (-1)^{i+1} \frac{1}{i} x^i) \right| \\ &= \left| \sum_{i=1}^{n-1} \left(\sum_{j=1}^i \xi_j \right) (-1)^{i+1} \frac{1}{i} x^i + \left(\sum_{j=1}^{n-1} \xi_j \right) (-1)^n \frac{1}{n} x^n \right| \\ &\leq \sum_{i=1}^{n-1} \left(\sum_{j=1}^i \epsilon \right) \frac{1}{i} |x^i| + \left(\sum_{j=1}^{n-1} \epsilon \right) \frac{1}{n} |x^n| \\ &= \epsilon \sum_{i=1}^{n-1} |x^i| + \epsilon \frac{n-1}{n} |x^n| \\ &\leq \epsilon \sum_{i=1}^n \frac{1}{2^i} \\ &= \epsilon \left(1 - \left(\frac{1}{2} \right)^n \right) \\ &\leq \epsilon \end{aligned}$$

and we add the error due to just storing the coefficients of the polynomial on L bits: for instance $\frac{1}{3} = 0.010101\dots$ is rounded when storing in binary. If \tilde{a}_i is the rounded value of $a_i = (-1)^{i+1} \frac{1}{i}$, the error will be:

$$\begin{aligned} |P(x) - \tilde{P}(x)| &\leq \sum_{i=1}^n |a_i - \tilde{a}_i| |x^i| \\ &\leq \sum_{i=1}^n \epsilon |a_i| |x^i| \\ &= \epsilon \sum_{i=1}^n \frac{1}{i} |x^i| \\ &\leq \epsilon \sum_{i=1}^n |x^i| \\ &\leq \epsilon \end{aligned}$$

Taking into consideration the three types of error, we see that the Taylor series of order L is a approximation to $\ln(x)$ on range $[\frac{3}{4}, \frac{1}{2}[$ with precision 2^{-L} since :

$$\begin{aligned} & \frac{1}{2^{L+1}(L+1)} + 2\epsilon \leq 2^{-L} \\ \Leftrightarrow & \frac{2^{-L-1}}{L} + 2^{-L} \leq 2^{-L} \\ \Leftrightarrow & 2^{-L-1}(\frac{1}{L} + 1) \leq 2^{-L} \\ \Leftrightarrow & L \geq 1 \end{aligned}$$

This analysis shows that the procedure LOG2 computes an approximation of $\log(N)$ to precision 2^{-L} . Binary addition-substraction costs $\Theta(L)$ operations, grade-school multiplication-division costs $\Theta(L^2)$. Multiplication complexity can be improved to:

- $O(L^{\log_2(3)})$ using Karatsuba algorithm [2].
- $O(L \log(L) \log \log(L))$ using Schönhage-Strassen algorithm [2].
- $O(L \log L \log^* L)$ using Furer algorithm [8].

Faster division $x \div y$ consists in computing $\frac{1}{y}$ in $O(\log(L))$ multiplications, then doing $x \div y = x \times \frac{1}{y}$ (cf. [9]).

In the end computing $\log_2 N$ has an $O(L^3)$ time complexity. If we are given an approximating polynomial and are assured it gives the desired precision for any input size considered, the complexity is $O(L^2)$. The complexity of finding $\lfloor \log_2(N) \rfloor$ given the binary representation of N is $O(L)$.

LOG2(N, L)

```
//  $L \geq l + 1$  where  $l = \lfloor \log_2(N) \rfloor$ , i.e.  $2^l \leq N < 2^{l+1}$ .
for  $j = 1$  to  $L$ 
     $A[j] = (-1)^{j+1} \frac{1}{j}$ 
 $m = \lfloor \log_2(N) \rfloor$ 
 $f = \frac{N}{2^m} - 1$ 
if  $f \geq \frac{1}{2}$ 
     $f = \frac{1/2 - f}{2}$ 
     $m = m + 1$ 
 $q = 0$ 
for  $j = L$  downto  $0$ 
     $q = q \times f + A[j]$ 
 $q = q \div \ln(2)$ 
return  $q + m$ 
```

18.

$$\begin{aligned} x^2 &= 16 \\ x^3 &= 64 = -27 \\ x^4 &= 108 = 17 \\ x^5 &= 68 = -23 \\ x^6 &= 92 = 1 \end{aligned}$$

shows that the order of x is 6.

19.

1 is not composite and all the odd integers less than 15 are prime except $9 = 3^2$.

20.

Let $l \in \llbracket 0, N-1 \rrbracket$.

$$\begin{aligned}
\sum_{x=0}^{N-1} e^{-\frac{2i\pi lx}{N}} f(x) &= \sum_{k=0}^{\frac{N}{r}-1} \sum_{x=0}^{r-1} e^{-\frac{2i\pi l(kr+x)}{N}} f(kr+x) \\
&= \sum_{k=0}^{\frac{N}{r}-1} \sum_{x=0}^{r-1} e^{-\frac{2i\pi lkr}{N}} e^{-\frac{2i\pi lx}{N}} f(x) \\
&= \sum_{x=0}^{r-1} \left(\sum_{k=0}^{\frac{N}{r}-1} e^{-\frac{2i\pi lkr}{N}} \right) e^{-\frac{2i\pi lx}{N}} f(x) \\
&= \sum_{x=0}^{r-1} \left(\sum_{k=0}^{\frac{N}{r}-1} e^{-\frac{2i\pi lkr}{N}} \right) e^{-\frac{2i\pi lx}{N}} f(x)
\end{aligned}$$

we have

$$\sum_{k=0}^{\frac{N}{r}-1} e^{-\frac{2i\pi lkr}{N}} = \begin{cases} \frac{N}{r} & \text{if } \frac{lr}{N} \in \mathbb{N}, \\ \frac{1 - (e^{-\frac{2i\pi lr}{N}})^{\frac{N}{r}}}{1 - e^{-\frac{2i\pi lr}{N}}} = 0 & \text{otherwise.} \end{cases}$$

so if $l = l' \frac{N}{r}$, with $l' \in \llbracket 0, r-1 \rrbracket$,

$$\frac{1}{\sqrt{N}} \sum_{x=0}^{N-1} e^{-\frac{2i\pi lx}{N}} f(x) = \sqrt{\frac{N}{r}} \frac{1}{\sqrt{r}} \sum_{x=0}^{r-1} e^{-\frac{2i\pi l'x}{r}} f(x)$$

otherwise

$$\frac{1}{\sqrt{N}} \sum_{x=0}^{N-1} e^{-\frac{2i\pi lx}{N}} f(x) = 0$$

22.

First we observe that because of the periodicity, we have

$$\begin{aligned}
f(x_1, x_2) &= f(x_1 - 1, x_2 + s) \\
&= \dots \\
&= f(1, x_2 + (x_1 - 1)s) \\
&= f(0, x_2 + x_1 s)
\end{aligned}$$

Second, for a fixed x_1 , the application

$$\begin{aligned}
\varphi_{x_1} : \llbracket 0, r-1 \rrbracket &\rightarrow \llbracket 0, r-1 \rrbracket \\
x_2 &\mapsto x_2 + x_1 s \pmod{r}
\end{aligned}$$

is a permutation of $\llbracket 0, r-1 \rrbracket$, i.e. for each $j \in \llbracket 0, r-1 \rrbracket$, there is exactly one x_2 such that $x_2 + x_1 s = j \pmod{r}$. Finally, if $x_2 + x_1 s = j \pmod{r}$,

$$\begin{aligned}
e^{-\frac{2i\pi(l_1 x_1 + l_2 x_2)}{r}} &= e^{-\frac{2i\pi(l_1 x_1 + l_2(j - x_1 s + kr))}{r}} \\
&= e^{-\frac{2i\pi((l_1 - l_2 s)x_1 + l_2 j)}{r}}
\end{aligned}$$

FIGURE 4. Periodicity of f with $r = 15$ and $s = 4$.

Let's now rewrite the sum. Let $l_1, l_2 \in \llbracket 0, r-1 \rrbracket$:

$$\begin{aligned}
 |\hat{f}(l_1, l_2)\rangle &= \sum_{x_1, x_2=0}^{r-1} e^{-\frac{2i\pi(l_1 x_1 + l_2 x_2)}{r}} |f(x_1, x_2)\rangle \\
 &= \sum_{x_1=0}^{r-1} \sum_{x_2=0}^{r-1} e^{-\frac{2i\pi(l_1 x_1 + l_2 x_2)}{r}} |f(x_1, x_2)\rangle \\
 &= \sum_{x_1=0}^{r-1} e^{-\frac{2i\pi l_1 x_1}{r}} \sum_{x_2=0}^{r-1} e^{-\frac{2i\pi l_2 x_2}{r}} |f(0, x_2 + x_1 s)\rangle \\
 &= \sum_{x_1=0}^{r-1} e^{-\frac{2i\pi l_1 x_1}{r}} \sum_{j=0}^{r-1} e^{-\frac{2i\pi l_2 (-x_1 s + j)}{r}} |f(0, j)\rangle \\
 &= \sum_{x_1=0}^{r-1} e^{-\frac{2i\pi(l_1 - l_2 s)x_1}{r}} \sum_{j=0}^{r-1} e^{-\frac{2i\pi l_2 j}{r}} |f(0, j)\rangle \\
 &= \sum_{x_1=0}^{r-1} (e^{-\frac{2i\pi(l_1 - l_2 s)}{r}})^{x_1} \sum_{j=0}^{r-1} e^{-\frac{2i\pi l_2 j}{r}} |f(0, j)\rangle
 \end{aligned}$$

Using the usual argument, the first factor which is a geometric sum is 0 unless $l_1 - l_2 s = kr$ with $k \in \mathbb{Z}$ and in that case

$$\sum_{x_1, x_2=0}^{r-1} e^{-\frac{2i\pi(l_1 x_1 + l_2 x_2)}{r}} |f(x_1, x_2)\rangle = r \sum_{j=0}^{r-1} e^{-\frac{2i\pi l_2 j}{r}} |f(0, j)\rangle$$

23.

Let $x_1, x_2 \in \llbracket 0, r-1 \rrbracket$.

$$\sum_{l_1, l_2=0}^{r-1} e^{\frac{2i\pi(x_1 l_1 + x_2 l_2)}{r}} |\hat{f}(l_1, l_2)\rangle = \sum_{l_2=0}^{r-1} \sum_{l_1=0}^{r-1} e^{\frac{2i\pi(x_1 l_1 + x_2 l_2)}{r}} |\hat{f}(l_1, l_2)\rangle$$

for a given value of l_2 , there is exactly one $l_1 \in \llbracket 0, r-1 \rrbracket$ such that $l_1 = l_2 s \pmod r$, so there is exactly one term in each inner sum which is non zero and

$$\begin{aligned}
 \sum_{l_2=0}^{r-1} \sum_{l_1=0}^{r-1} e^{\frac{2i\pi(x_1 l_1 + x_2 l_2)}{r}} |\hat{f}(l_1, l_2)\rangle &= r \sum_{l_2=0}^{r-1} e^{\frac{2i\pi(x_1 l_2 s + x_2 l_2)}{r}} \sum_{j=0}^{r-1} e^{-\frac{2i\pi l_2 j}{r}} |f(0, j)\rangle \\
 &= r \sum_{j=0}^{r-1} \left(\sum_{l_2=0}^{r-1} e^{\frac{2i\pi(x_1 l_2 s + x_2 l_2 - j l_2)}{r}} \right) |f(0, j)\rangle \\
 &= r \sum_{j=0}^{r-1} \left(\sum_{l_2=0}^{r-1} (e^{\frac{2i\pi(x_1 s + x_2 - j)}{r}})^{l_2} \right) |f(0, j)\rangle
 \end{aligned}$$

Again a geometric sum

$$\sum_{l_2=0}^{r-1} (e^{\frac{2i\pi(x_1 s + x_2 - j)}{r}})^{l_2} = \begin{cases} r & \text{if } j = x_2 + x_1 s \pmod r, \\ 0 & \text{otherwise.} \end{cases}$$

So finally

$$\begin{aligned}
 \sum_{l_2=0}^{r-1} \sum_{l_1=0}^{r-1} e^{\frac{2i\pi(x_1 l_1 + x_2 l_2)}{r}} |\hat{f}(l_1, l_2)\rangle &= r^2 |f(0, x_2 + x_1 s + kr)\rangle \\
 &= r^2 |f(0, x_2 + x_1 s)\rangle \\
 &= r^2 |f(x_1, x_2)\rangle
 \end{aligned}$$

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