School of Mathematics **Spring 2020**

QUANTUM COMPUTATION

Exercise sheet 3

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1. **The QFT and periodicity.**

   (a) Multiply out the matrices corresponding to the gates in the circuit for the quantum Fourier transform Q_4, in the computational basis, and check that the result is what you expect.

   (b) Write the state $Q_8|3\rangle$ as a tensor product of three single-qubit states, each of the form $\frac{1}{\sqrt{2}}(|0\rangle + e^{2\pi i z}|1\rangle)$ for some binary fraction z (i.e. something of the form $(.x_{j-1} \dots x_0)$). Expand out the resulting state and check that the answer is what you expect.

   (c) Let $f : \mathbb{Z}_{16} \to \mathbb{Z}_4$ be the periodic function such that $f(0) = 2$, $f(1) = 1$, $f(2) = 3$, $f(3) = 0$, and $f(x) = f(x - 4)$ for all x (so $f(4) = 2$, etc.).

      i. Work through all the steps of the periodicity determination algorithm, writing down the state at each stage, and assuming that the measurement outcome in step 3 is 1, and the measurement outcome in step 5 is 12. Does the algorithm succeed?

      ii. Now assume that the measurement outcome in step 5 is 8. Does the algorithm succeed?

2. **Shor's algorithm.**

   (a) Suppose we would like to factorise $N = 85$ and we choose $a = 3$, which is coprime to N. Follow steps 3-5 of the integer factorisation algorithm to factorise 85 using this value of a (calculating the order of a classically!). You might like to use a computer.

   (b) Imagine we want to factorise $N = 21$ and we choose $a = 4$. Does the integer factorisation algorithm work or not?

3. **Approximate implementation of the QFT (optional).** This part proves a claim made at the end of Section 4 of the lecture notes. Define the distance $D(U, V)$ between unitary operators U and V as the maximum over all states $|\psi\rangle$ of $\||U|\psi\rangle - V|\psi\rangle\||$.

   (a) Show that $D(\cdot, \cdot)$ is subadditive: $D(U_1U_2, V_1V_2) \le D(U_1, V_1) + D(U_2, V_2)$.

(b) Show that $D(R_d, I) = O(2^{-d})$ and argue that the same holds for controlled-R_d.

(c) Describe how to produce a quantum circuit for an operator $\widetilde{Q}_{2^n}$ on n qubits such that $\widetilde{Q}_{2^n}$ uses $O(n \log n)$ gates and $D(\widetilde{Q}_{2^n}, Q_{2^n}) = O(1/n)$.