Tradeoffs in the Quantum Search Algorithm

Lov K. Grover
lkgrover@bell-labs.com
1D435 Bell Laboratories, Lucent Technologies,
600-700 Mountain Avenue, Murray Hill, NJ 07974

Abstract

Quantum search is a quantum mechanical technique for searching \( N \) possibilities in only \( \sqrt{N} \) steps. This has been proved to be the best possible algorithm for the exhaustive search problem in the sense the number of queries it requires cannot be reduced. However, as this paper shows, the number of non-query operations, and thus the total number of operations, can be reduced. The number of non-query unitary operations can be reduced by a factor of \( \log N/\alpha \log(\log N) \) while increasing the number of queries by a factor of only \( 1 + (\log N)^{-\alpha} \). Various choices of \( \alpha \) yield different variants of the algorithm. For example, by choosing \( \alpha \) to be \( O(\log N/\log(\log N)) \), the number of non-query unitary operations can be reduced by 40% while increasing the number of queries by just two.

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1 Introduction

The quantum search algorithm was a somewhat surprising result since it gave a means of searching $N$ items in only $\sqrt{N}$ steps \[1\]. It was surprising because unlike most computer science applications, the problem under consideration did not have any structure that the algorithm could make use of. It is easy to see that any classical algorithm, whether probabilistic or deterministic, would need $O(N)$ oracle queries - it had generally been assumed that $O(N)$ steps would be required by any algorithm. However, quantum mechanical systems can be in multiple states simultaneously and there is no clearly defined bound on how rapidly they can search.

It was proved through subtle properties of unitary transformations that any quantum system would need at least $O(\sqrt{N})$ queries to search $N$ items \[2\]. Subsequently, after the quantum search algorithm was invented, it was proved that the number of queries required by the algorithm was optimal and could not be improved even by one \[3\]. This is usually expressed by saying that “the quantum search algorithm is the best possible algorithm for exhaustive search.”

It is true that the number of queries required probably cannot be reduced, however, as this paper shows, there is scope for improvement in the total number of operations required by the algorithm. This is achieved by breaking up the non-query transformations into bitwise operations in a way somewhat reminiscent of the techniques used to improve the sorting algorithm beyond the information theoretic limit \[4\].

It is shown that by slightly increasing the number of queries, the total number of operations can be reduced by a logarithmic factor. This is accomplished by making use of the amplitude amplification principle.

2 Amplitude Amplification

A few years after the invention of the quantum search algorithm, it was generalized to a much larger class of applications known as the amplitude amplification algorithms \[5\] (similar results are independently proved in \[6\]). In these algorithms, the amplitude produced in a particular state by a unitary operation $U$, can be amplified by successively repeating the sequence of operations: $Q = I_s U^\dagger I_t U$. It was proved that if we start from the $s$ state and repeat the operation sequence $I_s U^\dagger I_t U$, $\eta$ times followed by a single repetition of $U$, then the amplitude in the $t$ state becomes approximately $2^\eta U_{ts}$ (provided $\eta U_{ts} \ll 1$). Also, if we start from $s$ and carry out $\frac{\pi}{4\|U_{ts}\|}$ repetitions of $Q$ followed by a single repetition of $U$, we reach $t$ with certainty. The quantum search algorithm is a
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particular case of this with $U$ being the Walsh-Hadamard Transformation ($W$) and $s$ being the $0$ state.

The power of the amplitude amplification technique lies in the fact that $U$ can be any unitary operation. Once we can design a unitary operation (or a sequence of unitary operations) $U$, that produce a certain amplitude in the target state, the amplitude amplification principle gives a prescription for amplifying this amplitude. The amount of amplification increases linearly with the number of repetitions of $Q$ and hence the probability of detecting $t$ goes up quadratically. For many applications this results in a square-root speed up over the equivalent classical algorithm.

In this paper we use the amplitude amplification principle for enhancing the quantum search algorithm. This is achieved by designing a sequence of bitwise operations that produce almost the same amplitude in the $t$ state while requiring a much smaller number of operations.

There have been several extensions of the quantum search algorithm as well as several applications of the algorithm to problems not immediately related to searching; however the result presented in this paper is the first improvement of the quantum search algorithm for the original exhaustive search problem.

3 The Quantum Search Algorithm

As mentioned before, the quantum search algorithm is a particular case of amplitude amplification with the Walsh-Hadamard Transformation being the $U$ operation and $s$ being the $\tilde{0}$ state. For any $t$, $|U_{ts}| = 1/\sqrt{N}$. It follows from the amplitude amplification principle that if we start from $\tilde{0}$ and carry out $\frac{\pi \sqrt{N}}{4}$ repetitions of the sequence of operations $-I_0WI_tW$, followed by $W$, we reach the $t$ state with certainty. Equivalently:

$$W(-I_0WI_tW)\ldots(-I_0WI_tW)(-I_0WI_tW)(-I_0WI_tW)|\tilde{0}\rangle = |t\rangle$$

Let $N$ be the number of items being searched. Then $I_\sigma$ requires us to calculate the AND of $\log_2 N$ boolean variables which can be carried out by $\log_2 N$ $C^2$NOT operations. $W$ requires $\log_2 N$ one-qubit operations. Thus the total number of additional (non-query) qubit operations required by the algorithm is $\frac{\pi \sqrt{N}}{4} \times 3 \times \log_2 N$ while the number of queries required is $\frac{\pi \sqrt{N}}{4}$. In the following section we show how to reduce the number of additional (non-query) qubit operations while keeping the number of queries approximately the same.
4 Inversion about Average

There have been several interpretations of the quantum search algorithm [7]. One of the ways the algorithm was first presented was in terms of an inversion about average transformation [1]. In this paper, the inversion about average transformation is combined with the amplitude amplification technique to obtain a faster algorithm for exhaustive search. Before presenting the new algorithm, we first recall the inversion about average transformation.

Consider the operation sequence: \((-W I W)\). This may be written as: 

\[-W \begin{pmatrix} I & -2 \langle 0 | \rangle \langle 0 | W \end{pmatrix} \text{ or equivalently } \begin{pmatrix} 2W \langle 0 | \rangle \langle 0 | W - I \end{pmatrix}.\]

The transformation \(W \langle 0 | \rangle \langle 0 | W\) can be represented as an \(N \times N\) matrix with each entry equal to \(\frac{1}{\sqrt{N}}\). To see this recall that \(W_{xy} = (-1)^{x \cdot y} \frac{1}{\sqrt{N}}\) where \(x, y\) denote the binary representation of \(x, y\); \(x \cdot y\) denotes the bitwise dot product of \(x, y\). Clearly if either \(x\) or \(y\) is 0 then \(x \cdot y = 0\) and \(W_{xy} = \frac{1}{\sqrt{N}}\). Therefore \(W \langle 0 | \rangle \langle 0 | W\) is an \(N \times N\) matrix with each entry equal to \(\frac{1}{\sqrt{N}}\) and each element of the transformed vector is equal to the average of all elements of the initial vector, i.e. if the \(i^{th}\) component of the input vector, \(\alpha_i\), is \(\alpha_i\), then each component of the transformed vector \(\alpha_{AV}\) where \(\alpha_{AV} = \frac{1}{N} \sum_i \alpha_i\). Hence the \(i^{th}\) component in the transformed vector is as much below the average as the \(i^{th}\) component in the initial vector was above the average, i.e. this transformation is an inversion about average.

As mentioned before, the quantum search algorithm consists of the operation sequence: \(W(-W I W)\ldots(-W I W)\). As described above, this is the inversion about average transformation. The average amplitude \((\alpha_{AV})\) is approximately equal to the amplitude of the \((N - 1)\) non-target states. Therefore as a result of this

1. \(W \langle 0 \rangle\). The \(W\) operation applied to \(\langle 0 \rangle\) creates a superposition with equal amplitude in each of the \(N\) states.
2. \(I_t\) selectively inverts the amplitude in the target state.

Next the following sequence of operations (3-4) is repeated \(\frac{2\sqrt{N}}{4}\) times:

3. \((-W I W)\). As described above, this is the inversion about average transformation. The average amplitude \((\alpha_{AV})\) is approximately equal to the amplitude of the \((N - 1)\) non-target states. Therefore as a result of this
transformation, the amplitude in the non-target states is unaltered. Since
the \( t \) state is inverted, its amplitude is below the average. As described in
\[ \text{[1]} \], its amplitude changes sign and its magnitude increases by \( 2\alpha_{AV} \).

4. \( I_1 \) selectively inverts the amplitude in the target state thus undoing the
sign change in (3). This prepares the system for the next inversion about
average operation through which the magnitude of the amplitude in the \( t \)
state is increased.

Figure 1 (see attached file): The transformation \( - \left( W^{(S)} I^{(S)} W^{(S)} \right) \)
performs an inversion about average in each of the four subsets of
states - the four subsets are defined by the condition that the qubits
not in \( S \) stay fixed (in the above figure, the qubits not in \( S \) are qubits
1 & 2), e.g. in the first subset, qubits 1 & 2 are both 0.

5 Partial Inversion About Average

Assume there to be \( n \) qubits, then as described in the previous section, \( (-W I W) \)
does an inversion about average transformation on the entire set of \( N = 2^n \)
states. Consider a set that contains \( m \) of the \( n \) qubits, denote this set by
\( S \). Define the Walsh-Hadamard transformation on \( S \) as the operation
\[ H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \]
applied to each qubit in the set \( S \) and denote this by \( W^{(S)} \).
Similarly define the operation \( I^{(S)} \) as the selective inversion of the state in
which each qubit in \( S \) is 0.

Consider the following transformation \( - \left( W^{(S)} I^{(S)} W^{(S)} \right) \). Its effect is to
partition the states into subsets such that in each subset the qubits that are not
in \( S \) stay fixed. This transformation leaves the total probability in each subset
the same - within each subset, an inversion about average transformation takes
place. In the above figure the set \( S \) contains qubits 3 & 4. It partitions the
state into 4 subsets in which the qubits not in the set are fixed, e.g. in the first
subset, qubits 1 & 2 are both 0. The transformation \( - \left( W^{(S)} I^{(S)} W^{(S)} \right) \), does
an inversion about average separately in each of the four subsets.

6 Improved Quantum Search Algorithm

As discussed above, the quantum search algorithm increases the amplitude in
the \( t \) state through successive repetitions of selective inversion and inversion
about average. The inversion about average operation increases the amplitude
in the $t$ state by an amount equal to the average amplitude over all states. The inversion about average requires three transformations: $W$, $I_t$ & $W$ each of which requires $\log_2 N$ qubit operations. In the following, we show how to carry out the inversion about average transformations over a smaller subset of states thus requiring fewer than $\log_2 N$ qubit operations.

### 6.1 Basic $U$ operation

As mentioned earlier in section 3, the amplitude amplification principle requires a basic transformation $U$ that produces a certain transition amplitude, $U_{ts}$ from $s$ to $t$. This can then be iterated as in section 3, to amplify the amplitude in $t$.

Divide the $\log_2 N$ qubits used to represent the $N$ items into sets of $\alpha \log_2 (\log_2 N)$ qubits ($\alpha > 1$). Since there are $\log_2 N$ qubits, there will be $\eta \equiv \frac{\log_2 N}{\alpha \log_2 (\log_2 N)}$ sets. Define the Walsh-Hadamard transformation on the $i^{th}$ set as the operation

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix},$$

applied to each qubit in the set and denote this by $W^{(i)}$.

Similarly define the operation $I^{(i)}_0$ as the selective inversion of the state in which each qubit in the $i^{th}$ set is 0.

Next consider the following transformation:

$$U = \left(-W^{(\eta)} I^{(\eta)}_0 W^{(\eta)}\right) I_t \ldots \left(-W^{(i)} I^{(i)}_0 W^{(i)}\right) I_t \ldots \left(-W^{(1)} I^{(1)}_0 W^{(1)}\right) I_t \ W$$

*Figure 2 - (see attached file) - The inversion about average transformation in the standard quantum search algorithm is replaced by two such operations - one that acts on the horizontal sets & the other on the vertical sets.*

When applied to the $|\overline{\eta}\rangle$ state, it has the following effect:

1. The first application of $W$ produces a superposition with equal amplitudes in all states.
   After this, each application of $\left(-W^{(i)} I^{(i)}_0 W^{(i)}\right) I_t$ does the following.
2. $I_t$ inverts the amplitude in the target state.
3. $\left(-W^{(i)} I^{(i)}_0 W^{(i)}\right)$ does a partial *inversion about average* in each subset of states defined by the condition that the state of all qubits not in the $i^{th}$ set stays constant (as shown in figure 1).
Next consider the effect of steps 2 & 3 on the subset of states that contains $t$. Let the amplitude of the $t$ state be $\frac{a}{\sqrt{N}}$. After step 2, the amplitude of $t$ becomes $-\frac{a}{\sqrt{N}}$. After step 2, the amplitude of each of the other states in the subset containing $t$ is the same as after step 1, i.e. $\frac{1}{\sqrt{N}}$. This is because the first $(i-1)$ inversion about average transformations act on subsets of states in which the value of the $i^{th}$ qubit is constant. Hence they produce no change in the amplitude of any state in which the value of the $i^{th}$ qubit is different from the value of the $i^{th}$ qubit in the $t$ state.

The number of states in each subset is $2^{\alpha \log_2(\log_2 N)}$ which is $(\log_2 N)^\alpha$. Therefore the average amplitude in the $i^{th}$ subset of states containing $t$ is $\frac{1}{\sqrt{N}} - \frac{a+1}{(\log_2 N)^\alpha \sqrt{N}}$. Step 3 (the partial inversion about average), increases the amplitude in $t$ to $\frac{1}{\sqrt{N}} + 2 \left( \frac{1}{\sqrt{N}} - \frac{a+1}{(\log_2 N)^\alpha \sqrt{N}} \right)$. Assuming $a < \log_2 N$, the increase in amplitude of $t$ due to 2 & 3 is at least $2 \left( \frac{1}{\sqrt{N}} - \frac{1}{(\log_2 N)^\alpha \sqrt{N}} \right)$. Therefore in the $\eta$ repetitions of 2 & 3, the amplitude of $t$ increases by at least $2\eta \left( \frac{1}{\sqrt{N}} - \frac{1}{(\log_2 N)^\alpha \sqrt{N}} \right)$.

The operation $U$ described by 1, 2 & 3 above, forms the building block for the amplitude amplification algorithm described in the following section.

### 6.2 Amplitude Amplification

As described in the analysis above, the composite operation $U$ when applied to $|0\rangle$ produces an amplitude of at least $\frac{1}{\sqrt{N}} \left( 2\eta \left( 1 - \frac{1}{(\log_2 N)^\alpha - 1} \right) + 1 \right)$ in $t$. Therefore by the amplitude amplification principle, $\frac{\pi \sqrt{N}}{4 \eta \left( 1 - \frac{1}{(\log_2 N)^\alpha - 1} \right) + 1}$ repetitions of the $I_s U^\dagger I_t U$ operation sequence followed by a single application of $U$, will concentrate the amplitude in the $t$ state.

Note that $U^\dagger$ consists of the same operations as $U$ but in the opposite order:

$$U^\dagger \equiv W I_t \left( -W^{(1)} I_{\eta}^{(1)} W^{(1)} \right) \ldots I_t \left( -W^{(i)} I_{\eta}^{(i)} W^{(i)} \right) \ldots I_t \left( -W^{(\eta)} I_{\eta}^{(\eta)} W^{(\eta)} \right)$$

### 6.3 Analysis

Each application of $U$ requires $\eta$ queries. Therefore in each application of $I_s U^\dagger I_t U$ there are $(2\eta + 1)$ queries. Neglecting the single application of $U$ at
the end, it follows that the total number of queries is:

\[(2\eta + 1) \times \frac{\pi \sqrt{N}}{4} \frac{1}{2\eta \left(1 - \frac{1}{(\log_2 N)^{\alpha - 1}}\right) + 1}.
\]

This is less than \(\frac{\pi \sqrt{N}}{4} \frac{1}{(1 - (\log_2 N)^{\alpha - 1})}\).

The total number of applications of \(U\) in the algorithm is \(2 \times \frac{\pi \sqrt{N}}{4} \frac{1}{2\eta \left(1 - \frac{1}{(\log_2 N)^{\alpha - 1}}\right) + 1}\) (as before, neglecting the single application of \(U\) at the end). The number of additional (non-query) qubit operations required in each application of \(U\) is \(\log_2 N + 3 \times \eta \times \alpha \log_2 (\log_2 N)\) which is equal to \(4 \log_2 N\). The total number of additional (non-query) qubit operations due to the \(U \& U^\dagger\) hence becomes \(\frac{2\pi \sqrt{N} \log_2 N}{2\eta \left(1 - (\log_2 N)^{\alpha - 1}\right) + 1}\). In addition there are \(\frac{\pi \sqrt{N}}{4} \frac{1}{2\eta \left(1 - (\log_2 N)^{\alpha - 1}\right) + 1}\) \(I_s\) operations, each of which requires \(\log_2 N\) operations. Therefore the total number of additional (non-query) qubit operations required is \(\frac{2\pi \sqrt{N} \log_2 N}{2\eta \left(1 - (\log_2 N)^{\alpha - 1}\right) + 1} \times \frac{9}{4}\). This is less than \(\frac{9}{8} \pi \alpha \sqrt{N} \log_2 (\log_2 N)\) provided \(\alpha \geq 2\).

7 Comparison

The quantum search algorithm needs \(\frac{\pi \sqrt{N}}{4}\) queries and \(\frac{3\pi \sqrt{N} \log_2 N}{4}\) additional (non-query) qubit operations.

The algorithm of the previous section needs fewer than \(\frac{\pi \sqrt{N}}{4} \frac{1}{\left(1 - (\log_2 N)^{\alpha - 1}\right)}\) queries and less than \(\frac{9}{8} \pi \alpha \sqrt{N} \log_2 (\log_2 N)\) additional (non-query) qubit operations (provided \(\alpha \geq 2\), note that the ratio of the additional (non-query) qubit operations required by the two algorithms is \(\frac{3}{2\eta}\).

7.1 Smallest increase in the number of queries

In case \((\alpha - 1) = \frac{\log_2 N}{2 \log_2 (\log_2 N)}\), then the number of queries required by the improved algorithm is less than \(\frac{\pi \sqrt{N}}{4} \frac{1}{\left(1 - \frac{1}{\log_2 N}\right)}\), i.e. the increase in the number of queries as compared to that required by the standard quantum search algorithm seems to be less than one. However this is only suggestive since several other effects become significant when \(\alpha\) becomes this large (and therefore \(\eta\), the number of sets of qubits, which was \(\frac{\log_2 N}{\alpha \log_2 (\log_2 N)}\), becomes small). In fact the smallest value for this is 2. We analyze this case separately below.

This is perhaps the simplest example of the partial inversion about average. The qubits are partitioned into two sets with \(\frac{1}{2} \log N\) qubits in each set. Then the basic \(U\) operation is the following:
7.2 Minimizing the total number of operations

\[ U \equiv \left(-W^{(2)} I_0 W^{(2)}\right) I_t \left(-W^{(1)} I_0^{(2)} W^{(1)}\right) I_t W \]

A simple analysis shows that the amplitude in the \( t \) state after applying \( U \) to the 0 state (which is \( U_{ts} \)) becomes \( \frac{5}{\sqrt{N}} - \frac{12}{N^2} + O\left(\frac{1}{N^4}\right) \). An amplitude amplification as described previously in this paper will now amplify this amplitude.

To compare this to the standard quantum search algorithm, observe that the standard quantum search algorithm is obtained by taking \( U \) to be as follows:

\[ U \equiv (-W I_0 W) I_t (-W I_0 W) I_t W \]

This produces a \( U_{ts} \) of \( \frac{5}{\sqrt{N}} + O\left(\frac{1}{N^4}\right) \). Since the number of queries is known to be proportional to \( U_{ts} \), the number of additional queries required by the new algorithm is obtained by scaling the queries required by the standard quantum search. This gives the number of additional queries as approximately: \[ \frac{\pi \sqrt{N}}{4} \times \frac{12}{5\sqrt{N}} \simeq 2 \]. Note that such a small increase in the number of queries is not likely to be significant since it would typically take the quantum search algorithm \( \frac{\pi \sqrt{N}}{4} + O(1) \) queries to go from an approximate to the exact solution.

The number of additional (non-query) qubit operations required can be compared to the standard quantum search by comparing the two \( U \) operations. Assuming each \( W \) and \( I_0 \) need twice the number of operations as compared to \( W^{(1)}, W^{(2)}, I_0^{(1)}, I_0^{(2)} \), it follows that the new algorithm will need only \( \frac{5}{9} \) as many operations as compared to standard quantum searching.

### 7.2 Minimizing the total number of operations

If we permit a very slight increase in the number of queries, the number of additional unitary operations and hence the total number of operations can be significantly reduced.

Assume that each query requires \( K \log_2 N \) qubit operations, where \( K \) is order 1. This is plausible since the query is a function of \( \log_2 N \) qubits and so would need \( O(\log_2 N) \) steps to evaluate. The total number of qubit operations is hence approximately:

\[
K \log_2 N \times \frac{\pi \sqrt{N}}{4} \left(1 - \frac{1}{(\log_2 N)^{\alpha - 1}}\right) + \frac{9}{8} \pi \alpha \sqrt{N} \log_2 (\log_2 N)
\]

\[
\approx K \log_2 N \times \frac{\pi \sqrt{N}}{4} \left(1 + \frac{1}{(\log_2 N)^{\alpha - 1}}\right) + \frac{9}{8} \pi \alpha \sqrt{N} \log_2 (\log_2 N)
\]
Differentiating with respect to $\alpha$ and setting the derivative to zero gives the condition:

$$-K \log_2 N \times \frac{\pi \sqrt{N} \log_e (\log_2 N)}{4 (\log_2 N)^{\alpha-1}} + \pi \sqrt{N} \log_2 (\log_2 N) = 0$$

This gives $(\log_2 N)^{\alpha-2} = \frac{K \log_2 2}{4}$. Substituting in the expression for the total number of operations gives:

$$\frac{\pi \sqrt{N}}{4} K \log_2 N + \frac{\pi \sqrt{N}}{\log_e 2} + \frac{9}{4} \pi \sqrt{N} \log_2 (\log_2 N) + \pi \sqrt{N} \log_2 \frac{K \log_e 2}{4}$$

In comparison the standard quantum search algorithm requires $\frac{\pi \sqrt{N}}{4} K \log_2 N + \frac{3 \pi \sqrt{N} \log_2 N}{4} \text{ qubit operations}$. Therefore the number of additional two-qubit operations has been reduced by a factor of $\frac{\log_2 N}{3 \log_2 (\log_2 N)}$.

8 Further Improvements?

The goal of this paper is to make a statement that the quantum search algorithm can be further improved. It is hoped that this will lead to further research in this direction. There is scope for further improvements in the algorithm presented in this paper, though at the cost of more complicated calculations. Some of these improvements, such as modifying the $U$ operation to include multiple inversions about average in each subset, are being explored and will be presented in more detail later.

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