Minimal resources for linear optical one-way computing

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We address the question of how many maximally entangled photon pairs are needed to build up cluster states for quantum computing using the toolbox of linear optics. As the needed gates in dual-rail encoding are necessarily probabilistic with known optimal success probability, this question amounts to finding the optimal strategy for building up cluster states, from the perspective of classical control. We develop a notion of classical strategies and present rigorous statements on the ultimate maximal and minimal uses of resources of the globally optimal strategy. We find that this strategy—being also the most robust with respect to decoherence—gives rise to an advantage of already more than an order of magnitude in the number of maximally entangled pairs when building chains with an expected length of $L=40$, compared with other legitimate strategies. For two-dimensional cluster states, we present a first scheme achieving the optimal quadratic asymptotic scaling. This analysis shows that the choice of appropriate classical control leads to a significant reduction in resource consumption. © 2007 Optical Society of America

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1. INTRODUCTION

To actually experimentally realize a fully fletched universal quantum computer constitutes a tremendous challenge. Among the promising candidates for possible architectures are the ones entirely relying on optical systems. State manipulation can then be realized using sources of single photons or entangled pairs, arrays of linear optical elements, and photon detectors.[1–7] Some of the advantages of such an approach are obvious: accurate state manipulation is available using linear optical elements, and photons are comparably robust with respect to decoherence. In turn, there is a price to pay when avoiding the exploitation of any physical nonlinearities and effectively realizing them via measurements: owing to the small success probability of elementary gates,[8–11] a significant overhead in optical elements and additional photons is required to render the overall protocol near-deterministic.

Consequently, one of the primary goals of theoretical work toward the realization of a linear optical quantum computer is to find ways to reduce the necessary overhead in resources. For the seminal scheme of Ref. 1, this overhead cannot be reduced by simply building better elementary sign-shift gates.[8] Schemes based on the model of one-way computation[12,13] point toward a reduction of resource consumption by orders of magnitude,[3,4] a perspective that has attracted considerable interest in recent research.[2–4,14–19] This development reminds one of an inverse Moore's law of the known minimally required resources for linear optical computing as a function of time. The central ingredient to these realizations is cluster states[12,13] or graph states,[20–22] which can be built up from maximally entangled photon pairs (4-qubit cluster states have already been experimentally prepared[23,24]). Fusion gates of types I and II have been applied to the task of creating cluster states,[4,25,26] derived from parity-check gates[7] and partial Bell projections. However, these gates are inherently probabilistic, in that in each step the experiment can either succeed or fail with the outcome being known.

In fact, it is not difficult to show that the maximal probability of success of a quantum gate realizing a fusion of two dual-rail encoded linear cluster states is $p_s=1/2$, by relating this to the optimal success probability of a Bell measurement with linear optics.[27,28] When preparing linear cluster states from EPR (maximally entangled) pairs, the only freedom we have for improvement is to identify the optimal classical strategy for fusing cluster-state pieces. As the possible patterns of failure and success increase exponentially, an overwhelming wealth of situations can potentially occur. Deciding how to optimally react to any of these situations constitutes a hard problem indeed but may have tremendous implications on the amount of resources needed. A similar situation occurs when two-dimensional (2-D) cluster states are prepared.

In this work we will address the latter question; i.e., what is the optimal strategy to cope with the probabilistic nature of fusion gates in constructing one-dimensional (1-D) and 2-D cluster states? Although previous research has more strongly focused on saving resources by devising ingenious ways of implementing quantum gates, it is found in the present paper that choosing an optimal classical control strategy can cut the needed entanglement by further orders of magnitude. In this way, we can also bound the resources that any scheme within the above-mentioned set of rules would require.

2. CLASSICAL STRATEGIES IN ONE DIMENSION

We begin the specific investigation with the 1-D case. Linear cluster states can be pictured as chains of qubits, characterized by their length l given in the number of edges. Maximally entangled qubit pairs (EPR pairs) correspond to chains with a single edge. By a configuration we mean a set of chains of specific individual lengths. Type-I fusion[4] allows for operations involving end qubits of two pieces (lengths l_1 and l_2), resulting in success ($p_s = 1/2$) in a single piece of length $l_1 + l_2$ or in failure ($p_f = 1/2$) in two pieces of lengths $l_1 - 1$ and $l_2 - 1$. The process starts with a collection of EPR pairs and ends when only a single piece is left. A strategy decides which chains to fuse, given a configuration. It is assessed by the expected length of the final cluster. The vast majority of strategies allow for no simple description and can be specified solely by a look-up table listing all configurations with the respective proposed action. Since the number of configurations scales as $O\{N^{1/2}\exp[\pi(2N/3)^{1/2}]\}$ (this derives from the sum of all integer partitions of $k \le N$, cf. Ref. 29) as a function of the total number of edges N, a single strategy is already an extremely complex object, and any form of brute-force optimization is completely out of reach.

However, there is one simple strategy that might reasonably be conjectured to be optimal. Indeed, we face a probabilistic process, and we lose entangled resources on average. Hence, it seems advantageous to quickly build up long clusters by always fusing the largest available pieces together. This strategy we call GREED:

- GREED: Always fuse the largest available pieces. In turn, one can also be conservative and always fuse the smallest available pieces. This apparently inferior strategy, dubbed MODESTY, will not deliver long chains in early steps.
- MODESTY: Always fuse the smallest available pieces. Quite surprisingly, it will turn out that not only is MODESTY vastly more effective than GREED but even extremely close to the globally optimal strategy.

Let us further formalize these notions. A (pure) configuration consisting of n_i pieces of length l_i, $i = 1, \ldots, c$, will be denoted $C := \{l_1^{(n_1)}, \ldots, l_c^{(n_c)}\}$. The total number of edges is given by $N(C) := \Sigma_i n_i l_i$, and $C_N := \{C | N(C) \le N\}$ is the configuration space for $N \in \mathbb{N}$. A mixed configuration is a probability distribution p defined on the elements of C_N. The expected total length of a mixed configuration is

$$\langle L \rangle(p) := \sum_C p(C) N(C).$$

Strategies act naturally as stochastic matrices[30] on mixed configurations by acting on every pure configuration in its support independently. Repeated application of a strategy will eventually lead to a probability distribution p_{final} over configurations $\{l^{(1)}\}$ with only a single chain each. The quantity $\tilde{Q}(C) := \langle L \rangle (p_{\text{final}})$ is the expected yield of C with respect to the given strategy. Of central importance is the quality

$$Q(C) := \sup \tilde{Q}(C),$$

the best possible expected length that can be achieved starting from C by means of any strategy. We abbreviate $Q(\{1^{(N)}\})$ by $Q(N)$. Note that the quantum nature of the cluster states does not enter the consideration. Q displays a smooth behavior when regarded as a function on either only even or only odd values of N. The respective graphs appear to be slightly displaced with respect to each other. For simplicity, we generally restrict our attention to even values.

Observation 1 (lower bound for globally optimal strategy). Starting with N EPR pairs and using type-I fusion gates, the globally optimal strategy yields a cluster state of expected length

$$Q(N) \ge \tilde{Q}(N_0) + \alpha(N - N_0)$$

for all $N > N_0$. The constants are $N_0 = 92$, $\tilde{Q}(N_0) = 16.1061$, $\alpha = 0.153336$ (known as rational numbers[31]).

For $N \le 2N_0$, a desktop computer can symbolically compute the performance of MODESTY $\tilde{Q}(N) \le Q(N)$. One finds that the above relation is valid in this case. For $N > 2N_0$ input pairs we adopt the following strategy. First, the input is divided into k blocks of length n_i, where $N_0 \le n_i \le 2N_0$ and MODESTY is used to convert any such block into a single chain; second, the resulting chains are fused together.

If C is a configuration consisting of only two chains of length $l_1 \ge l_2$, one easily finds that

$$Q(C) = l_1 + l_2 - 2\sum_{i=0}^{l_2} 2^{-i} \ge l_1 + l_2 - 2.$$

More generally, it can be shown[28] that $Q(N) \ge \Sigma_i Q(n_i) - 2(k-1)$. Now set $\alpha := [\tilde{Q}(N_0) - 2]/N_0$. From the computed data we know that $(\tilde{Q}(n_j) - 2)/n_i \ge \alpha$ for all i. Imposing without loss of generality $n_1 = N_0$, we see that

$$\begin{aligned} Q(N) &\ge \tilde{Q}(N_0) + \sum_{i=2}^{k} n_i \frac{\tilde{Q}(n_i) - 2}{n_i} \\ &\ge \tilde{Q}(N_0) + \alpha \sum_{i=2}^{k} n_i = \tilde{Q}(N_0) + \alpha(N - N_0). \end{aligned}$$

Observation 2 (upper bound to globally optimal strategy). The quality is bounded from above by $Q(N) \le N/5 + 2$.

Although the performance of any strategy delivers a lower bound for the optimal one, giving an upper bound is considerably harder. The following paragraphs show key ideas of a rigorous proof (details can be found in Ref. 28). We proceed in three steps. Every attempted fusion fails with probability of one half and destroys two edges in the case of failure. One is thus led to assume that the expected number of lost edges equals the expected number of fusion attempts $T(C)$ a strategy undertakes acting on some configuration C. However, care must be taken, as there are two kinds of average involved: on the one hand the "global" average of the amount of edges lost in the entire process; on the other hand the "local" average of the amount of edges expected to be lost in the next step. In Ref. 28 we consider the problem carefully and find that the intuitive reasoning can be rigorously justified. Because the average final length $Q(C)$ is nothing other than the initial number of edges $N(C)$ minus the expected number of losses, we have $Q(C)=N(C)-T(C)$. Hence any lower bound on T will supply an upper bound for $Q(N)$.

Second, we pass to a greatly simplified model—dubbed the razor model—from which we can extract bounds for T. This is done by introducing a quite radical new rule: after every step all chains will be cut to a maximum length of 2. It turns out that there exists a strategy in the razor model that terminates using fewer fusion attempts on average T_R than the optimal strategy for the full model. Intuitively, this is the case as the cutting operation increases the probability for chains to be completely destroyed owing to failed fusions. However, making this argument precise is greatly impeded by the fact that one needs to compare strategies that are defined on different models. Indeed, given the optimal strategy of the full setup, there is no direct way of turning it into a strategy for the razor model. We solve the problem as follows. Let C be a configuration and C' be the result of removing a single edge from one chain in C. In Ref. 28 we derive the estimate $Q(C)\geq Q(C')\geq Q(C)-1$. Combining the findings of the last paragraph with $N(C')=N(C)-1$, we arrive at

$$Q(C')\geq Q(C)-1 \Leftrightarrow N(C)-1-T(C')\geq N(C)-T(C)-1$$

and hence $T(C')\leq T(C)$. Thus removing a single edge from a chain decreases the expected number of fusion attempts performed by the optimal strategy. As the passage to the razor model can be perceived as a repeated removal of single edges, we can use these observations to prove $T\geq T_R$.

In a last step we further simplify the problem in order to obtain a lower bound for T_R. A configuration C of the razor model is specified by two natural numbers (l_1,l_2) giving the number of chains of lengths 1 and 2, respectively. In each step a strategy has three options: try to fuse (a) two short chains, (b) two long ones, or (c) a long chain and a short chain. Consider the choice (a). In the case of failure the chains are destroyed, and so $C\mapsto C+a_F$ where $a_F:=(-2,0)$. An analogous relation holds for successful fusions where $a_S:=(-2,1)$, and similar rules can be formulated for options (b) and (c). We are thus naturally led to interpret the problem as a random walk on a 2-D lattice. As initially there are N single-edge chains in the configuration, the walk starts at $(N,0)$. It will end when there is no more than one chain left, so at positions (1,0), (0,1), (0,0). So how many steps does a probabilistic process require—on average—to cover that distance? If a strategy decides at some point in the walk to choose action (a), then on average the configuration will move by $\bar{a}:=(a_S+a_F)/2=(-2,1/2)$ on the lattice. Denote by $\langle a\rangle$ the expected number of times a given strategy opts for action (a) when acting no $(N,0)$. Define $\bar{b}$,$\langle b\rangle$, $\bar{c}$, $\langle c\rangle$ similarly. From the discussion it is intuitive (and can be made precise[28]) that any strategy fulfills

$$\langle a\rangle\bar{a}+\langle b\rangle\bar{b}+\langle c\rangle\bar{c}\leq(-N+1,1).$$

As the expected number of fusion attempts T_R equals $\langle a\rangle+\langle b\rangle+\langle c\rangle$, one can obtain a lower bound by solving the linear program: minimize T_R subject to the constraints given above. By passing to the dual problem,[32] one can find an analytic solution that gives rise to the estimate stated in Observation 2.

Observation 3 (symbolic calculation of optimal length). The globally optimal strategy can be computed with an effort of $O[|C_N|(\log|C_N|)^5]$.

We have implemented a backtracking algorithm that in effect recursively computes the quality of all configurations up to some arbitrary total length. The results are stored in a look-up table, which causes memory consumption—rather than time—to limit the practical applicability of the program. This explains the dominating factor $|C_N|$ in the estimate of the computational effort: every configuration has to be examined at least once. A closer analysis[28] reveals the poly-log correction. Note that, even though the effort scales exponentially in N, the algorithm is vastly more efficient than a naïve approach, which would enumerate all strategies to select the optimal one by directly comparing their performances.

The algorithm has been implemented using the computer algebra system MATHEMATICA and employed to derive in closed form an optimal strategy for all configurations in C_{46}.[31] A desktop computer is capable of performing the derivation in a few hours. Starting with $\{l^{(N)}\}$, MODESTY turns out to be the optimal strategy for all $N\leq 10$. For configurations containing more edges, slight deviations from MODESTY can be advantageous. However, the difference relative to $Q(N)$ is smaller than 1.1×10^{-3} for $N\leq 46$.

Observation 4 (asymptotic performance of GREED). Starting with N EPR pairs and fusing them with type-1 fusion under GREED result in an expected length of

$$\tilde{Q}(N)=(2N/\pi)^{1/2}+O(1).$$

It is interesting to see how MODESTY compares with the asymptotic performance of the equally reasonable strategy GREED. Starting from $\{1^{(N)}\}$, only pieces of length 1 and one single piece of length $l>1$ may occur during the fusion process. Hence, the support of the probability distribution is $\{C=\{l^{(1)},1^{(m)}\}:m=0,1,\ldots;l=2,3,\ldots;l+m\leq N\}\cup\{l^{(m)}:m\leq N\}$. The implementation of GREED gives rise to a Markov chain on this set with a reflecting boundary.[30] From this, one may determine the asymptotic behavior of the expected length by using a Gaussian approximation. This means the linear chain grows as a square root in the number of available pairs N rather than linearly.

Observation 5 (comparison of GREED and the optimal strategy). For realizing an expected length of 40 in a linear cluster state, the resources N required by GREED and the optimal strategy already differ by more than an order of magnitude.

Results for the expected length using symbolic algebraic calculations are shown in Fig. 1, for the strategies MODESTY; for the globally optimal strategy, GREED; and the lower bound of Observation 1, almost identical with

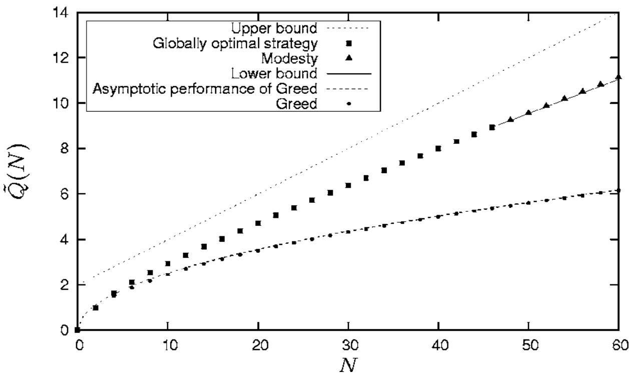

Fig. 1. Expected lengths for the globally optimal strategy, for MODESTY (in this plot indistinguishable from the globally optimal strategy), for a lower bound (with $N_0=46$), for GREED, for its asymptotic performance, and for the upper bound, as functions of even N.

the curve of MODESTY. The difference between the performance of MODESTY and GREED is enormous: hence, it does matter indeed, concerning resource consumption, what classical strategy one adopts. When one prepares the appropriate graph state for a single, unconnected Controlled NOT (CNOT) gate[12,13,20–22] with $P_s=0.99$, linear clusters of lengths (15, 12, 15) are required. The difference in the number of EPR pairs used between GREED and the optimal strategy (resulting in these lengths on average) is almost a factor of 4. In a full scheme, the overhead for a reliable connection would additionally have to be included.

Recall that the expected length equals the total number of edges in the original configuration minus the expected number of losses. The latter number, in turn, is proportional to the number of fusion attempts on average. Therefore, the optimum strategy is also the one employing the smallest number of fusion steps and is hence also the most robust with respect to decoherence processes associated with operation of these gates. Note that the presented analysis, needless to say, can also be applied to other physical architectures in which one has to cope with a probabilistic character of fusion gates, such as in matter qubits coupled via optical systems.[33,34]

3. SCALING IN TWO DIMENSIONS

Observation 6 (optimal scaling for 2-D cluster states). An $n\times n$ cluster state can be prepared using $O(n^2)$ EPR pairs—employing x measurements and type-II fusion—such that the overall success probability satisfies

$$\lim_{n\to\infty} P_s(n) \to 1.$$

We now turn to 2D structures, to be built by weaving cluster chains. Using the type-II fusion gate[4] in succession to an x measurement (consuming two edges) delivers on success ($p_s=1/2$) a vertex incorporating both linear clusters, hence an elementary 2-D structure. In the case of failure (losing two edges without splitting the original chains), the scheme described in Ref. 4 can be used for subsequent attempts, consuming $3+2f$ edges, with f being the number of failures. With these tools, we can again consider classical strategies as in the 1-D case, rather than exploit local unitaries' graph isomorphisms (e.g., Ref. 18). Obviously, no such scheme can result in more economical asymptotics than $O(n^2)$ in the use of entangled resources. In any preparation scheme, however, overhead has to be taken into account to ensure a near-deterministic outcome, as a single failure may endanger the already generated 2-D cluster.

Finding the overall success probability $P_s(n)$ in a closed form is impeded by the fact that failures on earlier vertices influence the number of resources left and therefore the number of possible failures on later vertices. We are able to decouple these problems by considering a weaving pattern as depicted in Fig. 2. Let us denote with m the overhead in each of the horizontal linear cluster states of length $l=n+m$ and take a single linear cluster state of length $L=n(l+1)$. We will show that a choice of $n\mapsto an=m$ for $a>2$ will be an appropriate choice for the scaling of the overhead.

To start with the more formal part, on the basis of the above prescription, we can write the probability $P_s(n)$ of succeeding to prepare an $n\times n$ cluster state as $P_s(n)=\pi_s(n)^n$. Here,

$$\pi_s(n) = \frac{1}{2^{an}}\sum_{k=n}^{an}\binom{an}{k} = 1 - F(n-1,an,1/2)$$

is the success probability of fusing a single chain of length $m=an$ into the cluster, with F denoting the standard cumulative distribution function of the binomial distribution. Since $2n-2\leq an$ for all n, we can hence bound $\pi_s(n)$ from below by means of Hoeffding's inequality.[35] This gives rise to the lower bound

$$\pi_s(n) \geq 1 - \exp[-2(an/2-n+1)^2/(an)].$$

As $a>2$, one can show that $\liminf_{n\mapsto\infty}\pi_s(n)^n\geq 1$, and hence

$$\lim_{n\to\infty} P_s(n) = \lim_{n\to\infty} \pi_s(n)^n = 1,$$

which is the argument to be shown. It is remarkable that, for $2>a>1$, then $\lim_{n\to\infty}P_s(n)=0$, and the preparation will fail, asymptotically even with certainty. This argument proves that a 2-D cluster state can indeed be prepared using $O(n^2)$ EPR pairs, making use of probabilistic quantum gates. This may be considered good news, as it proves that the natural scaling in the resources can be met with negligible error.

4. SUMMARY AND OUTLOOK

In this work, we have addressed the question of how to build optical linear and 2-D cluster states from the perspective of classical strategies. We have introduced tools

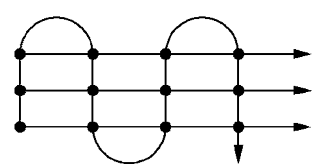

Fig. 2. Possible pattern of how to arrange $n+1$ linear clusters (threads) to weave a carpet of width n. Fusion operations have to be applied at the solid circles along the long linear cluster state. Arrows mark free ends.

to assess the performance of several protocols, including the globally optimal strategy. Further, we have shown that 2-D cluster states can be generated with resource requirements of $O(n^2)$, which is the most economical scaling. It has hence turned out that the mere classical control indeed does matter and that differences in resource requirements of orders of magnitude can be expected, depending on the chosen strategy. The presented techniques may, after all, be expected to provide powerful tools to assess and develop techniques for building redundancy encoding resource states[25,26] or to prepare states rendering linear optical schemes fault tolerant.[36–38]

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