Lists Revisited: Cache Conscious STL Lists

Leonor Frias*, Jordi Petit**, and Salvador Roura***

Departament de Llenguatges i Sistemes Informàtics
Universitat Politècnica de Catalunya
Campus Nord, edifici Omega
08034 Barcelona (Spain).
{lfrias,jpetit,roura}@lsi.upc.edu

Abstract. We present three cache conscious implementations of STL standard compliant lists. Up to now, one could either find simple double linked list implementations that easily cope with standard strict requirements, or theoretical approaches that do not take into account any of these requirements in their design. In contrast, we have merged both approaches, paying special attention to iterators constraints. In this paper, we show the competitiveness of our implementations with an extensive experimental analysis. This shows, for instance, 5-10 times faster traversals and 3-5 times faster internal sort.

1 Introduction

The Standard Template Library (STL) is the algorithmic core of the C++ standard library. The STL is made up of containers, iterators and algorithms. Containers consist on basic data structures such as lists, vectors, maps or sets. Iterators are a kind of high-level pointers used to access and traverse the elements in a container. Algorithms are basic operations such as sort, reverse or find. The C++ standard library [1] specifies the functionality of these objects and algorithms, and also their temporal and spatial efficiency, using asymptotical notation.

From a theoretical point of view, the knowledge required to implement the STL is well laid down on basic textbooks on algorithms and data structures (e.g. [2]). In fact, the design of current widely used STL implementations (including SGI, GCC, VC++, ...) is based on these.

Nevertheless, the performance of some data structures can be improved taking advantage of the underlying memory hierarchy of modern computers. Not in vain, in the last years the algorithmic community has realized that the old unitary cost memory model is turning more inaccurate with the changes in computer architecture. This has raised an interest on cache conscious algorithms

* This author has been supported by grant number 2005FI 00856 of the *Agència de Gestió d'Ajuts Universitaris i de Recerca* with funds of the European Social Fund and ALINEX project under grant TIN2005-05446.

** This author has been supported by GRAMARS project under grant TIN2004-07925-C03-01 and ALINEX project under grant TIN2005-05446.

*** This author has been supported by AEDRI-II project under grant MCYT TIC2002-00190 and ALINEX project under grant TIN2005-05446.

and data structures that take into account the existence of a memory hierarchy, mainly studied under the so-called cache aware (see e.g. [3,4]) and cache oblivious models (see e.g. [5,6]).

However, if these data structures are to be part of a standard software library, they must conform to its requirements. As far as we know, no piece of work has taken this into account. Our aim in this paper is to propose standard compliant alternatives that perform better than traditional implementations in most common settings. Specifically, we have analyzed one of the most simple but essential objects in the STL: lists. We have implemented and experimentally evaluated three different variants of cache conscious lists supporting fully standard iterator functionality. The diverse set of experiments shows that great speedups can be obtained compared to traditional double linked lists found for instance in the GCC STL implementation and in the LEDA library [7].

The remainder of the paper is organized as follows: In Sect. 2, we describe STL lists and the cache behavior of a traditional double linked implementation. The observations drawn there motivate the design of cache conscious STL lists that we present in Sect. 3. Our implementations are presented and experimentally analyzed in Sect. 4. Conclusions are given in Sect. 5.

2 Motivation for cache conscious STL lists

A list in the STL library is a generic sequential container that supports forward and backward traversal using iterators, as well as single insertion and deletion at any iterator position in $O(1)$ time. Additionally, it offers internal sorting, several splice operations, and others (see further documentation in [8]). Finally, it must also be able to deal with an arbitrary number of iterators on it and ensure that operations cannot invalidate them. That is, iterators must point to the same element after any operation has been applied (except if the element is deleted).

In order to fulfill all these requirements, a classical double linked list together with pointers for iterators suffices. Indeed, this is what all known STL implementations do.

The key property of any pointer-based data structure as this is that even though the physical position of each element is permanent, its logical position can be changed just modifying the pointers in the data structure. Consequently, iterators are not affected by these movements.

Further, pointer-based data structures use memory allocators to get and free nodes. These allocators typically answer consecutive memory requests with consecutive addresses of memory (whenever possible). In the list case, if we add elements at one end (and no other allocations are performed at the same time), there is a good chance that logically consecutive elements are also physically consecutive, which leads to a good cache performance. However, if elements are inserted at random points or if the list is shuffled, logically consecutive elements will be rarely at physically nearby locations. Therefore, a traversal may incur in a cache miss per access, thus increasing dramatically the execution time.

In order to give evidence of the above statement, we have performed the following experiment with the GCC list implementation: Given an empty list,

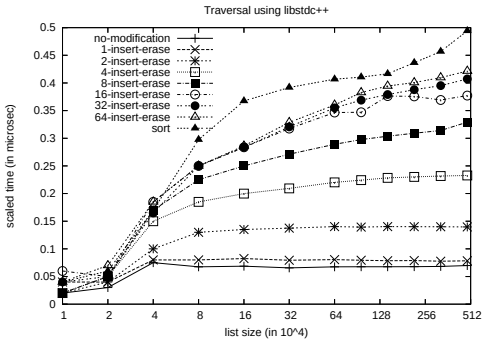


Fig. 1. Time measurements for list traversal before modifying it and after being modified in several ways. The vertical axis is scaled to the list size (that is, time has been divided by the list size before being plotted).

n random integers are pushed back one by one. Then, we measure the time to fully traverse it. Afterwards, we modify the list, and again we measure the time to fully traverse it. The modification consists either on sorting (thus randomly shuffling the links between nodes), or on k iterations of the so-called *k-insertion-erase* test. In the i-th iteration of this test ($1 \leq i \leq k$): first, the list is traversed and an element is inserted at each position with probability $1/(3+i)$, then the list is traversed again and each element is erased with probability $1/(4+i)$. Traversal times before modifying the list and after each kind of modification are shown in Fig. 2. Except for very small lists, it can be seen that the traversal of the shuffled list is about ten times slower than the traversal of the original list; and the only difference can be in the memory layout (and so, in the number of cache misses). Besides, note that four iterations of the insertion-erase test are enough to register half the worst case time.

Taking into account that lists are used when elements are often reorganized (e.g. sorted) or inserted and deleted at arbitrary positions (if we only wished to perform insertions at the ends, we would better have used a vector, stack, queue or dequeue rather than a list), it is worth to try to improve the performance of lists using a cache conscious approach.

3 Design of cache conscious STL lists

In this section we first consider previous work on cache conscious lists. Then, we present the main issues on combining them with STL list requirements. Finally, we present our proposed solutions.

3.1 Previous work

Cache conscious lists have already been analyzed before; see a good summary in [5]. The operations taken into account are traversal (as a whole), insertion and deletion and their cost measured as the number of memory transfers.

Let be n the list size and B be the cache line size. The *cache aware* solution consists on a partition of $\Theta(n/B)$ pieces, each between $B/2$ an B consecutive elements, achieving $O(n/B)$ amortized traversal cost and constant update cost. The *cache oblivious* solutions are based on the packed memory structure [9], basically an array of $\Theta(n)$ size with uniformly distributed gaps. To guarantee

this uniformity updates require $O((\log^2 n)/B)$, which can be slightly lowered by partitioning the array in smaller arrays. Finally, *self-organizing structures* [9] achieve the same bounds as the cache aware but amortized. There, updates breaking the uniformity are allowed until the list is reorganized when traversed.

Therefore, theory shows that cache conscious lists fasten scan based operations and hopefully, do not rise significantly update costs compared to traditional double linked lists. However, none of the previous designs take into account common requirements of software libraries. In particular, combining iterator requirements and cache consciousness rule out some of the more attractive choices.

3.2 Preliminaries

Before proceeding to the actual design, the main problems to be addressed must be identified. In our case, these concern to iterators. Secondly, it may be useful to determine common scenarios in which lists appear to guide the design.

Iterators concerns. In cache conscious structures, the physical and logical locations of an element are heavily related. In the case of STL list, this makes difficult to implement iterators trivially with pointers while enforces being able to reach iterators to keep them coherent whenever a modification in the list occurs.

The main issue is that an unbounded number of iterators can point to the same element. Therefore, $\Theta(1)$ modifying operations can be guaranteed only if the number of iterators is arbitrarily restricted, or if iterators pointing to the same element share some data that is updated when a modification occurs.

Hypotheses on common list usages. From our experience as STL programmers, it can be stated that a lot of common list usages are in keeping with the following:

- A particular list instance has typically only a few iterators on it.
- Given that lists are based on sequential access, many traversals are expected.
- The list is often modified and at any position: insertions, deletions, splices.
- The stored elements are not very big (e.g. integers, doubles, ...).

Note that the last hypothesis, which also appears implicitly or explicitly in general cache conscious data structures literature, can be checked in compile time. In case it did not hold, a traditional implementation could be used instead and this can be neatly achieved with template specialization.

3.3 Our design

Our design combines cache efficient data access with full iterator functionality and (constant) worst case costs compliant with the Standard. Besides, our approach is specially convenient when the hypotheses on common list usages hold.

The data structure core is inspired by the cache aware solution previously mentioned (note that self-organizing strategies are not convenient here because STL lists are not traversed as a whole but step by step via iterators). Specifically, it is a double linked list of *buckets*. A bucket contains a small array of *bucket capacity* elements, pointers to the next and previous buckets, and extra fields to manage the data in the array. This data structure ensures locality inside the bucket, but logically consecutive buckets are let to be physically far.

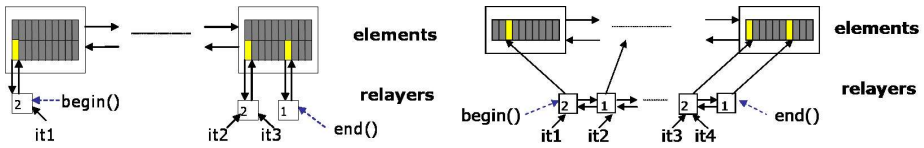
Finally, it must be decided a) how to arrange the elements inside a bucket, b) how to reorganize the buckets when inserting or deleting elements, and c) how to manage iterators. Besides, the appropriate bucket capacity must be fixed (this has been studied experimentally, see end of Sect. 4.1).

a) *Arrangement of elements.* We devise three possible ways to arrange the elements inside a bucket:
   - *Contiguous*: The elements are stored contiguously from left to right and so, insertions and deletions must shift all the elements on its left or right.
   - *With gaps*: Elements are still stored from left to right but gaps between elements are allowed. In this way, we expect to reduce the average number of shifts. However, an extra field per element is needed to distinguish real elements from gaps. Additionally, more computation may be needed.
   - *Linked*: The order of the elements inside the bucket is set by internal links instead of the implicit left to right order. This requires extra space for the links, but avoids shifts inside the bucket. Thus, this solution is scalable for large bucket (and cache line) sizes.

b) *Reorganization of buckets.* The algorithms involved in the reorganization of buckets preserve the data structure invariant after an insertion or deletion. This includes: keeping a minimum bucket occupancy to guarantee the locality of accesses, preserving the arrangement coherency (e.g. if contiguous arrangement is used, gaps between the elements cannot be created),...
   The main issue is keeping a good balance between high occupancy, few bucket accesses per operation, and few elements movements. Besides, it should be guaranteed that no sequence of alternated insertions and deletions can toggle infinitely between creating and destroying a bucket. This is a must for performance unless we fully manage bucket allocation/deallocation.

c) *Iterator management.* Finally, it must be decided how iterators are implemented. Recall from Sect. 3.2 that this cannot be done trivially with pointers. Specifically, we have decided to identify all the iterators referred to an element with a dynamic node (relayer) that points to it. The relayer must be found in constant time and keep count of how many iterators are referring the element (so that it can be destroyed when there are none). Besides, we only need to update the relayer when the physical location of the element changes. We propose two possible solutions (see Fig. 2):
   - *Bucket of pairs*: In this solution, for each element, a pointer to its relayer is kept. This is easy to do and still uses less space than a traditional double linked list because it needs two pointers per element.
   - *2-level*: In this solution, we maintain a double linked list of active relayers. Note that $O(1)$ time access to the relayers can be guaranteed because STL lists are always accessed through iterators. This solution uses less space compared to the previous one (if there are not much iterators).

   Unfortunately, the locality of iterator accesses decreases with the number of elements with iterators because relayers addresses can be unrelated. Anyway, dealing with just a few iterators is not a big matter because in particular, there is a good chance to find them in cache memory. In any case, our two approaches conform the Standard whatever the number of iterators.



(a) Bucket of pairs (b) 2-level list

Fig. 2. Standard compliant iterators policies.

4 Performance evaluation

We developed three implementations. Two of them use contiguous bucket arrangement, one of which uses *bucket of pairs* iterator solution and another *bucket of pairs*. The last implementation uses a linked bucket arrangement and the *2-level* iterator solution. All these can be found under
http://www.lsi.upc.edu/∼lfrias/lists/lists.zip. Notice that in contrast to a flat double linked list, our operations deal with several cases and each of them with more instructions. This makes our code 3 or 4 times longer (in code lines).

In this section, we experimentally analyze the performance of our implementations and show their competitiveness in a lot of common settings.

The results are shown for a Sun workstation with Linux and an AMD Opteron CPU at 2.4 GHz, 1 GB main memory, 64 KB + 64 KB 2-associative L1 cache, 1024 KB 16-associative L2 cache and 64 bytes per cache line. The programs were compiled using the GCC 4.0.1 compiler with optimization flag `-O3`. Comparisons were made against the current STL GCC implementation and LEDA 4.0 (in the latter case the compiler was GCC 2.95 for compatibility reasons).

All the experiments were carried with lists of integers considering several list sizes that fit in main memory. Besides, all the plotted measurements are scaled to list size for a better visualization.

With regard to performance measures, we collected wall-clock times, that were repeated enough times to obtain significative averages (variance was always observed to be very low). Furthermore, to get some insight on the behavior of the cache, we used Pin [10], a tool for the dynamic instrumentation of programs. Specifically, we have used a Pin tool that simulates and gives statistics of the cache hierarchy (using typical values of the AMD Opteron).

In the following we present the most significant results. Firstly, we analyze the behavior of lists with no iterators involving basic operations and common access patterns. Then, we consider lists with iterators. Finally, we compare our implementations against LEDA, and consider other hardware environments.

4.1 Basic operations with no iterator load

Insertion at the back and at the front. Given an initially empty list, this experiment compares the time to get a list of n elements by successively applying n calls to either the `push_back` or `push_front` methods.

The results for `push_front` are shown in Fig. 3(a); a similar behavior was observed for `push_back`. In these operations, we observe that our three implementations perform significantly better than GCC. This must be due to manage memory more efficiently: firstly, the allocator is called only once for all elements in a bucket and not for every element. Secondly, our implementations ensure that buckets get full or almost full in these operations, and so, less total memory space is allocated.

Traversal. Consider the following experiment: First, build a list; then, create an iterator at its begin and advance it up to its end four times. At each step, add the current element to a counter. We measure the time taken by all traversals.

Here, the way to construct the list plays an important role. If we just build the list as in the previous experiment, the traversal times are those summarized in Fig. 3(b). These show that performance does not depend on list size and that our 2-level contiguous list implementation is specially efficient even compared to the other 2-level implementation. Our linked bucket implementation is slower than the contiguous implementation because, firstly, its buckets are bigger for the same capacity and so, there are more memory accesses (and misses). Secondly, the increment operation of the linked implementation requires more instructions.

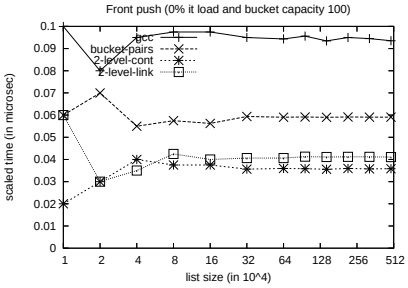
Rather, if we sort this list before doing the traversals, and then measure the time, we obtain the results shown in Fig. 3(c). Now, the difference between GCC's implementation and ours becomes very significant and increases with list size (our implementation turns to be more than 5 times faster). Notice also that there is a big slope just beginning at lists with 20000 elements.

The difference in performance is due to the different physical arrangement of elements in memory (in relation to their logical positions). To prove this claim, we repeated the same experiment using the Pin tool, counting the number of instructions and L1 and L2 cache accesses and misses. Some of these results are given in Fig. 4(a). Firstly, these show that indeed our implementations incur in less caches misses (both in L1 and L2). Secondly, the scaled ratio of L1 misses is almost constant because even small lists do not fit in L1. Besides, the big slope in time performance for the GCC implementation coincides with a sudden rise in L2 cache miss ratio, which leads to a state in which almost every access to L2 is a miss. This transition also occurs in our implementations, but much more smoothly. Nevertheless, the L2 access ratio (that is, L1 miss ratio) is much lower because logically close elements are in most cases in the same bucket and so, already in the L1 cache (because bucket capacity is not too big).

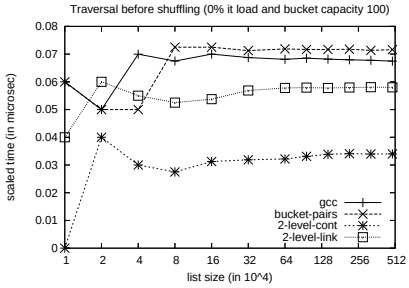
Insertion. In this experiment, we deal with insertions at arbitrary points. Firstly, a list is built (using the two abovementioned ways). Then, it is forwardly traversed four times. At each step, with probability $\frac{1}{2}$, an element is inserted before the current. We measure the time of doing the traversal plus the insertions.

Results are shown in Figs. 3(d) and 3(e), whose horizontal axis corresponds to the initial list size. Similar results were obtained with the erase operation.

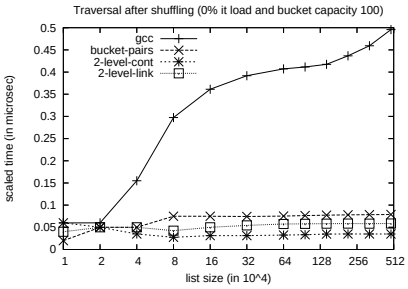
Analogously to plain traversal, performance depends on the way the list is built. However, as in this case the computation cost is greater, the differences are smoother. In fact, when the list has not been shuffled, the bucket of pairs list



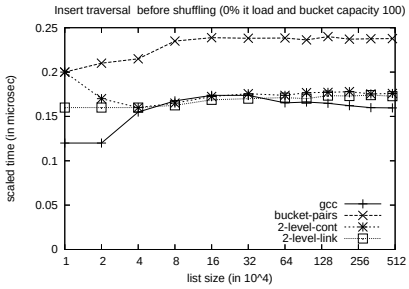
(a) `push_front`



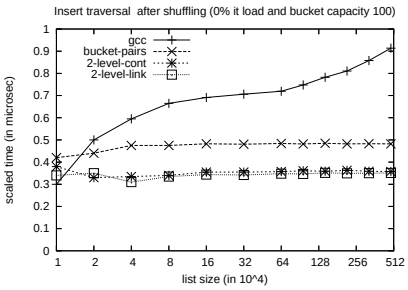
(b) Traversal before shuffling



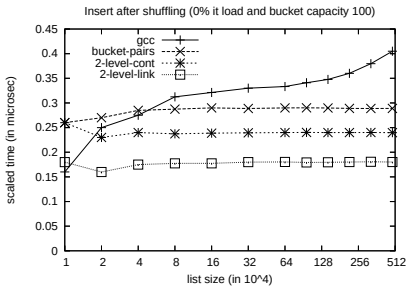
(c) Traversal after shuffling



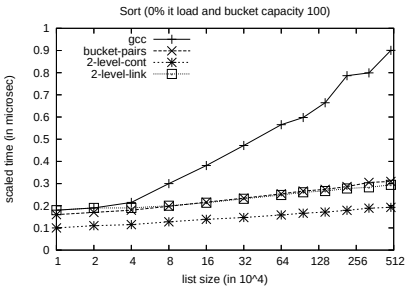
(d) Insertion before shuffling



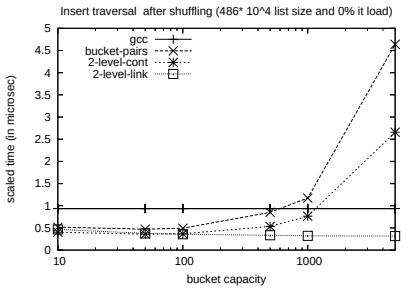
(e) Insertion after shuffling



(f) Intensive insertion

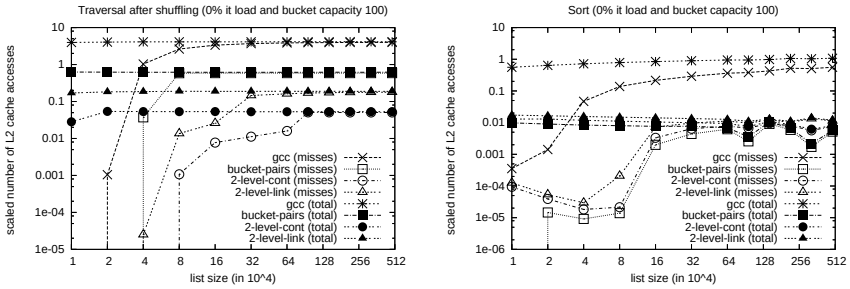


(g) Internal sort



(h) Effect of bucket capacity: Insertion after shuffling (list size 486000)

Fig. 3. Experimental results for basic operations with no iterator load.



(a) Traversal (b) Internal Sort

Fig. 4. Simulation results on the cache performance (the vertical axis is logarithmic).

performs worse than GCC's. Our two other implementations perform similarly to GCC's though. On the other hand, when the list has been shuffled, GCC's time highly increases, while ours is almost not affected.

It is interesting to observe that the linked arrangement implementation does not outperform the contiguous ones even though it does not require shifting elements inside the bucket. This must be due to the fact that more memory accesses (and misses) are performed and this is still dominant. This was confirmed performing the analogous Pin experiment. Instead, if an intensive insertion test is performed, in which a lot of insertions per element are done and almost no traversal is performed, then this gain is not negligible. This is shown in Fig. 3(f).

Internal sort. The STL requires an $O(n \log n)$ `sort` method that preserves the iterators on its elements. Our implementations use a customized implementation of merge sort.

Results of executing the sort method are given in Fig. 3(g). These show that our implementations are between 3 and 4 times faster than GCC. Taking into account that GCC also implements a merge sort, we claim that the significant speedup is due to the locality of data accesses inside the buckets. To confirm this, Fig. 4(b) shows the Pin results. Indeed, GCC does about 30 times more cache accesses and misses than our implementations.

Effect of bucket capacity. The previous results were obtained for buckets with capacity of 100 elements. Anyway, this choice did not appear to be critical. Specifically, we repeated the previous tests with lists with other capacities, and observed that once the bucket capacity was not very small (less than 8-12 elements), a wide range of values behaved neatly. Note that a bucket of integers with capacity of 8 elements is yet 40-80 bytes long (depending on the implementation and address length) and a typical cache line is 64 or 128 bytes long.

To illustrate the previous claims, we show in Fig. 3(h) insertion results on a shuffled list with initially about 5 million elements. These show that for contiguous arrangement implementations, time decreases until a certain point and then starts to increase. In these cases, increasing the bucket size increases the intrabucket movements which finally results more costly than the achieved locality of accesses. In contrast, the linked arrangement implementation seems to be

not affected because no such operations are performed, accesses of a bucket do not interfere between them, and our insert reorganization algorithm takes into account at most three buckets at a time.

If we perform the last test with several instances at the same time, a smooth rise in time for all implementations can be seen, in particular for big bucket capacities. In fact, it is common dealing with several data structures at the same time. In this case, some interferences within the different objects accesses can occur, which are more probable as the number of instances grows. Therefore, it is advisable to keep a relatively low bucket size.

4.2 Basic operations with iterator load

Now, we repeat the previous experiments on lists that do have iterators on their elements. We use the term *iterator load* to refer to the percentage of elements of a list that have one or more iterator on them.

Results are shown for tests in which elements have already been shuffled, iterator loads range from 0% to 100% and a big list size is fixed (about 5 million elements) because then is crucial to manage data in the cache efficiently.

Traversal. When there are no iterators on the list, our implementations traversal is very fast because the increment operation is simple and elements are accessed with high locality. However, when there are some iterators, it may turn slower because the increment operation depends whether there are other iterators pointing to the element or its successor. In contrast, the increment operation on traditional double linked lists is independent of it, and so, performance must be not affected. When the list has not been shuffled, this is exactly the case.

In contrast, when the elements are shuffled, which changes iterators logical order, iterators accesses may score low locality. Results for this case are shown in Fig. 5(a), which show indeed that the memory overhead become the most important factor in performance. Nevertheless, the good locality of accesses to the elements themselves makes our implementations more competitive than GCC's up to 80% iterator load even for relatively small lists (about 100000 elements).

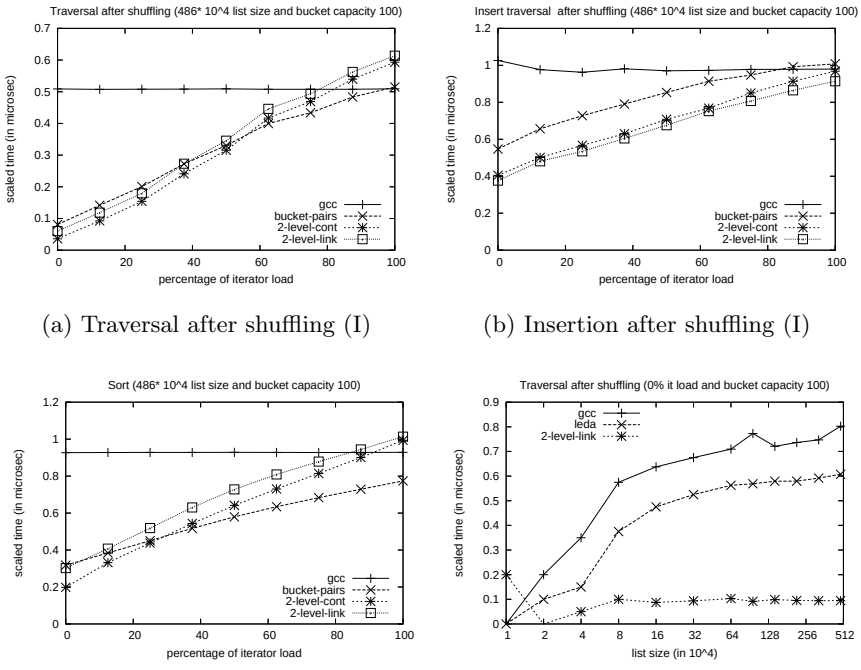
Insertion. When an element is inserted in a bucket with several iterators, some extra operations must be done but are much less than in the traversal case in relative terms. Therefore, performance should be less affected.

Results are shown after the elements have been shuffled in Fig. 5(b).

The results are analogous to the traversal test but with smoother slopes, as happened with no iterator load. Specifically, when the list has been shuffled, our implementations are more convenient up to 80% iterator load.

Internal sort. Guaranteeing iterators consistency in our customized merge sort is not straightforward, specially in the case of 2-level approaches that need some (though small) auxiliary arrays. Performance results are shown in Fig. 5(c).

The results indeed show that the 2-level implementations are more sensitive to the iterator load. Anyway, any of our implementation are faster than GCC for iterators loads lower than 90%.



(a) Traversal after shuffling (I)

(b) Insertion after shuffling (I)

(c) Internal sort (I)

(d) Traversal after shuffling (L)

Fig. 5. Experimental results depending on the iterator load for a list of size $4.86*10^6$ (I) and LEDA results (L).

4.3 Comparison with LEDA

Here, we compare our lists with the LEDA well-known implementation, which uses a customized memory allocator. Although LEDA does not follow the STL, its interface is very similar and as GCC, it uses classical double linked lists.

In Fig. 5(d), we show the results for traversal operation after shuffling. These make evident the limitations in performance of using a double linked list compared to our cache conscious approach. LEDA's times are just slightly better than GCC's, but remain worse than our implementations.

We omit the rest of plots with LEDA, because its results are just slightly better than GCC. The only exception is its internal sort (a quicksort) which is very competitive. Nevertheless, it requires linear extra space, does not keep iterators (items in LEDA jargon) and is not faster than ours.

4.4 Other environments

The previous experiments have been run in a AMD Opteron machine. We have verified that the results we claim also hold on other environments. These include an older AMD K6 3D Processor at 450 MHz with a 32 KB + 32 KB L1 cache, 512 KB L2 off-chip (66 MHz) and a Pentium 4 CPU at 3.06 GHz, with a 8KB + 8KB L1 cache and 512 KB L2 cache. On both machines, similar results are obtained in relative terms, and better as newer the machine and compiler.

5 Conclusions

In this paper we have presented three cache conscious lists implementations that are compliant with the C++ standard library. Cache conscious lists were studied before but did not cope with library requirements. Indeed, these goals enter in conflict, particularly preserving both constant costs and iterators requirements.

This paper shows that it is possible to combine efficiently and effectively cache consciousness with STL requirements. Furthermore, our implementations are useful in many situations, as is shown by our wide range of experiments. The experiments compare our implementations against double linked list implementations such as GCC and LEDA. These show for instance that our lists can offer 5-10 times faster traversals, 3-5 times faster internal sort and even with an (unusual) big load of iterators be still competitive. Besides, in contrast to double linked lists, our data structure does not degenerate when the list is shuffled.

Further, the experiments show that the 2-level implementations are specially efficient. In particular, we would recommend using the linked bucket implementation, although its benefits only evince when the modifying operations are really frequent, because it can make more profit of eventually bigger cache lines.

Given that the use of caches is growing in computer architecture (in size and in number) we believe that cache conscious design will be even more important in the future. Therefore, we think that it is time that standard libraries take into account this knowledge. In this sense, this article sets a precedence but there is still a lot of work to do. To begin with, similar techniques could be applied to more complicated data structures. Moreover, current trends indicate that in the near future it will be common to have multi-threaded and multi-core computers. So, we should start thinking how to enhance these features in modern libraries.

References

1. International Standard ISO/IEC 14882: Programming languages — C++. 1st edn. American National Standard Institute (1998)
2. Cormen, T.H., Leiserson, C., Rivest, R., Stein, C.: Introduction to algorithms. 2 edn. The MIT Press, Cambridge (2001)
3. Lamarca, A.: Caches and algorithms. PhD thesis, University of Washington (1996)
4. Sen, S., Chatterjee, S.: Towards a theory of cache-efficient algorithms. In: SODA '00, SIAM (2000) 829–838
5. Demaine, E.: Cache-oblivious algorithms and data structures. In: EEF Summer School on Massive Data Sets. LNCS. (2002)
6. Frigo, M., Leiserson, C., Prokop, H., Ramachandran, S.: Cache-oblivious algorithms. In: FOCS '99, IEEE Computer Society (1999) 285
7. Mehlhorn, K., Naher, S.: LEDA — A platform for combinatorial and geometric computing. Cambridge University Press (1999)
8. Josuttis, N.: The C++ Standard Library : A Tutorial and Reference. Addison-Wesley (1999)
9. Bender, M., Cole, R., Demaine, E., Farach-Colton, M.: Scanning and traversing: Maintaining data for traversals in memory hierarchy. In: ESA '02. (2002) 152–164
10. Luk, C., Cohn, R., Muth, R., Patil, H., Klauser, A., Lowney, G., Wallace, S., Reddi, V.J., Hazelwood, K.: Pin: Building customized program analysis tools with dynamic instrumentation. In: PLDI '05, Chicago, IL (2005)