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Project: Introduction of std::colony to the standard library
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Foreword/Response to Committee feedback for Revision 1:

First of all thanks to the previous review team for your points and comments, and in particular for Jonathan Wakely's generous post-review critique. Since I will not be there in person, I'm taking the opportunity to respond to some of the points made here, in the event that neither of my esteemed colleagues (Patrice Roy or Guy Davidson) happen to be available to make the points for me. I've checked with John Spicer and this appears to be valid.
To start off with, I realize the name was not explained well in the initial draft - this was purely because I felt it was obvious when actually it wasn't. I've made an attempt to show the 'behind-the-scenes' of the metaphor in the introduction.
I think 'bag' is a bad name, partially because it's synonymous with multiset (and colony is not one of those) and partially because it doesn't cover how a colony actually works internally. But I have yet to come up with an alternate name that fits as well as 'colony' does.
At any rate, more discussion welcome.

The second point was that the form of the structure was not explained incredibly well in the introduction - I have made an attempt to fix this, but would advise people to take the structure on it's own terms, rather than trying to pidgeonhole it into preconceived structures. Otherwise misunderstandings will typically arise.

"Be clearer about what operations this supports, early in the paper." - done (V. Technical Specifications). "Be clear about the O() time of each operation, early in the paper." - done (for main operations V. Technical Specifications). "Unordered and no associative lookup, so this only supports use cases where you're going to do something to every element." - As noted the container is designed for highly object-oriented situations where you have many elements in different containers referring to many other elements in other containers. This can be done with pointers or iterators in colony (insert returns an iterator which can be dereferenced to get a pointer, pointers can be converted into iterators with the supplied functions (for erase etc)) and because pointers/iterators stay stable regardless of insertion/erasure, this usage is unproblematic. You could say the pointer is equivalent to a key in this case (but without the overhead). That is the first access pattern, the second is straight iteration over the container, as you say.

"Do we really need the Skipfield_Type template argument?" - If it is possible to relegate this to a constructor argument (I'm not sure how but Petra suggests one approach) I would welcome it, but the fact is this argument promotes use of the container in heavy-constrained memory environments, and in high-performance small-N collections. Unfortunately it also means `operator =` and some other functions won't work on colonies of the same type but differing skipfield types. See more explanation in V. Technical Specifications.

Thanks once again,
Matt

Introduction of std::colony to the standard library

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I. Introduction

In a human colony, people move into dwellings, then when they move on their rooms are filled with other people - assuming limited resources. New dwellings are not built unless necessary. If a dwelling becomes empty it may be demolished and the land cleared to make way for a future dwelling. The same principles apply to this structure. The memory locations of erased elements are marked as empty and 'recycled', with new elements utilizing them upon future insertions. New memory blocks are not allocated unless necessary - and when a memory block becomes empty, it is freed to the OS (under certain circumstances it may be retained for performance reasons - see clear() and erase()).

Colony is a higher-performance container for situations where the ratio of insertions/erasures to iterations is relatively high. Structurally it is a series of memory blocks with per-block metadata and skipfields, accompanied by a mechanism for recording erased element memory locations (this mechanism can take many forms). In default usage the memory blocks have a growth factor. It allows only for unordered insertion but is sortable, has fast iteration and gives the programmer direct pointer/iterator access to elements without the possibility of those pointers/iterators being invalidated by subsequent insertions or erasure. On the basis of the reference implementation (plf::colony) the following attributes have been established:

Colonies have better overall performance than any standard library container or container modification when:

a. Insertion order is unimportant

b. Insertions and erasures to the container occur frequently in performance-critical code, ***and***

c. Pointers/iterators to non-erased container elements may not be invalidated by insertion or erasure.

The performance characteristics compared to other containers, for the most-commonly-used operations in the above circumstance are:

- *Singular (non-fill, unordered) insertion*: better than any std:: library container except some implementations of deque.
- *Erasure (from random location)*: better or equal to any std:: library container.
- *Iteration*: better than any std:: library container capable of preserving pointer/iterator validity post-erasure (eg. map, multiset, list). Where pointer/iterator validity is unimportant, better than any std:: library container except deque and vector.

There are some vector/deque modifications/workarounds which can outperform colony for iteration while maintaining link validity, but which have slower insertion and erasure speeds, and also typically have a cost to usability or memory requirements. Under scenarios involving high levels of modification colony will outperform these as well. These results, along with performance comparisons to the unmodified std:: containers, are explored in detail in the Appendix B Benchmarks.

II. Motivation and Scope

Sometimes there are situations where data is heavily interlinked, iterated over frequently, and changing often. An example is a central 'entity' class in a video game engine. These are 'has a'-style objects rather than 'is a'-style objects, which reference other shared resources like sprites, sounds and suchforth. These resources are typically located in separate containers/arrays. The entities are, in turn, referenced by other structures like quadtrees/octrees, level structures and the like. The entities could be erased at any time (for example, a wall gets destroyed and no longer requires processing) and new entities may be inserted (for example, a new enemy is created). All the while, inter-linkages between entities, resources and superstructures such as levels and quadtrees, are required to stay valid in order for the game to run. The order of the entities and resources themselves within the containers is, in the context of a game, typically unimportant.

What is needed is a container (or modification of a container) such that these insertions and erasures may occur without invalidating all the interlinkages between elements within containers. Unfortunately the container with the best iteration performance in the standard library, vector[1], also loses pointer validity to elements within it upon insertion, and also pointer/index validity upon erasure. This tends to lead to sophisticated, and often restrictive, workarounds when developers attempt to utilize vector or similar containers under the above circumstances.

While these situations above are common across multiple domains, for the benefit of those unfamiliar with any specific scenarios, I will present some more specific requirements with regards to game engines. When working on game engines we are predominantly dealing with situations where:

a. Elements within data collections refer to elements within other data collections (through a variety of methods - indices, pointers, etc). These references must stay valid throughout the course of the game/level. Any container which causes pointer or index invalidation can create difficulties or necessitate workarounds.
b. Order is unimportant for the most part. The majority of data is simply iterated over, transformed, referred to and utilized with no regard to order.
c. Erasing or otherwise "deactivating" objects occurs frequently in performance-critical code. For this reason methods of erasure which create strong performance penalties are avoided.
d. Inserting new objects in performance-critical code (during gameplay) is also common - for example, a tree drops leaves every so often, or a player spawns in a multiplayer game.
e. It is not always clear in advance how many elements there will be in a container at the beginning of development, or even at the beginning of a level during play. Genericized game engines in particular have to adapt to considerably different user requirements and scopes. For this reason extensible containers which can expand and contract in realtime are often necessary.
f. For modern performance reasons, memory storage which is more-or-less contiguous is preferred.
g. Memory waste is avoided.

Unfortunately, std::vector in it's default state, does not meet these requirements due to:

1. Poor (non-fill) singular insertion performance (regardless of insertion position) due to the need for reallocation upon reaching capacity
2. Insert invalidates pointers/iterators to all elements
3. Erase invalidates pointers/iterators/indexes to all elements afer the erased element

Hence game developers tend to either simply develop custom solutions for each scenario or implement a workaround for vector. Workarounds vary, but the most common are most likely:

1. Using a boolean flag or similar to indicate the inactivity of an object (as opposed to actually erasing from the vector). Elements flagged as inactive are skipped during iteration.

   Advantages: Fast "deactivation".
   Disadvantages: Slow to iterate due to branching.

2. Using a vector of data and a secondary vector of indexes. When erasing, the erasure occurs only in the vector of indexes, not the vector of data. When iterating it iterates over the vector of indexes and accesses the data from the vector of data via the remaining indexes.

   Advantages: Fast iteration.
   Disadvantages: Erasure still incurs some reallocation cost which can increase jitter.

3. Combining a swap-and-pop approach to erasure with some form of dereferenced lookup system to enable contiguous element iteration (sometimes called a 'packed array': http://bitsquid.blogspot.ca/2011/09/managing-decoupling-part-4-id-lookup.html). When iterating over the data we simply iterate through the vector of elements. When erasing, the back element of the vector is swapped with the element being erased, then the new back element is popped. A typical dereferencing system follows:
   To maintain valid external references to elements (which may be swapped from the back to an erased element location), a vector of indexes (V1) is maintained and updated when erasures or insertions occur. External objects referring to elements within the container store a pointer (or index) to the entry in V1 corresponding to the element in question. In addition the data vector (Vd) has a second vector of indexes (V2). This is used by the structure to update the entry in V1 upon movement of an element. Lastly, a free-list of erased entries in V1 is maintained (entries in V1 are erased when their corresponding elements in Vd are erased) and these locations are reused upon subsequent insertions.

   Advantages: Iteration is at standard vector speed.
   Disadvantages: Erase could be slow if objects are large and/or non-trivially copyable, thereby making swap costs large. All link-based access to elements incur additional costs due to the dereferencing system.

Each of these techniques has the disadvantage of slow singular insertions, and the first two will also continually expand memory usage when erasing and inserting over periods of time. Colony is an attempt to bring a more generic solution to these situations. It has the advantage of good iteration speed, a similar erasure speed to the boolean technique described above, and an insertion speed which is much faster than a vector's. It also never causes pointer invalidation to non-erased elements during erasure or insertion and the memory locations of erased elements are either reused during subsequent insertions, or released on-the-fly when the element's memory block becomes empty.

III. Impact On the Standard

This is a pure library addition, no changes necessary to the standard asides from the introduction of the colony container.
A reference implementation of colony is available for download and use: http://www.plflib.org/colony.htm

IV. Design Decisions

The key technical features of this container are:

- Unordered non-associative data
- Never invalidates pointers/iterators to non-erased elements (iterators pointing to end() excluded)
- Reuses or frees memory from erased elements
- In a high-modification context ie. where ratio of insertion/erasure to iteration is high, it should be faster than any std:: library container or container workaround

The abstract requirements needed to support these features are:

- It must use multiple memory-blocks (this prevents element reallocation on insertion and associated pointer invalidation)
- Memory blocks must be freed or taken out of active use once empty (otherwise O(1) ++ iteration operations become impossible)
- Memory blocks must be removable with low performance cost and without invalidating pointers to elements in other memory blocks
- There must be some mechanism for reusing erased element memory locations upon subsequent insertions, to ensure greater element contiguousness
- Erased elements must also be recorded in a skipfield or similar structure so they can be skipped over during iteration (this prevents the necessity for element reallocation upon erasure)
- Skipfield (or similar structures') design must allow for O(1) ++ and -- iterations

To condense the above we can say that there are three aspects to a colony which define any implementation:

1. A multiple-memory-block based allocation pattern which allows for the fast removal of memory blocks when they become empty of elements without causing element pointer invalidation within other memory blocks.
2. A skipfield to enable the skipping over of erased elements during iteration.
3. A mechanism for reusing erased element locations upon subsequent insertions.

Obviously these three things can be achieved in a variety of different ways. We'll examine how the reference implementation achieves them now:

Memory blocks - chained group allocation pattern

This is essentially a doubly-linked list of nodes (groups) containing (a) memory blocks, (b) memory block metadata and (c) skipfields. The memory blocks themselves have a growth factor of 2, which reduces the number of memory allocations necessary for the container when expanding upon insertion. The metadata in question includes information necessary for an iterator to iterate over colony elements, such as the last insertion point within the memory block, and other information useful to specific functions, such as the total number of non-erased elements in the node. This approach keeps the operation of freeing empty memory blocks from the colony structure at O(1) time complexity; compared to, say, a vector of memory blocks. Further information is available here: http://www.plflib.org/chained_group_allocation_pattern.htm

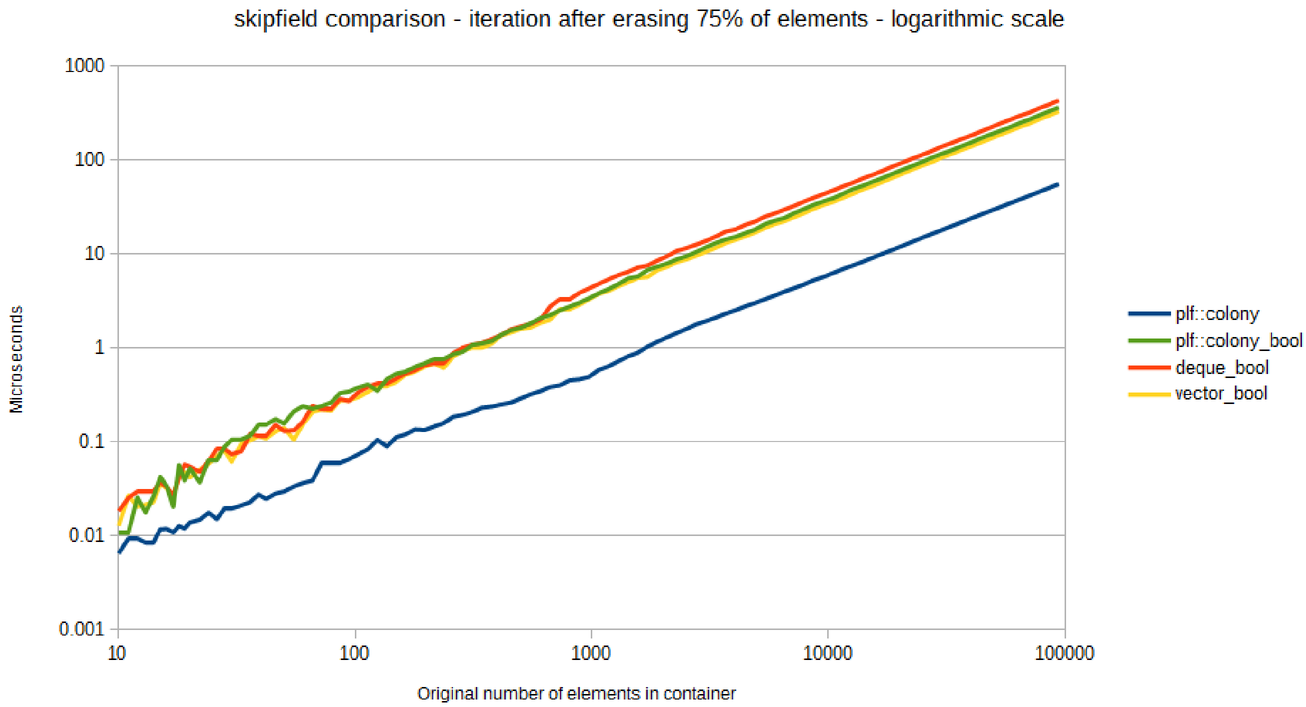
This is the best known approach currently for colony in terms of performance. A vector of groups will not work, as a colony iterator must store a pointer (or index) to it's current group in order for iteration to work, and groups must be removed when empty in order to enable standards-compliant iteration and avoid cache misses. Erasing a group in a vector would invalidate pointers/indexes to all groups after the erased group, and inserting new groups would invalidate pointers to existing groups. A vector of pointers to dynamically-allocated groups is possible, but represents little performance advantage and could cause jitter due to the additional overhead when non-back groups are removed, where large numbers of groups are involved. Benchmarking would be required.

Keeping all memory block metadata separate from the memory blocks themselves and in a central repository is possible, but it is hard to see a performance advantage to doing so.

Skipfield - jump-counting skipfield pattern

This numeric pattern allows for O(1) time complexity iterator operations and fast iteration compared to alternative skipfields. It stores and modifies (during insertion and erasure) numbers which correspond to the number of elements in runs of consecutive erased elements, and during iteration adds these numbers to the current iterator location. This avoids the looping branching code necessary for iteration with a boolean skipfield (as an aside, a colony could not actually use a boolean skipfield because ++ iteration becomes O(random), which violates the C++ iterator specifications). The now-published reference paper for the advanced version of the jump-counting skipfield pattern is available here: http://rdcu.be/ty6U),

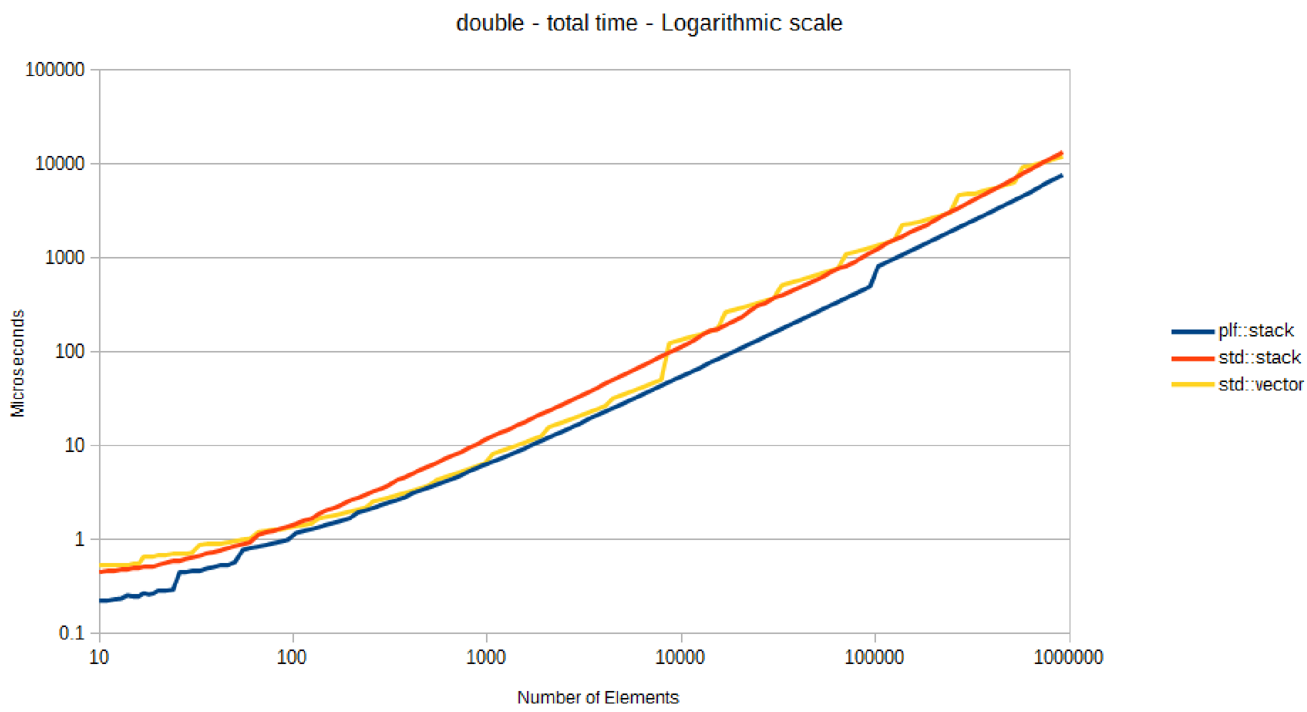
Iterative performance after having previously erased 75% of all elements in the containers at random, for a std::vector, std::deque and a colony with boolean skipfields, versus a colony with a jump-counting skipfield (GCC 5.1 x64) - storing a small struct type:



Memory re-use mechanism - reduced_stack

This is a stripped-down custom internal stack class based on plf::stack (http://www.plflib.org/stack.htm), which outperforms all other std:: containers in a stack context, for all datatypes and across compilers (based on benchmarks shown on the page provided). plf::stack uses the same chained-group allocation pattern as plf::colony. The stack stores erased element memory locations and these are popped during subsequent colony insertions. If a memory block becomes empty and is subsequently removed, the stack is processed internally and any memory locations from within that block are removed.

Time to push all elements then read-and-pop all elements, plf::stack vs std::stack (std::deque) and std::vector (GCC 5.1 x64) - storing type double:



An alternative approach, using a "free list" (explanation of this concept: http://bitsquid.blogspot.ca/2011/09/managing-decoupling-part-4-id-lookup.html) to record the erased element memory locations, by creating a union between T and T*, has been explored and the following issues identified:

1. The most obvious is that unions in C++ (11 or otherwise) do not support object unions in a way that preserves fundamental functionality of the object being unioned (n4567, 9.5/2). Copy/move assignment/constructors, constructors and destructors would be lost. This makes this approach untenable for non-trivial types.
2. A colony element could be smaller in size than a pointer and thus a union with such would dramatically increase the amount of wasted space in circumstances with low numbers of erasures - moreso if the pointer type supplied by the allocator is non-trivial.
3. Because a free list will (assuming a non-linear erasure pattern) jump between random memory locations continuously, consolidating a free list when a memory block becomes empty (and is therefore removed, meaning the free list must be purged of links to memory locations within that group) will result in an operation filled with cache misses. In the context of jitter-sensitive work this would likely become unacceptable. It is possible to work around this issue by using per-memory-block free lists, which are joined to each other with per-memory-block next and previous pointers, in combination with a global free list head pointer. In this scenario the removal of a memory block's free list from a global free-list chain requires only a similar action to removing an item in a linked list (re-writing the next and previous pointers of the previous and next memory-blocks in the free list group chain).

V. Technical Specifications

Colony meets the requirements of the C++ Container, AllocatorAwareContainer, and ReversibleContainer concepts.

For the most part the syntax and semantics of colony functions are very similar to current existing std:: C++ libraries. Formal description is as follows:

```
template <class T, class Allocator = std::allocator<T>, typename T_skipfield_type = unsigned short> class colony
```

`T` - the element type. In general T must meet the requirements of Erasable, CopyAssignable and CopyConstructible.
However, if emplace is utilized to insert elements into the colony, and no functions which involve copying or moving are utilized, T is only required to meet the requirements of Erasable. If move-insert is utilized instead of emplace, T must also meet the requirements of MoveConstructible .

`Allocator` - an allocator that is used to acquire memory to store the elements. The type must meet the requirements of Allocator. The behavior is undefined if `Allocator::value_type` is not the same as T.

T_skipfield_type - an unsigned integer type. This type is used to form the skipfield which skips over erased T elements. The maximum size of element memory blocks is constrained by this type's bit-depth (due to the nature of a jump-counting skipfield). The default type, `unsigned short`, is 16-bit on most platforms which constrains the size of individual memory blocks to a maximum of 65535 elements. `unsigned short` has been found to be the optimal type for performance based on benchmarking, however making this type user-defined has performance benefits in some scenarios. In the case of small collections (eg. < 512 elements) in a memory-constrained environment, reducing the skipfield bit depth to a Uint8 type will reduce both memory usage and cache saturation without impacting iteration performance.

In the case of very large collections (millions) where memory usage is not a concern and where erasure is less common, one might think that changing the skipfield bitdepth to a larger type may lead to slightly increased iteration performance due to the larger memory block sizes made possible by the larger bit depth and the fewer subsequent block transitions. However in practice the performance benefits appear to be little-to-none, and introduce substantial performance issues if erasures are frequent, as with this approach it takes more erasures for a group to become empty - increasing the frequency of large skips between elements and subsequent cache misses, as well as skipfield update times. From this we can assume it is unlikely for a user to want to use types other than unsigned short and unsigned char. But since these scenarios are on a per-case basis, it has been considered best to leave control in the hands of the user.

Basic example of usage

```
#include <iostream>
#include "plf_colony.h"

int main(int argc, char **argv)
{
  plf::colony<int> i_colony;

  // Insert 100 ints:
  for (int i = 0; i != 100; ++i)
  {
    i_colony.insert(i);
  }

  // Erase half of them:
  for (plf::colony<int>::iterator it = i_colony.begin(); it != i_colony.end(); ++it)
  {
    it = i_colony.erase(it);
  }

  // Total the remaining ints:
  int total = 0;

  for (plf::colony<int>::iterator it = i_colony.begin(); it != i_colony.end(); ++it)
  {
    total += *it;
  }

  std::cout << "Total: " << total << std::endl;
  std::cin.get();
  return 0;
}
```

Example demonstrating pointer stability

```
#include <iostream>
#include "plf_colony.h"

int main(int argc, char **argv)
{
  plf::colony<int> i_colony;
  plf::colony<int>::iterator it;
  plf::colony<int *> p_colony;
  plf::colony<int *>::iterator p_it;

  // Insert 100 ints to i_colony and pointers to those ints to p_colony:
  for (int i = 0; i != 100; ++i)
  {
    it = i_colony.insert(i);
```

```
    p_colony.insert(&(*it));
  }

  // Erase half of the ints:
  for (it = i_colony.begin(); it != i_colony.end(); ++it)
  {
    it = i_colony.erase(it);
  }

  // Erase half of the int pointers:
  for (p_it = p_colony.begin(); p_it != p_colony.end(); ++p_it)
  {
    p_it = p_colony.erase(p_it);
  }

  // Total the remaining ints via the pointer colony:
  int total = 0;

  for (p_it = p_colony.begin(); p_it != p_colony.end(); ++p_it)
  {
    total += *(*p_it);
  }

  std::cout << "Total: " << total << std::endl;

  if (total == 2500)
  {
    std::cout << "Pointers still valid!" << std::endl;
  }

  std::cin.get();
  return 0;
}
```

Time complexity of main operations

Insert/emplace (single): O(1) amortised unless prior erasures have occurred in the usage lifetime of the colony instance. If prior erasures have occurred, updating the skipfield may require a memmove operation, which creates a variable time complexity depending on the range of skipfield needing to be copied (though in practice this will resolve to a singular raw memory block copy in most scenarios). This is O(random) with the range of the random number being between O(1) and O(std::numeric_limits<skipfield_type>::max() - 2). Average time complexity varies based on erasure pattern. With a random erasure pattern it will be closer to O(1) amortized.

Insert (multiple): O(N) unless prior erasures have occurred. See Insertion(single) for rules in this case.

Erase (single): If erasures to elements consecutive with the element being erased have not occurred, or only consecutive erasures before the element being erased have occurred, O(1) amortised. If consecutive erasures after the element being erased have occurred, updating of the skipfield requires a memmove operation or vectorized update of O(n) complexity, where n is the number of consecutive erased elements after the element being erased. This is O(random) with the range of the random number being between from 1 and std::numeric_limits<skipfield_type>::max() - 2. Average time complexity varies based on erasure pattern, but with a random erasure pattern it's closer to O(1) amortized.

Erase (multiple): ~O(log N).

std::find: O(n)

Iterator operations:
++ and -- : O(1) amortized
begin()/end(): O(1)
advance/next/prev, get_iterator_from_index: between O(1) and O(n), depending on current location, end location and state of colony. Average ~O(log N).

Time complexity of other operations

size(), capacity, max_size(), empty(): O(1)

shrink_to_fit(), operator =, operator == and != : O(N)

free_unused_memory(): O(1)

change_group_sizes, change_minimum_group_size, change_maximum_group_size: O(N)

Swap, operator = (move), get_allocator(): O(1)

Operations whose complexity does not have a strong correlation with number of elements:

(*ie. other factors such as trivial destructability of elements more important*)

~colony, clear(), reinitialize(), sort(), get_iterator_from_pointer(), get_index_from_iterator(), get_index_from_reverse_iterator().

Iterator Invalidation

All read-only operations, swap, std::swap, free_unused_memory	Never
clear, sort, reinitialize, operator =	Always
reserve, shrink_to_fit	Only if capacity is changed
change_group_sizes, change_minimum_group_size, change_maximum_group_size	Only if supplied minimum group size is larger than smallest group in colony, or supplied maximum group size is smaller than largest group in colony.
erase	Only for the erased element
insert, emplace	If an iterator is == end() it may be invalidated by a subsequent insert/emplace. Otherwise it will not be invalidated. Pointers will never be invalidated.

Member types

Member type	Definition
`value_type`	`T`
`allocator_type`	`Allocator`
`skipfield_type`	`T_skipfield_type`
`size_type`	`std::allocator_traits<Allocator>::size_type`
`difference_type`	`std::allocator_traits<Allocator>::difference_type`
`reference`	`value_type &`
`const_reference`	`const value_type &`
`pointer`	`std::allocator_traits<Allocator>::pointer`
`const_pointer`	`std::allocator_traits<Allocator>::const_pointer`
`iterator`	`BidirectionalIterator`
`const_iterator`	`Constant BidirectionalIterator`
`reverse_iterator`	`BidirectionalIterator`
`const_reverse_iterator`	`Constant BidirectionalIterator`

Colony iterators cannot be random access due to the use of a skipfield. This constrains +, -, += or -= operators into being non-O(1). But member overloads for the standard library functions advance(), next(), prev() and distance() are available in the reference implementation, and are significantly faster than O(n) in the majority of scenarios.

A full list of the current reference implementation's constructors and member functions can be found in Appendix A.

VI. Acknowledgements

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VII. Appendixes

Appendix A - Member functions

Constructors

Default	colony() explicit colony(const allocator_type &alloc)
fill	explicit colony(size_type n, skipfield_type min_group_size = 8, skipfield_type max_group_size = std::numeric_limits<skipfield_type>::max(), const allocator_type &alloc = allocator_type()) explicit colony(size_type n, const value_type &element, skipfield_type min_group_size = 8, skipfield_type max_group_size = std::numeric_limits<skipfield_type>::max(), const allocator_type &alloc = allocator_type())
range	template<typename InputIterator> colony(const InputIterator &first, const InputIterator &last, skipfield_type min_group_size = 8, skipfield_type max_group_size = std::numeric_limits<skipfield_type>::max(), const allocator_type &alloc = allocator_type())
copy	colony(const colony &source) colony(const colony &source, const allocator_type &alloc)
move	colony(colony &&source) noexcept colony(colony &&source, const allocator_type &alloc)
initializer list	colony(const std::initializer_list<value_type> &element_list, skipfield_type min_group_size = 8, skipfield_type max_group_size = std::numeric_limits<skipfield_type>::max(), const allocator_type &alloc = allocator_type())

Some constructor usage examples

- colony<T> a_colony

  Default constructor - default minimum group size is 8, default maximum group size is std::numeric_limits<skipfield_type>::max() (typically 65535). You cannot set the group sizes from the constructor in this scenario, but you can call the change_group_sizes() member function after construction has occurred.
  Example:
  ```
  plf::colony<int> int_colony;
  ```

- colony<T, the_allocator<T> > a_colony(const allocator_type &alloc = allocator_type())

  Default constructor, but using a custom memory allocator eg. something other than std::allocator.
  Example:
  ```
  plf::colony<int, tbb::allocator<int> > int_colony;
  ```
  Example2:
  ```
  // Using an instance of an allocator as well as it's type
  tbb::allocator<int> alloc_instance;
  plf::colony<int, tbb::allocator<int> > int_colony(alloc_instance);
  ```

- colony<T> colony(size_type n, skipfield_type min_group_size = 8, skipfield_type max_group_size = std::numeric_limits<skipfield_type>::max())

  Fill constructor with value_type unspecified, so the value_type's default constructor is used. n specifies the number of elements to create upon construction. If n is larger than min_group_size, the size of the groups created will either be n and max_group_size, depending on which is smaller. min_group_size (ie. the smallest possible number of elements which can be stored in a colony group) can be defined, as can the max_group_size. Setting the group sizes can be a performance advantage if you know in advance roughly how many objects are likely to be stored in your colony long-term - or at least the rough scale of storage. If that case, using this can stop many small initial groups

being allocated.
Example: `plf::colony<int> int_colony(62);`

- `colony<T> colony(const std::initializer_list<value_type> &element_list, skipfield_type min_group_size = 8, skipfield_type max_group_size = std::numeric_limits<skipfield_type>::max())`

  Using an initialiser list to insert into the colony upon construction.
  Example: `std::initializer_list<int> &el = {3, 5, 2, 1000};`
  `plf::colony<int> int_colony(el, 64, 512);`

- `colony<T> a_colony(const colony &source)`

  Copy all contents from source colony, removes any empty (erased) element locations in the process. Size of groups created is either the total size of the source colony, or the maximum group size of the source colony, whichever is the smaller.
  Example: `plf::colony<int> int_colony_2(int_colony_1);`

- `colony<T> a_colony(colony &&source)`

  Move all contents from source colony, does not remove any erased element locations or alter any of the source group sizes. Source colony is now void of contents and can be safely destructed.
  Example: `plf::colony<int> int_colony_1(50, 5, 512, 512); // Create colony with min and max group sizes set at 512 elements. Fill with 50 instances of int = 5.`
  `plf::colony<int> int_colony_2(std::move(int_colony_1)); // Move all data to int_colony_2. All of the above characteristics are now applied to int_colony2.`

Iterators

All iterators are bidirectional but also provide >, <, >= and <= for convenience (for example, for comparisons against end() when doing multiple increments within for loops) and within some functions (`distance()` uses these for example). Functions for iterator, reverse_iterator, const_iterator and const_reverse_iterator follow:

```
operator * const
operator -> const noexcept
operator ++
operator --
operator = noexcept
operator == const noexcept
operator != const noexcept
operator < const noexcept
operator > const noexcept
operator <= const noexcept
operator >= const noexcept
base() const (reverse_iterator and const_reverse_iterator only)
```

All operators have O(1) amortised time-complexity. Originally there were +=, -=, + and - operators, however the time complexity of these varied from O(n) to O(1) depending on the underlying state of the colony, averaging in at O(log n). As such they were not includable in the iterator functions (as per C++ standards). These have been transplanted to colony's advance(), next(), prev() and distance() member functions. Greater-than/lesser-than operator usage indicates whether an iterator is higher/lower in position compared to another iterator in the same colony (ie. closer to the end/beginning of the colony).

Member functions

Insert

single element	`iterator insert (const value_type &val)`
fill	`iterator insert (size_type n, const value_type &val)`
range	`template <class InputIterator> iterator insert (const InputIterator &first, const InputIterator &last)`
move	`iterator insert (value_type&& val)`
initializer list	`iterator insert (const std::initializer_list<value_type> &il)`

- `iterator insert(const value_type &element)`

  Inserts the element supplied to the colony, using the object's copy-constructor. Will insert the element into a previously erased element slot if one exists, otherwise will insert to back of colony. Returns iterator to location of inserted element. Example:

```
plf::colony<unsigned int> i_colony;
i_colony.insert(23);
```

- `iterator insert (const size_type n, const value_type &val)`

  Inserts `n` copies of `val` into the colony. Will insert the element into a previously erased element slot if one exists, otherwise will insert to back of colony. Returns iterator to location of first inserted element. Example:

```
plf::colony<unsigned int> i_colony;
i_colony.insert(10, 3);
```

- `template <class InputIterator> iterator insert (const InputIterator &first, const InputIterator &last)`

  Inserts a series of `value_type` elements from an external source into a colony holding the same `value_type` (eg. int, float, a particular class, etcetera). Stops inserting once it reaches `last`. Example:

```
// Insert all contents of colony2 into colony1:
colony1.insert(colony2.begin(), colony2.end());
```

- `iterator insert(value_type &&element)`

  Moves the element supplied to the colony, using the object's move-constructor. Will insert the element in a previously erased element slot if one exists, otherwise will insert to back of colony. Returns iterator to location of inserted element. Example:

```
std::string string1 = "Some text";

plf::colony<std::string> data_colony;
data_colony.insert(std::move(string1));
```

- `iterator insert (const std::initializer_list<value_type> &il)`

  Moves the element supplied to the colony, using the object's move-constructor. Will insert the element in a previously erased element slot if one exists, otherwise will insert to back of colony. Returns iterator to location of inserted element. Example:

```
std::initializer_list<int> some_ints = {4, 3, 2, 5};

plf::colony<int> i_colony;
i_colony.insert(some_ints);
```

Erase

single element	`iterator erase(const_iterator it)`
range	`void erase(const_iterator first, const_iterator last)`

- `iterator erase(const_iterator it)`

  Removes the element pointed to by the supplied iterator, from the colony. Returns an iterator pointing to the next non-erased element in the colony (or to end() if no more elements are available). This must return an iterator because if a colony group becomes entirely empty, it may be removed from the colony, invalidating the existing iterator. A group may either be removed when it becomes empty, or moved to the back of the colony for future insertions and made inactive. The decision to either remove or move should be (largely) implementation-defined, but testing has suggested that the best performance under high-modification occurs when groups are removed unless they meet the maximum group size, or are either of the last two active groups at the back of the colony. Certainly there is no performance advantage to removing the end group, and doing so may introduce edge case performance issues (where multiple insertions/erasures occur frequently and sequentially). The reference implementation currently removes all groups when empty. Example:

```
plf::colony<unsigned int> data_colony(50);
plf::colony<unsigned int>::iterator an_iterator;
an_iterator = data_colony.insert(23);
an_iterator = data_colony.erase(an_iterator);
```

- `void erase(const_iterator first, const_iterator last)`

Erases all contents of a given colony from `first` to the element before the `last` iterator. The same principles from singular erasure apply to this function regards group retention/removal, etc.Example:

```
plf::colony<int> iterator1 = colony1.begin();
colony1.advance(iterator1, 10);
plf::colony<int> iterator2 = colony1.begin();
colony1.advance(iterator2, 20);
colony1.erase(iterator1, iterator2);
```

Other functions

- `iterator emplace(Arguments &&... parameters)`

  Constructs new element directly within colony. Will insert the element in a previously erased element slot if one exists, otherwise will insert to back of colony. Returns iterator to location of inserted element. "...parameters" are whatever parameters are required by the object's constructor. Example:

```
class simple_class
{
private:
int number;
public:
simple_class(int a_number): number (a_number) {};
};

plf::colony<simple_class> simple_classes;
simple_classes.emplace(45);
```

- `bool empty() const noexcept`

  Returns a boolean indicating whether the colony is currently empty of elements.
  Example: `if (object_colony.empty()) return;`

- `size_type size() const noexcept`

  Returns total number of elements currently stored in container.
  Example: `std::cout << i_colony.size() << std::endl;`

- `size_type max_size() const noexcept`

  Returns the maximum number of elements that the allocator can store in the container. This is an approximation as it does attempt to measure the memory overhead of the container's internal memory structures. It is not possible to measure the latter because a copy operation may change the number of groups utilized for the same amount of elements, if the maximum or minimum group sizes are different in the source container.
  Example: `std::cout << i_colony.max_size() << std::endl;`

- `size_type capacity() const noexcept`

  Returns total number of elements currently able to be stored in container without expansion.
  Example: `std::cout << i_colony.capacity() << std::endl;`

- `void shrink_to_fit()`

  Reduces container capacity to the amount necessary to store all currently stored elements. If the total number of elements is larger than the maximum group size, the resultant capacity will be equal to `((total_elements / max_group_size) + 1) * max_group_size` (rounding down at division). Invalidates all pointers, iterators and references to elements within the container.
  Example: `i_colony.shrink_to_fit();`

- `void free_unused_memory()`

  Deallocates any unused groups retained during erase() or unused since the last reserve(). Unlike shrink_to_fit(), this function cannot invalidate iterators or pointers to elements, nor will it shrink the capacity to match size(). Currently not implemented in the reference implementation (waiting on implementation of group retention in erase functionality).
  Example: `i_colony.remove();`

- `void reserve(size_type reserve_amount)`

  Preallocates memory space sufficient to store the number of elements indicated by `reserve_amount`. In the implementation the maximum size for this number is limited to the maximum group size of the colony and will be truncated if necessary. This restriction will be lifted in a future version.
  Example: `i_colony.reserve(15);`

- `void clear()`

  Empties the colony and removes all elements, but retains the empty memory blocks rather than deallocating (current implementation deallocates all memory blocks, but in the future this should be changed to reduce needless reallocation/deallocations).
  Example: `object_colony.clear();`

- `void change_group_sizes(const unsigned short min_group_size, const unsigned short max_group_size)`

  Changes the minimum and maximum internal group sizes, in terms of number of elements stored per group. If the colony is not empty and either min_group_size is larger than the smallest group in the colony, or max_group_size is smaller than the largest group in the colony, the colony will be internally copy-constructed into a new colony which uses the new group sizes, invalidating all pointers/iterators/references.
  Example: `object_colony.change_group_sizes(1000, 10000);`

- `void change_minimum_group_size(const unsigned short min_group_size)`

  Changes the minimum internal group size only, in terms of minimum number of elements stored per group. If the colony is not empty and min_group_size is larger than the smallest group in the colony, the colony will be internally copy-constructed into a new colony which uses the new minimum group size, invalidating all pointers/iterators/references.
  Example: `object_colony.change_minimum_group_size(100);`

- `void change_maximum_group_size(const unsigned short min_group_size)`

  Changes the maximum internal group size only, in terms of maximum number of elements stored per group. If the colony is not empty and either max_group_size is smaller than the largest group in the colony, the colony will be internally copy-constructed into a new colony which uses the new maximum group size, invalidating all pointers/iterators/references.
  Example: `object_colony.change_maximum_group_size(1000);`

- `void reinitialize(const unsigned short min_group_size, const unsigned short max_group_size)`

  Semantics of function are the same as "clear(); change_group_sizes(min_group_size, max_group_size);", but without the copy-construction code of the change_group_sizes() function - this means it can be used with element types which are non-copy-constructible, unlike change_group_sizes().
  Example: `object_colony.reinitialize(1000, 10000);`

- `void swap(colony &source) noexcept(std::allocator_traits<the_allocator>::propagate_on_container_swap::value || std::allocator_traits<the_allocator>::is_always_equal::value)`

  Swaps the colony's contents with that of `source`.
  Example: `object_colony.swap(other_colony);`

- ```
  void sort();
  template <class comparison_function>
  void sort(comparison_function compare);
  ```

  Sort the content of the colony. By default this compares the colony content using a less-than operator, unless the user supplies a comparison function (ie. same conditions as std::list's sort).
  Example:
  ```
  // Sort a colony of integers in ascending order:
  int_colony.sort();
  // Sort a colony of doubles in descending order:
  double_colony.sort(std::greater());
  ```

- `colony & operator = (const colony &source)`

  Copy the elements from another colony to this colony, clearing this colony of existing elements first.
  Example:
  ```
  // Manually swap data_colony1 and data_colony2 in C++03
  data_colony3 = data_colony1;
  data_colony1 = data_colony2;
  data_colony2 = data_colony3;
  ```

- `colony & operator = (const colony &&source)`

  Move the elements from another colony to this colony, clearing this colony of existing elements first. Source colony becomes invalid but can be safely destructed without undefined behaviour.
  Example:
  ```
  // Manually swap data_colony1 and data_colony2 in C++11
  data_colony3 = std::move(data_colony1);
  data_colony1 = std::move(data_colony2);
  data_colony2 = std::move(data_colony3);
  ```

- `bool operator == (const colony &source) const noexcept`

  Compare contents of another colony to this colony. Returns a boolean as to whether they are equal.
  Example: `if (object_colony == object_colony2) return;`
  ```

- `bool operator != (const colony &source) const noexcept`

  Compare contents of another colony to this colony. Returns a boolean as to whether they are not equal.
  Example: `if (object_colony != object_colony2) return;`

- `iterator begin() const noexcept, iterator end() const noexcept, const_iterator cbegin() const noexcept, const_iterator cend() const noexcept`

  Return iterators pointing to, respectively, the first element of the colony and the element one-past the end of the colony.

- `reverse_iterator rbegin() const noexcept, reverse_iterator rend() const noexcept, const_reverse_iterator crbegin() const noexcept, const_reverse_iterator crend() const noexcept`

  Return reverse iterators pointing to, respectively, the last element of the colony and the element one-before the first element of the colony. (note: as the reference implementation's crbegin() and rbegin() are derived from --end(), they will throw an exception if the colony is empty of elements and are not noexcept).

- `iterator get_iterator_from_pointer(const element_pointer_type the_pointer) const noexcept`

  Getting a pointer from an iterator is simple - simply dereference it then grab the address ie. "`&(*the_iterator);`". Getting an iterator from a pointer is typically not so simple. This function enables the user to do exactly that. This is expected to be useful in the use-case where external containers are storing pointers to colony elements instead of iterators (as iterators for colonies have 3 times the size of an element pointer) and the program wants to erase the element being pointed to or possibly change the element being pointed to. Converting a pointer to an iterator using this method and then erasing, is about 20% slower on average than erasing when you already have the iterator. This is less dramatic than it sounds, as it is still faster than all other std:: container erasure times. If the function doesn't find a non-erased element within the colony, based on that pointer, it returns `end()`. Otherwise it returns an iterator pointing to the element in question. Example:

  ```
  plf::colony<a_struct> data_colony;
  plf::colony<a_struct>::iterator an_iterator;
  a_struct struct_instance;
  an_iterator = data_colony.insert(struct_instance);
  a_struct *struct_pointer = &(*an_iterator);
  iterator another_iterator = data_colony.get_iterator_from_pointer(struct_pointer);
  if (an_iterator == another_iterator) std::cout << "Iterator is correct" << std::endl;
  ```

- `template <iterator_type>size_type get_index_from_iterator(iterator_type &the_iterator) const`

  While colony is a container with unordered insertion (and is therefore unordered), it still has a (transitory) order which may change upon erasure or insertion. *Temporary* index numbers are therefore obtainable. These can be useful, for example, when creating a saved-game file in a computer game, where certain elements in a container may need to be re-linked to other elements in other container upon reloading the save file. Example:

  ```
  plf::colony<a_struct> data_colony;
  plf::colony<a_struct>::iterator an_iterator;
  a_struct struct_instance;
  data_colony.insert(struct_instance);
  data_colony.insert(struct_instance);
  an_iterator = data_colony.insert(struct_instance);
  unsigned int index = data_colony.get_index_from_iterator(an_iterator);
  if (index == 2) std::cout << "Index is correct" << std::endl;
  ```

- `template <iterator_type>size_type get_index_from_reverse_iterator(const iterator_type &the_iterator) const`

  The same as get_index_from_iterator, but for reverse_iterators and const_reverse_iterators. Index is measured from front of colony (same as iterator), not back of colony. Example:

  ```
  plf::colony<a_struct> data_colony;
  plf::colony<a_struct>::reverse_iterator r_iterator;
  a_struct struct_instance;
  data_colony.insert(struct_instance);
  data_colony.insert(struct_instance);
  r_iterator = data_colony.rend();
  unsigned int index = data_colony.get_index_from_reverse_iterator(r_iterator);
  if (index == 1) std::cout << "Index is correct" << std::endl;
  ```

- `iterator get_iterator_from_index(const size_type index) const`

  As described above, there may be situations where obtaining iterators to specific elements based on an index can be useful, for example, when reloading save files. This function is basically a shorthand to avoid typing "`iterator it = colony.begin(); colony.advance(it, 50);`". Example:

```
plf::colony<a_struct> data_colony;
plf::colony<a_struct>::iterator an_iterator;
a_struct struct_instance;
data_colony.insert(struct_instance);
data_colony.insert(struct_instance);
iterator an_iterator = data_colony.insert(struct_instance);
iterator another_iterator = data_colony.get_iterator_from_index(2);
if (an_iterator == another_iterator) std::cout << "Iterator is correct" << std::endl;
```

- ```
  allocator_type get_allocator() const noexcept
  ```

  Returns a copy of the allocator used by the colony instance.

Non-member functions

Note: these are in fact member functions in the reference implementation in order to avoid an unfixed template bug in MSVC2013 (this bug is not present in any other compiler including MSVC2010/15/17).

- ```
  template <iterator_type> void advance(iterator_type iterator, distance_type distance)
  ```

  Increments/decrements the iterator supplied by the positive or negative amount indicated by *distance*. Speed of incrementation will almost always be faster than using the ++ operator on the iterator for increments greater than 1. In some cases it may be O(1). The iterator_type can be an iterator, const_iterator, reverse_iterator or const_reverse_iterator.
  Example:
  ```
  colony<int>::iterator it = i_colony.begin();
  i_colony.advance(it, 20);
  ```

- ```
  template <iterator_type> iterator_type next(const iterator_type &iterator, distance_type distance)
  ```

  Creates a copy of the iterator supplied, then increments/decrements this iterator by the positive or negative amount indicated by *distance*.
  Example:
  ```
  colony<int>::iterator it = i_colony.next(i_colony.begin(), 20);
  ```

- ```
  template <iterator_type> iterator_type prev(const iterator_type &iterator, distance_type distance)
  ```

  Creates a copy of the iterator supplied, then decrements/increments this iterator by the positive or negative amount indicated by *distance*.
  Example:
  ```
  colony<int>::iterator it2 = i_colony.prev(i_colony.end(), 20);
  ```

- ```
  template <iterator_type> difference_type distance(const iterator_type &first, const iterator_type &last) const
  ```

  Measures the distance between two iterators, returning the result, which will be negative if the second iterator supplied is before the first iterator supplied in terms of it's location in the colony. If either iterator is uninitialized, behaviour is undefined.
  Example:
  ```
  colony<int>::iterator it = i_colony.next(i_colony.begin(), 20);
  colony<int>::iterator it2 = i_colony.prev(i_colony.end(), 20);
  std::cout "Distance: " i_colony.distance(it, it2) std::endl;
  ```

Non-member functions

- ```
  template <class T, class allocator_type, typename skipfield_type&gt
  void swap (colony<T, allocator_type, skipfield_type> &A, colony<T, allocator_type, skipfield_type> &B)
  noexcept(std::allocator_traits<allocator_type>::propagate_on_container_swap::value ||
  std::allocator_traits<the_allocator>::is_always_equal::value)
  ```

  Swaps colony A's contents with that of colony B.
  Example:
  ```
  swap(object_colony, other_colony);
  ```

Appendix B - reference implementation benchmarks

Last updated 8-2-2017 v3.87

1. Test setup
2. Tests design
3. Raw performance benchmarks (against standard containers)
4. Comparitive performance benchmarks (against modified standard containers)

Test machine setup

The test setup is an Intel E8500, 8GB ram, running GCC 5.1 x64 as compiler. OS is a stripped-back Windows 7 x64 SP1 installation with the most services, background tasks (including explorer) and all networking disabled. Build settings are "-O2 -march=native -std=c++11 -fomit-frame-pointer". Results under MSVC 2015 update 3, on an Intel Xeon E3-1241 (Haswell core) can be viewed here: http://www.plflib.org/colony_benchmark_msvc_results.htm. There is no commentary for the MSVC results.

Source code for the benchmarks and the container itself can be found in the reference implementation's downloads section: http://www.plflib.org/colony.htm#download

Additional independent tests by Baptiste Wicht have been conducted on colony with numbers of elements greater than 100000. Since my testing is focussed on < 100000 elements (this was partially due to the initial use case of gaming where > 100000 elements is unlikely), this is useful balancing information. While some results follow from previously known results, others do not (and may point to issues with the current version of the reference implementation). https://baptiste-wicht.com/posts/2017/05/cpp-containers-benchmark-vector-list-deque-plf-colony.html

General test design

Tests are based on a sliding scale of number of runs vs number of elements, so a test with only 10 elements in a container may average 100000 runs to guarantee a more stable result average, whereas a test with 100000 elements may only average 10 runs. This tends to give adequate results without overly lengthening test times. I have not included results involving 'reserve()' functions as the differences to overall insertion performance were not adequate.

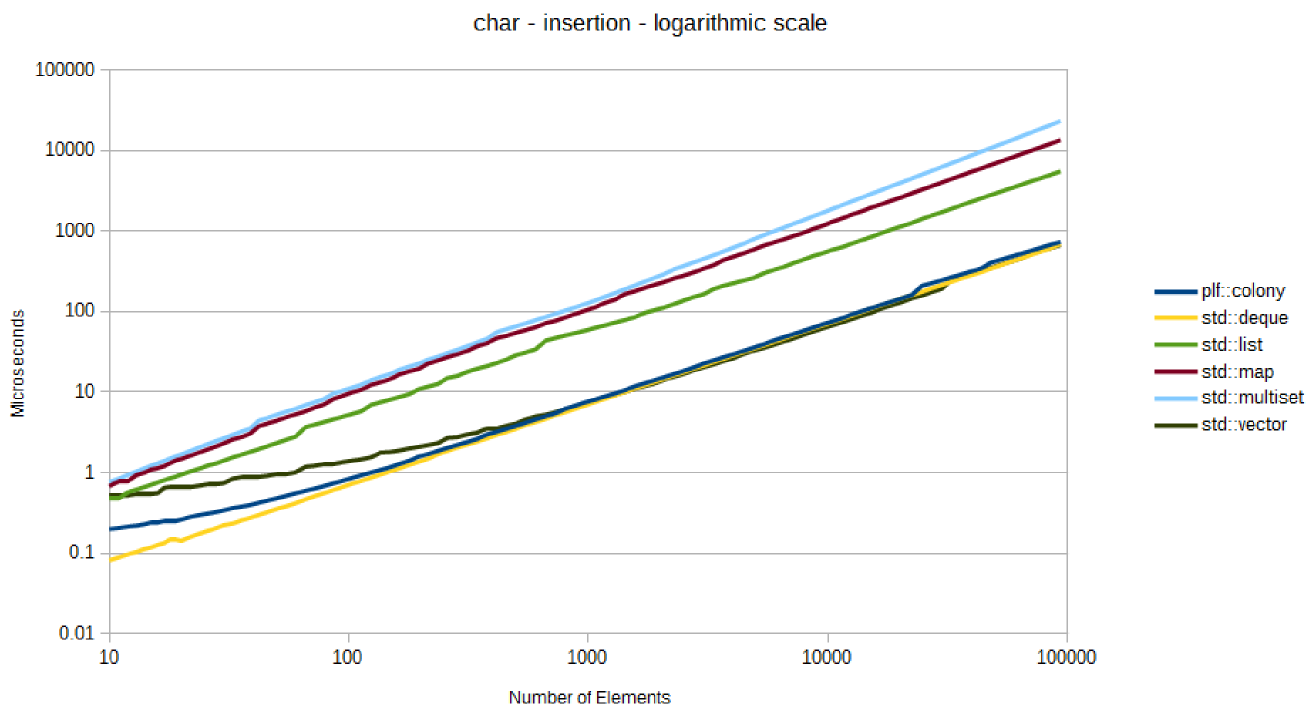
Insertion: is into empty containers for the raw and comparitive tests, entering single elements at a time. For the 'scenario' tests there is also ongoing insertion at random intervals. This matches the use case of colony, where insertion on-the-fly is expected to be one of the driving factors of usage. Insertion is always at the most performant location for the specific container, for example front for list, or back for vector.
Erasure: initially takes place in an iterative fashion for the raw tests, erasing elements at random as we iterate through the container. The exception to this is the tests involving a remove_if pattern (pointer_deque and indexed_vector) which have a secondary pass when using this pattern.
Iteration: is straightforward iteration from the start to end of any containers. Typically there are more runs for iteration than the other tests due to iteration being a much quicker procedure, so more runs deliver a more stable average.

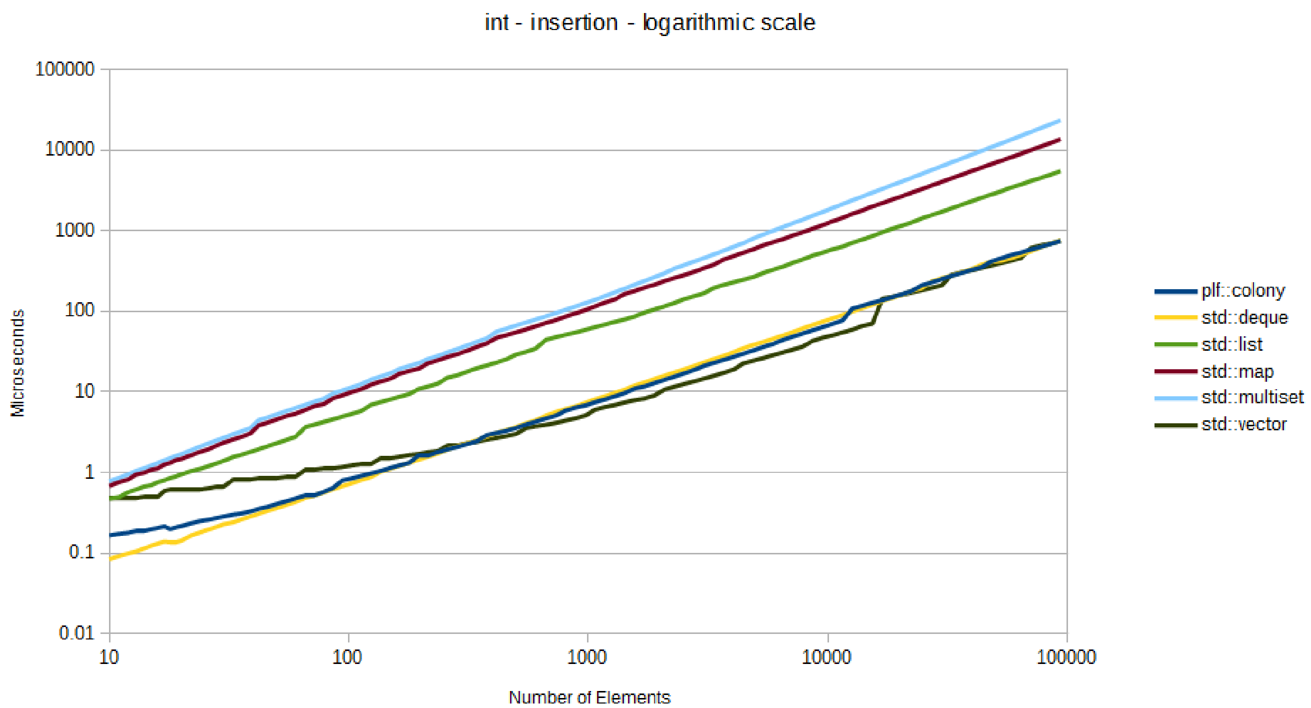
Raw performance tests

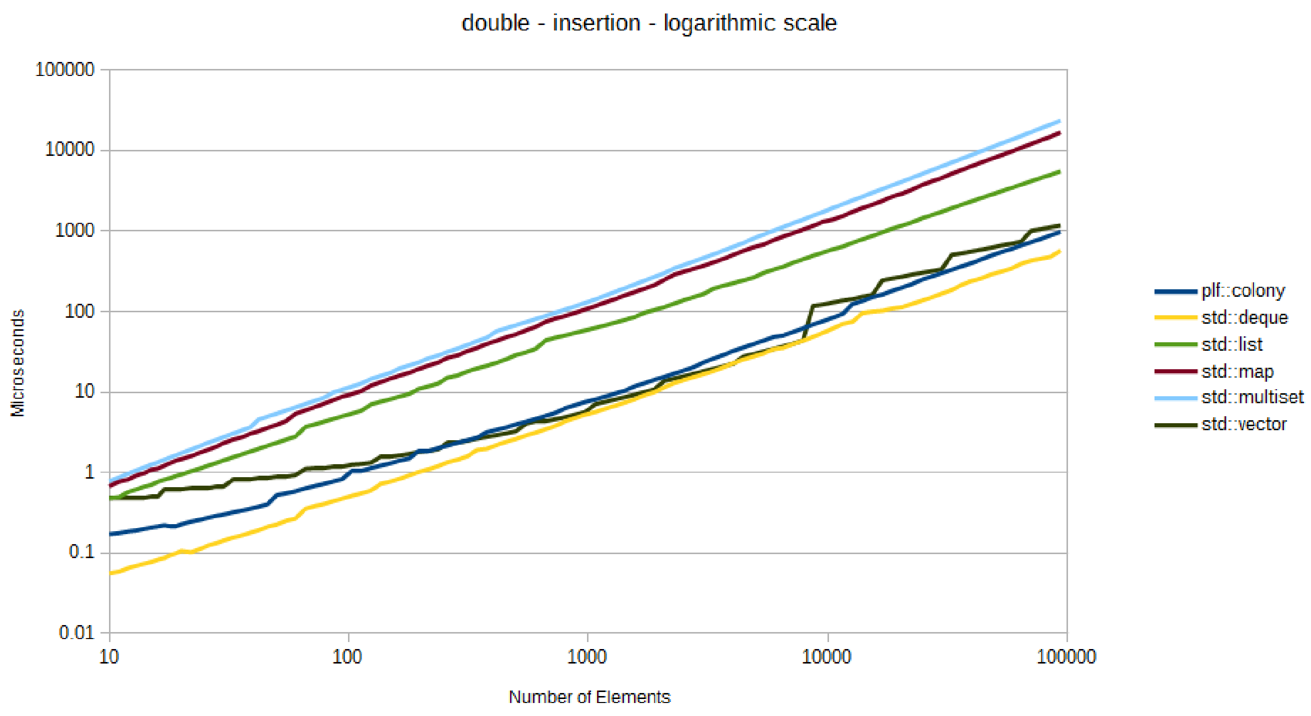
Before we begin measuring colony against containers or container modifications which do not invalidate links on erasure or insertion, we need to identify which containers are good candidates for comparison based on raw performance without regard to linkage invalidation. With that in mind the following tests compare colony against the main standard library containers. Tests are carried out on the following types: (a) a 8-bit type ie. char, (b) a 32-bit type ie. int, (c) a 64-bit type ie. double, (d) a small struct containing two pointers and four scalar types, and (e) a large struct containing 2 pointers, 4 scalar types, a large array of ints and a small array of chars.

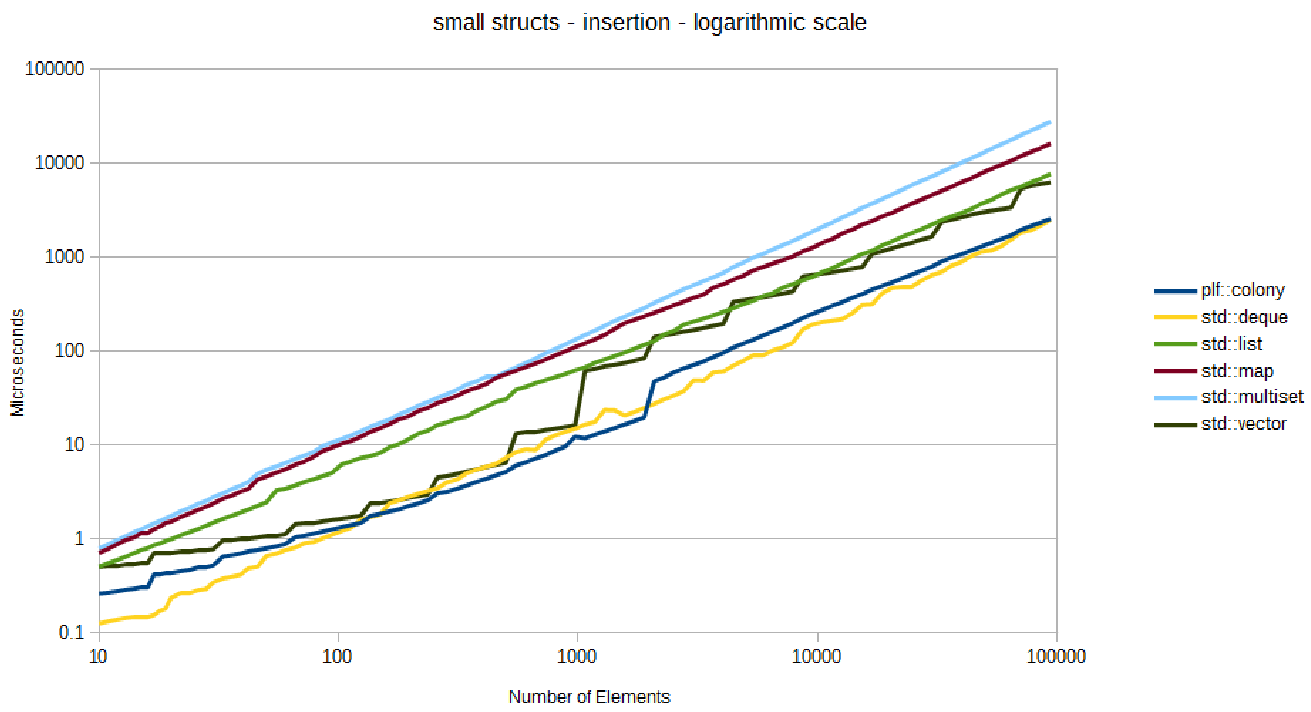
The first test measures time to insert N elements into a given container, the second measures the time taken to erase 25% of those same elements from the container, and the third test measures iteration performance after the erasure has taken place. Erasure tests avoid the remove_if pattern for the moment to show standard random-access erasure performance more clearly (this pattern is explored in the second test). Both linear and logarithmic views of each benchmark are provided in order to better show the performance of lower element amounts.

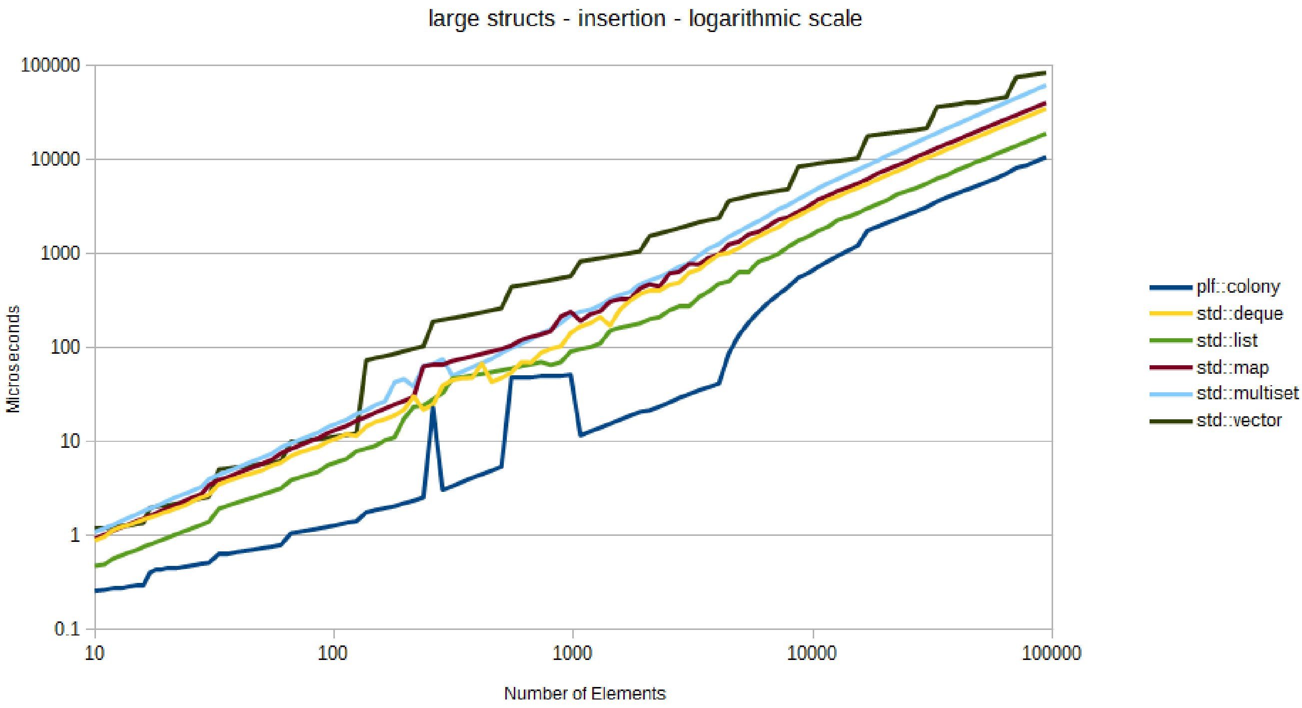
Insertion Performance


char - insertion - logarithmic scale
100000
10000
1000
100
10
1
0.1
0.01
Microseconds
10
100
1000
10000
100000
Number of Elements
plf::colony
std::deque
std::list
std::map
std::multiset
std::vector


int - insertion - logarithmic scale
100000
10000
1000
100
10
1
0.1
0.01
Microseconds
10
100
1000
10000
100000
Number of Elements
plf::colony
std::deque
std::list
std::map
std::multiset
std::vector


double - insertion - logarithmic scale
100000
10000
1000
100
10
1
0.1
0.01
Microseconds
10
100
1000
10000
100000
Number of Elements
plf::colony
std::deque
std::list
std::map
std::multiset
std::vector

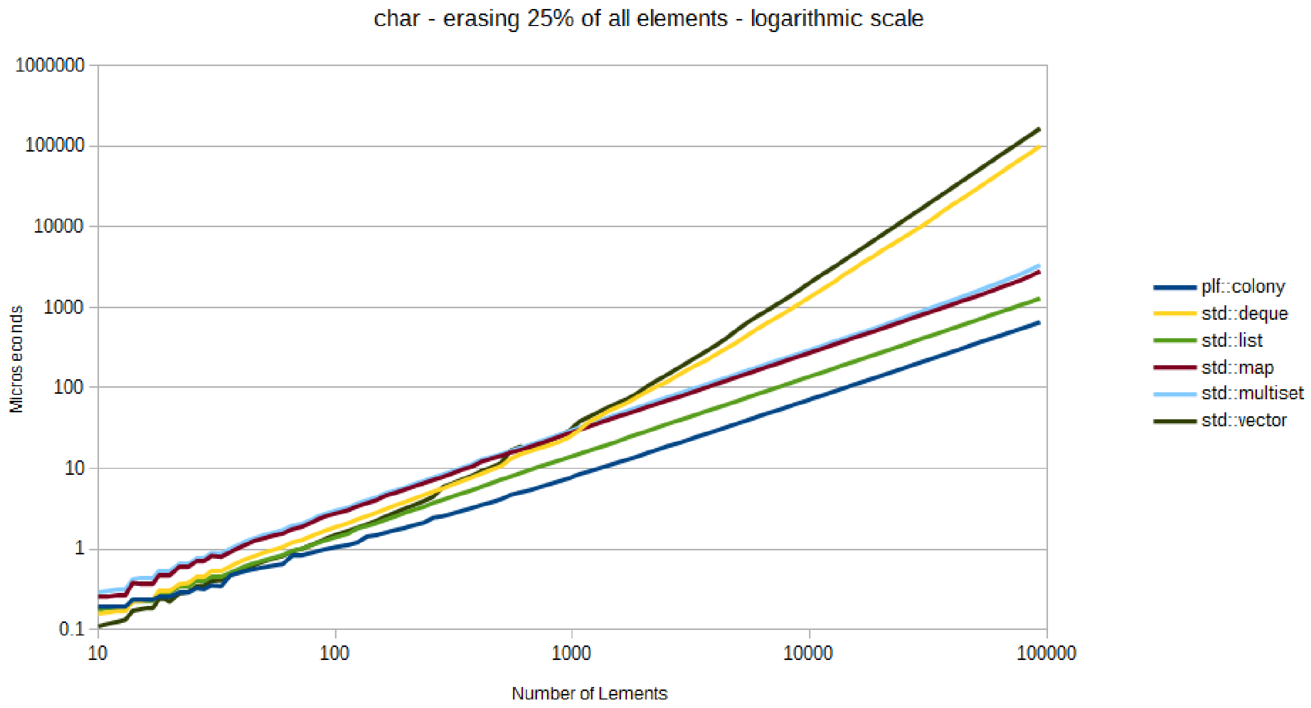

small structs - insertion - logarithmic scale
100000
10000
1000
100
10
1
0.1
Microseconds
10
100
1000
10000
100000
Number of Elements
plf::colony
std::deque
std::list
std::map
std::multiset
std::vector

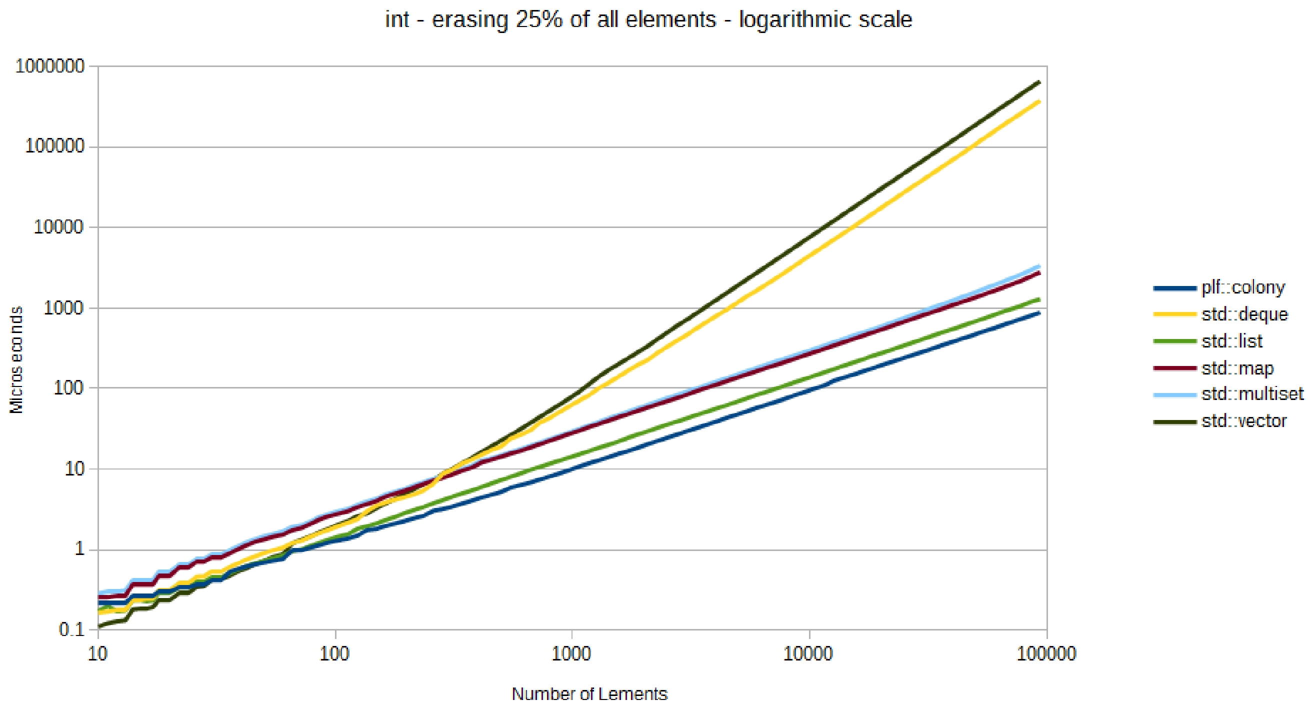


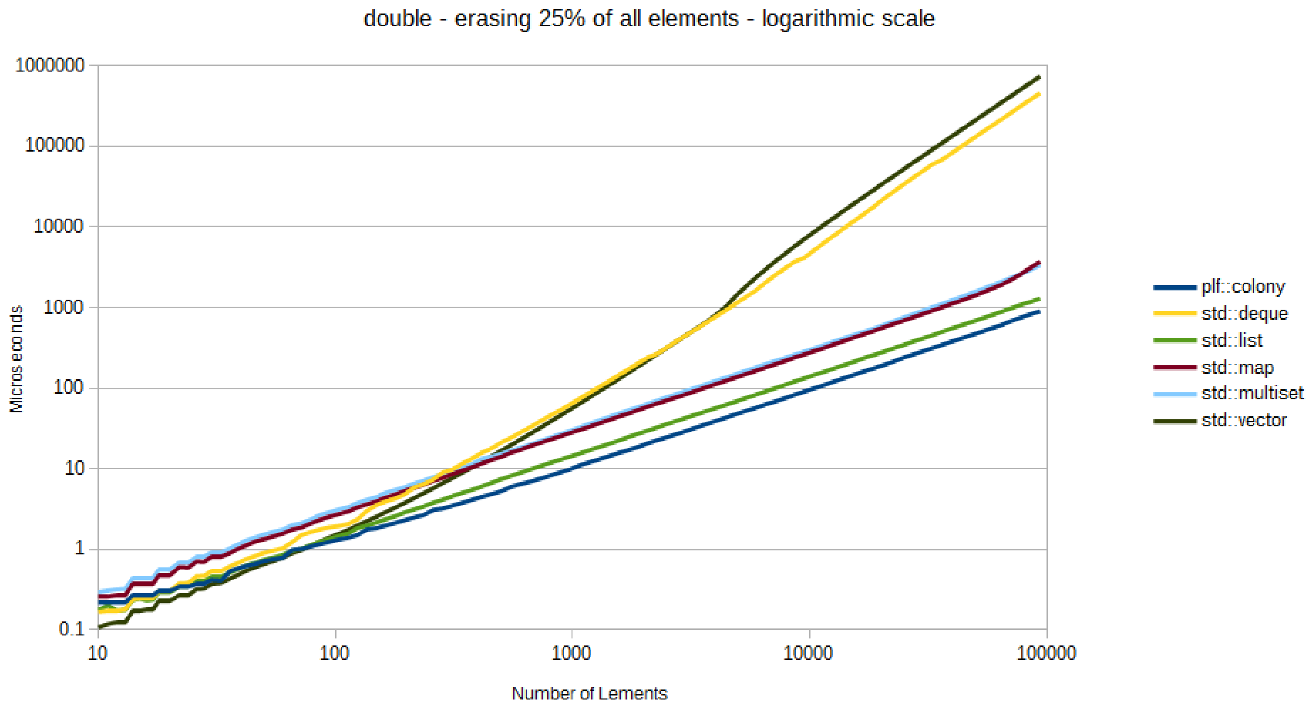
A predictable pattern for all but the large struct test is shown for insertion:
std::deque dominates insertion, with plf::colony equal after about 100 elements, but then for large structs it's performance completely eclipses std::deque. This is because libstdc++'s implementation of deque caps the memory block size at 512 bytes, whereas the large struct in question is ~506 bytes (depending on platform), meaning it, essentially, becomes a std::list but with additional overheads. Colony avoids this downfall due to it's memory allocation pattern of basing memory block sizes on fixed numbers of elements with a growth factor of 2, not fixed numbers of bytes. std::vector is nearly on a par with std::deque for very small element types with element numbers greater than a thousand, but becomes worse and worse the larger the size of the stored type is, and the fewer stored elements there are.
std::list, std::map and std::multiset all perform poorly by contrast, with the exception of large structs, where std::list comes in 2nd place to colony. Overall, plf::colony and std::deque dominate.

Erase Performance

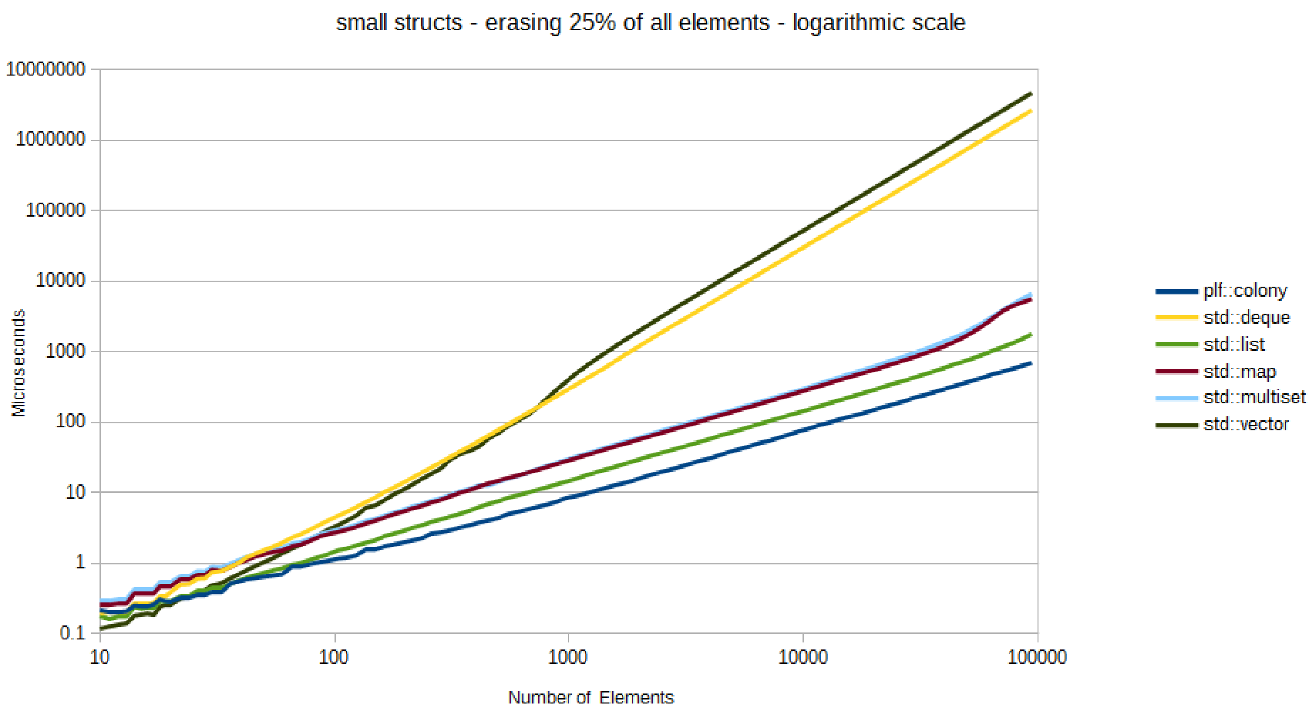
Here we forward-iterate over each container and erase 25% of all elements at random. If (due to the variability of random number generators) 25% of all elements have not been erased by the end of the container iteration, the test will reverse-iterate through the container and randomly erase the remaining necessary number of elements until that 25% has been reached.


char - erasing 25% of all elements - logarithmic scale
Micros econds
1000000
100000
10000
1000
100
10
1
0.1
10
100
1000
10000
100000
Number of Lements
plf::colony
std::deque
std::list
std::map
std::multiset
std::vector

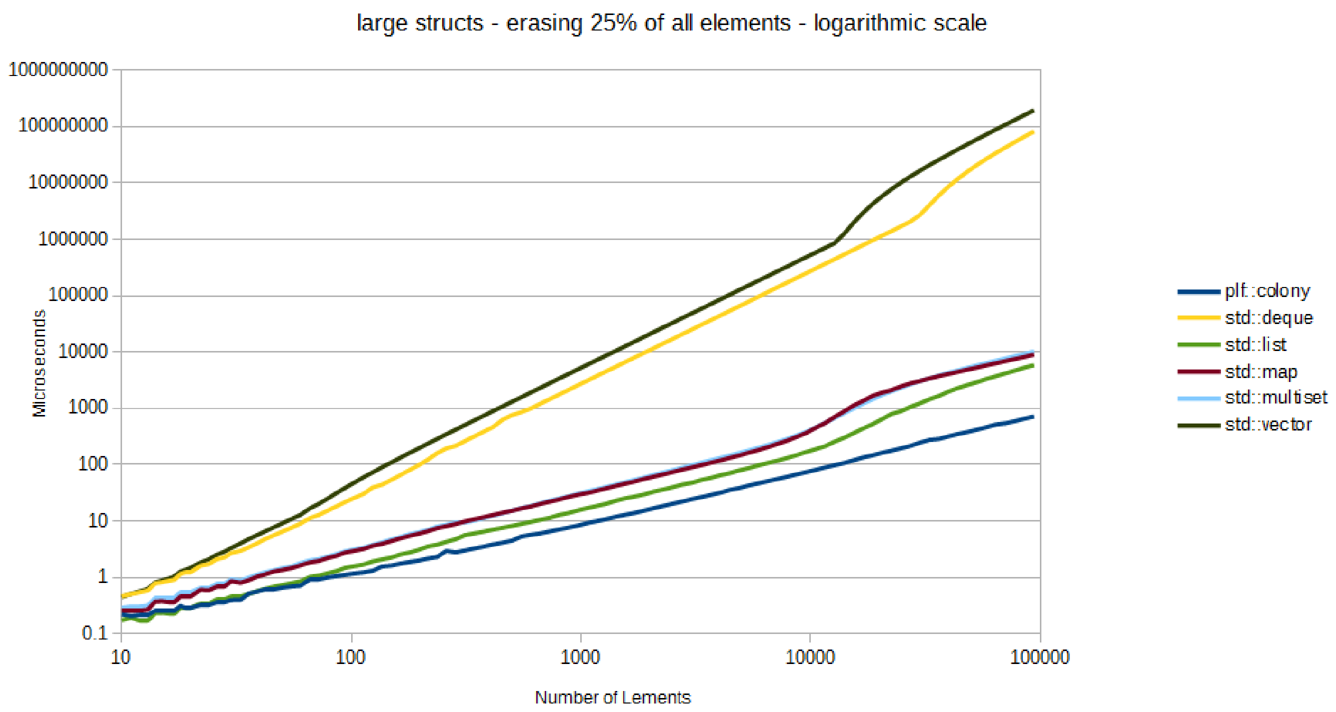

int - erasing 25% of all elements - logarithmic scale
Micros econds
1000000
100000
10000
1000
100
10
1
0.1
10
100
1000
10000
100000
Number of Lements
plf::colony
std::deque
std::list
std::map
std::multiset
std::vector



double - erasing 25% of all elements - logarithmic scale
1000000
100000
10000
1000
100
10
1
0.1
Micros econds
10
100
1000
10000
100000
Number of Lements
plf::colony
std::deque
std::list
std::map
std::multiset
std::vector



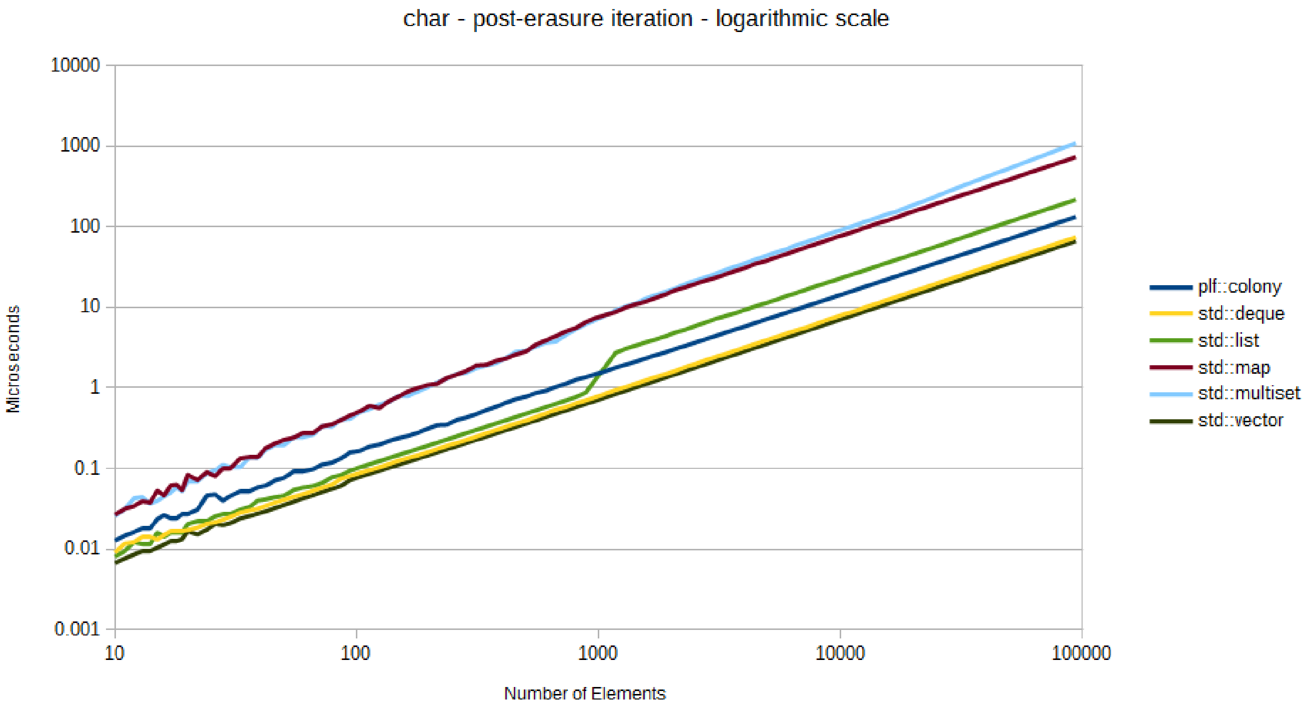
small structs - erasing 25% of all elements - logarithmic scale
10000000
1000000
100000
10000
1000
100
10
1
0.1
Microseconds
10
100
1000
10000
100000
Number of Elements
plf::colony
std::deque
std::list
std::map
std::multiset
std::vector

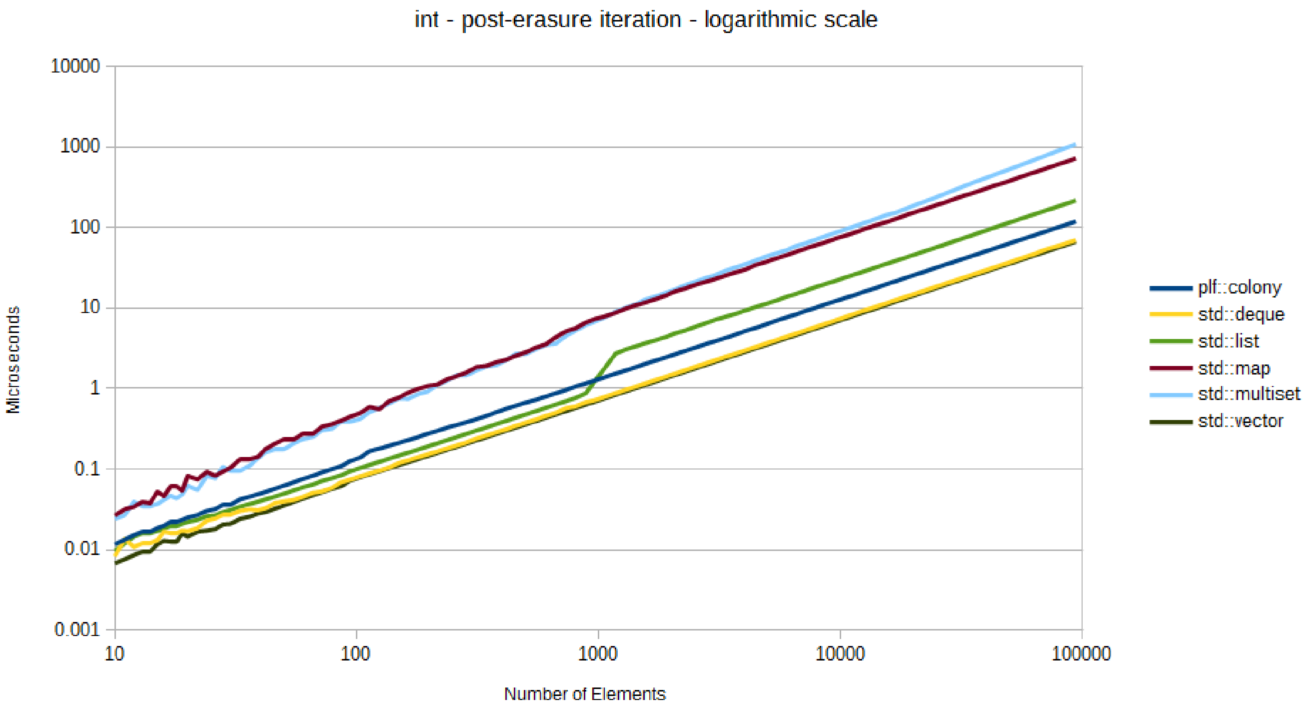


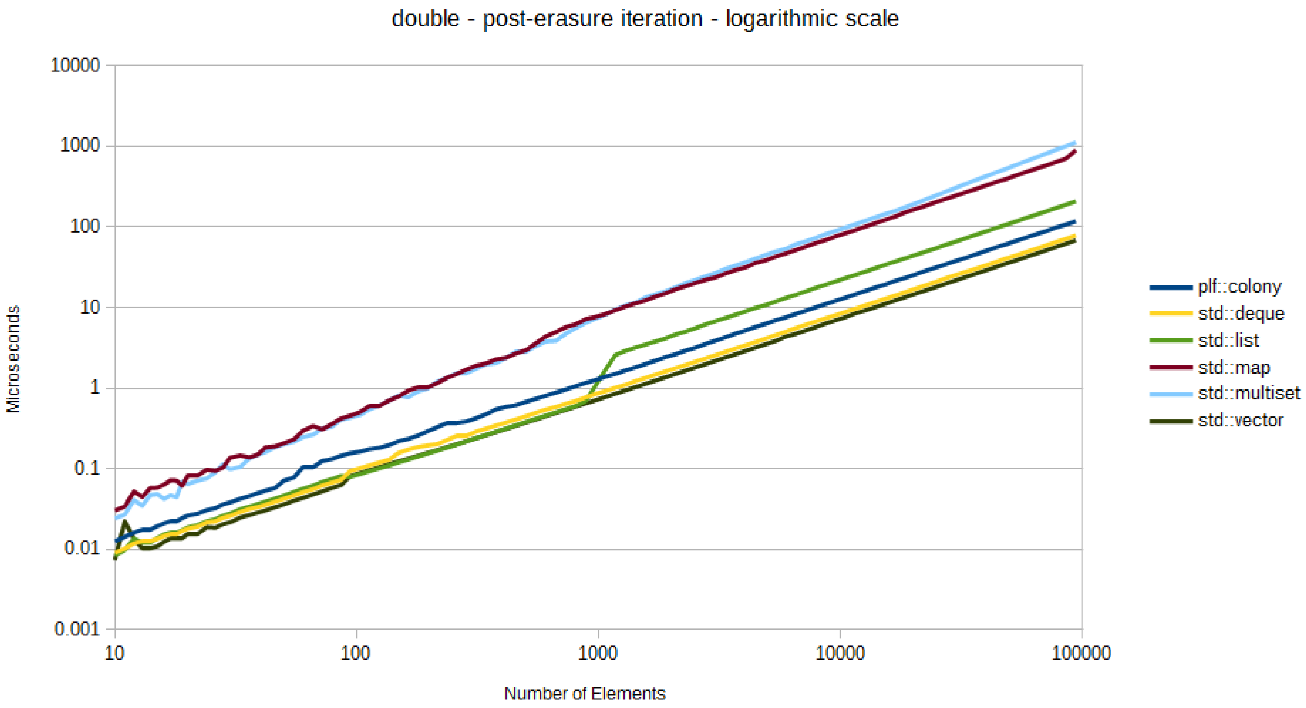
Across all types plf::colony dominates performance, with std::list coming close behind. std::deque and std::vector have predictably poor performance as a remove_if pattern is not being used, as much as 100000x worse than plf::colony and std::list for large numbers of large types.

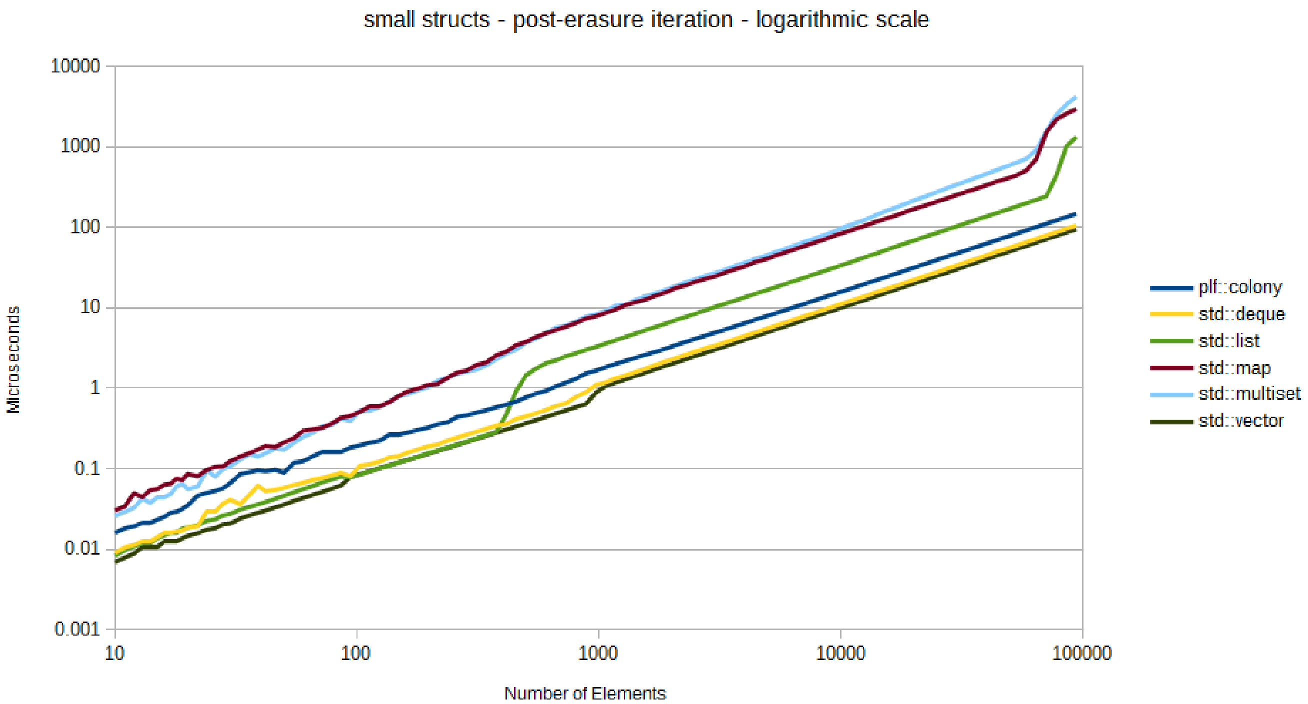
Post-erasure Iteration Performance

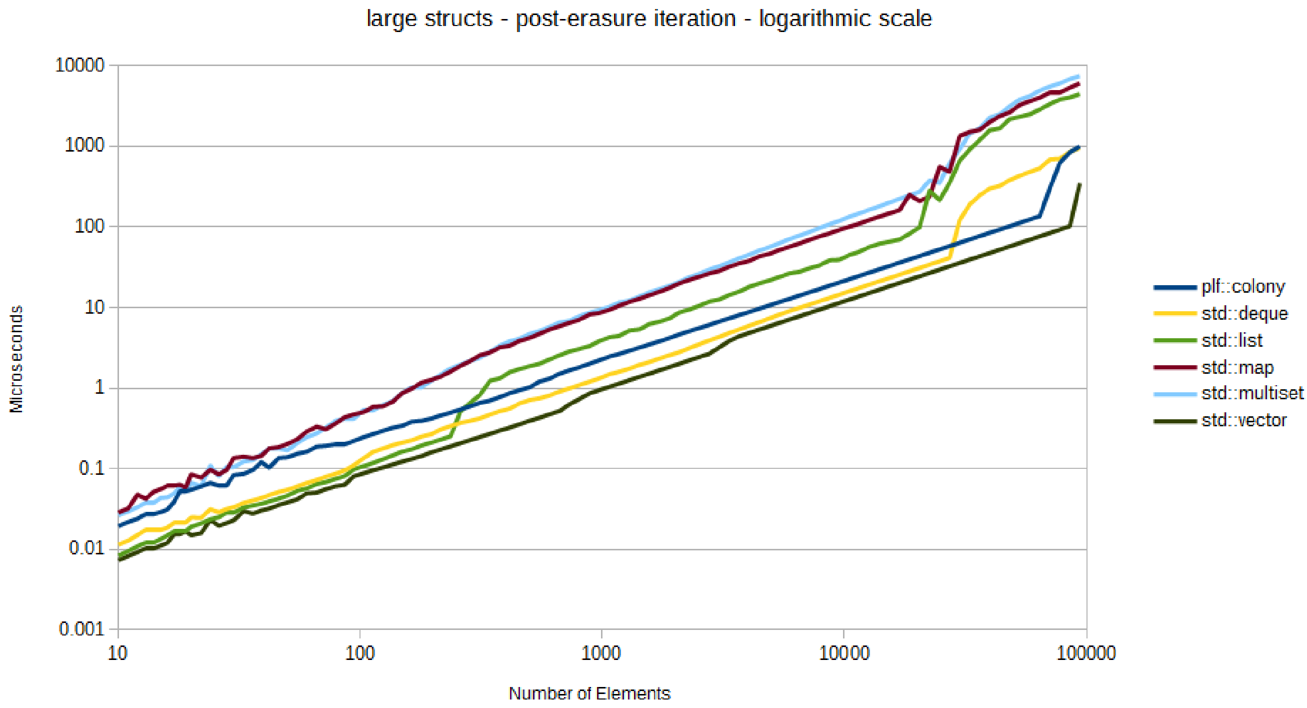
Since data is typically iterated across more than it is erased or inserted, iteration speed is, for many areas, more important than erase or insertion performance, despite the fact that it almost always takes factors of ten less time than either of those two.


char - post-erasure iteration - logarithmic scale
Microseconds
10000
1000
100
10
1
0.1
0.01
0.001
10
100
1000
10000
100000
Number of Elements
plf::colony
std::deque
std::list
std::map
std::multiset
std::vector


int - post-erasure iteration - logarithmic scale
Microseconds
10000
1000
100
10
1
0.1
0.01
0.001
10
100
1000
10000
100000
Number of Elements
plf::colony
std::deque
std::list
std::map
std::multiset
std::vector


double - post-erasure iteration - logarithmic scale
10000
1000
100
10
1
0.1
0.01
0.001
Microseconds
10
100
1000
10000
100000
Number of Elements
plf::colony
std::deque
std::list
std::map
std::multiset
std::vector


small structs - post-erasure iteration - logarithmic scale
10000
1000
100
10
1
0.1
0.01
0.001
Microseconds
10
100
1000
10000
100000
Number of Elements
plf::colony
std::deque
std::list
std::map
std::multiset
std::vector



std::vector and std::deque come in first and second place for most types, with colony in third place - the only place where this does not occur is for large structs, where colony dominates std::deque after approximately 20000 elements are inserted. Once again this is due to the structure of deque as explained in the insertion conclusion above.

For under 1000 elements, std::list is about on par with both std::deque and std::vector, both of which dominate these tests, with std::vector taking 1st place. However the number of elements necessary before this effect occurs on std::list decreases according to how large the stored type is, suggesting that performance in this case is due to some effect of the cpu cache or implementation. Querying the GCC mailing list about this resulted in the following response, which I believe to be accurate due to the correlation between std::list iteration performance and type size: "I suspect that for working sets which fit into the first-level cache of the CPU, the simpler iterators for std::list are faster than std::deque because the additional memory accesses in std::list are cheaper than the fairly complicated iterator implementation in std::deque". What this suggests is that for typical programs, where more than one data set is competing for space in the L1 or L2 caches, std::list performance will not follow the pattern above and generally will be poor.

Raw tests Conclusion

From the above data we can see that std::list is not a good contendor against plf::colony, as it has weaker insertion and erase performance, and the only scenario where it has good iteration performance is where (a) the amount of data in the container is small enough to fit entirely into the cache and (b) where that data set is the only data set being operated on by the program in question, and in fact the computer as a whole. That being a relatively uncommon case, std::list is not a general contendor.

std::deque is a contendor, having strong insertion performance and excellent iteration performance but poor non-remove_if erasure performance - however std::deque invalidates pointers upon erasure, meaning it requires modification to be used in a way comparable to colony. std::vector is a slightly weaker contendor, having weak insertion performance and worse non-remove_if erasure performance than std::deque, however it's iteration performance is always the best, being entirely contiguous in memory, rather than deque which is only partially contiguous. std::vector invalidates pointers on both insertion and erasure, meaning it will also require modification to compare to colony.

Comparative performance tests

Colony is primarily designed for scenarios where good insertion/erasure/iteration performance is required while guarantee'ing linkage stability for outside elements referring to elements within the container, and where ordered insertion is unimportant. The two containers from the raw performance tests which may compare both in performance and usage (after modification) are std::deque and std::vector. std::list does not meet these requirements as it has poor insertion and iteration performance.

pointer_deque and indexed_vector

Because std::deque does not invalidate pointers to elements upon insertion to the back or front, we can guarantee that pointers won't be invalidated during unordered insertion. This means we can use a modification called a 'pointer-to-deque deque', or pointer_deque. Here we take a deque of elements and construct a secondary deque containing pointers to each element in the first deque. The second deque functions as an erasable iteration field for the first deque ie. when we erase we only erase from the pointer deque, and when we iterate, we iterate over the pointer deque and access only those elements pointed to by the pointer deque. In doing so we reduce erase times for larger-than-scalar types, as it is computationally cheaper to reallocate pointers (upon erasure) than larger structs. By doing this we avoid reallocation during erasure for the element deque, meaning pointers to elements within the element deque stay valid.

We cannot employ quite the same technique with std::vector because it reallocates during insertion to the back of the vector upon capacity being reached. But since indexes stay valid regardless of a vector reallocates, we can employ a similar tactic using indexes instead of pointers; which we'll call an indexed_vector. In this case we use a secondary vector of indexes to iterate over the vector of elements, and only erase from the vector of indexes. This strategy has the advantage of potentially lower memory usage, as the bitdepth of the indexes can be reduced to match the maximum known number of elements, but it will lose a small amount of performance due to the pointer addition necessary to utilise indexes instead of pointers. In addition outside objects refering to elements within the indexed_vector must use indexes instead of pointers to refer to the elements, and this means the outside object must know both the index and the container it is indexing; whereas a pointer approach can ignore this and simply point to the element in question.

We will also compare these two container modifications using a *remove_if* pattern for erasure vs regular erasure, by adding an additional boolean field to indicate erasure to the original stored struct type, and utilizing two passes - the first to randomly flag elements as being ready for erasure via the boolean field, the second using the *remove_if* pattern.

vector_bool and deque_bool

A second modification approach, which we'll call a vector_bool, is a very common approach in a lot of game engines - a bool or similar type is added to the original struct or class, and this field is tested against to see whether or not the object is 'active' (true) - if inactive (false), it is skipped over. We will also compare this approach using a deque.

packed_deque

packed_deque is an implementation of a ['packed_array'] as described in the motivation section earlier, but using deques instead of vectors or arrays. As we've seen in the raw performance benchmarks, (GCC) libstdc++'s deque is almost as fast as vector for iteration, but about twice as fast for back insertion and random location erasure. It also doesn't invalidate pointers upon insertion, which is also a good thing. These things become important when designing a container which is meant to handle large numbers of insertions and random-location erasures. Although in the case of a packed-array, random location erasures don't really happen, the 'erased' elements just get replaced with elements from the back, so erasure speed is not as critical, but insertion speed is critical as it will always consume significantly more CPU time than iteration.

With that in mind my implementation uses two std::deque's internally: one containing structs which package together the container's element type and a pointer, and one containing pointers to each of the 'package' structs in the first deque. The latter is what is used by the container's 'handle' class to enable external objects to refer to container elements. The pointer in the package itself in turn points to the package's corresponding 'handle' pointer in the second deque. This enables the container to update the handle pointer when and if a package is moved from the back upon an erasure.

Anyone familiar with packed array-style implementations can skip this paragraph. For anyone who isn't, this is how it works when an element is erased from packed_deque, unless the element in question is already at the back of the deque. It:

1. Uses the pointer within the package to find the 'handle' pointer which pointed to the erased element, and adds it to a free list.
2. Moves the package at the back of the container to the location of the package containing the element being erased.
3. Uses the pointer in the package which has just been moved to update the corresponding handle pointer, to correctly point to the package's new location.
4. Pops the back package off the first deque (should be safe to destruct after the move - if it's not, the element's implementation is broke).

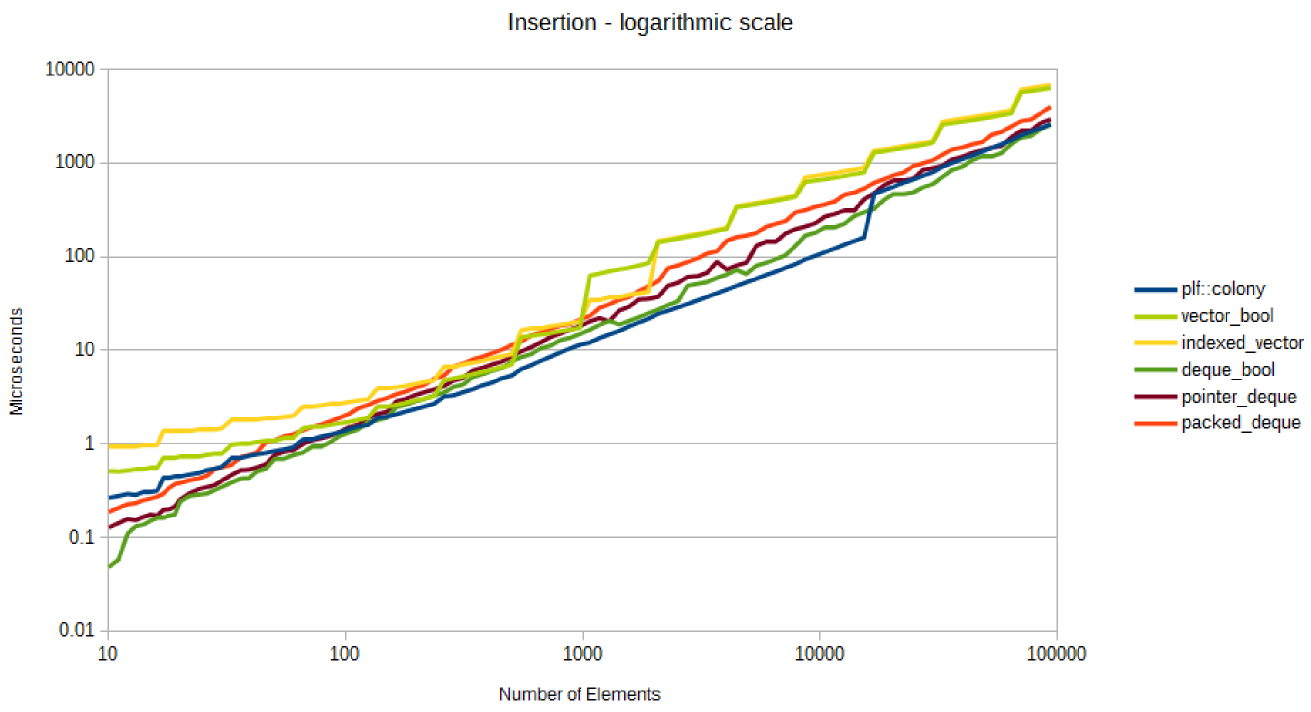
In this way, the data in the first deque stays contiguous and is hence fast to iterate over. And any handles referring to the back element which got moved stay valid after the erasure.

This implementation will not work well under MSVC as MSVC's deque implementation performs badly.

Tests

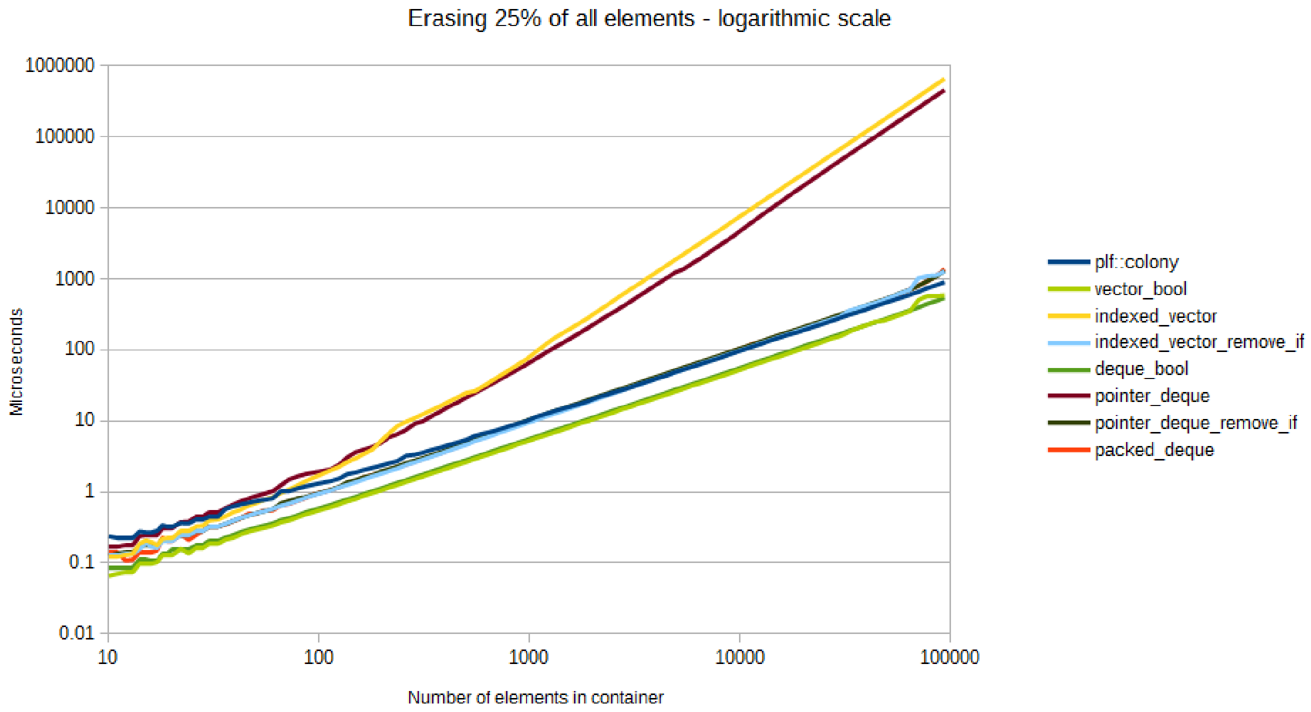
Since neither indexed_vector nor pointer_deque will have erasure time benefits for small scalar types, and because game development is predominantly concerned with storage of larger-than-scalar types, we will only test using small structs from this point onwards. In addition, we will test 4 levels of erasure and subsequent iteration performance: 0% of all elements, 25% of all elements, 50% of all elements, and 75% of all elements.

Insertion

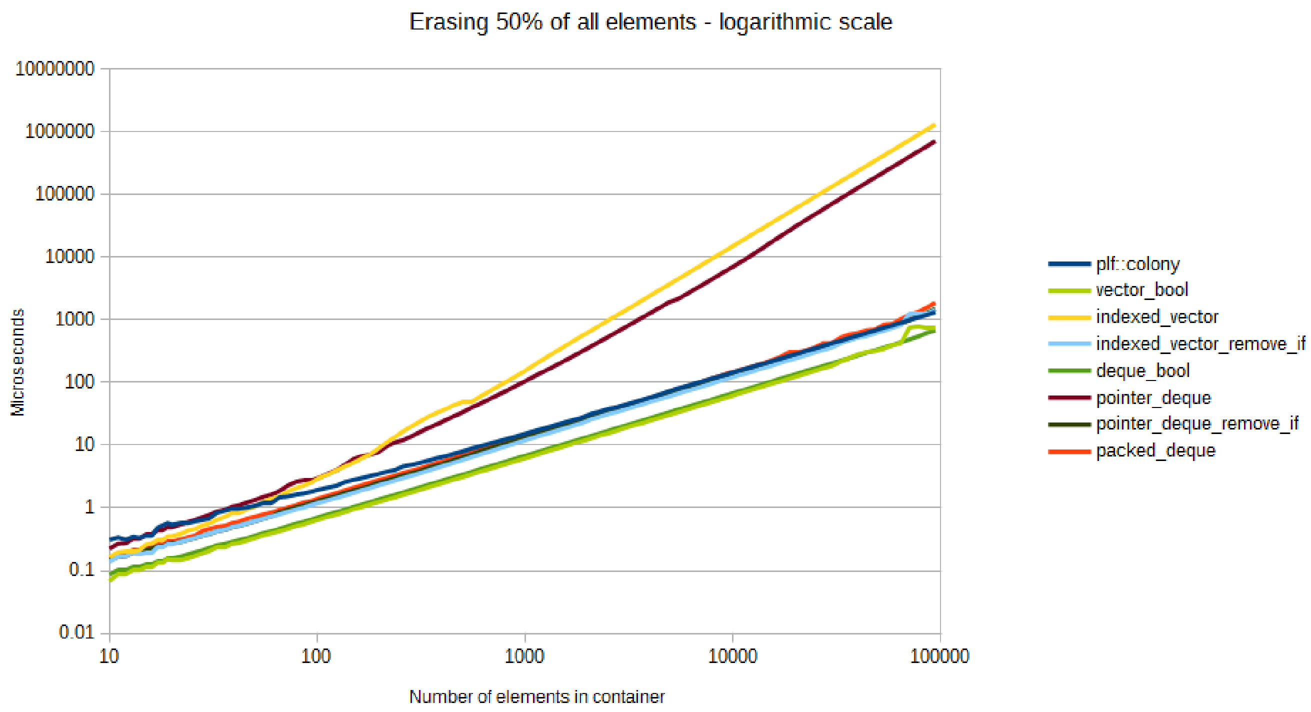


For insertion plf::colony outperforms the others for greater than 100 and less than 20000 elements. Below 100 elements it is outperformed by pointer_deque and deque_bool, and above 20000 elements it is outperformed by deque_bool. packed_deque consistently comes 4th, and both vector methods perform poorly by contrast.

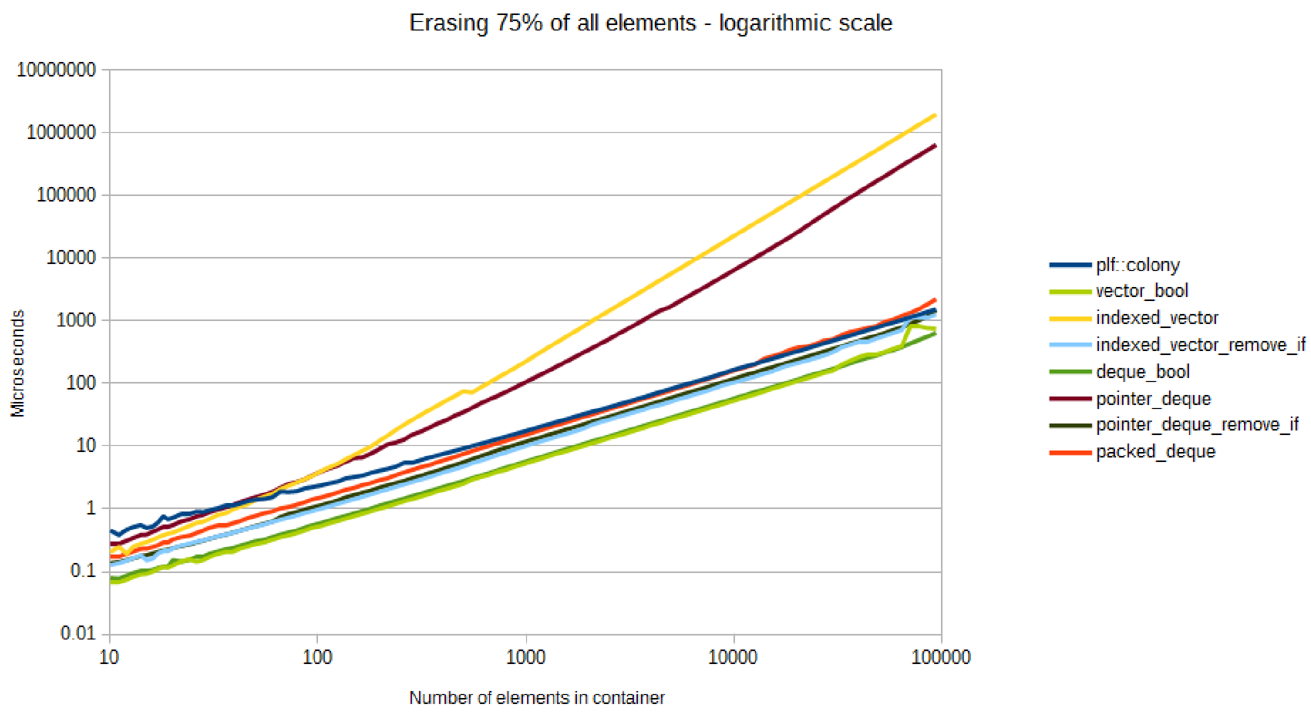
Erasure



Erasing 25% of all elements - logarithmic scale
1000000
100000
10000
1000
100
10
1
0.1
0.01
Microseconds
10
100
1000
10000
100000
Number of elements in container
plf::colony
vector_bool
indexed_vector
indexed_vector_remove_if
deque_bool
pointer_deque
pointer_deque_remove_if
packed_deque

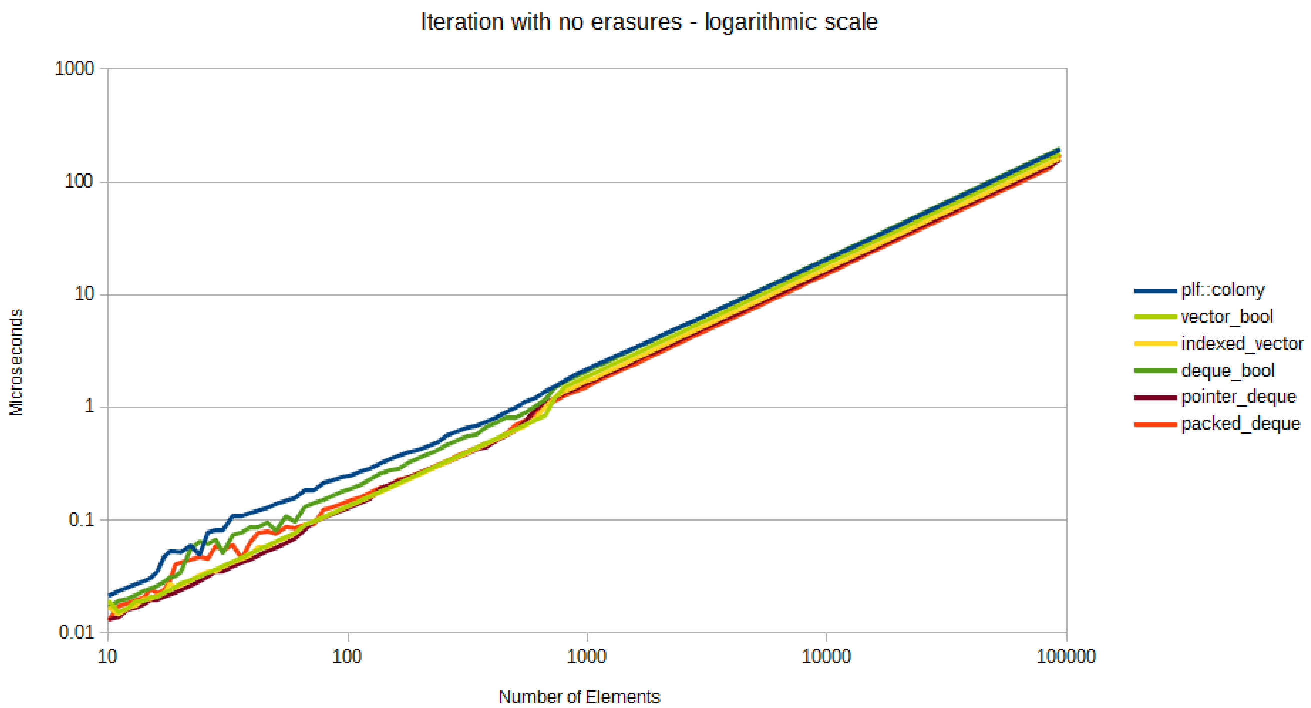


Erasing 50% of all elements - logarithmic scale
10000000
1000000
100000
10000
1000
100
10
1
0.1
0.01
Microseconds
10
100
1000
10000
100000
Number of elements in container
plf::colony
vector_bool
indexed_vector
indexed_vector_remove_if
deque_bool
pointer_deque
pointer_deque_remove_if
packed_deque

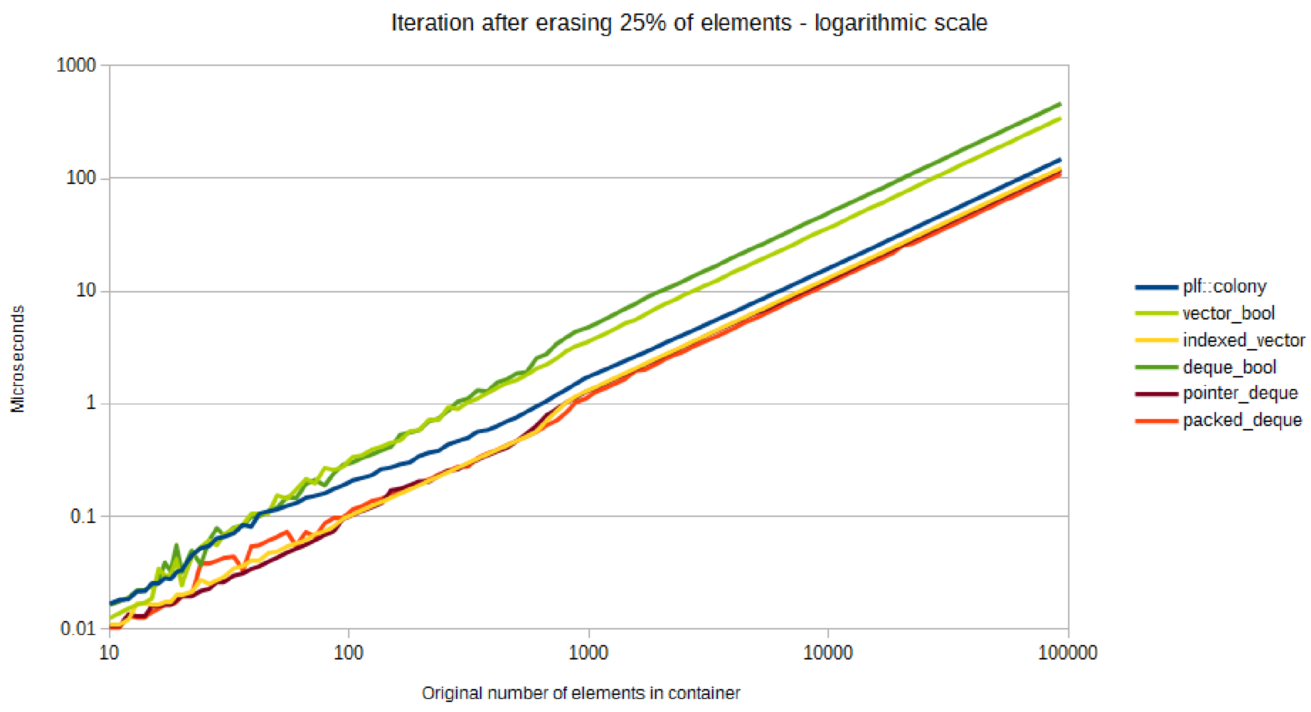


Here the gap consistently widens between the candidates as erasure percentage increases. The two boolean skipfield methods obviously dominate performance, being the easiest and fastest to implement in terms of erasure. Above 25% erasure both of the remove_if variants outperform the others, with packed_deque and colony criss-crossing each other in terms of performance. The non-remove_if variants of pointer_deque and indexed_vector of course perform poorly.

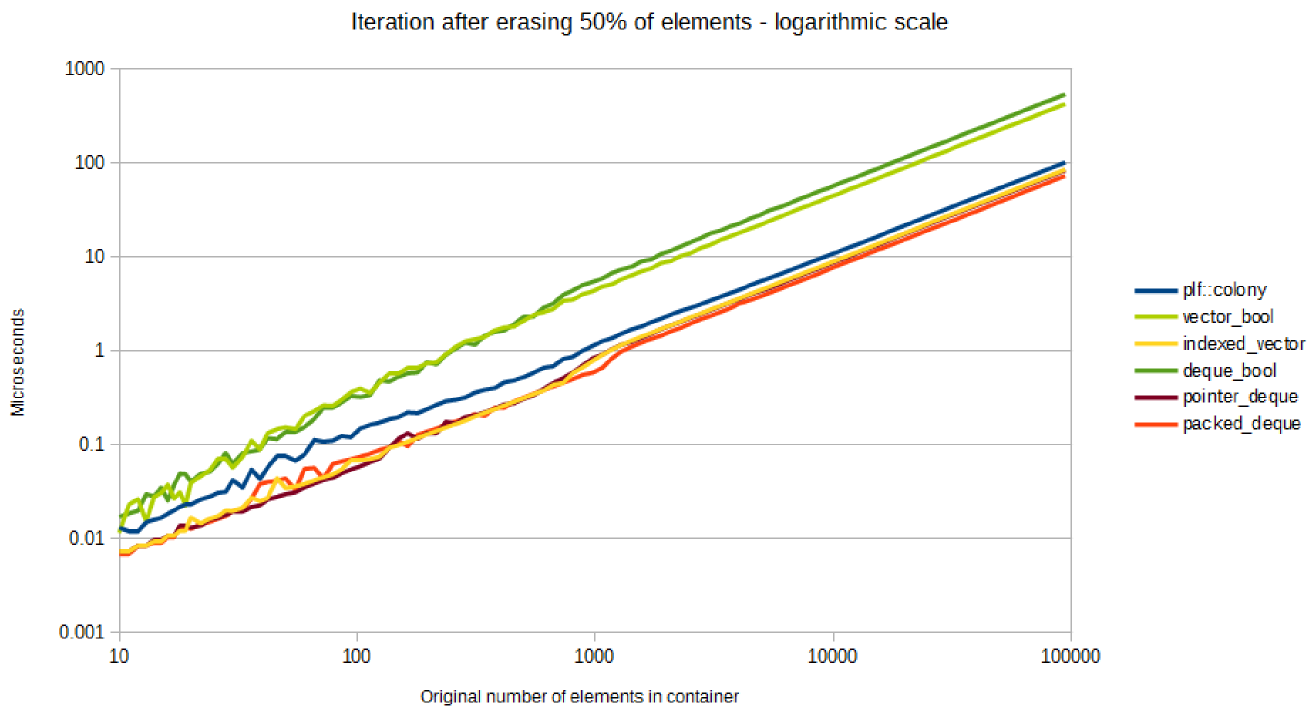
Post-erasure Iteration



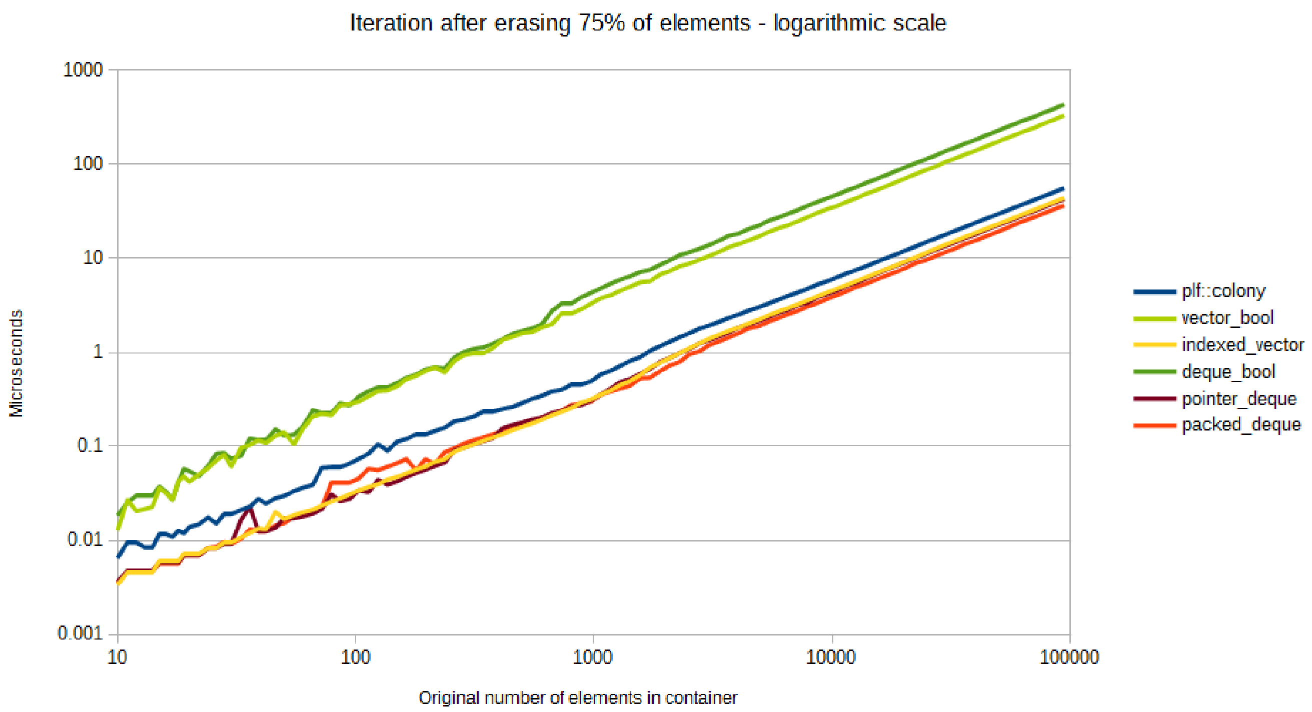
Colony performs the worst out of the lot for iteration with zero erasures, with deque_bool coming in slightly worse only for large numbers of elements. Unsurprisingly packed_deque performs the best out of the lot as this constitutes pure contiguous iterative performance with no skipfield or iteration field. While close, the pointer_deque approach has a slight performance advantage over the indexed_vector.



Now we begin to see the advantage of a jump-counting skipfield over a boolean skipfield. Because boolean skipfields require branching code to iterate over, and 25% of all elements being erased represents a large number of cache misses. Other than that the results are much the same as the 0% test.



At 50% randomised erasures, a CPU's branch prediction cannot work at all, and so the boolean approaches degrade significantly.



At this point we can clearly see that the boolean approaches are not useful in terms of iteration.

Summary: for iteration packed_deque comes 1st, pointer_deque 2nd, indexed_vector 3rd, colony 4th, vector_bool 5th and deque_bool 6th.

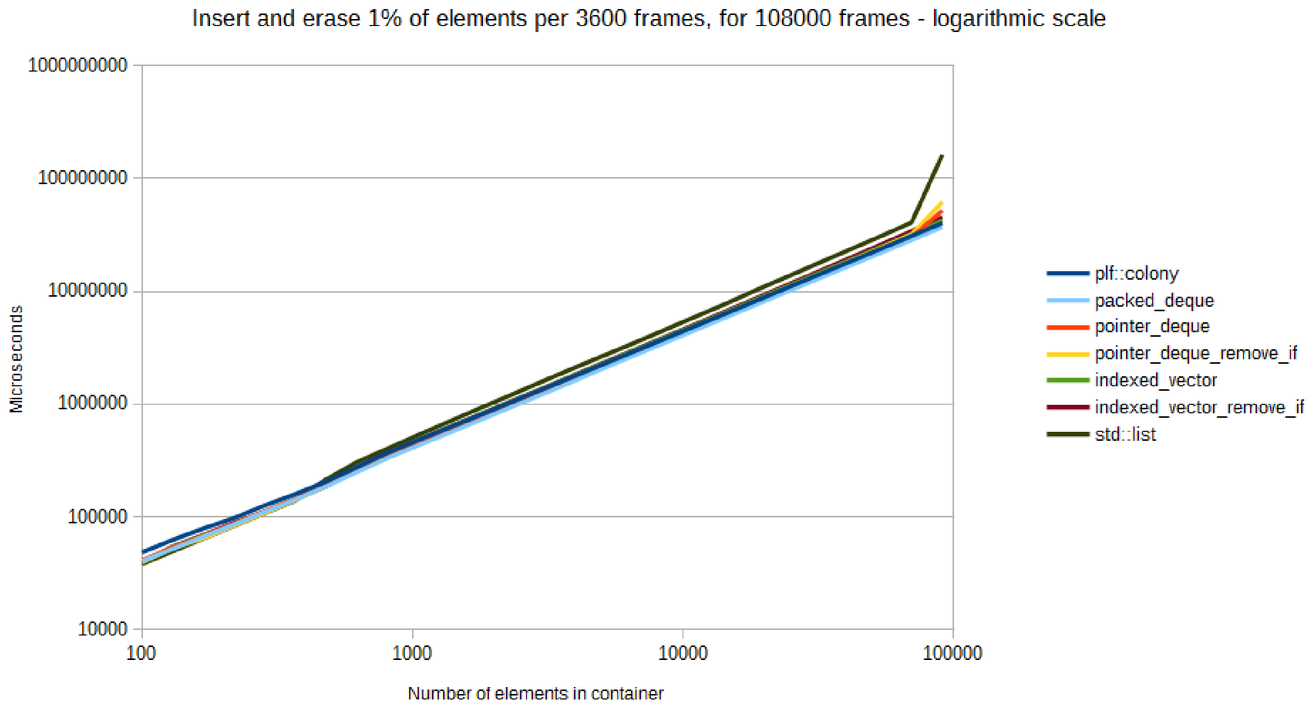
'Real-world' scenario testing - low modification

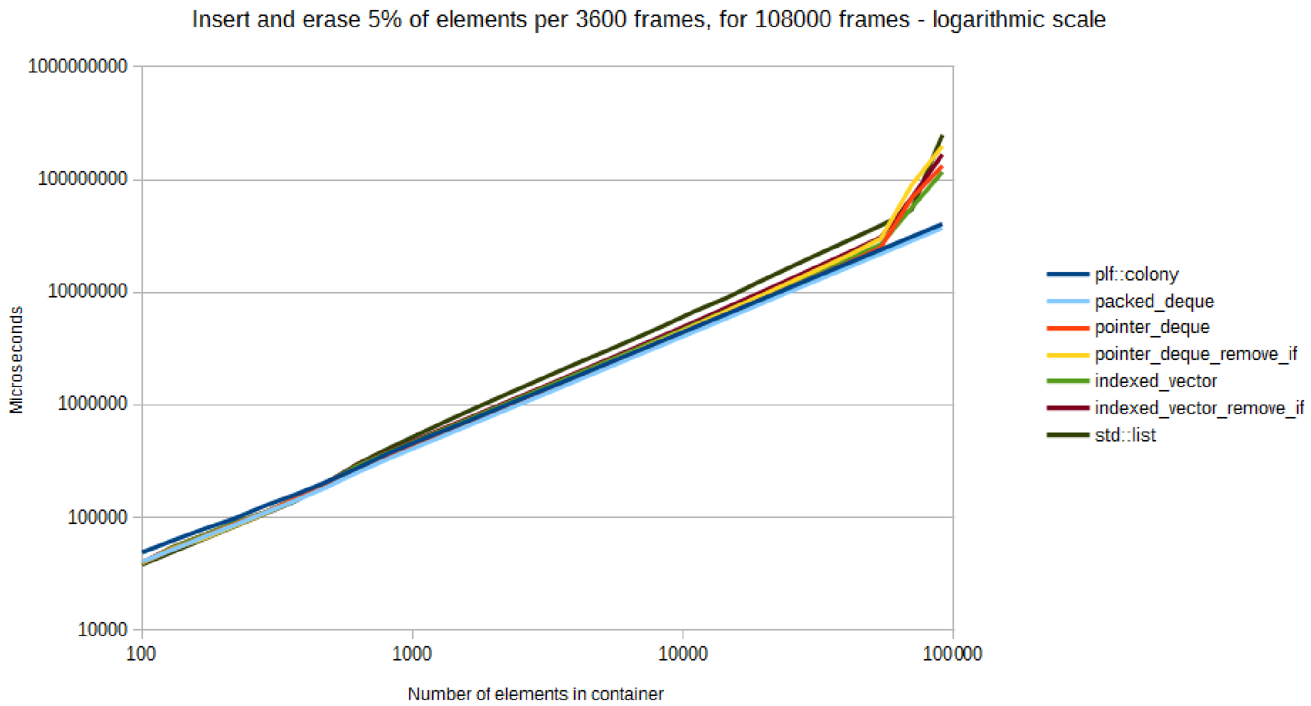
While testing iteration, erasure and insertion separately can be a useful tool, they don't tell us how containers perform under real-world conditions, as under most use-cases we will not be simply inserting a bunch of elements, erasing some of them, then iterating once over the data. To get more valid results, we need to think about the kinds of use-cases we may have for different types of data, in this cas, video-game data.

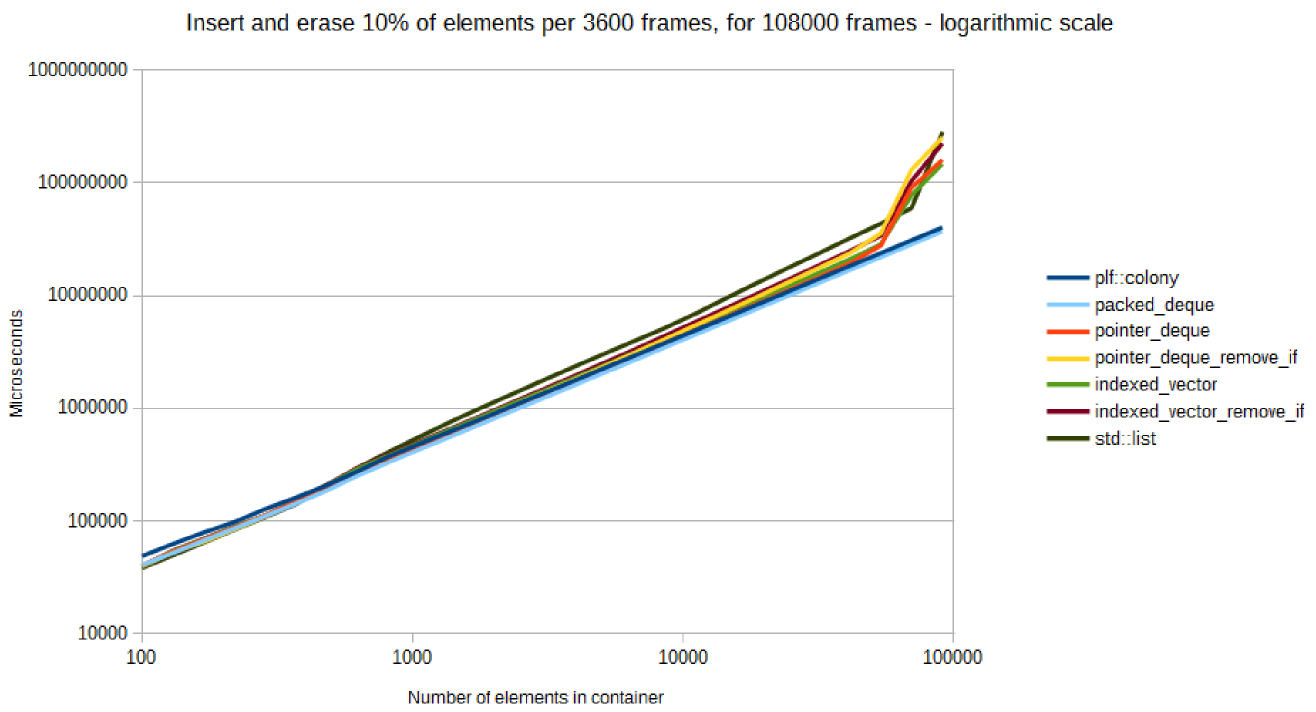
In this test we simulate the use-case of a container for general video game objects, actors/entities, enemies etc. Initially we insert a number of small structs into the container, then simulate in-game 'frames'. We iterating over container elements every frame, and erase(at random locations)/insert 1% of the original number of elements for every minute of gametime ie. 3600 frames assuming 60 frames-per-second. We measure the total time taken to simulate this scenario for 108000 frames (half an hour of simulated game-time, assuming 60 frames per second), as well as the amount of memory used by the container at the end of the test. We then re-test this scenario with 5% of all elements being inserted/erased, then 10%.

With some reluctance I have also included the results for std::list in this test and the high modification tests, despite the fact that the earlier 'raw' performance tests show that it is not a contendor for colony, at least in the same problem domain. This is because some people were not able to relate the raw performance test outcomes to the expected outcomes of subsequent tests. By contrast there is less point again in including std::map/std::multiset for these tests, as their raw iteration, erasure, and insertion outcomes were significantly worse than other containers.

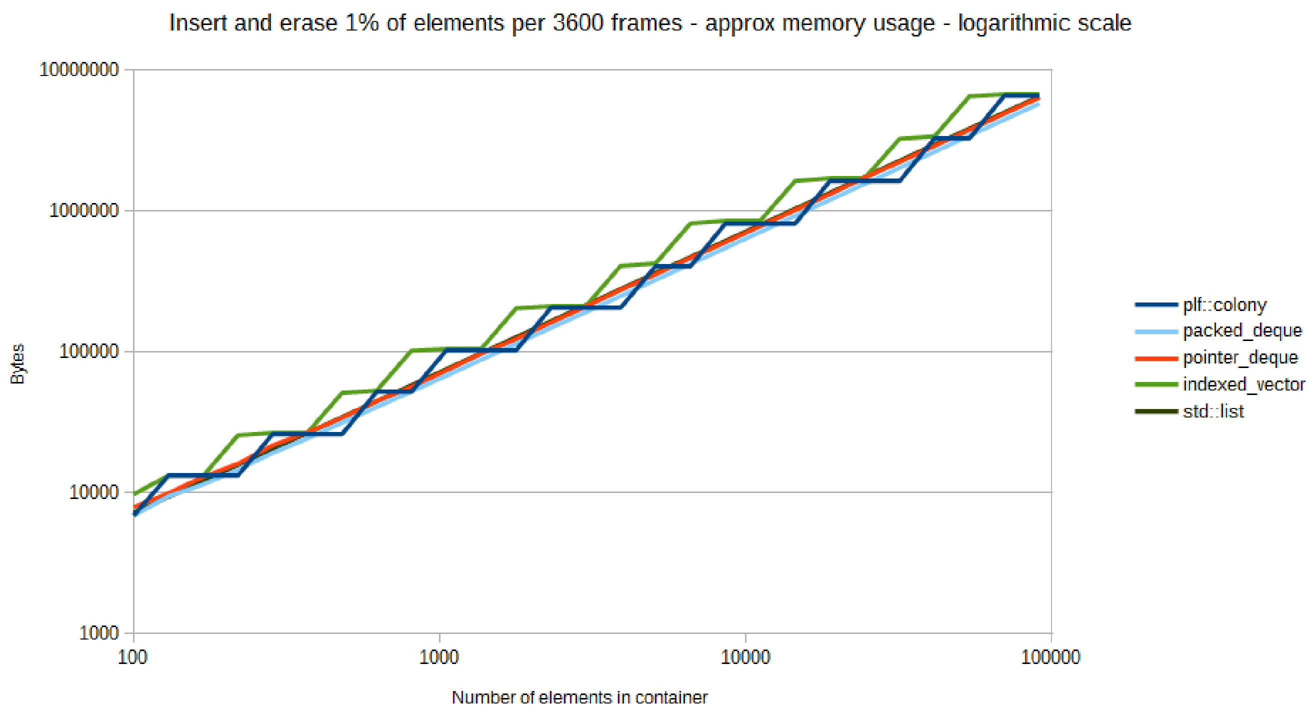
Performance results


Insert and erase 1% of elements per 3600 frames, for 108000 frames - logarithmic scale
1000000000
100000000
10000000
1000000
100000
10000
Microseconds
100
1000
10000
100000
Number of elements in container
plf::colony
packed_deque
pointer_deque
pointer_deque_remove_if
indexed_vector
indexed_vector_remove_if
std::list

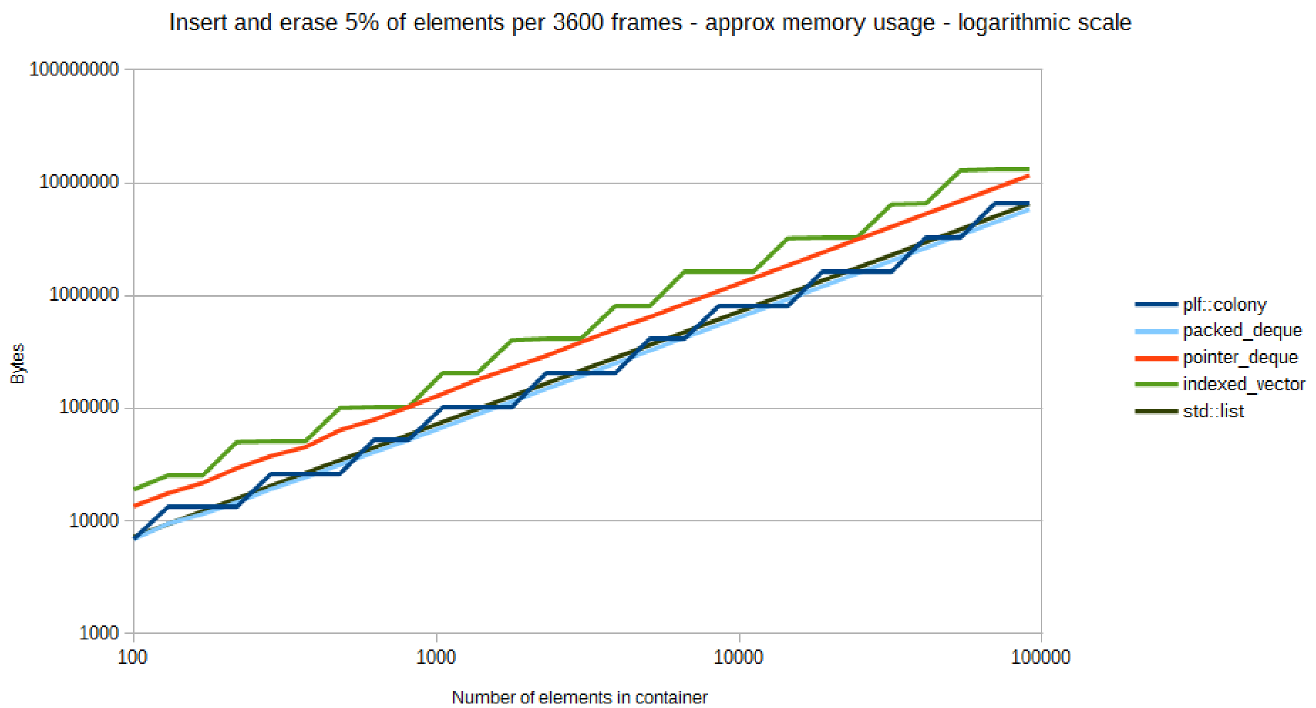

Insert and erase 5% of elements per 3600 frames, for 108000 frames - logarithmic scale
1000000000
100000000
10000000
1000000
100000
10000
Microseconds
100
1000
10000
100000
Number of elements in container
plf::colony
packed_deque
pointer_deque
pointer_deque_remove_if
indexed_vector
indexed_vector_remove_if
std::list



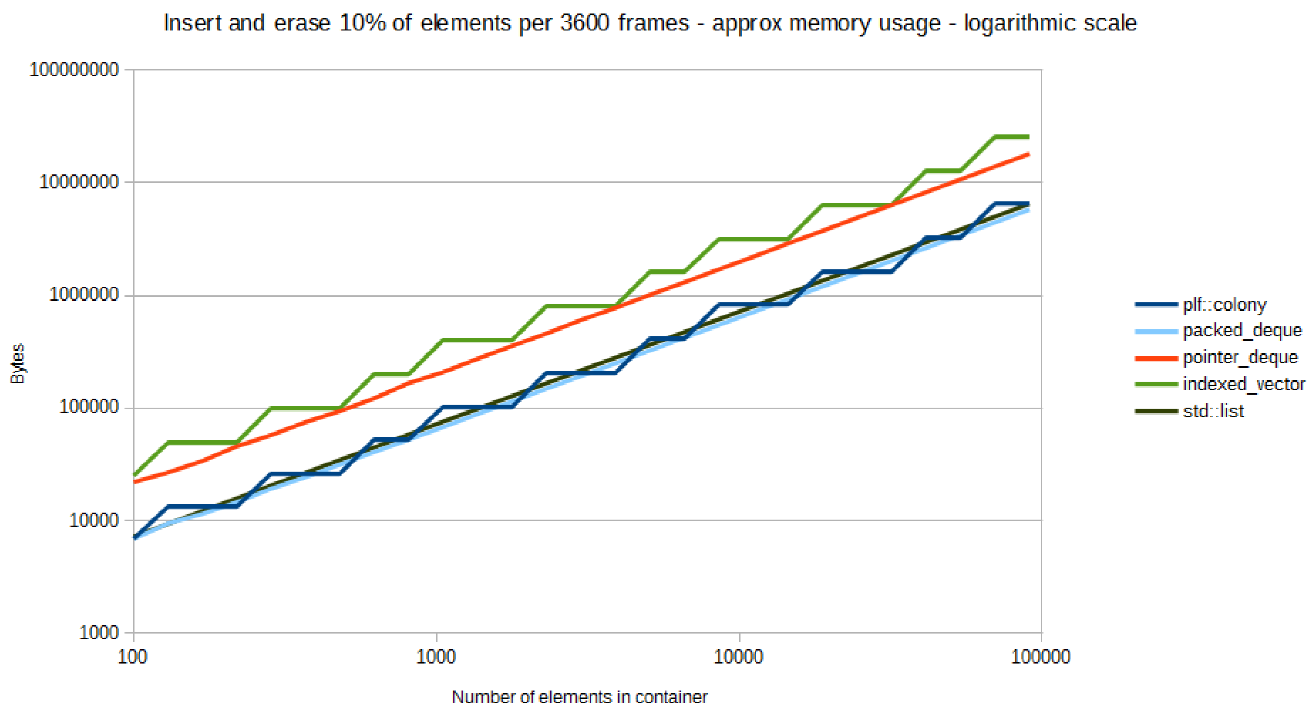
Memory results



Insert and erase 1% of elements per 3600 frames - approx memory usage - logarithmic scale
10000000
1000000
100000
10000
1000
Bytes
100
1000
10000
100000
Number of elements in container
plf::colony
packed_deque
pointer_deque
indexed_vector
std::list



Insert and erase 5% of elements per 3600 frames - approx memory usage - logarithmic scale
100000000
10000000
1000000
100000
10000
1000
Bytes
100
1000
10000
100000
Number of elements in container
plf::colony
packed_deque
pointer_deque
indexed_vector
std::list

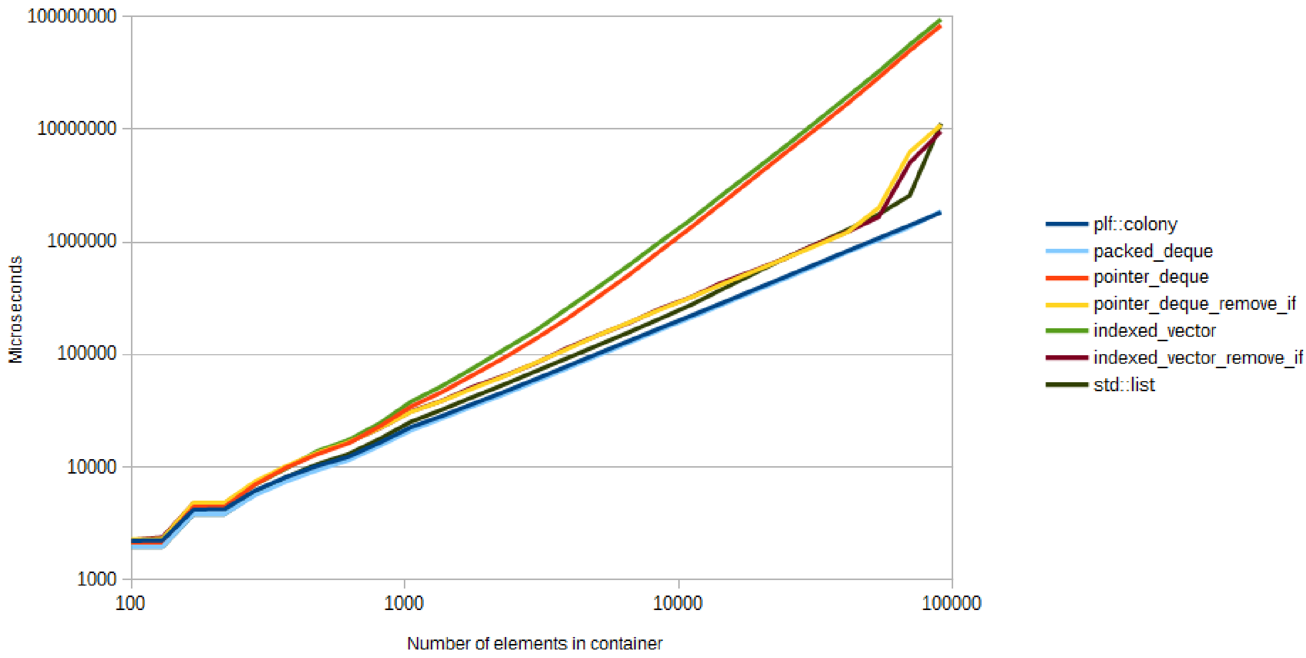


'Real-world' scenario testing - high modification

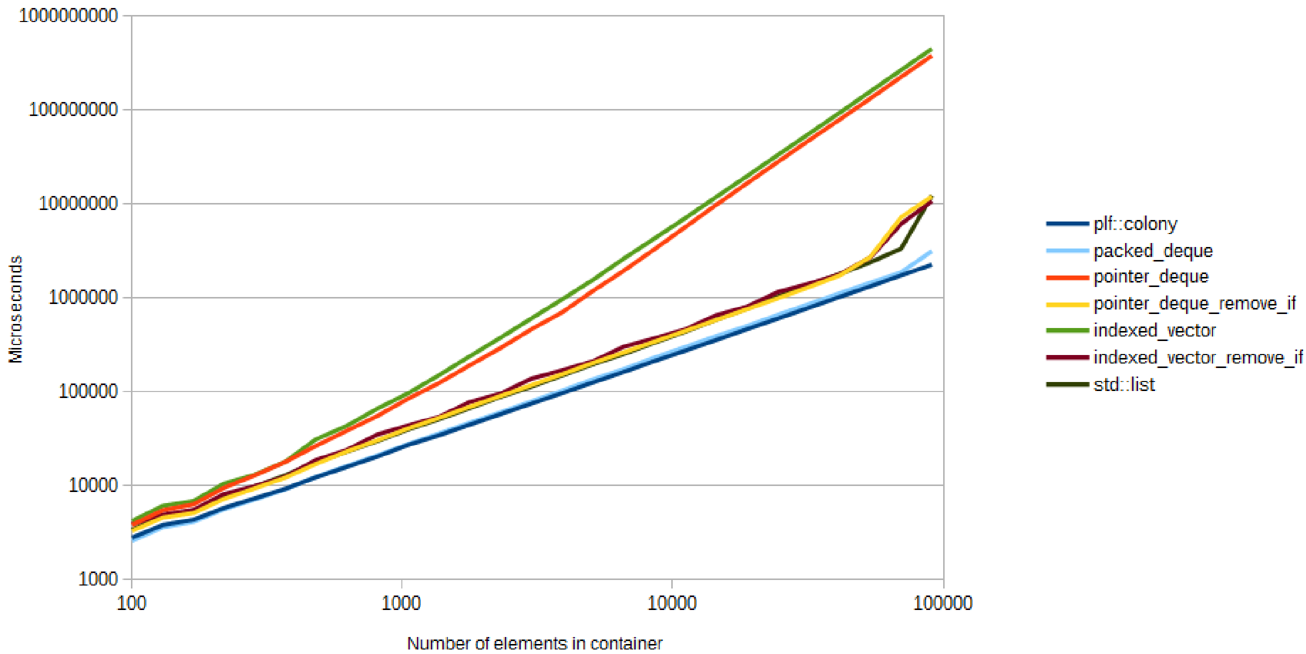
Same as the previous test but here we erase/insert 1% of all elements per-frame instead of per 3600 frames, then once again increase the percentage to 5% then 10% per-frame. This simulates the use-case of continuously-changing data, for example video game bullets, decals, quadtree/octree nodes, cellular/atomic simulation or weather simulation.

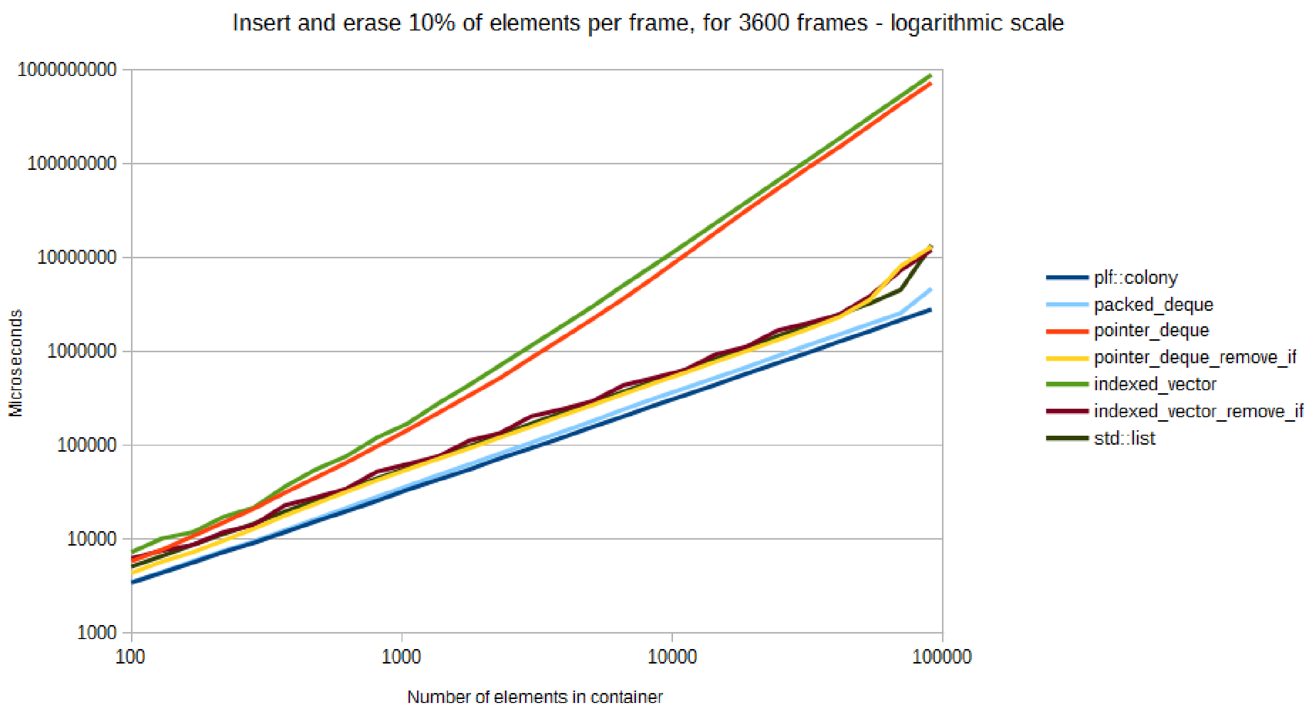
Performance results

Insert and erase 1% of elements per frame, for 3600 frames - logarithmic scale

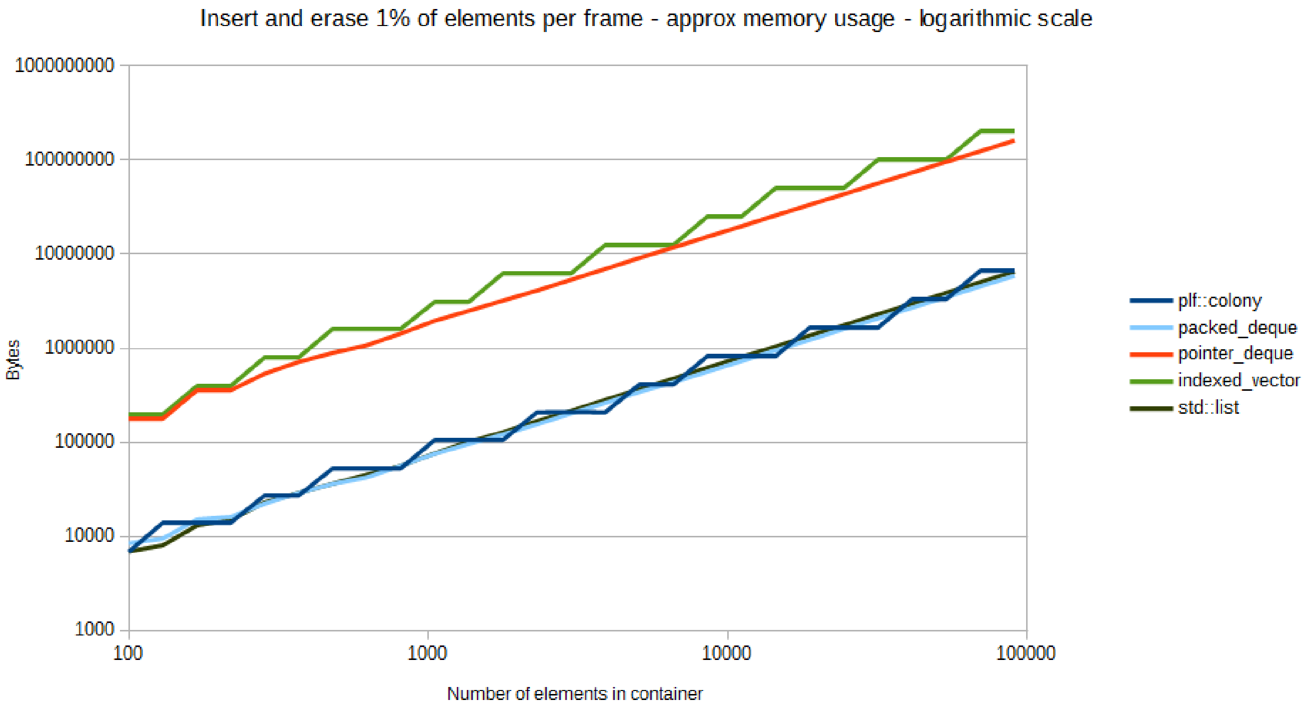


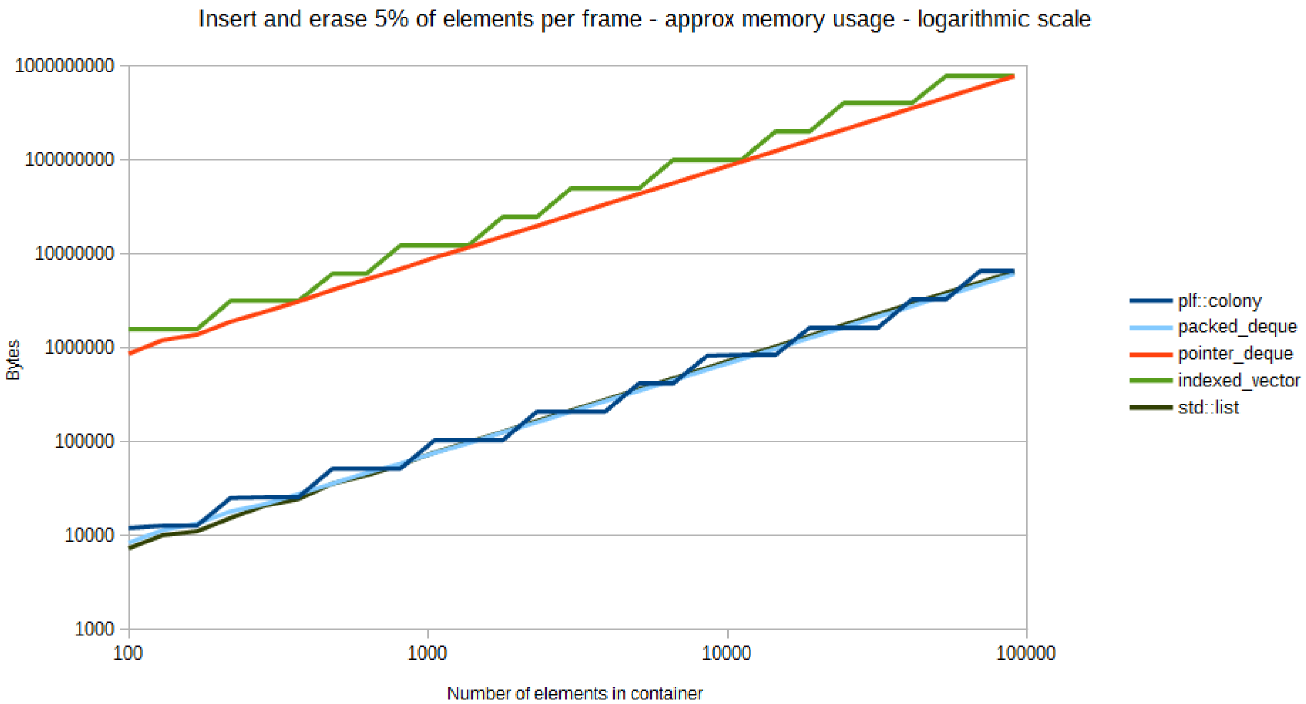
Insert and erase 5% of elements per frame, for 3600 frames - logarithmic scale

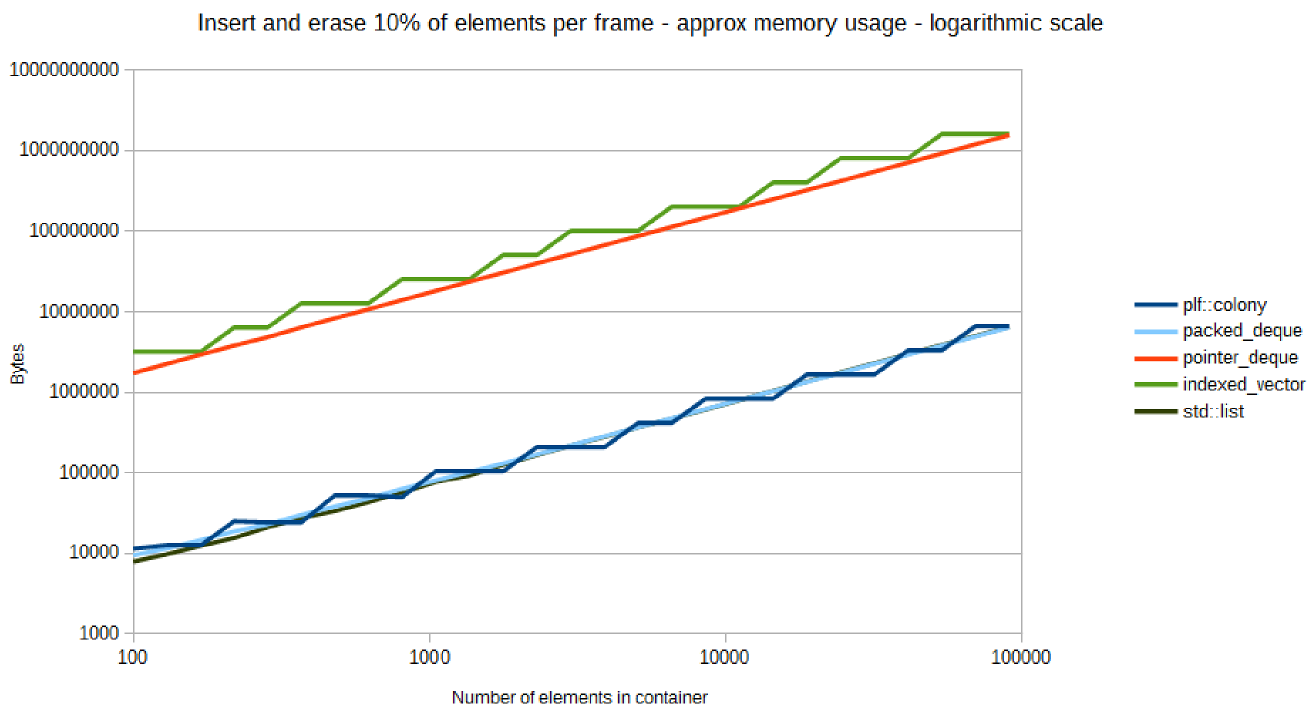




Memory results


Insert and erase 1% of elements per frame - approx memory usage - logarithmic scale
1000000000
100000000
10000000
1000000
100000
10000
1000
Bytes
100
1000
10000
100000
Number of elements in container
plf::colony
packed_deque
pointer_deque
indexed_vector
std::list


Insert and erase 5% of elements per frame - approx memory usage - logarithmic scale
1000000000
100000000
10000000
1000000
100000
10000
1000
Bytes
100
1000
10000
100000
Number of elements in container
plf::colony
packed_deque
pointer_deque
indexed_vector
std::list



Obviously if you are doing a lot of referencing into a packed_deque from outside objects, you may encounter some speed problems due to the dereferencing system - which the next test will cover. On the other hand, if you are mainly iterating over unordered data, erasing occasionally, and only ever referring *outwards from* elements within the packed_deque, it will be an ideal solution.

'Real-world' scenario-testing: referencing with interlinked containers

In order to completely test plf::colony against a packed-array-style implementation, it is necessary to measure performance while exploiting both container's linking mechanisms - for colony this is pointers or iterators, for a packed array this is a handle, or more specifically a pointer to a pointer (or the equivalent index-based solution). Because that additional dereferencing is a performance loss and potential cache miss, any test which involves a large amount of inter-linking between elements in multiple containers should lose some small amount of performance when using a packed_deque instead of a colony. Since games typically have high levels of interlinking between elements in multiple containers (as described in the motivation section), this is relevant to performance concerns.

Consequently, this test utilizes four instances of the same container type, each containing different element types:

1. A 'collisions' container (which could represent collision rectangles within a quadtree/octree/grid/etc)
2. An 'entities' container (which could representing general game objects) and
3. Two subcomponent containers (these could be sprites, sounds, or anything else).

test class diagram

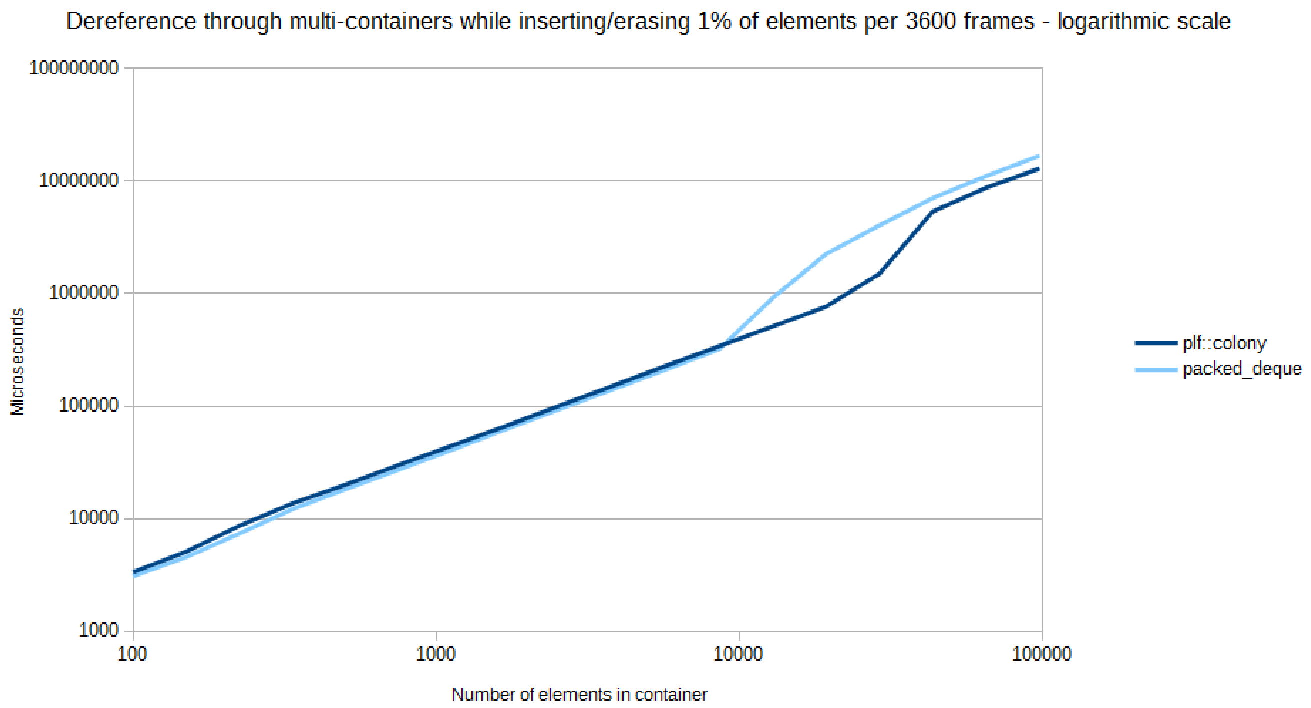
This is actually a very low number of inter-related containers for a game, but we're reducing the number of components in this case just to simplify the test. Elements in the 'entities' container link to elements in all three of the other containers. In turn, the elements in the collisions container link back to the corresponding elements in the entities container. The subcomponent containers do not link to anything.

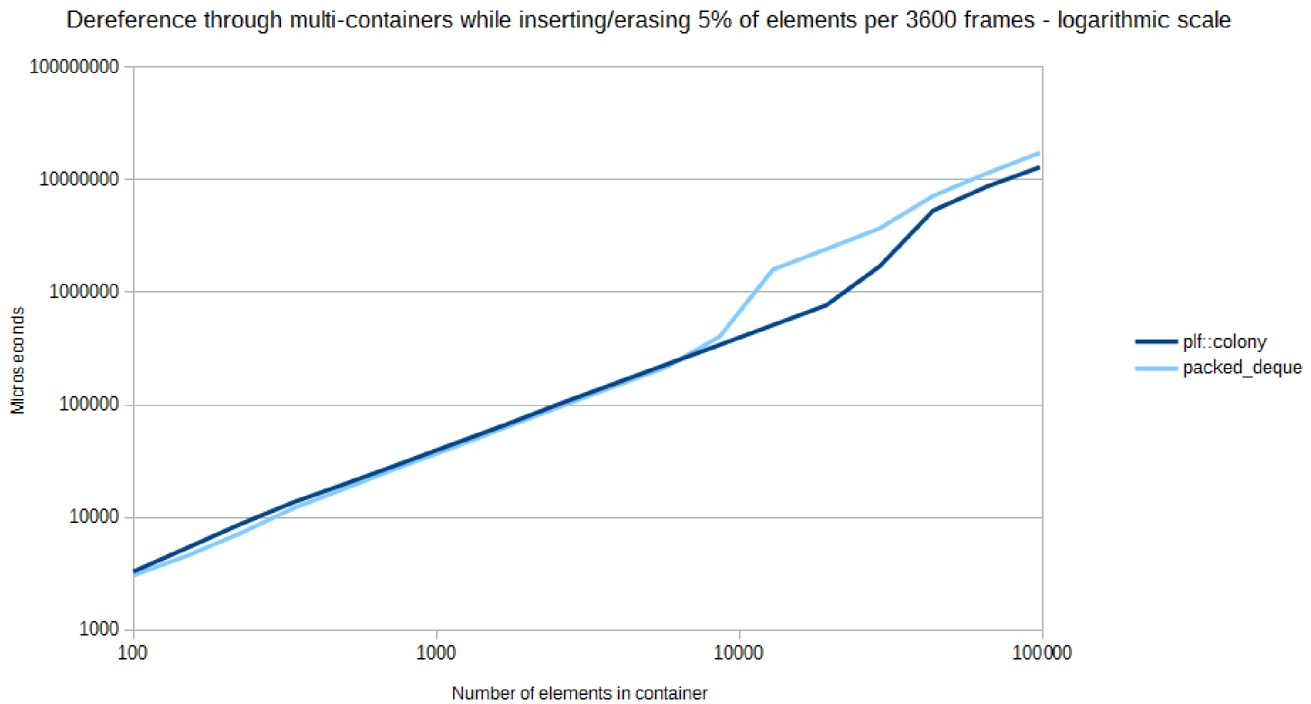
In the test, elements are first added to all four containers and interlinked (as this is a simplified test, there's a one-to-one ratio of entity elements to 'collision' and subcomponent elements). The core test process after this point is similar to the modification scenarios tested earlier: we iterate over the entity container once every frame, adding a number from both the entities and subcomponents to a total. We also erase a percentage of entities per-frame (and their corresponding subcomponents and collision blocks) - similar to the earlier tests.

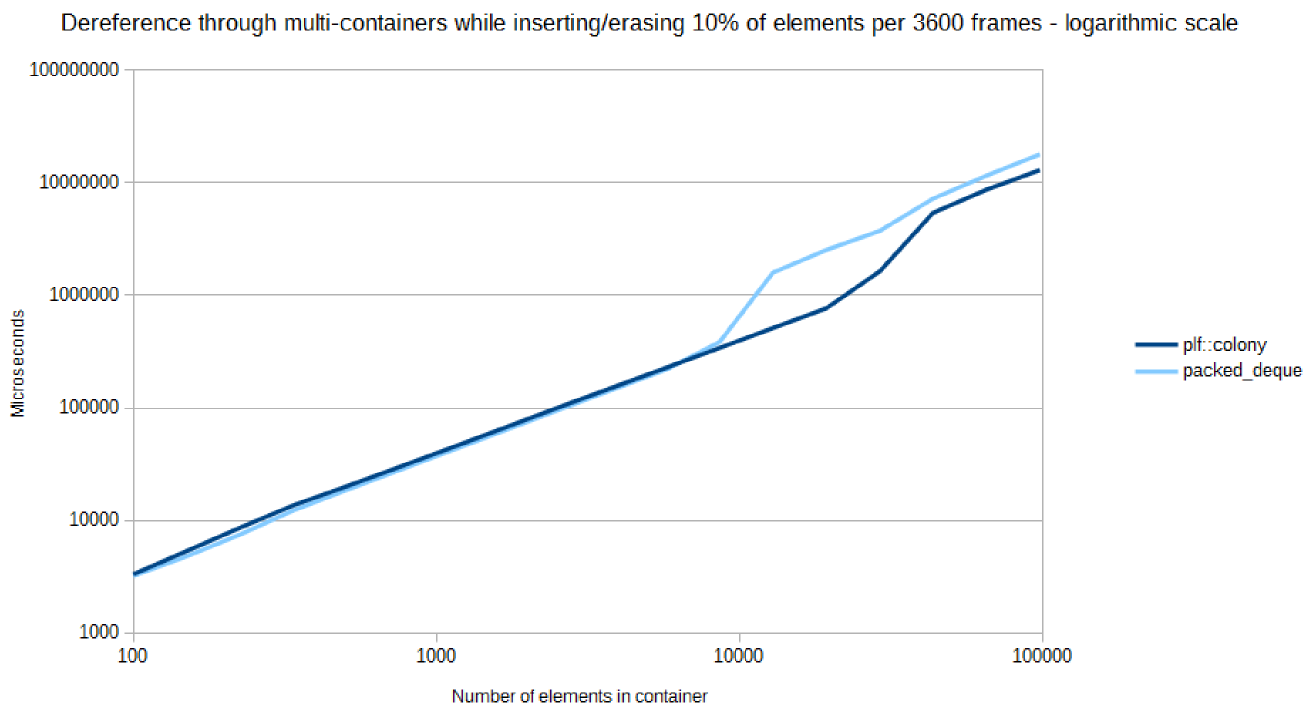
However during each frame we also iterate over the 'collisions' container and erase a percentage of these elements (and their corresponding entities and subcomponents) at random as well. This could be seen as simulating entities being removed from the game based on collisions occurring, but is mainly to test the performance effects of accessing the subcomponents via a chain of handles versus a chain of pointers. Then, again during each frame, we re-add a certain number of entities, collision blocks and subcomponents back into the containers based on the supplied percentage value. Since both colony and packed_deque essentially re-use erased-element memory locations, this tests the efficacy of each containers mechanism for doing so (packed_deque's move-and-pop + handle free-list, versus colony's stack + skipfield).

Since neither container will grow substantially in memory usage over time as a result of this process, a longer test length is not necessary like it was for the earlier modification scenario-testing with indexed_vector and pointer_deque. Testing on both plf::colony and plf::packed_deque showed that both of their test results increased linearly according to the number of simulated frames in the test (indexed_vector and pointer_deque have a more exponential growth). Similarly to the modification tests above, we will start with 1% of all elements being erased/inserted per 3600 frames, then 5% and 10%, then move up to 1% of all elements being erased/inserted per-frame, then 5% per-frame, then 10% per-frame.

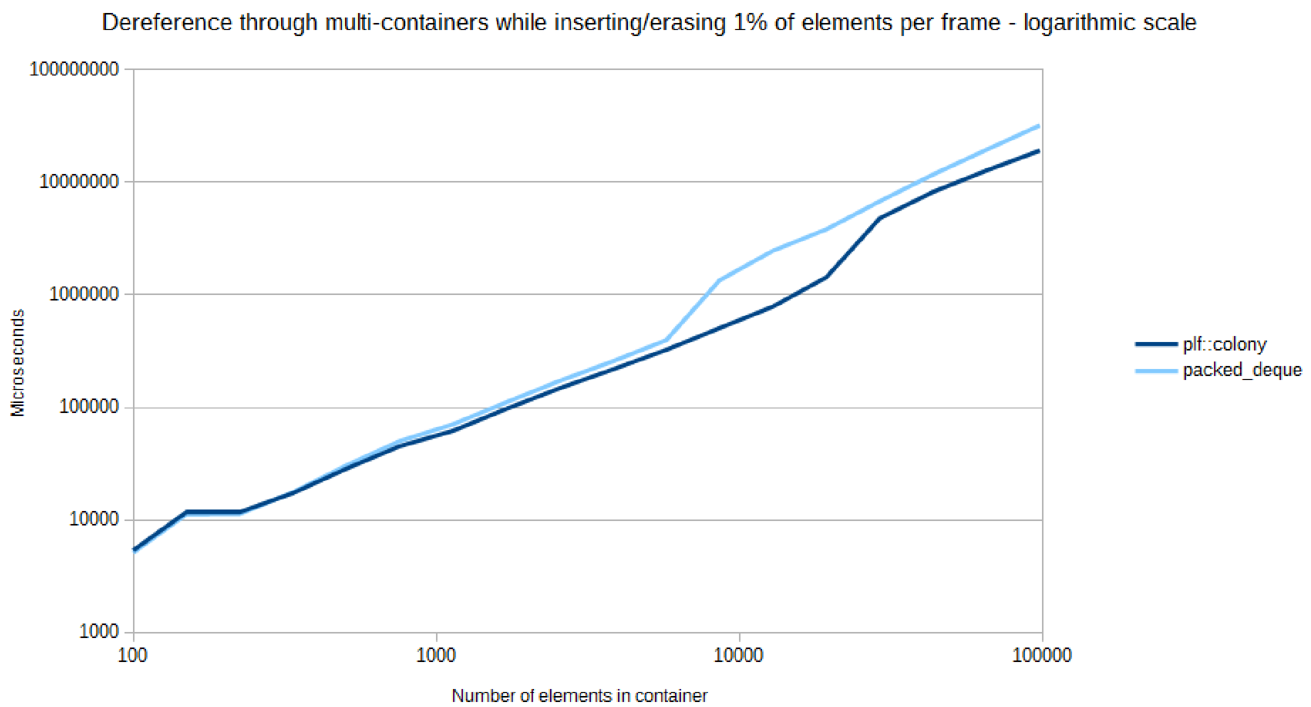
Performance results



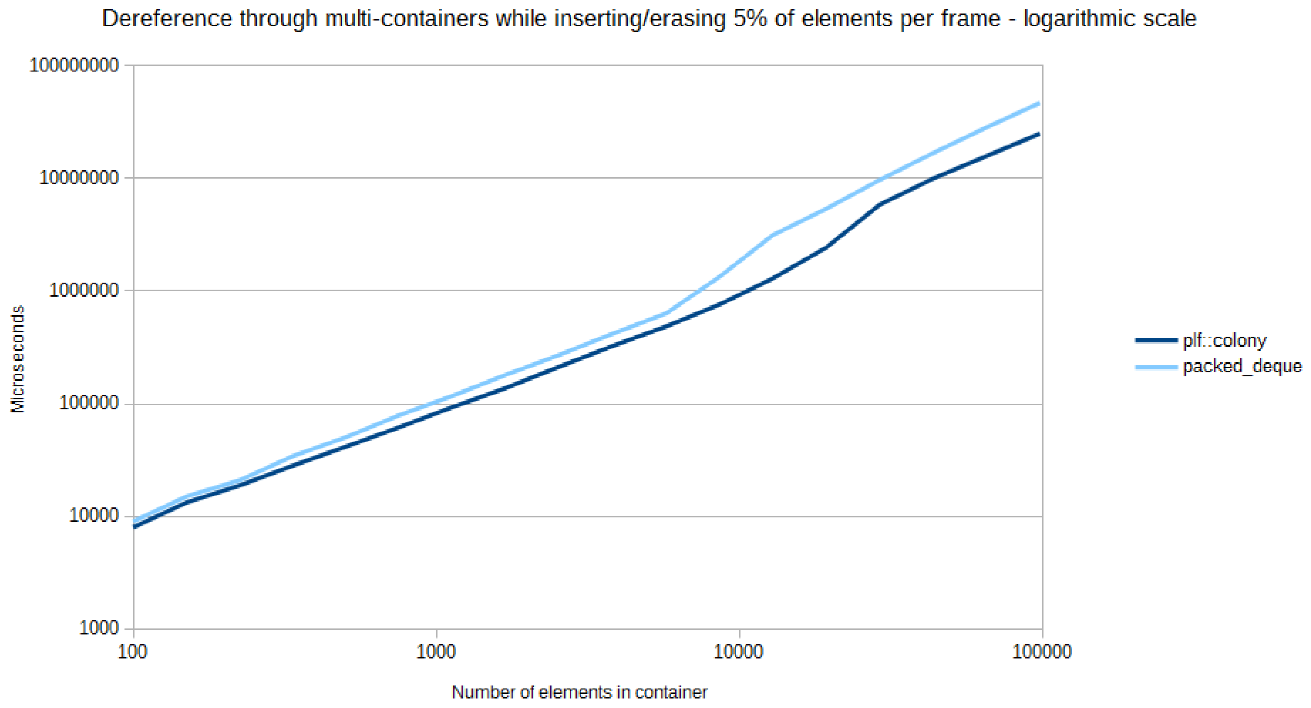


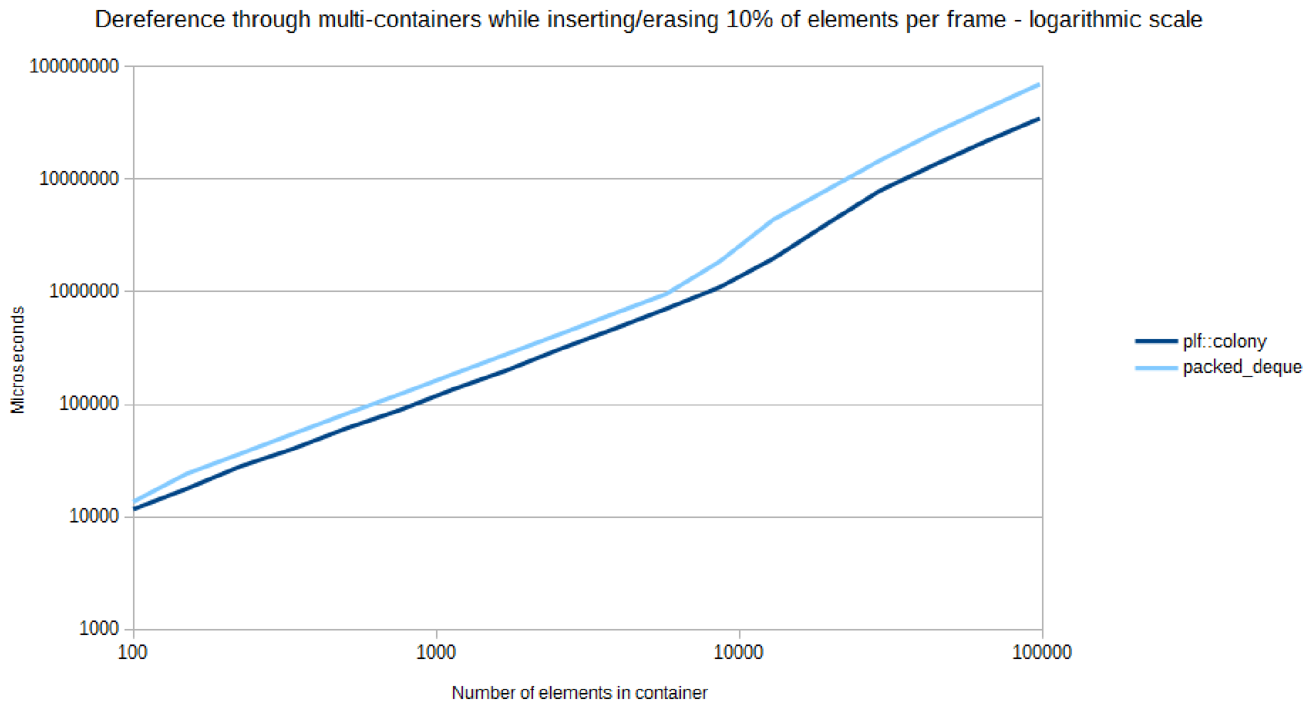


Dereference through multi-containers while inserting/erasing 10% of elements per 3600 frames - logarithmic scale
100000000
10000000
1000000
100000
10000
1000
Microseconds
100
1000
10000
100000
Number of elements in container
plf::colony
packed_deque



Dereference through multi-containers while inserting/erasing 1% of elements per frame - logarithmic scale
100000000
10000000
1000000
100000
10000
1000
Microseconds
100
1000
10000
100000
Number of elements in container
plf::colony
packed_deque

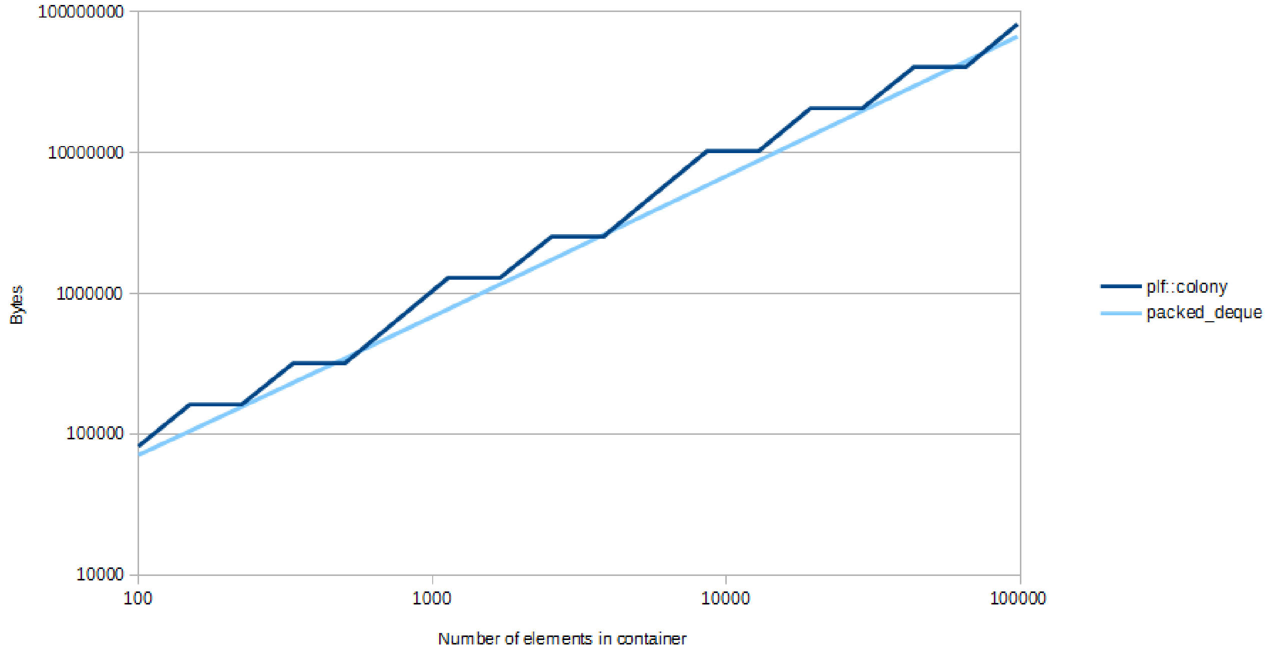




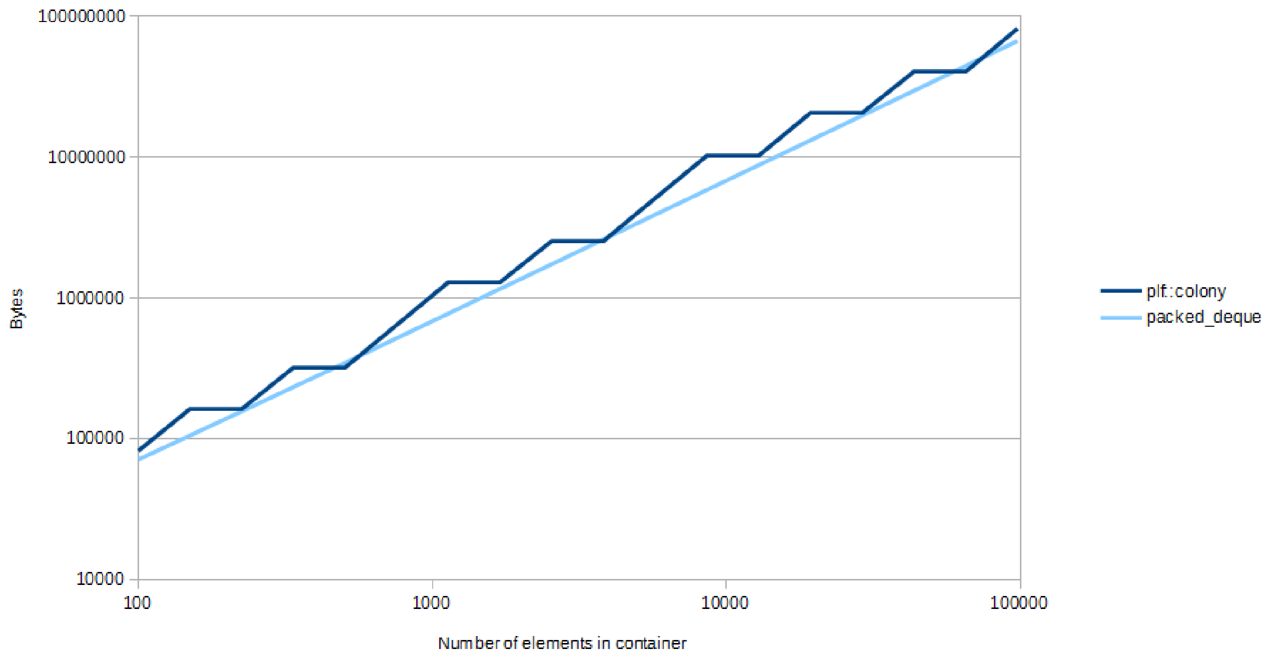
As we can see from the performance results, at low levels of modification packed_deque has a small performance advantage over colony, until about 9000 elements. After 9000 elements, colony has a larger performance advantage. And the higher the level of modification, the fewer elements there have to be in the containers before colony has an advantage. At 1% modification per frame, only 200 elements are needed, while at 5% per-frame and above, colony always has a strong advantage.

Memory results

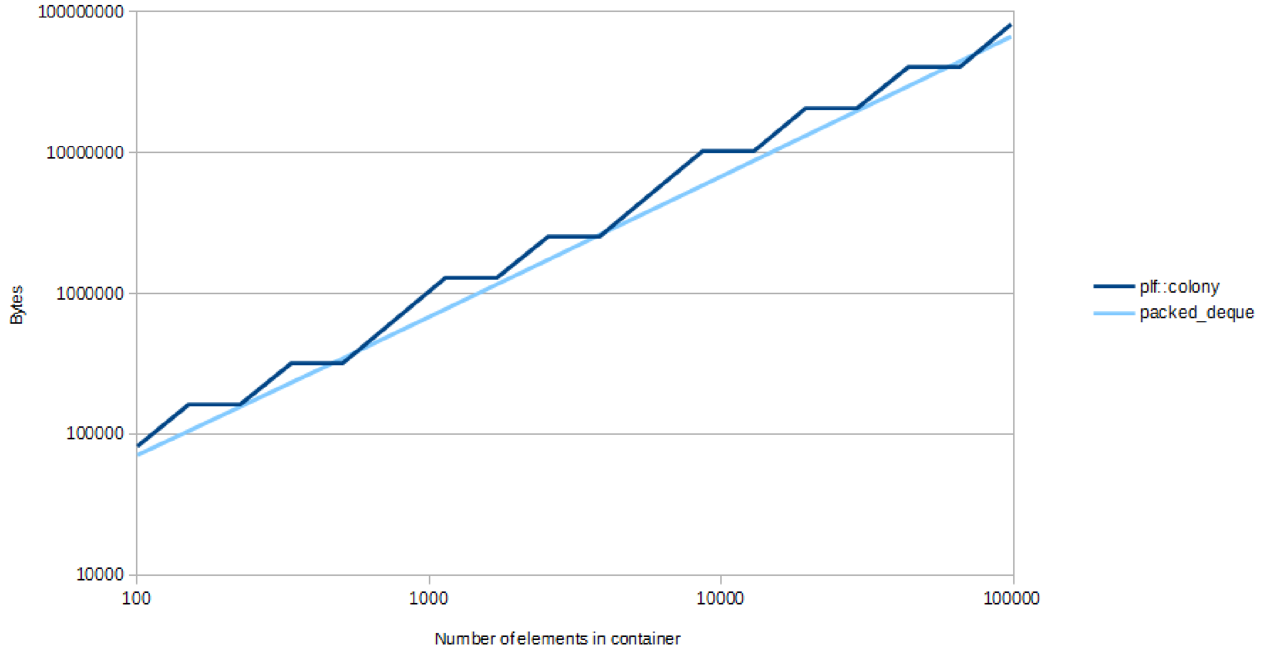
Dereference through multi-containers while inserting/erasing 1% per 3600 frames - approx memory usage - logarithmic scale



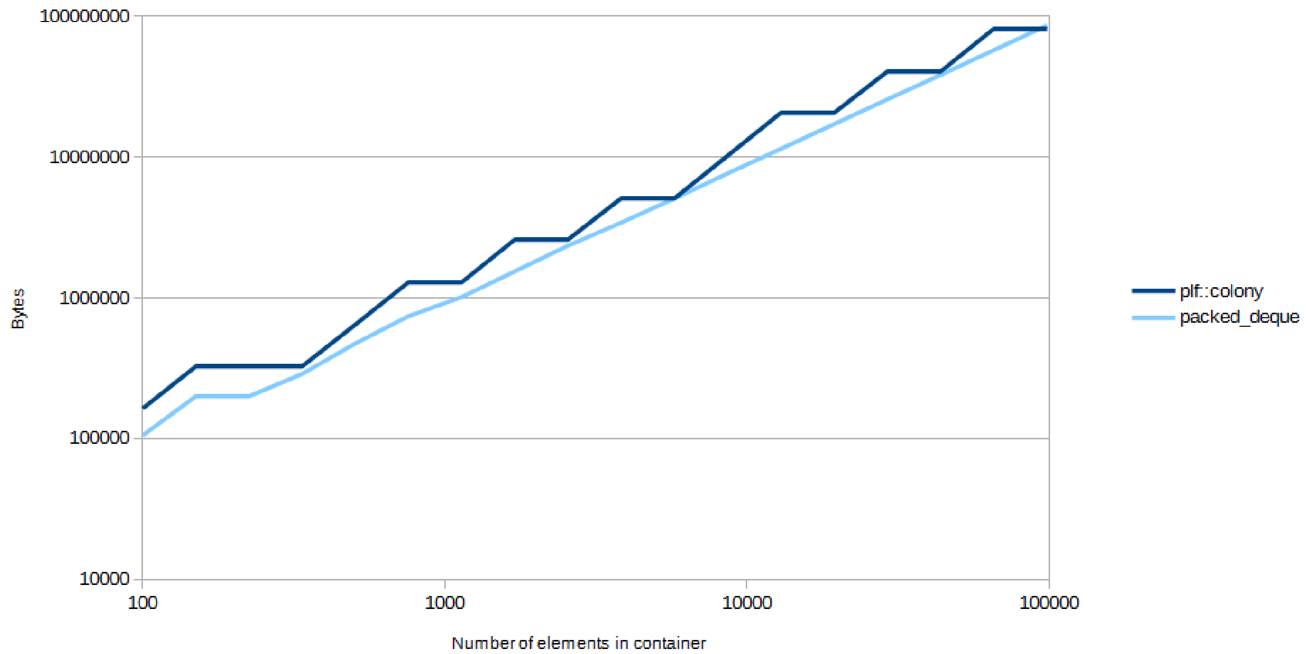
Dereference through multi-containers while inserting/erasing 5% per 3600 frames - approx memory usage - logarithmic scale

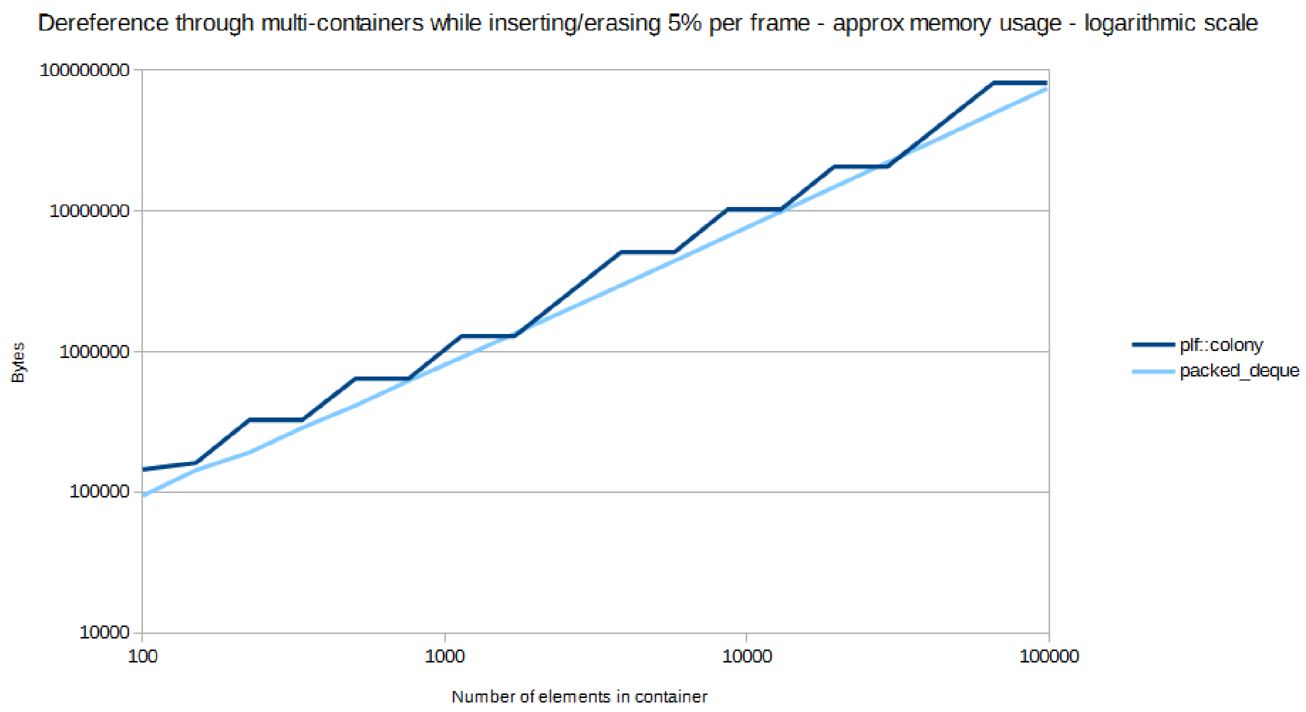


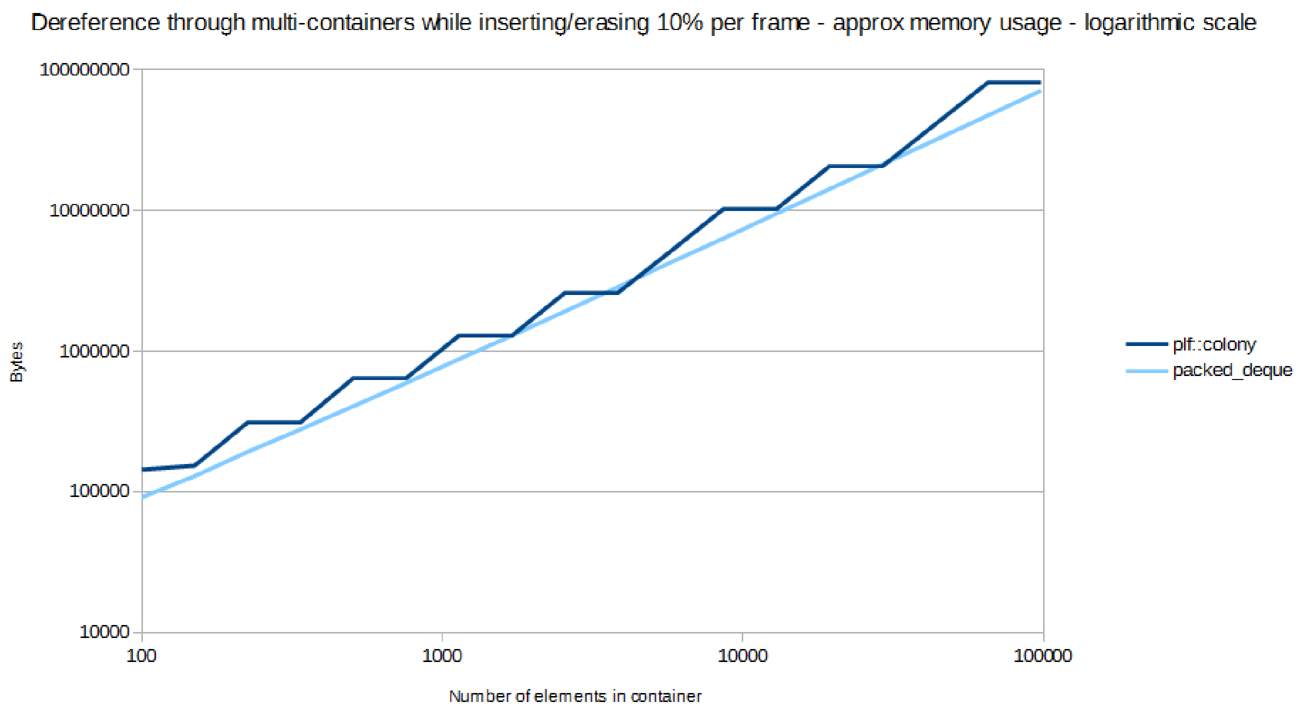
Dereference through multi-containers while inserting/erasing 10% per 3600 frames - approx memory usage - logarithmic scale



Dereference through multi-containers while inserting/erasing 1% per frame - approx memory usage - logarithmic scale







As we can see the memory results don't really change between different levels of modification - packed_deque always has an advantage over colony, though not a huge one. The memory difference can be mitigated somewhat by setting a smaller maximum group size for colony, but this will likely come at an expense of speed.

Overall Performance Conclusions

For situations where unordered, often-inserted/erased content is required, colony provides a convenient solution, while also outperforming the alternatives for the most part. Where modification rates and the number of elements are low, a packed-array-style structure like packed_deque may be your best solution both in terms of performance and memory usage. However once the numbers of elements and rates of modification begin to rise, a colony shines forth. In addition, a packed array will be affected adversely when the type is larger or non-trivially movable, due to the neccessity of moving elements from the back when erasing.

Using a boolean skipfield in combination with a vector or deque is of course a no-go, due to it's poor iteration performance once the number of erasures increases. Similarly, using an erasable iteration field as was used with indexed_vector and pointer_deque results in both wasteful memory consumption and poor performance once the number of modifications or elements becomes too high.

In short, use a packed-array where both the rate of modification is <= 10% of all elements per 3600 iterations over data and the number of elements is <= 9000, or if external object access to container elements via the dereferencing system is uncommon. In all other areas, for unordered data use a colony.

Appendix C - Frequently Asked Questions

1. **What are some examples of situations where a colony might improve performance?**

   Some ideal situations to use a colony: cellular/atomic simulation, persistent octtrees/quadtrees, game entities or destructible-objects in a video game, particle physics, anywhere where objects are being created and destroyed continuously. Also, anywhere where a vector of pointers to dynamically-allocated objects or a std::list would typically end up being used in order to preserve object references but where order is unimportant.

2. **What situations should you explicitly *not* use a colony for?**

   A colony should not be used as a stack, ie. erasing backwards from the back, and then filling, then erasing from the back, etcetera. In this case you should use a stack-capable container ie. plf::stack, std::vector or std::deque. The reason is that erasing backwards sequentially creates the greatest time complexity for skipfield updates, as does reinserting to the start of a sequentially-erased skipblock (which is what stack usage will entail). This effect is mitigated somewhat if an entire group is erased, in which case it is released to the OS and subsequent insertions will simply be pushing to back without the need to update a skipfield, but you'd still incur the skipfield update cost during erasure. Although in practice the performance difference is small due to the low cost of the operations and the small size of the skipfield, in general you should avoid erasing sequentially during reverse iteration except where neccessary, as the jump-counting skipfield format is optimized for either random erasure or sequential erasure while iterating forwards.

3. **If the time complexities of the insert/erase functions are (mostly) O(random, ranged), why are they still fast?**

   The time complexities are largely based on the skipfield updates necessary for the jump-counting skipfield pattern. The skipfield for each group is contiguous and separate from the skipfields for other groups, and so fits into the cache easily (unless the skipfield type is large), thus any changes to it can occur quickly - time complexity is no indicator of performance on a modern CPU for anything less than very large amounts of N (or when the type of N is large). The colony implementation uses `memmove` to modify the skipfield instead of iterative updates for all but one of the insert/erase operations, which decreases performance cost. `memmove` will typically be implemented as a single raw memory chunk copy. There is one rarer case in erase which does not use `memmove`, when an element is erased and is surrounded on both sides by consecutive erased elements. In this case it isn't possible to update the skipfield using memmove because the requisite numbers do not exist in the skipfield and therefore cannot be copied, so it is implemented as a vectorized iterative update instead. Again, due to a low amount of branching and the small size of each skipfield the time taken for this update is still small.

4. **Is it similar to a deque?**

   A deque is reasonably dissimilar to a colony - being a double-ended queue, it requires a different internal framework. It typically uses a vector of memory blocks, whereas the colony implementation uses a linked list of memory blocks, essentially. A deque can't technically use a linked list of memory blocks because it will make some random_access iterator operations (eg. + operator) non-O(1). In addition, being a double-ended queue makes having a growth factor for memory blocks problematic because the rules for growth at each end of the queue become difficult to implement in a way which increase performance for all scenarios without memory bloat.

   A deque and colony have no comparable performance characteristics except for insertion (assuming a good deque implementation). Deque erasure performance varies wildly depending on the implementation compared to std::vector, but is generally similar to vector erasure performance. A deque invalidates pointers to subsequent container elements when erasing elements, which a colony does not.

5. **What are the thread-safe guarantees?**

   Unlike a std::vector, a colony can be read from and written to at the same time (assuming different locations for read and write), however it cannot be iterated over and written to at the same time. If we look at a (non-concurrent implementation of) std::vector's threadsafe matrix to see which basic operations can occur at the same time, it reads as follows (please note push_back() is the same as insertion in this regard):

std::vector	Insertion	Erasure	Iteration	Read
Insertion	No	No	No	No
Erasure	No	No	No	No
Iteration	No	No	Yes	Yes
Read	No	No	Yes	Yes

In other words, multiple reads and iterations over iterators can happen simultaneously, but the potential reallocation and pointer/iterator invalidation caused by insertion/push_back and erasure means those operations cannot occur at the same time as anything else.

Colony on the other hand does not invalidate pointers/iterators to non-erased elements during insertion and erasure, resulting in the following matrix:

plf::colony	Insertion	Erasure	Iteration	Read
Insertion	No	No	No	Yes
Erasure	No	No	No	Mostly*
Iteration	No	No	Yes	Yes
Read	Yes	Mostly*	Yes	Yes

* Erasures will not invalidate iterators unless the iterator points to the erased element.

In other words, reads may occur at the same time as insertions and erasures (provided that the element being erased is not the element being read), multiple reads and iterations may occur at the same time, but iterations may not occur at the same time as an erasure or insertion, as either of these may change the state of the skipfield which's being iterated over. Note that iterators pointing to end() may be invalidated by insertion.

So, colony could be considered more inherently threadsafe than a (non-concurrent implementation of) std::vector, but still has some areas which would require mutexes or atomics to navigate in a multithreaded environment.

For a more fully concurrent version of colony, an atomic boolean skipfield could be utilized instead of a jump-counting one, if one were allowed to ignore time complexity rules for iterator operations. This would enable largely lock-free operation of a colony, at the expense of iteration speed.

6. **Any pitfalls to watch out for?**

    1. Because erased-element memory locations will be reused by `insert()` and `emplace()`, insertion position is essentially random unless no erasures have been made, or an equal number of erasures and insertions have been made.
    2. For architectural reasons (empty groups cannot be present), reserve can only reserve a number of elements up to the maximum bit-depth of the skipfield type.

7. **Am I better off storing iterators or pointers to colony elements?**

    Testing so far indicates that storing pointers and then using `get_iterator_from_pointer()` when or if you need to do an erase operation on the element being pointed to, yields better performance than storing iterators and performing erase directly on the iterator. This is simply due to the size of iterators (3 pointers) in the reference implementation.

8. **Any special-case uses?**

    In the special case where many, many elements are being continually erased/inserted in realtime, you might want to experiment with limiting the size of your internal memory groups in the constructor. The form of this is as follows:
    ```
    plf::vector<object> a_vector;
    a_vector.change_group_sizes(500, 5000);
    ```
    where the first number is the minimum size of the internal memory groups and the second is the maximum size. Note these can be the same size, resulting in an unchanging group size for the lifetime of the colony (unless `change_group_sizes` is called again or operator = is called).

    One reason to do this is that it is slightly slower to pop an element location off the internal erased-location-recycling stack, than it is to insert a new element to the end of the colony (the default behaviour when there are no previously-erased elements). If there are any erased elements in the colony, the colony will recycle those memory locations, unless the entire group is empty, at which point it is freed to memory. So if a group size is large and many, many erasures occur but the group is not completely emptied, (a) the number of erased element locations in the recycling stack could get large and increase memory usage and (b) iteration performance may suffer due to large memory gaps between any two non-erased elements. In that scenario you may want to exeriment with benchmarking and limiting the minimum/maximum sizes of the groups, and find the optimal size for a specific use case.

Please note that the the fill, range and initializer-list constructors can also take group size parameters, making it possible to construct filled colonies using custom group sizes.

9. **What is colony's Abstract Data Type (ADT)?**

   Though I am happy to be proven wrong I suspect colony is it's own abstract data type. While it is similar to a multiset or bag, those utilize key values and are not sortable (by means other than automatically by key value). Colony does not utilize key values, is sortable, and does not provide the sort of functionality one would find in a bag (eg. counting the number of times a specific value occurs). Some have suggested simiarities to deque - but as described earlier the three core aspects of colony are:

   a. A multiple-memory-block based allocation pattern which allows for the removal of memory blocks when they become empty of elements.
   b. A skipfield to indicate erasures instead of reallocating elements, the iteration of which should typically not necessitate the use of branching code.
   c. A mechanism for recording erased element locations to allow for reuse of erased element memory space upon subsequent insertion.

   The only aspect out of these which deque also shares is a multiple-memory-block allocation pattern - not a strong association. As a result, deques do not guarantee pointer validity to non-erased elements post insertion or erasure, as colony does. Similarly if we look at a multiset, an unordered one could be implemented on top of a colony by utilizing a hash table (and would in fact be more efficient than most non-flat implementations) but the fact that there is a necessity to add something to make it a multiset (to take and store key values) means colony is not an multiset.

10. **Why must groups be removed when empty, or moved to the back of the chain?**

    Two reasons:

    a. Standards compliance: if groups aren't removed then `++` and `--` iterator operations become O(random) in terms of time complexity, making them non-compliant with the C++ standard. At the moment they are O(1) amortised, typically one update for both skipfield and element pointers, but two if a skipfield jump takes the iterator beyond the bounds of the current group and into the next group. But if empty groups are allowed, there could be anywhere between 1 and `size_type` empty groups between the current element and the next. Essentially you get the same scenario as you do when iterating over a boolean skipfield. While it is possible to move these to the back of the colony as trailing groups, and remove their entries from the erased locations stack, this may create performance issues if any of the groups are not at their maximum size (see below).
    b. Performance: iterating over empty groups is slower than them not being present, cache wise - but also if you have to allow for empty groups while iterating, then you have to include a while loop in every iteration operation, which increases cache misses and code size. The strategy of removing groups when they become empty also removes (assuming randomized erasure) smaller groups from the colony before larger groups, which has a net result of improving iteration (as with a larger group, more iterations within the group can occur before the end-of-group condition is reached and a transfer to the next group (and subsequent cache miss) occurs). Lastly, pushing to the back of a colony is faster than recycling memory locations as each insertion occurs to a similar memory location and less work is necessary. When a group is removed or moved to the back of the group chain (past end()), it's recyclable memory locations are also removed from memory, hence subsequent insertions are more likely to be pushed to the back of the colony.

11. **Group sizes - what are they based on, how do they expand, etc**

    In the reference implementation group sizes start from the either the default minimum size (8 elements, larger if the type stored is small) or an amount defined by the programmer (with a minimum of 3 elements). Subsequent group sizes then increase the *total capacity* of the colony by a factor of 2 (so, 1st group 8 elements, 2nd 8 elements, 3rd 16 elements, 4th 32 elements etcetera) until the maximum group size is reached. The default maximum group size is the maximum possible number that the skipfield bitdepth is capable of representing (std::numeric_limits<skipfield_type>::max()). By default the skipfield type is unsigned short so on most platforms the maximum size of a group would be 65535 elements. Unsigned short (guaranteed to be at least 16 bit, equivalent to C++11's uint_least16_t type) was found to have the best performance in real-world testing due to the balance between memory contiguousness, memory waste and the restriction on skipfield update time complexity. Initially the design also fitted the use-case of gaming better (as games tend to utilize lower numbers of elements than some other fields), and that was the primary development field at the time.