A Standard `flat_map`

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1 Introduction

This paper outlines what a (mostly) API-compatible, non-node-based `map` might look like. Rather than presenting a final design, this paper is intended as a starting point for discussion and as a basis for future work. Specifically, there is no mention of `multimap`, `set`, or `multiset`. Those will be added in later papers.

2 Motivation and Scope

There has been a strong desire for a more space- and/or runtime-efficient representation for `map` among C++ users for some time now. This has motivated discussions among the members of SG14 resulting in a paper[1], numerous articles and talks, and an implementation in Boost, `boost::container::flat_map`[2]. Virtually everyone who makes games, embedded, or system software in C++ uses the Boost implementation or one that they rolled themselves.

Here are some numbers that show why. The graphs that follow show runtimes for different `map`-like associative containers. The containers used are Boost.FlatMap, `map`, `unordered_map`, and two thin wrappers over a sorted `vector`. The "custom pair" version of the sorted `vector` uses a simple `struct` instead of `pair` for its value type. All containers use either `<int, int>` or `<std::string, std::string>` for the value type.

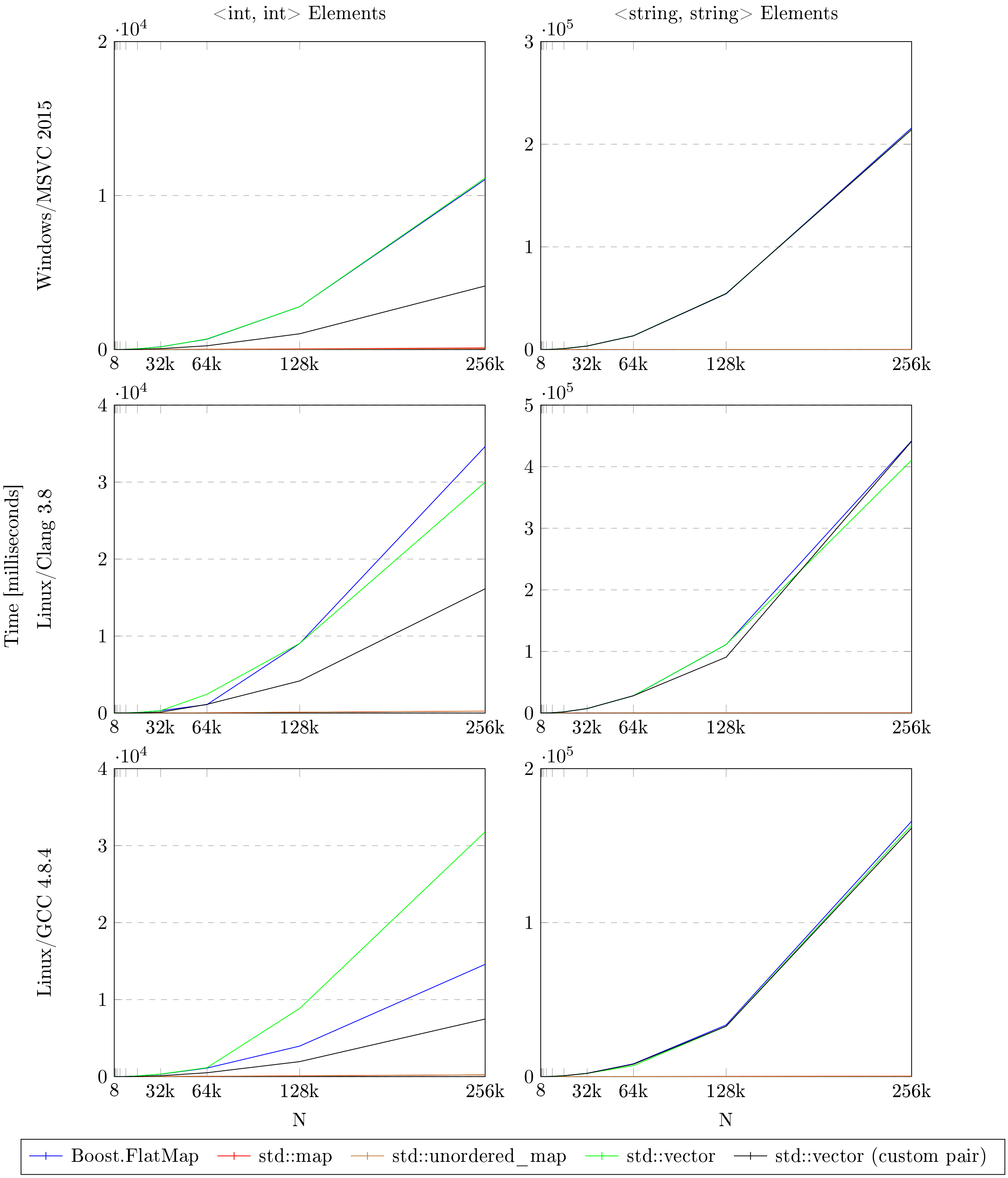
All data in the graphs below were produced on Windows with MSVC 2015, on Linux with Clang 3.8 and libc++, or on Linux with g++ 4.8.4 and libstdc++.

Each set of six graphs shows the performance of a single operation on all map-variants. The left column shows the `<int, int>` runs, and the right column shows the `<std::string, std::string>` ones. Each row shows one platform/compiler configuration.

These four sets of graphs cover the most commonly-used operations. The first set shows insertion of N elements with random keys; the second shows full iteration across all N elements; the third shows `map.find()` called once for each key used in the original insertions; and the fourth shows erasure of all N elements, by the keys used in the original insertions.

[1] See P0038R0, here.
[2] Part of Boost.Container, here.

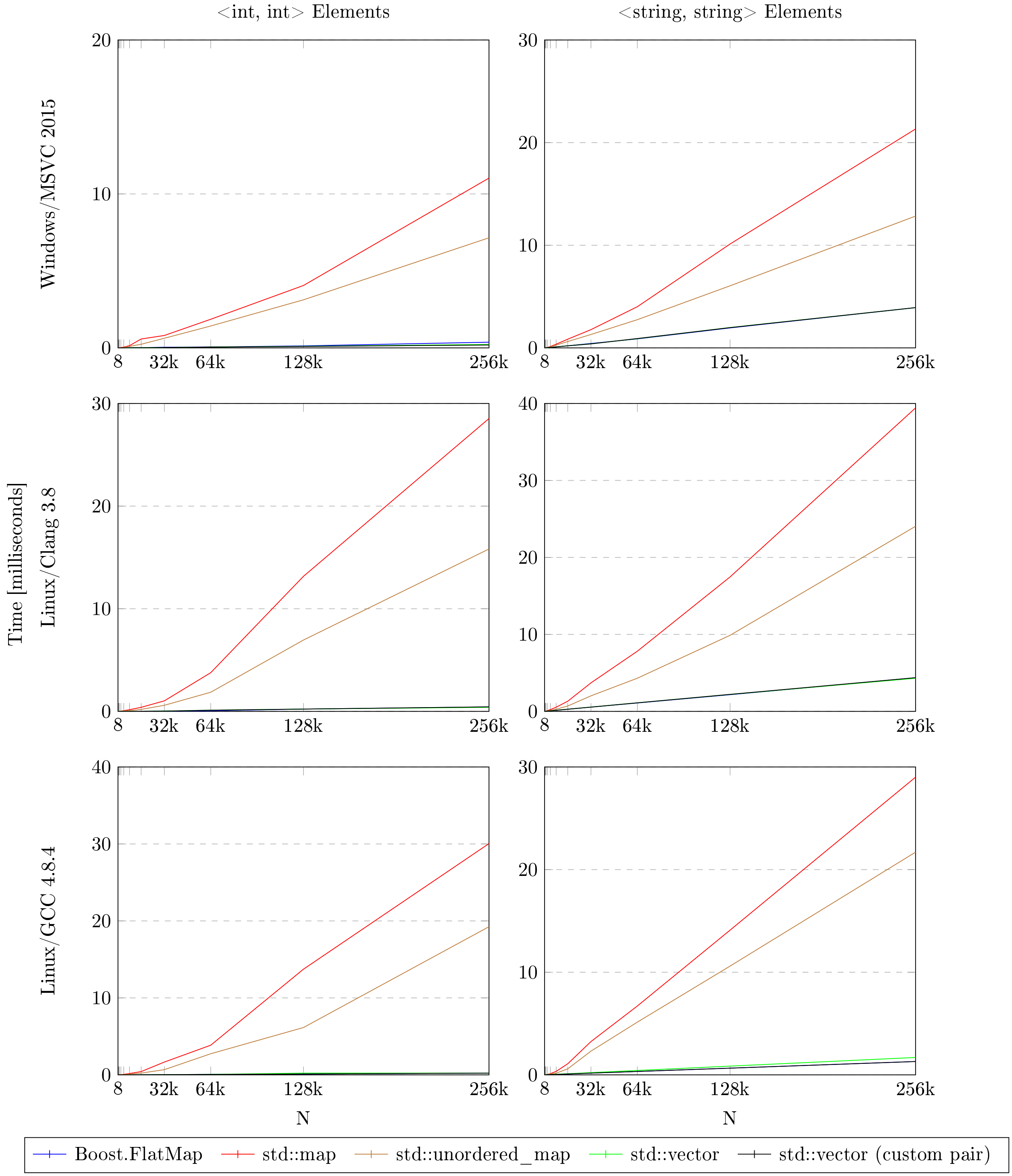
2.1 Insert



Unsurprisingly, insertion takes longer in contiguous-storage implementations. Boost.FlatMap and a sorted vector<pair<int, in have the steepest growth curves. The curve for sorted vector using a custom struct is dramatically flatter in its growth in the <int, int> runs. Note that the custom-pair vector does about the same as the vector of pair in the

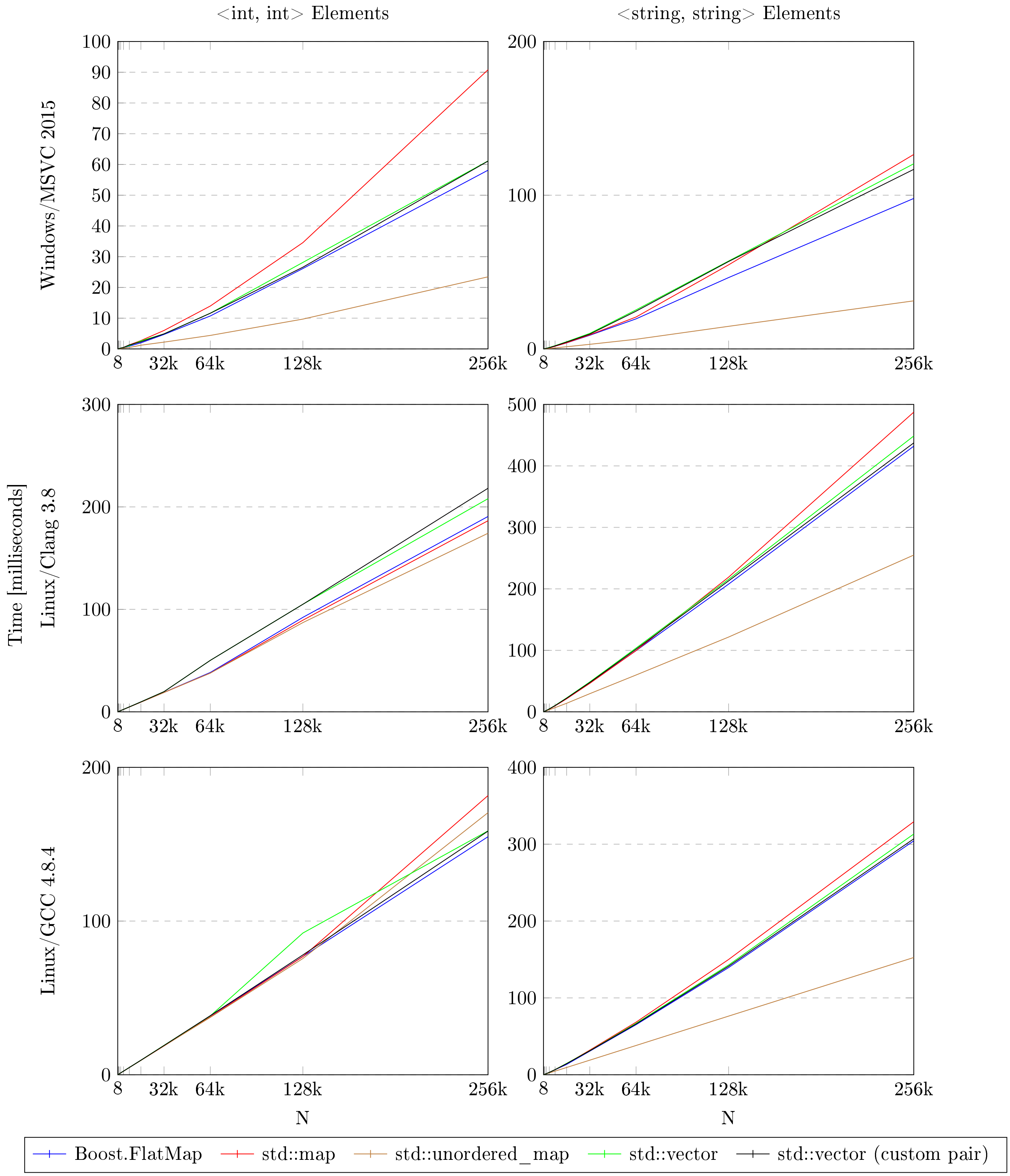
`<std::string, std::string>` runs.

2.2 Iterate



For all variants but `map` and `unordered_map`, iteration is relatively similar, and much faster than `map`'s.

2.3 Find

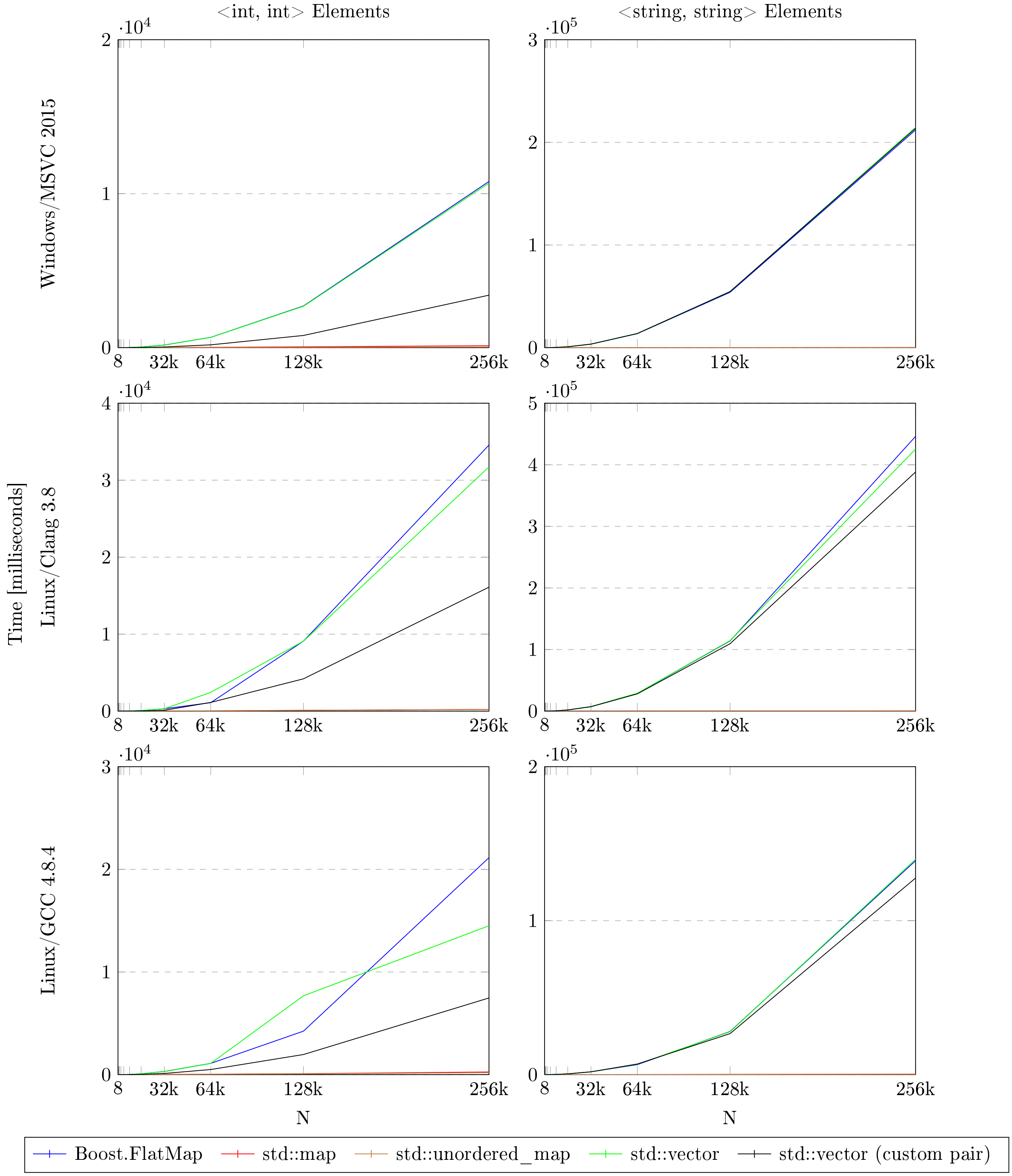


`find()` performance is where things get interesting. The different platforms produce strikingly different results.

In the MSVC runs, there is a large differentiation between Boost.FlatMap and `map`; in fact, Boost.FlatMap even beats both the sorted `vector` variants. Also, `unordered_map` is the clear winner, regardless of valkue type.

GCC and Clang on Linux produce nearly identical results. For `<int, int>` runs, all implementations are nearly identical. `unordered_map` is faster in the `<std::string, std::string>` runs, but all other variants are very close.

2.4 Erase



Erasure has a nearly identical performance profile to insertion.

2.5 Implications

Iteration is vastly cheaper for contiguous-storage variants. Any node-based associative container will always be slower than a flattened one for iteration. For use cases where there is a lot of iteration, this can be the deciding runtime performance consideration.

In all the graphs above, the reason the custom-`pair` sorted vector performs so much better than `vector<pair<int, int>>` seems to be that the custom-`pair` type has `nothrow` special functions. Implementing all the special functions and adding `nothrow(false)` to each makes the custom-`pair` version perform identically to the `pair<int, int>` version.

Boost.FlatMap differs significantly from a sorted `vector`. Clearly there are a lot of QOI choices that affect the runtime performance of a standard `flat_map`.

The fact that insertion and erasure operations produce such similar results implies that pre-`reserve()`ing space will probably not make much difference when using a flat map.

Use cases in which the runtime performance of a flat map would be no better than `map` or `unordered_map`, the user may still decide to use a flat implementation for the storage savings.

3 Proposed Design

3.1 Design Goals

Overall, `flat_map` is meant to be a drop-in replacement for `map`, jsut with better time- and space-efficiency. Functionally it is not meant to do anything other than what we do with `map` now.

The Boost.Container documentation gives a nice summary of the tradeoffs between node-based and flat associative containers (quoted here, mostly verbatim). Note that they are not purely positive:

- Faster lookup than standard associative containers.
- Much faster iteration than standard associative containers.
- Random-access iterators instead of bidirectional iterators.
- Less memory consumption for each element.
- Improved cache performance (data is stored in contiguous memory).
- Non-stable iterators (iterators are invalidated when inserting and erasing elements).
- Non-copyable and non-movable values types can't be stored.
- Weaker exception safety than standard associative containers (copy/move constructors can throw when shifting values in erasures and insertions).
- Slower insertion and erasure than standard associative containers (specially for non-movable types).

The overarching goal of this proposal is to define a `flat_map` for standardization that fits the above gross profile, while leaving maximum room for customization by users.

3.2 Design

3.2.1 `flat_map` Is Based On Boost.FlatMap

This proposal represents existing practice in widespread use – Boost.FlatMap has been available since 2011 (Boost 1.48).

3.2.2 `flat_map` Is Nearly API-Compatible With `map`

Most of `flat_map`'s interface is identical to `map`'s. Some of the differences are required (more on this later), but a couple of interface changes are optional:

- The overloads that take sorted containers or sequences.
- Making `flat_map` a container adapter.

Both of these interface changes were added to increase optimization opportunities.

3.2.3 `flat_map` Is a Container Adapter

`flat_map` is an adapter for an underlying storage type. This storage type is configurable via the template parameter `Container`. `Container` must be a *contiguous container* (§23.2.1/13). `vector` is a great candidate for this, but limiting `flat_map` only to use `vector` for its storage would be a mistake. Many other suitable replacements exist, each suited to a certain use. A user may have a small-buffer implementation of `vector`, like LLVM's `SmallVector`, or `boost::container::small_vector`. The user may also want to avoid allocations altogether, if the maximum number of elements N is known *a priori*. If so, `boost::container::static_vector` could be used. The user's specific performance requirements will dictate which of these is most appropriate.

There are certain optimization opportunities that are lost to the user of a non-adapter `flat_map`. For instance, if one does not care about the strong or weak exception guarantees in the code that uses `flat_map`, one can use a `Container` that blindly uses `move` all the time, even if exceptions may occur. This allows performance curves more like the `<int, int>` custom-pair sorted `vector` in the graphs above.

While this may not be a use case for a majority of users, there are numerous such niche use cases, and these niches are not well served by a fixed underlying storage implementation.

3.2.4 Interface Differences From `map`

- Members `capacity()`, `reserve()`, and `shrik_to_fit()` have been added, with the same semantics as the corresponding members of `vector`.
- Several new constructors have been added that take objects of the `Container` type. These members must only be used if the given container is already sorted.
- The `extract()` overloads from `map` are replaced with `Container extract()`, that moves out the entire storage of the `flat_map`. Similarly, the `insert()` members taking a node have been replaced with a member `void replace(Container&&)`, that moves in the entire storage.

  Many users have noted that M insertions of elements into a map of size N is O(M·log(N+M)), and when M is known it should be possible instead to append M times, and then re-sort, as one might with a sorted `vector`. This makes the insertion of multiple elements closer to O(N), depending on the implementation of `sort()`.

  Such users have often asked for an API in `boost::container::flat_map` that allows this pattern of use. Other flat-map implementations have undoubtedly added such an API. The extract/replace API instead allows the same optimization opportunities without violating the class invariants.
- Several new constructors and an `insert()` overload use a new tag type, `ordered_unique_sequence_tag`. These members must only be used if the given sequence is already sorted. This can allow much more efficient construction and insertion.

3.2.5 `flat_map` Requirements

Since the underlying container is contiguous and elements may be moved or copied during inserts and erases, the element type of `Container` must be `pair<Key, T>`, not `pair<const Key, T>`. Even so, the element type of `flat_map` should still be `pair<const Key, T>`, for drop-in compatibility with `map` (§23.2.4/5). This requires `flat_map` to have an iterator that adapts the underlying `Container` iterator.

Only the underlying container is allocator-aware. §23.2.4/7 regarding allocator awareness does not apply to `flat_map`.

Validity of iterators is not preserved when mutating the underlying container (i.e. §23.2.4/9 does not apply).

The exception safety guarantees for associative containers (§23.2.4.1) do not apply.

The rest of the requirements follow the ones in (§23.2.4 Associative containers), except §23.2.4/10 (which applies to members not in `flat_map`) and some portions of the table in §23.2.4/8; these table differences are outlined in "Member Semantics" below.

3.2.6 `Container` Requirements

Any contiguous container supporting operations `capacity()`, `reserve()`, and `shrik_to_fit()` can be used for the `Container` template parameter. `Container` must have a `value_type` of `pair<Key, T>`.

3.2.7 Member Semantics

Members `capacity()`, `reserve()`, and `shrik_to_fit()` have the same semantics as the corresponding members of `vector`.

Each member taking a `Container` reference or taking a parameter of type `ordered_unique_sequence_tag` has the precondition that the given elements are already sorted by `Compare`, and that the elements are unique.

Each member taking an `Alloc` template parameter only participates in overload resolution if `uses_allocator_v<Container, Allo` is `true`.

Other member semantics are the same as for `map`.

3.2.8 `flat_map` Synopsis

```
namespace std {

struct ordered_unique_sequence_tag { };

template <class Key, class T, class Compare = default_order_t<Key>,
          class Container = vector<pair<Key, T>>>
class flat_map {
public:
    // types:
    using key_type               = Key;
    using mapped_type            = T;
    using value_type             = pair<const Key, T>;
    using key_compare            = Compare;
    using allocator_type         = typename Container::allocator_type;
    using pointer                = value_type*;
    using const_pointer          = const value_type*;
    using reference              = value_type&;
    using const_reference        = const value_type&;
    using size_type              = typename Container::size_type;
    using iterator               = implementation-defined;
    using const_iterator         = implementation-defined;
    using reverse_iterator       = implementation-defined;
    using const_reverse_iterator = implementation-defined;
    using container_type         = Container;

    class value_compare {
      friend class flat_map;
    protected:
      Compare comp;
      value_compare(Compare c) : comp(c) { }
    public:
      bool operator()(const value_type& x, const value_type& y) const {
        return comp(x.first, y.first);
      }
    };

    // construct/copy/destroy:
    explicit flat_map(const Container&);
    template <class Alloc>
```

```
  flat_map(const Container&, const Alloc&);
explicit flat_map(Container&& = Container());
template <class Alloc>
  flat_map(Container&&, const Alloc&);

explicit flat_map(const Compare& comp);
template <class Alloc>
  flat_map(const Compare& comp, const Alloc&);
template <class Alloc>
  explicit flat_map(const Alloc&);
template <class InputIterator>
  flat_map(InputIterator first, InputIterator last,
           const Compare& comp = Compare());
template <class InputIterator, class Alloc>
  flat_map(InputIterator first, InputIterator last,
           const Compare& comp, const Alloc&);
template <class InputIterator, class Alloc>
  flat_map(InputIterator first, InputIterator last, const Alloc& a)
    : flat_map(first, last, Compare(), a) { }

template <class InputIterator>
  flat_map(ordered_unique_sequence_tag, InputIterator first, InputIterator last,
           const Compare& comp = Compare());
template <class InputIterator, class Alloc>
  flat_map(ordered_unique_sequence_tag, InputIterator first, InputIterator last,
           const Compare& comp, const Alloc&);
template <class InputIterator, class Alloc>
  flat_map(ordered_unique_sequence_tag, InputIterator first, InputIterator last,
           const Alloc& a)
    : flat_map(first, last, Compare(), a) { }

template <class Alloc>
  flat_map(const flat_map&, const Alloc&);
template <class Alloc>
  flat_map(flat_map&&, const Alloc&);

flat_map(initializer_list<value_type>,
         const Compare& = Compare());
 template <class Alloc>
  flat_map(initializer_list<value_type>,
           const Compare&,
           const Alloc&);
template <class Alloc>
  flat_map(initializer_list<value_type> il, const Alloc& a)
    : flat_map(il, Compare(), a) { }
flat_map& operator=(initializer_list<value_type>);

// iterators:
iterator                  begin() noexcept;
const_iterator            begin() const noexcept;
iterator                  end() noexcept;
const_iterator            end() const noexcept;
reverse_iterator          rbegin() noexcept;
const_reverse_iterator    rbegin() const noexcept;
reverse_iterator          rend() noexcept;
const_reverse_iterator    rend() const noexcept;
const_iterator            cbegin() const noexcept;
const_iterator            cend() const noexcept;
const_reverse_iterator    crbegin() const noexcept;
const_reverse_iterator    crend() const noexcept;

// capacity:
```

```
bool      empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;
size_type capacity() const noexcept;
void reserve(size_type x);
void shrink_to_fit();

// element access:
T& operator[](const key_type& x);
T& operator[](key_type&& x);
T& at(const key_type& x);
const T& at(const key_type& x) const;

// modifiers:
template <class... Args> pair<iterator, bool> emplace(Args&&... args);
template <class... Args> iterator emplace_hint(const_iterator position, Args&&... args);
pair<iterator, bool> insert(const value_type& x);
pair<iterator, bool> insert(value_type&& x);
template <class P> pair<iterator, bool> insert(P&& x);
iterator insert(const_iterator position, const value_type& x);
iterator insert(const_iterator position, value_type&& x);
template <class P>
  iterator insert(const_iterator position, P&&);
template <class InputIterator>
  void insert(InputIterator first, InputIterator last);
template <class InputIterator>
  void insert(ordered_unique_sequence_tag, InputIterator first, InputIterator last);
void insert(initializer_list<value_type>);

Container extract();
void replace(Container&&);

template <class... Args>
  pair<iterator, bool> try_emplace(const key_type& k, Args&&... args);
template <class... Args>
  pair<iterator, bool> try_emplace(key_type&& k, Args&&... args);
template <class... Args>
  iterator try_emplace(const_iterator hint, const key_type& k, Args&&... args);
template <class... Args>
  iterator try_emplace(const_iterator hint, key_type&& k, Args&&... args);
template <class M>
  pair<iterator, bool> insert_or_assign(const key_type& k, M&& obj);
template <class M>
  pair<iterator, bool> insert_or_assign(key_type&& k, M&& obj);
template <class M>
  iterator insert_or_assign(const_iterator hint, const key_type& k, M&& obj);
template <class M>
  iterator insert_or_assign(const_iterator hint, key_type&& k, M&& obj);

iterator erase(iterator position);
iterator erase(const_iterator position);
size_type erase(const key_type& x);
iterator erase(const_iterator first, const_iterator last);

void swap(flat_map& fm)
    noexcept(noexcept(declval<Container>().swap(declval<Container&>())));
void clear() noexcept;

template<class C2>
  void merge(flat_map<Key, T, C2, Container>& source);
template<class C2>
  void merge(flat_map<Key, T, C2, Container>&& source);
```

```
    template<class C2>
      void merge(flat_multimap<Key, T, C2, Container>& source);
    template<class C2>
      void merge(flat_multimap<Key, T, C2, Container>&& source);

    // observers:
    key_compare key_comp() const;
    value_compare value_comp() const;

    // map operations:
    iterator find(const key_type& x);
    const_iterator find(const key_type& x) const;
    template <class K> iterator find(const K& x);
    template <class K> const_iterator find(const K& x) const;
      size_type count(const key_type& x) const;
    template <class K> size_type count(const K& x) const;
    iterator lower_bound(const key_type& x);
    const_iterator lower_bound(const key_type& x) const;
    template <class K> iterator lower_bound(const K& x);
    template <class K> const_iterator lower_bound(const K& x) const;
    iterator upper_bound(const key_type& x);
    const_iterator upper_bound(const key_type& x) const;
    template <class K> iterator upper_bound(const K& x);
    template <class K> const_iterator upper_bound(const K& x) const;
    pair<iterator, iterator> equal_range(const key_type& x);
    pair<const_iterator, const_iterator> equal_range(const key_type& x) const;
    template <class K>
      pair<iterator, iterator> equal_range(const K& x);
    template <class K>
      pair<const_iterator, const_iterator> equal_range(const K& x) const;
};

template <class Key, class T, class Compare, class Container>
  bool operator==(const flat_map<Key, T, Compare, Container>& x,
                  const flat_map<Key, T, Compare, Container>& y);
template <class Key, class T, class Compare, class Container>
  bool operator< (const flat_map<Key, T, Compare, Container>& x,
                  const flat_map<Key, T, Compare, Container>& y);
template <class Key, class T, class Compare, class Container>
  bool operator!=(const flat_map<Key, T, Compare, Container>& x,
                  const flat_map<Key, T, Compare, Container>& y);
template <class Key, class T, class Compare, class Container>
  bool operator> (const flat_map<Key, T, Compare, Container>& x,
                  const flat_map<Key, T, Compare, Container>& y);
template <class Key, class T, class Compare, class Container>
  bool operator>=(const flat_map<Key, T, Compare, Container>& x,
                  const flat_map<Key, T, Compare, Container>& y);
template <class Key, class T, class Compare, class Container>
  bool operator<=(const flat_map<Key, T, Compare, Container>& x,
                  const flat_map<Key, T, Compare, Container>& y);

// specialized algorithms:
template <class Key, class T, class Compare, class Container>
  void swap(flat_map<Key, T, Compare, Container>& x,
            flat_map<Key, T, Compare, Container>& y)
    noexcept(noexcept(x.swap(y)));

}
```

4 Acknowledgements

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