1 Revisions

1.1 Changes from R0

- Drop the requirement on container contiguity; sequence container will do.
- Remove `capacity()`, `reserve()`, and `shrink_to_fit()` from container requirements and from `flat_map` API.
- Drop redundant implementation variants from charts.
- Drop erase operation charts.
- Use more recent compilers for comparisons.
- Add analysis of separated key and value storage.

2 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.

3 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`, and an implementation of a flat map with separate vector storage for keys and values (“split storage”). 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 2017, on Mac OSX with Clang 4.0 and libc++, or on Linux with g++ 6.2 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.

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\(^1\) See P0038R0, [here](#).
\(^2\) Part of Boost.Container, [here](#).
These three sets of graphs cover the most commonly-used operations (erasure is left out, since it is nearly identical to insertion). The first set shows insertion of $N$ elements with random keys; the second shows full iteration across all $N$ elements; and the third shows `map.find()` called once for each key used in the original insertions.

3.1 Insert

![Graphs showing insertion times for different types of elements](image-url)
Unsurprisingly, insertion takes longer in contiguous-storage implementations. Boost.FlatMap has the steepest growth curves by far. Interestingly, the split storage implementation is roughly halfway in between `map` and Boost.FlatMap for `<int, int>` runs.
3.2 Iterate

For the variants other than `map`, iteration is relatively similar, and much faster than `map`'s.
3.3 Find

![Graphs showing performance comparison between Boost.FlatMap, std::map, and split_map_t for different platforms and data types.](image)

`find()` performance is where things get interesting. The different platforms produce somewhat similar results. Though the curves look different for GCC, in all cases `find()` is markedly slower for `map` than for the flat imple-
3.4 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.

Find operations are also cheaper for contiguous-storage variants, though not as clearly as so as iteration operations.

Use cases in which iteration and lookup are much more frequent than insertion and deletion suggest the use of a flat implementation.

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.

4 Proposed Design

4.1 Design Goals

Overall, `flat_map` is meant to be a drop-in replacement for `map`, just with different time- and space-efficiency properties. 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.

4.2 Design

4.2.1 `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).

4.2.2 `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.
4.2.3 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 sequence container (§23.2.3). 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.

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.

4.2.4 Interface Differences From map

- 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.

4.2.5 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.

4.2.6 Container Requirements

Any sequence container with random access iterator can be used for the Container template parameter. Container must have a value_type of pair<Key, T>.
4.2.7 Member Semantics

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, Alloc>` is `true`.

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

4.2.8 `flat_map` Synopsis

```cpp
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& a) {
}

// 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;

// size:
bool empty() const noexcept;
size_type size() const noexcept;
size_type max_size() const noexcept;

// 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);

// insert from range

iterator insert(const_iterator position, const value_type& x);
iterator insert(const_iterator position, value_type&& x);

// insert from range

template <class P>
iterator insert(const_iterator position, P&& x);

// insert from range

template <class InputIterator>
void insert(InputIterator first, InputIterator last);

// insert from range

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);

// try_emplace

template <class... Args>

pair<iterator, bool> try_emplace(key_type&& k, Args&&... args);

// try_emplace

template <class... Args>

iterator try_emplace(const_iterator hint, const key_type& k, Args&&... args);

// try_emplace

template <class... Args>

iterator try_emplace(const_iterator hint, key_type&& k, Args&&... args);

// try_emplace

template <class M>
pair<iterator, bool> insert_or_assign(const key_type& k, M&& obj);

// insert_or_assign

template <class M>
pair<iterator, bool> insert_or_assign(key_type&& k, M&& obj);

// insert_or_assign

template <class M>
iterator insert_or_assign(const_iterator hint, const key_type& k, M&& obj);

// insert_or_assign

template <class M>
iterator insert_or_assign(const_iterator hint, key_type&& k, M&& obj);

// insert_or_assign

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&>())))
    noexcept;
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;
5 Future Work

Though splitting the key and value storage in a flat map has significant insertion performance benefits for small types, I've not proposed a split_flat_map type here. This would definitely be a useful type to standardize, but its iterator would be a proxy iterator, something for which we as a community have not yet settled on a best practice.

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