Implementing Ranges and Views

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Hi, I'm Roi

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Slides

Outline

- Ranges and Views - Brief Intro
  - What are they
  - What's cool about them
  - Views we currently have
- Implementation Details - Several Perspectives
  - Object ⇌ Algorithm ⇌ Data
  - Concepts and Selection/Constraints
  - Lazy ⇌ Eager
- Case Study

Ranges and Composition

Ranges is a Breakthrough Library

- One of C++20 big-four features
- Rests on decades of existing libraries and experience
  - C++98 iterator-based algorithms
  - Fundamentals of functional / vectoric languages (APL, BQN, R, Julia, NumPy) Conor Hoekstra
  - Libraries of similar languages (D, Rust, Java) Barry Revzin, Alexandrescu BoostCon 2009.
- Main Innovation - Composability
  - Many algorithms take ranges as input and return ranges as output
    - Opposed to in-place or output-iterator nature of C++98 algorithms
  - Range Adaptors - algorithms encalsupated as ‘lazy ranges’ (views)
    - Algorithms as composable objects - ‘expression templates’
  - Projections - unary transformations of the ranges we inspect.

Terminology

- Range - Abstraction for a sequence of elements
  - begin-iterator and end-sentinel
- Range Algorithm - Function operating on ranges
  - Evolved from C++98 iterator based algorithms
  - Input: one or more ranges; potentially more arguments
  - Output: anything. If range: either in-place or via “output-iterator” or a subrange
- View - Ranges that are “cheap” to pass/hold
  - constant-time move, if-copyable-then-const-time (semantic nature → `enable_view<Rng>`)
- Range-Adaptor - range-to-range manipulations
  - Most adaptors are views and reside in `std::ranges::views`
  - View adaptors in the STL are ‘lazy’.
  - Adaptors are meant for chaining. The cheapness of views eases chain creation

Composability of Ranges

- Chaining algorithms due to range arguments and results
```
ranges::reverse(ranges::search(str,"abc"sv));
```
godbolt
- Views as composable lazy ranges
```
str | views::split(' ') | views::take(2);
```
godbolt
- Views have a value/algorithm duality
```
auto square_evens =
        views::filter([](auto x) { return int(x) % 2 == 0; }) |
        views::transform([](auto x) { return x * x; });
```
godbolt
- Simple combinations can enrich our vocabulary:
```
auto histogram =
    views::chunk_by(std::equals{}) |
    views::transform([](const auto& rng) {
        return make_pair(begin(rng), distance(rng));}
```

The Views in the Standard (C++20, C++23*)

- Factories: **`empty`**, **`single`**, **`iota`**, **`istream`**, **`repeat*`**
- Rank preserving: **`all`**, **`filter`**, **`transform`**, **`take{_while}`**, **`drop{_while}`**, **`subrange`**, **`counted`**, **`common`**, **`reverse`**, **`stride*`**, **`zip_transform*`**, **`adjacent_transform*`**, **`as_{const,rvalue}*`**
- Rank decreasing - tuples: **`elements`**, **`keys`**, **`values`**
- Rank decreasing - ranges: **`join{_with*}`**
- Rank increasing - tuples: **`zip*`**, **`enumerate*`**, **`cartesian_product*`**, **`adjacent*`**
- Rank increasing - ranges: **`{lazy_}split`**, **`slide*`**, **`chunk{_by}*`**
- Committee plan for C++26 is in [P2760]

Adaptor Chain Fundamentals

Creating Composition Chains

- Adaptors support nesting as well as pipeline/infix composition
  - `views::take(views::split(str, ' '), 2)`
    equivalent to
    `str | views::split(' ') | views::take(2)` godbolt
- *RangeAdaptorClosure*: chains without a starting range
  - Objects that exist to be chained to some range
  - Semantically they are generic algorithms, not ranges
  - `std::ranges::range_adaptor_closure` is a CRTP helper for creating adaptors that have this nesting ⇌ pipeline duality.

Simplest Range Adaptor

Reference may dangle

```
struct First : range_adaptor_closure<First> {
    constexpr auto operator()(forward_range auto&& rng) const {
        return subrange(begin(rng), empty(rng) ? begin(rng) : next(begin(rng)));
    }
};
constexpr First first;

int main() {
    string s = "aa bb cc";
    auto x = s | split(' ');
    println("{}", x | first);
    return 0;
}
```

godbolt

```
Program returned: 0
  [['a', 'a']]
```

Dealing with Dangling

- Chains involve creation (and destruction) of temporary objects
- Solution - aggregate the chain into “expression templates”:
    - `typeid("x"s | split(' ') | take(3))` ≈ **`take_view<split_view<string>>`**
- Adaptors themselves are typically small and cheap to pass as the chain grows
- Ranges can be expensive to pass → hence we use Views.

Simplest Range Adaptor + View

```
template <view Inner> requires forward_range<Inner>
class FirstItemView : public view_interface<FirstItemView<Inner>> {
    [[no_unique_address]] Inner inner;
   public:
    constexpr FirstItemView(Inner inner_) : inner(std::move(inner_)) {}
    constexpr auto begin() { return std::ranges::begin(inner); }
    constexpr auto end() { return empty(inner) ? begin() : next(begin()); }
    constexpr std::size_t size() { return empty(inner) ? 0 : 1; }
};
template <forward_range Range>
FirstItemView(Range&&) -> FirstItemView<views::all_t<Range>>;
struct First : range_adaptor_closure<First> {
    constexpr auto operator()(forward_range auto&& rng) const { return FirstItemView{rng};}
};
```
godbolt

Details About Views

- **`view_interface`** - helper CRTP which opts-in to the **`view`** concept
- Constructor - pass inner view by-value, **`std::move()`** inside
- **`begin()/end()`** - must be implemented.
  - **`const`** correctness is tricky (see [Nico Josutis]())
- **`size()`** - constant-time, opt-in a a **`sized_range`**.
- Deduction guide - use **`views::all_t`** to allow non-view inputs
  - more about all_t in the next slide
- Range adaptor closure - simply return the view.
  - Some adaptors can have optimizations here, e.g. **`reverse | reverse`**.

Lifetime Management with `views::all`

- Chains of adaptors need to outlive their base range (otherwise UB).
- STL uses value categories (lvalue vs. rvalue) to try and avoid such cases
  - `ref_view` - A view that points to another range (reference semantics), and cannot be constructed if the range is rvalue (about to go away)
  - `owning_view` - A view that *takes ownership* of another range (moves it inside the view), and can be constructed only from rvalues. Move-only semantics (like `unique_ptr`).
- `views::all(rng)` will return one 3 different types of views:
  - If `rng` is a view - simply return it
  - else-if `rng` is a lvalue - return a `ref_view` pointing to it (be careful of lifetimes
  - else return an `owning_view` that now owns the contents of the range.
- Range adaptor views in the STL use `views:all` to assist them.

Examples - views, all

```
//temporaries create an owning view
static_assert( not view<decltype(string{""}     )>);
static_assert(     view<decltype(string{""}| all)>);
static_assert(is_same_v<decltype(string{""}| all),
                        owning_view<string>.     >);

//lvalues create a ref view
string s = "some string";
static_assert( not view<decltype(s              )>);
static_assert(     view<decltype(s           | all)>);
static_assert(is_same_v<decltype(s           | all),
                        ref_view<string>.        >);
```
godbolt

Examples - views, all (2)

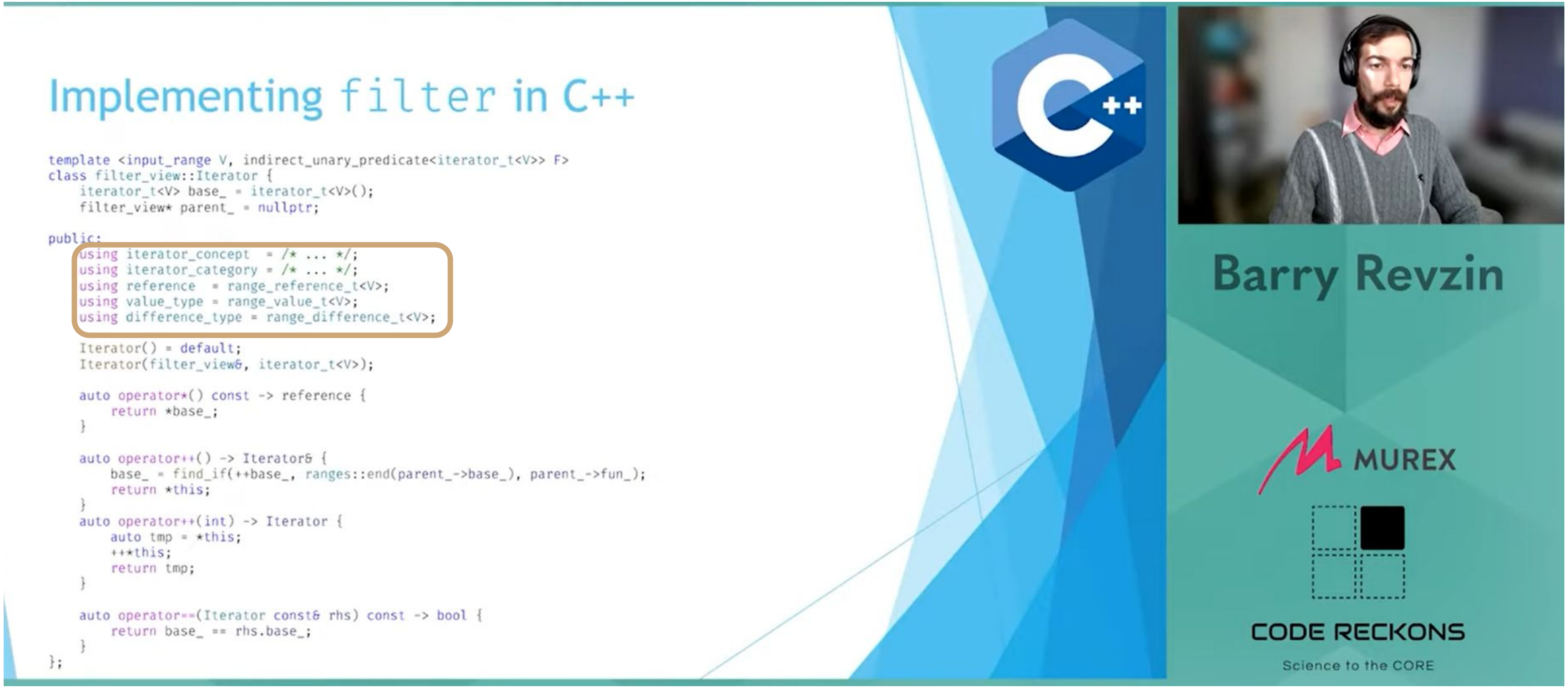
```
//views stay views
auto x = s | split(' ');
static_assert(     view<decltype(x              )>);
static_assert(     view<decltype(x         | all)>);
static_assert(is_same_v<decltype(x         | all),
                         decltype(x              )>);
//Careful - all_t<array> can be expensive-to-move
static_assert( not view<decltype(array<int,1000>{}     )>);
static_assert(     view<decltype(array<int,1000>{}| all)>);
static_assert(is_same_v<decltype(array<int,1000>{}| all),
                         owning_view<array<int,1000>>.   >);
static_assert(sizeof(decltype(array<int,1000>{}| all)) >= 4000);
```

godbolt

Range Adaptor Iterators - Being Lazy

- Most views implement their own iterator (and/or sentinel) types, and achieve their functionality through the iterator member functions
  - `transform` - utilizing `operator*()`
  - `filter/stride/reverse` - utilizing `operator++()`
  - `take_while` - utilizing `operator!=(const sentinel&)`
  - `chunk/split` - utilizing `operator*()` and `operator++()`.
- The lazy approach has many benefits
  - Pay only for what you need
  - Better support for potentially infinite ranges
  - More data locality and less need for extra RAM
  - Compiler known expression-templates has potential for performance gains.

See Barry About the Iterators



CPPP21

Take(5)

Range Categories and Refinements

- Ranges are categorized by their power of iteration, similar to the C++98 iterator category model
  - input → forward → bidirectional → random-access → contiguous
  - Similarly to C++98 category is associated via opt-in of iterator_category tags.
- On top of the power of iteration, ranges have additional *orthogonal* refinements:
  - borrowed - iterators can outlive the range. opt-in **`enable_borrowed_range`**
  - sized - number of elements in amortized constant time. opt-out **`disable_sized_range`**
  - common - **`begin()`** and **`end()`** return the same type
  - constant - range into read-only values.
- Range Adaptors must correctly publish their effect on their input.

Refinement Motivation - Algorithm Selection

- Sometimes the same goal can be achieved in several ways
  - **`ranges::ssize`** - returns a signed integer equal to the size of a range
  - **`ranges::distance`** - returns the distance between the beginning and end of a range
  - **`ssize`** only works for *sized* ranges (constant-time calculation) **`distance`** allows linear calculation if necessary. [Ben Deane recommends it].
- The library uses concepts to constrain which ranges are applicable for which algorithm/view, and to know the best method of reaching the intended goal
- Before C++20 other mechanisms were used to achieve this goal - and with concepts we have a way to be more precise and more flexible where needed.

Digression - How Lazy are We

- Recall histogram. How many passes does it perform over the data

```
auto histogram =
    views::chunk_by(std::equals{}) |
    views::transform([](const auto& rng) {
        return make_pair(begin(rng), distance(rng));}
```

- Intuitively a single pass is enough.
- Depends on if `range_reference_t<chunk_by_view<...>>` is sized
    - i.e. depends on if `subrange<...>` is sized.
    - Could potentially be controlled via `subrange_kind` but not possible in existing adaptors
- Alternative implementation can `enumerate` and properly chunk/transform the pairs.

Range/Iterator `const` Correctness

- Remember that iterators have indirect semantics.
- Still, ranges were meant to differentiate between **`iterator`** and **`const_iterator`** for ‘deep’ constness.
- Views are thus allowed to differentiate and have 2 different iterator types.
- C++23 now has **`std::basic_const_iterator`** which can be used as a drop in iterator adaptor.
- Views are notoriously tricky (bad) when it comes to const-correctness
  - Due to caching behavior
  - Due to **`owning_view`** vs. **`ref_view`** being so interchangeable
  - See Nico Josutis.

Iterator Customization Points

- Apart of the basic operators (**`*`**, **`!=`**, **`++`**, **`–`**, **`+=`**, …), iterators are allowed implement two more functions, which the ranges library must use for their purpose:
- **`iter_move(iterator)`** - instead if **`std::move(*iterator)`**
- **`iter_swap(it1, it2)`** - instead if **`std::ranges::swap(*it1, *it2)`**
- Main motivation: proxy-iterators (e.g. **`zip_view`**)
  - More on that from Jacob Rice.
- Typically implemented as "hidden friends" and invoked via **`std::ranges::iter_{move,swap}`** - which are CPOs

CPO - Customization Point Objects

- Customization points - ways in which a library (ranges) allows its users (specific range-adaptor implementers) to dictate how it behaves in certain cases.
- Before C++20 the STL had “clunky” customization point mechanisms
  - Template specialization (e.g. **`std::hash`**) [unord.hash]
  - Overload resolution and ADL (e.g. **`std::swap`**) [swappable.requirements].
- CPOs are actually objects (global variables) with template **`operator()`** function which knows to perform the correct search for customized implementations (typically via **`if constexpr`** or **`requires`** clauses)
  - More on that from Gašper Ažman.

Case Study

Views for Sorted Ranges (More Ranges Please)

- Suggestion - views for `merge`, `set_union`, `set_intersection`, `set_{symmetric_}difference`
  - Most algorithms can benefit from multi-input implementations
  - Heap (`priority_queue`) is needed for efficient `set_union, merge, ….`
- STL contains several algorithms for sorted ranges: `{inplace_}merge`, `includes`, `set_{union,intersection,{symmetric_}difference}`
  - Also search algorithms: `{upper,lower}_bound`, `equal_range`, `(unique).`
- All the operations are lazy in nature
- Ranges-v3 has views for `set_{union,intersection,{symmetric_}difference}` with 2 input ranges
- D-lang has merge and multiWayMerge.

Implementation Approach

- Every STL algorithm with an output-iterator result can be conceptually converted to a lazy range-adaptor view.
- Basic approach - the unified iterator holds all sub-iterators, an indication of the 'current' one and a pointer to the range.
    - Key idea is that every call to **`operator++()`** should iteratively increment the lowest sub-iterator until a condition (based on the specific algorithm) is satisfied.
- Various details and opportunities exist for the different algorithms

Set Operation Details

- `begin()` in constant-time
    - Trivial for union, merge. Caching needed for intersection, difference.
- Iterator category
    - input iteration seems enough (single pass)
    - forward/bidirectional iteration can be preserved - bidirectional needs a second heap.
    - random-access on either input can be utilized, mostly for intersection and difference (e.g. lower_bound)
    - random-access cannot be preserved.
- `common_range` can be preserved.
- `sized_range` can be preserved for merge.

Set Operations on Multiple Inputs

- Variadic (compile time) input-count should be simple
  - Potentially use **`array<variant<iterator_t<Views>…>, sizeof...(Views)>`** with heap operations like **`make_heap`**, **`pop_heap`**, **`push_heap`**.
- Dynamic Range-of-Ranges is more tricky due to potential RAM needs. Potential approaches:
  - Take a random-access container as extra argument.
  - Take a (PMR) allocator as extra argument.
  - Expect the input range (of ranges) to be random-access and use it (like D-lang multiWayMerge)

```
auto carsByPrice =
    carsByMakerThenPrice | chunk_by([](const Car& a, const Car& b) {
                                    return a.maker == b.maker;
    }) | to<vector> |
    merge([](const Car& a, const Car& b) { return a.price < b.price; });
```

Alternative Approach - `std::generator`

- C++23's first library addition utilizing coroutines.
- A **`generator`** exposes a coroutine with **`co_yield`** calls as a **`view`**.
- Main advantage - simplicity:
  - All the intermediate state can be stored in variables
  - Procedural style instead of callback style
  - I don't think one **`generator`** can be implemented for all output-iterator range alrogrithms - "the coloring problem".
- Main disadvantages:
  - Exposes an input_range, not more
  - Performance is compiler/optimizer dependent.

Summary

- The C++ ranges library is an exemplar of composability
- Ranges were developed to be enhanced and extended
- Implementing ranges code requires know-how
    - Not rocket science
- Now it’s our turn

- Thank you !!
    - Questions and comments are welcome

[Slides]