C++ now 2025

Missing (and Future?) C++ Range Concepts

Jonathan Müller

think-cell

- The world's leading business presentation software
- Founded in 2002, now with 1,000,000+ users at 25,000+ companies
- Seamlessly integrated into PowerPoint, streamlining every aspect of presentation creation
- Reverse-engineer Microsoft's code, develop unique layout algorithm
- Member of the Standard C++ Foundation

And we do everything in C++!

think-cell standard library

think-cell standard library: **Heavily** built around ranges.

- Predates `std::ranges` and `range-v3`
- Like `range-v3` evolution from Boost.Ranges
- Like `flux`, implemented in terms of cursors
- Unlike `flux`, cursors are an implementation detail

Partially public: github.com/think-cell/think-cell-library

See also: C++Now 2023: The New C++ Library: Strong Library Foundation for Future Projects

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- Talk will present them using C++23 and C++26 features for convenience
- Talk will use `std::ranges` not `tc` ranges (where there is an equivalent) for easier understanding

Disclaimer: No promise that any of this actually makes it into the standard library!

Structure of this talk

Problem #1	Optimizations for better performance
Problem #2	Metaprogramming for compile-time magic
Bonus	Unresolved standardese lawyering

Conventions

Existing ranges and views:

```
namespace stdv = std::views;
namespace stdr = std::ranges;
```

Potentially future ranges and views:

```
namespace std2v;
namespace std2r;
```

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Problem #1

Normalize tabs to spaces

Problem: Read a file normalizing all tab characters to four spaces.

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```
std::string read_file_normalized(std::string_view path) {
    return read_file(path)
        | stdv::transform([](char c) {
            if (c == '\t')
                return std::string(4, ' ');
            else
                return std::string(1, c);
        })
        | stdv::join
        | stdr::to<std::string>();
}
```

read_file

```
stdr::input_range auto read_file(std::string_view path);
```

read_file

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```

```
class read_file_iterator {
    const char* _buffer_cur;
    const char* _buffer_end;

public:
    char operator*() const { return *_buffer_cur; }

    read_file_iterator& operator++() {
        if (++_buffer_cur == _buffer_end)
            read_more();
        return *this;
    }
};
```

Approximately sized ranges

Implementing `stdr::to<std::string>`

`sized_range | stdr::to<std::string>`:

```
std::string result;
result.reserve(stdr::size(rng));
stdr::copy(rng, std::back_inserter(result));
```

Implementing `stdr::to<std::string>`

`sized_range | stdr::to<std::string>`:

```
std::string result;
result.reserve(stdr::size(rng));
stdr::copy(rng, std::back_inserter(result));
```

`forward_range | stdr::to<std::string>`:

```
std::string result;
result.reserve(stdr::distance(rng));
stdr::copy(rng, std::back_inserter(result));
```

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Implementing `stdr::to<std::string>`

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`forward_range | stdr::to<std::string>`:

```
std::string result;
result.reserve(stdr::distance(rng));
stdr::copy(rng, std::back_inserter(result));
```

`input_range | stdr::to<std::string>`:

```
std::string result;
// reserve is not possible
stdr::copy(rng, std::back_inserter(result));
```

Our range is not sized

```
return read_file(path)                         // sized input range
    | stdv::transform([](char c) { … }) // sized input range (of sized ranges)
    | stdv::join                               // not sized!
    | stdr::to<std::string>();
```

… but we know it's approximate size!

Assumption: Most of the time, the file does not contain tabs.

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```
return read_file(path)                          // sized input range
    | stdv::transform([](char c) { … }) // sized input range (of sized ranges)
    | stdv::join                                // ~same size as the input
    | stdr::to<std::string>();
```

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C++26: Approximately sized ranges

`approximately_sized_range | stdr::to<std::string>`:

```
std::string result;
result.reserve(stdr::reserve_hint(rng));
stdr::copy(rng, std::back_inserter(result));
```

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C++26: Approximately sized ranges

`approximately_sized_range | stdr::to<std::string>`:

```
std::string result;
result.reserve(stdr::reserve_hint(rng));
stdr::copy(rng, std::back_inserter(result));
```

`stdr::reserve_hint` is expression equivalent to:

- `stdr::size(rng)`, or
- `rng.reserve_hint()`, or
- `reserve_hint(rng)`

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Views propagate approximately sizedness:

- `stdv::transform`, `stdv::reverse`, `stdv::enumerate`, ...
- `stdv::take`, `stdv::drop`, `stdv::adjacent`, `stdv::chunk`, `stdv::stride`, ...

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C++26: Approximately sized ranges

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Views propagate approximately sizedness:

- `stdv::transform`, `stdv::reverse`, `stdv::enumerate`, ...
- `stdv::take`, `stdv::drop`, `stdv::adjacent`, `stdv::chunk`, `stdv::stride`, ...

But not `stdv::join`!

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std2r::approximately_sized_view

```
template <stdr::input_range V>
class std2r::approximately_sized_view
{
    V _base;
    std::size_t _approximate_size;

public:
    explicit approximately_sized_view(std::size_t approximate_size, V base)
    : _base(std::move(base)), _approximate_size(approximate_size) {}

    std::size_t reserve_hint() const { return _approximate_size; }

    …
};
```

Using `std2r::approximately_sized_view`

```
auto rng = read_file(path)
    | stdv::transform([](char c) { … });

return std2v::approximately_sized(stdr::size(rng),
        std::move(rng) | stdv::join
    ) | stdr::to<std::string>();
```

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Using std2r::approximately_sized_view

```
return read_file(path)
    | stdv::transform([](char c) { … })
    | std2v::approximately_unchanged_size(stdv::join)
    | stdr::to<std::string>();
```

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Implementing `std2v::approximately_unchanged_size`

```
template <typename C> // models RangeAdaptorClosureObject
struct approximately_unchanged_size
: stdr::range_apaptor_closure<approximately_unchanged_size_closure<C> {
    C closure;

    explicit approximately_unchanged_size(C closure)
    : closure(std::move(closure)) {}

    template <stdr::approximately_sized_range R>
    auto operator()(R&& r) const {
        return std2r::approximately_sized_view(
            stdr::reserve_hint(r), std::forward<R>(r) | closure
        );
    }
};
```

Generators

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Iterators vs. imperative code

```
auto rng = read_file(path) | stdv::transform(…) | stdv::join;
```

Iterators vs. imperative code

```
auto rng = read_file(path) | stdv::transform(…) | stdv::join;
```

```
while (true) {
    std::span<const char> buffer = read_more();
    if (buffer.empty()) break;

    for (char c : buffer) { // ^^^ read_file
        for (char translated : fn(c)) { // transform | join
            …
        }
    }
}
```

Iterator state

```
auto rng = read_file(path) | stdv::transform(…) | stdv::join;
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auto rng = read_file(path) | stdv::transform(…) | stdv::join;
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```
class join_iterator {
    transform_iterator    _outer;
    std::string::iterator _inner;
};
```

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Iterator state

```
auto rng = read_file(path) | stdv::transform(…) | stdv::join;
```

```
class join_iterator {
    transform_iterator    _outer;
    std::string::iterator _inner;
};
```

```
class transform_iterator {
    read_file_iterator _base;
};
```

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Iterator state

```
auto rng = read_file(path) | stdv::transform(…) | stdv::join;
```

```
class join_iterator {
    transform_iterator    _outer;
    std::string::iterator _inner;
};
```

```
class transform_iterator {
    read_file_iterator _base;
};
```

```
class read_file_iterator {
    const char* _buffer_cur;
    const char* _buffer_end;
};
```

Iterator dereference

```
auto rng = read_file(path) | stdv::transform(…) | stdv::join;
```

```
char join_iterator::operator*() {
    return *_inner;
}
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Iterator dereference

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auto rng = read_file(path) | stdv::transform(…) | stdv::join;
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```
char join_iterator::operator*() {
    return *_inner;
}
```

```
std::string transform_iterator::operator*() {
    return _fn(*_base);
}
```

Iterator dereference

```
auto rng = read_file(path) | stdv::transform(…) | stdv::join;
```

```
char join_iterator::operator*() {
    return *_inner;
}
```

```
std::string transform_iterator::operator*() {
    return _fn(*_base);
}
```

```
char read_file_iterator::operator*() {
    return *_buffer_cur;
}
```

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Iterator increment

```
auto rng = read_file(path) | stdv::transform(…) | stdv::join;
```

```
auto& join_iterator::operator++() {
    if (++_inner == stdr::end(*_outer)) {
        do { ++_outer; } while (stdr::empty(*_outer));
        _inner = stdr::begin(*_outer);
    }
}
```

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Iterator increment

```
auto rng = read_file(path) | stdv::transform(…) | stdv::join;
```

```
auto& join_iterator::operator++() {
    if (++_inner == stdr::end(*_outer)) {
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        _inner = stdr::begin(*_outer);
    }
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```
auto& transform_iterator::operator++() {
    ++_base;
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```

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Iterator increment

```
auto rng = read_file(path) | stdv::transform(…) | stdv::join;
```

```
auto& join_iterator::operator++() {
    if (++_inner == stdr::end(*_outer)) {
        do { ++_outer; } while (stdr::empty(*_outer));
        _inner = stdr::begin(*_outer);
    }
}
```

```
auto& transform_iterator::operator++() {
    ++_base;
}
```

```
auto& read_file_iterator::operator++() {
    if (++_buffer_cur == _buffer_end)
        read_more();
}
```

Iterators vs. imperative code

Imperative code:

- Nested loops.

Iterators:

- State machine.
- Loops split into read and advance.
- Arbitrarily deeply nested sub-state machines.

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Iterators have overhead.

Problematic state machine iterators

- `stdv::join`: logically two nested loops

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- `stdv::concat`: logically `N` loops in sequence

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Problematic state machine iterators

- `stdv::join`: logically two nested loops
- `stdv::concat`: logically `N` loops in sequence
- `stdv::transform(f) | stdv::filter(p)`: logically one loop with `if`

Why state machines?

Pull model: Range consumer is in control.

Why state machines?

Pull model: Range consumer is in control.

```
auto rng = …;

auto it = stdr::begin(rng);
use(*it);
++it; // skip
use(*it);
use_again(*it);
++it; // skip
++it; // skip
use(*it);
// stop at this point
```

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State machine often unnecessary

```
auto rng = …;
stdr::for_each(rng, [&](auto&& x) { … });
```

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State machine often unnecessary

```cpp
auto rng = …;
stdr::for_each(rng, [&](auto&& x) { … });
```

User does not need control.

State machine often unnecessary

```
auto rng = …;
stdr::for_each(rng, [&](auto&& x) { … });
```

User does not need control.

Every time a range-based `for` loop is used:

1. The range is represented by a (complex) state machine.
2. The state machine is repeatedly advanced until completion.

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Better: Express the loop directly

Push model: Range producer is in control.

- Range pushes value onto the consumer using a sink function object.
- Consumer processes values as they arrive.

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Push model: Range producer is in control.

- Range pushes value onto the consumer using a sink function object.
- Consumer processes values as they arrive.

Goal: Direct customization of the entire loop.

- Language proposal: P2881 (rejected)
- Reflection token injection: https://brevzin.github.io/c++/2025/04/03/token-sequence-for/

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Library solution: `for_each_while` customization point

New customization point: `std2r::for_each_while(rng, sink)`

Iterates over `rng` and calls `sink` for each element while the `sink` returns `true`.

Library solution: `for_each_while` customization point

New customization point: `std2r::for_each_while(rng, sink)`

Iterates over `rng` and calls `sink` for each element while the `sink` returns `true`.

Default implementation:

```
template <std::input_range Rng, typename Sink>
bool for_each_while(Rng&& rng, Sink s) {
    for (auto&& x : rng) {
        if (!s(x)) return false;
    }
    return true;
}
```

for_each_while customization point implementations

```
bool for_each_while(transform_view& rng, auto s) {
    return std2r::for_each_while(rng._base, [s](auto&& x) {
        return s(rng._fn(x));
    });
}
```

for_each_while customization point implementations

```
bool for_each_while(transform_view& rng, auto s) {
    return std2r::for_each_while(rng._base, [s](auto&& x) {
        return s(rng._fn(x));
    });
}
```

```
bool for_each_while(join_view& rng, auto s) {
    return std2r::for_each_while(rng._base, [s](auto&& x) {
        return std2r::for_each_while(x, s);
    });
}
```

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for_each_while customization point implementations

```
bool for_each_while(read_file_view& rng, auto s) {
    while (true) {
        std::span<const char> buffer = read_more();
        if (buffer.empty()) break;

        if (!std2r::for_each_while(buffer, s)) return false;
    }
    return true;
}
```

Use `for_each_while` in the algorithm implementations

Loops:

- `stdr::for_each`
- `stdr::copy`, `std::move`, `stdr::to`
- `stdr::transform`
- `stdr::min`, `stdr::max`
- `stdr::count`

Short-circuiting loops:

- `stdr::all_of`, `stdr::any_of`, `stdr::none_of`
- `stdr::equal`
- `stdr::contains`

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Range code with `for_each_while`

```
std2r::for_each_while(read_file(path) | stdv::transform(…) | stdv::join, s);
```

After inlining:

```
return std2r::for_each_while(rng._base, [s](std::string&& str) {
    return std2r::for_each_while(str, s);
});
```

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Range code with `for_each_while`

```
std2r::for_each_while(read_file(path) | stdv::transform(…) | stdv::join, s);
```

After inlining:

```
return std2r::for_each_while(rng._base, [s](std::string&& str) {
    for (char c : str) {
        if (!s(c)) return false;
    }
    return true;
});
```

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Range code with `for_each_while`

```
std2r::for_each_while(read_file(path) | stdv::transform(…) | stdv::join, s);
```

After inlining:

```
return std2r::for_each_while(rng._base._base, [s](char c) {
    for (char translated : fn(x)) {
        if (!s(translated)) return false;
    }
    return true;
});
```

Range code with `for_each_while`

```
std2r::for_each_while(read_file(path) | stdv::transform(…) | stdv::join, s);
```

After inlining:

```
while (true) {
    std::span<const char> buffer = read_more();
    if (buffer.empty()) break;

    for (char c : buffer) {
        for (char translated : fn(c)) {
            if (!s(translated)) return false;
        }
    }
}
return true;
```

Why not coroutines?

`std::generator`: Write loop with `co_yield`.

```
std::generator<char> read_file_normalized(std::string_view path) {
    …
    while (true) {
        std::span<const char> buffer = read_more();
        if (buffer.empty()) break;

        for (char c : buffer) {
            for (char translated : fn(c))
                co_yield translated;
        }
    }
}
```

Coroutines are state machines

- Compiler generates iterator state machine for you.
- Still pull model, not push.
- Additional coroutine overhead (heap allocation)

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We need better optimizations for `std::generator`.

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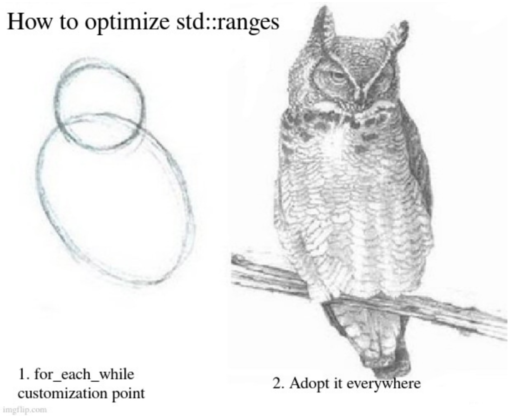
We need better optimizations for `std::generator`.

Natural syntax, bad performance:

`for_each_while` is to `co_yield` what senders/receivers is to `co_await`.

The rest of the owl



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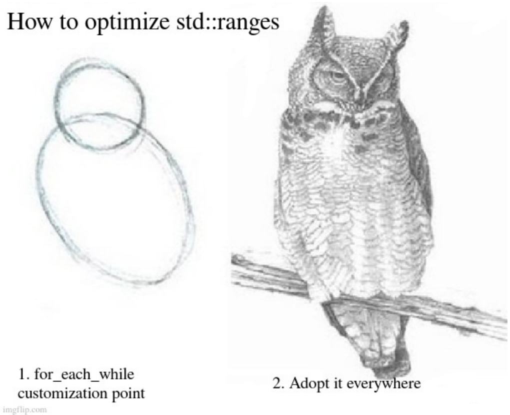

- **`stdv::reverse`**: `std2r::for_each_while_reversed?`

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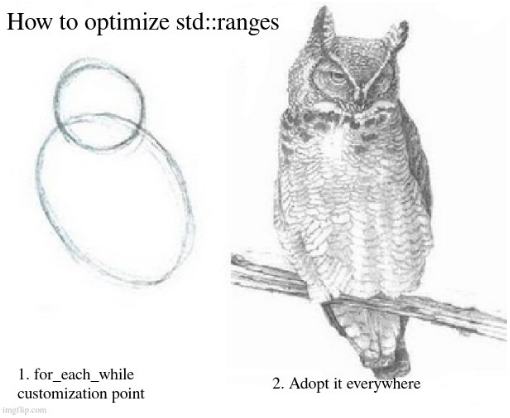
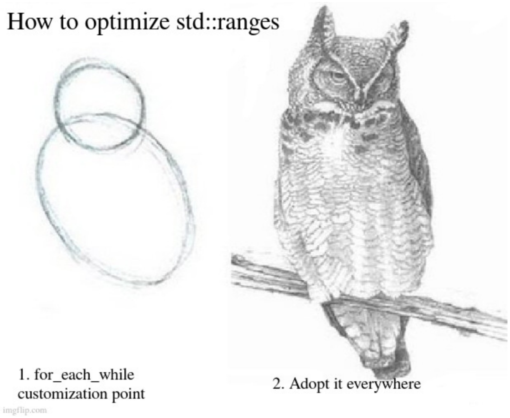
The rest of the owl



- **`stdv::reverse`:** `std2r::for_each_while_reversed`?
- **`stdv::zip`:** Can only use `std2r::for_each_while` once, all other ranges use iterators, so which one should use it?

The rest of the owl



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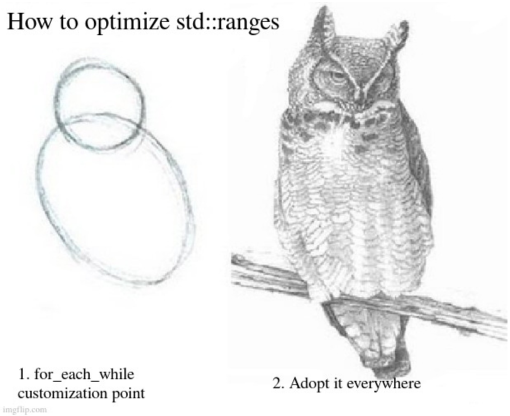

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- **`stdr::find` and variants:** `std2r::for_each_iterator_while`?
- **Generators:** Ranges that only support `std2r::for_each_while` but don't have iterators?

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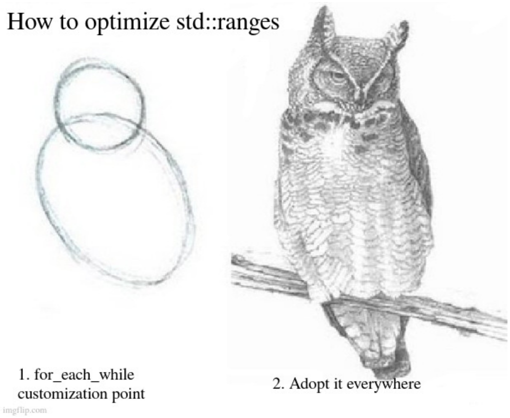
The rest of the owl



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- **`stdr::find` and variants:** `std2r::for_each_iterator_while`?
- **Generators:** Ranges that only support `std2r::for_each_while` but don't have iterators?
- **Optimizations ignore range-based for loop**

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Convenience: Implicitly no short-circuit

Common case:

```
std2r::for_each_while(rng, [&](auto&& x) {
    …
    return true;
});
```

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```
std2r::for_each_while(rng, [&](auto&& x) {
    …
    // implicit: return true
});
```

Convenience: Implicitly no short-circuit

Common case:

```
std2r::for_each_while(rng, [&](auto&& x) {
    …
    // implicit: return std::true_type{}
});
```

Optimization: Skip short-circuit

```
template <std::input_range Rng, typename Sink>
auto for_each_while(Rng&& rng, Sink s)
    -> compute-return-type
{
    for (auto&& x : rng) {
        if constexpr (std::same_as<decltype(s(x)), void>
            || std::same_as<decltype(s(x)), std::true_type>
        ) {
            s(x);
        } else {
            if (!s(x)) return false;
        }
    }
    return std::true_type{};
}
```

Wishlist: Control flow operator

P2561

```
template <std::input_range Rng, typename Sink>
auto for_each_while(Rng&& rng, Sink s)
    -> compute-return-type
{
    for (auto&& x : rng) {
        s(x)??;
    }
    return std::true_type{};
}
```

Chunked ranges

Implementing stdr::to<std::string>

`rng | stdr::to<std::string>`:

```
std::string result;
if constexpr (stdr::approximately_sized_range<decltype(rng)>)
    result.reserve(stdr::reserve_hint(rng));
else if constexpr (stdr::forward_range<decltype(rng)>)
    result.reserve(stdr::distance(rng));
else
    /* reserve is not possible */;
stdr::copy(rng, std::back_inserter(result));
```

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Implementing `stdr::to<std::string>`

`rng | stdr::to<std::string>`:

```
std::string result;
if constexpr (stdr::approximately_sized_range<decltype(rng)>)
    result.reserve(stdr::reserve_hint(rng));
else if constexpr (stdr::forward_range<decltype(rng)>)
    result.reserve(stdr::distance(rng));
else
    /* reserve is not possible */;
stdr::copy(rng, std::back_inserter(result));
```

`contiguous_range | stdr::to<std::string>`

```
std::string result;
result.append(stdr::distance(rng), stdr::data(rng));
```

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Contiguous and ranges with contiguous chunks

Contiguous ranges:

- `std::vector<T>`
- `std::array<T, N>`
- `std::string`
- `std::span<T>`

Ranges with contiguous chunks:

- `std::deque<T>`
- `stdv::concat(vec1, vec2)`
- `range_of_spans | stdv::join`
- `read_file(path)`

Some ranges have natural segmentation into chunks.

How to express this chunking?

We already did!

We already did!

```
bool for_each_while(join_view& rng, auto s) {
    return std2r::for_each_while(rng._base, [s](auto&& x) {
        return std2r::for_each_while(x, s);
    });
}
```

We already did!

```
bool for_each_while(join_view& rng, auto s) {
    return std2r::for_each_while(rng._base, [s](auto&& x) {
        return std2r::for_each_while(x, s);
    });
}
```

```
bool for_each_while(read_file_view& rng, auto s) {
    while (true) {
        std::span<const char> buffer = read_more();
        if (buffer.empty()) break;

        if (!std2r::for_each_while(buffer, s)) return false;
    }
    return true;
}
```

Changing `stdr::for_each_while`

`stdr::for_each_while(rng, s)` is expression-equivalent to:

1. `s.chunk(rng)` if that is well-formed, otherwise
2. ADL-based `for_each_while(rng, s)` overload if one exists, otherwise
3.
```
do {
    for (auto&& x : rng) {
        if (!s(x)) do_return false;
    }
    do_return true;
}
```

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Changing `stdr::for_each_while`

`stdr::for_each_while(rng, s)` is expression-equivalent to:

1. `s.chunk(rng)` if that is well-formed, otherwise
2. ADL-based `for_each_while(rng, s)` overload if one exists, otherwise
3. ```
   do {
       for (auto&& x : rng) {
           if (!s(x)) do_return false;
       }
       do_return true;
   }
   ```

Crucially: Sink gets to customize first, before the range!

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   ```

Implementing a sink for string appending

```
struct string_appender_sink {
    std::string& _result;

    bool operator()(char c) const {
        _result.push_back(c);
        return true;
    }

    bool chunk(std::contiguous_range auto&& chunk) const {
        _result.append(
            stdr::distance(chunk),
            stdr::data(chunk)
        );
        return true;
    }
};
```

Implementing `stdr::to<std::string>` more efficiently

`rng | stdr::to<std::string>`:

```
std::string result;

if constexpr (stdr::approximately_sized_range<decltype(rng)>)
    result.reserve(stdr::reserve_hint(rng));
else if constexpr (stdr::forward_range<decltype(rng)>)
    result.reserve(stdr::distance(rng));
else
    /* reserve is not possible */;

stdr::for_each_while(rng, string_appender_sink{result});
```

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Using the optimized `stdr::to<std::string>`

```
stdr::for_each_while(
    range_of_spans | stdv::join,
    string_appender_sink{result}
);
```

After inlining:

```
return std2r::for_each_while(rng._base, [s](std::span<const char> x) {
    return std2r::for_each_while(x, s);
});
```

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Using the optimized `stdr::to<std::string>`

```
stdr::for_each_while(
    range_of_spans | stdv::join,
    string_appender_sink{result}
);
```

After inlining:

```
return std2r::for_each_while(rng._base, [s](std::span<const char> x) {
    return s.chunk(x);
});
```

Sinks instead of output iterators?

Output iterators:

- Clunky overloads of `operator++`, `operator*`
- No ability to receive chunks

Sinks:

- Only overload `operator()`
- Can receive chunks

Sinks instead of output iterators?

Output iterators:

- Clunky overloads of `operator++`, `operator*`
- No ability to receive chunks

Sinks:

- Only overload `operator()`
- Can receive chunks

The standard library should support the output iterator interface only for backwards compatibility and also allow sinks.

```
std2r::copy(rng, std2r::append_to(container));
```

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Pipelines should express chunking

```cpp
std::string read_file_normalized(std::string_view path) {
    return read_file(path) // big contiguous chunks
        | stdv::transform([](char c) {
            if (c == '\t')
                return std::string(4, ' ');
            else
                return std::string(1, c);
        }) // not contiguous
        | stdv::join // tiny contiguous chunks
        | stdr::to<std::string>();
}
```

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Pipelines should express chunking

```
std::string read_file_normalized(std::string_view path) {
    return read_file(path)              // big contiguous chunks
        | stdv::split("\t"sv)           // not contiguous
        | stdv::join_with("    "sv)     // big contiguous chunks
        | stdr::to<std::string>();
}
```

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Chunked join_with implementation

```
bool for_each_while(join_with_view& rng, auto s) {
    auto first = true;
    return std2r::for_each_while(rng._base, [s](auto&& x) {
        if (first)
            first = false;
        else
            if (!std2r::for_each_while(rng._seperator, s)) return false;

        return std2r::for_each_while(x, s);
    });
}
```

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Except it doesn't work

```
std::string read_file_normalized(std::string_view path) {
    return read_file(path)
        | stdv::split("\t"sv)
        | stdv::join_with("    "sv)
        | stdr::to<std::string>();
}
```

Except it doesn't work

```
std::string read_file_normalized(std::string_view path) {
    return read_file(path)
        | stdv::split("\t"sv)
        | stdv::join_with("    "sv)
        | stdr::to<std::string>();
}
```

But: `stdv::split` requires a forward range, `read_file` is input!

(And `stdv::lazy_split` does not keep the contiguous chunks property.)

Except it doesn't work

```
std::string read_file_normalized(std::string_view path) {
    return read_file(path)
        | stdv::split("\t"sv)
        | stdv::join_with("    "sv)
        | stdr::to<std::string>();
}
```

But: `stdv::split` requires a forward range, `read_file` is input!

(And `stdv::lazy_split` does not keep the contiguous chunks property.)

However: We are fine with treating each contiguous chunk separately.

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Pipelines should express chunking completely

```
// Returns a range of `std::span<const char>`.
std::input_range auto read_file_buffers(std::string_view path);

std::input_range auto read_file(std::string_view path)
{
    return read_file_buffers(path) | stdv::join;
}
```

Pipelines should express chunking completely

```cpp
// Returns a range of `std::span<const char>`.
std::input_range auto read_file_buffers(std::string_view path);

std::input_range auto read_file(std::string_view path)
{
    return read_file_buffers(path) | stdv::join;
}
```

```cpp
std::string read_file_normalized(std::string_view path) {
    return read_file_buffers(path)
        | stdv::transform([](std::span<const char> chunk) {
            return chunk | stdv::split("\t"sv) | stdv::join_with("    "sv);
        });
        | stdv::join | stdr::to<std::string>();
}
```

A generator implementation of `read_file_buffers` on top of `read_file`

```
class read_file_buffers_generator {
    read_file_range _base;

    template <typename Sink>
    struct sink_adaptor {
        Sink s;

        bool chunk(std::span<const char> chunk) const {
            return s(chunk);
        }
    };

    friend bool for_each_while(read_file_buffers_generator& gen, auto s) {
        return stdr::for_each_while(gen._base, sink_adaptor{s});
    }
};
```

Problem #2

Generating SQL statements at compile-time

Problem: Describe SQL schema in a compile-time DSL and generate SQL statements.

```
using People = Table<
    "people"_tc,
    Column<"id"_tc, "INTEGER PRIMARY KEY"_tc>,
    Column<"name"_tc, "TEXT NOT NULL"_tc>
>;
```

```
constexpr std::string_view stmt = People::Create();
assert(stmt
  == "CREATE TABLE people(id INTEGER PRIMARY KEY, name TEXT NOT NULL)"
);
```

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Compile-time vs. “compile-time”

Fundamental C++ Limitation: Within a `consteval` function, arguments aren’t `consteval`.

```
std::array<char, constexpr_strlen("CREATE")> array; // okay
```

```
consteval void do_sth(const char* str)
{
    std::array<char, constexpr_strlen(str)> array; // error
}
```

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Compile-time vs. “compile-time”

Fundamental C++ Limitation: Within a `consteval` function, arguments aren’t `consteval`.

```
std::array<char, constexpr_strlen("CREATE")> array; // okay
```

```
consteval void do_sth(const char* str)
{
    std::array<char, constexpr_strlen(str)> array; // error
}
```

Solution: Embed the relevant information in the type of the argument.

Convention: “early compile-time” vs “late compile-time”.

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Size of string literal ranges

```
stdr::size("abc")
```

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Size of string literal ranges

```
stdr::size("abc")
```

4

Size of string literal ranges

```
stdr::size("abc")
```

4

Solution: Wrap string literals in a custom type.

_tc string literals

```
template <typename T, T ... Ts>
struct literal_range {
    static consteval const T* begin();
    static consteval const T* end();
};
```

```
template <string_template_param String>
consteval auto operator""_tc /* _tc == think-cell */ () {
    auto [...Is] = std::make_index_sequence<String.size()>{};
    return literal_range<typename decltype(String)::char_type, String[Is]...>{};
}
```

- `stdr::size("abc"_tc)` is 3
- Size of `literal_range` parameter is a compile-time expression

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Compile-time sized ranges

Concatenating fixed strings

```
template <auto type, auto name>
struct Object {
    static consteval std::string_view Create() {
        return "CREATE " + type + " " + name; // pseudo code
    }
};
```

Concatenating fixed strings

```
template <auto type, auto name>
struct Object {
    static consteval std::string_view Create() {
        return "CREATE " + type + " " + name; // pseudo code
    }
};
```

Wishlist: Just use range algorithms.

```
static consteval std::string_view Create() {
    static constexpr auto result
        = stdv::concat("CREATE "_tc, type, " "_tc, name)
        | std2r::to<std::array>();
    return result;
}
```

`std2r::to<std::array>()` needs the size early

```
template <template <typename, std::size_t> class Container, typename Rng>
auto to(Rng&& rng)
    -> Container<stdr::range_value_t<Rng>, stdr::size(rng)> {
    …
}
```

Unfortunately, `rng` is a parameter which is not `constexpr` inside the body, so this doesn't work.

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`std2r::to<std::array>()` needs the size early

```
template <template <typename, std::size_t> class Container, typename Rng>
auto to(Rng&& rng)
    -> Container<stdr::range_value_t<Rng>, stdr::size(rng)> {
    …
}
```

Unfortunately, `rng` is a parameter which is not `constexpr` inside the body, so this doesn’t work.

… or does it?

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P2280: Using unknown references in in constant expressions

rhh6e31E6

P2280 (adopted in C++23) makes it just work:

```
auto rng = stdv::concat("abc"_tc, std::array<char, 3>{'d', 'e', 'f'});
static_assert(stdr::size(rng) == 6);
```

Essentially: as long as you don't access runtime values, you can use local objects in `constexpr`!

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P2280: Using unknown references in in constant expressions

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P2280 (adopted in C++23) makes it just work:

```
auto rng = stdv::concat("abc"_tc, std::array<char, 3>{'d', 'e', 'f'});
static_assert(stdr::size(rng) == 6);
```

Essentially: as long as you don't access runtime values, you can use local objects in `constexpr`!

```
template <typename T, T ... Ts>
constexpr std::size_t literal_range<T, Ts...>::size() const {
    return sizeof...(Ts);
}

template <typename ... Rng>
constexpr std::size_t concat_view<Rng...>::size() const {
    auto [...Is] = std::make_index_sequence<sizeof...(Rng)>{};
    return (stdr::size(std::get<Is>(_base)) + ...);
}
```

New concept: Compile-time sized ranges

```
template <typename T>
concept constexpr_sized_range = stdr::sized_range<T> && requires(T& t) {
    typename std::constant_wrapper<stdr::size(t)>;
};
```

Or `compile_time_sized_range`, `statically_sized_range`, `fixed_sized_range`, ...

New concept: Compile-time sized ranges

```
template <typename T>
concept constexpr_sized_range = stdr::sized_range<T> && requires(T& t) {
    typename std::constant_wrapper<stdr::size(t)>;
};
```

Or `compile_time_sized_range`, `statically_sized_range`, `fixed_sized_range`, ...

```
template <constexpr_sized_range Rng>
constexpr auto constexpr_size = stdr::size(std::declval<Rng>());
```

Or `compile_time_size`, `static_size`, `fixed_size`, ...

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New concept: Compile-time sized ranges

```
template <typename T>
concept constexpr_sized_range = stdr::sized_range<T> && requires(T& t) {
    typename std::constant_wrapper<stdr::size(t)>;
};
```

Or `compile_time_sized_range`, `statically_sized_range`, `fixed_sized_range`, ...

```
template <constexpr_sized_range Rng>
constexpr auto constexpr_size = decltype([](Rng& rng) {
    return std::cw<std::ranges::size(rng)>;
}(std::declval<Rng&>()))::value;
```

Or `compile_time_size`, `static_size`, `fixed_size`, ...

General tool: Constexpr `declval`

Compute a constant expression involving unknown references without providing the references.

```
template <auto Fn, typename ... T>
constexpr auto constexpr_declval = decltype([](T&&... args) {
    return std::cw<Fn(args...)>;
}(std::declval<T>()...))::value;
```

General tool: Constexpr `declval`

Compute a constant expression involving unknown references without providing the references.

```
template <auto Fn, typename ... T>
constexpr auto constexpr_declval = decltype([](T&&... args) {
    return std::cw<Fn(args...)>;
}(std::declval<T>()...))::value;
```

```
template <constexpr_sized_range Rng>
constexpr auto constexpr_size = constexpr_declval<stdr::size, Rng>;
```

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Aside: Pre-C++23 Compile-time sized ranges

```
template <typename Rng>
constexpr auto constexpr_size = nullptr;

template <typename T, std::size_t N>
constexpr auto constexpr_size<std::array<T, N>> = N;

template <typename Rng>
    requires requires { decltype(std::declval<Rng&>().size())::value; }
constexpr auto constexpr_size<Rng>
    = decltype(std::declval<Rng&>().size())::value;
```

See: Compile-time sizes for range adaptors —
www.think-cell.com/en/career/devblog/compile-time-sizes-for-range-adaptors

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Implementing std2r::to<std::array>()

```
template <template <typename, std::size_t> class Container, typename Rng>
auto to(Rng&& rng) {
    Container<stdr::range_value_t<Rng>, stdr::size(rng)> result;
    stdr::copy(rng, ptr_appender(result.data()));
    return result;
}
```

Implementing std2r::to<std::array>()

```
template <template <typename, std::size_t> class Container, typename Rng>
auto to(Rng&& rng) {
    auto [...Is] = std::make_index_sequence<stdr::size(rng)>{};
    auto it = stdr::begin(rng);
    return Container<stdr::range_value_t<Rng>, stdr::size(rng)>{{it[Is]...}};
}
```

Concatenating fixed strings

```
template <auto type, auto name>
struct Object {
    static consteval std::string_view Create() {
        static constexpr auto result
            = stdv::concat("CREATE "_tc, type, " "_tc, name)
            | std2r::to<std::array>();
        return result;
    }
};
```

Heterogeneous generators

Concatening fixed strings with separator

```
template <auto type, auto name>
struct Object {
    static consteval std::string_view Create() {
        static constexpr auto result
            = stdv::concat("CREATE "_tc, type, " "_tc, name)
            | std2r::to<std::array>();
        return result;
    }
};
```

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Concatening fixed strings with separator

```
template <auto type, auto name>
struct Object {
    static consteval std::string_view Create() {
        static constexpr auto result
            = concat_with(" "_tc, "CREATE"_tc, type, name)
            | std2r::to<std::array>();
        return result;
    }
};
```

Concatening fixed strings with separator

```
template <auto type, auto name>
struct Object {
    static consteval std::string_view Create() {
        static constexpr auto result
            = concat_with(" "_tc, "CREATE"_tc, type, name)
            | std2r::to<std::array>();
        return result;
    }
};
```

```
auto concat_with(auto&& rngSep, auto&& rng0, auto&&... rngs) {
    return stdv::concat(
        rng0, stdv::concat(rngSep, rngs)...
    );
}
```

Concatening fixed strings with separator

```
template <auto qualifiers, auto type, auto name>
struct Object {
    static consteval std::string_view Create() {
        static constexpr auto result
          = concat_with(" "_tc, "CREATE"_tc, qualifiers, type, name)
          | std2r::to<std::array>();
        return result;
    }
};
```

Concatening fixed strings with separator

```cpp
template <auto qualifiers, auto type, auto name>
struct Object {
    static consteval std::string_view Create() {
        static constexpr auto result
          = concat_nonempty_with(" "_tc, "CREATE"_tc, qualifiers, type, name)
          | std2r::to<std::array>();
        return result;
    }
};
```

Concatenating non-empty ranges with separator

```
auto concat_nonempty_with(auto&& rngSep, auto&&... rngs) {
    return make_range(rngs...)
        | stdv::filter([](auto&& rng) {
            return !stdr::empty(rng);
        })
        | stdv::join_with(rngSep);
}
```

1. Turn the parameter pack into a range.
2. Filter out empty ranges.
3. Join the remaining ranges with the separator.

Concatenating non-empty ranges with separator

```
auto concat_nonempty_with(auto&& rngSep, auto&&... rngs) {
    return [&](auto&&... non_empty_rngs) {
        return concat_with(rngSep, non_empty_rngs...);
    }(/* filter out empty ranges from rngs */...);
}
```

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Concatenating non-empty ranges with separator

```
auto concat_nonempty_with(auto&& rngSep, auto&&... rngs) {
    return make_range(rngs...)
        | stdv::filter([](auto&& rng) {
            return !stdr::empty(rng);
        })
        | stdv::join_with(rngSep);
}
```

1. Turn the parameter pack into a range.
2. Filter out empty ranges.
3. Join the remaining ranges with the separator.

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Implementing make_range

```
template <typename... Rngs>
auto make_range(Rngs&&... rngs) {
    using rng_t = std::common_type_t<stdv::all_t<Rngs>...>;
    return std::array<rng_t, sizeof...(rngs)>{stdv::all(std::forward<Rng>(rngs)).
}
```

Implementing make_range

```
template <typename... Rngs>
auto make_range(Rngs&&... rngs) {
    using rng_t = std::common_type_t<stdv::all_t<Rngs>...>;
    return std::array<rng_t, sizeof...(rngs)>{stdv::all(std::forward<Rng>(rngs)).
}
```

Problem: Each element of the resulting range has the same type.

Implementing make_range

```
template <typename... Rngs>
auto make_range(Rngs&&... rngs) {
    using rng_t = std::common_type_t<stdv::all_t<Rngs>...>;
    return std::array<rng_t, sizeof...(rngs)>{stdv::all(std::forward<Rng>(rngs)).
}
```

Problem: Each element of the resulting range has the same type.

```
std::array<std::span<const char>, 3> result
    = make_range("CREATE"_tc, "TABLE"_tc, "people"_tc);
constexpr auto size = stdr::size(result[0]); // error: not a constant expression
```

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Better implementation of make_range

```cpp
template <typename ... Rng>
auto make_range(Rng&&... rngs) {
    return std::make_tuple(stdv::all(std::forward<Rng>(rngs))...);
}
```

Better implementation of `make_range`

```
template <typename ... Rng>
auto make_range(Rng&&... rngs) {
    return std::make_tuple(stdv::all(std::forward<Rng>(rngs))...);
}
```

But a tuple isn't a range!

Tuple ranges

```cpp
std::tuple<int, float, char> tuple;
auto x = stdr::begin(tuple)[n];
// What is the type of x?
```

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Tuple ranges

```
std::tuple<int, float, char> tuple;
auto x = stdr::begin(tuple)[n];
// What is the type of x?
```

```
template <typename ... T>
auto std::tuple<T...>::iterator::operator*() const
    -> std::variant<T...>
{
    …
}
```

Overhead.

Tuple ranges

```
std::tuple<int, float, char> tuple;
auto x = stdr::begin(tuple)[n];
// What is the type of x?
```

```
template <typename ... T, typename Sink>
bool for_each_while(std::tuple<T...>& tuple, Sink s) {
    auto [...Is] = std::make_index_sequence<sizeof...(T)>{};
    return (s(std::get<Is>(tuple)) && ...);
}
```

No overhead!

Homogeneous ranges vs. Heterogeneous generators

Homogeneous ranges:

- `stdr::begin`/`stdr::end` (and optionally `std2r::for_each_while`)
- Single `stdr::range_value_t` type
- Can use all iterator-based algorithms/views
- Can use range-based for loop

Heterogeneous generators:

- Only `std2r::for_each_while`
- Variadic `stdr::generator_output_t` type list
- Can only use `std2r::for_each_while`-based algorithm/views
- Can only use `std2r::for_each_while` with a generic lambda

Every homogeneous range is-a heterogeneous generator, but not vice versa.

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Heterogeneous generators

`std::tuple`:

```
std2r::for_each_while(tuple, [](auto&& x) {
    // do something with `x`
});
```

Heterogeneous generators

`std::tuple`:

```
std2r::for_each_while(tuple, [](auto&& x) {
    // do something with `x`
});
```

`std::index_sequence`:

```
std2r::for_each_while(seq, []<std::size_t I>(std::constant_wrapper<I>) {
    // do something with `I`
});
```

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Heterogeneous generators

`std::tuple`:

```
std2r::for_each_while(tuple, [](auto&& x) {
    // do something with `x`
});
```

`std::index_sequence`:

```
std2r::for_each_while(seq, []<std::size_t I>(std::constant_wrapper<I>) {
    // do something with `I`
});
```

`boost::mp11::mp_list`:

```
std2r::for_each_while(type_list, []<typename T>(std::type_identity<T>) {
    // do something with `T`
});
```

Matt Godbolt ACCU 2025 keynote: Teaching an old dog new tricks

Goal: Compile each opcode of Z80 machine code into a function that executes it.

```
using Z80Func = void (*)(Z80 &);

constexpr std::array<Z80Func *, 256> compiled_opcodes =
  stdv::iota(0, 256)
  | stdv::transform([](auto opcode) {
      constexpr Instruction decoded_instr = decode(opcode);
      return compile(decoded_instr);
  })
  | stdr::to<std::array>{};
```

Not valid C++!

think-cell

Matt Godbolt ACCU 2025 keynote: Teaching an old dog new tricks

Goal: Compile each opcode of Z80 machine code into a function that executes it.

```
using Z80Func = void (*)(Z80 &);

constexpr std::array<Z80Func *, 256> compiled_opcodes =
  std::make_integer_sequence<unsigned char, 256>{}
  | stdv::transform([]<unsigned char Opcode>(std::constant_wrapper<Opcode>) {
      constexpr Instruction decoded_instr = decode(Opcode);
      return compile<decoded_instr>();
  })
  | std2r::to<std::array>{};
```

Valid C++!

think-cell

Filtering based on type

```
bool for_each_while(filter_view& rng, auto s) {
    return std2r::for_each_while(rng._base, [s](auto&& x) {
        return rng._predicate(x) ? s(x) : true;
    });
}
```

think-cell

Filtering based on type

```
bool for_each_while(filter_view& rng, auto s) {
    return std2r::for_each_while(rng._base, [s](auto&& x) {
        if constexpr (requires { std::cw<rng._predicate(x)>; }) {
            if constexpr (rng._predicate(x)) {
                return s(x);
            } else {
                return true;
            }
        } else {
            return rng._predicate(x) ? s(x) : true;
        }
    });
}
```

think-cell

Using filtering based on type

```
std::make_tuple(1, 2.0, "hello")
  | stdv::filter([](auto&& x) {
      return std::is_integral_v<decltype(x)>;
  })
  | stdr::to<std::vector>(); // std::vector<int>
```

Concatenating non-empty ranges with separator

```
auto concat_nonempty_with(auto&& rngSep, auto&&... rngs) {
    return make_range(rngs...)
        // compile-time sized with compile-time sized elements
        | stdv::filter([](auto&& rng) {
            return !stdr::empty(rng);
        })
        | stdv::join_with(rngSep);
}
```

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Tuple Generators

Concatenating non-empty ranges with separator

```cpp
auto concat_nonempty_with(auto&& rngSep, auto&&... rngs) {
    return make_range(rngs...)
        // compile-time sized with compile-time sized elements
        | stdv::filter([](auto&& rng) {
            return !stdr::empty(rng);
        }) // no longer compile-time sized
        | stdv::join_with(rngSep);
}
```

Sized filter_view

```
template <typename Base, typename Predicate>
std::size_t filter_view<Base, Predicate>::size() const {
    return stdr::count_if(_base, _predicate);
}
```

Sized `filter_view`

```
template <typename Base, typename Predicate>
    requires std2r::constexpr_sized_range<Base>
std::size_t filter_view<Base, Predicate>::size() const {
    return stdr::count_if(_base, _predicate); // O(1)
}
```

Sized `filter_view`

```
template <typename Base, typename Predicate>
std::size_t filter_view<Base, Predicate>::size() const
    requires std2r::constexpr_sized_range<Base>
        && (stdr::all_of(std2r::generator_output_t<Base>{},
            []<typename T>(std::type_identity<T>) {
                return requires(Predicate p, T t) { std::cw<p(t)>; };
            }))
{
    return stdr::count_if(_base, _predicate); // O(1), hopefully optimized
}
```

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Sized `filter_view`

Pre-C++23:

```
template <typename Base, typename Predicate>
    requires std2r::constexpr_sized_range<Base>
        && (stdr::all_of(std2r::generator_output_t<Base>{},
            []<typename T>(std::type_identity<T>) {
                return requires(Predicate p, T t) { std::cw<p(t)>; };
            }))
constexpr auto constexpr_size<filter_view<Base, Predicate>>
    = stdr::count_if(std::declval<Base>(), std::declval<Predicate>()); // ???
```

Conditional range

```
std::string reverse_words(std::string const& str)
{
    return str // "Hello World!"
      | stdv::chunk_by([](char left, char right) {
          return std::isalpha(left) != std::isalpha(right);
      }) // ["Hello", " ", "World", "!"]
      | stdv::transform([](auto chunk) {
          if (std::isalpha(chunk.front()))
              return chunk | stdv::reverse;
          else
              return chunk;
      }) // ["olleH", " ", "dlroW", "!"]
      | stdv::join | stdr::to<std::string>(); // "olleH dlroW!"
}
```

Conditional range

```
std::string reverse_words(std::string const& str)
{
    return str // "Hello World!"
      | stdv::chunk_by([](char left, char right) {
          return std::isalpha(left) != std::isalpha(right);
      }) // ["Hello", " ", "World", "!"]
      | stdv::transform([](auto chunk) {
          if (std::isalpha(chunk.front()))
              return chunk | stdv::reverse | stdr::to<std::string>();
          else
              return chunk | stdr::to<std::string>();
      }) // ["olleH", " ", "dlroW", "!"]
      | stdv::join | stdr::to<std::string>(); // "olleH dlroW!"
}
```

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Conditional range

```cpp
std::string reverse_words(std::string const& str)
{
    return str // "Hello World!"
      | stdv::chunk_by([](char left, char right) {
          return std::isalpha(left) != std::isalpha(right);
      }) // ["Hello", " ", "World", "!"]
      | stdv::transform([](auto chunk) {
          return std2v::conditional_range(
              std::isalpha(chunk.front()),
                  chunk | stdv::reverse,
                  chunk
          );
      }) // ["olleH", " ", "dlroW", "!"]
      | stdv::join | stdr::to<std::string>(); // "olleH dlroW!"
}
```

Conditional range and filter

```cpp
auto gen1 = std::make_tuple(1, 2, 3);
static_assert(stdr::size(gen1) == 3);

auto gen2 = std::make_tuple(1.0, 2.0, 3.0);
static_assert(stdr::size(gen2) == 3);
```

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Conditional range and filter

```
auto gen1 = std::make_tuple(1, 2, 3);
static_assert(stdr::size(gen1) == 3);

auto gen2 = std::make_tuple(1.0, 2.0, 3.0);
static_assert(stdr::size(gen2) == 3);
```

```
auto conditional = std2v::conditional_range(getchar() % 2 == 0, gen1, gen2);
static_assert(stdr::size(conditional) == 3);
```

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Conditional range and filter

```cpp
auto gen1 = std::make_tuple(1, 2, 3);
static_assert(stdr::size(gen1) == 3);

auto gen2 = std::make_tuple(1.0, 2.0, 3.0);
static_assert(stdr::size(gen2) == 3);
```

```cpp
auto conditional = std2v::conditional_range(getchar() % 2 == 0, gen1, gen2);
static_assert(stdr::size(conditional) == 3);
```

```cpp
auto filtered = conditional
    | stdv::filter([](auto&& x) { return std::is_integral_v<decltype(x)>; });
static_assert(stdr::size(filtered) == ???); // error: not a constant expression
```

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Sized filter view

`stdv::filter(rng, p)` has a compile-time size if:

1. `rng` has a compile-time size
2. `p` depends only on the type of the elements in `rng`
3. We can get the type of each element at compile-time.

New concept: Tuple generators

Types that are:

1. Generators: `std2r::for_each_while(gen, sink)`
2. Compile-time sized: `std::cw<stdr::size(gen)>`
3. Tuple-like: `std2r::get<Idx>(gen)`

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New concept: Tuple generators

Types that are:

1. Generators: `std2r::for_each_while(gen, sink)`
2. Compile-time sized: `std::cw<stdr::size(gen)>`
3. Tuple-like: `std2r::get<Idx>(gen)`

Most views of tuple-like generators can themselves become tuple-like generators.

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Generators, tuple generators, and ranges

Generators:

```
std2r::for_each_while(gen, [](auto&& x) {
    …
});
```

Tuple generators:

```
template for (auto&& x : gen) {
    …
}
```

Ranges:

```
for (auto&& x : rng) {
    …
}
```

Sized filter view

```
template <typename Base, typename Predicate>
std::size_t filter_view<Base, Predicate>::size() const
    requires std2r::tuple_generator<Base>
        && (stdr::all_of(std2r::generator_output_t<Base>{},
            []<typename T>(std::type_identity<T>) {
                return requires(Predicate p, T t) { std::cw<p(t)>; };
            }))
{
    return constexpr_declval<[](Base b, Predicate p) {
        return std2r::count_if(std::make_index_sequence<stdr::size(b)>{},
          [&]<std::size_t I>(std::constant_wrapper<I>) {
              return p(std2r::get<I>(b));
          }
        );
    }, Base, Predicate>;
}
```

Tuple-like filter view

```
template <std::size_t I, typename Base, typename Predicate>
decltype(auto) get(filter_view<Base, Predicate>& rng) {
    constexpr auto base_i
        = /* index accounting for skipped elements */;
    return std2r::get<base_i>(rng._base);
}
```

Concatenating non-empty ranges with separator

```
auto concat_nonempty_with(auto&& rngSep, auto&&... rngs) {
    return make_range(rngs...)
        | stdv::filter([](auto&& rng) {
            return !stdr::empty(rng);
        })
        // compile-time sized with compile-time sized elements
        | stdv::join_with(rngSep);
        // no longer compile-time sized
}
```

Sized join

```
template <typename RngRng>
    requires stdr::sized_range<RngRng>
        && all_same_constexpr_size<std2r::generator_output_t<RngRng>>
std::size_t join_view<RngRng>::size() const
{
    auto common_constexpr_size = …;
    return stdr::size(_base) * common_constexpr_size;
}
```

Sized join

```
template <typename RngRng>
    requires stdr::sized_range<RngRng>
      && (std2r::tuple_generator<RngRng>
            || all_same_constexpr_size<std2r::generator_output_t<RngRng>>)
std::size_t join_view<RngRng>::size() const
{
    if constexpr (std2r::tuple_generator<RngRng>) {
        auto [...Is] = std::make_index_sequence<stdr::size(_base)>{};
        return (stdr::size(std2r::get<Is>(_base)) + ...);
    } else {
        auto common_constexpr_size = …;
        return stdr::size(_base) * common_constexpr_size;
    }
}
```

join vs. concat

```
template <typename RngRng>
    requires stdr::sized_range<RngRng>
      && std2r::tuple_generator<RngRng>
std::size_t join_view<RngRng>::size() const
{
    auto [...Is] = std::make_index_sequence<stdr::size(_base)>{};
    return (stdr::size(std2r::get<Is>(_base)) + ...);
}
```

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join vs. concat

```cpp
template <typename RngRng>
    requires stdr::sized_range<RngRng>
      && std2r::tuple_generator<RngRng>
std::size_t join_view<RngRng>::size() const
{
    auto [...Is] = std::make_index_sequence<stdr::size(_base)>{};
    return (stdr::size(std2r::get<Is>(_base)) + ...);
}
```

```cpp
template <typename ... Rng>
std::size_t concat_view<Rng...>::size() const {
    auto [...Is] = std::make_index_sequence<sizeof...(Rng)>{};
    return (stdr::size(std::get<Is>(_base)) + ...);
}
```

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join vs. concat

```
bool for_each_while(join_view& rng, auto s) {
    return std2r::for_each_while(rng._base, [s](auto&& x) {
        return std2r::for_each_while(x, s);
    });
}
```

join vs. concat

```
bool for_each_while(join_view& rng, auto s) {
    return std2r::for_each_while(rng._base, [s](auto&& x) {
        return std2r::for_each_while(x, s);
    });
}
```

```
bool for_each_while(concat_view& rng, auto s) {
    return std2r::for_each_while(rng._base, [s](auto&& x) {
        return std2r::for_each_while(x, s);
    });
}
```

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`concat` is just a `join` of a tuple!

concat is just a join of a tuple!

```
template <typename ... Rng>
auto concat(Rng&&... rng) {
    return stdv::join(std::make_tuple(stdv::all(std::forward<Rng>(rng))...));
}
```

- tuple-based `join_view` that corresponds to `concat_view`
- range-based `join_view` that corresponds to traditional `join_view`
- generator `join_view` that is shared and just implementes `for_each_while`

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Concatenating non-empty ranges with separator

```
auto concat_nonempty_with(auto&& rngSep, auto&&... rngs) {
    return [&](auto&&... non_empty_rngs) {
        return concat_with(rngSep, non_empty_rngs...);
    }(/* filter out empty ranges from rngs */...);
}
```

```
auto concat_nonempty_with(auto&& rngSep, auto&&... rngs) {
    return make_range(rngs...)
        | stdv::filter([](auto&& rng) {
            return !stdr::empty(rng);
        })
        | stdv::join_with(rngSep);
}
```

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Concatenating non-empty ranges with separator

```
auto concat_nonempty_with(auto&& rngSep, auto&&... rngs) {
    return [&](auto&&... non_empty_rngs) {
        return concat_with(rngSep, non_empty_rngs...);
    }(/* filter out empty ranges from rngs */...);
}
```

```
auto concat_nonempty_with(auto&& rr            ...  rngs) {
    return make_range(rngs
        | stdv::filt            rng) {
            retu        ..empty(rng);
        })
        | stdv::join_with(rngSep);
}
```

They're the same algorithm!

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Generating SQL statements at compile-time

Library infrastructure updates:

```
84 files changed, 969 insertions(+), 730 deletions(-)
```

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Generating SQL statements at compile-time

Library infrastructure updates:

```
84 files changed, 969 insertions(+), 730 deletions(-)
```

Make `concat_nonempty_with` work:

```
  template<typename RngSep, typename... Rngs>
-   auto concat_nonempty_with(RngSep&& rngSep, Rngs&&... rngs) {
+   constexpr auto concat_nonempty_with(RngSep&& rngSep, Rngs&&... rngs) {
```

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Bonus

Unbounded stdv::iota

```
int fib(int n) { … }

int smallest_fib_above(int x) {
    auto all_fibonacci_numbers =
        stdv::iota(0)              // [0, 1, 2, 3, ...]
        | stdv::transform(fib); // [0, 1, 1, 2, ...]

    return *stdr::find_if(
        all_fibonacci_numbers,
        [x](int f) { return f > x; }
    );
}
```

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Range requirements

[iterator.requirements.general]/8

> *Most of the library's algorithmic templates that operate on data structures have interfaces that use ranges. A range is an iterator and a sentinel that designate the beginning and end of the computation […]*

Range requirements

[iterator.requirements.general]/8

> *Most of the library's algorithmic templates that operate on data structures have interfaces that use ranges. A range is an iterator and a sentinel that designate the beginning and end of the computation […]*

[iterator.requirements.general]/9

> *An iterator and a sentinel denoting a range are comparable. A range `[i, s)` is empty if `i == s`; otherwise, `[i, s)` refers to the elements in the data structure starting with the element pointed to by `i` and up to but not including the element, if any, pointed to by the first iterator `j` such that `j == s`.*

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Range requirements

[iterator.requirements.general]/10

> *A sentinel `s` is called reachable from an iterator `i` if and only if there is a finite sequence of applications of the expression `++i` that makes `i == s`.*

Range requirements

[iterator.requirements.general]/10

> *A sentinel `s` is called reachable from an iterator `i` if and only if there is a* ***finite sequence*** *of applications of the expression `++i` that makes `i == s`. [...]*

Range requirements

[iterator.requirements.general]/10

> *A sentinel `s` is called reachable from an iterator `i` if and only if there is a* ***finite sequence*** *of applications of the expression `++i` that makes `i == s`. [...]*

```
auto rng = stdv::iota(0u);
auto i = rng.begin();
auto s = rng.end();
for (;;)
{
    assert(i != s);
    ++i;
}
```

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Range requirements

[iterator.requirements.general]/10

> *A sentinel `s` is called reachable from an iterator `i` if and only if there is a* ***finite sequence*** *of applications of the expression `++i` that makes `i == s`. [...]*

```
auto rng = stdv::iota(0u);
auto i = rng.begin();
auto s = rng.end();
for (;;)
{
    assert(i != s);
    ++i;
}
```

`decltype(s)` is `std::unreachable_sentinel_t`.

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Range requirements

[iterator.requirements.general]/10

> *[…] If `s` is reachable from `i`, `[i, s)` denotes a valid range.*

Range requirements

[iterator.requirements.general]/10

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Hmmm…

Range requirements

[iterator.requirements.general]/10

> *[…] If `s` is reachable from `i`, `[i, s)` denotes a valid range.*

Hmmm…

[iterator.requirements.general]/12

> *The result of the application of library functions to invalid ranges is undefined.*

Range requirements

[iterator.requirements.general]/10

> *[...] If `s` is reachable from `i`, `[i, s)` denotes a valid range.*

Hmmm...

[iterator.requirements.general]/12

> *The result of the application of library functions to invalid ranges is undefined.*

Oh.

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Range requirements

```
auto rng = stdv::iota(0u);
stdr::find_if(rng, p); // UB
```

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Range requirements

```cpp
auto rng = stdv::iota(0u);
stdr::find_if(rng, p); // UB
```

```cpp
auto rng = stdv::iota(0u);
rng | stdv::take(10); // UB
```

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Range requirements

```
auto rng = stdv::iota(0u);
stdr::find_if(rng, p); // UB
```

```
auto rng = stdv::iota(0u);
rng | stdv::take(10); // UB
```

```
auto rng = stdv::iota(0u);
for (auto x : rng) { /* ... */ } // UB (calls `.begin()`)
```

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Range requirements

```cpp
auto rng = stdv::iota(0u);
stdr::find_if(rng, p); // UB
```

```cpp
auto rng = stdv::iota(0u);
rng | stdv::take(10); // UB
```

```cpp
auto rng = stdv::iota(0u);
for (auto x : rng) { /* ... */ } // UB (calls `.begin()`)
```

```cpp
auto rng = stdv::iota(0u); // UB (calls `~iota_view()`)
```

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This is undesirable

The standard library should not provide facilities that only cause undefined behavior.

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SF	F	N	A	SA
9	4	1	0	0

Actual poll had different wording.

This is undesirable

The standard library should not provide facilities that only cause undefined behavior.

SF	F	N	A	SA
9	4	1	0	0

Actual poll had different wording.

But how to fix it?

Problem space

True invalid ranges:

- `stdr::subrange(array + 10, array)`
- `stdr::subrange(vec1.begin(), vec2.end())`

Problem space

True invalid ranges:

- `stdr::subrange(array + 10, array)`
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True infinite ranges:

- `stdv::repeat(42)`
- `stdv::iota(unsigned(0))`

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Problem space

True invalid ranges:

- `stdr::subrange(array + 10, array)`
- `stdr::subrange(vec1.begin(), vec2.end())`

True infinite ranges:

- `stdv::repeat(42)`
- `stdv::iota(unsigned(0))`

Ranges where `.end()` lies:

- `stdv::iota(int(0))`
- `stdr::subrange(ptr, stdr::unreachable_sentinel) // trust me`

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Problem space

True invalid ranges:

- `stdr::subrange(array + 10, array)`
- `stdr::subrange(vec1.begin(), vec2.end())`

True infinite ranges:

- `stdv::repeat(42)`
- `stdv::iota(unsigned(0))`

Ranges where `.end()` lies:

- `stdv::iota(int(0))`
- `stdr::subrange(ptr, stdr::unreachable_sentinel) // trust me`

Ranges where we don't know:

- `stdv::istream`
- `std::generator<T>`

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What even is infinity?

Infinite range:

```
for (auto x : stdv::repeat(42)) {
    std::print("{}\n", x);
}
```

What even is infinity?

Infinite range:

```
for (auto x : stdv::repeat(42)) {
    std::print("{}\n", x);
}
```

Infinite range?

```
for (auto c : stdv::istream<char>(std::cin)) {
    std::print("{}\n", c);
}
```

What even is infinity?

Infinite range:

```
for (auto x : stdv::repeat(42)) {
    std::print("{}\n", x);
}
```

Infinite range?

```
for (auto c : stdv::istream<char>(std::cin)) {
    std::print("{}\n", c);
}
```

Infinite range?

```
bool operator==(iterator it, sentinel s) {
    return dice_roll() == 6;
}
```

Infinite vs. finite usage

Infinite usage:

```
for (auto x : input) {
    output(process(x));
}
```

Finite usage:

```
stdv::zip(rng, stdv::iota(0))
```

```
stdr::transform(rng, stdv::iota(0), out, fn);
```

```
return *stdr::find_if(
    all_fibonacci_numbers,
    [x](int f) { return f > x; }
);
```

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New definition attempt: Infinity sentinel

Infinity sentinel: No matter how many times you do `++i`, you will not encounter undefined behavior, and `i == s` is false.

- `stdv::repeat(42)`
- `stdv::iota(unsigned(0))`
- potentially `stdv::istream<T>`
- potentially `std::generator<T>`

think-cell

New definition attempt: Infinity sentinel

Infinity sentinel: No matter how many times you do `++i`, you will not encounter undefined behavior, and `i == s` is false.

- `stdv::repeat(42)`
- `stdv::iota(unsigned(0))`
- potentially `stdv::istream<T>`
- potentially `std::generator<T>`

But not:

- `stdv::iota(int(0))`
- `stdr::subrange(ptr, stdr::unreachable_sentinel)`
- `stdr::subrange(array + 10, array)`
- `stdr::subrange(vec1.begin(), vec2.end())`

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New definition attempt #1: Unbounded sentinel

Unbounded sentinel: No matter how many times you do `++i`, `i == s` is false, but you can only do it a finite amount of times before encountering undefined behavior; the true range is a finite prefix of `[i, s)`.

- `stdv::iota(int(0))`
- `stdr::subrange(ptr, stdr::unreachable_sentinel)`
- potentially `std::generator<T>`

think-cell

New definition attempt #1: Unbounded sentinel

Unbounded sentinel: No matter how many times you do `++i`, `i == s` is false, but you can only do it a finite amount of times before encountering undefined behavior; the true range is a finite prefix of `[i, s)`.

- `stdv::iota(int(0))`
- `stdr::subrange(ptr, stdr::unreachable_sentinel)`
- potentially `std::generator<T>`

But also (!):

- `stdr::subrange(array + 10, array)`
- `stdr::subrange(vec1.begin(), vec2.end())`
- any iterator-sentinel-pair where `i == s` compiles

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New definition attempt #2: Unbounded sentinel

Unbounded sentinel: `s` has type `std::unreachable_sentinel_t` but you can only do `++i` a finite amount of times before encountering undefined behavior; the true range is a finite prefix of `[i, s)`.

- `stdv::iota(int(0))`
- `stdr::subrange(ptr, stdr::unreachable_sentinel)`

But not:

- `stdr::subrange(array + 10, array)`
- `stdr::subrange(vec1.begin(), vec2.end())`

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New definition attempt #2: Unbounded sentinel

Unbounded sentinel: `s` has type `std::unreachable_sentinel_t` but you can only do `++i` a finite amount of times before encountering undefined behavior; the true range is a finite prefix of `[i, s)`.

- `stdv::iota(int(0))`
- `stdr::subrange(ptr, stdr::unreachable_sentinel)`

But not:

- `stdr::subrange(array + 10, array)`
- `stdr::subrange(vec1.begin(), vec2.end())`

But also not (!):

- `std::generator<T>`

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Do we care about unbounded generators?

```
std::generator<int> infinite_range() {
    while (true) {
        co_yield 0;
    }
}
```

```
std::generator<int> unbounded_range() {
    for (auto i = 0; true; ++i) {
        if (i == 10) undefined_behavior();
        co_yield 0;
    }
}
```

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After an infinite number of `++i`, `i - begin()` does not fit in `ptrdiff_t`.

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`ptrdiff_t` on 32 bit system:

```
std::span<unsigned char> memory = allocate_virtual_memory(3 * 1024 * 1024 * 1024
memory.end() - memory.begin();
```

What about cyclic ranges?

```
void foo(stdr::iota_view<unsigned> rng, stdr::iota_view<unsigned>::iterator it) {
    assert(*rng.begin() == 0);
    assert(*it == 4);
    std::print("{}\n", it - rng.begin());
}
```

What is the difference?

- `4?`
- `UINT_MAX + 4?`
- `10 * UINT_MAX + 4?`

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New sizing hierarchy

- `stdr::sized_range`: Range has a known finite size.
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- `stdr::range`: Range could be finite, infinite, unbounded — we don't know statically.

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stdr::transform(std::execution::par, rng, stdv::iota(0u), out, fn);
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Proposed by P3555R0.

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Conclusion

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- `std2v::conditional_range`
- `std2r::for_each_while` customization point as a hidden optimization
- Sink-based appenders as better output iterators
- Compile-time sized ranges, `std2r::to<std::array>`
- A fix for infinite ranges

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Can be somewhat emulated using a range of `std::meta::info`.

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Proposals welcome!

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