What Is a Range?

Šimon Tóth

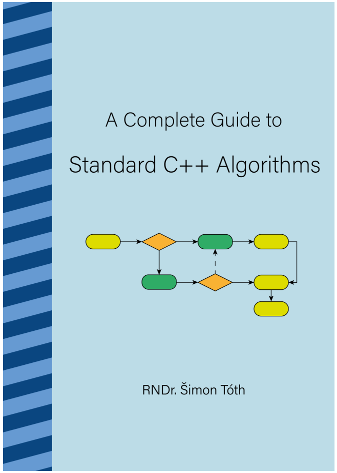
2024

Slides

https://github.com/HappyCerberus/what-is-a-range

Ask questions!

A Complete Guide to Standard C++ Algorithms


A Complete Guide to

Standard C++ Algorithms

RNDr. Šimon Tóth

- Content complete for C++20
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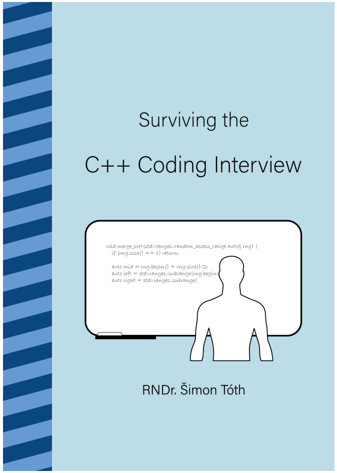
Surviving the C++ Coding Interview


Surviving the

C++ Coding Interview

```
void merge_sort(std::ranges::random_access_range auto& rng) {
  if (rng.size() == 1) return;

  auto mid = rng.begin() + rng.size()/2;
  auto left = std::ranges::subrange(rng.begin(
  auto right = std::ranges::subrange(
```

RNDr. Šimon Tóth

- Work in progress (95 pages)
- Free Community Edition: leanpub.com/cpp-coding-interview/signup
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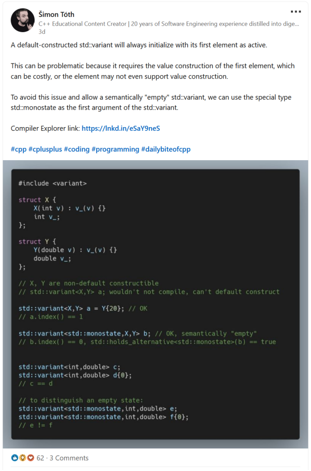
Daily bit(e) of C++



Šimon Tóth

C++ Educational Content Creator | 20 years of Software Engineering experience distilled into dige...

3d

A default-constructed std::variant will always initialize with its first element as active.

This can be problematic because it requires the value construction of the first element, which can be costly, or the element may not even support value construction.

To avoid this issue and allow a semantically "empty" std::variant, we can use the special type std::monostate as the first argument of the std::variant.

Compiler Explorer link: https://lnkd.in/eSaY9neS

#cpp #cplusplus #coding #programming #dailybiteofcpp

```cpp
#include <variant>

struct X {
    X(int v) : v_(v) {}
    int v_;
};

struct Y {
    Y(double v) : v_(v) {}
    double v_;
};

// X, Y are non-default constructible
// std::variant<X,Y> a; wouldn't not compile, can't default construct

std::variant<X,Y> a = Y{20}; // OK
// a.index() == 1

std::variant<std::monostate,X,Y> b; // OK, semantically "empty"
// b.index() == 0, std::holds_alternative<std::monostate>(b) == true


std::variant<int,double> c;
std::variant<int,double> d{0};
// c == d

// to distinguish an empty state:
std::variant<std::monostate,int,double> e;
std::variant<std::monostate,int,double> f{0};
// e != f
```

62 · 3 Comments

- ▶ linkedin.com/in/simontoth
- ▶ hachyderm.io/@simontoth
- ▶ medium.com/@simontoth
- ▶ simontoth.substack.com
- ▶ github.com/HappyCerberus/daily-bite-cpp

What is a range? (pre-C++20)

```
auto first = container.begin();
auto last = container.end();
```

```cpp
auto first = container.begin();
auto last = container.end();

using std::begin;
auto first = begin(container);
using std::end;
auto last = end(container);
```

```cpp
struct Member {
    struct Iterator {};
    Iterator begin() { return {}; }
};

using std::begin;

Member m;
auto it = begin(m);
// decltype(it) == Member::Iterator
```

https://compiler-explorer.com/z/qnTxYcr7z

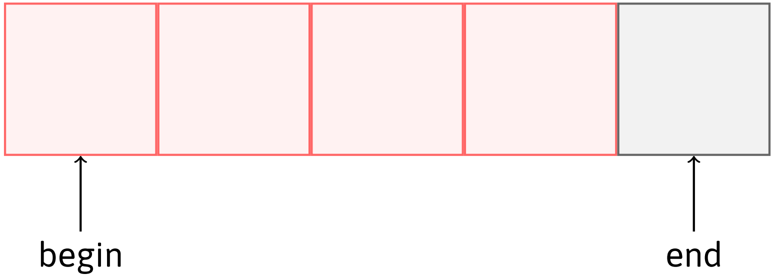
```cpp
int arr[5];

using std::begin;

auto it = begin(arr);
// it == arr
// decltype(it) == int*
```

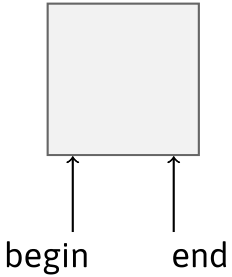
https://compiler-explorer.com/z/qnTxYcr7z

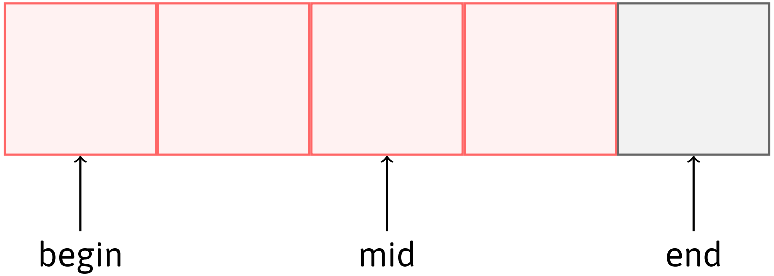
```cpp
struct Friend {
    struct Iterator {};
    friend Iterator begin(const Friend&) { return {}; }
};

using std::begin;

Friend f;
auto it = begin(f);
// decltype(it) == Friend::Iterator
```

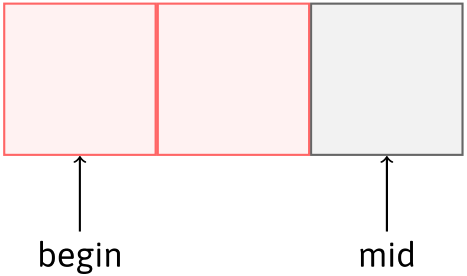
https://compiler-explorer.com/z/qnTxYcr7z

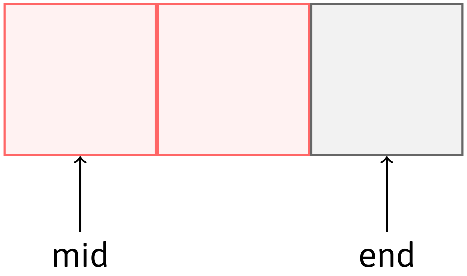
```cpp
auto first = container.begin();
auto last = container.end();

for (auto it = first; it != last; ++it)
    std::println("{}", *it);
```


begin
end


begin
end


begin
mid
end


begin
mid


mid
end

`[first, last)`

```
{0, 1, 2, 3, 4, 5, 6, 7, 8, 9}
[0, 10)
```

```
int data[5] = {1,2,3,4,5};
```

https://compiler-explorer.com/z/89d5f6h7b

```cpp
int data[5] = {1,2,3,4,5};

int* first = data;
int* last = first + 5; // one past
```

https://compiler-explorer.com/z/89d5f6h7b

```cpp
int data[5] = {1,2,3,4,5};

int* first = data;
int* last = first + 5; // one past

for (int* it = first; it != last; ++it)
    std::println("{}", *it);
```

https://compiler-explorer.com/z/89d5f6h7b

```cpp
List list = {1,2,3,4,5};

Node* first = list.head();
Node* last = nullptr;

for (Node* it = first; it != last; it = it->next)
    std::println("{}", it->value);
```

https://compiler-explorer.com/z/5Ecdhqaa4

```cpp
for (int* it = first; it != last; ++it)
    std::println("{}", *it);

for (Node* it = first; it != last; it = it->next)
    std::println("{}", it->value);
```

```cpp
std::forward_list<int> list{1,2,3,4,5};

auto first = list.begin();
auto last = list.end();

for (auto it = first; it != last; ++it)
    std::println("{}", *it);
```

https://compiler-explorer.com/z/jrP9GeG5e

input/output

- `std::istream_iterator`, `std::ostream_iterator`
- *base:* `*it`, `++it`, `it++`

forward

- `std::forward_list`
- base: `*it`, `++it`, `it++`
- *multi-access:* `auto it2 = it1; ++it1; *it1; *it2;`

bidirectional

- `std::set`, `std::map`
- base: `*it`, `++it`, `it++`
- multi-access: `auto it2 = it1; ++it1; *it1; *it2;`
- *bidirectional:* `--it`, `it--`

random access

- `std::deque`
- base: `*it`, `++it`, `it++`
- multi-access: `auto it2 = it1; ++it1; *it1; *it2;`
- bidirectional: `--it`, `it--`
- *random access:* `it + offset`, `it - offset`
- *distance:* `it1 - it2`

contiguous

- `std::array`, `std::vector`
- base: `*it`, `++it`, `it++`
- multi-access: `auto it2 = it1; ++it1; *it1; *it2;`
- bidirectional: `--it`, `it--`
- random access: `it + offset`, `it - offset`
- distance: `it1 - it2`
- *contiguous memory*

What is a range?

- `for (auto e : rng) {}`

- `for (auto e : rng) {}`
- `begin(rng),end(rng)`

- `for (auto e : rng) {}`
- `begin(rng)`, `end(rng)`
- input or output iterator

- `for (auto e : rng) {}`
- `begin(rng)`, `end(rng)`
- input or output iterator
- `[begin(rng), end(rng))`

```
namespace std::ranges {
    template<class T>
    concept range = requires(T& t) {
        ranges::begin(t);
        ranges::end  (t);
    };
}
```

```cpp
int arr[5] = {1,2,3,4,5};

auto first = std::ranges::begin(arr);
auto last = std::ranges::end(arr);

for (auto it = first; it != last; ++it)
    std::println("{}", *it);
```

https://compiler-explorer.com/z/b67PnGWP8

```cpp
int arr[5] = {1,2,3,4,5};

auto first = std::ranges::begin(arr);
auto last = std::ranges::end(arr);

for (auto& e : std::ranges::subrange(first, last))
    std::println("{}", e);
```

https://compiler-explorer.com/z/dMozG7j8h

Range concepts

- `ranges::input_range`
- `ranges::output_range`
- `ranges::forward_range`
- `ranges::bidirectional_range`
- `ranges::random_access_range`
- `ranges::contiguous_range`

```cpp
auto sum(std::ranges::input_range auto&& rng) {
    auto result = std::ranges::range_value_t<decltype(rng)>{};
    for (auto& e : rng)
        result += e;
    return result;
}
```

https://compiler-explorer.com/z/f5h7jYnjP

```cpp
template <std::ranges::input_range Rng>
auto sum(Rng&& rng) {
    auto result = std::ranges::range_value_t<Rng>{};
    for (auto& e : rng)
        result += e;
    return result;
}
```

https://compiler-explorer.com/z/a9qx5rWh1

Universal reference

```cpp
const char& find_second(const std::string& str, char c) {
    static char not_found = '\0';

    size_t idx = str.find(c);
    if (idx == std::string::npos) return not_found;

    idx = str.find(c, idx+1);
    if (idx == std::string::npos) return not_found;

    return str[idx];
}
```

https://compiler-explorer.com/z/E6EqjzTKr

```cpp
const char& find_second(const std::string& str, char c) {
    static char not_found = '\0';

    size_t idx = str.find(c);
    if (idx == std::string::npos) return not_found;

    idx = str.find(c, idx+1);
    if (idx == std::string::npos) return not_found;

    return str[idx];
}

const char &c = find_second("Hello World!", 'o');
```

https://compiler-explorer.com/z/E6EqjzTKr

```cpp
const char& find_second(const std::string_view& str, char c) {
    static char not_found = '\0';

    size_t idx = str.find(c);
    if (idx == std::string::npos) return not_found;

    idx = str.find(c, idx+1);
    if (idx == std::string::npos) return not_found;

    return str[idx];
}

const char &c = find_second("Hello World!", 'o');
```

https://compiler-explorer.com/z/79Wej378n

Borrowed range

- `std::string_view`
- `std::span`

Range algorithms

```cpp
auto it1 = std::ranges::find(std::string_view("Hello World!"), 'o');
// decltype(it1) == std::string_view::iterator
// *it1 == 'o'
```

https://compiler-explorer.com/z/E5cMG4qqT

Range algorithms

```cpp
auto it1 = std::ranges::find(std::string_view("Hello World!"), 'o');
// decltype(it1) == std::string_view::iterator
// *it1 == 'o'

auto it2 = std::ranges::find(std::string("Hello World!"), 'o');
// decltype(it2) == std::ranges::dangling
```

https://compiler-explorer.com/z/E5cMG4qqT

Range algorithms

```cpp
auto it1 = std::ranges::find(std::string_view("Hello World!"), 'o');
// decltype(it1) == std::string_view::iterator
// *it1 == 'o'

auto it2 = std::ranges::find(std::string("Hello World!"), 'o');
// decltype(it2) == std::ranges::dangling

std::string str1("Hello World!");
auto it3 = std::ranges::find(str1, 'o');
// decltype(it3) == std::string::iterator

std::string_view str2("Hello World!");
auto it4 = std::ranges::find(str2, 'o');
// decltype(it4) == std::string_view::iterator
```

https://compiler-explorer.com/z/E5cMG4qqT

```cpp
void fun(const std::string& rng) {}

fun(std::string("")); // taking ownership

std::string str;
fun(str);             // borrowing
```

```cpp
void fun(auto&& rng) {
    if constexpr (std::ranges::borrowed_range<decltype(rng)>) {
        // borrowing
    } else {
        // taking ownership
    }
}

fun(std::string(""));      // taking ownership
fun(std::string_view("")); // borrowing

std::string str;
fun(str);                  // borrowing
fun(std::as_const(str));   // borrowing
```

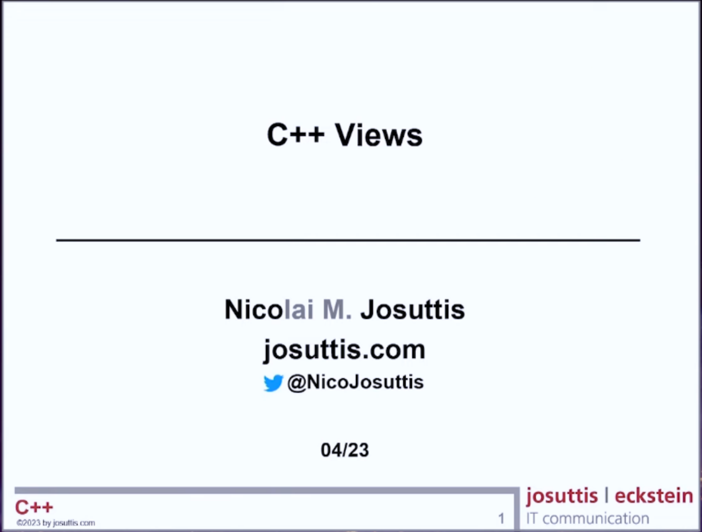
https://compiler-explorer.com/z/h436jzTaq

```cpp
template <std::ranges::forward_range Str>
requires std::ranges::borrowed_range<Str>
    && std::same_as<std::ranges::range_value_t<Str>,char>
const char& find_second(Str&& str, char c) {
    /* ... */
}
```

https://compiler-explorer.com/z/x68W8PGEq

```cpp
template <std::ranges::input_range Rng>
auto sum(Rng&& rng) {
    auto result = std::ranges::range_value_t<Rng>{};
    for (auto& e : rng)
        result += e;
    return result;
}
```

Views



C++ Views

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04/23

C++
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View

- cheap to move
- cheap to destroy when moved-from
- cheap to copy if copyable

Not a borrowed range

```cpp
std::vector<int> data{1,2,3,4,5};
auto rng1 = std::views::all(data);
// borrowed, decltype(rng1) == std::ranges::ref_view<...>

auto rng2 = std::views::all(std::vector<int>{1,2,3,4,5});
// not borrowed, decltype(rng2) == std::ranges::owning_view<...>
```

https://compiler-explorer.com/z/T74ffK1dz

Views as code

```
std::vector<int> data{1,2,3,4,5};

auto view = data |
    std::views::transform([](int v) { return v * 2; }) |
    std::views::transform([](int v) { return v + 1; });
// view == {3, 5, 7, 9, 11}
```

https://compiler-explorer.com/z/vWE9hq7Mq

Views as code

```
std::vector<int> data{1,2,3,4,5};

auto view = data |
    std::views::transform([](int v) { return v * 2; }) |
    std::views::transform([](int v) { return v + 1; });
// view == {3, 5, 7, 9, 11}

auto manifested = view |
    std::ranges::to<std::vector>();
// decltype(manifested) == std::vector<int>
// manifested == {3, 5, 7, 9, 11}
```

https://compiler-explorer.com/z/6Ejjz8b7Y

Views as code

```
std::vector<int> data{1,2,3,4,5};

auto view = data |
    std::views::filter([](int v) { return v % 2 == 0; });
// view == {2, 4}
```

https://compiler-explorer.com/z/fbsPc9EYx

Views as code

```
std::vector<int> data{1,3,5,7,9};

auto view = data |
    std::views::filter([](int v) { return v % 2 == 0; });
// view == {}

bool empty = view.begin() == view.end();
// empty == true
```

https://compiler-explorer.com/z/j86jKrb5f

Views as code

```
std::list<int> data{1,3,5,7,9};

auto view = data |
    std::views::filter([](int v) { return v % 2 == 0; });
// view == {}

bool empty = view.begin() == view.end();
// empty == true

data.push_front(2);

empty = view.begin() == view.end();
// empty == true
```

https://compiler-explorer.com/z/WedM1eE8z

Views as code

```
void fn(const auto& rng) {
    auto b = rng.begin();
}

fn(std::vector<int>{1,3,5,7,9} |
    std::views::filter([](int v) { return v % 2 == 0; }));
```

https://compiler-explorer.com/z/hzd5Ksezd

Views as code

```cpp
void fn(auto&& rng) {
    auto b = rng.begin();
}

fn(std::vector<int>{1,3,5,7,9} |
    std::views::filter([](int v) { return v % 2 == 0; }));
```

---

https://compiler-explorer.com/z/G1Tzf3ePa

When taking a range as an argument, always use a universal reference.

Input ranges

std::views::istream

```
// standard input: 1 2 3 4 5 6 7 8 9
```

https://compiler-explorer.com/z/YGvb57K6P

std::views::istream

```
// standard input: 1 2 3 4 5 6 7 8 9

std::vector<int> out1;
std::ranges::copy(
    std::views::istream<int>(std::cin) | std::views::take(3),
    std::back_inserter(out1)
);

std::vector<int> out2;
std::ranges::copy(
    std::views::istream<int>(std::cin) | std::views::take(3),
    std::back_inserter(out2)
);
```

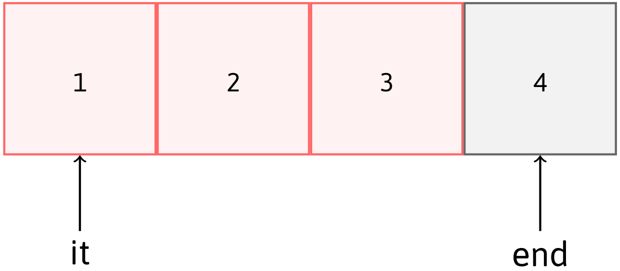
---

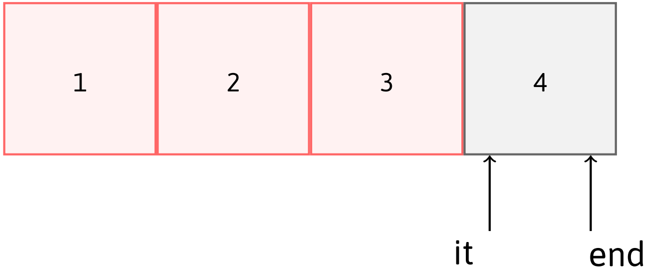
https://compiler-explorer.com/z/YGvb57K6P

std::views::istream

```
// standard input: 1 2 3 4 5 6 7 8 9

std::vector<int> out1;
std::ranges::copy(
    std::views::istream<int>(std::cin) | std::views::take(3),
    std::back_inserter(out1)
);

std::vector<int> out2;
std::ranges::copy(
    std::views::istream<int>(std::cin) | std::views::take(3),
    std::back_inserter(out2)
);

// out1 == {1, 2, 3}
// out2 == {5, 6, 7}
```

https://compiler-explorer.com/z/YGvb57K6P


1
2
3
4
it
end


1
2
3
4
it
end

std::views::istream

```cpp
// standard input: 1 2 3 4 5 6 7 8 9

std::vector<int> out1;
std::ranges::copy(
    std::views::istream<int>(std::cin) | std::views::take(3),
    std::back_inserter(out1)
);

std::vector<int> out2;
std::ranges::copy(
    std::views::istream<int>(std::cin) | std::views::take(3),
    std::back_inserter(out2)
);

// out1 == {1, 2, 3}
// out2 == {5, 6, 7}
```

https://compiler-explorer.com/z/YGvb57K6P

std::views::istream

```
// standard input: 1 2 3 4 5 6 7 8 9

std::vector<int> out1;
auto [in, out] = std::ranges::copy(
    std::views::istream<int>(std::cin) | std::views::take(3),
    std::back_inserter(out1)
);
```

https://compiler-explorer.com/z/8Kvjse9PY

std::views::istream

```
// standard input: 1 2 3 4 5 6 7 8 9

std::vector<int> out1;
auto [in, out] = std::ranges::copy(
    std::views::istream<int>(std::cin) | std::views::take(3),
    std::back_inserter(out1)
);
// decltype(in) == std::ranges::dangling
```

---

https://compiler-explorer.com/z/8Kvjse9PY

std::views::istream

```cpp
// standard input: 1 2 3 4 5 6 7 8 9

auto view = std::views::istream<int>(std::cin) | std::views::take(3);

std::vector<int> out1;
auto [in, out] = std::ranges::copy(
    view,
    std::back_inserter(out1)
);
// out1 == {1,2,3}
// *in == 4
```

https://compiler-explorer.com/z/zPdjrvhzx

Sized range

```cpp
auto count_to_five = std::views::iota(1) |
    std::views::take(5);

std::vector<int> store;
```

https://compiler-explorer.com/z/138hEf7bj

```
auto count_to_five = std::views::iota(1) |
    std::views::take(5);

std::vector<int> store;

store.reserve(count_to_five.size());
```

https://compiler-explorer.com/z/138hEf7bj

```cpp
auto count_to_five = std::views::iota(1) |
    std::views::take(5);

std::vector<int> store;

store.reserve(count_to_five.size()); // Will not compile
std::ranges::copy(count_to_five, std::back_inserter(store));
// std::ranges::sized_range<decltype(count_to_five)> == false
```

---

https://compiler-explorer.com/z/138hEf7bj

```cpp
auto count_to_five = std::views::iota(1) |
    std::views::take(5);

auto wrapped = std::ranges::subrange(count_to_five, 5);

std::vector<int> store;

store.reserve(wrapped.size());
std::ranges::copy(wrapped, std::back_inserter(store));
// std::ranges::sized_range<decltype(count_to_five)> == false
// std::ranges::sized_range<decltype(wrapped)> == true
```

https://compiler-explorer.com/z/77s55j7qY

Common range

```
namespace std::ranges {
    template<class T>
    concept range = requires(T& t) {
        ranges::begin(t);
        ranges::end  (t);
    };
}
```

```cpp
std::vector<int> data{1,2,3,4,5};
// std::ranges::common_range<decltype(data)> == true
```

https://compiler-explorer.com/z/86nocb3ra

```cpp
std::vector<int> data{1,2,3,4,5};
// std::ranges::common_range<decltype(data)> == true

auto first = data.begin();
// decltype(first) == std::vector<int>::iterator
auto last = data.end();
// decltype(last) == std::vector<int>::iterator
```

https://compiler-explorer.com/z/86nocb3ra

```cpp
std::vector<int> data{1,2,3,4,5};
// std::ranges::common_range<decltype(data)> == true

auto first = data.begin();
// decltype(first) == std::vector<int>::iterator
auto last = data.end();
// decltype(last) == std::vector<int>::iterator

int sum = std::accumulate(first, last, 0);
// OK, sum == 15
```

https://compiler-explorer.com/z/86nocb3ra

```cpp
auto iota = std::views::iota(1) |
    std::views::take(5);
// std::ranges::common_range<decltype(iota)> == false
```

https://compiler-explorer.com/z/Yd3qj4515

```cpp
auto iota = std::views::iota(1) |
    std::views::take(5);
// std::ranges::common_range<decltype(iota)> == false

auto first = iota.begin();
auto last = iota.end();
// decltype(first) != decltype(last)

// Will not compile
int sum = std::accumulate(first, last, 0);
```

---

https://compiler-explorer.com/z/Yd3qj4515

```cpp
auto iota = std::views::iota(1) |
    std::views::take(5) |
    std::views::common;
// std::ranges::common_range<decltype(iota)> == true

auto first = iota.begin();
auto last = iota.end();
// decltype(first) == decltype(last)

int sum = std::accumulate(first, last, 0);
// OK, sum == 15
```

https://compiler-explorer.com/z/7sqGdsPqP

```cpp
auto iota = std::views::iota(1) |
    std::views::take(5);
// std::ranges::common_range<decltype(iota)> == false

int sum = std::ranges::fold_left(iota, 0, std::plus<>{});
// OK, sum == 15
```

https://compiler-explorer.com/z/7f3YTY9TT

```
struct count_to_five {
    struct iterator {
        int v{1};
        iterator& operator++() { ++v; return *this; }
        int operator*() { return v; }
        bool operator==(const std::default_sentinel_t&) const {
            return v > 5;
        }
    };
    iterator begin() { return {}; }
    std::default_sentinel_t end() { return {}; }
};

for (auto v : count_to_five{}) {}
// {1, 2, 3, 4, 5}
```

https://compiler-explorer.com/z/fjzxq44cq

```cpp
std::string text = "first line\nsecond line\n";
assert(text.back() == '\n');

auto delim = std::ranges::find(text, '\n');
auto line = std::ranges::subrange(text.begin(), delim);
```

https://compiler-explorer.com/z/q9MYxPqv7

```cpp
std::string text = "first line\nsecond line\n";
assert(text.back() == '\n');

auto first = text.begin();
auto last = text.end();
auto delim = first;
for (; delim != last; ++delim)
    if (*delim == '\n')
        break;

auto line = std::ranges::subrange(text.begin(), delim);
```

https://compiler-explorer.com/z/5GPs44adT

```cpp
std::string text = "first line\nsecond line\n";
assert(text.back() == '\n');

auto first = text.begin();
auto delim = first;
for (; *delim != '\n'; ++delim);

auto line = std::ranges::subrange(text.begin(), delim);
```

https://compiler-explorer.com/z/1M4cTsG9x

```cpp
std::string text = "first line\nsecond line\n";
assert(text.back() == '\n');

auto unbounded = std::ranges::subrange(
    text.begin(), std::unreachable_sentinel);

auto delim = std::ranges::find(unbounded, '\n');
auto line = std::ranges::subrange(text.begin(), delim);
```

https://compiler-explorer.com/z/h1eE4T168

```cpp
template <
    std::input_iterator It,
    std::sentinel_for<It> Sentinel>
void fn(It first, Sentinel last) {
    for (auto it = first; it != last; ++it)
        std::println("{}", *it);
}

auto view = std::views::iota(1) |
    std::views::take(5);

fn(view.begin(), view.end());
```

https://compiler-explorer.com/z/Yhna9eEd7

Summary

- `ranges::input_range`, `ranges::output_range`, `ranges::forward_range`, `ranges::bidirectional_range`, `ranges::random_access_range`, `ranges::contiguous_range`

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When taking a range as an argument, always use universal reference.

Thank you!

Questions?

Books:

- A Complete Guide to Standard C++ Algorithms
  leanpub.com/cpp-algorithms-guide
- Surviving the C++ Coding Interview
  leanpub.com/cpp-coding-interview

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