



Efficient C++ Programming

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ESC25 — Bertinoro, 29 September – 9 October 2025

<https://agenda.infn.it/event/45177>



Introduction

Algorithms and functions

Containers

Resource management

Move semantics

Compile-time computation

Additional material

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- general-purpose
- multi-paradigm
- good from low-level programming to high-level abstractions
- efficient (*“you don't pay for what you don't use”*)
- standard

- Start from
 - <https://isocpp.org/>
 - <https://cppreference.com/>
 - <https://isocpp.github.io/CppCoreGuidelines/CppCoreGuidelines>
- Main C++ conferences
 - <https://github.com/cppcon>,
<https://youtube.com/cppcon>
 - <https://github.com/boostcon>,
<https://youtube.com/boostcon>

- A new standard is published every three years.
- *Working drafts*, almost the same as the final published document

C++03 <https://wg21.link/n1905>

C++11 <https://wg21.link/std11>

C++14 <https://wg21.link/std14>

C++17 <https://wg21.link/std17>

C++20 <https://wg21.link/std20>

C++23 <https://wg21.link/std23>

\LaTeX sources at <https://github.com/cplusplus/draft>,
rendered as HTML at <https://eel.is/c++draft/>

- *Working papers* at
<http://www.open-std.org/jtc1/sc22/wg21/docs/papers/>

- The ESC machines provide at least two C++ compilers: use gcc 14.2.1 (see instructions on how to enable it), but the default gcc 11.5 is also available
- Additionally, you can edit and try your code online with multiple compilers at
 - <https://godbolt.org/>
 - <https://coliru.stacked-crooked.com/>
 - <https://wandbox.org/>

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The C++ standard library

- The standard library contains components of general use
 - containers (data structures)
 - algorithms
 - strings
 - input/output
 - random numbers
 - regular expressions
 - concurrency and parallelism
 - filesystem
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- But templates are everywhere

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Modifying `copy` `fill` `generate` `transform` `remove`
`replace` `swap` `reverse` `rotate` `shuffle` `sample`
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Numeric iota accumulate reduce inner_product
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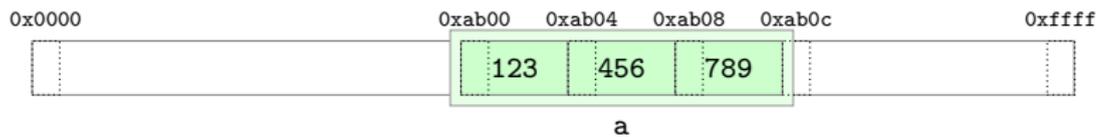
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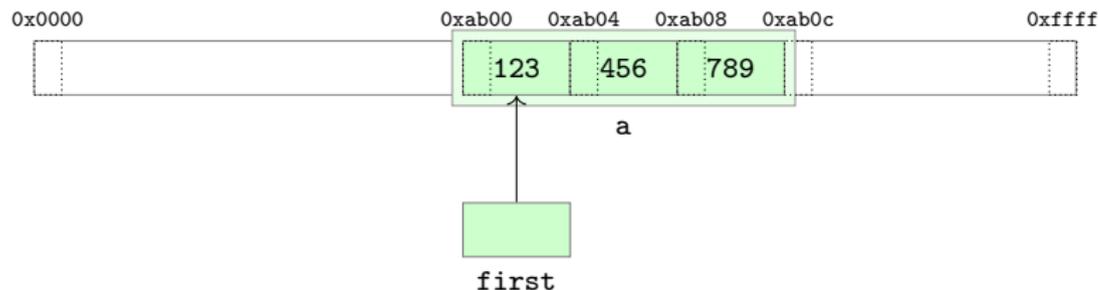
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- An iterator is a generalization of a pointer
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- C++20 introduced **ranges**, a new library of *concepts* and components for dealing with ranges of objects (not discussed here)

Range (cont.)



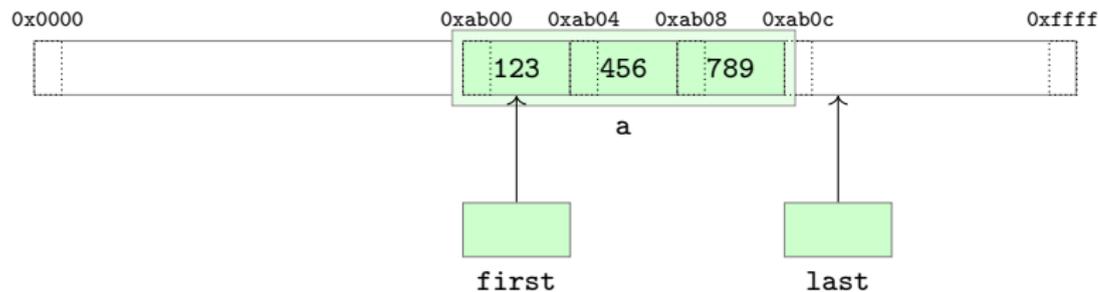
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Range (cont.)



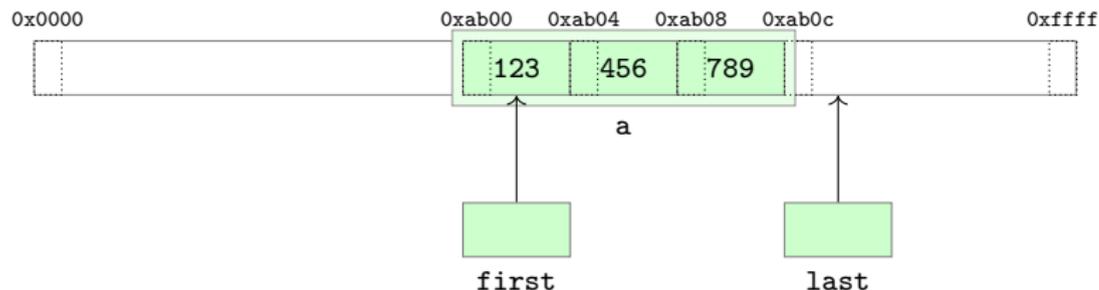
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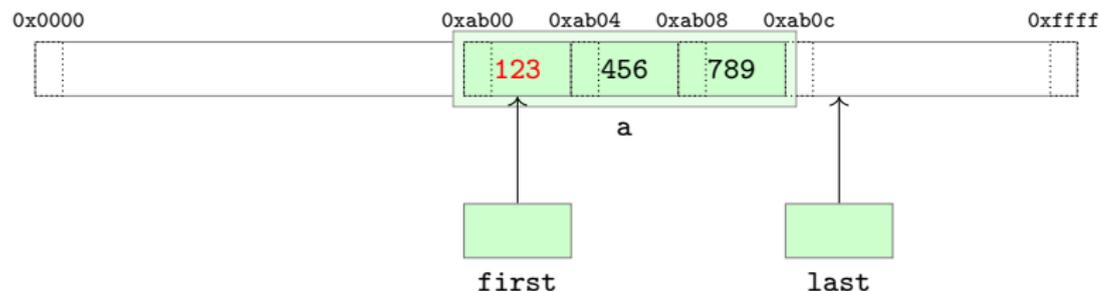
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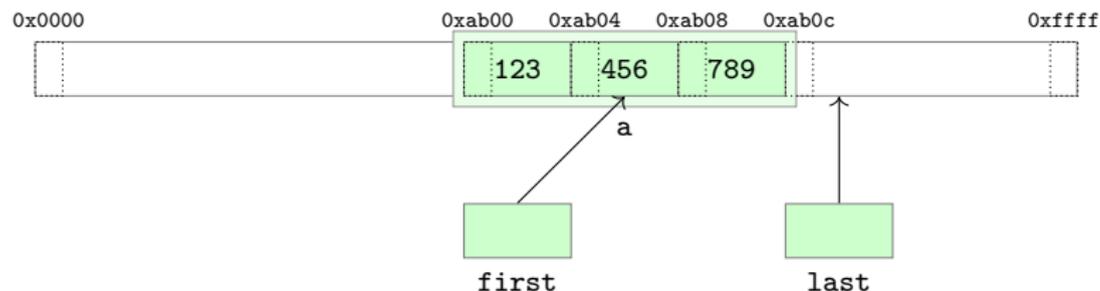
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std::array<int,3> a{123, 456, 789};  
auto first = a.begin();           // or std::begin(a)  
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    ... *first ...;             // access  
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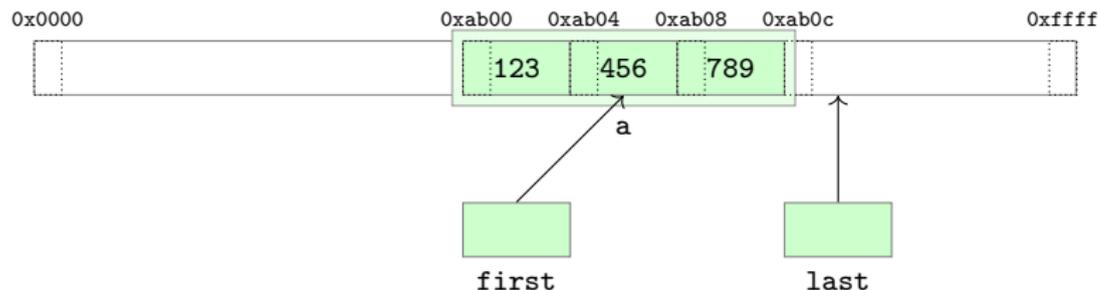
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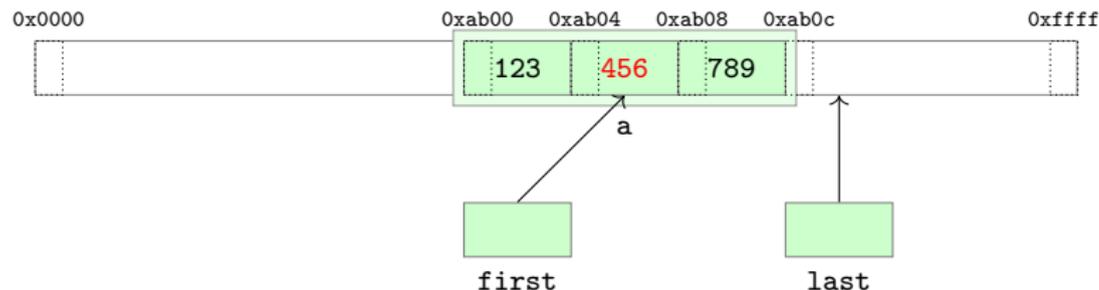
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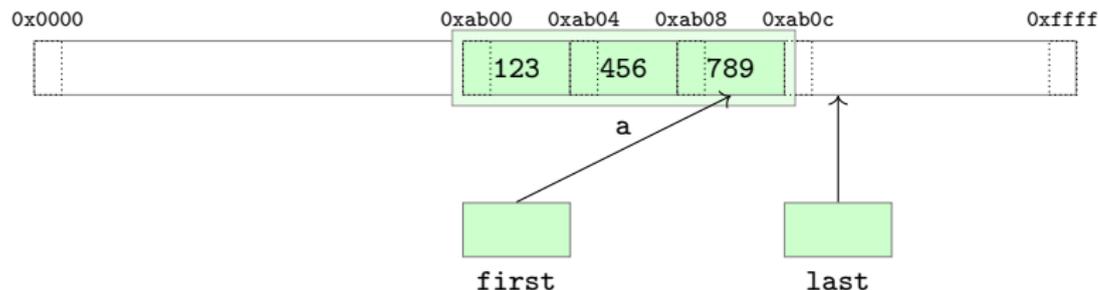
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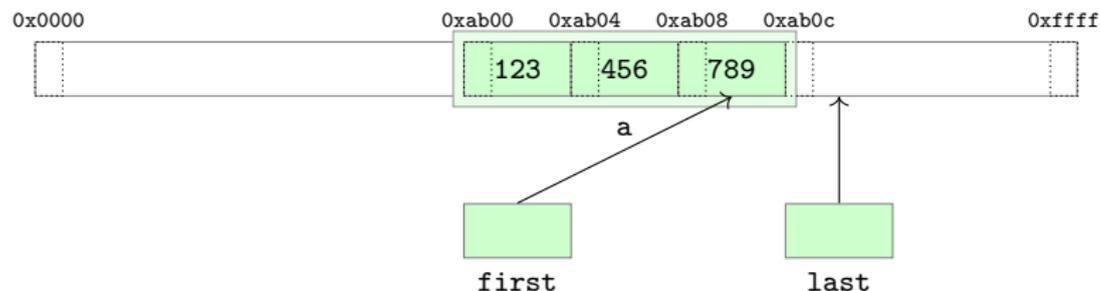
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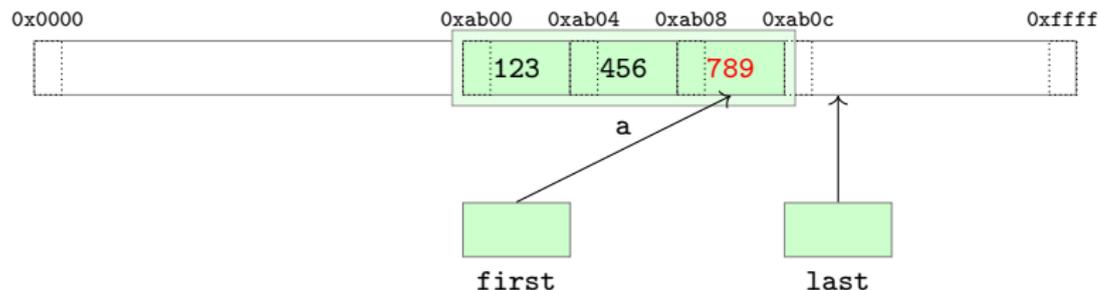
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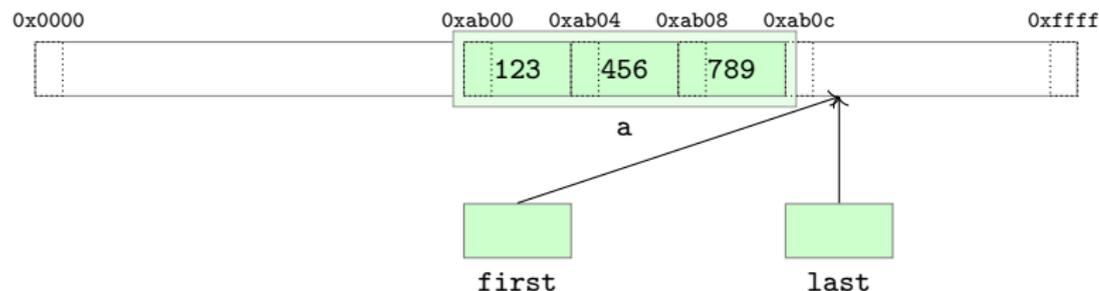
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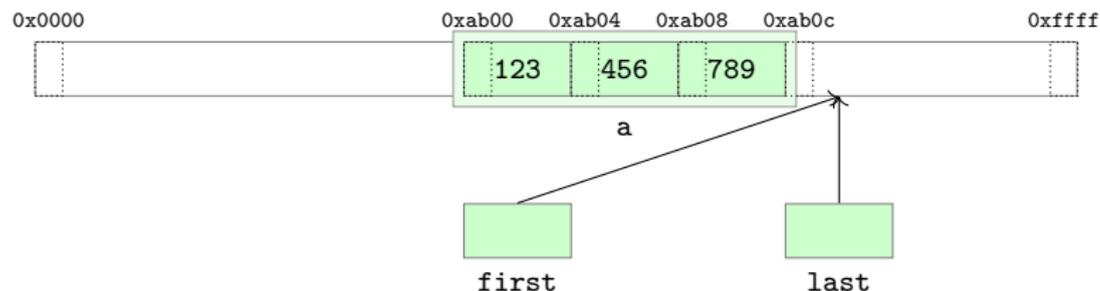
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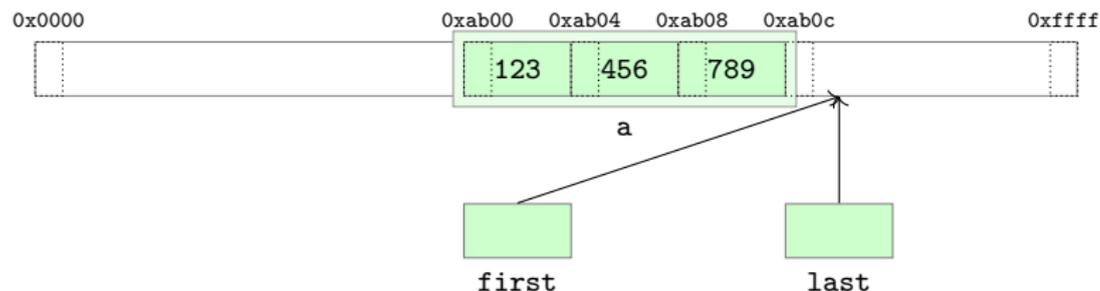
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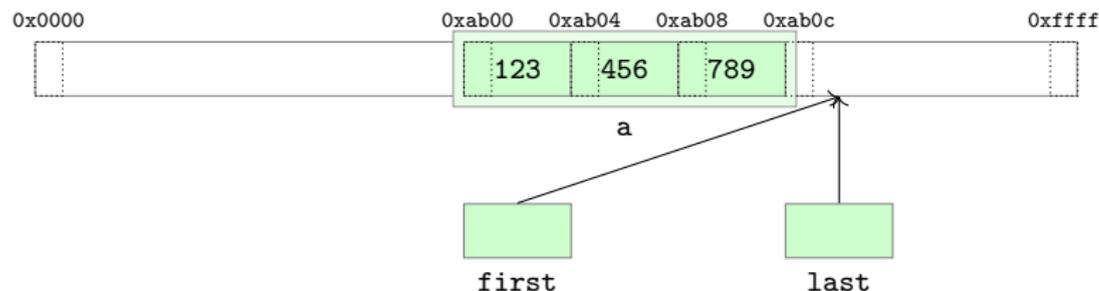
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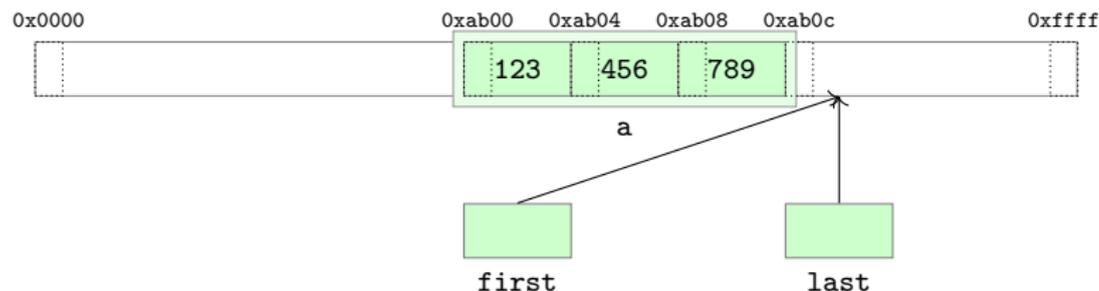
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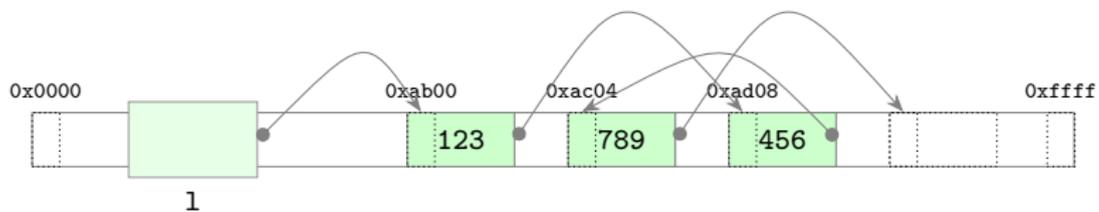
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template <class Iterator, class T>
Iterator
find(Iterator first, Iterator last, const T& value)
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    for (; first != last; ++first)
        if (*first == value)
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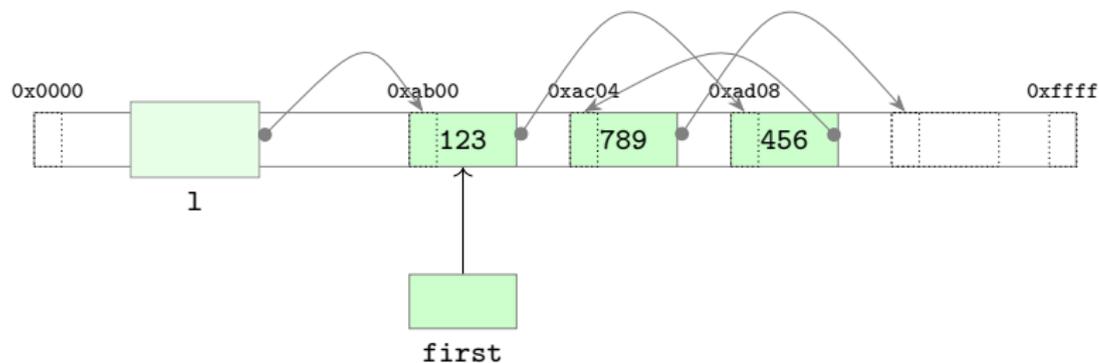
- A concept is a set of requirements that a type needs to satisfy
 - e.g. supported expressions, nested types, memory layout, ...

Range (cont.)



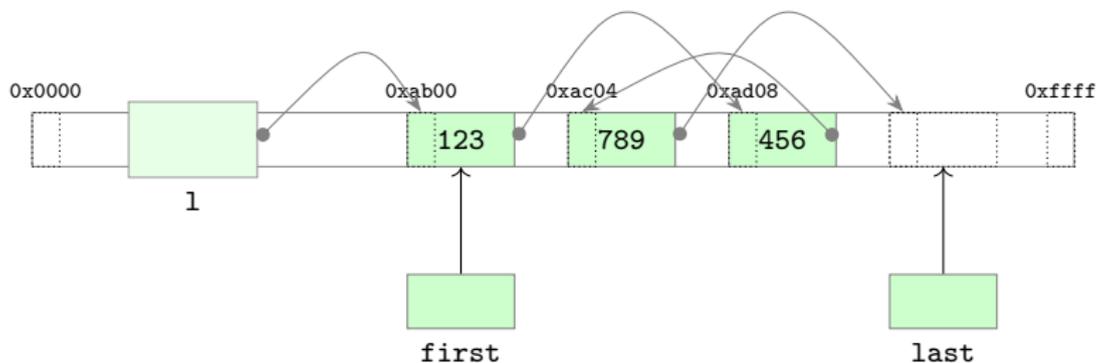
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std::forward_list l{123, 456, 789};
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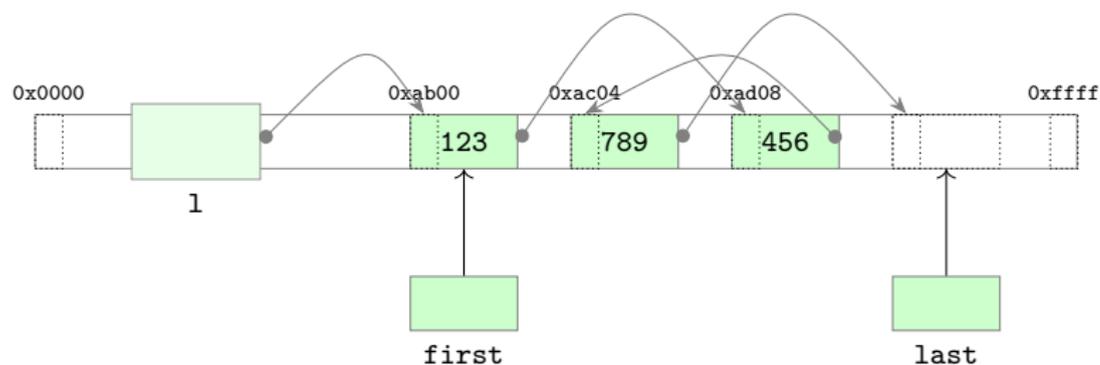
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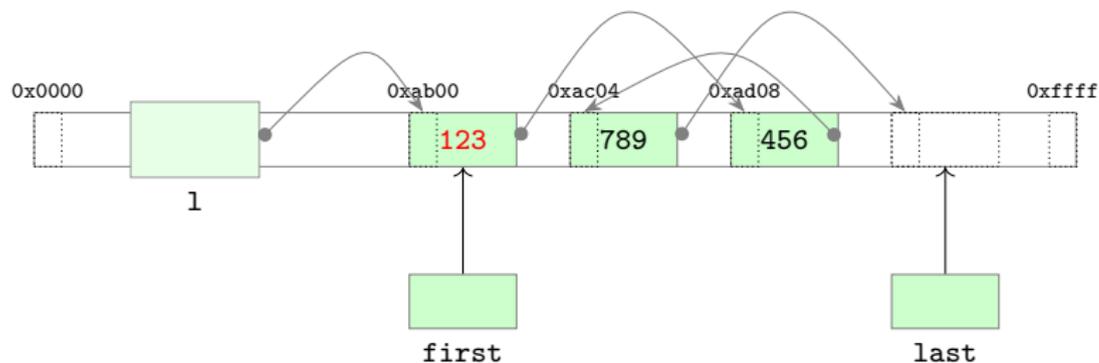
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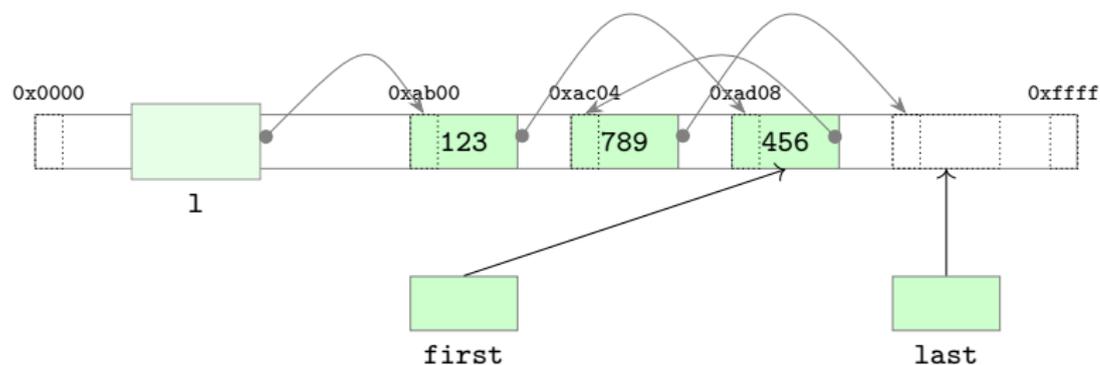
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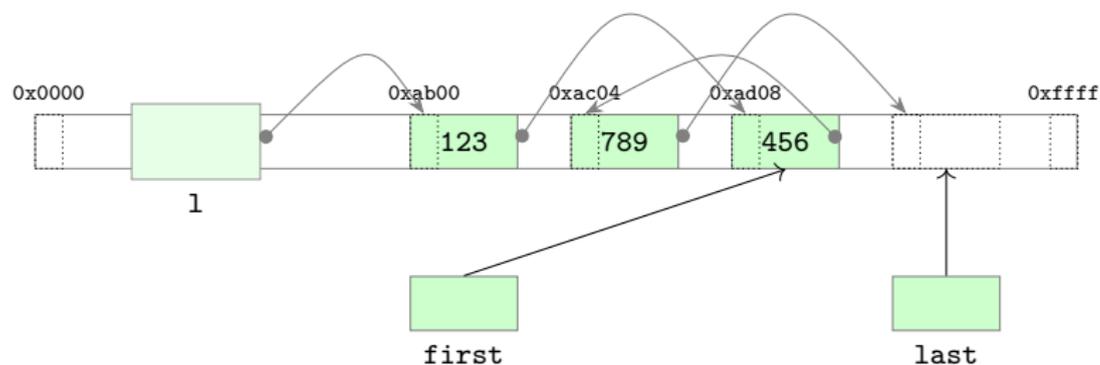
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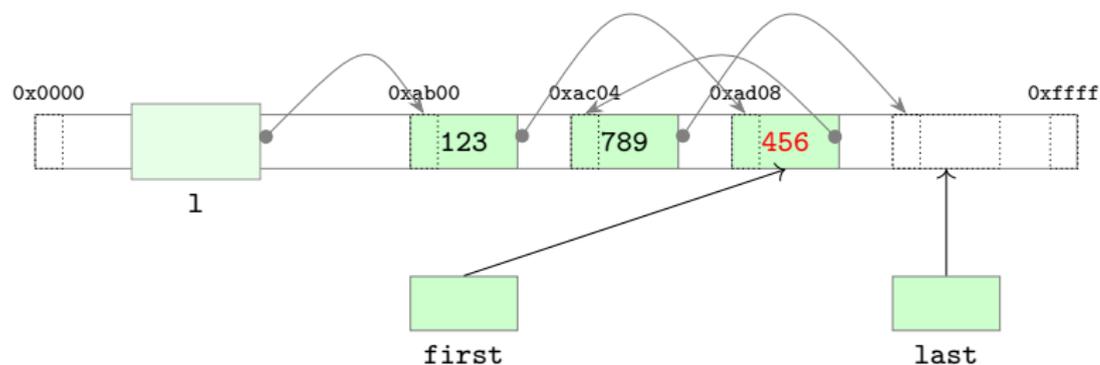
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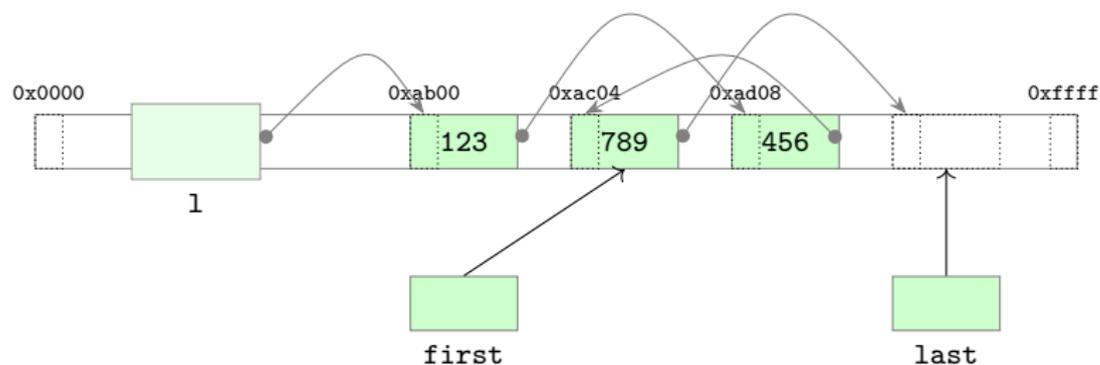
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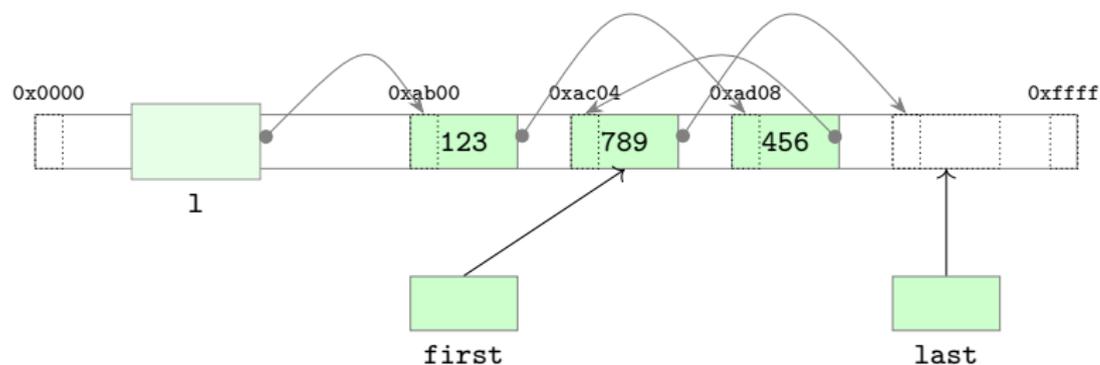
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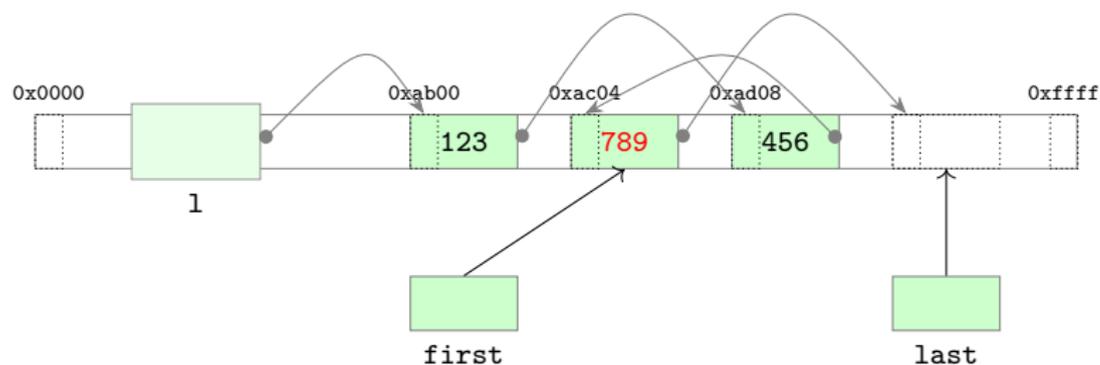
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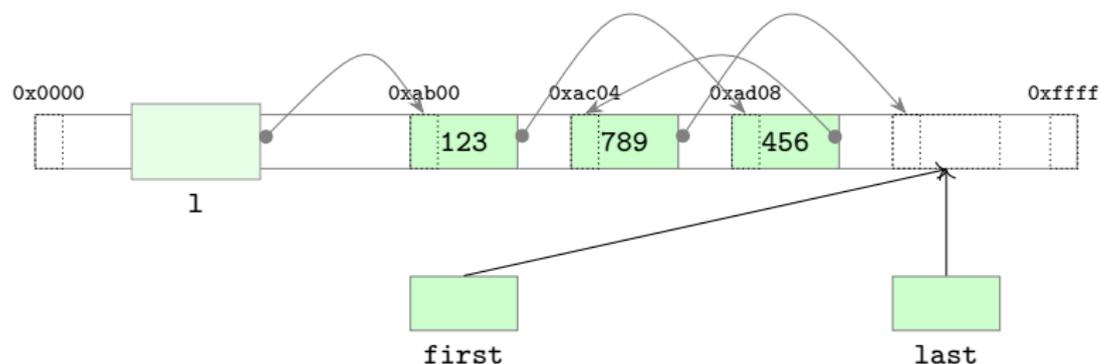
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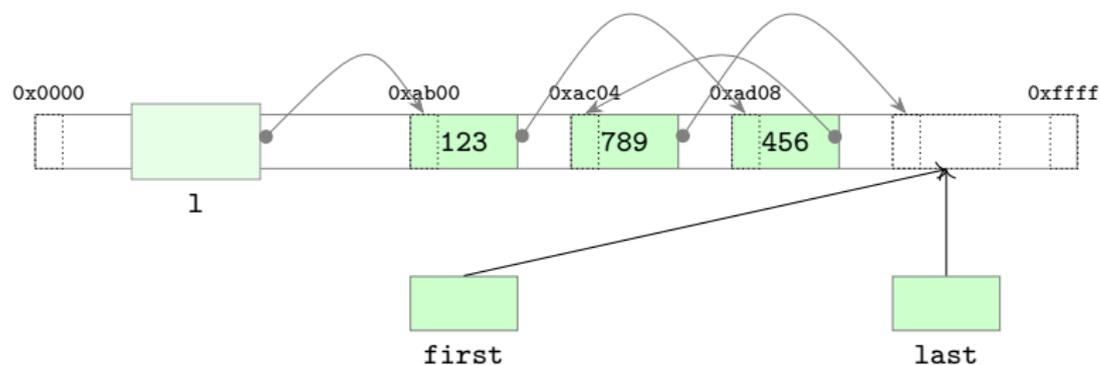
```
std::forward_list l{123, 456, 789};
auto first = l.begin();
auto const last = l.end();
while (first != last) {
    ... *first ...;
    ++first;
}
```

Range (cont.)



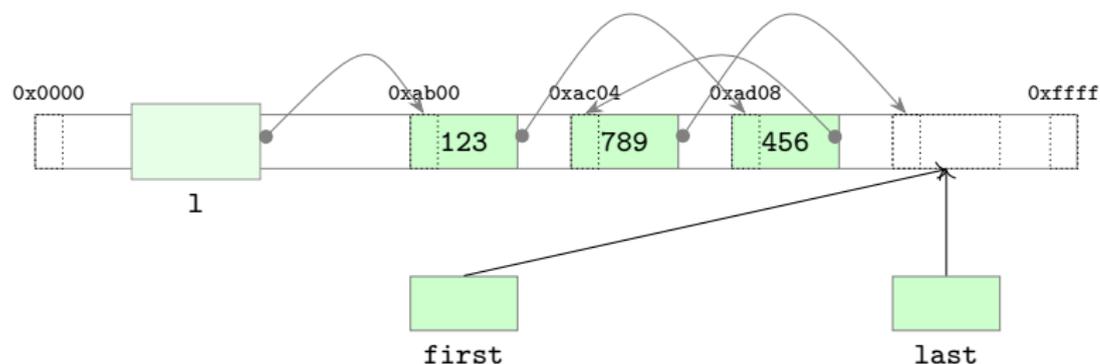
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std::forward_list l{123, 456, 789};  
auto first = l.begin();  
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while (first != last) {  
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}
```

Range (cont.)



```
std::forward_list l{123, 456, 789};
auto first = l.begin();
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while (first != last) {
    ... *first ...;
    ++first;
}
```

Range (cont.)



```
std::forward_list l{123, 456, 789};
auto first = l.begin();
auto const last = l.end();
while (first != last) {
    ... *first ...;
    ++first;
}
```

- `std::forward_list<T>::iterator` models the *ForwardIterator* concept

Algorithms and ranges

- Examples

```
std::vector v{ 23, 54, 41, 0, 18 };

// sort the vector in ascending order
std::sort(std::begin(v), std::end(v));

// sum up the vector elements, initializing the sum to 0
auto s = std::accumulate(std::begin(v), std::end(v), 0);
auto r = std::reduce(std::begin(v), std::end(v));

// append the partial sums of the vector elements into a list
std::list<int> lst;
std::partial_sum(std::begin(v), std::end(v), std::back_inserter(lst));

// find the first element with value 42
auto it = std::find(std::begin(v), std::end(v), 42);
```

- Some algorithms are customizable passing a function

```
auto it = std::find_if(v.begin(), v.end(), function);
```

- C++ → Algorithms
- Starting from `algo.cpp` and following the hints, write code to
 - sum all the elements of the vector
 - compute the average of the first half and of the second half of the vector
 - remove duplicate elements
 - move the three central numbers to the beginning
 - ...

Why using standard algorithms

- They are correct

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- They express intent more clearly than a raw `for` loop

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 - parallel algorithms available from C++17

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- They are correct
- They express intent more clearly than a raw for loop
- They provide easy access to *parallelism*
 - parallel algorithms available from C++17

```
#include <execution>

std::vector v{ ... };
std::sort(std::execution::par, v.begin(), v.end());
auto it = std::find(std::execution::par, v.begin(), v.end(), 42);
```

Computational complexity

- A measure of how many resources a computation will need for a given input size
 - Typically the resource is time but can be space (memory)
 - For example: how many comparisons does the sort algorithm do for a range of one million elements?
- Of typical interest are the average case and the worst case

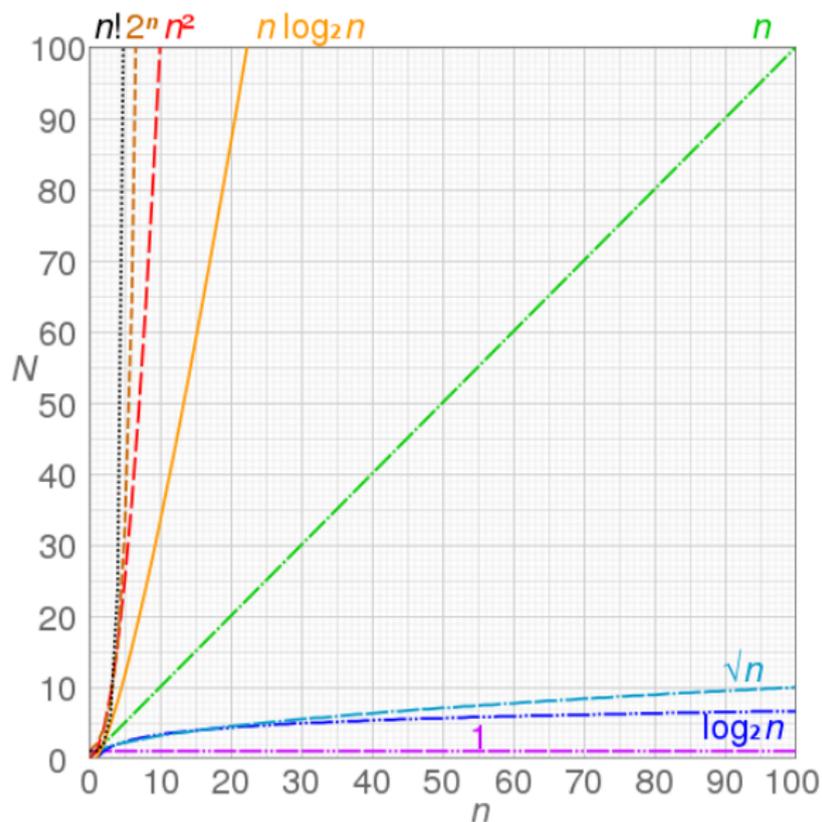
Computational complexity

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- The complexity is a function f of the input size n , but usually only the asymptotic behaviour is given
 - Big-O notation
 - $\mathcal{O}(g(n))$ means that, for a large n , $f(n) \leq cg(n)$, for some constant c
 - Note how constant factors don't matter in big-O notation

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 - Note how constant factors don't matter in big-O notation
- For example
 - `std::vector<T>::push_back` is (amortized) $\mathcal{O}(1)$
 - `std::binary_search` is $\mathcal{O}(\log n)$
 - `std::find` is $\mathcal{O}(n)$
 - `std::sort` is $\mathcal{O}(n \log n)$

Computational complexity (cont.)



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- C++ → Algorithms
- Starting from `algo_par.cpp` and following the hints, write code to
 - sum all the elements of the vector, with and without parallelization
 - sort the vector, with and without parallelization
 - ...

and compare the execution times.

- A function associates a sequence of statements (the function *body*) with a name and a list of zero or more parameters
- A function may return a value
- Multiple functions can have the same name → *overloading*
 - different parameter lists

- A function associates a sequence of statements (the function *body*) with a name and a list of zero or more parameters
- A function may return a value
- Multiple functions can have the same name → *overloading*
 - different parameter lists
- A function returning a `bool` is called a *predicate*

```
bool less(int n, int m) { return n < m; }
```

Algorithms and functions

```
template <class Iterator, class T>
Iterator find(Iterator first, Iterator last, const T& value)
{
    for (; first != last; ++first)
        if (*first == value)
            break;
    return first;
}

auto it = find(v.begin(), v.end(), 42);
```

Algorithms and functions

```
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Iterator find(Iterator first, Iterator last, const T& value)
{
    for (; first != last; ++first)
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```
auto it = find(v.begin(), v.end(), 42);
```

```
template <class Iterator, class Predicate>
Iterator find_if(Iterator first, Iterator last, Predicate pred)
{
    for (; first != last; ++first)
        if (pred(*first)) // unary predicate
            break;
    return first;
}
```

Algorithms and functions

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```
bool lt42(int n) { return n < 42; }
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Iterator find_if(Iterator first, Iterator last, Predicate pred)
{
    for (; first != last; ++first)
        if (pred(*first)) // unary predicate
            break;
    return first;
}

bool lt42(int n) { return n < 42; }

auto it = find_if(v.begin(), v.end(), lt42);
```

Algorithms and functions

```
template <class Iterator, class T>
Iterator find(Iterator first, Iterator last, const T& value)
{
    for (; first != last; ++first)
        if (*first == value)
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Some algorithms are customizable passing a function

Algorithms and functions

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template <class Iterator, class Predicate>
Iterator find_if(Iterator first, Iterator last, Predicate pred)
{
    for (; first != last; ++first)
        if (pred(*first)) // unary predicate
            break;
    return first;
}

bool lt42(int n) { return n < 42; }

auto it = find_if(v.begin(), v.end(), lt42);
auto it = find_if(v.begin(), v.end(), [](int n) { return n < 42; } );
```

Some algorithms are customizable passing a function

Function objects

A mechanism to define *something-callable-like-a-function*

Function objects

A mechanism to define *something-callable-like-a-function*

```
auto lt42(int n)
{
    return n < 42;
}
```

```
auto b = lt42(32); // true
```

Function objects

A mechanism to define *something-callable-like-a-function*

```
auto lt42(int n)
{
    return n < 42;
}

auto b = lt42(32); // true

std::vector v {61,32,51};
auto it = std::find_if(
    v.begin(), v.end(),
    lt42
); // *it == 32
```

Function objects

A mechanism to define *something-callable-like-a-function*

- A class with an operator()

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auto lt42(int n)
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```
std::vector v {61,32,51};
auto it = std::find_if(
    v.begin(), v.end(),
    lt42
); // *it == 32
```

```
struct LessThan42 {
    auto operator()(int n) const
    {
        return n < 42;
    }
};
```

Function objects

A mechanism to define *something-callable-like-a-function*

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auto lt42(int n)
{
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    lt42
); // *it == 32
```

```
struct LessThan42 {
    auto operator()(int n) const
    {
        return n < 42;
    }
};

LessThan42 lt42{};
```

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auto lt42(int n)
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```
struct LessThan42 {
    auto operator()(int n) const
    {
        return n < 42;
    }
};

LessThan42 lt42{};
// or: auto lt42 = LessThan42{};
```

Function objects

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auto lt42(int n)
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auto it = std::find_if(
    v.begin(), v.end(),
    lt42
); // *it == 32
```

```
struct LessThan42 {
    auto operator()(int n) const
    {
        return n < 42;
    }
};

LessThan42 lt42{};
// or: auto lt42 = LessThan42{};
auto b = lt42(32); // true

std::vector v {61,32,51};
auto it = std::find_if(
    v.begin(), v.end(),
    lt42 // or directly: LessThan42{}
); // *it == 32
```

Function objects (cont.)

A function object, being the instance of a class, can have state

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A function object, being the instance of a class, can have state

```
class LessThan {
    int m_;
public:
    explicit LessThan(int m) : m_{m} {}
    auto operator()(int n) const {
        return n < m_;
    }
};
```

Function objects (cont.)

A function object, being the instance of a class, can have state

```
class LessThan {
    int m_;
public:
    explicit LessThan(int m) : m_{m} {}
    auto operator()(int n) const {
        return n < m_;
    }
};

LessThan lt42 {42};
auto b1 = lt42(32); // true
```

Function objects (cont.)

A function object, being the instance of a class, can have state

```
class LessThan {
    int m_;
public:
    explicit LessThan(int m) : m_{m} {}
    auto operator()(int n) const {
        return n < m_;
    }
};

LessThan lt42 {42};
auto b1 = lt42(32); // true

LessThan lt24 {24};
auto b2 = lt24(32); // false
```

Function objects (cont.)

A function object, being the instance of a class, can have state

```
class LessThan {
    int m_;
public:
    explicit LessThan(int m) : m_{m} {}
    auto operator()(int n) const {
        return n < m_;
    }
};

LessThan lt42 {42};
auto b1 = lt42(32); // true

LessThan lt24 {24};
auto b2 = lt24(32); // false

std::vector v {61,32,51};
auto i1 = std::find_if(..., lt42); // *i1 == 32

auto i2 = std::find_if(..., lt24); // i2 == v.end(), i.e. not found
```

Function objects (cont.)

A function object, being the instance of a class, can have state

```
class LessThan {
    int m_;
public:
    explicit LessThan(int m) : m_{m} {}
    auto operator()(int n) const {
        return n < m_;
    }
};

LessThan lt42 {42};
auto b1 = lt42(32); // true
// or: auto b1 = LessThan{42}(32);
LessThan lt24 {24};
auto b2 = lt24(32); // false
// or: auto b2 = LessThan{24}(32);

std::vector v {61,32,51};
auto i1 = std::find_if(..., lt42); // *i1 == 32
// or: auto i1 = std::find_if(..., LessThan{42});
auto i2 = std::find_if(..., lt24); // i2 == v.end(), i.e. not found
// or: auto i2 = std::find_if(..., LessThan{24});
```

Function objects (cont.)

An example from the standard library

```
#include <random>

// random bit generator
std::default_random_engine eng;

// generate N 32-bit unsigned integer numbers
for (int n = 0; n != N; ++n) {
    std::cout << eng() << '\n';
}

// generate N floats distributed normally (mean: 0., stddev: 1.)
std::normal_distribution<float> dist;
for (int n = 0; n != N; ++n) {
    std::cout << dist(eng) << '\n';
}

// generate N ints distributed uniformly between 1 and 6 included
std::uniform_int_distribution<> roll_dice(1, 6);
for (int n = 0; n != N; ++n) {
    std::cout << roll_dice(eng) << '\n';
}
```

Exercise: Let's implement `std::default_random_engine`

`std::default_random_engine` usually is an alias for a *linear congruential generator*. Let's consider `minstd_rand0`, which produces a sequence according to

$$x_{n+1} = 16807x_n \pmod{2^{31} - 1}$$

Write a class `LinearCongruential` whose constructor initializes the sequence with a seed (with a default value of 1) and an `operator()` that updates the internal value (the x_n) and returns it. The type of the numbers involved in the computations is `unsigned long int`.

Print a few numbers and check that they correspond to what is produced by `std::default_random_engine`.

Lambda expression

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- Useful to pass actions/callbacks to algorithms, threads, frameworks, ...

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struct LessThan42 {
    auto operator()(int n)
    {
        return n < 42;
    }
};

class LessThan {
    int m_;
public:
    explicit LessThan(int m)
        : m_{m} {}
    auto operator()(int n) const
    {
        return n < m_;
    }
};
```

```
std::find_if(..., LessThan42{});
```

```
std::find_if(..., LessThan{m});
```

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struct LessThan42 {
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    {
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    }
};

class LessThan {
    int m_;
public:
    explicit LessThan(int m)
        : m_{m} {}
    auto operator()(int n) const
    {
        return n < m_;
    }
};
```

```
std::find_if(..., LessThan42{});

std::find_if(..., [](int n) {
    return n < 42;
});

std::find_if(..., LessThan{m});
```

Lambda expression

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    }
};

class LessThan {
    int m_;
public:
    explicit LessThan(int m)
        : m_{m} {}
    auto operator()(int n) const
    {
        return n < m_;
    }
};
```

```
std::find_if(..., LessThan42{});

std::find_if(..., [](int n) {
    return n < 42;
});

std::find_if(..., LessThan{m});

auto m = ...;
std::find_if(..., [=](int n) {
    return n < m;
});
```

Lambda expression

- A concise way to create an unnamed function object
- Useful to pass actions/callbacks to algorithms, threads, frameworks, ...

```
struct LessThan42 {
    auto operator()(int n)
    {
        return n < 42;
    }
};

class LessThan {
    int m_;
public:
    explicit LessThan(int m)
        : m_{m} {}
    auto operator()(int n) const
    {
        return n < m_;
    }
};
```

```
std::find_if(..., LessThan42{});

std::find_if(..., [](int n) {
    return n < 42;
});

std::find_if(..., LessThan{m});

auto m = ...;
std::find_if(..., [=](int n) {
    return n < m;
});

std::find_if(..., [m = ...](int n) {
    return n < m;
});
```

Lambda closure

The evaluation of a lambda expression produces an unnamed function object (a *closure*)

- The `operator()` corresponds to the code of the body of the lambda expression
- The data members are the captured local variables

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```
auto lt = [ ]
```

```
class SomeUniqueName {  
    public:  
  
    auto operator()      const  
};  
  
auto lt = SomeUniqueName{ };
```

Lambda closure

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```
auto lt = [ ](int n)
        { return n < v; }
```

```
class SomeUniqueName {
public:

    auto operator()(int n) const
    { return n < v; }
};

auto lt = SomeUniqueName{ };
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```
auto v = 42;  
  
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        { return n < v; }
```

```
class SomeUniqueName {  
  
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```
auto v = 42;  
  
auto lt = [v](int n)  
    { return n < v; }
```

```
class SomeUniqueName {  
    int v;  
public:  
    explicit SomeUniqueName(int v)  
        : v{v} {}  
    auto operator()(int n) const  
    { return n < v; }  
};  
  
auto v = 42;  
auto lt = SomeUniqueName{v};
```

Lambda closure

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- The `operator()` corresponds to the code of the body of the lambda expression
- The data members are the captured local variables

```
auto v = 42;

auto lt = [v](int n)
    { return n < v; }

auto r = lt(5); // true
```

```
class SomeUniqueName {
    int v;
public:
    explicit SomeUniqueName(int v)
        : v{v} {}
    auto operator()(int n) const
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auto v = 42;
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    explicit SomeUniqueName(int v)
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auto v = 42;
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```

- Two lambda expressions produce objects of different types, even if they are identical

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 - [&k] capture k by reference

```
auto v = 3;  
auto l = [&v] {};
```

```
class SomeUniqueName {  
    int& v;  
public:  
    explicit SomeUniqueName(int& v)  
        : v{v} {}  
    ...  
};  
  
auto l = SomeUniqueName{v};
```

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 - [&k] capture k by reference
 - [=, &k] capture all by value but k by reference
 - [&, k] capture all by reference but k by value

```
auto v = 3;  
auto l = [&v] {};
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```
class SomeUniqueName {  
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public:  
    explicit SomeUniqueName(int& v)  
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};  
  
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```
auto v = 3;  
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```

```
class SomeUniqueName {  
    int& v;  
public:  
    explicit SomeUniqueName(int& v)  
        : v{v} {}  
    ...  
};  
  
auto l = SomeUniqueName{v};
```

- Global variables are available without being captured

Lambda explicit return type

- The return type of the call operator can be explicitly specified

```
[=](int n) -> bool { return n < v; }
```

becomes

```
class SomeUniqueName {  
    ...  
    bool operator()(int n) const  
    { return n < v; }  
};
```

Generic lambda

- If a parameter of the lambda expression is `auto`, the lambda expression is *generic*
- The call operator is a template

```
[](auto n) { ... }
```

becomes

```
class SomeUniqueName {  
    ...  
    template<typename T>  
    auto operator()(T n) const { ... }  
};
```

Lambda: const and mutable

- By default the call to a lambda is const
 - Variables captured by value are not modifiable

```
[i]                {... ++i ...}
```

```
class SomeUniqueName {  
    int i;  
    ...  
    auto operator()() const {... ++i ...}  
};
```

Lambda: const and mutable

- By default the call to a lambda is `const`
 - Variables captured by value are not modifiable
- A lambda can be declared `mutable`
 - The parameter list is mandatory

```
[i] () mutable { ... ++i ... }
```

```
class SomeUniqueName {  
    int i;  
    ...  
    auto operator()() { ... ++i ... }  
};
```

Lambda: const and mutable

- By default the call to a lambda is const
 - Variables captured by value are not modifiable
- A lambda can be declared mutable
 - The parameter list is mandatory
- If present, the explicit return type goes after mutable

```
[i]() mutable -> bool {... ++i ...}
```

```
class SomeUniqueName {  
    int i;  
    ...  
    bool operator()() {... ++i ...}  
};
```

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class SomeUniqueName {  
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    ...  
    bool operator()() {... ++i ...}  
};
```

- Variables captured by reference can be modified

```
int v{3};  
[&v] { ++v; } (); // NB the lambda is immediately invoked  
assert(v == 4);
```

Lambda: const and mutable

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};
```

- Variables captured by reference can be modified

```
int v{3};  
[&v] { ++v; } (); // NB the lambda is immediately invoked  
assert(v == 4);
```

- There is no direct way to capture by const&, but you can use `std::as_const`

Lambda: dangling reference

- Be careful not to have dangling references in a closure
- It's similar to a function returning a reference to a local variable

```
auto make_lambda() // auto here is unavoidable
{
    int v{3};
    return [&] { return v; }; // return a closure
}

auto l = make_lambda();
auto d = l(); // the captured variable is dangling here
```

Lambda: dangling reference

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    int v{3};
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}

auto l = make_lambda();
auto d = l(); // the captured variable is dangling here
```

- Capture by reference only if the lambda closure doesn't survive the current scope

- C++ → Algorithms
- Starting from `algo_functions.cpp` and following the hints, write code to
 - multiply the elements of the vector
 - compute the mean and the standard deviation
 - sort the vector in descending order
 - move the even numbers to the beginning
 - create another vector with the squares of the numbers in the first vector
 - find the first multiple of 3 or 7
 - erase from the vector all the multiples of 3 or 7
 - ...

`std::function`

- *Type-erased* wrapper that can store and invoke any callable entity with a certain signature
 - function, function object, lambda, member function

std::function

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 - function, function object, lambda, member function

```
#include <functional>

using Function = std::function<int(int,int)>; // signature

Function f1 { std::plus<int>{} };
Function f2 { [](int a, int b) { return a * b; } };
Function f3 { [](auto a, auto b) { return std::gcd(a,b); } };
```

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```

- Some space and time overhead, so use only if a template parameter is not satisfactory

```
std::vector<Function> functions { f1, f2, f3 };

for (auto& f : functions) {
    std::cout << f(121, 42) << '\n'; // 163 5082 1
}
```

Introduction

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Move semantics

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Additional material

Dynamic memory allocation

It's not always possible to know at compile time which type of objects is needed or how many of them

Dynamic memory allocation

It's not always possible to know at compile time which type of objects is needed or how many of them

- run-time polymorphism

```
struct Shape { ... };
struct Rectangle : Shape { ... };
struct Circle : Shape { ... };

Shape* s{nullptr};
char c; std::cin >> c;
switch (c) {
    case 'r': s = new Rectangle; break;
    case 'c': s = new Circle; break;
}
```

Dynamic memory allocation

It's not always possible to know at compile time which type of objects is needed or how many of them

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struct Shape { ... };
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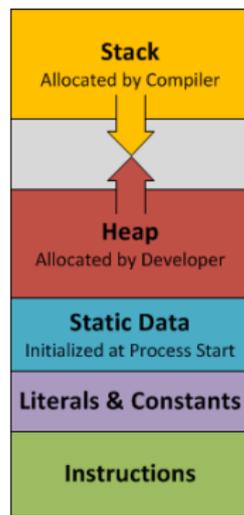
Shape* s{nullptr};
char c; std::cin >> c;
switch (c) {
    case 'r': s = new Rectangle; break;
    case 'c': s = new Circle; break;
}
```

- dynamic collections of objects

```
int n; std::cin >> n;
std::vector<Particle> v;
for (int i = 0; i != n; ++i) {
    v.emplace_back(...);
}
```

Memory layout of a process

- A process is a running program
- When a program is started the operating system brings the contents of the corresponding file into memory according to well-defined conventions
 - Stack
 - function local variables
 - function call bookkeeping
 - Heap
 - dynamic allocation
 - Global data
 - literals and variables
 - initialized and uninitialized (set to 0)
 - Program instructions

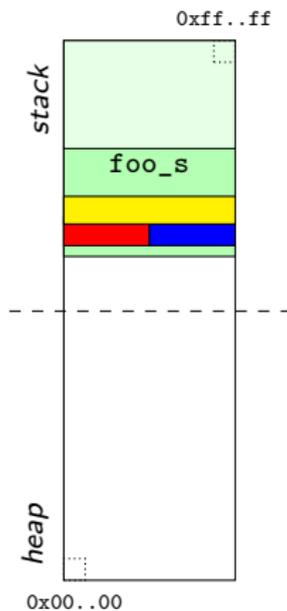


Stack vs Heap: space

```
struct S {  
    int    n;  
    float  f;  
    double d;  
};
```

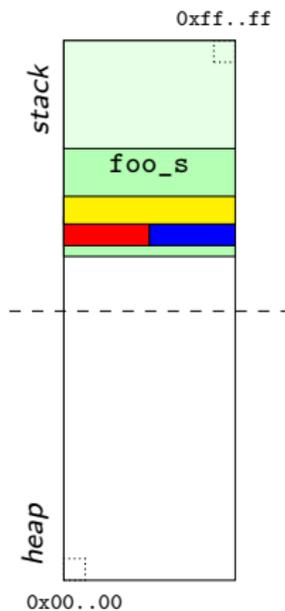
Stack vs Heap: space

```
struct S {  
    int    n;  
    float  f;  
    double d;  
};  
  
auto foo_s() {  
    S s;  
    ...  
}
```



Stack vs Heap: space

```
struct S {  
    int    n;  
    float  f;  
    double d;  
};  
  
auto foo_s() {  
    S s;  
    ...  
}
```

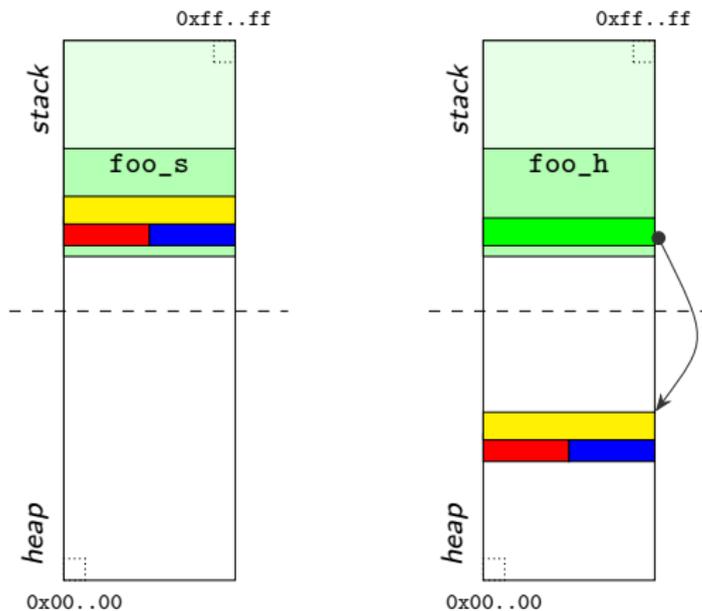


Occupancy:

- sizeof(S)

Stack vs Heap: space

```
struct S {  
    int    n;  
    float  f;  
    double d;  
};  
  
auto foo_s() {  
    S s;  
    ...  
}  
  
auto foo_h() {  
    S* s = new S;  
    ...  
}
```

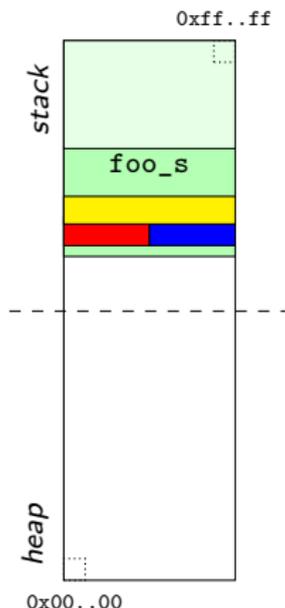


Occupancy:

- `sizeof(S)`

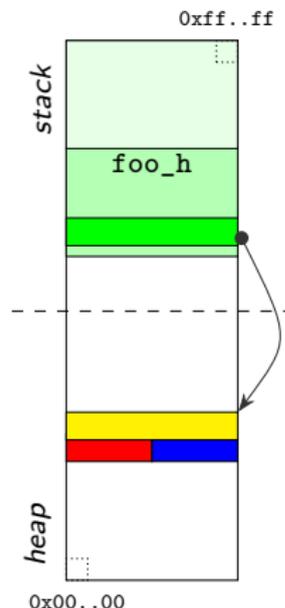
Stack vs Heap: space

```
struct S {  
    int    n;  
    float  f;  
    double d;  
};  
  
auto foo_s() {  
    S s;  
    ...  
}  
  
auto foo_h() {  
    S* s = new S;  
    ...  
}
```



Occupancy:

- `sizeof(S)`



Occupancy:

- `sizeof(S) + sizeof(S*)`
- plus new internal space overhead

Stack vs Heap: time

Stack

```
void stack()
{
    int m{123};
    ...
}
```

Heap

```
void heap()
{
    int* m = new int{123};
    ...
    delete m;
}
```

Stack vs Heap: time

Stack

```
void stack()
{
    int m{123};
    ...
}
```

```
stack():
    subq %4, %rsp
    movl $123, (%rsp)
    ...
    addq $4, %rsp
    ret
```

Heap

```
void heap()
{
    int* m = new int{123};
    ...
    delete m;
}
```

Stack vs Heap: time

Stack

```
void stack()
{
    int m{123};
    ...
}
```

```
stack():
    subq $4, %rsp
    movl $123, (%rsp)
    ...
    addq $4, %rsp
    ret
```

Heap

```
void heap()
{
    int* m = new int{123};
    ...
    delete m;
}
```

```
heap():
    subq $8, %rsp
    movl $4, %edi
    call operator new(unsigned long)
    movl $123, (%rax)
    movq %rax, (%rsp)
    ...
    movl $4, %esi
    movq %rax, %rdi
    call operator delete(void*, unsigned long)
    addq $8, %rsp
    ret
```

Stack vs Heap: time

Stack

```
void stack()
{
    int m{123};
    ...
}
```

```
stack():
    subq %4, %rsp
    movl $123, (%rsp)
    ...
    addq %4, %rsp
    ret
```

Heap

```
void heap()
{
    int* m = new int{123};
    ...
    delete m;
}
```

```
heap():
    subq $8, %rsp
    movl $4, %edi
    call operator new(unsigned long)
    movl $123, (%rax)
    movq %rax, (%rsp)
    ...
    movl $4, %esi
    movq %rax, %rdi
    call operator delete(void*, unsigned long)
    addq $8, %rsp
    ret
```

```
$ g++ -O3 heap.cpp && ./a.out
100000000 iterations: 14 ns
```

i.e. 14 ns just to allocate/deallocate an int

Google Benchmark

- <https://github.com/google/benchmark>

```
static void BM_Stack(benchmark::State& state) {
    while (state.KeepRunning()) {
        int m{123};
    }
}
BENCHMARK(BM_Stack);
```

```
static void BM_Heap(benchmark::State& state) {
    while (state.KeepRunning()) {
        auto m = new int{123};
        delete m;
    }
}
BENCHMARK(BM_Heap);
```

- Hands-on
 - start from https://quick-bench.com/q/h_mTt5vkhekwyGJ880BXLof2KQg
 - note the use of `benchmark::DoNotOptimize()`
 - play with the optimization level and the code

- Objects that contain and own other objects
- Different characteristics and operations, some common traits
- Implemented as class templates

Sequence The client decides where an element gets inserted

- array, deque, forward_list, list, vector

Associative The container decides where an element gets inserted

Ordered The elements are sorted

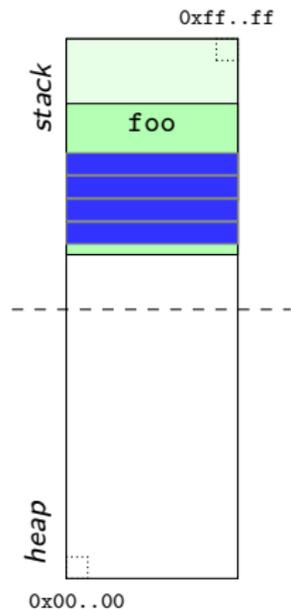
- map, multimap, set, multiset

Unordered The elements are hashed

- unordered_*

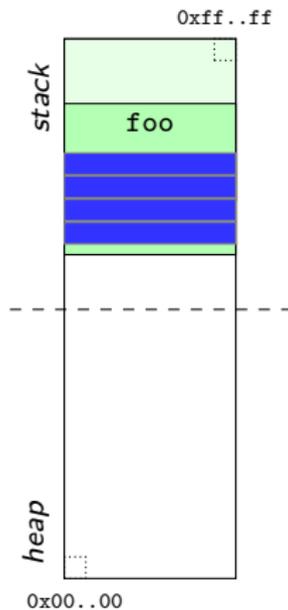
Sequence containers

`std::array`

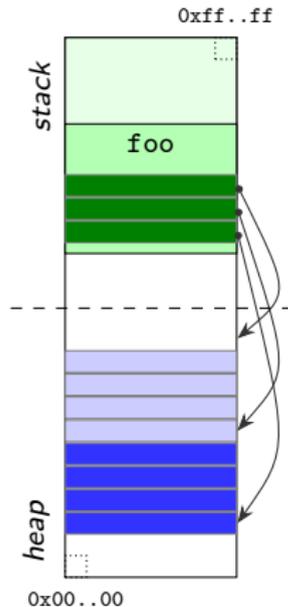


Sequence containers

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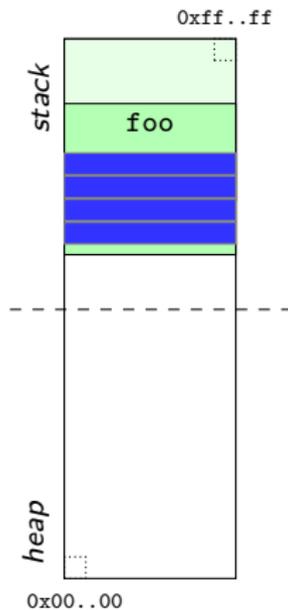


`std::vector`

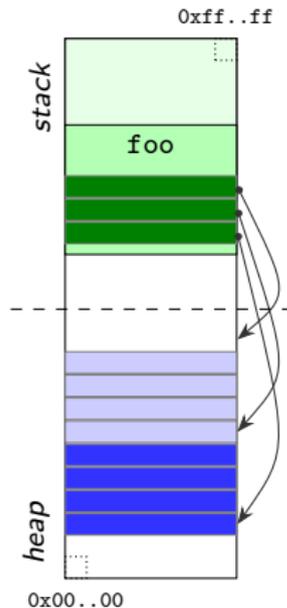


Sequence containers

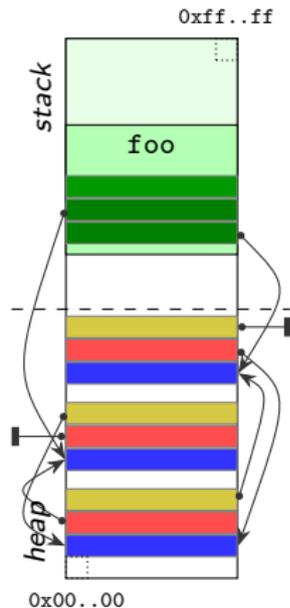
`std::array`



`std::vector`



`std::list`

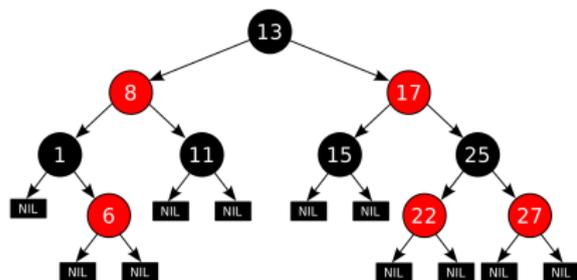


Associative ordered containers

- They contain ordered values (`set` and `multiset`) or key-value pairs (`map` and `multimap`)
- Search, removal and insertion have logarithmic complexity

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- They contain ordered values (set and multiset) or key-value pairs (map and multimap)
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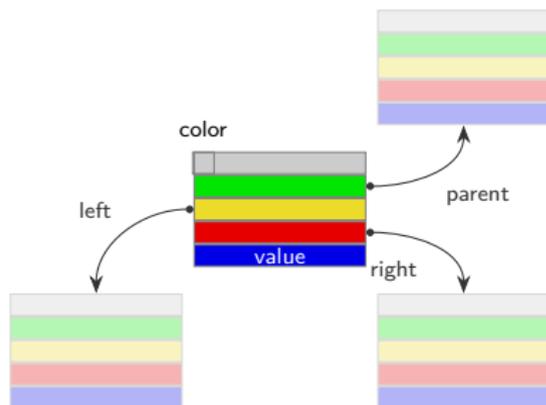
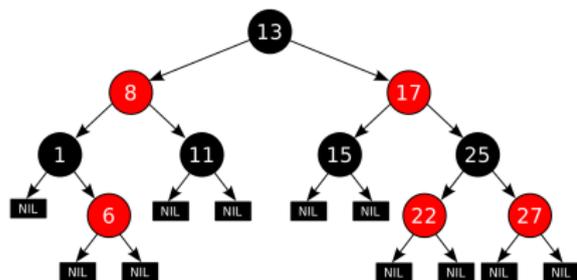


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- C++ → Containers
- Inspect, build and run `containers.cpp`, also using `perf`
- Extend it to manage an `std::list`
- Compare the performance obtained with the two containers

Introduction

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Weaknesses of a T*

- Critical information is not encoded in the type
 - Am I the owner of the pointee? Should I delete it?
 - Is the pointee an object or an array of objects? of what size?
 - Was it allocated with `new`, `malloc` or even something else (e.g. `fopen` returns a `FILE*`)?

```
T* p = create_something();
```

Weaknesses of a T*

- Critical information is not encoded in the type
- Owing pointers are prone to leaks and double deletes

```
{
  T* p = new T{};
  ...
  // ops, forgot to delete p
}
{
  T* p = new T;
  ...
  delete p;
  ...
  delete p; // ops, delete again
}
```

Weaknesses of a T*

- Critical information is not encoded in the type
- Owing pointers are prone to leaks and double deletes
- Owing pointers are unsafe in presence of exceptions

```
{  
  T* p = new T;  
  ... // potentially throwing code  
  delete p;  
}
```

Weaknesses of a T*

- Critical information is not encoded in the type
- Owing pointers are prone to leaks and double deletes
- Owing pointers are unsafe in presence of exceptions
- Runtime overhead
 - dynamic allocation/deallocation
 - indirection

Debugging memory problems

- Valgrind is a suite of debugging and profiling tools for memory management, threading, caching, etc.
- Valgrind Memcheck can detect
 - invalid memory accesses
 - use of uninitialized values
 - memory leaks
 - bad frees
- It's precise, but slow

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 - invalid memory accesses
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 - memory leaks
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```
$ g++ leak.cpp
$ valgrind ./a.out
==18331== Memcheck, a memory error detector
...
```

Debugging memory problems (cont.)

- *Address Sanitizer* (ASan)
- The compiler instruments the executable so that at runtime ASan can catch problems similar, but not identical, to valgrind
- Faster than valgrind

Debugging memory problems (cont.)

- *Address Sanitizer* (ASan)
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```
$ g++ -fsanitize=address leak.cpp  
$ ./a.out
```

```
=====  
==18338==ERROR: LeakSanitizer: detected memory leaks  
...
```

- C++ → Memory issues
- Get familiar with Valgrind (if available) and memory sanitizers
- Inspect, compile, run directly and run through valgrind or memory sanitizers (not both together)
 - `non_owning_pointer.cpp`
 - `array_too_small.cpp`
 - `leak.cpp`
 - `double_delete.cpp`
 - `missed_delete.cpp`
- Try and fix the problems

When to use a T*

- To represent a *link* to an object when
 - the object is not owned, and
 - the link may be null or the link can be re-bound
- Mutable and immutable scenarios
 - T* vs T const*

When not to use a T*

- To represent a link to an object when
 - the object is owned, or
 - the link can never be null, and the link cannot be re-bound
- Alternatives
 - use a copy
 - use a (const) reference

```
T& tr = t1; // tr is an alias for t1  
tr = t2;   // doesn't re-bind tr, assigns t2 to t1
```

```
T* tp = &t1; // tp points to t1  
tp = &t2;   // re-binds tp, it now points to t2
```

- use a resource-managing object
 - `std::array`, `std::vector`, `std::string`, *smart pointers*, ...

- Dynamic memory is just one of the many types of resources manipulated by a program:
 - thread, mutex, socket, file, ...
- C++ offers powerful tools to manage resources
 - *"C++ is my favorite garbage collected language because it generates so little garbage"*

- Objects that behave like pointers, but also manage the lifetime of the pointee

- Objects that behave like pointers, but also manage the lifetime of the pointee
- Leverage the RAII idiom
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 - Resource (e.g. memory) is acquired in the constructor
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- Importance of how the destructor is designed in C++
 - deterministic: guaranteed execution at the end of the scope
 - order of execution opposite to order of construction
- Guaranteed no leak nor double release, even in presence of exceptions

Smart pointers (cont.)

```
template<typename Pointee>
class SmartPointer {
    Pointee* m_p;
public:
    explicit SmartPointer(Pointee* p): m_p{p} {}
    ~SmartPointer() { delete m_p; }

};

class Histo { ... };

{
    SmartPointer<Histo> sp{new Histo{}};

}
```

At the end of the scope (i.e. at the closing `}`) `sp` is destroyed and its destructor deletes the pointee

Smart pointers (cont.)

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class SmartPointer {
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    sp->fill();
    (*sp).fill();
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Smart pointers (cont.)

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    ~SmartPointer() { delete m_p; }
    Pointee* operator->() { return m_p; }
    Pointee& operator*() { return *m_p; }
};

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    ...
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Standard smart pointer

- Exclusive ownership
- No space nor time overhead
- Non-copyable, movable

std::unique_ptr<T>

Standard smart pointer

- Exclusive ownership
- No space nor time overhead
- Non-copyable, movable

```
class Histo { ... };  
  
void take(std::unique_ptr<Histo> ph);
```

Standard smart pointer

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- Non-copyable, movable

```
class Histo { ... };  
  
void take(std::unique_ptr<Histo> ph);  
  
std::unique_ptr<Histo> ph{new Histo{}}; // explicit new
```

Standard smart pointer

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```
class Histo { ... };  
  
void take(std::unique_ptr<Histo> ph);  
  
std::unique_ptr<Histo> ph{new Histo{}}; // explicit new  
auto ph = std::make_unique<Histo>(); // better
```

Standard smart pointer

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- No space nor time overhead
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class Histo { ... };  
  
void take(std::unique_ptr<Histo> ph);  
  
std::unique_ptr<Histo> ph{new Histo{}}; // explicit new  
auto ph = std::make_unique<Histo>(); // better  
take(ph);
```

std::unique_ptr<T>

Standard smart pointer

- Exclusive ownership
- No space nor time overhead
- Non-copyable, movable

```
class Histo { ... };  
  
void take(std::unique_ptr<Histo> ph);           // by value  
  
std::unique_ptr<Histo> ph{new Histo{}};       // explicit new  
auto ph = std::make_unique<Histo>();         // better  
take(ph);                                     // error, non-copyable
```

std::unique_ptr<T>

Standard smart pointer

- Exclusive ownership
- No space nor time overhead
- Non-copyable, movable

```
class Histo { ... };

void take(std::unique_ptr<Histo> ph);

std::unique_ptr<Histo> ph{new Histo{}}; // explicit new
auto ph = std::make_unique<Histo>(); // better
take(ph); // error, non-copyable
take(std::move(ph));
```

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NB: `std::move` doesn't actually move anything. It just signals to the compiler that it's ok to move the object

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 - for the management, not for access
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 - e.g. to pass to legacy APIs
 - `smart_ptr<T>::get()`
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 - `smart_ptr<T>::get()`
 - returns a **non-owning** `T*`
 - `unique_ptr<T>::release()`
 - returns an **owning** `T*`
 - must be explicitly managed
- Arrays are supported

```
std::unique_ptr<int[]> p{new int[n]}; // destructor calls 'delete []'
```

smart_ptr and functions

Pass a smart pointer to a function only if the function needs to rely on the smart pointer itself

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- by value of a `shared_ptr`, to keep the resource alive

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auto s = std::make_shared<Histo>();  
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- by value of a `shared_ptr`, to keep the resource alive

```
auto s = std::make_shared<Histo>();
std::thread t{ [=] { do_something_with(s); } };
```

- by reference, to interact with the smart pointer itself

```
void print_count(std::shared_ptr<Histo> const& s) {
    std::cout << s.use_count() << '\n';
};
auto s = std::make_shared<Histo>();
print_count(s);
```

smart_ptr and functions (cont.)

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```
auto s = make_shared<Histo>();
```

smart_ptr and functions (cont.)

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```
void fill(std::shared_ptr<Histo> s) { if (s) s->fill(); }
```

```
auto s = make_shared<Histo>();  
fill(s);
```

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void fill(std::shared_ptr<Histo> s) { if (s) s->fill(); }  
void fill(Histo* t)                { if (t) t->fill(); } // better
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auto s = make_shared<Histo>();  
fill(s);  
fill(s.get());
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void fill(std::shared_ptr<Histo> s) { if (s) s->fill(); }
void fill(Histo* t)                { if (t) t->fill(); } // better
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- Return a *smart_ptr* from a function if the function has dynamically allocated a resource that is passed to the caller

```
auto factory() { return std::make_unique<Histo>(); }
```

smart_ptr and functions (cont.)

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void fill(std::shared_ptr<Histo> s) { if (s) s->fill(); }
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auto factory() { return std::make_unique<Histo>(); }

auto u = factory(); // std::unique_ptr<Histo>
std::shared_ptr<Histo> s = std::move(u);
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smart_ptr and functions (cont.)

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std::shared_ptr<Histo> s = factory();
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smart_ptr custom deleter

- *smart_ptr* is a general-purpose resource handler
- The resource release is not necessarily done with `delete`
- *unique_ptr* and *shared_ptr* support a *custom deleter*

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- Who owns the resource?
- Forgetting to release
- Releasing twice
- Early return/throw

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FILE* f = std::fopen(...);  
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Usual problems:

- Who owns the resource?
- Forgetting to release
- Releasing twice
- Early return/throw
- Wrap the deallocation function in a lambda to be safe in presence of multiple overloads
- A bit more involved for *unique_ptr*

- C++ → Memory issues
 - Adapt the exercises to use smart pointers, when applicable
 - Remember to compile with `-fsanitize=address`
- C++ → Managing resources
- Adapt `c_alloc.cpp` to manage memory via a smart pointer.
- Starting from `dir.cpp` and following the hints in the file, write code to:
 - create a smart pointer managing a DIR resource obtained with the `opendir` function call
 - associate a deleter to that smart pointer
 - implement a function to read the names of the files in that directory
 - check if the deleter is called at the right moment
 - hide the creation of the smart pointer behind a factory function
 - populate a vector of FILEs, properly wrapped in a smart pointer, obtained opening the regular files in that directory
 - ...

Introduction

Algorithms and functions

Containers

Resource management

Move semantics

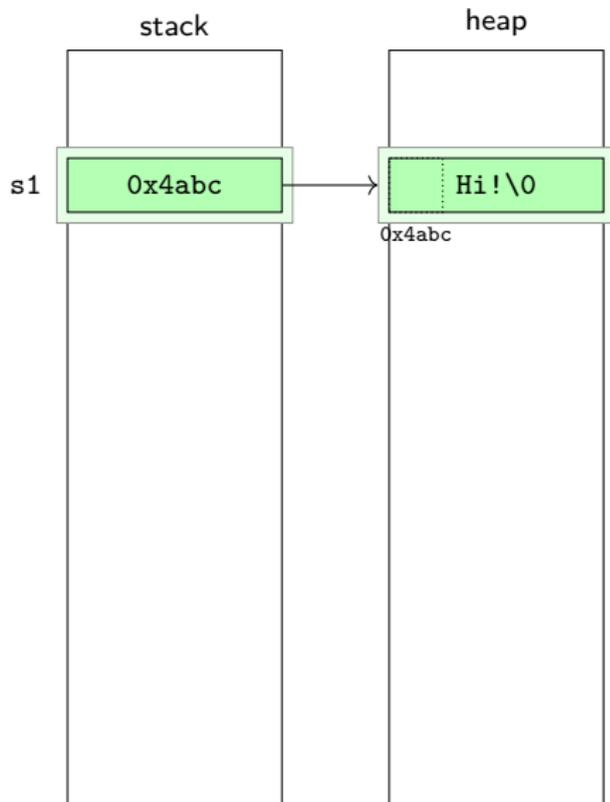
Compile-time computation

Additional material

We can do better than copying

```
class String {  
    char* s_;  
    ...  
};
```

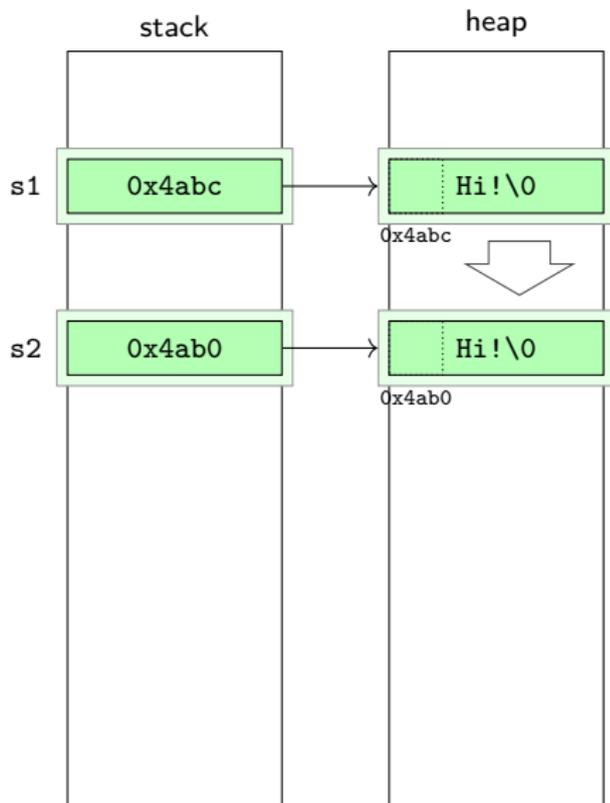
```
String s1{"Hi!"};
```



We can do better than copying

```
class String {  
    char* s_;  
    ...  
};
```

```
String s1{"Hi!"};  
String s2{s1};
```

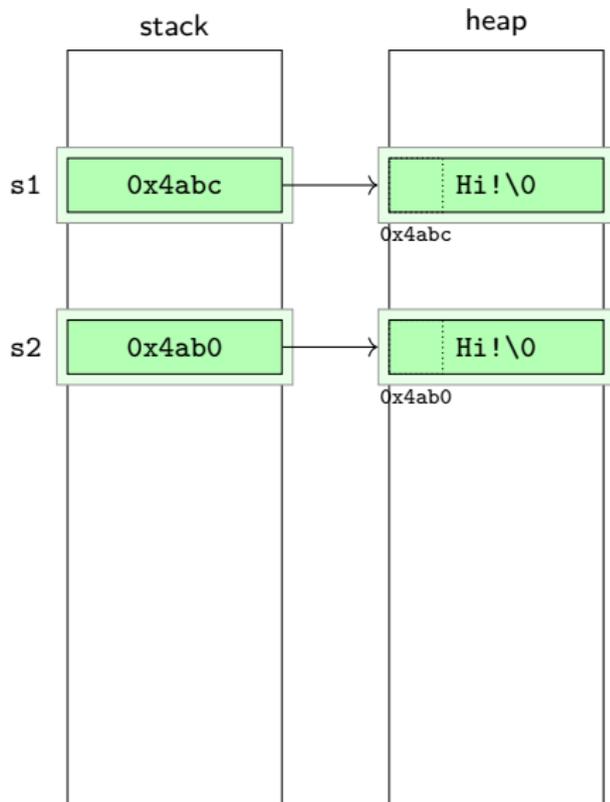


We can do better than copying

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class String {  
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    ...  
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String s1{"Hi!"};  
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- Both s1 and s2 exist at the end
- The “deep” copy is needed



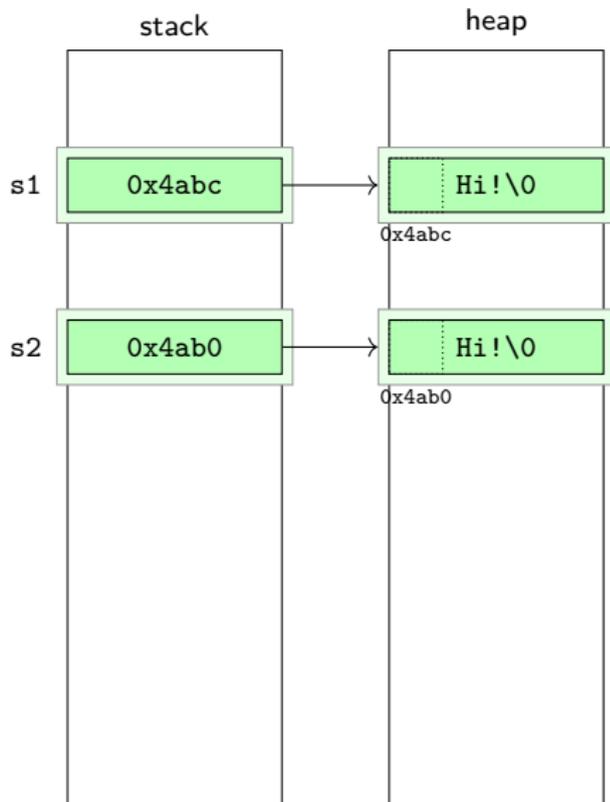
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String get_string() { return "Hi!"; }  
String s3{get_string()};
```



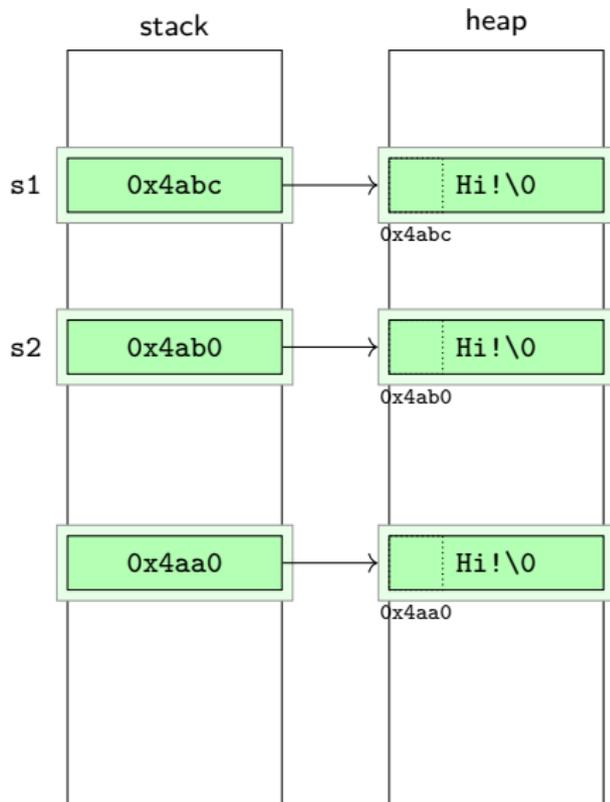
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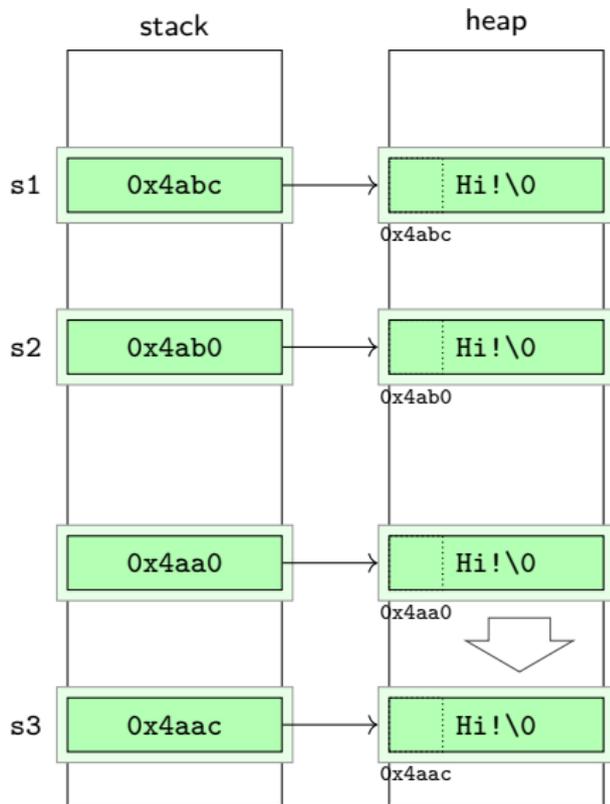
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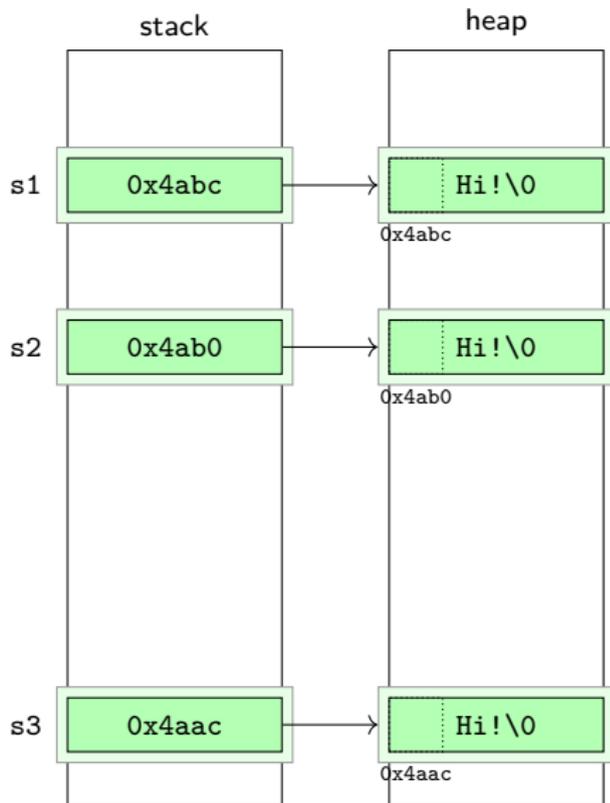
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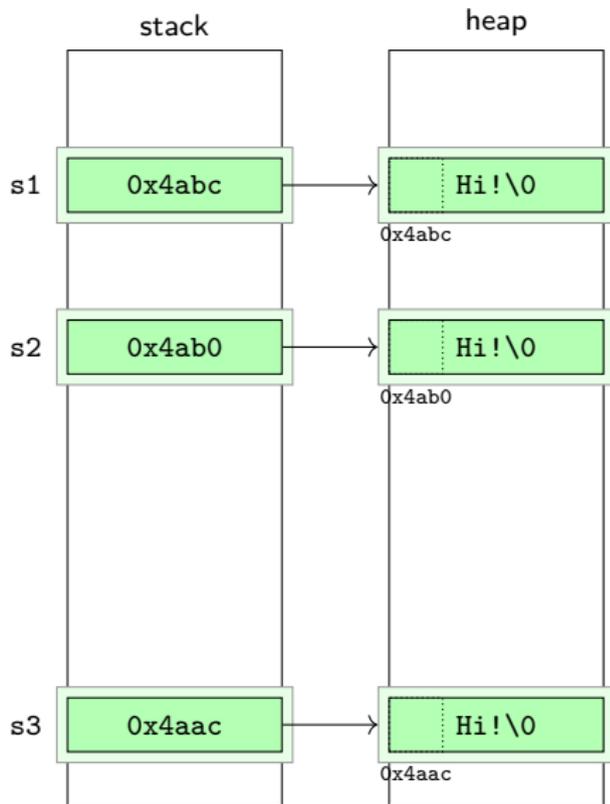
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- Both s1 and s2 exist at the end
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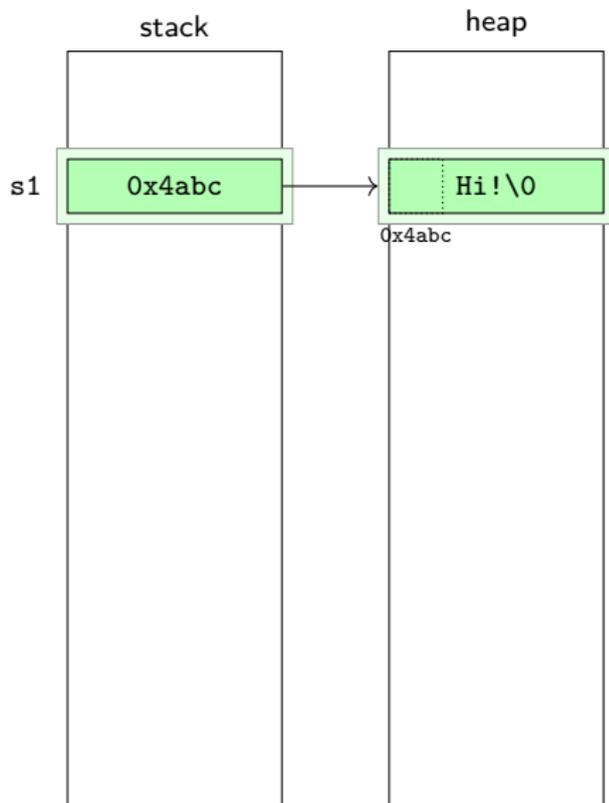
```
String get_string() { return "Hi!"; }  
String s3{get_string()};
```

- Only s3 exists at the end
- The “deep” copy is a waste



Copy vs move

```
class String {  
    char* s_;  
public:  
    String(char const* s) {  
        size_t size = strlen(s) + 1;  
        s_ = new char[size];  
        memcpy(s_, s, size);  
    }  
    ~String() { delete [] s_; }  
  
    ...  
};  
  
String s1{"Hi!"};
```

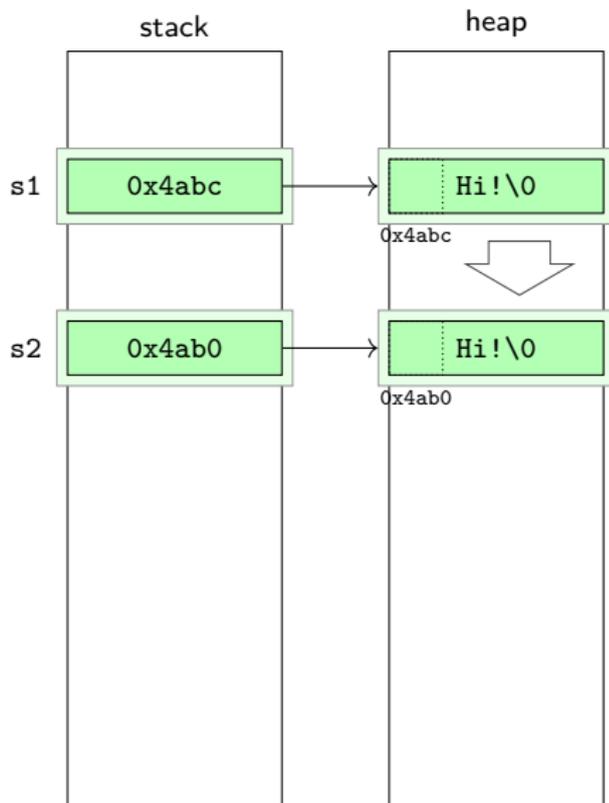


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    }
    ~String() { delete [] s_; }
    // copy
    String(String const& other) {
        size_t size = strlen(other.s_) + 1;
        s_ = new char[size];
        memcpy(s_, other.s_, size);
    }

    ...
};

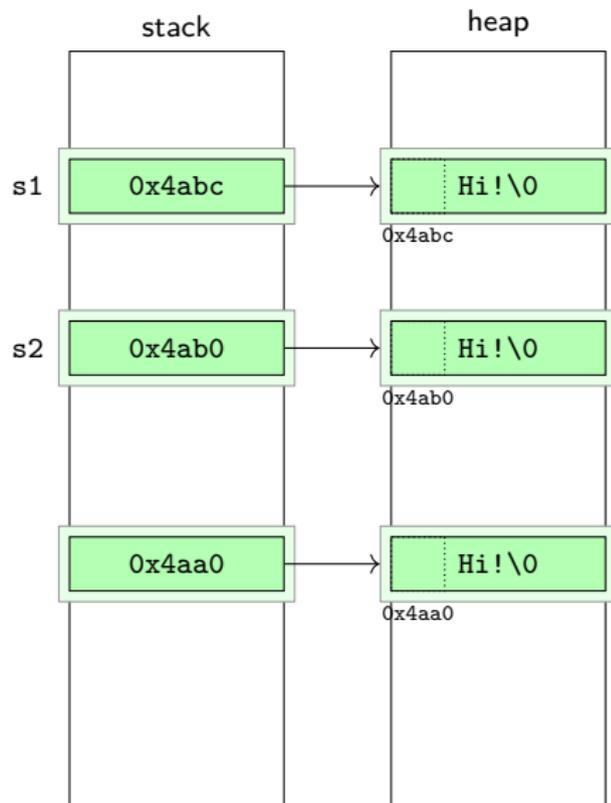
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    ...
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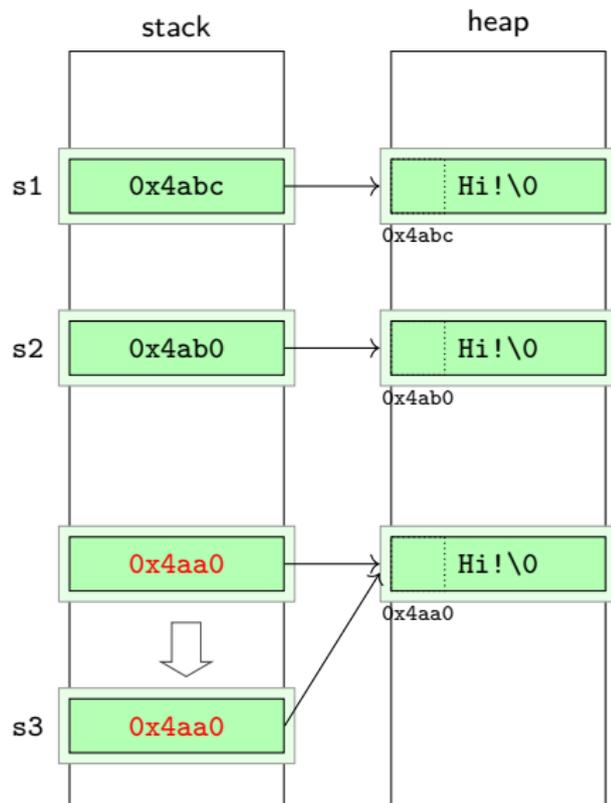
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        memcpy(s_, other.s_, size);
    }
    // move
    String(??? tmp): s_(tmp.s_) {
    }
    ...
};

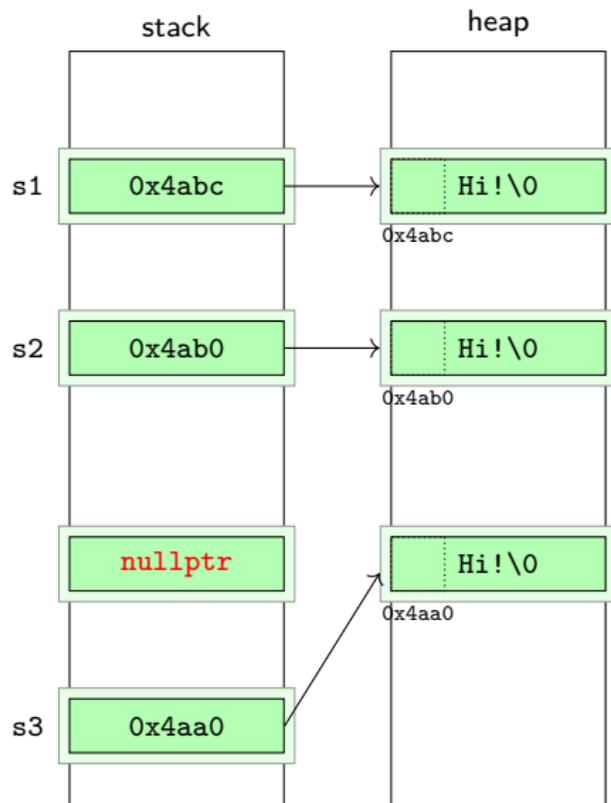
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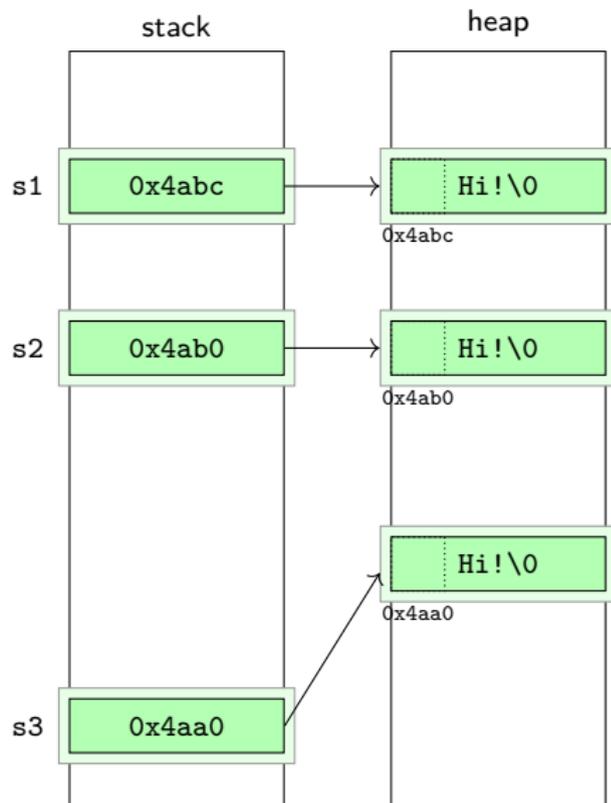
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Copy vs move

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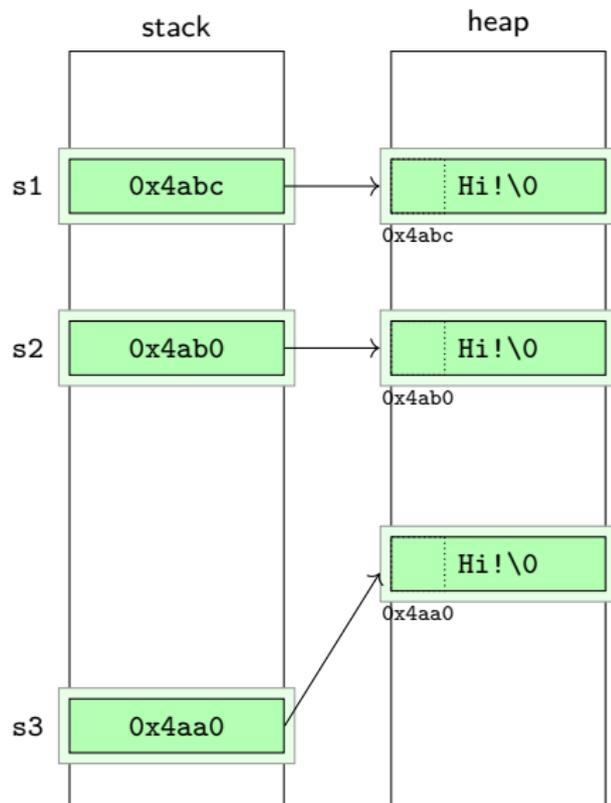
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};

String s1{"Hi!"};
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```



- The taxonomy of values in C++ is complex
 - glvalue, prvalue, xvalue, lvalue, rvalue
- We can assume
 - lvalue** A named object
 - for which you can take the address
 - **l** stands for “left” because it used to represent the **l**eft-hand side of an assignment
 - rvalue** An unnamed (temporary) object
 - for which you can't take the address
 - **r** stands for “right” because it used to represent the **r**ight-hand side of an assignment

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

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```
class String {  
    // copy constructor  
    String(String const& other) { ... }  
    // move constructor  
    String(String&& tmp) { ... }  
};
```

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- A `T&&` is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class String {  
    // copy constructor  
    String(String const& other) { ... }  
    // move constructor  
    String(String&& tmp) { ... }  
};  
  
String s2{s1};           // call String::String(String const&)
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class String {  
    // copy constructor  
    String(String const& other) { ... }  
    // move constructor  
    String(String&& tmp) { ... }  
};  
  
String s2{s1};           // call String::String(String const&)  
String s3{get_string()}; // call String::String(String&&)
```

Special member functions

- A class has five special member functions
 - Plus the default constructor

```
class Widget {  
    Widget(Widget const&);           // copy constructor  
    Widget& operator=(Widget const&); // copy assignment  
    Widget(Widget&&);               // move constructor  
    Widget& operator=(Widget&&);    // move assignment  
    ~Widget();                       // destructor  
};
```

Special member functions

- A class has five special member functions
 - Plus the default constructor

```
class Widget {  
    Widget(Widget const&);           // copy constructor  
    Widget& operator=(Widget const&); // copy assignment  
    Widget(Widget&&);               // move constructor  
    Widget& operator=(Widget&&);    // move assignment  
    ~Widget();                       // destructor  
};
```

- The compiler can generate them automatically according to some convoluted rules
 - The behavior depends on the behavior of data members

Special member functions

- A class has five special member functions
 - Plus the default constructor

```
class Widget {  
    Widget(Widget const&);           // copy constructor  
    Widget& operator=(Widget const&); // copy assignment  
    Widget(Widget&&);               // move constructor  
    Widget& operator=(Widget&&);    // move assignment  
    ~Widget();                       // destructor  
};
```

- The compiler can generate them automatically according to some convoluted rules
 - The behavior depends on the behavior of data members
- Rules of thumb
 - Rule of zero** Don't declare them and rely on the compiler
 - Rule of five** If you need to declare one, declare them all
 - Consider = default and = delete

- C++ → Move operations
- Open the program `string.cpp` and complete the existing code to:
 - Complete the set of the special member functions so that `String` is copyable and movable
 - Instead of a raw pointer, keep a `unique_ptr` in the private part of `String`
 - ...

Return a value from a function

- Returning a large value from a function is often perceived as slow

Return a value from a function

- Returning a large value from a function is often perceived as slow
 - Return “by pointer”

```
std::unique_ptr<LargeObject> make_large_object() {  
    return std::make_unique<LargeObject>();  
}
```

```
auto lo = make_large_object();  
lo->...; // use the object, via a pointer
```

Return a value from a function

- Returning a large value from a function is often perceived as slow
 - Return “by pointer”

```
std::unique_ptr<LargeObject> make_large_object() {  
    return std::make_unique<LargeObject>();  
}
```

```
auto lo = make_large_object();  
lo->...; // use the object, via a pointer
```

- Use “out” arguments

```
void make_large_object(LargeObject& o) {  
    o = LargeObject{}; // requires copy assignment  
}
```

```
LargeObject lo; // requires default constructor  
make_large_object(lo);  
lo... // use the object
```

Return a value from a function (cont.)

- There are very few reasons for not doing the obvious

```
LargeObject make_large_object() {  
    return LargeObject{};  
}  
  
auto lo = make_large_object(); // possibly auto const  
lo...                          // use the object
```

- In fact the compiler is allowed or even obliged in some circumstances to elide the copy of the returned value into the final destination
 - (N)RVO – (Named) Return Value Optimization
- If (N)RVO is not applied, a move is done, if available
- If the move is not available, copy

Return value optimization

Unnamed

```
Widget make_widget()
{
    if (...) {
        return Widget{};
    }
    return Widget{};
}

auto w = make_widget();
```

Named

```
Widget make_widget()
{
    Widget result;
    if (...) {
        result = Widget{};
    }
    return result;
}

auto w = make_widget();
```

Return value optimization

Unnamed

```
Widget make_widget()
{
    if (...) {
        return Widget{};
    }
    return Widget{};
}

auto w = make_widget();
```

Named

```
Widget make_widget()
{
    Widget result;
    if (...) {
        result = Widget{};
    }
    return result;
}

auto w = make_widget();
```

- Try not to mix named and unnamed returns in the same function
- Avoid return `std::move(result)`, unless necessary

- C++ → Return Value Optimization
- Open the program `rvo.cpp`. Implement variations of the `make_vector` function so that:
 - the result is returned from the function
 - the result is passed to the function as an output parameter (by reference or by pointer)
- Measure the time it takes to execute them. Discuss the results.

Introduction

Algorithms and functions

Containers

Resource management

Move semantics

Compile-time computation

Additional material

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Algorithms and functions

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Additional material

Let the compiler deduce the type of a variable from the initializer

```
auto i = 0;           // int
auto u = 0U;         // unsigned int
auto p = &i;         // int*
auto d = 1.;         // double
auto c = 'a';        // char
auto s = "a";        // char const*
```

Let the compiler deduce the type of a variable from the initializer

```
auto i = 0;           // int
auto u = 0U;         // unsigned int
auto p = &i;         // int*
auto d = 1.;         // double
auto c = 'a';        // char
auto s = "a";        // char const*
auto t = std::string{"a"}; // std::string
std::vector<std::string> v;
auto it = std::begin(v); // std::vector<std::string>::iterator
```

Let the compiler deduce the type of a variable from the initializer

```
auto i = 0;           // int
auto u = 0U;         // unsigned int
auto p = &i;        // int*
auto d = 1.;        // double
auto c = 'a';       // char
auto s = "a";       // char const*
auto t = std::string{"a"}; // std::string
std::vector<std::string> v;
auto it = std::begin(v); // std::vector<std::string>::iterator
using namespace std::chrono_literals;
auto u = 1234us;     // std::chrono::microseconds
```

Let the compiler deduce the type of a variable from the initializer

```
auto i = 0;           // int
auto u = 0U;         // unsigned int
auto p = &i;         // int*
auto d = 1.;         // double
auto c = 'a';        // char
auto s = "a";        // char const*
auto t = std::string{"a"}; // std::string
std::vector<std::string> v;
auto it = std::begin(v); // std::vector<std::string>::iterator
using namespace std::chrono_literals;
auto u = 1234us;     // std::chrono::microseconds
auto e;              // error
```

- auto never deduces a reference
- if needed, & must be added explicitly

```
T v;  
  
auto v1 = v;      // T - v1 is a copy of v  
auto& v2 = v;    // T& - v2 is an alias of v  
auto v3 = v2;    // T - v2 is a copy of v
```

auto and const

- auto makes a mutable copy
- auto const (or const auto) makes a non-mutable copy
- auto& preserves const-ness

```
T v;
```

```
auto          v1 = v; // T          - v1 is a mutable copy of v
auto const    v2 = v; // T const    - v2 is a non-mutable copy of v
auto&         v3 = v; // T&         - v3 is a mutable alias of v
auto const&   v4 = v; // T const&   - v4 is a non-mutable alias of v
```

```
T const v;
```

```
auto          v1 = v; // T          - v1 is a mutable copy of v
auto const    v2 = v; // T const    - v2 is a non-mutable copy of v
auto&         v3 = v; // T const&   - v3 is a non-mutable alias of v
auto const&   v4 = v; // T const&   - v4 is a non-mutable alias of v
```

How to check the deduced type?

- Trick by S. Meyers

```
template<typename T> struct D;  
  
auto k = 0U;  
D<decltype(k)> d; // error: aggregate 'D<unsigned int> d'...  
  
auto const o = 0.;  
D<decltype(o)> d; // error: aggregate 'D<const double> d'...  
  
auto const& f = 0.f;  
D<decltype(f)> d; // error: aggregate 'D<const float&> td'...  
  
auto s = "hello";  
D<decltype(s)> d; // error: aggregate 'D<const char*> d'...  
  
auto& t = "hello";  
D<decltype(t)> d; // error: aggregate 'D<const char (&)[6]> d'...
```

- `decltype` returns the type of an expression
 - at compile time

Lambda: closure

The evaluation of a lambda expression produces an unnamed function object (a *closure*)

- The operator `()` corresponds to the code of the body of the lambda expression
- The data members are the captured local variables

Lambda: closure

The evaluation of a lambda expression produces an unnamed function object (a *closure*)

- The `operator()` corresponds to the code of the body of the lambda expression
- The data members are the captured local variables

```
auto l = []
```

```
class SomeUniqueName {  
    public:  
  
    auto operator()  
};  
  
auto l = SomeUniqueName{ };
```

Lambda: closure

The evaluation of a lambda expression produces an unnamed function object (a *closure*)

- The operator() corresponds to the code of the body of the lambda expression
- The data members are the captured local variables

```
auto l = [](int i)
{ return i + v; }
```

```
class SomeUniqueName {
public:

    auto operator()(int i)
    { return i + v ; }
};

auto l = SomeUniqueName{ };
```

Lambda: closure

The evaluation of a lambda expression produces an unnamed function object (a *closure*)

- The operator() corresponds to the code of the body of the lambda expression
- The data members are the captured local variables

```
int v = 3;

auto l = [](int i)
{ return i + v; }
```

```
class SomeUniqueName {

public:

    auto operator()(int i)
    { return i + v ; }
};

int v = 3;
auto l = SomeUniqueName{ };
```

Lambda: closure

The evaluation of a lambda expression produces an unnamed function object (a *closure*)

- The operator() corresponds to the code of the body of the lambda expression
- The data members are the captured local variables

```
int v = 3;

auto l = [=](int i)
{ return i + v; }
```

```
class SomeUniqueName {
    int v_;
public:
    explicit SomeUniqueName(int v)
        : v_{v} {}

    auto operator()(int i)
    { return i + v_; }
};

int v = 3;
auto l = SomeUniqueName{v};
```

Lambda: closure

The evaluation of a lambda expression produces an unnamed function object (a *closure*)

- The operator() corresponds to the code of the body of the lambda expression
- The data members are the captured local variables

```
int v = 3;

auto l = [=](int i)
{ return i + v; }

auto r = l(5); // 8
```

```
class SomeUniqueName {
    int v_;
public:
    explicit SomeUniqueName(int v)
        : v_{v} {}

    auto operator()(int i)
    { return i + v_; }
};

int v = 3;
auto l = SomeUniqueName{v};
auto r = l(5); // 8
```

Lambda: closure

The evaluation of a lambda expression produces an unnamed function object (a *closure*)

- The operator() corresponds to the code of the body of the lambda expression
- The data members are the captured local variables

```
auto l = [v = 3](int i)
{ return i + v; }

auto r = l(5); // 8
```

```
class SomeUniqueName {
    int v_;
public:
    explicit SomeUniqueName(int v)
        : v_{v} {}

    auto operator()(int i)
    { return i + v_; }
};

int v = 3;
auto l = SomeUniqueName{v};
auto r = l(5); // 8
```

Lambda: closure

The evaluation of a lambda expression produces an unnamed function object (a *closure*)

- The operator() corresponds to the code of the body of the lambda expression
- The data members are the captured local variables

```
auto l = [v = 3](auto i)
{ return i + v; }

auto r = l(5); // 8
```

```
class SomeUniqueName {
    int v_;
public:
    explicit SomeUniqueName(int v)
        : v_{v} {}
    template<typename T>
    auto operator()(T i)
    { return i + v_; }
};

int v = 3;
auto l = SomeUniqueName{v};
auto r = l(5); // 8
```

Lambda: closure

The evaluation of a lambda expression produces an unnamed function object (a *closure*)

- The operator() corresponds to the code of the body of the lambda expression
- The data members are the captured local variables

```
auto l = [v = 3](auto i) -> int  
{ return i + v; }  
  
auto r = l(5); // 8
```

```
class SomeUniqueName {  
    int v_;  
public:  
    explicit SomeUniqueName(int v)  
        : v_{v} {}  
    template<typename T>  
    int operator()(T i)  
    { return i + v_; }  
};  
  
int v = 3;  
auto l = SomeUniqueName{v};  
auto r = l(5); // 8
```

Lambda: capturing

- Automatic variables used in the body need to be captured
 - `[]` capture nothing
 - `[=]` capture all by value
 - `[k]` capture `k` by value
 - `[&]` capture all by reference
 - `[&k]` capture `k` by reference
 - `[=, &k]` capture all by value but `k` by reference
 - `[&, k]` capture all by reference but `k` by value

Lambda: capturing

- Automatic variables used in the body need to be captured
 - [] capture nothing
 - [=] capture all by value
 - [k] capture k by value
 - [&] capture all by reference
 - [&k] capture k by reference
 - [=, &k] capture all by value but k by reference
 - [&, k] capture all by reference but k by value

```
int v = 3;  
auto l = [v] {};
```

```
class SomeUniqueName {  
    int v_;  
public:  
    explicit SomeUniqueName(int v)  
        : v_{v} {}  
    ...  
};  
  
auto l = SomeUniqueName{v};
```

Lambda: capturing

- Automatic variables used in the body need to be captured
 - [] capture nothing
 - [=] capture all by value
 - [k] capture k by value
 - [&] capture all by reference
 - [&k] capture k by reference
 - [=, &k] capture all by value but k by reference
 - [&, k] capture all by reference but k by value

```
int v = 3;  
auto l = [&v] {};
```

```
class SomeUniqueName {  
    int& v_  
public:  
    explicit SomeUniqueName(int& v)  
        : v_{v} {}  
    ...  
};  
  
auto l = SomeUniqueName{v};
```

Lambda: capturing

- Automatic variables used in the body need to be captured
 - [] capture nothing
 - [=] capture all by value
 - [k] capture k by value
 - [&] capture all by reference
 - [&k] capture k by reference
 - [=, &k] capture all by value but k by reference
 - [&, k] capture all by reference but k by value

```
int v = 3;  
auto l = [&v] {};
```

```
class SomeUniqueName {  
    int& v_  
public:  
    explicit SomeUniqueName(int& v)  
        : v_{v} {}  
    ...  
};  
  
auto l = SomeUniqueName{v};
```

- Global variables are available without being captured

Lambda: const and mutable

- By default the call to a lambda is const
 - Variables captured by value are not modifiable

```
[] {};
```

```
struct SomeUniqueName {  
    auto operator()() const {}  
};
```

Lambda: const and mutable

- By default the call to a lambda is const
 - Variables captured by value are not modifiable
- A lambda can be declared mutable

```
[] () mutable {};
```

```
struct SomeUniqueName {  
    auto operator()() {}  
};
```

Lambda: const and mutable

- By default the call to a lambda is const
 - Variables captured by value are not modifiable
- A lambda can be declared mutable

```
[]() mutable -> void {};
```

```
struct SomeUniqueName {  
    void operator()() {}  
};
```

Lambda: const and mutable

- By default the call to a lambda is const
 - Variables captured by value are not modifiable
- A lambda can be declared mutable

```
[]() mutable -> void {};
```

```
struct SomeUniqueName {  
    void operator()() {}  
};
```

- Variables captured by reference can be modified
 - There is no way to capture by const&

```
int v = 3;  
[&v] { ++v; }();  
assert(v == 4);
```

Lambda: dangling reference

Be careful not to have dangling references in a closure

- It's similar to a function returning a reference to a local variable

```
auto make_lambda()
{
    int v = 3;
    return [&] { return v; }; // return a closure
}
```

```
auto l = make_lambda();
auto d = l(); // the captured variable is dangling here
```

```
auto start_in_thread()
{
    int v = 3;
    return std::async([&] { return v; });
}
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

Rvalue reference

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 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class Thing;  
Thing make_thing();  
  
Thing t;
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class Thing;
Thing make_thing();

Thing t;

Thing && r = t;
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class Thing;
Thing make_thing();

Thing t;

Thing && r = t;           // ok
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class Thing;
Thing make_thing();

Thing t;

Thing & r = t;           // ok
Thing && r = t;
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class Thing;
Thing make_thing();

Thing t;

Thing    & r = t;           // ok
Thing    && r = t;          // error
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class Thing;
Thing make_thing();

Thing t;

Thing & r = t;           // ok
Thing && r = t;          // error
Thing & r = make_thing();
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class Thing;
Thing make_thing();

Thing t;

Thing & r = t;           // ok
Thing && r = t;          // error
Thing & r = make_thing(); // error
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class Thing;
Thing make_thing();

Thing t;

Thing    & r = t;           // ok
Thing    && r = t;          // error
Thing    & r = make_thing(); // error
Thing    && r = make_thing();
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class Thing;
Thing make_thing();

Thing t;

Thing    & r = t;           // ok
Thing    && r = t;          // error
Thing    & r = make_thing(); // error
Thing    && r = make_thing(); // ok
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class Thing;
Thing make_thing();

Thing t;

Thing    & r = t;           // ok
Thing    && r = t;          // error
Thing    & r = make_thing(); // error
Thing    && r = make_thing(); // ok
Thing    const& r = make_thing();
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class Thing;
Thing make_thing();

Thing t;

Thing    & r = t;           // ok
Thing    && r = t;          // error
Thing    & r = make_thing(); // error
Thing    && r = make_thing(); // ok
Thing    const& r = make_thing(); // ok (!)
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class Thing;
Thing make_thing();

Thing t;

Thing    & r = t;           // ok
Thing    && r = t;          // error
Thing    & r = make_thing(); // error
Thing    && r = make_thing(); // ok
Thing    const& r = make_thing(); // ok (!)
Thing    const&& r = make_thing();
```

Rvalue reference

- A **T&&** is an rvalue reference
 - introduced in C++11
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```
class Thing;
Thing make_thing();

Thing t;

Thing    & r = t;           // ok
Thing    && r = t;          // error
Thing    & r = make_thing(); // error
Thing    && r = make_thing(); // ok
Thing const& r = make_thing(); // ok (!)
Thing const&& r = make_thing(); // ok, but what for?
```

Rvalue reference

- A `T&&` is an rvalue reference
 - introduced in C++11
- It binds to rvalues but not to lvalues

```
class Thing;
Thing make_thing();

Thing t;

Thing    & r = t;           // ok
Thing    && r = t;          // error
Thing    & r = make_thing(); // error
Thing    && r = make_thing(); // ok
Thing const& r = make_thing(); // ok (!)
Thing const&& r = make_thing(); // ok, but what for?
```

```
class String {
    // move constructor
    String(String&& tmp) : s_(tmp.s_) {
        tmp.s_ = nullptr;
    }
};

String s2{s1};           // call String::String(String const&)
String s3{get_string()}; // call String::String(String&&)
```

Rvalue reference (cont.)

- Any function can accept rvalue references

```
void foo(String&&);  
  
foo(get_string());  
foo(String{"hello"});
```

- lvalues can be explicitly transformed into rvalues

```
String s;  
foo(s);           // error  
foo(std::move(s)); // ok, I don't care any more about s  
s.size();        // dangerous
```

Overloading on &&

- A function can be overloaded for temporaries
 - useful if there are significant opportunities of optimization

```
void foo(Widget const&) {...}
void foo(Widget&&) {...}

Widget w{...};
foo(w);           // calls foo(Widget const&)
foo(Widget{...}); // calls foo(Widget&&)
```

Overloading on &&

- A function can be overloaded for temporaries
 - useful if there are significant opportunities of optimization

```
void foo(Widget const&) {...}
void foo(Widget&&) {...}

Widget w{...};
foo(w);           // calls foo(Widget const&)
foo(Widget{...}); // calls foo(Widget&&)
```

- For more than one parameter it becomes less desirable
 - consider pass by value, if move is cheap
 - especially useful for "sinks", e.g. in constructors

```
struct S {
    T1 t1_; T2 t2_;
    S(T1 t1, T2 t2) : t1_(std::move(t1)), t2_(std::move(t2)) {...}
};

T1 t1; T2 t2;
S s{t1, make_t2()};
S s{make_t1(), t2};
```

Copy operations

```
class Widget {  
    ...  
    Widget(Widget const& other);  
    Widget& operator=(Widget const& other);  
};
```

Copy operations

```
class Widget {  
    ...  
    Widget(Widget const& other);  
    Widget& operator=(Widget const& other);  
};
```

copy constructor Allows the **construction** of an object as a copy of another object

```
Widget w1;  
Widget w2{w1};
```

copy assignment Allows to change the value of an **existing** object as a copy of another object

```
Widget w1, w2;  
w2 = w1;
```

Copy operations

```
class Widget {  
    ...  
    Widget(Widget const& other);  
    Widget& operator=(Widget const& other);  
};
```

copy constructor Allows the **construction** of an object as a copy of another object

```
Widget w1;  
Widget w2{w1};
```

copy assignment Allows to change the value of an **existing** object as a copy of another object

```
Widget w1, w2;  
w2 = w1;
```

- The two objects are/remain distinct
- The copied-from object is not changed
- After the copy the two objects should compare equal

Move operations

```
class Widget {  
    ...  
    Widget(Widget&& other);  
    Widget& operator=(Widget&& other);  
};
```

Move operations

```
class Widget {  
    ...  
    Widget(Widget&& other);  
    Widget& operator=(Widget&& other);  
};
```

move constructor Allows the **construction** of an object stealing the internals of another object

```
Widget w{make_widget()};
```

move assignment Allows to change the value of an **existing** object stealing the internals of another object

```
Widget w;  
w = make_widget();
```

Move operations

```
class Widget {  
    ...  
    Widget(Widget&& other);  
    Widget& operator=(Widget&& other);  
};
```

move constructor Allows the **construction** of an object stealing the internals of another object

```
Widget w{make_widget()};
```

move assignment Allows to change the value of an **existing** object stealing the internals of another object

```
Widget w;  
w = make_widget();
```

- The two objects are/remain distinct
- The moved-from object is usually changed
 - to a *valid but unspecified* state
 - it must be at least destructible and possibly reassignable

- A move is typically cheaper than a copy, but it can be as expensive

On move

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- If the *Return Value Optimization* is not applied, the return value of a function is moved, not copied, into destination

- A move is typically cheaper than a copy, but it can be as expensive
- If the *Return Value Optimization* is not applied, the return value of a function is moved, not copied, into destination
- `operator=(T&&)` can assume that the argument is a temporary, hence different from `this`
 - There is no need to check for self-assignment
 - But be sure that in such event there is no crash
 - Rule of thumb: `std::swap` must work

```
template<typename T>
void swap(T& a, T& b) {
    T t{std::move(a)};
    a = std::move(b);
    b = std::move(t);
}
```

= default

- Explicitly tell the compiler to generate a special member function according to the default implementation

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```
class Widget {  
    int i = 0;  
public:  
    Widget(Widget const&);  
  
};  
  
static_assert(std::is_copy_constructible<Widget>::value);  
static_assert(!std::is_default_constructible<Widget>::value);
```

- Explicitly tell the compiler to generate a special member function according to the default implementation

```
class Widget {
    int i = 0;
public:
    Widget(Widget const&);
    Widget() = default;
};

static_assert(std::is_copy_constructible<Widget>::value);
static_assert(std::is_default_constructible<Widget>::value);
```

= delete

- A function can be declared as *deleted*, marking it with
= delete

```
template<typename P>
class SmartPointer {
    ...
    SmartPointer(SmartPointer const&) = delete;
    SmartPointer& operator=(SmartPointer const&) = delete;
};
```

= delete

- A function can be declared as *deleted*, marking it with **= delete**
- For example, a class can be made **non copyable** deleting its copy operations

```
template<typename P>
class SmartPointer {
    ...
    SmartPointer(SmartPointer const&) = delete;
    SmartPointer& operator=(SmartPointer const&) = delete;
};

using SPI = SmartPointer<int>;

static_assert(!std::is_copy_constructible<SPI>::value);
static_assert(!std::is_copy_assignable<SPI>::value);
```

= delete

- A function can be declared as *deleted*, marking it with **= delete**
- For example, a class can be made **non copyable** deleting its copy operations
- Calling a deleted functions causes a compilation error

```
template<typename P>
class SmartPointer {
    ...
    SmartPointer(SmartPointer const&) = delete;
    SmartPointer& operator=(SmartPointer const&) = delete;
};

using SPI = SmartPointer<int>;

static_assert(!std::is_copy_constructible<SPI>::value);
static_assert(!std::is_copy_assignable<SPI>::value);

SPI sp1, sp2;
SPI sp3{sp1}; // error
```

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- For example, a class can be made **non copyable** deleting its copy operations
- Calling a deleted functions causes a compilation error

```
template<typename P>
class SmartPointer {
    ...
    SmartPointer(SmartPointer const&) = delete;
    SmartPointer& operator=(SmartPointer const&) = delete;
};

using SPI = SmartPointer<int>;

static_assert(!std::is_copy_constructible<SPI>::value);
static_assert(!std::is_copy_assignable<SPI>::value);

SPI sp1, sp2;
SPI sp3{sp1}; // error
sp2 = sp1;    // error
```

= delete

- A function can be declared as *deleted*, marking it with **= delete**
- For example, a class can be made **non copyable** deleting its copy operations
- Calling a deleted functions causes a compilation error
- Any function can be deleted

```
template<typename P>
class SmartPointer {
    ...
    SmartPointer(SmartPointer const&) = delete;
    SmartPointer& operator=(SmartPointer const&) = delete;
};

using SPI = SmartPointer<int>;

static_assert(!std::is_copy_constructible<SPI>::value);
static_assert(!std::is_copy_assignable<SPI>::value);

SPI sp1, sp2;
SPI sp3{sp1}; // error
sp2 = sp1;    // error
```

The sooner the errors are identified, the better

- `static_assert`
 - Logical assertion that must be valid at compile time
- `assert`
 - Logical assertion that must be valid at run time
- Exceptions
 - To express an error condition happening at run time, typically related to a lack of resource
- C-style error codes
 - They can be ignored (but they should not!)
- ...

static_assert

Check that a certain constant boolean expression is satisfied during compilation

- If not, fail compilation with the specified message

static_assert

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- If not, fail compilation with the specified message

```
#include <type_traits>

struct C {
    C(C const&) = default;
    C& operator=(C const&) = delete;
};

static_assert(!std::is_default_constructible<C>::value, "");
static_assert( std::is_copy_constructible_v<C>);
static_assert(!std::is_copy_assignable_v<C>);
static_assert( std::is_move_constructible_v<C>);
static_assert(!std::is_move_assignable_v<C>);
static_assert( std::is_destructible_v<C>);
static_assert(sizeof(C) == 1);
```

static_assert

Check that a certain constant boolean expression is satisfied during compilation

- If not, fail compilation with the specified message

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struct C {
    C(C const&) = default;
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static_assert( std::is_copy_constructible_v<C>);
static_assert(!std::is_copy_assignable_v<C>);
static_assert( std::is_nothrow_move_constructible_v<C>);
static_assert(!std::is_move_assignable_v<C>);
static_assert( std::is_destructible_v<C>);
static_assert(sizeof(C) == 1);
```

static_assert

Check that a certain constant boolean expression is satisfied during compilation

- If not, fail compilation with the specified message

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#include <type_traits>

struct C {
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static_assert(!std::is_move_assignable_v<C>);
static_assert( std::is_destructible_v<C>);
static_assert(sizeof(C) == 1);
```

A static assertion declaration can appear practically anywhere

- There is no effect, hence no overhead, at run time

Check that a certain boolean expression is satisfied at run time

- If not satisfied, it means that the state of the program is corrupted → better to close the program as soon as possible (calling `std::abort`)

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```
template<class T> class Vector {  
    T* p;  
    ...  
    T& operator[](int n) {  
  
        return p[n];  
    }  
};
```

Check that a certain boolean expression is satisfied at run time

- If not satisfied, it means that the state of the program is corrupted → better to close the program as soon as possible (calling `std::abort`)

```
template<class T> class Vector {
    T* p;
    ...
    T& operator[](int n) {
        assert(p != nullptr);           // class invariant (sort of)

        return p[n];
    }
};
```

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template<class T> class Vector {
    T* p;
    ...
    T& operator[](int n) {
        assert(p != nullptr);           // class invariant (sort of)
        assert(n >= 0 && n < size()); // function pre-condition
        return p[n];
    }
};
```

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    ...  
    T& operator[](int n) {  
        assert(p != nullptr);           // class invariant (sort of)  
        assert(n >= 0 && n < size()); // function pre-condition  
        return p[n];  
    }  
};
```

Useful during testing/debugging

- Can be disabled for performance reasons (`-DNDEBUG`)
- Avoid side effects in asserts

Exceptions

- Mechanism to report errors out of a function, stopping its execution
- Useful to express *post-conditions*
- Help separate application logic from error management

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```
class Thing {...};  
  
auto make_thing() {  
  
    return Thing{ };  
}
```

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```
class Thing {...};

auto make_thing() {
    auto res = acquire_resources_to_build_thing();

    return Thing{res};
}
```

Exceptions

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- Useful to express *post-conditions*
- Help separate application logic from error management

```
class Thing {...};

auto make_thing() {
    auto res = acquire_resources_to_build_thing();
    if (!success(res)) {

    }
    return Thing{res};
}
```

Exceptions

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- Useful to express *post-conditions*
- Help separate application logic from error management

```
class Thing {...};
class Exception {...};

auto make_thing() {
    auto res = acquire_resources_to_build_thing();
    if (!success(res)) {
        Exception e{...};
        throw e;
    }
    return Thing{res};
}
```

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- Useful to express *post-conditions*
- Help separate application logic from error management

```
class Thing {...};
class Exception {...};

auto make_thing() {
    auto res = acquire_resources_to_build_thing();
    if (!success(res)) {
        Exception e{...};
        throw e;
    }
    return Thing{res}; // not executed in case of exception
}
```

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    auto res = acquire_resources_to_build_thing();
    if (!success(res)) {

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    }
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```
class Thing {...};
class Exception {...};

auto make_thing() {
    auto res = acquire_resources_to_build_thing();
    if (!success(res)) {

        throw Exception{...};
    }
    return Thing{res}; // not executed in case of exception
}
```

Note that all local variables (e.g. `res`) are properly destroyed when exiting the function, be it via `return` or via `throw`

Exception propagation

```
auto high() {  
  
    mid();  
  
}  
  
auto mid() {  
  
    low();  
  
}  
  
auto low() {  
  
  
}
```

Exception propagation

```
auto high() {  
    // this part is executed  
    mid();  
  
}  
  
auto mid() {  
    low();  
  
}  
  
auto low() {  
  
}
```

Exception propagation

```
auto high() {  
  
    // this part is executed  
    mid();  
  
}  
  
auto mid() {  
    T t; // this part is executed  
    low();  
  
}  
  
auto low() {  
  
}
```

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auto high() {  
  
    // this part is executed  
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auto low() {  
    // this part is executed  
  
}
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auto mid() {  
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    low();  
  
}  
  
auto low() {  
    // this part is executed  
    throw E{};  
  
}
```

Exception propagation

```
auto high() {  
  
    // this part is executed  
    mid();  
  
}  
  
auto mid() {  
    T t; // this part is executed  
    low();  
  
}  
  
auto low() {  
    // this part is executed  
    throw E{};  
    // this part is not executed  
}
```

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    // this part is executed  
    throw E{};  
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    T t; // this part is executed  
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    // this part is not executed  
    // T is properly destroyed  
}  
  
auto low() {  
    // this part is executed  
    throw E{};  
    // this part is not executed  
}
```

Exception propagation

```
auto high() {
    try {
        // this part is executed
        mid();

    } catch (E& e) {

    }
}

auto mid() {
    T t; // this part is executed
    low();
    // this part is not executed
    // T is properly destroyed
}

auto low() {
    // this part is executed
    throw E{};
    // this part is not executed
}
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    } catch (E& e) {

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    T t; // this part is executed
    low();
    // this part is not executed
    // T is properly destroyed
}

auto low() {
    // this part is executed
    throw E{};
    // this part is not executed
}
```

Exception propagation

```
auto high() {  
    try {  
        // this part is executed  
        mid();  
        // this part is not executed  
    } catch (E& e) {  
        // use e  
    }  
}
```

```
auto mid() {  
    T t; // this part is executed  
    low();  
    // this part is not executed  
    // T is properly destroyed  
}
```

```
auto low() {  
    // this part is executed  
    throw E{};  
    // this part is not executed  
}
```

Exception propagation

```
auto high() {
    try {
        // this part is executed
        mid();
        // this part is not executed
    } catch (E& e) { // by reference
        // use e
    }
}

auto mid() {
    T t; // this part is executed
    low();
    // this part is not executed
    // T is properly destroyed
}

auto low() {
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Exception propagation

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    T t; // this part is executed
    low();
    // this part is not executed
    // T is properly destroyed
}

auto low() {
    // this part is executed
    throw E{};
    // this part is not executed
}
```

- An exception is propagated up the stack of function calls until a suitable catch clause is found
- If no suitable catch clause is found the program is terminated
- During stack unwinding all automatic objects are properly destroyed
 - Remember smart pointers!

Different levels of safety guarantees (for member functions):

basic If an exception is thrown, no resource is leaked and the object is left in a *valid but unspecified* state

- the object should be at least safely assignable and destroyable
- every class should provide at least the basic guarantee

strong Transaction semantics: if an exception is thrown, the object's state is as it was before the function was called

no-throw The operation is always successful and no exception leaves the function

- A function can be declared `noexcept`, telling the compiler that the function
 - doesn't throw, or

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```
class Handle {  
    Handle(Handle&& o) noexcept : ... { ... }  
    ...  
};
```

- A function can be declared `noexcept`, telling the compiler that the function
 - doesn't throw, or
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```
class Handle {  
    Handle(Handle&& o) noexcept : ... { ... }  
    ...  
};
```

- Declaring functions (not only member functions) `noexcept` helps the compiler to optimize the code
- If move operations, especially the constructor, are `noexcept` the compiler/library can apply **significant** optimizations
 - E.g. in order to provide the strong guarantee `std::vector::push_back` must copy, not move, objects, if the move can throw

Move and noexcept

- `T& T::operator=(T&& tmp)` is typically easy to make `noexcept`

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- `T::T(T&& tmp)` may be more difficult
 - Start with one object (`tmp`), end up with two (`*this` and `tmp`)

- `T& T::operator=(T&& tmp)` is typically easy to make `noexcept`
 - Rely on the `noexcept`-ness of data members' move-assignments
- `T::T(T&& tmp)` may be more difficult
 - Start with one object (`tmp`), end up with two (`*this` and `tmp`)
 - Can rely on `T::T()` being `noexcept` as well
 - Which is not obvious if a resource has to be acquired

Destructor and noexcept

- The destructor is by default noexcept
 - i.e. releasing a resource should not fail

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- Don't do anything overly complicated in the destructor or swallow all exceptions locally

```
class Thing {
    ~Thing()
    {
        try {
            :
        } catch (...) { // catch all exceptions
            // e.g. log something, provided logging doesn't throw
        }
    }
};
```

Destructor and noexcept

- The destructor is by default noexcept
 - i.e. releasing a resource should not fail
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class Thing {
    ~Thing()
    {
        try {
            :
        } catch (...) { // catch all exceptions
            // e.g. log something, provided logging doesn't throw
        }
    }
};
```

- It's always possible to declare a destructor, like any other function, noexcept(false)