Efficient C++ Programming

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INFN-CNAF

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https://baltig.infn.it/giaco/cpp-esc18

Outline

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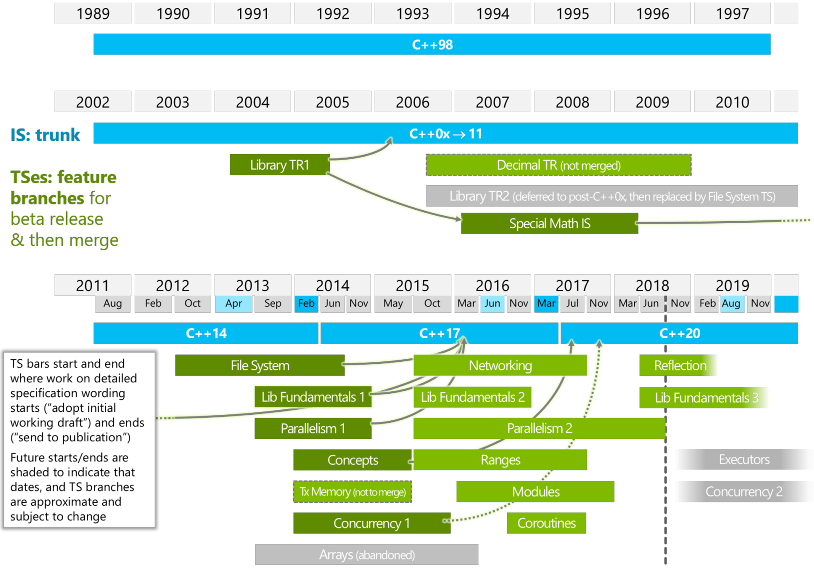
- efficient (*"you don't pay for what you don't use"*)
- standard

Learn more

- Start from
  - `https://isocpp.org/`
  - `https://en.cppreference.com/`
  - `https://github.com/isocpp/CppCoreGuidelines`
- Main C++ conferences
  - `https://github.com/cppcon`, `https://youtube.com/cppcon`
  - `https://github.com/boostcon`, `https://youtube.com/boostcon`
- Standard Committee papers
  - `http://www.open-std.org/jtc1/sc22/wg21/docs/papers/`

C++ timeline



1989
1990
1991
1992
1993
1994
1995
1996
1997
C++98
2002
2003
2004
2005
2006
2007
2008
2009
2010
IS: trunk
C++0x → 11
TSes: feature branches for beta release & then merge
Library TR1
Decimal TR (not merged)
Library TR2 (deferred to post-C++0x, then replaced by File System TS)
Special Math IS
2011
2012
2013
2014
2015
2016
2017
2018
2019
Aug
Feb
Oct
Apr
Sep
Feb
Jun
Nov
May
Oct
Mar
Jun
Nov
Mar
Jul
Nov
Mar
Jun
Nov
Feb
Aug
Nov
C++14
C++17
C++20
File System
Networking
Reflection
Lib Fundamentals 1
Lib Fundamentals 2
Lib Fundamentals 3
Parallelism 1
Parallelism 2
Concepts
Ranges
Executors
Tx Memory (not to merge)
Modules
Concurrency 2
Concurrency 1
Coroutines
Arrays (abandoned)
TS bars start and end where work on detailed specification wording starts ("adopt initial working draft") and ends ("send to publication")
Future starts/ends are shaded to indicate that dates, and TS branches are approximate and subject to change

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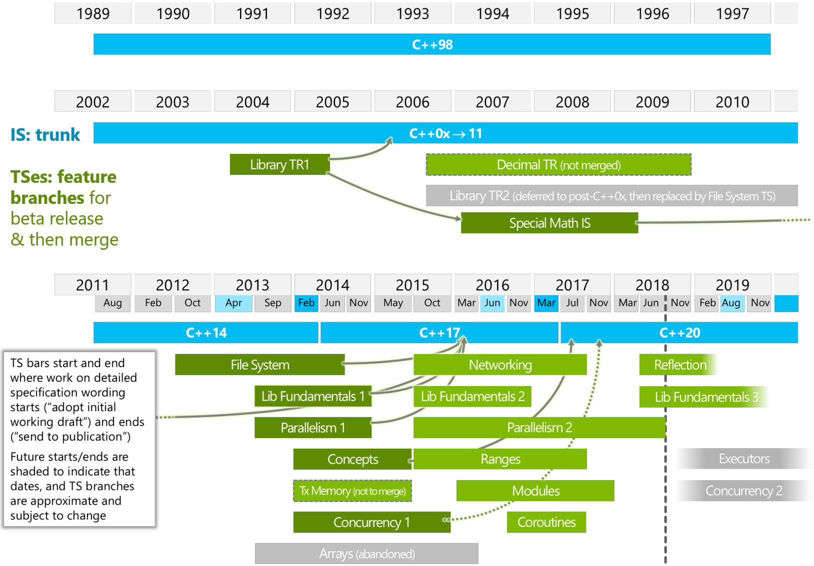

"Modern C++ feels like a new language"

Standards

Working drafts, almost the same as the final published document

- C++03 `https://wg21.link/n1905`
- C++11 `https://wg21.link/n3242`
- C++14 `https://wg21.link/n4296`
- C++17 `https://wg21.link/n4659`

For the LaTeXsources see
`https://github.com/cplusplus/draft`

Compilers

- The ESC machines provide gcc 7.3 and clang 5.0
- You can also edit and try your code online with multiple compilers at
  - `https://godbolt.org/`
  - `https://coliru.stacked-crooked.com/`

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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
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  - ...

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- But templates are everywhere

STL Algorithms

- Generic functions that operate on ranges of objects
- Implemented as function templates

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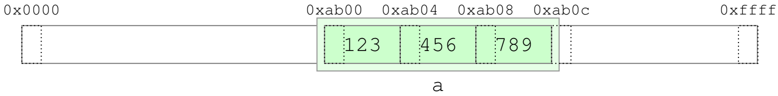
Numeric	`iota accumulate inner_product partial_sum adjacent_difference ...`

Range

- A range is defined by a pair of iterators [*first*, *last*), with *last* referring to one past the last element in the range
  - the range is *half-open*
  - *first* == *last* means the range is empty
  - *last* can be used to return failure
- An iterator allows to go through the elements of the associated range
  - operations to advance, access, compare
  - typically obtained from containers calling specific methods
- An iterator is a generalization of a pointer
  - it supports the same operations, possibly through overloaded operators
  - certainly `*` `++` `->` `==` `!=`, maybe `--` `+` `-` `+=` `-=` `<`

Range (cont.)

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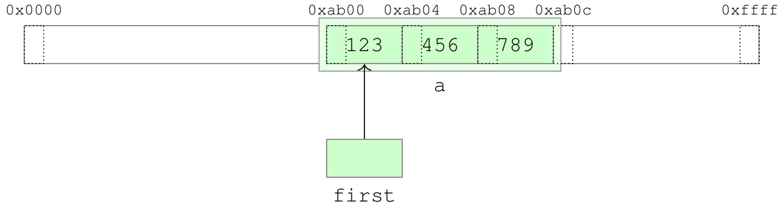


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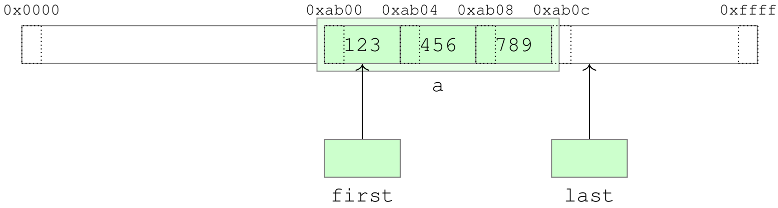


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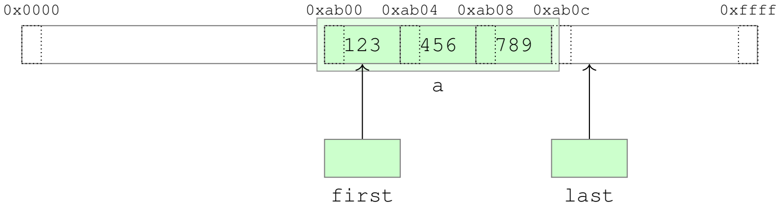


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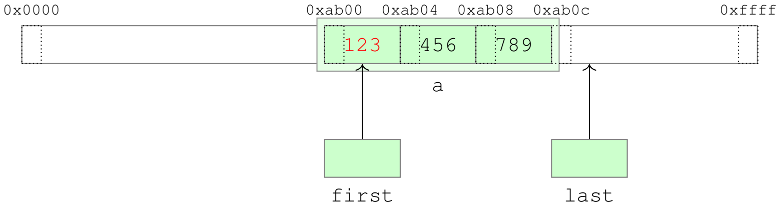


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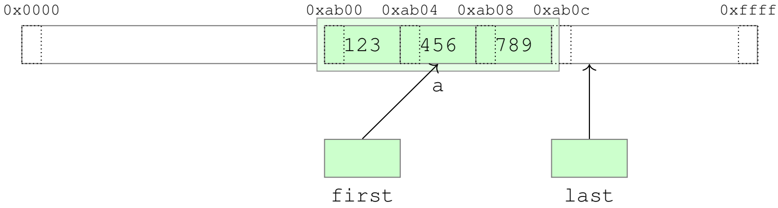


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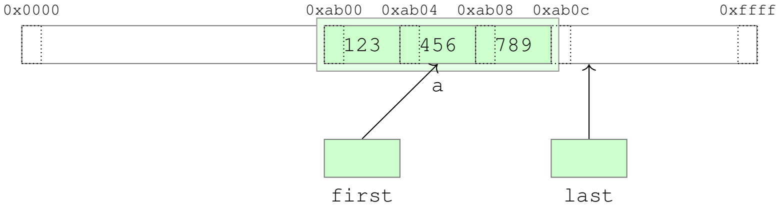


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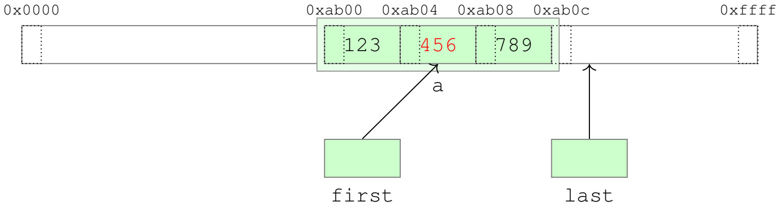


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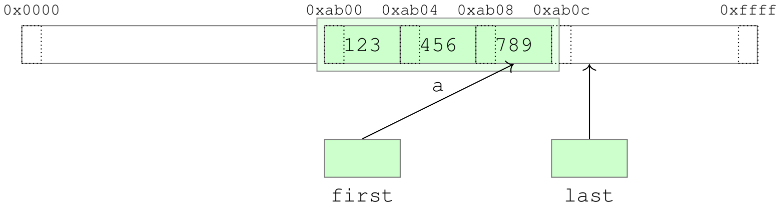


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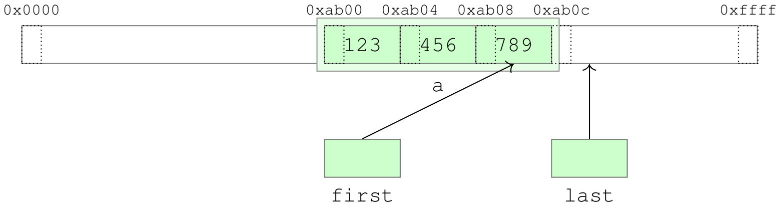


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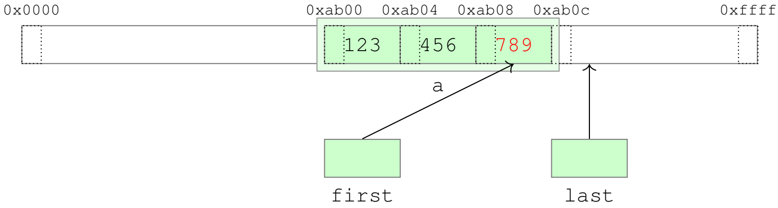


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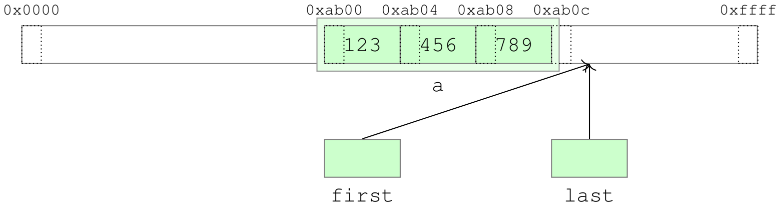


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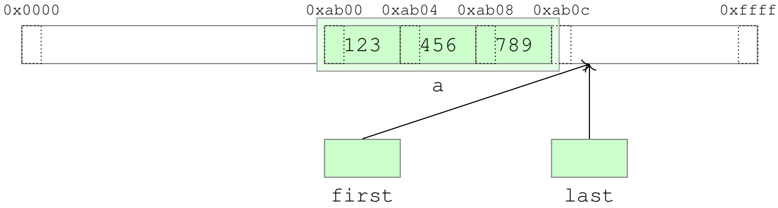


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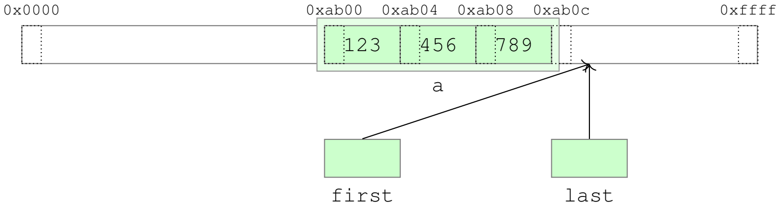


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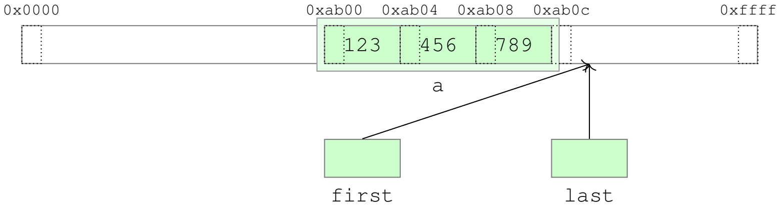


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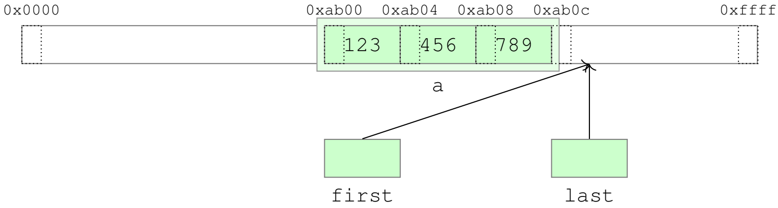


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std::array         a = {123, 456, 789}; // CTAD
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```
template <class Iterator, class T>
Iterator
find(Iterator first, Iterator last, const T& value)
{
  for (; first != last; ++first)
    if (*first == value)
      break;
  return first;
}
```

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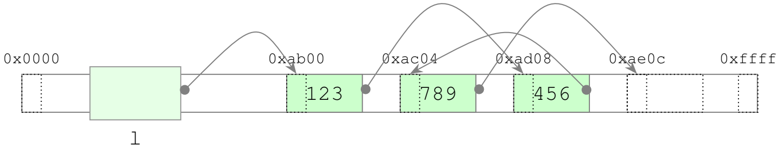


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std::forward_list<int> l = {123, 456, 789};
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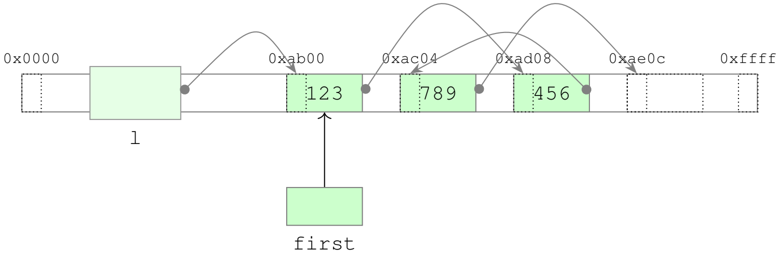


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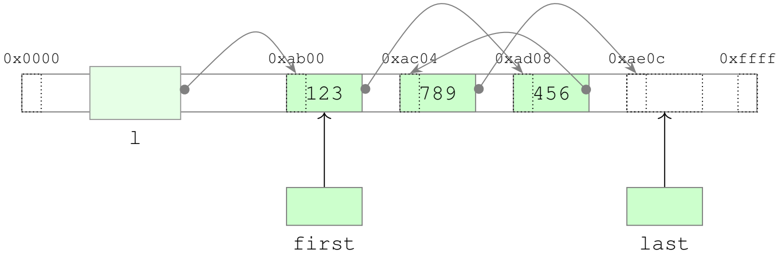


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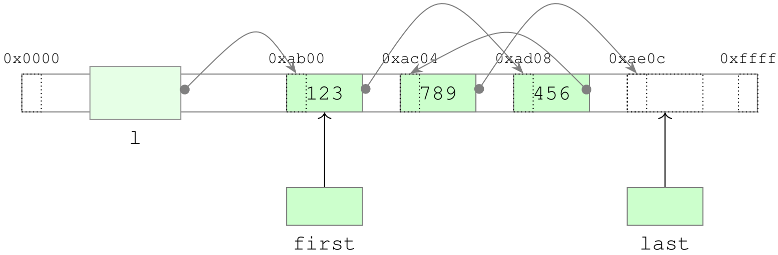


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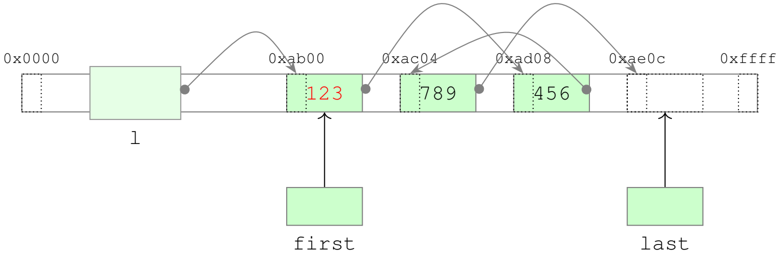


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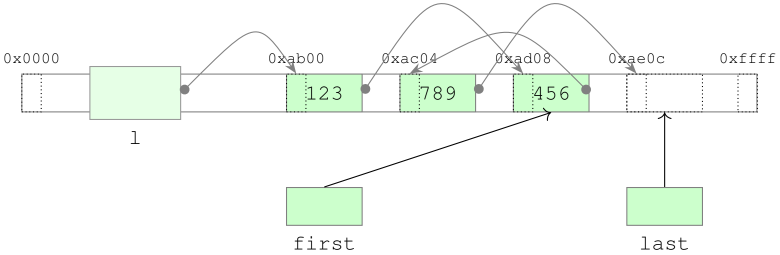


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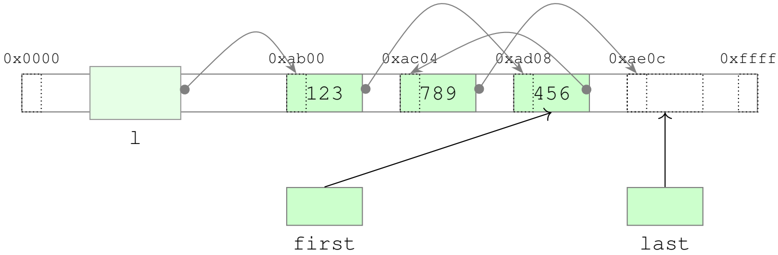


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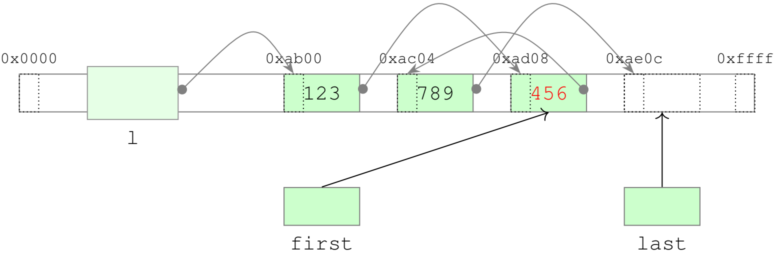


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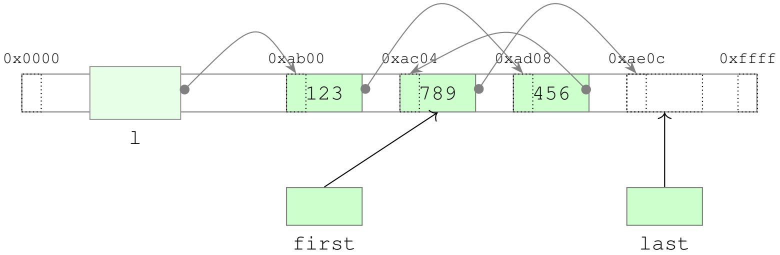


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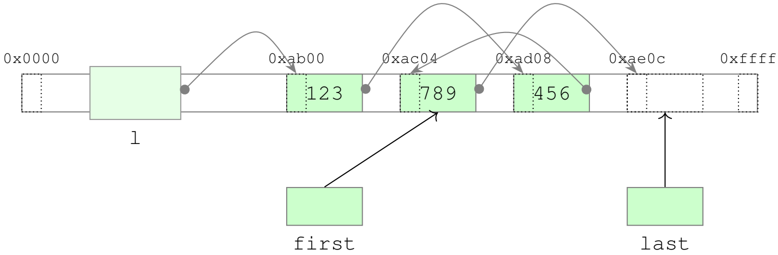


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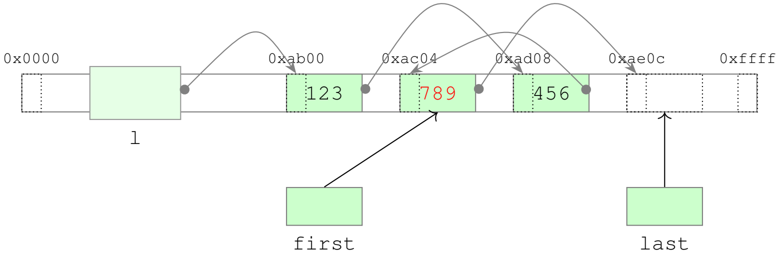


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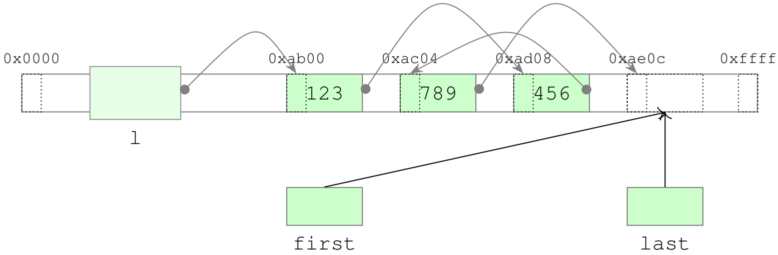


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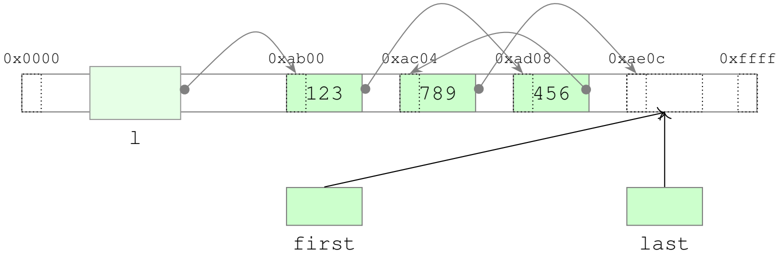


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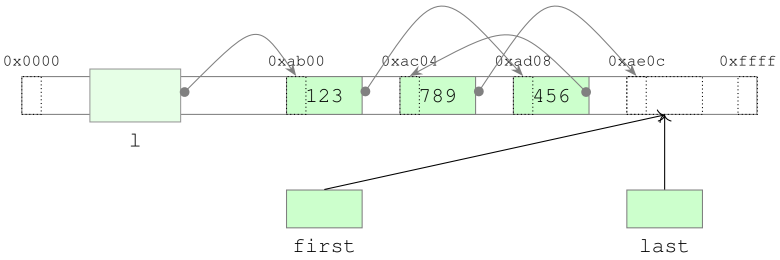
}
```

Range (cont.)




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

- `std::forward_list<T>::iterators` 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> l;
std::partial_sum(std::begin(v), std::end(v), std::back_inserter(l));

// 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(), filter);
```

Hands-on

- C++ $\rightarrow$ 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
  - move the three central numbers to the beginning
  - remove duplicate elements
  - ...

Why using standard algorithms

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- They express intent more clearly than a raw `for` loop
- They enable *parallelism for the masses*
  - parallel algorithms available in C++17, implementations are appearing

```
#include <execution>

std::vector<int> v = ···;
std::sort(std::execution::par, v.begin(), v.end());
auto it = std::find(std::execution::par, v.begin(), v.end(), 42);
```

Functions

- A function associates a sequence of statements (the function *body*) with a name and a list of zero or more parameters

```
std::string join(std::string const& s, int i)
{
  return s + '-' + std::to_string(i);
}

join("XYZ", 5); // std::string{"XYZ-5"}
```

- A function may return a value
- A function returning a `bool` is called a *predicate*

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

- Multiple functions can have the same name → *overloading*
  - different parameter lists

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

```
template <class Iterator, class T>
Iterator find_if(Iterator first, Iterator last, T 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, T 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);
```

Function objects

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

Function objects

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```
auto lt42(int n)
{
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Function objects

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

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

vector v{61,32,51};
auto it = find_if(
    begin(v), end(v),
    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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```
struct LessThan42 {
  auto operator()(int n) const
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};
```

Function objects

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```

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

LessThan42 lt42{};
```

Function objects

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};

auto lt42 = LessThan42{};
```

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struct LessThan42 {
  auto operator()(int n) const
  {
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auto lt42 = LessThan42{};
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Function objects

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    lt42
); // *it == 32
```

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

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

vector v{61,32,51};
auto it = find_if(
    begin(v), end(v),
    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 lt6{6};
auto b1 = lt6(5); // 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 lt6{6};
auto b1 = lt6(5); // true

LessThan lt4{4};
auto b2 = lt4(5); // 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 lt6{6};
auto b1 = lt6(5); // true

LessThan lt4{4};
auto b2 = lt4(5); // false

vector v{8,4,5};
auto i1 = find_if(..., lt6); // *i1 == 4
auto i2 = find_if(..., lt4); // i2 == 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 lt6{6};
auto b1 = LessThan{6}(5); // true

LessThan lt4{4};
auto b2 = LessThan{4}(5); // false

vector v{8,4,5};
auto i1 = find_if(..., LessThan{6}); // *i1 == 4
auto i2 = find_if(..., LessThan{4}); // i2 == end, i.e. not found
```

Function objects (cont.)

An example from the standard library

```
#include <random>

// random bit generator (mersenne twister)
std::mt19937 gen;

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

Lambda expression

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

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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_;
  }
};
```

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

```
find_if(..., LessThan{42});
```

Lambda expression

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

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

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

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

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

find_if(..., LessThan{42});
```

Lambda expression

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

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struct LessThan42 {
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  }
};

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

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

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

find_if(..., LessThan{42});

int m{42};
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_;
  }
};
```

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

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

find_if(..., LessThan{42});


find_if(..., [m = 42](int n) {
                return n < m;
               }
);
```

Lambda expression (cont.)

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
    - `[]` 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
- Global variables are available without being captured

Hands-on

- C++ → Algorithms
- Starting from `algo_functions.cpp` and following the hints, write code to
    - multiply all the elements of the vector
    - 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
- Some space and time overhead, so use only if a template parameter is not satisfactory

std::function

- Type-erased wrapper that can store and invoke any callable entity with a certain signature
  - function, function object, lambda, member function
- Some space and time overhead, so use only if a template parameter is not satisfactory

```
#include <functional>

int sum_squares(int x, int y) { return x * x + y * y; }

int main() {
  std::vector<std::function<int(int, int)>> v {
    std::plus<>{},        // has a compatible operator()
    std::multiplies<>{}, // idem
    &sum_squares)
  };
  for (int k = 10; k <= 1000; k *= 10) {
    v.push_back([k](int x, int y) -> int { return k * x + y; });
  }

  for (auto const& f : v) { std::cout << f(4, 5) << '\n'; }
}
```

Outline

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
- Owning 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
- Owning pointers are prone to leaks and double deletes
- Owning 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
- Owning pointers are prone to leaks and double deletes
- Owning 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
  - bad frees
- It's precise, but slow

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

```
$ g++ -fsanitize=address leak.cpp
$ ./a.out

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

Hands-on

- C++ $\rightarrow$ Memory issues
- Get familiar with Valgrind and memory sanitizers
- Compile, run directly and run through valgrind and/or memory sanitizers
  - `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 <u>not</u> 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*, ...

Resource management

- 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"*

Smart pointers

- Objects that behave like pointers, but also manage the lifetime of the pointee
- Leverage the RAII idiom
  - Resource Acquisition Is Initialization
  - Resource (e.g. memory) is acquired in the constructor
  - Resource (e.g. memory) is released in the destructor
- 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 `delete`s the pointee

Smart pointers (cont.)

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class Histo { ··· };

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  SmartPointer<Histo> sp{new Histo{}};
  sp->fill();
  (*sp).fill();
}
```

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

Smart pointers (cont.)

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class SmartPointer {
  Pointee* m_p;
 public:
  explicit SmartPointer(Pointee* p): m_p{p} {}
  ~SmartPointer() { delete m_p; }
  Pointee* operator->() { return m_p; }
  Pointee& operator*() { return *m_p; }

};

class Histo { ··· };

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  Pointee* operator->() { return m_p; }
  Pointee& operator*() { return *m_p; }
  ...
};

class Histo { ··· };

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`std::unique_ptr<T>`

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
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```
class Histo { ··· };

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

std::unique_ptr<Histo> ph{new Histo{}}; // explicit new
```

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
```

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);
```

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));
```

std::unique_ptr<T>

Standard smart pointer

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

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take(std::move(ph));                      // ok, movable
```

`std::shared_ptr<T>`

Standard smart pointer

- Shared ownership (reference counted)
- Some space and time overhead
  - for the management, not for access
- Copyable and movable

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void take(std::shared_ptr<Histo> px);
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take(px);
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take(px);                                       // ok, copyable
take(std::move(px));                            // ok, movable
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On *smart_ptr<T>*

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```
std::unique_ptr<int[]> p{new int[n]};
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```
std::unique_ptr<int[]> p{new int[n]};
auto p = std::make_unique<int[]>(n);
```

- Access to the raw pointer is available
  - e.g. to pass to legacy APIs
  - *smart_ptr<T>*`::get()`
    - returns a **non-owning** `T*`
  - `unique_ptr<T>::release()`
    - returns an **owning** `T*`
    - must be explicitly managed

`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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take(u);              // error
take(std::move(u)); // ok
```

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

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```
void take(std::unique_ptr<Histo> u);
auto u = std::make_unique<Histo>();
take(u);             // error
take(std::move(u)); // ok
```

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

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

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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

```
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.)

- Otherwise pass the pointee by (const) reference/pointer

`smart_ptr` and functions (cont.)

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

smart_ptr and functions (cont.)

- Otherwise pass the pointee by (const) reference/pointer

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



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

`smart_ptr` and functions (cont.)

- Otherwise pass the pointee by (const) reference/pointer

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


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

`smart_ptr` and functions (cont.)

- Otherwise pass the pointee by (const) reference/pointer

```
void fill(std::shared_ptr<Histo> s) { if (s) s->fill(); }
void fill(Histo* t)                 { if (t) t->fill(); } // better
void fill(Histo& t)                 { t.fill(); }         // better

auto s = make_shared<Histo>();
fill(s);
fill(s->get());
if (s) fill(*s);
```

smart_ptr and functions (cont.)

- Otherwise pass the pointee by (const) reference/pointer

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

- Otherwise pass the pointee by (const) reference/pointer

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

- 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>(); }

auto u = factory();      // std::unique_ptr<Histo>
std::shared_ptr<Histo> s = std::move(u);
```

smart_ptr and functions (cont.)

- Otherwise pass the pointee by (const) reference/pointer

```
void fill(std::shared_ptr<Histo> s) { if (s) s->fill(); }
void fill(Histo* t)                 { if (t) t->fill(); } // better
void fill(Histo& t)                 { t.fill(); }         // better

auto s = make_shared<Histo>();
fill(s);
fill(s->get());
if (s) fill(*s);
```

- 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>(); }

auto u = factory();      // std::unique_ptr<Histo>
std::shared_ptr<Histo> s = std::move(u);

std::shared_ptr<Histo> s = factory();
```

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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```
FILE* f = std::fopen(···);
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std::fclose(f);
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Usual problems:

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

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```
auto s = std::shared_ptr<FILE>{
  std::fopen(···),
  std::fclose
};
```

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FILE* f = std::fopen(...);
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```

Usual problems:

- Who owns the resource?
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```
auto s = std::shared_ptr<FILE>{
  std::fopen(...),
  std::fclose
};

auto u = std::unique_ptr<
    FILE,
    int(*)(FILE*)
  >{
  std::fopen(...),
  &std::fclose
};
```

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```
auto s = std::shared_ptr<FILE>{
  std::fopen(···),
  std::fclose
};

auto u = std::unique_ptr<
    FILE,
    decltype(&std::fclose)
  >{
  std::fopen(···),
  &std::fclose
};
```

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```
auto s = std::shared_ptr<FILE>{
  std::fopen(···),
  std::fclose
};

auto u = std::unique_ptr<
    FILE,
    std::function<int(FILE*)>
  >{
  std::fopen(···),
  std::fclose
};
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auto s = std::shared_ptr<FILE>{
  std::fopen(...),
  std::fclose
};

auto u = std::unique_ptr<
    FILE,
    std::function<void(FILE*)>
  >{
  std::fopen(...),
  std::fclose
};
```

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  std::fclose
};

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    FILE,
    std::function<void(FILE*)>
  >{
  std::fopen(···),
  [](FILE* f){ std::fclose(f); }
};
```

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std::fclose(f);
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auto s = std::shared_ptr<FILE>{
  std::fopen(···),
  std::fclose
};

auto u = std::unique_ptr<
    FILE,
    std::function<void(FILE*)>
  >{
  std::fopen(···),
  [](auto f){ std::fclose(f); }
};
```

Hands-on

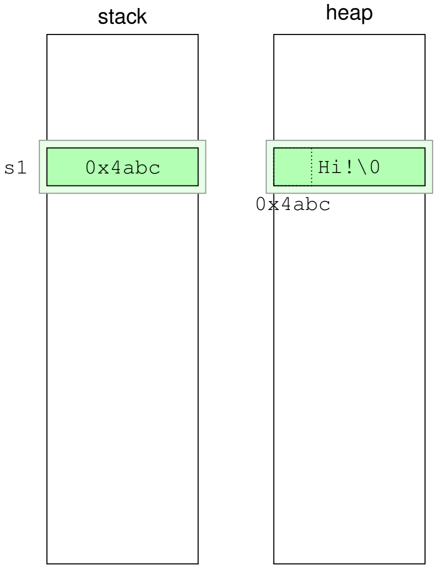
- C++ → Memory issues
  - Adapt the exercises to use smart pointers, when applicable
- C++ → Managing resources
- Starting from `dir.cpp` and following the hints in the file, write code to:
  - create a smart pointer managing a `DIR` resource obtained with the `opendir` function call
  - associate a 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
  - ...

Outline

We can do better than copying

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

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



We can do better than copying

```
class String {
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};
```

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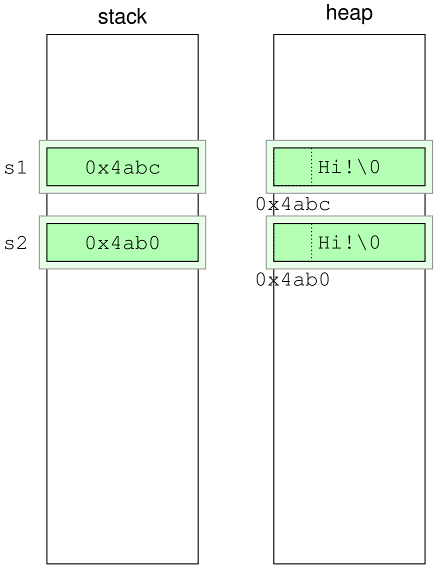

We can do better than copying

```
class String {
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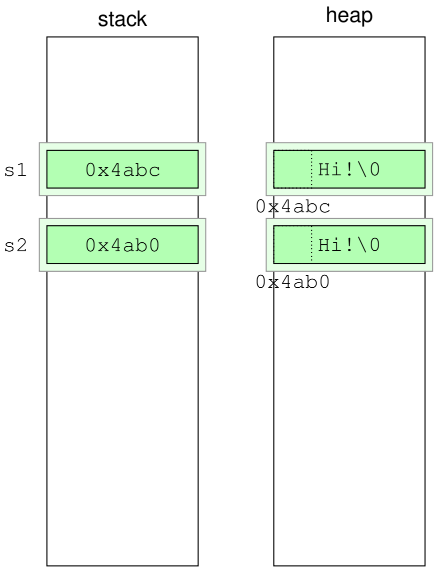
```

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

- Both `s1` and `s2` exist at the end
- The “deep” copy is needed



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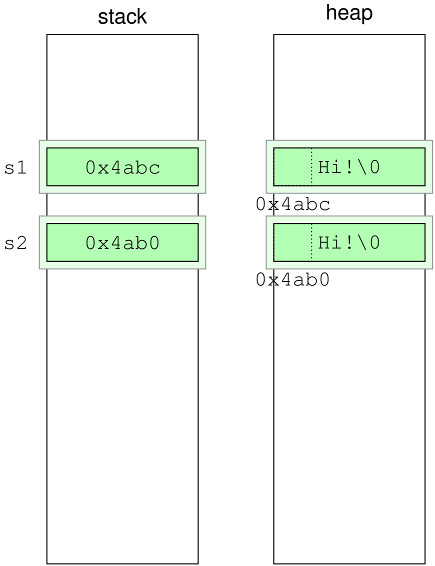
```
String get_string() { return "Hi!"; }
String s3{get_string()};
```



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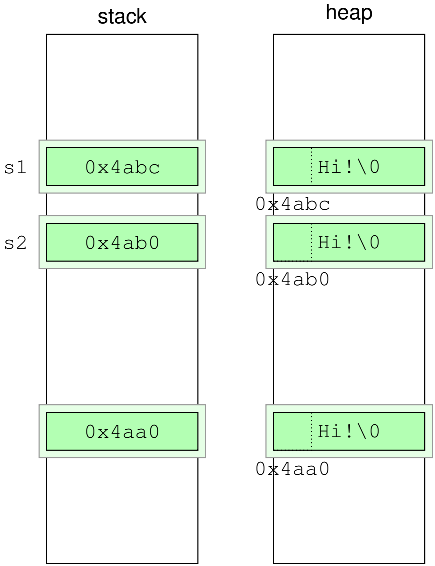

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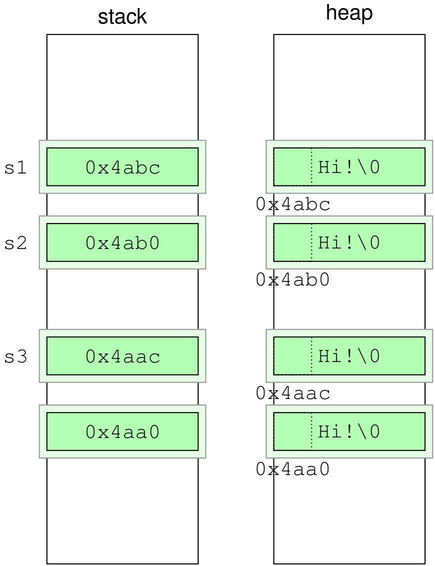

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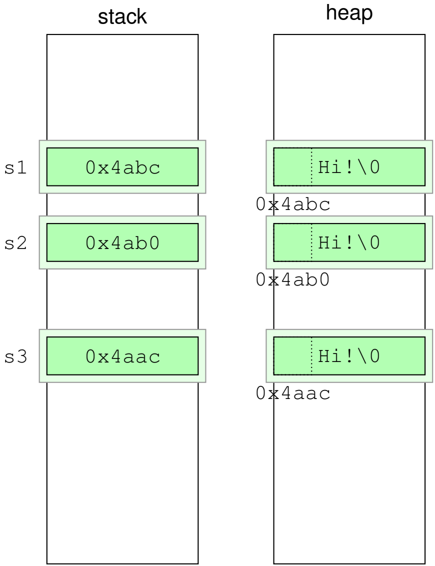

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class String {
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};
```
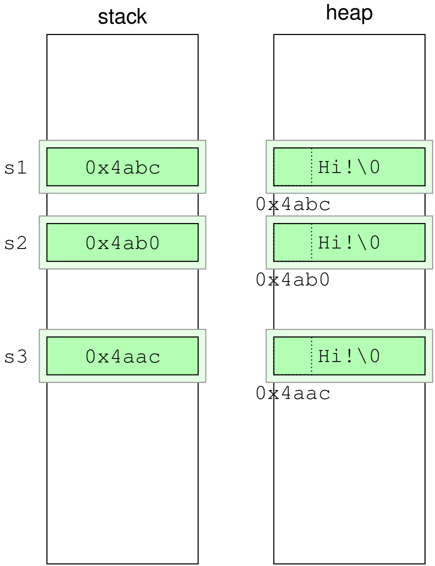

```
String s1{"Hi!"};
String s2{s1};
```

- Both `s1` and `s2` exist at the end
- The “deep” copy is needed

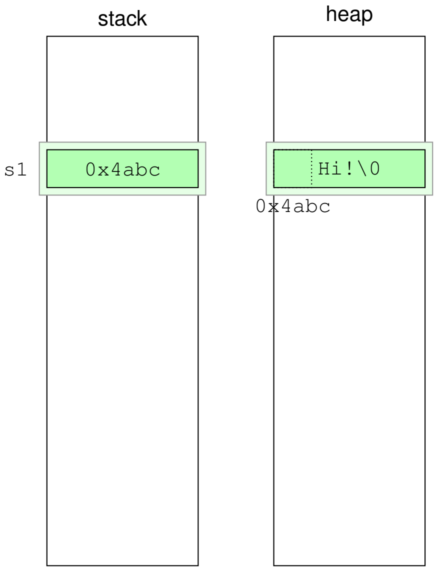
```
String get_string() { return "Hi!"; }
String s3{get_string()};
```

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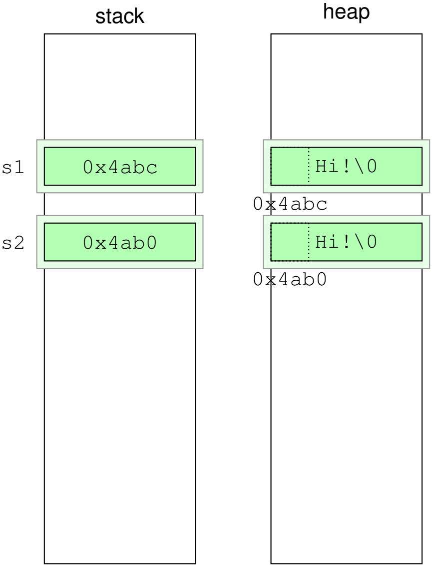
    size_t size = strlen(s) + 1;
    s_ = new char[size];
    memcpy(s_, s, size);
  }
  ~String() { delete [] s_; }
  // copy
  String(String const& other) {
    size_t size = strlen(other.s_) + 1;
    s_ = new char[size];
    memcpy(s_, other.s_, size);
  }




  ...
};

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



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  ~String() { delete [] s_; }
  // copy
  String(String const& other) {
    size_t size = strlen(other.s_) + 1;
    s_ = new char[size];
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  ...
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String s1{"Hi!"};
String s2{s1};
String s3{get_string()};
```

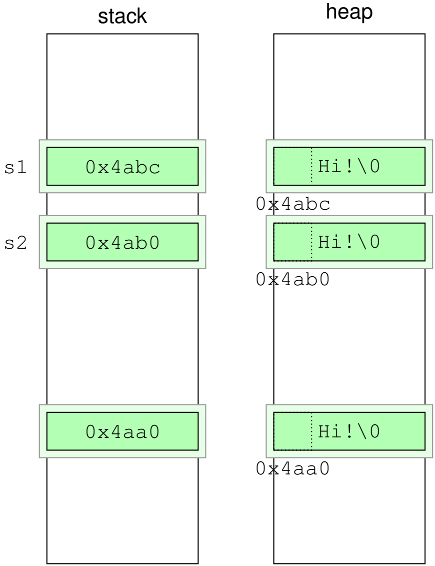

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  }
  // move
  String(??? tmp): s_(tmp.s_) {

  }
  ...
};

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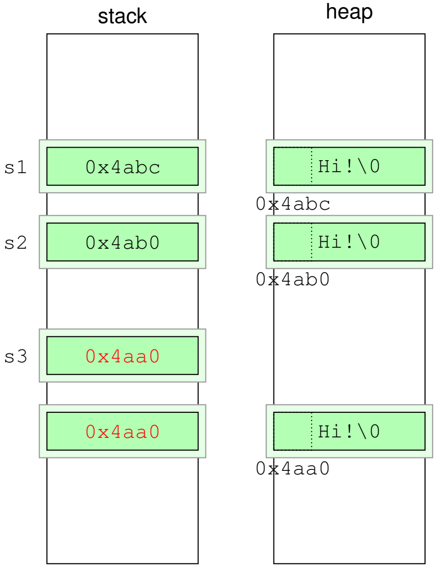

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    s_ = new char[size];
    memcpy(s_, s, size);
  }
  ~String() { delete [] s_; }
  // copy
  String(String const& other) {
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    s_ = new char[size];
    memcpy(s_, other.s_, size);
  }
  // move
  String(??? tmp): s_(tmp.s_) {
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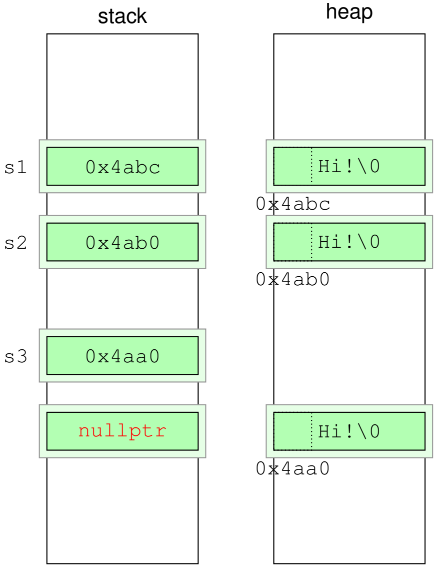

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 public:
  String(char const* s) {
    size_t size = strlen(s) + 1;
    s_ = new char[size];
    memcpy(s_, s, size);
  }
  ~String() { delete [] s_; }
  // copy
  String(String const& other) {
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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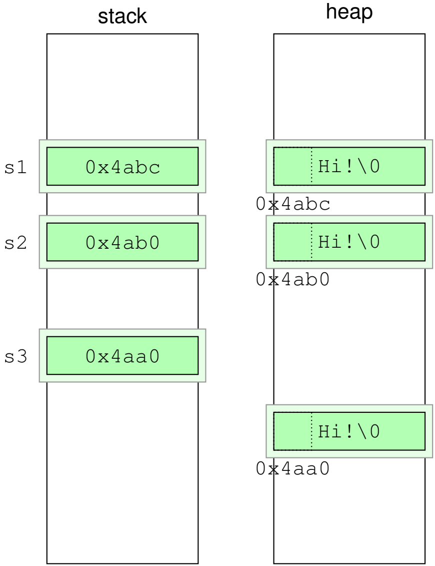
};

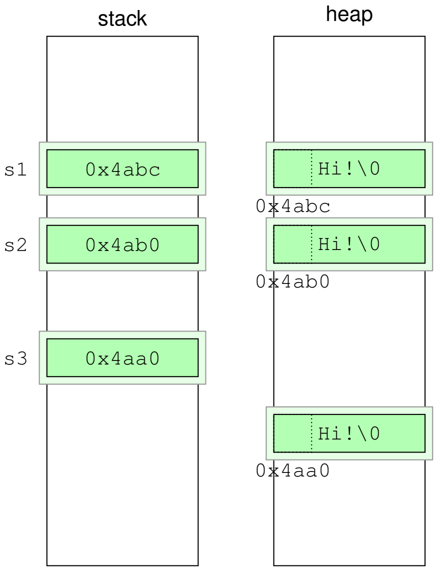
String s1{"Hi!"};
String s2{s1};
String s3{get_string()};
```



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_; }
  // copy
  String(String const& other) {
    size_t size = strlen(other.s_) + 1;
    s_ = new char[size];
    memcpy(s_, other.s_, size);
  }
  // move
  String(??? tmp): s_(tmp.s_) {
    tmp.s_ = nullptr;
  }
  ...
};

String s1{"Hi!"};
String s2{s1};
String s3{get_string()};
```



lvalues vs rvalues

- 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 left-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 right-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

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) { ··· }
};
```

Rvalue reference

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  - 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

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class Widget {
  Widget(Widget const&);              // copy constructor
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```

- 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

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class Widget {
  Widget(Widget const&);              // copy constructor
  Widget& operator=(Widget const&);   // copy assignment
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  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`

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 unamed `return`s in the same function
- Avoid `return std::move(result)`, unless necessary

Hands-on

- C++ → Move
- Open the program `move.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)
    - the result is returned from the function, but the Return Value Optimization is disabled (how?)
- Measure the time it takes to execute them. Discuss the results.

Outline

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 { ··· };

std::unique_ptr<Shape> s;
char c; std::cin >> c;
switch (c) {
 case 'r': s = std::make_unique<Rectangle>(); break;
 case 'c': s = std::make_unique<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 { ··· };
struct Rectangle : Shape { ··· };
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std::unique_ptr<Shape> s;
char c; std::cin >> c;
switch (c) {
 case 'r': s = std::make_unique<Rectangle>(); break;
 case 'c': s = std::make_unique<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(···);
}
```

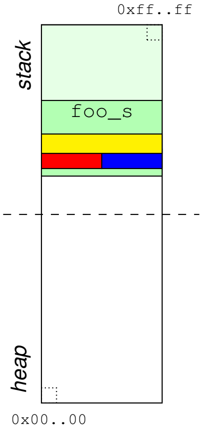
Stack vs Heap: space

```
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

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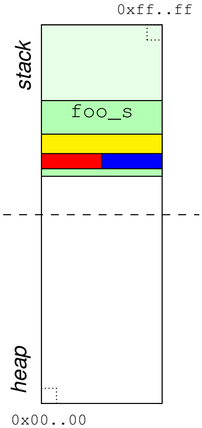


Occupancy:

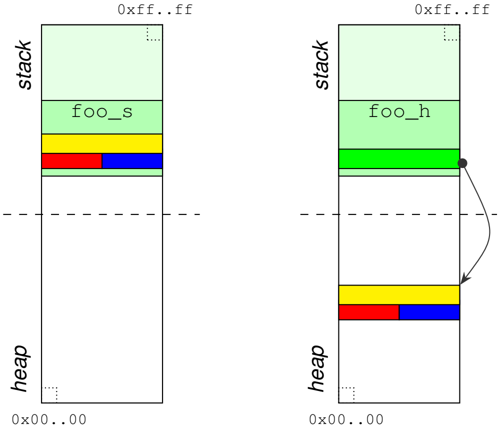
- `sizeof(S)`

Stack vs Heap: space

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

auto foo_s() {
  S s;
  ...
}

auto foo_h() {
  S* s = new S;
  ...
}
```



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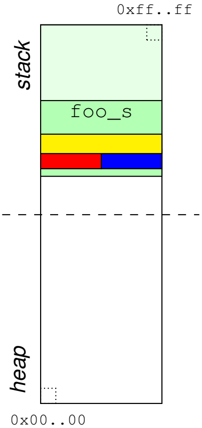
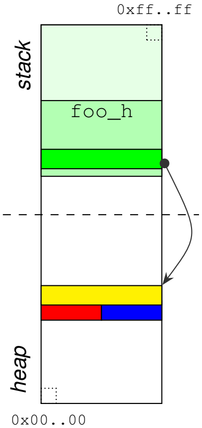


Occupancy:

- `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
1000000 iterations: 0.0494411 s
```

i.e. ~50 ns for each `new`/`delete`

STL Containers

- 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

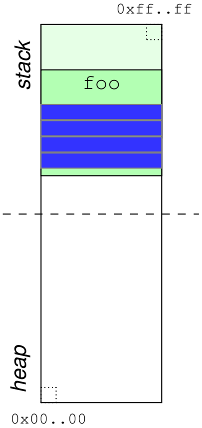
- `map`, `multimap`, `set`, `multiset`

Unordered The elements are hashed

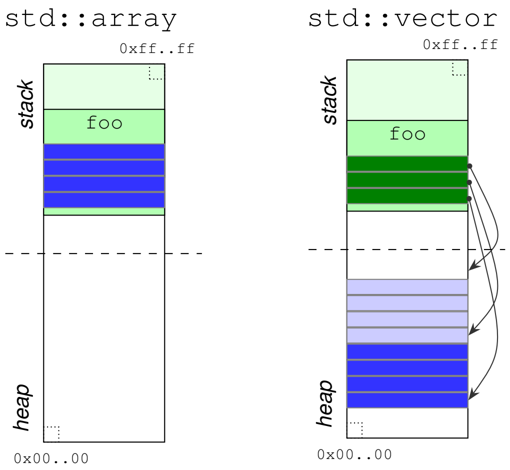
- `unordered_*`

Sequence containers

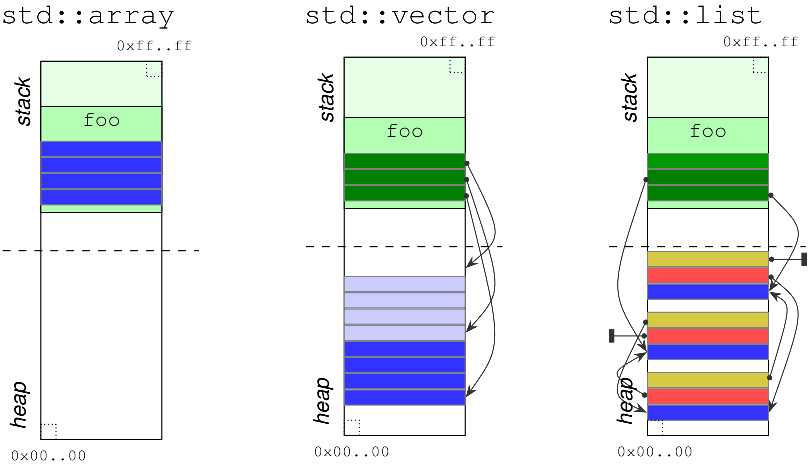
std::array



Sequence containers



Sequence containers



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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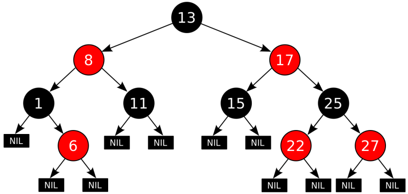

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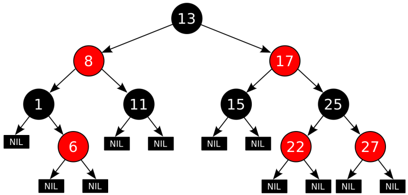

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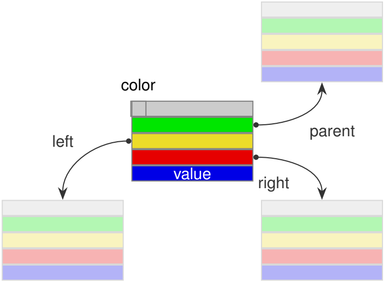


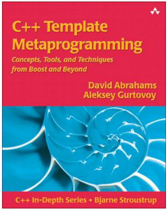
Hands-on

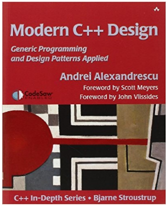
- C++ $\rightarrow$ Containers
- Inspect, build and run `containers.cpp`, also using `perf`
- Extend it to manage an `std::list`
- Compare the performance obtained with the two containers

Outline

Doing things at compile-time

- C++ has always been very strong in compile-time manipulation of program entities
- Thanks mainly to its support for templates





- Let's see two use cases
  - Type introspection
  - Computation

Type introspection

Query the type system to get information about types:

- how big is this type? `sizeof(T)`
- is this type default constructible? `is_default_constructible_v<T>`
- is this type move-assignable? `is_move_assignable_v<T>`
- can the move assignment throw? `is_nothrow_move_assignable_v<T>`
- are these two types the same? `is_same_v<T1, T2>`
- what's the common type for these types? `common_type_t<int, unsigned, float>`

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- are these two types the same? `is_same_v<T1, T2>`
- what's the common type for these types? `common_type_t<int, unsigned, float>`

```
template<typename T>
class uniform_real_distribution {
  static_assert(std::is_floating_point_v<T>);
  ...
};
```

Iterator traits

`std::iterator_traits` is a class template that provides properties about an iterator in terms of member types

- `difference_type` is a signed integer to identify the distance between iterators
- `value_type` is the type obtained dereferencing an iterator
- `pointer` is the type of pointer to `value_type`
- `reference` is the type of reference to `value_type`
- `iterator_category` is one of input, output, forward, bidirectional, random-access

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- `iterator_category` is one of input, output, forward, bidirectional, random-access

```
template<typename T>
struct iterator_traits<T*> // specialization for a pointer
{
  typedef random_access_iterator_tag iterator_category;
  typedef T                          value_type;
  typedef ptrdiff_t                  difference_type;
  typedef T*                         pointer;
  typedef T&                         reference;
};
```

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Tag dispatching

```
template<class It>
typename iterator_traits<It>::difference_type
distance(It first, It last) {

}
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}
```

Tag dispatching

```
template<class It>
typename iterator_traits<It>::difference_type
__distance(It first, It last) { // for random-access iterators
  return last - first;
}









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Tag dispatching

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typename iterator_traits<It>::difference_type
__distance(It first, It last) { // for random-access iterators
  return last - first;
}

template<class It>
typename iterator_traits<It>::difference_type
__distance(It first, It last) { // for input iterators
  typename iterator_traits<It>::difference_type n = 0;
  while (first != last) { ++first; ++n; }
  return n;
}

template<class It>
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}
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Tag dispatching

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  return n;
}

template<class It>
typename iterator_traits<It>::difference_type
distance(It first, It last) {
  return __distance(first, last); // which one?
}
```

Tag dispatching

```
template<class It>
typename iterator_traits<It>::difference_type
__distance(It first, It last, random_access_iterator_tag tag) {
  return last - first;
}

template<class It>
typename iterator_traits<It>::difference_type
__distance(It first, It last, input_iterator_tag tag) {
  typename iterator_traits<It>::difference_type n = 0;
  while (first != last) { ++first; ++n; }
  return n;
}

template<class It>
typename iterator_traits<It>::difference_type
distance(It first, It last) {
  return __distance(first, last, iterator_traits<It>::category{});
}
```

Tag dispatching

```
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typename iterator_traits<It>::difference_type
__distance(It first, It last, random_access_iterator_tag tag) {
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Tag dispatching

```
template<class It>
auto
__distance(It first, It last, random_access_iterator_tag tag) {
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```

Compile-time computation

- Compute values to be used in contexts where a constant expression is required:
  - boolean condition in a `static_assert`
  - size of an `std::array`
  - ...
- Statically initialize constant objects
- Reduce as much as possible the computation needed at runtime
- ...

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- Statically initialize constant objects
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- ...

Let's compute the factorial of a number at compile time

Factorial with templates

Using a class template and non-type template parameters

```
template<int N>
struct F
{
  static const int value =                  ;
};




static_assert(F<5>::value == 120);
```

Factorial with templates

Using a class template and non-type template parameters

```
template<int N>
struct F
{
  static const int value = N * F<N-1>::value;
};




static_assert(F<5>::value == 120);
```

Factorial with templates

Using a class template and non-type template parameters

```
template<int N>
struct F         // general (recursive) case
{
  static const int value = N * F<N-1>::value;
};

template<>
struct F<0>      // base case
{
  static const int value = 1;
};

static_assert(F<5>::value == 120);
```

Factorial with templates

Using a class template and non-type template parameters

```
template<int N>
struct F        // general (recursive) case
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  static const int value = 1;
};

static_assert(F<5>::value == 120);
std::array<char, F<5>::value> buffer;
```

Factorial with a function

Iterative function

```
int factorial(int N) {
  int r = 1;
  while (N > 0) { r *= N--; }
  return r;
}
```

Recursive function

```
int factorial(int N) {
  return N == 0 ? 1 : N * factorial(N-1);
}
```

Iterative function

```
int factorial(int N) {
  int r = 1;
  while (N > 0) { r *= N-; }
  return r;
}
```

Recursive function

```
int factorial(int N) {
  return N == 0 ? 1 : N * factorial(N-1);
}
```

```
static_assert(factorial(5) == 120);     // error
std::array<char, factorial(5)> buffer; // error
```

`constexpr`

- The `constexpr` specifier specifies that the value of a variable or function can appear in a constant expression
- The variable or the function can be evaluated at compile-time
- A function can be evaluated at compile-time only if the arguments are known at compile-time

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  return r;
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}

static_assert(factorial(5) == 120);
constexpr auto f5 = factorial(5);
std::array<char, f5> buffer;
```

`if constexpr`

Factorial using a function template with a *constexpr if*

if constexpr

Factorial using a function template with a *constexpr if*

```
template<int N>
constexpr auto Factorial()
{
  if constexpr(N > 0) {
    return N * Factorial<N-1>();
  } else {
    return 1;
  }
}
```

Factorial using a function template with a *constexpr if*

```
template<int N>
constexpr auto Factorial()
{
  if constexpr(N > 0) {
    return N * Factorial<N-1>();
  } else {
    return 1;
  }
}

static_assert(Factorial<5>() == 120);
constexpr auto f5 = Factorial<5>();
std::array<char, f5> buffer;
```

Hands-on

- What happens when `N < 0` both in the solution based on a class template and in the solution based on functions? Fix the code if it doesn't work properly
- Take the `pi` function in `pi_time.cpp` and make it `constexpr`
- Implement a `constexpr` function that checks if a number is prime

Outline

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
```

auto

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 std::literals::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 std::literals::chrono_literals;
auto u = 1234us;              // std::chrono::microseconds
auto e;                       // error
```

`auto` and references

- `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

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```
auto l = []
```

```
class SomeUniqueName {

 public:



  auto operator()

};


auto l = SomeUniqueName{ };
```

Lambda: closure

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- 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
```

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class SomeUniqueName {
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 public:
  explicit SomeUniqueName(int v)
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  auto operator()(int i)
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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

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  - `[&, 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};
```

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  - `[]` capture nothing
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  - `[=, &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};
```

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- 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

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```
class Thing;
Thing make_thing();

Thing t;
```

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class Thing;
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Thing t;

Thing      &   r = t;
```

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```
class Thing;
Thing make_thing();

Thing t;

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

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```
class Thing;
Thing make_thing();

Thing t;

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

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Thing t;

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

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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 (!)
```

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class Thing;
Thing make_thing();

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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

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class Widget {
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```

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

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class Widget {
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Widget w1;
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```

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

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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

On move

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

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

On move

- 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);
```

= default

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```
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

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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

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class SmartPointer {
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};

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

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class SmartPointer {
  ...
  SmartPointer(SmartPointer const&) = delete;
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};

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

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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
```

Mechanisms for error management

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

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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

```
#include <type_traits>

struct C {
  C(C const&) = default;
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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 {
  C(C const&) = default;
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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 $\rightarrow$ better to `terminate` as soon as possible

assert

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


    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)

    return p[n];
  }
};
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    assert(n >= 0 && n < size()); // function pre-condition
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    return p[n];
  }
};
```

Useful during testing/debugging

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

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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```
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  return Thing{res};
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class Thing {...};


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  if (!success(res)) {


  }
  return Thing{res};
}
```

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- Useful to express *post-conditions*
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```
class Thing {...};
class Exception {...};

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

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class Thing {...};
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  if (!success(res)) {
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  }
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  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
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auto low() {



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  // this part is executed
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Exception propagation

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auto high() {
  try {
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  } catch (E& e) {

  }
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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
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}

auto low() {
  // this part is executed
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Exception propagation

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

auto mid() {
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  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 `terminate`d
- During stack unwinding all automatic objects are properly destroyed
  - Remember smart pointers!

Exception safety

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

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    - Start with one object (`tmp`), end up with two (`*this` and `tmp`)

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  - 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

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

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  {
    try {
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    } 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)`