Department I - C Plus Plus

Modern and Lucid C++ Advanced for Professional Programmers

Week 4 – Heap Memory Management

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OST
Ostschweizer Fachhochschule

- **Topics:**
  - Recap Week 3
  - Pointers
  - Reading Declarations Correctly
  - Heap Memory (De)Allocation

Goals

- **You understand how raw pointers work in C++**
- **You can read declarations correctly**
- **You can use basic heap memory management when necessary**

Recap Week 3

Summary: Type Deduction

```
template <typename T>
auto f(ParamType param) -> void;
```

- **ParamType is a value/pointer type**
  - `<expr>` is a reference type: ignore the reference
  - Ignore `const` of `<expr>` type (outermost)
  - Pattern match `<expr>`'s type against ParamType to figure out T
- **ParamType is a reference**
  - `<expr>` is a reference type: ignore the reference
  - Pattern match `<expr>`'s type against ParamType to figure out T
- **ParamType is a forwarding reference (T&& / auto&&)**
  - `<expr>` is an lvalue: T and ParamType become lvalue references!
  - Otherwise (if `<expr>` is an rvalue): Rules for pointer/references apply

- **We need something that is aware of the actual template parameter type**
- **Recap from Forwarding References: We know whether param was an lvalue or an rvalue**

```
int          x   = 23;
int const    cx  = x;
int const&   crx = x;
```

```
log_and_do(x)                   -> T = int&
log_and_do(cx)                  -> T = int const&
log_and_do(crx)                 -> T = int const&
log_and_do(27)                  -> T = int
log_and_do(std::move(x))        -> T = int
```

lvalues

rvalues

- **If T is of reference type we need to pass an lvalue otherwise we need to pass an rvalue**
- **How can we do it?**
  - std::forward

```
template <typename T>
auto log_and_do(T&& param) -> void {
  //log
  do_something(std::forward<T>(param));
}
```

- **What does `std::forward` do?**
  - It’s a "conditional" cast to an rvalue reference...
  - This allows arguments to be treated as what they originally were (lvalue or rvalue references)
- **Implementation is similar to the following (there is also an overload for rvalue references):**

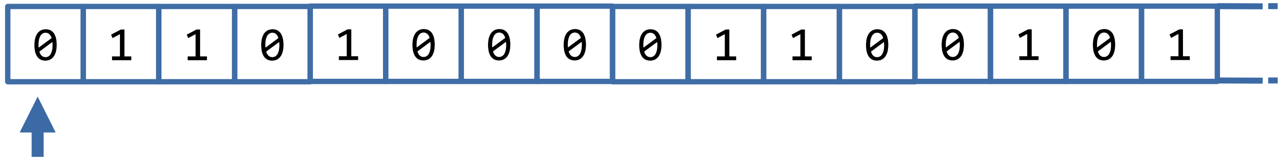
```
template<typename T>
decltype(auto) forward(std::remove_reference_t<T>& param) {
  return static_cast<T&&>(param);
}
```

- **If `T` is of value type, `T &&` is an rvalue reference in the return expression**
- **If `T` is of lvalue reference type, the resulting type is an rvalue reference to an lvalue reference**
  - Example: if `T = int &` then `T &&` would mean `int & &&`
- **What is `<Type> & &&` supposed to mean?**
  - As you know from reference collapsing: `<Type> &`

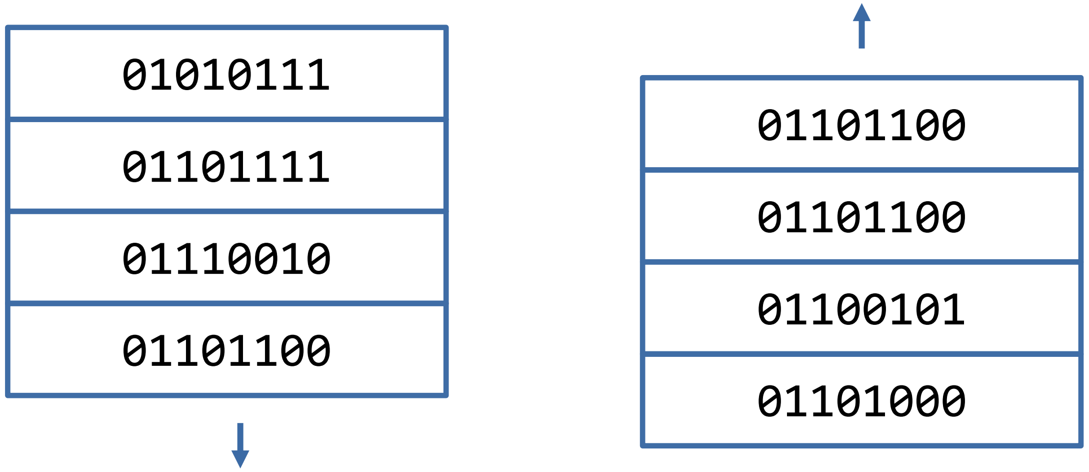
Pointers

The pointers, memory locations and sizes in this lecture are freely invented!

- **Turing Machine (Model)**
  - Unlimited Space



- **Stack / Heap (Reality)**
  - Limited Space



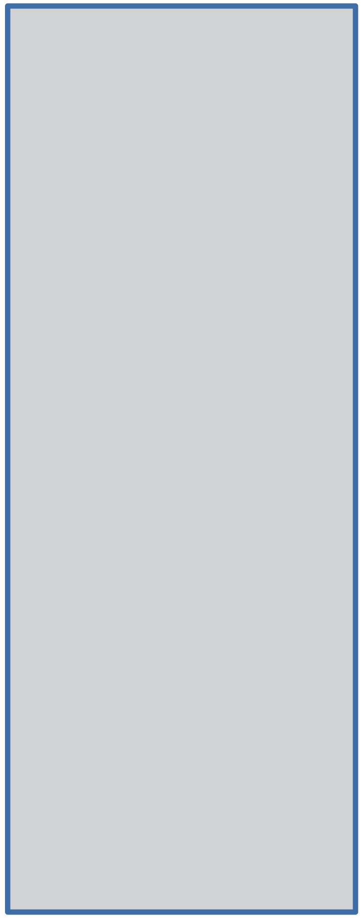
Lifetime on Stack

- **Deterministic**
- **Local variables get deleted automatically upon leaving their scope**

```
auto foo() -> void {
  int i{5};
  {
    double d = 23.0;
  }
}

auto main() -> int {
  ...
  foo();
  ...
}
```

Stack



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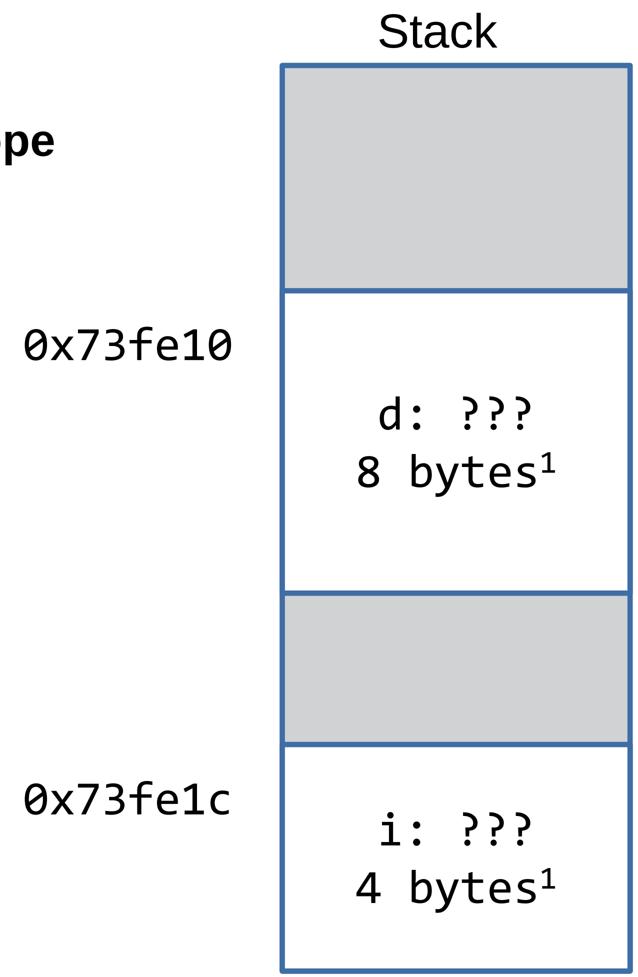

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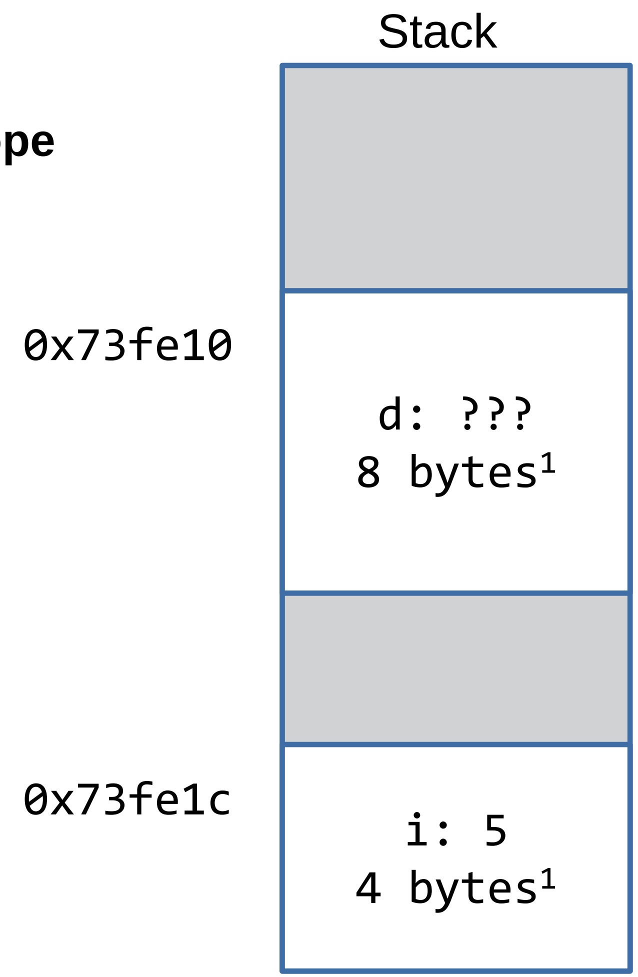

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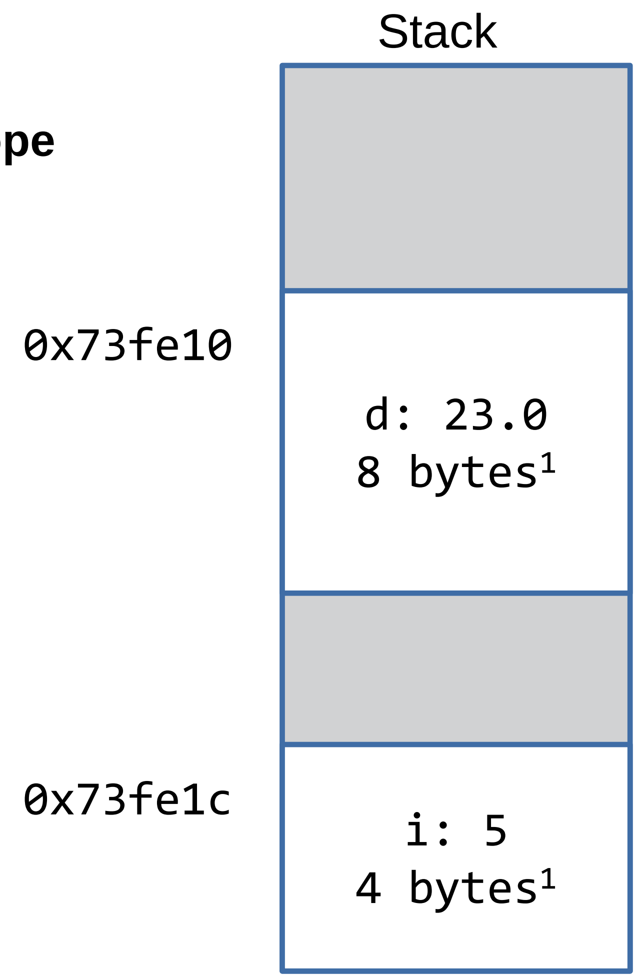

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  ...
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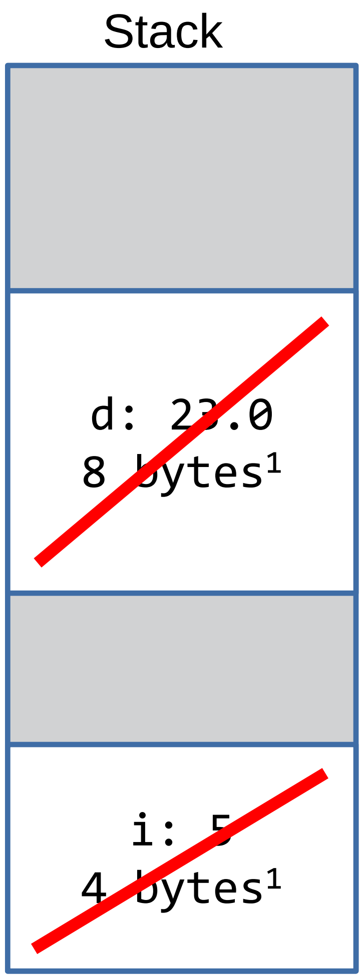
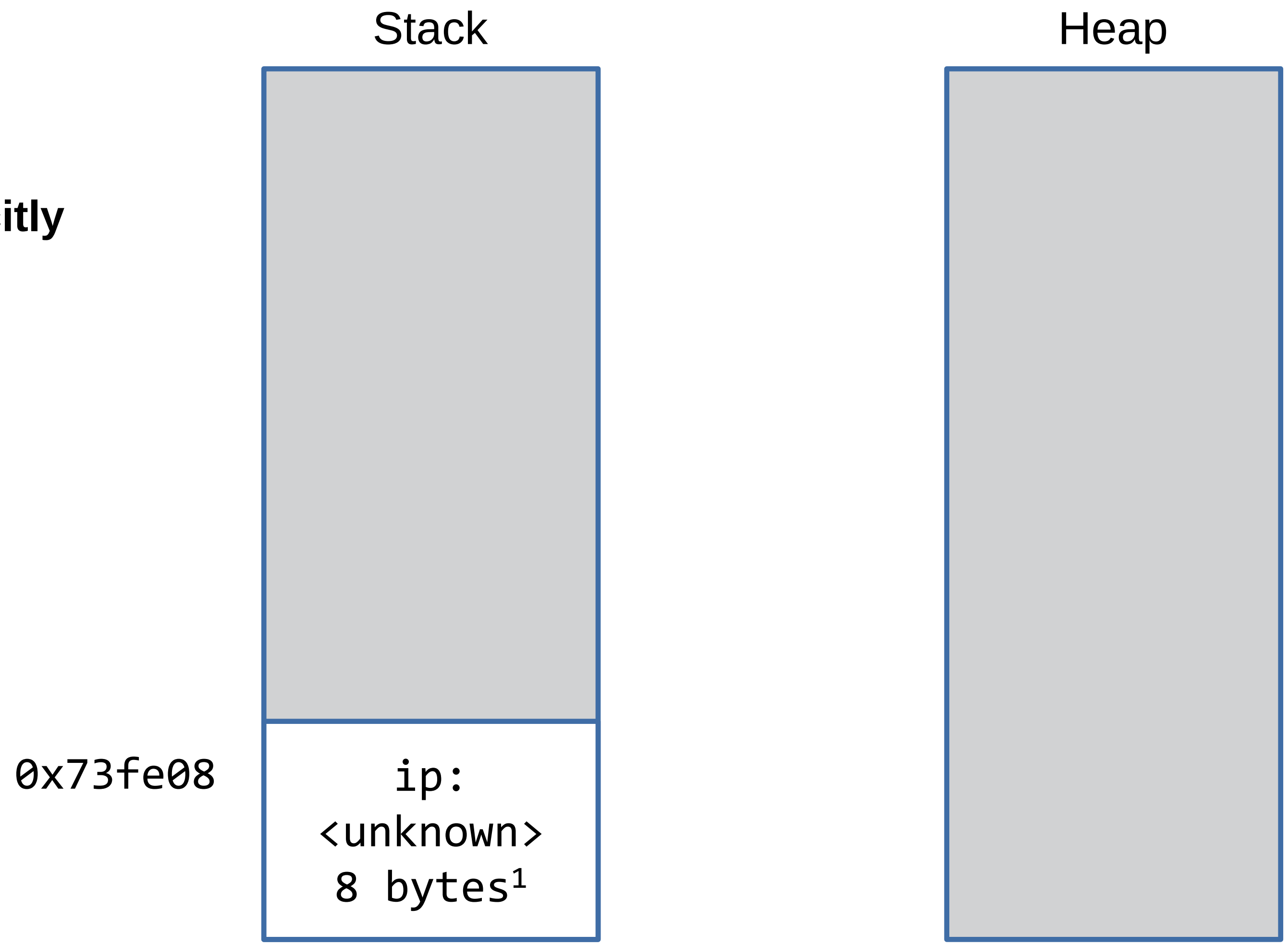


[1] Sizes depend on the platform

Lifetime on Heap

- **Deterministic (too)**
- **Creation and deletion happens explicitly**

```cpp
auto foo() -> void {
  auto ip = new int{5};
  ...
  delete ip;
}
```



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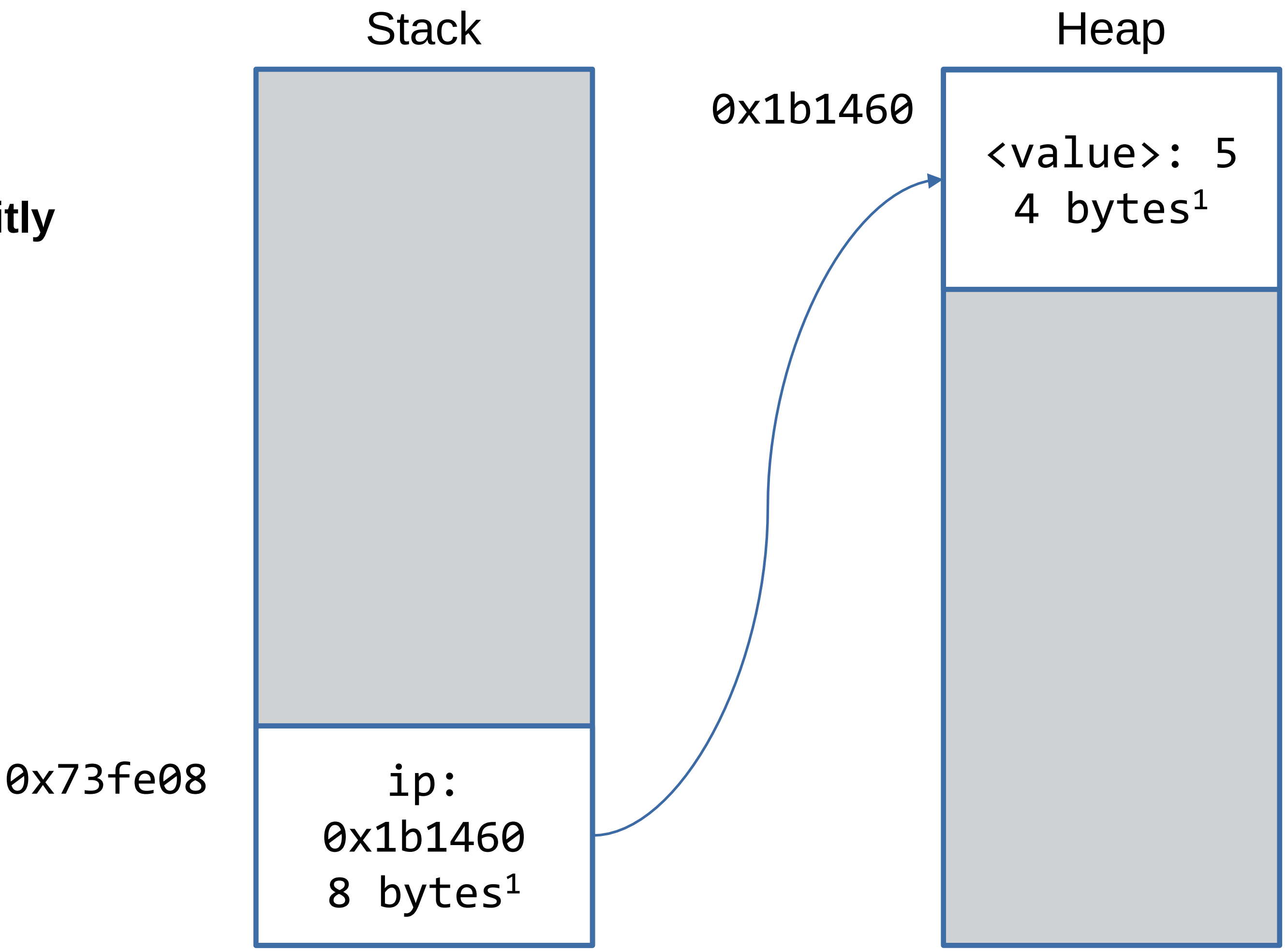

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Lifetime on Heap

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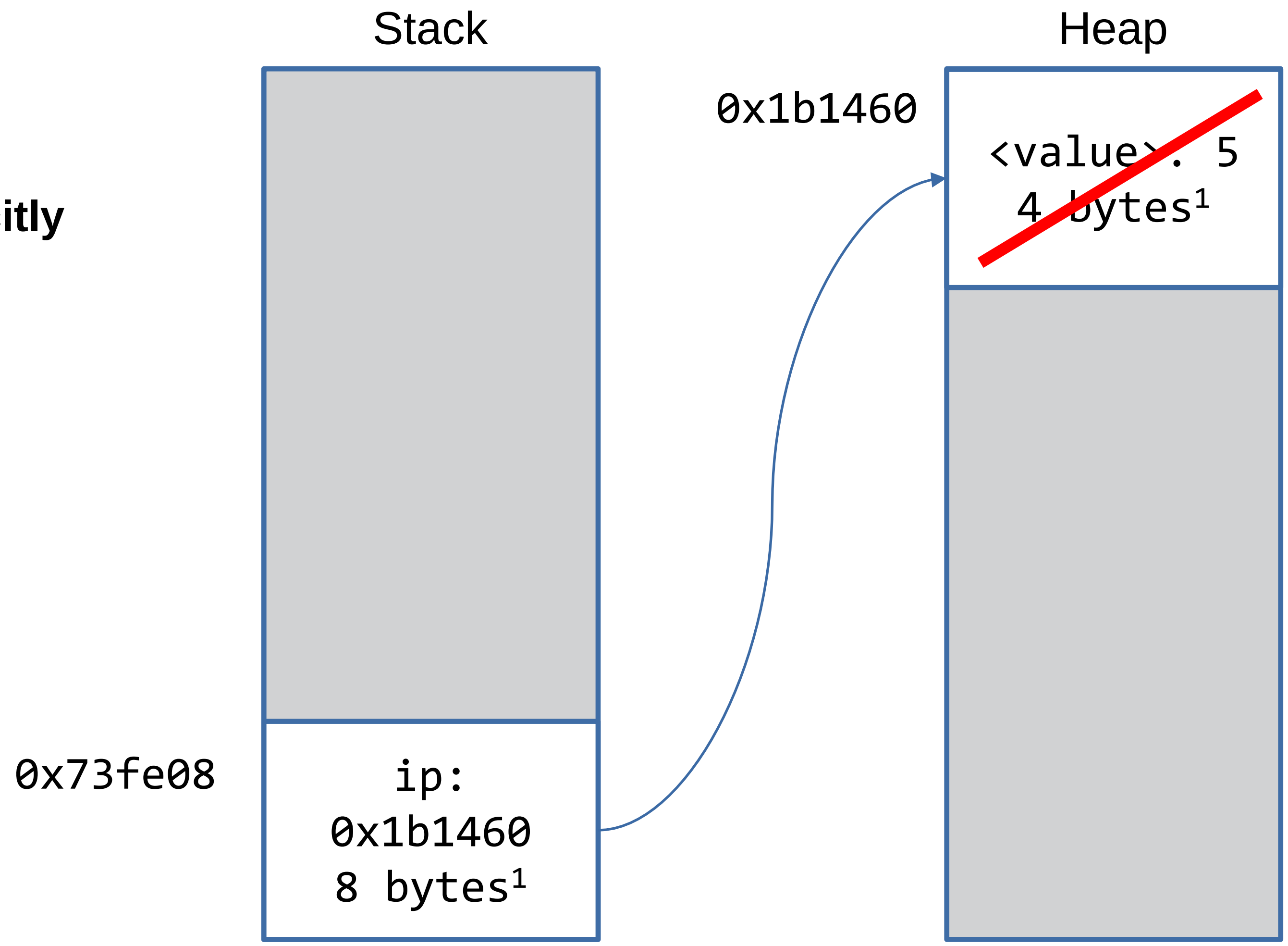

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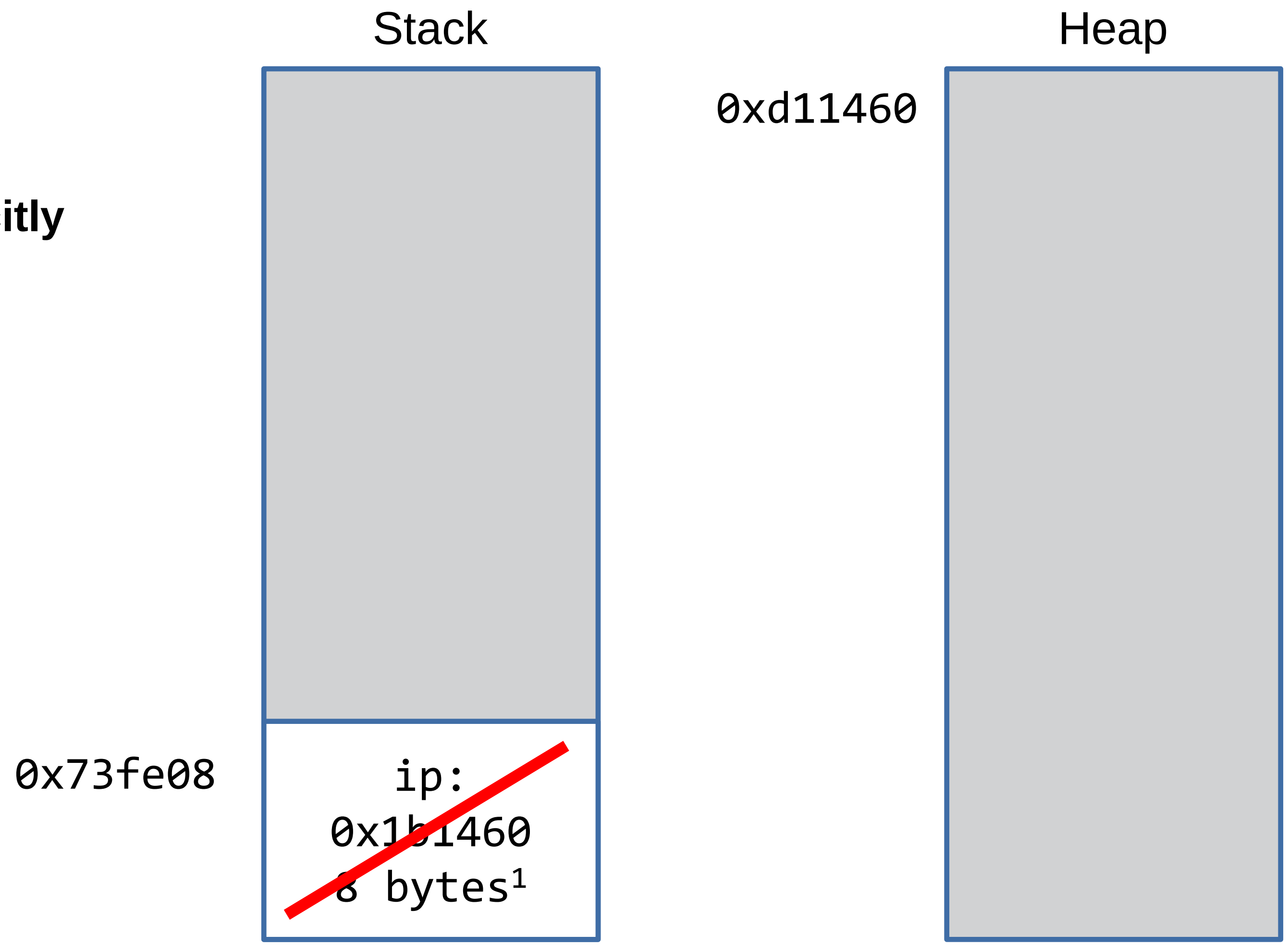
- **Deterministic (too)**
- **Creation and deletion happens explicitly**

```
auto foo() -> void {
  auto ip = new int{5};
  ...
  delete ip;
}
```



[1] Sizes depend on the platform

- **What is the type of `ip` in the example?**

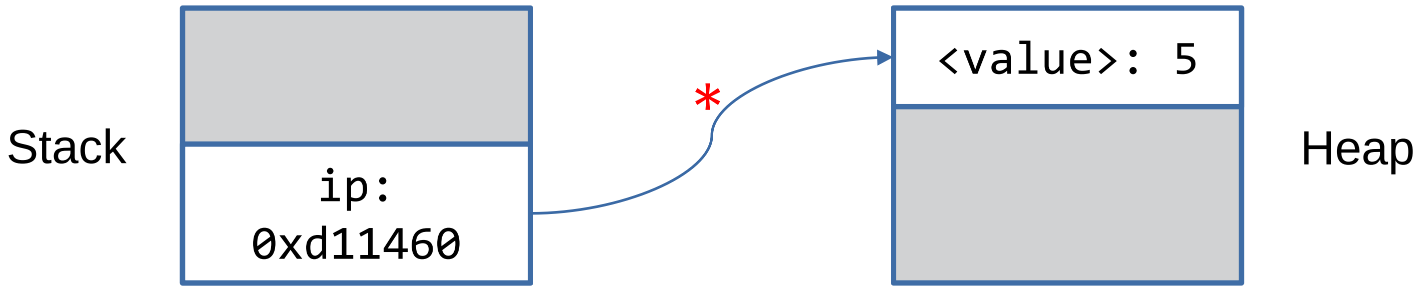
```
auto ip = new int{5};
```

- **Explicit declaration**

```
int * ip = new int{5};
```

- **Accessing the value at a pointer**

```
int v = * ip; //v == 5
```



- **What is the type of `arr` in the example?**

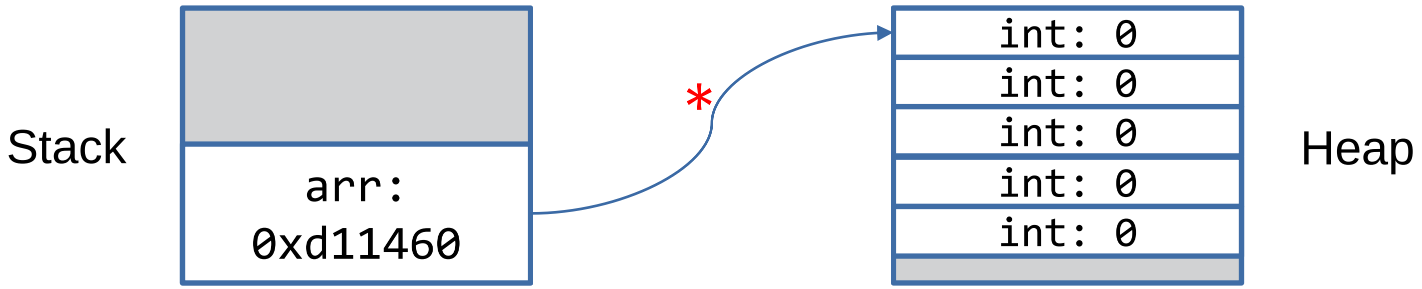
```
auto arr = new int[5]{};
```

- **Explicit declaration**

```
int * arr = new int[5]{};
```

- **Accessing elements with index operator []**

```
int v = arr[4];
```

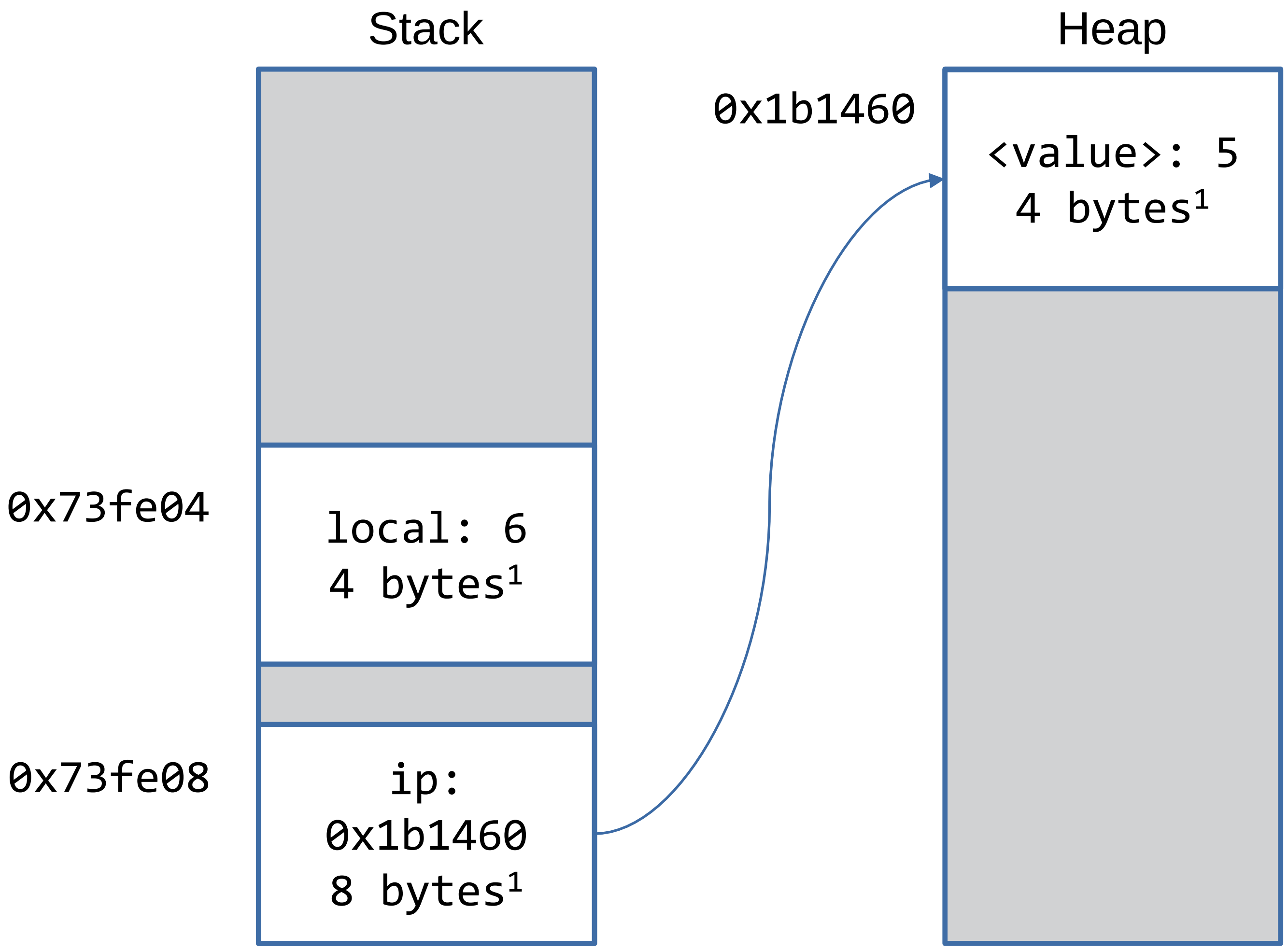


- **Direct Member Access (->)**
- **this is a pointer**

```
struct S {
  auto member() -> void {
    this->value = ...;
  }
  int value;
};

auto foo() -> void {
  S* sp = new S{};
  sp->member();

  //same as
  (*sp).member();
}
```

- **Pointers can be used as parameters**
- **Addresses can be taken with (&)**
  - Or `std::addressof()`

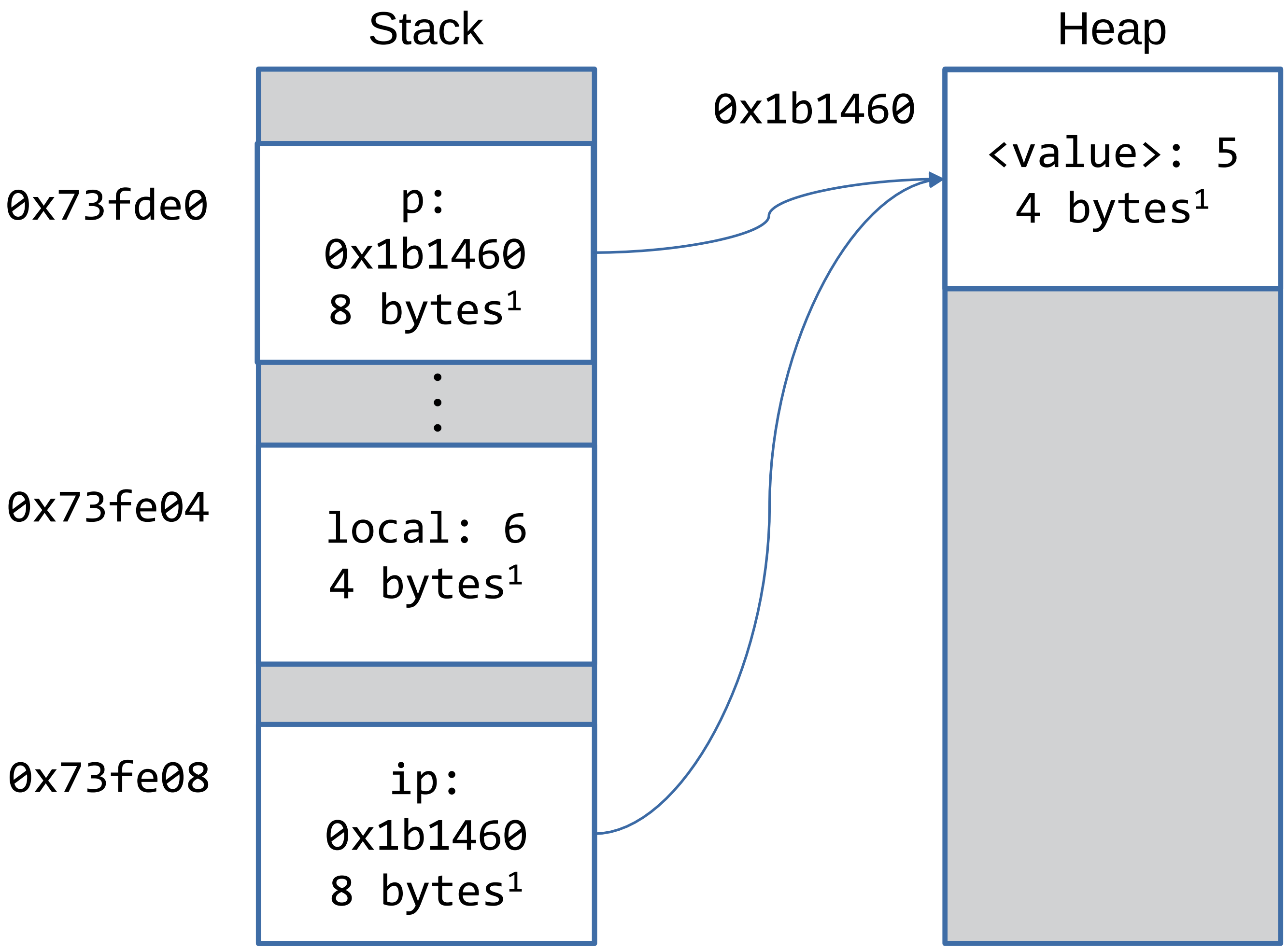
```
auto foo(int* p) -> void {
}

auto bar() -> void {
  int* ip = new int{5};
  int local = 6;
  foo(ip);
  foo(&local);
}
```



[1] Sizes depend on the platform

Pointer Parameters


```cpp
auto foo(int* p) -> void {
}

auto bar() -> void {
  int* ip = new int{5};
  int local = 6;
  foo(ip);
  foo(&local);
}
```



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```cpp
auto foo(int* p) -> void {
}

auto bar() -> void {
  int* ip = new int{5};
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  foo(ip);
  foo(&local);
}
```
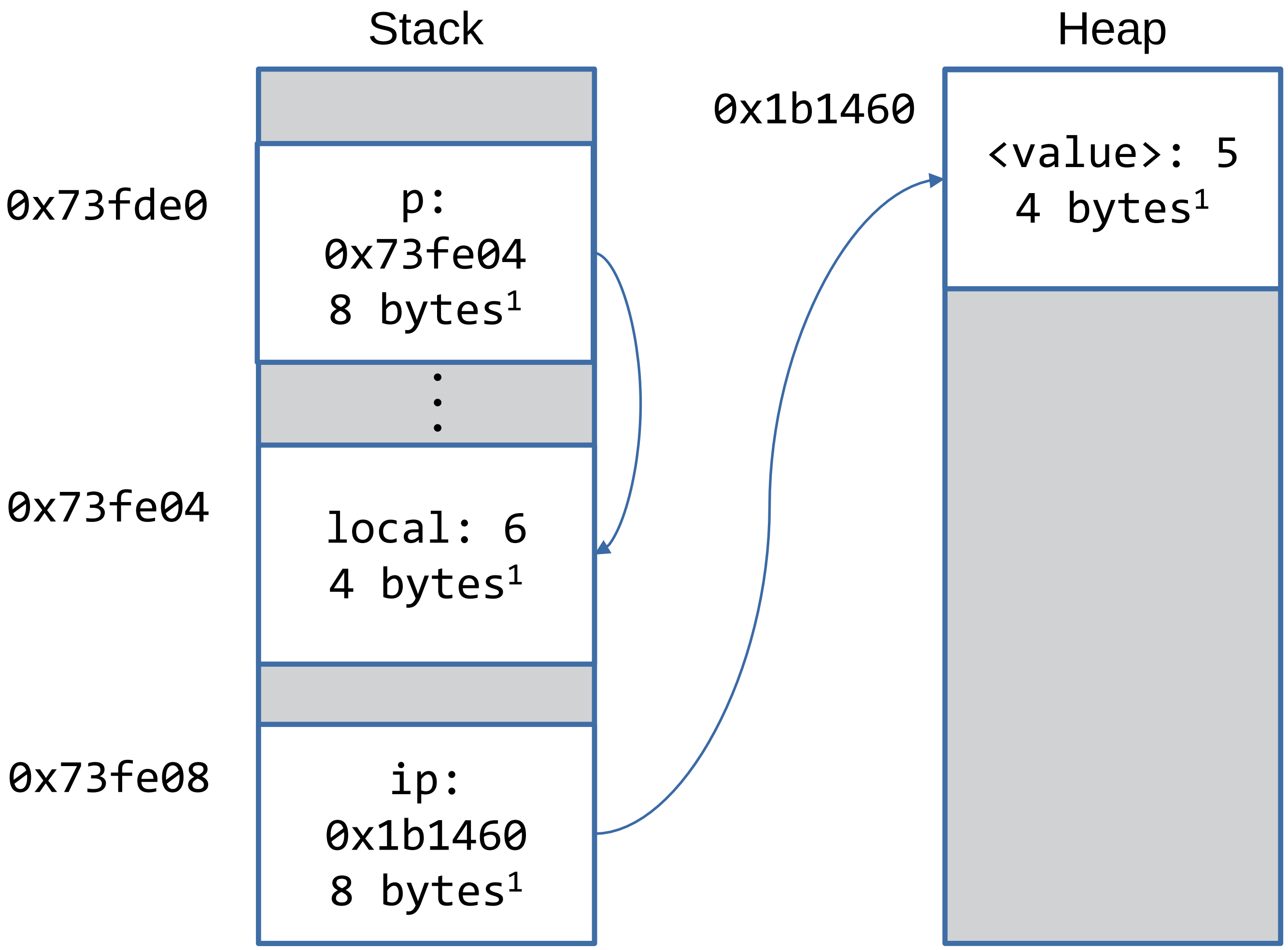
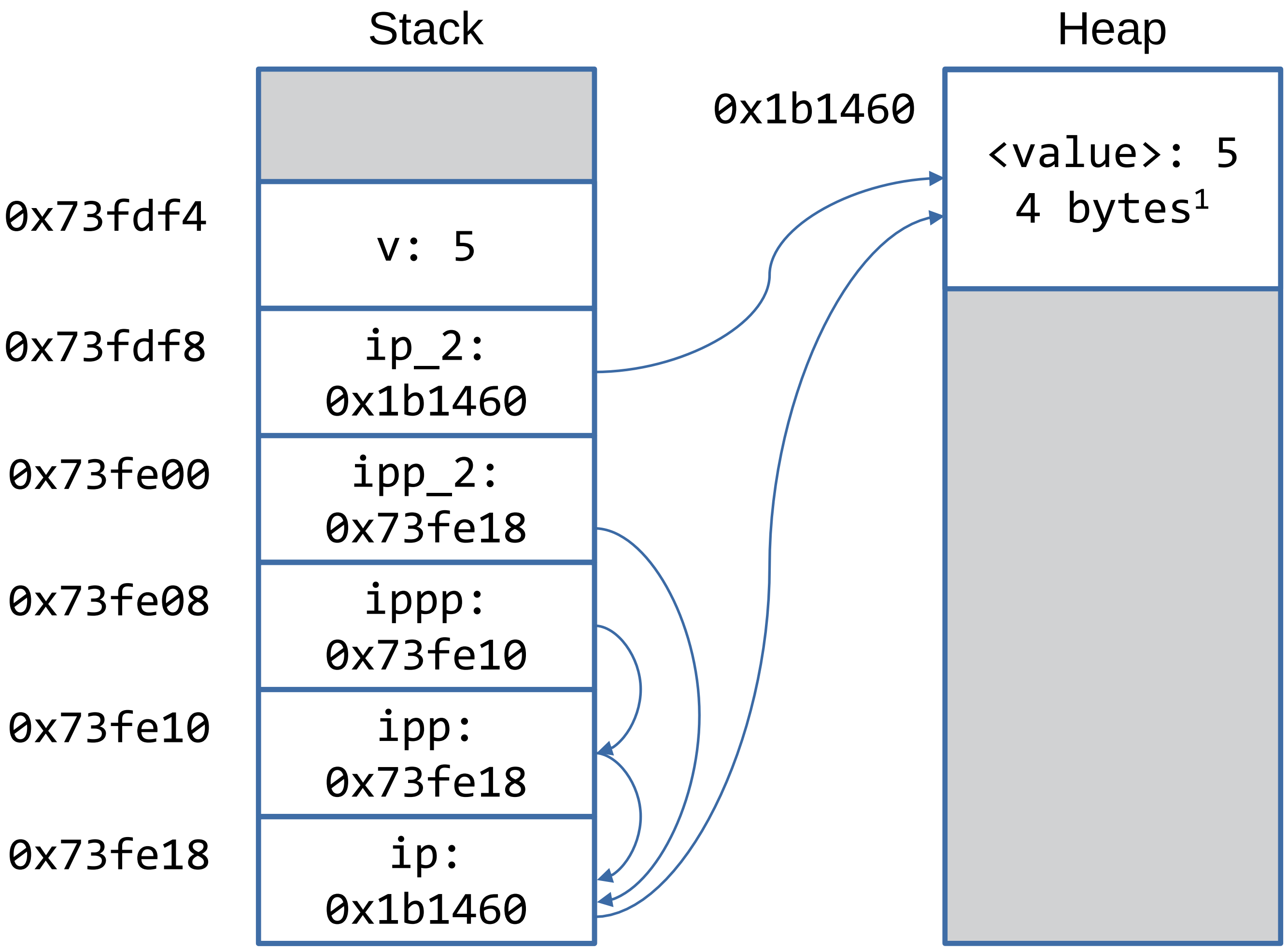



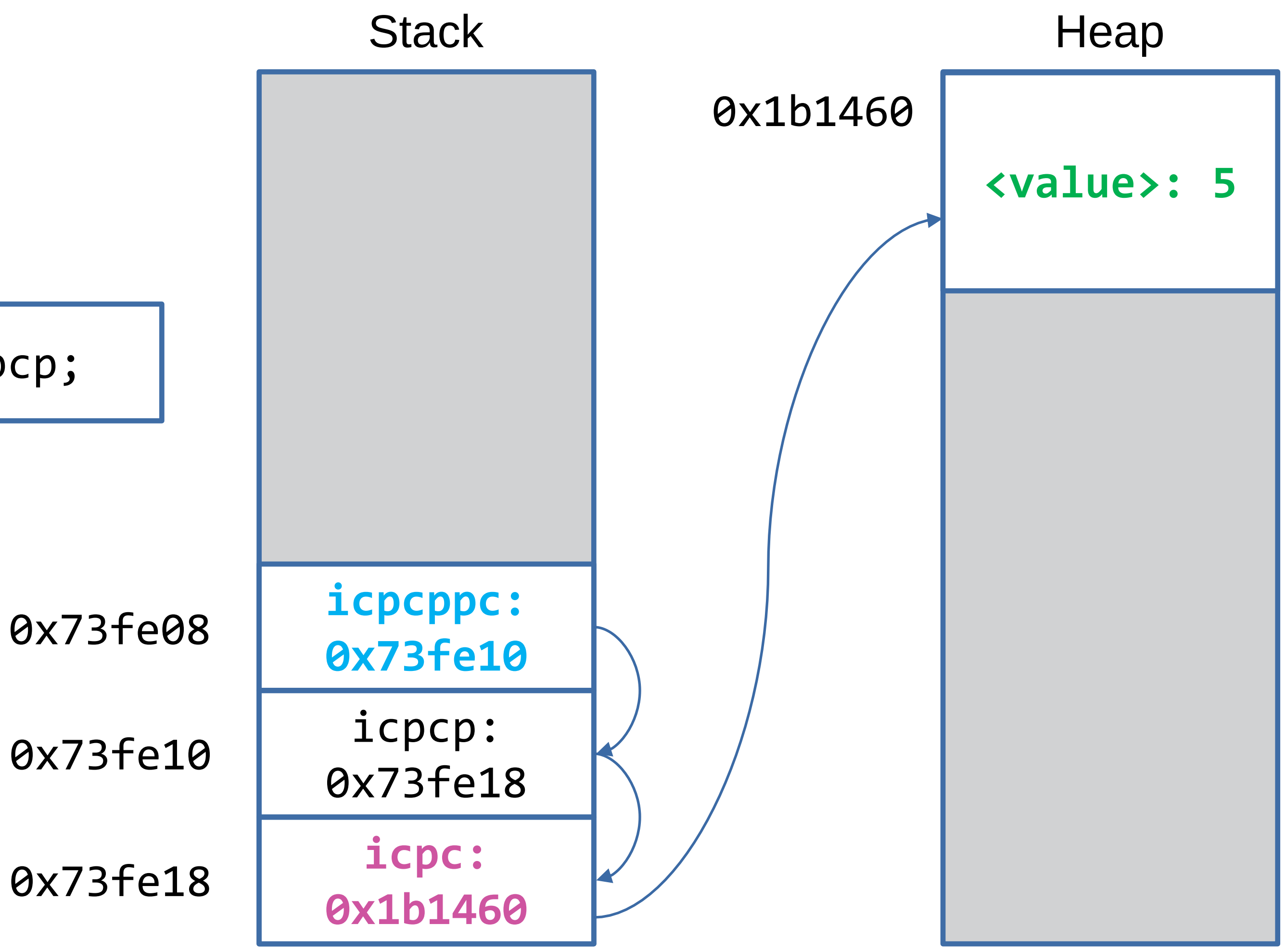
[1] Sizes depend on the platform

```
auto bar() -> void {
  int * ip = new int{5};
  int ** ipp = &ip;
  int *** ippp = &ipp;
  int ** ipp_2 = ipp;
  int * ip_2 = *ipp;
  int v = ***ippp;
}
```



- **Pointers can be const**
  - **`const`** is on the RIGHT side of the *****

```
int const * const * * const icpcppc = &icpcp;
```



- **Represents a null-Pointer**
- **Literal (prvalue)**
- **Type: `nullptr_t`**
- **Implicit conversion to any pointer type: `T *`**
- **Prefer `nullptr` over `0` and `NULL`**
  - No implicit conversion to integral type
  - No ambiguity on overload with integral type (discouraged)
  - Significant for template type deduction

```
auto bar(int i) -> void;
auto bar(S* ps) -> void;

//calls
bar(0);         //bar(int)
bar(NULL);      //surprising
bar(nullptr); //bar(S*)
```

Reading Declarations

- **Declarations are read starting by the declarator**
  - First read to the right until a closing parenthesis is encountered)
  - Second read to the left until an opening parenthesis is encountered (
  - Third jump out of the parentheses and start over ()

`int const`	`* const`	`*`	`* const`	`icpcppc;`
(5)	(4)	(3)	(2)	(1)

- **`icpcppc` is the declarator (name)**
  - there is nothing to the right
  - to the left: const pointer to a pointer to a const pointer to a const int

- **Reading the example**
  - icpcppc is a const pointer to a pointer to a const pointer to a const int

    (1) (2) (3) (4) (5)

Reading Declarators Correctly

- **Modifiers right to the declarator**
  - **Array Declarator: [ ]**
  - **Function Parameter List: (<parameter declarations>)**
- **Modifiers left to the declarator**
  - **References: &&, &**
  - **Pointers: ***
  - **Type: e.g. int**

```
void (* f)(int &, double)
 (4)  (2)(1)     (3)
```

(1) f is)
(2) (a pointer to
(3) a function, taking a reference to int and a double, returning
(4) void

- **Array example**

`int const`	`* (`	`*`	`f`	`[2]`	`[3]`	`) [5];`

f is an array of 2 elements of arrays of 3 elements of pointers to arrays of 5 elements of pointers to const int

- **In extremis**

```
int (*f(int(*)(int))) (int);
```

```
int (*f(int(*)(int))) (int);
```

f is a function
  this function takes a pointer to a function as argument (1)
  and returns a pointer to a function (2)
(1) this function takes an int and returns an int
(2) this function takes an int and returns an int

- Never do something like this without proper type aliases!

```
using alias = int(*)(int);
alias f(alias);
```

Placement of `const`

- **const might be written to the left of the type it qualifies**

```
int const i; //both declarations
const int i; //are the same
```

`const` applies to its left neighbor; only if there is no left neighbor it applies to its right neighbor

- **`const` might be written to the left of the type it qualifies**

```
int const i; //both declarations
const int i; //are the same
```

- **Let's add an alias**

```
using alias = int;
alias const i; //both declarations
const alias i; //are the same
```

- **What about more complex types**

```
int const * const icpc; //both declarations
const int * const cipc; //are the same
```

- **Aliasas worked well before**

```
//Extract the int const * part
using alias = int const *;
alias const icpc;  //works well
```

```
//Extract the int * const part
using alias = int * const;
const alias cipc; //not good
```

The type is int * const const now

- **Always write const to the right of the type**
  - It's consistent with every other placement of const (e.g. pointers)
  - It avoids surprises with type aliases

Confusing Mix of `mutable` and `const`

- **The `mutable` specifier refers to the declared name**
- **What does the following mean?**

```
mutable const int * mutable_const_int_pointer;
```

- **`const` makes the pointee `int` immutable**
- **`mutable` makes the pointer mutable**
- **When does this make sense? Shouldn't the non-const `mutable_const_int_pointer` always be mutable?**

HEAP Memory (De)Allocation

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- **Explicit heap memory allocation**
  - new expression
- **Syntax**

```
new <type> <initializer>
```

- **Allocates memory for an instance of `<type>`**
- **Returns a pointer to the object or array created (on the heap)**
  - of type `<type> *`
- **The arguments in the `<initializer>` are passed to the constructor of `<type>`**

```
struct Point {
  Point(int x, int y) :
        x {x}, y {y}{}
  int x, y;
};

auto createPoint(int x, int y) -> Point* {
  return new Point{x, y}; //constructor
}

auto createCorners(int x, int y) -> Point* {
  return new Point[2]{{0, 0}, {x, y}};
}
```

- **Explicit heap memory deallocation**
  - `delete` expression
- **Syntax**

```
delete <pointer>
```

- **Deallocates the memory (of a single object) pointed to by the `<pointer>`**
- **Calls the Destructor of the destroyed type**
- **`delete nullptr` is well defined**
  - it does nothing
- **Deleting the same object twice is Undefined Behavior!**

```cpp
struct Point {
  Point(int x, int y) :
      x {x}, y {y} {}
  int x, y;
}

auto funWithPoint(int x, int y) -> void {
  Point * pp = new Point{x, y};
  //pp member access with pp->
  //pp is the pointer value
  delete pp; //destructor
}
```

Array Memory Deallocation (with `delete[]`)

- **Explicit heap memory deallocation**
  - `delete[]` expression
- **Syntax**

```
delete[] <pointer-to-array>
```

- **Deallocates the memory (of an array) pointed to by the `<pointer-to-array>`**
- **Calls the Destructor of the destroyed objects**
- **Also deletes multidimensional arrays**

```cpp
struct Point {
  Point(int x, int y) :
         x {x}, y {y}{}
  int x, y;
}

auto funWithPoint(int x, int y) -> void {
  Point * arr = new Point[2]{{0, 0},
                             {x, y}};
  //element access with [], e.g. arr[1]
  //arr points to the first element
  delete[] arr; //destructors
}
```

- **Construction of an object at an already allocated memory location**
- **Syntax**

```
new (<location>) <type> <initializer>
```

- **Does NOT allocate new memory**
  - You need to make sure that the memory at `<location>` is suitable for construction of a new object and any element there must be destroyed properly before (or be uninitialized)
- **Calls the Constructor for creating the object at the given location (`<location>`)**
- **Returns the given memory location**

```
struct Point {
  Point(int x, int y) :
        x {x}, y {y}{}
  int x, y;
};

auto funWithPoint() -> void {
  auto ptr = new Point{9, 8};
  //must release Point{9, 8}
  new (ptr) Point{7, 6};
  delete ptr;
}
```

- **Does not exist, but a destructor can be called explicitly**
- **Syntax**
  - Call like any other member function

```
S * ptr = ...;
ptr->~S();
```

- **Destroys the object, but does not free its memory**
- **You cannot destroy an array in this way as a whole**
  - You need to create your own infrastructure, which keeps track of arrays to achieve this
- **Better use `std::destroy_at(ptr);`**

```
struct Resource {
  Resource() {
    /*allocate resource*/
  }
  ~Resource() {
    /*deallocate resource*/
  }
};

auto funWithPoint() -> void {
  auto ptr = new Resource{};
  ptr->~Resource();
  new (ptr) Resource{};
  delete ptr;
}
```

```cpp
struct Point {
  Point(int x, int y);
  ~Point();
  int x, y;
};
```

- **`Point` is not default constructible**
  - We cannot allocate arrays of default-constructed Points

```cpp
new Point[2];
```

- **We can allocate the plain memory (`std::byte[]`)**

```cpp
auto memory = std::make_unique<std::byte[]>(sizeof(Point) * 2);
```

- **And initialize it later**

```cpp
new (memory.get()) Point{1, 2};
```

- **Accessing the elements is tedious. Let's add a helper function**

```
auto elementAt(std::byte * memory, size_t index) -> Point& {
  return reinterpret_cast<Point *>(memory)[index];
}
```

- **We must not use the `Point` if it is uninitialized**

```
auto memory = std::make_unique<std::byte[]>(sizeof(Point) * 2);
Point * first = &elementAt(memory.get(), 0);
new (first) Point{1, 2};
Point * second = &elementAt(memory.get(), 1);
new (second) Point{4, 5};
```

Non-Default Constructible Type Deallocation

- **Before our memory is deallocated, we have to destroy the elements**
  - Call the destructor explicitly or use `std::destroy_at`

```
Point * first = &elementAt(memory.get(), 0);
new (first) Point{1, 2};
first->~Point();
```

```
auto memory = std::make_unique<std::byte[]>(sizeof(Point) * 2));
Point * first = &elementAt(memory.get(), 0);
new (first) Point{1, 2};
Point * second = &elementAt(memory.get(), 1);
new (second) Point{4, 5};

std::destroy_at(second);
std::destroy_at(first);
```

- **Overloading new and delete operators for a class can inhibit heap allocation**

```cpp
struct not_on_heap {
    static auto operator new(std::size_t sz) -> void * {
        throw std::bad_alloc{};
    }
    static auto operator new[](std::size_t sz) -> void * {
        throw std::bad_alloc{};
    }
    static auto operator delete(void *ptr) -> void noexcept {
        // do nothing, never called, but should come in pairs
    }
    static auto operator delete[](void *ptr) -> void noexcept {
        // do nothing, never called, but should come in pairs
    }
};
```

- **Experiment in exercises**

- **Overloading `new` and `delete` operators for a class can be used to provide efficient allocation**
  - useful with a memory pool for small instances
  - useful if thread-local pools are used
    - heap-memory is a shared resource
  - can log or limit number of heap-allocated instances
    - for testing purposes, figuring bottlenecks
- **But in general, not advisable**
  - if used in standard-containers you need to adjust their `Allocator` template argument instead

```
struct not_on_heap {
//...
};

struct small_but_many {
//...
};

std::vector<X, PoolAllocator> vp;
```

- **Simple rules**
  - Delete every object you allocated
  - Do not delete an object twice
  - Do not access a deleted object
- **Just don't do the following**

```
auto foo() -> void {
  int * ip = new int{5};
  //exit without deleting
  //location ip points to
}
```

DANGER

Memory Leak

```
auto foo() -> void {
  int * ip = new int{5};
  delete ip;
  delete ip;
}
```

DANGER

Double Delete

```
auto foo() -> void {
  int * ip = new int{5};
  delete ip;
  int dead = *ip;
}
```

DANGER

Invalid Access

- **More cases**

```
auto bar() -> void;

auto foo() -> void  {
  int * ip = new int{5};
  bar(); //exception?!
  delete ip;
}
```

```
auto foo(int * p) -> void  {
  //is it up to me to
  //delete p? likely not
}
```

```
auto create() -> int * {
  int * ip = new int{5};
  return ip;
}
auto foo() -> void {
  int * ip = create();
  //My turn to delete?
  //Probably yes
}
```

- **It gets even more tricky when pointers are used for shared members**

```
struct Node {
  Node(Node * parent = nullptr) :
      parent{parent}, children{} {
    if (parent)
      parent->children.push_back(this);
  }
  Node * parent;
  std::vector<Node *> children;
};
```

```
auto createTree() -> Node * {
  Node * root = new Node{};
  new Node{root}; new Node{root};
  return root;
}
auto find_child_X() -> Node * {
  Node * root = createTree();
  Node * child_X = ...; //find child X
  delete root;
  return child_X;
}
```

- **The mistakes here can be discovered with reasonable effort, but it is a much bigger issue in a large code base**

- **Getting familiar with the syntax of pointers is important**
  - You will come across them in most real world C++ (legacy) applications
- **Use pointers only if necessary and only in confined code areas**
  - Reasoning about the life-time of the heap-allocated objects must be easy
- **Prefer smart pointers to make reasoning about object life-time easier**
- **You can use `emplace` to directly create objects into standard containers**

Resource Management with RAII
Container's `emplace()`
Overloading `new`/`delete`

Self-Study

Ostschweizer Fachhochschule

Resource Aquisition Is Initialization (RAII)

- **Alternative to allocating and deallocating a resource explicitly**
  - Wrap allocation and deallocation in a class
  - Constructor for allocation
  - Destructor for deallocation
- **The automatic destruction at the end of a scope will take care of the resource deallocation**
- **Works with exceptions**
  - No `finally` required
- **STL classes for heap memory**
  - `std::unique_ptr` / `std::shared_ptr`

```
struct Resource {
  Resource() {
    //Allocate Resource
  }
  ~Resource() {
    //Deallocate Resource
  }
  //API for accessing the resource
  //Don't leak the resource!
private:
  WrappedResource * wrappedResource;
};
```

```
auto workWithResource() -> void {
  Resource item{};
  functionThatMightThrow();
  //Resource is released automatically
}
```

```
std::unique_ptr<char> cPtr = std::make_unique<char>('*');
```

- **std::unique_ptr<T>**
  - Wraps a plain pointer
  - unique_ptr have zero runtime overhead
  - A custom deleter could be supplied if required that is called instead of the destructor

```
//Template
template<typename T, typename Deleter =
         std::default_delete<T>>
class unique_ptr;

//Specialization for unbound arrays
template<typename T, typename Deleter>
class unique_ptr<T[], Deleter>;
```

```
std::unique_ptr<char> cPtr = std::make_unique<char>('*');
```

- **std::make_unique<T>**
  - Always use make_unique if possible

```
template<typename T, typename...Args>
std::unique_ptr<T>
make_unique(Args&&...args) {
  return std::unique_ptr<T> {
    new T(std::forward<Args>(args)...)};
}
```

  - You **can** create unbound arrays

```
std::make_unique<char[]>(42)
```

  - You **cannot** create arrays of fixed size

```
std::make_unique<char[42]>(...)
```

Container Member Function `emplace`

- **Putting elements into a container...**
  - Copying big objects into standard containers might be inefficient
  - Moving big objects into standard containers might be more efficient
  - Creating big objects into the space already allocated for a standard container might be even better
- **Syntax for emplace, example for `std::stack`**

```
template<typename... Args>
auto emplace(Args&&... args) -> void;
```

- **Constructs an element of type T from the forwarded arguments in-place**
  - Can put objects into a container that can neither be copied nor moved
- **Not available for `std::array`**
  - Has fixed size

- **It is possible to overload the `new` and `delete` operators**

```
//Global new
auto operator new      (std::size_t) -> void *
auto operator new[]    (std::size_t) -> void *

//Placement new
auto operator new      (std::size_t, void * ptr) -> void *
auto operator new[]    (std::size_t, void * ptr) -> void *

//For specific type T
auto T::operator new   (std::size_t) -> void *
auto T::operator new[] (std::size_t) -> void *

//more new operators & delete operators
```

- **See http://en.cppreference.com/w/cpp/memory/new for more details**

- **A type is non-default-constructible when...**
  - ... there is no explicit default constructor and ...
  - ... there is no implicit default constructor!
- **Why can't we use `new T[capacity]` for allocating a T array?**
  - If T is of class type it must be default-constructible to allow this call.
  - That is not the case for fundamental types!
- **Alternative**
  - Allocate a `std::byte` array and manage the objects "manually"

`std::byte` Array as Memory for NDC Elements

- **Static**
  - Local
  - Size known at compile-time (no_of_bytes)

```
std::array<std::byte, no_of_bytes> values_memory;
```

- **Dynamic**
  - On heap
  - Size known at run-time

```
std::unique_ptr<std::byte[]> values_memory;
```

- **Given:**
  - An array of elements of type T is accessible through a pointer to `std::byte`.
  - Declaration of `data`: `std::byte * data;`
  - How to correctly access the fifth element in this array?

a) `data[4]`

b) `reinterpret_cast<T*>(data)[4]`

c) `*reinterpret_cast<T*>(data + 4)`

d) `*reinterpret_cast<T*>(data) + 4`

- **Note you can access the raw memory behind an `std::array` with `.data()` or for `std::unique_ptr<T[]>` with `.get()`**