

Lifetime of the C++ object

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Agenda

Theory

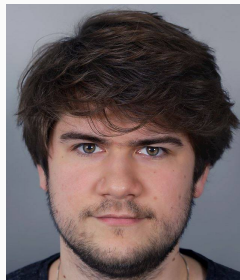
Object model intuition

Pointers and `std::launder`

Who am I?

Dawid Pilarski

- Senior Software Developer in TomTom
- Member of the ISO/JTC1/SC22/WG21
- Member of the PKN KT (programming languages)
- C++ blog writer



Questions.

Questions...

Question...

Do you think, that understanding objects and their lifetimes is **basics**?

What we talk about are basics.

6 Basics

[basic]

6.7 Memory and objects

[basic.memobj]

6.7.2 Object model

[intro.object]

¹ The constructs in a C++ program create, destroy, refer to, access, and manipulate objects. An *object* is created by a *definition*, by a *new-expression*, when implicitly changing the active member of a *union*, or when a temporary object is created ([conv.rval], [class.temporary]). An object occupies a region of storage in its period of construction ([class.ctor]), throughout its *lifetime*, and in its period of destruction ([class.ctor]). [*Note:* A function is not an object, regardless of whether or not it occupies storage in the way that objects do. — *end note*] The properties of an object are determined when the object is created. An object can have a name ([basic.pre]). An object has a storage duration ([basic.stc]) which influences its lifetime ([basic.life]). An object has a type ([basic.types]). Some objects are polymorphic ([class.virtual]); the implementation generates information associated with each such object that makes it possible to determine that object's type during program execution. For other objects, the interpretation of the values found therein is determined by the type of the *expressions* ([expr.compound]) used to access them.

² Objects can contain other objects, called *subobjects*. A subobject can be a *member subobject* ([class.mem]), a *base class subobject* ([class.derived]), or an array element. An object that is not a subobject of any other object is called a *complete object*. If an object is created in storage associated with a member subobject or array element *e* (which may or may not be within its lifetime), the created object is a subobject of *e*'s containing object if:

- (2.1) — the lifetime of *e*'s containing object has begun and not ended, and
- (2.2) — the storage for the new object exactly overlays the storage location associated with *e*, and
- (2.3) — the new object is of the same type as *e* (ignoring cv-qualification).

³ If a complete object is created ([expr.new]) in storage associated with another object *e* of type "array of *N* *unsigned char*" or of type "array of *N* *std::byte*" ([cstddef.syn]), that array *provides storage* for the created object if:

- (3.1) — the lifetime of *e* has begun and not ended, and
- (3.2) — the storage for the new object fits entirely within *e*, and

Theory

Title decomposition

What's the lifetime of your object?

Title decomposition

What's the **lifetime** of your object?

- What is a lifetime?

Title decomposition

What's the **lifetime** of your **object**?

- What is a lifetime?
- What is an object?

Objects

The object

Objects are entities, that can be:

- created
- destroyed
- referred to
- accessed
- manipulated

The Object

Is created:

- by the definition

```
int a;
```

The Object

Is created:

- by the definition
- by the new expression

```
new int(5);
```

The Object

Is created:

- by the definition
- by the new expression
- when changing active member of a union

```
union U{int x; int y;};
```

```
U u;
```

```
u.y = 2; // active member y;
```

The Object

Is created:

- by the definition
- by the new expression
- when changing active member of a union
- by creation of the temporary

```
int{};
```


The object

Has:

- optional name

The object

Has:

- optional name
- lifetime

The object

Has:

- optional name
- lifetime
- storage and it's duration

The object

Has:

- optional name
- lifetime
- storage and it's duration

- static

program duration

The object

Has:

- optional name
- lifetime
- storage and it's duration
 - static
 - thread

thread duration

The object

Has:

- optional name
- lifetime
- storage and it's duration
 - static
 - thread
 - automatic

enclosing scope duration

The object

Has:

- optional name
- lifetime
- storage and it's duration
 - static
 - thread
 - automatic
 - dynamic

controlled by user

The object

Has:

- optional name
- lifetime
- storage and it's duration
 - static
 - thread
 - automatic
 - dynamic
- type

The object

Has:

- optional name
- lifetime
- storage and it's duration
 - static
 - thread
 - automatic
 - dynamic
- type
- value

The reference

Is not an object (although reference has lifetime)
functions are not objects as well

The variable

Is created by a **declaration** of an **object** or the **reference**.

The variable

Is created by a **declaration** of an **object** or the **reference**.

```
int x;
```

Is a variable.

The variable

Is created by a **declaration** of an **object** or the **reference**.

```
int x;
```

Is a variable.

```
int& x = ...
```

Is a variable.

The variable

Is created by a **declaration** of an **object** or the **reference**.

```
int x;
```

Is a variable.

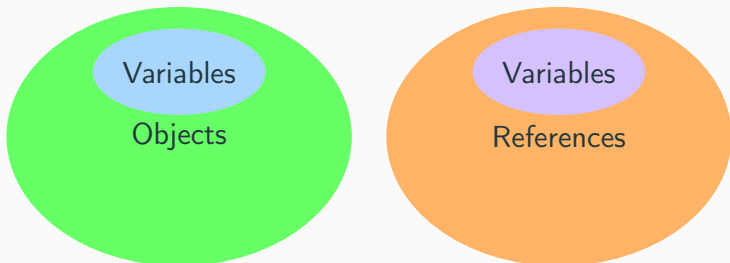
```
int& x = ...
```

Is a variable.

```
struct X{int y;}z;
```

Neither X nor y are
variables.
z is a variable.

Summary: variable, reference, object



Lifetime

What is a lifetime?

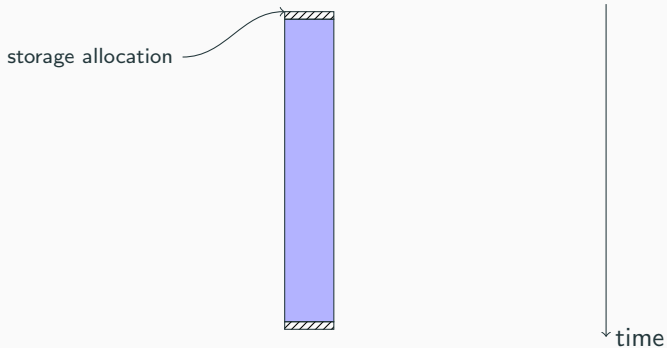
Lifetime is a property of an object.

During the lifetime of an object you can use it without additional restrictions.

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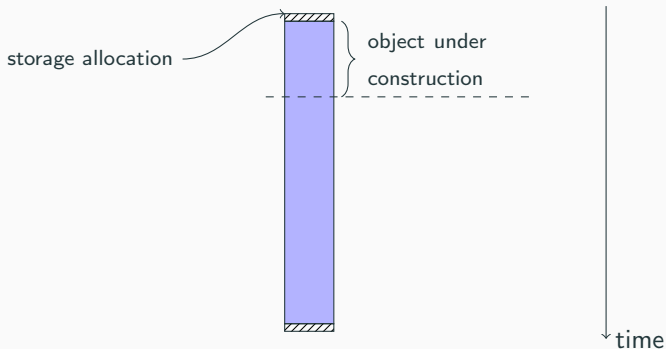
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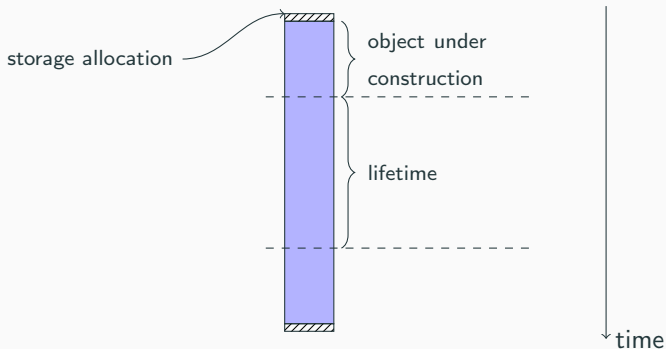
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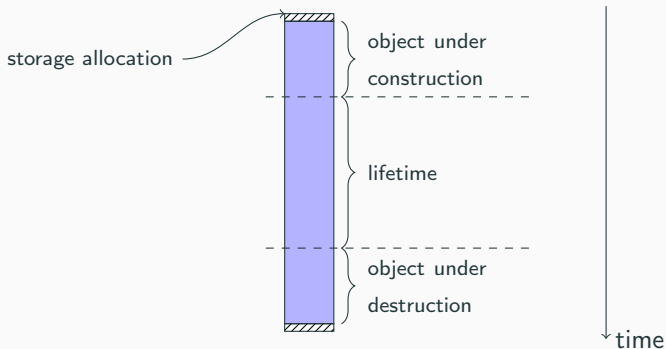
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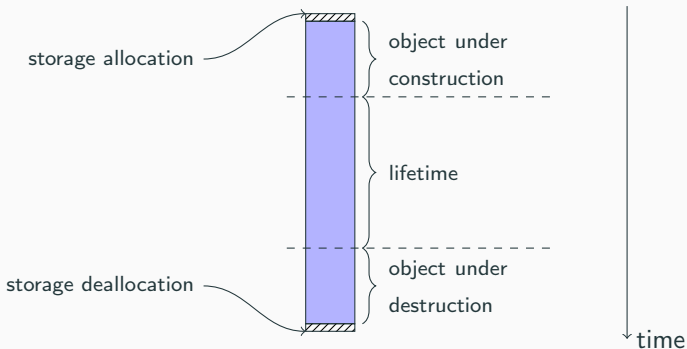
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What is a lifetime?

Lifetime is a property of an object.

During the lifetime of an object you can use it without additional restrictions.



When does the lifetime start?

The lifetime of an object **starts**, when:

- storage with the proper alignment and size for type T is obtained

When does the lifetime start?

The lifetime of an object **starts**, when:

- storage with the proper alignment and size for type T is obtained
- its initialization (if any)* is complete

*In case of default construction of trivial type, there is no initialization performed

When does the lifetime start?

The lifetime of an object **starts**, when:

- storage with the proper alignment and size for type T is obtained
- its initialization (if any)* is complete
- if the object is a union member or subobject thereof, its lifetime only begins if that union member is the initialized member

When does the lifetime end?

The lifetime of an object **ends**:

class types when it's destructor is called,

When does the lifetime end?

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class types when it's destructor is called,

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- when object exits the scope,
- delete expression,
- **when temporary ends its lifetime etc.**

When does the lifetime end?

The lifetime of an object **ends**:

class types when it's destructor is called,

non-class types when we expect it to end its lifetime,

- when object exits the scope,
- delete expression,
- when temporary ends its lifetime etc.

any type when storage occupied by an object is reused or released.

Limitations on objects

Limitations on objects - Storage allocated ctor not yet called

During this phase you must treat every pointer/reference to such object as if it was raw storage.

During construction you cannot:

- pass pointer as `delete` argument,

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 - `std::byte*`

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During construction you cannot:

- pass pointer as `delete` argument,
- access any non-static members (unless type has trivial ctor),
- `static_cast` to types other than:
 - `void*`
 - `char*`
 - `unsigned char*`
 - `std::byte*`
- `dynamic_cast` it.

Limitations on objects - object under (con|de)struction

You can access non-static members of a class, but only via `this` pointer.

Example...

Limitations on objects - object under (con|de)struction

```
struct C {  
    int c;  
    C() : c(0) { no_opt(); }  
};
```

```
const C cobj;  
void no_opt() {  
    int i = cobj.c * 100; //unspecified value  
    std::cout << i << std::endl;  
}
```

Limitations on objects - object under (con|de)struction

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}
```

Limitations on objects - object under (con|de)struction

During object creation and destruction, **base object, whose constructor is running is considered most derived object.**

Example...

Limitations on objects - object under (con|de)struction

```
struct Base{  
    Base();  
    virtual void foo(){}  
};  
struct Derived : Base{};
```

```
Base::Base(){  
    std::cout << typeid(*this).name() << std::endl;  
    std::cout << dynamic_cast<Derived*>(this) << std::endl;  
}
```

```
Derived d;
```


Limitations on objects - object under (con|de)struction

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struct Base{
    Base();
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    std::cout << typeid(*this).name() << std::endl;
    std::cout << dynamic_cast<Derived*>(this) << std::endl;
}

Derived d;
```

Output:

4Base

Limitations on objects - object under (con|de)struction

```
struct Base{
    Base();
    virtual void foo(){}
};
struct Derived : Base{};

Base::~Base(){
    std::cout << typeid(*this).name() << std::endl;
    std::cout << dynamic_cast<Derived*>(this) << std::endl;
}

Derived d;
```

Output:

0

Limitations on objects - object under (con|de)struction

Watch out for `vptr` - its not thread safe.

Example...

Limitations on objects - object under (con|de)struction

```
struct runnable{
void execute(){
    run();
    lock_guard lck(m_);
    done = true;
    cv_.notify_one();
}
~runnable(){
    unique_lock<mutex> lck(m_);
    cv.wait(lck,
        [this]{return done_;});
}
private:
    virtual void run()=0;
    //...
};
```

Limitations on objects - object under (con|de)struction

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};
```

```
runnable* d = new Derived;
thread th1([d]{d->execute();});
thread th2([d]{delete d;});
```

Limitations on objects - object under (con|de)struction

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```

vptr read

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Limitations on objects - object under (con|de)struction

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vp_{tr} read

vp_{tr} write

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```

vp_{tr} read

vp_{tr} write

data race!

The diagram illustrates a data race in a C++ program. A pink arrow labeled 'vp_{tr} read' points from the `execute()` method to the `[d]{d->execute()};` line in the thread `th1`. A blue arrow labeled 'vp_{tr} write' points from the `delete d;` line in the thread `th2` to the `~runnable()` destructor. A red text label 'data race!' is placed to the right of the code, indicating that the read and write of the pointer `d` are not synchronized, leading to undefined behavior.

Limitations on objects - object under (con|de)struction

When casting **this** pointer to a base subobject, if any of the subobjects involved in the casting path didn't have their constructor started, the behavior is undefined.

Example...

Limitations on objects - object under (con|de)struction

```
struct A{  
    A(A*){}  
};  
struct B : A{  
    B() : A(this){}  
};
```

→ pointer to object, which ctor didn't start

Limitations on objects - object under (con|de)struction

```
struct C;  
struct B{  
    B(C*);  
};  
struct C{  
    C(B*);  
};  
struct D{  
    D() :  
        c(&b), // UB, b's ctor didn't start yet.  
        b(&c){}  
    C c; // constructed first  
    B b;  
};
```


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Lifetime of an object

No previously mentioned limitations exists when object is in its lifetime.

Object model intuition

The usual mindset towards object

- We have got a memory

...
24
42
...

The usual mindset towards object

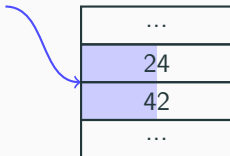
- We have got a memory
- Objects are the way to represent value in that memory

...
24
42
...

The usual mindset towards object

- We have got a memory
- Objects are the way to represent value in that memory

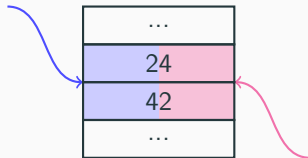
`std::complex<int8_t>`



The usual mindset towards object

- We have got a memory
- Objects are the way to represent value in that memory

`std::complex<int8_t>`



`std::pair<int8_t, int8_t>`

Examples of invalid C++ - union type punning

```
struct rgba{  
    uint8_t red;  
    uint8_t green;  
    uint8_t blue;  
    uint8_t alpha;  
};
```

```
union color{  
    rgba color;  
    uint32_t as_int;  
};
```

```
color c = {255, 120, 0, 50};  
display(c.as_int);
```

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Examples of invalid C++ - reinterpret_cast

```
struct T{  
    // ...  
};
```

```
T process_element(Stream& s){  
    alignas(T) unsigned char buff[sizeof(T)];  
    read_stream(s, buff);  
  
    auto* element = reinterpret_cast<T*>(buff);  
    return *element;  
}
```

Examples of invalid C++ - reinterpret_cast

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    alignas(T) unsigned char buff[sizeof(T)];  
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    auto* element = reinterpret_cast<T*>(buff);  
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}
```


Examples of invalid C++ - reinterpret_cast

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struct T{
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reinterpret_cast attempt 2

```
struct T{  
    // ...  
};  
  
T process_element(Stream& s){  
    alignas(T) char buff[sizeof(T)];  
    read_stream(s, buff);  
  
    T* element = new(buff) T;  
    return *element;  
}
```

But... why?

Why all the attempts are wrong?

Compiler **doesn't** think in terms of **objects and memory**

Why all the attempts are wrong?

Compiler **doesn't** think in terms of **objects and memory**

Compiler thinks in terms of **objects and their types**.

Test with two different class types

```
struct S{  
    int a;  
};
```

```
struct T {  
    int a;  
};
```

```
int test(S& val1, T& val2){  
    val1.a = 10;  
    val2.a = 2;  
  
    return val1.a+val2.a;  
}
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Q: What is the return value?

Test with two same structures

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}
```

Q: What is the return value now?

Assumptions, that compiler does

Code:

```
int test(S& val1, T& val2){  
    val1.a = 10;  
    val2.a = 2;  
  
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}
```

Assembly:

```
test(S&, T&):  
    mov r2, #10  
    mov r3, #2  
    str r2, [r0]  
    str r3, [r1]  
    mov r0, #12  
    bx lr
```

Assumptions, that compiler does

Code:

```
int test(S& val1, S& val2){  
    val1.a = 10;  
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}
```

Assembly:

```
test(S&, S&):  
    mov r3, #2  
    mov r2, #10  
    str r2, [r0]  
    str r3, [r1]  
    ldr r0, [r0]  
    add r0, r0, r3  
    bx lr
```


Conclusion

We cannot allow 2 complete objects of different types (not subobjects) live:

- in the same space.
- at the same time.

Explanations: type punning in union

```
struct rgba{  
    uint8_t red;  
    uint8_t green;  
    uint8_t blue;  
    uint8_t alpha;  
};
```

```
union color{  
    rgba color;  
    uint32_t as_int;  
};
```

```
color c = {255, 120, 0, 50};  
display(c.as_int);
```

errors:

- Accessing inactive member of union,

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```

```
color c = {255, 120, 0, 50};  
display(c.as_int);
```

errors:

- Accessing inactive member of union,
- Reading not existing object.

How to do it right?

```
struct color{
    uint8_t red(){
        return as_int>>24;
    }

    void red(uint8_t value){
        uint32_t r32 = static_cast<uint32_t>(red()) << (24);
        as_int ^= r32;
        as_int |= (static_cast<uint32_t>(value) << (24));
    }

    uint32_t as_int;
};
```

How to do it right?

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uint32_t as_int;  
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How to do it right?

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        as_int |= (static_cast<uint32_t>(value) << (24));
    }

    uint32_t as_int;
};
```

Explanations: reading from a stream

errors:


- reading object of type T, that was not created

```
struct T{  
    // ...  
};
```

```
T process_element(Stream& s){  
    alignas(T) unsigned char buff[sizeof(T)];  
    read_stream(s, buff);  
  
    auto* element = reinterpret_cast<T*>(buff);  
    return *element;  
}
```

How to do it right?

```
struct T{  
    // ...  
};
```



trivially copyable

```
T process_element(Stream& s){  
    unsigned char buff[sizeof(T)];  
    read_stream(s, buff);  
  
    T element;  
    std::memcpy(&element, buff, sizeof(T));  
    return element;  
}
```


How to do it right?

```
struct T{  
    // ...  
};
```



trivially copyable

```
T process_element(Stream& s){  
    unsigned char buff[sizeof(T)];  
    read_stream(s, buff);
```

```
    T element;  
    std::memcpy(&element, buff, sizeof(T));  
    return element;  
}
```

```
struct T{  
    // ...  
};  
  
T process_element(Stream& s){  
    unsigned char buff[sizeof(T)];  
    read_stream(s, buff);  
  
    return std::bit_cast<T>(buff);  
}
```

Explanations: reading from a stream - placement new

```
struct T{  
    // ...  
};
```

- placement new reuses the storage (ends lifetime of buff),

```
T process_element(Stream& s){  
    alignas(T) char buff[sizeof(T)];  
    read_stream(s, buff);  
  
    T* element = new(buff) T;  
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- placement new reuses the storage (ends lifetime of buff),
- value is a property of an object (doesn't exist outside of it's lifetime)
- T is created uninitialized
- reading T is reading indeterminate value, which is UB

Pointers and `std::launder`

But first... values

Value is **unique** and **abstract**. Noone can modify a value. (Cannot change '5' to mean '4').

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Objects have value. Objects can be changed and manipulated (Object can have value '5' or '4' in different time).

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Objects have their representation - a set of contiguous bytes in a memory.

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Objects have value. Objects can be changed and manipulated (Object can have value '5' or '4' in different time).

Objects have their representation - a set of contiguous bytes in a memory.

Values have their representations. In case of C++ it is a subset of object representation, that contributes to value.

Values and value representations

There might be multiple value representations of the same value.

Values and value representations

There might be **multiple value representations** of the same **value**.

Example:

floating point NaN - (exponent = 0xff, mantissa != 0)

Values of pointers

Values of pointers fall into one of the following categories:

- pointer to an object (set of many values)

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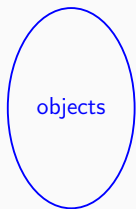
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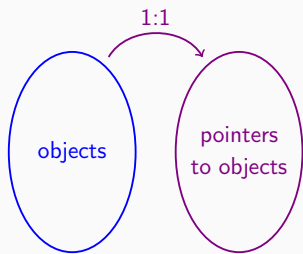
- pointer to an object (set of many values)
- pointer past an object (set of many values)
- invalid pointer (one value with many value representations)
- null pointer (one value with one representation)

Pointer to an object and invalid pointers



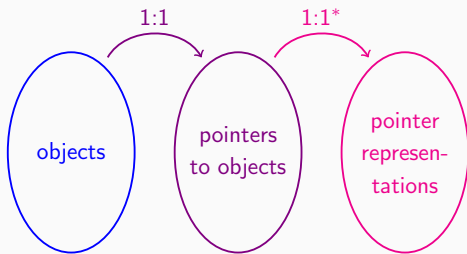
*with some simplifications.

Pointer to an object and invalid pointers



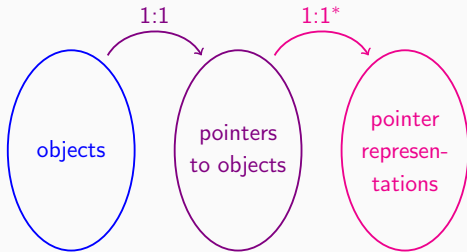
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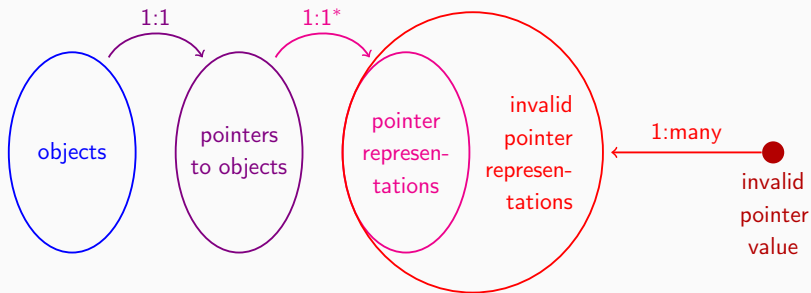
Pointer to an object and invalid pointers



●
invalid
pointer
value

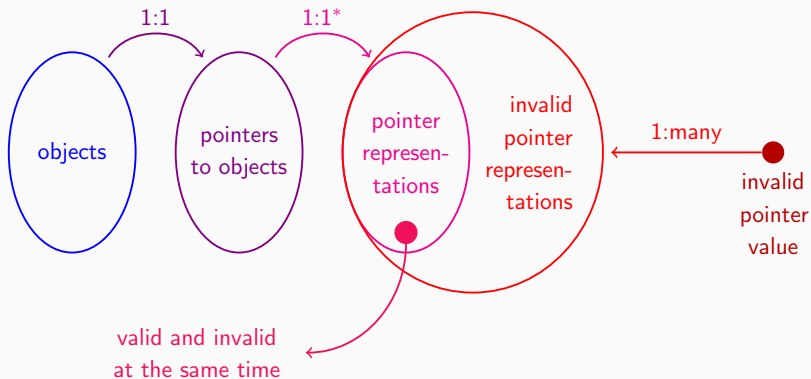
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Pointer to an object and invalid pointers



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Summary - pointers

value change \Rightarrow value representation change.

Pointers are exception to the rule!

You can change value of the pointer without changing its value representation.

Example:

```
struct T{
    //...
};

alignas(T) unsigned char
buff[sizeof(T)];
new(buff) T;
T* ptr =
    reinterpret_cast<T*>(buff);
//use ptr
```

- sometimes you know, there is an object of given type under given address.

Example:

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struct T{
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alignas(T) unsigned char
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```

- sometimes you know, there is an object of given type under given address.
- but you cannot just `reinterpret_cast` the pointer to get to the object.

What's the solution to the problem?

Until C++14 No solution. Go on with UB.

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Until C++14 No solution. Go on with UB.

Since C++17 `std::launder`.

What is std::launder?

Reading [cppreference](#):

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template <class T>  
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Usage of std::launder

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struct T{  
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};  
  
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valid

Other use-cases of the std::launder

```
struct T{  
    //...  
};
```



not assignable

```
T a;
```

```
T b;
```

```
// wild desire to assign ends with:
```

```
T* newa = new(&a) T(b);
```

```
use(*newa);
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Are those correct?

Rules for placement new for such cases

You can do placement new on old object with same type and keep using old object.

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With some exceptions (until C++20). For example:

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Rules for placement new for such cases

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With some exceptions (until C++20). For example:

- We cannot use original object when it has:
 - references
 - `const` members

Example: const member or reference

```
struct T{  
    const int a;  
    int& b;  
};
```

```
T a{/**/};
```

```
T b{/**/};
```

```
T* newa = new(&a) T(b);
```

```
use(*newa); // correct
```

```
use(a); // correct since C++20
```

```
use(*std::launder(&a)); // correct, possible since C++17
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Example: standard layout types

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    int a;  
    int b;  
};
```

```
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Implicit object creation

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Until C++20 there is one case of implicit object creation:

for defaulted, trivial assignment operators of union members.

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for defaulted, trivial assignment operators of union members.

What does that mean?

Implicit object creation for unions

```
struct T{  
    int a;  
    int b;  
};
```

```
union U{  
    T t;  
    char b;  
};
```

```
U u;  
u.t = T{42, 24};  
u.b = 'a';
```

Implicit object creation for unions

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    int a;  
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```
U u;  
u.t = T{42, 24};  
u.b = 'a';
```



correct

Implicit object creation for unions

```
struct T{  
    int a;  
    int b;  
    T& operator=(const T&){/**/}  
};
```

```
union U{  
    T t;  
    char b;  
};
```

```
U u;  
u.t = T{42, 24}; //UB  
u.b = 'a';
```


Implicit object creation for C++20

Implicit object creation in the C++20 will be extended for:

- malloc-like functions

```
struct T{/**/};  
struct T* ptr = (T*)  
    malloc(sizeof(struct T));
```

Implicit object creation for C++20

Implicit object creation in the C++20 will be extended for:

- malloc-like functions
- `operator new`

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struct T{/**/};  
T* ptr = (T*)  
           operator new(sizeof(T));
```

Implicit object creation for C++20

Implicit object creation in the C++20 will be extended for:

- malloc-like functions
- operator new
- `std::allocator<T>::allocate`

```
struct T{/**/};  
std::allocator<T> allocator;  
T* ptr = allocator.allocate(1);
```

Implicit object creation for C++20

Implicit object creation in the C++20 will be extended for:

- malloc-like functions
- operator new
- `std::allocator<T>::allocate`
- `memcpy`, `memmove`

```
alignas(T) unsigned char  
buff2[sizeof(T)];  
std::memcpy(buff2, buff1,  
            sizeof(buff2));  
T* ptr = (T*)buff;
```

Implicit object creation for C++20

Implicit object creation in the C++20 will be extended for:

- malloc-like functions
- operator new
- `std::allocator<T>::allocate`
- `memcpy`, `memmove`
- creation of arrays of:
 - `char`
 - `unsigned char`
 - `std::byte`

```
alignas(float) unsigned char  
buff[sizeof(float)];  
float* ptr = (float*)buff;
```

Summary

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- Do think about objects and its type not memory,

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Summary

- Do think about objects and its type not memory,
- Don't do the type-punning in C++,
- Be careful when using objects outside of their lifetimes.

Thank you!

I would like to say thank you to:

- All the people on CppLang [standardese] in helping me to understand standard wording,
- Richard Smith on making the implicit object creation proposal.

Further readings

blog.panicsoftware.com

Further readings

blog.panicsoftware.com

github.com/dawidpilarski/LifetimePresentation

Further readings

blog.panicsoftware.com

github.com/dawidpilarski/LifetimePresentation

Slack: [nav-cpp-cop](#)

Thank you!

Questions?

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