Lifetime of the C++ object

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Agenda

Theory

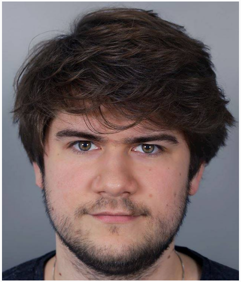
Object model intuition

Beyond the object lifetime.

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.cdtor]), throughout its lifetime, and in its period of destruction ([class.cdtor]). [*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
- refered 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;
```

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

Is a variable.

Is variable.

The variable

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

```
int x;
```

Is a variable.

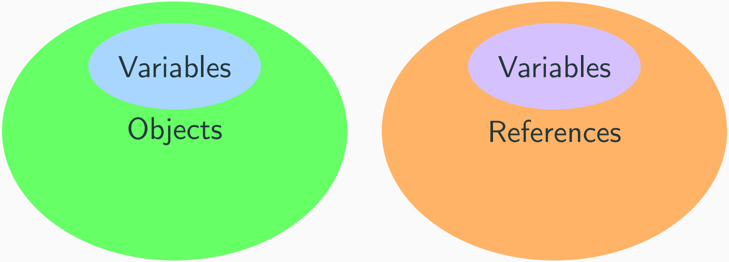
```
int& x = ...
```

Is variable.

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

Neither `X` nor `z` are variables.
`x` is a variable.

Summary: variable, reference, object



Definitions

If you want to get precise definitions, you need to look at standard draft.
In case of cppreference:

- The object has been recently updated.

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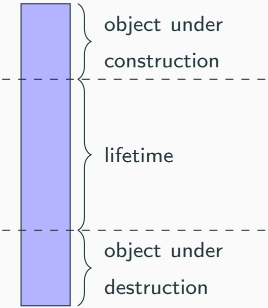
If you want to get precise definitions, you need to look at standard draft.
In case of cppreference:

- The object has been recently updated.
- The variable definition is unmaintained and unsupported.
- Same about references...

Lifetime

What is a lifetime?

Lifetime is a runtime 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

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- 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,

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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.

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

...
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The usual mindset towards object

- We have got a memory
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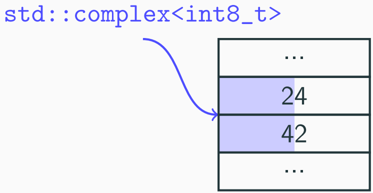
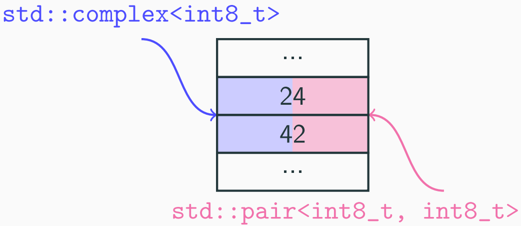


The usual mindset towards object

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



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);
```

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;
}
```

reinterpret_cast attempt 2

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

T process_element(Stream& s){
  alignas(T) unsigned 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 - int + float

```
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;
}
```

Test - int + float

```
struct S{
    int a;
};

struct T {
    int a;
};

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

Q: What is the return value?

Test - int + int

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struct S{
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Test - int + int

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struct S{
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int test(S& val1, S& val2){
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}
```

Q: What is the return value?

Assumptions, that compiler does

Code:

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

  return val1.a+val2.a;
}
```

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;
  val2.a = 2;

  return val1.a+val2.a;
}
```

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 different objects (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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  uint32_t as_int;
};

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){
      auto* as_bytes =
            reinterpret_cast<unsigned char*>(&as_int);
      as_bytes[3] = value;
  }

  uint32_t as_int;
};
```

How to do it right?

```
struct color{
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      as_bytes[3] = value;
  }

  uint32_t as_int;
};
```

Additional benefit: No endianess issue here!

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{
  // ...
};

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

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

Or with C++20

```
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{
  // ...
};

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

  T* element = new(buff) T;
  return *element;
}
```

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

Explanations: reading from a stream - placement new

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struct T{
  // ...
};

T process_element(Stream& s){
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- placement new reuses the storage (ends lifetime of buff),
- value is a runtime property of an object (doesn't exist outside of it's lifetime)

Explanations: reading from a stream - placement new

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- placement new reuses the storage (ends lifetime of buff),
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- T is created uninitialized

Explanations: reading from a stream - placement new

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  T* element = new(buff) T;
  return *element;
}
```

- placement new reuses the storage (ends lifetime of buff),
- value is a runtime 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

std::launder

Tricky placement new

```
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.

Tricky placement new

```
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.
- 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:

```
template <class T>
constexpr T* launder(T* p) noexcept;
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What is std::launder?

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Obtains a pointer to the object located at the address represented by p.

What is std::launder?

Reading cppreference:

```
template <class T>
constexpr T* launder(T* p) noexcept;
```

Obtains a pointer to the object located at the address represented by p.

Usage of std::launder

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

alignas(T) unsigned char
buff[sizeof(T)];
new(buff) T;
T* ptr = std::launder((T*)buff);
//use ptr
```

Other use-cases of the std::launder

```
struct T{
  // not assignable
};

T a;
T b;

//...

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

use(*newa);
use(a);
```

Is this code valid? (drawings)

Rules for placement new for such cases

You can do placement new on old object.

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Not always we can use original object (until C++20). For example:

- We cannot use original object when it has:

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  - references

Rules for placement new for such cases

You can do placement new on old object.
Not always we can use original object (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
```

Example: standard layout types

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

T a{/**/};
T b{/**/};

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

use(*newa); // correct
use(a); // correct
use(*std::launder(&a)); // correct, possible since C++17
```

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

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

```
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{/**/};
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

```
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 = std::launder((T*)buff);
```

Implicit object creation for C++20

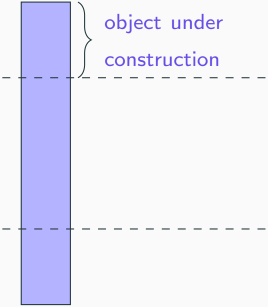
Implicit object creation in the C++20 will be extended for:

- 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 = std::launder(
                  (float*)buff);
```

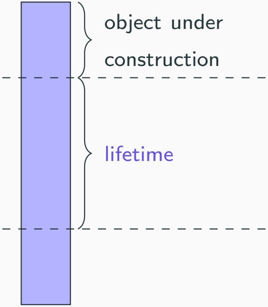
Beyond the object lifetime.

Lifetime

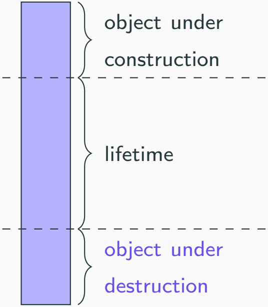


Not for `trivially_constructible` types

Lifetime



Lifetime



Not for `trivially_destructible` types. Optional for other types.

Concurrent access and vptr

```
struct A{
  A(){foo();}
  virtual void foo(){
    std::cout << "A" << std::endl;
  }
};

struct B : A{
  void foo() override {
    std::cout << "B" << std::endl;
  }
}

B b;
```

Concurrent access and vptr

```
struct A{
  ~A(){foo();}
  virtual void foo(){
    std::cout << "A" << std::endl;
  }
};

struct B : A{
  void foo() override {
    std::cout << "B" << std::endl;
  }
}

B b;
```

Avoid synchronisation in dtors

```
struct container : containerInterface{
  // some implementation

  ~container{
    m_.lock();
    // perform cleanup
    m_.unlock();
  }

private:
  std::mutex m_;
  //...
};
```

Summary

Do not call virtual functions beyond the lifetime of an object!

dynamic_cast and type_id

`Dynamic cast` and `typeid` cannot be used during construction or destruction if they don't refer to the base or current objects.

dynamic_cast and type_id examples

```
struct V { virtual void f();};
struct A : virtual V {};
struct B : virtual V { B(V*, A*);};

struct D : A, B {
  D() : B((A*)this, this) { }
};

B::B(V* v, A* a) {
  //B ctor - the D object is not yet fully constructed
  typeid(*this);        // correct: type_info for B.
  typeid(*v);           // correct: v points the V subobject, which is the base
  typeid(*a);           // undefined behavior: A is not a base of B - might be n
  dynamic_cast<B*>(v); // correct: v points V subobject, which is the base of B
  dynamic_cast<B*>(a); // undefined behavior, a points the  A subobject, which
}
```

dynamic_cast and type_id examples

```
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;
    std::cout << dynamic_cast<void*>(this) << std::endl;
}

Derived d;
```

Output:

4Base 0 0x7ffe5133e4c8

Summary

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- Do think about objects and its type not memory,

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- Don't do the type-punning in C++,

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- 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!

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Thank you!

Questions?

Thank you!

Thank you!