EDAF50 – C++ Programming

4. Classes

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Outline

User-defined types
Categories

- Concrete classes
- Abstract classes
- Class hierarchies

User-defined types
Concrete classes

A concrete type

- "behaves just like a built-in type"
- its representation is part of its definition,
  That allows us to
  - refer to objects directly (not just using pointers or references)
  - initialize objects directly and completely (with a *constructor*)
  - place objects
    - on the stack (i.e., local variables)
    - in other objects (i.e., member variables)
    - in statically allocated memory (e.g., global variables)
  - copy objects
    - assignment of a variable
    - copy-constructing an object
    - value parameter of a function

Constructors

Default constructor

- A constructor that can be called without arguments
  - May have parameters that all have default values
- Automatically defined if *no constructor is defined* (in declaration: `=default`, cannot be called if `=delete`)
- If not defined, the type is *not default constructible*

Default constructor with member initializer list.

```
class Bar {
public:
    Bar(int v=100, bool b=false) :value{v},flag{b} {}
private:
    int value;
    bool flag;
};
```

Constructors
Default constructor

Default arguments

- If a constructor can be called without arguments, it is a default constructor.

```
class KomplextTal {
public:
    KomplextTal(float x=1):re(x),im(0) {}
    //...
};
```

gives the same default constructor as the explicit

```
    KomplextTal():re{1},im{0} {}
```

Constructors
Two ways of initializing members

With member initializer list in constructor

```
class Bar {
public:
    Bar(int v, bool b) :value{v},flag{b} {}
private:
    int value;
    bool flag;
};
```

Members can have a *default initializer*, in C++11:

```
class Foo {
public:
    Foo() =default;
private:
    int value {0};
    bool flag {false};
};
```

- prefer default initializer to overloaded constructors or default arguments

Constructors
Initialization and assignment

It is (often) *possible* to write like in Java, but

- it is less efficient
- the members must be *default constructible* and *assignable*

Java-style: assignment in constructor

```
class Foo {
public:
    Foo(const Bar& v) {
        value = v;  NB! assignment, not initialization
    }
private:
    Bar value; is default constructed before the body of the constructor
};
```

*An object is initialized **before** the body of the constructor is run*

```cpp
class Foo{
public:
    Foo(int x) :x{x} {}
    // ...
private:
    int x{};
};

class Bar{
public:
    Bar(int x) {x = x;}
    // ...
private:
    int x{};
};
```

```
warning: explicitly assigning value of variable of type 'int'
        to itself; did you mean to assign to member 'x'?
        [-Wself-assign]
    Bar(int x) {x = x;}
                ~ ^ ~
                this->
```

Constructors
Member initialization rules

```
class Bar {
public:
    Bar() =default;
    Bar(int v, bool b) :value{v},flag{b} {}
private:
    int value {0};
    bool flag {true};
};
```

- If a member has both *default initializer* and a member initializer in the constructor, the constructor is used.
- Members are initialized *in declaration order*. (Compiler warning if member initializers are in different order.)
- `Bar() =default;` is necessary to make the compiler generate a default constructor (as another constructor is defined)

.

Constructors
Prefer default member initializers

Use default member initializers if class member variables have default values.

Default argument values and overloaded ctors: risk of inconsistency

```
class Simple {
public:
    Simple()                               :a(1), b(2), c(3) {}
    Simple(int aa)                         :a(aa), b(0), c(0) {}
    Simple(int aa, int bb, int cc=-1) :a(aa), b(bb), c(cc) {}
private:
    int a;
    int b;
    int c;
};
```

Constructors
Prefer default member initializers

Use default member initializers if class member variables have default values.

With default initializers: consistent

```
class Simple {
public:
    Simple() =default;
    Simple(int aa)                  :a(aa) {}
    Simple(int aa, int bb)          :a(aa), b(bb) {}
    Simple(int aa, int bb, int cc) :a(aa), b(bb), c(cc) {}
private:
    int a {-1};
    int b {-1};
    int c {-1};
};
```

Constructors
Default constructor and parentheses

In a variable declaration, the default constructor *cannot be called with empty parentheses*.

```
Bar b1;
Bar b2{};
Bar be();   // Not a variable declaration!  "most vexing parse"
Bar b3(25); // OK

Bar* bp1 = new Bar;
Bar* bp2 = new Bar{};
Bar* bp3 = new Bar(); //OK
```

NB! The compiler error will be at the *use* of `be` e.g.,

```
be.fun();
```

```
request for member 'fun' in 'be', which is of non-class type 'Bar()'
```

Default constructor and initialization

- *automatically generated* default constructor (=**default**) *does not always* initialize members
  - *global variables* are initialized to 0 (or corresponding)
  - *local variables* are not initialized *(different meaning from Java)*

```
struct A { int x; };

int i; // i is initialized to 0 (global variable)
A a;   // a.x is initialized to  0 (global variable)

int main() {
    int j;          // j is uninitialized
    int k = int();  // k is initialized to 0
    int l{};        // l is initialized to 0

    A b;            // b.x is uninitialized
    A c = A();      // c.x is initialized to 0
    A d{};          // d.x is initialized to 0
}
```

Default constructor and initialization
Advice

- The *automatically generated* default constructor (=**`default`**) *does not always* initialize members

- To be on the safe side:
  - *always initialize variables*
  - *always implement default constructor (or =**`delete`**)*
    (incl. giving all members default initializers and use =**`default`**)

In C++11 a constructor can call another (like `this(...)` in Java).

```
struct Test{
    int val;

    Test(int v) :val{v} {}

    Test(int v, int scale) :Test(v*scale) {};     // delegation

    Test(int a, int b, int c) :Test(a+b+c) {};    // delegation
};
```

A delegating constructor call shall be *the only member-initializer.*
(A constructor initializes an object *completely*.)

A concrete type

- "behaves just like a built-in type"
- the representation is part if the definition,
  That allows us to
  - place objects
    - on the stack (i.e., local variables)
    - in other objects (i.e., member variables)
    - in statically allocated memory (e.g., global variables)
  - copy objects
    - assignment of a variable
    - copy-constructing an object
    - value parameter of a function
  - refer to objects directly (not just using pointers or references)
  - initialize objects directly and completely (with a *constructor*)

Constructors

Copy Constructor

- Is called when initializing an object
- Is *not called* on assignment
- Can be defined, otherwise a standard copy constructor is generated (`=default`, `=delete`)

```
Bar b1(10,false);

Bar b2{b1};          // the copy constructor is called
Bar b3(b2);          // the copy constructor is called
Bar b4 = b2;         // the copy constructor is called

void function(Bar); // by-value parameter

function(b2);        // the copy constructor is called
```

Copy Constructors
default

- Declaration:

```
class C {
public:
    C(const C&) =default;
};
```

- default copy constructor
  - Is automatically generated if not defined in the code
    - exception: if there are members that cannot be copied
  - But do declare it `=default` when you want it.
  - *shallow copy* of each member
    - Works for member variables of built-in types,
    - or *classes that behave like built-in types* (RAII-types)
    - *Does not work* for classes which manage resources "manually" (More on this later)

Classes
Example: Copying the Vector class

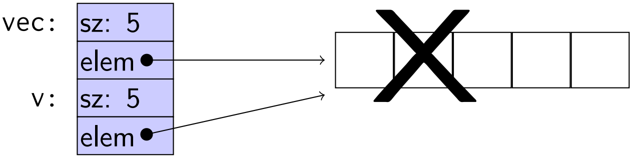
```
class Vector{
public:
    Vector(int s) :sz{s},elem{new double[s]} {}
    ~Vector() {delete[] elem;}
    double& operator[](int i) {return elem[i];}
    int size() {return sz;}
private:
    int sz;
    double* elem;
};
```

No copy constructor defined ⇒ default generated.

Classes
Default copy construction: shallow copy

```
void f(Vector v);

void test()
{
    Vector vec(5);
    f(vec); // call by value -> copy
    // ... other uses of vec
}
```



- The parameter `v` is default copy constructed: the value of each member variable is copied
- When `f()` returns, the destructor of `v` is executed: `delete[] elem;`
- The array pointed to *by both copies* is deleted. Disaster!

Constructors
Special cases: zero or one argument

Copy Constructor

- Has the same class as parameter: `Bar::Bar(const Bar& b);`

Converting constructor

- A constructor that can be called with one argument defines an *implicit type conversion* from the type of the parameter

```
class ComplexNumber {
public:
    ComplexNumber():re{0},im{0} {}
    ComplexNumber(const ComplexNumber& k) :re{k.re},im{k.im} {}
    ComplexNumber(double x, double i=0):re{x},im{i} {}
    //...
private:
    double re;
    double im;
};
```

default constructor   copy constructor   converting constructor

Converting constructor
Warning - implicit conversion

```
class Vector{
public:
    Vector(int s);    // create Vector with size s
    ...
    int size() const; // return size of Vector
    ...
};

void example_vector()
{
    Vector v = 7;

    std::cout << "v.size(): " << v.size() << std::endl;

}
```

```
v.size(): 7
```

In `std::vector` the corresponding constructor is declared

```
    explicit vector( size_type count );
```

Converting constructor and `explicit`

`explicit` specifies that a constructor does not allow implicit type conversion.

```
struct A                          struct B
{                                 {
  A(int);                           explicit B(int);
  // ...                            // ...
};                                };
```

```
A a1(2);       // OK               B b1(2);       // OK
A a2 = 1;      // OK               B b2 = 1;      // Error! [2]
A a3 = (A)1;   // OK               B b3 = (B)1;   // OK: explicit cast

a3 = 17;       // OK [1]           b3 = 17;       // Error! [3]
```

```
[1]: construct an A(17), and then copy
[2]: conversion from 'int' to non-scalar type 'B' requested
[3]: no match for 'operator=' (operand types are 'B' and 'int')
```

Copying objects
Difference between *construction* and *assignment*

```
Bar b1(10,false};

Bar b2{b1};          // the copy constructor is called
Bar b3(b2);          // the copy constructor is called
Bar b4 = b2;         // the copy constructor is called

void function(Bar); // by-value parameter

function(b2);        // the copy constructor is called

b4 = b3;             // the copy constructor is not called
```

copy assignment – not construction

Copying objects
the *copy assignment* operator: `operator=`

The *copy assignment operator* is implicitly defined

- with the type `T& T::operator=(const T&)`
- if no copy assignment operator is declared for the type
- if all member variables can be copied
  - i.e., define a copy-assignment operator
- If all members are of built-in (and RAII) types the default variant works (same problems as with copy ctor).
- More on copy control when we discuss resource management

Preventing copying

- Declaration:

```
class C {
public:
    C(const C&) =delete;
    C& operator=(const C&) =delete;
};
```

- A class without copy constructor and copy assignment operator cannot be copied.
  - C++-98: declare private and don't define

Operator overloading

A user-defined type can behave like a built-in type

- Operators can be overloaded
  - as member functions (sometimes)
  - as free functions

Syntax: `return_type` **`operator`**$\otimes$ `(parameters...)`
for an operator $\otimes$ e.g. $==$ or $+$

E.g, `bool operator==(const Foo&, const Foo&);`

Operator overloading

Most operators can be overloaded, except

```
sizeof  .  .*  ::  ?:
```

E.g., these operators can be overloaded

```
=
+ - * / %
^ & | ~
<< >>
&& || !
!= == < >
++ -- += *= .......
() []
-> ->*
&
new delete new[] delete[]
```

Operator overloading

For classes, two possibilities:

- as a member function
  - for binary operators, if the order of operands is suitable
    - a binary operator takes *one argument*
    - `*this` is the left operand,
    - the function argument is the right operand
- as a *free* function
  - if the public interface is enough, *or*
  - if the function is declared **friend**

friend

Functions or classes with access to all members in a class without being members themselves

Friend declaration in the class ComplexNumber

```
class ComplexNumber{
    //...
private:
    int re;
    int im;
    friend ostream& operator<<(ostream&, const ComplexNumber&);
};
```

Definition of the free function **operator**<<

```
ostream& operator<<(ostream& o, const ComplexNumber& c) {
    return o << c.re << "+" c.im << "i";
}
```

The free function **operator**<<(ostream&, **const** ComplexNumber&) can access private members in ComplexNumber.

friend

Functions or classes with *full access to all members* in a class without being members themselves

- Free functions,
- member functions of other classes, or
- entire classes can be friends.
- cf. package visibility in Java
- A friend declaration is not part of the class interface, and can be placed *anywhere in the class definition*.

Operator overloading
as member function and as free function

Example: declaration as member functions

```
class Komplex {
public:
    Komplex(double r, double i) : re(r), im(i) {}
    Komplex operator+(const Komplex& rhs) const;
    Komplex operator*(const Komplex& rhs) const;
    // ...
private:
    double re, im;
};
```

Example: declaration of `operator+` as `friend`

Declaration inside the class definition of `Komplex`:

```
friend Komplex operator+(const Komplex& l, const Komplex& r);
```

Note the number of parameters

Operator overloading

Defining **operator+** in two ways:

- As member function (one parameter)

```
Komplex Komplex::operator+(const Komplex& rhs)const{
    return Komplex(re + rhs.re, im + rhs.im);
}
```

- As a free function (two parameters)

```
Komplex operator+(const Komplex& lhs, const Komplex& rhs){
    return Komplex(lhs.re + rhs.re, lhs.im + rhs.im);
}
```

*NB! the **friend** declaration is only in the class definition*

Operator overloading

Defining **operator+** in two ways:

- As member function

```
Komplex Komplex::operator+(const Komplex& rhs)const{
    return Komplex(re + rhs.re, im + rhs.im);
}
```

the right operand cannot be changed

the left operand cannot be changed

- As a free function

```
Komplex operator+(const Komplex& lhs, const Komplex& rhs){
    return Komplex(lhs.re + rhs.re, lhs.im + rhs.im);
}
```

NB! the **friend** *declaration is only in the class definition*

Operator overloading
Another implementation of +, using +=

Class definition

```
class Komplex {
public:
    Komplex& operator+=(const Komplex& z) {
        re += z.re;
        im += z.im;
        return *this;
    }
    // ...
};
```

Free function, does not need to be `friend`

```
Komplex operator+(Komplex a, const Komplex& b) {
    return a+=b;
}
```

NB! *call by value*: we want to return *a copy*.

Conversion and increment operators
Exempel: `Counter`

Conversion to **int**

```
struct Counter{
    Counter(int c=0) :cnt{c} {};
    operator int() const {return cnt;}
    Counter& operator++() {++cnt; return *this;}
    Counter operator++(int) {Counter res(cnt++); return res;}
private:
    int cnt;
};
```

Note: **operator** `T()`.

- no return type in declaration (must obviously be `T`)
- can be declared **explicit**
- two overloads for **operator**++. Dummy int parameter for postincrement.

Function calls and results
Returning objects by value

- A function cannot return references to local variables
  - the object is destroyed at **`return`** – *dangling reference*
- How (in)efficient is it to return objects by value (a copy)?

return value optimization (RVO)

The compiler may optimize away copies of objects on **`return`** from functions

- *return by value* often efficient, also for larger objects
- RVO allowed *even if the copy-constructor or destructor has side effects*
- avoid such side effects to make code portable

Rules of thumb for function parameters

- Return by value more often
- Do not over-use call-by-value

"reasonable defaults"

	cheap to copy	moderately cheap to copy	expensive to copy
In	`f(X)`	`f(const X&)`	
In/Out	`f(X&)`		
Out	`X f()`		`f(X&)`

For results, if the cost of copying is

- small, or moderate ($< 1k$, contiguous): return by value (modern copilers do RVO: return value optimization)
- large : call by reference as *out parameter*
  - or maybe allocate with **new** and return pointer

Call by reference or by value?
Rules of thumb

For passing an object to a function when

- you may want *to change the value* of the object
  - reference: `void f(T&);` or
  - pointer: `void f(T*);`
- you *will not* change it, it is *large* (or impossible to copy)
  - constant reference: `void f(const T&);`
- otherwise, *call by value*
  - `void f(T);`

reference or pointer?

- required parameter: pass reference
- optional parameter: pass pointer (can be `nullptr`)

```
void f(widget& w)
{
    use(w); //required parameter
}

void g(widget* w)
{
    if(w) use(w); //optional parameter
}
```

Call by reference or by value?

- How big is "large"?
  - more than a few *words*
- When to use out parameters?
  - prefer code that is obvious

    Example: two functions:

    ```
    void incr1(int& x)
    {
        ++x;
    }

    int incr2(int x)
    {
      return x + 1;
    }
    ```

    Use:

    ```
    int v = 0;
    ...
    incr1(v);
    ...
    v = incr2(v);
    ```

    Here it is much clearer that v = incr2(v) changes v
  - For multiple output values, consider returning a **struct**, a std::pair or a std::tuple

Rules of thumb for function parameters

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- Do not over-use call-by-value

"reasonable defaults"

	cheap to copy	moderately cheap to copy	expensive to copy
In	`f(X)`	`f(const X&)`	
In/Out	`f(X&)`		
Out	`X f()`		`f(X&)`

Static members

static members: shared by all objects of the type (like Java)

- *declared* in the class definition
- *defined* outside class definition (if not **`const`**)
- can be **`public`** or **`private`** (or **`protected`**)

Static members
Example: count allocations and deallocations

```
class Foo {
private:
    static int created;
    static int alive;
public:
    Foo() {++created; ++alive;}
    ~Foo() {--alive;}

    static void print_counts();
};
```

Definitions: *NB! without static*

```
int Foo::created{0};
int Foo::alive{0};

void Foo::print_counts()
{
    cout << alive << " / ";
    cout << created << endl;
}
```

```
void test_lifetimes()
{
    {
        Foo a;
        a.print_counts();

        Foo b;
        b.print_counts();
    }

    {
        Foo c;
        Foo::print_counts();
    }
    Foo::print_counts();
}
```

```
1 / 1
2 / 2
1 / 3
0 / 3
```

Static members
Example: count allocations and deallocations

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class Foo {
private:
    static int created;
    static int alive;
public:
    Foo() {++created; ++alive;}
    ~Foo() {--alive;}

    static void print_counts();
};
```

Definitions: *NB! without static*

```
int Foo::created{0};
int Foo::alive{0};

void Foo::print_counts()
{
    cout << alive << " / ";
    cout << created << endl;
}
```

```
void test_lifetimes()
{
    {
        Foo a;
        a.print_counts();

        Foo b;
        b.print_counts();
    }

    {
        Foo c;
        Foo::print_counts();
    }
    Foo::print_counts();
}
```

```
1 / 1
2 / 2
1 / 3
0 / 3
```

Static members

Example: count allocations and deallocations

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    Foo() {++created; ++alive;}
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    static void print_counts();
};
```

Definitions: *NB! without static*

```
int Foo::created{0};
int Foo::alive{0};

void Foo::print_counts()
{
    cout << alive << " / ";
    cout << created << endl;
}
```

```
void test_lifetimes()
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    {
        Foo a;
        a.print_counts();

        Foo b;
        b.print_counts();
    }

    {
        Foo c;
        Foo::print_counts();
    }
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}
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1 / 1
2 / 2
1 / 3
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Static members
Example: count allocations and deallocations

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    static int created;
    static int alive;
public:
    Foo() {++created; ++alive;}
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    static void print_counts();
};
```

Definitions: *NB! without static*

```
int Foo::created{0};
int Foo::alive{0};

void Foo::print_counts()
{
    cout << alive << " / ";
    cout << created << endl;
}
```

```
void test_lifetimes()
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    {
        Foo a;
        a.print_counts();

        Foo b;
        b.print_counts();
    }

    {
        Foo c;
        Foo::print_counts();
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    Foo::print_counts();
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1 / 1
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Static members
Example: count allocations and deallocations

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class Foo {
private:
    static int created;
    static int alive;
public:
    Foo() {++created; ++alive;}
    ~Foo() {--alive;}

    static void print_counts();
};
```

Definitions: *NB! without static*

```
int Foo::created{0};
int Foo::alive{0};

void Foo::print_counts()
{
    cout << alive << " / ";
    cout << created << endl;
}
```

```
void test_lifetimes()
{
    {
        Foo a;
        a.print_counts();

        Foo b;
        b.print_counts();
    }

    {
        Foo c;
        Foo::print_counts();
    }
    Foo::print_counts();
}
```

```
1 / 1
2 / 2
1 / 3
0 / 3
```

Suggested reading

References to sections in Lippman

Classes	2.6, 7.1.4, 7.1.5
Constructors	7.5–7.5.4
(Aggregate classes)	("C structs" without constructors) 7.5.5
Destructors	13.1.3
this and const	p 257–258
inline	6.5.2, p 273
friend	7.2.1
static members	7.6
Copying	13.1.1
Assignment	13.1.2
Operator overloading	14.1 – 14.3

Next lecture

References to sections in Lippman

Dynamic memory and smart pointers 12.1

Dynamically allocated arrays 12.2.1

Classes, resource management 13.1, 13.2

Moving objects 13.6

Type casts 4.11

Function calls and results
Returning objects by value

- A function cannot return references to local variables
  - the object is destroyed at **`return`** – *dangling reference*
- How (in)efficient is it to return objects by value (a copy)?

return value optimization (RVO)

The compiler may optimize away copies of objects on **`return`** from functions

- *return by value* often efficient, also for larger objects
- RVO allowed *even if the copy-constructor or destructor has side effects*
- avoid such side effects to make code portable

Rules of thumb for function parameters

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- Do not over-use call-by-value

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- large : call by reference as *out parameter*
  - or maybe allocate with **new** and return pointer

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  - reference: `void f(T&);` or
  - pointer: `void f(T*);`
- you *will not* change it, it is *large* (or impossible to copy)
  - constant reference: `void f(const T&);`
- otherwise, *call by value*
  - `void f(T);`

reference or pointer?

- required parameter: pass reference
- optional parameter: pass pointer (can be `nullptr`)

```
void f(widget& w)
{
    use(w); //required parameter
}

void g(widget* w)
{
    if(w) use(w); //optional parameter
}
```

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- How big is "large"?
  - more than a few *words*
- When to use out parameters?
  - prefer code that is obvious

    Example: two functions:

    ```
    void incr1(int& x)
    {
        ++x;
    }

    int incr2(int x)
    {
      return x + 1;
    }
    ```

    Use:

    ```
    int v = 0;
    ...
    incr1(v);

    ...
    v = incr2(v);
    ```

    Here it is much clearer that `v = incr2(v)` changes v
  - For multiple output values, consider returning a **struct**, a `std::pair` or a `std::tuple`

Rules of thumb for function parameters

- Return by value more often
- Do not over-use call-by-value

"reasonable defaults"

	cheap to copy	moderately cheap to copy	expensive to copy
In	`f(X)`	`f(const X&)`	
In/Out	`f(X&)`		
Out	`X f()`		`f(X&)`

Static members

static members: shared by all objects of the type (like Java)

- *declared* in the class definition
- *defined* outside class definition (if not **`const`**)
- can be **`public`** or **`private`** (or **`protected`**)

Static members
Example: count allocations and deallocations

```
class Foo {
private:
    static int created;
    static int alive;
public:
    Foo() {++created; ++alive;}
    ~Foo() {--alive;}

    static void print_counts();
};
```

Definitions: *NB! without static*

```
int Foo::created{0};
int Foo::alive{0};

void Foo::print_counts()
{
    cout << alive << " / ";
    cout << created << endl;
}
```

```
void test_lifetimes()
{
    {
        Foo a;
        a.print_counts();

        Foo b;
        b.print_counts();
    }

    {
        Foo c;
        Foo::print_counts();
    }
    Foo::print_counts();
}
```

```
1 / 1
2 / 2
1 / 3
0 / 3
```

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