C++ Course 8 : Classes 2

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Operator overloading

Operator **+** :

int a = 3 + 2; // int + int : built-in, no questions

string s1 = "Hello "s + "World"s; // string + string, how does it work ?

string s2 = string("Hello ") + "World"; // string + const char[] ???

Suppose we have created our own class **MyClass**.

How can we implement operator **+** for it?

MyClass m1(1), m2(2);

MyClass m3 = m1 + m2; // How to do this?

MyClass m4 = MyClass(1) + MyClass(2); // Or like this

Solution: C++ *operator overloading*: **m1 + m2** is a shortcut for either

MyClass m = operator+(m1, m2); // Overloaded function, a "non-member operator"

OR

MyClass m = m1.operator+(m2); // Method, a "member operator"

Operators that can be overloaded

<table>
<tr><th colspan="6">Table 14.1: Operators</th></tr>
<tr><th colspan="6">Operators That May Be Overloaded</th></tr>
<tr><td>+</td><td>-</td><td>*</td><td>/</td><td>%</td><td>^</td></tr>
<tr><td>&</td><td>|</td><td>~</td><td>!</td><td>,</td><td>=</td></tr>
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<tr><td><<</td><td>>></td><td>==</td><td>!=</td><td>&&</td><td>||</td></tr>
<tr><td>+=</td><td>-=</td><td>/=</td><td>%=</td><td>^=</td><td>&=</td></tr>
<tr><td>|=</td><td>*=</td><td><<=</td><td>>>=</td><td>[]</td><td>()</td></tr>
<tr><td>-></td><td>->*</td><td>new</td><td>new []</td><td>delete</td><td>delete []</td></tr>
<tr><th colspan="6">Operators That Cannot Be Overloaded</th></tr>
<tr><td></td><td>::</td><td>.*</td><td>.</td><td>?:</td><td></td></tr>
</table>

Cannot create new operators !

Operators are often **inline**. **noexcept** is a good idea.

Non-member operators are usually **friend**.

Operator parameter types, return type, behavior

??? operator+ (??? lhs, ??? rhs) { ... }

Operator parameter types and return type can be (almost) anything.
But usually we want **+** to have some kind of "addition" semantics.
Typically parameters and the return type are of the same type:
MyClass operator+ (const MyClass & lhs, const MyClass & rhs) { ... }

Note: Overloaded operators often include versions for implicit type conversion.
For example, for **string**, there are several overloaded versions of **operator+**:
string operator+ (const string & lhs, const string & rhs);
string operator+ (const string & lhs, const char * rhs);
string operator+ (const char * lhs, const string & rhs);
You can add a **std::string** to a C-string (but not two C-strings !)
Remember, functions **operator+** are all overloads of the same name!
Beware of *ambiguity* ! Especially with *non*-**explicit** constructors and cast operators!

Example 1: Vec2 : 2-dimensional vector (x, y)

Let us design our own class: a 2D vector.

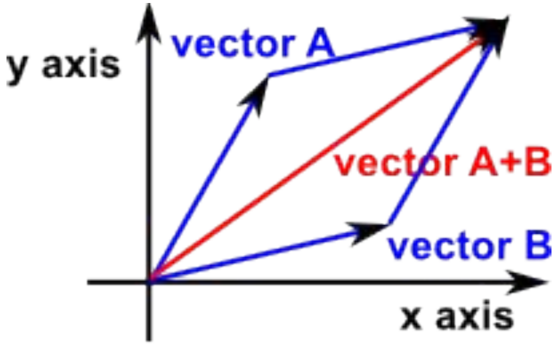
Let us overload various operators (**+**, **==** etc.).

Two private fields : **x**, **y**.

Getters and setters are not shown (see the full example in the repo).

Note: No custom copy/move operation in this class ! Standard copy behavior is OK.

```
class Vec2{
public:  //===== Methods
        Vec2(double x, double y) : x(x), y(y) {}        /// xy ctor
        Vec2() = default;                          /// Default (no-par) ctor
        ...
private: //===== Data
    double x = std::nan("");   // Two private fields
    double y = std::nan("");
};
```



Operators: Members or Non-Members :

Operators can be members (methods) or non-members (friend functions) :

```
class Vec2 { ...
    Vec2 operator+(const Vec2 & rhs);   // Member
    friend Vec2 operator-(const Vec2 & lhs, const Vec2 & rhs); // Declare as friend
};   // End of class Vec2
Vec2 operator-(const Vec2 & lhs, const Vec2 & rhs);   // Non-Member
```

1. Must be members: **=, [], (), ->**

2. Usually members: special assignment and unary: **+=, ++,** unary ***, - ...**

3. Usually non-members: regular binary: **+, <, ==, ...**

Comparison : operator==, operator!=

Non-member:

```
class Vec2 { ... // Binary operators are usually non-members (friend functions)
    friend bool operator==(const Vec2 & lhs, const Vec2 & rhs)  noexcept; // Returns bool
    ...
};   // End of class Vec2
inline bool operator==(const Vec2 & lhs, const Vec2 & rhs)  noexcept {
   if (& lhs == & rhs)              // Optional, check if it is the same object
      return true;
   else  // Compare all fields
      return (lhs.x == rhs.x) && (lhs.y == rhs.y);
} // reflexive, symmetric and transitive
inline bool operator!=(const Vec2 & lhs, const Vec2 & rhs)  noexcept {
   return !(lhs == rhs);   // The proper way to define operator!= is via operator==
}  // Now operator== and operator!= are consistent !
```

Note : *inheritance* and **operator==** is a *bad* combination!

Comparison: operator<

Non-member binary operators: should be consistent with each other !

```
inline bool operator<(const Vec2 & lhs, const Vec2 & rhs) noexcept  {
        if (lhs.x == rhs.x)   // The only comparison actually implemented !
                return lhs.y < rhs.y;          // In our example, x is more important that y
        else
                return lhs.x < rhs.x ;
}  // I know 2D vectors cannot be compared, just an example !
inline bool operator>(const Vec2 & lhs, const Vec2 & rhs) noexcept {
    return rhs < lhs;    // Use existing operator<
}
inline bool operator<=(const Vec2 & lhs, const Vec2 & rhs) noexcept  {
    return !(lhs > rhs);   // Use existing operator>
}
inline bool operator>=(const Vec2 & lhs, const Vec2 & rhs) noexcept  {
    return !(lhs < rhs);   // Use existing operator<
}
```

istream input, ostream output: overload bit shifts

Write a vector to a stream. Allowed to throw exceptions.

Note: Different argument types. The stream is a *non-const* ref, returns the stream.

```
inline std::ostream & operator<< (std::ostream & os, const Vec2 & v){
    os << std::setw(10) << v.x << " " << std::setw(10) << v.y;  // No endl !
    return os;
}
```

Read a vector from a stream.

```
inline std::istream & operator>> (std::istream & is, Vec2 & v) {
    is >> v.x >> v.y;
    if (!is)
        v = Vec2();   // Default (NaN) vector on IO error
    return is;
}
```

Do this for all your classes, if you want to read/write them !

operator+=, operator-=, operator*=, operator/=

Binary + assign operators, member operators by convention.

Add two vectors:

```
Vec2 & operator+= (const Vec2 & rhs) noexcept {
        x += rhs.x;
        y += rhs.y;
        return *this;  // Return the current object (self) by reference !
}
```

Multiply vector by a number:

```
Vec2 & operator*= (double rhs) noexcept {
        x *= rhs;
        y *= rhs;
        return *this;   // Return self by reference !
 }
```

Note: Always return ***this**, so that assignments can be chained (**a=b=c=d+=Vec2(3, 4)**).

operator+, operator-, operator*, operator/

Non-member binary operators. Use existing **operator+=** etc.

```
inline Vec2 operator+(const Vec2 & lhs, const Vec2 & rhs) noexcept {
    Vec2 temp = lhs;    // Make a copy of lhs
    temp += rhs;   // Based on the existing operator+ ! Add rhs to it.
    return temp;  // Return the result by value
} // Better pass lhs by value and avoid the explicit copy !
inline Vec2 operator-(Vec2 lhs, const Vec2 & rhs) noexcept {
    lhs -= rhs;  // DO like this !
    return lhs; // MOVE will be used if lhs is an rvalue
}
inline Vec2 operator*(Vec2 lhs, double rhs) noexcept {
    lhs *= rhs;  // Multiply vector by double: different types
    return lhs;
}
inline Vec2 operator*(double lhs, const Vec2 & rhs) noexcept { return rhs*lhs; }
```

operator++, operator--

Member operators (Note: Not a proper vector operation !):

Prefix version (**++v**):

```
Vec2 & operator++() noexcept {
        ++x;                    // Increase both x, y by 1
        ++y;
        return *this;    // Return self by reference
}
```

Postfix version (**v++**): Dummy **(int)** argument signifies postfix !

```
Vec2 operator++(int) noexcept {
        Vec2 temp{*this};            // Make a copy of self
        ++*this;            // Call prefix like this
        return temp;   // Return the copy by value. Less efficient !
}
```

Prefer the prefix version (**++v**) for class types to avoid copying!

operator[]: Index vector components !

Member operator:

Non-**const** version:

```
double & operator[] (int i) {
      switch (i) {
      case 0:
          return x;
      case 1:
          return y;
      default:
          throw std::out_of_range("Vec2::operator[]");
      }
}
```

const version, needed for indexing const objects!

```
const double & operator[] (int i) const { ... }
```

operator()

Member operator, prints the vector to console:

```
void operator()(const std::string &s) noexcept  {
        std::cout << s << *this << std::endl;
}
```

Now we can use **Vec2** as a function:

```
Vec2 a{1.0, 2.5};
a("Terrible Vector");
```

Any better uses for **operator()**? OpenCV and Eigen use it often.

operator double (Cast operator to double)

Member operator (of class **Vec2**) : Casts **Vec2** to **double**, "inverse constructor".

```
double len(){   // A regular method: Norm of the vector
        return std::sqrt(x*x + y*y);
}
explicit operator double() noexcept {
        return len();
}
```

explicit version can only be used in explicit casts:

```
Vec2 a{1.0, 2.5};
double d1 = (double) a;                        // OK
double d2 = static_cast<double>( a );     // OK
double d3 = a;                                 // ERROR ! Forbidden by explicit !
double d4 = sqrt( a );                         // ERROR ! Forbidden by explicit !
```

Without **explicit** : can be used for implicit type conversions ! Dangerous !

operator bool

Member operator (of class **Vec2**) : Casts **Vec2** to **bool**. Semantics: "non-zero" or "non-empty".

```
explicit operator bool() noexcept {
        return x || y;   // false is x == y == 0
}
```

Usage:

```
Vec2 a{1.0, 2.5};
bool b1 = (bool) a;                      // OK
bool b2 = static_cast<bool>( a );     // OK
bool b3 = a;                          // ERROR ! Forbidden by explicit !
```

Principle function of **operator bool** : use in **if** statements.

if and **?:** work fine even with **explicit** :

```
if (a) ...     // OK

int z = a ? 13 : 25;   // OK
```

Vec2 is now complete! Hurray!

The rule of five (previously "three")

Normally, a class has the following default methods (auto-created by the compiler)

- copy constructor (copy all fields)
- move constructor (move all fields)
- copy assignment (copy all fields)
- move assignment (move all fields)
- destructor (empty)

Rule of five: If you implement *any* of these methods, the defaults are no longer generated, you will have to implement *all* of them. Idea: you might have custom memory management, or some external resources (streams, sockets), thus default behavior is wrong.

Use **default** + **delete** to override this behavior if needed.

Note: This has nothing to do with the default (no-param) Ctor, like **Warrior()**.
It is generated if and only if there are no other (explicitly defined) constructors.
Nothing like this in our **Vec2** ! Only default copy behavior which copies two fields !

Copy and move constructors and assignment operators

```
Tjej(const Tjej & rhs) : name(rhs.name){}              // Copy Ctor

Tjej(Tjej && rhs) : name(std::move(rhs.name)){}        // Move Ctor

Tjej & operator= (const Tjej & rhs) {               // Copy assignment
    if (this != &rhs)      // Check for self-assignment
        name = rhs.name;
    return *this;      // Return self by ref
}

Tjej & operator= (Tjej && rhs) {                   // Move assignment
    if (this != &rhs)      // Check for self-assignment
        name = std::move(rhs.name);
    return *this;      // Return self by ref
}
```

Tjej && is an *rvalue* reference, e.g. ref to temp object, e.g. **Tjej("Bettan")**

Terminology comes from C: **lvalue = rvalue;**

For example: **w = Tjej("Bettan");**

Classes with custom memory usage?

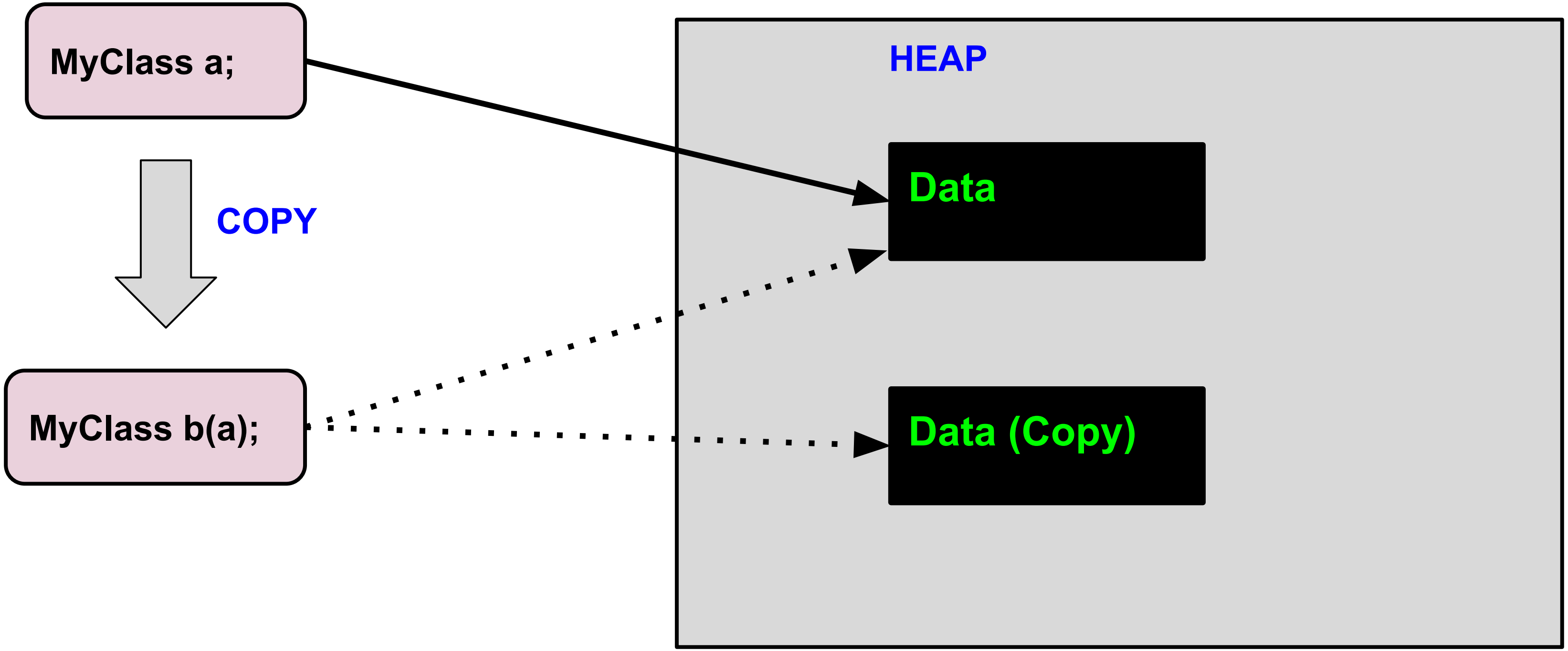
Our first example **Vec2** had no custom memory management.
Many classes do, though. How to create one? And why?

sizeof(C) (object size) is fixed *at compile time* for every C++ class **C**!
You cannot change or set the size of the object at runtime!
But "dynamic data size" is possible with the heap, **new[]** and **delete[]** (or **malloc**/**free**).

Warning: For your class it is better to employ existing **vector** or **cv::Mat** something !
Just create a **vector** field in your class. Don't reinvent the wheel!
Example 2 below (**IntBox**) is just for better understanding!
Don't try to reproduce it in real life!

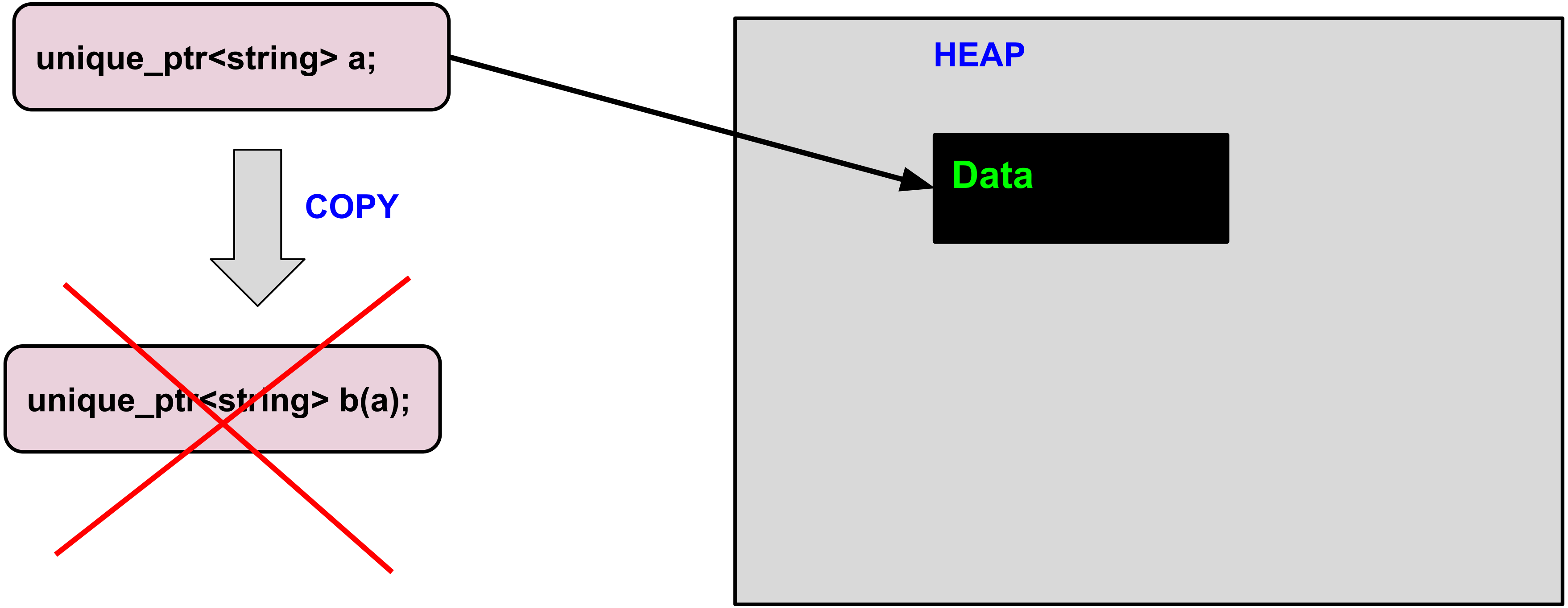
Classes which use the heap. How do they behave when copied?
Value behaviour : **vector** and other C++ containers. Copies data.
Pointer behavior: **cv::Mat** , **shared_ptr**. Copies reference, not data.
Unique behavior: **unique_ptr, istream, ostream**. Cannot be copied.

Class with heap resources:



What happens to the heap data when we copy an object ?

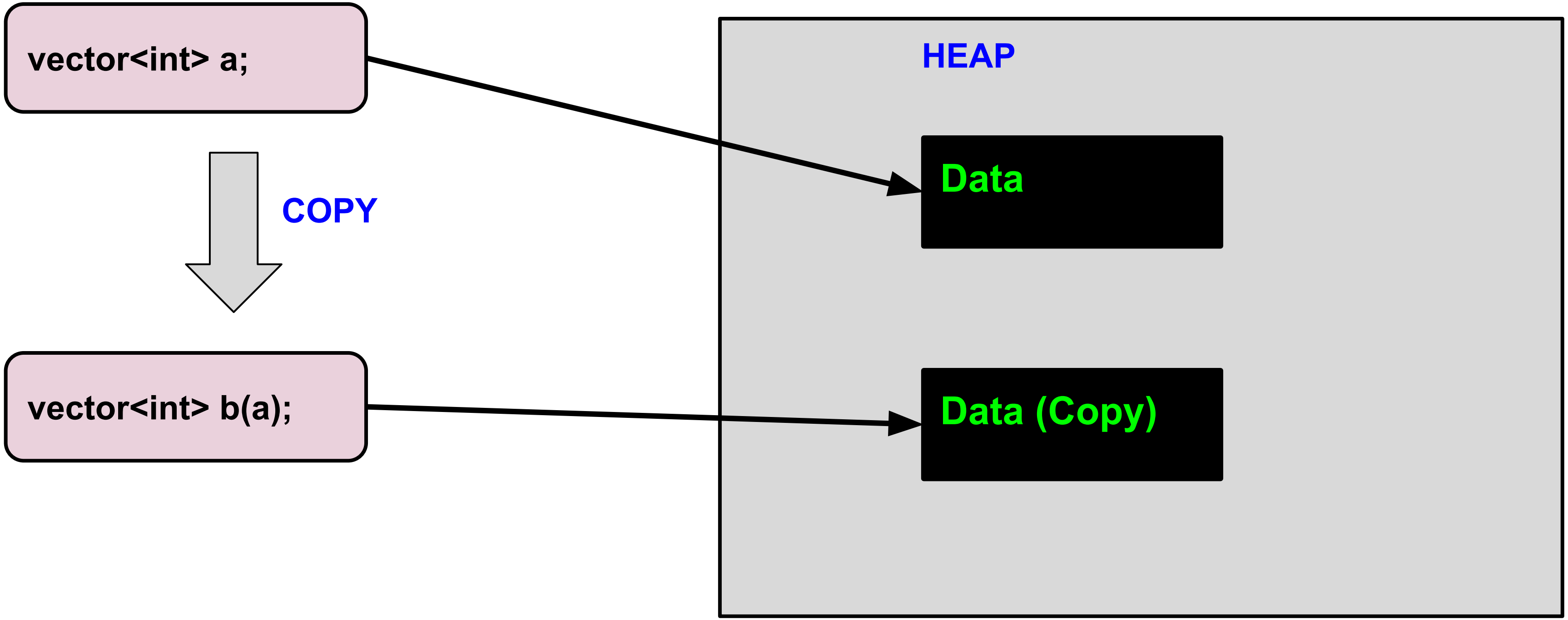
Unique object: Copying is forbidden



unique_ptr, istream, ostream

If you have a **unique_ptr** field, object of your class cannot be copied !

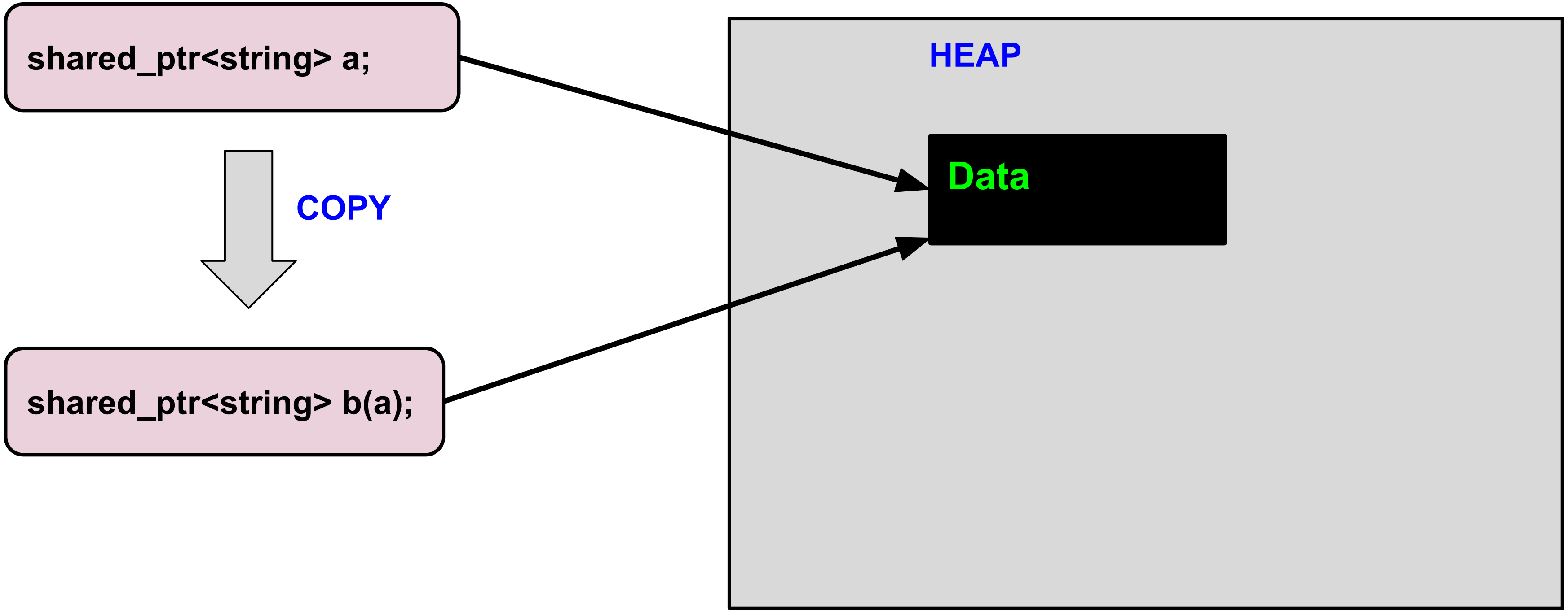
Value behavior: Copy resources



std::vector and most containers behave like this.

You can use container (e.g. **std::vector**) fields in your class for value behavior.

Pointer behavior: Do not copy resources



shared_ptr and **cv::Mat** (from OpenCV) behave like this. You have to count references !

Use **shared_ptr** fields in your class for pointer behavior !

Example 2: Implementing value behavior with raw pointers.

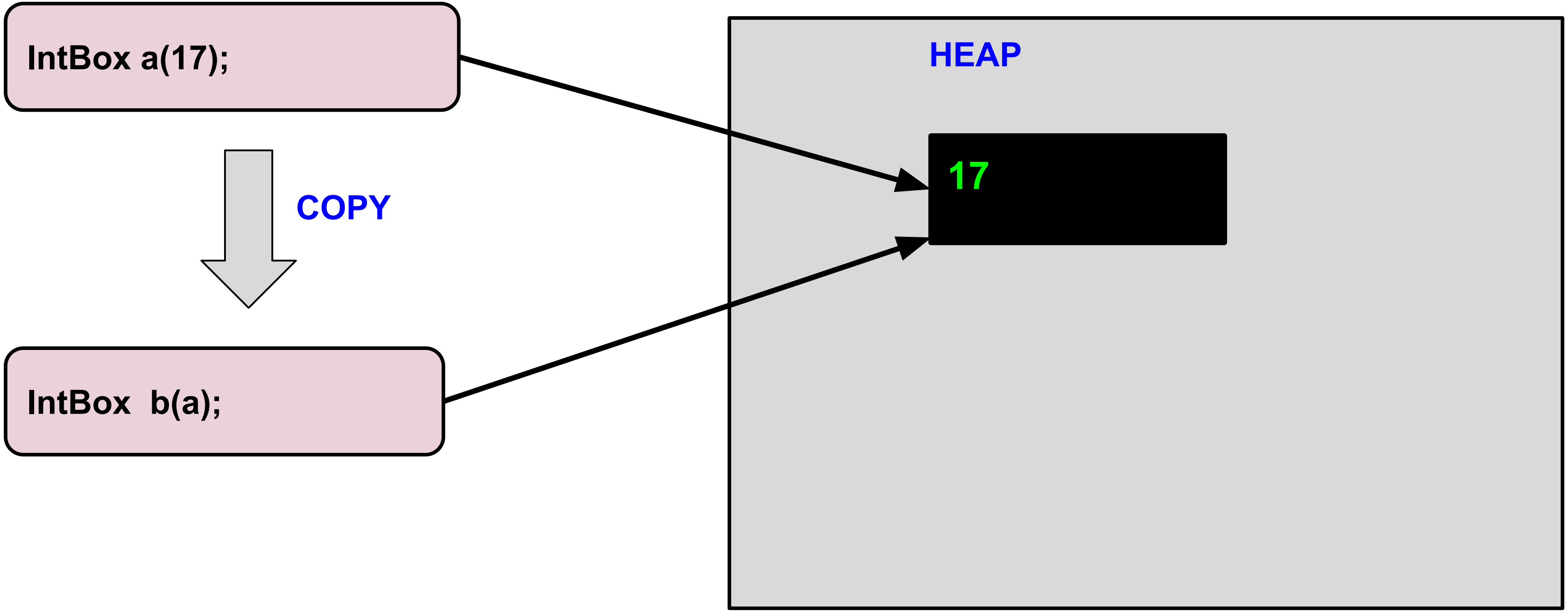
Let us design our own class: a trivial container for an **int** value.

But it uses heap memory. Can be empty (**nullptr**).

Let us manage heap with raw pointers (reinventing the wheel !).

```
class IntBox{   // Let us reinvent the wheel
public:
        IntBox() { }      // Empty Ctor
        IntBox(int n) :  data(new int(n)) { }      // Ctor, creates new heap object
        ~IntBox(){          // Dtor
                if (data)     // nullptr check
                        delete data;
        }
        ...
private:
        int * data = nullptr;     // Pointer to data, nullptr if empty
}
```

Can we copy InBox using default copy ctor+assignment ?



Two pointers to a heap object ! Double **delete** by the destructor !!!
And we wanted to COPY the heap data ! Pointer is copied instead !

clear() method makes IntBox empty

```
class IntBox{
public:
        ..
        void clear(){
                if (data) {    // nullptr check
                        delete data;  // Free the heap memory
                        data = nullptr;  // Don't forget to set data to nullptr
                 }
        }
        ...
private:
        int * data = nullptr;     // Pointer to data, nullptr if empty
}
```

Copy and move constructors:

Copy constructor: clone a heap object

```
IntBox(const IntBox & rhs) {     // Copy Ctor : Deep Clone
    if (rhs.data) {                  // If rhs is not empty
        data = new int(*rhs.data);   // Deep clone the heap object
    } // Otherwise data stays nullptr
}
```

Move constructor, move heap block from rhs to *this :

```
IntBox(IntBox && rhs) {
    data = rhs.data;              // Copy the pointer from rhs to *this !
    rhs.data = nullptr;           // Set rhs to empty without delete !
}
```

Copy assignment (operator=)

```
IntBox & operator=(const IntBox & rhs) {
    if (this != &rhs) {            // Check for self-assign
        clear();                   // Clear self first ! Before any copy/move !
        if (rhs.data) {            // If rhs is not empty
            data = new int(*rhs.data);     // Deep clone the heap object
        }  // Otherwise data stays nullptr
    }
    return *this;  // As usual, return self by ref
}
```

Self - assignment: **a = a;** We must always check for this stupid possibility!
Otherwise something will always go wrong.
For example, **clear()** will screw up things!

Move assignment (operator=)

```
IntBox & operator=(IntBox && rhs) {
    if (this != &rhs) {          // Check for self-assign
        clear();                 // Clear self first
        data = rhs.data;         // Copy the pointer
        rhs.data = nullptr;      // Set rhs to empty without delete
    }
    return *this;
}
```

Extra slides: Implementing efficient swap()

C++ numerics : special algorithms

Sum all numbers in a container:

```
vector<double> v{1., 2., 4., 7., 10.};
double res = accumulate(cbegin(v), cend(v), 0.);
```

Product of all numbers in a container: use lambda, start with 1:

```
accumulate(cbegin(v), cend(v), 1., [](double x, double y) {return x*y;} );
```

Product of all numbers in a container: use **std::multiplies** (wrapper of *):

```
accumulate(cbegin(v), cend(v), 1., multiplies<int>() );
```

Range : create vector {2., 3., .. , 11.}:

```
iota(v.begin(), v.end(), 2.);
```

Scalar product of two vectors:

```
inner_product(cbegin(v1), cend(v1), cbegin(v2), 0.)
```

Read yourself: more numerics, complex, cmath. But use Eigen for linear algebra !

Technology of the day : Profiling

Profiling = Run your code and examine CPU time usage.

!!! Profiling takes skills !!! It is easy to misunderstand the results !!!

Flat profile = CPU time used by each function + number of calls.

Call tree = All function calls (number+time) from each function.

Self time = Time spent by the function itself (excluding other functions called from it).

Inclusive (cumulative) time = Time spent by the function, including function it calls.

Profiling is typically done in Release:

cmake -DCMAKE_BUILD_TYPE=Release ..

But with debug symbols !

set(CMAKE_CXX_FLAGS_RELEASE "${CMAKE_CXX_FLAGS_RELEASE} -g")

Pitfalls:

1. C++ name mangling (Encode classes, labdas, templates, namespaces etc.)
2. Threads
3. Calling functions from external .so libraries (e.g. OpenCV), gprof has problems with that

Using gprof (Built-in profiler for gcc, probably not the best)

1. Set compiler flags "**-pg**" in CMakeLists.txt:

set(CMAKE_CXX_FLAGS_RELEASE "${CMAKE_CXX_FLAGS_RELEASE} -pg")

2. Run the program (generates file gmon.out):

./demo

3. Run the profiler:

gprof ./demo gmon.out > analysis.txt

Result: flat profile and call tree (Note : C++ names hurt !):

```
Flat profile:
Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls  ms/call  ms/call  name
 55.56      1.30     1.30     4002     0.32     0.32  std::_Function_handler<std::unique_ptr<std::__future_base::_Result_base,
std::__future_base::_Result_base::_Deleter> (),
std::__future_base::_Task_setter<std::unique_ptr<std::__future_base::_Result<unsigned long>,
std::__future_base::_Result_base::_Deleter>, std::__future_base::_Task_state<linelib::mcmlsd::findMax(double*, unsigned long*,
unsigned long, ctpl::thread_pool&)::{lambda(int)#1}, std::allocator<int>, unsigned long (int)>::_M_run(int&&)::{lambda()#1},
unsigned long> >::_M_invoke(std::_Any_data const&)
```

Using google profiler (gperftools)

1. Set compiler flags "**-g**" in CMakeLists.txt (no **-p** !):

set(CMAKE_CXX_FLAGS_RELEASE "${CMAKE_CXX_FLAGS_RELEASE} -g")

2. Run the program with the profiler, generate file main.prof :

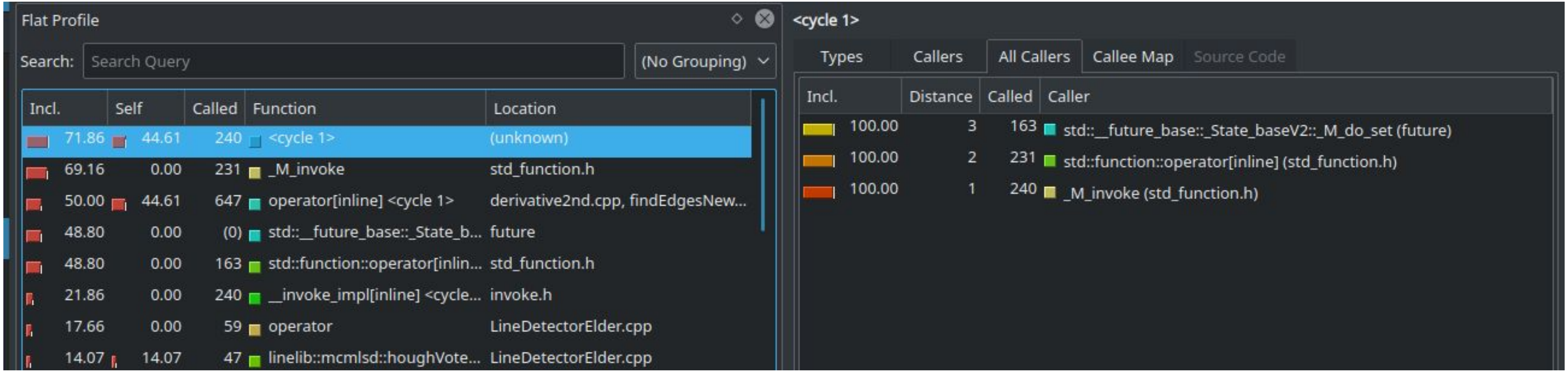
LD_PRELOAD=/usr/lib/x86_64-linux-gnu/libprofiler.so.0 CPUPROFILE=main.prof demo

3. Output the profile info in callgrind format (also available : text, PS etc.):

google-pprof --callgrind ./demo main.prof > demo.callgrind

4. View the callgrind profile using KCacheGrind (nice interactive GUI):

kcachegrind demo.callgrind &



Using valgrind

Valgrind runs programs in a x64 emulator (20-30 times slower).
It has many tools:

Look for memory leaks (memcheck, the default tool):
valgrind demo 2>result.txt

CPU usage profiling (callgrind):
valgrind --tool=callgrind demo
kcachegrind callgrind.out.12653

CPU cache profiling (cachegrind):
valgrind --tool=cachegrind demo
kcachegrind cachegrind.out.13200

Other GUI tools : Valkyrie, Alleyoop for memcheck.

Thank you for your attention !

title

text

Implementing efficient swap()

```
void swap(IntBox &lhs, IntBox &rhs) noexcept {
    using std::swap;
    swap(lhs.data, rhs.data);          // Swap pointers, uses std::swap
}
```

Usage :

```
using std::swap;   // Or using namespace std;
IntBox a(17), b(42);
swap(a, b);  // NOT std::swap() !!!
```

std::swap() is not very efficient.

We use **swap()** for a class specific version of swap.

We fall back to **std::swap()** if no class-specific version exists.