

6. C++ advanced (I)

Repetition: vectors, pointers and iterators, range for, keyword auto, a class for vectors, subscript-operator, move-construction, iterators

What do we learn today?

- Keyword `auto`
- Ranged `for`
- Short recap of the Rule of Three
- Subscript operator
- Move Semantics, X-Values and the Rule of Five
- Custom Iterators

We look back...

```
#include <iostream>
#include <vector>
using iterator = std::vector<int>::iterator;

int main(){
    // Vector of length 10
    std::vector<int> v(10);
    // Input
    for (int i = 0; i < v.size(); ++i)
        std::cin >> v[i];
    // Output
    for (iterator it = v.begin(); it != v.end(); ++it)
        std::cout << *it << " ";
}
```

We look back...

```
#include <iostream>
#include <vector>
using iterator = std::vector<int>::iterator;

int main(){
    // Vector of length 10
    std::vector<int> v(10);
    // Input
    for (int i = 0; i < v.size(); ++i)
        std::cin >> v[i];
    // Output
    for (iterator it = v.begin(); it != v.end(); ++it)
        std::cout << *it << " ";
}
```

We want to understand this in depth!

We look back...

```
#include <iostream>
#include <vector>
using iterator = std::vector<int>::iterator;
```

```
int main(){
```

We want to understand this in depth!

```
// Vector of length 10
```

```
std::vector<int> v(10);
```

```
// Input
```

```
for (int i = 0; i < v.size(); ++i)
```

```
    std::cin >> v[i];
```

```
// Output
```

```
for (iterator it = v.begin(); it != v.end(); ++it)
```

```
    std::cout << *it << " ";
```

```
}
```

This looks too pedestrian

Useful tools (1): `auto` (C++11)

The keyword `auto`:

The type of a variable is inferred from the initializer.

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Examples

```
int x = 10;
```

Useful tools (1): `auto` (C++11)

The keyword `auto`:

The type of a variable is inferred from the initializer.

Examples

```
int x = 10;  
auto y = x; // int
```


Useful tools (1): `auto` (C++11)

The keyword `auto`:

The type of a variable is inferred from the initializer.

Examples

```
int x = 10;  
auto y = x; // int  
auto z = 3; // int
```

Useful tools (1): `auto` (C++11)

The keyword `auto`:

The type of a variable is inferred from the initializer.

Examples

```
int x = 10;  
auto y = x; // int  
auto z = 3; // int  
std::vector<double> v(5);
```

Useful tools (1): `auto` (C++11)

The keyword `auto`:

The type of a variable is inferred from the initializer.

Examples

```
int x = 10;  
auto y = x; // int  
auto z = 3; // int  
std::vector<double> v(5);  
auto i = v[3]; // double
```

Slightly better...

```
#include <iostream>
#include <vector>

int main(){
    std::vector<int> v(10); // Vector of length 10

    for (int i = 0; i < v.size(); ++i)
        std::cin >> v[i];

    for (auto it = v.begin(); it != v.end(); ++it){
        std::cout << *it << " ";
    }
}
```

Useful tools (2): range for (C++11)

```
for (range-declaration : range-expression)
    statement;
```

range-declaration: named variable of element type specified via the sequence in range-expression

range-expression: Expression that represents a sequence of elements via iterator pair `begin()`, `end()` or in the form of an initializer list.

Useful tools (2): range `for` (C++11)

```
for (range-declaration : range-expression)
    statement;
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range-declaration: named variable of element type specified via the sequence in range-expression

range-expression: Expression that represents a sequence of elements via iterator pair `begin()`, `end()` or in the form of an initializer list.

Examples

Useful tools (2): range `for` (C++11)

```
for (range-declaration : range-expression)
    statement;
```

range-declaration: named variable of element type specified via the sequence in range-expression

range-expression: Expression that represents a sequence of elements via iterator pair `begin()`, `end()` or in the form of an initializer list.

Examples

```
std::vector<double> v(5);
```

Useful tools (2): range `for` (C++11)

```
for (range-declaration : range-expression)
    statement;
```

range-declaration: named variable of element type specified via the sequence in range-expression

range-expression: Expression that represents a sequence of elements via iterator pair `begin()`, `end()` or in the form of an initializer list.

Examples

```
std::vector<double> v(5);
for (double x: v) std::cout << x; // 00000
```


Useful tools (2): range `for` (C++11)

```
for (range-declaration : range-expression)
    statement;
```

range-declaration: named variable of element type specified via the sequence in range-expression

range-expression: Expression that represents a sequence of elements via iterator pair `begin()`, `end()` or in the form of an initializer list.

Examples

```
std::vector<double> v(5);
for (double x: v) std::cout << x; // 00000
for (int x: {1,2,5}) std::cout << x; // 125
```

Useful tools (2): range `for` (C++11)

```
for (range-declaration : range-expression)
    statement;
```

range-declaration: named variable of element type specified via the sequence in range-expression

range-expression: Expression that represents a sequence of elements via iterator pair `begin()`, `end()` or in the form of an initializer list.

Examples

```
std::vector<double> v(5);
for (double x: v) std::cout << x; // 00000
for (int x: {1,2,5}) std::cout << x; // 125
for (double& x: v) x=5;
```

That is indeed cool!

```
#include <iostream>
#include <vector>

int main(){
    std::vector<int> v(10); // Vector of length 10

    for (auto& x: v)
        std::cin >> x;

    for (const auto x: v)
        std::cout << x << " ";
}
```

For our detailed understanding

We build a vector class with the same capabilities ourselves!

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On the way we learn about

- RAII (Resource Acquisition is Initialization) and move construction

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- Subscript operators and other utilities

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- RAI (Resource Acquisition is Initialization) and move construction
- Subscript operators and other utilities
- Templates

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- RAI (Resource Acquisition is Initialization) and move construction
- Subscript operators and other utilities
- Templates
- Exception Handling

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- Functors and lambda expressions

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We build a vector class with the same capabilities ourselves!

On the way we learn about

- RAII (Resource Acquisition is Initialization) and move construction
- Subscript operators and other utilities
- Templates
- Exception Handling
- Functors and lambda expressions

today

A class for (double) vectors

```
class Vector{
public:
    // constructors
    Vector(): sz{0}, elem{nullptr} {};
    Vector(std::size_t s): sz{s}, elem{new double[s]} {}
    // destructor
    ~Vector(){
        delete[] elem;
    }
    // (something is missing here)
private:
    std::size_t sz;
    double* elem;
}
```

Element access

```
class Vector{
    ...
    // getter. pre: 0 <= i < sz;
    double get(std::size_t i) const{
        return elem[i];
    }
    // setter. pre: 0 <= i < sz;
    void set(std::size_t i, double d){
        elem[i] = d;
    }
    // size property
    std::size_t size() const {
        return sz;
    }
}
```

```
class Vector{
public:
    Vector();
    Vector(std::size_t s);
    ~Vector();
    double get(std::size_t i) const;
    void set(std::size_t i, double d);
    std::size_t size() const;
}
```

(Vector Interface)

What's the problem here?

```
int main(){
    Vector v(32);
    for (std::size_t i = 0; i!=v.size(); ++i)
        v.set(i, i);
    Vector w = v;
    for (std::size_t i = 0; i!=w.size(); ++i)
        w.set(i, i*i);
    return 0;
}
```

```
class Vector{
public:
    Vector();
    Vector(std::size_t s);
    ~Vector();
    double get(std::size_t i) const;
    void set(std::size_t i, double d);
    std::size_t size() const;
}
```

(Vector Interface)

What's the problem here?

```
int main(){
    Vector v(32);
    for (std::size_t i = 0; i!=v.size(); ++i)
        v.set(i, i);
    Vector w = v;
    for (std::size_t i = 0; i!=w.size(); ++i)
        w.set(i, i*i);
    return 0;
}
```

```
class Vector{
public:
    Vector();
    Vector(std::size_t s);
    ~Vector();
    double get(std::size_t i) const;
    void set(std::size_t i, double d);
    std::size_t size() const;
}
```

(Vector Interface)

```
*** Error in 'vector1': double free or corruption
(!prev): 0x0000000000d23c20 ***
===== Backtrace: =====
/lib/x86_64-linux-gnu/libc.so.6(+0x777e5) [0x7fe5a5ac97e5]
```

Rule of Three!

```
class Vector{  
...  
public:  
    // copy constructor  
    Vector(const Vector &v)  
        : sz{v.sz}, elem{new double[v.sz]} {  
        std::copy(v.elem, v.elem + v.sz, elem);  
    }  
}
```

```
class Vector{  
public:  
    Vector();  
    Vector(std::size_t s);  
    ~Vector();  
    Vector(const Vector &v);  
    double get(std::size_t i) const;  
    void set(std::size_t i, double d);  
    std::size_t size() const;  
}
```

(Vector Interface)

Rule of Three!

```
class Vector{  
...  
    // assignment operator  
    Vector& operator=(const Vector& v){  
        if (v.elem == elem) return *this;  
        if (elem != nullptr) delete[] elem;  
        sz = v.sz;  
        elem = new double[sz];  
        std::copy(v.elem, v.elem+v.sz, elem);  
        return *this;  
    }  
}
```

```
class Vector{  
public:  
    Vector();  
    Vector(std::size_t s);  
    ~Vector();  
    Vector(const Vector &v);  
    Vector& operator=(const Vector&v);  
    double get(std::size_t i) const;  
    void set(std::size_t i, double d);  
    std::size_t size() const;  
}
```

(Vector Interface)

Rule of Three!

```
class Vector{
...
// assignment operator
Vector& operator=(const Vector& v){
    if (v.elem == elem) return *this;
    if (elem != nullptr) delete[] elem;
    sz = v.sz;
    elem = new double[sz];
    std::copy(v.elem, v.elem+v.sz, elem);
    return *this;
}
}
```

```
class Vector{
public:
    Vector();
    Vector(std::size_t s);
    ~Vector();
    Vector(const Vector& v);
    Vector& operator=(const Vector& v);
    double get(std::size_t i) const;
    void set(std::size_t i, double d);
    std::size_t size() const;
}
```

(Vector Interface)

Now it is correct, but cumbersome.

More elegant this way (part 1):

```
public:  
// copy constructor  
// (with constructor delegation)  
Vector(const Vector &v): Vector(v.sz)  
{  
    std::copy(v.elem, v.elem + v.sz, elem);  
}
```

More elegant this way (part 2):

```
class Vector{
...
    // Assignment operator
    Vector& operator= (const Vector&v){
        Vector cpy(v);
        swap(cpy);
        return *this;
    }
private:
    // helper function
    void swap(Vector& v){
        std::swap(sz, v.sz);
        std::swap(elem, v.elem);
    }
}
```

More elegant this way (part 2):

```
class Vector{
...
    // Assignment operator
    Vector& operator= (const Vector&v){
        Vector cpy(v);
        swap(cpy);
        return *this;
    }
private:
    // helper function
    void swap(Vector& v){
        std::swap(sz, v.sz);
        std::swap(elem, v.elem);
    }
}
```

copy-and-swap idiom: all members of `*this` are exchanged with members of `cpy`. When leaving `operator=`, `cpy` is cleaned up (deconstructed), while the copy of the data of `v` stay in `*this`.

Syntactic sugar.

Getters and setters are poor. We want a subscript (index) operator.

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Overloading!

Syntactic sugar.

Getters and setters are poor. We want a subscript (index) operator.

Overloading! So?

```
class Vector{
...
    double operator[] (std::size_t pos) const{
        return elem[pos];
    }

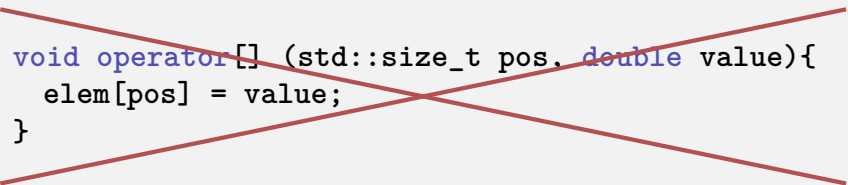
    void operator[] (std::size_t pos, double value){
        elem[pos] = value;
    }
}
```

Syntactic sugar.

Getters and setters are poor. We want a subscript (index) operator.

Overloading! So?

```
class Vector{  
...  
    double operator[] (std::size_t pos) const{  
        return elem[pos];  
    }  
  
    void operator[] (std::size_t pos, double value){  
        elem[pos] = value;  
    }  
}
```



No!

Reference types!

```
class Vector{
...
    // for non-const objects
    double& operator[] (std::size_t pos){
        return elem[pos]; // return by reference!
    }
    // for const objects
    const double& operator[] (std::size_t pos) const{
        return elem[pos];
    }
}
```

So far so good.

```
int main(){
    Vector v(32); // constructor
    for (int i = 0; i<v.size(); ++i)
        v[i] = i; // subscript operator

    Vector w = v; // copy constructor
    for (int i = 0; i<w.size(); ++i)
        w[i] = i*i;

    const auto u = w;
    for (int i = 0; i<u.size(); ++i)
        std::cout << v[i] << ":" << u[i] << " "; // 0:0 1:1 2:4 ...
    return 0;
}
```

So far so good.

```
int main(){
    Vector v(32); // constructor
    for (int i = 0; i<v.size(); ++i)
        v[i] = i; // subscript operator

    Vector w = v; // copy constructor
    for (int i = 0; i<w.size(); ++i)
        w[i] = i*i;

    const auto u = w;
    for (int i = 0; i<u.size(); ++i)
        std::cout << v[i] << ":" << u[i] << " "; // 0:0 1:1 2:4 ...
    return 0;
}
```

```
class Vector{
public:
    Vector();
    Vector(std::size_t s);
    ~Vector();
    Vector(const Vector &v);
    Vector& operator=(const Vector&v);
    const double& operator[] (std::size_t pos) const;
    double& operator[] (std::size_t pos);
    std::size_t size() const;
}
```

Number copies

How often is `v` being copied?

```
Vector operator+ (const Vector& l, double r){
    Vector result (l);
    for (std::size_t i = 0; i < l.size(); ++i)
        result[i] = l[i] + r;
    return result;
}

int main(){
    Vector v(16);
    v = v + 1;
    return 0;
}
```

Number copies

How often is `v` being copied?

```
Vector operator+ (const Vector& l, double r){
    Vector result (l); // copy of l to result
    for (std::size_t i = 0; i < l.size(); ++i)
        result[i] = l[i] + r;
    return result; // deconstruction of result after assignment
}

int main(){
    Vector v(16); // allocation of elems[16]
    v = v + 1;   // copy when assigned!
    return 0;   // deconstruction of v
}
```

Number copies

How often is `v` being copied?

```
Vector operator+ (const Vector& l, double r){
    Vector result (l);
    for (std::size_t i = 0; i < l.size(); ++i)
        result[i] = l[i] + r;
    return result;
}

int main(){
    Vector v(16);
    v = v + 1;
    return 0;
}
```

`v` is copied (at least) twice

Move construction and move assignment

```
class Vector{  
    ...  
    // move constructor  
    Vector (Vector&& v): Vector() {  
        swap(v);  
    };  
    // move assignment  
    Vector& operator=(Vector&& v){  
        swap(v);  
        return *this;  
    };  
}
```

Move construction and move assignment

```
class Vector{
...
    // move constructor
    Vector (Vector&& v): Vector() {
        swap(v);
    };
    // move assignment
    Vector& operator=(Vector&& v){
        swap(v);
        return *this;
    };
}
```

```
class Vector{
public:
    Vector();
    Vector(std::size_t s);
    ~Vector();
    Vector(const Vector &v);
    Vector& operator=(const Vector&v);
    Vector (Vector&& v);
    Vector& operator=(Vector&& v);
    const double& operator[] (std::size_t pos) const;
    double& operator[] (std::size_t pos);
    std::size_t size() const;
}
```


Explanation

When the source object of an assignment will not continue existing after an assignment the compiler can use the move assignment instead of the assignment operator.⁵ Expensive copy operations are then avoided.

Number of copies in the previous example goes down to 1.

⁵Analogously so for the copy-constructor and the move constructor

Illustration of the Move-Semantics

```
// nonsense implementation of a "vector" for demonstration purposes
class Vec{
public:
    Vec () {
        std::cout << "default constructor\n";}
    Vec (const Vec&) {
        std::cout << "copy constructor\n";}
    Vec& operator = (const Vec&) {
        std::cout << "copy assignment\n"; return *this;}
    ~Vec() {}
};
```

How many Copy Operations?

```
Vec operator + (const Vec& a, const Vec& b){  
    Vec tmp = a;  
    // add b to tmp  
    return tmp;  
}
```

```
int main (){  
    Vec f;  
    f = f + f + f + f;  
}
```

How many Copy Operations?

```
Vec operator + (const Vec& a, const Vec& b){  
    Vec tmp = a;  
    // add b to tmp  
    return tmp;  
}  
  
int main (){  
    Vec f;  
    f = f + f + f + f;  
}
```

Output

default constructor

copy constructor

copy constructor

copy constructor

copy assignment

4 copies of the vector

Illustration of the Move-Semantics

```
// nonsense implementation of a "vector" for demonstration purposes
class Vec{
public:
    Vec () { std::cout << "default constructor\n";}
    Vec (const Vec&) { std::cout << "copy constructor\n";}
    Vec& operator = (const Vec&) {
        std::cout << "copy assignment\n"; return *this;}
    ~Vec() {}
    // new: move constructor and assignment
    Vec (Vec&&) {
        std::cout << "move constructor\n";}
    Vec& operator = (Vec&&) {
        std::cout << "move assignment\n"; return *this;}
};
```

How many Copy Operations?

```
Vec operator + (const Vec& a, const Vec& b){  
    Vec tmp = a;  
    // add b to tmp  
    return tmp;  
}
```

```
int main (){  
    Vec f;  
    f = f + f + f + f;  
}
```

How many Copy Operations?

```
Vec operator + (const Vec& a, const Vec& b){  
    Vec tmp = a;  
    // add b to tmp  
    return tmp;  
}  
  
int main (){  
    Vec f;  
    f = f + f + f + f;  
}
```

Output

default constructor

copy constructor

copy constructor

copy constructor

move assignment

3 copies of the vector

How many Copy Operations?

```
Vec operator + (Vec a, const Vec& b){  
    // add b to a  
    return a;  
}
```

```
int main (){  
    Vec f;  
    f = f + f + f + f;  
}
```


How many Copy Operations?

```
Vec operator + (Vec a, const Vec& b){  
    // add b to a  
    return a;  
}
```

```
int main (){  
    Vec f;  
    f = f + f + f + f;  
}
```

Output

default constructor

copy constructor

move constructor

move constructor

move constructor

move assignment

1 copy of the vector

How many Copy Operations?

```
Vec operator + (Vec a, const Vec& b){  
    // add b to a  
    return a;  
}  
  
int main (){  
    Vec f;  
    f = f + f + f + f;  
}
```

Output

default constructor

copy constructor

move constructor

move constructor

move constructor

move assignment

1 copy of the vector

Explanation: move semantics are applied when an x-value (expired value) is assigned. R-value return values of a function are examples of x-values.

How many Copy Operations?

```
void swap(Vec& a, Vec& b){  
    Vec tmp = a;  
    a=b;  
    b=tmp;  
}
```

```
int main (){  
    Vec f;  
    Vec g;  
    swap(f,g);  
}
```

How many Copy Operations?

```
void swap(Vec& a, Vec& b){  
    Vec tmp = a;  
    a=b;  
    b=tmp;  
}
```

```
int main (){  
    Vec f;  
    Vec g;  
    swap(f,g);  
}
```

Output

default constructor
default constructor
copy constructor
copy assignment
copy assignment

3 copies of the vector

Forcing x-values

```
void swap(Vec& a, Vec& b){  
    Vec tmp = std::move(a);  
    a=std::move(b);  
    b=std::move(tmp);  
}  
int main (){  
    Vec f;  
    Vec g;  
    swap(f,g);  
}
```

Forcing x-values

```
void swap(Vec& a, Vec& b){  
    Vec tmp = std::move(a);  
    a=std::move(b);  
    b=std::move(tmp);  
}  
int main (){  
    Vec f;  
    Vec g;  
    swap(f,g);  
}
```

Output

default constructor
default constructor
move constructor
move assignment
move assignment

0 copies of the vector

Forcing x-values

```
void swap(Vec& a, Vec& b){  
    Vec tmp = std::move(a);  
    a=std::move(b);  
    b=std::move(tmp);  
}  
  
int main (){  
    Vec f;  
    Vec g;  
    swap(f,g);  
}
```

Output

default constructor
default constructor
move constructor
move assignment
move assignment

0 copies of the vector

Explanation: With `std::move` an l-value expression can be forced into an x-value. Then move-semantics are applied. <http://en.cppreference.com/w/cpp/utility/move>

std::swap & std::move

std::swap is implemented as above (using templates)

std::move can be used to move the elements of a container into another

```
std::move(va.begin(), va.end(), vb.begin())
```


Range for

We wanted this:

```
Vector v = ...;  
for (auto x: v)  
    std::cout << x << " ";
```

Range for

We wanted this:

```
Vector v = ...;  
for (auto x: v)  
    std::cout << x << " ";
```

In order to support this, an iterator must be provided via `begin` and `end`.

Iterator for the vector

```
class Vector{  
...  
    // Iterator  
    double* begin(){  
        return elem;  
    }  
    double* end(){  
        return elem+sz;  
    }  
}
```

Iterator for the vector

```
class Vector{  
...  
    // Iterator  
    double* begin(){  
        return elem;  
    }  
    double* end(){  
        return elem+sz;  
    }  
}
```

(Pointers support iteration)

```
class Vector{  
public:  
    Vector();  
    Vector(std::size_t s);  
    ~Vector();  
    Vector(const Vector &v);  
    Vector& operator=(const Vector&v);  
    Vector (Vector&& v);  
    Vector& operator=(Vector&& v);  
    const double& operator[] (std::size_t pos) const;  
    double& operator[] (std::size_t pos);  
    std::size_t size() const;  
    double* begin();  
    double* end();  
}
```

Const Iterator for the vector

```
class Vector{
...
    // Const-Iterator
    const double* begin() const{
        return elem;
    }
    const double* end() const{
        return elem+sz;
    }
}
```

Const Iterator for the vector

```
class Vector{  
...  
    // Const-Iterator  
    const double* begin() const{  
        return elem;  
    }  
    const double* end() const{  
        return elem+sz;  
    }  
}
```

```
class Vector{  
public:  
    Vector();  
    Vector(std::size_t s);  
    ~Vector();  
    Vector(const Vector &v);  
    Vector& operator=(const Vector&v);  
    Vector (Vector&& v);  
    Vector& operator=(Vector&& v);  
    const double& operator[] (std::size_t pos) const;  
    double& operator[] (std::size_t pos);  
    std::size_t size() const;  
    double* begin();  
    double* end();  
    const double* begin() const;  
    const double* end() const;  
}
```

Intermediate result

```
Vector Natural(int from, int to){
    Vector v(to-from+1);
    for (auto& x: v) x = from++;
    return v;
}

int main(){
    auto v = Natural(5,12);
    for (auto x: v)
        std::cout << x << " "; // 5 6 7 8 9 10 11 12
    std::cout << std::endl;
        << "sum = "
        << std::accumulate(v.begin(), v.end(),0); // sum = 68
    return 0;
}
```

Today's Conclusion

- Use `auto` to infer a type from the initializer.
- X-values are values where the compiler can determine that they go out of scope.
- Use move constructors in order to move X-values instead of copying.
- When you know what you are doing then you can enforce the use of X-Values.
- Subscript operators can be overloaded. In order to write, references are used.
- Behind a ranged `for` there is an iterator working.
- Iteration is supported by implementing an iterator following the syntactic convention of the standard library.