Move Semantics in C++

A fancy way to say “how can we avoid making unnecessary copies of resources?”

Definition: l-values vs r-values

- **l-values** can appear on the **left** or **right** of an =

Definition: l-values vs r-values

- l-values can appear on the **left** or **right** of an =
- `x` is an l-value

```
int x = 3;
int y = x;
```

Definition: l-values vs r-values

- **l-values** can appear on the **left** or **right** of an =
- `x` is an **l-value**

```
int x = 3;
int y = x;
```

l-values have names

l-values are **not temporary**

Definition: l-values vs r-values

- l-values can appear on the **left** or **right** of an =
- `x` is an l-value

```
int x = 3;
int y = x;
```

l-values have names

l-values are **not temporary**

- r-values can ONLY appear on the **right** of an =

Definition: l-values vs r-values

- l-values can appear on the **left** or **right** of an =
- `x` is an l-value

```
int x = 3;
int y = x;
```

- r-values can ONLY appear on the **right** of an =
- `3` is an r-value

```
int x = 3;
int y = x;
```

l-values have names

l-values are **not temporary**

Definition: l-values vs r-values

- **l-values** can appear on the **left** or **right** of an =
- `x` is an **l-value**

```
int x = 3;
int y = x;
```

l-values have names

l-values are **<u>not temporary</u>**

- **r-values** can ONLY appear on the **right** of an =
- `3` is an **r-value**

```
int x = 3;
int y = x;
```

r-values don't have names

r-values are **<u>temporary</u>**

l-values live until the end of the scope

r-values live until the end of the line

l-values live until the end of the scope

r-values live until the end of the line

(unless you artificially extend their lifetimes)

...more on this later

Find the r-values!

```
int x = 3;
int *ptr = 0x02248837;
vector<int> v1{1, 2, 3};
auto v4 = v1 + v2;
size_t size = v.size();
v1[1] = 4*i;
ptr = &x;
v1[2] = *ptr;
MyClass obj;
x = obj.public_member_variable;
```

Find the r-values! (Only consider the items on the *right* of `=` signs)

```
int x = 3;
int *ptr = 0x02248837;
vector<int> v1{1, 2, 3};
auto v4 = v1 + v2;
size_t size = v.size();
v1[1] = 4*i;
ptr = &x;
v1[2] = *ptr;
MyClass obj;
x = obj.public_member_variable;
```

Find the r-values! (Only consider the items on the *right* of = signs)

```
int x = 3;                    //3 is an r-value
int *ptr = 0x02248837;
vector<int> v1{1, 2, 3};
auto v4 = v1 + v2;
size_t size = v.size();
v1[1] = 4*i;
ptr = &x;
v1[2] = *ptr;
MyClass obj;
x = obj.public_member_variable;
```

Find the r-values! (Only consider the items on the *right* of = signs)

```
int x = 3;                    //3 is an r-value
int *ptr = 0x02248837;        //0x02248837 is an r-value
vector<int> v1{1, 2, 3};
auto v4 = v1 + v2;
size_t size = v.size();
v1[1] = 4*i;
ptr = &x;
v1[2] = *ptr;
MyClass obj;
x = obj.public_member_variable;
```

Find the r-values! (Only consider the items on the *right* of `=` signs)

```
int x = 3;                      //3 is an r-value
int *ptr = 0x02248837;          //0x02248837 is an r-value
vector<int> v1{1, 2, 3};        //{1, 2, 3} is an r-value,v1 is an l-value
auto v4 = v1 + v2;
size_t size = v.size();
v1[1] = 4*i;
ptr = &x;
v1[2] = *ptr;
MyClass obj;
x = obj.public_member_variable;
```

Find the r-values! (Only consider the items on the *right* of `=` signs)

```
int x = 3;                          //3 is an r-value
int *ptr = 0x02248837;              //0x02248837 is an r-value
vector<int> v1{1, 2, 3};            //{1, 2, 3} is an r-value,v1 is an l-value
auto v4 = v1 + v2;                  //v1 + v2 is an r-value
size_t size = v.size();
v1[1] = 4*i;
ptr = &x;
v1[2] = *ptr;
MyClass obj;
x = obj.public_member_variable;
```

Find the r-values! (Only consider the items on the *right* of = signs)

```
int x = 3;                      //3 is an r-value
int *ptr = 0x02248837;          //0x02248837 is an r-value
vector<int> v1{1, 2, 3};        //{1, 2, 3} is an r-value,v1 is an l-value
auto v4 = v1 + v2;              //v1 + v2 is an r-value
size_t size = v.size();         //v.size()is an r-value
v1[1] = 4*i;
ptr = &x;
v1[2] = *ptr;
MyClass obj;
x = obj.public_member_variable;
```

Find the r-values! (Only consider the items on the *right* of = signs)

```
int x = 3;                        //3 is an r-value
int *ptr = 0x02248837;            //0x02248837 is an r-value
vector<int> v1{1, 2, 3};          //{1, 2, 3} is an r-value,v1 is an l-value
auto v4 = v1 + v2;                //v1 + v2 is an r-value
size_t size = v.size();           //v.size()is an r-value
v1[1] = 4*i;                      //4*i is an r-value, v1[1] is an l-value
ptr = &x;
v1[2] = *ptr;
MyClass obj;
x = obj.public_member_variable;
```

Find the r-values! (Only consider the items on the *right* of = signs)

```
int x = 3;                          //3 is an r-value
int *ptr = 0x02248837;              //0x02248837 is an r-value
vector<int> v1{1, 2, 3};            //{1, 2, 3} is an r-value,v1 is an l-value
auto v4 = v1 + v2;                  //v1 + v2 is an r-value
size_t size = v.size();             //v.size()is an r-value
v1[1] = 4*i;                        //4*i is an r-value, v1[1] is an l-value
ptr = &x;                           //&x is an r-value
v1[2] = *ptr;
MyClass obj;
x = obj.public_member_variable;
```

Find the r-values! (Only consider the items on the *right* of = signs)

```
int x = 3;                            //3 is an r-value
int *ptr = 0x02248837;                //0x02248837 is an r-value
vector<int> v1{1, 2, 3};              //{1, 2, 3} is an r-value,v1 is an l-value
auto v4 = v1 + v2;                    //v1 + v2 is an r-value
size_t size = v.size();               //v.size()is an r-value
v1[1] = 4*i;                          //4*i is an r-value, v1[1] is an l-value
ptr = &x;                             //&x is an r-value
v1[2] = *ptr;                         //*ptr is an l-value
MyClass obj;
x = obj.public_member_variable;
```

Find the r-values! (Only consider the items on the *right* of = signs)

```
int x = 3;                     //3 is an r-value
int *ptr = 0x02248837;         //0x02248837 is an r-value
vector<int> v1{1, 2, 3};       //{1, 2, 3} is an r-value,v1 is an l-value
auto v4 = v1 + v2;             //v1 + v2 is an r-value
size_t size = v.size();        //v.size()is an r-value
v1[1] = 4*i;                   //4*i is an r-value, v1[1] is an l-value
ptr = &x;                      //&x is an r-value
v1[2] = *ptr;                  //*ptr is an l-value
MyClass obj;                   //obj is an l-value
x = obj.public_member_variable;
```

Find the r-values! (Only consider the items on the *right* of = signs)

```
int x = 3;                        //3 is an r-value
int *ptr = 0x02248837;            //0x02248837 is an r-value
vector<int> v1{1, 2, 3};          //{1, 2, 3} is an r-value,v1 is an l-value
auto v4 = v1 + v2;                //v1 + v2 is an r-value
size_t size = v.size();           //v.size()is an r-value
v1[1] = 4*i;                      //4*i is an r-value, v1[1] is an l-value
ptr = &x;                         //&x is an r-value
v1[2] = *ptr;                     //*ptr is an l-value
MyClass obj;                      //obj is an l-value
x = obj.public_member_variable; //obj.public_member_variable is l-value
```

Questions?

Only l-values can be referenced using &

```
int main() {
    vector<int> vec;
    change(vec);
}

void change(vector<int>& v){...}
//v is a reference to vec
```

```
int main() {
    change(7);
    //this will compile error
}
//we cannot take a reference to
//a literal!
void change(int& v){...}
```

Recall: Vector Copy Assignment

```
template <typename T>
vector<T>& vector<T>::operator=(const vector<T>& other) {
    if (&other == this) return *this;
    _size = other._size;
    _capacity = other._capacity;
    delete[] _elems;
    _elems = new T[other._capacity];
    std::copy(other._elems, other._elems + other._size, _elems);
    return *this;
}
```

Recall: Vector Copy Assignment

```
template <typename T>
vector<T>& vector<T>::operator=(const vector<T>& other) {
```

but wait ...

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123);
}
```

Recall: Vector Copy Constructor

Only l-values can be referenced using &!

```
template <typename T>
vector<T>& vector<T>::operator=(const vector<T>& other) {
```

but wait ...

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123); //make_me_a_vec(123) is an r-value
}
```

why is this possible?

Recall: Vector Copy Constructor

Only l-values can be referenced using &!

```
template <typename T>
vector<T>& vector<T>::operator=(const vector<T>& other) {
```

but wait ...

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123); //make_me_a_vec(123) is an r-value
}
```

rvalues can be bound to `const &` (we promise not to change them)

Recall: Vector Copy Constructor

```
template <typename T>
vector<T>& vector<T>::operator=(const vector<T>& other) {
```

rvalues can be bound to `const &` (we promise not to change them)

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123); //make_me_a_vec(123) is an r-value
}
```

passing by & avoids making unnecessary copies… but does it?

How many arrays will be allocated, copied and destroyed here?

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123);
}
```

```
vector<int> make_me_a_vec(int num) {
    vector<int> res;
    while (num != 0) {
        res.push_back(num%10);
        num /= 10;
     }
    return res;
}
```

code

How many arrays will be allocated, copied and destroyed here?

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123); //make_me_a_vec(123) is an r-value
}
```

- vec is created using the **default constructor**
- make_me_a_vec creates a vector using the **default constructor** and returns it
- vec is reassigned to a **copy** of that return value using **copy assignment**
- **copy assignment** creates a new array and **copies** the contents of the old one
- The original return value's lifetime ends and it calls its **destructor**
- vec's lifetime ends and it calls its **destructor**

How many arrays will be allocated, copied and destroyed here?

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123); //make_me_a_vec(123) is an r-value
}
```

- vec is created using the **default constructor**
- make_me_a_vec creates a vector using the **default constructor** and returns it
- vec is reassigned to a **copy** of that return value using **copy assignment**
- **copy assignment** creates a new array and **copies** the contents of the old one
- The original return value’s lifetime ends and it calls its **destructor**
- vec’s lifetime ends and it calls its **destructor**

copy assignment creates a new array and copies the contents of the old one...

```
template <typename T>
vector<T>& vector<T>::operator=(const vector<T>& other) {
    if (&other == this) return *this;
    _size = other._size;
    _capacity = other._capacity;
    delete[] _elems;
    _elems = new T[other._capacity];
    std::copy(other._elems, other._elems + other._size, _elems);
    return *this;
}
```

copy assignment creates a new array and copies the contents of the old one… what if it didn't?

```
template <typename T>
vector<T>& vector<T>::operator=(const vector<T>& other) {
    if (&other == this) return *this;
    _size = other._size;
    _capacity = other._capacity;
    _elems = other._elems;
    return *this;
}
```

Let's call this move assignment

Is this allowed?

This works!

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123);
}
```

This works!

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123);
}
```

But what about this?

```
int main() {
    vector<string> vec1 = {“hello”, “world”}
    vector<string> vec2 = vec1;
    vec1.push_back(“Sure hope vec2 doesn’t see this!”)
 }
```

This works!

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123);
}
```

But what about this?

```
int main() {
    vector<string> vec1 = {“hello”, “world”}
    vector<string> vec2 = vec1;
    vec1.push_back(“Sure hope vec2 doesn’t see this!”)
 } //BAD!
```

How do we know when to use move assignment and when to use copy assignment?

How do we know when to use move assignment and when to use copy assignment?

When the item on the right of the = is an r-value we should use move assignment

How do we know when to use move assignment and when to use copy assignment?

When the item on the right of the = is an r-value we should use move assignment

Why? r-values are always about to die, so we can steal their resources

Using move assignment

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123);
}
```

Using copy assignment

```
int main() {
    vector<string> vec1 = {“hello”, “world”}
    vector<string> vec2 = vec1;
    vec1.push_back(“Sure hope vec2 doesn’t see this!”)
 } //and vec2 never saw a thing
```

Questions?

How to make two different assignment operators?
Overload `vector::operator=` !

How to make two different assignment operators? Overload `vector::operator=` !

How? Introducing... the r-value reference

`&&`

(This is different from the l-value reference `&` you have see before)

(it has one more ampersand)

Overloading with `&&`

```
int main() {
    int x = 1;
    change(x); //this will call version 2
    change(7); //this will call version 1
}

void change(int&& num){...} //version 1 takes r-values

void change(int& num){...}  //version 2 takes l-values
//num is a reference to vec
```

Copy assignment

```
vector<T>& operator=(const vector<T>& other)
{

    if (&other == this) return *this;
    _size = other._size;
    _capacity = other._capacity;

    //must copy entire array
    delete[] _elems;
    _elems = new T[other._capacity];
    std::copy(other._elems,
    other._elems + other._size,
    _elems);
    return *this;
}
```

Move assignment

```
vector<T>& operator=(vector<T>&& other)
```

Copy assignment

```
vector<T>& operator=(const vector<T>& other)
{

    if (&other == this) return *this;
    _size = other._size;
    _capacity = other._capacity;

    //must copy entire array
    delete[] _elems;
    _elems = new T[other._capacity];
    std::copy(other._elems,
    other._elems + other._size,
    _elems);
    return *this;
}
```

Move assignment

```
vector<T>& operator=(vector<T>&& other)
{
    if (&other == this) return *this;
    _size = other._size;
    _capacity = other._capacity;

    //we can steal the array
    delete[] _elems;
    _elems = other._elems
    return *this;
}
```

This works!

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123); //this will use move assignment
    vector<string> vec1 = {“hello”, “world”}
    vector<string> vec2 = vec1; //this will use copy assignment
    vec1.push_back(“Sure hope vec2 doesn’t see this!”)
}
```

The compiler will pick which vector::operator= to use based on whether the RHS is an l-value or an r-value

Can we make it even better?

Move assignment

```
vector<T>& operator=(vector<T>&& other)
{
    if (&other == this) return *this;
    _size = other._size;
    _capacity = other._capacity;

    //we can steal the array
    delete[] _elems;
    _elems = other._elems
    return *this;
}
```

Can we make it even better?

Move assignment

```
vector<T>& operator=(vector<T>&& other)
{
    if (&other == this) return *this;
    _size = other._size;
    _capacity = other._capacity;

    //we can steal the array
    delete[] _elems;
    _elems = other._elems
    return *this;
}
```

Technically, these are also making copies (using int/ptr copy assignment)

Introducing... `std::move`

- std::move(x) doesn't do anything except **cast x as an r-value**
- It is a way to force C++ to choose the && version of a function

```
int main() {
    int x = 1;
    change(x); //this will call version 2
    change(std::move(x)); //this will call version 1
}

void change(int&& num){...} //version 1 takes r-values

void change(int& num){...}  //version 2 takes l-values
```

Can we make it even better?

Move assignment

```
vector<T>& operator=(vector<T>&& other)
{
    if (&other == this) return *this;
    _size = other._size;
    _capacity = other._capacity;

    //we can steal the array
    delete[] _elems;
    _elems = other._elems
    return *this;
}
```

We can force move assignment rather than copy assignment of these ints by using std::move!

Can we make it even better?

Move assignment

```
vector<T>& operator=(vector<T>&& other)
{
     if (&other == this) return *this;
     _size = std::move(other._size);
     _capacity = std::move(other._capacity);

     //we can steal the array
     delete[] _elems;
     _elems = std::move(other._elems);
     return *this;
}
```

We can force move assignment rather than copy assignment of these ints by using std::move!

This works!

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123); //this will use move assignment
    vector<string> vec1 = {“hello”, “world”}
    vector<string> vec2 = vec1; //this will use copy assignment
    vec1.push_back(“Sure hope vec2 doesn’t see this!”)
}
```

The compiler will pick which vector::operator= to use based on whether the RHS is an l-value or an r-value

This works!

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123); //this will use move assignment
    vector<string> vec1 = {"hello", "world"}
    vector<string> vec2 = vec1; //this will use copy assignment
    vec1.push_back("Sure hope vec2 doesn't see this!")
}
```

The compiler will pick which vector::operator= to use based on whether the RHS is an l-value or an r-value

This works!

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123); //this will use move assignment
    vector<string> vec1 = {“hello”, “world”}
    vector<string> vec2 = vec1; //this will use copy construction
    vec1.push_back(“Sure hope vec2 doesn’t see this!”)
}
```

The compiler will pick which vector::operator= to use based on whether the RHS is an l-value or an r-value

This works!

```
int main() {
    vector<int> vec;
    vec = make_me_a_vec(123); //this will use move assignment
    vector<string> vec1 = {“hello”, “world”} //this should use move
    vector<string> vec2 = vec1; //this will use copy construction
    vec1.push_back(“Sure hope vec2 doesn’t see this!”)
}
```

The compiler will pick which vector::operator= to use based on whether the RHS is an l-value or an r-value

Let's do it with our copy constructor!

copy constructor

```
vector<T>(const vector<T>& other) {
    if (&other == this) return *this;
    _size = other._size;
    _capacity = other._capacity;

    //must copy entire array
    delete[] _elems;
    _elems = new T[other._capacity];
    std::copy(other._elems,
    other._elems + other._size,
    _elems);
    return *this;
}
```

move constructor

Let's do it with our copy constructor!

copy constructor

```
vector<T>(const vector<T>& other) {
    if (&other == this) return *this;
    _size = other._size;
    _capacity = other._capacity;

    //must copy entire array
    delete[] _elems;
    _elems = new T[other._capacity];
    std::copy(other._elems,
    other._elems + other._size,
    _elems);
    return *this;
}
```

move constructor

```
vector<T>(vector<T>&& other)
```

Let’s do it with our copy constructor!

copy constructor

```
vector<T>(const vector<T>& other) {
    if (&other == this) return *this;
    _size = other._size;
    _capacity = other._capacity;

    //must copy entire array
    delete[] _elems;
    _elems = new T[other._capacity];
    std::copy(other._elems,
    other._elems + other._size,
    _elems);
    return *this;
}
```

move constructor

```
vector<T>(vector<T>&& other) {
    if (&other == this) return *this;

    _size = std::move(other._size);
    _capacity =
        std::move(other._capacity);

    //we can steal the array
    delete[] _elems;
    _elems = std::move(other._elems);
    return *this;
}
```

Where else should we use `std::move`?

Where else should we use `std::move`?

Rule of Thumb: Wherever we take in a `const &` parameter in a class member function and assign it to something else in our function

vector::push_back

Copy push_back

```
void push_back(const T& element) {
    elems[_size++] = element;
    //this is copy assignment
}
```

Move push_back

```
void push_back(T&& element) {
    elems[_size++] =
        std::move(element);
    //this forces T’s move
    //assignment
}
```

Be careful with `std::move`

```
int main() {
    vector<string> vec1 = {“hello”, “world”}
    vector<string> vec2 = std::move(vec1);
    vec1.push_back(“Sure hope vec2 doesn’t see this!”)
}
```

Be careful with `std::move`

```
int main() {
    vector<string> vec1 = {“hello”, “world”}
    vector<string> vec2 = std::move(vec1);
    vec1.push_back(“Sure hope vec2 doesn’t see this!”)
}
```

- After a variable is moved via `std::move`, it should never be used until it is reassigned to a new variable!
- The C++ compiler *might* warn you about this mistake, but the code above compiles!

Where else should we use `std::move`?

Rule of Thumb: Wherever we take in a `const &` parameter in a class member function and assign it to something else in our function

Don't use `std::move` outside of class definitions, never use it in application code!

TLDR: Move Semantics

- If your class has copy constructor and copy assignment defined, you should also define a move constructor and move assignment
- Define these by overloading your copy constructor and assignment to be defined for `Type&& other` as well as `Type& other`

- Use `std::move` to force the use of other types' move assignments and constructors
- All `std::move(x)` does is cast `x` as an rvalue
- Be wary of `std::move(x)` in main function code!

Bonus: `std::move` and RAII

- Recall: RAII means all resources required by an object are acquired in its constructor and destroyed in its destructor
- To be consistent with RAII, you should have **no half-ready** resources, such as a vector whose underlying array has been deallocated

Bonus: `std::move` and RAII

- Recall: RAII means all resources required by an object are acquired in its constructor and destroyed in its destructor
- To be consistent with RAII, you should have **no half-ready** resources, such as a vector whose underlying array has been deallocated

Is `std::move` consistent with RAII?

Bonus: `std::move` and RAII

- Recall: RAII means all resources required by an object are acquired in its constructor and destroyed in its destructor
- To be consistent with RAII, you should have **no half-ready** resources, such as a vector whose underlying array has been deallocated

Is `std::move` consistent with RAII?

- I say NO!
- This is a sticky language design flaw, C++ has a lot of those! On your own: what other solutions to the overloading problem can you think of?