Move Semantics in C++

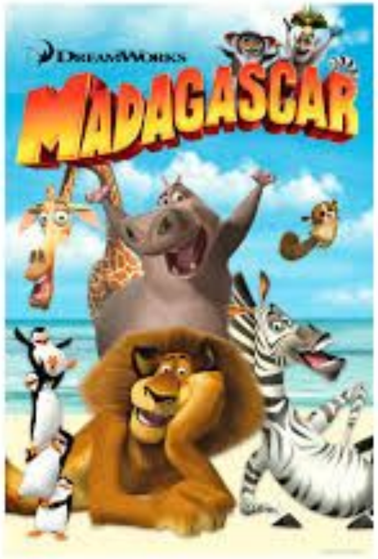
•••

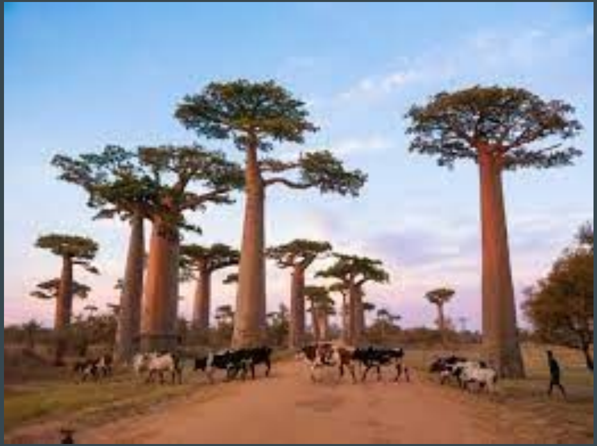
A fancy way to say “how can we avoid making unnecessary copies of resources?”

😷 masks required

Attendance

bit.ly/3UEprqT





Announcements

- Assignment 1 grades are out! Go to paperless.stanford.edu to view your grade and feedback!
- Assignment 2 due date moved to Friday, December 2nd @ 11:59pm PT
    - Partners allowed!

Today

- L values vs r values
- SMF Recap
- What the heck is &&??
    - Aka move assignment operator and move constructor the last two special member functions

Definition: l-values vs r-values

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

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- `x` is an l-value

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int x = 3;
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l-values have names

l-values are **not temporary**

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l-values have names

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

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

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```

l-values have names

l-values are **not temporary**

Definition: l-values vs r-values

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- `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 =
- `3` is an r-value

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

r-values don’t have names

r-values are **temporary**

l-values live until the end of the scope

r-values live until the end of the line

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};
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int x = 3;                    //3 is an r-value
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auto v4 = v1 + v2;
size_t size = v.size();
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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;
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Find the r-values! (Only consider the items on the *right* of `=` signs)

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

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

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int x = 3;                     //3 is an r-value
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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;
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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
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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;
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Find the r-values! (Only consider the items on the *right* of = signs)

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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
```

Last time...

- Special Member Functions (SMFs) get called for specific tasks
    - **Copy constructor:** create a new object as a **copy** of an existing object
      Type::Type(const Type& other)
    - **Copy assignment:** reassign a new object to be a **copy** of an existing object
      Type::operator=(const Type& other)
    - **Destructor:** deallocate the memory of an existing object
      Type::~Type()

Last time...

- Special Member Functions (SMFs) get called for specific tasks
    - Copy **constructor:** create a new object as a copy of an existing object
      Type::Type(const Type& other)
    - Copy **assignment:** reassign a new object to be a copy of an existing object
      Type::operator=(const Type& other)
    - Destructor: deallocate the memory of an existing object
      Type::~Type()

- SMFs are automatically generated for you
    - But if you're managing pointers to allocated to memory, do it yourself

Quick Intertude: make_me_a_vec

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

Example:
vector<int> myvec = make_me_a_vec(123);
// myvec = {3, 2, 1}

What Special Member Function gets called at each point?

```
int main() {
    vector<int> nums1 = make_me_a_vec(12345);  // (1)

    vector<int> nums2;                         // (2)

    nums2 = make_me_a_vec(23456);              // (3)
}
```

What Special Member Function gets called at each point?

copy constructor

```
int main() {
    vector<int> nums1 = make_me_a_vec(12345);  // (1)

    vector<int> nums2;                          // (2)

    nums2 = make_me_a_vec(23456);               // (3)
}
```

destructor

copy assignment

destructor

The Central Problem

```
nums2 = make_me_a_vec(23456);
```

We need to find a way to **move** the result of **make_me_a_vec** to nums2, so that we don't create two objects (and immediately destroy one)

Question: Why don't we just return vector& instead of vector in make_me_a_vec?

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){...}
```

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;
}
```

std::copy is a generic copy function used to copy a range of elements from one container to another.

Recall: Vector Copy Assignment

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

but wait ...

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

```
vector<int> make_me_a_vec(int num);
```

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?

Only l-values can be referenced using &!

Recall: Vector Copy Constructor

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

but wait …

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

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

Recall: Vector Copy Constructor

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

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
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- vec's lifetime ends and it calls its **destructor**

Recall: 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?

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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 seen 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

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

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

Move assignment

```cpp
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;
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    _elems = other._elems
    return *this;
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Move assignment

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    _size = other._size;
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    //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!”)
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    vector<int> vec;
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```
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

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    _elems = new T[other._capacity];
    std::copy(other._elems,
    other._elems + other._size,
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    return *this;
}
```

move constructor

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

Let’s do it with our copy constructor!

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```
vector<T>(const vector<T>& other) {
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    _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!