CS100
Introduction to Programming

Lecture 22. Rvalue references and their use

Today's learning objectives

- Leading Example: Smart pointers
- Move semantics
- Lvalues and Rvalues
- Rvalue references
- Move construction and move assignment
- std::move
- Efficiency considerations

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Smart pointers: motivation

- Consider the following function:

```
void someFunction()
{
    Resource *ptr = new Resource; // Resource is a struct or class

    // do stuff with ptr here

    delete ptr;
}
```

- Problems:
  - Easy to forget deallocating ptr
  - Even if we don't, early exit could lead to leak

Smart pointers: motivation

- Example:

```
#include <iostream>

void someFunction()
{
    Resource *ptr = new Resource;

    int x;
    std::cout << "Enter an integer: ";
    std::cin >> x;

    if (x == 0)
        return; // function returns early, ptr won't be deleted!

    // do stuff with ptr here

    delete ptr;
}
```

What are the good things of classes?

- Contain destructors
  - Get executed when object goes out of scope
  - Can deallocate memory that is owned by the class
  - Guarantees memory is free'ed up
  - RAII idiom:
    - Resource Acquisition Is Initialization
    - Resources are allocated upon object construction
    - Resources are de-allocated upon object destruction

Smart Pointer

- A class
- Manages and cleans up pointers
  - It "holds" the pointer
  - It lets us use the pointer
  - It automatically cleans up frees the allocated memory upon destruction

Smart pointer

- Example:

```
#include <iostream>

template<class T>
class Auto_ptr1 {
T* m_ptr;
 public:
  // Pass in a pointer to "own" via the constructor
  Auto_ptr1(T* ptr=nullptr) : m_ptr(ptr) {}

  // The destructor will make sure it gets deallocated
  ~Auto_ptr1() {
    delete m_ptr;
  }

  // Overload dereference and operator->
  // lets us use Auto_ptr1 like m_ptr.
  T& operator*() const { return *m_ptr; }
  T* operator->() const { return m_ptr; }
};
```

Smart pointer

- Usage:

```
// A sample class to prove the above works
class Resource {
 public:
  Resource() { std::cout << "Resource acquired\n"; }
  ~Resource() { std::cout << "Resource destroyed\n"; }
};

int main() {
  // Allocation of memory here:
  Auto_ptr1<Resource> res(new Resource);

  // ... but no explicit delete needed

  // Note: Resource in angled braces doesn't need
  // a * symbol, it is supplied by the template

  return 0;
} // res goes out of scope here, and destroys
  // allocated Resource for us
```

Passed to res, res owns new Resource (composition)

Dynamic allocation

Output:
Resource acquired
Resource destroyed

res goes out of scope and is destroyed

Destructor of Auto_ptr1 will delete Resource

Smart pointer

- Similarly:

```
void someFunction()
{
    Auto_ptr1<Resource> ptr(new Resource); // ptr now owns the Resource
    int x;
    std::cout << "Enter an integer: ";
    std::cin >> x;
    if (x == 0)
        return; // the function returns early
    // do stuff with ptr here
    ptr->sayHi();
}

int main()
{
    someFunction();

    return 0;
}
```

- If x is not 0, output will be:

  Resource acquired
  Hi!
  Resource destroyed

- If x is 0, output will be:

  Resource acquired
  Resource destroyed

Auto-pointer flaw

- Consider the following code

```
int main() {
  Auto_ptr1<Resource> res1(new Resource);
  Auto_ptr1<Resource> res2(res1);

  return 0;
}
```

or

```
int main() {
  Auto_ptr1<Resource> res1(new Resource);
  Auto_ptr1<Resource> res2;
  res2 = res1;

  return 0;
}
```

- Hits

  Resource acquired
  Resource destroyed
  Segmentation fault

Auto-pointer flaw

- C++ automatically provides
  - copy-constructor
  - assignment operator
  - Are simply copying over the pointer inside Auto-pointer
    → shallow copy

Auto-pointer flaw

- Consider the following code

```
int main() {
  Auto_ptr1<Resource> res1(new Resource);
  Auto_ptr1<Resource> res2(res1);

  return 0;
}
```

Both res1 and res2 are now pointing at the same resource

- res1 and res2 go out of scope
- the first one deletes Resource already
- the second one aims at doing so too → crash

or

```
int main() {
  Auto_ptr1<Resource> res1(new Resource);
  Auto_ptr1<Resource> res2;
  res2 = res1;

  return 0;
}
```

Auto-pointer flaw

- Similar problem is caused by this:

```
void passByValue(Auto_ptr1<Resource> res) {}

int main() {
  Auto_ptr1<Resource> res1(new Resource);
  passByValue(res1)
  return 0;
}
```

- Call to passByValue will make a (shallow) copy of res1
- passByValue will use this copy
- passByValue will destroy this copy upon completion of the function body
- this will destroy the resource!

Solution 1

- Prevent the copy constructor and the assignment operator to be “available”, thereby preventing copying and assignment alltogether

- Solution 1, method 1 (the old way):
  - Explicitly declare them and make them private!

Solution 1, method 1

```
template<class T>
class Auto_ptr1 {
T* m_ptr;
 public:
   // Pass in a pointer to "own" via the constructor
   Auto_ptr1(T* ptr=nullptr) : m_ptr(ptr) {}

   // The destructor will make sure it gets deallocated
   ~Auto_ptr1() {
     delete m_ptr;
   }

   // …
 private:
   Auto_ptr1( const Auto_ptr1 & );
   Auto_ptr1& operator= ( const Auto_ptr1 & );
};
```

Explicit, private declaration

Solution 1, method 1

- What are the problems with this approach?
  - Automatic generation of default constructor does not happen (not a problem here)
  - The explicitly defined default constructor is less efficient than the automatically provided default constructor
  - Member functions and friends can still call the privately defined copy-constructor etc.
    - → Linking error if declared but not defined
  - Unclear

Solution 1

- Prevent the copy constructor and the assignment operator to be “available”, thereby preventing copying and assignment altogether

- Solution 1, method 2 (the C++11 way):

  - Bringing back default constructor
  - No performance loss!

```
struct noncopyable {
  noncopyable() = default;
  noncopyable(const noncopyable&) = delete;
  noncopyable& operator=(const noncopyable&) = delete;
};
```

  - Explicitly deleted
  - Calling them would lead to a compile time error!

Solution 1, method2

```
template<class T>
class Auto_ptr1 {
T* m_ptr;
 public:
  // Pass in a pointer to "own" via the constructor
  Auto_ptr1(T* ptr=nullptr) : m_ptr(ptr) {}

  // The destructor will make sure it gets deallocated
  ~Auto_ptr1() {
    delete m_ptr;
  }

  Auto_ptr1( const Auto_ptr1 & ) = delete;
  Auto_ptr1& operator= ( const Auto_ptr1 & ) = delete;

  …
};
```

Auto-pointer

- Consequence:
  - Pass by value is no longer possible
    → Not a big problem, just pass by reference
  - However, how to do this?

```
??? generateResource() {
  Resource *r = new Resource;
  return Auto_ptr1(r);
}
```

- Can't return by reference! → Object will be destroyed at the end of generateResource
- Can't return by value → copy-constructor is no longer available
- Can't just return pointer r, because that would defy the entire purpose of using the smart pointers

Auto-pointer

- What about just doing deep copies?
  - Not desirable
  - We just want to return a pointer from a function

Today's learning objectives

- Leading Example: Smart pointers
- Move semantics
- Lvalues and Rvalues
- Rvalue references
- Move construction and move assignment
- std::move
- Efficiency considerations

What are move-semantics?

- Do not copy values!
- Simply move ownership!

Example: Auto-pointer 2

```
#include <iostream>

template<class T>
class Auto_ptr2 {
T* m_ptr;
 public:
  Auto_ptr2(T* ptr=nullptr) : m_ptr(ptr) {}
  ~Auto_ptr2() {
    delete m_ptr;
  }

  T& operator*() const { return *m_ptr; }
  T* operator->() const { return m_ptr; }
  bool isNull() const { return m_ptr == nullptr; }

  …
```

…

Example: Auto-pointer 2

```
// Copy constructor with move semantics
Auto_ptr2(Auto_ptr2 &a) { // note: not const anymore!
  m_ptr = a.m_ptr;        // transfer dumb pointer
  a.m_ptr = nullptr;      // remove ownership from source
}

// Assignment operator with move semantics
Auto_ptr2&
operator=(Auto_ptr2& a) { // note: not const anymore!
  if (&a == this)
    return *this;

  delete m_ptr;      // deallocate ptr “this” already holds
  m_ptr = a.m_ptr;   // transfer dumb pointer
  a.m_ptr = nullptr; // remove ownership from source
  return *this;
}
};
```

Example: Auto-pointer 2

- Usage

```
class Resource {
 public:
  Resource() { std::cout << "Resource acquired\n"; }
  ~Resource() { std::cout << "Resource destroyed\n"; }
};
```

Example: Auto-pointer 2

- Usage

```
int main() {
  Auto_ptr2<Resource> res1(new Resource);
  Auto_ptr2<Resource> res2; // Start as nullptr

  std::cout << "res1 is " << (res1.isNull() ? "null\n" : "not null\n");
  std::cout << "res2 is " << (res2.isNull() ? "null\n" : "not null\n");

  res2 = res1; // res2 assumes ownership, res1 is set to null

  std::cout << "Ownership transferred\n";
  std::cout << "res1 is " << (res1.isNull() ? "null\n" : "not null\n");
  std::cout << "res2 is " << (res2.isNull() ? "null\n" : "not null\n");

  return 0;
}
```

Output:

Resource acquired
res1 is not null
res2 is null
Ownership transferred
res1 is null
res2 is not null
Resource destroyed

Auto-pointer 2

- Remaining problems:
  - std::auto_ptr is implemented exactly like this in the original C++98 standard
  - Problems occur if passed by value
  - Deprecated and to be fully removed since C++17
- General problems with move-semantics pre C++11:
  - Copy semantics and move semantics can't be differentiated
  - Overwriting copy-constructor leads to weird behavior
  - res1= res2 is unclear

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Lvalues and Rvalues

- Every expression has two properties
  - A type
  - A “value” property
    - Checks for example whether an expression can be assigned to
- Do not denote properties of values per se, but properties of expressions

Lvalues and Rvalues

$$\underbrace{\overbrace{\texttt{int}}^{\text{type}}\ \texttt{thisNumber}}_{\text{expression}}\ \texttt{=}\ \underbrace{\texttt{2 + anotherNumber}}_{\text{expression}}\texttt{;}$$

- Historically:
  - Lvalues suitable for **<u>left</u>** side of assignment expression
  - Rvalues suitable for **<u>right</u>** side of assignment expression

Distinguish Lvalues and Rvalues

- Every expression either an lvalue or an rvalue
  - Terms historical, now essentially arbitrary
- Lvalues:
  - Refer to objects accessible at more than one point in source code
    - Named objects + objects accessible via pointers/references (locator values)
    - **General rule: If you can take its address, it's an lvalue**
  - Conceptual motivation: Lvalues may not be moved from
- Rvalues:
  - Everything that is not an lvalue
  - Refer to objects accessible at exactly one point in source code
    - Conceptually: temporary objects, e.g,. by-value function returns
      - Unnamed + pointers/references to them not possible
  - Conceptual motivation: Rvalues may be moved from

Lvalues and Rvalues

```
int x;
x = 10;
```

- **`x`** is lvalue:
  - Named object, address can be taken
  - Could be referred to multiple times
- 10 is rvalue:
  - Can’t take its address
  - All build-in numeric literals are rvalues

Lvalues and Rvalues

```
template<typename T1, typename T2>        //return size
int sizeDiff(const T1& c1, const T2& c2) //difference of
{return c1.size() - c2.size();}          //two containers
```

- `sizeDiff,c1,c2` are lvalues:
  - Named objects, addresses can be taken
  - Could be referred to multiple times
- Return value is rvalue
  - Address can’t be taken.
  - No way to get pointer/reference to it

Lvalues and Rvalues

```
int *px;
std::vector<int> v;
std::unordered_set<int> s;
…
*px = sizeDiff(v,s);
```

- `*px` is an lvalue:
  - Address can be taken
  - Pointed-to object could be referred to multiple times
- `sizeDiff(v,s)` value is rvalue
  - Address can't be taken
  - No way to get pointer/reference to it

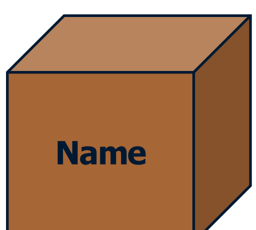
Lvalues and Rvalues

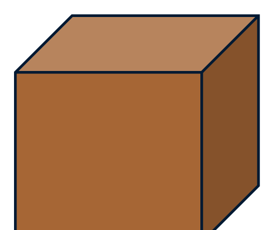
```
std::ifstream myinput( std::string("/some/path.txt") );
```

- Anonymous objects are rvalues

Lvalues and Rvalues

- A way to think about it:
  - Expressions are boxes with a certain content
    - Content has a type and a (real) value
    - Content may be a literal, an object, the result of another expression
    - In order to refer to a box (e.g. to modify it), the box needs to have a name
      - Lvalues: boxes with names
      - Rvalues: boxes without names





Rvalues

- Have expression scope
  - They die at the end of an expression
- They are typically evaluated for their values
- Cannot be assigned to
  - Reason:
    - They are part of an expression
    - Assigning to them could change them before they have been used

Lvalues and Rvalues

- Consider the following function

An lvalue (object with name and address)

```
void printSomething( const std::string & str ) {
  std::cout << str << std::endl;
}
```

Special case: local const reference can be used to prolong the lifetime of temporary value and refers to it until the end of the containing scope (does not incur the cost of a copy-construction!)

and the following call

```
printSomething( std::string("Hello") );
```

An rvalue!!

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C++11: lvalue and rvalue references

- Lvalue references are just “normal” reference as known pre-C++11
- 2 types:

L-value reference	Can be initialized with	Can modify
Modifiable Lvalues	Yes	Yes
Non-modifiable Lvalues	No	No
R-values	No	No

C++11: lvalue and rvalue references

- Lvalue references are just “normal” reference as known pre-C++11
- 2 types:

L-value reference to const	Can be initialized with	Can modify
Modifiable Lvalues	Yes	No
Non-modifiable Lvalues	Yes	No
R-values	Yes	No

C++11: lvalue and rvalue references

- What is an rvalue reference?
  - As the name says: a reference to an r-value
- Initialization:
  - Use double ampersand

```
int x = 5;
int &lref = x;  // l-value reference
                // initialized with l-value x
int &&rref = 5; // r-value reference initialized
                // with r-value 5
```

Rvalue references

- Again, 2 types

R-value reference	Can be initialized with	Can modify
Modifiable Lvalues	No	No
Non-modifiable Lvalues	No	No
R-values	Yes	Yes

Rvalue references

- Again, 2 types

R-value reference to const	Can be initialized with	Can modify
Modifiable Lvalues	No	No
Non-modifiable Lvalues	No	No
R-values	Yes	No

Rvalue references

- Allow us to:
  - Extend the lifespan of the (rvalue) object they are initialized with by the lifespan of the Rvalue reference
  - Modify the Rvalue!

Rvalue references

- Example:

```
#include <iostream>

class Fraction {
 private:
  int m_numerator;
  int m_denominator;

 public:
  Fraction(int numerator = 0, int denominator = 1) :
    m_numerator(numerator), m_denominator(denominator) {}

  friend std::ostream& operator<<( std::ostream& out,
                                   const Fraction &f1 ) {
    out << f1.m_numerator << "/" << f1.m_denominator;
    return out;
  }
};
```

Rvalue references

- Usage:

```
int main() {
  Fraction &&rref = Fraction(3, 5); // r-value reference
                                    // to temporary Fraction
  std::cout << rref << '\n';

  return 0;
} // rref (and the temporary Fraction) goes out of scope here
```

Output: 3/5

Rvalue references

- May hide creation of temporaries!

```
#include <iostream>

int main() {
  int &&rref = 5; // because we're initializing an
                  // r-value reference with a literal,
                  // a temporary with value 5 is
                  // created here
  rref = 10;
  std::cout << rref;
  return 0;
}
```

Output: 10

Rvalue references

- Typically used as function parameters:

```
void fun(const int &lref) { // l-value args select this function
  std::cout << "l-value reference to const\n";
}

void fun(int &&rref) { // r-value arguments will select this function
  std::cout << "r-value reference\n";
}

int main() {
  int x = 5;
  fun(x); // l-value argument calls l-value version of function
  fun(5); // r-value argument calls r-value version of function

  return 0;
}
```

l-value reference to const
r-value reference

Rvalue references

- temporaries can be passed as a const lvalue reference
- **<u>However:</u>** rvalue reference is considered a better match!
- Tricky:

```
int &&ref = 5;
fun(ref);
```

- Has type rvalue reference
- Is an lvalue itself (it has a name)

- Calls the lvalue version!

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Back to our pointer example

- Auto_ptr2:
  - Overriding the default (shallow) copy constructor/ assignment operator to implement move semantics
  - Unsafe
    - Example: pass by value to another function

- Let's make Auto_ptr3:
  - Simply does deep copy everytime
    - Guaranteed safe

Auto_ptr3

```
template<class T>
class Auto_ptr3 {
  T* m_ptr;
 public:
  Auto_ptr3(T* ptr = nullptr) : m_ptr(ptr) {}
  ~Auto_ptr3() { delete m_ptr; }

  // Copy constructor: Do deep copy of a.m_ptr to m_ptr
  Auto_ptr3(const Auto_ptr3& a) {
    m_ptr = new T;
    *m_ptr = *a.m_ptr;
  }

  …
```

Auto_ptr3 (continued)

```
…
// Copy assignment: Do deep copy of a.m_ptr to m_ptr
Auto_ptr3& operator=(const Auto_ptr3& a) {
  // Self-assignment detection
  if (&a == this)
    return *this;

  // Release any resource we're holding
  delete m_ptr;

  // Copy the resource
  m_ptr = new T;
  *m_ptr = *a.m_ptr;

  return *this;
}

T& operator*() const { return *m_ptr; }
T* operator->() const { return m_ptr; }
bool isNull() const { return m_ptr == nullptr; }
};
```

Using Auto_ptr3

Output:
Resource acquired
Resource acquired
Resource destroyed
Resource acquired
Resource destroyed
Resource destroyed

```
class Resource {
 public:
  Resource() { std::cout << "Resource acquired\n"; }
  ~Resource() { std::cout << "Resource destroyed\n"; }
};

Auto_ptr3<Resource> generateResource() {
  Auto_ptr3<Resource> res(new Resource);
  return res; // return value invokes copy constructor
}

int main() {
  Auto_ptr3<Resource> mainres;
  mainres = generateResource(); // assign invokes copy assignment

  return 0;
}
```

Very inefficient!

- 3 Resource allocations just to create an object
- But at least it is safe!

Move construction/assignment

- Role
  - Move ownership from one object to another
  - Use instead of copying to gain efficiency

- How to define?
  - Somewhat similar to regular copy constructor/ assignment operator
  - **But:** Take non-const r-value reference instead of const l-value reference!

Auto_ptr4

- Beginning stays unchanged

```
#include <iostream>

template<class T>
class Auto_ptr4 {
  T* m_ptr;
 public:
  Auto_ptr4(T* ptr = nullptr) : m_ptr(ptr) {}
  ~Auto_ptr4() {
    delete m_ptr;
  }

  …
```

Auto_ptr4

- Move constructor:

```
…
// Copy constructor: Do deep copy of a.m_ptr to m_ptr
Auto_ptr4(const Auto_ptr4& a) {
  m_ptr = new T;
  *m_ptr = *a.m_ptr;
}
```

Important:
- Remove ownership
- Prevent a from destroying resource
- Prevent a from causing dangling pointers

```
// Move constructor: Transfer ownership of a.m_ptr to m_ptr
Auto_ptr4(Auto_ptr4&& a) : m_ptr(a.m_ptr) {
  a.m_ptr = nullptr;
}

// Copy assignment: Do deep copy of a.m_ptr to m_ptr
Auto_ptr4& operator=(const Auto_ptr4& a) {
  …
} …
```

Auto_ptr4

- Move assignment operator

```
…
// Move assignment: Transfer ownership of a.m_ptr to m_ptr
Auto_ptr4& operator=(Auto_ptr4&& a) {
  // Self-assignment detection
  if (&a == this)
    return *this;

  // Release any resource we're holding
  delete m_ptr;

  // Transfer ownership of a.m_ptr to m_ptr
  m_ptr = a.m_ptr;
  a.m_ptr = nullptr;

  return *this;
} …
```

Important:
- Remove ownership
- Prevent **a** from destroying resource
- Prevent **a** from causing dangling pointers

Auto_ptr4: Usage

```
…
Auto_ptr4<Resource> generateResource() {
  Auto_ptr4<Resource> res(new Resource);
  return res; // return value invokes move constructor
}

int main() {
  Auto_ptr4<Resource> mainres;
  mainres = generateResource(); // assign invokes move assignment

  return 0;
}
```

When res goes out of scope, it has no more ownership. Return value was move constructed. **Why!?**

generateResource returns temporary, move assignment is chosen!

Output:
Resource acquired
Resource destroyed

Move construction/assignment

- When?
  - When defined and argument is an r-value (literal, temporary)
  - **Exception: Automatic l-values returned by value!**
    - Special C++ specification
    - Makes sense: automatic l-values will be destroyed at end of function call anyway → just make r-values out of them!

- In most cases, they are not provided by default
    - → If you want them, you need to implement them

Move construction/assignment

- Key insights:
  - If an l-value is used:
    - Copying is the only reasonable alternative
    - Example: `a = b;` should make a (deep) copy, and not alter `b`
  - If an r-value is used:
    - R-value is just a temporary about to be destroyed
    - It is reasonable to steal ownership and avoid copying! (which is more efficient)
    - Example: `a = b + c;`

Disable copy constructor/assignment

- In some cases they are undesirable
  - Example:
    - Auto_ptr4
    - Is move assigned/constructed if returned by another function
    - No need to copy, can be passed by value

```
…
// Copy constructor -- no copying allowed!
Auto_ptr4(const Auto_ptr4& a) = delete;

// Copy assignment -- no copying allowed!
Auto_ptr4& operator=(const Auto_ptr4& a) = delete;
…
```

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std::move

- Extension of move semantics to l-values!
- Example:

```
int main() {
  std::string x{ "abc" };
  std::string y{ "de" };

  std::cout << "x: " << x << '\n';
  std::cout << "y: " << y << '\n';

  swap(x, y);

  std::cout << "x: " << x << '\n';
  std::cout << "y: " << y << '\n';

  return 0;
}
```

Output:
x: abc
y: de
x: de
y: abc

std::move

- Extension of move semantics to l-values!
- Example:

```
#include <iostream>
#include <string>

template<class T>
void swap(T& a, T& b) {
  T tmp { a }; // invokes copy constructor
  a = b;       // invokes copy assignment
  b = tmp;     // invokes copy assignment
}
```

Involves 3 copies!

std::move

- Doing 3 copies is unnecessary
- Could be done with 3 moves instead!
- Solution: Cast the l-values to r-values
  - Done using **`std::move`**

```
#include <iostream>
#include <string>

template<class T>
void swap(T& a, T& b) {
  T tmp { std::move(a) }; // invokes move constructor
  a = std::move(b);       // invokes move assignment
  b = std::move(tmp);     // invokes move assignment
}
```

std::move

- However:
  - What happens to the original l-value!?
  - Let's do another Example/test

```cpp
#include <iostream>
#include <string>
#include <utility>
#include <vector>

int main() {
  std::vector<std::string> v;
  std::string str = "Knock";

  std::cout << "Copying str\n";
  v.push_back(str); // calls l-value version of push_back
                    // which copies str to array
  std::cout << "str: " << str << '\n';
  std::cout << "vector: " << v[0] << '\n';

  std::cout << "\nMoving str\n";

  v.push_back(std::move(str)); // calls r-value version
                               // moving str into array
  std::cout << "str: " << str << '\n';
  std::cout << "vector:" << v[0] << ' ' << v[1] << '\n';
  return 0;
}
```

Output:
Copying str
str: Knock
vector: Knock

Moving str
str:
vector: Knock Knock

std::move

- What has happened to original l-value?
- It has changed!
    - Reset to null string
- This is good:
    - Objects that are being stolen from need to be left in a defined “null state”
    - They are not a temporary after all, and may be used again later!

Today’s learning objectives

- Leading Example: Smart pointers
- Move semantics
- Lvalues and Rvalues
- Rvalue references
- Move construction and move assignment
- std::move
- Efficiency considerations

Efficiency considerations

- Consider the following example:

```
class MyInteger {
 public:
  MyInteger( int value ) : _value(value) {};
  virtual ~MyInteger() {};

  MyInteger operator+( const MyInteger & op ) const {
    return MyInteger( _value + op._value );
  }

 private:
  int _value;
};

int main() {
  MyInteger val1(2);
  MyInteger val2(3);
  MyInteger sum = val1 + val2;
  return 0;
}
```

How many copies are being made?

Efficiency considerations

- Consider the following example:

```
class MyInteger {
 public:
  MyInteger( int value ) : _value(value) {};
  virtual ~MyInteger() {};
```

Return by value: 1 copy

```
  MyInteger operator+( const MyInteger & op ) const {
    return MyInteger( _value + op._value );
  }
```

Pass by value: 2 copies

```
 private:
  int _value;
};

int main() {
  MyInteger val1(2);
  MyInteger val2(3);
  MyInteger sum = val1 + val2;
  return 0;
}
```

Copy-construction: 1 copy

How many copies are made in worst case?

Efficiency considerations

- Why is this just a “worst-case”?
  - In reality, there is hardly any copy being done here!

- What is copy elision?
  - Copy elision happens if the compiler applies some optimization technique to bypass a copying process!

Efficiency considerations

- Copy elision can and most likely will be applied in in several occasions in our example:
  - If passing a temporary by value (an rvalue), why copy it and not immediately use that temporary inside the function? It is up for destruction after the function call anyway!
  - If returning a temporary or even a locally initialized lvalue from a function, why make a copy? Why not prevent destruction and immediately use that as the rvalue returned by the function?
    - This is called RVO (Return value optimization)
    - Compiler reserves space for that rvalue before function call

Efficiency considerations

- Copy elision can and most likely will be applied in in several occasions in our example:
  - If initializing an object using the copy constructor and from a temporary that is up for destruction, the compiler may choose automatically to install move semantics

Why bother about move constructors etc.?

- RVO and copy elision will be done by the compiler automatically and only when it is sure to not alter the behavior of the code.
- With move constructors and move assignment operators, this behavior can be explicitly controlled.