



COMP 2012H Honors Object-Oriented Programming and Data Structures

Self-study: rvalue Reference and Move Semantics

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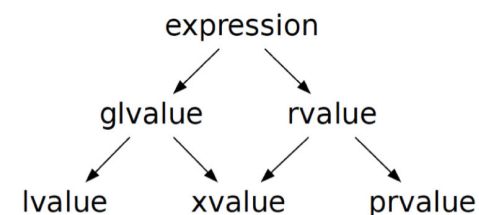
Review: lvalue & rvalue of a Variable

- A **variable** is a symbolic name assigned to some memory storage.
- The difference between a **variable** and a **literal constant** is that a variable is **addressable**. E.g., `x = 100;` `x` is a variable and 100 is a literal constant; `x` has an **address** and 100 doesn't.
- A variable has **dual** roles, depending on where it appears.

`x = x + 1;`

- **lvalue**: its **location** (**read-write**)
- **prvalue** (**pure rvalue**) [C++11]: its **value** (**read-only**)

```
int x;          // OK
4 = 1;          // Error! Why?
(x + 10) = 6;  // Error! Why?
```



Standard for Programming Language C++ Section 3.10

- An **lvalue** (so called, historically, because lvalues could appear on the left-hand side of an assignment expression) designates a function or an object.
 - Example: If `E` is an expression of pointer type, then `*E` is an lvalue expression referring to the object or function to which `E` points. As another example, the result of calling a function whose return type is an lvalue reference is an lvalue.
- An **xvalue** (an “eXpiring” value) also refers to an object, usually near the end of its lifetime (so that its resources may be moved, for example). An xvalue is the result of certain kinds of expressions involving rvalue references.
 - Example: The result of calling a function whose return type is an rvalue reference is an xvalue.
- A **glvalue** (“generalized” lvalue) is an lvalue or an xvalue.
- An **rvalue** (so called, historically, because rvalues could appear on the right-hand side of an assignment expressions) is an xvalue, a temporary object or subobject thereof, or a value that is not associated with an object.
- A **prvalue** (“pure” rvalue) is an rvalue that is not an xvalue.
 - Example: The result of calling a function whose return type is not a reference is a prvalue. The value of a literal such as 12, 7.3e5, or true is also a prvalue.

Part I

Temporary Objects and rvalue References



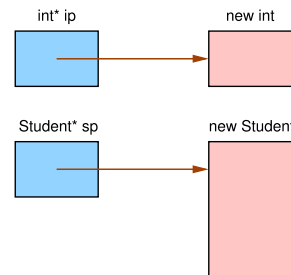
Unnamed Objects I: Dynamically Allocated Objects/Values

Syntax: **Pointer** Variable Definition

T* <variable> = <dynamic object>;

Examples of Pointers

```
int* ip = new int;  
Word* wp = new Word;  
Student* sp = new Student;
```



Dynamic objects allocated and returned by the **new** operator are **unnamed**. You need to use **pointers** to hold them.

- Dynamic objects are managed by the **heap**.
- If you lose all pointers to a dynamic object, you lose the object — resulting in a **memory leak**.

Unnamed Objects II: Temporary Objects/Values

Syntax: **rvalue** Reference Definition

T&& <variable> = <temporary object>;

Temporary objects/values are another kind of **unnamed** objects/values created **automatically** on the **stack** during

- {T01} **const reference initialization**
- {T02} **argument passing** (e.g., type conversion)
- {T03} **function returned value** (by copying)
- {T04} **evaluation of expressions** (e.g., result of sub-expressions)
 - Temporary objects are managed by the **stack**.
 - They are **destructed automatically** by the **stack** when they are no longer needed.
 - An **rvalue reference** is an **alias** of a **temporary object/value**.

Before C++11: const T&

Syntax before C++11

const T& <variable> = <temporary object>;

- In the past, you may prolong the life of a **temporary object** by assigning it to a **const reference**.
- You can't modify a **temporary object** through its **const reference** because a **temporary object** is considered as an **rvalue**.
- Now C++11 allows you to create a **rvalue reference** to hold **temporary objects** so that you may **explicitly** manipulate them in some **safe** ways.
- Once created as an **alias** of a **temporary object**, an **rvalue reference** variable is just like a regular lvalue variable: it has both the roles of **lvalue** or **prvalue** of the **temporary object**, depending on where it is used.

Temporary Values 1, 3, 4 with Basic Types

```
1  #include <iostream>      /* File: T0-int.cpp */  
2  using namespace std;  
3  
4  int square(int x) { return x*x; }  
5  void cbv(int x) { cout << "call-by-value: " << x << endl; }  
6  void cbr(int& x) { cout << "call-by-ref: " << x << endl; }  
7  void cbr(const int& x) { cout << "call-by-const-ref: " << x << endl; }  
8  
9  int main()  
10 {  
11     int a = 3;  
12     int& b = 4;           // Error! Why?  
13     const int& c = 5;     // T01: const ref initialization  
14     int d = square(3);    // T03: function returned value  
15     int e = a + c + d;    // T04: result of sub-expression  
16     cbv(a);              // OK: int x = a  
17     cbr(a);              // OK: int& x = a  
18     cbr(8);              // Error: int& x = 8  
19     cbr(8); return 0;    // T01: const int& x = 8  
20 }
```

- **lvalue reference** only binds to another **lvalue**.
- **const lvalue reference** accepts an **rvalue** because a **temporary value** is created which can be referenced (lines #13, #19).

Class Word: word.h I

```
1  #include <iostream>      /* File: word.h */
2  #include <cstring>
3  using namespace std;
4
5  class Word
6  {
7  private:
8      int freq = 0;
9      char* str = nullptr;
10
11 public:
12     Word() { cout << "default constructor" << endl; }
13
14     Word(const char* s, int f = 1) : freq(f), str(new char [strlen(s)+1])
15     { strcpy(str, s); cout << "conversion: "; print(); }
16
17     Word(const Word& w) : freq(w.freq), str(new char [strlen(w.str)+1])
18     { strcpy(str, w.str); cout << "copy: "; print(); }
19
20     ~Word() { cout << "destructor: "; print(); delete [] str; }
21
22     void print() const
23     { cout << (str ? str : "null") << " ; " << freq << endl; }
24
```

Class Word: word.h II

```
25     Word operator+(const Word& w) const
26     {
27         cout << "\n~~~ " << str << " + " << w.str << " ~~~\n";
28         Word x;          // Which constructor?
29
30         x.freq = freq + w.freq;
31         x.str = new char [strlen(str) + strlen(w.str) + 1];
32         strcpy(x.str, str);
33         strcat(x.str, w.str);
34
35         return x;        // How is x returned?
36     }
37
38     Word to_upper_case() const
39     {
40         Word x(*this);   // Which constructor?
41
42         for (char* p = x.str; *p != '\0'; p++)
43             *p += 'A' - 'a';
44
45         return x;        // How is x returned?
46     }
47 };
```

Temporary Objects with User-defined Types: TO-word.cpp

```
1  #include "word.h"      /* File: TO-word.cpp */
2
3  void print_word(const Word& x)
4  {
5      cout << "<<<\n"; x.print(); cout << ">>>\n";
6  }
7
8  int main()
9  {
10     const Word& w1 = "batman";    // T01: const ref initialization
11     w1.print();
12     print_word("superman");       // T02: argument passing
13
14     Word w2 = w1.to_upper_case(); // T03: function returned value
15     w2.print();
16     ((w1 + " or ") + w2).print(); // T04: result of sub-expression
17
18     cout << "\n*** It's all destructions now ***" << endl;
19     return 0;
20 } /* g++ -std=c++11 -fno-elide-constructors TO-word.cpp */
```

TO-word.cpp Output

```
conversion: batman ; 1
batman ; 1
conversion: superman ; 1
<<<
superman ; 1
>>>
destructor: superman ; 1
copy: batman ; 1
copy: BATMAN ; 1
destructor: BATMAN ; 1
copy: BATMAN ; 1
destructor: BATMAN ; 1
BATMAN ; 1
conversion: or ; 1

~~~ batman + or ~~~
default constructor
copy: batman or ; 2
destructor: batman or ; 2

~~~ batman or + BATMAN ~~~
default constructor
copy: batman or BATMAN ; 3
destructor: batman or BATMAN ; 3
batman or BATMAN ; 3
destructor: batman or BATMAN ; 3
destructor: batman or ; 2
destructor: or ; 1

*** It's all destructions now ***
destructor: BATMAN ; 1
destructor: batman ; 1
```

Temporary Objects of User-defined Types: Remarks

- **Temporary Word** objects are created on lines #10, #12, #14, and #16.
- On lines #10 and #12, C-strings are converted to **temporary Word** objects which are then bound to the **const Word&**.
- `w1.to_upper_case()` returns a **temporary Word** object that is copied to `w2`.
- `(w1 + " or ")` returns a **temporary Word** object which is added to `w2`.
- `((w1 + " or ") + w2)` returns another **temporary Word** object which calls `print()`.
- The lifetime of a **temporary Word** object is at the end of the expression that creates it unless it is held by a **rvalue reference** or **const reference**.
- A **temporary object** that is held by a **rvalue reference** or **const reference** dies as its reference variable goes **out of scope**, or until the completion of the full expression containing it.

rvalue Reference && (C++11) for int

```
1  #include <iostream>      /* File: rvalue-ref-int.cpp */
2  using namespace std;
3
4  int square(int x) { return x*x; }
5
6  int main()
7  {
8      /* rvalue reference with values of basic types */
9      int a = 8;
10     int&& b;           // Error: rvalue ref must be initialized
11     int&& c = a;        // Error: rvalue ref can't bind to lvalue
12
13     int&& d = 5; cout << d << endl;
14     int&& e = square(5); cout << e << endl;
15
16     d = e = 10;          // d, e used as lvalues
17     cout << d << '\t' << e << endl << endl; // d, e used as rvalues
18     return 0;
19 }
```

rvalue Reference && to Hold Temporary Objects

- The term **rvalue reference** sounds contradictory as it seems to be a reference to an **rvalue**! In the past,
 - A **reference (alias)** can only be created for an **lvalue** which is mutable.
 - **Temporary objects** are treated as **rvalues** as they are not supposed to be changed. Why would you want to modify a **temporary object** which will disappear soon?
- An **rvalue reference** allows you to give a name to a **temporary object**, manipulate it, and **modify** it if it is **safe** to do so.
- **rvalue references** are mainly used for real “objects” to improve **code efficiency** in certain scenarios (e.g., **move** operations).
- Like its **lvalue reference** counterpart, an **rvalue reference**
 - must be **initialized** when it is created
 - once bound, **cannot** be re-bound to another **temporary object**
- An **rvalue reference cannot** be bound to an **lvalue** but only to a **temporary object**.

Temporary Word Objects and rvalue Reference

```
1  #include "word.h"        /* File: temp-word.cpp */
2  void print_word(const Word& w) { cout << "print const Word&: "; w.print(); }
3  void print_word(Word&& w) { cout << "print Word&&: "; w.print(); }
4
5  int main()
6  {
7      /* Use const Word& to hold a temporary Word object */
8      Word song("imagine"); cout << endl;
9      const Word& w1 = song.to_upper_case(); cout << endl;
10     song.print(); w1.print(); cout << "\n*****" << endl;
11
12     /* Use Word&& to hold a temporary Word object */
13     Word movie("batman", 2); cout << endl;
14     Word&& w2 = movie.to_upper_case(); cout << endl;
15     movie.print(); w2.print(); cout << endl;
16
17     print_word(song); print_word(movie);
18     print_word(w1); print_word(w2); cout << "\n*****" << endl;
19
20     /* Directly pass a temporary Word object to a function */
21     print_word(movie.to_upper_case()); cout << endl;
22     print_word("Beatles"); cout << "\n*****" << endl; return 0;
23 } /* g++ -std=c++11 -fno-elide-constructors temp-word.cpp */
```

Temporary Word Objects and rvalue Reference: Output

```
conversion: imagine ; 1      print const Word&: imagine ; 1
                             print const Word&: batman ; 2
copy: imagine ; 1           print const Word&: IMAGINE ; 1
copy: IMAGINE ; 1          print const Word&: BATMAN ; 2
destructor: IMAGINE ; 1

                             *****
imagine ; 1                copy: batman ; 2
IMAGINE ; 1                copy: BATMAN ; 2
                             destructor: BATMAN ; 2
                             print Word&&: BATMAN ; 2
                             destructor: BATMAN ; 2

                             *****
conversion: batman ; 2      print Word&&: Beatles ; 1
                             print Word&&: Beatles ; 1
                             destructor: Beatles ; 1

copy: batman ; 2            conversion: Beatles ; 1
copy: BATMAN ; 2           print Word&&: Beatles ; 1
destructor: BATMAN ; 2      destructor: Beatles ; 1

batman ; 2                  *****
BATMAN ; 2                 destructor: BATMAN ; 2
                             destructor: batman ; 2
                             destructor: IMAGINE ; 1
                             destructor: imagine ; 1
```

Temporary Word Objects and rvalue Reference: Quiz

Will the program still compile and if it will, what is the output if

1. the function `print_word(const Word&)` is removed?
2. the function `print_word(Word&&)` is removed?
3. “temp-word.cpp” is compiled without the compilation flag “-fno-elide-constructors”?

const lvalue Reference vs. rvalue Reference

Similarities:

- Both **const T&** and **T&&** can be bound to a **temporary** value/object.
- Both are **references** and must be initialized when they are created.

Differences:

- **const T&** can't be modified but **T&&** can be. In fact, once created, an **T&&** can be used like a **regular variable**.
- `f(const T&)` can take almost any arguments: (const) rvalue/lvalue, **temporary** value/object, and even **rvalue reference**!
- `f(T&&)` can take only **temporary** value/object.
- If you have both `f(const T&)` and `f(T&&)`, and the input argument is a **temporary** value/object \Rightarrow **T&&**.

Part II

Move Semantics



The move Trick with rvalue References

- A **temporary object** is not supposed to be used after it is read.
- **Trick**: So we can cheat while reading it and **steal** its resources.
- However, there is a **catch**: since the **temporary object** will be destructed after it is used, it must be left in a state where its destructor can be **safely** called.
- Example: instead of implementing **deep copy** in a **copy constructor**, we now may have a **move constructor** which will simply **move** (sometimes swap) resources from its input argument **if** it is a **temporary object** of the same class.
⇒ more **efficient** as no memory allocation is needed.
- Similarly, the trick may be used to define a **move assignment operator** instead of a **copy assignment operator**.
- The normal **copy constructors** and **copy assignment operators** are still useful if the input argument must be preserved and **cannot** be modified on return.

Move Constructor and Move Assignment I

```
1  #include <iostream>      /* File: word-move.h */
2  #include <cstring>
3  using namespace std;
4
5  class Word
6  {
7  private:
8      int freq = 0; char* str = nullptr;
9  public:
10     Word() { cout << "default constructor" << endl; }
11     Word(const char* s, int f = 1) : freq(f), str(new char [strlen(s)+1])
12         { strcpy(str, s); cout << "conversion: "; print(); }
13     Word(const Word& w) : freq(w.freq), str(new char [strlen(w.str)+1])
14         { strcpy(str, w.str); cout << "copy: "; print(); }
15     Word(Word&& w) : freq(w.freq), str(w.str) // Move constructor
16         { w.freq = 0; w.str = nullptr; cout << "move: "; print(); }
17     ~Word() { cout << "destructor: "; print(); delete [] str; }
18
19     Word to_upper_case() const
20     {
21         Word x(*this);
22         for (char* p = x.str; *p != '\0'; p++) *p += 'A' - 'a';
23         return (x); // If there is no move constructor, RBV is done by copying
24                     // Now, is done by move!
25     } // (Actually another requirement is that x is not global)
```

Move Constructor and Move Assignment II

```
26
27 void print() const
28 { cout << (str ? str : "null") << " ; " << freq << endl; }
29
30 Word& operator=(const Word& w) { // Copy assignment
31     if (this != &w) { // No assignment for the same Word
32         delete [] str;
33         str = new char [strlen(w.str)+1];
34         freq = w.freq; strcpy(str, w.str);
35         cout << "copy assignment: "; print();
36     }
37     return *this;
38 }
39
40 Word& operator=(Word&& w) { // Move assignment
41     if (this != &w) { // No assignment for the same Word
42         delete [] str;
43         freq = w.freq; str = w.str;
44         w.freq = 0; w.str = nullptr;
45         cout << "move assignment: "; print();
46     }
47     return *this;
48 }
49 };
```

Move Constructor and Move Assignment ..

```
1  #include "word-move.h" /* File: "word-move.cpp" */
2
3  void print_word(const Word& w) { cout << "print const Word&: "; w.print(); }
4  void print_word(Word&& w) { cout << "print Word&&: "; w.print(); }
5
6  int main()
7  {
8      cout << "*** Copy Semantics ***" << endl;
9      Word book {"batman"};
10     Word movie(book);
11     Word song("imagine");
12     movie = song;
13     print_word(book); cout << endl;
14
15     cout << "*** Move Semantics ***" << endl;
16     Word novel {"outliers"}; cout << endl;
17     Word novel2 = novel.to_upper_case(); // move constructions
18     cout << endl; novel.print(); novel2.print(); cout << endl;
19
20     Word band = "Beatles"; cout << endl; // move construction
21     band = "Eagles"; cout << endl; // move assignment
22
23     cout << "*** It's all destructions now ***" << endl;
24     return 0;
25 } /* g++ -std=c++11 -fno-elide-constructors word-move.cpp */
```

Move Constructor and Move Assignment: Output

```
*** Copy Semantics ***
conversion: batman ; 1
copy: batman ; 1
conversion: imagine ; 1
copy assignment: imagine ; 1
print const Word&: batman ; 1

*** Move Semantics ***
conversion: outliers ; 1
copy: outliers ; 1
move: OUTLIERS ; 1
destructor: null ; 0
move: OUTLIERS ; 1
destructor: null ; 0

outliers ; 1
OUTLIERS ; 1

conversion: Beatles ; 1
move: Beatles ; 1
destructor: null ; 0

conversion: Eagles ; 1
move assignment: Eagles ; 1
destructor: null ; 0

*** It's all destructions now ***
destructor: Eagles ; 1
destructor: OUTLIERS ; 1
destructor: outliers ; 1
destructor: imagine ; 1
destructor: imagine ; 1
destructor: batman ; 1
```

std::move() — Casting Into rvalue Reference

Syntax: Casting into rvalue Reference

`std::move(lvalue object)` \equiv rvalue reference of the object

- A standard C++ library function.
- The function `std::move()` actually does NOT move anything.
- It only does **static casting**.

std::move() Example: word-pair.h

```
1 #include "word-move.h" /* File: word-pair.h */
2 class Word_Pair
3 {
4     private:
5         Word w1; Word w2;
6
7     public:
8         // Pass by const&, construct by copying
9         Word_Pair(const Word& a, const Word& b) : w1(a), w2(b)
10         { cout << "-- Copy inputs --\n"; a.print(); b.print(); }
11
12         // Pass by &, construct by moving
13         Word_Pair(Word& a, Word& b) : w1(std::move(a)), w2(std::move(b))
14         { cout << "-- Move with inputs --\n"; a.print(); b.print(); }
15
16         // Pass by rvalue reference &&, construct by moving
17         Word_Pair(Word&& a, Word&& b) : w1(std::move(a)), w2(std::move(b))
18         { cout << "-- Another move with inputs --\n"; a.print(); b.print(); }
19
20         void print() const
21         {
22             cout << "word1 = "; w1.print();
23             cout << "word2 = "; w2.print();
24         }
25 };
```

std::move() Example: word-pair1.cpp

```
1 #include "word-pair.h" /* File: "word-pair1.cpp" */
2
3 int main()
4 {
5     cout << "\n*** Print the book's info ***" << endl;
6     Word author { "Stephen Hawking" };
7     Word title { "Brief History of Time" };
8     Word_Pair book { author, title };
9     book.print();
10
11     cout << "\n*** Print the book2's info ***" << endl;
12     Word_Pair book2 { book }; // Really memberwise copy
13     book2.print();
14
15     cout << "\n*** Print the couple's info ***" << endl;
16     Word husband { "Mr. C++" };
17     Word wife { "Mrs. C++" };
18     Word_Pair couple { std::move(husband), std::move(wife) };
19     couple.print();
20
21     cout << "\n*** It's all destructions now ***" << endl;
22     return 0;
23 } /* g++ -std=c++11 word-pair1.cpp */ // What is the output?
```

std::move() Example: word-pair1.cpp Output

```
*** Print the book's info ***
conversion: Stephen Hawking ; 1
conversion: Brief History of Time ; 1
move: Stephen Hawking ; 1
move: Brief History of Time ; 1
-- Move with inputs --
null ; 0
null ; 0
word1 = Stephen Hawking ; 1
word2 = Brief History of Time ; 1

*** Print the book2's info ***
copy: Stephen Hawking ; 1
copy: Brief History of Time ; 1
word1 = Stephen Hawking ; 1
word2 = Brief History of Time ; 1

*** Print the couple's info ***
conversion: Mr. C++ ; 1
conversion: Mrs. C++ ; 1
move: Mr. C++ ; 1
move: Mrs. C++ ; 1
-- Another move with inputs --
null ; 0
null ; 0
word1 = Mr. C++ ; 1
word2 = Mrs. C++ ; 1

*** It's all destructions now ***
destructor: Mrs. C++ ; 1
destructor: Mr. C++ ; 1
destructor: null ; 0
destructor: null ; 0
destructor: Brief History of Time ; 1
destructor: Stephen Hawking ; 1
destructor: Brief History of Time ; 1
destructor: Stephen Hawking ; 1
destructor: null ; 0
destructor: null ; 0
```

word-pair1.cpp Output Explained

```
Word_Pair(const Word& a, const Word& b): w1(a), w2(b) ...

Word_Pair(Word& a, Word& b): w1(std::move(a)), w2(std::move(b)) ...
```

- word-pair1::line#8: the construction of **Word_Pair book** has 2 choices above, but the 2nd constructor has a higher **precedence** as the arguments match exactly.
- word-pair1::line#12: **Word_Pair book2** is created by the **compiler-generated copy constructor** of **Word_Pair**, which will do **memberwise copy** for each of w1 and w2.
- word-pair1::line#18: by converting the arguments **husband** and **wife** to their **rvalue references**, **Word_Pair couple** is created by the 3rd constructor in word-pair.h.
- **Temporary objects** are destructed at the end of the expression creating them unless they are held by rvalue/const references.
- **Non-temporary objects** are destructed in the reverse order of their constructions.

Summary: Compiler-generated Member Functions (Again)

Unless you define the following, they will be **implicitly** generated by the compiler for you (under some conditions):

1. **default constructor**
(but only if you don't define other constructors)
2. **default copy constructor**
3. **default (copy) assignment operator** function
4. **default move constructor** (C++11)
5. **default move assignment operator** function (C++11)
6. **default destructor**

C++11 allows you to **explicitly** generate or not generate them:

- to generate: **= default;**
- not to generate: **= delete;**

Further Reading



rvalue Reference && (C++11) for string

```
1  #include <iostream>      /* File: rvalue-ref-string.cpp */
2  using namespace std;
3
4  string wrap(string s) { return "begin." + s + ".end"; }
5
6  int main()
7  {
8      /* rvalue reference with user-defined objects */
9      string s1 {"w"};
10     string&& s2;          // Error: rvalue ref must be initialized
11     string&& s3 = s1;      // Error: rvalue ref can't bind to lvalue
12
13     string&& s4 = "x"; cout << s4 << endl;
14     string&& s5 = wrap("x"); cout << s5 << endl;
15
16     s4 = "z";             // s4 used as lvalue
17     cout << s4 << endl; // s4 used as rvalue
18     s5 = s1;              // s5 used as lvalue
19     cout << s5 << endl; // s4 used as rvalue
20     return 0;
21 }
```

std::move() Example: word-pair2.cpp

```
1  #include "word-pair.h"      /* File: "word-pair2.cpp" */
2
3  int main()
4  {
5      cout << "\n*** Print the synonym's info ***" << endl;
6      Word_Pair synonym { Word("happy"), Word("delighted") };
7      synonym.print();
8
9      cout << "\n*** Print the const name's info ***" << endl;
10     const Word first_name { "Albert" };
11     const Word last_name { "Einstein" };
12     Word_Pair name { first_name, last_name };
13     name.print();
14
15     cout << "\n*** It's all destructions now ***" << endl;
16     return 0;
17 } /* g++ -std=c++11 word-pair2.cpp */ // What is the output?
```

std::move() Example: word-pair2.cpp Output

```
*** Print the synonym's info ***      **** Print the const name's info ***
conversion: happy ; 1                 conversion: Albert ; 1
conversion: delighted ; 1             conversion: Einstein ; 1
move: happy ; 1                       copy: Albert ; 1
move: delighted ; 1                  copy: Einstein ; 1
-- Another move with inputs --        -- Copy inputs --
null ; 0                             Albert ; 1
null ; 0                             Einstein ; 1
destructor: null ; 0                 word1 = Albert ; 1
destructor: null ; 0                 word2 = Einstein ; 1
word1 = happy ; 1
word2 = delighted ; 1

*** It's all destructions now ***
destructor: Einstein ; 1
destructor: Albert ; 1
destructor: Einstein ; 1
destructor: Albert ; 1
destructor: delighted ; 1
destructor: happy ; 1
```

That's all!

Any questions?

