# Object-Oriented Programming and Data Structures

# COMP2012: rvalue Reference and Move Semantics

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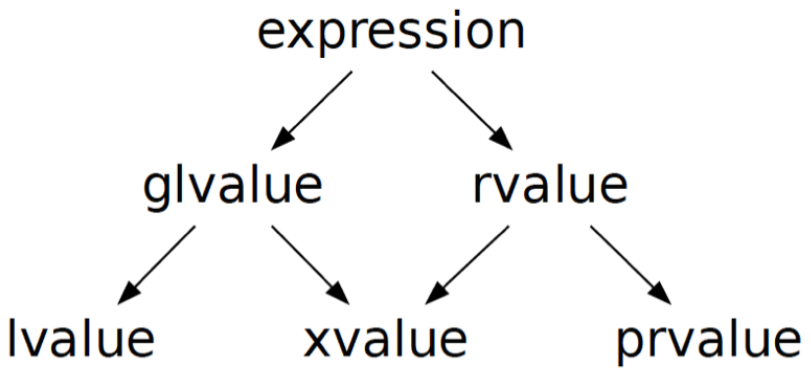
# lvalue, rvalue & xvalue of a Variable

- 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?
```



# Part I

# Temporary Objects and rvalue References

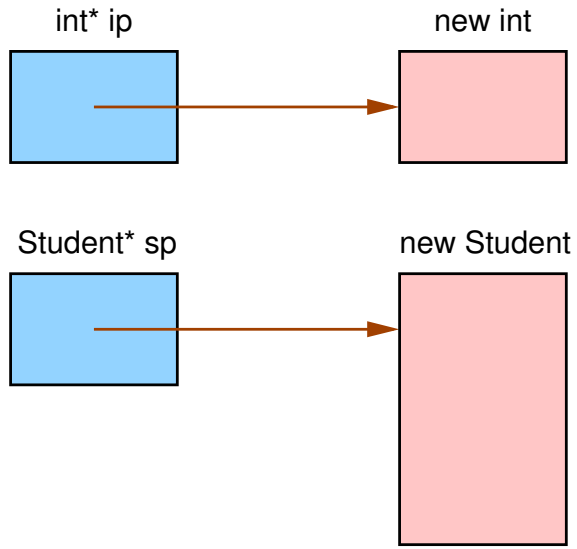
# Unnamed Objects I: Dynamically Allocated Objects/Values

## 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: Temporay Objects/Values

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

{TO1} const reference initialization

{TO2} argument passing (e.g., type conversion)

{TO3} function returned value (by copying)

{TO4} 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.

# 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.

# Temporary Values 1, 3, 4 with Basic Types

```
1   #include <iostream>     /* File: TO-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 cbcr(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;           // TO1: const ref initialization
14      int d = square(3);          // TO3: function returned value
15      int e = a + c + d;          // TO4: 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      cbcr(8); return 0;          // TO1: 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

```
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; }
```

# Class Word: word.h ..

```
24
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";     // TO1: const ref initialization
11     w1.print();
12     print_word("superman");        // TO2: argument passing
13
14     Word w2 = w1.to_upper_case(); // TO3: function returned value
15     w2.print();
16     ((w1 + " or ") + w2).print();   // TO4: 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 const reference.
- A temporary object held by a const reference dies as its reference variable goes out of scope, BUT if the reference is a function parameter, it will persist until the completion of the full expression containing the function call.

# After C++11: rvalue Reference

**Syntax: rvalue Reference Definition**

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

- An rvalue reference is an alias of a temporary object/value.
- C++11 allows an rvalue reference to hold a temporary object so that you may explicitly manipulate it in some safe ways.
- Once created as an alias, 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 how it is used.
- The lifetime of a temporary object is at the end of the expression that creates it unless it is held by an rvalue/const reference.
- A temporary object that is held by an rvalue/const reference dies as its reference variable goes out of scope, BUT if the reference is a function parameter, it will persist until the completion of the full expression containing the function call.

# 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

copy: imagine ; 1
copy: IMAGINE ; 1
destructor: IMAGINE ; 1

imagine ; 1
IMAGINE ; 1

**********
conversion: batman ; 2

copy: batman ; 2
copy: BATMAN ; 2
destructor: BATMAN ; 2

batman ; 2
BATMAN ; 2
```

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

**********
copy: batman ; 2
copy: BATMAN ; 2
destructor: BATMAN ; 2
print Word&&: BATMAN ; 2
destructor: BATMAN ; 2

conversion: Beatles ; 1
print Word&&: Beatles ; 1
destructor: Beatles ; 1

**********
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.
  $\Rightarrow$ 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

```
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      Word to_upper_case() const
19      {
20          Word x(*this);
21          for (char* p = x.str; *p != '\0'; p++) *p += 'A' - 'a';
22          return (x);  // If there is no move constructor, RBV is done by copying,
23                       // Now is done by move!
24      }                // (Actually another requirement is that x is not global)
```

# Move Constructor and Move Assignment ..

```
25
26      void print() const
27          { cout << (str ? str : "null") << " ; " << freq << endl; }
28
29      Word& operator=(const Word& w) { // Copy assignment
30          if (this != &w) {            // No assignment for the same Word
31              delete [] str;
32              str = new char [strlen(w.str)+1];
33              freq = w.freq; strcpy(str, w.str);
34              cout << "copy assignment: "; print();
35          }
36          return *this;
37      }
38
39      Word& operator=(Word&& w) {   // Move assignment
40          if (this != &w) {         // No assignment for the same Word
41              delete [] str;
42              freq = w.freq; str = w.str;
43              w.freq = 0; w.str = nullptr;
44              cout << "move assignment: "; print();
45          }
46          return *this;
47      }
48  };
```

# 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) ≡ 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;

# Part III

# More Examples

# 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 ***
conversion: happy ; 1
conversion: delighted ; 1
move: happy ; 1
move: delighted ; 1
-- Another move with inputs --
null ; 0
null ; 0
destructor: null ; 0
destructor: null ; 0
word1 = happy ; 1
word2 = delighted ; 1
```

```
**** Print the const name's info ***
conversion: Albert ; 1
conversion: Einstein ; 1
copy: Albert ; 1
copy: Einstein ; 1
-- Copy inputs --
Albert ; 1
Einstein ; 1
word1 = Albert ; 1
word2 = Einstein ; 1

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