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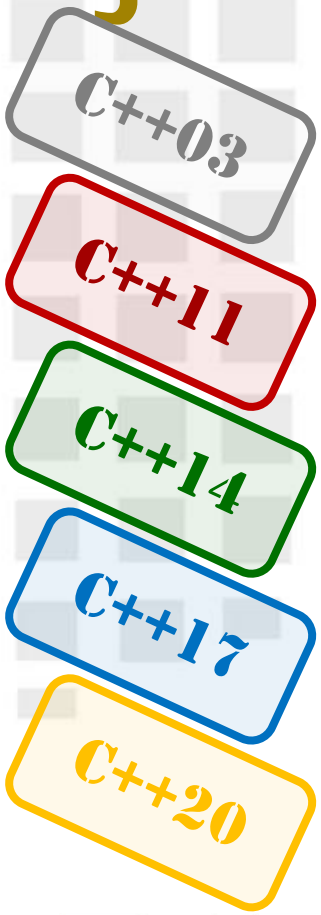
Advanced C++ programming



- **Introduction to C++**
  - → C++: from C and beyond
  - → Classes, objects and lifetime (vs. JAVA)
  - → Oriented-Object Programming (inheritance, polymorphism)
- **Memory management & object manipulation**

Slot 4

  - → References, operators, « copy » object construction
  - → « move » object construction, lambda functions
- **Template vs OO programming**
  - → Template functions and classes
- **The Standard Template Library**
  - → Containers, iterators and algorithms
  - → Using sequence & associative containers …
- **Smart pointers (STL & Boost)**

References (1/6)

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- **Reference vs. pointer?**
  - Link to an existing object (≃ alias).

    ⇒a reference always references an object (valid or not)

```
// i is an integer variable set to 10
int i = 10 ;

// j is another integer variable
int j = i ;

// r references i (i is an alias for r)
int& r = i ;

// Access to variable I through reference r
r = 20 ;
// now, i value is 20
```

```
// r is a not-initialized reference (error)
int& r ;

// r is a reference on i
int& r = i ;

// p1 is a pointer to variable i
int* p1 = &i ;

// p2 is a pointer to variable i (too)
int* p2 = &r ;
```

- Referenced object lifetime must be longer than a reference on it: e.g., a function that returns a reference on function local variable produces a non-valid reference!

References (2/6)

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- **Basic need: editable function parameters?**
  - C++: parameter function passed by value
  - One idea: pass a reference as a parameter so that the referenced variable may be editable...

```
void increment (int& v) {
  // Add one to the variable referenced by v
  v++ ;
}
```

```
// i is an integer variable set to 10
int i = 10 ;

// 'increment' expects a reference to an integer:
// when 'i' is given when calling 'increment',
// 'v' becomes a reference to 'i'
increment (i) ;

// now the value of 'i' is 11
```

TP 4.3

References (3/6)

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- **Useful for non-editable parameters (1/2)?**
  - How to pass a « big object » as a parameter ?
    - the full object is copied onto the stack when calling ▶ may be costly
  - One idea: pass a reference to such an object, but also specifying the compiler, this reference shouldn't be used to modify this object ▶ **`const`** keyword
    - Reduced cost : only an address is copied (like a pointer)
    - Though the reference, access to the object is read-only

```
void increment (const int& v) {
  // Error when compiling : the reference v does not allow
  // to modify the underlaying
  v++ ;
}
```

References (4/6)

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- Useful for non-editable parameters (2/2)
  - Convenient for reference to read-only object!
    - Though the reference, object attribute modifications are forbidden
    - Though the reference, only object « **const** » methods are allowed

compilation

```
class Point {
  int x ;
  // ft may modify the attributes
  // of one type Point object
  void ft () ;
}
```

```
void increment (const Point& p) {
  // Compilation error: the object referenced through p
  // is not editable using reference p
  p.x = 30 ;
  // Compilation error if « ft » method isn't
  // a « const » method i.e. declared as a method
  // not modifying the object on which it is called
  p.ft() ;
}
```

```
class Point {
  int x ;
  // ft cannot modify
  // Point attributes
  void ft () const ;
}
```

```
void increment (const Point& p) {
  // No compilation error
  p.ft() ;
}
```

References (5/6)

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- **Function returned value may be a reference (1/2)**
  - C++: result is returned by value (copied onto the stack)
  - A reference may be returned (for cost optimization)
    - Be extremely careful to underlaying object lifetime

```
Point& Milieu (const Point& A , const Point& B) {
  Point I ((A.x+B.x)/2 , (A.y+B.y)/2) ;

  // A reference to local object I is returned. I being local, is destroyed
  // when the function ends: the returned reference does not reference
  // an existing valid object anymore.
  return I ;
}
```


```
Point A(10,10) , B(20,20) ;
Point& I = Milieu (A , B) ;
```

```
Point Milieu (const Point& A , const Point& B) {
  Point I ((A.x+B.x)/2 , (A.y+B.y)/2) ;

  // A copy of object I is put onto the stack. Object I, still local, is
  // destroyed when the function ends. The copied object can then be caught
  // as a result, by the caller, being a valid object.
  return I ;
}
```

```
Point A(10,10) , B(20,20) ;
Point I = Milieu (A , B) ;
```

References (6/6)

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- **Function returned value may be a reference (2/2)**
  - A returned reference may be used as a L-value (editable)
  - If you don't want this behavior, use **`const`**!

```
int tab[20] ;

// Two functions returning a reference to a cell of 'tab'.
//   'tab' being global, its lifetime exceeds these functions
//    ranges: returning a reference to 'tab' is not an issue.
int&       elt1 (int i) { return tab[i] ; }
const int& elt2 (int i) { return tab[i] ; }

// Returning a non-const reference
int k = elt1(10) ;  // k value is set to the tab[10] value
elt1(10) = 50 ;     // tab[10] value is set to 50 (k is unchanged)

// Returning a const reference
int m = elt2(10) ;  // m value is set to 50 (tab[10] value)
elt2(10) = 80 ;     // Compiler error as elt2 returns a const reference:
                    //   the referenced object (11th cell of 'tab')
                    //   cannot be modified through this reference.
```

compilation

What is RVO?

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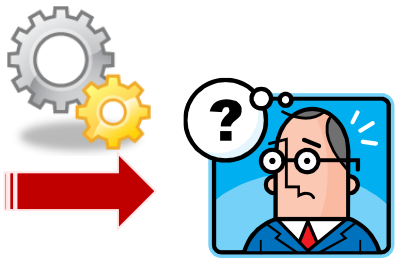
- RVO: « Return Value Optimization »
  - Goal: prevent useless copies when object returned by value
  - The compiler decides whether to perform RVO. If YES:
    - the "collecting" object is directly initialized from inside the function (when returning the value)
    - guaranteed with C++17 ▶ you can return results by value at "no cost"!

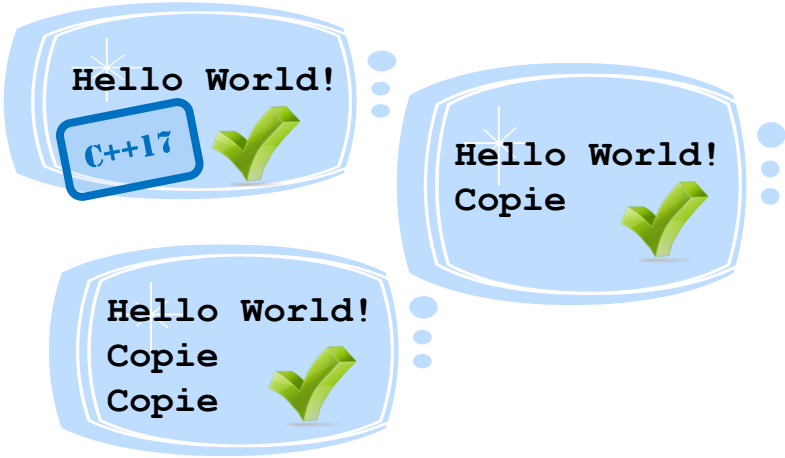
```
struct C {
  C () {}
  C (const C&) { cout << "Copie\n" ; }
} ;

C f() {
  return C() ;
}
```

```
int main() {
  cout << "Hello World!\n" ;
  C obj = f() ;
}
```

g++ -o rvo rvo.cpp -std=c++11





g++ -o rvo rvo.cpp -std=c++11 –fno-elide-constructors

Operators

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- C++ concept
  - An operator performs specific computations on values.
  - Built-in operators are provided but they can be overloaded.
- Unary operators (arithmetic, logical, ...)
  - `+ - * & ~ ! ++ -- -> ->*`
- Binary operators (arithmetic, logical, assignment, ...)
  - `+ - * / % ^ & | << >> > < == != += -= *= /= %= ^= |= && ||`
  - `() , = , [] , << , new new[] delete delete[]`

- You may define operators for your classes
  - coded semantics vs. commonly expected semantics

Overloading operators (1/2)

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- **Goal: provide user-defined classes with operators**
  - Initial operators arity and signatures must be respected
- **Example: define a + operator for class `Point`**
  - Method signature

```
class Point {
  int x , y ;

  Point operator+ (const Point& A) {
    return Point (A.x+this->x , A.y+this->y) ;
  }
}
```

  - Function signature

```
Point operator+ (const Point& A, const Point& B) {
  return Point (A.x+B.x , A.y+B.y) ;
}
```

- **Easy use & excellent readability!**

```
Point A , B ;
Point C = A + B ;
```

Overloading operators (2/2)

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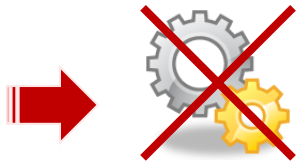
- Are the two definitions equivalent ?

```
struct Point {
  int x , y ;

  Point (int i) : x(i) , y(i) { }

  Point (int xp , int yp) : x(xp) , y(yp) { }

  Point operator+ (const Point& A) {
    return Point (A.x+this->x , A.y+this->y) ;
  }
}
```




```
Point A ;
int   x(4) ;

Point C = A + x ;
Point C = x + A ;
```

no cast on method call

If you define these constructors, the compiler can silently cast one `int` into a `Point`

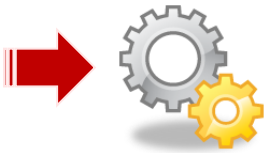
```
Point A = 4 ;   // OK sauf si ctor
                //     explicit
```

```
struct Point {
  int x , y ;

  Point (int i) : x(i) , y(i) { }

  Point (int xp , int yp) : x(xp) , y(yp) { }
}

Point operator+ (const Point& A , const Point& B) {
  return Point (A.x+B.x , A.y+B.y) ;
}
```



```
Point A ;
int   x(4) ;

Point C = A + x ;
Point C = x + A ;
```

Overloading ≪ operator (1/2)

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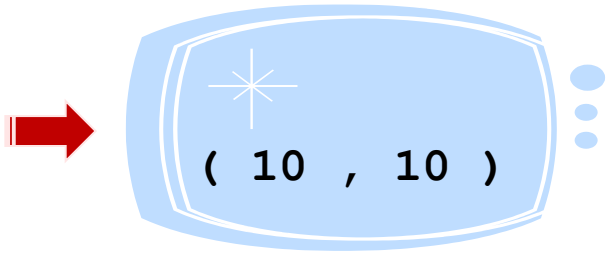
TP 6.3

- How to "print" a user-defined object?
  - C++: insert an object in a I/O stream (output here)
    - Define the << operator for the user-defined class
  - Respect the << operator signature: it is a function only

```
#include <iostream>

class Point {
public :
  int x , y ;
}
```

```
std::ostream& operator<< (std::ostream& flot , const Point& p)
{
  flot << "( " << P.x << " , "  << P.y << " )" ;

  return flot ;
}
```

```
// Point B is being created
Point B (10 , 10) ;

// 'B' is inserted in the 'cout' stream
//  => displayed on screen
std::cout << B << std::endl ;
```



Overloading « operator (2/2)

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- **Implementation variations**
  - Encapsulation

```
class Point {
private :
  int x , y ;
public :
  int getX () const { return x ; }
  int getY () const { return y ; }
}
```

```
std::ostream& operator<< (std::ostream& flot , const Point& p)
{
  flot << "( " << P.getX() << " , "  << P.getY() << " )" ;

  return flot ;
}
```

  - Introducing `friend` functions
    - Function (not method) declared in the class with keyword **`friend`**
    - This function may access all attributes and methods (even private)

```
class Point {
private :
  int x , y ;
…
  friend std::ostream& operator<< (std::ostream& flot , const Point& p) ;
}
```

```
std::ostream& operator<< (std::ostream& flot , const Point& p){
  flot << "( " << P.x << " , "  << P.y << " )" ;
  return flot ;
}
```

Copy constructor (1/2)

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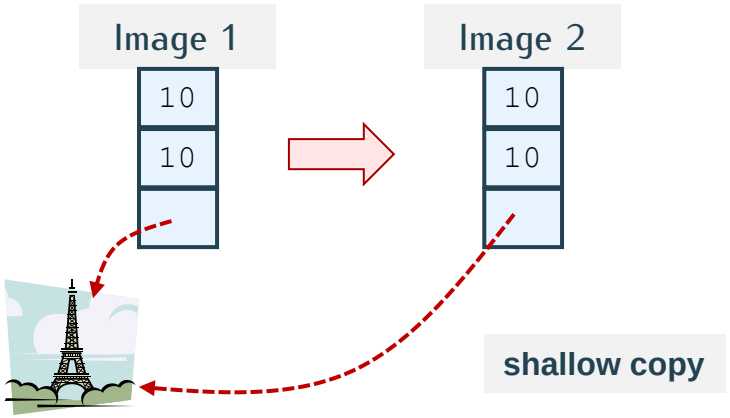
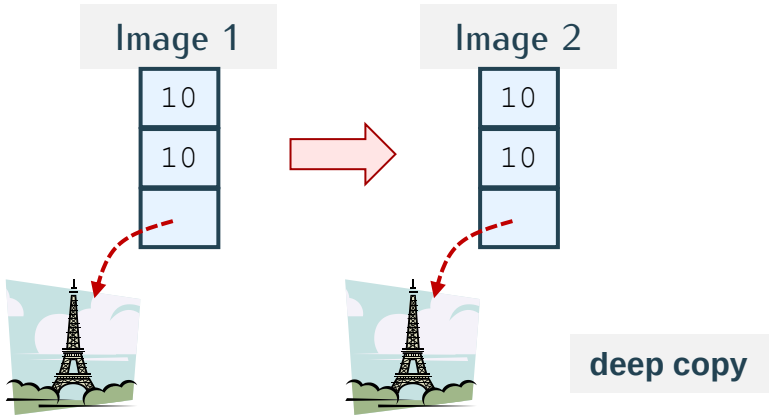
TP 7.1

- Goal
  - Build a new object, copying an existent one
  - By default, for all classes, the compiler define such a constructor but it only performs a shallow copy





▶ You must define your own copy constructor if a shallow copy is not enough to copy objects of your class.

Copy constructor (2/2)

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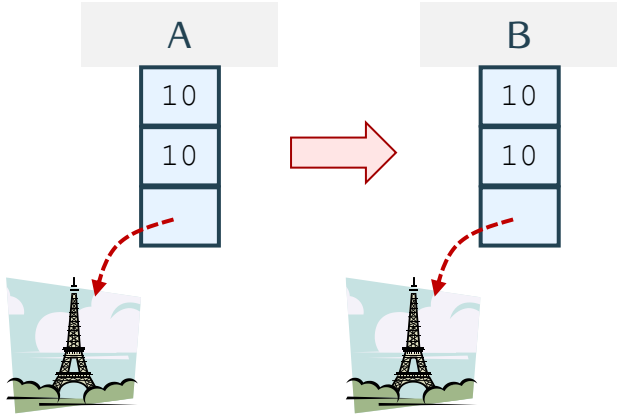
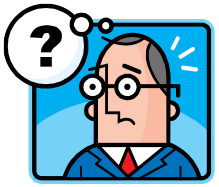
- How to define a copy constructor?

```
class Image {
  int   width , height ;
  byte* image ;

  Image (int w , int h) : width(w) , height(h) {
    image = new byte [w*h] ;
  }

  Image (const Image& I) :
                    width(I.width) , height(I.height) {
    image = new byte [I.width * I.height] ;
    memcpy (image , I.image , I.width*I.height) ;
  }

  ~Image () {
    delete [] image ;
  }
}
```

This is the used-defined copy constructor for `Image` class

```
// Creating an Image A
Image A (10 , 10) ;

// Creating another Image B
// being a copy of A through
// the copy constructor
Image B (A) ;
Image B = A ;
```





- But … how to copy an object into an existing object?

This is an **assignment** operation not a construction one.

Operators

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- C++ concept
  - An operator performs specific computations on values.
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  - `+ - * & ~ ! ++ -- -> ->*`
- Binary operators (arithmetic, logical, assignment, ...)
  - `+ - * / % ^ & | << >> > < == != += -= *= /= %= ^= |= && ||`
  - `() , = , [] , << , new new[] delete delete[]`

- You may define operators for your classes
  - Coded semantics vs. commonly expected semantics

Overloading operator = (1/2)

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TP 7.2

- **Operator = takes only care of assignment**
  - Copy constructor is called when creating new objects.
  - Assignment « `A = B` » means A and B already exist

```
class Point {
  int x , y ;

  Point (int xp , int yp) : x(xp) , y(yp) { }

  Point (Point& P) : x(P.x) , y(P.y) { }

  Point& operator= (const Point& A) {
    if (this != &A) {
      x = A.x ;
      y = A.y ;
    }
    return *this ;
  }
}
```

Prevent self-assignment!

```
// Default ctor (error as not defined)
Point B ;

// Only existing constructor
Point B (10 , 10) ;

// Calling copy constructor
Point A (B) ;

// Calling copy constructor
Point C = B ;

// Calling assignment operator
B = A ;
```

- In this example, this = operator does a shallow copy assignment (not necessary as the compiler default assignment does that)

Overloading operator = (2/2)

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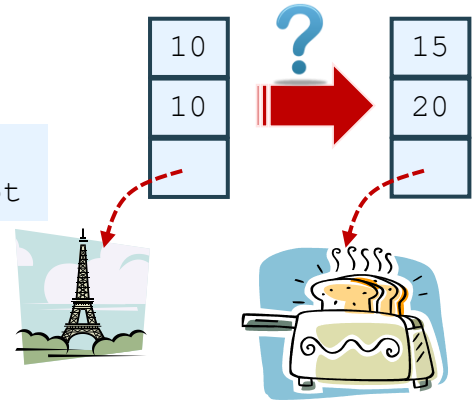
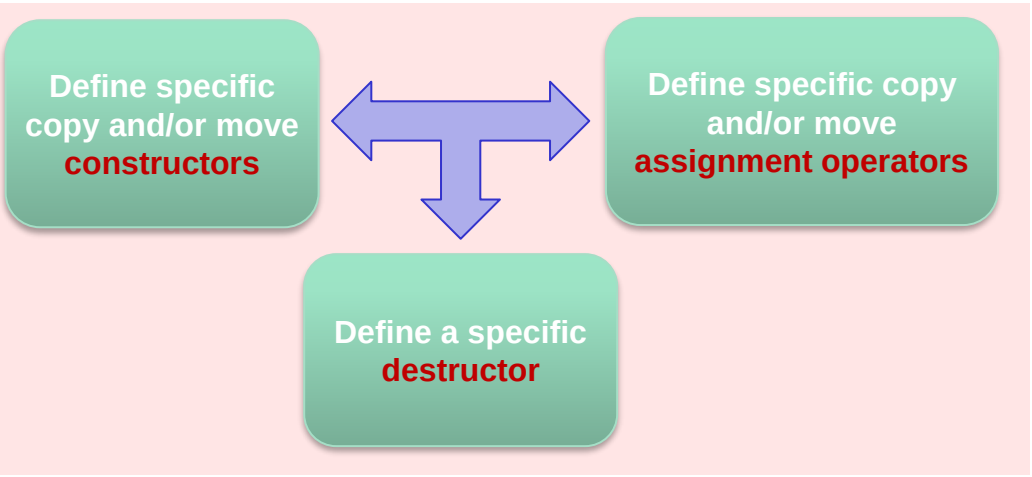
- Two signatures for assignment operator
  - « copy » or « move »

```
// Copy assignment
T& operator= (const T& other)
```

```
// Move assignment
T& operator= (T&& other) noexcept
```



- Respect the “rule of three”



- If a class needs to define one of them, the others two must also be defined

Some construction tips (1/2)

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C++11

- **Why delegating construction?**
  - Prevent initialization code duplication
- **Calling another constructor of the same class from one constructor**

```
class Point {
  int x , y ;

public :
  Point (int a , int b) : x(a) , y(b) {}

  // Using another constructor from the same class
  // to initialize an object:
  // forbidden prior to C++11
  Point () : Point (0 , 0) {}
} ;
```

Delegation the construction

```
// Creating a point A
Point A (10 , 10) ;

// Creating a point B
Point B () ;
```

- **C++11 also allows:**

```
class Point {
  int x = 0 ;
  int y = 0 ; …
```

Some construction tips (2/2)

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C++11

- **Spell out what you really want ...**
  - Make your code easier to understand
  - Let the compiler do the checking for you
    - "**`default`**": actual default ctor / dtor / assignment?
    - "**`delete`**": prohibit specific behaviors (copy, move, ...)

```
struct Point {
  int x , y ;

public :
  Point() = default ;
  Point (int a , int b) : x(a) , y(b) {}
} ;
```

```
struct Point {
  int x , y ;

public :
  Point() = default ;
  Point (const Point &) = delete ;
  Point& operator= (const Point &) = delete ;
  Point (Point &&) = delete ;
  Point& operator= (Point &&) = delete ;
  ~Point() = delete ;
} ;
```

You prohibit explicitly, the creation of one `Point` from another one: NonCopyable class behavior

About initialization… (1/3)

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C++03

- **What it is possible to do:**
  - Built-in types: '**=**' or '**()**'

```
int n = 0 ;
void *p = 0 ;
char c = 'A' ;
```

```
int n (0) ;
void *p (0) ;
char c ('A') ;
```

  - Classes & attributes : '**()**'

≠ POD (Plain Old Data)

```
struct S {
  explicit S (int n , int m) : x(n), y(m) {}
private :
  int x , y ;
} ;
```

```
// Object initialization
S s1(0,1) ;

// Compilation error
S s2 = {0,1} ;
```

  - Aggregates types: '**{}**'

```
// POD arrays and structs are aggregates
int  c1[2] = {0,2} ;
char c2[]  = "message" ;
char c3[]  = {'m','e','s','s','a','g','e','\0'} ;

struct S {
  int a , b ;
} ;
S s = {0,1} ;
```

variable = {…} ;

About initialization... (2/3)

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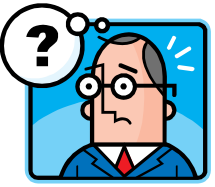
C++03

- What it is not possible to do:
  - Array direct initialization



```
class C {
  int x[100] ;

  C() ;  // no proper way to initialize x
} ;
```

  - Direct initialization of heap allocated array of POD

```
char *buff = new char[1024] ;   //no proper way to initialize the elements of buff
```

  - Direct initialization of STL containers

```
vector <string> vs ;
vs.push_back("alpha") ;
vs.push_back("beta") ;
vs.push_back("gamma") ;
```

➡ C++11 brings universal initialization {}

About initialization… (3/3)

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C++11

- Universal initialization: {}

```
int a{0} ;
string s{"hello"} ;
string s2{s} ;      // copy construction

vector <string> vs{"alpha", "beta", "gamma"} ;
map<string, string> stars {
  {"Superman", "+1 (212) 545-7890"},
  {"Batman", "+1 (212) 545-0987"}} ;

double *pd= new double [3] {0.5, 1.2, 12.99} ;

class C {
  int x[4] ;
public :
  C(): x{0,1,2,3} {}
} ;

vector<int> vi {1,2,3,4,5,6} ;
vector<double> vd {0.5, 1.33, 2.66} ;
```

No sign '=' before {…} ;

```
int a{} ;     // binary zeros for POD
string s{} ;

C obj{} ;     // default constructor
```

Direct default values via {}

Construction through an initialization list: `std::initializer_list<T>`

- Attributes direct initialization

```
class C {
  int x = 7 ;         // class member initializer

  C() ;               // x is initialized to 7 when the default ctor is invoked
  C(int y) : x(y) {} // overrides the class member initializer
} ;
```

```
C c1 ;     // c1.x = 7
C c2(5) ; // c2.x = 5
```

Practice

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- **Managing heap-allocated memory…**
  - Constructor & allocating resources
  - Destructor & releasing resources
- **What about copying objects?**
  - Construction?
  - Assignment?
- **Going further…**
  - Runtime user interaction for object type selection and creation
  - '<<' operator & streams