容器与算法

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Vector and Free Store

- Vector is not just the most useful standard container.
- It provides examples of the most important implementation techniques.

Vector

- Vector is the most useful container
  - Simple
  - Compactly stores elements of a given type
  - Efficient access
  - Expands to hold any number of elements
  - Optionally range-checked access
- How is that done?
  - That is, how is vector implemented?
    - We'll answer that gradually, feature after feature
- Vector is the default container
  - Prefer vector for storing elements unless there's a good reason not to

Building from the ground up

- The hardware provides memory and addresses
  - Low level
  - Untyped
  - Fixed-sized chunks of memory
  - No checking
  - As fast as the hardware architects can make it
- The application builder needs something like a vector
  - Higher-level operations
  - Type checked
  - Size varies (as we get more data)
  - Run-time range checking
  - Close to optimally fast

Building from the ground up

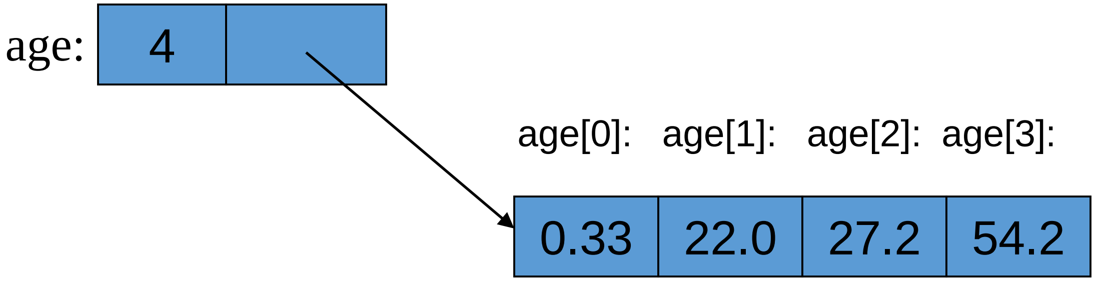
- At the lowest level, close to the hardware, life's simple and brutal
  - You have to program everything yourself
  - You have no type checking to help you
  - Run-time errors are found when data is corrupted or the program crashes
- We want to get to a higher level as quickly as we can
  - To become productive and reliable
  - To use a language "fit for humans"
- Chapters 17-19 basically show all the steps needed
  - The alternative to understanding is to believe in "magic"
  - The techniques for building vector are the ones underlying all higher-level work with data structures

Vector

- A **vector**
  - Can hold an arbitrary number of elements
    - Up to whatever physical memory and the operating system can handle
  - That number can vary over time
    - E.g. by using **push_back()**
  - Example

vector<double> age(4);

age[0]=.33;   age[1]=22.0;   age[2]=27.2;   age[3]=54.2;



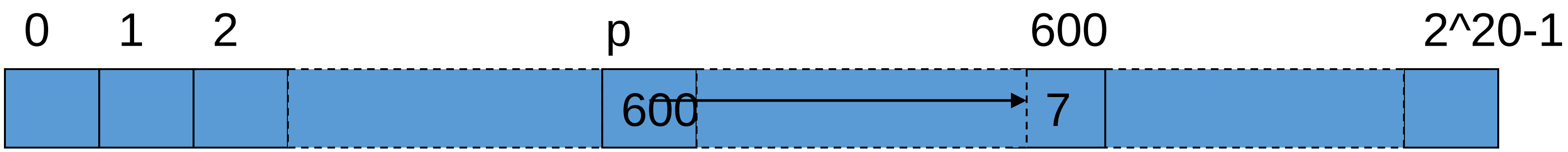
Vector

```
// a very simplified vector of doubles (like vector<double>):
class vector {
  int sz;                 // the number of elements ("the size")
  double* elem;           // pointer to the first element
public:
  vector(int s);                  // constructor: allocate s elements,
                          // let elem point to them,
                          // store s in sz
  int size() const { return sz; }        // the current size
};
```

- ***** means "pointer to" so **double*** is a "pointer to **double**"
  - What is a "pointer"?
  - How do we make a pointer "point to" elements?
  - How do we "allocate" elements?

Pointer values

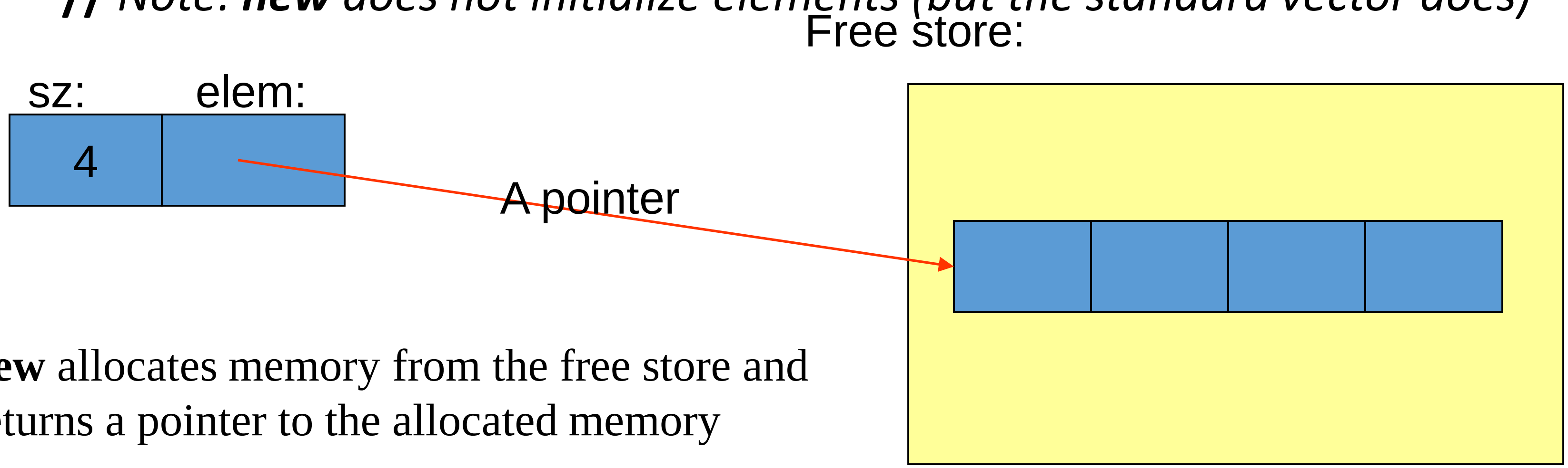
- Pointer values are memory addresses
  - Think of them as a kind of integer values
  - The first byte of memory is 0, the next 1, and so on
  - A pointer **p** can hold the address of a memory location



- A pointer points to an object of a given type
  - E.g. a **double*** points to a **double**, not to a **string**
- A pointer’s type determines how the memory referred to by the pointer’s value is used
  - E.g. what a **double*** points to can be added but not, say, concatenated

Vector (constructor)

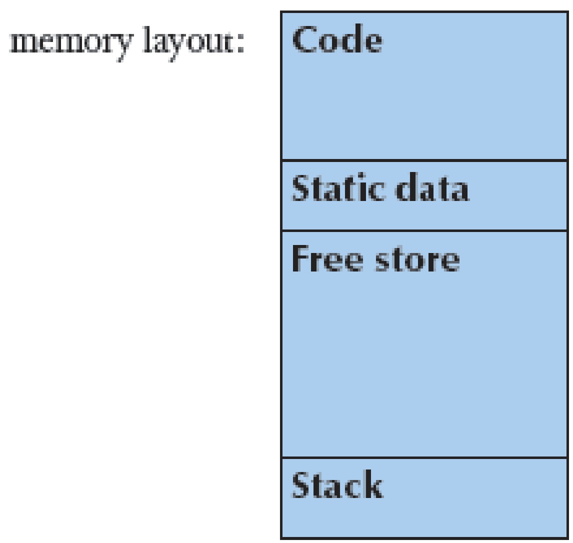
```
vector::vector(int s)          // vector's constructor
  :sz(s),                      // store the size s in sz
   elem(new double[s])         // allocate s doubles on the free store
                               // store a pointer to those doubles in elem
{
}
// Note: new does not initialize elements (but the standard vector does)
```



new allocates memory from the free store and returns a pointer to the allocated memory

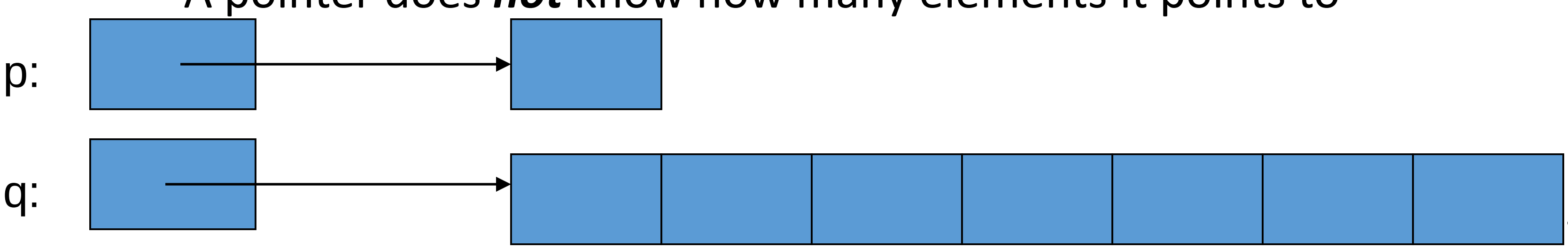
The computer’s memory

- As a program sees it
  - Local variables “live on the stack”
  - Global variables are “static data”
  - The executable code is in “the code section”



The free store
(sometimes called "the heap")

- You request memory “to be allocated” “on the free store” by the **new** operator
  - The **new** operator returns a pointer to the allocated memory
  - A pointer is the address of the first byte of the memory
  - For example
    - **int* p = new int;** **//** *allocate one uninitialized* ***int***
      // ***int**** *means “pointer to* ***int****”*
    - **int* q = new int[7];** **//** *allocate seven uninitialized* ***int****s*
      // *“an array of 7* ***int****s”*
    - **double* pd = new double[n];** **//** *allocate* ***n*** *uninitialized* ***double****s*
  - A pointer points to an object of its specified type
  - A pointer does ***not*** know how many elements it points to

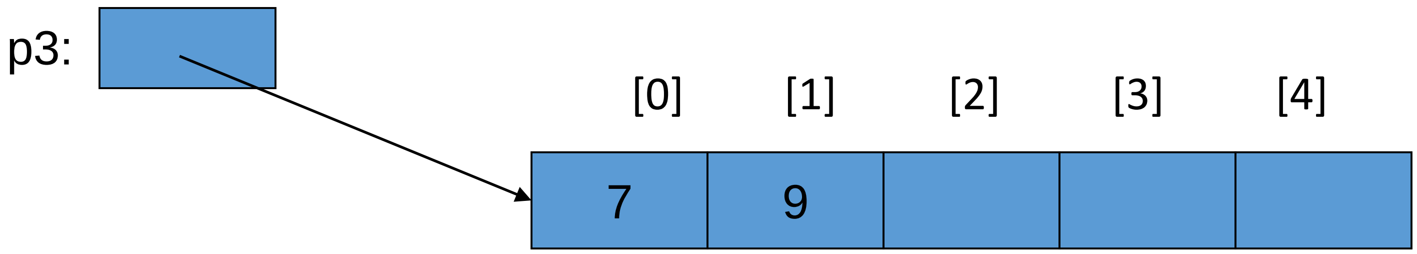


Access

- Individual elements

```
int* p1 = new int;      // get (allocate) a new uninitialized int
int* p2 = new int(5);   // get a new int initialized to 5

int x = *p2;            // get/read the value pointed to by p2
                        // (or "get the contents of what p2 points to")
                        // in this case, the integer 5
int y = *p1;         // undefined: y gets an undefined value; don't do that
```

Access



- Arrays (sequences of elements)

int* p3 = new int[5]; ***//*** *get (allocate) 5* ***int****s*

// array elements are numbered [0], [1], [2], …

p3[0] = 7; ***//*** *write to ("set") the 1st element of p3*

p3[1] = 9;

int x2 = p3[1]; ***//*** *get the value of the 2nd element of p3*

int x3 = *p3; ***//*** *we can also use the dereference operator * for an array*

// **p3 means p3[0] (and vice versa)*

Why use free store?

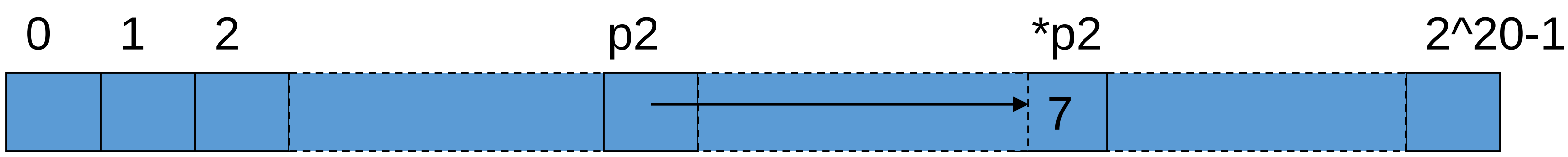
- To allocate objects that have to outlive the function that creates them:
  - For example

```
double* make(int n)        // allocate n ints
{
    return new double[n];
}
```

  - Another example: vector’s constructor

Pointer values

- Pointer values are memory addresses
  - Think of them as a kind of integer values
  - The first byte of memory is 0, the next 1, and so on

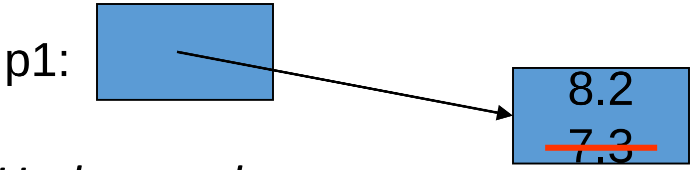



```
// you can see a pointer value (but you rarely need/want to):
int* p1 = new int(7);                      // allocate an int and initialize it to 7
double* p2 = new double(7);                // allocate a double and initialize it to 7.0
cout << "p1==" << p1 << " *p1==" << *p1 << "\n";  // p1==??? *p1==c
cout << "p2==" << p2 << " *p2==" << *p2 << "\n";  // p2==??? *p2=7
```

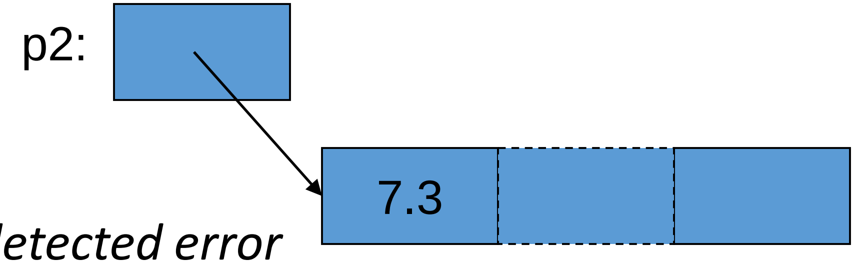
Access

- A pointer does **not** know the number of elements that it's pointing to (only the address of the first element)

```
double* p1 = new double;
*p1 = 7.3;              // ok
p1[0] = 8.2;            // ok
p1[17] = 9.4;           // ouch! Undetected error
p1[-4] = 2.4;           // ouch! Another undetected error
```




```
double* p2 = new double[100];
*p2 = 7.3;              // ok
p2[17] = 9.4;           // ok
p2[-4] = 2.4;           // ouch! Undetected error
```

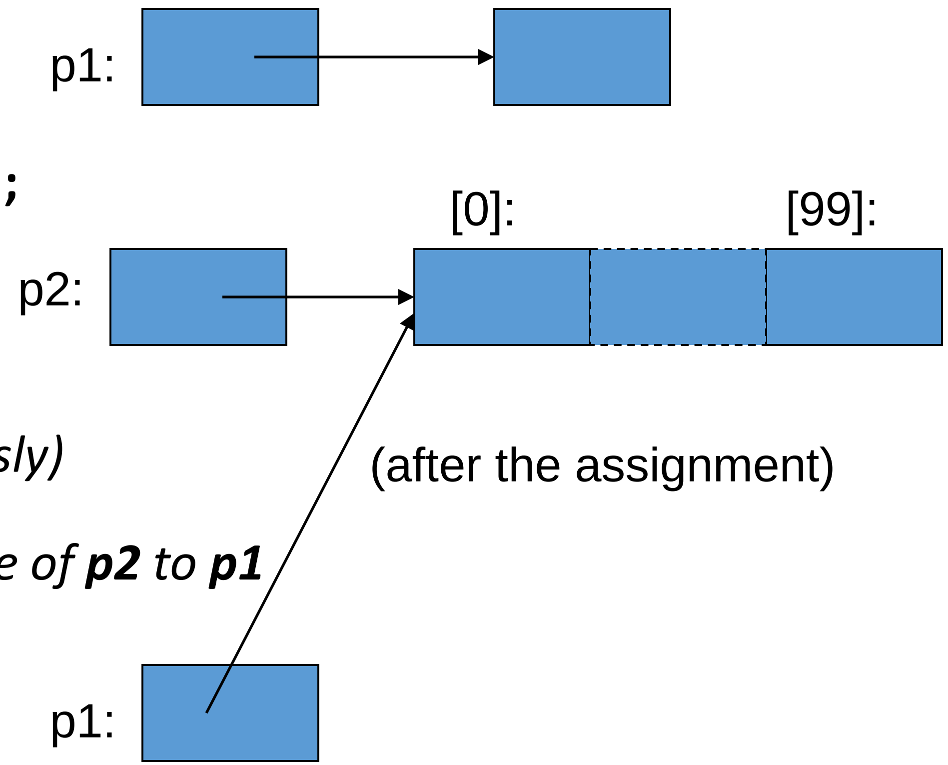


Access

- A pointer does ***not*** know the number of elements that it's pointing to

  double* p1 = new double;

  double* p2 = new double[100];



  p1[17] = 9.4; ***//*** *error (obviously)*

  p1 = p2; ***//*** *assign the value of* ***p2*** *to* ***p1***

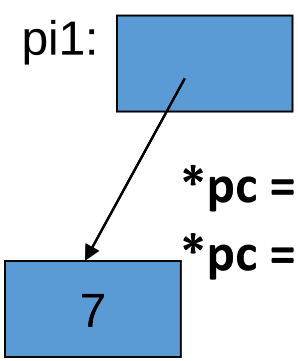
  p1[17] = 9.4; ***//*** *now ok:* ***p1*** *now points to the array of 100* ***doubles***

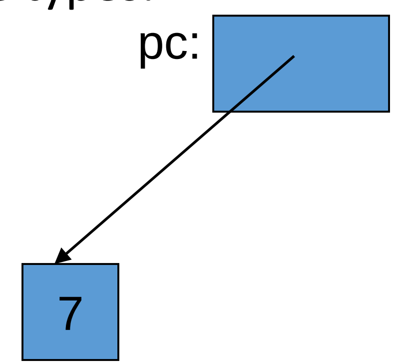
Access

- A pointer ***does*** know the type of the object that it's pointing to

```
int* pi1 = new int(7);
int* pi2 = pi1;          // ok: pi2 points to the same object as pi1
double* pd = pi1;        // error: can't assign an int* to a double*
char* pc = pi1;          // error: can't assign an int* to a char*
```

  - There are no implicit conversions between a pointer to one value type to a pointer to another value type
  - However, there are implicit conversions between value types:





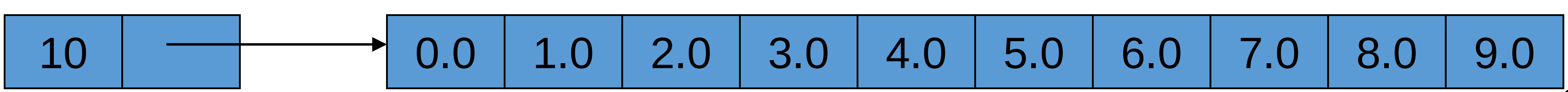

```
*pc = 8;    // ok: we can assign an int to a char
*pc = *pi1;         // ok: we can assign an int to a char
```

Pointers, arrays, and vector

- Note
  - With pointers and arrays we are "touching" hardware directly with only the most minimal help from the language. Here is where serious programming errors can most easily be made, resulting in malfunctioning programs and obscure bugs
    - Be careful and operate at this level only when you really need to
    - If you get "segmentation fault", "bus error", or "core dumped", suspect an uninitialized or otherwise invalid pointer
  - vector is one way of getting almost all of the flexibility and performance of arrays with greater support from the language (read: fewer bugs and less debug time).

Vector (construction and primitive access)

```
// a very simplified vector of doubles:
class vector {
  int sz;                 // the size
  double* elem;           // a pointer to the elements
public:
  vector(int s) :sz(s), elem(new double[s]) { }      // constructor
  double get(int n) const { return elem[n]; }        // access: read
  void set(int n, double v) { elem[n]=v; }           // access: write
  int size() const { return sz; }                    // the current size
};

vector v(10);
for (int i=0; i<v.size(); ++i) { v.set(i,i); cout << v.get(i) << ' '; }
```



A problem: memory leak

```
double* calc(int result_size, int max)
{
   double* p = new double[max];            // allocate another max doubles
                                           // i.e., get max doubles from the free store
   double* result = new double[result_size];
   // … use p to calculate results to be put in result …
   return result;
}

double* r = calc(200,100);       // oops! We “forgot” to give the memory
                                 // allocated for p back to the free store
```

- Lack of de-allocation (usually called “memory leaks”) can be a serious problem in real-world programs
- A program that must run for a long time can’t afford any memory leaks

A problem: memory leak

```
double* calc(int result_size, int max)
{
  double* p = new double[max];   // allocate another max doubles
                                 // i.e., get max doubles from the free store
  double* result = new double[result_size];
  // … use p to calculate results to be put in result …
  delete[ ] p;                   // de-allocate (free) that array
                                 // i.e., give the array back to the free store
  return result;
}

double* r = calc(200,100);
// use r
delete[ ] r;                     // easy to forget
```

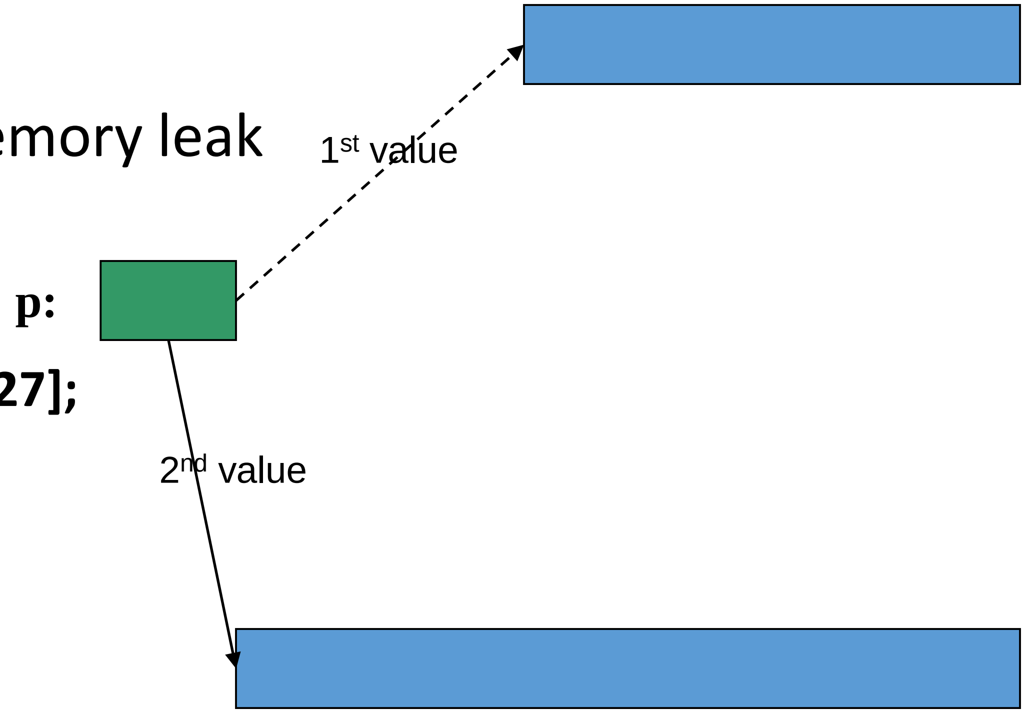
Memory leaks

- A program that needs to run “forever” can’t afford any memory leaks
  - An operating system is an example of a program that “runs forever”
- If a function leaks 8 bytes every time it is called, how many days can it run before it has leaked/lost a megabyte?
  - Trick question: not enough data to answer, but about 130,000 calls
- All memory is returned to the system at the end of the program
  - If you run using an operating system (Windows, Unix, whatever)
- Program that runs to completion with predictable memory usage may leak without causing problems
  - *i.e.,* memory leaks aren’t “good/bad” but they can be a major problem in specific circumstances

Memory leaks

- Another way to get a memory leak

```
void f()
{
  double* p = new double[27];
  // …
  p = new double[42];
  // …
  delete[] p;
}

// 1st array (of 27 doubles) leaked
```



Memory leaks

- How do we systematically and simply avoid memory leaks?
  - don't mess directly with **new** and **delete**
    - Use **vector**, etc.
  - Or use a garbage collector
    - A garbage collector is a program the keeps track of all of your allocations and returns unused free-store allocated memory to the free store (not covered in this course; see http://www.stroustrup.com/C++.html)
    - Unfortunately, even a garbage collector doesn’t prevent all leaks
    - See also Chapter 25

A problem: memory leak

```
void f(int x)
{
  vector v(x);// define a vector
              // (which allocates x doubles on the free store)
  // … use v …

  // give the memory allocated by v back to the free store
  // but how? (vector's elem data member is private)
}
```

Vector (destructor)

```
// a very simplified vector of doubles:
class vector {
  int sz;                 // the size
  double* elem;           // a pointer to the elements
public:
  vector(int s)           // constructor: allocates/acquires memory
        :sz(s), elem(new double[s]) { }
  ~vector()               // destructor: de-allocates/releases memory
        { delete[ ] elem; }
  // …
};
```

- Note: this is an example of a general and important technique:
  - acquire resources in a constructor
  - release them in the destructor
- Examples of resources: memory, files, locks, threads, sockets

A problem: memory leak

```
void f(int x)
{
  int* p = new int[x];          // allocate x ints
  vector v(x);                  // define a vector (which allocates another x ints)
  // … use p and v …
  delete[ ] p;  // deallocate the array pointed to by p
  // the memory allocated by v is implicitly deleted here by vector's destructor
}
```

- The **delete** now looks verbose and ugly
  - How do we avoid forgetting to **delete[ ] p**?
  - Experience shows that we often forget
- Prefer **delete**s in destructors

Free store summary

- Allocate using **new**
  - New allocates an object on the free store, sometimes initializes it, and returns a pointer to it
    - **int* pi = new int;** **//** *default initialization (none for* ***int****)*
    - **char* pc = new char('a');** **//** *explicit initialization*
    - **double* pd = new double[10];** **//** *allocation of (uninitialized) array*
  - New throws a **bad_alloc** exception if it can't allocate (out of memory)
- Deallocate using **delete** and **delete[ ]**
  - **delete** and **delete[ ]** return the memory of an object allocated by **new** to the free store so that the free store can use it for new allocations
    - **delete pi;** **//** *deallocate an individual object*
    - **delete pc;** **//** *deallocate an individual object*
    - **delete[ ] pd;** **//** *deallocate an array*
  - Delete of a zero-valued pointer ("the null pointer") does nothing
    - **char* p = 0;** **//** *C++11 would say* **char* p = nullptr;**
    - **delete p;** **//** *harmless*

Vector: Initialization, Copy and Move

Initialization: initializer lists

- We would like simple, general, and flexible initialization
  - So we provide suitable constructors, including

```
class vector {
  // …
public:
      vector(int s);          // constructor (s is the element count)

      vector(std::initializer_list<double> lst);   // initializer-list constructor
      // …
};

vector v1(20);             // 20 elements, each initialized to 0
vector v2 {1,2,3,4,5};     // 5 elements: 1,2,3,4,5
```

Initialization: initializer lists

- We would like simple, general, and flexible initialization
  - So we provide suitable constructors

```
vector::vector(int s)        // constructor (s is the element count)
   :sz{s}, elem{new double[s]} { }
{
   for (int i=0; i<sz; ++i) elem[i]=0;
}

vector::vector(std::initializer_list<double> lst)   // initializer-list constructor
   :sz{lst.size()}, elem{new double[sz]} { }
{
   std::copy(lst.begin(),lst.end(),elem); // copy lst to elem
}
vector v1(20);       // 20 elements, each initialized to 0
vector v2 {1,2,3,4,5};       // 5 elements: 1,2,3,4,5
```

Initialization: lists and sizes

- If we initialize a vector by 17 is it
  - 17 elements (with value 0)?
  - 1 element with value 17?
- By convention use
  - () for number of elements
  - {} for elements
- For example
  - **vector v1(17); //** *17 elements, each with the value 0*
  - **vector v2 {17}; //** *1 element with value 17*

A problem

- Copy doesn't work as we would have hoped (expected?)

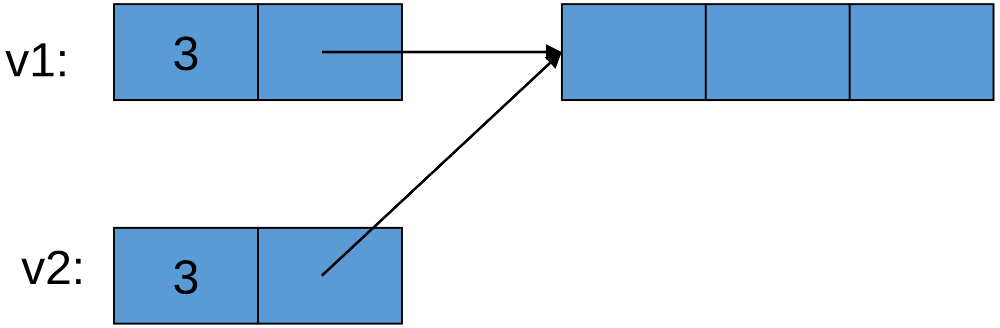
```
void f(int n)
{
  vector v(n);           // define a vector
  vector v2 = v;         // what happens here?
                         // what would we like to happen?
  vector v3;
  v3 = v;                // what happens here?
                         // what would we like to happen?
  // …
}
```

- Ideally: **v2** and **v3** become copies of **v** (that is, **=** makes copies**)**
  - And all memory is returned to the free store upon exit from **f()**
- That's what the standard **vector** does,
  - but it's not what happens for our still-too-simple **vector**

Naïve copy initialization (the default)

- By default "copy" means "copy the data members"

```
void f(int n)
{
  vector v1(n);
  vector v2 = v1;      // initialization:
                       // by default, a copy of a class copies its members
                       // so sz and elem are copied
}
```

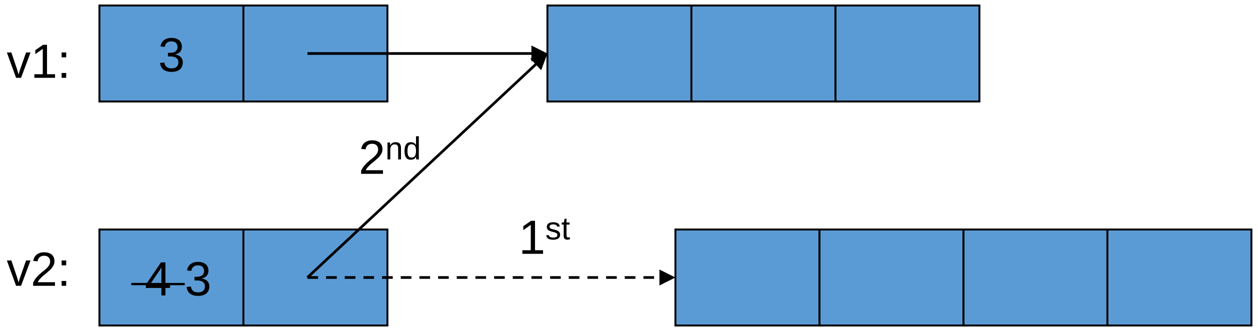


Disaster when we leave f()!

v1's elements are deleted twice (by the destructor)

Naïve copy assignment (the default)

```
void f(int n)
{
  vector v1(n);
  vector v2(4);
  v2 = v1;      // assignment:
                // by default, a copy of a class copies its members
                // so sz and elem are copied
}
```



Disaster when we leave f()!

v1's elements are deleted twice (by the destructor)

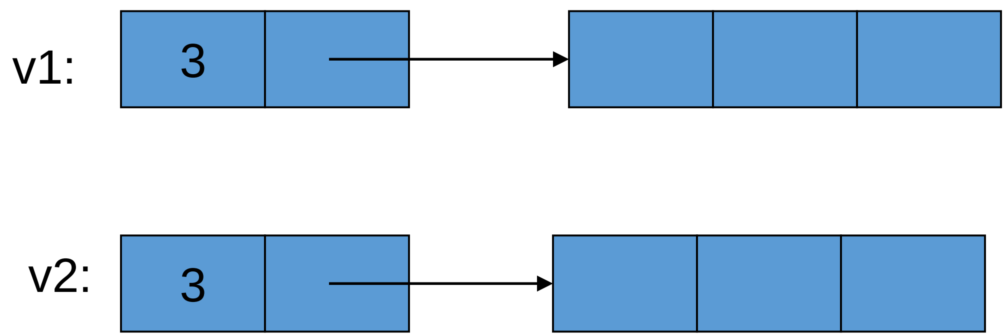
memory leak: v2's elements are not deleted

Copy constructor (initialization)

```
class vector {
   int sz;
   double* elem;
public:
   vector(const vector&) ;     // copy constructor: define copy (below)
   // …
};

vector::vector(const vector& a)
   :sz{a.sz},  elem{new double[a.sz]}
   // allocate space for elements, then initialize them (by copying)
{
   for (int i = 0; i<sz; ++i) elem[i] = a.elem[i];
}
```

Copy with copy constructor

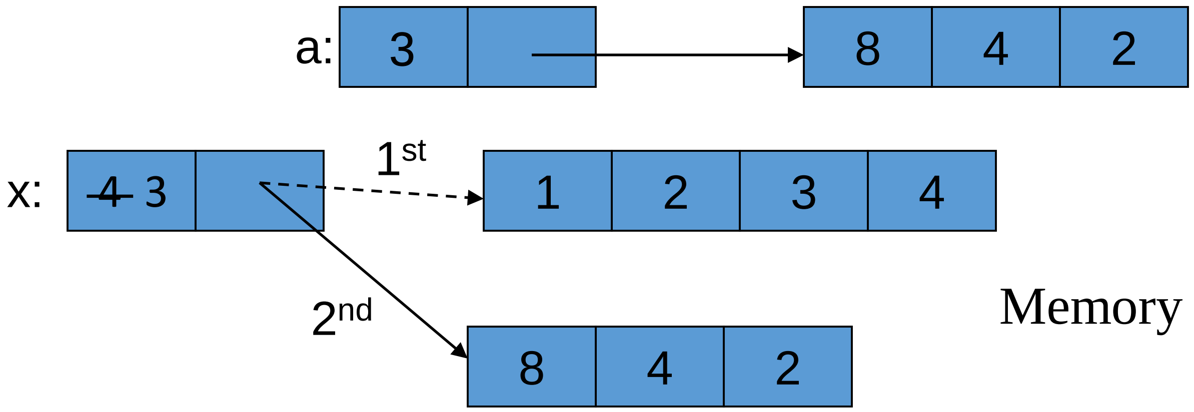
```
void f(int n)
{
  vector v1(n);
  vector v2 = v1;     // copy using the copy constructor
                      // the for loop copies each value from v1 into v2
}
```



The destructor correctly deletes all elements (once only for each vector)

Copy assignment

```
class vector {
  int sz;
  double* elem;
public:
  vector& operator=(const vector& a); // copy assignment: define copy (below)
  // ...
};
```



x=a;

Memory leak?

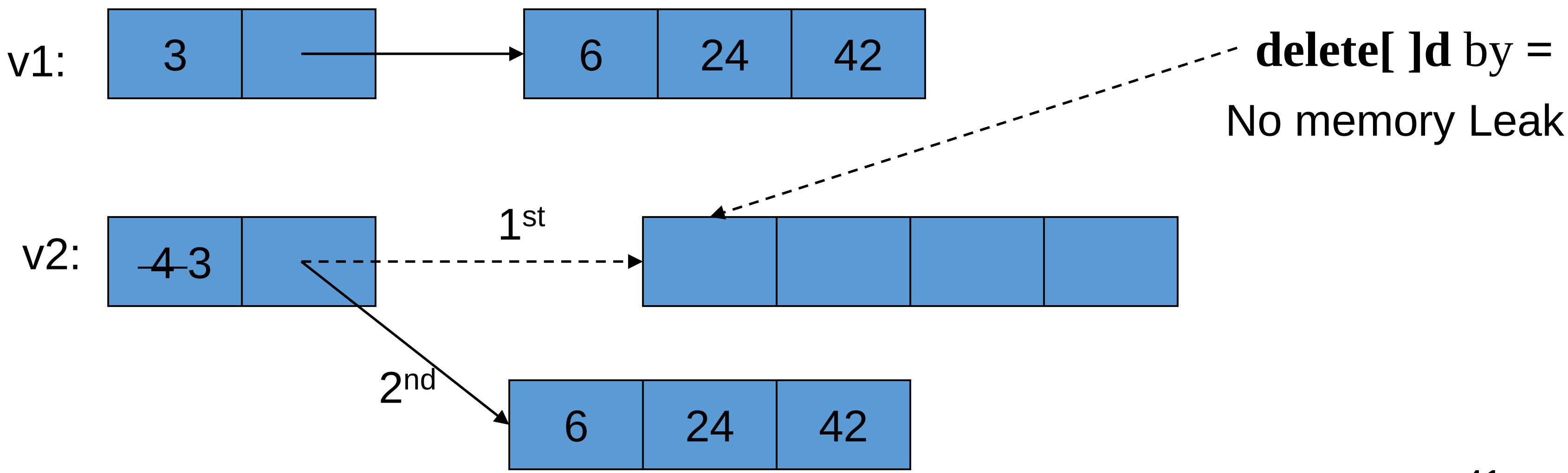
Operator = must copy a's elements

Copy assignment

```
vector& vector::operator=(const vector& a)
  // like copy constructor, but we must deal with old elements
  // make a copy of a then replace the current sz and elem with a's
{
  double* p = new double[a.sz];                       // allocate new space
  for (int i = 0; i<a.sz; ++i) p[i] = a.elem[i];      // copy elements
  delete[ ] elem;                                     // deallocate old space
  sz = a.sz;                                          // set new size
  elem = p;                                           // set new elements
  return *this;                 //  return a self-reference
                                // The this pointer is explained in 17.10
}
```

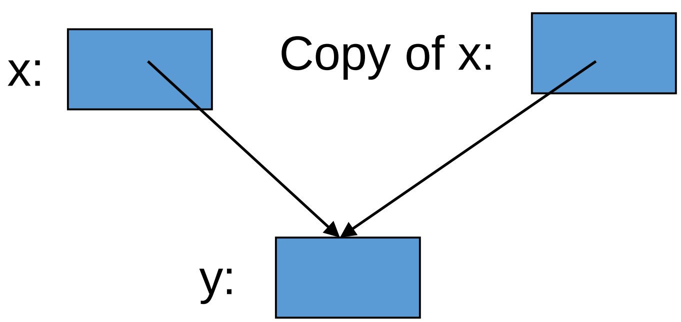
Copy with copy assignment

```
void f(int n)
{
  vector v1 {6,24,42};
  vector v2(4);
  v2 = v1;              // assignment
}
```

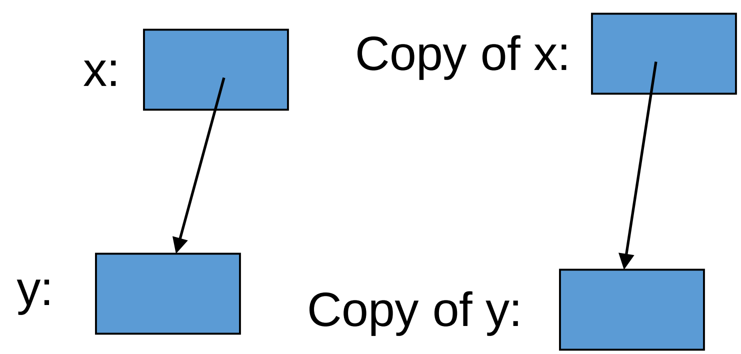


Copy terminology

- Shallow copy: copy only a pointer so that the two pointers now refer to the same object
  - What pointers and references do
- Deep copy: copy what the pointer points to so that the two pointers now each refer to a distinct object
  - What **vector**, **string**, etc. do
  - Requires copy constructors and copy assignments for container classes
  - Must copy “all the way down” if there are more levels in the object

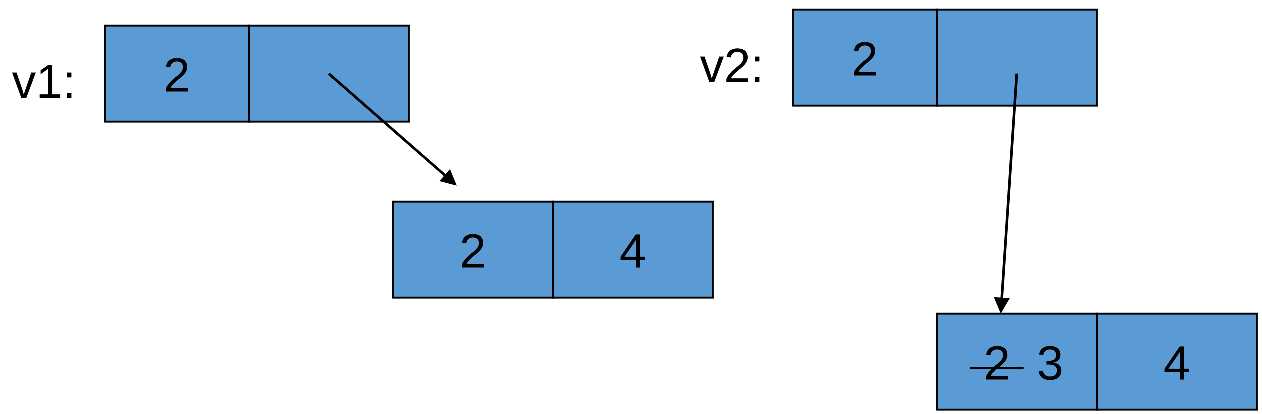


Shallow copy



Deep copy

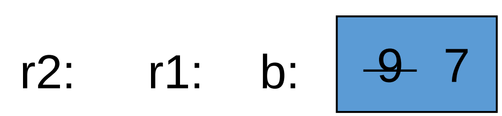
Deep and shallow copy



vector<int> v1 {2,4};

vector<int> v2 = v1; *// deep copy (**v2** gets its own copy of **v1**'s elements)*

v2[0] = 3; *// **v1[0]** is still 2*



int b = 9;

int& r1 = b;

int& r2 = r1; *// shallow copy (**r2** refers to the same variable as **r1**)*

r2 = 7; *// **b** becomes 7*

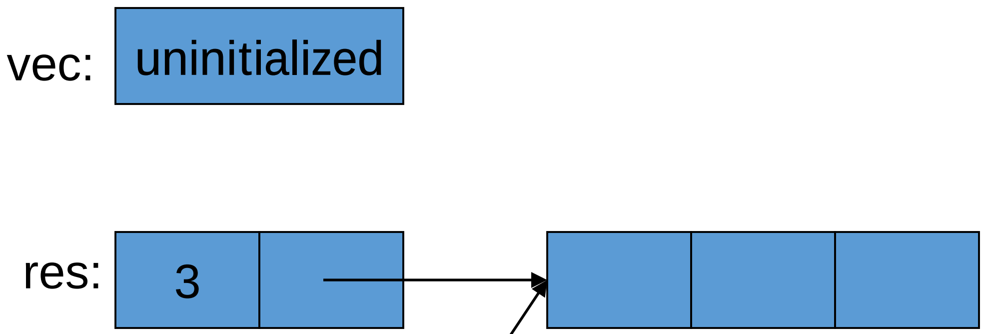
Move

- Consider

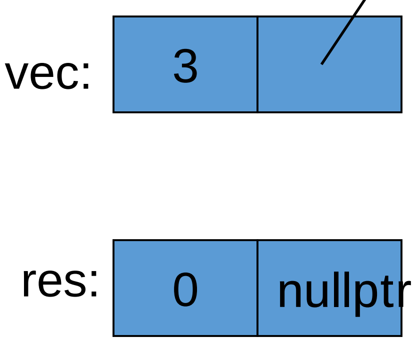
```
vector fill(istream& is)
{
    vector res;
    for (double x; is>>x; ) res.push_back(x);
    return res;    // returning a copy of res could be expensive
                   // returning a copy of res would be silly!
}

void use()
{
    vector vec = fill(cin);
    // … use vec …
}
```

What we want: Move

- Before **return res;** in **fill()**



- After **return res;** (after **vector vec = fill(cin);**)



Move Constructor and assignment

- Define move operations to “steal” representation

&& indicates “move”

```
class vector {
     int sz;
     double* elem;
public:
    vector(vector&&);                    // move constructor: "steal" the elements

    vector& operator=(vector&&);         // move assignment:
                                         //   destroy target and "steal" the elements

    // . . .
};
```

Move implementation

```
vector::vector(vector&& a)          // move constructor
  :sz{a.sz}, elem{a.elem}           // copy a's elem and sz
{
  a.sz = 0;                         // make a the empty vector
  a.elem = nullptr;
}
```

Move implementation

```
vector& vector::operator=(vector&& a)        // move assignment
{
    delete[] elem;              // deallocate old space
    elem = a.elem;              // copy a's elem and sz
    sz = a.sz;
    a.elem = nullptr;           // make a the empty vector
    a.sz = 0;
    return *this;               // return a self-reference (see §17.10)
}
```

Essential operations

- Constructors from one or more arguments
- Default constructor

- Copy constructor (copy object of same type)
- Copy assignment (copy object of same type)
- Move constructor (move object of same type)
- Move assignment (move object of same type)
- Destructor

- If you define one of the last 5, define them all