Chapter 18
Vectors and Arrays

Bjarne Stroustrup
www.stroustrup.com/Programming

Abstract

- arrays, pointers, copy semantics, elements access, references
- Next lecture: parameterization of a type with a type (templates), and range checking (exceptions).

Overview

- Vector revisited
  - How are they implemented?
- Pointers and free store
- Destructors
- Copy constructor and copy assignment
- Arrays
- Array and pointer problems
- Changing size
- Templates
- Range checking and exceptions

Reminder

- Why look at the vector implementation?
  - To see how the standard library vector really works
  - To introduce basic concepts and language features
    - Free store (heap)
    - Copying
    - Dynamically growing data structures
  - To see how to directly deal with memory
  - To see the techniques and concepts you need to understand C
    - Including the dangerous ones
  - To demonstrate class design techniques
  - To see examples of "neat" code and good design

vector

```
// a very simplified vector of doubles (as far as we got in chapter 17):

class vector {
    int sz;          // the size
    double* elem;    // pointer to elements
public:
    vector(int s) :sz(s), elem(new double[s]) { }  // constructor
                                    // new allocates memory
    ~vector() { delete[ ] elem; }          // destructor
                         // delete[] deallocates memory

    double get(int n) { return elem[n]; }     // access: read
    void set(int n, double v) { elem[n]=v; }  // access: write
    int size() const { return sz; }           // the number of elements
};
```


A problem

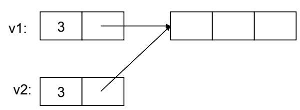
- Copy doesn't work as we would have hoped (expected?)

```
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)

```
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
}
```

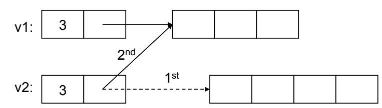


Disaster when we leave f()!

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)

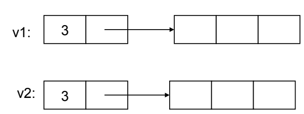
memory leak: v2's elements are not deleted

Copy constructor (initialization)

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

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

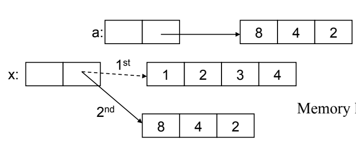
```
void f(int n)
{
    vector v1(n);
    vector v2 = v1;    // copy using the copy constructor
            // a for loop copies each value from v1 into v2
}
```



The destructor correctly deletes all elements (once only)

Copy assignment

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



Memory leak? (no)

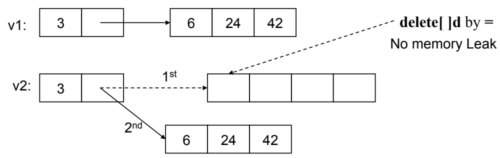
Operator = must copy a's elements

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 Lecture 19
            // and in 17.10
}
```

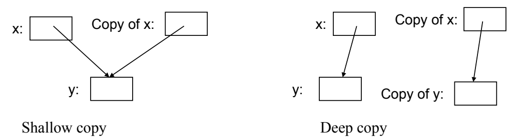
Copy with copy assignment

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

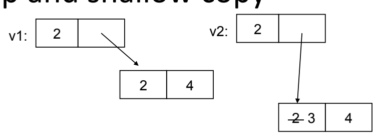


Copy terminology

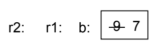
- Shallow copy: copy only a pointer so that the two pointers now refer to the same object
  - What pointers and references do
- Deep copy: copy the pointer and also what it points to so that the two pointers now each refer to a distinct object
  - What **vector**, **string**, etc. do
  - Requires copy constructors and copy assignments for container classes



Deep and shallow copy




```
vector<int> v1;
v1.push_back(2);
v1.push_back(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
```

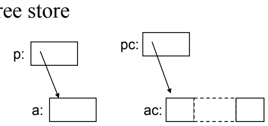

Arrays

- Arrays don't have to be on the free store

```
char ac[7];       // global array – "lives" forever – "in static storage"
int max = 100;
int ai[max];

int f(int n)
{
    char lc[20];    // local array – "lives" until the end of scope – on stack
    int li[60];
    double lx[n];   // error: a local array size must be known at compile time
                    // vector<double> lx(n); would work
    // …
}
```


Address of: &

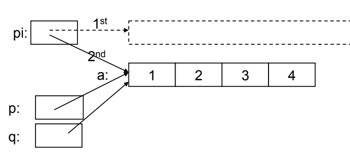
- You can get a pointer to any object
  – not just to objects on the free store




```
int a;
char ac[20];

void f(int n)
{
    int b;
    int* p = &b;    // pointer to individual variable
    p = &a;
    char* pc = ac;// the name of an array names a pointer to its first element
    pc = &ac[0];   // equivalent to pc = ac
    pc = &ac[n];   // pointer to ac's nth element (starting at 0th)
                   // warning: range is not checked
    // …
}
```


Arrays (often) convert to pointers

```
void f(int pi[ ])   // equivalent to void f(int* pi)
{
    int a[ ] = { 1, 2, 3, 4 };
    int b[ ] = a;    // error: copy isn't defined for arrays
    b = pi;     // error: copy isn't defined for arrays. Think of a
                // (non-argument) array name as an immutable pointer
    pi = a;     // ok: but it doesn't copy: pi now points to a's first element
                // Is this a memory leak? (maybe)
    int* p = a;     // p points to the first element of a
    int* q = pi;    // q points to the first element of a
}
```



Arrays don't know their own size

```
void f(int pi[ ], int n, char pc[ ])
    // equivalent to void f(int* pi, int n, char* pc)
    // warning: very dangerous code, for illustration only,
    // never "hope" that sizes will always be correct
{
    char buf1[200];
    strcpy(buf1,pc);    // copy characters from pc into buf1
                        // strcpy terminates when a '\0' character is found
                        // hope that pc holds less than 200 characters
    strncpy(buf1,pc,200); // copy 200 characters from pc to buf1
                        // padded if necessary, but final '\0' not guaranteed
    int buf2[300];      // you can't say char buf2[n]; n is a variable
    if (300 < n) error("not enough space");
    for (int i=0; i<n; ++i) buf2[i] = pi[i];    // hope that pi really has space for
                                                // n ints; it might have less
}
```


Be careful with arrays and pointers

```
char* f()
{
    char ch[20];
    char* p = &ch[90];
    // …
    *p = 'a';       // we don't know what this'll overwrite
    char* q;        // forgot to initialize
    *q = 'b';       // we don't know what this'll overwrite
    return &ch[10]; // oops: ch disappear upon return from f()
                    // (an infamous "dangling pointer")
}
void g()
{
    char* pp = f();
    // …
    *pp = 'c';// we don't know what this'll overwrite
              // (f's ch are gone for good after the return from f)
}
```


Why bother with arrays?

- It's all that C has
  - In particular, C does not have vectors
  - There is a lot of C code "out there"
    - Here "a lot" means N*1B lines
  - There is a lot of C++ code in C style "out there"
    - Here "a lot" means N*100M lines
  - You'll eventually encounter code full of arrays and pointers
- They represent primitive memory in C++ programs
  - We need them (mostly on free store allocated by **new**) to implement better container types
- Avoid arrays whenever you can
  - They are the largest single source of bugs in C and (unnecessarily) in C++ programs
  - They are among the largest sources of security violations (usually (avoidable) buffer overflows)

Types of memory

```
vector glob(10);        // global vector – "lives" forever

vector* some_fct(int n)
{
    vector v(n);        // local vector – "lives" until the end of scope
    vector* p = new vector(n);    // free-store vector – "lives" until we delete it
    // …
    return p;
}

void f()
{
    vector* pp = some_fct(17);
    // …
    delete pp;    // deallocate the free-store vector allocated in some_fct()
}
```

- it's easy to forget to delete free-store allocated objects
  - so avoid **new**/**delete** when you can

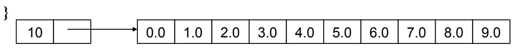
Initialization syntax

(array's one advantage over vector)

```
char ac[ ] = "Hello, world";  // array of 13 chars, not 12 (the compiler
                              // counts them and then adds a null
                              // character at the end
char* pc = "Howdy";           // pc points to an array of 6 chars
char* pp = {'H', 'o', 'w', 'd', 'y', 0 };  // another way of saying the same

int ai[ ] = { 1, 2, 3, 4, 5, 6 };  // array of 6 ints
                                   // not 7 – the "add a null character at the end"
                                   // rule is for literal character strings only
int ai2[100] = { 0,1,2,3,4,5,6,7,8,9 };  // the last 90 elements are initialized to 0
double ad3[100] = { };        // all elements initialized to 0.0
```


Vector (primitive access)

```
// a very simplified vector of doubles:

vector v(10);
for (int i=0; i<v.size(); ++i) {  // pretty ugly:
    v.set(i,i);
    cout << v.get(i);
}

for (int i=0; i<v.size(); ++i) { // we're used to this:
    v[i]=i;
    cout << v[i];
}
```



Vector (we could use pointers for access)

```
// a very simplified vector of doubles:
class vector {
    int sz;           // the size
    double* elem;     // pointer to elements
public:
    vector(int s) :sz(s), elem(new double[s]) { }  // constructor
    // …
    double* operator[ ](int n) { return &elem[n]; }  // access: return pointer
};

vector v(10);
for (int i=0; i<v.size(); ++i) {   // works, but still too ugly:
    *v[i] = i;        // means *(v[i]), that is return a pointer to
                      // the ith element, and dereference it
    cout << *v[i];
}
```

10	→	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0

Vector (we use references for access)

```
// a very simplified vector of doubles:
class vector {
    int sz;           // the size
    double* elem;     // pointer to elements
public:
    vector(int s) :sz(s), elem(new double[s]) { }  // constructor
    // …
    double& operator[ ](int n) { return elem[n]; }  // access: return reference
};

vector v(10);
for (int i=0; i<v.size(); ++i) {   // works and looks right!
    v[i] = i;         // v[i] returns a reference to the ith element
    cout << v[i];
}
```

10	→	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0

Pointer and reference

- You can think of a reference as an automatically dereferenced immutable pointer, or as an alternative name for an object
  - Assignment to a pointer changes the pointer's value
  - Assignment to a reference changes the object referred to
  - You cannot make a reference refer to a different object

```
int a = 10;
int* p = &a;  // you need & to get a pointer
*p = 7;   // assign to a through p
          // you need * (or [ ]) to get to what a pointer points to
int x1 = *p;   // read a through p

int& r = a;   // r is a synonym for a
r = 9;    // assign to a through r
int x2 = r;   // read a through r

p = &x1;    // you can make a pointer point to a different object
r = &x1; // error: you can't change the value of a reference
```


Next lecture

- We'll see how we can change vector's implementation to better allow for changes in the number of elements. Then we'll modify vector to take elements of an arbitrary type and add range checking. That'll imply looking at templates and revisiting exceptions.