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Chapter 18
Vectors and Arrays

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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
- Initialization
- Copy and move
- Arrays
- Array and pointer problems
- Changing size
- Templates
- Range checking and exceptions

Reminder

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- 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)
    - Copy and move
    - 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
};
```

Initialization: initializer lists

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

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

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

    // …
 };

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

Initialization: explicit constructors

- A problem
  - A constructor taking a single argument defines a conversion from the argument type to the constructor's type
  - Our vector had `vector::vector(int)`, so

```
vector v1 = 7;   // equivalent to: vector v1 = vector(7);
                 // v1 has 7 elements, each with the value 0
void do_something(vector v)

// call do_something() with a vector of 7 elements
do_something(7); // equivalent to: do_something(vector(7));
```

- *This is very error-prone.*
  - Unless, of course, that's what we wanted
  - For example

```
complex<double> d = 2.3; // convert from double to complex<double>
```

Initialization: explicit constructors

- A solution
  - Declare constructors taking a single argument **explicit**
    - unless you want a conversion from the argument type to the constructor's type

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

vector v1 = 7;   // error: no implicit conversion from int

void do_something(vector v);
do_something(7); // error: no implicit conversion from int
```

A problem

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

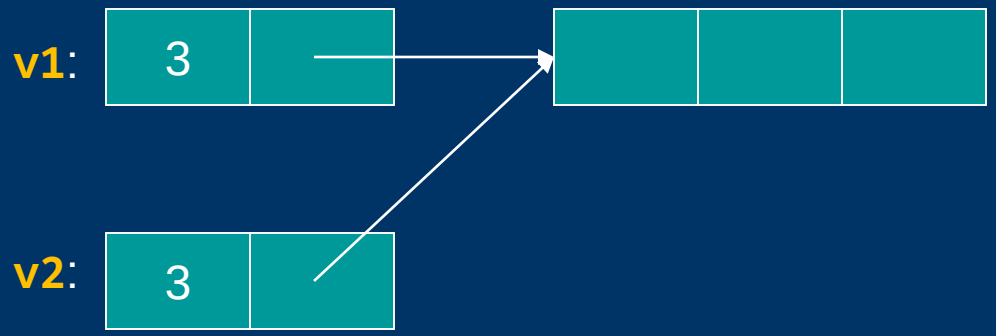
```
void f(int n)
{
    vector v(n);          // define a vector
    vector v2 = v;        // what happens here?
                          // what would we like to happen?
    vector v3;
    v3 = v;               // what happens here?
                          // what would we like to happen?
    //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

- 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
}
```

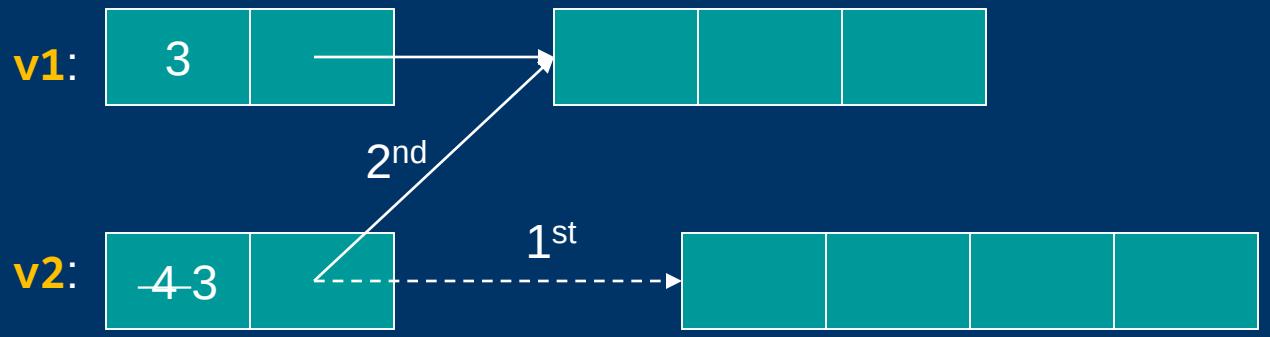


Disaster when we leave `f()`!

`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

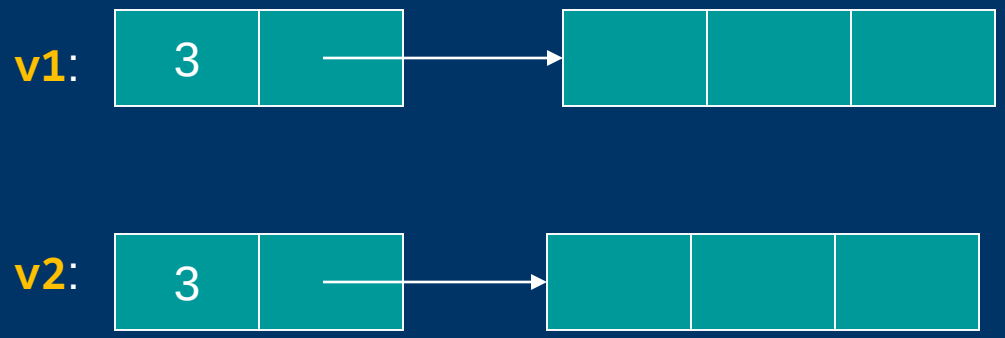
Copy constructor (initialization)

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

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
}
```

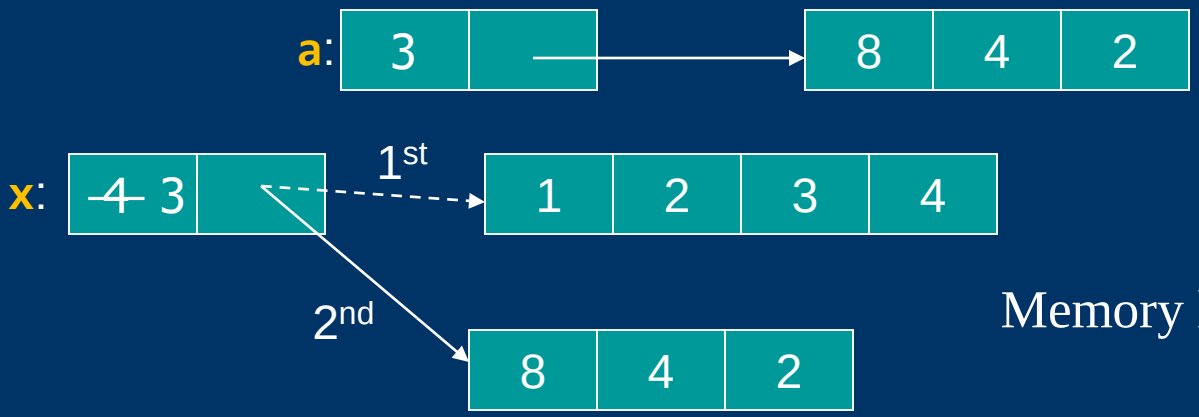


The destructor correctly deletes all elements (once only for each vector)

Copy assignment

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

```
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 a self-reference
    // The this pointer is explained in Lecture 19
    // and in 17.10
    return *this;
}
```

Copy assignment

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    // make a copy of a then replace the current sz and elem with a's
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    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
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    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
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Copy assignment

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    // make a copy of a then replace the current sz and elem with a's
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    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

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Copy assignment

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    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

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    return *this;
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Copy assignment

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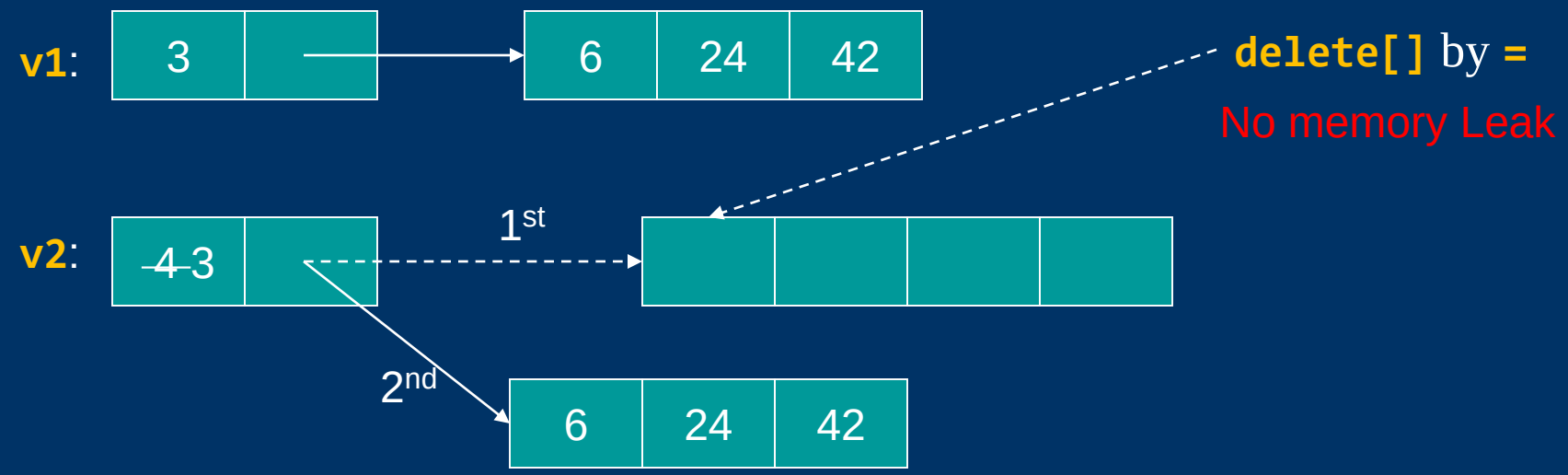
    // make a copy of a then replace the current sz and elem with a's
{
    double* p = new double[a.sz];              // allocate new space
    for (int i = 0; i<a.sz; ++i) p[i] = a.elem[i];  // copy elements
    delete[ ] elem;                 // deallocate old space
    sz = a.sz;                      // set new size
    elem = p;                       // set new elements

    // return a self-reference
    // The this pointer is explained in Lecture 19
    // and in 17.10
    return *this;
}
```

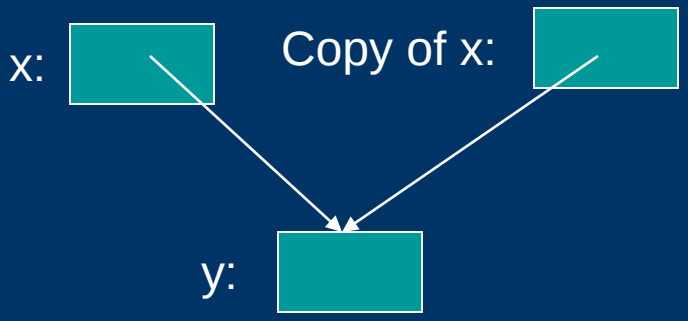
Copy with copy assignment

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

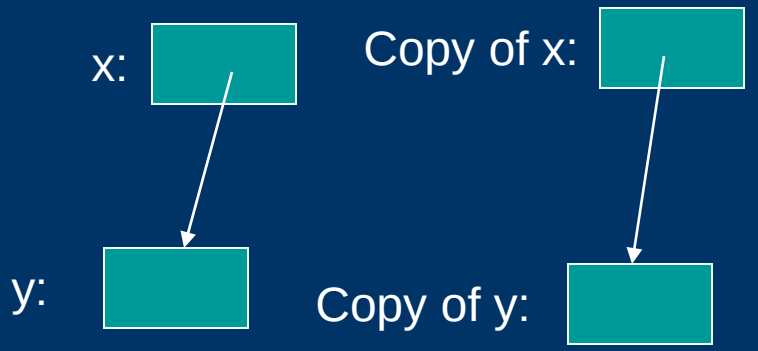


Copy terminology

- 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

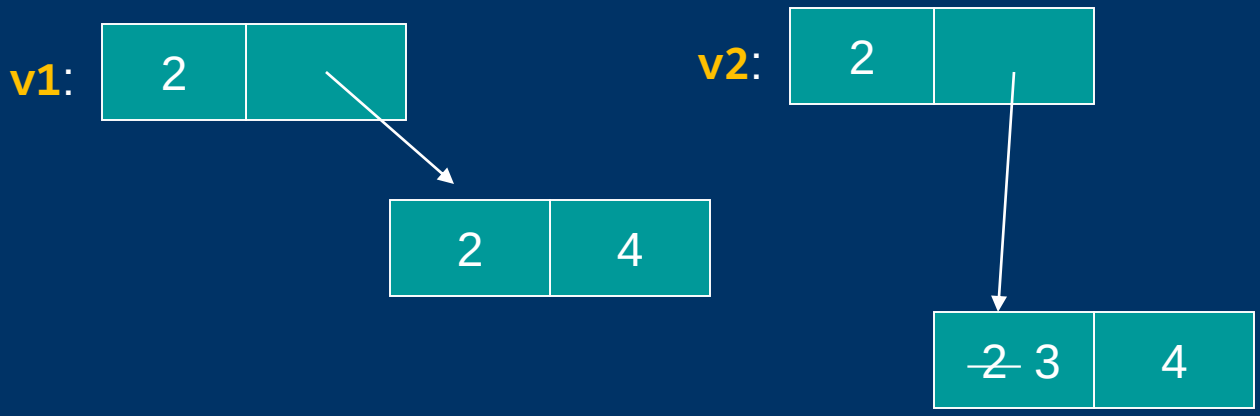


Shallow copy



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

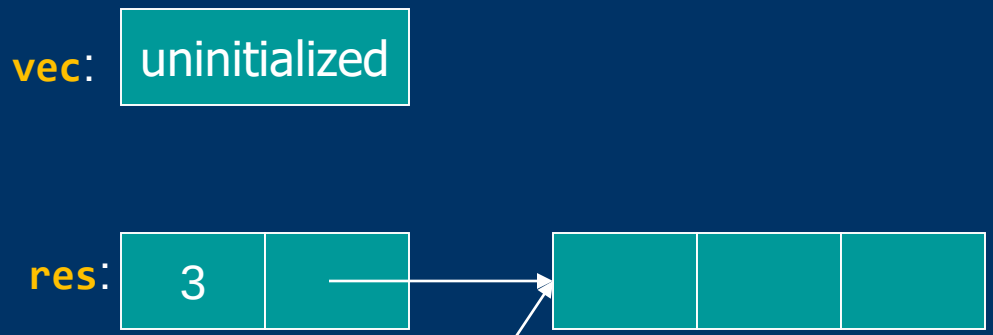
```
vector fill(istream& is)
{
    vector res;
    for (double x; is>>x; ) res.push_back(x);

    // returning a copy of res could be expensive
    // returning a copy of res would be silly!
    return res;
}

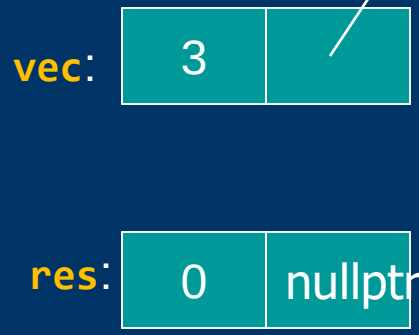
void use()
{
     vector vec = fill(cin);
     // … use vec …
}
```

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

```
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
      // . . .
};
```

&& indicates "move"

https://blog.smartbear.com/c-plus-plus/c11-tutorial-introducing-the-move-constructor-and-the-move-assignment-operator/

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
}
```

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

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)
{
   // local array – "lives" until the end of scope – on stack
   char lc[20];
   int li[60];

   // error: a local array size must be known at compile time
   // vector<double> lx(n); would work
   double lx[n];
   // …
}
```

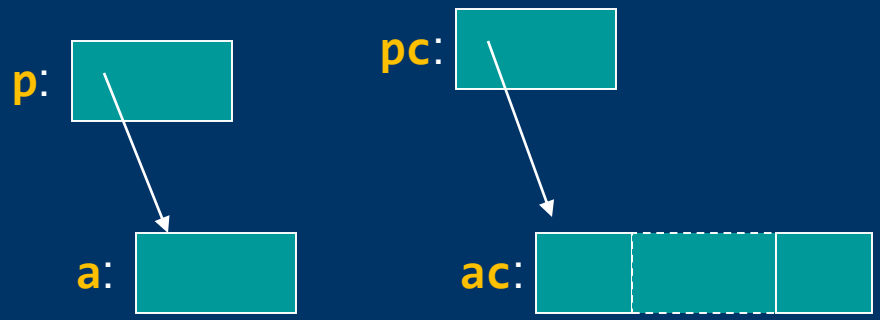
Address of: &

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

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

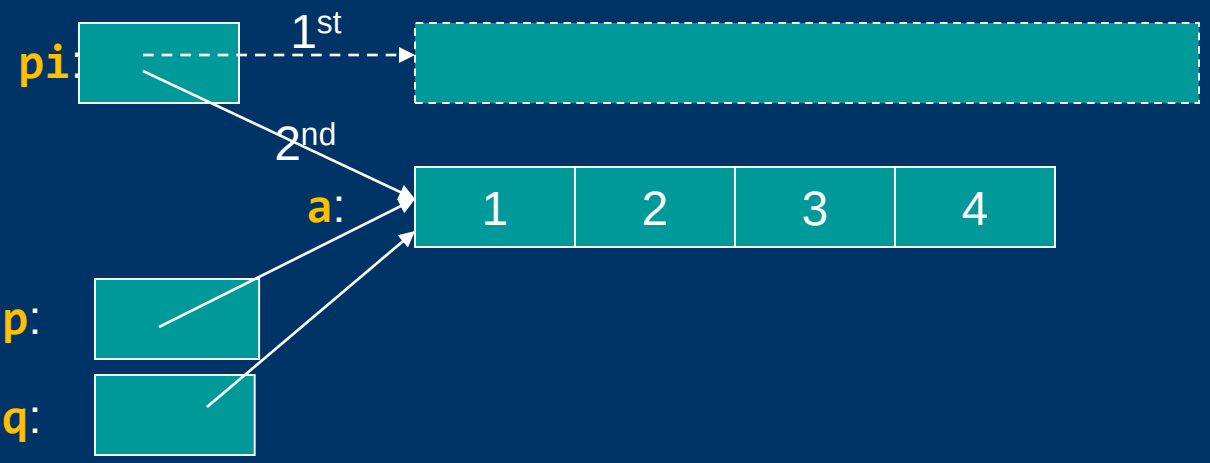
void f(int n)
{
   int b;
   int* p = &b;      // pointer to individual variable
   p = &a;           // now point to a different variable
   char* pc = ac;    // the name of an array: a pointer to 1st element
   pc = &ac[0];      // equivalent to pc = ac
   pc = &ac[n];      // pointer to ac's nth element (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 int buf2[n]; n is a variable
    if (300 < n) error("not enough space");

    // hope that pi really has space for n ints; it might have less
    for (int i=0; i<n; ++i) buf2[i] = pi[i];
}
```

Be careful with arrays and pointers

```
char* f()
{
    char ch[20];
    char* p = &ch[90];
    // …
    *p = 'a';              // we don't know what this will overwrite
    char* q;               // forgot to initialize
    *q = 'b';              // we don't know what this will overwrite
    return &ch[10];        // oops: ch disappears upon return from f()
                           // (an infamous  "dangling pointer")
}

void g()
{
    char* pp = f();
    // …
    *pp = 'c';     // we don't know what this will overwrite
                   // (f's ch is gone for good after the return from f)
}
```

Why bother with arrays?

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- It's all that C has
  - In particular, C does not have `vector`
  - There is a lot of C code "out there"
    - Here "a lot" means N*1B lines (B: billion)
  - There is a lot of C++ code in C style "out there"
    - Here "a lot" means N*100M lines (M: million)
  - 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)
{
    // local vector – "lives" until the end of scope
    vector v(n);

    // free-store vector – "lives"  until we delete it
    vector* p = new vector(n);
    // …
    return p;
}

void f()
{
    vector* pp = some_fct(17);

    // deallocate the free-store vector allocated in some_fct()
    delete pp;
}
```

- it's easy to forget to delete free-store allocated objects
  - so avoid **new**/**delete** when you can (and that's most of the time)

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:
    explicit vector(int s) :sz{s}, elem{new double[s]} { } // constructor
    // …
    // access: return pointer
    double* operator[ ](int n) { return &elem[n]; }
};

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];
}
```

Vector (we use references for access)

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

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];
}
```

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.