

DM560  
Introduction to Programming in C++

## Vector and Free Store (Vectors and Arrays)

Marco Chiarandini

Department of Mathematics & Computer Science  
University of Southern Denmark

*[Based on slides by Bjarne Stroustrup]*

# Outline

1. Initialization

2. Copy

3. Move

4. Arrays

# 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

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 so far):

```
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
};
```

# Outline

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# Initialization: Initializer Lists

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

```
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:

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

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};
```

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

```
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
}
```



# Initialization

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;          // v1 has 7 elements, each with the value 0

void do_something(vector v)
do_something(7);        // call do_something() with a vector of 7 elements
```

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:  
    explicit vector(int s);    // constructor (s is the element count)  
    // ...  
};
```

```
vector v1 = 7;    // error: no implicit conversion from int  
  
void do_something(vector v);  
do_something(7);    // error: no implicit conversion from int
```

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# 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)

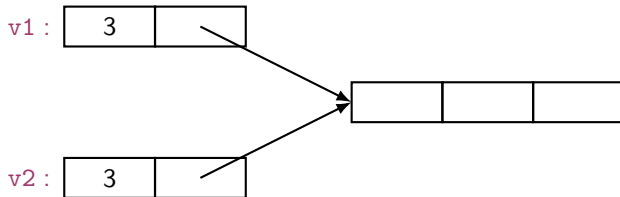
By default **copy** means **copy the data members**

```
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
}
```

# 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
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}
```



Disaster when we leave `f()`!  
`v1`'s elements are deleted twice (by the destructor)

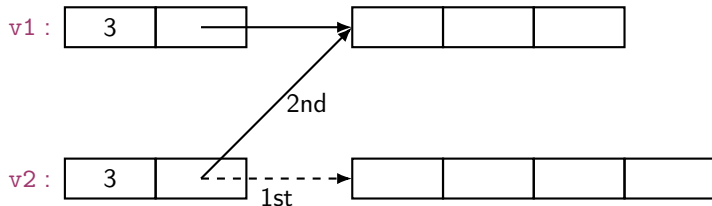
## Naïve Copy Assignment (the Default)

```
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
}
```



# 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

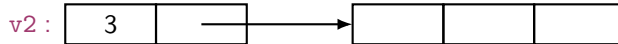
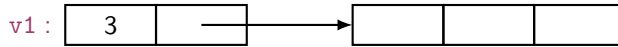
# Copy Constructor (Initialization)

```
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

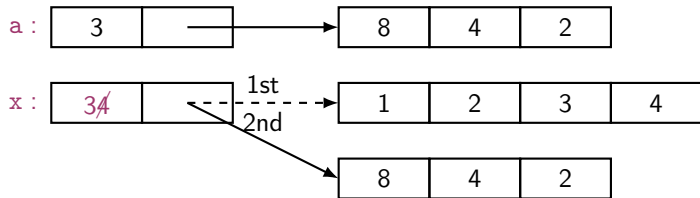
```
class vector {  
    int sz;  
    double* elem;  
public:  
    vector& operator=(const vector& a); // copy assignment: define copy (next slide)  
    // ...  
};
```

```
x=a;
```

# Copy Assignment

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

```
x=a;
```



Memory leak? (no)

Operator = must copy `a`'s elements

# Copy Assignment (Implementation)

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

```
vector& vector::operator=(const vector& a)
{
    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
}
```

# Copy Assignment (Implementation)

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

```
vector& vector::operator=(const vector& a)
{
    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 identifier **this** is a pointer that points to the object for which the member function was called (see par. 17.10).
- It is **immutable**

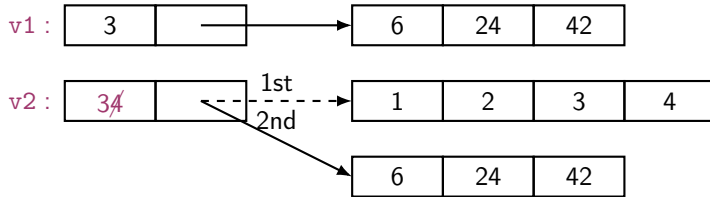
# Copy with Copy Assignment (Implementation)

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



# Copy with Copy Assignment (Implementation)

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



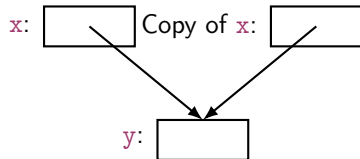
`delete[]` by `=` in  
previous slide. No  
memory leak

Operator `=` must copy `a`'s elements

# Copy Terminology

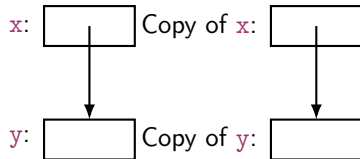
**Shallow copy:** copy only a pointer so that the two pointers now refer to the same object

- What pointers and references do



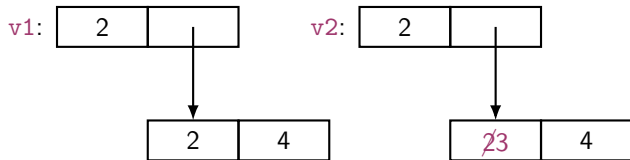
**Deep copy:** copy what the pointer points to so that the two pointers now each refer to a distinct object

- 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



# 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
```

r2: r1: b: 7

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# Move

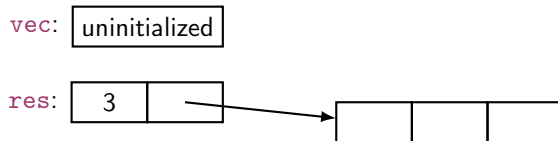
Consider

```
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!
}
```

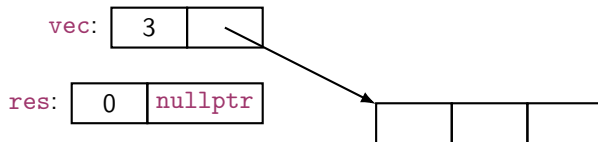
```
void use()
{
    vector vec = fill(cin);
    // ... use vec ...
}
```

# Move: What We Want

Before `return res` in `fill()`:



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



# Move Constructor and Move 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**

# Move Constructor and Assignment (Implementation)

move constructor: “steal” the elements

```
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 Constructor and Assignment (Implementation)

move constructor: “steal” the elements


```
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 assignment: destroy target and “steal” the elements

```
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 par. 17.10)
}
```

# Essential Operations

- Default constructor
- Constructors from one or more arguments
- 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 these,  
define them all

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# 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
```

# 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  
}
```

# 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 names a pointer to its first element
```

# Address of &

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

```
int a;  
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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 names a pointer to its first element  
    pc = &ac[0]; // equivalent to pc = ac
```



# Address of &

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

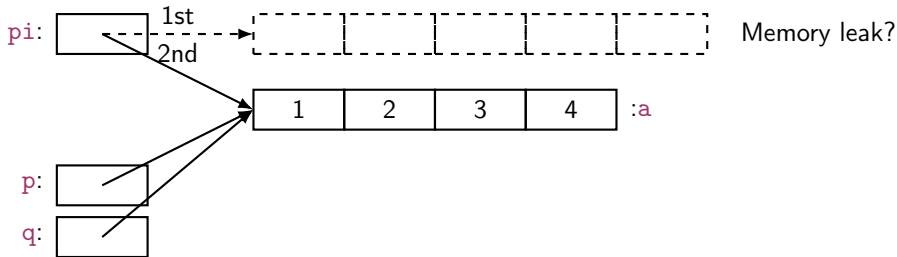
```
int a;  
char ac[20];  
  
void f(int n)  
{  
    int b;  
    int* p = &b; // pointer to individual variable  
    p = &a;      // now point to a different variable  
    char* pc = ac; // the name of an array names a pointer to its first element  
    pc = &ac[0]; // equivalent to pc = ac  
    pc = &ac[n]; // pointer to ac's nth element (starting at 0th)  
                // warning: range is not checked  
    // ...  
}
```

# Arrays 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 Convert to Pointers

```
void f(int pi[ ])          // equivalent to void f(int* pi)
{
    int a[ ] = { 1, 2, 3, 4 };
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                          // 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 Size

Warning: very dangerous code, for illustration only: never “hope” that sizes will always be correct

```
void f(char pc[ ], int n) // equivalent to void f(char* pc, int n)
{
    char buf1[200];        // you can't say 'char buf1[n];' n is a variable
    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
}
```

# Arrays don't Know Their Size

Warning: very dangerous code, for illustration only: never “hope” that sizes will always be correct

```
void f(char pc[ ], int n) // equivalent to void f(char* pc, int n)
{
    char buf1[200];        // you can't say 'char buf1[n];' n is a variable
    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
    // alternative that hedges against pc holding > 200 chars
    strncpy(buf1,pc,200);    // copy 200 characters from pc to buf1
                           // padded if necessary, but final '\0' not guaranteed
}
```

# Arrays don't Know Their Size

Warning: very dangerous code, for illustration only: never “hope” that sizes will always be correct

```
void f(char pc[ ], int n) // equivalent to void f(char* pc, int n)
{
    char buf1[200];        // you can't say 'char buf1[n];' n is a variable
    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
    // alternative that hedges against pc holding > 200 chars
    strncpy(buf1,pc,200);    // copy 200 characters from pc to buf1
                           // padded if necessary, but final '\0' not guaranteed
}
```

Similarly:

```
void f(int pi[ ], int n) // equivalent to void f(int* pi, int n)
{
    int buf2[300];         // you can't say 'int 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

Watch out on [dangling pointers](#) (pointers to deleted memory)

```
char* f()  
{  
    char ch[20];  
    char* p = &ch[90];  
    // ...  
}
```

# Be Careful with Arrays and Pointers

Watch out on [dangling pointers](#) (pointers to deleted memory)

```
char* f()
{
    char ch[20];
    char* p = &ch[90];
    // ...
    *p = 'a';           // we don't know what this will overwrite
```



# Be Careful with Arrays and Pointers

Watch out on [dangling pointers](#) (pointers to deleted memory)

```
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
}
```

# Be Careful with Arrays and Pointers

Watch out on [dangling pointers](#) (pointers to deleted memory)

```
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?

- It's all that C has
  - In particular, C does not have **vector**
  - There is a lot of C code “out there”
  - There is a lot of C++ code in C style “out there”
  - 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

## Recap: 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
}
```

## Recap: 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 (and that's most of the time)

# Vector: Primitive Access

A very simplified vector of doubles:

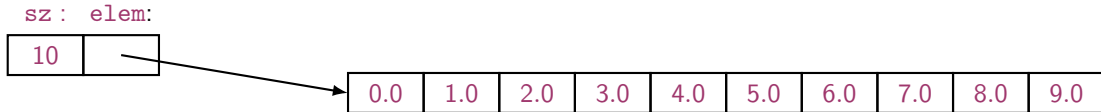
```
vector v(10);
```

Pretty ugly access:

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

We're used to this way of accessing:

```
for (int i=0; i<v.size(); ++i) {  
    v[i]=i;  
    cout << v[i];  
}
```



# Vector: 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
    // ...
    double* operator[ ](int n) { return &elem[n]; } // access: return pointer
};

vector v(10);
```

Access via pointers:

```
for (int i=0; i<v.size(); ++i) {
    *v[i] = i;                // means *(v[i]), that is, return a pointer to
                             // the ith element, and dereference it

    cout << *v[i];
}
```

It works, but still too ugly.

# Vector: References for Access

A very simplified vector of doubles:

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

vector v(10);
```

Access via references:

```
for (int i=0; i<v.size(); ++i) {
    v[i] = i;                // v[i] returns a reference to the ith element
    cout << v[i];
}
```

It works and it looks right!!



# Pointer and Reference

You can think of a **reference** as an [automatically dereferenced immutable pointer](#), or as an alternative name (alias) for an object

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int a = 10;  
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int& r = a; // 'r' is an alias 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 'r'
```



# Summary

1. Initialization

2. Copy

3. Move

4. Arrays