Chapter 19
Vectors, templates, and exceptions

Abstract

- This is the third of the lectures exploring the design of the standard library vector and the techniques and language features used to implement it. Here, we deal with changing the size of a vector, parameterization of a vector with an element 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
  - resize() and push_back()
- Templates
- Range checking and exceptions

Changing vector size

- Fundamental problem addressed
  - We (humans) want abstractions that can change size (*e.g.*, a vector where we can change the number of elements). However, in computer memory everything must have a fixed size, so how do we create the illusion of change?
- Given

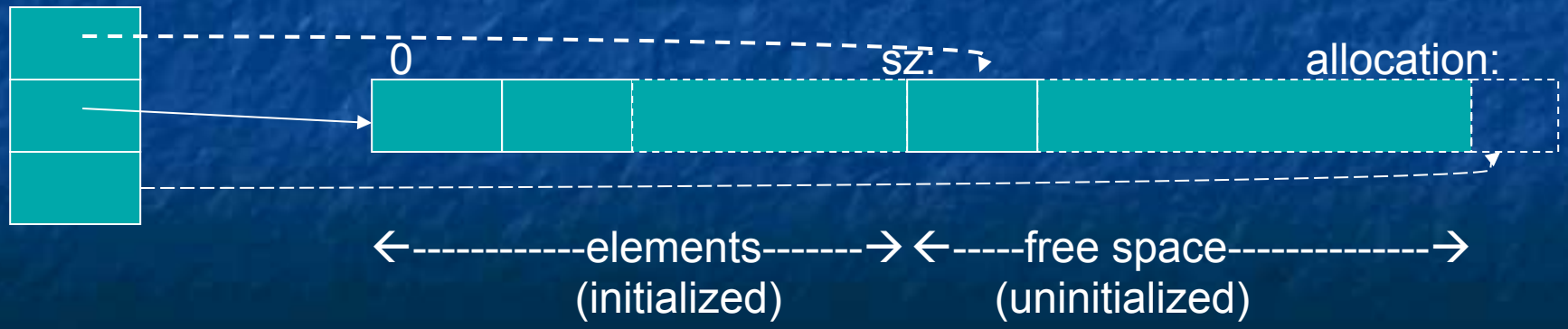
```
vector v(n);                    // v.size()==n
```

  we can change its size in three ways
  - Resize it
    - `v.resize(10);` // *v now has **10** elements*
  - Add an element
    - `v.push_back(7);` // *add an element with the value 7 to the end of **v***
      // ***v.size()** increases by **1***
  - Assign to it
    - `v = v2;` // ***v** is now a copy of **v2***
      // ***v.size()** now equals **v2.size()***

Representing vector

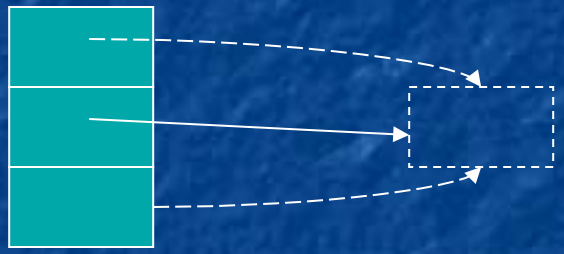
- If you **resize()** or **push_back()** once, you'll probably do it again;
  - let's prepare for that by sometimes keeping a bit of free space for future expansion

```
class vector {
    int sz;
    double* elem;
    int space;      // number of elements plus "free space"
                    // (the number of "slots" for new elements)
public:
    // …
};
```

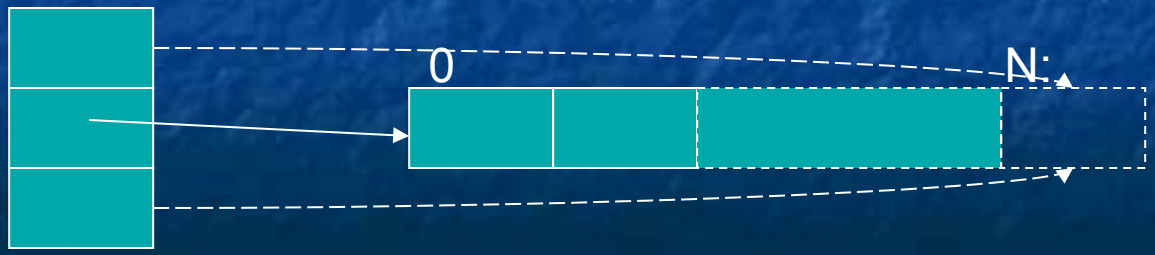


Representing vector

- An empty vector (no free store use):



- A vector(N) (no free space):



vector::reserve()

- First deal with space (allocation); given space all else is easy
  - Note: **reserve()** doesn't mess with size or element values

```
void vector::reserve(int newalloc)
    // make the vector have space for newalloc elements
{
    if (newalloc<=space) return;              // never decrease allocation
    double* p = new double[newalloc];         // allocate new space
    for (int i=0; i<sz; ++i) p[i]=elem[i];    // copy old elements
    delete[ ] elem;                           // deallocate old space
    elem = p;
    space = newalloc;
}
```

vector::resize()

- Given **reserve()**, **resize()** is easy
  - **reserve()** deals with space/allocation
  - **resize()** deals with element values

```
void vector::resize(int newsize)
    // make the vector have newsize elements
    // initialize each new element with the default value 0.0
{
    reserve(newsize);                   // make sure we have sufficient space
    for(int i = sz; i<newsize; ++i) elem[i] = 0;          // initialize new elements
    sz = newsize;
}
```

vector::push_back()

- Given **reserve()**, **push_back()** is easy
  - **reserve()** deals with space/allocation
  - **push_back()** just adds a value

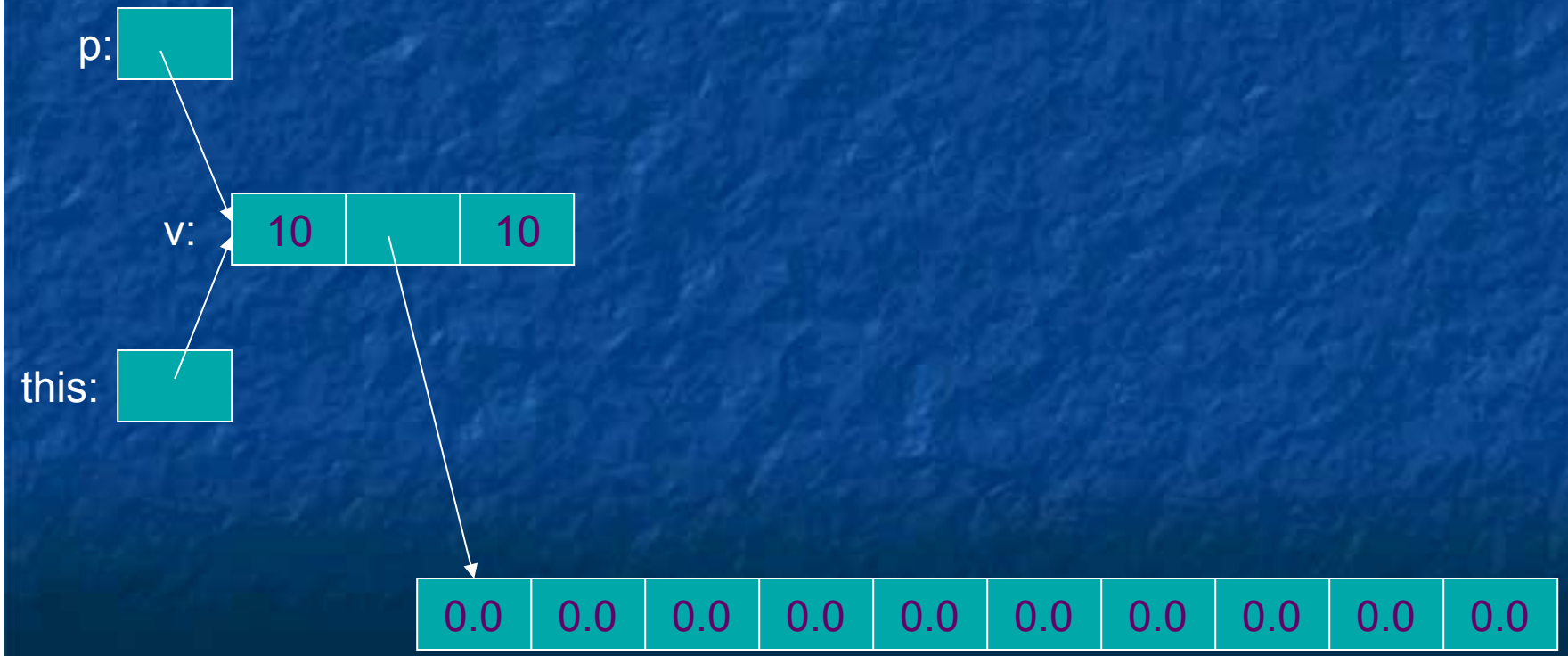
```
void vector::push_back(double d)
    // increase vector size by one
    // initialize the new element with d
{
    if (sz==0)                  // no space: grab some
            reserve(8);
    else if (sz==space)         // no more free space: get more space
            reserve(2*space);
    elem[sz] = d;               // add d at end
    ++sz;                       // and increase the size (sz is the number of elements)
}
```

resize() and push_back()

```
class vector {          // an almost real vector of doubles
    int sz;                     // the size
    double* elem;               // a pointer to the elements
    int space;                  // size+free_space
public:
    vector() : sz(0), elem(0), space(0) { }                 // default constructor
    vector(int s) :sz(s), elem(new double[s]) , space(s) { } // constructor
    vector(const vector&);                                  // copy constructor
    vector& operator=(const vector&);                       // copy assignment
    ~vector() { delete[ ] elem; }                           // destructor

    double& operator[ ](int n) { return elem[n]; }          // access: return reference
    int size() const { return sz; }                         // current size

    void resize(int newsize);                               // grow (or shrink)
    void push_back(double d);                               // add element

    void reserve(int newalloc);                             // get more space
    int capacity() const { return space; }                  // current available space
};
```

The **this** pointer

- A vector is an object
  - **vector v(10);**
  - **vector* p = &v;** *// we can point to a **vector** object*
- Sometimes, **vector**'s member functions need to refer to that object
  - The name of that "pointer to self" in a member function is **this**



The **this** pointer

```
vector& vector::operator=(const vector& a)
    // copy assignment from chap 18 -- like copy constructor, but we must deal with old elements
{
    // …
    return *this;    // by convention,
                     // assignment returns a reference to its object: *this
}

void f(vector v1, vector v2, vector v3)
{
    // …
    v1 = v2 = v3;    // rare use made possible by operator=() returning *this
    // …
}
```

- The **this** pointer has uses that are less obscure
  - one of which we'll get to in two minutes

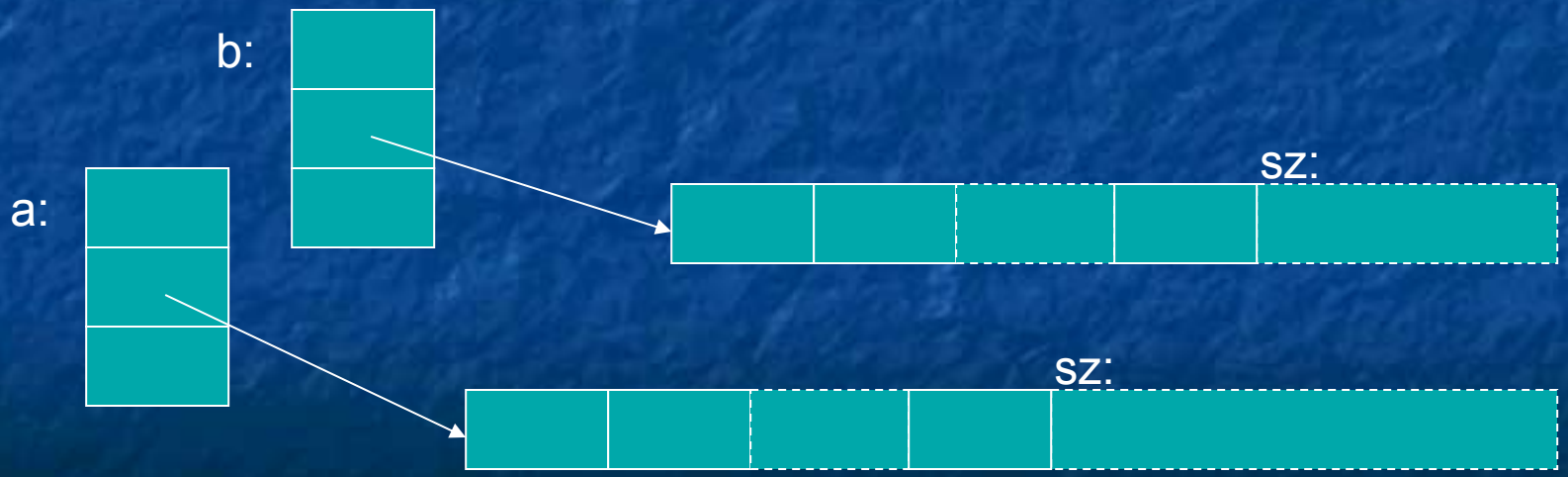
Assignment (*from chap 18*)

- Copy and swap is a powerful general idea

```
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
}
```

Optimize assignment

- "Copy and swap" is the most general idea
  - but not always the most efficient
  - What if there already is sufficient space in the target vector?
    - Then just copy!
    - For example: **a = b;**



Optimized assignment

```
vector& vector::operator=(const vector& a)
{
    if (this==&a) return *this;          // self-assignment, no work needed

    if (a.sz<=space) {                   // enough space, no need for new allocation
        for (int i = 0; i<a.sz; ++i) elem[i] = a.elem[i];    // copy elements
        space += sz-a.sz;                                    // increase free space
        sz = a.sz;
        return *this;
    }

    double* p = new double[a.sz];        // copy and swap
    for (int i = 0; i<a.sz; ++i) p[i] = a.elem[i];
    delete[ ] elem;
    sz = a.sz;
    space = a.sz;
    elem = p;
    return *this;
}
```

Templates

- But we don't just want vector of double
- We want vectors with element types we specify
  - **vector<double>**
  - **vector<int>**
  - **vector<Month>**
  - **vector<Record*>** *// vector of pointers*
  - **vector< vector<Record> >** *// vector of vectors*
  - **vector<char>**
- We must make the element type a parameter to **vector**
- **vector** must be able to take both built-in types and user-defined types as element types
- This is not some magic reserved for the compiler, we can define our own parameterized types, called "templates"

Templates

- The basis for generic programming in C++
  - Sometimes called "parametric polymorphism"
    - Parameterization of types (and functions) by types (and integers)
  - Unsurpassed flexibility and performance
    - Used where performance is essential (*e.g.*, hard real time and numerics)
    - Used where flexibility is essential (*e.g.*, the C++ standard library)
- Template definitions

  template<class T, int N> class Buffer { /* ... */ }; *// class, could be many params*
  template<class T, int N> void fill(Buffer<T,N>& b) { /* ... */ } *// function*
- Template specializations (instantiations)

  // for a class template, you specify the template arguments:
  Buffer<char,1024> buf; *// for **buf, T** is **char** and **N** is **1024***

  // for a function template, the compiler deduces the template arguments:
  fill(buf); *// for **fill(), T** is **char** and **N** is **1024;** that's what **buf** has*

Parameterize with element type

```
// an almost real vector of Ts:
template<class T> class vector {
    // ...
};

vector<double> vd;                  // T is double
vector<int> vi;                     // T is int
vector< vector<int> > vvi;          // T is vector<int>
                                    // in which T is int
vector<char> vc;                    // T is char
vector<double*> vpd;                // T is double*
vector< vector<double>* > vvpd;     // T is vector<double>*
                                    // in which T is double
```

Basically, **vector<double>** is

```
// an almost real vector of doubles:
class vector {
    int sz;                 // the size
    double* elem;           // a pointer to the elements
    int space;              // size+free_space
public:
    vector() : sz(0), elem(0), space(0) { }                 // default constructor
    explicit vector(int s) :sz(s), elem(new double[s]), space(s) { } // constructor
    vector(const vector&);                                  // copy constructor
    vector& operator=(const vector&);                       // copy assignment
    ~vector() { delete[ ] elem; }                           // destructor

    double& operator[ ] (int n) { return elem[n]; }  // access: return reference
    int size() const { return sz; }                  // the current size

    // …
};
```

explicit deserves attention

- A constructor that takes a single argument defines a conversion from its argument type to its class

```
class vector {
        // …
        vector(int); // constructor with one arg
}
vector v = 10; // makes a vector of 10 doubles!
v = 20; // assigns a new vector of 20 doubles to v!
void f(const vector&);
f(10); // calls f with a new vector of 10 doubles!
```

explicit deserves attention

- It is simple to suppress the use of constructor as an implicit conversion

```
class vector {
        // …
        explicit vector(int); // constructor with one arg
}
vector v = 10; // error: no int-to-vector conversion
v = 20; // error: no int-to-vector<double> conversion
vector v0(10); // ok
void f(const vector&);
f(10); // error: no int-to-vector<double> conversion
f(vector(10)); //  ok
```

Basically, **vector<char>** is

```
// an almost real vector of chars:
class vector {
    int sz;                 // the size
    char* elem;             // a pointer to the elements
    int space;              // size+free_space
public:
    vector() : sz(0), elem(0), space(0) { }                 // default constructor
    explicit vector(int s) :sz(s), elem(new char[s]), space(s) { } // constructor
    vector(const vector&);                                  // copy constructor
    vector& operator=(const vector&);                       // copy assignment
    ~vector() { delete[ ] elem; }                           // destructor

    char& operator[ ] (int n) { return elem[n]; }           // access: return reference
    int size() const { return sz; }                         // the current size

    // ...
};
```

Basically, vector<T> is

```
// an almost real vector of Ts:
template<class T> class vector {   // read "for all types T" (just like in math)
    int sz;                        // the size
    T* elem;                       // a pointer to the elements
    int space;                     // size+free_space
public:
    vector() : sz(0), elem(0), space(0);                    // default constructor
    explicit vector(int s) :sz(s), elem(new T[s]), space(s) { }   // constructor
    vector(const vector&);                                  // copy constructor
    vector& operator=(const vector&);                       // copy assignment
    ~vector() { delete[ ] elem; }                           // destructor

    T& operator[ ] (int n) { return elem[n]; }              // access: return reference
    int size() const { return sz; }                         // the current size

    // ...
};
```

Templates

- Problems ("there's no free lunch")
  - Poor error diagnostics
    - Often spectacularly poor
  - Delayed error messages
    - Often at link time
  - All templates must be fully defined in each translation unit
    - (the facility for separate compilation of templates, called "export", is not widely available)
    - So place template definitions in header files
- Recommendation
  - Use template-based libraries
    - Such as the C++ standard library
      - *E.g.,* **vector**, **sort()**
      - Soon to be described in some detail
  - Initially, write only very simple templates yourself
    - Until you get more experience

Range checking

```
// an almost real vector of Ts:

struct out_of_range { /* ... */ };

template<class T> class vector {
    // ...
    T& operator[ ](int n);              // access
    // ...
};

template<class T>  T& vector<T>::operator[ ](int n)
{
    if (n<0 || sz<=n) throw out_of_range();
    return elem[n];
}
```

Range checking

```
void fill_vec(vector<int>& v, int n)          // initialize v with factorials
{
    for (int i=0; i<n; ++i) v.push_back(factorial(i));
}

int main()
{
    vector<int> v;
    try {
        fill_vec(v,10);
        for (int i=0; i<=v.size(); ++i)
            cout << "v[" << i << "]==" << v[i] << '\n';
    }
    catch (out_of_range) {                    // we'll get here (why?)
        cout << "out of range error";
        return 1;
    }
}
```

Exception handling (primitive)

```
// sometimes we cannot do a complete cleanup

vector<int>* some_function()      // make a filled vector
{
    vector<int>* p = new vector<int>;      // we allocate on free store,
                                           // someone must deallocate
    try {
        fill_vec(*p,10);
        // ...
        return p;          // all's well; return the filled vector
    }
    catch (…) {
        delete p;          // do our local cleanup
        throw;             // re-throw to allow our caller to deal
    }
}
```

Exception handling
(simpler and more structured)

```
// When we use scoped variables cleanup is automatic

vector<int> glob;

void some_other_function()          // make a filled vector
{
    vector<int> v;              // note: vector handles the deallocation of elements

    fill_vec(v,10);
    // use v
    fill_vec(glob,10);
    // ...
}
```

- if you feel that you need a try-block: think.
  - You might be able to do without it

RAII (Resource Acquisition Is Initialization)

- Vector
  - acquires memory for elements in its constructor
  - Manage it (changing size, controlling access, etc.)
  - Gives back (releases) the memory in the destructor
- This is a special case of the general resource management strategy called RAII
  - Also called "scoped resource management"
  - Use it wherever you can
  - It is simpler and cheaper than anything else
  - It interacts beautifully with error handling using exceptions
  - Examples of "resources":
    - Memory, file handles, sockets, I/O connections (iostreams handle those using RAII), locks, widgets, threads.

A confession

- The standard library **vector** doesn't guarantee range checking of **[ ]**
- You have been using
  - *Either* our debug version, called **Vector**, which does check
  - *Or* a standard library version that does check (several do)

- Unless your version of the standard library checks, we "cheated"
  - In **std_lib_facilities.h**, we use the nasty trick (a macro substitution) of redefining **vector** to mean **Vector**

    #define vector Vector

    (This trick is nasty because what you see looking at the code is not what compiler sees – in real code macros are a significant source of obscure errors)
  - We did the same for **string**

What the standard guarantees

```
// the standard library vector doesn't guarantee a range check in operator[ ]:
template<class T> class vector {
    // …
    T& at(int n);                   // checked access
    T& operator[ ](int n);          // unchecked access
};

template<class T>  T& vector<T>::at (int n)
{
    if (n<0 || sz<=n) throw out_of_range();
    return elem[n];
}

template<class T>  T& vector<T>::operator[ ](int n)
{
    return elem[n];
}
```

What the standard guarantees

- Why doesn't the standard guarantee checking?
  - Checking cost in speed and code size
    - Not much; don't worry
      - No student project needs to worry
      - Few real-world projects need to worry
  - Some projects need optimal performance
    - Think huge (e.g., Google) and tiny (e.g., cell phone)
  - The standard must serve everybody
    - You can build checked on top of optimal
    - You can't build optimal on top of checked
  - Some projects are not allowed to use exceptions
    - Old projects with pre-exception parts
    - High reliability, hard-real-time code (think airplanes)

String

- A **string** is rather similar to a vector<char>
  - E.g. **size(), [ ], push_back()**
  - Built with the same language features and techniques
- A **string** is optimized for character string manipulation
  - Concatenation (+)
  - Can produce C-style string (**c_str()**)
  - >> input terminated by whitespace