Chapter 19
Vectors, templates, and exceptions

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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
- Initialization
- Copy and move
- 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
```

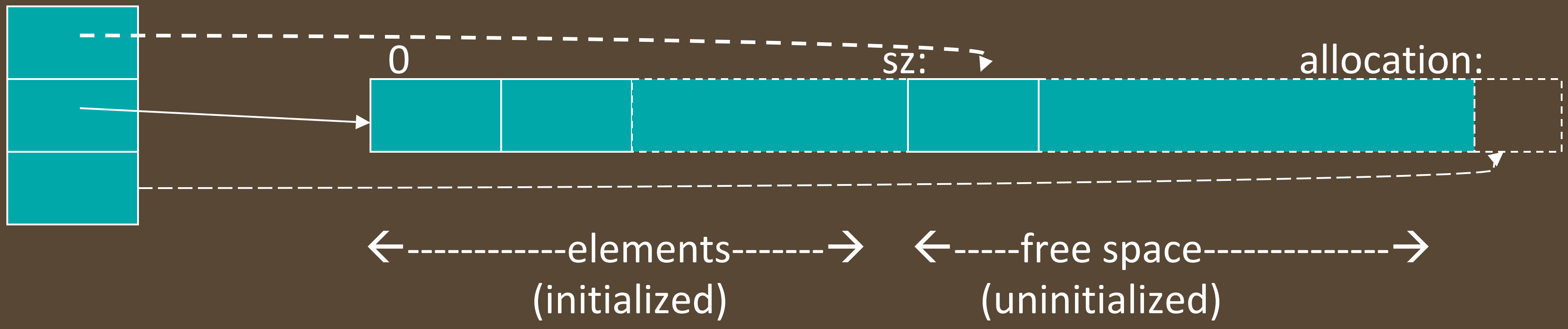
we can change its size in three ways

  - 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

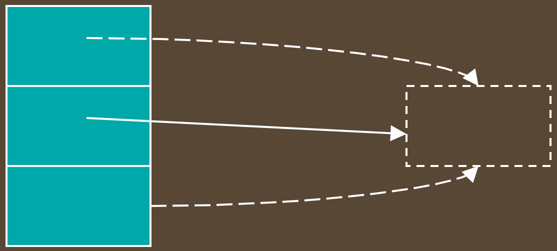
- If you **resize()** or **push_back()** once, you'll probably do it again;
  - let's prepare for that by sometimes keeping a bit of free space for future expansion

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

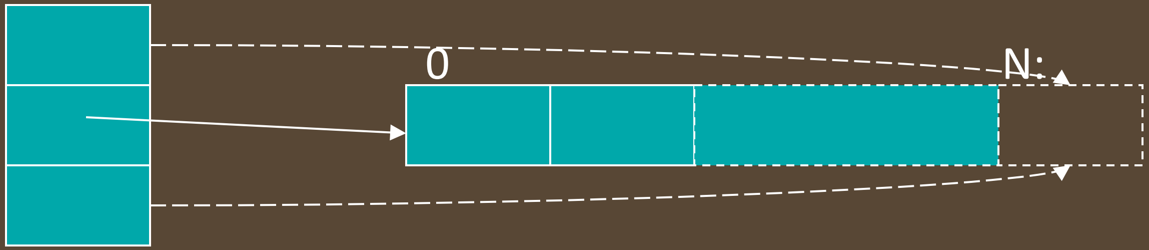


Representing vector

- 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

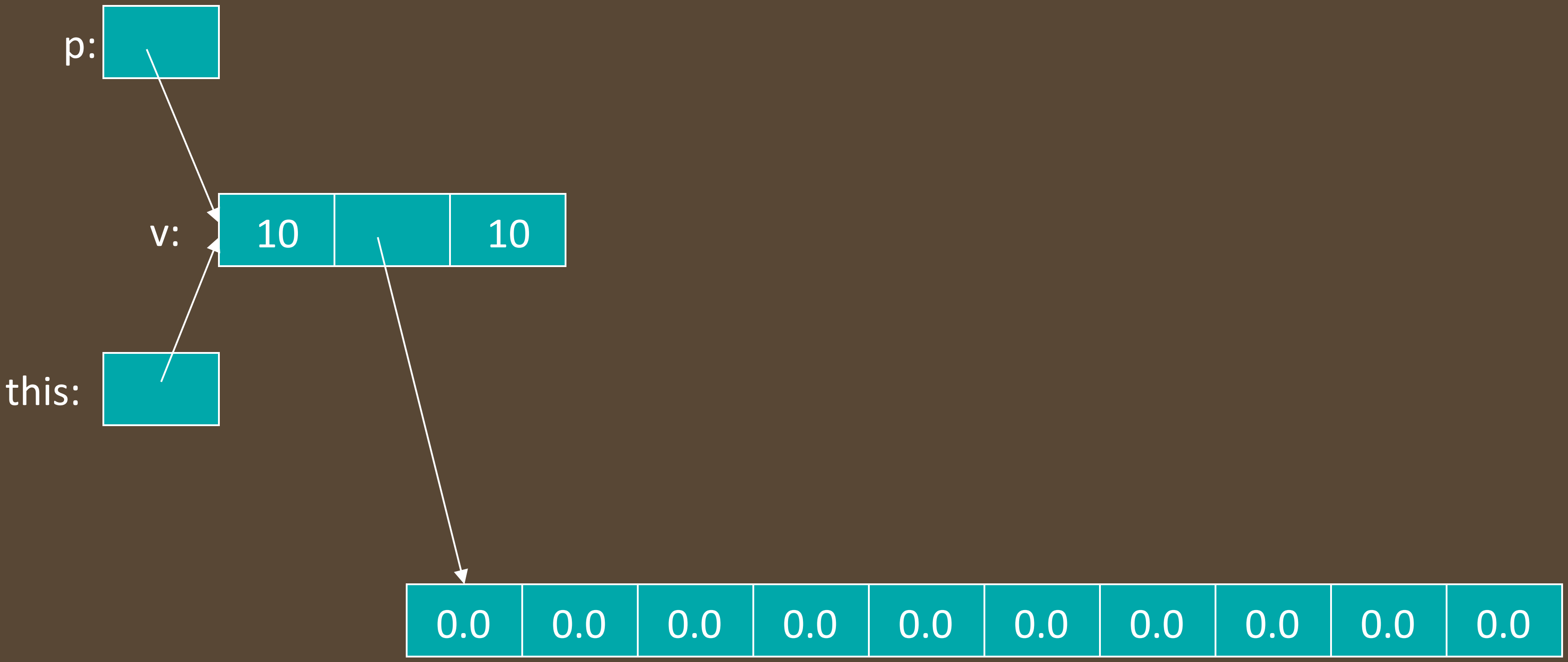
```
void vector::push_back(double d)
    // increase vector size by one
    // initialize the new element with d
{
    if (sz==0)                  // no space: grab some
            reserve(8);
    else if (sz==space)         // no more free space: get more space
            reserve(2*space);
    elem[sz] = 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:
    // … constructors and destructors …

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

    void resize(int newsize);                               // grow
    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)
	// 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

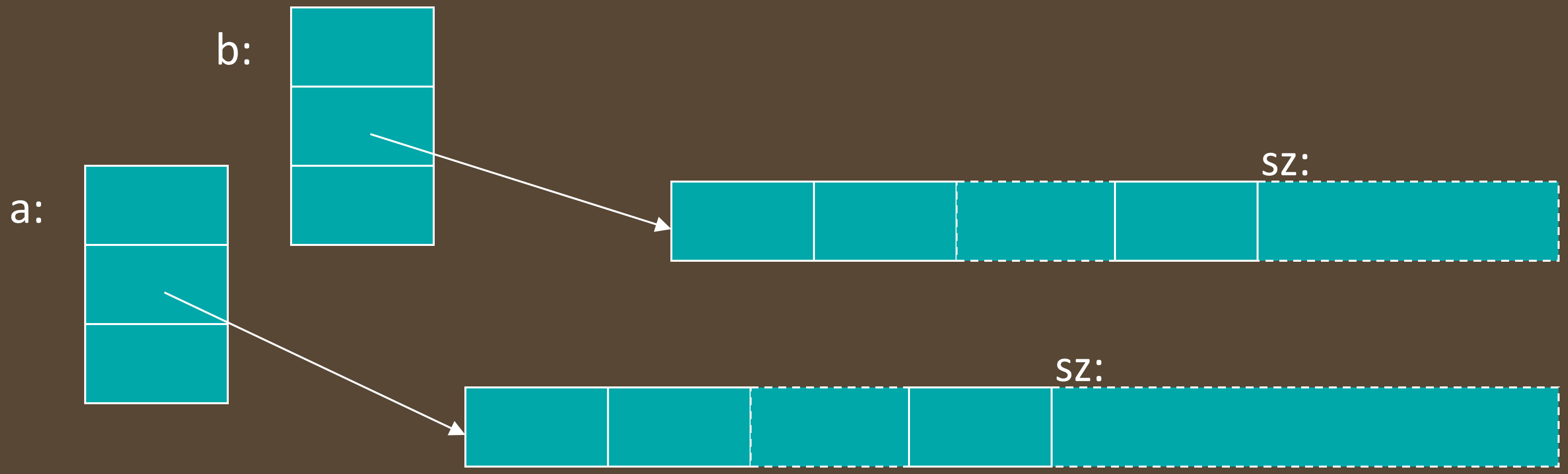
Assignment

- 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 { /* … */ };
template<class T, int N> void fill(Buffer<T,N>& b) { /* … */  }
```

- 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

    // …
};
```

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(const vector&&);                               // move constructor
    vector& operator=(vector&&);              // move assignment

    ~vector() { delete[ ] elem; }                          // destructor

    // …
};
```

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:
    // … constructors and destructors …

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

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

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

    // …
};
```

Templates

- Problems ("there is no free lunch")
  - Poor error diagnostics
    - Often spectacularly poor (but getting better in C++11; much better in C++14)
  - Delayed error messages
    - Often at link time
  - All templates must be fully defined in each translation unit
    - (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

- We use exceptions to report errors
- We must ensure that use of exceptions
  - Doesn’t introduce new sources of errors
  - Doesn’t complicate our code
  - Doesn’t lead to resource leaks

Resource management

- A resource is something that has to be acquired and must be released (explicitly and implicitly)
- Examples of resources
  - Memory
  - Locks
  - File handles
  - Thread handles
  - Sockets
  - Windows

```
void suspicious(int s, int x)
{
        int* p = new int[s];      // acquire memory
        // . . .
        delete[] p;               // release memory
}
```

Resource management

- Why suspicious?
  - It is easy to make mistakes with pointers and delete

```
void suspicious(int s, int x)
{
	int* p = new int[s];	// acquire memory
	// . . .
	if (x) p = q;		// make p point to another object
	// . . .
	delete[] p;		// release memory (but the wrong memory)
}
```

Resource management

- Why suspicious?
  - It’s easy not to get to the end of the function

```
void suspicious(int s, int x)
{
      int* p = new int[s];        // acquire memory
      // . . .
   if (x) return;                 // maybe we don’t get to the end: leak
     // . . .
     delete[] p;                  // release memory
}
```

Resource management

- Why suspicious?
  - It’s easy not to get to the end of the function

```
void suspicious(int s, int x)
{
        int* p = new int[s];          // acquire memory
        // . . .
    if (x) p[x] = v[x];               // v[x] may throw an exception: leak
       // . . .
       delete[] p;                    // release memory
}
```

Resource management

- Naïve, ugly, fix

```
void suspicious(int s, int x)  // messy code
{
        int* p = new int[s];                    // acquire memory
        vector<int> v;
        // . . .
        try {
                if (x) p[x] = v[x];             // may throw
                // . . .
        } catch (. . .) {                       // catch every exception
                delete[] p;                     // release memory
                throw;                          // re-throw the exception
        }
        // . . .
        delete[] p;                             // release memory
}
```

Resource management

- Simple, general solution
  - RAII: “Resource Acquisition is initialization”
  - Also known as scoped resource management

```
void f(vector<int>& v, int s)
{
        vector<int> p(s);
        vector<int> q(s);
        // . . .
}  // vector’s destructor releases memory upon scope exit
```

Resource management

- But what about functions creating objects?
  - Traditional, error-prone solution: return a pointer

```
vector<int>* make_vec()        // make a filled vector
{
        vector<int>* p = new vector<int>;  // we allocate on free store
        // . . . fill the vector with data; this may throw an exception . . .
        return p;
}

// now users have to remember to delete
// they will occasionally forget: leak!
```

Resource management

- But what about functions creating objects?
  - Improved solution: use **std::unique_ptr**

```
unique_ptr<vector<int>> make_vec()       // make a filled vector
{
        unique_ptr<vector<int>> p {new vector<int>};  // allocate on free store
        // … fill the vector with data; this may throw an exception …
        return p;
}

// users don't have to delete; no delete in user code
// a unique_ptr owns its object and deletes it automatically
```

Resource management

- But what about functions creating objects?
  - Even better solution: use **std::make_unique**
  - C++14 only (unless you have an implementation of **make_unique**)

```
unique_ptr<vector<int>> make_vec()      // make a filled vector
{
        auto p = make_unique{vector<int>};  // allocate on free store
        // … fill the vector with data; this may throw an exception …
        return p;
}
```

*// no **new** in user code*

Resource management

- But what about functions creating objects?
  - Best solution: don't mess with pointers (of any sort) at all
  - Return the object itself

```
vector<int> make_vec()      // make a filled vector
{
        vector<int> res;
        // . . . fill the vector with data; this may throw an exception . . .
        return res;    // vector's move constructor efficiently transfers ownership
}

// don't use pointers unless you really need them
```

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

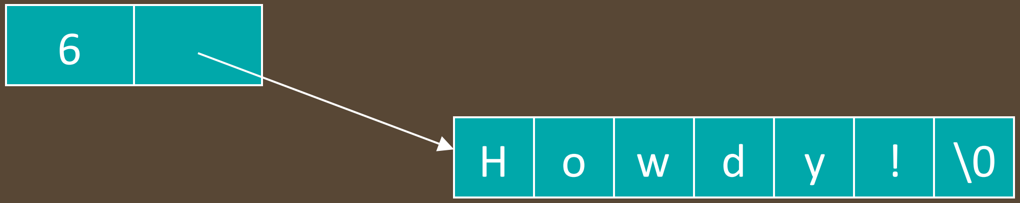
- Why doesn't the standard guarantee checking?
  - Checking cost in speed and code size
    - Not much; don't worry
      - No student project needs to worry
      - Few real-world projects need to worry
  - Some projects need optimal performance
    - Think huge (e.g., Google) and tiny (e.g., cell phone)
  - 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)

Access to const vectors

```
template<class T> class vector {
    // …
    T& at(int n);                                // checked access
    const T& at(int n) const;                    // checked access

    T& operator[ ](int n);                       // unchecked access
    const T& operator[ ](int n) const;           // unchecked access
    // …
};

void f(const vector<double> cvd, vector<double> vd)
{
    // …
    double d1 = cvd[7];     // call the const version of [ ]
    double d2 = vd[7];      // call the non-const version of [ ]
    cvd[7] = 9;             // error: call the const version of [ ]
    vd[7] = 9;              // call the non-const version of [ ]: ok
}
```

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 a C-style string (**c_str()**)
  - >> input terminated by whitespace
  - Small strings don't use free store (characters are stored in the handle)



Next lecture

- An introduction to the STL, the containers and algorithms part of the C++ standard library. Here we' ll meet sequences, iterators, and containers (such as **vector, list**, and **map**). The algorithms include **find()**, **find_if()**, **sort()**, **copy()**, **copy_if()**, and **accumulate()**.