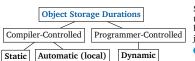
Fundamentals and Machine Model

Machine/Memory Model and the Function Call Stack

Object: a piece of data that's stored at a particular location in memory during runtime.

Variable: a name in source code that is associated with an object at compile time.

- 1 Not all objects are associated with variables; e.g. dynamically-stored objects and string literals are not.
- 1 The value stored by a variable's memory object may change, but the association between a variable and an object itself can only change when the variable goes out of scope.



Static objects "live" for essentially a program's runtime. Local objects' lifetimes are tied to scope (e.g. a block of code or pair of curly braces). Dynamic objects are manually created/destroyed.

① Objects declared in a loop body (between the {}) are created/destroyed each time the loop repeats.

Atomic (primitive) types: objects that can't be subdivided into smaller objects; includes int, double, bool, float, char, and all pointer types. Atomic objects are default-initialized to undefined values. The memory allocated to store a function's parameters and local variables during runtime is called a stack frame or activation record. The memory frame for the most-recently called function is added to the "top" of the function call stack and is destroyed when the function returns ("Last In First Out" ordering).

1 Assignments inside of return statements (e.g. return x = y;) "take effect" before the return.

Procedural Abstraction and Program Design

Procedural Abstraction involves using functions to break down a complex procedure into sub-tasks and separate the interface of a procedure (what it does) from implementation (how it works).

Interface examples: declarations in ...h files, valid/invalid inputs, RME statements, signature (function name and parameter types), return type, and ADT representation invariants.

Implementation examples: definitions in .cpp files and code/comments inside function bodies.

Pointers, Arrays and Reference

A pointer is a type of object that stores another object's memory address as its value.

• An int* pointer can only point to an int; an int** pointer can only point to an int*; and so on. (Trying to, for example, make an int* pointer point to a double will cause a compile error.)

Dereferencing: getting the object at an address. Note that the * operator is used both to declare pointers and to dereference them (and the @ operator is used both to get an object's address and to declare references).

```
int x = 3; int y = 4;
int* ptrl = &x; int* ptr2 = &y;
int** ptrl_ptr = &ptrl;
ptr2 = ptrl, // copies x's address from ptrl to ptr2
ptrl = &y; // ptrl now points at y
**ptrl_ptr = 6; // now y == 6
*ptr2 = 2; // ptr2 still points to x, so now x == 2
```

5

- f Printing a non- char pointer prints the address that it stores.
- 1 A reference to a reference is really another reference for the "original" object.
- int x = 5; int& a = x;
 int* y = &x; // creates pointer to x
 int* z = y; // creates another pointer to x
 int* &b = z; // creates reference b to pointer z
 cout << *b << endl; // Prints 5
 cout << y << endl; // prints 0x2710
 cout << &(*z) << endl; // equiv. to cout << &x
 cout << *(&z) << endl; // equiv. to cout << z</pre> 0x2710 0x2714 0x2710 y 0x271c 0x2710 z,b

Null pointer: a pointer that holds address 0x0 (which no object can be located at) and implicitly converts to false. Any pointer can be nulled by setting it equal to nullptr (or 0, or NULL).

Differences Between Pointers and References:

- References are aliases for existing objects, whereas pointers are distinct objects in memory.
- Pointers must be dereferenced to access the objects they point at, while references are used "as-is".
- You can change what a (non-const) pointer points to, but you can't change what a reference refers to. Common Pointer/Reference Errors

- A Dereferencing an uninitialized pointer results in undefined behavior, as (like all atomic objects) pointers that aren't explicitly initialized are default-initialized to an undefined value (not nullptr).
- ▲ Dereferencing a null pointer also leads to undefined behavior (almost always a program crash).

returns), dereferencing that pointer or using that reference produces undefined behavior.

- An uninitialized reference or a reference-to-non- const. that's bound to a "literal" value won't compile.
- ⚠ If a function returns a pointer or reference to one of its local variables (which die when the function

A Be careful with mixing incrementing and dereferencing (and parentheses).

```
int x = 5;
int* ptr = &x;
// Output: 5 and 6
cout << (*ptr)++ << endl;
cout << x << endl;
// ptr == &x</pre>
int x = 5;
int* ptr = &x;
// Output: 5 and 5
cout << x << endl;
cout << x << endl;
cout << x << endl;
// ptr == junk (++&x)</pre>
                                                                                                                                                                                                                          int x = 5;
int* ptr = &x;
// Output: 6 and 6
cout << ++*ptr << endl;
cout << x << endl;
// ptr == &x</pre>
                                                                                                                                                                                                                                                                                                                                       int x = 5;
int* ptr = &x;
// Output: 6 and 6
cout << ++(*ptr) << endl;
cout << x << endl;
// others or cout</pre>
                                                                                                                                                                                                                                                                                                                                        // ptr == &x
```

Arrays and Pointer Arithmetic

Arrays: fixed-size containers that store objects of the same type (and same size) in contiguous memory.

```
int D[][2] = {1,2,3}; // {{1,2},{3,0}} int E[][3] = {1,2,3}; // {{1,2,3}} int F[3]; // CAUTION: uninitialized! int \underline{I}[2][] = {1,2,3,4}; // Same
int A[3] = {1,2}; // {1,2,0}
int B[3] = {}; // {0,0,0}
int C[] = {1,2}; // size == 2
```

Array decay: using an array in a context where a value is required causes the compiler to convert the array into a pointer to its first element. Array decay is why it's necessary to pass an array's size separately from the array to a function (or to indicate the end of an array with a sentinel character like C-strings do).

A Dereferencing a pointer that goes past the bounds of an array results in undefined behavior. But

merely using a pointer that goes just past the end of an array without dereferencing it is well-defined.

```
void reverseArray(int arr[], int size) {
    for (int i = 0; i < (size / 2); ++i) {
        int temp = arr[i];
        arr[i] = arr[(size - i - 1)];
        arr[(size - i - 1)] = temp;
        } // Note: arr[i] == *(arr + i) == i[arr]
} // Therefore, &arr[i] == (arr + i)</pre>
```

Passing an array by value passes a pointer to its first element by value, so functions with array parameters like this one actually have pointer parameters.

1 The number of elements in an array arr is equal to (sizeof(arr) / sizeof(*arr)).

```
f cout << &arr[0] and
   cout << &arr would
   also print 0x1000.
```

You can create refer-

ences to array elements

int arr[3] = { 5, 10, 15 };
int* ptr = Sarr[2];
int* ptr2 = (arr + 1);
cut << arr << end1; // prints 0x1000
5 cout << 6ptr2 << end1; // prints 0x1014
cout << ptr[-1] << end1; // prints 10</pre>

0x1000 arr[0] arr { 0x1004 0x1008 10 arr[1] 15 arr[2] 0x1008 ptr 0x100c 0x1014 0x1004 ptr2

Pointer Operations

Pointer arithmetic: adding an integer n to a pointer yields a pointer that is n objects forward in memory.

Pointer subtraction: Subtracting two pointers of the same type yields an integer (possibly a negative one) equal to the number of objects between them.

Pointer comparison: comparing pointers of the same type compares the addresses they store.

Using & on an array (without an index) creates a pointer to the entire array, not a pointer to the first element or a pointer to a pointer.

```
// Mainly for pointers into the same array
int arr[4] = { 5, 10, 15, 20 };
int* ptrl = &arr[0], *ptr2 = &arr[3];
cout << *arr << endt; // prints 5
cout << (ptr2 - ptrl) << endt; // prints 3
cout << (ptr1 - ptr2) << endt; // prints -3
assert(ptrl < ptr2); // true
ptrl += 2; // ptrl now points at arr[2]
int arr[4] = { 1, 2, 3, 4 };
int (*arr_ptr)[4] = &arr; // pointer to entire array
cout << (*arr_ptr)[2] << endl; // prints 3
// ++arr_ptr would increment by the size of 4 ints</pre>
```

Array traversal: arrays can be traversed by index or pointer (differentiated by what gets incremented).

```
Traversal By Pointer: Pattern 1
                                                                                                   Traversal by Pointer: Pattern 2 (C-String Sanitization)
int computeRange(const int arr[], int N) {
  const int* min = arr; // Need const here
  const int* max = arr;
  const int* end = (arr + N);
  // end is actually "1-past-the-end"
  for Cconst int* p = arr; p < end; ++p) {
  if (*p < *min) { min = p; }
  if (*p > *max) { max = p; }
  } // "wall" the pointer across arr
  return (*max - *min);
}
                                                                                                          ++fast; // ++fast every loop
                                                                                                         | *slow = '\0'; // null-terminate when done
|} // NOTE: '\0' is the only char considered "false"
```

The const type qualifier stops objects from being modified after initialization. Note: const scalars must be explicitly-initialized to compile, and const class-type objects must have their data members initialized.

const pointers: pointers that can modify what they point at but cannot be re-pointed to different objects. Pointer-to- const: read-only pointers; pointers that can be re-bound but can't modify what they point at.

 A const pointer must be initialized to compile, but a pointer-to-const doesn't need to be.

Reference-to- const: a read-only alias.

const array: an array of const elements. Note that the placement of const matters for arrays of pointers.

const int* A[] = {...}; // pointer-to-const array int* const B[] = {...}; // const pointer array

```
int x = 5;
int * const ptr_a = &x; // const pointer
const int * ptr_b = &x; // pointer-to-const
int const * ptr_c = &x; // pointer-to-const
const int * const ptr_d = &x; // both
int const * const ptr_e = &x; // both
const int &ref a = x; // reference-to-const
int const &ref b = 42; // reference-to-const
const int arra[2] = {1, 2}; // array of consts
int const arr_b[2] = {3, 4}; // array of consts
```

Special const Type Syntax

const Conversions and Passing

The compiler treats every pointer-to-const as if they point to a const object and every reference-toconst as if they're aliased to a const object. It won't allow conversions that could bypass existing const protections (so, e.g., you can assign a const pointer to a pointer-to-const, but the converse is not true).

```
void foo(string& a) { · · }
void bar(string b) { · · }
void func(const string& c) { · · · }
const string& s = "Hello World";
bar(s); func(s); // both ok
foo(s); foo("Hello"); // ERRORS
                                                                                                                                                                                    1 const int x = 3;
2 int y = x; // 0k
3 const int* cptr = &x; // 0k
4 const int& cref = x; // 0k
5 int* ptr = cptr; // ERROR 2
6 int& ref = cref; // ERROR 2
                                                                                                                                                                                                                                                                                                                                                                         int x = 2, y = 5;
const int *x_ptr = &x;
int *y_ptr = &y;
*y_ptr = *x_ptr; // Ok
y_ptr = x_ptr; /* ERROR (even
though x isn't const!) */
```

- Pass by pointer/reference: if you need to modify the original object (as opposed to a local copy).
- Pass by value: if an object is small (e.g., an int) and you can't/don't need to modify the original.
- Pass by pointer/reference-to-const: if you want to pass a large object without modifying it.

Strings, Streams and I/O

Creating/Using Strings (and C-Strings)

```
char color[] = "00274C"; // Create 7-element array (including \0) and copy a string literal to it const char* cstr = "abcd"; // Only works for string literals; use .c_str() on string variables cout << cstr << " " <* *cstr << " " << * &cstr[0] <* endl; // prints "abcd a abcd" cout << (cstr + 1) <- " " << * (str + 1) <- / prints "bd b 98" ('a' == 97) string str = string(cstr); // Explicitly copy cstring to a string (implicit copy would work too)
```

Length			gnment	Index		Concatenation	on	Comparison		
s.length();	s.size();	s1 = s2;	str = cstr;	str[i];	s1 += s2;	str += 'a';	str += cstr;	s1 != s2;	s1 < s2;	

Streams and File I/O

stdin Redirection	stdout Redirection	Pipeline	Combined Redirection
./main.exe < input.txt	./main.exe > output.txt	./output.exe input.exe	./main.exe < input.in > output.out

```
Ex 2: Copy One File's Contents to Another
        File I/O Ex 1: Print Lines From File
                                                                                                                                                  minclude <fstream>
void copyFile(string file_in, string file_out) {
    // file streams also accept C-strings as argumulifstream inFS(file_in);
    ofstream outFS(file_out);
}
#include <fstream> // defines if/ofstreams
int main() {
int main() {
   ifstream inFS; // or inFS("file.txt");
   inFS.open("file.txt");
   if (linFS.is_open()) { return 1; }
   string str; // defaults to empty string
   while (getline(inFS, str)) {
   | cout << str << endl;
   } // could close inFS via inFS.close();
} // inFS also closes when scope ends</pre>
                                                                                                                                                         brstream outstrite_out;
string input_str;
while (inFS >> input_str) {
    outFS << input_str << endl;
} // could use '\n' instead of endl</pre>
```

1 The insertion << and extraction >> operators "stop" at the first white space (spaces/line breaks/etc).

istringstream : an object that "simulates" input with a string as its source. Note: an istringstream an ifstream and cin can all be passed to a function with a std::istream& parameter.

ostringstream: an object that captures output and stores it in a string. Note: an ostringstream, an ofstream and cout can all be passed to a function with a std::ostream& parameter.

#include <sstream> // defines stringstreams
void printPlusOne(istream& is, ostream& os) {
 int num = 0;
 while (is >> num) { os << (++num) << " "; }
} // Note: can't pass or return streams by value</pre> istringstream inSS("1 3 5"); ostringstream outSS; printPlusOne(inSS, outSS); cout << outSS.str() << endl; // Prints "2 4 6 "

Command-Line Arguments

argc: an int parameter of main() representing the number of a command's arguments.

argv: an array of the arguments passed to a program. (Technically, argv is an array of pointers to Cstrings—so argv is passed to main() as a pointer to an array of pointers to C-strings).

```
#include <string> // defines stoi()/stod()
#Inctude <string> // defines stoi()/stod()
int main(int argc, char* argv[1]) { // char** argv also OK
| if (string(argv[1]) == "add") {
| int sum = 0;
| for (int i = 2; i < argc; ++i) {
| | sum += stoi(argv[i]);
| }</pre>
| cout << "Sum: " << sum << ", argc: " << argc << endl;
|} // pay attention to where the "actual" arguments start
} // Also remember to use stoi()/string() when needed
```

okim@ubuntu:~\$./main.exe add 7 2 Sum: 9, argc: 4 hugokim@ubuntu:~\$./main.exe add 1 2 3 Sum: 6, argc: 5 hugokim@ubuntu:~\$.

ADTs, Structs and Classes

C-Style Structs and ADTs

A struct is a class-type object composed of member subobjects (heterogeneous data). They're passed by value by default, and they support assignment and initialization via the = operator. A struct or class object can also be declared as const, which prevents it and all of its data members from being modified.

- You cannot call non-const member functions on a const instance of a class or struct. Also, you can't call non-const member functions from within a const member function.
- You can't use an implicit default ctor for a class-type object with a const non-static data member. Arrow -> operator: shorthand for a dereference followed by member access. (*ptr).x == ptr->x;

1 Without parentheses, the dot and arrow operators have greater precedence than dereferencing. Abstract Data Type: a data type that separates its behavior and implementation. ADTs encompass both

data and behaviors/functions that act upon it. Not all struct s are ADTs, some are "plain old data".

In C++, the only real difference between classes and structs are that classes have private member access and private inheritance by default while struct's default to public access/inheritance.

Constructors

- 1 The compiler implicitly creates a default ctor iff there are no user-defined ctors (same for dtors).
- 1 The order in which members are declared in a class body is always the order they're initialized in.
- Initialization values from a member init, list take precedence over initializations made at declaration.
- A You can't initialize members within a constructor body-attempting to do so actually performs default-initialization followed by assignment.
- A delegating ctor must contain a call to the other ctor (and nothing else) in its member init. list.

```
Constructor Definition Example
    class Animal {
private: string name;
                and to the content of the conte
  | Animal() : Animal("Blank") { } // Default ctor }; // Default ctor delegates to other ctor
class Duck : public Bird {
private: int age;
  public:
| Duck(string name_in, bool fly_in, int age_in) |
| : Bird(name_in, fly_in), age(age_in) { }
}; // Calling Bird ctor also calls Animal ctor
    // This is how to define a ctor OUTSIDE of body
Bird::Bird(string name_in, bool fly_in)
|: Animal(name_in), can_fly(fly_in) { }
```

C-Style Struct vs C++ Class Syntax

```
ADT Function Definition
// C-Style Struct
 void Triangle_scale(Triangle* t, double s) {
    t->a *= s; // "->" is necessary here
// C++ Class (Inside Body)
class Triangle { // "this->" optional
| void scale(double s) { this->a *= s; }
}; // this-> implicit iff no name conflicts
// C++ Class (Outside Body)
void Triangle::scale(double s) {...}
```

```
Object Creation/Manipulation
// C-Style Struct
Triangle t1;
Triangle_init(&t1, 3, 4, 5);
 // C++ Class
// C++ Class
Triangle t1; // Calls default ctor
Triangle t2(3,4,5); // calls 3-argument ctor
Triangle t3 = Triangle(3,4,5); // ditto
Triangle t43, 4, 5}; // ditto
Triangle t5 = {3, 4, 5}; // ditto
Triangle t6 = Triangle{3, 4, 5}; // ditto
// The last 3 work for classes and structs
```

```
const Function Definition
// C-Style Struct
double area(const Triangle* t) {...}
// const goes inside argument list
// C++ Class (Inside Body)
class Triangle {
   double area() const {...}
}; // const comes after signature
// C++ Class (Outside Body)
double Triangle::area() const {...}
```

Inheritance and Polymorphism

Function Overloading (Ad Hoc Polymorphism) and Operator Overloading

Function Overloading: using one name for functions with different signatures. Functions can only be overloaded in the same scope (otherwise the "closer" scope takes priority). Note: const /non-const passing only alters the signature if a function has pointer/reference parameters (or implicit this-> pointers). Operator Overloading: operators like +, -, <<, etc. must be "overloaded" either as top-level or class

member functions to work properly with custom class types. • An operator must be overloaded as a top level function if the first operand is an atomic type or a class

type whose definition we can't access (e.g. ostream). Also, the =, (), [] and -> operators can only be overloaded as member functions (along with overloads that require access to private members).

```
[] Overload Example (Member)
class IntSet {
    ... // contains() is also a member function
   bool operator[](int v) const;
};
bool IntSet::operator[](int v) const {
    return contains(v);
```

```
<< and == Overload Examples (Top-Lev
1 class Line { /* start/end are public */ ... };
 ostream& operator<<(ostream& os, Line line) {
   return os << line.start << line.end;</pre>
 } // os needs to be passed by non-const ref here
   bool operator==(const Line& a, const Line& b) {
   return (a.start == b.start && a.end == b.end);
  } // Don't pass by non-const ref here
```

class Base {
public:
 void print() {cout << "B" << endl;}
 ~Base() { } // custom dtor syntax
}; // Base::~Base() outside class body</pre>

void print() {cout << "D" << endl;}
void printB() { Base::print(); }</pre>

Derived d;
d.print(); // prints "D"
d.print8(); // prints "B"
d.Base::print(); // prints "B"
Base* ptr = &d; // Base == static type
ptr->print(); // prints "B"

Access Modifier Out-of-scope access Derived class access

✓ Yes

class B : public A {
public: // Derived class
| B() {cout << "B_ctor";}
| ~B() {cout << "B_dtor";}</pre>

× No

class Derived : public Base {

Inheritance and Derived Classes

All base class members (EXCEPT ctors and dtors) become implicit members of derived classes. So you can call any public base class function on derived class objects or access inherited base class public members via ./->

▲ Creating a derived class object always calls a base class ctor. If you don't call one explicitly, the base class default ctor is implicitly called. Also, a base class dtor is always called when a derived object dies.

Member name lookup begins in the static type of a receiver/object and moves up the inheritance hierarchy (to the base class) if no match is found. It stops when it finds a matching name or reaches the top of the hierarchy.

- 1 Access levels are only checked after name lookup ends.
- Member name lookup searches by name. Virtual function resolution at runtime searches by signature.

Constructor/destructor ordering: constructors are called in "top-down" order on derived class objects (i.e., the base-class ctor is called first). Destructors follow bottom-up ordering (the derived class's dtor is called first, and the base class's dtor is called last).

1 Non-dynamic objects are destroyed in reverse of the order they were created in.

Subtype Polymorphism and Class Casting

Subtype polymorphism (a form of runtime polymorphism) allows a publicly-derived class object to be used in place of a base class object through a base-class reference or pointer to the derived object.

```
class Bird { }; // Base class
Chicken: public Bird { };
1 class Bird { }; // Base class
2 class Chicken : public Bird { };
3 class Duck : public Bird { };
5 class Duck : public Bird { };
5 b = c; // Legal, but "slices" c's data
6 Bird* b.ptr = &c; // Good, no slicing
7 c = b; // ERROR: illegal assignment
8 Chicken* c.ptr = &c; // ERROR: downcast
9 Duck* d.ptr = &c; // ERROR
```

C++ allows implicit upcasts (i.e. base pointers/refs to publicly derived objects), but all downcasts must be explicit via static_cast or (less preferably) dynamic_cast.

int main() {
2 | A obj_a; // Prints "A_ctor "
3 | B obj_b; // Prints "A_ctor B_ctor "
4 | A* b_ptr = &obj_b; // Doesn't print anything
5 } // When main() returns: "B_dtor A_dtor "

private

class A {
public: // Base class

A() {cout << "A_ctor ";}
~A() {cout << "A_dtor ";}

```
// Be careful - validity not checked at runtime:
Chicken* cPtr_a = static_cast<Chicken*>(bird_ptr);
// Bird needs at least 1 virtual function for this:
Chicken* cPtr_b = dynamic_cast<Chicken*>(bird_ptr);
```

Virtual Functions and the override Keyword Here, the receiver of the call to talk() on line 13 has a static type known at compile time (Bird) and a dynamic type known at runtime (Duck). Member lookup starts in the static class, so Duck::talk() won't hide Bird::talk(). Instead, Bird::talk() is declared as virtual to

Declare a function as virtual in the base class to use the "most-derived" version on a receiver whose static and dynamic types are different.

make it dynamically-bound.

```
class Bird {
... // Can't use virtual outside class body
    virtual void talk() const { cout << "tweet"; }
}</pre>
Duck duck;
Bird* duck_ptr = &duck;
duck_ptr->talk(); // prints "Quack"
// Scope resolution operator can suppress virtual
duck_ptr->Bird::talk(); // prints "tweet"
```

1 Placing override at the end of a function's signature tells the compiler to verify that it overrides a base-class virtual function with a matching signature (a compile error occurs if no override is found).

Pure Virtual Functions and Abstract Classes

Pure virtual function: a virtual function with no implementation (their purpose is to specify the interface of derived classes). To declare a function as pure virtual, add = 0; to the end of its signature.

Abstract class: a class with at least one pure virtual member function. Note that derived classes of an abstract class will also be abstract unless they override (define) every pure virtual function they inherit.

Interface (pure abstract class): a class that contains ① Don't try to call a pure virtual function or nothing but pure virtual member functions.

class Abstract { // Abstract Class public: virtual void foo() = 0; }; // Note the lack of braces after the = 0; class Concrete : public Abstract { public: void foo() { cout << "foo"; } };</pre> Concrete c; Abstract* ptr = &c; Abstract& ref = c; // ok Abstract abstract_object; // COMPILE ERROR c.Abstract::foo(); // RUNTIME ERROR (U.B.)

create an abstract class object.

Containers and Data Structures

Container ADTs

static keyword: used to make one copy of a class data member "shared" between all instances of that class. A static data member has static storage duration but exists only within the scope of a class.

stack: a one-ended container that's designed to operate in a LIFO order.

queue: a container data structure that supports first-in/first-out (FIFO) access.

	St	tacl	c	6	6		Qι	ıeu	e		A
1	2	3	4	\prec		5	4	3	2	~	(
			top	5					front	1	٠

Container	ontainer Interface Operations - Optimal Implementation						
Stack	.empty()	.size()	.top()	.push(val)	.pop()		
Queue	.empty()	.size()	.front()	.push(val)	.pop()		

All operations on stacks/queues run in O(1) amortized time push occasionally takes $\hat{O}(n)$ time if it causes a reallocation).

An efficient way to implement a queue is to create a vector with free space at both ends, i.e., a circular buffer.

Size() $V[1]$ /.at(1) .pusn_back(vat) .pop_back() .resize(n) search $O(n)$ $O(\log n)$ $O(n)$ $O(n)$ $O(n)$ $O(n)$		Useful std::v	ector Functions a	nd Constructo	Operation	Unsorted Set*	Sorted Set*	Stack	Queue	Array	List	
.front() .back() .erase(iterator) .empty() .clear() search O(n) O(logn) O(n) O(n)	size()	v[i]/ at(i)	nush hack(val)	non hack()	rosize(n)	insert/remove	O(n)	O(n)	O(1)	O(1)	O(n)	O(1)
access O(1) O(1) O(1) O(1) O(1)						search	O(n)	$O(\log n)$	O(n)	O(n)	O(n)	O(n)
vector <t> v2(v1.begin(), v1.end()) vector<t> v2(v1) * These refer to the array-based sets we saw in class, not STI, sets.</t></t>						access	O(1)	O(1)	O(n)	O(n)	O(1)	O(n)
	vector<	T> v2(v1.beg	in(), v1.end())	* These refer	to the array-ba	sed sets we s	aw in c	lass, not	STL se	ets.		

C++ Standard Library Containers

std::array: Containers with compile-time constant sizes that store elements in contiguous memory.

```
int x = 5;
array<int, x> arr;
// invalid constant
                                                                                                                void foo(const int z) {
   array<int, z> arr;
} // invalid constant
                                                                                                                                                                                      int a = 5; const int b = a;
array<int, b> arr;
// still not a valid constant
                                                       const int y = 10;
array<int, y> arr;
// okay
```

std::vector: resizable containers that store elements at the front and free space at the back

std::list: a container whose elements are linked via pointers in non-contiguous memory. This property enables constant-time insertion/deletion at arbitrary positions at the cost of random access.

std::map: an associative array that maps unique keys to values (keys act like indexes for a map). std::set: an associative sorted container that only stores unique keys.

⚠ Objects can't be used as keys in a std::map (or a std::set) if they can't be compared.

```
C++ Standard Library Containers
std::array<int, 4> arr = {-4,0,3,6};
std::array arr2{1, 2}; // Only way to omit size
std::list<int> doubly_linked = {1,2,3};
std::vector<int> v(3, -1); // {-1,-1,-1};
std::set<int> nums = {3,2,2,1}; // {1,2,3}
std::map<string, int> EECS = { "Bill", 183} };
cout << EECS["Bill"] << endl; // prints 183
// Two ways to insert into a map:
EECS["Emily"] = 203;
EECS.insert(pair<string, int>("James", 280));
```

```
Useful std::map functions
// Returns iterator to the pair with Key == k
// Returns .end() iterator if no such pair exists
iterator find(const Key_type& k) const;
// Inserts a <key, value> std::pair into a map
// Returns <iterator, false> if Key already in use
pair<iterator,bool> insert(const Pair_type& pair);
 returns a reference to the associated value */
Value_type& operator[](const Key_type& key);
```

1 Using comparison operators like < with the containers listed above will lexicographically compare their elements (for std::map s, their keys are compared).

Class	Ordering	Sorting	Resizable	Contiguous	Duplicate Items	Modifying Items	Index[]	Insert/Erase	Search
<array></array>	Sequential	Unsorted	× No	Yes	✓ Allowed	✓ Allowed	O(1)	-	O(n)
<vector></vector>	Sequential	Unsorted	✓ Yes	✓ Yes	✓ Allowed	✓ Allowed	O(1)	O(n) (<end) <math="">O(1) (end)</end)>	O(n)
st>	Sequential	Unsorted	✓ Yes	× No	✓ Allowed	✓ Allowed	-	O(1)	O(n)
<set></set>	Associative	Asc. key	✓ Yes	× No	✗ Not Allowed	✗ Not Allowed	-	$O(\log n)$	$O(\log n)$
<map></map>	Associative	Asc. Key	✓ Yes	× No	X Keys/ ✓ Vals	X Keys/ ✓ Vals	$O(\log n)$	$O(\log n)$	$O(\log n)$

Most STL containers allow you to use range-based loops to iterate over every item they contain. For a std::map, you'll need to access the .first and .second elements of the loop variable to get keys/values.

```
vectorint> v = { 1, 2, 3, 4 };
// for (<type> <variable> : <sequence>) {...}
for (int item : v) { // works with arrays too
| cout << item << endl;
} // could also declare item as const or a ref</pre>
                                                                                                                                               // Compiler translation of range-based for loop
for (auto it = v.begin(); it != v.end(); ++it) {
  int item = *it;
  cout << item << endl;</pre>
                                                                                                                                          5 } // auto keyword makes compiler deduce type
```

Templates (Parametric Polymorphism)

Templates: special functions that take a data type as a parameter and instantiate an object or function compatible with that type (at compile time). They help reduce code duplication in container interfaces.

```
Class Template Syntax
    template <typename T
class UnsortedSet {</pre>
    class onsored
public:
   void insert(T my_val);
   bool contains(T my_val) const;
   int size() const;
        T elts[ELTS_CAPACITY];
int elts_size;
11 }; // Syntax: UnsortedSet<type> s;
```

```
Function Template Syntax
    // Note: "class" also works in place of "typename"
template <typename T> // "!" is also an arbitrary name
T maxValue(const T &valA, const T &valB) {
  return (valB > valA) ? valB: valA;
    } // This function returns the greater of valA and valB
// Syntax to call it: maxValue<int/double/etc>(...);
                Templated Class Member Function Syntax
1 template <typename T> // Necessary if outside class body
2 void UnsortedSet<T>::insert(T my_val) {...}
```

A You can't pass auto or a const -qualified type to an STL container's template as a type argument (the C++ standard doesn't allow containers of const elements).

Time Complexity

Determining Asymptotic/Big-O Complexity

General rules for finding the time complexity of an algorithm:

- Multiply the complexities of nested procedures, e.g. two nested O(n) loops are $O(n^2)$.
- For sequential procedures, the most complex operation determines the overall runtime of the algorithm (e.g. an $O(\log n)$ step followed by an O(n) step makes for an O(n) algorithm).
- Ignore constant coefficients unless they're part of an exponent.

 $\boxed{ O(1) \quad O(\log n) \quad O(\sqrt{n}) \quad O(n) \quad O(n\log n), \, O(\log(n!)) \quad O(n^2) \quad O(n^3) \quad O(2^n) \quad O(3^n) \quad O(n!) \quad O(n^n) \quad O(2^{2^n}) }$ Inserting/Erasing: inserting into or erasing Searching: searching an unsorted sequence for a value from the middle of a contiguous container

elements. If contiguity is not an invariant, then the act of insertion/deletion is O(1). 1 Deleting an arbitrary node from a list is O(1), but deleting a specific node is O(n), because finding the node is O(n).

Indexing: If you store objects of the same

type contiguously, random access is O(1).

is O(n), since you'll need to shift the other

takes O(n) time. A sorted sequence can optimally be searched in $O(\log n)$ time with binary search.

```
int SortedIntSet::Search(int v, int L, int R) const {
    while (L < R) {
        int middle = L + (R - L) / 2;
        if (v == elts[middle]) { return middle; }
        else if (v < elts[middle]) { R = middle; }
        else E L = (middle + 1); }
        | // eliminates half the search space each loop 8 return -1; // if we didn't find v
        | // This is O(log n), but it requires sorted input</pre>
```