

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.

❗ Not all objects are associated with variables; e.g. dynamically-stored objects and string literals are not.

❗ 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.

❗ 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.

An **lvalue** is an object at some address in memory; an **rvalue** is a *value* with no meaningful address.

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).

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 References

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).

❗ Printing a non-`char` pointer prints an address. (char pointers get printed as C-strings.)

❗ A reference to a reference is really another reference for the "original" object.

```
1 int x = 3; int y = 4;
2 int* ptr1 = &x; int* ptr2 = &y;
3 int** ptr1_ptr = &ptr1;
4 ptr2 = ptr1; // copies x's address from ptr1 to ptr2
5 ptr1 = &y; // ptr1 now points to y
6 **ptr1_ptr = 6; // now y == 6
7 *ptr2 = 2; // ptr2 still points to x, so now x == 2
```

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`).

Common Pointer/Reference Errors

❗ 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).

❗ An uninitialized reference or a reference-to-non-`const` that's bound to an rvalue won't compile.

❗ If a function returns a pointer or reference to one of its local variables (which die when the function returns), dereferencing that pointer or using that reference produces undefined behavior.

```
1 int* danglingPtr(int x) { return &x; } // BUG
2 int& danglingRef(int x) { return x; } // BUG
```

Pointers vs References

References and pointers both enable working between stack frames (scopes) and indirection. Some ways they're different:

- References are simply aliases for existing objects, while pointers are distinct objects with distinct values.
- 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 a reference's binding to an object can't be changed.

Arrays and Pointer Arithmetic

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

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

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).

❗ 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.

```
1 void reverseArray(int arr[], int size) {
2   for (int i = 0; i < (size / 2); ++i) {
3     int temp = arr[i]; // needed for swapping
4     arr[i] = arr[size - 1 - i];
5     arr[size - 1 - i] = temp;
6   }
7 }
```

```
1 cout << &arr[0],
2 cout << arr, and
3 cout << &arr
4 would all print
5 0x1008.
```

```
1 int foo = 7;
2 int& bar = foo; // value of bar is foo (7)
3 int* ptr = &foo;
4 int arr[3] = {4, 5, 9};
5 cout << arr << endl; // prints 0x1008 (decay)
6 cout << (arr + 2) << endl; // prints 0x1010
```

```
0x1000 7 foo, bar
0x1004 0x1008 ptr
0x1008 4 arr[0]
0x100c 5 arr[1]
0x1010 9 arr[2]
```

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.

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

Pointer Operations

```
1 // Mainly for pointers into the same array
2 double arr[4] = { 2.5, 5.0, 8.0, 7.0 };
3 double* ptr1 = &arr[0], *ptr2 = &arr[3];
4 cout << *arr << endl; // prints 2.5
5 cout << (ptr2 - ptr1) << endl; // prints 3
6 cout << (ptr1 - ptr2) << endl; // prints -3
7 (ptr1 > ptr2); // equates to false (0)
8 ptr1 += 2; // ptr1 now points to arr[2]
```

```
1 int arr[4] = { 1, 2, 3, 4 };
2 int (*arr_ptr)[4] = &arr; // pointer to entire array
3 cout << (*arr_ptr)[2] << endl; // prints 3
4 // ++arr_ptr would increment by the size of 4 ints
```

Traversal By Pointer: arrays can be traversed by pointer (mostly used with C-strings and iterators).

Traversal By Pointer: Pattern 1	Traversal by Pointer: Pattern 2 (C-String Sanitization)
<pre>1 int const SIZE = 3; 2 int arr[SIZE] = {-1, 7, 2}; 3 int* ptr = arr; 4 int* end = arr + SIZE; 5 // int* end is "1-past-the-end" of arr 6 while (ptr < end) { 7 cout << *ptr << endl; 8 ++ptr; // "Walk" ptr across arr 9 } // Alternative to while loop below 1 for (; ptr < end; ++ptr) { ... }</pre>	<pre>1 void sanitizeUsername(Account* acc, char* to_remove) { 2 char* ptr1 = acc->username, *ptr2 = acc->username; 3 while (*ptr1 && *ptr2) { // while not '\0' 4 if (*ptr2 != to_remove) { 5 *ptr1 = *ptr2; 6 ++ptr1; // ++ptr1 only when a char gets copied 7 } 8 ++ptr2; // ++ptr2 every time the loop executes 9 } 10 *ptr1 = '\0'; // null-terminate string when done 11 } // NOTE: '\0' is the only char that evaluates to false</pre>

The const Keyword

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
```

const Conversions and Passing

The compiler treats every pointer-to-`const` as if they point to a `const` object and every reference-to-`const` 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).

```
1 void foo(string& a) { ... }
2 void bar(string b) { ... }
3 void func(const string& c) { ... }
4 const string s = "Hello World";
5 bar(s); func(s); // both ok
6 foo(s); foo("Hello"); // ERRORS
```

```
1 const int x = 3;
2 int y = x; // Ok
3 const int* cptr = &x; // Ok
4 const int& cref = x; // Ok
5 int* ptr = cptr; // ERROR 1
6 int& ref = cref; // ERROR 2
```

```
1 int x = 2, y = 5;
2 const int *x_ptr = &x;
3 int *y_ptr = &y;
4 *y_ptr = *x_ptr; // Ok
5 y_ptr = x_ptr; // ERROR (even
6 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 C-Strings and Strings

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

	Length	Copy Value	Index	Concatenate	Compare
<string>	str.length()	str1 = str2;	str[i];	str1 += str2;	str1 != str2;
<cstring>	strlen(cstr);	strcpy(cstr1, cstr2);	cstr[i];	strcat(cstr1, cstr2);	strcmp(cstr1, cstr2);

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

File I/O Ex 1: Print Lines From File	Ex 2: Copy One File's Contents to Another
<pre>1 #include <fstream> // defines if/ofstream 2 int main() { 3 ifstream inFS; // or inFS("file.txt"); 4 inFS.open("file.txt"); 5 if (!inFS.is_open()) { return 1; } 6 string str; // defaults to empty string 7 while (getline(inFS, str)) { 8 cout << str << endl; 9 } // could close inFS via inFS.close(); 10 } // inFS also closes when scope ends</pre>	<pre>1 #include <fstream> 2 void copyFile(string infile, string outfile) { 3 // fstreams can use C-strings as file names too 4 ifstream inFS(infile); 5 ofstream outFS(outfile); 6 string str; 7 while (inFS >> str) { 8 outFS << str << '\n'; 9 } // Note: >> and << stop at the first whitespace 10 } // Spaces and line breaks both act as separators</pre>

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

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

Command-Line Arguments

argv: an `int` parameter of `main` representing the number of a command's arguments.

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

```
1 #include <string> // defines stoi()/stod()
2 int main(int argc, char* argv[]) { // char** argv also OK
3   if (string(argv[1]) == "add") {
4     int sum = 0;
5     for (int i = 2; i < argc; i++) {
6       sum += stoi(argv[i]);
7     }
8     cout << "Sum: " << sum << " , argc: " << argc << endl;
9   } // pay attention to where the "actual" arguments start
10 } // Also remember to use stoi()/string() when needed
```

```
Terminal
hugokin@ubuntu:~$ ./main.exe add 7 2
Sum: 9, argc: 4
hugokin@ubuntu:~$ ./main.exe add 1 2 3
Sum: 6, argc: 5
hugokin@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.

Arrow -> operator: shorthand for a dereference followed by member access. `(*ptr).x == ptr->x`;

❗ 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".

❗ Avoid accessing the member data of an ADT directly (even in tests) because it breaks the interface.

C++ Classes

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.

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

```
1 class Animal {
2 private: string name;
3 public:
4   Animal(const string& name_in)
5     : name(name_in) {}
6   Animal() : Animal("Blank") {} // Default ctor
7 }; // Default ctor delegates to other ctor
8
9 class Bird : public Animal {
10 private: bool can_fly;
11 public: Bird(string name_in, bool fly_in)
12       : Animal(name_in), can_fly(fly_in) {}
13 }; // Derived class ctors must call a base ctor
14
15 class Duck : public Bird {
16 private: int age;
17 public:
18   Duck(string name_in, bool fly_in, int age_in)
19     : Bird(name_in, fly_in), age(age_in) {}
20 }; // Calling Bird ctor also calls Animal ctor
21
22 // This is how to define a ctor OUTSIDE of body
23 Bird::Bird(string name_in, bool fly_in)
24   : Animal(name_in), can_fly(fly_in) {}
```

```
ADT Function Definition
1 // C-Style Struct
2 void Triangle::scale(Triangle *t, double s) {
3   t->a *= s; // ">" is necessary here
4 }

1 // C++ Class (Inside Body)
2 class Triangle { // "this->" optional
3   void scale(double s) { this->a *= s; }
4 }; // This-> implicit iff no name conflicts
5
6 // C++ Class (Outside Body)
7 void Triangle::scale(double s) { ... }
```

```
Object Creation/Manipulation
1 // C-Style Struct
2 Triangle t1;
3 Triangle_init(&t1, 3, 4, 5);

1 // C++ Class
2 Triangle t1; // Calls default ctor
3 Triangle t2(3,4,5); // calls 3-argument ctor
4 Triangle t3 = Triangle(3,4,5); // ditto
5 // Syntax for classes AND structs:
6 Triangle t4(3, 4, 5);
7 Triangle t5 = {3, 4, 5};
8 Triangle t6 = Triangle{3, 4, 5};

const Function Definition
1 // C-Style Struct
2 double area(const Triangle *t) { ... }
3 // const goes inside argument list

1 // C++ Class (Inside Body)
2 class Triangle {
3   double area() const { ... }
4 }; // const comes after signature
5
6 // C++ Class (Outside Body)
7 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 a top-level or class member function to work properly with custom classes (at least 1 operand must be of class-type).

- 1 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 need to access private members).

```
[ ] Overload Example (Member)
1 class IntSet {
2 ... // contains() is also a member function
3 public:
4   bool operator[](int v) const;
5 };
6
7 bool IntSet::operator[](int v) const {
8   return contains(v);
9 }
```

```
<< and == Overload Examples (Top-Level)
1 class Line { ... }; // start/end are public members
2
3 ostream& operator<<(ostream& os, Line line) {
4   return os << line.start << line.end;
5 } // os needs to be passed by non-const ref here
6
7 bool operator==(const Line &a, const Line &b) {
8   return (a.start == b.start && a.end == b.end);
9 } // Don't pass by non-const ref here
```

Inheritance and Derived Classes

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

- 1 Creating a derived class object *always* calls a base class ctor. If you don't call one explicitly, the base class default ctor will be 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 at the first member with a matching *name* or the top of the hierarchy.

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

Modifier	Out-of-scope access	Derived class access
public	✓ Yes	✓ Yes
private	✗ No	✗ No
protected	✗ No	✓ Yes

Destructors: special functions that are invoked when a class object's lifetime ends. Constructors are called in *top-down* order for derived classes (the base ctor is called first), while destructors are *bottom-up* (the derived dtor is called first, and the base dtor last).

- 1 Non-dynamic objects are destroyed in the opposite order that they were created in.

Subtype Polymorphism and Class Casting

Subtype polymorphism allows a publicly-derived class object to be used in place of a base class object; to do this, a base class reference or pointer to a derived class object must be created.

```
1 class Bird { }; // Base class
2 class Chicken : public Bird { };
3 class Duck : public Bird { };
4 Bird b; Chicken c; Duck d;
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 = &b; // ERROR (downcast)
9 Duck* d_ptr = &c; // ERROR
```

```
class A {
public: // Base class
  A() { cout << "A_ctor "; }
  ~A() { cout << "A_dtor "; }
};

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

1 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 A_dtor "
```

```
1 class Bird {
2 ... // virtual can only be used in a class body
3   virtual void talk() const { cout << "tweet"; }
4 };
5 // Note: ctors can't be virtual, but dtors can
6 class Duck : public Bird {
7 ... // "virtual" is optional/implicit here
8   void talk() const override { cout << "Quack"; }
9 }; // override is an optional "sanity check"
10 // override always goes at end of signature
11 Duck duck;
12 Bird* duck_ptr = &duck;
13 duck_ptr->talk(); // prints "Quack"
14 // Scope resolution operator can suppress virtual
15 duck_ptr->Bird::talk(); // prints "tweet"
```

override keyword: tells the compiler to verify that a function overrides a base-class virtual function with a matching signature (if no override is found, override causes a compile error).

Pure Virtual Functions and Abstract Classes

Pure virtual function: a virtual base-class function that has no meaning or implementation (their purpose is to specify the interface of derived classes). To declare one, add = 0; to the end of a function's 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 (i.e., implement) every pure virtual function they inherit.

Interface (pure abstract class): a class that contains nothing but pure virtual member functions.

```
1 class Abst { // Abstract class
2 public: virtual void foo() = 0;
3 }; // Note the lack of empty braces
4
5 class Concrete : public Abst {
6 public: void foo() { cout << "foo"; }
7 }; // public/private doesn't matter here
8
9 Concrete c;
10 Abst* c_ptr = &c; Abst& c_ref = c; // ok
11 Abst abet-object; // COMPILER ERROR
12 c.Abst::foo(); // RUNTIME ERROR (or U.B.)
```

- 1 Don't call pure virtual functions or try to instantiate abstract classes.

Containers, Templates and Array-Based 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 container that's designed to operate in a LIFO order.

queue: a container designed to operate in a first-in/first-out (FIFO) order.

- 1 An efficient way to implement a queue is to create a vector with free space at both ends (a **ring/circular buffer**). To do so, keep track of the data using head (inclusive) and tail (exclusive) variables.

Useful std::vector Functions					Operation				
	size()	v[i]	.push_back(val)	.pop_back()	.resize(n)	insert/remove	Unsorted Set	Sorted Set	Stack
	O(1)	O(1)	O(1)	O(1)	O(1)	O(1)	O(n)	O(n)	O(1) ²
						search	O(n)	O(logn)	O(n)
						access	O(1)	O(1)	O(n)

C++ Standard Library Containers

std::array: Fixed-size containers that store elements in contiguous memory.

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 (i.e., in non-contiguous memory).

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.

```
C++ Standard Library Containers
1 std::array<int, 4> arr = {-4, 0, 3, 6};
2 std::vector<int> vec = {4, 7, 2};
3 // Note: can't index into a std::list
4 std::list<int> values = {1, 2, 3};
5
6 std::map<string, int> EECs; // <key, val>
7 EECs["Bill", 183]; EECs["Emily", 203];
8 EECs["James"] = 280; // This also works
9 cout << EECs["James"] << endl; // prints 280
10
11 std::set<int> unique = {3, 2, 2, 1}; // {1, 2, 3}
```

```
Useful std::map functions
// Returns an iterator to the value at the key k
// Returns .end() iterator if key isn't in the map
iterator find(const Key_type& key_val) const;

// Inserts a pair of <key, T value> into a map
// Returns <iterator, false> if key exists already
pair<iterator, bool> insert(const Pair_T &val);

// Returns a reference to a key's associated value
// If it doesn't exist, enters it into the map
Value_type& operator[](const Key_type& key_val);
```

Container	Ordering	Default Sort	Sizing	Default-Construction	Allocation	Value Type	Duplicate Values
std::array	Sequential	Unsorted	Fixed-size	Undefined values	Contiguous	T	Yes
std::vector	Sequential	Unsorted	Dynamic	Empty container	Contiguous	T	Yes
std::list	Sequential	Unsorted	Dynamic	Empty container	Not Contiguous	T	Yes
std::map	Associative	Ascending (by key)	Dynamic	Empty container	Not Contiguous	pair<const Key, T>	No repeat keys
std::set	Associative	Ascending	Dynamic	Empty container	Not Contiguous	Key	No

Templates (Parametric Polymorphism)

Templates: flexible models for producing code that take a data type as a parameter to create an object or call a function that works with that type. They help reduce code duplication in container ADT interfaces.

- 1 A template can accept an invalid type argument during instantiation (leading to a runtime error).

```
Class Template Syntax
1 template <typename T>
2 class UnsortedSet {
3 public:
4   void insert(T my_val);
5   bool contains(T my_val) const;
6   int size() const;
7 private:
8   T elts[ELTS_CAPACITY];
9   int elts_size;
10
11 }; // Syntax: UnsortedSet<type> s;
```

```
Function Template Syntax
1 template <typename T> // "T" = an arbitrary parameter name
2 // Note: "class" also works in place of "typename".
3 T maxVal(const T &valA, const T &valB) {
4   return (valB > valA) ? valB : valA; // ? == conditional
5 } // This function returns the greater of valA and valB
6 // Syntax to call it: maxVal<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) { ... }
```

Iterators, Traversal by Iterator and Range-Based Loops

Iterators: objects that have the same *interface* as pointers; they provide a general interface for traversing different types of container ADTs. To implement iterators for an ADT, define them as a nested class within the container's class and overload the * (dereference), ++, ==, and != operators.

- 1 std::begin() returns an iterator to the start of an STL container. std::end() returns an iterator that's 1 past the end of an STL container (the iterator returned by std::end() should not be dereferenced).

- 1 Using an *invalidated* iterator (e.g. an iterator pointing at a deleted element) causes undefined behavior.

Container	std::array	std::vector	std::list	std::map	std::set
Iterator	Random Access	Random Access	Bidirectional	Bidirectional	Bidirectional
Operations	->, [], ++, --, ==, !=, *, +, +=	->, [], ++, --, ==, !=, *, +, +=	++, --, ==, !=, *, +, +=	++, --, ==, !=, *, +, +=	++, --, ==, !=, *, +, +=

Traversal by iterator: a more general form of traversing a container data type by pointer.

```
1 vector<int> v(3, -1); // this syntax initializes v to {-1,-1,-1}
2 for (vector<int>::iterator it = v.begin(); it != v.end(); ++it)
3   { cout << *it << endl; } // ::const_iterator if const vector
```

```
Range-Based For Loop (Works on Any Sequence Traversable by Iterator)
1 vector<int> v = {1, 2, 3, 4};
2 for (const int& i : v) { ... }
3 for (int item = 1; item <= v.size(); ++item) { ... }
4 cout << item << endl;
5 // could also declare item as const or a ref
```

```
1 // Compiler translation of range-based for loop
2 for (auto it = v.begin(); it != v.end(); ++it) {
3   int item = *it;
4   cout << item << endl;
5 }
```

Time Complexity

We define **runtime complexity** in terms of *number of steps*, not literal runtime. Big-O notation represents an *upper-bound* of the magnitude of a function's growth rate with respect to input size (thus, all O(n) functions are also O(n²), O(n³), etc). Big-Θ and Big-Ω represent average and lower bounds, respectively.

O(1)	O(logn)	O(√n)	O(n)	O(nlogn)	O(log(n!))	O(n ²)	O(n ³)	O(2 ⁿ)	O(3 ⁿ)	O(n!)	O(n ⁿ)	O(2 ^{n²})
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- 1 Functions in the same complexity class should have growth rates that differ by a constant factor as n → ∞. So O(2ⁿ) and O(8ⁿ) are NOT in the same complexity class, but O(log₂ n) and O(log₃ n) are.

Determining Asymptotic/Big-O Complexity

Constant coefficients: if they're not part of an exponent, ignore them. Ex: O(3n) = O(0.5n) = O(n).

Addition (sequential procedures): the highest-complexity term dominates. Ex: O(n² + n + logn) = O(n²).

Multiplication: multiply the individual terms' complexities. Ex: O(n × logn) = O(nlogn).

Non-nested loops: sum the complexities of each operation *inside* the loop body and *multiply* that by the number of times the loop executes. Ex: a loop that runs from 0 to n with a O(logn) body is O(nlogn).

Nested loops: start at the innermost loop and work outwards (the individual complexities of the loops should multiply). Ex: two nested O(n) loops will do n work n times, so they're O(n²).

Partitioning/repeated division: procedures that divide the "remaining steps" by a constant number each time they execute (e.g. binary search, for-loops that double the loop counter) are usually O(logn).