Fundamentals and Machine Model

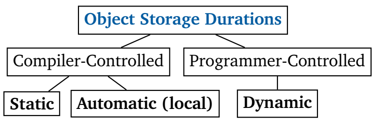
Machine/Memory Model and the Function Call Stack

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.

ℹ 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.

ℹ 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).

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.)

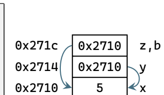
Dereferencing: getting the object at an address. Note that the `*` operator is used both to declare pointers and to dereference them (and the `&` operator is used both to get an object's address and to declare references).

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

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

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

```
int x = 5;
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
```



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, 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 you can't change what a reference refers to.

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

```
int* danglingPtr(int x) { return &x; } // BUGGY
```

```
int& danglingRef(int x) { return x; } // BUGGY
```

⚠ 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
```

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

```
int x = 5;
int* ptr = &x;
// Output: 6 and 6
cout << ++*ptr << endl;
cout << x << endl;
// ptr == &x
```

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

Arrays and Pointer Arithmetic

Arrays: fixed-sized 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[][2] = {1,2,3}; // {{1,2},{3,0}}
int E[][3] = {1,2,3}; // {{1,2,3}}
int F[3]; // CAUTION: uninitialized!
```

```
int G[]; // ERROR: unclear size
int H[2][] = {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.

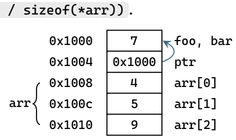
```
void reverseArray(int arr[], int size) {
  for (int i = 0; i < (size / 2); ++i) {
    int temp = arr[i]; // needed for swapping
    arr[i] = arr[(size - 1 - i)];
    arr[(size - 1 - i)] = temp;
  } // Note: arr[i] == *(arr + i) == i[arr]
} // Therefore, &arr[i] == (arr + i)
```

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.

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

ℹ `cout << &arr[0]`, `cout << arr`, and `cout << &arr` would all print `0x1008`.

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



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.

Pointer Operations

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

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.

```
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
```

Array traversal: arrays can be traversed by index or by pointer.

Traversal By Pointer: Pattern 1

```
int computeRange(int arr[], int N) {
  int* ptr = arr; int* end = (arr + N);
  // end is actually 1-past-the-end
  int* min = arr; int* max = arr;
  while (ptr < end) {
    if (*ptr < *min) { min = ptr; }
    if (*ptr > *max) { max = ptr; }
    ++ptr;
  } // "walk" ptr across arr
  return (*max - *min);
} // also could've used a for-loop
```

Traversal by Pointer: Pattern 2 (C-String Sanitization)

```
void sanitizeUsername(Account *acc, char to_remove) {
  char* ptr1 = acc->username, *ptr2 = acc->username;
  while (*ptr1 && *ptr2) { // while not '\0'
    if (*ptr2 != to_remove) {
      *ptr1 = *ptr2;
      ++ptr1; // ++ptr1 only when a char gets copied
    }
    ++ptr2; // ++ptr2 every time the loop executes
  }
  *ptr1 = '\0'; // null-terminate string when done
} // NOTE: '\0' is the only char considered "false"
```

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.

Special const Type Syntax

```
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 arr_a[2] = {1, 2}; // array of consts
int const arr_b[2] = {3, 4}; // array of consts
```

```
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).

```
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
```

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

```
int x = 2, y = 5;
const int *x_ptr = &x;
int *y_ptr = &y;
int *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 C-Strings and 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) << " " << *(cstr + 1) << " " << (*cstr + 1); // prints "bcd b 98" ('a' == 97)
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

```
#include <fstream> // defines if/ofstreams
int main() {
  ifstream inFS; // or inFS("file.txt");
  inFS.open("file.txt");
  if (!inFS.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
```

Ex 2: Copy One File's Contents to Another

```
#include <fstream>
void copyFile(string file_in, string file_out) {
  // fstreams can use C-strings as file names too
  ifstream inFS(file_in);
  ofstream outFS(file_out);
  string input_str;
  while (inFS >> input_str) {
    outFS << input_str << endl;
  } // could use '\n' instead of endl
}
```

ℹ The insertion `<<` and extraction `>>` operators "stop" at any 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.

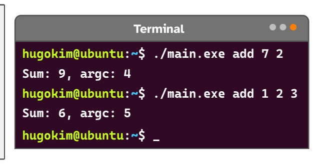
```
#include <sstream> // defines stringstreams
void printPlusOne(istream& is, ostream& os) {
  int num = 0;
  while (is >> num) { os << (++num) << " "; }
} // Note: can't pass or return streams by value
...
istringstream inSS("1 3 5");
ostringstream outSS;
printPlusOne(inSS, outSS);
cout << outSS.str() << 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 the start of a C-strings—so `argv` is passed to `main` as a pointer to an array of pointers to C-strings).

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



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;`

ℹ 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.

Constructors

- The compiler implicitly creates a default ctor iff there are no user-defined ctors (same for dtors).
- 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.
- ⚠ 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

```cpp
class Animal {
private: string name;
public:
  Animal(const string& name_in) // 1-argument ctor
    : name(name_in) { }
  Animal() : Animal("Blank") { } // Default ctor
}; // Default ctor delegates to other ctor

class Bird : public Animal {
private: bool can_fly;
public: Bird(string name_in, bool fly_in)
          : Animal(name_in), can_fly(fly_in) { }
}; // Derived class ctors must call a base 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
```

```cpp
// 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

```cpp
// C-Style Struct
void Triangle_scale(Triangle *t, double s) {
  t->a *= s; // "->" is necessary here
}
```

```cpp
// 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

```cpp
// C-Style Struct
Triangle t1;
Triangle_init(&t1, 3, 4, 5);
```

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

const Function Definition

```cpp
// C-Style Struct
double area(const Triangle *t) { ... }
// const goes inside argument list
```

```cpp
// 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 a top-level or class member function to work properly with custom classes (at least 1 operand must be of class-type).

- ❗ 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)

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

bool IntSet::operator[](int v) const {
  return contains(v);
}
```

<< and == Overload Examples (Top-Level)

```cpp
class Line {...}; // start/end are public members

ostream& operator<<(ostream& os, Line line) {
  return os << line.start << line.end;
} // 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
```

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 `.`/`->`

- ⚠ 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.

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

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

class Derived : public Base {
public:
  void print() {cout << "D" << endl;}
  void printB() { Base::print(); }
};

Derived d;
d.print(); // prints "D"
d.printB(); // prints "B"
d.Base::print(); // prints "B"
Base* b = &d;
b->print(); // prints "B"
```

Access 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).

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

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

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

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

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.

```cpp
class Bird { }; // Base class
class Chicken : public Bird { };
class Duck : public Bird { };
Bird b; Chicken c; Duck d;
b = c; // Legal, but "slices" c's data
Bird* b_ptr = &c; // Good, no slicing
c = b; // ERROR (illegal assignment)
Chicken* c_ptr = &b; // ERROR (downcast)
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`.

```cpp
// Be careful - validity not checked at runtime:
Chicken *cPtr = 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 make it dynamically-bound.

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.

```cpp
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 = 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.

```cpp
class Abst { // Abstract Class
public: virtual void foo() = 0;
}; // Note the lack of empty braces

class Concrete : public Abst {
public: void foo() { cout << "foo"; }
}; // public/private doesn't matter here

Concrete c;
Abst* c_ptr = &c; Abst& c_ref = c; // ok
Abst abst_object; // COMPILE ERROR
c.Abst::foo(); // RUNTIME ERROR (or U.B)
```

- ❗ 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.

Container	Interface Operations - Optimal Implementations are All O(1)					
Stack	`empty`	`size`	`back/top (next)`		`push_back`	`pop_back`
Queue	`empty`	`size`	`front (next)`	`back (last)`	`push_back`	`pop_front`

- 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				
`.size()`	`v[i]`	`.push_back(val)`	`.pop_back()`	`.resize(n)`
`.front()`	`.back()`	`.at(i)`	`.empty()`	`.clear()`

Operation	Unsorted Set	Sorted Set	Stack	Queue	Array	List
`insert/remove`	$O(n)$	$O(n)$	$O(1)^*$	$O(1)^*$	$O(n)$	$O(1)$
`search`	$O(n)$	$O(\log n)$	$O(n)$	$O(n)$	$O(n)$	$O(n)$
`access`	$O(1)$	$O(1)$	$O(n)$	$O(n)$	$O(1)$	$O(n)$

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

```cpp
std::array<int, 4> arr = {-4, 0, 3, 6};
std::vector<int> vec =  {4, 7, 2};
std::set<int> unique = {3,2,2,1}; // {1,2,3}
// Note: can't index into a std::list
std::list<int> values = {1, 2, 3};

// The elements of a map are <key, val> pairs
std::map<string, int> EECS = { {"Bill", 183} };
EECS["Emily"] = 203;
EECS.insert(pair<string, int>("James", 280));
cout << EECS["James"] << endl; // prints 280
```

Useful std::map functions

```cpp
// 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 pair of <Key, T value> into a map
// Returns <iterator, false> if Key in map already
pair<iterator, bool> insert(const Pair_type &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.

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

Class Template Syntax

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

Function Template Syntax

```cpp
template <typename T> // "T" = an arbitrary parameter name
// Note: "class" also works in place of "typename"
T maxValue(const T &valA, const T &valB) {
  return (valB > valA) ? valB : valA; // "?" == conditional
} // This function returns the greater of valA and valB
// Syntax to call it: maxValue<int/double/etc>(...);
```

Templated Class Member Function Syntax

```cpp
template <typename T> // Necessary if outside class body
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.

- `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).
- ⚠ 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	`->,[],++,--,==,!=,<,*it,+n`	`->,[],++,--,==,!=,<,*it,+n`	`++,--,==,!=,*it`	`++,--,==,!=,*it`	`++,--,==,!=,*it`

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

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

Range-Based For Loop (Works on Any Sequence Traversible by Iterator)

```cpp
vector<int> 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
```

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

- In general, use range-based loops to perform an action on each item in a sequence. Don't use them if you need to return an item's index or if you're working with an array that has decayed into a pointer.

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 $O(n^2)$, $O(n^3)$, etc). Big-Θ and Big-Ω represent average and lower bounds, respectively.

$O(1)$	$O(\log n)$	$O(\sqrt{n})$	$O(n)$	$O(n \log n)$, $O(\log(n!))$	$O(n^2)$	$O(n^3)$	$O(2^n)$	$O(3^n)$	$O(n!)$	$O(n^n)$	$O(2^{2^n})$

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: $O(n^2 + n + \log n) = O(n^2)$.

Multiplication: multiply the individual terms' complexities. Ex: $O(n \times \log n) = O(n \log n)$.

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 $O(\log n)$ body is $O(n \log n)$.

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 $O(n^2)$.

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 $O(\log n)$.