

Fundamentals and Machine Model

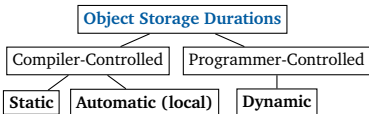
Machine/Memory Model and the Function Call Stack

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: types whose objects 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.

```
1 // Four different ways to initialize an int to 5
2 int a = 5; int b(5); int c{5}; int d = {5};

1 // Explicitly cast an int 'd' to a double 'e'
2 double e = static_cast<double>(d);
```

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 variable can *only* point to an `int`; an `int**` pointer variable can *only* point to an `int*`; and so on. (E.g. attempting to make an `int*` pointer point to a `double` will lead to a compile error.)

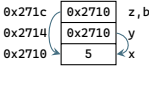
Dereferencing a pointer: getting the object at an address. Note that the star * operator is used both to declare pointers and to dereference them (and the & operator is used both to get an object's address and to declare a reference).

```
1 int x = 3; int y = 4;
2 int* p1 = &x; // p1 initialized to x's address
3 int* p2; // p2 initialized to undefined value
4 p2 = p1; // copies the address stored by p1 to p2
5 p1 = &y; // no star... assigns y's address to p1
6 *p1 = 6; // dereferences p1, now y == 6
7 *p2 = 2; // p2 still points to x, so now x == 2
```

❗ Printing a non-char pointer will print an address. (char pointers are special and get printed as C-strings.)

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

```
1 int x = 5;
2 int* y = &x; // creates pointer to x
3 int* z = y; // creates another pointer to x
4 int* &b = z; // creates reference b to pointer z
5 cout << *b << endl; // Prints 5
6 cout << &y << endl; // prints 0x2714
7 cout << y << endl; // prints 0x2710
8 cout << &(x) << endl; // equiv. to cout << &x
9 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 nullified; to do so, set it equal to `nullptr` (0 or `NULL` also work but are bad style).

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).

❗ Uninitialized references or references-to-non-const that are bound to "literal" values 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) // BUG
2 { return &x; }

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

1 int* returnPtr(int &x)
2 { return &x; } // OK
```

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 themselves 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 the object that a (non-const) pointer points to, while 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] = {1,2,3}; // {1,2,0}
int B[3] = { }; // {0,0,0}
int C[] = {1,2,3}; // 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[]; // 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.

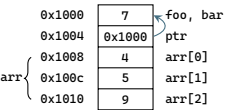
```
1 void add_five(int arr[], int size) {
2     for (int i = 0; i < size; i++) { arr[i] += 5; }
3 } // arr[i] += 5 is equiv. to *(arr + i) += 5

5 int main() {
6     int arr[] = { 10, 20, 30 };
7     add_five(arr, (sizeof(arr) / sizeof(*arr)));
8     cout << arr[1] << endl; // prints 25
9 } // i[arr] is equiv. to arr[i], but bad style
```

Passing `arr` by value passes a pointer to `arr[0]` by value. Also, `arr[i]` is shorthand for pointer arithmetic followed by a dereference, i.e., `arr[i] = *(arr + i)`.

❗ The `sizeof` operator returns the size of an object in *bytes*. In this example, `sizeof(arr)` alone would return 12, not 3.

```
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
7 cout << (&foo + 1) << endl; // prints 0x1004
```



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

```
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]
```

Using the & operator on an array produces a pointer to the entire array, not a pointer to the first element or a pointer to a pointer (& does not require a value, so it doesn't cause decay).

```
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

```
1 int const SIZE = 3;
2 int arr[SIZE] = { -1, 7, 2 };
3 int *ptr = arr;
4 while (*ptr <= arr + SIZE;
5 // int* end is just 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 foo( ); ptr < end; ++ptr) { ... }
```

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

```
1 void sanitize_username(Account *acc, char to_remove) {
2     char *ptr_a = acc->username, *ptr_b = acc->username;
3     while (*ptr_a && *ptr_b) { // while not '\0'
4         if (*ptr_b != to_remove) {
5             *ptr_a = *ptr_b;
6             ++ptr_a; // ++ptr_a only when a char gets copied
7         }
8         ++ptr_b; // ++ptr_b every time the loop executes
9     }
10    *ptr_a = '\0'; // null-terminate string when done
11 }
```

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.

```
1 const int* A[] = { ... }; // ptr-to-const array
1 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, for example, you can assign a `const` pointer to a pointer-to-const, but the converse is *not* true).

```
1 int foo(int* a) { ... }
2 int bar(int b) { ... }
3 int func(const int* c) { ... }
4 const int x = 3;
5 bar(x); func(&x); // both ok
6 int& ref = cref; // ERROR
```

```
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 const char* cstr = "abcd"; // Only works for string literals; use .c_str() on string variables
2 char color[] = "00270C"; // Create 7-element array (including \0) and copy a string literal to it
3 // Note: '\0' is the only char that evaluates to false (useful for traversal-by-pointer loops).
4 cout << cstr << " " << *cstr << " " << &cstr[0] << endl; // prints "abcd a bcd"
5 cout << (cstr + 1) << " " << (cstr + 1) << " " << (cstr + 1) << endl; // prints "bcd bcd" ('a' == 97)
6 string xyz = string(cstr); // Explicitly copy cstring to a string (implicit copy would work too)
```

	Length	Copy Value	Index	Concatenate	Compare
<string>	strlen(cstr);	strcpy(cstr1, cstr2);	cstr[1];	strcat(cstr1, cstr2);	strcmp(cstr1, cstr2);
<string>	str.length();	str1 = str2;	str[1];	str1 += str2;	str1 != str2;

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

```
1 #include <fstream> // defines (if/of)stream objects
2 int main() {
3     ifstream inFS; // could also do inFS("file.txt");
4     inFS.open("file.txt");
5     if (!inFS.is_open()) { return 1; }
6     string my_string; // initialized to empty string
7     while (getline(inFS, my_string)) {
8         cout << my_string << endl;
9     } // could close inFS manually via inFS.close();
10    // inFS also closes when scope ends/main returns
```

Ex 2: Copy One File's Contents to Another

```
1 #include <fstream> // defines stringstream
2 void printPlusOne(const istream& is, ostream& os) {
3     int num = 0;
4     while (is >= num) { os << (++num) << " "; }
5 } // Note: can't pass or return numbers by value
6 ...
7 stringstream inSS("1 3 5");
8 ostreamstream outSS;
9 printPlusOne(inSS, outSS);
10 cout << outSS.str() << endl; // Prints "2 4 6"
```

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.

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 that each point to the start of a C-string—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++) { sum += stoi(argv[i]); }
6         cout << "Sum: " << sum << " ", argv: " << argv << endl;
7     } // pay attention to where the "actual" arguments start
8 } // 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 can't 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 pointer dereferencing 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 structs 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 structs default to public access/inheritance.

Constructors

- 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 is *always* the order they're initialized in.
- 3 Initialization values from a member init. list over-write initializations made during declarations.
- 4 Data members that aren't included in a ctor's member initializer list or initialized at declaration get default-initialized/constructed.
- 5 A delegating ctor must contain a call to the other ctor (and nothing else) in its member init. list.

```
Constructor Definition Example
1 class Animal {
2 private: string name;
3 public:
4   Animal(string name,in) // Non-default ctor
5   : name(name.in) { // Member init. list
6   Animal() // Default ctor (no arguments)
7   : Animal("Blank") { // ctor delegation
8   }; // Note the semicolon here!
9
10 class Bird : public Animal {
11 private: bool has_wings;
12 public: Bird(string name, bool wings.in)
13   : Animal(name), has_wings(wings.in) { }
14 }; // Derived class ctors must call base ctor
15
16 class Duck : public Bird {
17 private: string color;
18 public: Duck(string name, bool wings, string rgb)
19   : Bird(name, wings), color(rgb) { }
20 }; // Calling Bird ctor also calls Animal ctor
21
22 // This is how to define a ctor OUTSIDE of body
23 Duck::Duck(string name, bool wings, string rgb)
24 : Bird(name, wings), color(rgb) { }
```

Nested Classes and Constructors

To initialize a nested class object, initialize it with a valid argument for the nested class's ctor.

Nested class objects in a const class object are also const.

```
1 class Book {
2 public:
3   Book(double price.in)
4   : price(price.in) { }
5 // Note: no default Book ctor
6 private:
7   double price;
8 };
9
10 class Person {
11 public:
12   Person(string& n, double p)
13   : name(n), favBook(p) { }
14 private:
15   string name;
16   Book favBook;
17 };
18
19 class ConstClass {
20 public:
21   ConstClass() { }
22 };
23
24 class NestedClass {
25 public:
26   NestedClass() { }
27 };
28
29 class Outer {
30 public:
31   Outer() { }
32   NestedClass nc;
33 };
34
35 class Inner {
36 public:
37   Inner() { }
38 };
39
40 class Outer {
41 public:
42   Outer() { }
43   Inner i;
44 };
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