CMPS 101
Algorithms and Abstract Data Types
ADTs and Modules in C

Introduction

This document introduces the concepts of Modules and ADTs, and describes how to implement them in the C programming language. If you are completely new to the C language, see the following assignments from CMPS 12B which give a rapid introduction.

> https://classes.soe.ucsc.edu/cmps012b/Spring19/lab3.pdf
> https://classes.soe.ucsc.edu/cmps012b/Spring19/lab4.pdf
> https://classes.soe.ucsc.edu/cmps012b/Spring19/lab5.pdf

Informally, an *Abstract Data Type* (ADT) is a collection of mathematical objects, together with some associated operations on those objects. When an ADT is used in a program, it is usually implemented in its own *module*. A module is a self-contained component of a program having a well-defined *interface* that details its role and relationship to the rest of the program. Why are ADTs necessary? The standard data types provided by most programming languages are not powerful enough to capture the way we think about the higher level objects in our programs. This is why most languages have a type declaration mechanism that allows the user to create high level types as desired. Often the implementation of these high level types gets spread throughout the program, creating complexity and confusion. Errors occur when the legal operations on the high level types are not well defined or are not consistently applied.

Definition

An Abstract Data Type consists of two things:

(1) A set *S* of "mathematical structures", the elements of which are called *states*.
(2) An associated set of operations which can be applied to the states in *S*.

Each ADT *instance* or *object* has a current state that is one of the elements of the set *S*. The operations on *S* fall (roughly) into two categories. *Manipulation procedures* are operations that cause an ADT object to change its state. *Access functions* are operations that return information about an ADT object, without altering its state. From time to time we will consider operations that fall into both categories, or into neither. An ADT is an abstract mathematical entity existing apart from any program or computing device. On the other hand, ADTs are frequently implemented by a program module. We will distinguish between the mathematical ADT and its implementation in a programming language. A single ADT could have many different implementations, all having various advantages and disadvantages.

Example Consider an *Integer Queue*. In this case *S* is the set of all finite sequences of integers, and the associated operations are: Enqueue(), Dequeue(), getFront(), getLength(), and isEmpty(). The meanings of these operations are given below. One possible state for this ADT is (5, 1, -7, 2, -3, 4, 2). (It is recommended that the reader who is unfamiliar with elementary data structures such as queues, stacks, and lists, review sections 10.1 and 10.2 of [CLRS].)

<u>Manipulation procedures</u>	
Enqueue()	Insert a new integer at the back of the queue
Dequeue()	Remove an integer from the front of the queue
<u>Access functions</u>	
getFront()	Return the integer at the front of the queue

getLength()	Return the number of integers in the queue
isEmpty()	Return true if length is zero, false otherwise

Other examples of mathematical structures which could form the basis for an ADT are: sets, graphs, trees, matrices, polynomials, or finite sequences of such structures. In principle, the underlying set *S* could be anything, but typically it is a set of discrete mathematical objects of some kind.

An ADT instance is always associated with a particular history of states, brought about by the application of ADT operations. In our queue example we could have the following sequence starting with the empty state ( ):

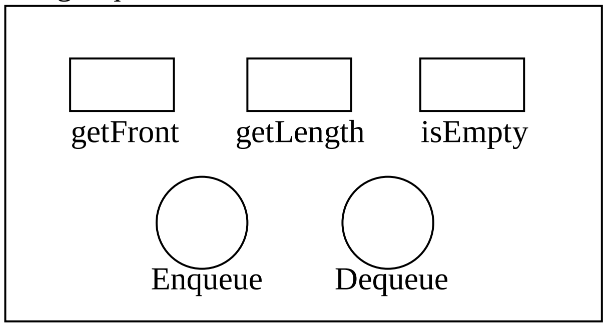
Operation	State
	( )
Enqueue(5)	(5)
Enqueue(1)	(5, 1)
Enqueue(7)	(5, 1, 7)
Dequeue()	(1, 7)
Enqueue(3)	(1, 7, 3)
getLength()	(1, 7, 3)

Observe that if isEmpty() is true for some state, then getFront() and Dequeue() are undefined on that state. One option to deal with this situation would be to make special definitions for Dequeue() and getFront() on an empty queue. We could for instance, define getFront() to return zero on an empty queue, and define Dequeue() to not change its state. Unfortunately, special definitions like these complicate the ADT and can easily lead to errors. A better solution is to establish *preconditions* for each operation indicating exactly when (i.e. to which states) that operation can be applied. Thus a precondition for both getFront() and Dequeue() is: "not isEmpty()". In order for an ADT to be useful, the user must be able to determine if the preconditions for each operation are satisfied. Good ADTs clearly indicate all preconditions for each operation, typically as a sequence of access function calls. Good ADTs may also document their *postconditions*, i.e. conditions which *will be* true after an operation is performed. For example, a postcondition of Enqueue() is "not isEmpty()". ADT operations are analogous to mathematical functions. Preconditions and postconditions in this analogy then define the function's domain and codomain. Only when all operations have been defined, along with all relevant preconditions and postconditions, can we say that an ADT has been fully specified.

We often consider multiple instances of the same ADT. For example, we may speak of several simultaneous integer queue objects. ADT operations should therefore specify which object is being operated on. It is also possible for some operations to refer to multiple objects. We could for instance have an access function called Equals() that operates on two queues and returns true if they are in the same state, and false otherwise. We could have a manipulation procedure called Concatenate() that empties one queue object and places its contents at the back of the another queue object.

It is sometimes helpful to think of an ADT object as being a ‘black box’ equipped with a control panel containing buttons that can be pushed (manipulation procedures), and indicator lights to be read (access functions).

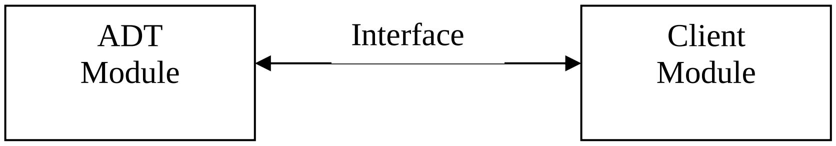
Integer queue



Some texts (including our own), define Dequeue() so as to return the front element, as well as to alter the state of the Queue, making it both an access function and a manipulation procedure. In our example, Dequeue() deletes the element at the front of the queue, but doesn't return a value, making it a pure manipulation procedure, rather than an operation of mixed type. Such changes in the set of ADT operations result in a *different* ADT. As a further example, suppose we implement our Queue by storing integers in an array of fixed size. We should then add an access function called isFull() that returns true if there is room left in the array for another integer, and false otherwise. Enqueue() would then have the precondition "not isFull()". This Queue ADT and our original Queue ADT can both be legitimately called Queues, but they are different ADTs.

Implementing ADTs in C
There is a straightforward way of implementing an ADT in C, once it has been specified. Many modern programming languages (like Python, C++ or Java) are in some sense, made for this purpose. The C language however pre-dates the invention of the ADT concept, so implementing an ADT requires some effort.

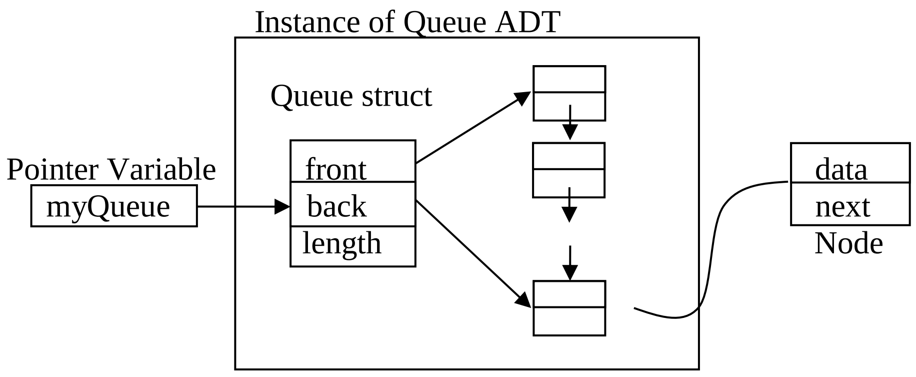
As previously mentioned, a *module* is a part of a program that is isolated from the rest of the program by a well-defined *interface*. We think of ADT modules as providing services (like functions or data types) to *clients*. A client is anything (program, person, computer, another module) that uses a module's services. These services are said to be *exported to* the client or *imported from* the ADT module.



The module concept supports the idea of *information hiding*: clients have no access to a module's implementation details (inside the black box). The client can access a the module's services only through its interface. The purpose of this principle is to reduce the complexity of the client's task by freeing it from the responsibility of knowing how an operation is performed. The client only knows that a given operation will be performed. To the client, a Queue is just a sequence of integers that can be manipulated in certain ways. (Would you drive a car that required you to know (in detail) how the engine works?)

In C, an ADT implementation contains a struct that implements the "mathematical structure". The client is then given a pointer (or *reference*) to this struct. One C function is defined for each of the ADT operations, and each such function takes this reference as an input argument. The reference type is defined in a way that prevents the client from following the pointer to access the interior of the "black box", enforcing the information hiding principle.

In our Queue example, we choose the underlying data structure to be a singly linked list. (Other choices are possible, such as an array.) Thus our C implementation will contain a private struct defining a Node object.



Two more C functions are necessary. One to create new objects (constructor) and one to free memory associated with ADT instances no longer in use (destructor). It is the responsibility of these functions to manage all of the memory inside the "black box", balancing calls to malloc(), calloc() and free().

The Queue ADT implementation module is split into two files: a .c file containing struct and function definitions, and a .h file containing typedefs and prototypes of exported functions. The ADT interface, by definition, consists of exactly that which appears in the .h file. Functions whose prototypes do not appear in this file cannot be accessed from outside the ADT implementation, and are therefore effectively private.

```
// Queue.h
typedef struct QueueObj* Queue;

// Constructor-Destructor
Queue newQueue(void);
void freeQueue(Queue* pQ);

// Access functions
int getFront(Queue Q);
int getLength(Queue Q);
int isEmpty(Queue Q);

// Manipulation procedures
void Enqueue(Queue Q, int data);
void Dequeue(Queue Q);

// Other functions
void printQueue(Queue Q, FILE* out);
```

The file Queue.h defines a pointer called Queue, to a struct called QueueObj, which is not defined in this file. The client module will `#include` Queue.h, so the compiler will recognize calls to the exported functions. The client can also declare variables of type Queue and define functions that take Queue arguments. Notice however that the client cannot dereference a Queue variable, since the struct to which it points is not defined in Queue.h. This is how data hiding is accomplished in C. The definition of QueueObj appears in the next file.

```
// Queue.c
#include<stdio.h>
#include<stdlib.h>
#include "Queue.h"

// private struct, not exported
typedef struct NodeObj{
   int data;
   struct NodeObj* next;
} NodeObj;

// private reference type, not exported
typedef NodeObj* Node;

Node newNode(int data) {...}    // fill in
void freeNode(Node* pN) {...}  // fill in

// Private QueueObj struct, constructor-destructor
typedef struct QueueObj{
   Node front;
   Node back;
   int length;
} QueueObj;

Queue newQueue(void){
   Queue Q = malloc(sizeof(QueueObj));
   Q->front = Q->back = NULL;
   Q->length = 0;
   return(Q);
}

void freeQueue(Queue* pQ) {...}    // fill in

// Access functions
int getFront(Queue Q) {...}        // fill in
int getLength(Queue Q) {...}       // fill in
int isEmpty(Queue Q) {...}         // fill in

// Manipulation procedures
void Enqueue(Queue Q, int data) {...}  // fill in
void Dequeue(Queue Q) {...}   // fill in

// Other functions
void printQueue(Queue Q, FILE* out) {...}  // fill in
```

Notice that the types `NodeObj` and `Node` as well as functions `newNode()` and `freeNode()`, do not appear in the file Queue.h, and are therefore not available to the client. Exporting these items would give the client access to the inside of the black box, violating the data hiding principle. Notice also that another public function called `printQueue()` is included in both Queue.h and Queue.c. This function prints the state of a Queue object to a FILE handle (which may be `stdout`.)

We have so far left aside the question of what to do if the client calls an ADT operation in such a way as to violate one of its preconditions. We adopt the following policy in all ADT implementations.

(1) All ADT operations must state their preconditions in a comment block which appears both before the function prototype in the .h file, and before the function definition in the .c file
(2) All ADT operations must check that those preconditions are satisfied before proceeding with nominal execution.
(3) If a precondition is violated, the ADT should cause the program to terminate with an error message giving: the name of the ADT module, the name of the ADT operation, and the particular precondition that was violated.

An ADT implementation should be fully tested in isolation before it is used in a larger program. The following program serves this purpose.

```
// QueueTest.c
#include<stdio.h>
#include<stdlib.h>
#include "Queue.h"

int main(int argc, char* argv[]){
   // Call all of the above functions at least once
   return(EXIT_SUCCESS);
}
```

Exercise Complete the definitions of the above functions by replacing { . . .} where it appears with some appropriate C code. A solution to this exercise will be posted on the webpage. See the handout entitled "More ADTs in C" for additional details before you do this exercise.

Some may (correctly) argue that our Integer Queue in C is not really a general purpose queue at all, and we should really write a Queue of "anythings". The problem is that C's type declaration mechanism is not advanced enough to properly deal with this issue. There are two possible solutions. The safer one is to edit your Integer Queue to be a Queue of whatever you need a Queue of. Simply changing the appropriate instances of `int` to the new type will create a ready-made Queue ADT. This change can be accomplished efficiently by defining the type `QueueElement` in the .h file as

```
typedef int QueueElement
```

The type `QueueElement` is used to refer to the things that are stored in a Queue. This methodology lets you change the element type by editing a single line of code. (We follow this procedure in the exercise solution posted on the webpage.)

This simple fix has the drawback that if you want `int` Queues and `double` Queues in the same program, then you need two different Queue modules. A more powerful (and difficult) technique is to make `QueueElement` a generic pointer, by doing

```
      typedef void* QueueElement
```

Now the Queue module can handle Queues holding any kind of pointer. The danger here is that a client might get confused and call `getFront()` or `Enqueue()` on the wrong kind of pointer. Using `void*` means that you will not find out about this problem until you run the program and get a segmentation fault. These types of pointer errors can be very difficult to debug. Given these warnings, I would recommend the safer solution for those students who do not have extensive C experience.