Modules in C

- A **module** is a set of type, variable, and function definitions that are only accessible through a defined **interface**
- The programming lanugage C has **no module system**
- Conventions allow emulation of a module system to a certain extent (Textbook 14.5)
- A module *Name* is represented by two files:
  - The **header file** *Name*`.h` contains type definitions, prototypes of exported functions, and ***(only if really necessary)*** `extern` declarations of exported global variables.
  - The **implementation file** *Name*`.c` contains the definitions of the exported functions (and exported global variables), and `static` definitions of non-exported functions and global variables.

How Does a Computer Run Your Program?

- You edit `myprogram.c`
- You **compile:** `cc -o myprogram myprogram.c`
  - **Preprocessor** generates **preprocessed source** (`myprogram.i`)
  - **Compiler proper** generates **assembly program** (`myprogram.s`)
  - **Assembler** generates **object code** (`myprogram.o`)
  - **Linker** generates **executable** (`myprogram`)
- You "**run**" it: `./myprogram`
  - **Operating system** generates a new process
  - **Dynamic linker** resolves references to shared libraries
  - **Loader** generates **executable in-memory image**
  - **CPU** runs machine code

Compilation of Multi-File Programs

- You edit `myprogram.c`, `utils.h`, `utils.c`
- `cc -c myprogram.c`
  `cc -c utils.c` (irrelevant which is compiled first)
  - **Preprocessor** generates **preprocessed source** (`myprogram.i`,`utils.i`), typically each including `utils.h`
  - **Compiler proper** generates **assembly modules** (`myprogram.s`, `utils.s`)
  - **Assembler** generates **object code** (`myprogram.o`,`utils.o`)
- `cc -o myprogram myprogram.o utils.o -lm`
  - **Linker** generates **executable** (`myprogram`)
  - Included object files: `myprogram.o`, `utils.o`
  - Library files indicated on command line: `/usr/lib/libm.a` or `/usr/lib/libm.so`
  - The C library: `/usr/lib/libc.a` or `/usr/lib/libc.so`

Linked Lists — Header File

```
/* CharList.h  ---  Linked lists containing character data */

typedef struct CharListNodeStruct {
   char data;
   struct CharListNodeStruct * nextPtr;  /* struct label necessary! */
 } CharListNode;

typedef CharListNode * CharList;

/* Access functions */
void printCharList(CharList p);             /* printing as raw character sequence */
void insert(CharList * p, char val);      /* insertion: recursive implementation */
void insertIter(CharList * p, char val); /*                iterative implementation */
void delete(CharList * p, char val);      /* deletion: recursive implementation */
void deleteIter(CharList * p, char val); /*                iterative implementation */
```

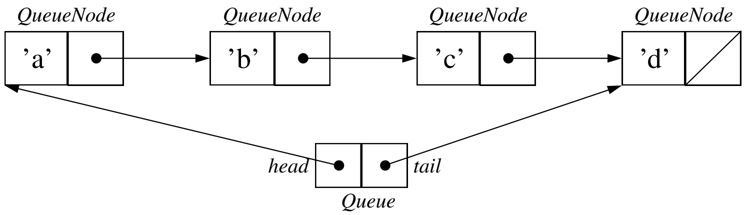
Linked Lists — *main()*

```
#include <stdio.h>                                   /* CharListTest.c */
#include <stdlib.h>
#include <stdbool.h>
#include "CharList.h"

int main() {
  CharList list = NULL;
  char c;
  bool inserting = 1;
  while((c = getchar()) ≠ EOF) {
    if ( c == '\n' ) continue;
    if ( c == '\t' ) {inserting = !inserting; continue; }
    if (inserting) { printf("Inserting “%c”\n", c); fflush(stdout);
                     insert(&list, c);                          }
    else {           printf("Deleting “%c”\n", c); fflush(stdout);
                     delete(&list, c);                          }
    printf("Current list: “"); printCharList(list); printf("”\n");
  }
  return 0;
```


Queues

For $O(1)$ appending-at-the-end we need $O(1)$ access to the end:




```
typedef struct QueueNodeStruct {                     /* queue.h */
      char data;
      struct QueueNodeStruct * nextPtr;  /* struct label necessary! */
  } QueueNode;

typedef struct {
      QueueNode * head, * tail;
  } Queue;
```


Queues — Implementation File

```
#include <stdio.h>                                   /* queue.c */
#include <stdlib.h>
#include <stdbool.h>
#include "queue.h"

void printQueue( Queue * q ) {
  QueueNode * n = q→head;
  while( n ≠ NULL ) {
    printf("%c", n→data);
    n = n→nextPtr;
  }
}
```


Queues — Initialisation and Construction

```
void initQueue(Queue * q) { /* q is assumed to be non-NULL */
   q→head = NULL;
   q→tail = NULL;
}
```

This can be used to initialise local *Queue* variables.

Dynamically allocated *Queue*s are initialised by the constructor:

```
Queue * newQueue() {
   Queue * q = malloc( sizeof(Queue) );
   if ( q == NULL )  { fprintf(stderr, "newQueue: out of memory!\n"); }
   else              { initQueue(q); }
   return q;
}
```

Queues — Adding an Item at the End

```
/* pass by reference — q is assumed to be non-NULL! */
bool enqueue( Queue * q, char c ) {
  QueueNode * n = malloc( sizeof(QueueNode) );
  if ( n == NULL ) {
    fprintf(stderr, "enqueue: out of memory!\n");
    return false;
  }
  else {
    n→data = c;
    n→nextPtr = NULL;
    if ( q→head == NULL )  { q→head = n; }
    else                     { q→tail→nextPtr = n; }
    q→tail = n;
    return true;
  }
}
```


Queues — Removing an Item from the Head

```
bool isEmpty( Queue * q ) { return q→head == NULL; }

/* pass by reference — q is assumed to be non-NULL and non-empty! */
char dequeue( Queue * q ) {
  QueueNode * oldHead = q→head;
  char c  = oldHead→data;
  q→head = oldHead→nextPtr;
  if ( q→head == NULL )
    { q→tail = NULL; }
  free( oldHead );
  return c;
}
```


List Operations, Complexity, and List Datatypes

Data Structure	Singly-linked list	Singly-linked list with tail pointer	Doubly-linked list with tail pointer
Insert at head	$O(1)$	$O(1)$	$O(1)$
Delete at head	$O(1)$	$O(1)$	$O(1)$
Insert at tail	$O(n)$	$O(1)$	$O(1)$
Concatenation	$O(n)$	$O(1)$	$O(1)$
Delete at tail	$O(n)$	$O(n)$	$O(1)$
Search	$O(n)$	$O(n)$	$O(n)$
Ordered insertion	$O(n)$	$O(n)$	$O(n)$
Typical datatype	**Stack**	**Queue**	**Deque**

Trees

- In the context of ***undirected graphs***, a **tree** is a graph where for **any two nodes** there is **exactly one path** connecting them.
- In the context of ***directed graphs***, a **tree** is a connected graph where every node has indegree at most one.
- As ***inductively defined data structure***, a **tree** is
  - either the **empty tree**
  - or a **node** containing some data and having some number of **successor trees**

  An important example are **terms:** A term is
  - either a variable v
  - or a constant c
  - or the application $f(t_1, \ldots, t_k)$ of a k-ary function symbol to k terms

  ⇒ structural representations of programs, formulae, sentences, …
- Important as implementation of sets and partial functions: **search trees**

Binary Trees: Type Definition

A **binary tree** with *int* data is

- either the empty tree (NULL)
- or (pointer to) a node with an *int* data field and two successor trees.

```
typedef struct TreeNodeStruct {
    struct TreeNodeStruct *leftPtr;    // pointer to left subtree
    int data;                          // node value
    struct TreeNodeStruct *rightPtr;   // pointer to right subtree
} TreeNode;

typedef TreeNode * Tree;
```


Tree Files

Also in Tree.h:

```
#include <stdbool.h>
```

```
/* Tree.c */
#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include "Tree.h"
```


Binary Trees: Construction

```
Tree MkBranch(Tree left, int value, Tree right) {
   TreeNode * result = malloc( sizeof( TreeNode ) );
   if ( result == NULL )
      fprintf(stderr, "MkBranch(%d): no memory available.\n", value);
   else {
      result->data = value;
      result->leftPtr = left;
      result->rightPtr = right;
   }
   return result;
}
```

```
int main() {
  Tree t1 = MkBranch( MkBranch( MkBranch (NULL, 7, NULL), 3, NULL)
                    , 6
                    , MkBranch( MkBranch (NULL, 4, NULL), 5
                              , MkBranch (NULL, 2, NULL))          );
  ...
```


Binary Trees: Ordered Insertion

In a **binary search tree** without duplicates, for every node *n* with data *d*,

- the data of all nodes in the **left** subtree of *n* are **less than** *d*;
- the data of all nodes in the **right** subtree of *n* are **greater than** *d*.

```
void treeInsert( Tree * t, int value )
{
  if ( *t == NULL ) { *t = MkBranch( NULL, value, NULL ); }
  else {
    if ( value < (*t)->data ) {
      treeInsert( &( (*t)->leftPtr ), value );
    }
    else if ( value > (*t)->data ) {
      treeInsert( &( (*t)->rightPtr ), value );
    }
    else {} /* value == (*t)->data — ignore duplicate values */
  }
}
```

Binary Trees: Ordered Insertion, Iterative

```
void treeInsertIter( Tree * t, int value )
{
  while ( *t ≠ NULL && value ≠ (*t)→data ) {
    if ( value < (*t)→data ) {
      t = &( (*t)→leftPtr );
    }
    else /* value > (*t)→data */ {
      t = &( (*t)→rightPtr );
    }
  }
  if ( *t == NULL ) { *t = MkBranch( NULL, value, NULL ); }
  else {} /* value == (*t)→data — ignore duplicate values */
}
```


Traversals

```
void inOrder( Tree t ) {
  if ( t ≠ NULL ) { inOrder( t→leftPtr );
                    printf( "%3d", t→data );
                    inOrder( t→rightPtr );    }
}

void preOrder( Tree t ) {
  if ( t ≠ NULL ) { printf( "%3d", t→data );
                    preOrder( t→leftPtr );
                    preOrder( t→rightPtr );   }
}

void postOrder( Tree t ) {
  if ( t ≠ NULL ) { postOrder( t→leftPtr );
                    postOrder( t→rightPtr );
                    printf( "%3d", t→data );   }
}
```


Tree Size

Simple recursive function:

```
int treeSize( Tree t ) {
  if ( t == NULL ) return 0;
  else return treeSize( t→left ) + 1 + treeSize ( t→right );
}
```

More complicated approach: updating a counter as side-effect:

```
void treeAddSizeToCounter( Tree t, int * count ) {
  if ( t == NULL ) return;
  else { (*count)++;
         treeAddSizeToCounter( t→left, count );
         treeAddSizeToCounter( t→right, count );
  }
}
int treeSize2( Tree t ) {
  int count = 0;
  treeAddSizeToCounter( t, &count );
  return count;
}
```


Tree Membership

Recursive version:

```
bool treeMember( Tree t, int q ) {
  if ( t == NULL ) return false;
  if ( q < t→data ) return treeMember ( t→left, q);
  if ( q > t→data ) return treeMember ( t→right, q);
  return true;                     // because here q == t->data
}
```

Transforming tail recursion into iteration:

```
void treeAddSizeToCounter( Tree t, int * count ) {
bool treeMemberIter( Tree t, int q ) {
  while ( t ≠ NULL && q ≠ t→data )
    if ( q < t→data ) t = t→left;
    else              t = t→right;
  return t ≠ NULL;                 // because then  q == t->data
}
```

Preparing Deletion: Cutting Off the Largest Node

Specification:

- The result is a one-node tree consisting of the node containing the largest value in *t* before the call
- *t* loses only that node, and is still an ordered binary tree after the call

```
Tree cutOffLargestNode(Tree * t) {
 Tree result;
 if ( *t == NULL ) return NULL;       /* refine specification! */
 else if ( (*t)→rightPtr ≠ NULL )   /* not yet found */
   return cutOffLargestNode( &( (*t)→rightPtr ) );
 else { /* ( (*t)→rightPtr == NULL ) — found largest node */
   result = *t;                     /* remembered largest node */
   *t = result→leftPtr;             /* redirected in-edge */
   result→leftPtr = NULL;           /* deleted out-edge */
   return result;
 }
}
```


Ordered Binary Trees: Deleting

```
void treeDelete( Tree * t, int value ) {
 Tree delNode;
 while ( *t ≠ NULL && value ≠ (*t)→data )
   if ( value < (*t)→data ) t = &( (*t)→leftPtr );
   else                     t = &( (*t)→rightPtr );
 if ( *t == NULL ) return;
 else { /* value == (*t)→data */
   delNode = *t;
   if      ( (*t)→leftPtr == NULL )  *t = (*t)→rightPtr;
   else if ( (*t)→rightPtr == NULL ) *t = (*t)→leftPtr;
   else { /* two succesors */
     delNode = cutOffLargestNode( &( (*t)→leftPtr ) );
     (*t)→data = delNode→data;
   }
   free( delNode );
 }
}
```


Stacks

- Also called **LIFO stacks** — **L**ast **I**n, **F**irst **O**ut
- Model-theoretically equivalent to lists
- Usual implementation: (singly) linked lists
- **Different Interface:** Insertion, inspection, and deletion all happen only at one end — the "**top**" of the stack
  - Test for empty stacks:

    `bool isEmpty( Stack s );`
  - Pushing an item on the top of the stack — **void** does not report out-of-memory errors!

    `void push( Stack * s, int n );`
  - "Popping" the top element from a **non-empty** stack — ***precondition!***

    `int pop( Stack * s ):`

Stacks — Implementation

```
typedef struct StackNodeStruct {
   int data;
   struct StackNodeStruct * nextPtr; /* struct label necessary! */
 } StackNode;

typedef StackNode * Stack;
```

Stack Interface: Insertion, inspection, and deletion all happen at the "**top**":

- Test for empty stacks:

  `bool isEmpty( Stack s );`
- Pushing an item on the top of the stack — false reports out-of-memory errors.

  `bool push( Stack * s, int n );`
- "Inspecting" the top element from a **non-empty** stack — ***precondition!***

  `int top( Stack s );`
- "Popping" (**side-effect!**) the top element from a **non-empty** stack

  `int pop( Stack * s );`

Stacks — Exercise

```
typedef struct StackNodeStruct {                    /* stack.h */
    int data;
    struct StackNodeStruct * nextPtr;  /* struct label necessary! */
  } StackNode;

typedef StackNode * Stack;

bool isEmpty( Stack s );
int  top( Stack s );
bool push( Stack * s, int n );
int  pop( Stack * s );
```

- What is missing from the interface?
- Provide an implementation file.
- Design and implement a "reverse Polish notation" calculator using a separate stack module.