Data Structures
Data Structures

- Queues
  - Queuing System Models
  - Queue Data Structures
  - A Queue Example
- Trees
  - Binary Trees
  - Tree Traversals
    - Inorder, preorder, postorder
- Stacks
  - A Stack Example
- Hashing
- Static Hashing
- Linear probing
- Chaining
Simple Queuing Model

Arrivals → Queue → Server
Router Node

Router Buffer

Server

Outgoing Link

packet

packet

15

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WPI Systems Programming: Data Structures
Performance Metrics
(General Definitions)

- **Utilization** :: the percentage of time a device is busy servicing a “customer”.
- **Throughput** :: the number of jobs processed by the “system” per unit time.
- **Response time** :: the time required to receive a response to a request (round-trip time).
- **Delay** :: the time to traverse from one end to the other in a system.
12.6 Queues

Queues

- Are very common structures in operating systems and computer networks.
- The abstraction in system queues is of customers queued with one customer in service.
- Customers are placed in the queue First-in, first-out (FIFO).
- Customers are removed from the head of the queue structure. When modeling a server, the customer at the head of the queue is in service.
- Customers are inserted at the back (or tail) of the queue.
- Queues can model either finite or infinite buffer space.
Round Robin Queuing

Round Robin Queue

expired time slice

1
2
3
n

I G X X

D

S
12.6 Queues

- Queues
  - When modeling a finite buffer, when the buffer is full, an arriving customer is dropped (normally from the tail). This is known as a drop-tail queue.

- Queue data structure operations:
  - Insert or enqueue
  - Remove or dequeue
Fig. 12.12 Queue graphical representation

```
headPtr

H   D   …   Q

tailPtr
```
Fig. 12.15 enqueue operation
Fig. 12.15 dequeue operation

(a) *headPtr
   R → A → D → N
   *tailPtr

(b) *headPtr
   R → A → D → N
   *tailPtr
   *tempPtr

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/* Fig. 12.13: fig12_13.c
   Operating and maintaining a queue */

#include <stdio.h>
#include <stdlib.h>

/* self-referential structure */
struct queueNode {
    char data;          /* define data as a char */
    struct queueNode *nextPtr; /* queueNode pointer */
}; /* end structure queueNode */

typedef struct queueNode QueueNode;
typedef QueueNode *QueueNodePtr;

/* function prototypes */
void printQueue( QueueNodePtr currentPtr );
int isEmpty( QueueNodePtr headPtr );
char dequeue( QueueNodePtr *headPtr, QueueNodePtr *tailPtr );
void enqueue( QueueNodePtr *headPtr, QueueNodePtr *tailPtr, char value );
void instructions( void );

/* function main begins program execution */
int main( void )
{
    QueueNodePtr headPtr = NULL; /* initialize headPtr */
    QueueNodePtr tailPtr = NULL; /* initialize tailPtr */
    int choice;                  /* user's menu choice */
    char item;                   /* char input by user */
Fig 12.13 Processing a Queue

```c
instructions(); /* display the menu */
printf( "? " );
scanf( "%d", &choice );

/* while user does not enter 3 */
while ( choice != 3 ) {

    switch( choice ) {

    /* enqueue value */
    case 1:
        printf( "Enter a character: " );
        scanf( "\n%c", &item );
        enqueue( &headPtr, &tailPtr, item );
        printQueue( headPtr );
        break;

    /* dequeue value */
    case 2:
        /* if queue is not empty */
        if ( isEmpty( headPtr ) ) {
            item = dequeue( &headPtr, &tailPtr );
            printf( "%s has been dequeued.\n", item );
        } /* end if */

        printQueue( headPtr );
        break;
```
```c
default:
    printf( "Invalid choice.\n\n" );
    instructions();
    break;
}

} /* end switch */

printf( "? " );
scanf( "%d", &choice );
} /* end while */

printf( "End of run.\n" );

return 0; /* Indicates successful termination */
}

} /* end main */

/* Display program instructions to user */
void instructions( void )
{
    printf( "Enter your choice:\n"
            " 1 to add an item to the queue\n"
            " 2 to remove an item from the queue\n"
            " 3 to end\n" );
} /* end function instructions */
```
# Fig 12.13 Processing a Queue

To insert a node into the queue, memory must first be allocated for that node.

Queue nodes are always inserted at the tail, so there is no need to search for the node’s place.

If the queue is empty, the inserted node becomes the new head in addition to the new tail.

Inserted node becomes the new tail.

---

To insert a node into the queue, memory must first be allocated for that node.

Queue nodes are always inserted at the tail, so there is no need to search for the node’s place.

If the queue is empty, the inserted node becomes the new head in addition to the new tail.

Inserted node becomes the new tail.

---

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/* remove node from queue head */

char dequeue( QueueNodePtr *headPtr, QueueNodePtr *tailPtr )
{
    char value;           /* node value */
    QueueNodePtr tempPtr; /* temporary node pointer */

    value = ( *headPtr )->data;
    tempPtr = *headPtr;
    *headPtr = ( *headPtr )->nextPtr;

    /* if queue is empty */
    if ( *headPtr == NULL ) {
        *tailPtr = NULL;
    } /* end if */

    free( tempPtr );

    return value;
} /* end function dequeue */

/* Return 1 if the list is empty, 0 otherwise */

int isEmpty( QueueNodePtr headPtr )
{
    return headPtr == NULL;
} /* end function isEmpty */
/* Print the queue */

void printQueue( QueueNodePtr currentPtr )
{
    /* if queue is empty */
    if ( currentPtr == NULL ) {
        printf( "Queue is empty.\n\n" );
    } /* end if */
    else {
        printf( "The queue is:\n" );
        /* while not end of queue */
        while ( currentPtr != NULL ) {
            printf( "%c --> ", currentPtr->data );
            currentPtr = currentPtr->nextPtr;
        } /* end while */
        printf( "NULL\n\n" );
    } /* end else */
} /* end function printQueue */
Enter your choice:
  1 to add an item to the queue
  2 to remove an item from the queue
  3 to end

? 1
Enter a character: A
The queue is:
A --> NULL

? 1
Enter a character: B
The queue is:
A --> B --> NULL

? 1
Enter a character: C
The queue is:
A --> B --> C --> NULL

? 2
A has been dequeued.
The queue is:
B --> C --> NULL

(continued on next slide…)
B has been dequeued.
The queue is:
C --> NULL

C has been dequeued.
Queue is empty.

Queue is empty.

Invalid choice.

Enter your choice:
1 to add an item to the queue
2 to remove an item from the queue
3 to end

End of run.
12.7 Trees

- Tree nodes contain two or more links.
  - All other data structures considered thus far have only contained one link.
- Binary trees
  - All nodes contain two links.
    - None, one, or both of which may be NULL
  - The root node is the first node in a tree.
  - Each link in the root node refers to a child.
  - A node with no children is called a leaf node.
  - A node can only be inserted as a leaf node in a binary search tree (i.e., a tree without duplicates.)
Common Programming Error 12.8

- Not setting to `NULL` the links in leaf nodes of a tree can lead to runtime errors.
- Remember, since tree traversals are normally recursive, this error can be 'deeply embedded'.
12.7 Trees

- Binary trees
  - The key value for nodes in the left subtree are less than the key value in the parent.
  - The key value for nodes in the right subtree are greater than the key value in the parent.
  - This data structure facilitates duplicate elimination!
  - Fast searches - for a balanced tree, maximum of $\log_2 n$ comparisons.
Fig. 12.18 Binary search tree

![Binary search tree diagram]

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1. Inorder traversal:

- visit the nodes in **ascending order** by key value.

1.1 Traverse the left subtree with an inorder traversal

1.2 Visit the node (process the value in the node, i.e., print the node value).

1.3 Traverse the right subtree with an inorder traversal.
The Three Standard Tree Traversals

2. Preorder traversal:

2.1 Visit the node (process the value in the node, i.e., print the node value).
2.2 Traverse the left subtree with a preorder traversal.
2.3 Traverse the right subtree with a preorder traversal.
3. Postorder traversal:

3.1 Traverse the left subtree with a postorder traversal.
3.2 Traverse the right subtree with a postorder traversal.
3.3 Visit the node (process the value in the node, i.e., print the node value).
/* Fig. 12.19: fig12_19.c */
Create a binary tree and traverse it
preorder, inorder, and postorder */
#include <stdio.h>
#include <stdlib.h>
#include <time.h>

/* self-referential structure */
struct treeNode {
    struct treeNode *leftPtr; /* pointer to left subtree */
    int data; /* node value */
    struct treeNode *rightPtr; /* pointer to right subtree */
}; /* end structure treeNode */

typedef struct treeNode TreeNode; /* synonym for struct treeNode */
typedef TreeNode *TreeNodePtr; /* synonym for TreeNode* */

/* prototypes */
void insertNode( TreeNodePtr *treePtr, int value );
void inOrder( TreeNodePtr treePtr );
void preOrder( TreeNodePtr treePtr );
void postOrder( TreeNodePtr treePtr );

/* function main begins program execution */
int main( void )
{
    int i; /* counter to loop from 1-10 */
    int item; /* variable to hold random values */
    TreeNodePtr rootPtr = NULL; /* tree initially empty */

Each node in the tree contains a data element and a pointer to the left and right child nodes.
srand( time( NULL ) );
printf( "The numbers being placed in the tree are:\n" );

/* insert random values between 0 and 14 in the tree */
for ( i = 1; i <= 10; i++ ) {
    item = rand() % 15;
    printf( "%d", item);
    insertNode( &rootPtr, item);
} /* end for */

/* traverse the tree preOrder */
printf( "\n\nThe preOrder traversal is:\n" );
preOrder( rootPtr );

/* traverse the tree inOrder */
printf( "\n\nThe inOrder traversal is:\n" );
inOrder( rootPtr );

/* traverse the tree postOrder */
printf( "\n\nThe postOrder traversal is:\n" );
postOrder( rootPtr );

return 0; /* indicates successful termination */
} /* end main */
To insert a node into the tree, memory must first be allocated for that node.

If the inserted node’s data is less than the current node’s, the program will attempt to insert the node at the current node’s left child.

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/* data to insert is greater than data in current node */
#else if ( value > (*treePtr)->data ) {
    insertNode( &( *treePtr )->rightPtr , value );
} /* end else if */
#else /* duplicate data value ignored */
    printf( "dup" );
} /* end else */
} /* end function insertNode */

/* begin inorder traversal of tree */
void inOrder( TreeNodePtr treePtr ) {
  /* if tree is not empty then traverse */
  if ( treePtr != NULL ) {
    inOrder( treePtr->leftPtr );
    printf( "%3d", treePtr->data );
    inOrder( treePtr->rightPtr );
  } /* end if */
} /* end function inOrder */

/* begin preorder traversal of tree */
void preOrder( TreeNodePtr treePtr ) {
  /* begin preorder traversal of tree */
  if ( treePtr != NULL ) {
    inOrder( treePtr->leftPtr );
    printf( "%3d", treePtr->data );
    inOrder( treePtr->rightPtr );
  } /* end if */
} /* end function preOrder */

If the inserted node’s data is greater than the current node’s, the program will attempt to insert the node at the current node’s right child.

The inorder traversal calls an inorder traversal on the node’s left child, then prints the node itself, then calls an inorder traversal on the right child.
The preorder traversal prints the node itself, then calls a preorder traversal on the node’s left child, then calls a preorder traversal on the right child.

The postorder traversal calls a postorder traversal on the node’s left child, then calls a postorder traversal on the right child, then prints the node itself.
12.5 Stacks

- Stack
  - New nodes are added and removed only at the top of the stack.
  - The classical analogy is a dishes stacker found in restaurants.
  - Last-in, first-out (LIFO) devices.
  - The bottom of stack is indicated by a link member to NULL.
  - Essentially, a constrained version of a linked list.
  - Stacks are important in computer languages because it is the data structure for calling and returning from function or subroutine calls.
12.5 Stacks

- Stack operations
  - **push**
    - Adds a new node to the top of the stack.
  - **pop**
    - Removes a node from the top of the stack.
    - Stores the popped value.
    - Returns true if pop was successful.
Fig. 12.10 push operation
Fig. 12.10 pop operation
/* Fig. 12.8: fig12_08.c
   dynamic stack program */
#include <stdio.h>
#include <stdlib.h>

/* self-referential structure */
struct stackNode {
    int data;          /* define data as an int */
    struct stackNode *nextPtr; /* stackNode pointer */
}; /* end structure stackNode */

typedef struct stackNode StackNode; /* synonym for struct stackNode */
typedef StackNode *StackNodePtr; /* synonym for StackNode* */

/* prototypes */
void push( StackNodePtr *topPtr, int info );
int pop( StackNodePtr *topPtr );
int isEmpty( StackNodePtr topPtr );
void printStack( StackNodePtr currentPtr );
void instructions( void );

/* function main begins program execution */
int main( void )
{
    StackNodePtr stackPtr = NULL; /* points to stack top */
    int choice; /* user's menu choice */
    int value; /* int input by user */
    instructions(); /* display the menu */
    printf( "? ");
A Stack Example

```c
scanf("%d", &choice);

/* while user does not enter 3 */
while (choice != 3) {

    switch (choice) {

     /* push value onto stack */
     case 1:
         printf("Enter an integer: ");
         scanf("%d", &value);
         push(&stackPtr, value);
         printStack(stackPtr);
         break;

     /* pop value off stack */
     case 2:
         /* if stack is not empty */
         if (!isEmpty(stackPtr)) {
             printf("The popped value is %d.\n", pop(&stackPtr));
         }
         printStack(stackPtr);
         break;

     default:
         printf("Invalid choice.\n\n");
         instructions();
         break;
    }
}
```

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} /* end switch */

printf( "? " );
scanf( "%d", &choice );
} /* end while */

printf( "End of run.\n" );

return 0; /* indicates successful termination */

} /* end main */

/* display program instructions to user */
void instructions( void )
{
    printf( "Enter choice:\n"
    "1 to push a value on the stack\n"
    "2 to pop a value off the stack\n"
    "3 to end program\n" );
} /* end function instructions */

/* Insert a node at the stack top */
void push( StackNodePtr *topPtr, int info )
{
    StackNodePtr newPtr; /* pointer to new node */
    newPtr = malloc( sizeof( StackNode ) );

To insert a node into the stack, memory must first be allocated for that node
A Stack Example

/* insert the node at stack top */
if ( newPtr != NULL ) {
    newPtr->data = info;
    newPtr->nextPtr = *topPtr;
    *topPtr = newPtr;
} /* end if */
else { /* no space available */
    printf( "%d not inserted. No memory available.\n", info );
} /* end else */

} /* end function push */

/* Remove a node from the stack top */
int pop( StackNodePtr *topPtr )
{
    StackNodePtr tempPtr; /* temporary node pointer */
    int popValue; /* node value */

    tempPtr = *topPtr;
    popValue = ( *topPtr )->data;
    *topPtr = ( *topPtr )->nextPtr;
    free( tempPtr );

    return popValue;
} /* end function pop */

Stack nodes are always inserted at the top, so there is no need to search for the node’s place
Inserted node becomes the new top

Stack nodes are always removed from the top, so there is no need to search for the node’s place
Second node becomes the new top

Free the memory of the popped node

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/* Print the stack */

void printStack( StackNodePtr currentPtr )
{

    /* if stack is empty */
    if ( currentPtr == NULL ) {
        printf( "The stack is empty.\n\n" );
    } /* end if */
    else {
        printf( "The stack is:\n" );

        /* while not the end of the stack */
        while ( currentPtr != NULL ) {
            printf( "%d --> ", currentPtr->data );
            currentPtr = currentPtr->nextPtr;
        } /* end while */

        printf( "NULL\n\n" );
    } /* end else */

} /* end function printList */

/* Return 1 if the stack is empty, 0 otherwise */

int isEmpty( StackNodePtr topPtr )
{

    return topPtr == NULL;

} /* end function isEmpty */
A Stack Example

Enter choice:
1 to push a value on the stack
2 to pop a value off the stack
3 to end program

? 1
Enter an integer: 5
The stack is:
5 --> NULL

Enter an integer: 6
The stack is:
6 --> 5 --> NULL

? 1
Enter an integer: 4
The stack is:
4 --> 6 --> 5 --> NULL

? 2
The popped value is 4.
The stack is:
6 --> 5 --> NULL

(continued on next slide…)
A Stack Example

(continued from previous slide…)

? 2
The popped value is 6.
The stack is:
5 --> NULL

? 2
The popped value is 5.
The stack is empty.

? 2
The stack is empty.

? 4
Invalid choice.

Enter choice:
1 to push a value on the stack
2 to pop a value off the stack
3 to end program
? 3
End of run.
Hashing

- Two classic examples of the use of hashing are:
  - {old example}
- Building a symbol table for a compiler, whereby a symbol table is similar to a dictionary, but with a set of name-attribute pairs.
- Standard operations on any symbol table are:
  1. Determine if the name is in the table.
  2. Retrieve the attributes of that name.
  3. Modify the attributes of that name.
  4. Insert a new name and its attributes in the table.
Tracking Flows in a Router Node

Router Buffer

{new example}
In static hashing, identifiers (names) are stored in a fixed size table called a hash table.

A hash function $f(x)$ is used to determine the location of an identifier $x$ in the table.

The hash table is stored into sequential memory locations that are partitioned into $b$ buckets. Each bucket has $s$ slots.
Hash Table
Hash Function

- A good hash function is easy to compute and minimizes bucket collisions (i.e., it should be unbiased).
- A good hash function hashes \( x \) such that \( x \) has an equal chance of hashing into any of the \( b \) buckets. Namely, the hash function should uniformly distribute the symbols into the \( b \) buckets.
- Examples of hash function are: mid-square, division \( f(x) = x \mod M \) and folding.
We need to initialize table where all slots are empty.

```c
Void init_table (element ht[])
{
    int i;
    for (i = 0; I < TABLE-SIZE; i++)
        ht[i].key[0] = NULL;
}
```
Hash Table with Linear Probing

There are four possibilities after hashing $x$ into a table bucket:

1. The bucket contains $x$. \{x is in the table already\}

2. The bucket is empty.

3. The bucket contains a nonempty entry other than $x$. \{a bucket collision\}. Here we either examine next slot or the next bucket.

4. We have exhausted all table memory and have wrapped around to the ‘home bucket’.
After running for awhile identifiers will tend to cluster and coalesce. Note, now the search time is likely to grow with each new addition to the symbol table.

Result = Bad Performance.

This is the motivation for implementing hash buckets using chaining (each bucket is implemented as a linked list with a header node).
Example of Chain insert into a hash table with a BAD hash function

[0] -> add -> asp -> attitude
[1] -> NULL
...
[9] -> jack -> jumbo
[10] -> king -> kinicki
...
[25] -> zac -> zebro -zits
More Advanced Hashing

- Dynamic Hashing
- Double Hashing
Summary of Data Structures

- Connected queuing computer systems with queuing data structures. Basic operations: enqueue and dequeue.
- Introduced tree terminology and structures
  - Binary Trees
  - Tree Traversals
    - Inorder, preorder, postorder
- Stacks
  - A Stack Example
- A quick look at Hashing including:
  - Static Hashing
  - Hash functions
  - Linear probing
  - Chaining (linked lists)