Lecture 7

- Review

- More about Pointers
  - Pointers to Pointers
  - Pointer Arrays
  - Multidimensional Arrays

- Data Structures
  - Stacks
  - Queues
  - Application: Calculator

Review: Compound data types

- **struct** -structure containing one or multiple fields, each with its own type (or compound type)
  - size is combined size of all the fields, padded for byte alignment
  - anonymous or named
- **union** -structure containing one of several fields, each with its own type (or compound type)
  - size is size of largest field
  - anonymous or named
- Bit fields -structure fields with width in bits
  - aligned and ordered in architecture-dependent manner
  - can result in inefficient code

Review: Compound data types

- Consider this compound data structure:

```
struct foo {
  short s;
  union {
    int i ;
    char c;
  } u;
  unsigned int flag _s : 1;
  unsigned int flag_u : 2;
  unsigned int bar ;
};
```

- Assuming a 32-bit x86 processor, evaluate
  `sizeof(struct foo)`

Review: Compound data types

- Consider this compound data structure:

```
struct  foo  {
   short  s;                                  ← 2 bytes
   union  {                                   ← 4 bytes,
      int   i ;                               4 byte-aligned
      char  c;
   }  u;
   unsigned  int  flag _s   :  1;             ← bit fields
   unsigned  int  flag_u    :  2;
   unsigned  int  bar ;                       ← 4 bytes,
};                                            4 byte-aligned
```

- Assuming a 32-bit x86 processor, evaluate
  sizeof(**struct** foo)

Review: Compound data types

- How can we rearrange the fields to minimize the size of **struct** foo?

Review: Compound data types

- How can we rearrange the fields to minimize the size of **struct** foo?
- Answer: order from largest to smallest:

```
struct foo {
  union {
    int i;
    char c;
  } u;
  unsigned int bar;
  short s;
  unsigned int flag_s : 1;
  unsigned int flag_u : 2;
};
```

sizeof(**struct** foo) $= 12$

Review: Linked lists and trees

- Linked list and tree dynamically grow as data is added/removed
- Node in list or tree usually implemented as a **struct**
- Use `malloc()`, `free()`, etc. to allocate/free memory dynamically
- Unlike arrays, do not provide fast random access by index (need to iterate)

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Pointer review

- Pointer represents address to variable in memory
- Examples:

  int *pn; – pointer to `int`

  struct div_t *pdiv; – pointer to structure `div_t`

- Addressing and indirection:

```
double  pi   =  3.14159;
double  *ppi   = &pi  ;
printf (  "pi = %g\n",  *ppi );
```

- Today: pointers to pointers, arrays of pointers, multidimensional arrays

Pointers to pointers

- Address stored by pointer also data in memory
- Can address location of address in memory – pointer to that pointer

```
int n = 3;
int *pn = &n;      /* pointer to n */
int **ppn = &pn;   /* pointer to address of n */
```

- Many uses in C: pointer arrays, string arrays

Pointer pointers example

- What does this function do?

```
void swap(int **a, int **b) {
   int *temp = *a;
   *a = *b;
   *b = temp;
}
```

Pointer pointers example

- What does this function do?

```
void swap( int **a, int **b) {
    int *temp = *a;
    *a= *b;
    *b = temp ;
}
```

- How does it compare to the familiar version of swap?

```
void swap( int *a, int *b) {
    int temp = *a;
    *a= *b;
    *b = temp ;
}
```

Pointer arrays

- Pointer array – array of pointers

  `int *arr [20];` – an array of pointers to `int`'s

  `char *arr[10];` – an array of pointers to `char`'s

- Pointers in array can point to arrays themselves

  `char *strs [10];` – an array of `char` arrays (or strings)

Pointer array example

- Have an array `int arr [100];` that contains some numbers
- Want to have a sorted version of the array, but not modify `arr`
- Can declare a pointer array `int *sorted_array[100];` containing pointers to elements of `arr` and sort the pointers instead of the numbers themselves
- Good approach for sorting arrays whose elements are very large (like strings)

Pointer array example

Insertion sort:

```
/* move previous elements down until
   insertion point reached */
void shift_element(unsigned int i) {
  int *pvalue;
  /* guard against going outside array */
  for (pvalue = sorted_array[i]; i &&
        *sorted_array[i-1] > *pvalue; i--) {
    /* move pointer down */
    sorted_array[i] = sorted_array[i-1];
  }
  sorted_array[i] = pvalue; /* insert pointer */
}
```

Pointer array example

Insertion sort (continued):

```
/* iterate until out-of-order element found;
   shift the element, and continue iterating */
void insertion_sort(void) {
  unsigned int i, len = array_length(arr);
  for (i = 1; i < len; i++)
    if (*sorted_array[i] < *sorted_array[i-1])
      shift_element(i);
}
```

String arrays

- An array of strings, each stored as a pointer to an array of chars
- Each string may be of different length

```
char str1[] = "hello";      /* length = 6 */
char str2[] = "goodbye";    /* length = 8 */
char str3[] = "ciao";       /* length = 5 */
char * strArray[] = {str1, str2, str3};
```

- Note that strArray contains only pointers, not the characters themselves!

Multidimensional arrays

- C also permits multidimensional arrays specified using [] brackets notation:

  int world [20][30]; is a 20x302-D array of int's

- Higher dimensions possible:

  char bigcharmatrix [15][7][35][4]; – what are the dimensions of this?

- Multidimensional arrays are rectangular; pointer arrays can be arbitrary shaped

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More data structures

- Last time: linked lists
- Today: stack, queue
- Can be implemented using linked list or array storage

The stack

- Special type of list -last element in (push) is first out (pop)
- Read and write from same end of list
- The stack (where local variables are stored) is implemented as a *gasp* stack

Stack as array

- Store as array buffer (static allocation or dynamic allocation):

```
int stack_buffer[100];
```

- Elements added and removed from end of array; need to track end:

```
int itop =0; /* end at zero => initialized for empty stack */
```

Stack as array

- Add element using void push(int);

```
void push ( int elem) {
   stack _buffer[itop++] = elem;
}
```

- Remove element using int pop(void);

```
int pop ( void ) {
   if ( itop > 0)
      return stack _buffer[ --itop ];
   else
      return 0; /* or other special value */
}
```

- Some implementations provide int top(void); to read last (top) element without removing it

Stack as linked list

- Store as linked list (dynamic allocation):

```
struct s_listnode {
   int element ;
   struct s_listnode * pnext;
};
```

```
struct s_listnode *stack_buffer = NULL;
```
– start empty

- "Top" is now at front of linked list (no need to track)

Stack as linked list

- Add element using **void** push(**int**);

```
void push ( int elem) {
    struct s_listnode *new_node = /* allocate new node */
      ( struct s_listnode *) malloc ( sizeof ( struct s_listnode ))
    new_node->pnext = stack _buffer ;
    new_node->element = elem ;
    stack _buffer = new_node;
}
```

- Adding an element pushes back the rest of the stack

Stack as linked list

- Remove element using **int** pop(**void**);

```
int pop ( void ) {
  if (stack_buffer) {
    struct s_listnode *pelem = stack_buffer;
    int elem = stack_buffer->element;
    stack_buffer = pelem->pnext;
    free(pelem); /* remove node from memory */
    return elem;
  } else
    return 0; /* or other special value */
}
```

- Some implementations provide **int** top(**void**); to read last (top) element without removing it

The queue

- Opposite of stack -first in (enqueue), first out (dequeue)
- Read and write from opposite ends of list
- Important for UIs (event/message queues), networking (Tx, Rx packet queues)
- Imposes an ordering on elements

Queue as array

- Again, store as array buffer (static or dynamic allocation);

  ```
  float queue_buffer[100];
  ```

- Elements added to end (rear), removed from beginning (front)
- Need to keep track of front and rear:

  ```
  int  ifront  = 0, irear = 0;
  ```

- Alternatively, we can track the front and number of elements:

  ```
  int  ifront  = 0, icount = 0;
  ```

- We’ll use the second way (reason apparent later)

Queue as array

- Add element using **void** enqueue(**float**);

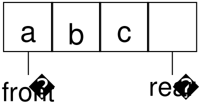
```
void enqueue ( float elem) {
    if ( icount < 100) {
        queue_buffer[ifront+icount] = elem;
        icount ++;
    }
}
```

- Remove element using **float** dequeue(**void**);

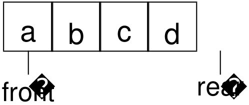
```
float dequeue ( void ) {
    if ( icount > 0) {
        icount --;
        return queue_buffer[ ifront++];
    } else
        return 0.; /* or other special value */
}
```

Queue as array

- This would make for a very poor queue! Observe a queue of capacity 4:



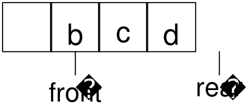
- Enqueue `'d'` to the rear of the queue:



The queue is now full.

Queue as array

- Dequeue `'a'`:



- Enqueue `'e'` to the rear: where should it go?
- Solution: use a circular (or “ring”) buffer
  - `'e'` would go in the beginning of the array

Queue as array

- Need to modify **void** enqueue(**float**); and **float** dequeue(**void**);
- New **void** enqueue(**float**);:

```
void   enqueue ( float    elem)    {
    if    ( icount     <   100)    {
        queue_buffer[(ifront+icount) % 100]                    =   elem;
        icount ++;
    }
}
```

Queue as array

- New float dequeue(void);:

```
float dequeue ( void ) {
  if ( icount > 0) {
    float elem = queue_buffer[ ifront ];
    icount --;
    ifront ++;
    if ( ifront == 100)
      ifront = 0;
    return elem ;
  } else
    return 0.; /* or other special value */
}
```

- Why would using “front” and “rear” counters instead make this harder?

Queue as linked list

- Store as linked list (dynamic allocation):

```
struct s_listnode {
    float element;
    struct s_listnode * pnext;
};
```

```
struct s_listnode *queue_buffer = NULL;
```
– start empty

- Let front be at beginning – no need to track front
- Rear is at end – we should track it:

```
struct s_listnode *prear = NULL;
```

Queue as linked list

- Add element using **void** enqueue(**float**);

```
void enqueue ( float elem) {
    struct s_listnode *new_node = /* allocate new node */
        ( struct s_listnode *) malloc ( sizeof ( struct s_listnode ))
    new_node->element = elem ;
    new_node->pnext = NULL; /* at rear */
    if ( prear )
        prear ->pnext = new_node;
    else /* empty */
        queue_buffer = new_node;
    prear = new_node;
}
```

- Adding an element doesn’t affect the front if the queue is not empty

Queue as linked list

- Remove element using **float** dequeue(**void**);

```
float   dequeue ( void )  {
    if  ( queue_buffer )    {
        struct   s_listnode    *pelem  =  queue_buffer ;
        float   elem  =  queue_buffer  ->element ;
        queue_buffer     =  pelem ->pnext ;
        if   (pelem   ==  prear )   /* at  end  */
            prear   = NULL;
        free(pelem);      /* remove  node  from  memory  */
        return    elem ;
    }  else
        return    0.;   /* or  other  special   value   */
}
```

- Removing element doesn’t affect rear unless resulting queue is empty

A simple calculator

- Stacks and queues allow us to design a simple expression evaluator
- Prefix, infix, postfix notation: operator before, between, and after operands, respectively

Infix	Prefix	Postfix
A+B	+AB	AB+
A*B-C	-*ABC	AB*C-
(A + B) * (C -D)	*+AB-CD	AB+CD-*

- Infix more natural to write, postfix easier to evaluate

Infix to postfix

- "Shunting yard algorithm" -Dijkstra (1961): input and output in queues, separate stack for holding operators
- Simplest version (operands and binary operators only):
  1. dequeue token from input
  2. if operand (number), add to output queue
  3. if operator, then pop operators off stack and add to output queue as long as
     - top operator on stack has higher precedence, or
     - top operator on stack has same precedence and is left-associative

     and push new operator onto stack
  4. return to step 1 as long as tokens remain in input
  5. pop remaining operators from stack and add to output queue

Infix to postfix example

- Infix expression: A + B * C -D

Token	Output queue	Operator stack
A	A	
+	A	+
B	AB	+
*	AB	+*
C	ABC	+*
-	ABC*+	-
D	ABC*+D	-
(end)	ABC*+D-	

- Postfix expression: A B C * + D -
- What if expression includes parentheses?

Example with parentheses

- Infix expression: (A + B) * (C -D)

Token	Output queue	Operator stack
(		(
A	A	(
+	A	(+
B	AB	(+
)	AB+	
*	AB+	*
(	AB+	*(
C	AB+C	*(
-	AB+C	*(-
D	AB+CD	*(-
)	AB+CD-	*
(end)	AB+CD-*	

- Postfix expression: A B + C D -*

Evaluating postfix

- Postfix evaluation very easy with a stack:
  1. dequeue a token from the postfix queue
  2. if token is an operand, push onto stack
  3. if token is an operator, pop operands off stack (2 for binary operator); push result onto stack
  4. repeat until queue is empty
  5. item remaining in stack is final result

Postfix evaluation example

- Postfix expression: 3 4 + 5 1 -*

Token	Stack
3	3
4	34
+	7
5	75
1	751
-	74
*	28
(end)	answer = 28

- Extends to expressions with functions, unary operators
- Performs evaluation in one pass, unlike with prefix notation

Summary

Topics covered:

- Pointers to pointers
  - pointer and string arrays
  - multidimensional arrays
- Data structures
  - stack and queue
  - implemented as arrays and linked lists
  - writing a calculator

6.087 Practical Programming in C
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