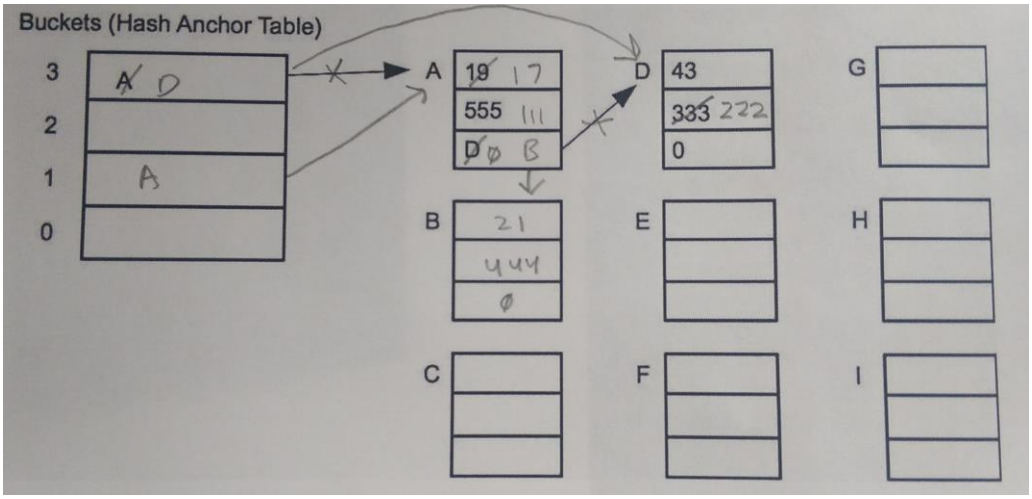
Problem 1 (2 parts, 32 points) **Hash Tables**

Part A (16 points) Consider an open hash table composed of a four-bucket table, with each bucket containing a variable length list. Each list entry has three slots <key, value, next> corresponding to the three word groupings in the entries section. The hash function is `key mod four`. Inserted entries are *appended to the end* of a bucket list. The initial state of the hash table is shown. List elements as allocated by malloc are shown in the figure. The symbol to the left of each list element (A, B, C,...) is the address returned by malloc. Entries that are freed are maintained in a last-in-first-out (LIFO) free list.

Execute the access trace shown in the table below. For ease of representation, you may use the allocated blocks in any order. Show pointers both by their (symbolic) value, and with an arrow. If a value changes, cross it out and place the new value to the right. If a pointer changes, also place an x on the corresponding arrow, and draw the new arrow.



Hash Table Access Trace

#	op	key	value	#	op	key	value
1	insert	43	222	3	insert	17	111
2	remove	19	n/a	4	insert	21	444

Part B (16 points) Consider a *different* hash table that contains a total of **270 entries**, evenly distributed across the hash table buckets. The buckets each containing an **unsorted singly linked list** of entries. An application performs lookups of various keys: **3 out of 4** lookups find the key in the hash table. The keys that are found are distributed throughout the buckets so that each position is equally likely to be where a key is found. The number of key comparisons required for the average lookup in the hash table is **17.25**.

Average bucket length = L. #Buckets = 270 entries/L.
Average # key comparisons = 17.25 = (3/4)(L+1)/2 + (1/4)L = (3L+3+2L)/8
138 = 5L+3, so L = 27.

How many buckets are in this hash table? **270 entries/27 entries/bucket = 10 buckets.**

This hashtable is **resized** so that the average number of key comparisons per lookup is **6**. The resized hash table still has a total of 270 entries that are evenly distributed across the buckets, which are unsorted singly linked lists. The same application is run in which 3 out of 4 lookups find the key in the resized hash table.

Average bucket length = L. #Buckets = 270 entries/L.
Average # key comparisons = 6 = (3/4)(L+1)/2 + (1/4)L = (3L+3+2L)/8
48 = 5L+3, so L = 9.

How many buckets are in the resized hash table? **270 entries/9 entries/bucket = 30 buckets.**

Problem 2 (2 parts, 36 points) **Doubly Linked Lists**

Consider a doubly linked list that is implemented using the following struct definitions.

```
typedef struct llnode_t {
    int              data;
    struct llnode_t* previous;
    struct llnode_t* next;
}LLNode;

typedef struct dll_t {
    struct llnode_t* head;
    struct llnode_t* tail;
    struct llnode_t* current;
} DLinkedList;
```

NOTE: These are the same as the structs used in Project 2-1, except the `data` field in `llnode_t` is of type `int` and the `DLinkedList` has no `size` field.

Part A (12 points) The following C function **`Insert_Node_After`** is buggy. It is supposed to take a pointer to an `LLNode` and insert it after the `current` node in the doubly linked list pointed to by the input parameter `DLL`. It should return 0 if the current node is `NULL`, otherwise return 1. DLL's `current` field should not change. What is the bug and what is the bug fix (show code modifications to the right)?

```
int Insert_Node_After (LLNode *N, DLinkedList *DLL) {
  if(DLL->current == NULL){
    return 0;
  }else{
    LLNode *C = DLL->current;
    N->previous = C;
    N->next = C->next;
    (C->next)->previous = N;
    C->next = N;
    return 1;
  }
}
```

// Show the bug fix here:

/* Replace the assignment statement in gray with the following statement. */

```
if (DLL->tail == C)
   DLL->tail = N;
else
    (C->next)->previous = N;
```

Description of the bug: **When current node is the tail, `(C->next)` is `NULL`, so `C->next)->previous` will cause an invalid memory access. This function also does not update `DLL`'s tail.**

Part B (24 points) The C function `Concatenate` takes two pointers (`DLL1` and `DLL2`) to two doubly linked lists. Complete this function to append `DLL2` to the end of `DLL1`. When the function returns, `DLL1` should contain all of its original nodes followed by the nodes of `DLL2` (all nodes should be in the same order as in the original lists). `DLL1`'s `current` should point to the head of the resulting list. Be sure to handle the cases where `DLL1` and/or `DLL2` are empty. Also, free up the struct pointed to by `DLL2`.

```
void Concatenate(DLinkedList* DLL1, DLinkedList* DLL2){
  if (DLL1->head == NULL){
    DLL1->head = DLL2->head;
    DLL1->tail = DLL2->tail;
  }
  else if (DLL2->head != NULL) {
    (DLL1->tail)->next = DLL2->head;
    (DLL2->head)->previous = DLL1->tail;
    DLL1->tail = DLL2->tail;
  }
  free(DLL2);
  DLL1->current = DLL1->head;
}
```

Problem 3 (4 parts, 32 points) **Heap Management**

Consider a memory allocator (malloc and free), such as described in class. Inside the C-code for the allocator, `unsigned *heapPtr` is the address of the next word that could be allocated in the heap, and `unsigned **freePtr` is the address of the first block (or object) on the free list (and the word at the address of each block on the free list is a pointer to the next block on the free list). The allocator uses a **best fit** strategy with an **unsorted** free list, and never splits blocks.

addr	value	addr	value	addr	value	addr	value	addr	value	addr	value
8000	8	**8032**	20	**8064**	4	**8096**	8048	**8128**	8	**8160**	0
8004	8072	**8036**	0	**8068**	12	**8100**	8104	**8132**	8004	**8164**	0
8008	4	**8040**	43	**8072**	8088	**8104**	4	**8136**	4	**8168**	22
8012	16	**8044**	12	**8076**	8144	**8108**	2	**8140**	12	**8172**	7000
8016	8072	**8048**	8096	**8080**	8	**8112**	12	**8144**	8004	**8176**	12
8020	8052	**8052**	12	**8084**	4	**8116**	0	**8148**	427	**8180**	41
8024	8132	**8056**	8	**8088**	0	**8120**	4	**8152**	8	**8184**	40
8028	8116	**8060**	8116	**8092**	16	**8124**	30	**8156**	0	**8188**	0

Suppose `heapPtr` = 8156 and `freePtr` = 8144. Consider each part below **independently**.

Free list: 8144 (12) –> 8004 (8) –> 8072 (12) –> 8088 (4).

a) (5) How many **blocks and useable bytes** are on the free list? blocks = **4** bytes = **36**

b) (9) What value would be returned by the call **`malloc(5);`** **8004**

Which (if any) values in the above map would be changed by the call in (b)?

addr **8144** value **8072** addr____ value_____ addr____ value_____ No change (✓) _____
(fill in the address/value pairs above. There may be more pairs than needed.)

Fill in the values at this point: `heapPtr` = **8156** `freePtr`= **8144**

c) (9) What value would be returned by the call **`malloc(18);`** **8160**
Which (if any) values in the above map would be changed by this call?

addr **8156** value **20** addr_____ value_____ addr_____ value_____ No change (✓) _____
Fill in the values at this point: `heapPtr` = **8180** `freePtr`= **8144**

d) (9) Which (if any) values in the above map would be changed by the call **`free(8016)`**?

addr **8016** value **8144** addr_____ value_____ addr_____ value_____ No change (✓) _____
Fill in the values at this point: `heapPtr` = **8156** `freePtr`= **8016**