This exam is based on the final exam given in Fall 2018. The class was taught by Cynthia Lee. This was a 3-hour paper exam.

Problem 1: Floating Point Representation (10pts)

A normalized IEEE 32-bit float is stored as the following bit pattern:

`N EEEEEEEE SSSSSSSSSSSSSSSSSSSSSSS`

where N is the sign bit (1 if negative), E is the 8-bit exponent (with a bias of 127), and S is the 23-bit significand, with an implicit leading "1".

Beyoncé and Jay-Z set up two bank accounts, one for each of their twins, but instead of using IEEE 32-bit floats to represent the account balances, they created a new made-up "minifloat" as a fittingly "mini" way to represent the account balances. A minifloat is structured the same as an IEEE float, but is 8 bits instead of 32, with 1 sign bit, 4 exponent bits, and 3 mantissa bits, and an exponent bias of 7.

(a) (3pts) Twin A's account balance is stored as the minifloat **`0 1110 010`**. What is the corresponding (simplified) decimal number that this represents?

(b) (3pts) Twin B's account balance is stored as the minifloat **`0 1011 001`**. What is the corresponding (simplified) decimal number that this represents?

(c) (4pts) After much thought, they decide to merge the two bank accounts together. The bank correctly performs minifloat addition to get the summed balance of **`0 1110 011`**, but this seems off to Beyoncé and Jay-Z. What is the corresponding (simplified) decimal number that this represents? Why is this the resulting total balance? Why do or don't you predict that this would have been an issue if they had used regular IEEE 32-bit floats instead?

Problem 2: Memory Diagram (10pts)

For this problem, you will draw a memory diagram of the state of memory as it would exist at the end of the execution of this code:

```
struct wakanda *shuri = malloc(2 * sizeof(struct wakanda));
shuri[0].king = 5;
shuri[0].army = malloc(8);
shuri[1].army = &(shuri[0].king);
int *panther =  shuri[0].army;
shuri[1].king = shuri[0].king + 1;
shuri[0].army = shuri[0].army + 1;
*(shuri[0].army) = 7;
```

```
struct wakanda {
   int *army;
   int king;
};
```

Instructions:

- Place each item in the appropriate segment of memory (stack, heap).
- Please write array index labels (0, 1, 2, ...) next to each box of an array, in addition to any applicable variable name label. (With the array index labels, it doesn't matter if you draw your array with increasing index going up, down, or sideways.)
- Draw strings as arrays (series of boxes), with individual box values filled in appropriately and array index labels as described above.
- Draw structs as a series of boxes, one box per struct field. (You may assume for this problem that no padding is added to structs.)
- Take care to have pointers clearly pointing to the correct part of an array.
- Leave boxes of uninitialized memory blank.
- NULL pointer is drawn as a slash through the box, and null character is drawn as `'\0'`.

Stack | Heap

Problem 3: Pointers and Generics (12pts)

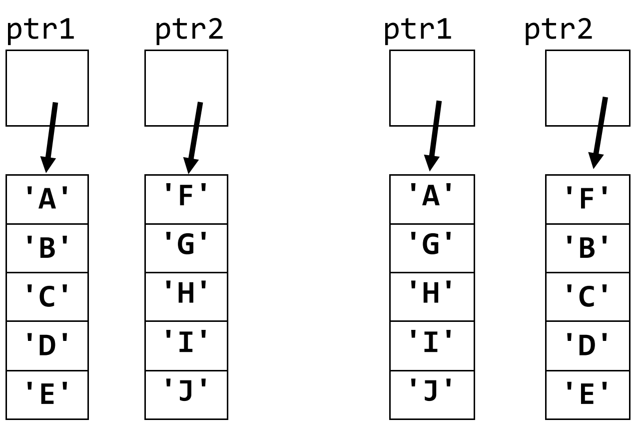
Recall our generic `swap` function from class (reproduced below). It is used to make two values trade places in memory, and is commonly used in sorting arrays. There's a right way to call this swap function in normal circumstances, but we're asking you to use it a bit "creatively" to achieve particular results. Here are some important constraints:

- As shown below, the third argument to `swap` is the return value of `sizeof`. Complete it with the name of a standard type.
- Do not move/change any memory outside the boxes shown in the diagram.
- Casting pointers is ok.

```
void swap(void *a, void *b, size_t sz) {
    char tmp[sz];
    memcpy(tmp, a, sz);
    memcpy(a, b, sz);
    memcpy(b, tmp, sz);
}
```

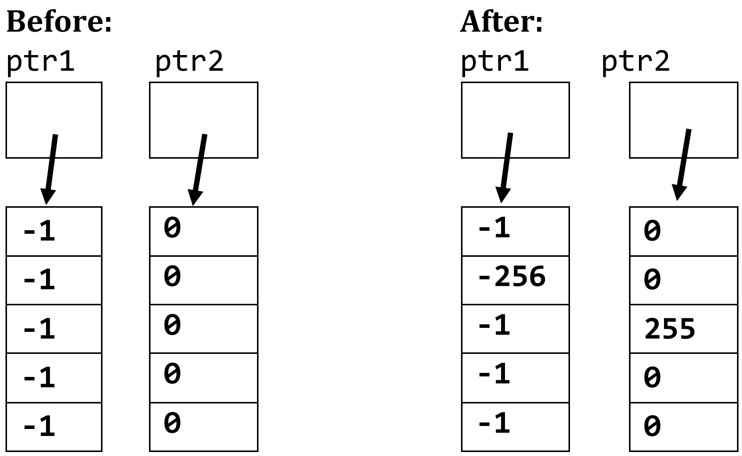
(a) (5pts) Complete the `mixup1` function to create this before and after result.

Before: **After:**




```
void mixup1(char *ptr1, char *ptr2) {
        swap(                    ,
                                 ,
             sizeof(             ));
}
```

Now consider the following before and after diagram, where `ptr1` and `ptr2` are `int *`s:



To help you think about how to solve this one, lets first look at the hexadecimal versions of the two new numbers that appear in the "after."

(b) (1pt) Write -256 in hexadecimal (32-bit):

(c) (1pt) Write 255 in hexadecimal (32-bit):

(d) (5pts) With those values in mind, now complete the `mixup2` function to create this before and after result. (Note: you do not need to be concerned with "endian-ness", or byte order – any endianness will be accepted).

```
void mixup2(int *ptr1, int *ptr2) {

        swap(                    ,
                                 ,
             sizeof(          ));
}
```

Problem 4: Assembly (23pts)

Consider the following code, generated by `gcc` with the usual `-Og` and other settings for this class:

```
0000000000400612 <vp>:
  400612:       push   %rbp
  400613:       push   %rbx
  400614:       sub    $0x8,%rsp
  400618:       mov    %edi,%ebp
  40061a:       mov    %rsi,%rbx
  40061d:       mov    %rsi,%rdi
  400620:       callq  400490 <strlen@plt>
  400625:       lea    (%rax,%rax,2),%edi
  400628:       cmp    $0xffffffef,%ebp
  40062b:       jbe    400632 <vp+0x20>
  40062d:       jmp    400652 <vp+0x40>
  40062f:       shr    $0x2,%edi
  400632:       cmp    $0x6,%edi
  400635:       ja     40062f <vp+0x1d>
  400637:       cmp    $0xff,%ebp
  40063d:       jbe    400646 <vp+0x34>
  40063f:       callq  4005f3 <pass_final_level>
  400644:       jmp    40065c <vp+0x4a>
  400646:       mov    $0x0,%eax
  40064b:       callq  4005d6 <explode_bomb>
  400650:       jmp    40065c <vp+0x4a>
  400652:       mov    $0x0,%eax
  400657:       callq  4005d6 <explode_bomb>
  40065c:       lea    0x3(%rbx),%rax
  400660:       add    $0x8,%rsp
  400664:       pop    %rbx
  400665:       pop    %rbp
  400666:       retq
```

(a) (17pts) Fill in the C code below so that it is consistent with the above x86-64 code. Your C code should fit the blanks as shown, so do not try to squeeze in additional lines or otherwise circumvent this (this may mean slightly adjusting the syntax or style of your initial decoding guess to an equivalent version that fits). **All constants of type signed/unsigned `int` must be written in decimal**. Your C code should not include any casting. The signatures for two functions called in the code are provided for your reference.

```
void explode_bomb();
void pass_final_level(unsigned int x);

char *vp(unsigned int aaron, char *burr)
{
    // see part (c)
    unsigned int leslie = strlen(burr) * [                    ];

    if ( [                              ] ) {

        while (leslie > [                    ] ) {

            //see part (c)
            [                  ] /= [                  ];
        }

        if (aaron >= 256) {
            [                                        ];

        } else {
            [                                        ];

        }
    } else {
        explode_bomb();
    }

    return [                                        ];
}
```

(b) (2pts) The assembly code includes several "push" and "pop" instructions. What kind of registers are being pushed (and popped), and why is `gcc` required to push and pop them, given how those registers are used in the body of the function?

(c) (2pts) The C code includes a multiply and a divide (marked with comments "`see part (c)`"), but there is no multiply (`imul`) or divide instruction in the assembly code. Which instructions are used instead (name both), and why would `gcc` generate the assembly code this way?

(d) (2pts) Is it possible to provide a value for `aaron` that would allow this function to complete **without** calling `explode_bomb`? (Check box for **one**.) ☐ **YES** ☐ **NO**

If **yes**, give such a value for `aaron`. If **no**, explain the constraints that prevent it.

Problem 5: Heap Allocator (24pts)

You are writing code for an allocator that uses a block header and maintains an explicit free list. Implementation details of this allocator include:

- All requests are rounded up to a multiple of 16-bytes and all returned pointers are aligned to 16-byte boundaries. The minimum payload size is 16 bytes.
- The header is 16 bytes as:
  - a `size_t` (8 bytes) storing the payload size, expressed as a **count of 8-byte words**
  - an unsigned long (8 bytes), 1 if block is in-use, 0 if free
- The allocator maintains an explicit free list as a doubly-linked list stored in the payload. A global variable points to the **payload** of a free block (or NULL if there are no free blocks).
- The **first** 8 payload bytes of each free block store a “next” pointer to the **payload** of another free block. The last free block on the list stores NULL as its “next.”
- The **next** 8 payload bytes of each free block store a “previous” pointer to the **payload** of another free block. The first free block on the list stores NULL as its “previous.”

Here is an example heap after a few requests have been serviced (box sizes not to scale):

0x20	0x28	0x30	0x50	0x58	0x60	0x68	0x70	0x78	0x80	0x90	0x98	0x100	0x108	
nwords 4	used 1		nwords 2	used 0	0x0	0x100	nwords 2	used 1		nwords 6	used 0	0x60	0x0	

This segment starts at address `0x20` and ends at `0x138` (`0x137` is the last byte of the last block). Two blocks are in-use, two are free. The in-use payloads are shown shaded in gray. The `free_list` points to the payload at `0x100`, and the payload at `0x100` stores a “next” pointer to the payload at `0x60`, and the payload at `0x60` stores a “next” pointer of `NULL`. The “previous” pointers of the two free blocks are also set accordingly.

Below are the allocator’s global variables, constants, and type definitions (you may assume that the structs’ memory layouts are as shown and described above).

```
struct Header { size_t nwords; unsigned long used; };
struct Node   { struct Node *next;  struct Node *prev; };
#define    HDRSIZE    sizeof(struct Header)
#define    NODSIZE    sizeof(struct Node)
static     void *segment_start;  //   base address of heap segment
static     void *segment_end;    //   end address of heap segment
static     void *free_list;      //   pointer to payload of first free block
                                 //   (NULL if no free blocks)
```

(a) (4pts) Implement `get_neighbor`. Given a pointer to a block's **header**, it returns a pointer to the **header** of the neighbor to the right, i.e., at the next higher address in the heap. If `hdr` has no right neighbor (i.e., it is the rightmost block in the heap segment), the function returns `NULL`.

```
struct Header *get_neighbor(struct Header *hdr)
{

}
```

(b) (2pts) You consider implementing a corresponding `get_left_neighbor` (given a pointer to a block's header, it would return a pointer to the header of the neighbor to the left), but soon realize that it while it would be possible, it would be much slower than getting the right neighbor. Briefly describe how is it possible (what actions would the function have to take), and why it would be slower in terms of Big-O cost.

(c) (3pts) As you think about your heap allocator design, you realize that in many places in your code, you will have a pointer to a block's payload, and you'll need to get a pointer to the header of the same block. Implement a helper function to do this conversion.

```
struct Header *pay_to_hdr(struct Node *payload)
{

}
```

Parts (d)-(f) concern helper functions that you plan to use in your `validate_heap` function. Specifically, you'd like to loop over every block in the entire heap and count how many free blocks you find, and then compare that count to the number of free blocks you encounter while traversing your explicit free list. In parts (d)-(f), you'll write and analyze functions to do these two counts.

(d) (4pts) Write a function `count_free_inorder` that starts at the leftmost block of the heap and proceeds to the right neighbor, then its right neighbor, and so on to the end of the heap, counting how many free blocks it encounters. For full credit, you should use other functions in this problem as helper functions if/when appropriate. In particular, while you won't be writing it yourself, you may assume there exists the following already-implemented function:

```
struct Node *hdr_to_pay(struct Header *header);
```

```
size_t count_free_inorder()
{
   size_t nfree = 0;
   for (struct Header *curr =                          ;
                                                       ;
                                                       ) {
      if (curr->used == 0) // see part (f)
         nfree++;
   }
   return nfree;
}
```

(e) (3pts) Now write a function that traverses the explicit free list and counts the number of free blocks it finds. Again, for full credit, you should use other functions in this problem as helper functions if/when appropriate.

```
size_t count_free_list()
{
   size_t nfree = 0;

   for (struct Node *curr = [                    ];
        [                    ];
        [                    ]) {

      if ([          ] == 0) // check if free - see part (f)
         nfree++;
   }
   return nfree;
}
```

(f) (2pts) Your coworker looks at your `count_free_list` and `count_free_inorder` functions above, and says that only one of them needs the "if" test (see the line marked "`see part (f)`" in each function; note that they both do need the line "`nfree++;`"). In other words, you could just cross out one of the lines marked "`see part (f)`" and the functionality would not change.

From which function could you safely remove the "if" test? (Check box for **one**.)

- ☐ `count_free_inorder`
- ☐ `count_free_list`

Explain why that function does NOT need the "if" test.

(g) (2pts) Your heap allocator does coalescing, that is, merging a pair of adjacent free blocks to create one big free block. The merge consumes the entire right block, including its header, adding it to the left block's payload. This involves a few steps, but one of them is to update the header of the left block of the pair to reflect the new size. Write a helper function `update_header` that takes a pointer to the header of the left block of a pair of free blocks (assume you've already checked they're both free) and updates its `nwords` field. Again, for full credit, you should use other functions in this problem as helper functions if/when appropriate.

```
void update_header(struct Header *left)
{
    left->nwords += [                    ];
}
```

(h) (4pts) In operations such as `malloc` and coalesce, you need to remove a block from the `free_list` and repair the doubly-linked list structure so it reconnects around the removed link node. Write a helper function that performs this task. It takes a pointer to the payload of the block to be removed from the `free_list`. We have divided the work into four cases. You may not need to write code for each case. If nothing needs to be done for a particular case, just write a semicolon in the box for that case.

```
void remove_node(struct Node *remove)
{
    if (remove->prev == NULL) {
        [                    ]
    } else {
        [                    ]
    }
    if (remove->next == NULL) {
        [                    ]
    } else {
        [                    ]
    }
}
```