

CS 110

Computer Architecture

Lecture 3: *Introduction to C II*

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<https://robotics.shanghaitech.edu.cn/courses/ca/20s/>

School of Information Science and Technology SIST

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Slides based on UC Berkley's CS61C



Admin

- TA Office hours:
 - In piazza -> resources -> staff
<https://piazza.com/shanghaitech.edu.cn/spring2020/cs110/staff>
 - Times are posted there
 - Contact TA in qq group during his OH



Admin

- Labs
 - Start on Monday – and Tuesday
 - TA will make a qq group for your lab
 - Send your TA your group via email
subject: [CA group]
 - During lab time:
 - Make a zoom meeting with your lab partner
 - Post zoom meeting id in your lab qq group
 - TA will join you at some time!



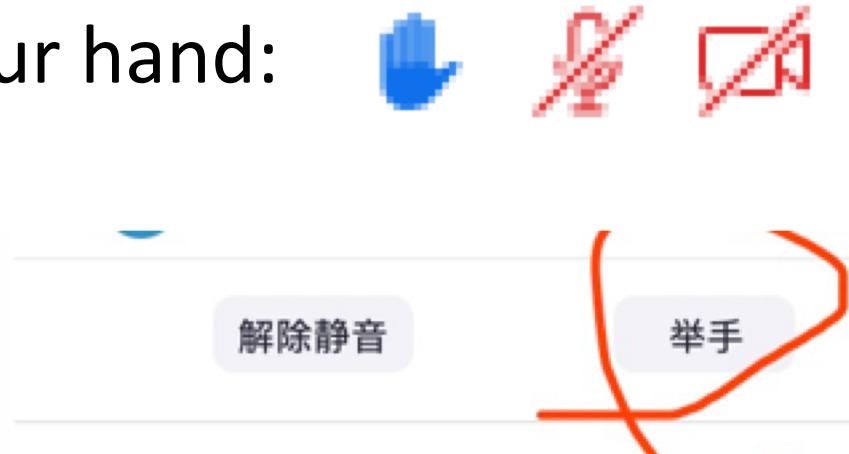
Admin

- HW 1 is due tomorrow!
 - So far 188 students submitted – out of 207!
- HW 2 is due Thursday, March 12
 - Start early!



Admin

- Zoom: You can raise your hand:
- Use to indicate that you want to ask a question.
- Can also ask questions in chat!





Admin

- TAs will give short (about 10 minutes) sessions in Chinese in every lecture.
- This replaces TA discussions for now.

Review

- Pointers and arrays are **virtually same**
- C knows how to **increment pointers**
- C is an efficient language, with little protection
 - Array bounds **not checked**
 - Variables **not** automatically initialized
- (Beware) The cost of efficiency is more overhead for the programmer.
 - “C gives you a lot of extra rope but be careful not to hang yourself with it!”

```

1 #include <libc.h>
2
3 int test(char str[], size_t size);
4
5 int main(int argc, char *argv[]){
6     double pi = 3.14;
7     char top[] = "CA is top!";
8     char * rulez = "CA is rulez!";
9
10    printf(" 1 %lu \n", sizeof(argc) );
11    printf(" 2 %lu \n", sizeof(argv) );
12    printf(" 3 %lu \n", sizeof(*argv) );
13    printf(" 4 %lu \n", sizeof(**argv) );
14
15    printf(" 5 %lu \n", sizeof(pi) );
16    printf(" 6 %lu \n", sizeof(3.14f) );
17    printf(" 7 %lu \n", sizeof(top) );
18    printf(" 8 %lu \n", strlen(top) );
19
20    printf(" 9 %lu \n", sizeof(rulez) );
21    printf("10 %lu \n", strlen(rulez) );
22    printf("11 %lu \n", sizeof(test) );
23    printf("12 %lu \n", sizeof(&test) );
24
25    return test(top, 4);
26 }
27
28 int test(char str[], size_t size){
29    printf("13 %lu \n", sizeof(str) );
30    printf("14 %lu \n", sizeof(size) );
31    printf("15 %lu \n", sizeof(size_t) );
32    printf("16 %lu \n", sizeof(void *) );
33
34    return 0;

```

What is printed? 32bit machine.



- | | |
|--------|---------------------------|
| 1. 4 | int |
| 2. 4 | pointer |
| 3. 4 | array (pointer) |
| 4. 1 | char |
| 5. 8 | double |
| 6. 4 | float |
| 7. 11 | string with 0-terminator |
| 8. 10 | string w/o 0-terminator |
| 9. 4 | pointer (to char/ string) |
| 10. 12 | string w/o 0-terminator |
| 11. 1 | invalid! undefined! |
| 12. 4 | pointer to function |
| 13. 4 | array (pointer) |
| 14. 4 | size_t |
| 15. 4 | size_t |
| 16. 4 | pointer |

C Memory Management

- How does the C compiler determine where to put all the variables in machine's memory?
- How to create dynamically sized objects?
- To simplify discussion, we assume one program runs at a time, with access to all of memory.
- Later, we'll discuss virtual memory, which lets multiple programs all run at same time, each thinking they own all of memory.

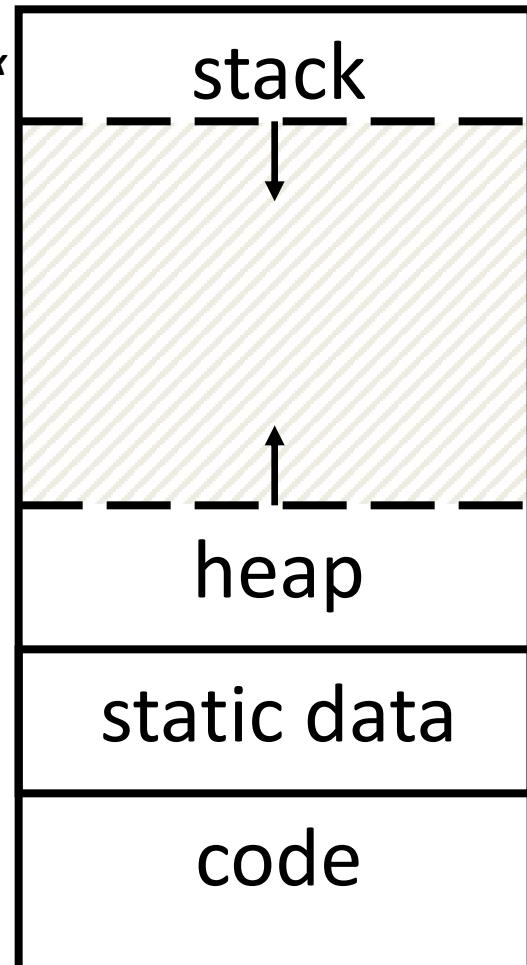
C Memory Management

- Program's *address space* contains 4 regions:
 - **stack**: local variables inside functions, grows downward
 - **heap**: space requested for dynamic data via `malloc()`; resizes dynamically, grows upward
 - **static data**: variables declared outside functions, does not grow or shrink. Loaded when program starts, can be modified.
 - **code**: loaded when program starts, does not change

Memory Address
(32 bits assumed here)

$\sim FFFF\ FFFF_{hex}$

$\sim 0000\ 0000_{hex}$



Where are Variables Allocated?

- If declared outside a function,
allocated in “static” storage
- If declared inside function,
allocated on the “stack”
and freed when function
returns
 - main() is treated like
a function

```
int myGlobal;  
main () {  
    int myTemp;  
}
```

The Stack

- Every time a function is called, a new frame is allocated on the stack
- Stack frame includes:
 - Return address (who called me?)
 - Arguments
 - Space for local variables
- Stack frames contiguous blocks of memory; stack pointer indicates start of stack frame
- When function ends, stack frame is tossed off the stack; frees memory for future stack frames
- We'll cover details later for RISC-V processor

```
fooA() { fooB(); }
fooB() { fooC(); }
fooC() { fooD(); }
```

fooA frame

fooB frame

fooC frame

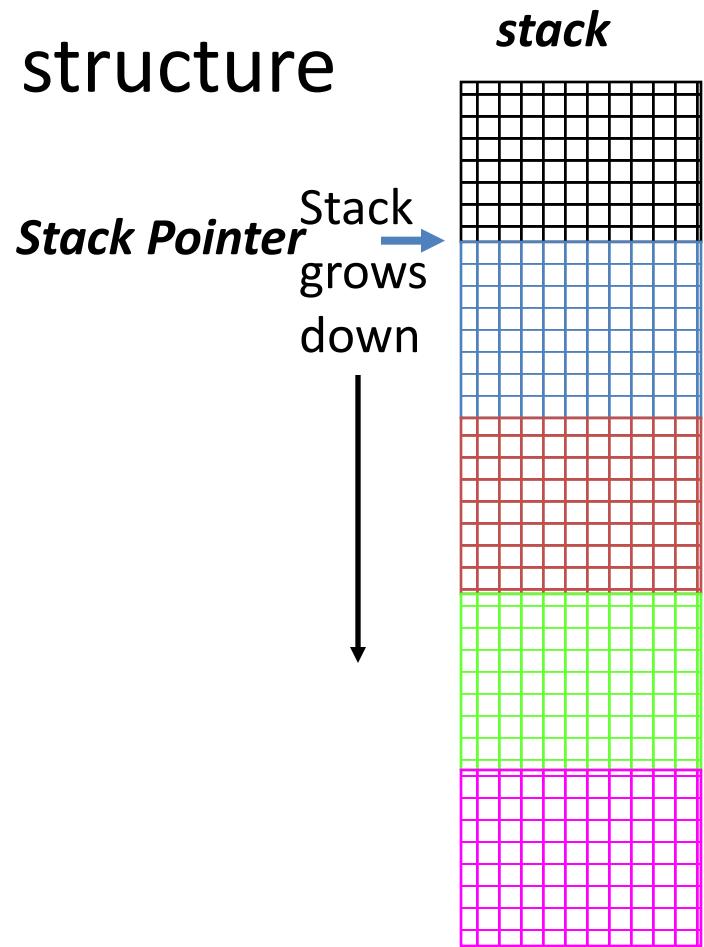
fooD frame

Stack Pointer →

Stack Animation

- Last In, First Out (LIFO) data structure

```
main ()  
{ a(0);  
}  
void a (int m)  
{ b(1);  
}  
void b (int n)  
{ c(2);  
}  
void c (int o)  
{ d(3);  
}  
void d (int p)  
{  
}
```



Managing the Heap

C supports five functions for heap management:

- **malloc()** allocate a block of uninitialized memory
- **calloc()** allocate a block of zeroed memory
- **free()** free previously allocated block of memory
- **realloc()** change size of previously allocated block
 - careful – it might move!

Malloc()

- **void *malloc(size_t n):**
 - Allocate a block of uninitialized memory
 - NOTE: Subsequent calls might not yield blocks in contiguous addresses
 - **n** is an integer, indicating size of allocated memory block in bytes
 - **size_t** is an unsigned integer type big enough to “count” memory bytes
 - **sizeof** returns size of given type in bytes, produces more portable code
 - Returns **void*** pointer to block; **NULL** return indicates no more memory
 - Think of pointer as a *handle* that describes the allocated block of memory; Additional control information stored in the heap around the allocated block!

“Cast” operation, changes type of a variable.

- Examples:

Here changes (**void ***) to (**int ***)

```
int *ip;  
ip = (int *) malloc(sizeof(int));
```

```
typedef struct { ... } TreeNode;  
TreeNode *tp = (TreeNode *) malloc(sizeof(TreeNode));
```

Managing the Heap

- **void free(void *p):**
 - Releases memory allocated by **malloc()**
 - **p** is pointer containing the address *originally* returned by **malloc()**

```
int *ip;
ip = (int *) malloc(sizeof(int));
...
free((void*) ip); /* Can you free(ip) after ip++ ? */
```



```
typedef struct {...} TreeNode;
TreeNode *tp = (TreeNode *) malloc(sizeof(TreeNode));
...
free((void *) tp);
```
 - When insufficient free memory, **malloc()** returns **NULL** pointer; **Check for it!**

```
if ((ip = (int *) malloc(sizeof(int))) == NULL){
    printf("\nMemory is FULL\n");
    exit(1); /* Crash and burn! */
}
```
 - When you free memory, you must be sure that you pass the **original address** returned from **malloc()** to **free()**; Otherwise, system exception (or worse)!

Using Dynamic Memory

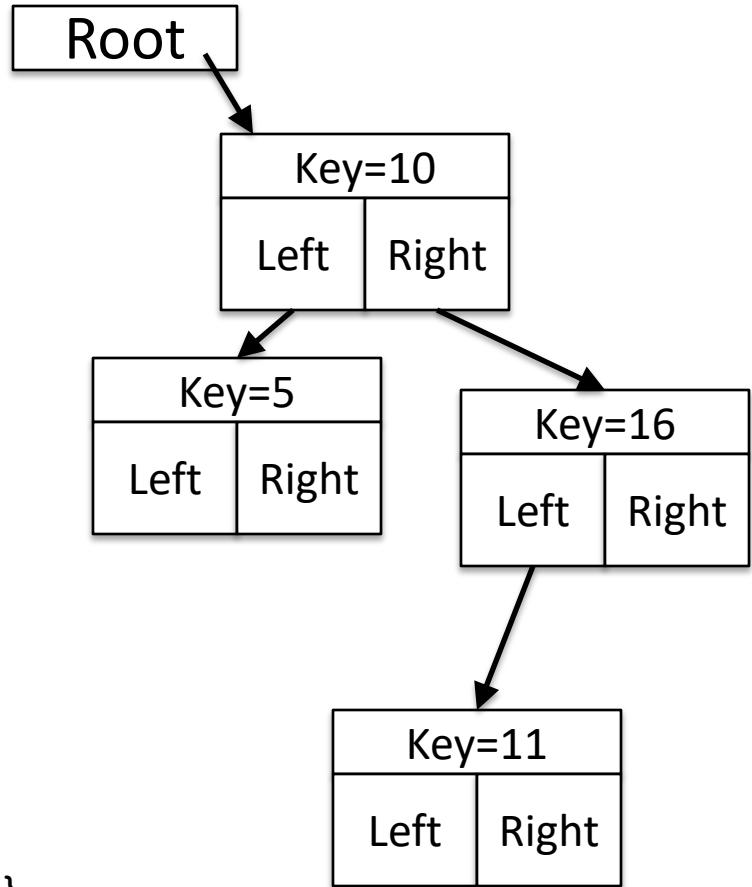
```
typedef struct node {
    int key;
    struct node *left;
    struct node *right;
} Node;

Node *root = 0;

Node *create_node(int key, Node *left, Node *right)
{
    Node *np;
    if ( (np = (Node*) malloc(sizeof(Node))) == NULL)
    { printf("Memory exhausted!\n"); exit(1); }
    else
    { np->key = key;
        np->left = left;
        np->right = right;
        return np;
    }
}

void insert(int key, Node **tree)
{
    if ( (*tree) == NULL)
    { (*tree) = create_node(key, NULL, NULL); return; }

    if (key <= (*tree)->key)
        insert(key, &((*tree)->left));
    else
        insert(key, &((*tree)->right));
}
```



Observations

- Code, Static storage are easy: they never grow or shrink
- Stack space is relatively easy: stack frames are created and destroyed in last-in, first-out (LIFO) order
- *Managing the heap is tricky*: memory can be allocated / deallocated at any time



```
1 #include <libc.h>
2
3 /* Takes a string and makes it awesome! */
4 int make_ca(char * str, size_t length){
5
6     char awesome[] = "CA is so awesome!";
7
8     /* if str is too small we need to get more memory! */
9     if(length < strlen(awesome) ){
10         str = malloc(sizeof(char) * strlen(awesome));
11     }
12
13     strcpy(str, awesome);
14 }
15
16 int main(int argc, char *argv[]){
17
18     char ca[] = "CA is OK.";
19     char * CA = malloc(6);
20     memcpy(CA, ca, strlen(ca));
21
22     make_ca(ca, strlen(ca));
23     make_ca(CA, strlen(CA));
24     /* We want to print an awesome string! */
25     printf(" %s %s ",ca, CA);
26
27 }
```



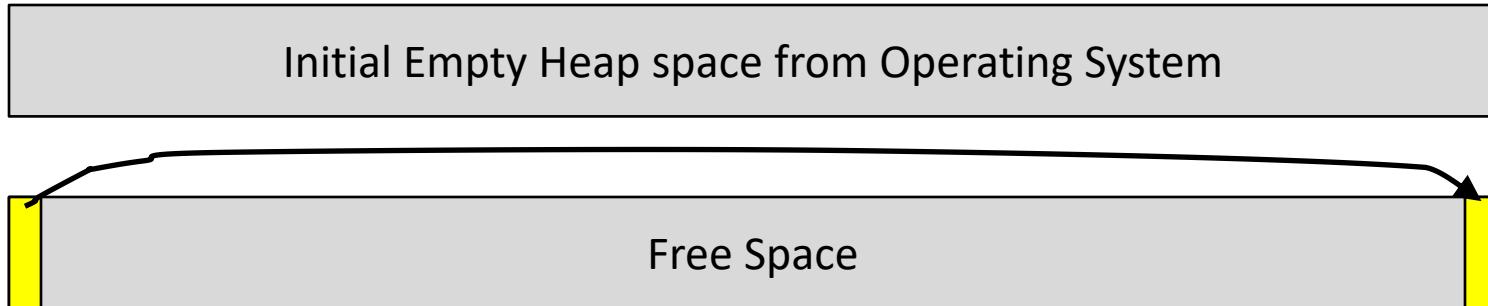
Bugs

- Line 9: comparison with strlen instead of sizeof (for 0-terminator)
- Line 10: strlen instead of sizeof (or +1) for malloc =>
 - Line 13: write past end of array (if malloc was used)
- Line 4: Ownership of pointer str not clear =>
 - Line 10: Potential memory leak
- Line 4: New pointer is not returned/ no pointer to pointer is used
- Line 20: memcpy over length of CA
- Line 20: 0-terminator is not copied!
- Line 22 &23: better: call with array size
- Line 14 & 27: return missing!

How are Malloc/Free implemented?

- Underlying operating system allows **malloc** library to ask for large blocks of memory to use in heap (e.g., using Unix **sbrk()** call)
- C standard **malloc** library creates data structure inside unused portions to track free space

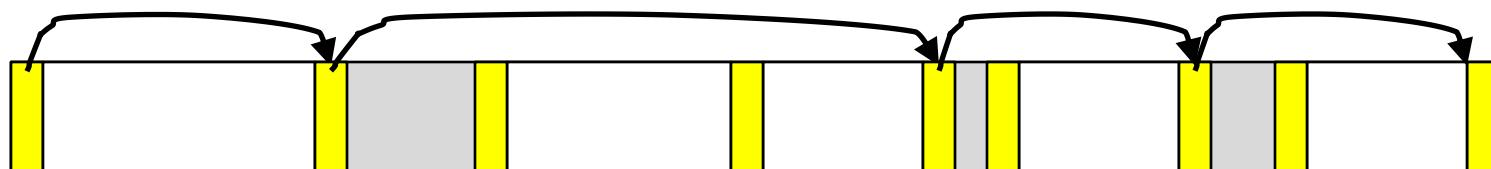
Simple Slow Malloc Implementation



Malloc library creates linked list of empty blocks (one block initially)



First allocation chews up space from start of free space

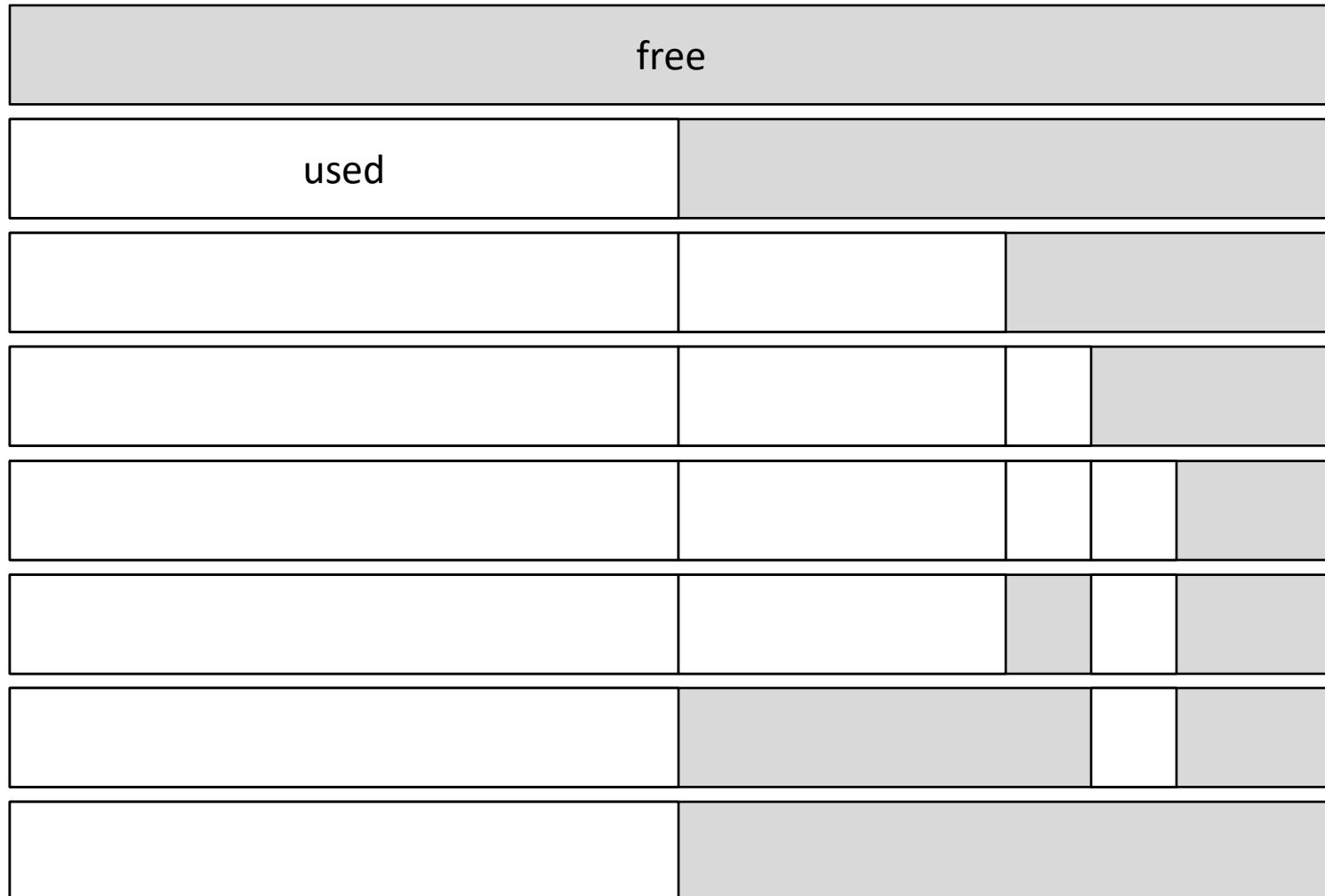


After many mallocs and frees, have potentially long linked list of odd-sized blocks
Frees link block back onto linked list – might merge with neighboring free space

Faster malloc implementations

- Keep separate pools of blocks for different sized objects
- “Buddy allocators” always round up to power-of-2 sized chunks to simplify finding correct size and merging neighboring blocks:

Power-of-2 “Buddy Allocator”



Malloc Implementations

- All provide the same library interface, but can have radically different implementations
- Uses headers at start of allocated blocks and space in unallocated memory to hold **malloc**'s internal data structures
- Rely on programmer remembering to free with same pointer returned by **malloc**
- Rely on programmer not messing with internal data structures accidentally!



Q & A



Quiz



Quiz!

```
int x = 3;          Piazza: "Online Lecture 2 Quiz"  
int result;  
  
int foo(int n)  
{    int y;  
    if (n <= 0) { printf("End case!\n"); return 0; }  
    else  
    {        y = n + foo(n-1);  
        return y;  
    }  
}  
result = foo(15);
```

Right after the **printf** executes but before the **return 0**, how many copies of **x** and **y** are there allocated in memory?

- A: #x = 1, #y = 2
- B: #x = 2, #y = 1
- C: #x = 1, #y = 1
- D: #x = 1, #y = 4
- E: #x = 1, #y = 5
- F: #x = 1, #y = 6

- G: #x = 4, #y = 1
- H: #x = 5, #y = 1
- I: #x = 6, #y = 1
- J: #x = 4, #y = 4
- K: #x = 5, #y = 5
- L: #x = 6, #y = 6

CS 110

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Video 3: Memory Bugs

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Common Memory Problems

- Using uninitialized values
- Using memory that you don't own
 - Deallocated stack or heap variable
 - Out-of-bounds reference to stack or heap array
 - Using NULL or garbage data as a pointer
- Improper use of free/realloc by messing with the pointer handle returned by malloc/calloc
- Memory leaks (you allocated something you forgot to later free)

Using Memory You Don't Own

- What is wrong with this code?
- Using pointers beyond the range that had been malloc'd
 - May look obvious, but what if mem refs had been result of pointer arithmetic that erroneously took them out of the allocated range?

```
int *ipr, *ipw;
void ReadMem() {
    int i, j;
    ipr = (*int) malloc(4 * sizeof(int));
    i = *(ipr - 1000); j = *(ipr + 1000);
    free(ipr);
}

void WriteMem() {
    ipw = (*int) malloc(5 * sizeof(int));
    *(ipw - 1000) = 0; *(ipw + 1000) = 0;
    free(ipw);
}
```



Faulty Heap Management

- What is wrong with this code?

```
int *pi;  
void foo() {  
    pi = malloc(8*sizeof(int));  
    ...  
    free(pi);  
}  
  
void main() {  
    pi = malloc(4*sizeof(int));  
    foo();  
    ...  
}
```



Faulty Heap Management

- Memory leak: *more mallocs than frees*

```
int *pi;
void foo() {
    pi = malloc(8*sizeof(int));
    /* Allocate memory for pi */
    /* Oops, leaked the old memory pointed to by pi */
    ...
    free(pi); /* foo() is done with pi, so free it */
}

void main() {
    pi = malloc(4*sizeof(int));
    foo(); /* Memory leak: foo leaks it */
    ...
}
```

Faulty Heap Management

- What is wrong with this code?

```
int *plk = NULL;  
void genPLK() {  
    plk = malloc(2 * sizeof(int));  
    ... ... ...  
    plk++;  
}
```



Faulty Heap Management

- Potential memory leak – handle has been changed, do you still have copy of it that can correctly be used in a later free?

```
int *plk = NULL;  
void genPLK() {  
    plk = malloc(2 * sizeof(int));  
    ... ... ...  
    plk++;  
}
```

Faulty Heap Management

- What is wrong with this code?

```
void FreeMemX() {  
    int fnh = 0;  
    free(&fnh);  
}
```

```
void FreeMemY() {  
    int *fum = malloc(4 * sizeof(int));  
    free(fum+1);  
    free(fum);  
    free(fum);  
}
```



Faulty Heap Management

- Can't free non-heap memory; Can't free memory that hasn't been allocated

```
void FreeMemX() {  
    int fnh = 0;  
    free(&fnh);  
}  
  
void FreeMemY() {  
    int *fum = malloc(4 * sizeof(int));  
    free(fum+1);  
    free(fum);  
    free(fum);  
}
```

Using Memory You Haven't Allocated

- What is wrong with this code?

```
void StringManipulate() {  
    const char *name = "Safety Critical";  
    char *str = malloc(10);  
    strncpy(str, name, 10);  
    str[10] = '\0';  
    printf("%s\n", str);  
}
```



Using Memory You Haven't Allocated

- Reference beyond array bounds

```
void StringManipulate() {  
    const char *name = "Safety Critical";  
    char *str = malloc(10);  
    strncpy(str, name, 10);  
    str[10] = '\0';  
    /* Write Beyond Array Bounds */  
    printf("%s\n", str);  
    /* Read Beyond Array Bounds */  
}
```

Using Memory You Don't Own

- What's wrong with this code?

```
char *append(const char* s1, const char *s2) {  
    const int MAXSIZE = 128;  
    char result[128];  
    int i=0, j=0;  
    for (j=0; i<MAXSIZE-1 && j<strlen(s1); i++,j++) {  
        result[i] = s1[j];  
    }  
    for (j=0; i<MAXSIZE-1 && j<strlen(s2); i++,j++) {  
        result[i] = s2[j];  
    }  
    result[++i] = '\0';  
    return result;  
}
```



Using Memory You Don't Own

- Beyond stack read/write

```
char *append(const char* s1, const char *s2) {  
    const int MAXSIZE = 128;  
    char result[128];  
    int i=0, j=0;  
    for (j=0; i<MAXSIZE-1 && j<strlen(s1); i++,j++) {  
        result[i] = s1[j];  
    }  
    for (j=0; i<MAXSIZE-1 && j<strlen(s2); i++,j++) {  
        result[i] = s2[j];  
    }  
    result[++i] = '\0';  
    return result;  
}
```

result is a local array name –
stack memory allocated

Function returns pointer to stack
memory – won't be valid after
function returns

Using Memory You Don't Own

- What is wrong with this code?

```
typedef struct node {  
    struct node* next;  
    int val;  
} Node;
```

```
int findLastNodeValue(Node* head) {  
    while (head->next != NULL) {  
        head = head->next;  
    }  
    return head->val;  
}
```



Using Memory You Don't Own

- Following a NULL pointer to mem addr 0!

```
typedef struct node {  
    struct node* next;  
    int val;  
} Node;  
  
int findLastNodeValue(Node* head) {  
    while (head->next != NULL) {  
        head = head->next;  
    }  
    return head->val;  
}
```

Managing the Heap

- `realloc(p, size)`:
 - Resize a previously allocated block at `p` to a new `size`
 - If `p` is `NULL`, then `realloc` behaves like `malloc`
 - If `size` is 0, then `realloc` behaves like `free`, deallocated the block from the heap
 - Returns new address of the memory block; NOTE: it is likely to have moved!

E.g.: allocate an array of 10 elements, expand to 20 elements later

```
int *ip;  
ip = (int *) malloc(10*sizeof(int));  
/* always check for ip == NULL */  
... ... ...  
ip = (int *) realloc(ip,20*sizeof(int));  
/* always check for ip == NULL */  
/* contents of first 10 elements retained */  
... ... ...  
realloc(ip,0); /* identical to free(ip) */
```

Using Memory You Don't Own

- What is wrong with this code?

```
int* init_array(int *ptr, int new_size) {  
    ptr = realloc(ptr, new_size*sizeof(int));  
    memset(ptr, 0, new_size*sizeof(int));  
    return ptr;  
}
```



```
int* fill_fibonacci(int *fib, int size) {  
    int i;  
    init_array(fib, size);  
    /* fib[0] = 0; */ fib[1] = 1;  
    for (i=2; i<size; i++)  
        fib[i] = fib[i-1] + fib[i-2];  
    return fib;  
}
```

Using Memory You Don't Own

- Improper matched usage of mem handles

```
int* init_array(int *ptr, int new_size) {  
    ptr = realloc(ptr, new_size*sizeof(int));  
    memset(ptr, 0, new_size*sizeof(int));  
    return ptr;  
}
```

Remember: `realloc` may move entire block

```
int* fill_fibonacci(int *fib, int size) {  
    int i;  
    /* oops, forgot: fib = */ init_array(fib, size);  
    /* fib[0] = 0; */ fib[1] = 1;  
    for (i=2; i<size; i++)  
        fib[i] = fib[i-1] + fib[i-2];  
    return fib;  
}
```

What if array is moved to
new location?

And In Conclusion, ...

- All data is in memory
 - Each memory location has an address to use to refer to it and a value stored in it
- Pointer is a C version (abstraction) of a data address
 - * “follows” a pointer to its value
 - & gets the address of a value
 - Arrays and strings are implemented as variations on pointers
- C is an efficient language, but leaves safety to the programmer
 - Variables not automatically initialized
 - Use pointers with care: they are a common source of bugs in programs

And In Conclusion, ...

- C has three main memory segments in which to allocate data:
 - Static Data: Variables outside functions
 - Stack: Variables local to function
 - Heap: Objects explicitly malloc-ed/free-d.
- Heap data is biggest source of bugs in C code