CS 61C:
Great Ideas in Computer Architecture
Lecture 4: *Introduction to C, Part III*

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ELECTRICAL ENGINEERING & COMPUTER SCIENCES

Review of Last Lecture

- Pointers are abstraction of machine memory addresses
- Pointer variables are held in memory, and pointer values are just numbers that can be manipulated by software
- In C, close relationship between array names and pointers
- Pointers know the type of the object they point to (except void *)
- Pointers are powerful but potentially dangerous

Review: C Strings

- String in C is just an array of characters

```
char string[] = "abc";
```

- How do you tell how long a string is?
  - Last character is followed by a 0 byte (aka “null terminator”)

```
int strlen(char s[])
{
    int n = 0;
    while (s[n] != 0) n++;
    return n;
}
```

Review: Point past end of array?

- Array size n; want to access from 0 to $n-1$, but test for exit by comparing to address one element past the array

```
int ar[10], *p, *q, sum = 0;
 ...
 p = &ar[0]; q = &ar[10];
 while (p != q)
     /* sum = sum + *p; p = p + 1; */
  sum += *p++;
```

  – Is this legal?

- C defines that one element past end of array must be a valid address, i.e., not cause an error

Clickers/Peer Instruction Time

How many of the following pointer ops will generate warnings or errors in the compiler?

1. pointer + integer
2. integer + pointer
3. pointer + pointer
4. pointer - integer
5. integer - pointer
6. pointer - pointer
7. compare pointer to pointer
8. compare pointer to integer
9. compare pointer to 0
10. compare pointer to NULL

 # invalid

a) 1
b) 2
c) 3
d) 4
e) 5

Review: Valid Pointer Arithmetic

- Add an integer to a pointer.
- Subtract 2 pointers (in the same array)
- Compare pointers (<, <=, ==, !=, >, >=)
- Compare pointer to NULL (indicates that the pointer points to nothing)

Everything else illegal since makes no sense:

- adding two pointers
- multiplying pointers
- subtract pointer from integer

Today:
C Memory Model and Memory Management

What can't we do with the C we know so far?

Allocate persistent data:

```
int* make_int_array(int n) {
   int a[n];
   return a;
}
```

If you compile this:

```
test3.c:7:12: warning: address of stack memory
associated with local variable
      'a' returned [-Wreturn-stack-address]
    return a;
           ^
1 warning generated.
```

What can't we do with the C we know so far?

Allocate persistent data:

```
int* make_int_array(int n) {
   int a[n];
   return a;
}
```

If you compile this:

```
test3.c:7:12: warning: address of stack memory
associated with local variable
      'a' returned [-Wreturn-stack-address]
    return a;
           ^
1 warning generated.
```

What can’t we do with the C we know so far?

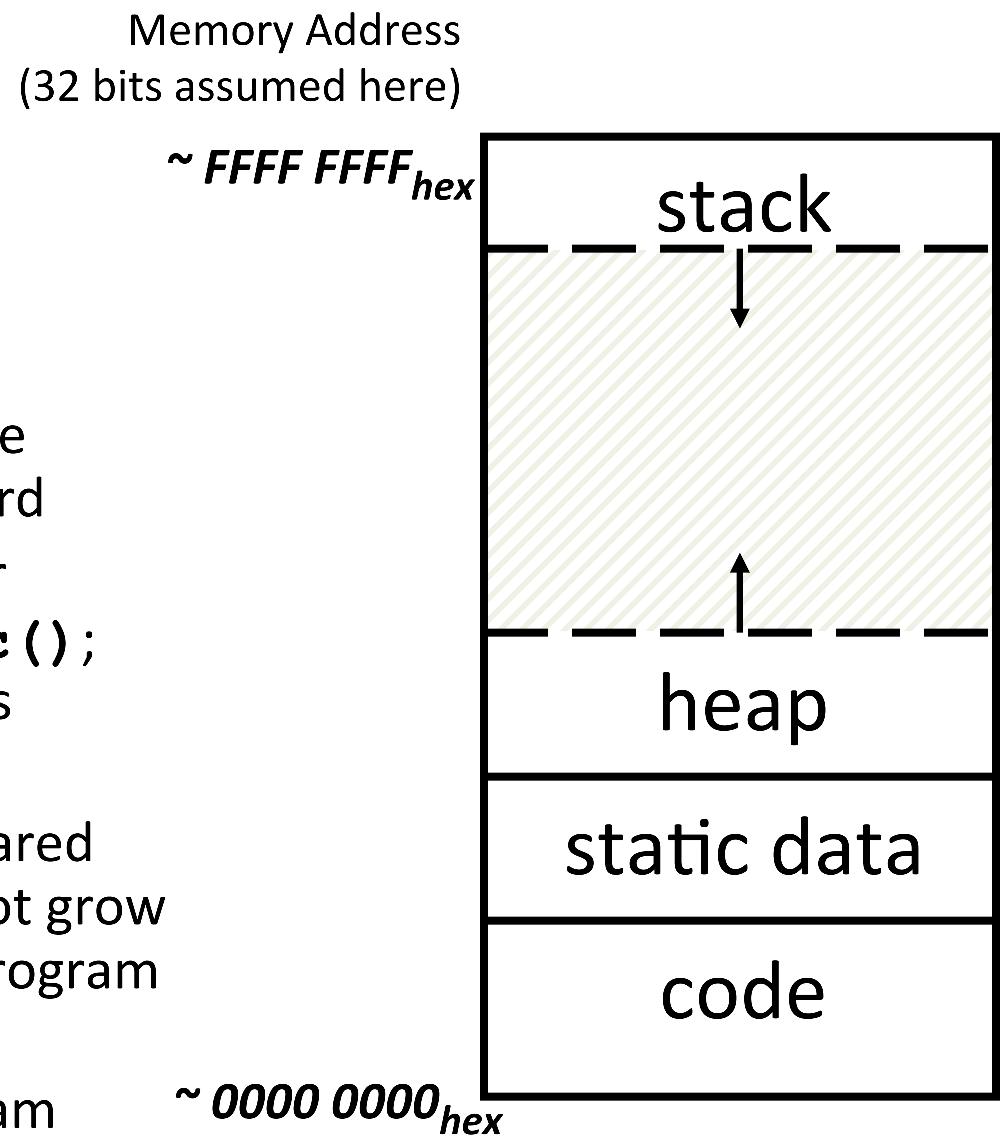
- Cleanly fail when we run out of memory

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



Where are Variables Allocated?

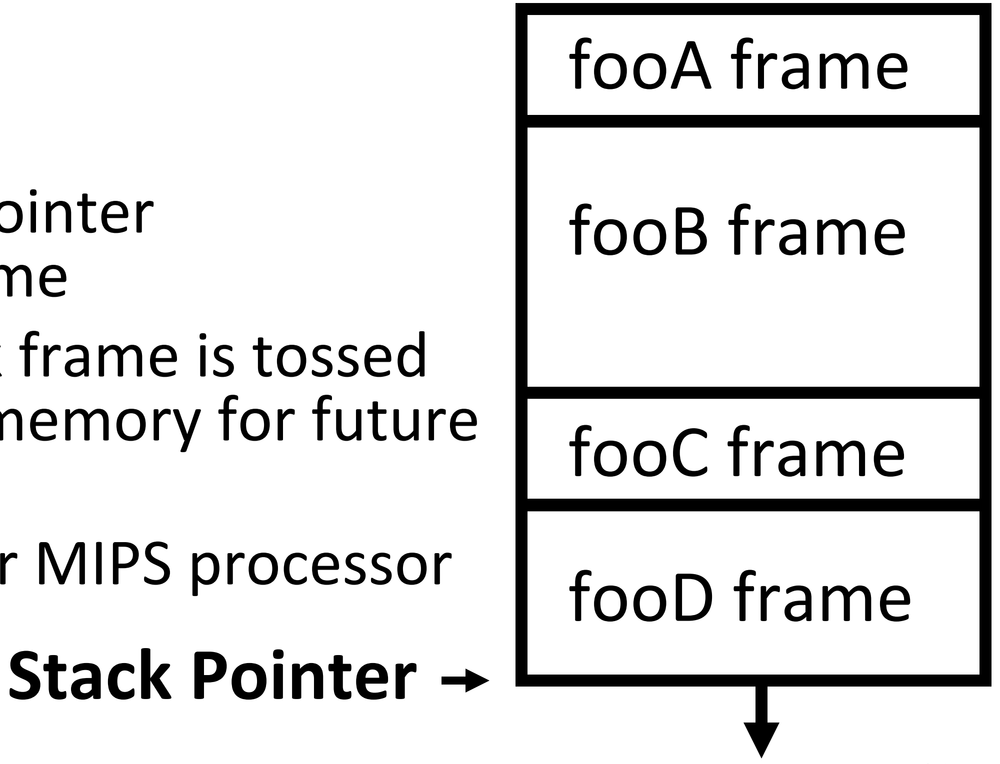
- If declared outside a function, allocated in “static” storage
- If declared inside function, allocated on the “stack” and deallocated when function returns
  - main() is treated like a function

```
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; deallocates memory for future stack frames
- We'll cover details later for MIPS processor

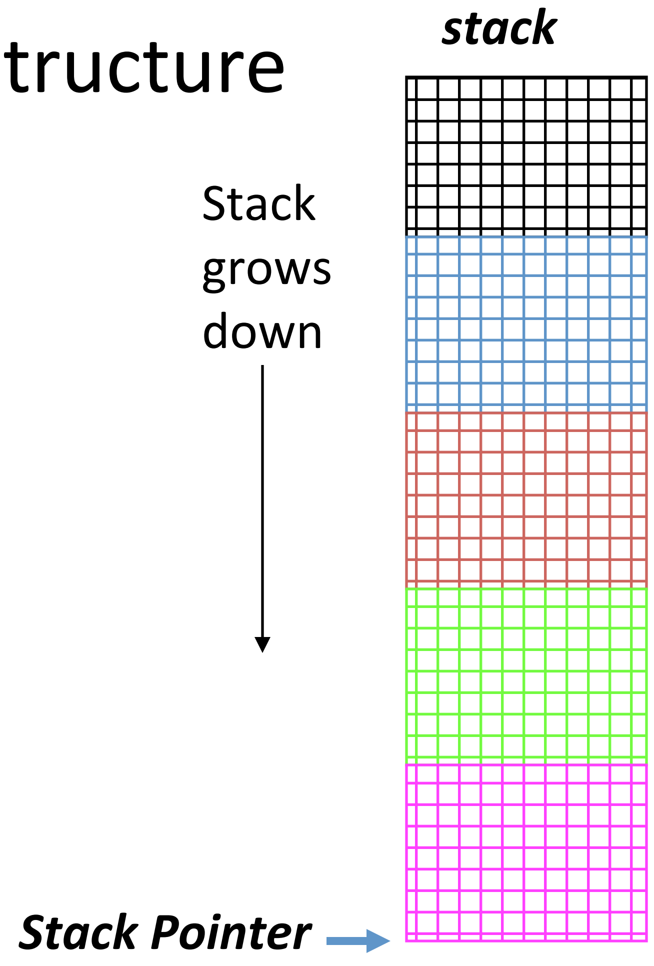
```
fooA() { fooB(); }
fooB() { fooC(); }
fooC() { fooD(); }
```



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
- **`cfree()`** DON'T USE THIS, USE FREE!
- **`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.
*Here changes **`(void *)`** to **`(int *)`***

- Examples:

```
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

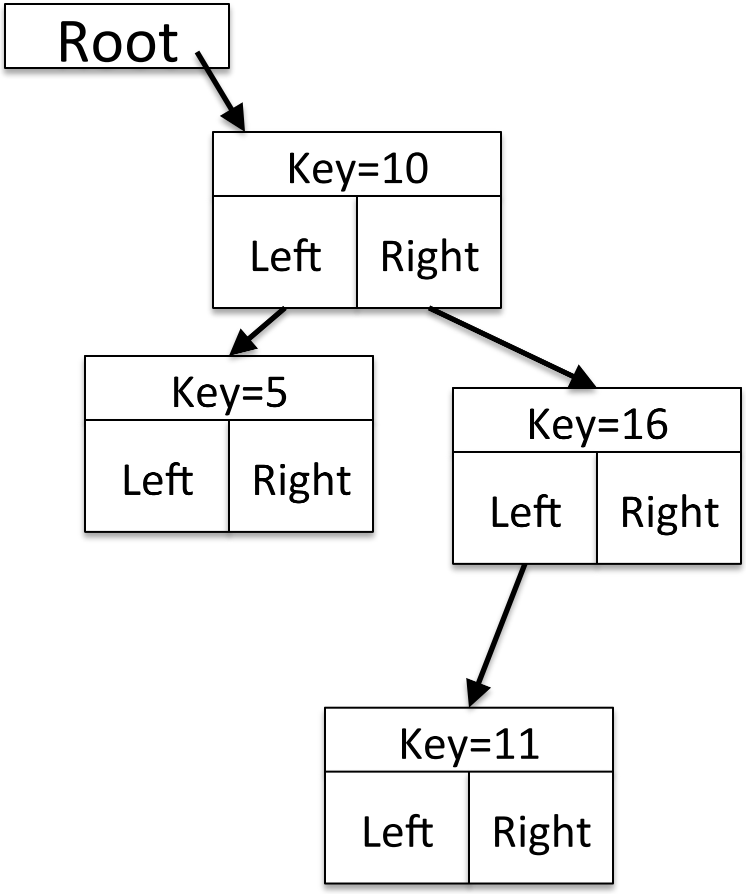
```
typedef struct node {
        int key;
        struct node *left;
        struct node *right;
} Node;

Node *root = NULL;

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));
}
insert(10, &root);
insert(16, &root);
insert(5, &root);
insert(11 , &root);
```



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

Clickers/Peer Instruction!

```
int x = 2;
int result;

int foo(int n)
{   int y;
    if (n <= 0) { printf("End case!\n"); return 0; }
    else
    {  y = n + foo(n-x);
       return y;
    }
}
result = foo(10);
```

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 = 1

B: #x = 1, #y = 5

C: #x = 5, #y = 1

D: #x = 1, #y = 6

E: #x = 6, #y = 6

Administrivia

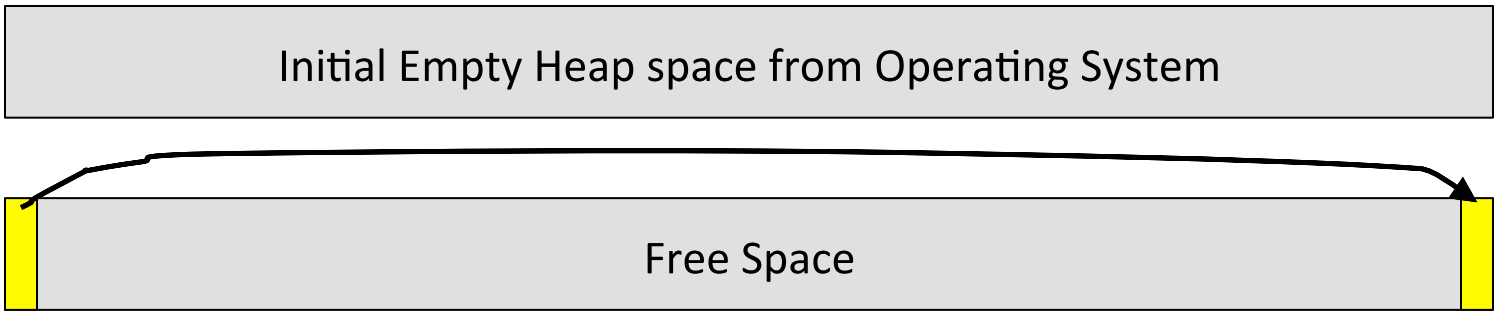
- HW0 out, everyone should have been added to edX
  - Due: Sunday @ 11:59:59pm
- HW0-mini-bio posted on course website
  - Give paper copy to your TA in lab next Tuesday
- First lab due at the beginning of your lab tomorrow
- Get Clickers!
- Let us know about exam conflicts by the end of this week
- Heads-up: First midterm is 2 weeks from today

Break

How are Malloc/Free implemented?

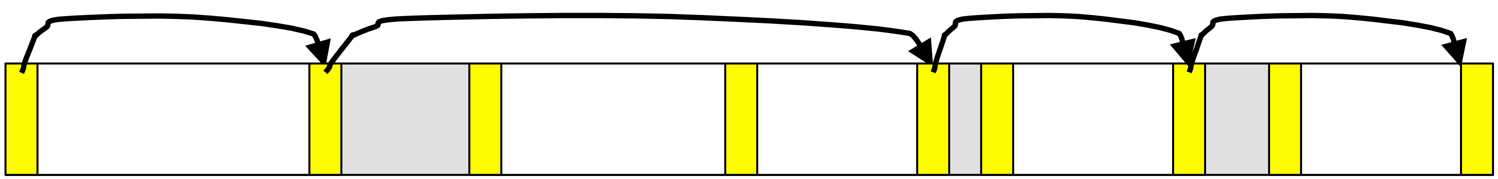
- Underlying operating system allows **`malloc`** library to ask for large blocks of memory to use in heap (e.g., using Unix **`sbrk()`** call)
- C standard **`malloc`** library creates data structure inside unused portions to track free space

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”

Step	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K
1	2^4															
2.1	2^3								2^3							
2.2	2^2				2^2				2^3							
2.3	2^1		2^1		2^2				2^3							
2.4	2^0	2^0	2^1		2^2				2^3							
2.5	A: 2^0	2^0	2^1		2^2				2^3							
3	A: 2^0	2^0	B: 2^1		2^2				2^3							
4	A: 2^0	C: 2^0	B: 2^1		2^2				2^3							
5.1	A: 2^0	C: 2^0	B: 2^1		2^1		2^1		2^3							
5.2	A: 2^0	C: 2^0	B: 2^1		D: 2^1		2^1		2^3							
6	A: 2^0	C: 2^0	2^1		D: 2^1		2^1		2^3							
7.1	A: 2^0	C: 2^0	2^1		2^1		2^1		2^3							
7.2	A: 2^0	C: 2^0	2^1		2^2				2^3							
8	2^0	C: 2^0	2^1		2^2				2^3							
9.1	2^0	2^0	2^1		2^2				2^3							
9.2	2^1		2^1		2^2				2^3							
9.3	2^2				2^2				2^3							
9.4	2^3								2^3							
9.5	2^4															

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!

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?

```
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);
   }
```

Using Memory You Don't Own

- 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++; /* Potential leak: pointer variable
  incremented past beginning of block! */
}
```

CS61C In the News: Smallest Chess Program

- Written by Olivier Poudade in x86 assembly code
- Fits in "a 512-byte x86 boot sector for Windows / Linux / OS X / DOS / BSD"

http://olivier.poudade.free.fr/src/BootChess.asm

Break

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); /* Oops! freeing stack memory */
}

void FreeMemY() {
   int *fum = malloc(4 * sizeof(int));
   free(fum+1);
   /* fum+1 is not a proper handle; points to middle
   of a block */
   free(fum);
   free(fum);
   /* Oops! Attempt to free already freed memory */
}
```

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) {
    /* What if head happens to be NULL? */
        head = head->next;
    }
    return head->val; /* What if head is NULL? */
}
```

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`, deallocating 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?

Clicker Time

Suppose the following appears in a function:

```
char *a = malloc(sizeof(char)*6);
a = “hello”;
return a;
```

Which part of memory does the returned pointer point to?

A: Code   B: Static   C: Heap   D: Stack   E: wat

Clicker Time – pt 2

Suppose the following appears in a function:

```
char *a = malloc(sizeof(char)*6);
a = "hello";
return a;
```

Are we able to safely use the returned pointer?

A: Yes B: No

Clicker Time – pt 3

Suppose the following appears in a function:

```
char *a = malloc(sizeof(char)*6);
a = “hello”;
return a;
```

Is there a memory leak in this function?

A: Yes B: No

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