Lecture 6

Memory Management and more

Berkeley EECS
ELECTRICAL ENGINEERING & COMPUTER SCIENCES

Administrivia

- My office hours: Monday 1pm-2pm, 424 SDH.
- Rasberry PI servers online today!

Agenda

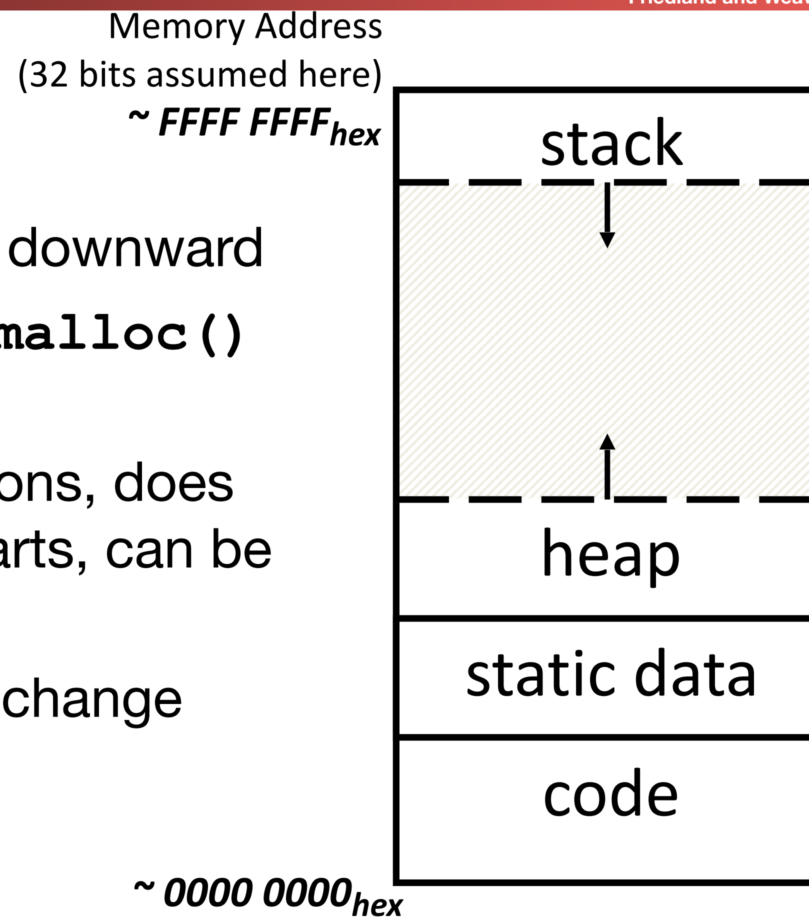
- Memory Management
- and more

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?

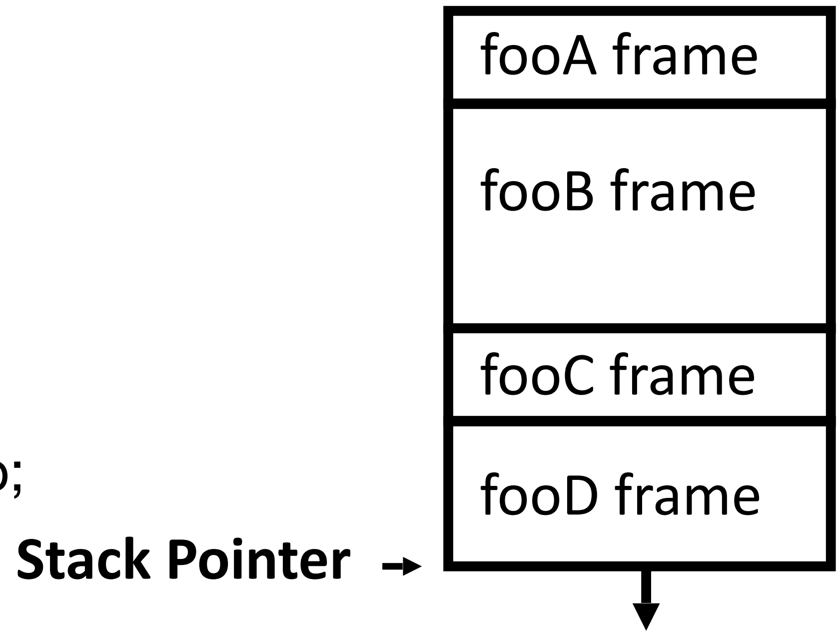
- If declared outside a function, allocated in “static” storage
- If declared inside function, allocated on the “stack” and freed when function returns
  - `main()` is treated like a function
- For both of these types of memory, the management is automatic:
  - You don't need to worry about deallocating when you are no longer using them

```
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 uses contiguous blocks of memory; stack pointer indicates start of stack frame
- When function ends, stack pointer moves up; frees memory for future stack frames
- We'll cover details later for MIPS processor

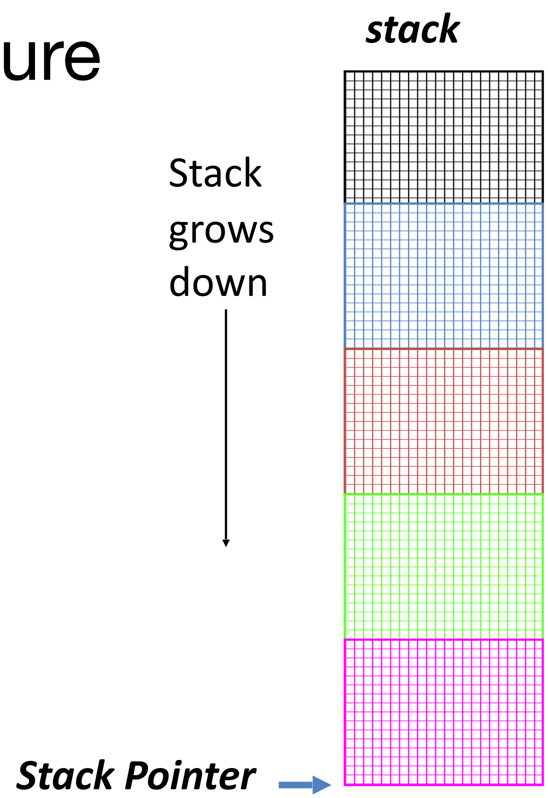
```
fooA() { fooB(); }
fooB() { fooC(); }
fooC() { fooD(); }
```



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 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!
    - And it ***will not update other pointers pointing to the same block of memory***

Malloc()

- **`void *malloc(size_t n)`**:
  - Allocate a block of uninitialized memory
  - NOTE: Subsequent calls probably will not yield adjacent blocks
  - **`n`** is an integer, indicating size of requested memory block in bytes
  - **`size_t`** is an unsigned integer type big enough to "count" memory bytes
  - Returns **`void*`** pointer to block; **`NULL`** return indicates no more memory (check for it!)
  - Additional control information (including size) stored in the heap for each allocated block.
- Examples:

  "Cast" operation, changes type of a variable.
  Here changes ***`(void *)`*** *to* ***`(int *)`***

  - ```
    int *ip;
    ip = (int *) malloc(sizeof(int));
    ```
  - ```
    typedef struct { … } TreeNode;
    TreeNode *tp = (TreeNode *) malloc(sizeof(TreeNode));
    ```
- **`sizeof`** returns size of given type in bytes, ***necessary if you want portable code!***

And then free()

- **`void free(void *p):`**
  - **`p`** is a pointer containing the address originally returned by **`malloc()`**
- Examples:
  - ```
    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 you free memory, you must be sure that you pass the original address returned from **`malloc()`** to **`free()`**; Otherwise, crash (or worse)!

Using Dynamic Memory

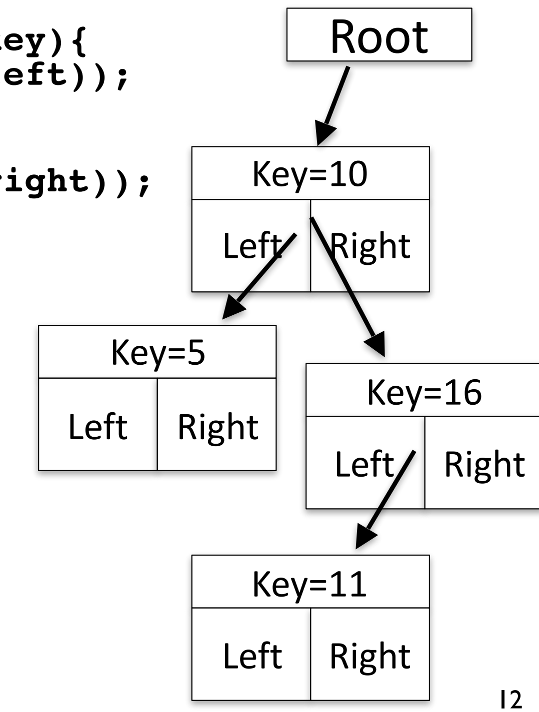

```
typedef struct node {
  int key;
  struct node *left; struct node
*right;
} Node;

Node *root = NULL;

Node *create_node(int key, Node
*left,
      Node *right){
  Node *np;
  if(!(np =
       (Node*) malloc(sizeof(Node)))){
     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);
   }
   else if (key <= (*tree)->key){
     insert(key, &((*tree)->left));
   }
   else{
     insert(key, &((*tree)->right));
   }
}

int main(){
  insert(10, &root);
  insert(16, &root);
  insert(5, &root);
  insert(11 , &root);
  return 0;
}
```



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
  - If you forget to deallocate memory: “Memory Leak”
    - Your program ***will eventually run out of memory***
  - If you call free twice on the same memory: “Double Free”
    - Possible ***crash or exploitable vulnerability***
  - If you use data after calling free: “Use after free”
    - Possible ***crash or exploitable vulnerability***

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

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