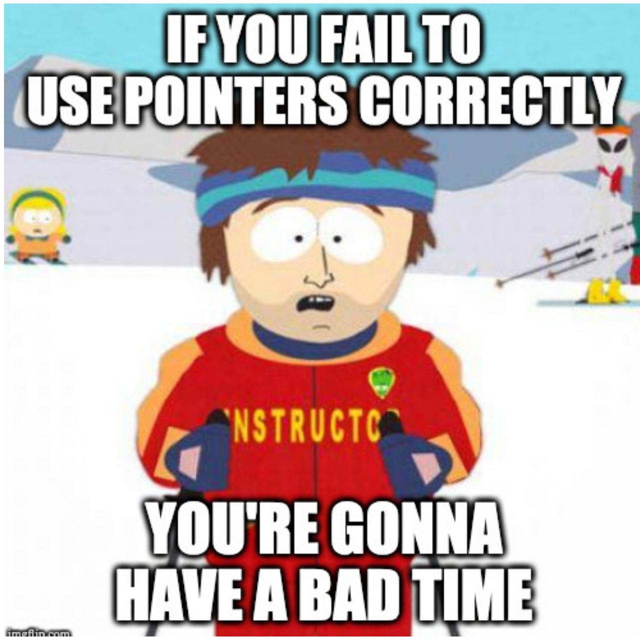
More Memory (Mis) Management)



Berkeley EECS
ELECTRICAL ENGINEERING & COMPUTER SCIENCES

Administrivia...

- After this lecture you should be able to do lab2, HW2, and Project 1
  - Do the lab and homework first to get up to speed on C in practice
- Reminder on project 1:
  It is ***subtle*** and covers a lot of the C language

Reminder: Remember What We Said Earlier About Buckets of Bits?

- C's memory model is that conceptually there is simply one ***yuge*** bucket of bits
  - Arranged in bytes
- Each byte has an ***address***
  - Starting at 0 and going up to the maximum value (0xFFFFFFFF on a 32b architecture)
    - 32b architecture means the # of bits in the address
- We commonly think in terms of "words"
  - Least significant bits of the address are the offset within the word
  - Word size is 32b for a 32b architecture, 64b for a 64b architecture:
    A word is big enough to hold an ***address***

0xFFFFFFFC	xxxx	xxxx	xxxx	xxxx
0xFFFFFFF8	xxxx	xxxx	xxxx	xxxx
0xFFFFFFF4	xxxx	xxxx	xxxx	xxxx
0xFFFFFFF0	xxxx	xxxx	xxxx	xxxx
0xFFFFFFEC	xxxx	xxxx	xxxx	xxxx
...	...	...	...	...
0x14	xxxx	xxxx	xxxx	xxxx
0x10	xxxx	xxxx	xxxx	xxxx
0x0C	xxxx	xxxx	xxxx	xxxx
0x08	xxxx	xxxx	xxxx	xxxx
0x04	xxxx	xxxx	xxxx	xxxx
0x00	xxxx	xxxx	xxxx	xxxx

And so for pointers...

- Declaring pointers
  - ```
    int a; /* An integer value */
    int *p; /* A pointer to an integer */
    char **q; /* A pointer to a pointer to a character */
    ```
- Getting the address of a variable/value
  - ```
    p = &a;
    ```
- Getting or setting the value held at a pointer
  - ```
    a = *p;
    *p = a;
    ```
- And pointer arithmetic & arrays:
  - ```
    p[10];
    *(p + 10); /* Since sizeof(int) == 4, the actual address is 40 + p */
    ```

Arguments in `main()`

- To get arguments to the main function, use:
  - **`int main(int argc, char *argv[])`**
- What does this mean?
  - **`argc`** contains the number of strings on the command line (the executable counts as one, plus one for each argument). Here **`argc`** is 2:
    - **`unix% sort myFile`**
  - **`argv`** is a pointer to an array containing the arguments as strings
    - Since it is an array of pointers to character arrays
    - Sometimes written as **`char **argv`**

Example

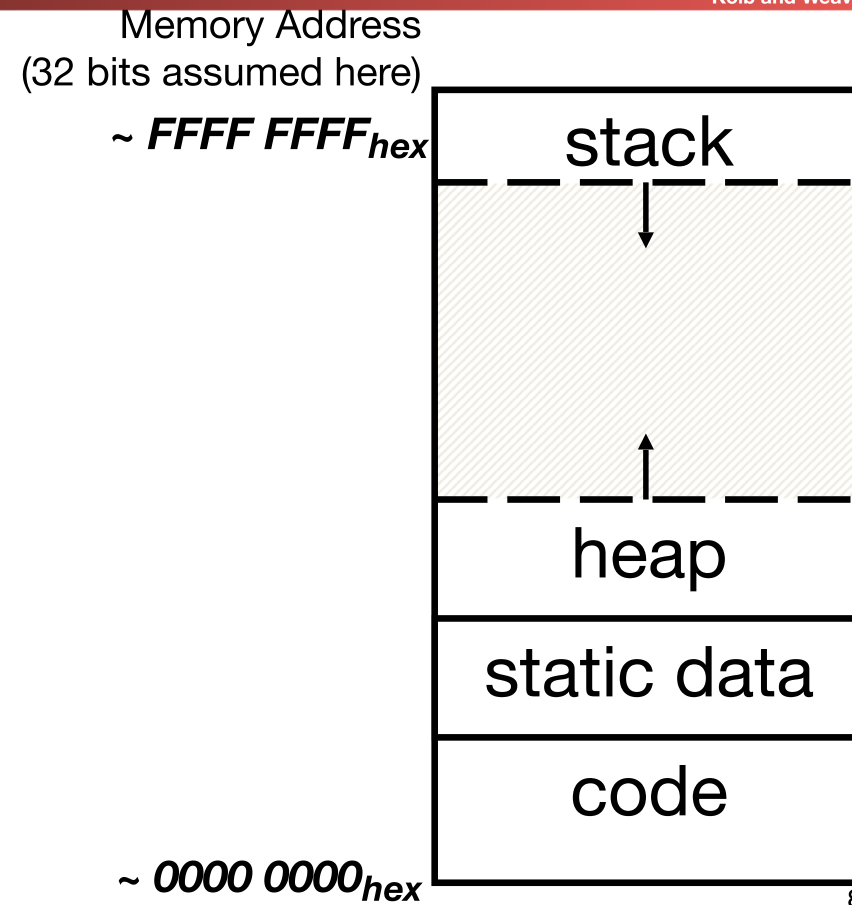
- `foo hello 87 "bar baz"`
- `argc = 4 /* number arguments */`
- ```
  argv[0] = "foo",
  argv[1] = "hello",
  argv[2] = "87",
  argv[3] = "bar baz",
  ```
  - Array of pointers to strings
  ```

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
  - The only real addition is the C runtime has to say "Hey operating system, gimme a big block of memory" when it needs more 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
  - 0x0000 0000 hunk is reserved and unwriteable/ unreadable so you crash on null pointer access



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

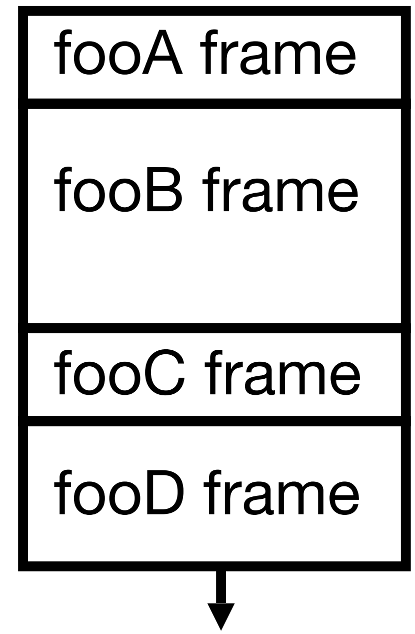
```
int myGlobal;
main() {
  int myTemp;
}
```

- 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
  - But a variable ***does not exist anymore*** once a function ends!
    Big difference from Java

The Stack

- Every time a function is called, a new "stack frame" is allocated on the stack
- Stack frame includes:
  - Return address (who called me?)
  - Arguments
  - 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 RISC-V processor

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

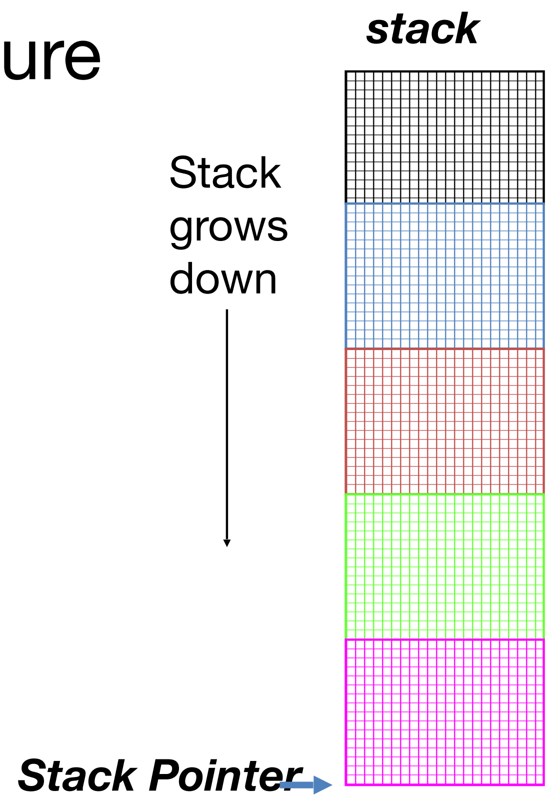


Stack Pointer →

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 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.
  - Basically the analogy to "new" in Java
- 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

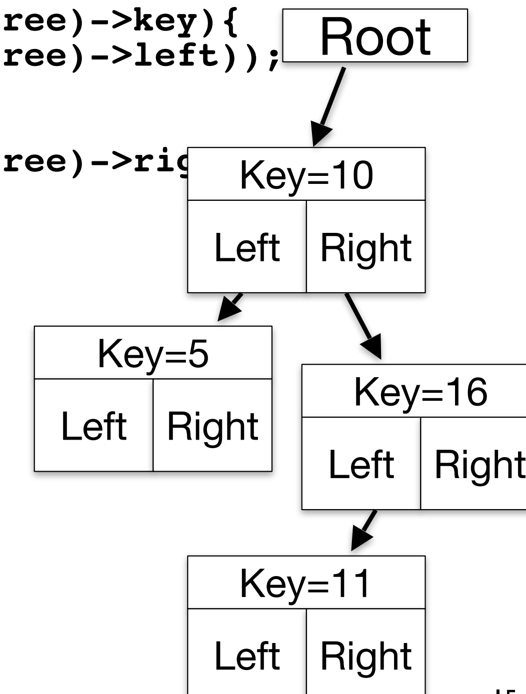

```
typedef struct node {
  int key;
  struct node *left; struct node *right;
} Node;

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)->rig
   }
}

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***

Strings...

- Reminder: Strings are just like any other C array...
  - You have a pointer to the start and no way of knowing the length
  - But you have an in-band "end of string" signal with the '\0' (0-byte) character
- Since you can have multiple pointers point to the same thing...
  - `char *a, *b;` ...
    `a = b;` ...
    `b[4] = 'x';` /* This will update a as well, since they are pointing to the same thing */
- So how do you copy a string?
  - Find the length (strlen), allocate a new array, and then call strcpy...
  - `a = malloc(sizeof(char) * (strlen(b) + 1) );`
    /* Forget the +1 at your own peril */
  - `strcpy(a, b)` or `strncpy(a, b, strlen(b) + 1);`
    - `strcpy` doesn't know the length of the destination, so it can be very unsafe
    - `strncpy` copies only n character for safety, but if its too short it ***will not copy the null terminator!***

And Constant Strings…

- Anything you put explicitly in quotes becomes a ***constant*** string
  - `char *foo = “this is a constant”;`
- For efficiency, these strings are stored as ***read only*** global variables
  - So if you also have `char *bar = “this is a constant”;` it is the same string
- It is, guess what, undefined behavior to write to a constant string
  - But fortunately it is usually an immediate crash.

String & Character Functions

- getc/getchar
  - Read single characters... Note return type!
- gets/fgets
  - Read strings up to a linefeed...
  - Note danger of gets(): it will write however much it wants to!
- printf/fprintf
  - Formatted printing functions
- scanf/fscanf
  - Formatted data input functions: Need to take pointers as argument
  - e.g.
    int i;
    scanf("%i", &i);

Pointer Ninjitsu: Pointers to Functions

- You have a function definition
  - `char *foo(char *a, int b){ … }`
- Can create a pointer of that type…
  - `char *(*f)(char *, int);`
    - Declares f as a function taking a char * and an int and returning a char *
- Can assign to it
  - `f = &foo`
    - Create a reference to function foo
- And can then call it...
  - `printf("%s\n", (*f)("cat", 3))`
- Necessary if you want to write generic code in C: E.g. a hashtable that can handle pointers of any type

C unions

- We've seen how structs can hold multiple elements addressed by name…
  - But what if you want to hold different types in the same location?
- ```
  union fubar {
      int a;
      char *b;
      void c;
  } Fubar;
  ```
- Accessed just like a struct, but…
  - ```
    Fubar *f = (Fubar *) malloc(sizeof(union fubar))…
    f->a = 1312;
    f->b = "baz"
    ```
- They are actually the same memory! It is just treated differently by the compiler!

How to Use Unions…

- Well, you also have to know what the type is… Because C won't do it for you
- Common pattern
  -
```
enum FieldType {a_type, b_type, c_type};
union bar {
          char *a;
          int b;
          float c;};
struct foo {
    FieldType type;
    union bar data; };
…
   struct foo *f;
…
   switch(f->type){
      case a_type:
            printf("%s\n", f->data.a); break;
```

Endianness...

- Consider the following
-
```
union confuzzle { int a; char b[4]; };
union confuzzle foo;
foo.a = 0x12345678;
```
- In a 32b architecture, what would foo.b[0] be?
  0x12? 0x78?
- Its actually dependent on the architecture's "endianness"
  - Big endian: The first character is the most significant byte: **`0x12`**
  - Little endian: The first character is the least significant byte: **`0x78`**

Endianness and You...

- It generally doesn't matter if you write portable C code running on one computer...
  - After all, you shouldn't be treating an integer as a series of raw bytes
  - Well, it matters when you take CS161: x86 is little endian and you may write an address as a string
- It does matter when you want to communicate across computers...
  - The "network byte order" is big-endian, but your computer may be little-endian
- Endian conversion functions:
  - **`ntohs()`**, **`htons()`**: Convert 16 bit values from your native architecture to network byte order and vice versa
  - **`ntohl()`**, **`htonl()`**: Convert 32 bit values from your native architecture to network byte order and vice versa

Structure Layout In Memory

- Everything in C is just buckets o bytes…
  - So how do we do structures? We lay out the structure starting at the 0th byte
-
```
struct foo {
    int a;
    char b;
    short c;
    char *d};
```
- It depends on the compiler and underlying architecture…

Alignment, Packing, & Structures…

- If the architecture did not ***not*** force alignment:
  - Just squish everything together (Sometimes seen on old exams)
  - ```
    struct foo {
        int a;     /* At 0  */
        char b;    /* At 4  */
        short c;   /* At 5  */
        char *d;   /* At 7  */
        char e;};  /* At 11 */
    ```
- But we already mention that computers don't actually like this!
  - They want things aligned
    ```

Default Alignment Rules…

- These are the ***default*** alignment rules for the class
  - Centered around a “32b architecture”:
    Integers and pointers are 32b values
- char: 1 byte, no alignment needed when stored in memory
- short: 2 bytes, 1/2 world aligned
  - So 0, 2, 4, 6…
- int: 4 bytes, word aligned
- pointers are the same size as ints
- Need to allow multiple instances of the same structure to be aligned!

So with alignment


- ```
  struct foo {
      int a;       /* At 0  */
      char b;      /* At 4  */
      short c;     /* At 6  */
      char *d;     /* At 8  */
      char e;};    /* At 13 */
  ```
- For the class we assume ***no reordering of fields***
- But **`sizeof(struct foo)`** == 16!
  - Need to add padding to the end as well, so that if we allocate two structures at the same time it is always aligned!
  ```

Pointer Ninjitsu:
Pointers to arrays of structures


- ```
  typedef struct foo_struct
      { int x;
        char *z;
        char y;} foo;
  ```
  - So how big is a foo?
    - assume an aligned architecture, sizeof(int) == sizeof(void *) == 4:
    - 12... It needs to be padded
- Dynamically allocated a single element:
  - `foo *f = (foo *) malloc(sizeof(foo))`
- Dynamically allocate a 10 entry array of foos:
  - `foo *f = (foo *) malloc(sizeof(foo) * 10);`
  ```

Pointer Ninjitsu Continued: Accessing that array...

- Accessing the 5th element's string pointer:
  - `f[4].z = "fubar";`
    `(f + 4)->z = "fubar"; /* Semantically equivalent but LESS READABLE! */`
    - Assigns the z pointer to point to the static string fubar
      - It is undefined behavior to then do
        `f[4].z[1] = 'X'`
      - If you want to modify the string pointed to by **`z`** you are going to have to do a string copy
- What does it look like "under the hood"?
  - The address written to in **`f[4].z = "fubar"`** is **`(f + 4 * 12 + 4)`**:
    - Note: This math is the 'under the hood' math: if you actually tried this in C it would not work right!
      But it is what the compiler produces in the assembly language
    - The 5th element of type **`foo`** is offset (4*12) from **`f`**
      - Since we want all elements in the array to have the same alignment
        this is why we had the padding
    - The field z is offset 4 from the start of a foo object

Pointer Ninjitsu Advanced: How C++ works...

- C++ is "Object Oriented C"
  - AKA "portable PDP8 assembly language with delusions of grandeur"
- C++ objects are C structures with an extra pointer at the beginning
  - The "vtable" pointer:
    Pointing to an array of pointers to functions
- For inherited ("virtual") functions...
  - To call that function, the compiler writes code that follows the vtable, gets the pointer to function, and calls that

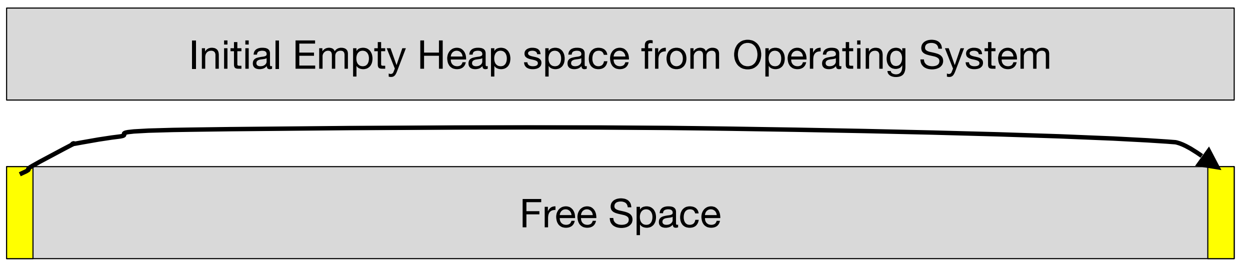
Managing the Heap

- Recall that 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!

How are Malloc/Free implemented?

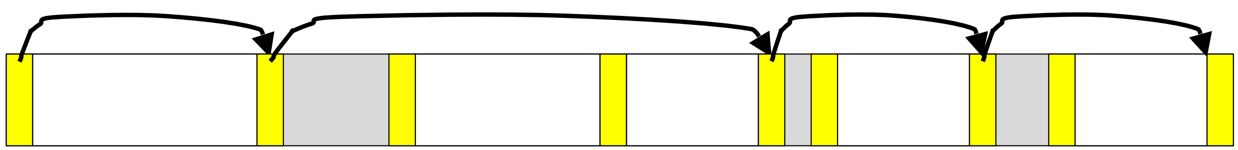
- Underlying operating system allows malloc library to ask for large blocks of memory to use in heap (e.g., using Unix **`sbrk()`** call)
  - This is one reason why your C code, when compiled, is dependent on a particular operating system
- C standard malloc library creates data structure inside unused portions to track free space
  - This class is about how computers work:
    How they allocate memory is a huge component

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

The Problem Here: Fragmentation

- That memory heirarchy we saw earlier likes things small…
  - And likes things contiguous
- Things start to work badly when stuff is scattered all over the place
  - Which will eventually happen with such a simple allocator

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:
  - Then can just use a simple bitmap to know what is free or occupied

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/or space in unallocated memory to hold `malloc`'s internal data structures
- Rely on programmer remembering to `free` with same pointer returned by `malloc`
  - Alternative is a "conservative garbage collector"
- Rely on programmer ***not messing with internal data structures accidentally***!
  - If you get a crash in `malloc`, it means that somewhere else you wrote off the end of an array

Conservative Mark/Sweep Garbage Collectors

- An alternative to **`malloc`** & **`free`**...
  - **`malloc`** works normally, but **`free`** just does nothing
- Instead, it starts with the stack & global variables as the "live" memory
  - But it doesn't know if those variables are pointers, integers, or whatevers...
- So assume that every piece of memory in the starting set is a pointer...
  - If it points to something that was allocated by malloc, that entire allocation is now considered live, and "mark it" as live
  - Iterate until there is no more newly discovered live memory
- Now any block of memory that isn't can be deallocated ("sweep")

The Problems: Fragmentation & Pauses...

- A conservative garbage collector can't move memory around
  - So it gets increasingly fragmented...
    When we get to both caches and virtual memory we will see how this causes problems
- A conservative collector needs to ***stop the program!***
  - What would happen if things changed underneath it? Ruh Roh...
  - So the system needs to pause
- Java, Go, and Python don't have this problem
  - Java and Go are designed to understand garbage collection:
    Able to have ***incremental*** collectors that don't require a long halt but only short halts
  - Python doesn't do real garbage collection:
    Just uses "reference counting". Every python object has a counter for the number of pointers pointing to it. When it gets to 0, free the object
    - Reference counter can't free cycles

Common Memory Problems: aka Common "Anti-patterns"

- Using uninitialized values
  - Especially bad to use uninitialized pointers
- 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
  - Writing to static strings
- 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)
- Valgrind is designed to catch ***most*** of these
  - It runs the program extra-super-duper-slow in order to add checks for these problems that C doesn't otherwise do

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);}
```

Out of bounds reads

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

Out of bounds writes

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();
  … }
```

The first `malloc` of pi leaks

Reflection on Memory Leaks

- Memory leaks are not a problem ***if your program terminates quickly***
  - Memory leaks become a much bigger problem when your program keeps running
  - Or when you are running on a small embedded system
- Three solutions:
  - Be very diligent about making sure you `free` all memory
    - Use a tool that helps you find leaked memory
    - Perhaps implement your own reference counter
  - Use a "Conservative Garbage Collector" **malloc**
  - Just quit and restart your program a lot ("burn down the frat-house")
    - Design your server to crash!
      But memory leaks will ***slow down your program*** long before it actually crashes

So Why Do Memory Leaks Slow Things Down?

- Remember at the start we saw that pyramid of memory?
  - Small & fast -> cache
    Big & slow -> main memory
- Memory leaks lead to ***fragmentation***
  - As a consequence you use more memory, and its more scattered around
- Computers are designed to access ***contiguous*** memory
  - So things that cause your working memory to be spread out more and in smaller pieces slow things down
- There also may be nonlinearities:
  - Fine... Fine... Fine... Hit-A-Brick-Wall!

Memory Leaks & The Project...

- We have a test which ***will*** cause your program to crash if you leak in **`processInput()`**
  - How do we do this? We tell the OS to not give your program very much memory...
- But we won't check for leaks in your dictionary/hashtable
  - After all, you have to have it in memory for the entire program lifetime
- So keep that in mind when running valgrind...
  - "Leaked memory" allocated in **`readDictionary()`** 🤷‍♂️
  - "Leaked memory" allocated in **`processInput()`** 🤔

Faulty Heap Management

- What is wrong with this code?

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

This MAY be a memory leak
if we don't keep somewhere else
a copy of the original malloc'ed
pointer
  ```

Faulty Heap Management

- How many things are wrong with this code?

- ```
  void FreeMemX() {
    int fnh[3] = 0;
    ...
    free(fnh);
  }
  ```

  Can't `free` memory allocated on the stack

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

  Can't `free` memory that isn't the pointer from `malloc`

  Can't `free` memory twice

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);
}
```

`sizeof(char)` is 1 but should have `sizeof` as a good habit

Write off of the end of the array!

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;
}
```

Returning a pointer to stack-allocated memory!

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;
}
```

What if head is null?
Always check arguments.
Your code may be good...
But you make mistakes!
PROGRAM DEFENSIVELY

Using Memory You Don't Own

- What is wrong with this code?

```
void muckString(char *str) {
    str[0] = 'b';
}
void main(void) {
    char *str = "abc";
    muckString(str);
    puts(str);
}
```

Pointing to a static string...
Ruh Roh...

So Why Was That A Problem...

- When the compiler sees
  - **`char *foo = "abc"`**
  - The compiler interprets it as 'have the constant string "abc" somewhere in static memory, and have foo point to this'
    - If you have the same string "abc" elsewhere, it will point to the same thing...
      If you are lucky, the compiler makes sure that these string constants are set so you can't write
      - "Access violation", "bus error", "segfault"
- There is something safe however...
  - **`char foo[] = "abc"`**
  - The compiler interprets this as 'create a 4 character array on the stack, and initialize it to "abc"'
  - But of course we can't now say **`return foo;`**
    - Because that would be returning a pointer to something on the stack...

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!
-
```
int *ip;
ip = (int *) malloc(10*sizeof(int));
/* always check for ip == NULL */
… … …
ip = (int *) realloc(ip,20*sizeof(int));
/* always check 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;
}
```

Realloc might move the block!

Which means this hasn't updated *fib!

And Now A Bit of Security: Overflow Attacks


- ```
  struct UnitedFlyer{
      ...
      char lastname[16];
      char status[32];
      /* C will almost certainly lay this out in memory
         so they are adjacent */
      ...
  };
  ...
  void updateLastname(char *name, struct UnitedFlyer *f){
      strcpy(f->lastname, name);
  }
  ```
  ```

So what...

- Well, United has my status as:
  - `name = "Weaver", status = "normal-person: hated"`
- So what I need to do is get United to update my name!!!
  - So I provide United with my new name as:
    `Weaver              super-elite: actually like`
  - `name = "Weaver              super-elite: actually like", status = "super-elite: actually like"`
- And then update my name ***again*** back to just "Weaver"
  - `name = "Weaver", status = "super-elite: actually like"`
- Basic premise of a ***buffer overflow*** attack:
  - An input that overwrites past the end of the buffer and leaves the resulting memory in a state suitable to the attacker's goals

And Valgrind...

- Valgrind slows down your program by an order of magnitude, but...
  - It adds a tons of checks designed to catch most (but not all) memory errors
- Memory leaks
- Misuse of free
- Writing over the end of arrays
- You ***must*** run your program in Valgrind before you ask for debugging help from a TA!
  - Tools like Valgrind are absolutely essential for debugging C code