More On Memory (mis)-Management
Reminder on 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.
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...

• 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;
Structure Layout In Memory

• Everything in C is just buckets of 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
  • `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 */

- 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"
    - 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
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!
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
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 \texttt{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

Initial Empty Heap space from Operating System

Free Space

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

Object 1 Free

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 hierarchy 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”

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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 and Python don't have this problem
  - Java is designed to understand garbage collection:
    Able to have incremental collectors that don't require a long halt
  - 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
Clicker Question

• What will the following print:

```c
int a, b, c, *d;
a = 0;
b = 1;
c = 2;
d = &a;
(*d) += b + c;
d = &b;
(*d) += a + b + c;
printf(“a=%i b=%i\n”, a, b);
```

• A) a=0, b=3
• B) a=3, b=3
• C) a=3, b=4
• D) a=3, b=7
• E) I ditched class today and had a friend "borrow" my clicker
Administrivia
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?

```c
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);
}
```

- Out of bounds reads
- 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!
Faulty Heap Management

• What is wrong with this code?

```c
int *plk = NULL;
void genPLK() {
    plk = malloc(2 * sizeof(int));
    ...
    plk++; // This MAY be a memory leak
}
```

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?

```c
• 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); /* Can't free memory that isn't the pointer from malloc */
    ...
    free(fum);
    ...
    free(fum); /* Can't free memory twice */
}
```
Using Memory You Haven’t Allocated

• What is wrong with this code?

```c
void StringManipulate() {
    const char *name = "Safety Critical";  // sizeof(char) is 1
    char *str = malloc(10);  // but should have sizeof as a good habit
    strncpy(str, name, 10);
    str[10] = '\0';  // Write off of the end of the array!
    printf("%s\n", str);
}
```
Using Memory You Don’t Own

What’s wrong with this code?

```c
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?

```c
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?

```c
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!

```c
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?

```c
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 */
  ...
};

  ...
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
Hijacking Control Flow
With Buffer Overflows...

• Reminder: The stack stores a lot of stuff...
  • Not just local variables, but where to return execution to when a function returns

• So if you write some code with a stack-allocated array
  • char foo[32];
  
    gets(foo); /* gets reads input into the string until a newline */

• A bad dude gets to provide your program a string (e.g. because it is a server)
  • His string is significantly longer than 32 characters...

• Result:
  • His string overwrites other local variables, including where the function is supposed to return!
  • And now your program is his program!
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
Levels of Representation/Interpretation

- **High Level Language Program (e.g., C)**
- **Assembly Language Program (e.g., MIPS)**
- **Machine Language Program (MIPS)**

**Compiler**

```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

Any data or instruction can be represented as a number, i.e., data or instructions.

**Assembler**

```
0000 1001 1100 0110 1010 1111 0101 1000
1010 1111 0101 1000 0000 1001 1100 0110
1100 0110 1010 1111 0101 1000 0000 1001
0101 1000 0000 1001 1100 0110 1010 1111
```

**Machine Interpretation**

- **Hardware Architecture Description (e.g., block diagrams)**
- **Architecture Implementation**

**Logic Circuit Description (Circuit Schematic Diagrams)**

**Register File**

**ALU**
Assembly Language

- Basic job of a CPU: execute lots of instructions.
- Instructions are the primitive operations that the CPU may execute
  - The stored program in "stored program computer"
- Different CPUs implement different sets of instructions. The set of instructions a particular CPU implements is an Instruction Set Architecture (ISA).
  - Examples: ARM, Intel x86, Intel x64 (64b x86), MIPS, RISC-V, IBM/Motorola PowerPC (old Mac), Motorola 68k (really old Mac), Intel IA64 (aka Itanic), ...
Instruction Set Architectures

• Early trend was to add more and more instructions to new CPUs to do elaborate operations
  • VAX architecture had an instruction to multiply polynomials!
• RISC philosophy (Cocke IBM, Patterson, Hennessy, 1980s)
  Reduced Instruction Set Computing
  • Keep the instruction set small and simple, makes it easier to build fast hardware
  • Let software do complicated operations by composing simpler ones
Berkeley Acknowledge for the first RISC computer
The RISC-V Instruction Set Architecture

RISC-V (pronounced "risk-five") is a new instruction set architecture (ISA) that was originally designed to support computer architecture research and education, which we now hope will become a standard open architecture for industry implementations. RISC-V was originally developed in the Computer Science Division of the EECS Department at the University of California, Berkeley.

Pretty much everything in Berkeley uses RISC-V
But at the same time... All RISCs are mostly the same except for one or two silly design decisions

- **MIPS:**
  - "The Branch Delay Slot": The instruction immediately after an if is always executed

- **SPARC:**
  - "Register Windows": Map a larger set of registers for “improved” function calling

- **ARM:**
  - 32b is ugly as sin...
  - But 64b is pretty much generic RISC with condition codes for instructions: Allow you to say "only do this instruction if a previous value was TRUE/FALSE"

- **RISC-V:**
  - You will hate how immediates are encoded until you understand how muxes work...
And x86s these days are really RISCs in disguise...

- They start by translating the x86/x64 CISC instructions into a series of "micro operations"
  - These instructions are then executed on something that looks very much like a RISC processor
- They just end up costing a fair bit more... Because they first have to turn x86/x64 into a RISC internal structure
  - Basically 2-3 pipeline stages...
- “With enough rocket boosters anything can fly, and Intel has strapped that pig to a Saturn V” -Me
So Why Do Some Architectures "Win"?

- The big winners: x86/x64 (desktop) and Arm (phones/embedded)
  - Neither are the cheapest nor the best architectures available...

- They won because of the legacy software stack...
  - x86 had Windows and then Linux for servers and a history of optimizing for performance *without breaking old things*.
  - For a decade+ you'd be able to just make everything run faster by throwing some money at the problem...
  - Arm became entrenched with Linux->Android in the phone market

- But since *our* focus is understanding how computers work, our software stack is RISC-V