CS 61C: Great Ideas in Computer Architecture

Memory Management and Usage

Instructor: Justin Hsia

Review of Last Lecture

- Arrays
  - Traverse using pointer or array syntax
  - If characters, call them “strings” and null-terminate
- Pointer arithmetic moves the pointer by the size of the thing it’s pointing to
  - C accommodates for pointing to structs and pointers
- From Discussion: Bit-masking

Great Idea #1: Levels of Representation/Interpretation

Higher-Level Language Program (e.g. C)

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

We are here

Compiler

Assembly Language Program (e.g. MIPS)

```
lw    $t0, 0($2)
lw    $t1, 4($2)
sw    $t1, 0($2)
sw    $t0, 4($2)
```

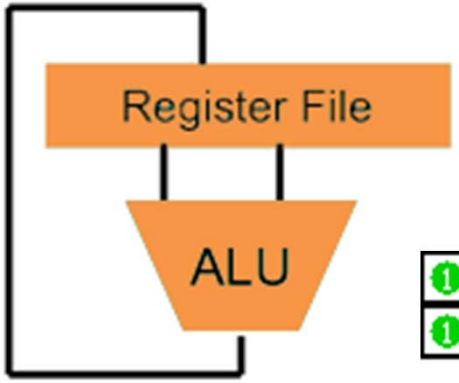
Assembler

Machine Language Program (MIPS)

```
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
```

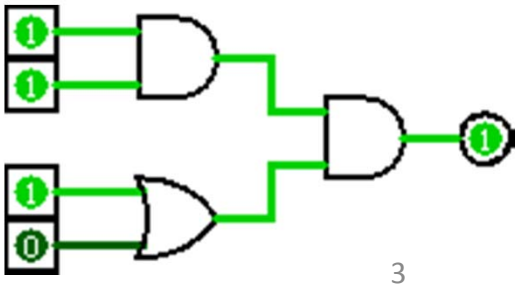
Machine Interpretation

Hardware Architecture Description (e.g. block diagrams)



Architecture Implementation

Logic Circuit Description (Circuit Schematic Diagrams)

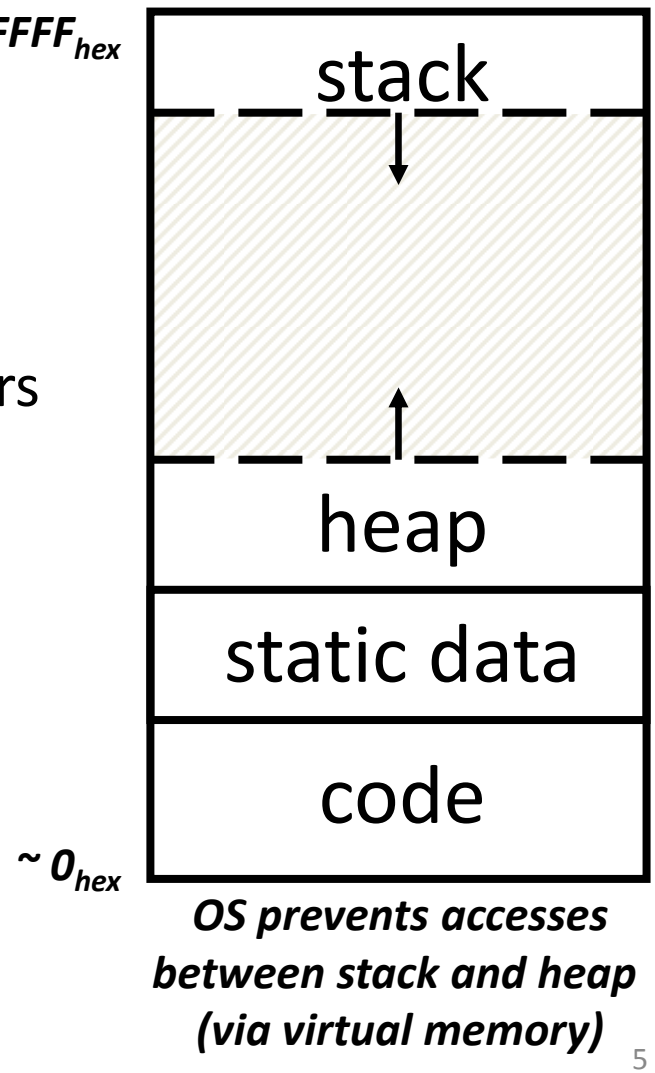


Agenda

- C Memory Layout
  - Stack, Static Data, and Code
- Administrivia
- Dynamic Memory Allocation
  - Heap
- Memory Management
- C Wrap-up: Linked List Example
- Bonus: Common Memory Problems

C Memory Layout

- Program's *address space* contains 4 regions:
  - Stack: local variables, grows downward
  - Heap: space requested for pointers via `malloc();` resizes dynamically, grows upward
  - Static Data: global and static variables, does not grow or shrink
  - Code: loaded when program starts, does not change



OS prevents accesses between stack and heap (via virtual memory)

Where Do the Variables Go?

- Declared outside a procedure:

  Static Data

- Declared inside a procedure:

  Stack

  – `main()` is a procedure

  – Freed when procedure returns

- Dynamically allocated:

  Heap

  – i.e. malloc (we will cover this shortly)

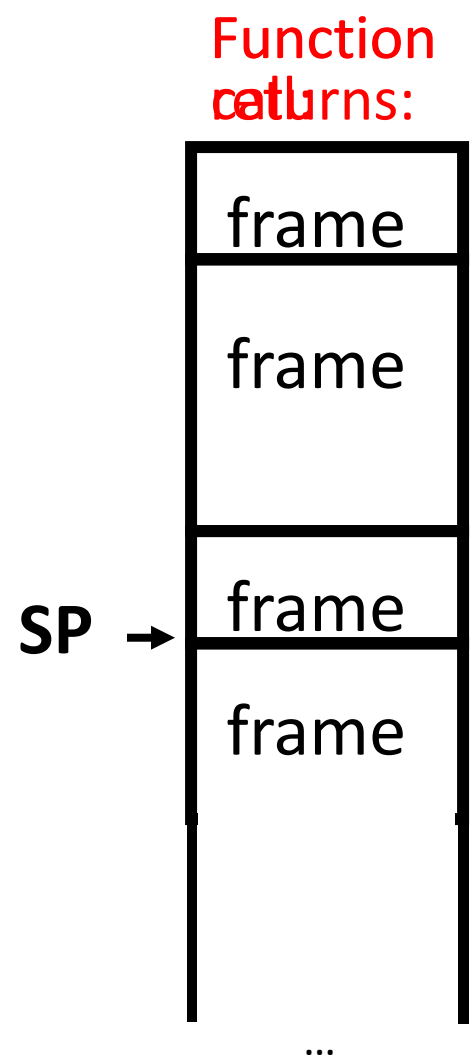
```
#include <stdio.h>

int varGlobal;

int main() {
  int varProc;
  int *varDyn =
    malloc(sizeof(int));
}
```

The Stack

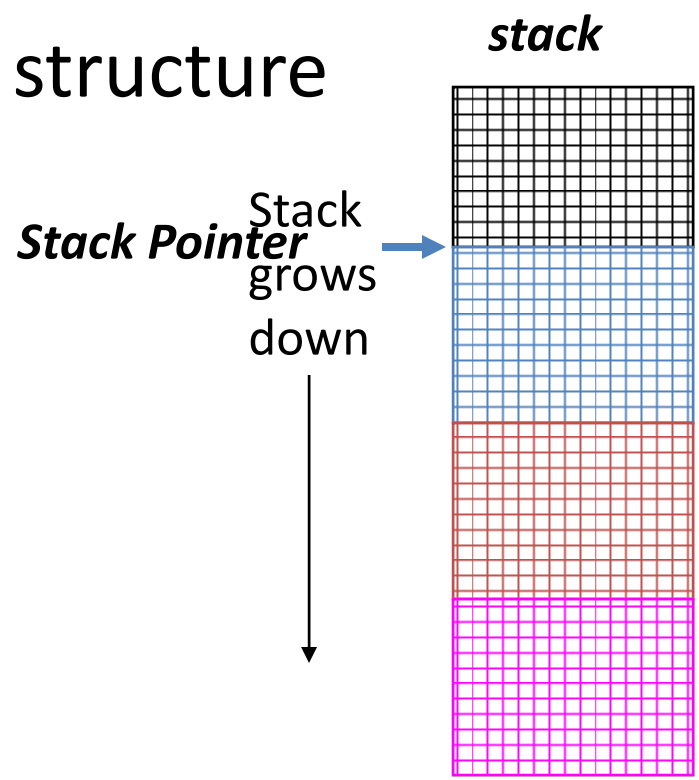
- Each stack frame is a contiguous block of memory holding the local variables of a single procedure
- A stack frame includes:
  - Location of caller function
  - Procedure arguments
  - Space for local variables
- Stack pointer (SP) tells where lowest (current) stack frame is
- When procedure ends, stack frame is tossed off the stack; frees memory for future stack frames



The Stack

- Last In, First Out (LIFO) data structure

```
int main() {
    a(0);
    return 1; }
void a(int m) {
    b(1); }
void b(int n) {
    c(2);
    e(4); }
void c(int o) {
    printf("c"); }
void d(int p) {
    printf("d"); }
```



Stack Misuse Example

```
int *getPtr() {
  int y;
  y = 3;
  return &y;
};

int main () {
  int *stackAddr,content;
  stackAddr = getPtr();
  content = *stackAddr;
  printf("%d", content); /* 3 */
  content = *stackAddr;
  printf("%d", content); /* 0 */
};
```

Never return pointers to local variable from functions

Your compiler will warn you about this – don't ignore such warnings!

printf overwrites stack frame

Static Data

- Place for variables that persist
  - Data not subject to comings and goings like function calls
  - Examples: String literals, global variables
- Size does not change, but its data can

Code

- Copy of your code goes here
  - C code becomes data too!
- Does not change

Question: Which statement below is FALSE?
All statements assume each variable exists.

```
void funcA() {int x; printf("A");}
void funcB() {
  int y;
  printf("B");
  funcA();
}
void main() {char *s = "s"; funcB();}
```

- ☐ x is at a lower address than y
- ☐ x and y are in adjacent frames
- ☐ x is at a lower address than *s
- ☐ y is in the 2nd frame from the top of the Stack

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Administrivia

- Meet your fellow classmates! Form study groups and get your questions answered
  - Utilize Piazza, labs, discussions, and OHs
- End of the first week!
  - HW1 due Sunday
  - TA and Instructor response time increase drastically (slower) over the weekend
  - Check key card access to lab today
  - Justin's OH (this week only): Sat @ 10-12 in lab
- Suggestion for weekend: finish HW1, try Lab3, then look at HW2Q1

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Dynamic Memory Allocation

- Sometimes you don't know how much memory you need beforehand
  - Examples: Input files, user input
- Dynamically allocated memory goes on the Heap – more permanent than Stack
- Need as much space as possible without interfering with Stack
  - Start at opposite end and grow towards Stack

Allocating Memory

- 3 functions for requesting memory: `malloc()`, `calloc()`, and `realloc()`
  - http://en.wikipedia.org/wiki/C_dynamic_memory_allocation#Overview_of_functions
- **`malloc(`*`n`*`)`**
  - Allocates a continuous block of ***n* bytes** of uninitialized memory (contains garbage!)
  - Returns a pointer to the beginning of the allocated block; NULL indicates failed request (check for this!)
  - Different blocks not necessarily adjacent

Using malloc()

- Almost always used for arrays or structs
- Good practice to use `sizeof()` and typecasting

```
int *p = (int *) malloc(n*sizeof(int));
```

  - `sizeof()` makes code more portable
  - `malloc()` returns `void *`, typecast will help you catch coding errors when pointer types don't match
- Can use array or pointer syntax to access
- Make sure you don't lose the original address
  - p++ is a **BAD IDEA**; use a separate pointer

Releasing Memory

- Release memory on the Heap using `free()`
  - Memory is limited, release when done
- **`free(p)`**
  - Pass it pointer p to beginning of allocated block; releases the whole block
  - p must be the address *originally* returned by `m/c/realloc()`, otherwise throws system exception
  - Don't call `free()` on a block that has already been released

Dynamic Memory Example

- Need `#include <stdlib.h>`

```
typedef struct {
   int x;
   int y;
} point;

point *rect; /* opposite corners = rectangle */
...
if( !(rect=(point *) malloc(2*sizeof(point))) ) {
   printf("\nOut of memory!\n");
   exit(1);
}
...
free(rect);
```

Joint struct definition and typedef

Check for returned NULL

Do NOT change `rect` during this time!!!

Question: Want output: a[] = {0,1,2} with no errors. Which lines do we need to change?

```
1   #define N 3
2   int *makeArray(int n) {
3     int *ar;
4     ar = (int *) malloc(n);
5     return ar;
6   }
7   void main() {
8     int i,*a = makeArray(N);
9     for(i=0; i<N; i++)
10      *a++ = i;
11    printf("a[] =
        {%i,%i,%i}",a[0],a[1],a[2]);
12    free(a);
13  }
```

- ☐ 4, 12
- ☐ 5, 12
- ☐ 4, 10
- ☐ 5, 10

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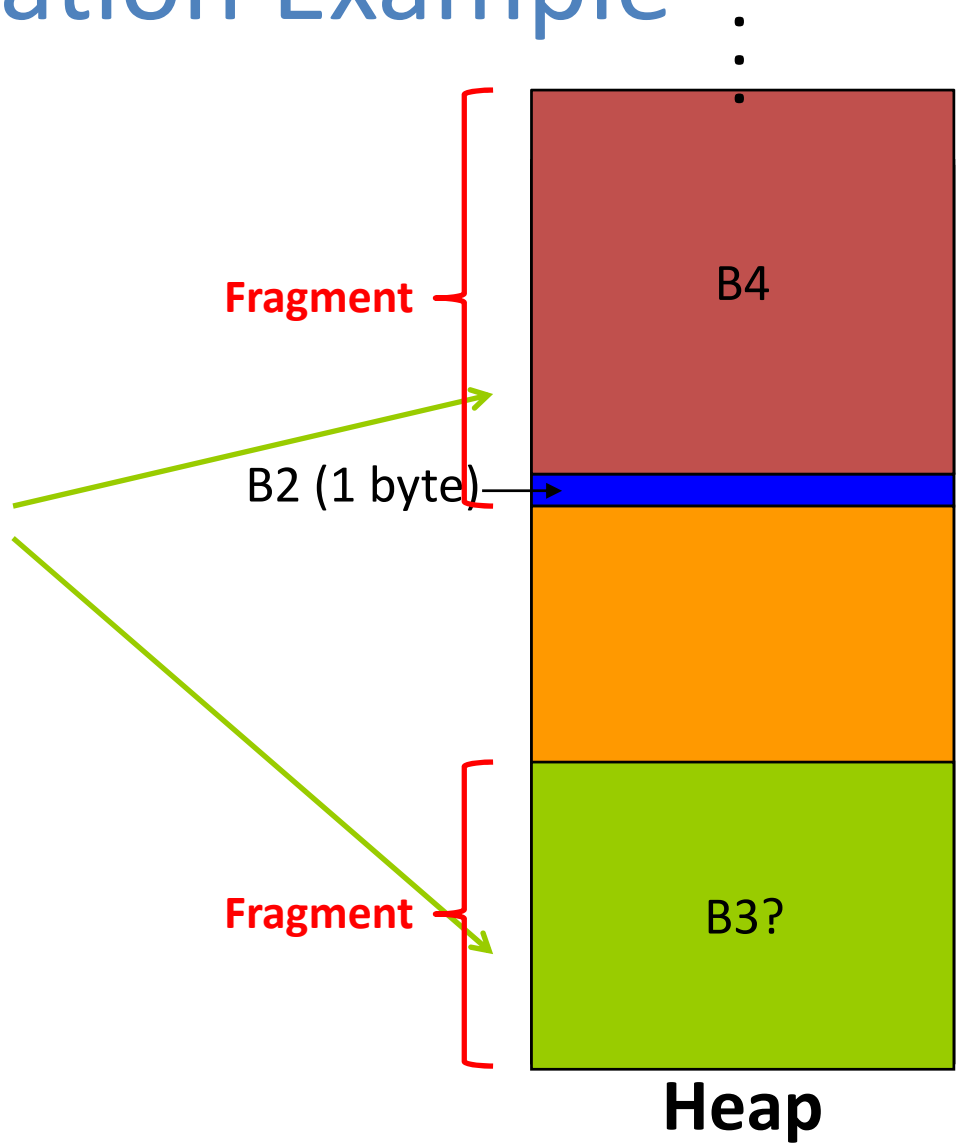
Memory Management

- Many calls to `malloc()` and `free()` with many different size blocks – where are they placed?
- Want system to be fast with minimal memory overhead
  - Versus automatic garbage collection of Java
- Want to avoid *fragmentation*, the tendency of free space on the heap to get separated into small chunks

Fragmentation Example

1) Block 1: malloc(100)
2) Block 2: malloc(1)
3) Block 1: free(B1)
4) Block 3: malloc(50)
   - What if malloc(101)?
5) Block 4: malloc(60)



Basic Allocation Strategy: K&R

- Section 8.7 offers an implementation of memory management (linked list of free blocks)
  - If you can decipher the code, you're well-versed in C!
- This is just one of many possible memory management algorithms
  - Just to give you a taste
  - No single best approach for every application

K&R Implementation

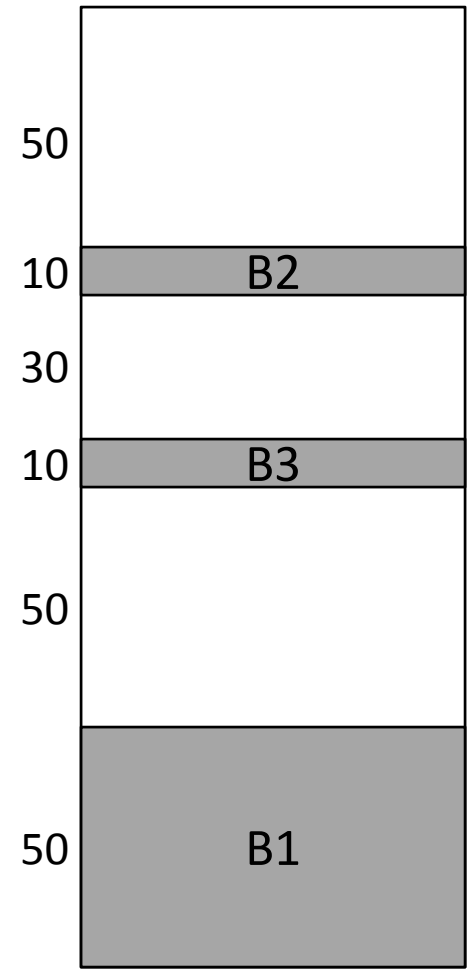
- Each block holds its own size and pointer to next block
- `free()` adds block to the list, combines with adjacent free blocks
- `malloc()` searches free list for block large enough to meet request
  - If multiple blocks fit request, which one do we use?

Choosing a Block in malloc()

- **Best-fit:** Choose smallest block that fits request
  - Tries to limit wasted fragmentation space, but takes more time and leaves lots of small blocks
- **First-fit:** Choose first block that is large enough (always starts from beginning)
  - Fast but tends to concentrate small blocks at beginning
- **Next-fit:** Like first-fit, but resume search from where we last left off
  - Fast and does not concentrate small blocks at front

Question: Which allocation system and set of requests will create a continuous block in the Heap? B3 was the last fulfilled request.

- ☐ Best-fit: `malloc(50),malloc(50)`
- ☐ First-fit: `malloc(50),malloc(30)`
- ☐ Next-fit: `malloc(30),malloc(50)`
- ☐ Next-fit: `malloc(50),malloc(30)`



Get To Know Your Instructor

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Linked List Example

- We want to generate a linked list of strings
  - This example uses structs, pointers, `malloc()`, and `free()`
- Create a structure for nodes of the list:

```
struct Node {
  char *value;
  struct Node *next;
};
```

Notice the recursive definition!

Simplify Code with `typedef`

- It gets annoying to type out `struct ListNode` over and over again
  - Define new variable type for struct:

Method 1:

```
struct Node {
    char *value;
    struct Node *next;
};
typedef struct Node ListNode;
```

Method 2:

```
typedef struct Node {
    char *value;
    struct Node *next;
} NodeStruct;
```

- Can further rename pointers:

```
typedef ListNode * List;   ──→  List myLinkedList;
typedef char * String;     ──→  String value;
```

Adding a Node to the List

- Want functionality as shown:

```
String s1 = "start", s2 = "middle";
String s3 = "end";
List theList = NULL;
theList = addNode(s3, theList);
theList = addNode(s2, theList);
theList = addNode(s1, theList);
```

In what part of memory are these stored?

Must be able to handle a NULL input

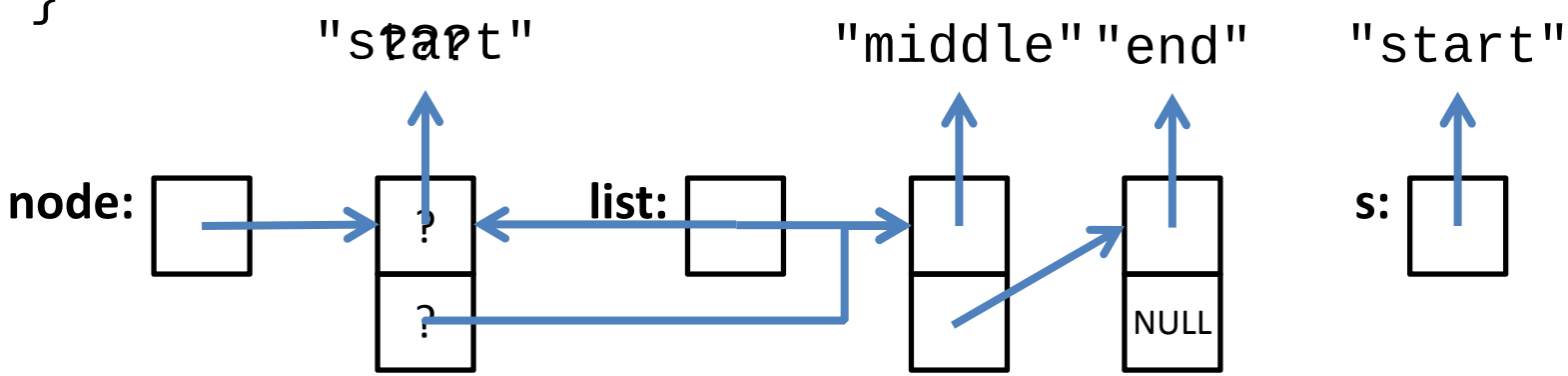
If you're more familiar with Lisp/Scheme, you could name this function `cons` instead.

Adding a Node to the List

- Let's examine the 3rd call (`"start"`):

```
List addNode(String s, List list) {
  List node = (List) malloc(sizeof(NodeStruct));
  node->value = (String) malloc (strlen(s) + 1);
  strcpy(node->value, s);
  node->next = list;
  return node;
}
```

Don't forget this for the null terminator!

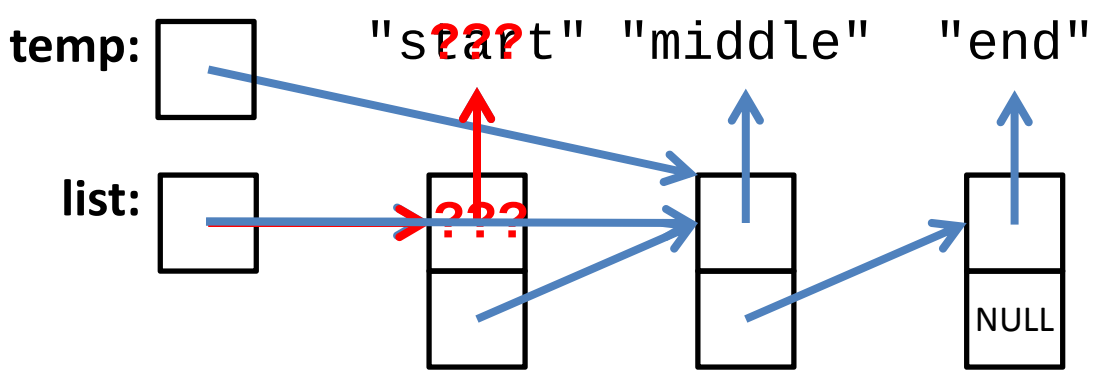


Removing a Node from the List

- Delete/free the first node (`"start"`):

```
List deleteNode(List list) {
  List temp = list->next;
  free(list->value);
  free(list);
  return temp;
}
```

What happens if you do these in the wrong order?



Additional Functionality

- How might you implement the following:
  - Append node to end of a list
  - Delete/free an entire list
  - Join two lists together
  - Reorder a list alphabetically (sort)

Summary

- C Memory Layout
  - **Static Data:** globals and string literals
  - **Code:** copy of machine code
  - **Stack:** local variables (grows & shrinks in LIFO manner)
  - **Heap:** dynamic storage using `malloc` and `free`
    The source of most memory bugs!
- Memory Management
  - Want fast with little *fragmentation*

BONUS SLIDES

You are responsible for the material contained on the following slides, though we may not have enough time to get to them in lecture.

They have been prepared in a way that should be easily readable and the material will be touched upon in the following lecture.

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Know Your Memory Errors

(Definitions taken from `http://www.hyperdictionary.com`)

- Segmentation Fault ← More common in 61C

  "An error in which a running Unix program attempts to access memory not allocated to it and terminates with a segmentation violation error and usually a core dump."

- Bus Error ← Less common in 61C

  "A fatal failure in the execution of a machine language instruction resulting from the processor detecting an anomalous condition on its bus. Such conditions include invalid address alignment (accessing a multi-byte number at an odd address), accessing a physical address that does not correspond to any device, or some other device-specific hardware error."

Common Memory Problems

1) Using uninitialized values
2) Using memory that you don't own
   - Using NULL or garbage data as a pointer
   - De-allocated stack or heap variable
   - Out of bounds reference to stack or heap array
3) Using memory you haven't allocated
4) Freeing invalid memory
5) Memory leaks

Using Uninitialized Values

- What is wrong with this code?

```
void foo(int *p) {
  int j;
  *p = j;
}

void bar() {
  int i=10;
  foo(&i);
  printf("i = %d\n", i);
}
```

`j` is uninitialized (garbage), copied into `*p`

Using `i` which now contains garbage

Using Memory You Don't Own (1)

- 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?

No warnings! Just Seg Fault that needs finding!

Using Memory You Don't Own (2)

- What's wrong with this code?

```
char *append(const char* s1, const char *s2) {
   const int MAXSIZE = 128;
   char result[MAXSIZE];
   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;
}
```

Local array appears on Stack

Pointer to Stack (array) no longer valid once function returns

Using Memory You Don't Own (3)

- What is wrong with this code?

```
typedef struct {
   char *name;
   int age;
} Profile;

Profile *person =(Profile *)malloc(sizeof(Profile));
char *name = getName();
person.name = malloc(sizeof(char)*strlen(name));
strcpy(person.name,name);
...   // Do stuff (that isn't buggy)
free(person);
free(person.name);
```

Did not allocate space for the null terminator!
Want `(strlen(name)+1)` here.

Accessing memory after you've freed it.
These statements should be switched.

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';          ← Write beyond array bounds
  printf("%s\n", str);     ← Read beyond array bounds
}
```

Using Memory You Haven't Allocated

- What is wrong with this code?

```
char buffer[1024]; /* global */
int main(int argc,char *argv[]) {
  strcpy(buffer,argv[1]);
  ...
}
```

What if more than a kibi characters?

This is called BUFFER OVERRUN or BUFFER OVERFLOW and is a major security flaw!!!

Freeing Invalid Memory

- What is wrong with this code?

```
void FreeMemX() {
  int fnh = 0;
  free(&fnh);  ← 1) Free of a Stack variable
}

void FreeMemY() {
  int *fum = malloc(4*sizeof(int));
  free(fum+1);  ← 2) Free of middle of block
  free(fum);
  free(fum);  ← 3) Free of already freed block
}
```

Memory Leaks

- What is wrong with this code?

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

Overrode old pointer!
No way to free those 4*sizeof(int) bytes now

foo( ) leaks memory

Memory Leaks

- **Rule of Thumb:** More `mallocs` than `frees` probably indicates a memory leak
- Potential memory leak: Changing pointer – do you still have copy to use with `free` later?

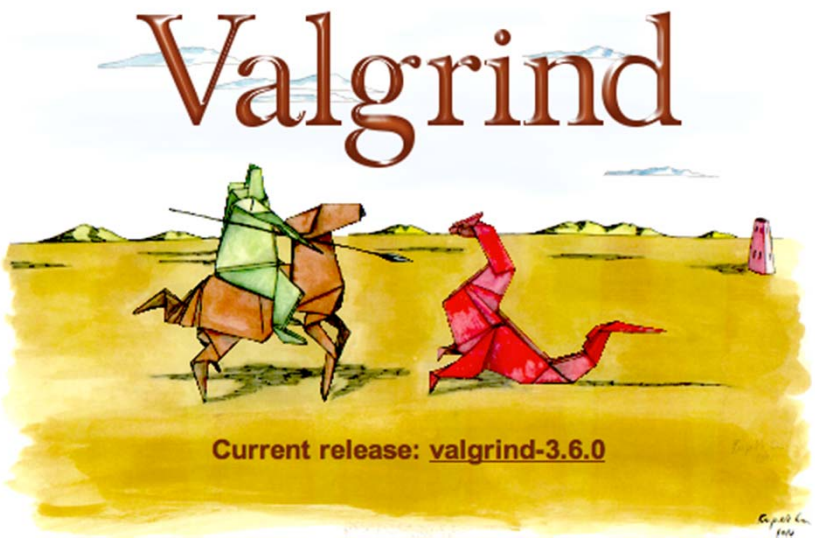
```
plk = (int *)malloc(2*sizeof(int));
...
plk++;
```

← Typically happens through incrementation or reassignment

Debugging Tools

- Runtime analysis tools for finding memory errors
  - Dynamic analysis tool:

    Collects information on memory management while program runs
  - No tool is guaranteed to find ALL memory bugs; this is a very challenging programming language research problem



http://valgrind.org

- You will be introduced to Valgrind in Lab 3