Great Ideas in Computer Architecture

C: Memory Management and Usage

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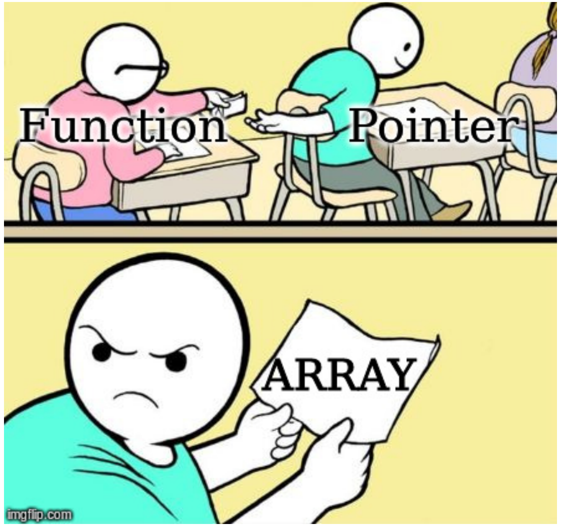


Review

- Pointers and arrays are very similar
- Strings are just char pointers/arrays with a null terminator at the end
- Pointer arithmetic moves the pointer by the size of the thing it's pointing to
- Pointers are the source of many C bugs!

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;
```

This week

Compiler

Assembly Language Program (e.g. RISC-V)

```
lw   t0, 0(S2)
lw   t1, 4(S2)
sw   t1, 0(S2)
sw   t0, 4(S2)
```

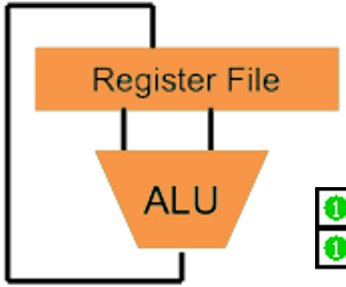
Assembler

Machine Language Program (RISC-V)

```
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
```

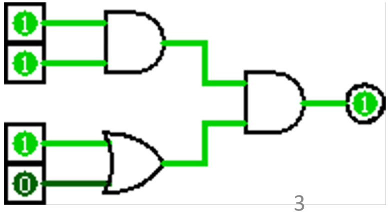
Machine Interpretation

Hardware Architecture Description (e.g. block diagrams)



Architecture Implementation

Logic Circuit Description (Circuit Schematic Diagrams)



Agenda

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

C Memory Layout

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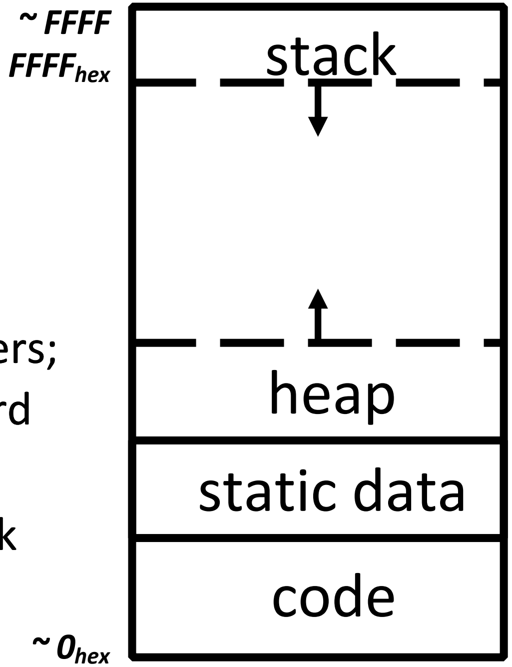


OS prevents accesses between stack and heap (via virtual memory)

Where Do the Variables Go?

- Declared outside a function:
  - Static Data
- Declared inside a function:
  - Stack
  - main() is a function
  - Freed when function returns
- Dynamically allocated:
  - Heap
  - i.e. malloc (we will cover this shortly)

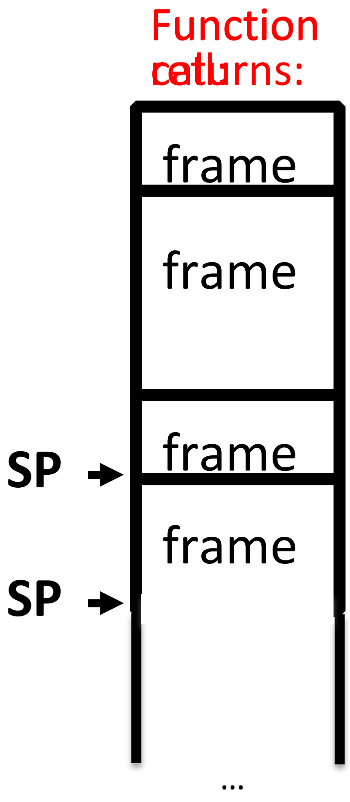
```
#include <stdio.h>

int varGlobal;

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

The Stack

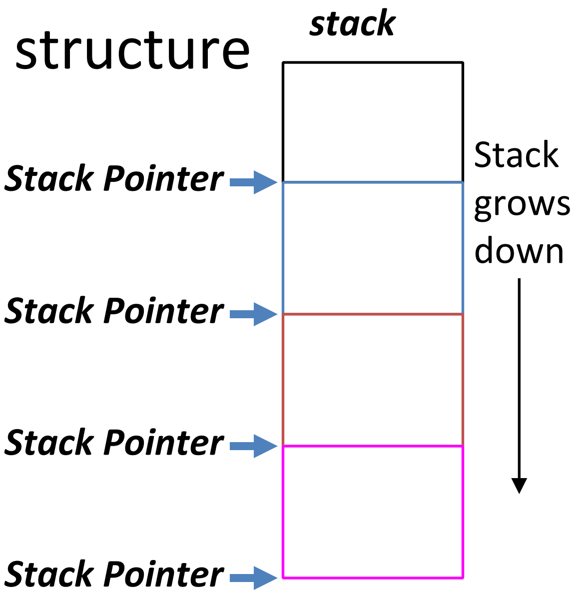
- Each stack frame is a contiguous block of memory holding the local variables of a single procedure
- A stack frame includes:
  - Location of caller function
  - Function arguments
  - Space for local variables
- Stack pointer (SP) tells where lowest (current) stack frame is
- When procedure ends, stack pointer is moved back (but data remains (garbage!)); 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);
   d(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); /* ? */
};
```

Never return pointers to local variable from functions

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

printf overwrites stack frame

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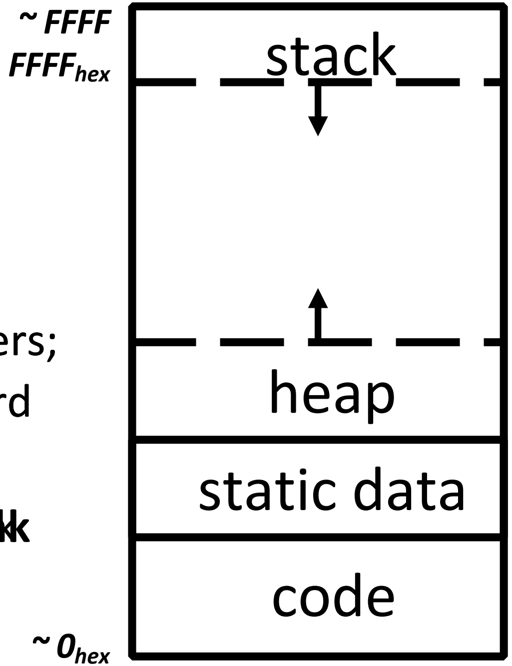

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Static Data

- Place for variables that persist
  - Data not subject to comings and goings like function calls
  - Examples: **String literals, global variables**
  - String literal example: char * str = “hi”;
  - Do not be mistaken with: char str[] = “hi”;
    - This will put str on the stack!
- Size does not change, but sometimes data can
  - Notably string literals cannot

Code

- Copy of your code goes here
  - C code becomes data too!
- Does (should) not change
  - Typically read only

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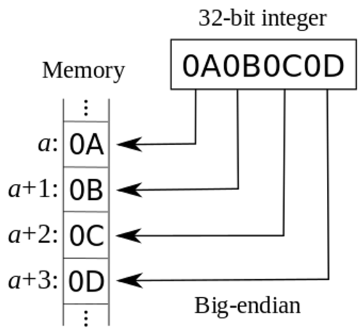
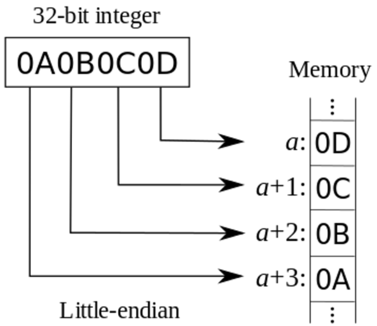
Addresses

- The size of an address (and thus, the size of a pointer) in bytes depends on architecture (eg: 32-bit Windows, 64-bit Mac OS)
  - eg: for 32-bit, have 2^{32} possible addresses
  - In this class, we will assume a machine is a 32-bit machine unless told otherwise
- If a machine is **byte-addressed**, then each of its addresses points to a unique **byte**
  - word-addresses = address points to a word
  - In this class, we will assume a machine is byte-addressed unless told otherwise.
- Question: on a byte-addressed machine, how can we order the bytes of an integer in mem?
  - Answer: it depends

Endianness

- Big Endian:
  - Descending numerical significance with ascending memory addresses
- Little Endian
  - Ascending numerical significance with ascending memory addresses

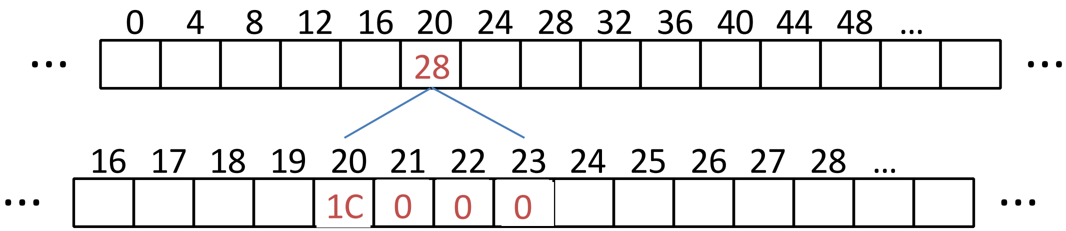




Source: https://en.wikipedia.org/wiki/Endianness

Endianness

- In what order are the bytes within a data type stored in memory? Remember: 28 = 0x 00 00 00 1C



- Big Endian:
  - Descending numerical significance with ascending memory addresses
- Little Endian
  - Ascending numerical significance with ascending memory addresses
  - In this class, we will assume a machine is little endian unless otherwise stated.

Common Mistakes

- Endianness ONLY APPLIES to values that occupy multiple bytes
- Endianness refers to STORAGE IN MEMORY NOT number representation
- Ex: char c = 97
  - c == 0b01100001 in both big and little endian
- Arrays and pointers still have the same order
  - int a[5] = {1, 2, 3, 4, 5} (assume address 0x40)
  - &(a[0]) == 0x40 && a[0] == 1
    - in both big and little endian

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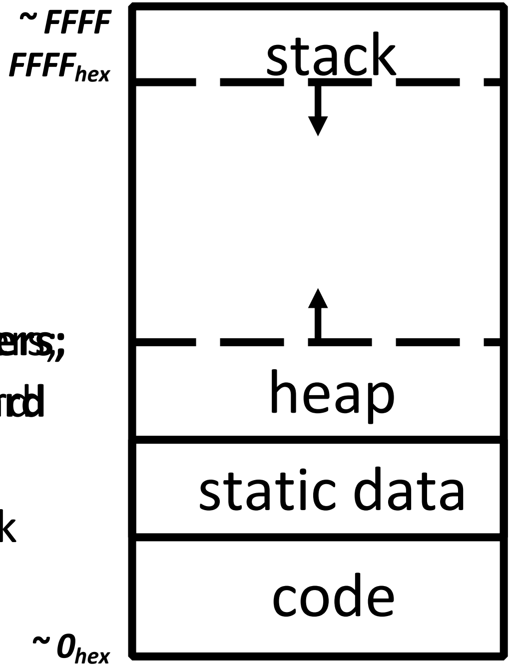

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Dynamic Memory Allocation

- Want persisting memory (like static) even when we don’t know size at compile time?
  - e.g. input files, user interaction
  - Stack won’t work because stack frames aren’t persistent
- 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

sizeof()

- If integer sizes are machine dependent, how do we tell?
- Use `sizeof()` operator
  - Returns size in number of `char-sized units` of a variable or data type name
    - Examples: `int x; sizeof(x); sizeof(int);`
  - `sizeof(char)` is ALWAYS 1!
    - Note the number of bits contained in a char is also not always 1 Byte though it generally is. This means sizeof is normally returning the number of Bytes which a variable or data type is.
    - In this class, we will assume a character is always 1 Byte unless otherwise stated.

sizeof() and Arrays

- Can we use sizeof to determine a length of an array?
  - **Generally no** but there is an exception!
    - `int a[61];`
    - If I was to perform `sizeof(a)`, I would get back the number of characters it would take to fill the array `a`.
    - To get the number of elements, I could do:
      - `sizeof(a) / sizeof(int)`
    - This **ONLY** works for arrays defined on the stack **IN THE SAME FUNCTION**.
  - This is just something fun you should know, but please do not do this! You should be keeping track of an array size elsewhere!

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

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 or on NULL
  - Make sure you don't lose the original address
    - `eg: p++` is a **BAD IDEA**; use a separate pointer

Calloc

- void *calloc(size_t nmemb, size_t size)
  - Like malloc, except it initializes the memory to 0
  - nmemb is the number of members
  - size is the size of each member
  - Ex for allocating space for 5 integers
    - int *p = (int *) calloc (5, sizeof (int));

Realloc

- What happens when I need more or less memory in an array
- void *realloc(void *ptr, size_t size)
  - Takes in a ptr that has been the return of malloc/calloc/realloc and a new size
  - Returns a pointer with now size space (or NULL) and copies any contents from ptr
- Realloc can move or keep the address the same
- DO NOT rely on old ptr values

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);
```

Check for returned NULL

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

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Know Your Memory Errors

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

- Segmentation Fault ← More common in 61C

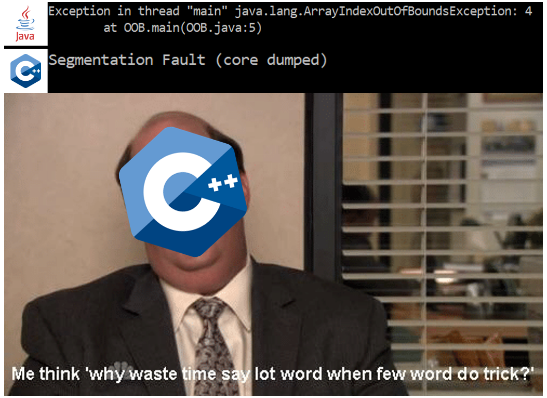
  "An error in which a running Unix program attempts to access memory not allocated to it and terminates with a segmentation violation error and usually a core dump."

- 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) Freeing invalid memory
4) 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 is 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 (; 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(sizeof (char) * 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 foo(char *str) {
   strcpy(buffer,str);
   ...
}
```

What if more than a kibi characters?

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

C String Standard Functions Revised

- Accessible with `#include <string.h>`
- `int strnlen(char *string,size_t n);`
  - Returns the length of string (not including null term), searching up to n
- `int strncmp(char *str1, char *str2, size_t n);`
  - Return 0 if `str1` and `str2` are identical (how is this different from `str1 == str2`?), comparing up to n bytes
- `char *strncpy(char *dst, char *src, size_t n);`
  - Copy up to the first n bytes of string `src` to the memory at `dst`. Caller must ensure that `dst` has enough memory to hold the data to be copied
  - Note: `dst = src` only copies *pointer* (the address)

A Safer Version

```
#define ARR_LEN 1024;
char buffer[ARR_LEN]; /* global */

  int foo(char *str) {
    strncpy(buffer,str, ARR_LEN);
    ...
  }
```

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);
   free(fum);
   free(fum);
}
```

2) Free of middle of block

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

- Remember that Java has garbage collection but C doesn't
- Memory Leak: when you allocate memory but lose the pointer necessary to free it
- **Rule of Thumb:** More `malloc`s than `free`s probably indicates a memory leak

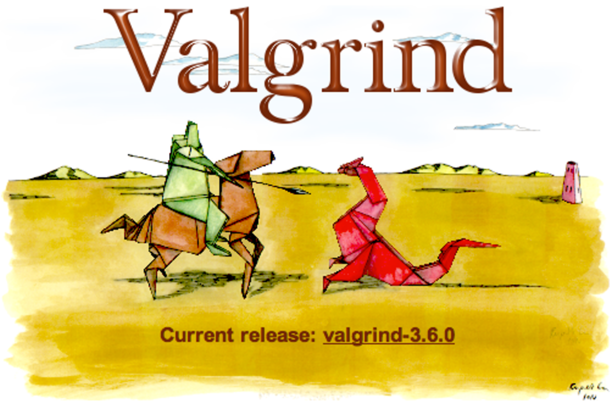
- Potential memory leak: Changing pointer – do you still have copy to use with `free` later?

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

Mem Leak! 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 1

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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;
} node;
```

The link of the linked list

Adding a Node to the List

- Want to write addNode to support functionality as shown:

```
char *s1 = "start", *s2 = "middle",
*s3 = "end";
struct node *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

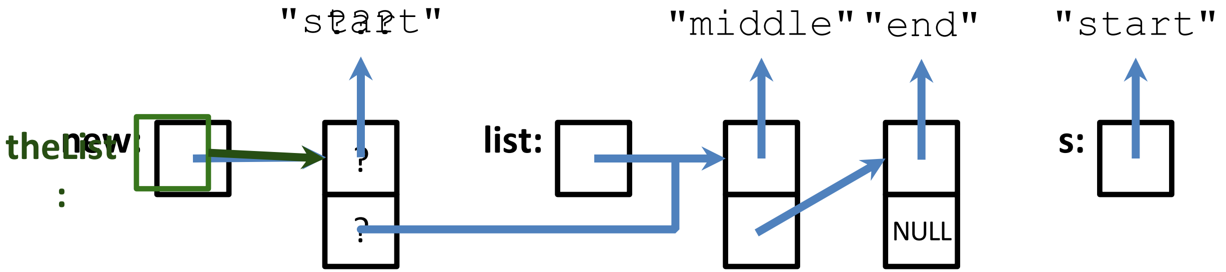
If you're more familiar with Lisp/Scheme, you could name this function `cons` instead.

Adding a Node to the List

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

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

Don't forget this for the null terminator!

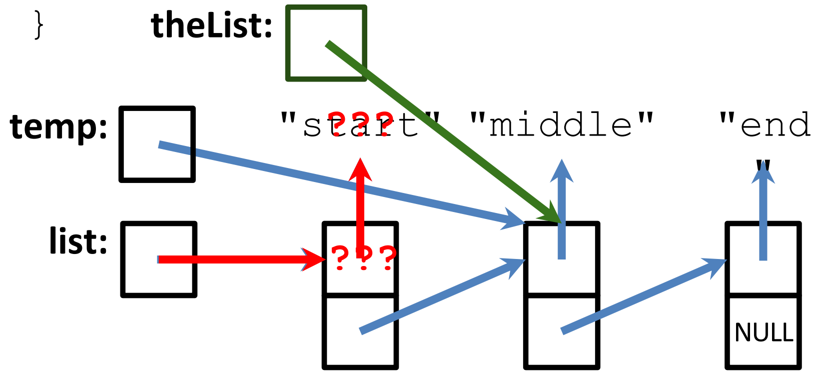


Removing a Node from the List

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

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

What happens if you do these in the wrong order?

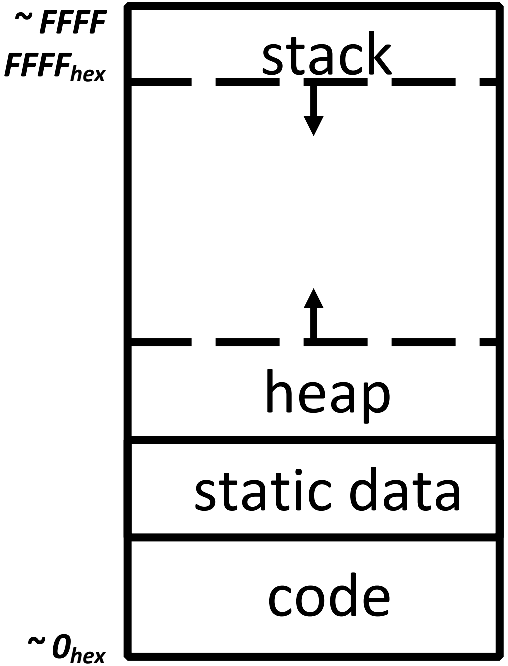


Additional Functionality

- 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
  - **Stack:** local variables (grows & shrinks in LIFO manner)
  - **Static Data:** globals and string literals
  - **Code:** copy of machine code
  - **Heap:** dynamic storage using `malloc` and `free`
    The source of most memory bugs!
- Common Memory Problems
- Last C Lecture!



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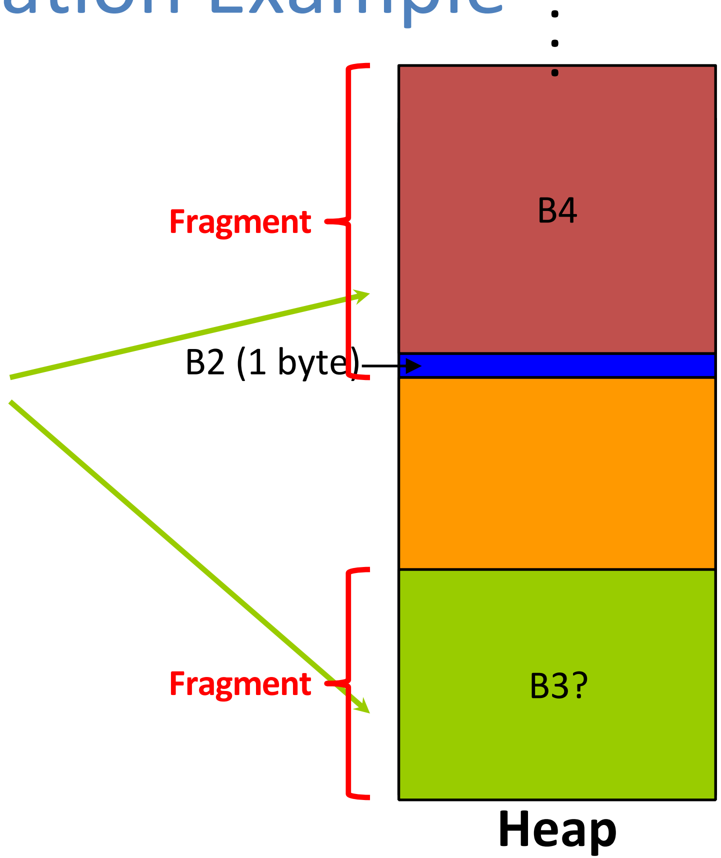
Bonus Slides!!!11!1!one!!

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