C Data Structures & Dynamic Mem

Introduction to Computer Systems, Fall 2024

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Meghana Vasireddy
Perrie Quek
Sidharth Roy
Sydnie-Shea Cohen
Vivi Li
Yousef AlRabiah

Poll Everywhere

pollev.com/cis2400

- How are you? Any Questions from last lecture?

Upcoming Due Dates

- HW01 Due tomorrow
  - Can always ask for extensions if you want
  - Reminder: only need to do 3 of the 5 "rating 4" puzzles
- Check-in out tonight or tomorrow, due before lecture on Tuesday
- 1-on-1 from is live
- Recitation was recorded ☺

Lecture Outline

- **Structs Warm-up**
- The Heap
  - malloc() & free()
- Modules & Header Files
- Dynamic Memory Pitfalls
- GDB & Valgrind

Poll Everywhere

Discuss

- What's the state after calling remaster()?

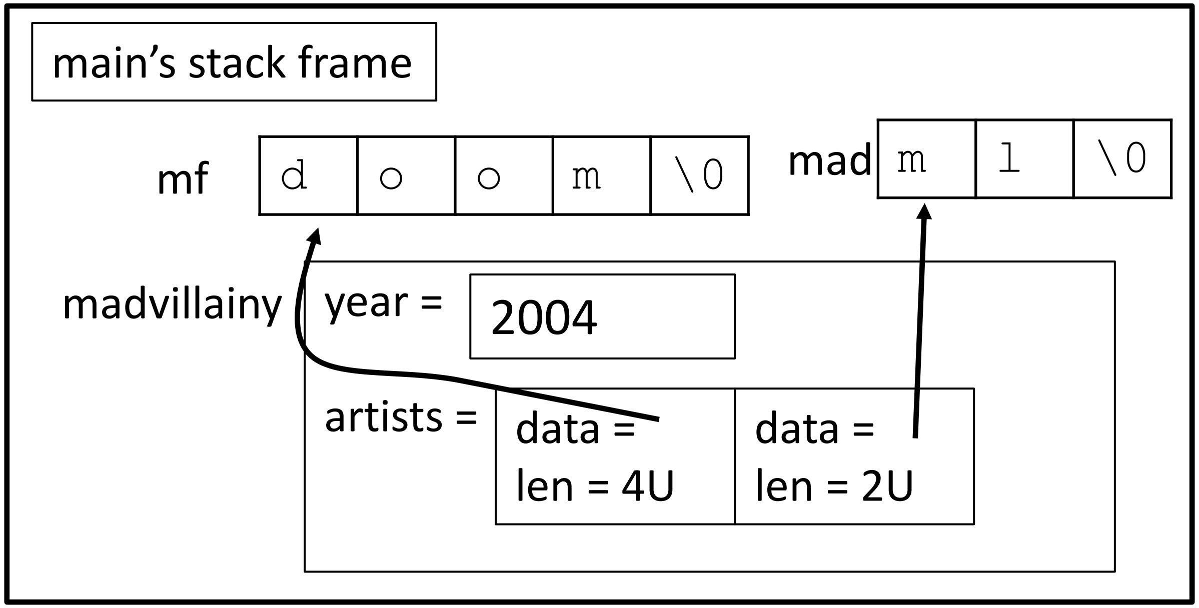
```
typedef struct {
  char* data;
  unsigned int len;
} string;

typedef struct {
  int release_year;
  string artists[2];
} album;
```

```
void ALL_CAPS(string name) {
  for (int i = 0; i < name.len; i++) {
    name.data[i] = toupper(name.data[i]);
  }
}
void remaster(album *a) {
  album copy = *a;
  copy.release_year = 2025;
  ALL_CAPS(copy.artists[0]);
  copy.artists[1] = { copy.artists[0].data, 4U};
  a = &copy;
}
int main() {
  char mf[] = "doom";
  char mad[] = "ml";
  album madvillainy = (album) {
    .release_year = 2004,
    .artists = { {mf, 4U}, {mad, 2U} },
  };

  remaster(&madvillainy);
  // what is the state here?
}
```

Visualization: Albums start



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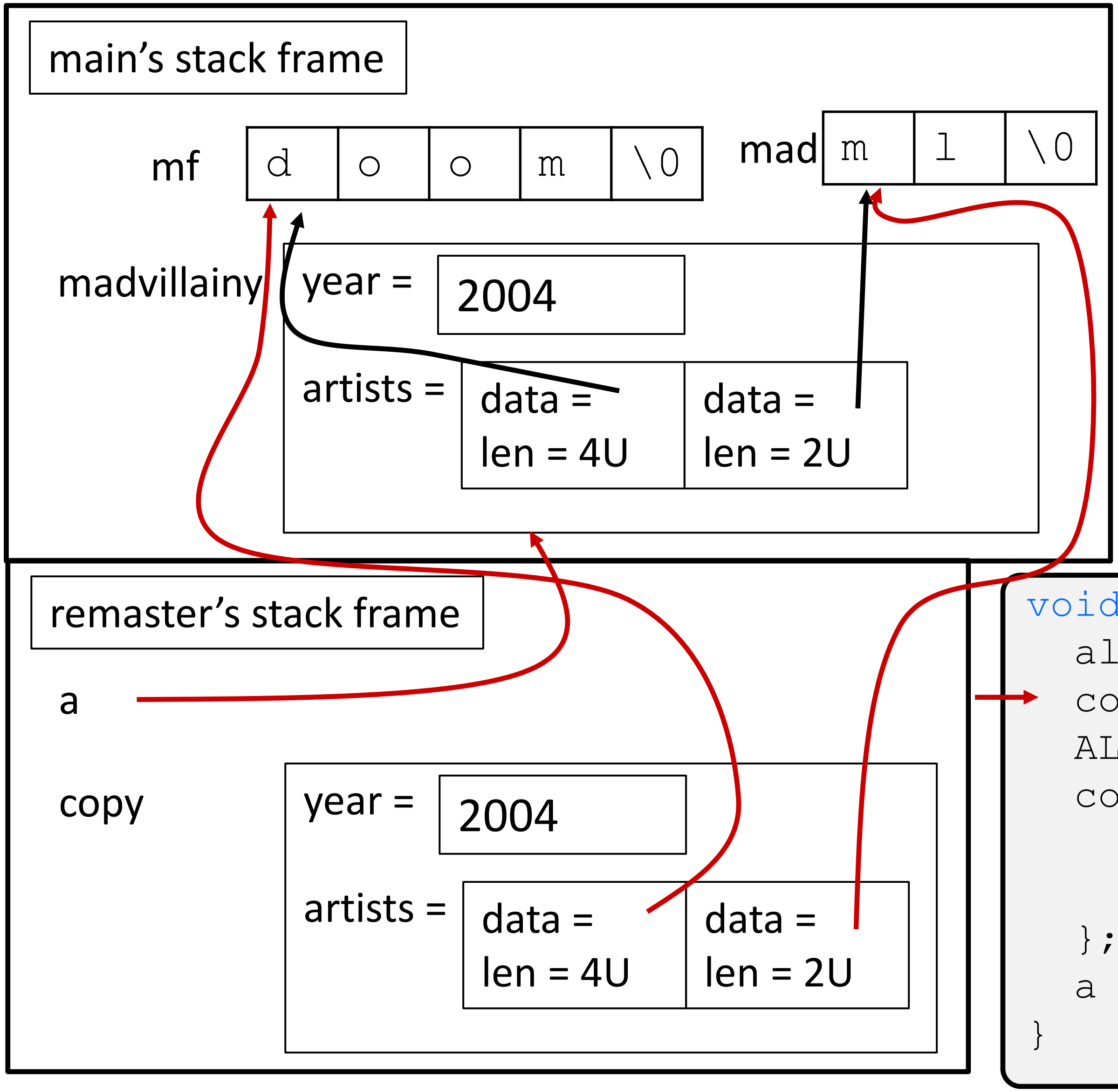

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```

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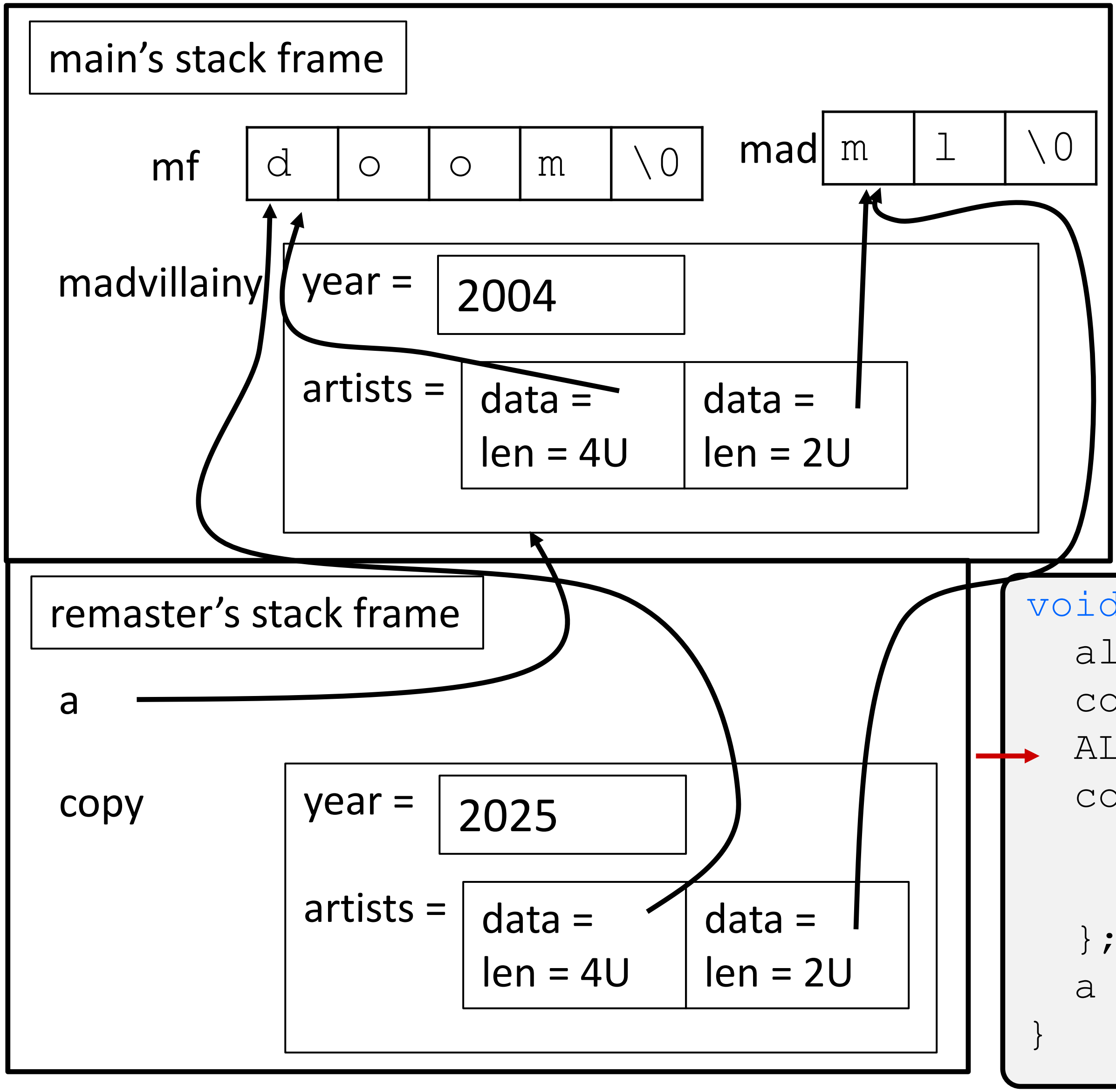

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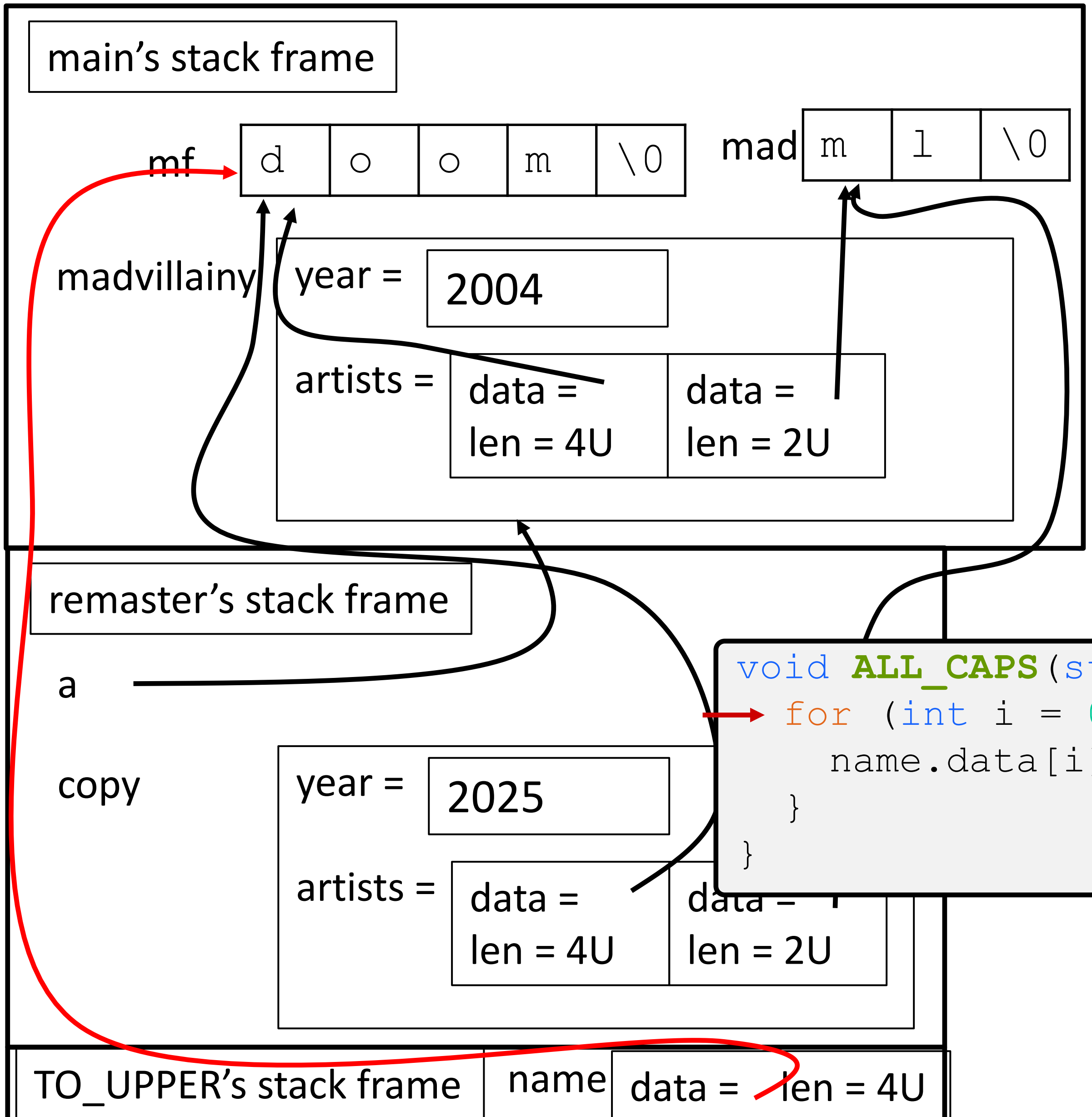


main's stack frame

mf `d` `o` `o` `m` `\0`

mad `m` `l` `\0`

madvillainy

year = 2004

artists = data = len = 4U | data = len = 2U

remaster's stack frame

a

copy

year = 2025

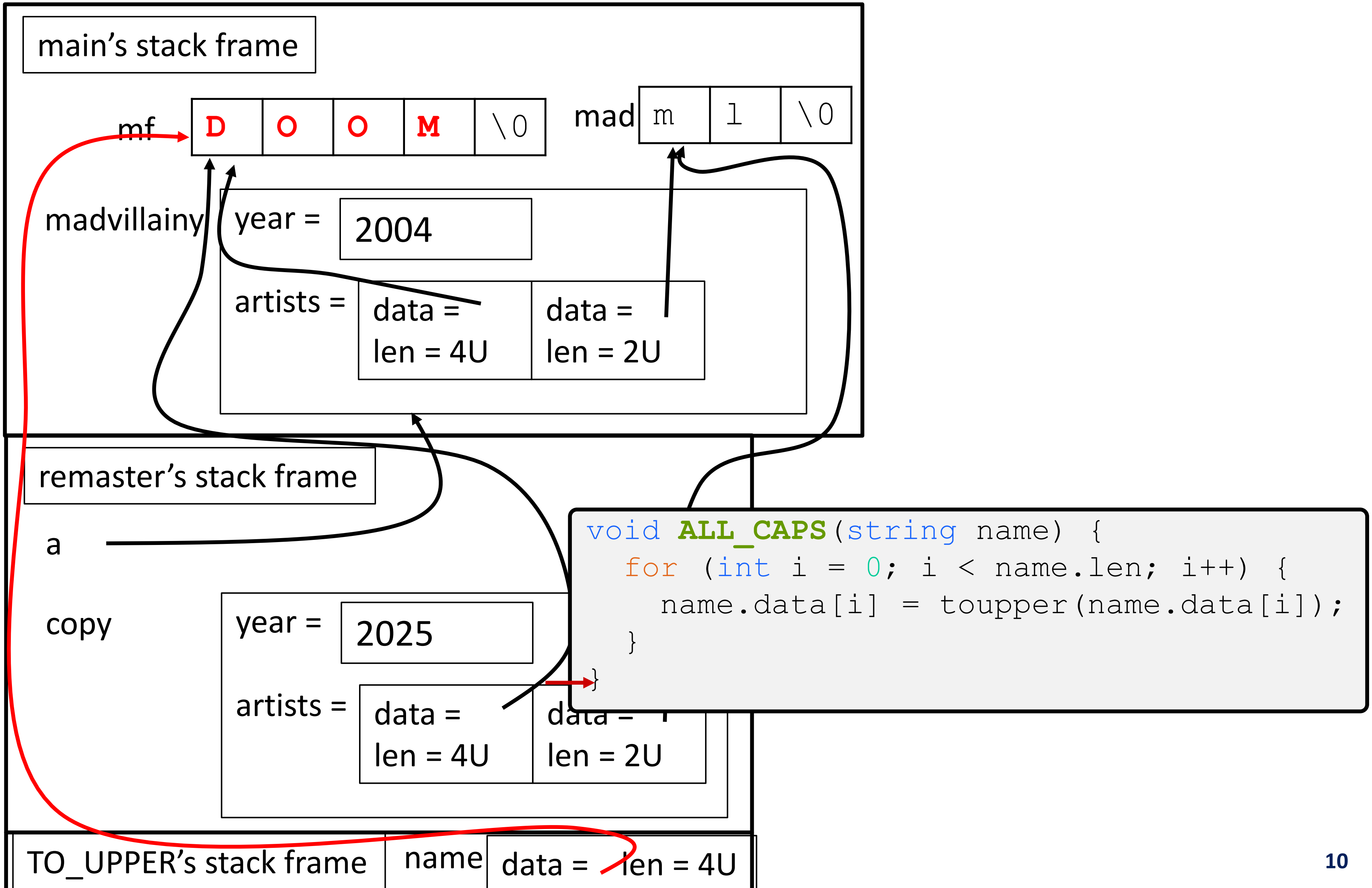
artists = data = len = 4U | data = len = 2U

TO_UPPER's stack frame

name data = len = 4U

```
void ALL_CAPS(string name) {
  for (int i = 0; i < name.len; i++) {
    name.data[i] = toupper(name.data[i]);
  }
}
```

Visualization: Albums start



main's stack frame

mf

D O O M \0

mad

m l \0

madvillainy

year = 2004

artists = data = len = 4U | data = len = 2U

remaster's stack frame

a

copy

year = 2025

artists = data = len = 4U | data = len = 2U

TO_UPPER's stack frame

name

data = len = 4U

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}
```

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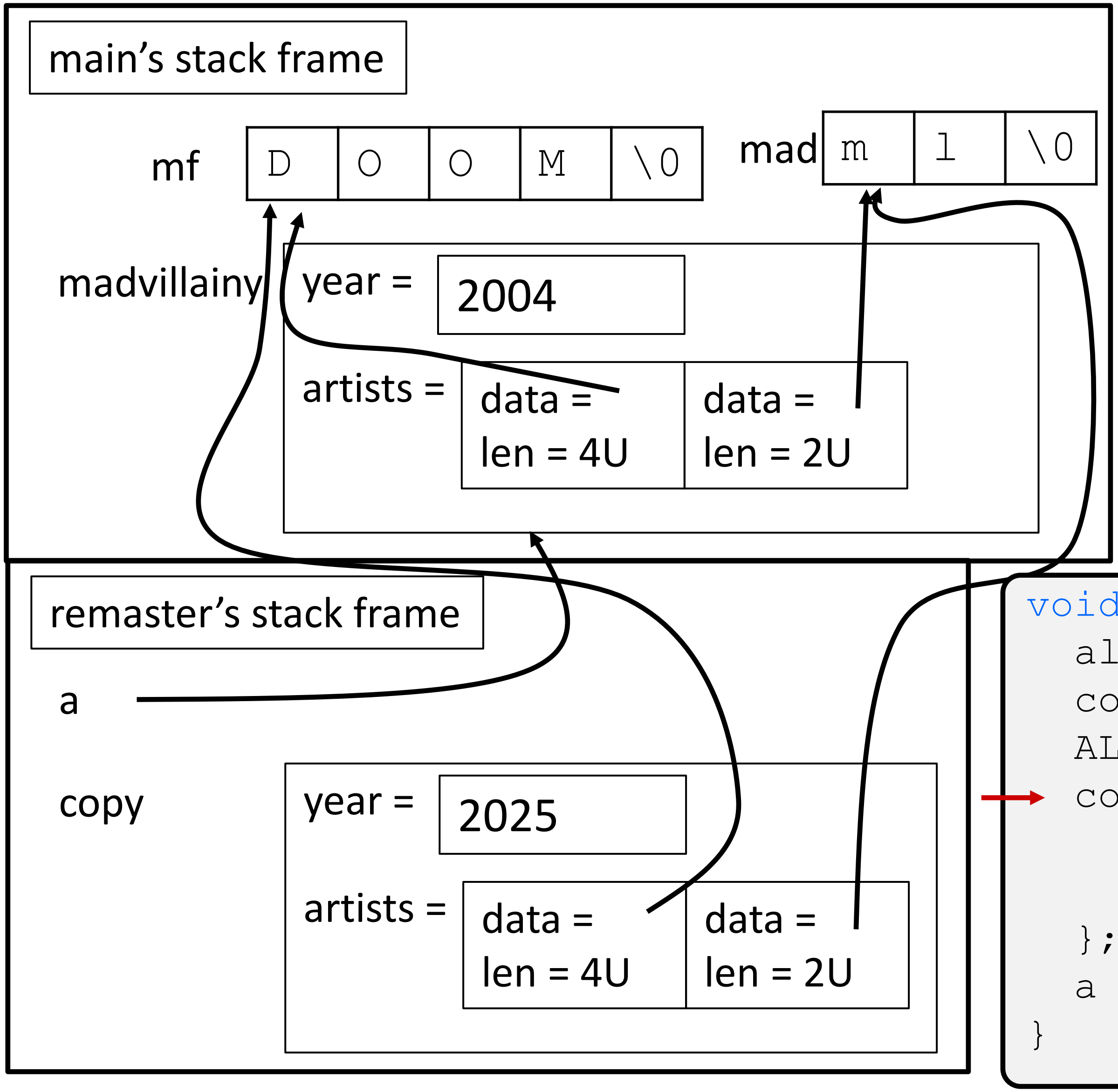

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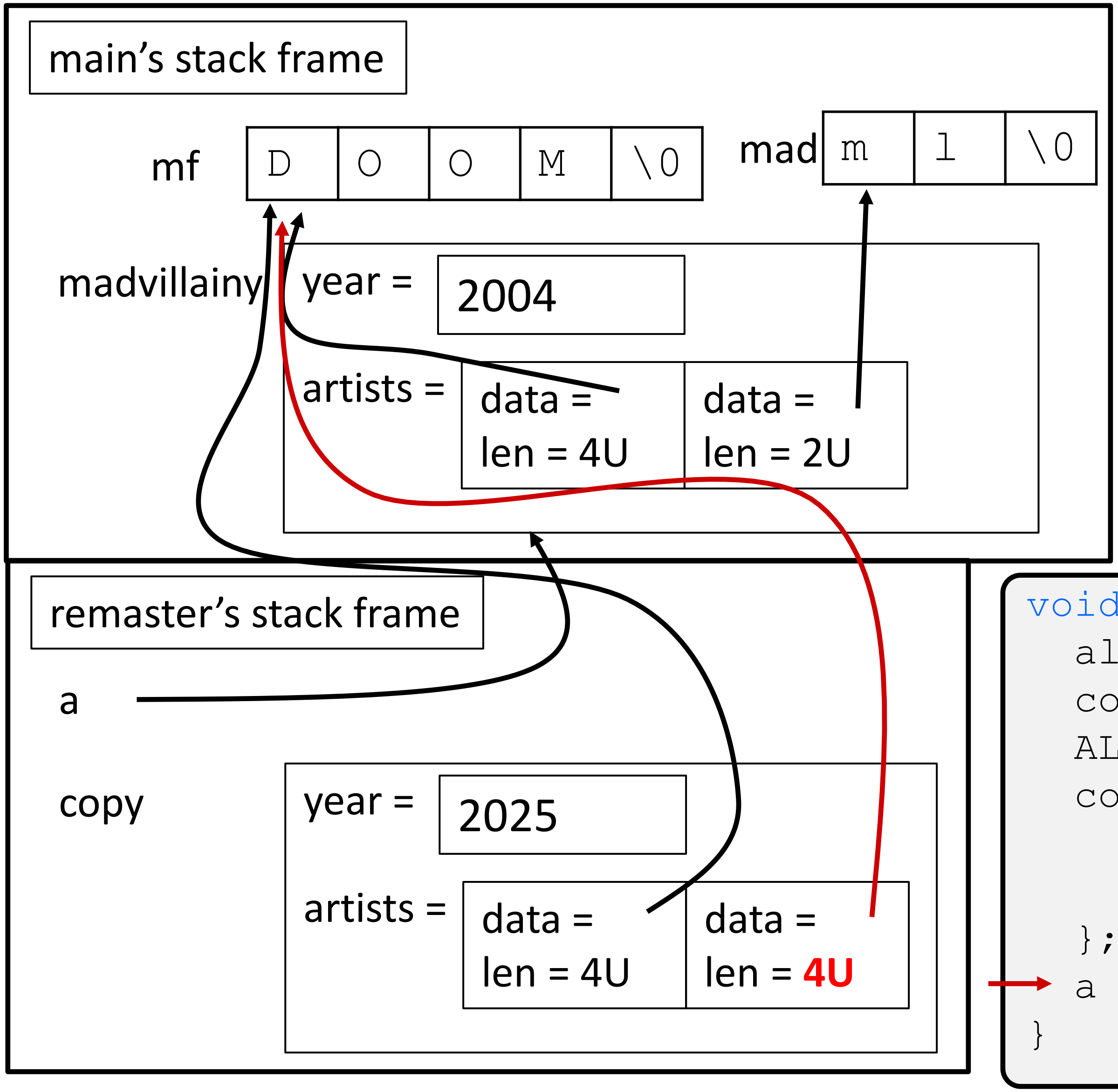

main's stack frame

mf | D | O | O | M | \0

mad | m | l | \0

madvillainy | year = 2004

artists = | data = len = 4U | data = len = 2U

remaster's stack frame

a

copy | year = 2025

artists = | data = len = 4U | data = len = **4U**

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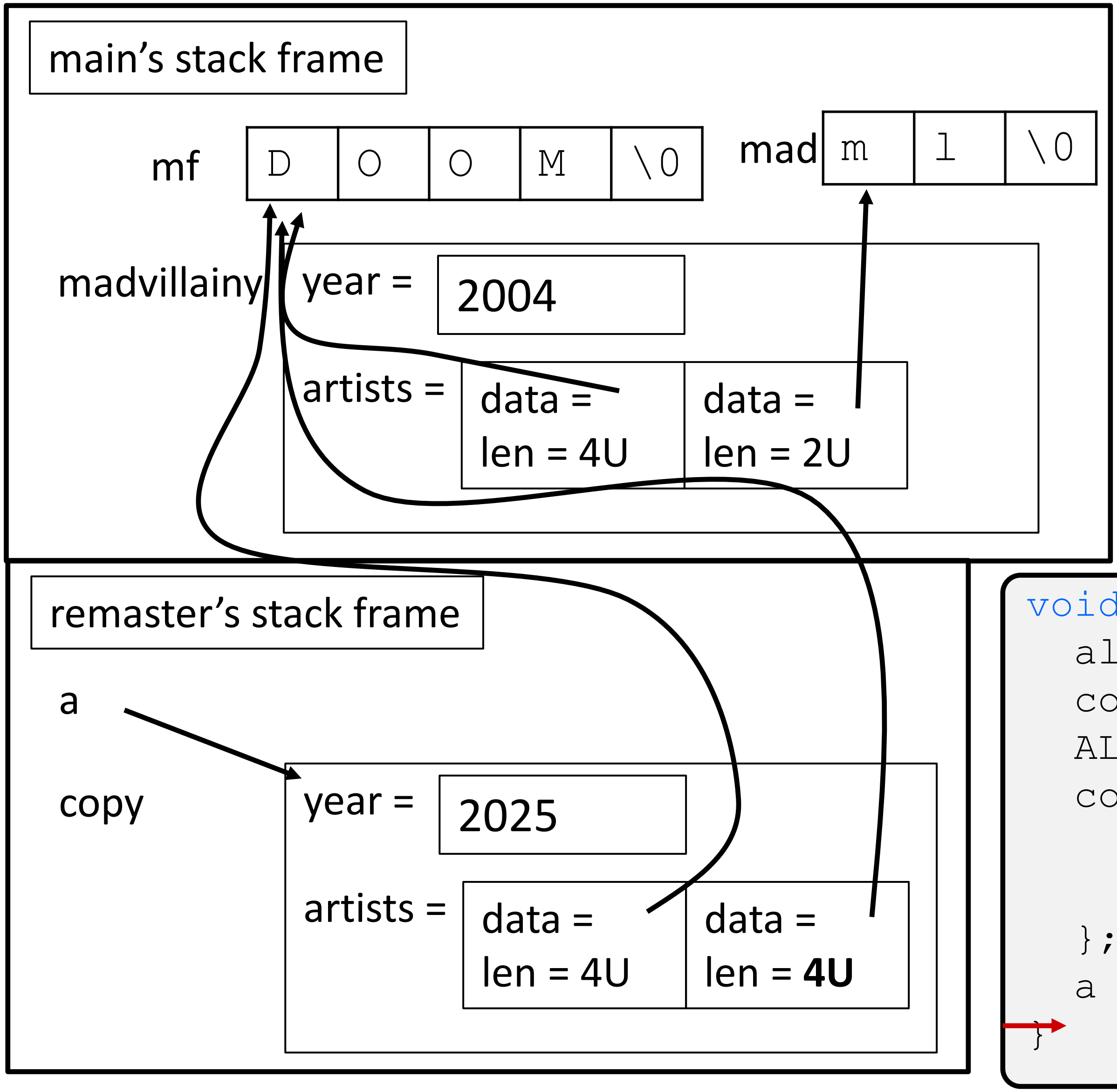

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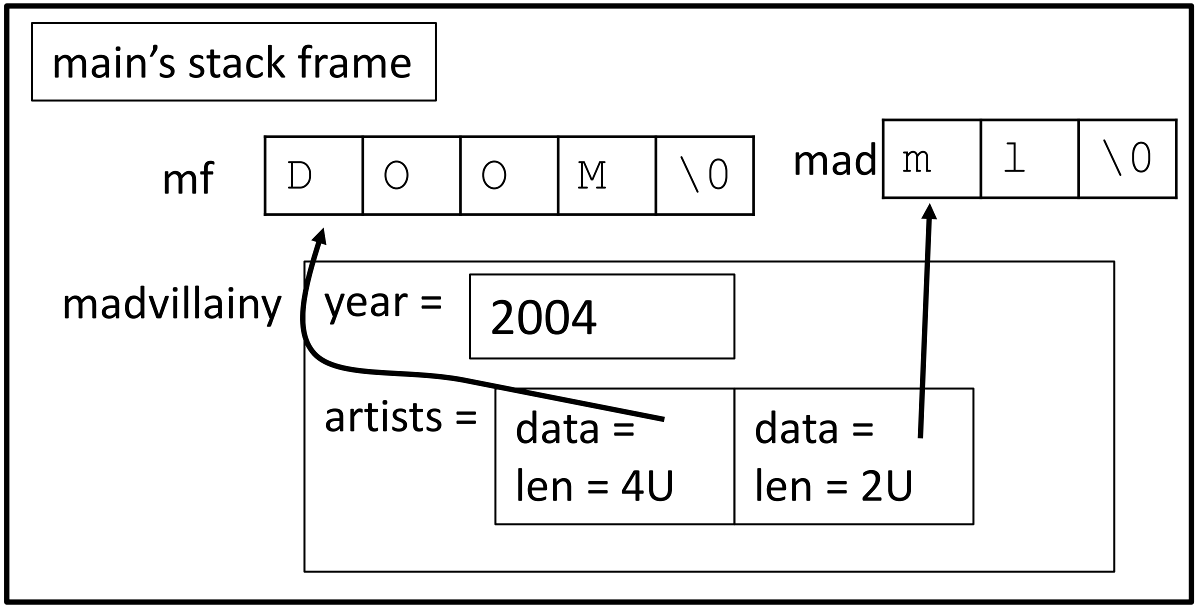

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}
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Lecture Outline

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- **The Heap**
  - **malloc() & free()**
- Modules & Header Files
- Dynamic Memory Pitfalls
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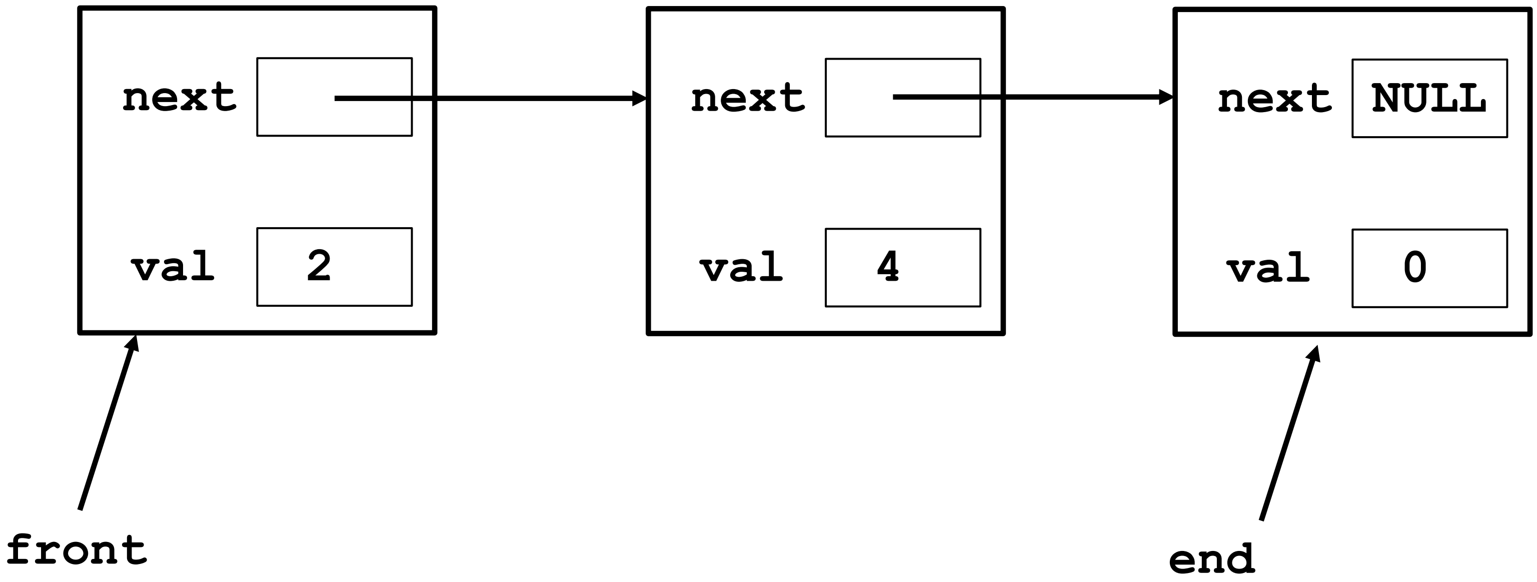
Queue Example

- Simple Data structure modeling a queue
  - Implemented with a singly linked list
- Items added to the end and removed from the front.
- We maintain a list of queue elements chained together with pointers.



Queue Implementation Demo

- Let’s create a naïve implementation for our queue

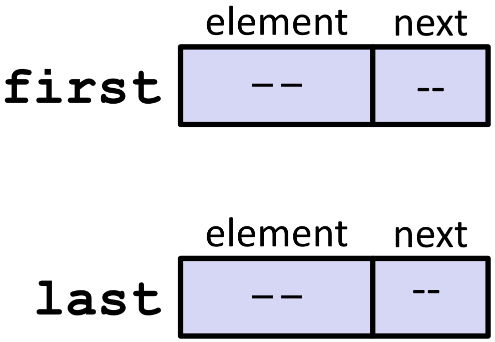
```
#include <stdio.h>

typedef struct node_st {
  struct node_st* next;
  int val;
} Node;

int main(int argc, char** argv) {
  Node first, last;

  first.val = 2;
  first.next = &last;
  last.val = 0;
  last.next = NULL;
  return 0;
}
```

naive_queue.c



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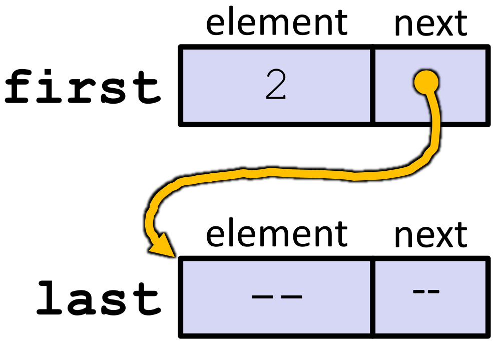

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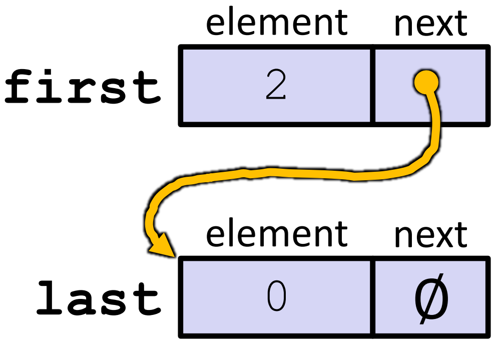
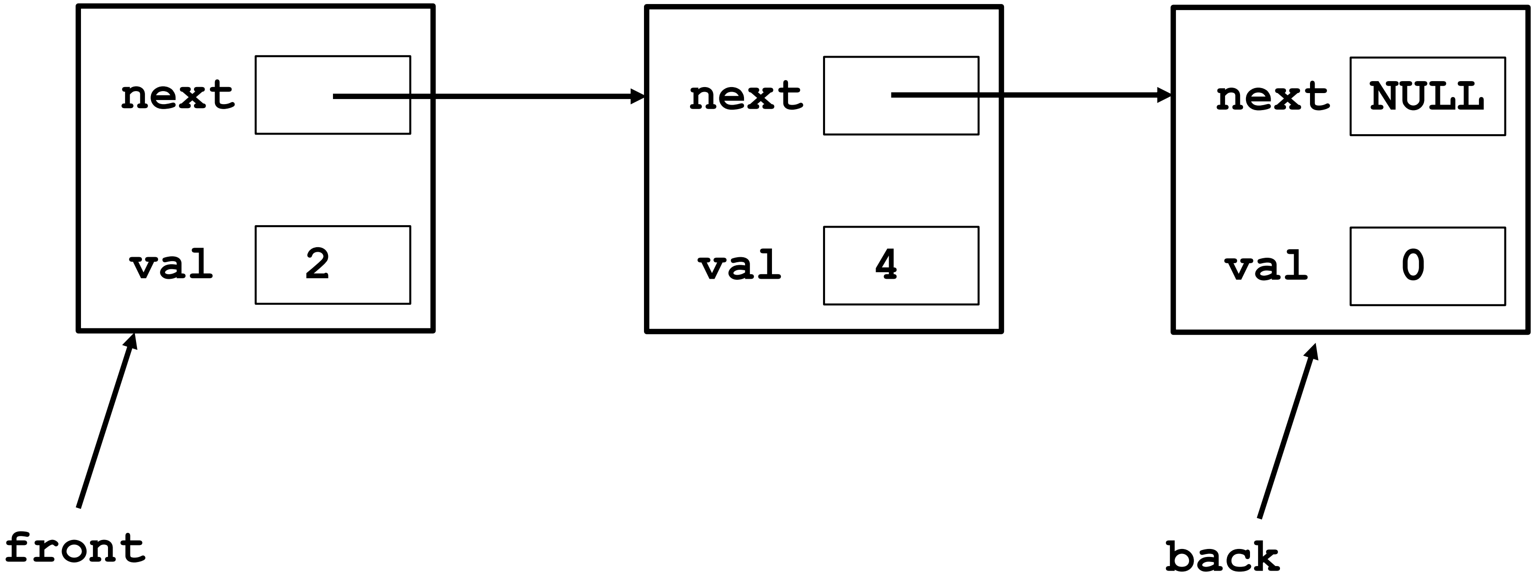


What happens if we want more than two elements?

What happens if we don't know the size we need until run-time?

Revisiting the Queue Example

- Simple Data structure modeling a queue
  - Implemented with a singly linked list
- Items added to the end and removed from the front.
- We maintain a list of queue elements chained together with pointers.
- We can use Dynamic Allocation to create new elements



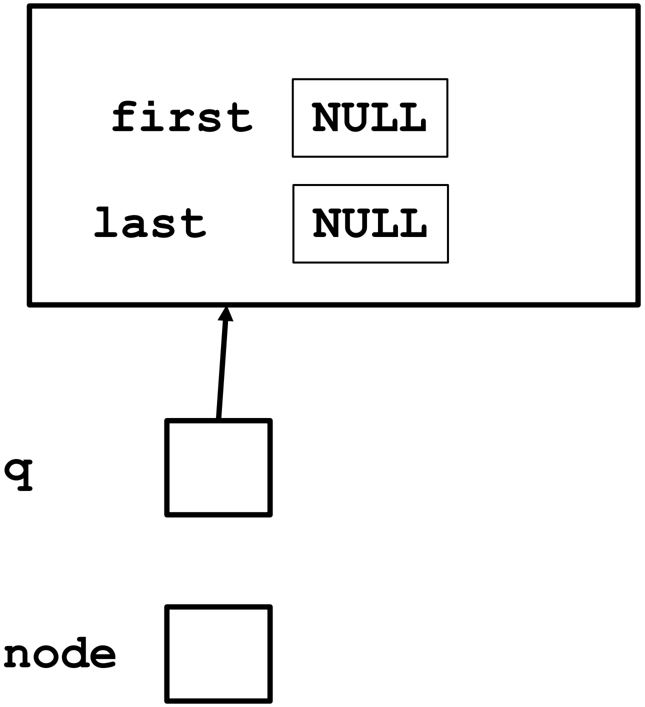
Dynamically Allocated Queue Demo

- See code on course website:
  - main_queue.c
  - queue.h
  - queue.c
  - Makefile

Queue_Add

```
void Queue_Add(Queue *q, int val) {
  Queue_Node* node;
  node = malloc(sizeof(Queue_Node));
  if (node == NULL) {
    printf("ERROR");
    exit(EXIT_FAILURE);
  }

  node->next = NULL;
  node-> val = val;
  if (q->last != NULL) {
    q->last->next = node;
    q->last = node;
  } else {
    q->first = node;
    q->last = node;
  }
}
```



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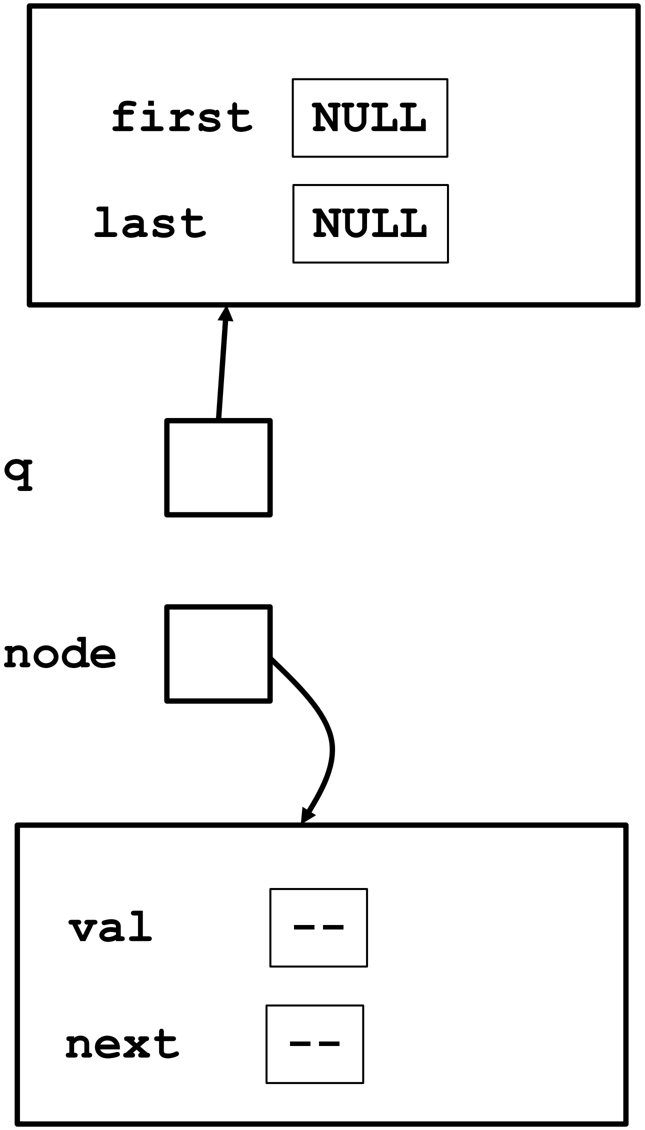

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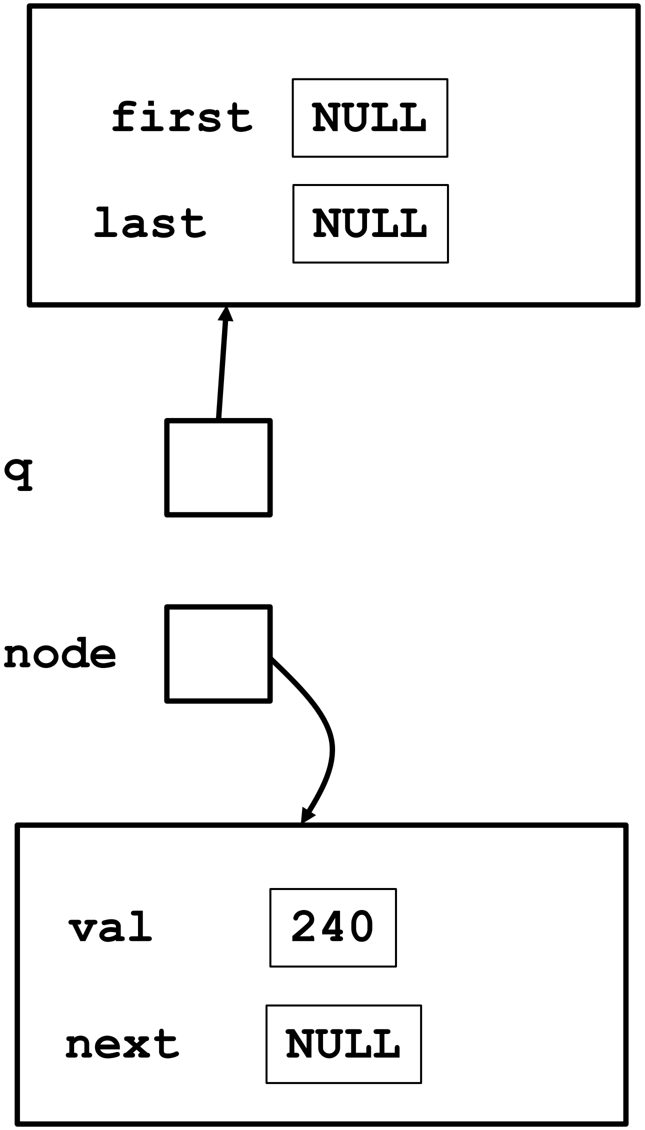

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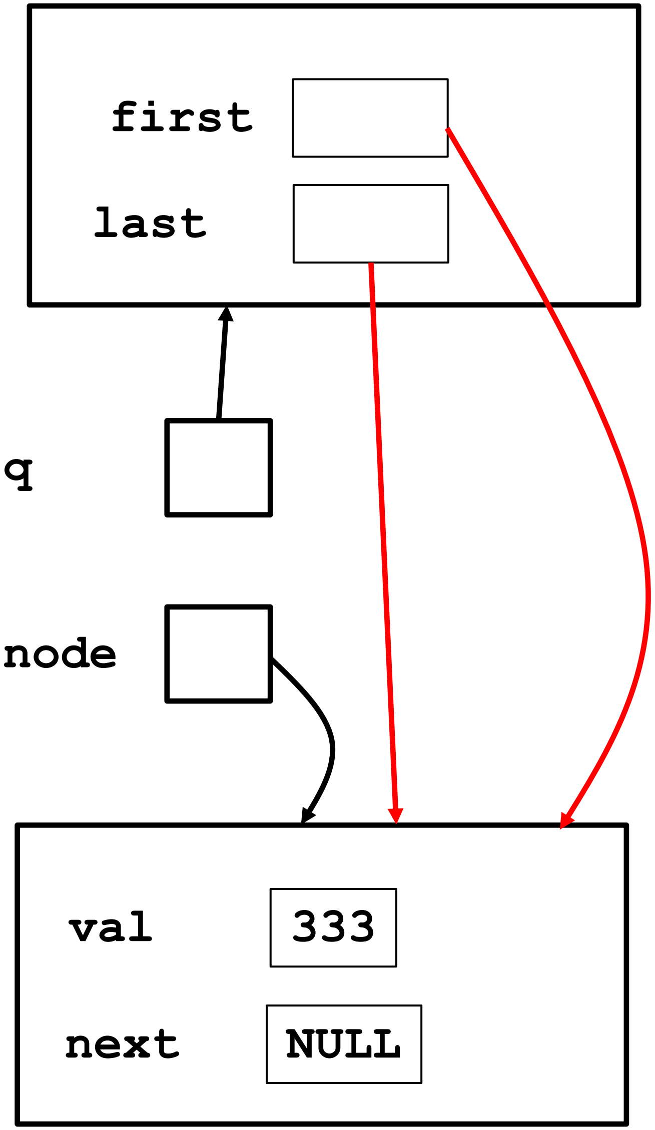

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    q->last = node;
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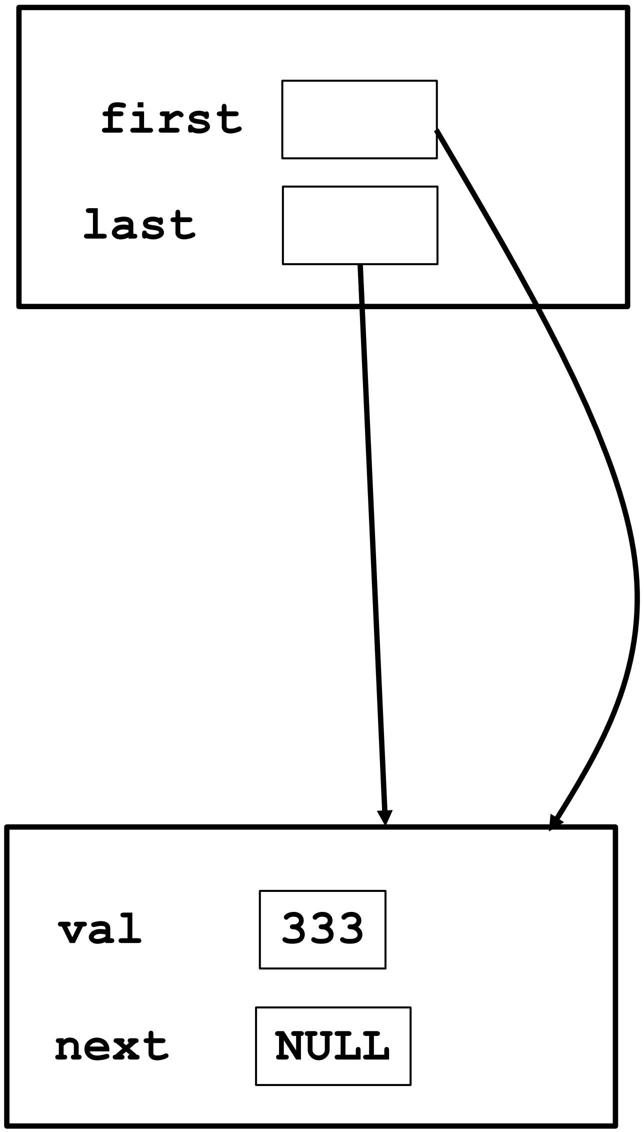
    q->last = node;
  }
}
```

Since node is dynamically allocated, it persists after the function returns



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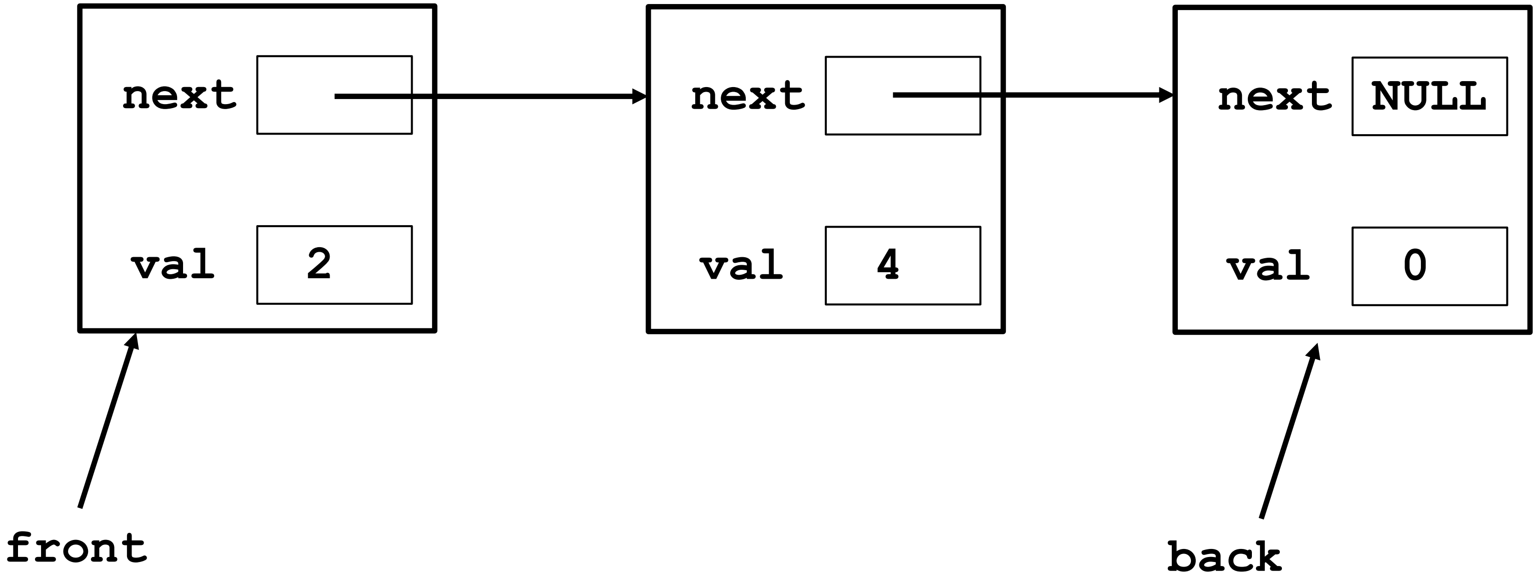

Lecture Outline

- Structs Warm-up
- The Heap
  - malloc() & free()
- **Modules & Header Files**
- Dynamic Memory Pitfalls
- GDB & Valgrind

Multi-File C Programs (Modules)

- In our previous example, we created a queue *module*

- A module is a self-contained piece of an overall program
  - Has externally visible functions that customers can invoke
  - Has externally visible typedefs, and perhaps global variables, that customers can use
  - May have internal functions, typedefs, or global variables that customers should not look at

- The module's *interface* is its set of public functions, typedefs, and global variables

C Header Files

- Header: a file whose only purpose is to be #include'd
  - Generally, has a filename `.h` extension
  - Holds the variables, types, and function prototype declarations that make up the interface to a module
  - There are <system-defined> and "programmer-defined" headers

```
#include <stdio.h>    #include "./cstring.h"
```

- Main Idea:
  - Every `name.c` is intended to be a module that has a `name.h`
  - `name.h` declares the interface to that module
  - Other modules can use name by `#include`-ing `name.h`
    - They should assume as little as possible about the implementation in name.c

C Module Conventions

- File contents:
  - `.h` files only contain declarations, **never** definitions
  - `.c` files never contain prototype declarations for functions that are intended to be exported through the module interface

- Including:
  - ***NEVER*** #include a .c file
  - Only #include .h files
  - #include all of headers you reference, even if another header (transitively) includes some of them

C Header Guards

- Header Files in C (and C++) need to have two lines at the top and a line at the bottom.
  - These are to prevent a file from being include'd twice (which would get an error from having multiple definitions of the same thing).

pair.h

```
#ifndef PAIR_H_
#define PAIR_H_

typedef struct {
  int a;
  int b;
} pair;

#endif // PAIR_H_
```

util.h

```
#ifndef UTIL_H_
#define UTIL_H_

#include "pair.h"

// a useful function
pair* make_pair(int a, int b);

#endif // UTIL_H_
```

Note the:
FILE_NAME_H_
naming convention

Last line ends the
header file

main.c

```
#include "pair.h"
#include "util.h"
int main(int atgc, char* argv[]) {
```

Lecture Outline

- Structs Warm-up
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- **Dynamic Memory Pitfalls**
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Dynamic Memory Pitfalls

- Buffer Overflows
  - E.g. ask for 10 bytes, but write 11 bytes
  - Could overwrite information needed to manage the heap
  - Common when forgetting the null-terminator on malloc'd strings
- Not checking for `NULL`
  - Malloc returns NULL if out of memory
  - Should check this after every call to malloc
- Giving `free()` a pointer to the middle of an allocated region
  - Free won't recognize the block of memory and may crash
- Giving free() a pointer that has already been freed
  - Will interfere with the management of the heap and likely crash
- `malloc` does NOT initialize memory
  - There are other functions like `calloc` that will zero out memory

Memory Leaks

- The most common Memory Pitfall
- What happens if we malloc something, but don’t free it?
  - That block of memory cannot be reallocated, even if we don’t use it anymore, until it is **`free`**d
  - If this happens enough, we run out of heap space and program may slow down and eventually crash

- Garbage Collection
  - Automatically “frees” anything once the program has lost all references to it
  - Affects performance, but avoid memory leaks
  - Java has this, C doesn’t

Poll Everywhere

pollev.com/tqm

- Which line below is first to cause a crash?
  - Yes, there are a lot of bugs, but not all cause a crash ☺
  - See if you can find all the bugs!

A. Line 1

B. Line 4

C. Line 6

D. Line 7

E. We're lost…

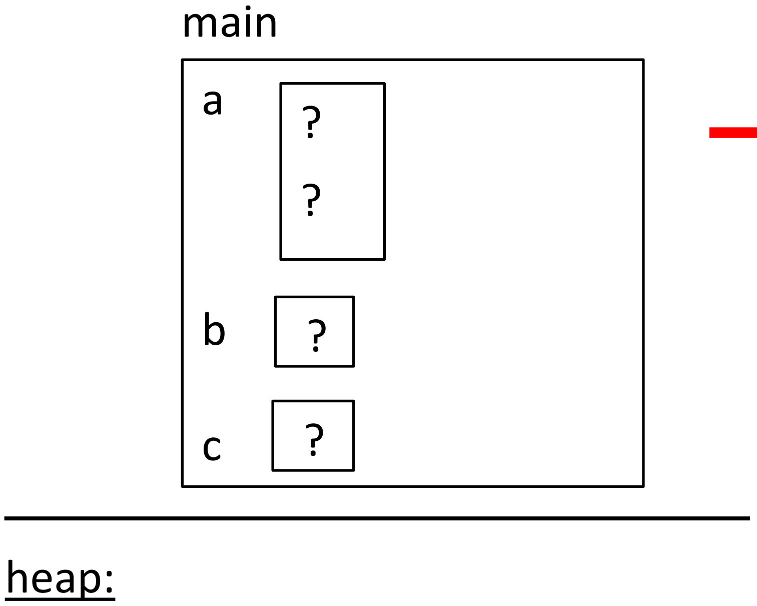
```
  #include <stdio.h>
  #include <stdlib.h>

  int main(int argc, char** argv) {
    int a[2];
    int* b = malloc(2*sizeof(int));
    int* c;

1   a[2] = 5;
2   b[0] += 2;
3   c = b+3;
4   free(&(a[0]));
5   free(b);
6   free(b);
7   b[0] = 5;

    return 0;
  }
```

Memory Corruption - What Happens?



```c
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int main(int argc, char** argv) {
  int a[2];
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  a[2] = 5;    // assigns past the end of an array
  b[0] += 2;   // assumes malloc zeros out memory
  c = b+3;     // Ok, but if we use c, problem
  free(&(a[0]));  // free something not malloc'ed
  free(b);
  free(b);     // double-free the same block
  b[0] = 5;    // use a freed (dangling) pointer

  // any many more!
  return 0;
}
```

Note: Arrow points to *next* instruction.

memcorrupt.c

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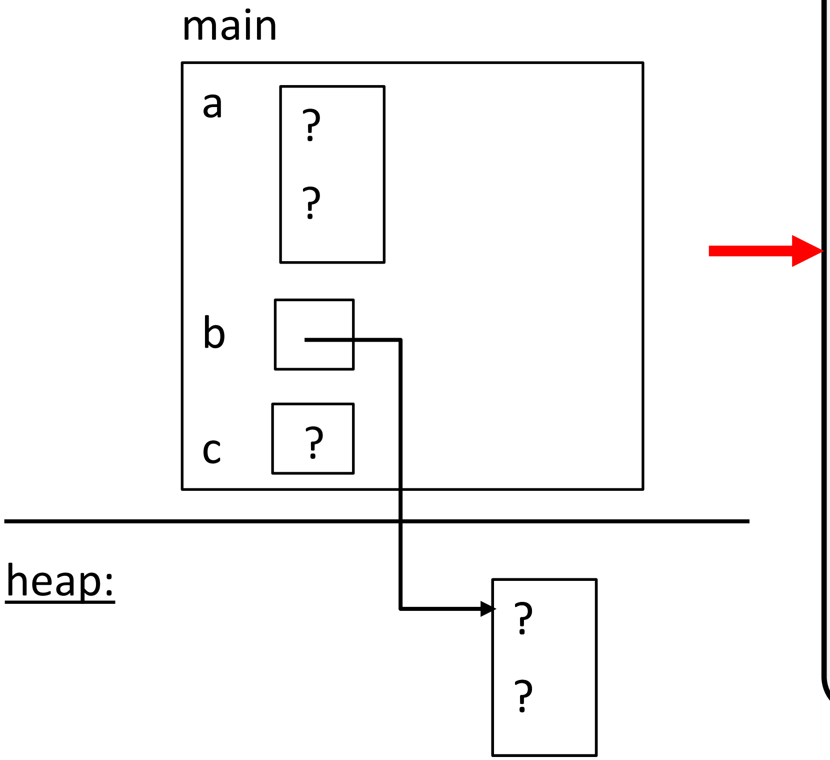

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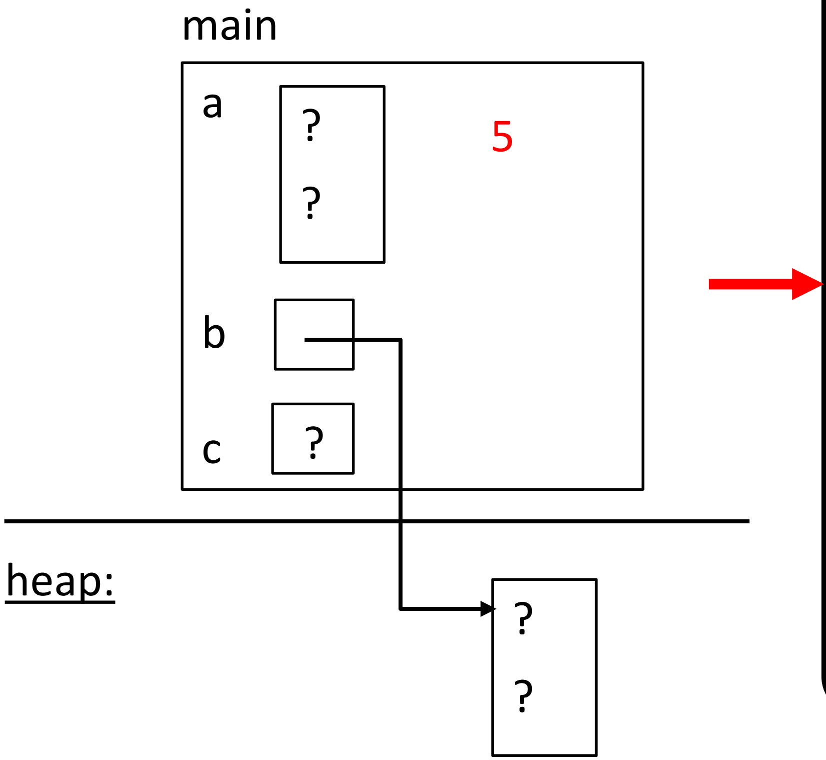

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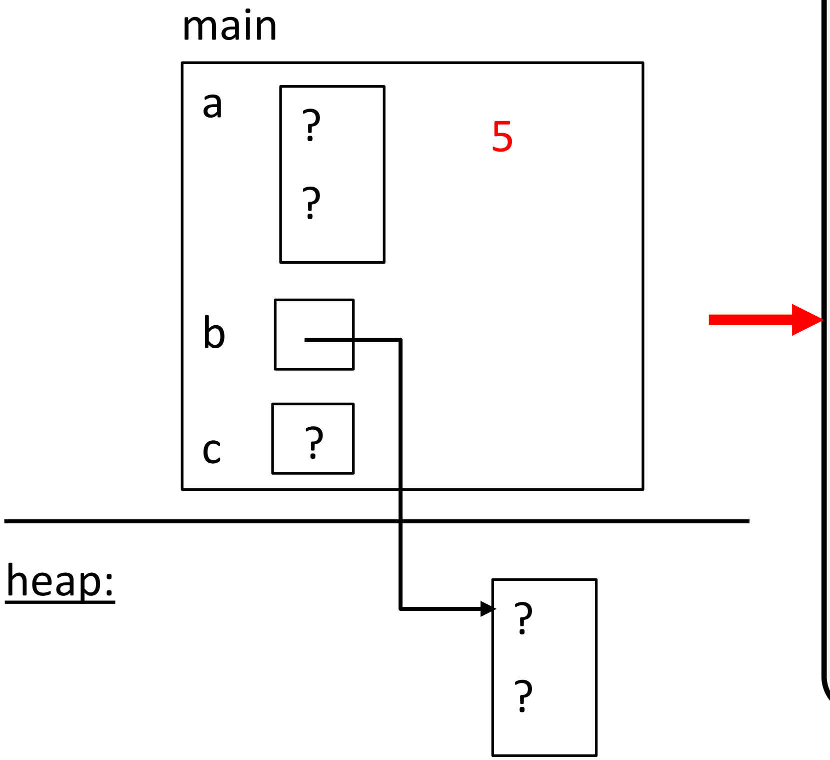

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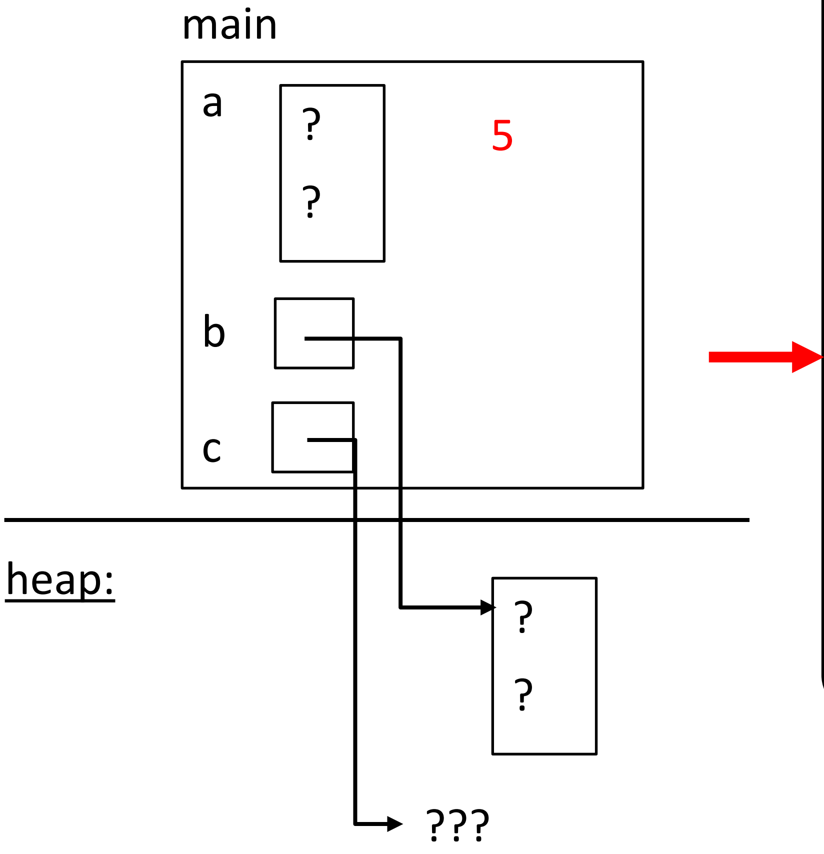
  c = b+3;     // Ok, but if we use c, problem
  free(&(a[0]));  // free something not malloc'ed
  free(b);
  free(b);     // double-free the same block
  b[0] = 5;    // use a freed (dangling) pointer

  // any many more!
  return 0;
}
```

Note: Arrow points to *next* instruction.

memcorrupt.c

Memory Corruption - What Happens?



```
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char** argv) {
  int a[2];
  int* b = malloc(2*sizeof(int));
  int* c;

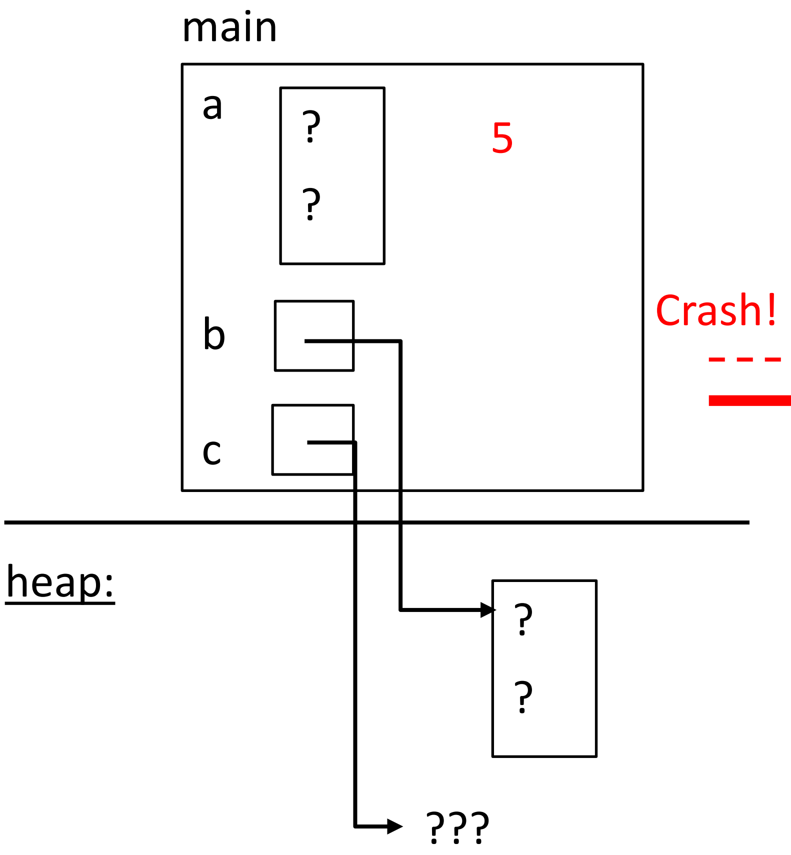
  a[2] = 5;    // assigns past the end of an array
  b[0] += 2;   // assumes malloc zeros out memory
  c = b+3;     // Ok, but if we use c, problem
  free(&(a[0]));   // free something not malloc'ed
  free(b);
  free(b);     // double-free the same block
  b[0] = 5;    // use a freed (dangling) pointer

  // any many more!
  return 0;
}
```

Note: Arrow points to *next* instruction.

memcorrupt.c

Memory Corruption - What Happens?



Crash!

```
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char** argv) {
  int a[2];
  int* b = malloc(2*sizeof(int));
  int* c;

  a[2] = 5;    // assigns past the end of an array
  b[0] += 2;   // assumes malloc zeros out memory
  c = b+3;     // Ok, but if we use c, problem
  free(&(a[0]));  // free something not malloc'ed
  free(b);
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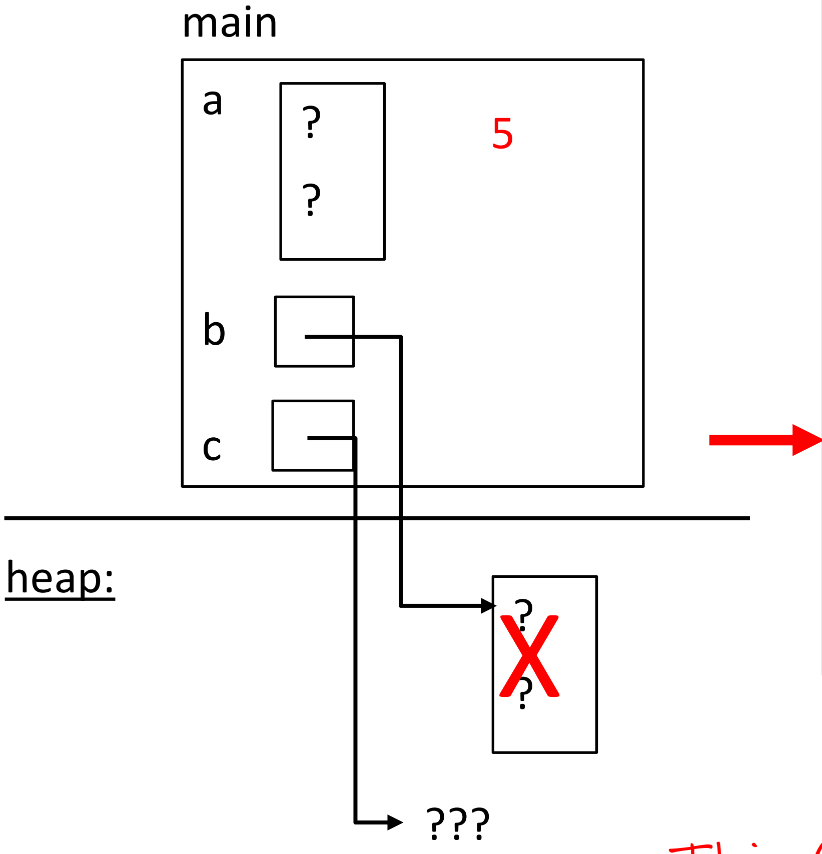
  // any many more!
  return 0;
}
```

Note: Arrow points to *next* instruction.

memcorrupt.c

Memory Corruption - What Happens?



```
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char** argv) {
  int a[2];
  int* b = malloc(2*sizeof(int));
  int* c;

  a[2] = 5;    // assigns past the end of an array
  b[0] += 2;   // assumes malloc zeros out memory
  c = b+3;     // Ok, but if we use c, problem
  free(&(a[0]));   // free something not malloc'ed
  free(b);
  free(b);     // double-free the same block
  b[0] = 5;    // use a freed (dangling) pointer

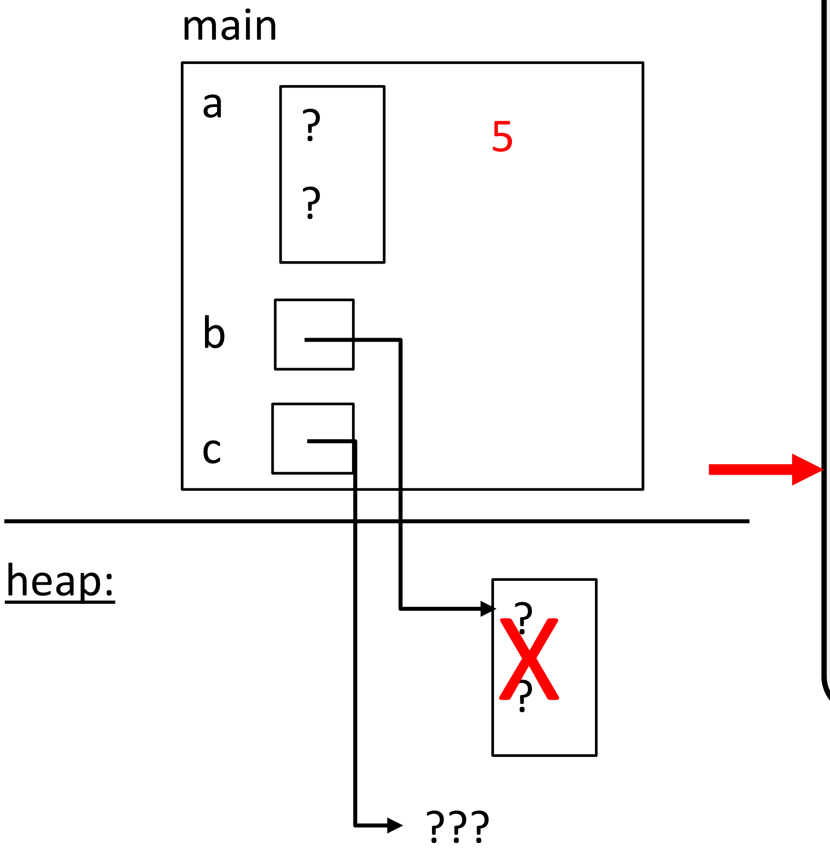
  // any many more!
  return 0;
}
```

Note: Arrow points to *next* instruction.

This "double free" would also cause the program to crash

memcorrupt.c

Memory Corruption - What Happens?



```
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char** argv) {
  int a[2];
  int* b = malloc(2*sizeof(int));
  int* c;

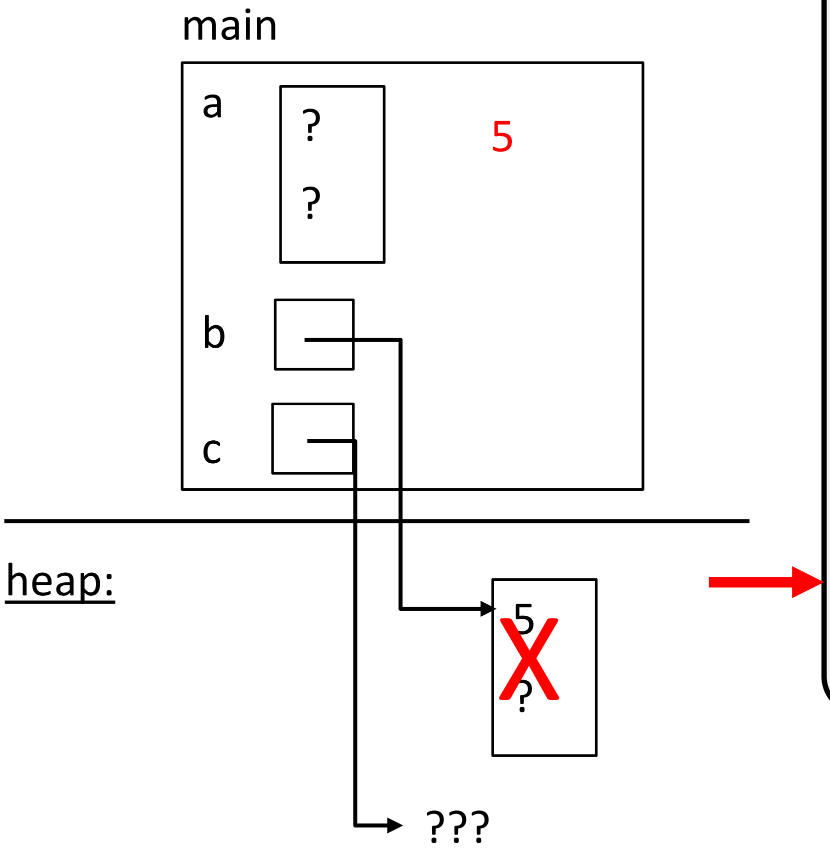
  a[2] = 5;    // assigns past the end of an array
  b[0] += 2;   // assumes malloc zeros out memory
  c = b+3;     // Ok, but if we use c, problem
  free(&(a[0]));   // free something not malloc'ed
  free(b);
  free(b);     // double-free the same block
  b[0] = 5;    // use a freed (dangling) pointer

  // any many more!
  return 0;
}
```

Note: Arrow points to *next* instruction.

memcorrupt.c

Memory Corruption - What Happens?



```
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char** argv) {
  int a[2];
  int* b = malloc(2*sizeof(int));
  int* c;

  a[2] = 5;   // assigns past the end of an array
  b[0] += 2;  // assumes malloc zeros out memory
  c = b+3;    // Ok, but if we use c, problem
  free(&(a[0]));  // free something not malloc'ed
  free(b);
  free(b);    // double-free the same block
  b[0] = 5;   // use a freed (dangling) pointer

  // any many more!
  return 0;
}
```

Note: Arrow points to *next* instruction.

memcorrupt.c

Lecture Outline

- Structs Warm-up
- The Heap
  - malloc() & free()
- Modules & Header Files
- Dynamic Memory Pitfalls
- **GDB & Valgrind**

Motivation

- The assignments will start getting bigger and are more open ended. Lots of potential for bugs

- **Debugging is a skill that you will need throughout your programming career**

- gdb (GNU Debugger) is a debugging tool
  - Very useful in tracking undefined behavior

- Valgrind
  - Checks for various memory errors
  - If you have odd behavior, valgrind may point out the cause.

Valgrind

- Tool used for identifying memory errors
- Will be used on your HW submissions going forward
- Detects:
  - Use of uninitialized memory
  - Reading/writing memory after it has been freed
  - Reading/writing to the end of malloc'd blocks
  - Reading/writing to inappropriate areas on the stack
  - Memory leaks where pointers to malloc'd blocks are lost

- Run with

  -
    ```
    valgrind --leak-check=full ./executable
    ```

Brief GDB & Valgrind Demo: Seg Faults

- IF NOTHING ELSE FROM GDB: GDB is very useful for finding a segmentation fault
  - Run the code on gdb till segmentation fault
  - Type in the command `backtrace`

- Commands:
  - `gdb ./executable`
  - `run`
  - `backtrace`

- `segfault.c`

Poll Everywhere

pollev.com/tqm

- What is the error here?

```c
28 int* range_array(int n, int m) {
29   int length = m - n + 1;
30 
31   // Heap allocate the array needed to return
32   int* array = malloc(sizeof(int) * length);
33 
34   // Initialized the elements
35   for (int i = 0; i <= length; i++) {
36     array[i] = i + n;
37   }
38 
39   return array;
40 }
```

```
==28602== Invalid write of size 4
==28602==    at 0x10926C: range_array (leaky.c:36)
==28602==    by 0x1091B6: main (leaky.c:15)
==28602==  Address 0x4a9404c is 0 bytes after a block of size 12 alloc'd
==28602==    at 0x4848899: malloc (in /usr/libexec/valgrind/vgpreload_memcheck-amd64-linux.s
==28602==    by 0x109246: range_array (leaky.c:32)
==28602==    by 0x1091B6: main (leaky.c:15)
```

Demo: The rest of Leaky.c

- Valgrind will tell you which line had bad memory accesses
- Valgrind will let you know when you have a memory leak, and where that leak was allocated
  - Note: where it is allocated is almost always different from where we need to free it.
- See course website:
  - **`leaky.c`**

Next Time

- Makefile
- #define constants
- Reading & parsing from stdin
  - getline
  - sscanf
- void* generics
- Maybe more GDB?
- Maybe more strings?