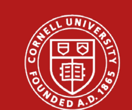
The Stack, The Heap, and Dynamic Memory Allocation

CS 3410: Computer System Organization and Programming

Spring 2025



[G. Guidi, A. Sampson, Z. Susag, and H. Weatherspoon]

Roadmap

1. Finish Pointers
    - Strings
    - Fun Pointer Tricks
2. The Call Stack
3. The Heap

Pointers, Revisited

"Every computer, at the unreachable memory address 0x-1, stores a secret. I found it, and it is that all humans ar-- SEGMENTATION FAULT."

Strings are Null-Terminated Character Arrays

- Recall that we told you a string has type `char*` in C
  - Strings are arrays of `char` values
  - A `char` is generally 1-byte (8-bits)
- Strings keep track of length by ending with a *null character* (`‘\0’`)
  - All strings *should* end with a *null character*
- Example:
  - `“CS3410” = { 'C', 'S', '3', '4', '1', '0', '\0’ }`
  - “CS3410” has length 7, not 6!

Demo: Strings

```
 1  void print_line(char *s) {
 2    for (int i = 0; s[i] != '\0'; ++i)
 3    {
 4      fputc(s[i], stdout);
 5    }
 6    fputc('\n', stdout);
 7  }
 8
 9  int main() {
10    char message[7] = {'H', 'e', 'l', 'l', 'o', '!', '\0'};
11    print_line(message);
12    return 0;
13  }
```

Roadmap

1. Finish Pointers
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    - Fun Pointer Tricks
2. The Call Stack
3. The Heap

Pass by Reference

```
1   #include <stdio.h>
2
3   void swap(int x, int y) {
4     int tmp = x;
5     x = y;
6     y = tmp;
7   }
8
9   int main() {
10    int a = 34;
11    int b = 10;
12    printf("a: %d; b: %d\n", a, b);
13    swap(a, b);
14    printf("a: %d; b: %d\n", a, b);
15  }
```

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What does the `printf` statement on line 14 print out?

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Pass by Reference

```
1   #include <stdio.h>
2
3   void swap(int x, int y) {
4     int tmp = x;
5     x = y;
6     y = tmp;
7   }
8
9   int main() {
10    int a = 34;
11    int b = 10;
12    printf("a: %d; b: %d\n", a, b);
13    swap(a, b);
14    printf("a: %d; b: %d\n", a, b);
15  }
```

Pass by Reference

```
1   #include <stdio.h>
2
3   void swap(int* x, int* y) {
4     int tmp = *x;
5     *x = *y;
6     *y = tmp;
7   }
8
9   int main() {
10    int a = 34;
11    int b = 10;
12    printf("a: %d; b: %d\n", a, b);
13    swap(&a, &b);
14    printf("a: %d; b: %d\n", a, b);
15  }
```

The Arrow Operator

```
1  #include <stdio.h>
2  typedef struct {
3    int x;
4    int y;
5  } point_t;
6
7  void print_point(point_t* p) {
8    printf("(%d, %d)\n", (*p).x, (*p).y);
9  }
10
11 int main() {
12   point_t my_point;
13   my_point.x = 3;
14   my_point.y = 7;
15
16   print_point(&my_point);
17
18   return 0;
19 }
```

The Arrow Operator

```c
1   #include <stdio.h>
2   typedef struct {
3     int x;
4     int y;
5   } point_t;
6
7   void print_point(point_t* p) {
8     printf("(%d, %d)\n", p->x, p->y);
9   }
10
11  int main() {
12    point_t my_point;
13    my_point.x = 3;
14    my_point.y = 7;
15
16    print_point(&my_point);
17
18    return 0;
19  }
```

`(*struct).field`

is equivalent to

`struct->field`

Cornell Bowers CIS
Computer Science

Null Pointers

- Pointers are just integers (i.e., bits!), so what does 0 mean?
- `NULL` is a pointer with value `0`
    - Often used to signal failure
- Be Careful!
    - NEVER dereference **`NULL`**
    - When in doubt, always check!

Pointers to Anything

```
1   #include <stdio.h>
2
3   void print_ptr(void* p) {
4     printf("%p\n", p);
5   }
6
7   int main() {
8     int x = 34;
9     float y = 10.0f;
10    print_ptr(&x);
11    print_ptr(&y);
12  }
```

- Pointers are just bits!
  - No difference between **int***, **float***, and **char***
- **void*** is a "pointer to something"

Roadmap

1. Finish Pointers
   - Strings
   - Fun Pointer Tricks
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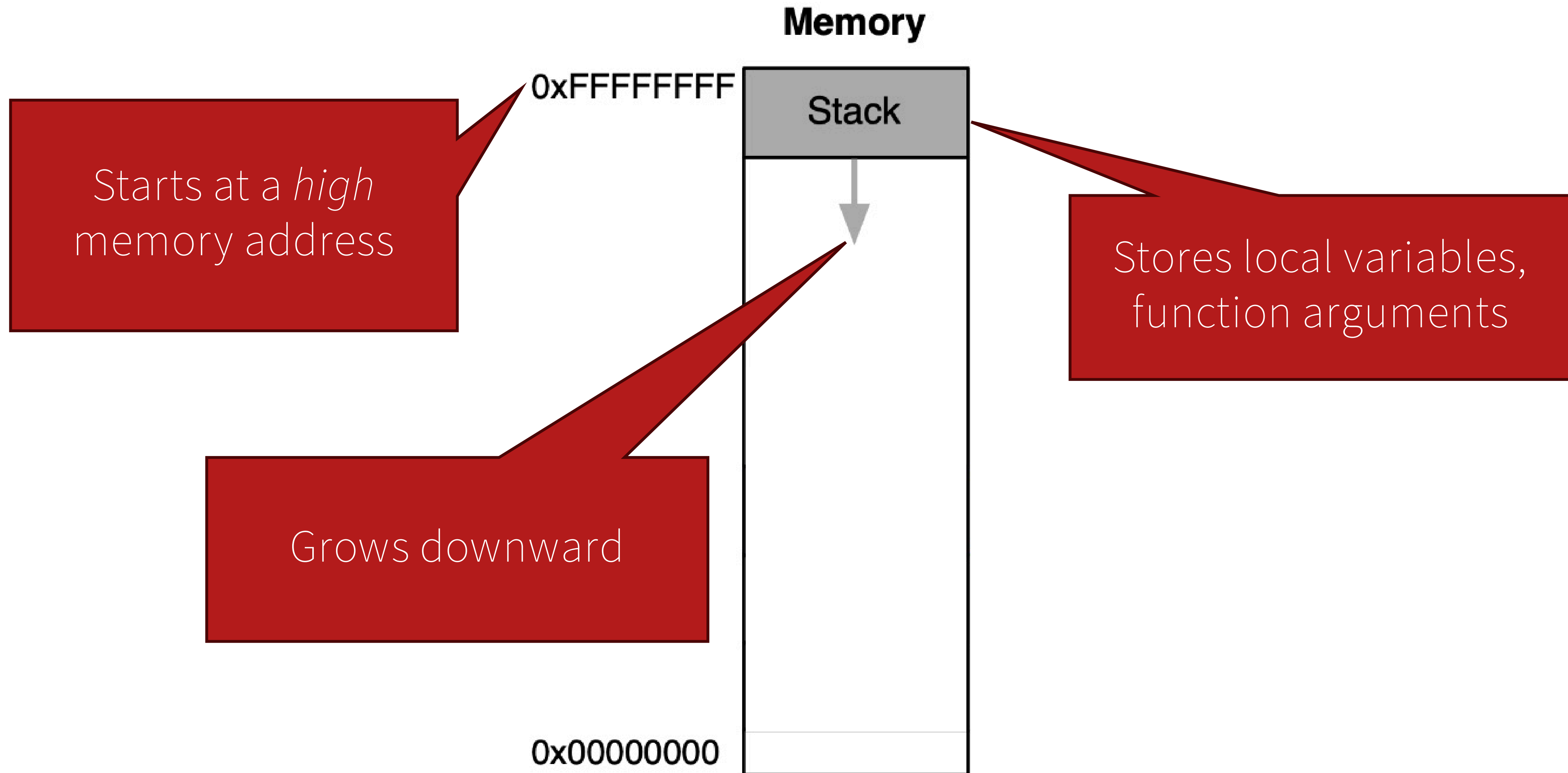
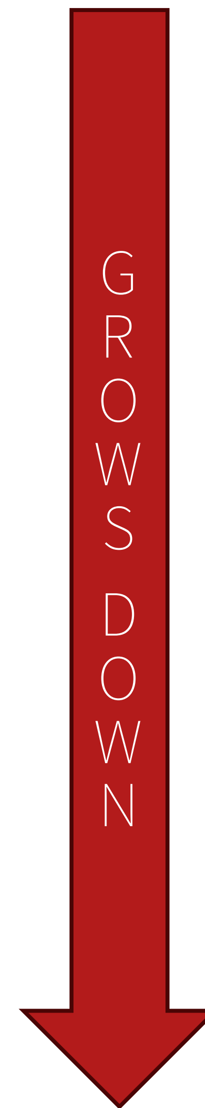
Overview: The Call Stack



```c
1   #include <stdio.h>
2
3   const float EULER = 2.71828f;
4   const int COUNT = 5;
5
6   void fill_exp(float* dest) {
7     dest[0] = 1.0f;
8     for (int i = 1; i < COUNT; ++i) {
9       dest[i] = dest[i - 1] * EULER;
10    }
11  }
12
13  void print_floats(float* vals, int n) {
14    for (int i = 0; i < n; ++i) {
15      printf("%f\n", vals[i]);
16    }
17  }
18
19  int main() {
20    float values[COUNT];
21    fill_exp(values);
22    print_floats(values, COUNT);
23    return 0;
24  }
```

Address	Var. (4 bytes)
0x1555d56bb0	
0x1555d56bac	
0x1555d56ba8	
0x1555d56ba4	
0x1555d56ba0	
...	...
0x1555d56b7c	
0x1555d56b78	
0x1555d56b74	
0x1555d56b70	
0x1555d56b6c	
0x1555d56b68	

The Stack



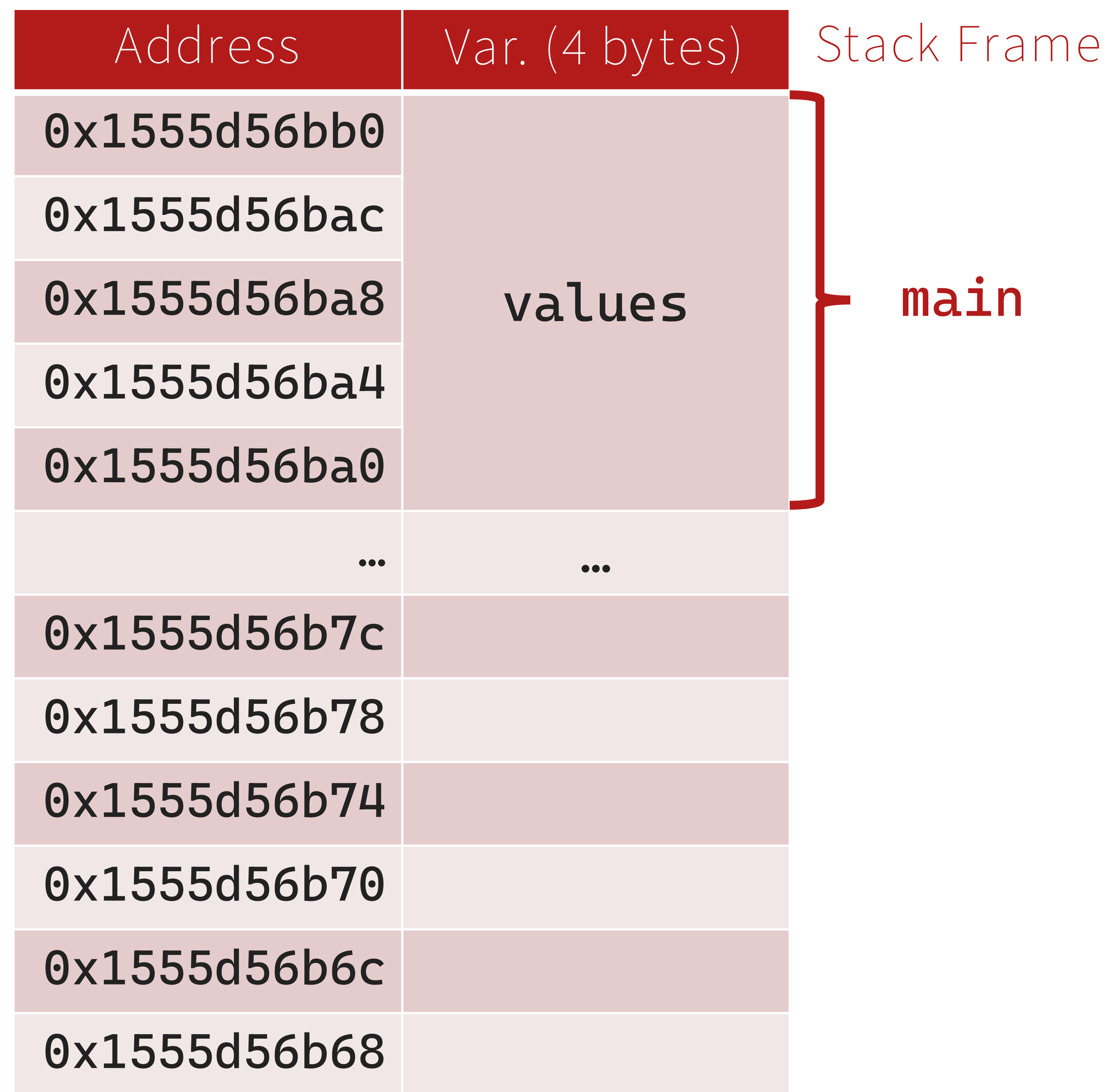
```c
#include <stdio.h>

const float EULER = 2.71828f;
const int COUNT = 5;

void fill_exp(float* dest) {
  dest[0] = 1.0f;
  for (int i = 1; i < COUNT; ++i) {
    dest[i] = dest[i - 1] * EULER;
  }
}

void print_floats(float* vals, int n) {
  for (int i = 0; i < n; ++i) {
    printf("%f\n", vals[i]);
  }
}

int main() {
  float values[COUNT];
  fill_exp(values);
  print_floats(values, COUNT);
  return 0;
}
```



```c
1  #include <stdio.h>
2
3  const float EULER = 2.71828f;
4  const int COUNT = 5;
5
6  void fill_exp(float* dest) {
7    dest[0] = 1.0f;
8    for (int i = 1; i < COUNT; ++i) {
9      dest[i] = dest[i - 1] * EULER;
10   }
11 }
12
13 void print_floats(float* vals, int n) {
14   for (int i = 0; i < n; ++i) {
15     printf("%f\n", vals[i]);
16   }
17 }
18
19 int main() {
20   float values[COUNT];
21   fill_exp(values);
22   print_floats(values, COUNT);
23   return 0;
24 }
```

Address	Var. (4 bytes)	Stack Frame
0x1555d56bb0	values	main
0x1555d56bac		
0x1555d56ba8		
0x1555d56ba4		
0x1555d56ba0		
…	…	
0x1555d56b7c		
0x1555d56b78		
0x1555d56b74		
0x1555d56b70		
0x1555d56b6c		
0x1555d56b68		

The Stack

```c
1   #include <stdio.h>
2
3   const float EULER = 2.71828f;
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7     dest[0] = 1.0f;
8     for (int i = 1; i < COUNT; ++i) {
9       dest[i] = dest[i - 1] * EULER;
10    }
11  }
12
13  void print_floats(float* vals, int n) {
14    for (int i = 0; i < n; ++i) {
15      printf("%f\n", vals[i]);
16    }
17  }
18
19  int main() {
20    float values[COUNT];
21    fill_exp(values);
22    print_floats(values, COUNT);
23    return 0;
24  }
```

Address	Var. (4 bytes)	Stack Frame
0x1555d56bb0	values	main
0x1555d56bac		
0x1555d56ba8		
0x1555d56ba4		
0x1555d56ba0		
…	…	
0x1555d56b7c	dest	fill_exp
0x1555d56b78		
0x1555d56b74	i	
0x1555d56b70		
0x1555d56b6c		
0x1555d56b68		

The Stack

```c
1  #include <stdio.h>
2
3  const float EULER = 2.71828f;
4  const int COUNT = 5;
5
6  void fill_exp(float* dest) {
7    dest[0] = 1.0f;
8    for (int i = 1; i < COUNT; ++i) {
9      dest[i] = dest[i - 1] * EULER;
10   }
11 }
12
13 void print_floats(float* vals, int n) {
14   for (int i = 0; i < n; ++i) {
15     printf("%f\n", vals[i]);
16   }
17 }
18
19 int main() {
20   float values[COUNT];
21   fill_exp(values);
22   print_floats(values, COUNT);
23   return 0;
24 }
```

Address	Var. (4 bytes)	Stack Frame
0x1555d56bb0	values	main
0x1555d56bac		
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0x1555d56ba4		
0x1555d56ba0		
…	…	
0x1555d56b7c		
0x1555d56b78		
0x1555d56b74		
0x1555d56b70		
0x1555d56b6c		
0x1555d56b68		

The Stack

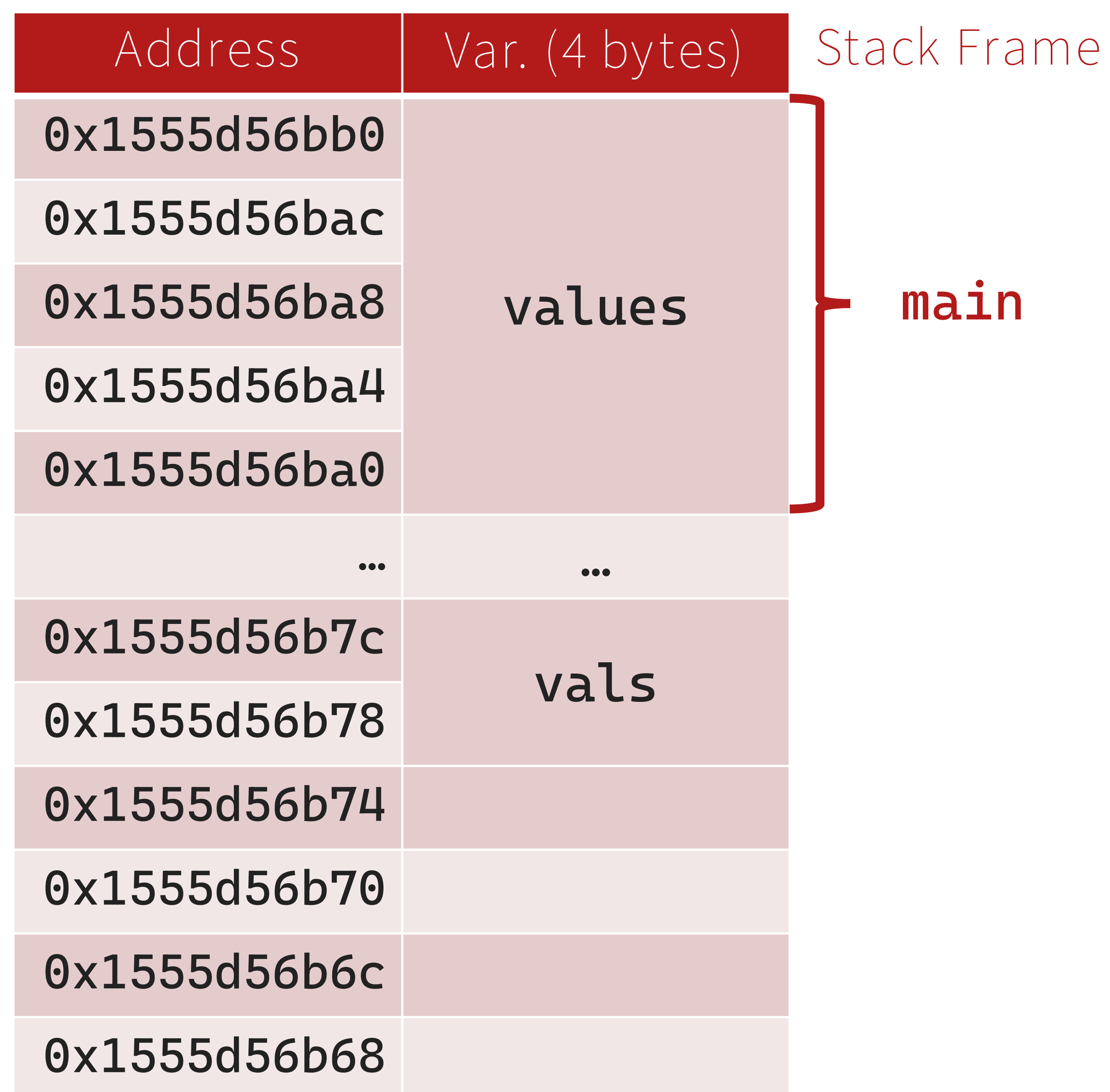
```c
#include <stdio.h>

const float EULER = 2.71828f;
const int COUNT = 5;

void fill_exp(float* dest) {
  dest[0] = 1.0f;
  for (int i = 1; i < COUNT; ++i) {
    dest[i] = dest[i - 1] * EULER;
  }
}

void print_floats(float* vals, int n) {
  for (int i = 0; i < n; ++i) {
    printf("%f\n", vals[i]);
  }
}

int main() {
  float values[COUNT];
  fill_exp(values);
  print_floats(values, COUNT);
  return 0;
}
```



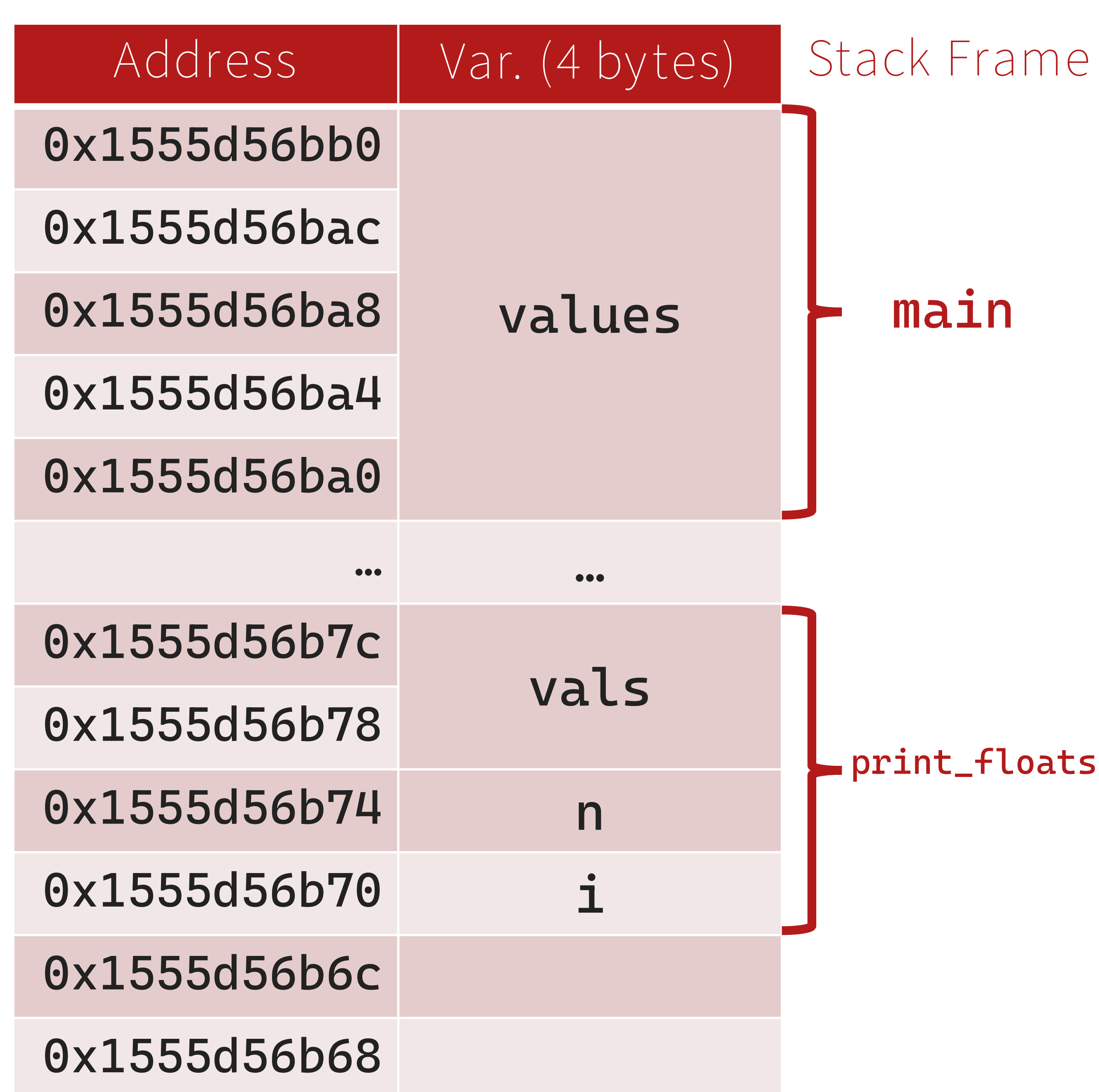
```c
#include <stdio.h>

const float EULER = 2.71828f;
const int COUNT = 5;

void fill_exp(float* dest) {
  dest[0] = 1.0f;
  for (int i = 1; i < COUNT; ++i) {
    dest[i] = dest[i - 1] * EULER;
  }
}

void print_floats(float* vals, int n) {
  for (int i = 0; i < n; ++i) {
    printf("%f\n", vals[i]);
  }
}

int main() {
  float values[COUNT];
  fill_exp(values);
  print_floats(values, COUNT);
  return 0;
}
```



```c
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void fill_exp(float* dest) {
  dest[0] = 1.0f;
  for (int i = 1; i < COUNT; ++i) {
    dest[i] = dest[i - 1] * EULER;
  }
}

void print_floats(float* vals, int n) {
  for (int i = 0; i < n; ++i) {
    printf("%f\n", vals[i]);
  }
}

int main() {
  float values[COUNT];
  fill_exp(values);
  print_floats(values, COUNT);
  return 0;
}
```

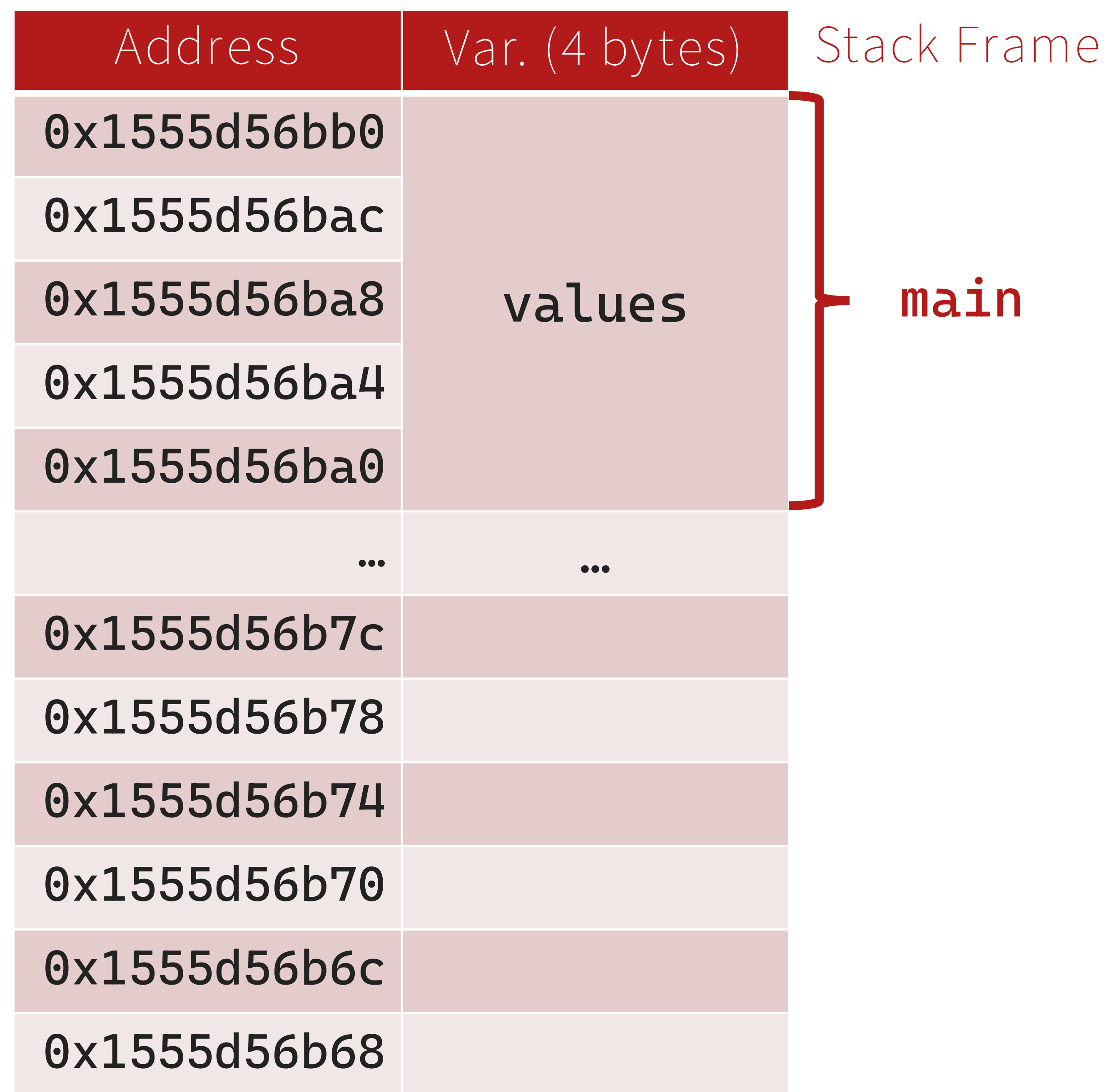

PollEv: create_exp()

```c
#include <stdio.h>

const float EULER = 2.71828f;
const int COUNT = 5;

float* create_exp() {
  float dest[COUNT];
  dest[0] = 1.0f;
  for (int i = 1; i < COUNT; ++i) {
      dest[i] = dest[i - 1] * EULER;
  }
  return dest;
}

void print_floats(float* vals, int n) {
  for (int i = 0; i < n; ++i) {
      printf("%f\n", vals[i]);
  }
}

int main() {
  float* values = create_exp();
  print_floats(values, COUNT);
  return 0;
}
```

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What does the program on the screen print?

Nobody has responded yet.

Hang tight! Responses are coming in.

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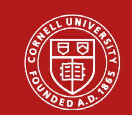
Limitations of The Call Stack

- Local variables only live as long as the function call
- Never return a pointer to a local variable!
  - Returning a pointer to data that is about to be "destroyed"
  - *Undefined behavior*
- Safe Operations:
  1. Passing a pointer to a local variable as an argument to a function
  2. Returning a non-pointer value
     - Compiler will handle copying these!

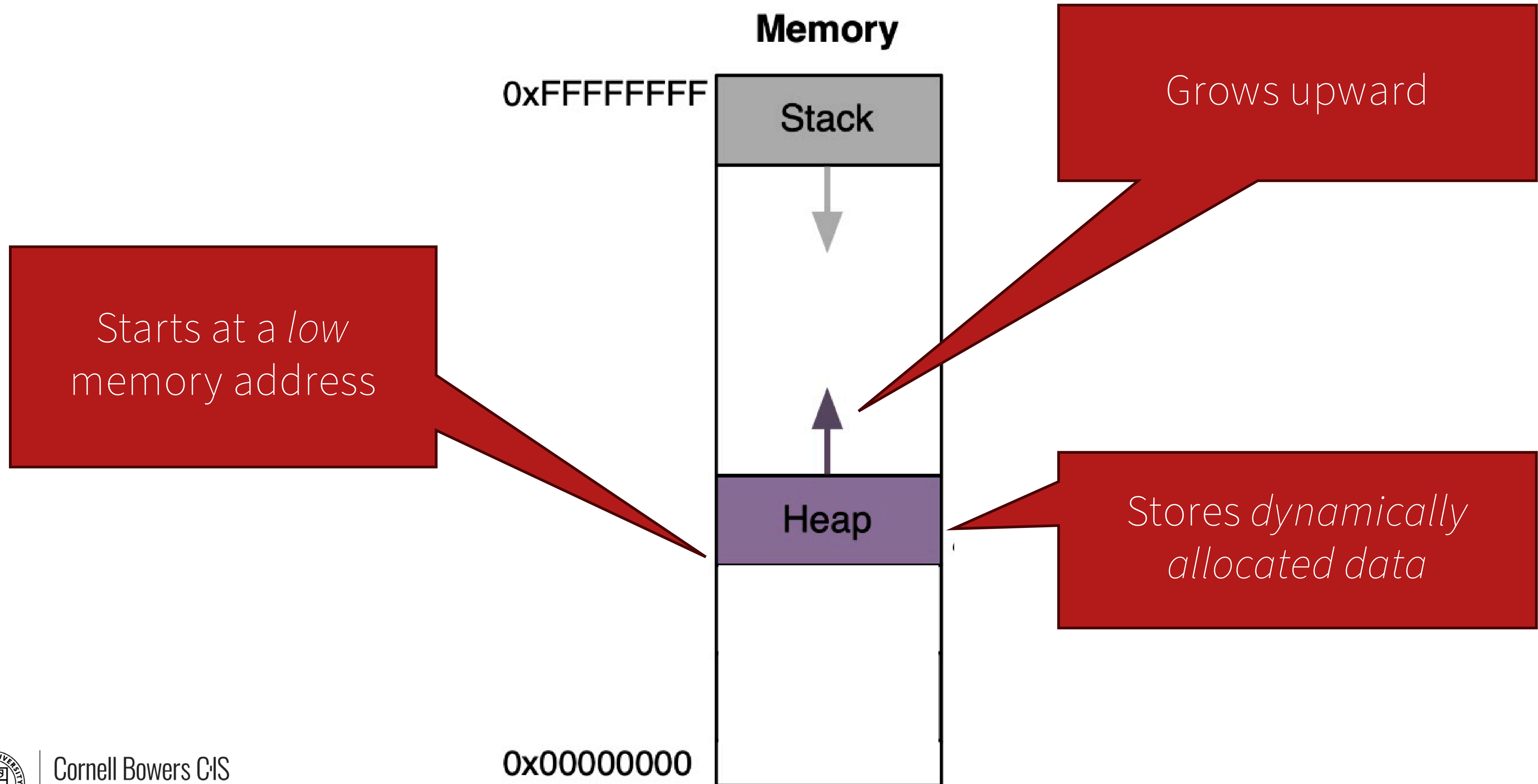
Demo: `create_exp()`



Roadmap

1. Finish Pointers
   - Strings
   - Fun Pointer Tricks
2. The Call Stack
3. The Heap

Overview: The Heap



The Stack vs. The Heap

The Stack

The Heap

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`malloc(…)` & `free(…)`

Located in
`stdlib.h`

Pointer to first byte in new block

Number of *bytes* to allocate

```
void* malloc(size_t size);
```

"Memory Allocate"

```
void free(void* ptr);
```

Pointer to the beginning of memory that was allocated by **`malloc`**

Demo: Heapified `create_exp()`

```
1  #include <stdio.h>
2  #include <stdlib.h>
3
4  const float EULER = 2.71828f;
5  const int COUNT = 10;
6
7  float* create_exp() {
8      float* dest = malloc(COUNT * sizeof(float));
9      dest[0] = 1.0f;
10     for (int i = 1; i < COUNT; ++i) {
11         dest[i] = dest[i - 1] * EULER;
12     }
13     return dest;
14 }
15
16 void print_floats(float* vals, int count) {
17     for (int i = 0; i < count; ++i) {
18         printf("%f\n", vals[i]);
19     }
20 }
21
22 int main() {
23     float* values = create_exp();
24     print_floats(values, 10);
25     free(values);
26     return 0;
27 }
```

The Laws of The Heap

Now we are really entering the "Danger Zone"!

The Laws of The Heap

1. Use after free: After you **`free`** memory, you can't use it.
2. Double free: You can only **`free`** memory once.
3. Memory leak: You must **`free`** all the memory you allocated with **`malloc`**
4. Out-of-bounds access: You can only access data *inside* allocated block.

The Laws of The Heap

```
1   int main() {
2     int *arr = malloc(10 * sizeof(int));
3     for (int i = 0; i < 10; i++) {
4       arr[i] = i + 1;
5     }
6     free(arr);
7
8     // This violates Law 1: Use after free!
9     printf("arr[0] = %d\n", arr[0]);
10
11    return 0;
12  }
```

1. Use after free: After you **free** memory, you can't use it.

The Laws of The Heap

```c
1  int main() {
2    int *arr = malloc(10 * sizeof(int));
3    for (int i = 0; i < 10; i++) {
4      arr[i] = i + 1;
5    }
6    free(arr);
7
8    // This violates Law 2: Double free!
9    free(arr);
10
11   return 0;
12 }
```

2. Double free: You can only **free** memory once.

The Laws of The Heap

```
1   int main() {
2     int *arr = malloc(10 * sizeof(int));
3     for (int i = 0; i < 10; i++) {
4       arr[i] = i + 1;
5     }
6
7     // This violates Law 3: Memory leak!
8     // no free :(
9
10    return 0;
11  }
```

3. Memory leak: You must **free** all the memory you allocated with **malloc**

The Laws of The Heap

```
1   int main() {
2     int *arr = malloc(10 * sizeof(int));
3     for (int i = 0; i < 10; i++) {
4       arr[i] = i + 1;
5     }
6
7     // This violates Law 4:
8     // Out-of-bounds Access!
9     printf("arr[10] = %d\n", arr[10]);
10
11    return 0;
12  }
```

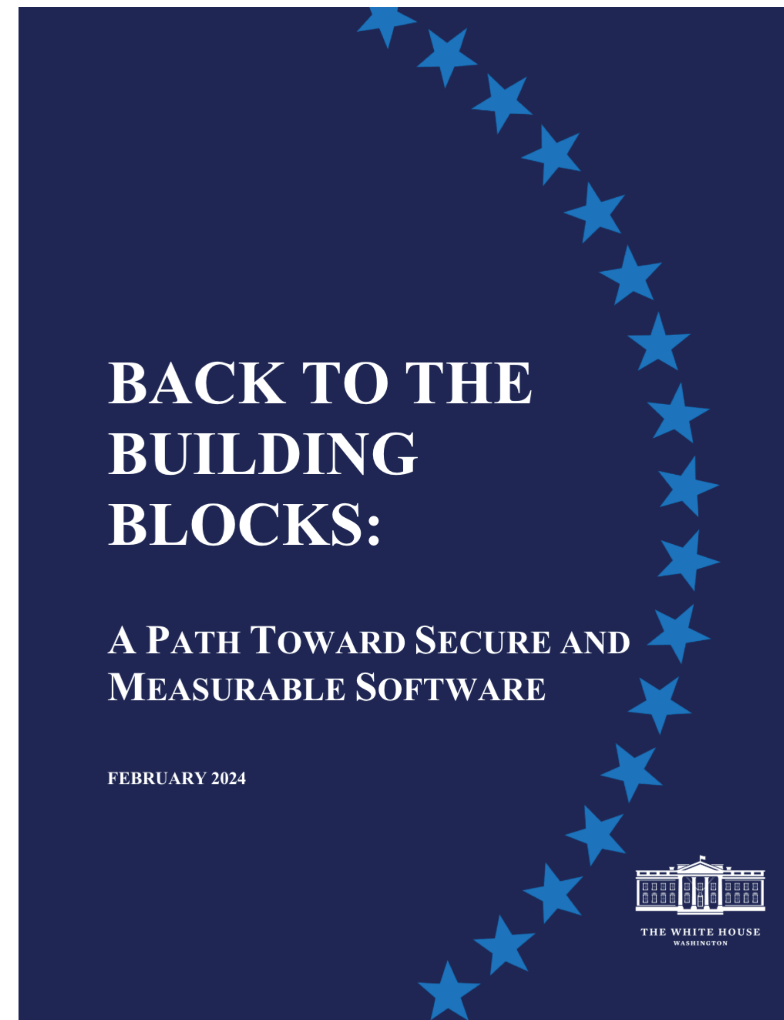
4. Out-of-bounds Access: You can only access data *inside* allocated block.

Demo: `memory_bugs.c`

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

const float EULER = 2.71828f;
const int COUNT = 10;

// Allocate a new array containing `COUNT` values from an exponential series.
float* create_exp() {
    float* dest = malloc(COUNT * sizeof(float));  // New!
    dest[0] = 1.0f;
    for (int i = 1; i < COUNT; ++i) {
        dest[i] = dest[i - 1] * EULER;
    }
    return dest;
}

// Print the first `count` values in a float array.
void print_floats(float* vals, int count) {
    for (int i = 0; i < count; ++i) {
        printf("%f\n", vals[i]);
    }

    // Let's see what's nearby...
    char* ptr = (char*)vals;
    for (int j = 0; j < 100; ++j) {
        char* byte = ptr - j;
        printf("%p: %d %c\n", byte, *byte, *byte);
    }
}

// Generate a secret.
char* gen_secret() {
    char* secret = malloc(16);
    strcpy(secret, "seekrit!");
    return secret;
}

int main() {
    char* password = gen_secret();
    float* values = create_exp();

    print_floats(values, COUNT);

    free(values);
    free(password);
    return 0;
}
```

Memory Safety is Hard

- In 2019, Microsoft found that 70% of all security vulnerabilities were memory safety violations
- These bugs are only possible in languages like C/C++
  - *Memory safe* languages: Python, Java, OCaml, Rust, Swift



2024 CrowdStrike Outage

- ~8.5 million PCs crashed and were unable to restart across the planet
- Estimated to cost ~$10 billion
- Ultimately due to an out-of-bounds access!

By Smishra1 - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=150535443

Demo: Address Sanitizer

```
1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <string.h>
4
5  const float EULER = 2.71828f;
6  const int COUNT = 10;
7
8  // Allocate a new array containing `COUNT` values from an exponential
series.
9  float* create_exp() {
10     float* dest = malloc(COUNT * sizeof(float));  // New!
11     dest[0] = 1.0f;
12     for (int i = 1; i < COUNT; ++i) {
13         dest[i] = dest[i - 1] * EULER;
14     }
15     return dest;
16 }
17
18 // Print the first `count` values in a float array.
19 void print_floats(float* vals, int count) {
20     for (int i = 0; i < count; ++i) {
21         printf("%f\n", vals[i]);
22     }
23
24     // Let's see what's nearby...
25     char* ptr = (char*)vals;
26     for (int j = 0; j < 100; ++j) {
27         char* byte = ptr - j;
28         printf("%p: %d %c\n", byte, *byte, *byte);
29     }
30 }
31
32 // Generate a secret.
33 char* gen_secret() {
34     char* secret = malloc(16);
35     strcpy(secret, "seekrit!");
36     return secret;
37 }
38
39 int main() {
40     char* password = gen_secret();
41     float* values = create_exp();
42
43     print_floats(values, COUNT);
44
45     free(values);
46     free(password);
47     return 0;
48 }
```

Memory Layout

Memory Layout