CS107, Lecture 10
Stack and Heap

Reading: K&R 5.6-5.9 or Essential C section 6 on the heap

CS107 Topic 3

How can we effectively manage all types of memory in our programs?

Why is answering this question important?

- Shows us how we can pass around data efficiently with pointers (last time)
- Introduces us to the heap and allocating memory that we manually manage (today)
- Helps us better understand use-after-free vulnerabilities, a common bug (next time)

assign3: implement a function using resizable arrays to read lines of any length from a file and write 2 programs using that function to print the last N lines of a file and print just the unique lines of a file. These programs emulate the **tail** and **uniq** Unix commands!

Learning Goals

- Learn about the differences between arrays and pointers
- Learn about the differences between the stack and the heap and when to use each one
- Become familiar with the **malloc** function for allocating memory on the heap

Lecture Plan

- **Recap:** Pointers So Far
- Arrays in Memory
- The Stack
- The Heap and Dynamic Memory
- Freeing Memory

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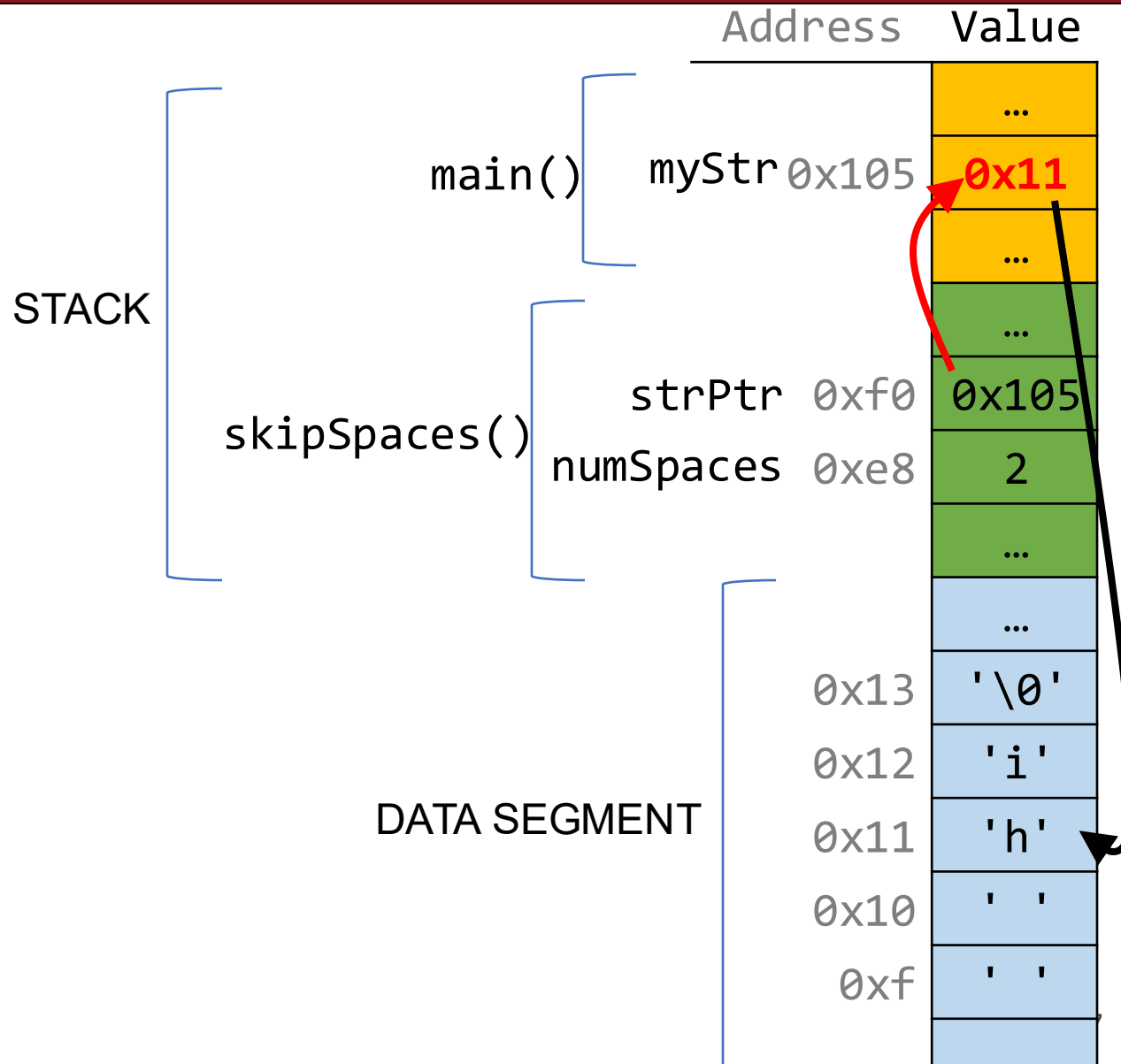
Pointers Summary

- If you are performing an operation with some input and do not care about any changes to the input, **pass the data type itself**.
- If you are modifying a specific instance of some value, **pass the location** of what you would like to modify.
- If a function takes an address (pointer) as a parameter, it can *go to* that address if it needs the actual value.
- Strings are one application of pointers, and they can help us understand pointers more generally.

Pointers to Strings

```
void skipSpaces(char **strPtr) {
    int numSpaces = strspn(*strPtr, " ");
    *strPtr += numSpaces;
}

int main(int argc, char *argv[]) {
    char *myStr = "  hi";
    skipSpaces(&myStr);
    printf("%s\n", myStr);        // hi
    return 0;
}
```



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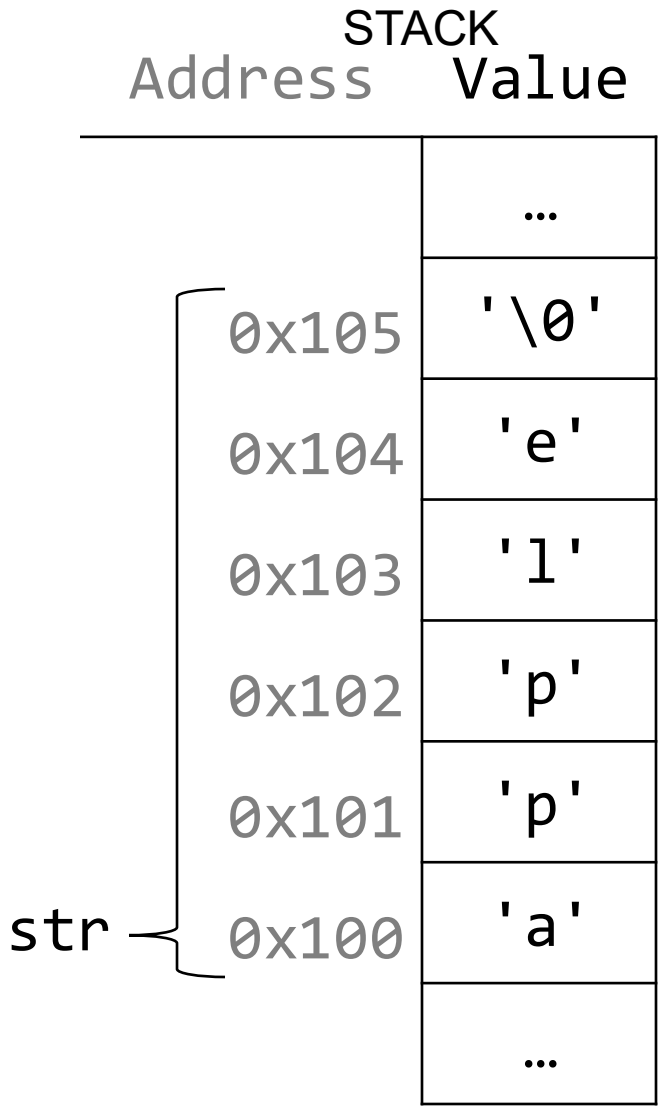
Arrays

When you declare an array, contiguous memory is allocated on the stack to store the contents of the entire array.

```
char str[6];
strcpy(str, "apple");
```

The array variable (e.g. **str**) is not a pointer; it refers to the entire array contents.

A stack array's size cannot be changed once you create it. You also cannot reassign an array (e.g. **arr = …**) once you create it.

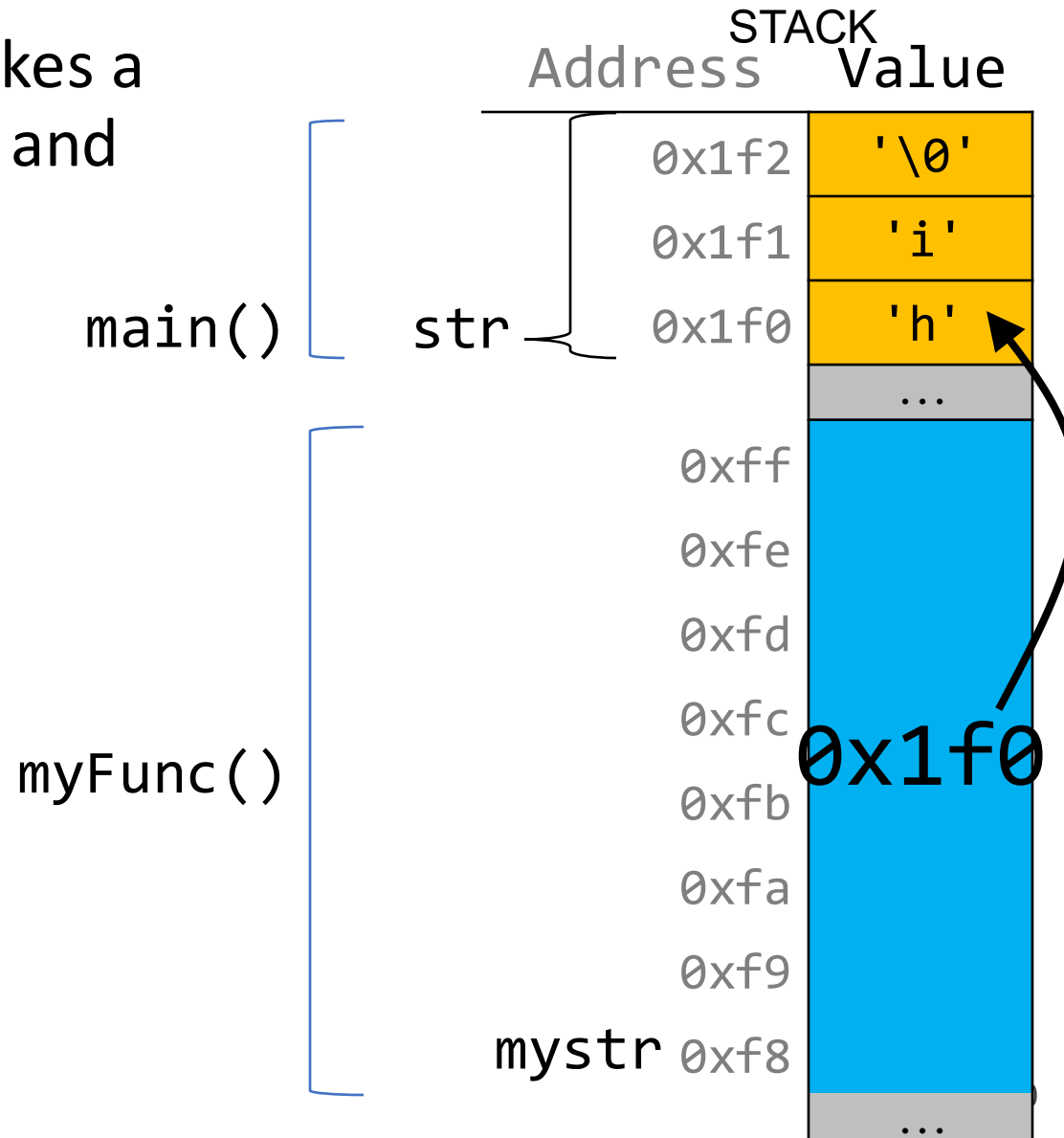


Arrays as Parameters

When you pass an **array** as a parameter, C makes a *copy of the address of the first array element*, and passes it (a pointer) to the function.

```
void myFunc(char *myStr) {
      ...
}

int main(int argc, char *argv[]) {
      char str[3];
      strcpy(str, "hi");
      myFunc(str);
      ...
}
```

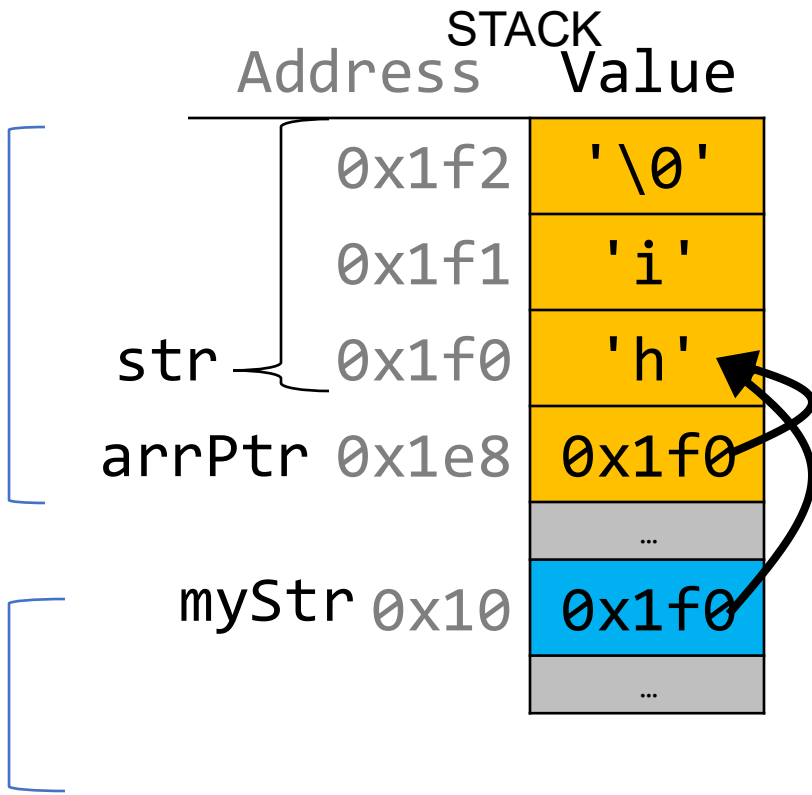


Arrays as Parameters

When you pass an **array** as a parameter, C makes a *copy of the address of the first array element and* passes it (a pointer) to the function.

```
void myFunc(char *myStr) {
      …
}

int main(int argc, char *argv[]) {
      char str[3];
      strcpy(str, "hi");
      // equivalent
      char *arrPtr = str;
      myFunc(arrPtr);
      ...
```



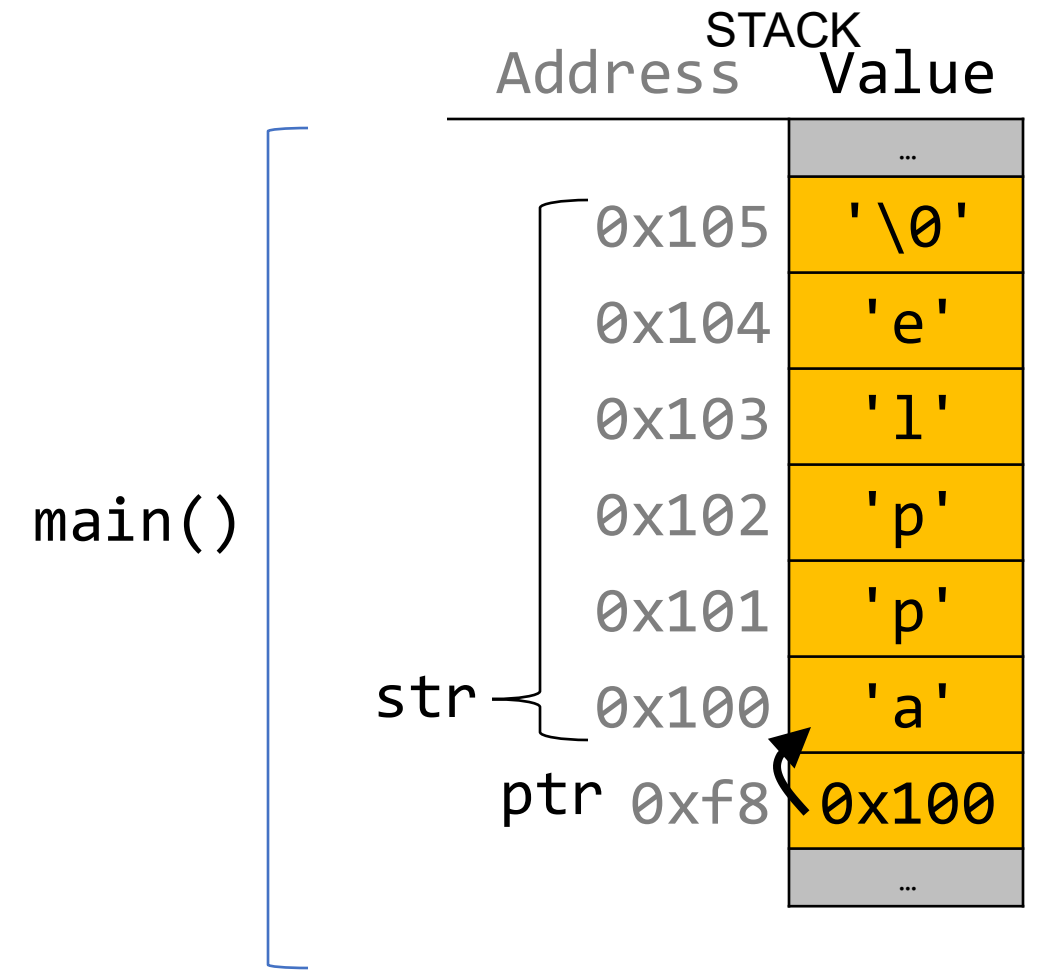
Arrays and Pointers

We can also make a pointer equal to an array; it will point to the first element in that array.

```
int main(int argc, char *argv[]) {
      char str[6];
      strcpy(str, "apple");
      char *ptr = str;

      // equivalent
      char *ptr = &str[0];

      // confusingly equivalent, avoid
      char *ptr = &str;
      ...
}
```

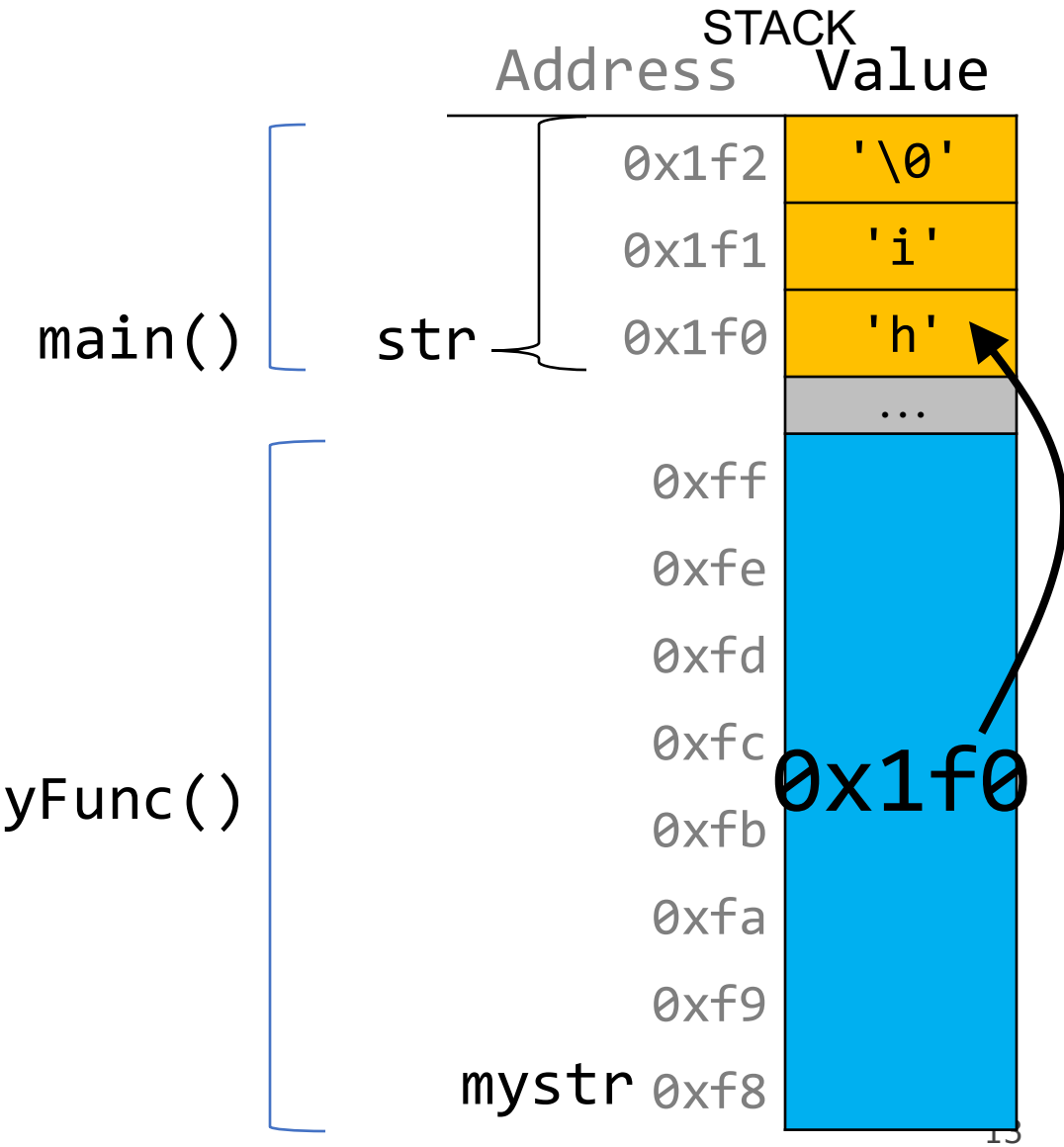


Arrays as Parameters

sizeof works (# bytes) for an array when used in the same scope where the array is declared. But it doesn't work on an array passed as a parameter from another function, because **sizeof(ptr)** is always 8.

```
void myFunc(char *myStr) {
      int size = sizeof(myStr); // 8
}

int main(int argc, char *argv[]) {
      char str[3];
      strcpy(str, "hi");
      int size = sizeof(str);   // 3
      myFunc(str);
      ...
```



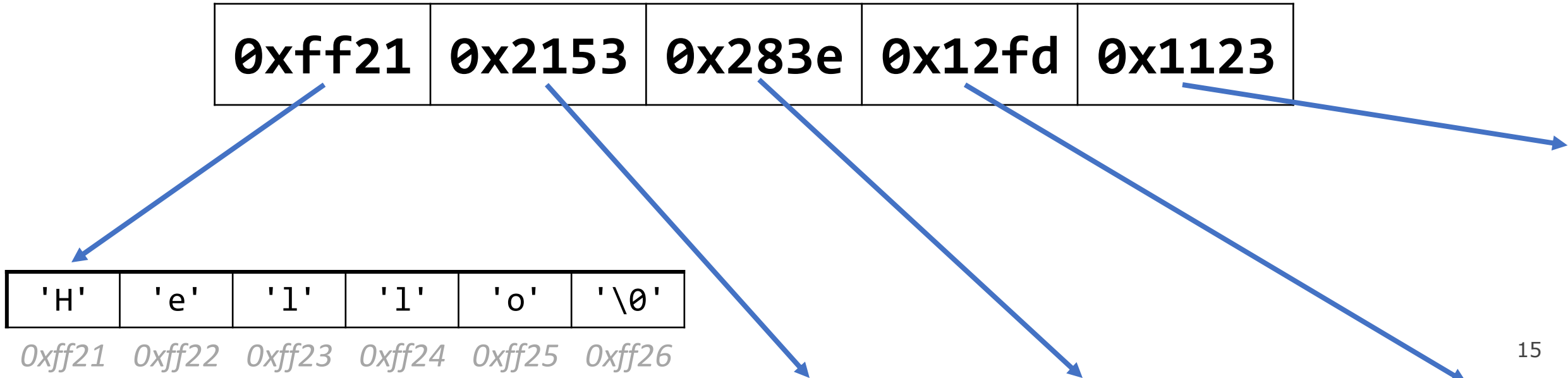
Arrays Summary

- When you create an array, you are making space for each element in the array.
- When you create a pointer, you are making space for an 8 byte address.
- Arrays ”decay to pointers” when you perform arithmetic or pass as parameters.
- You can set a pointer equal to an array; that pointer will point to the array’s first element
- &arr does nothing on arrays, but &ptr on pointers gets its address
- sizeof(arr) gets the size of an array in bytes, but sizeof(ptr) is always 8
- Only strings have null terminating characters at the end – other arrays do not

Arrays Of Pointers

You can make an array of pointers to e.g. group multiple strings together – this stores 5 pointers, *not* all of the characters for 5 strings!:

```
char *stringArray[5];   // space to store 5 char *s
```



Lecture Plan

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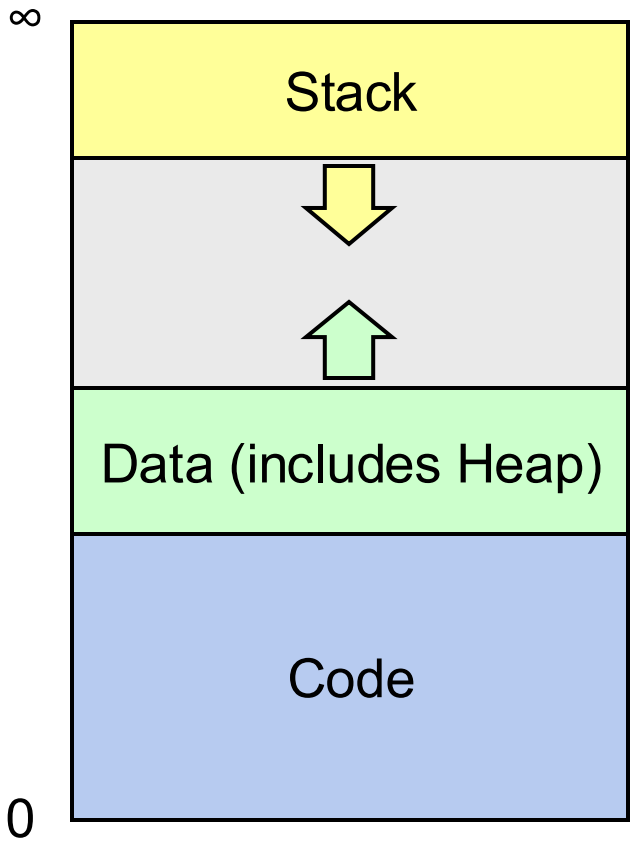
Memory Layout

Let's dive deeper into different areas of memory used by our programs. What does memory look like?

- A process's memory is a collection of *segments* (sections)
- **Code** ("text") – program code
- **Data** – constants, heap
- **Stack** – stack frames for functions (local variables, parameters). A function's stack frame goes away when the function returns, and the stack shrinks upwards.
- Stack grows down, heap grows up as more space is needed



The Stack

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void func2() {
    int d = 0;
}

void func1() {
    int c = 99;
    func2();
}

int main(int argc, char *argv[]) {
    int a = 42;
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    printf("Done.");
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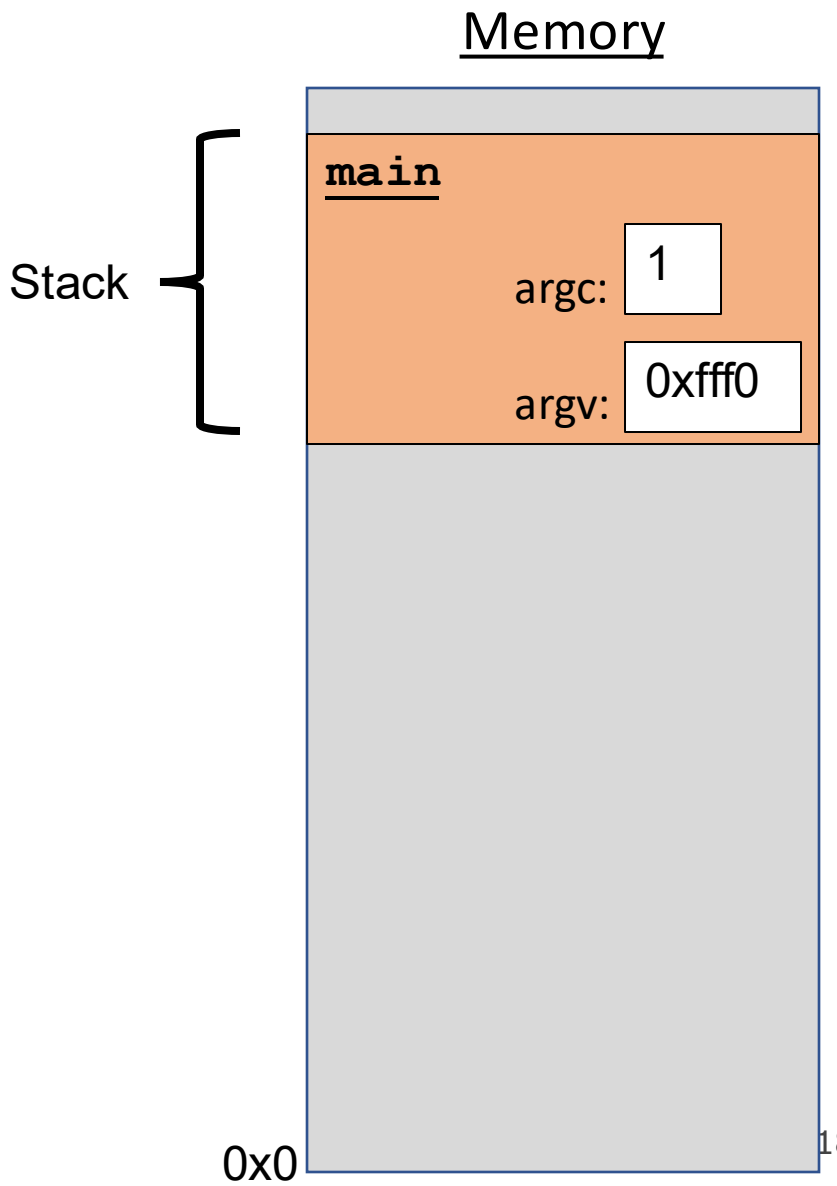
```



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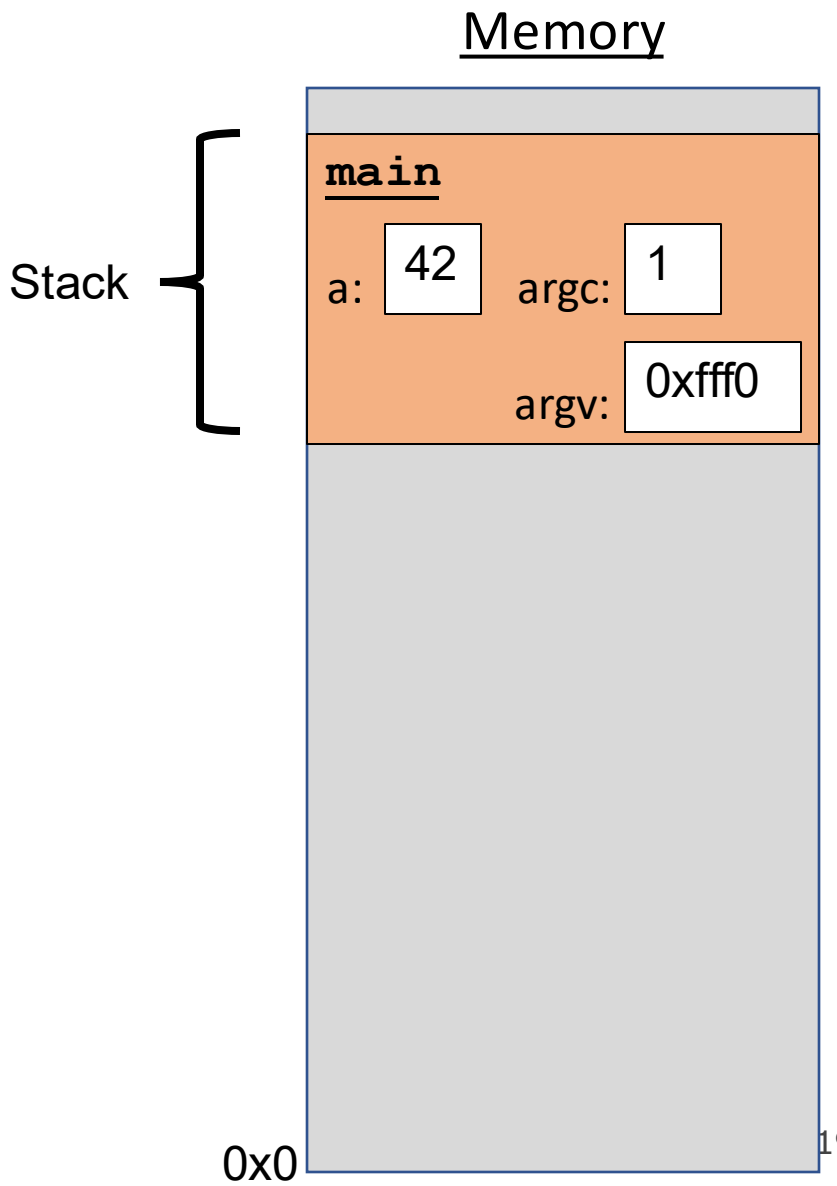

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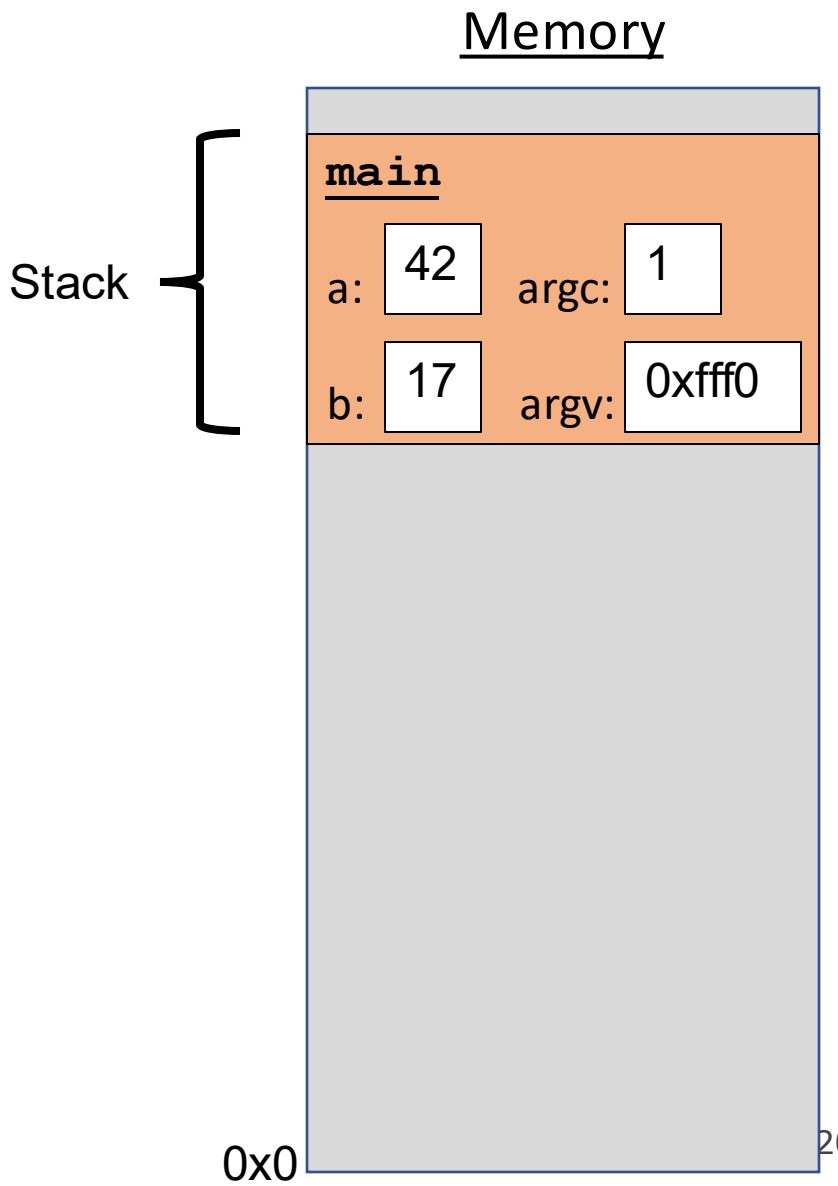

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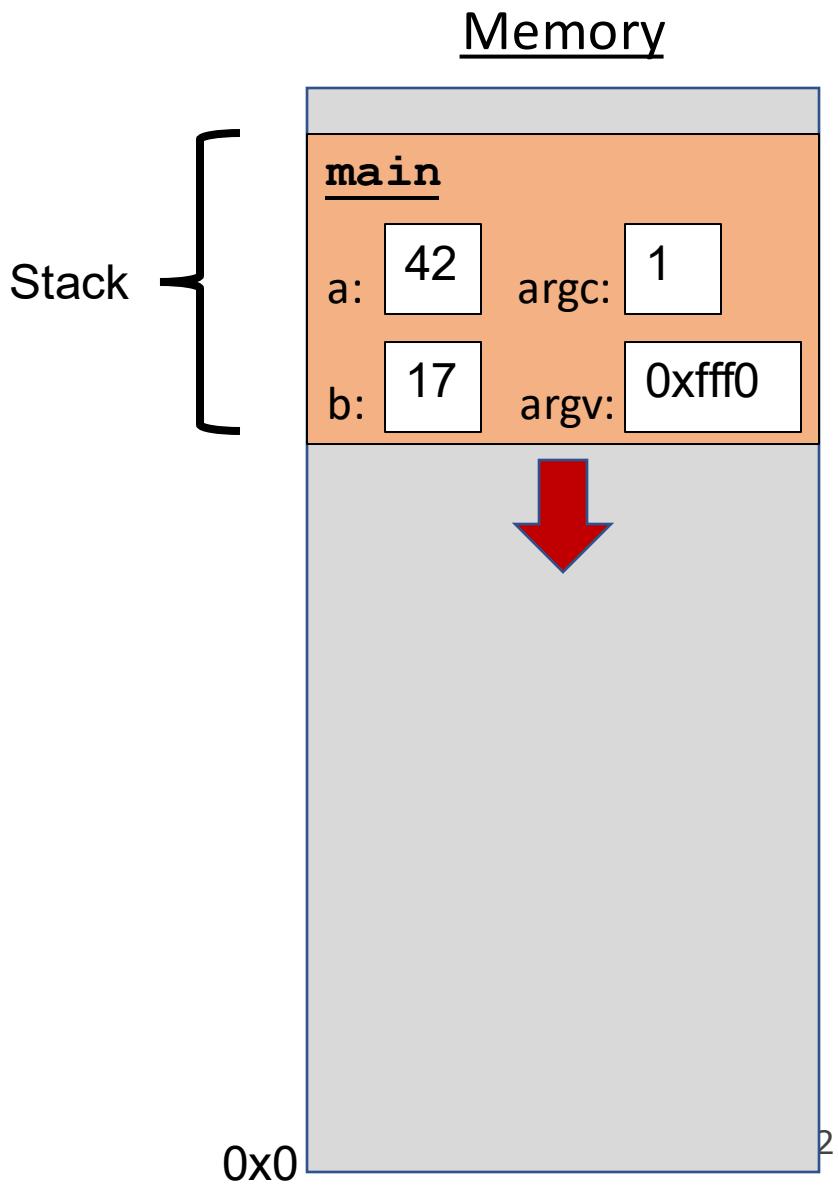

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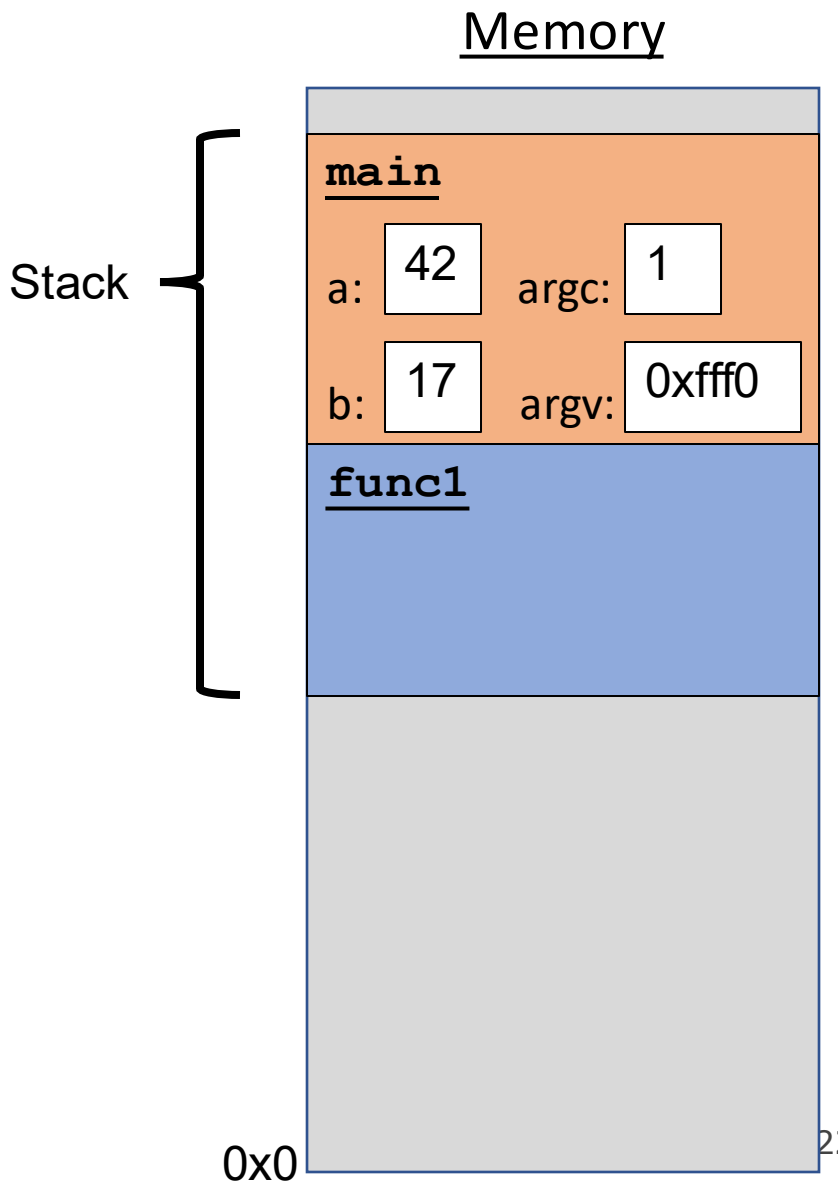

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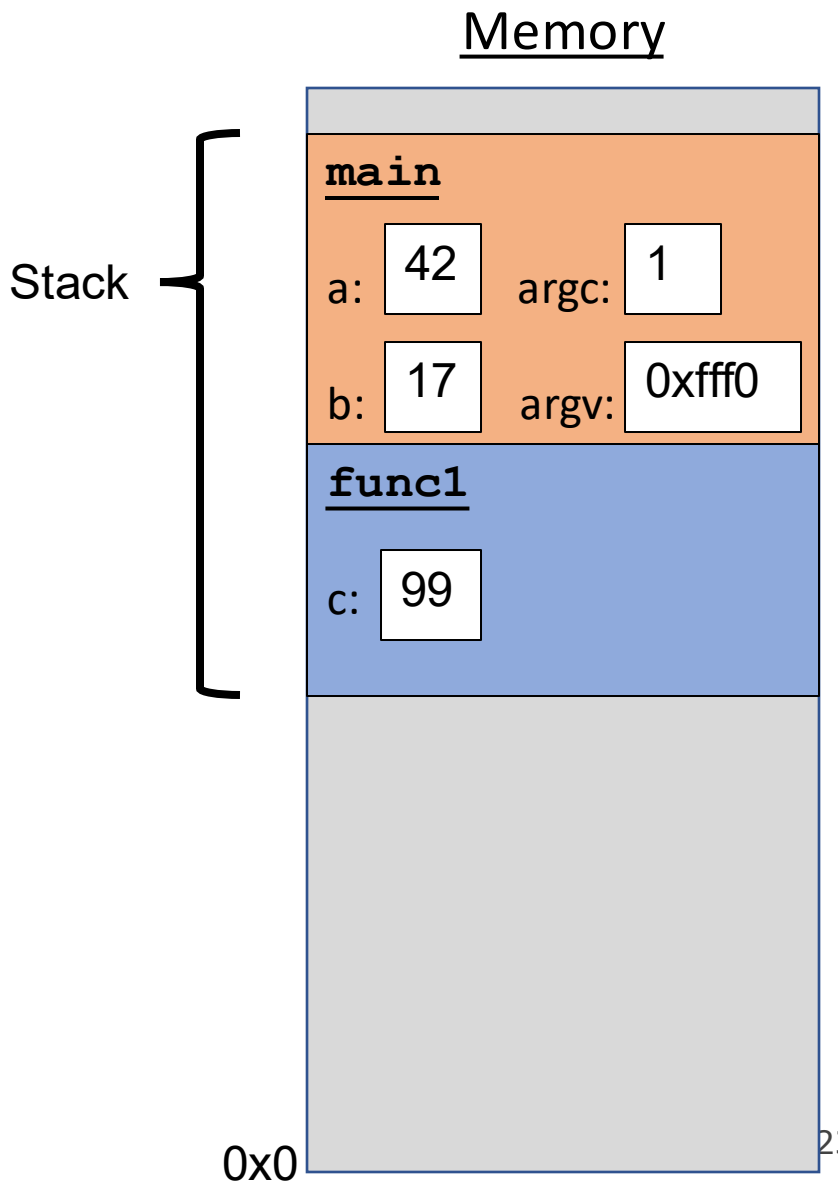

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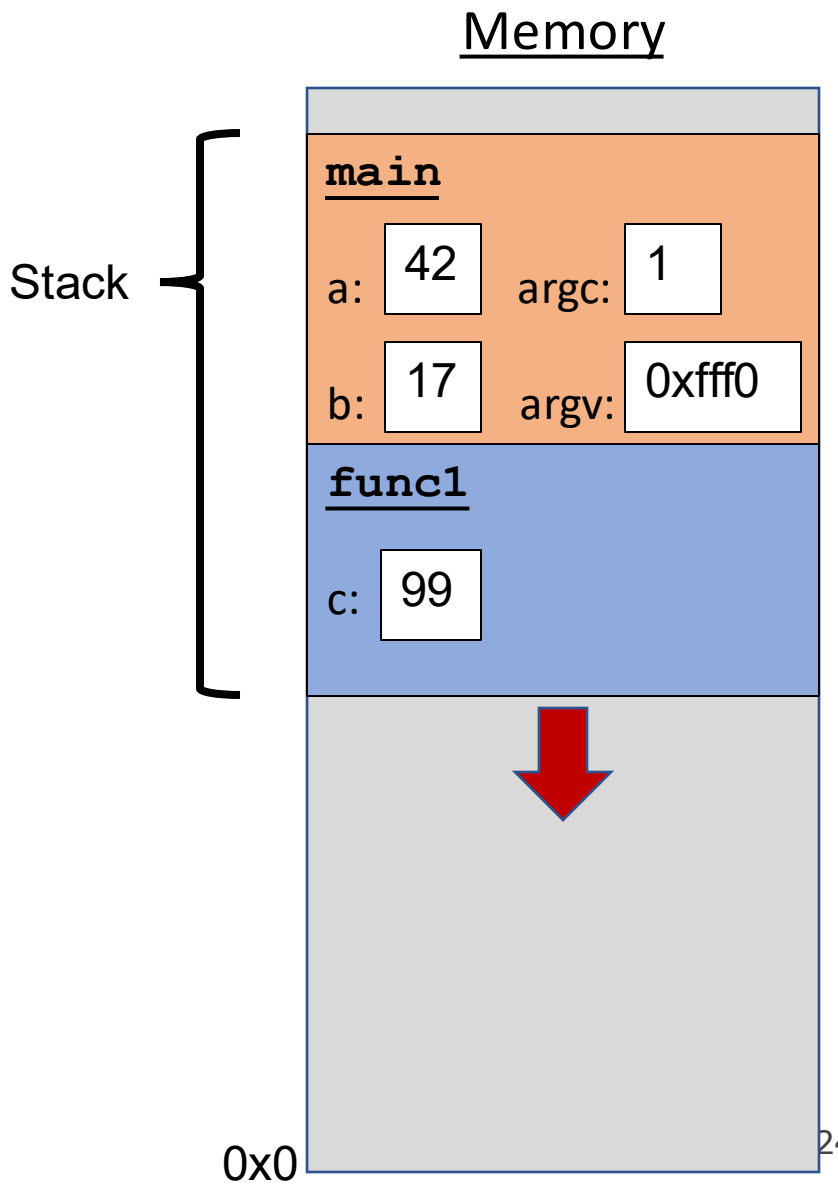

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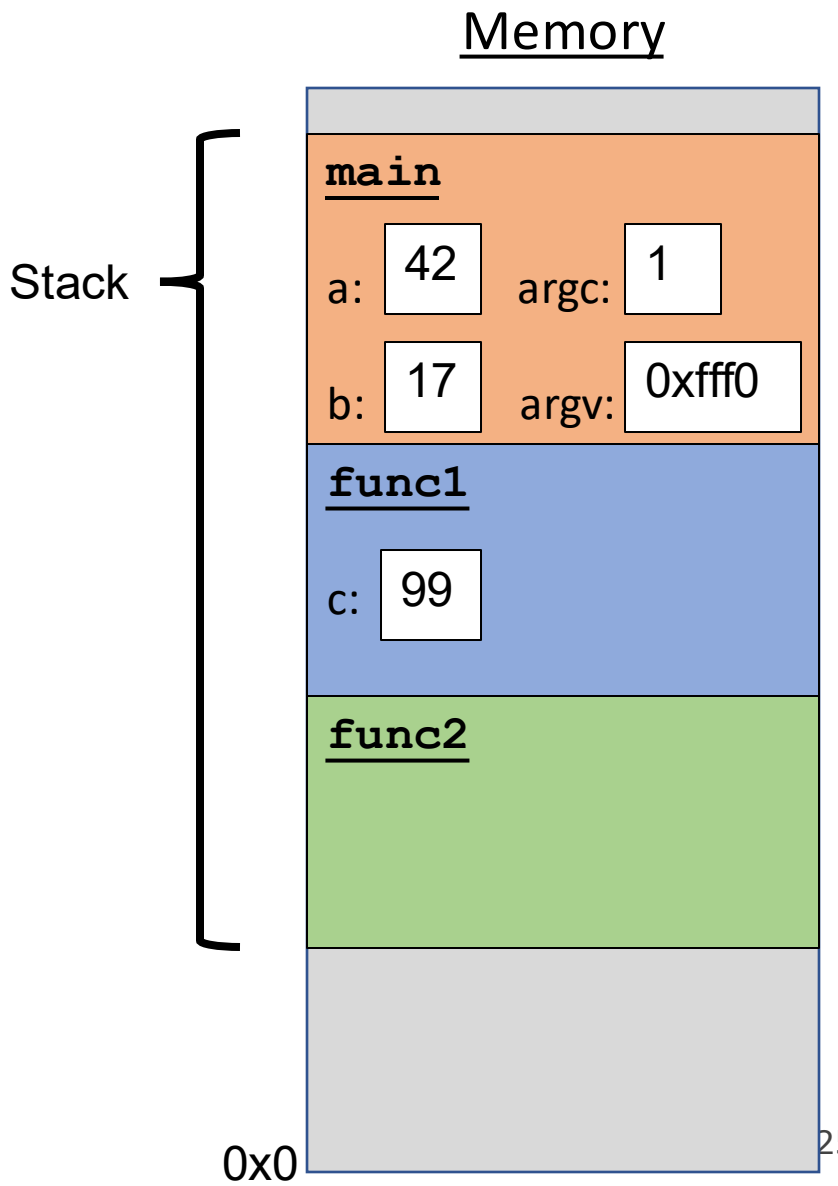

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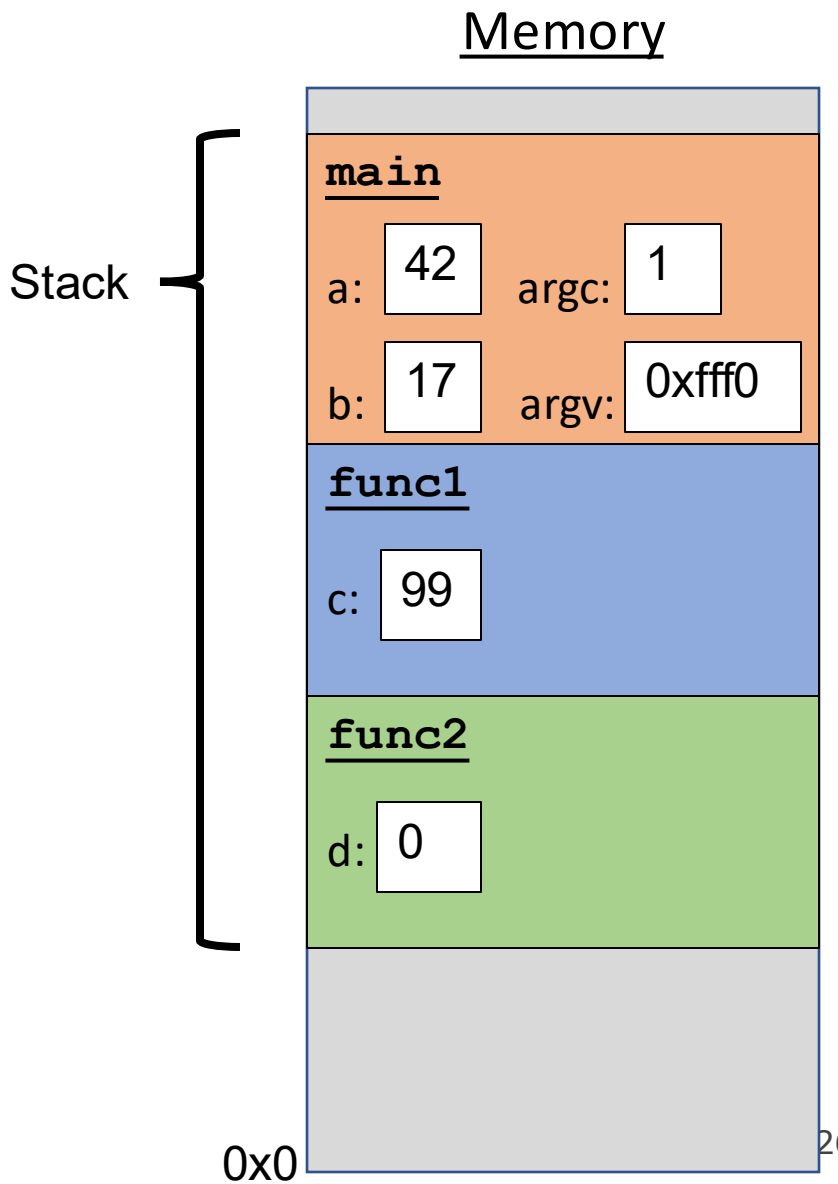

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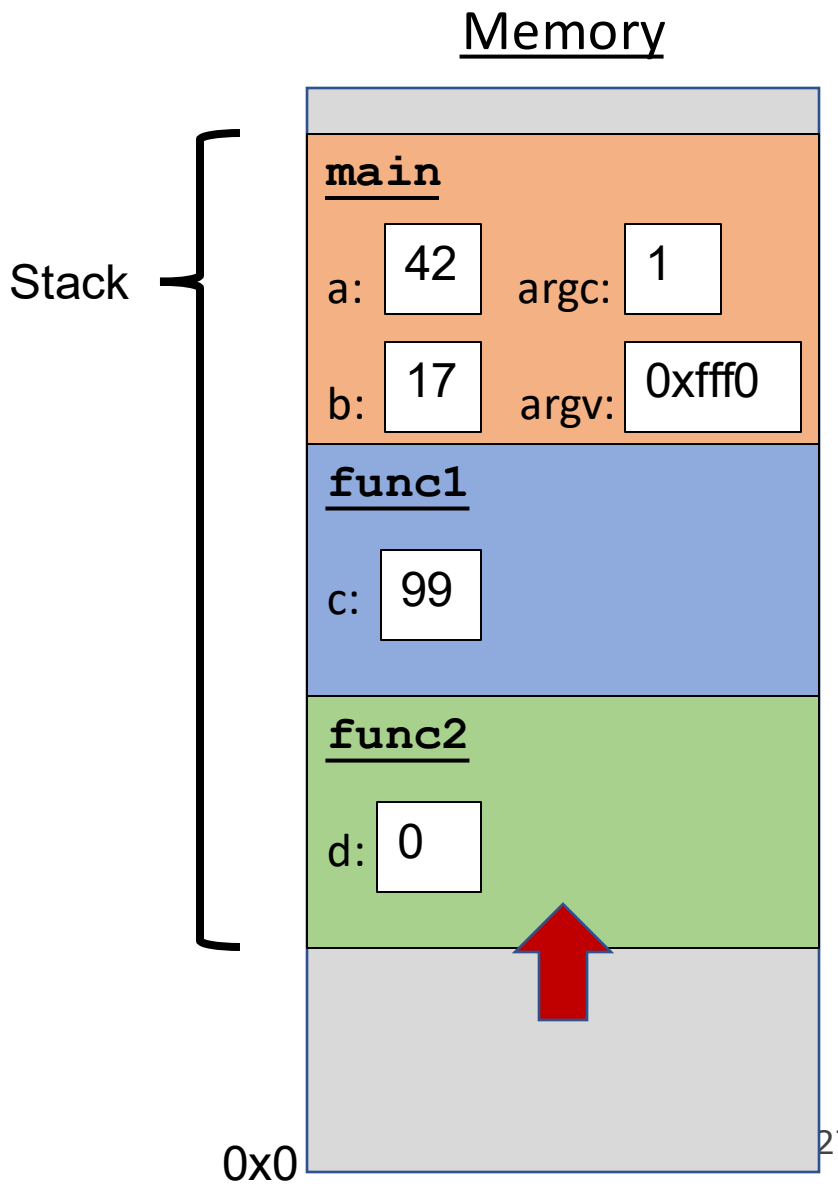

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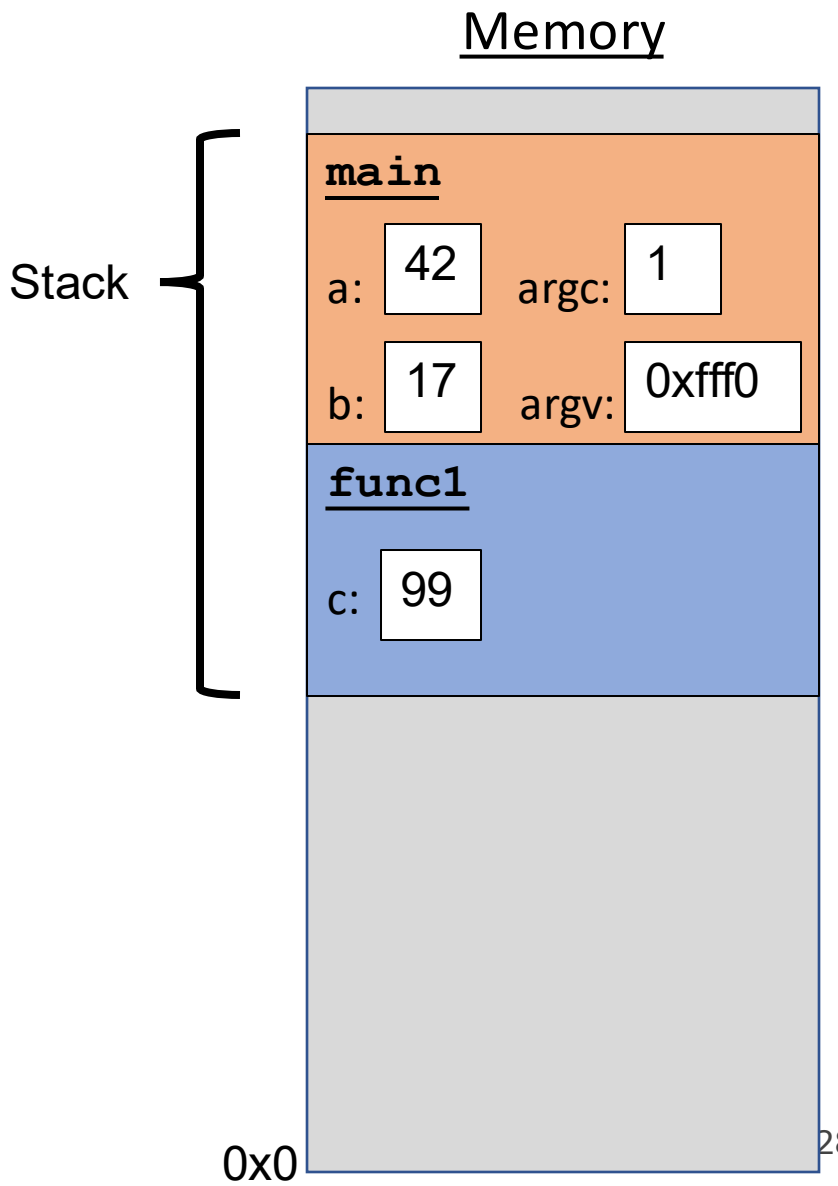

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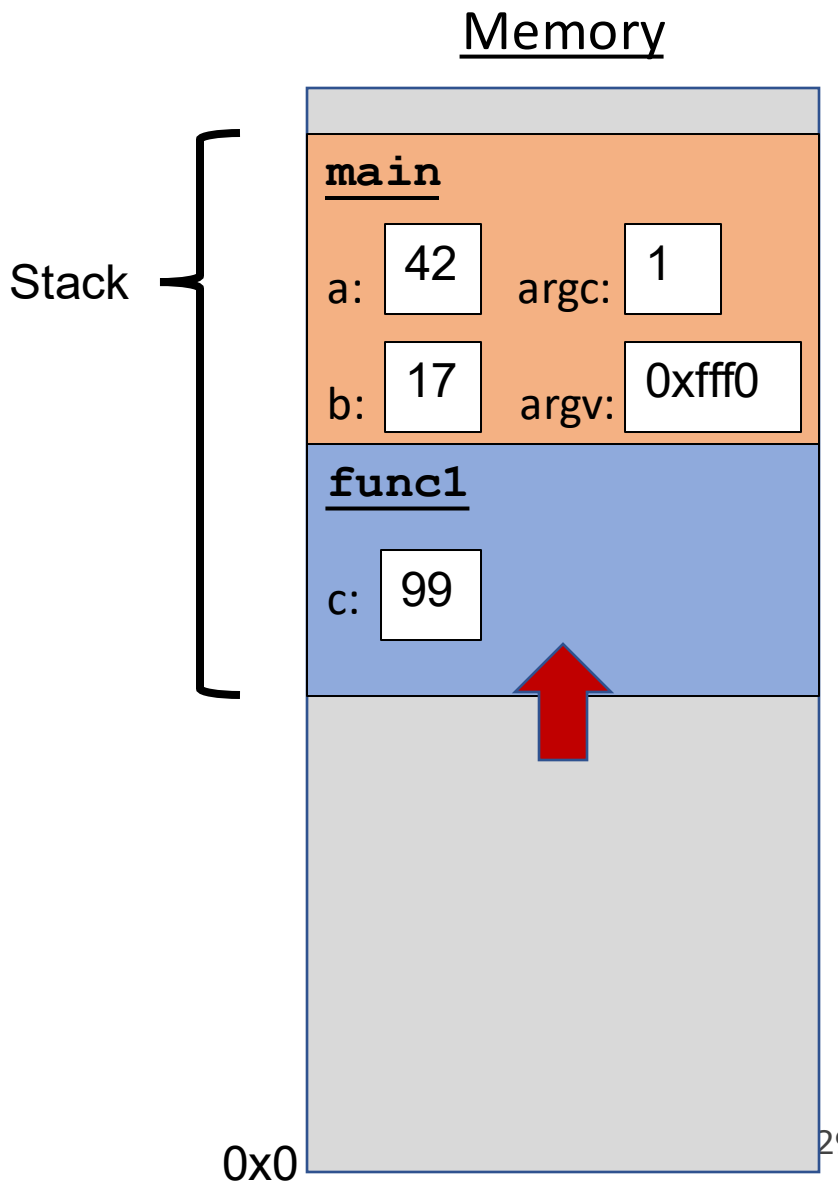

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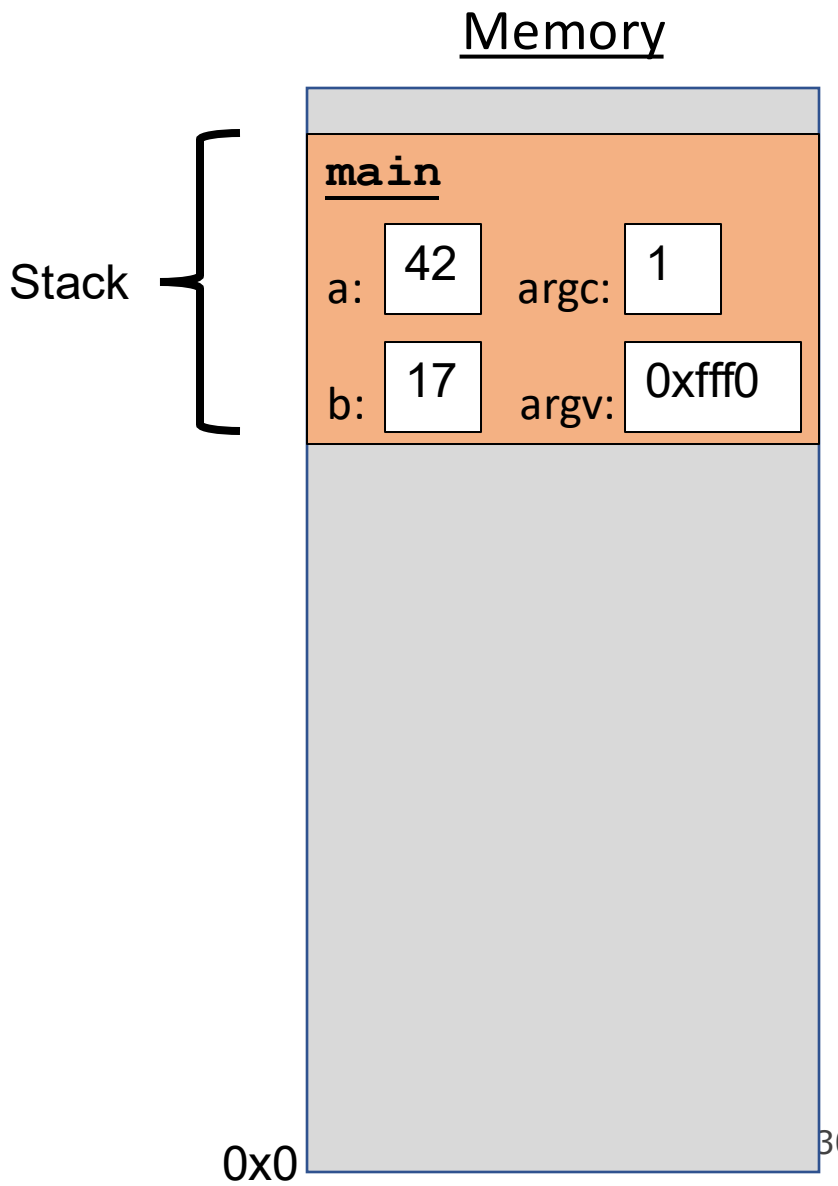

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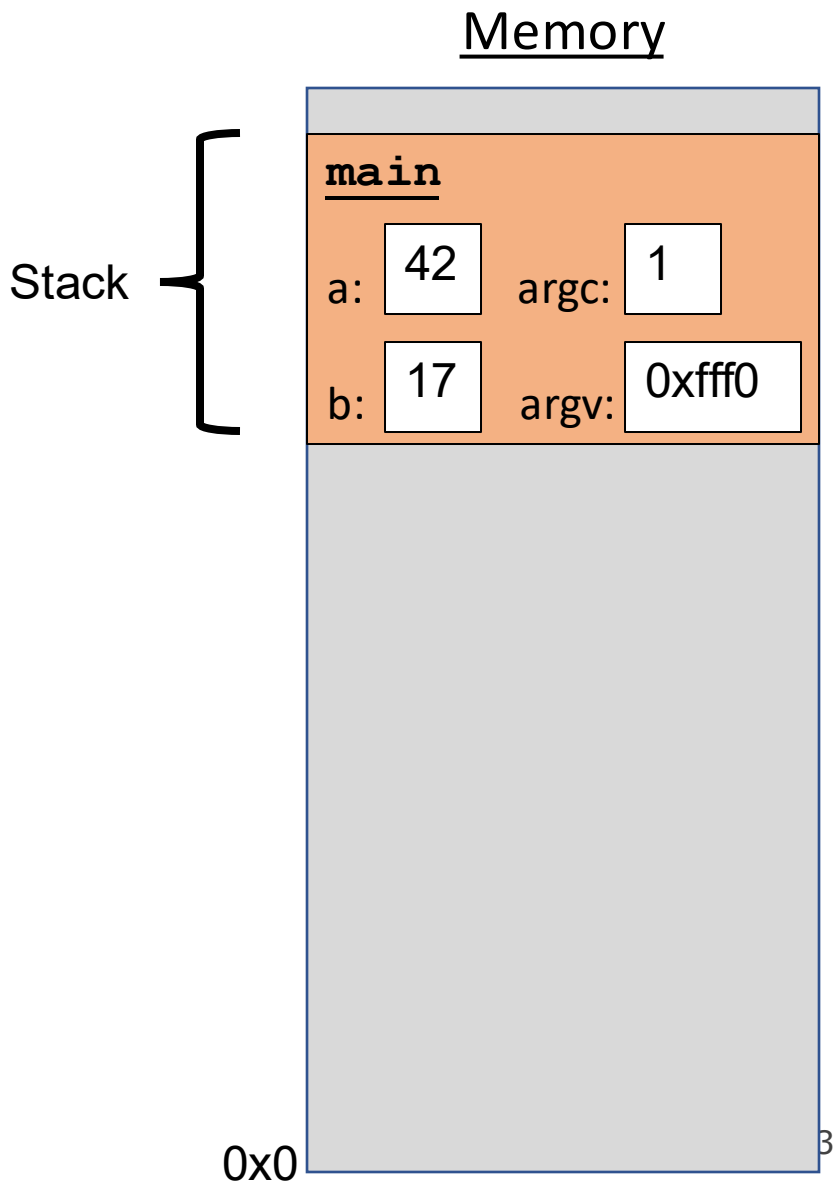

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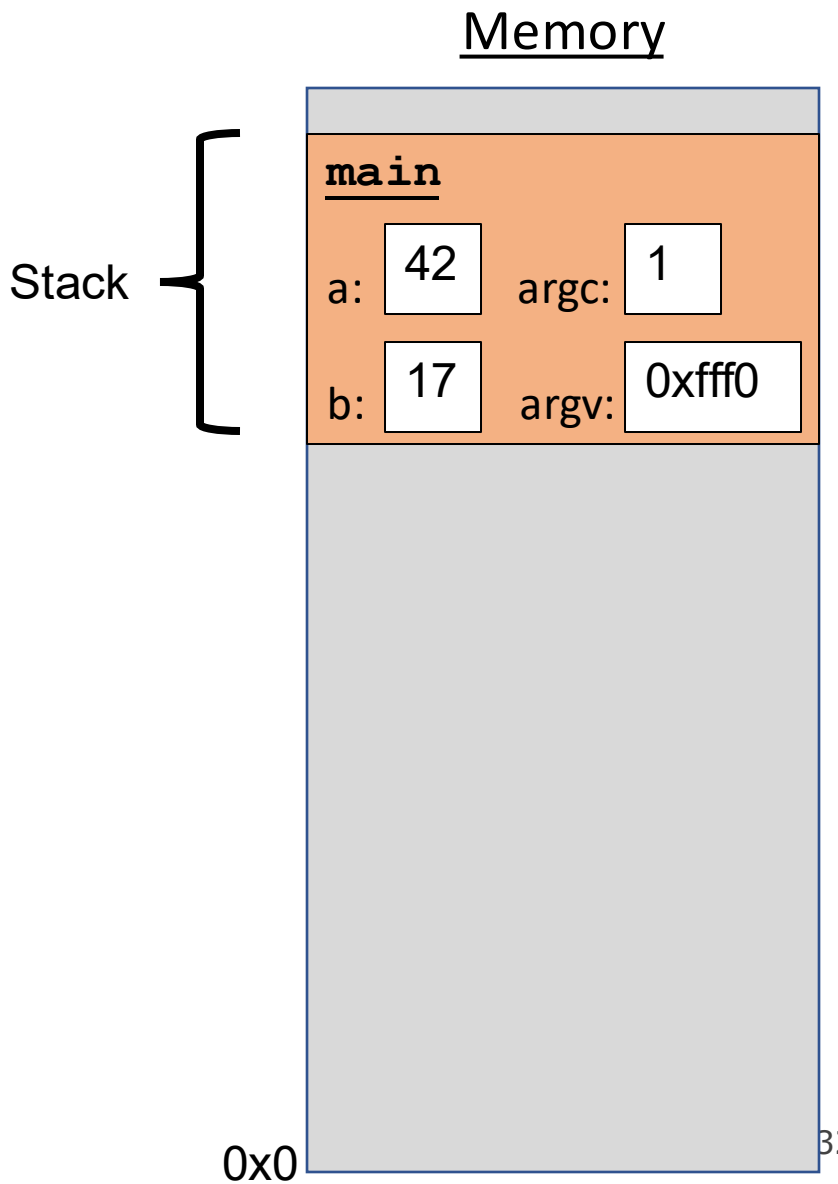

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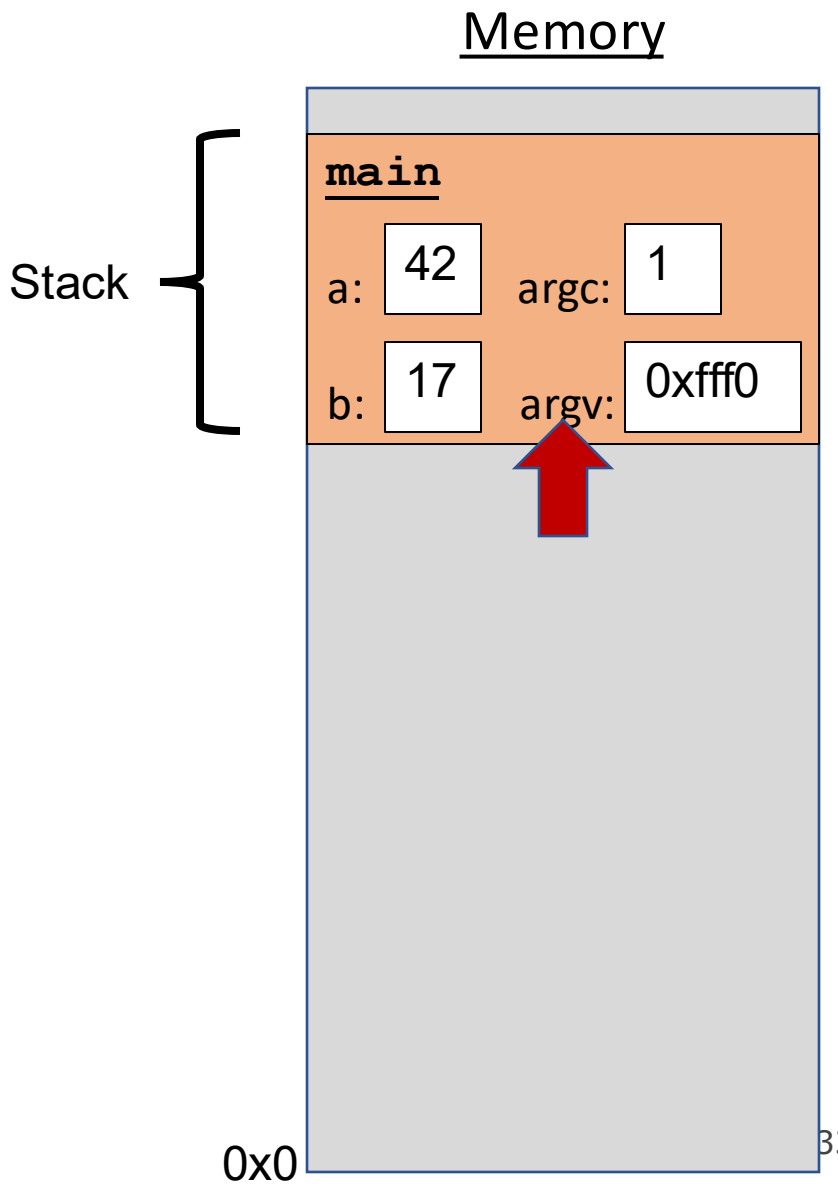

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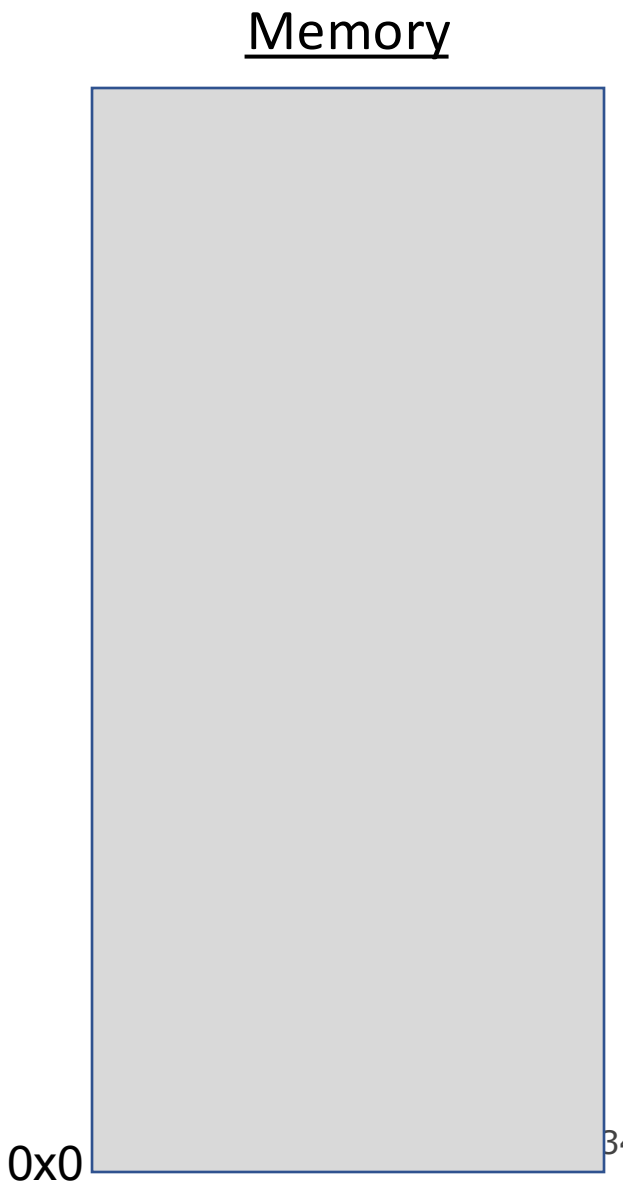
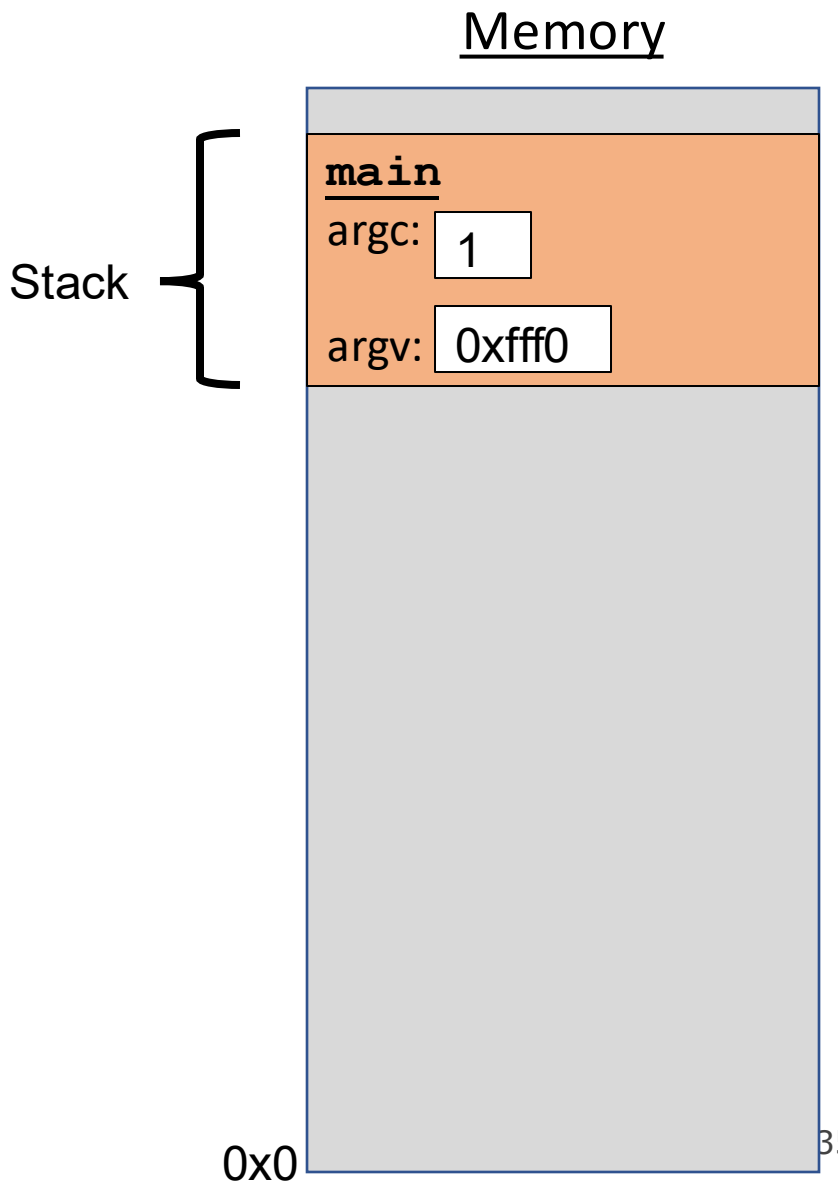


The Stack

Each function **call** has its own *stack frame* for its own copy of variables.

```
int factorial(int n) {
    if (n == 1) {
        return 1;
    } else {
        return n * factorial(n - 1);
    }
}

int main(int argc, char *argv[]) {
    printf("%d", factorial(4));
    return 0;
}
```



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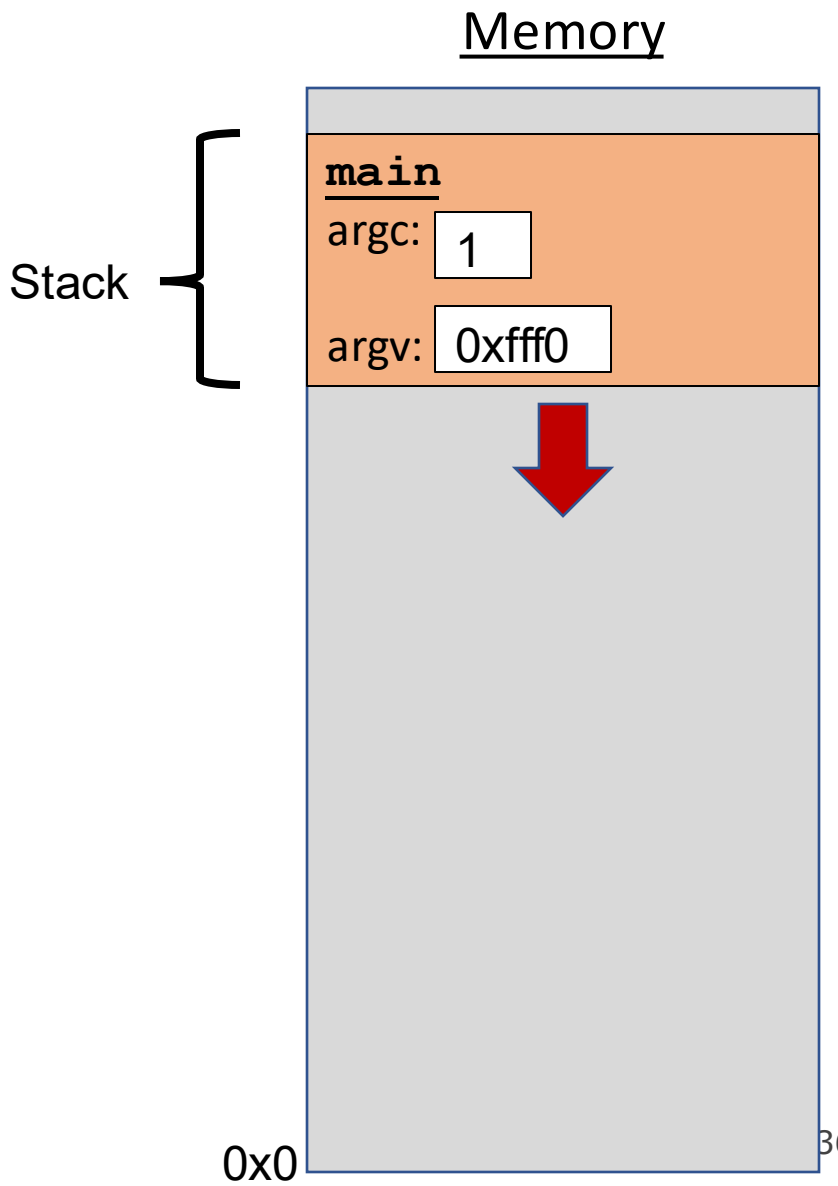

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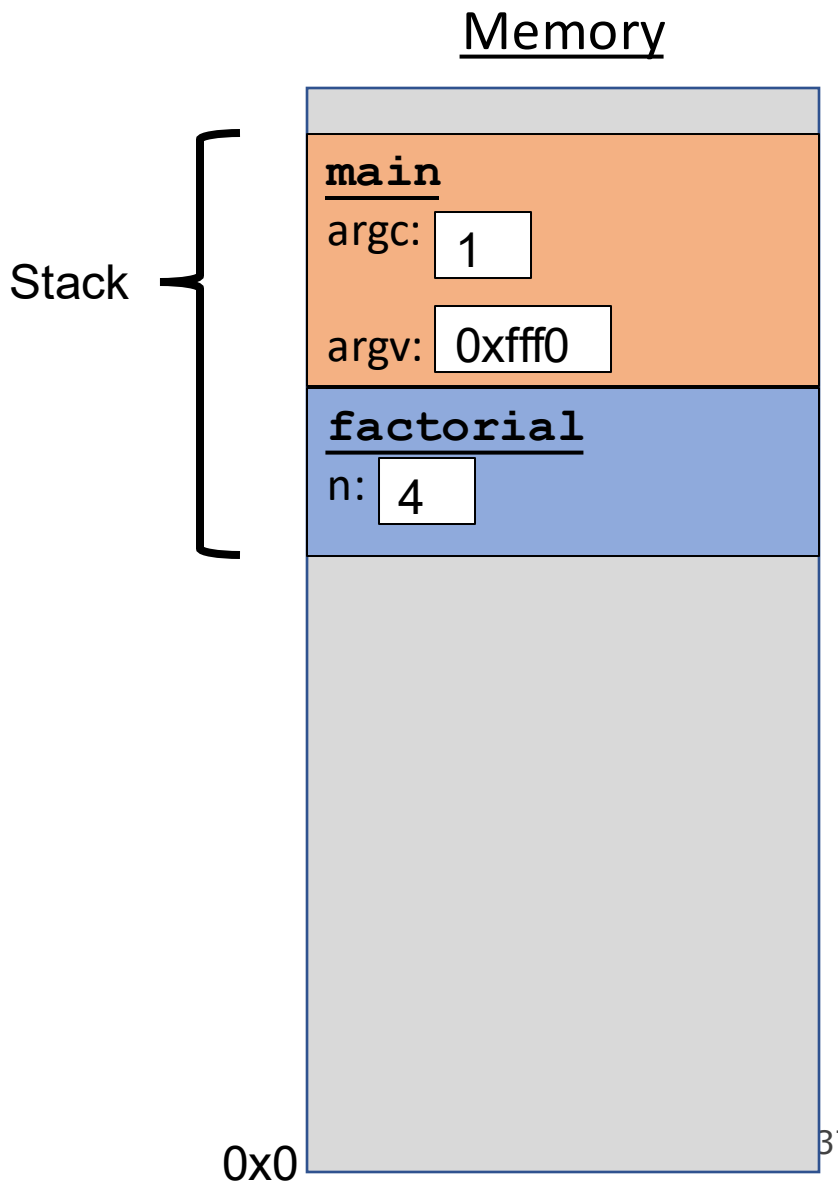

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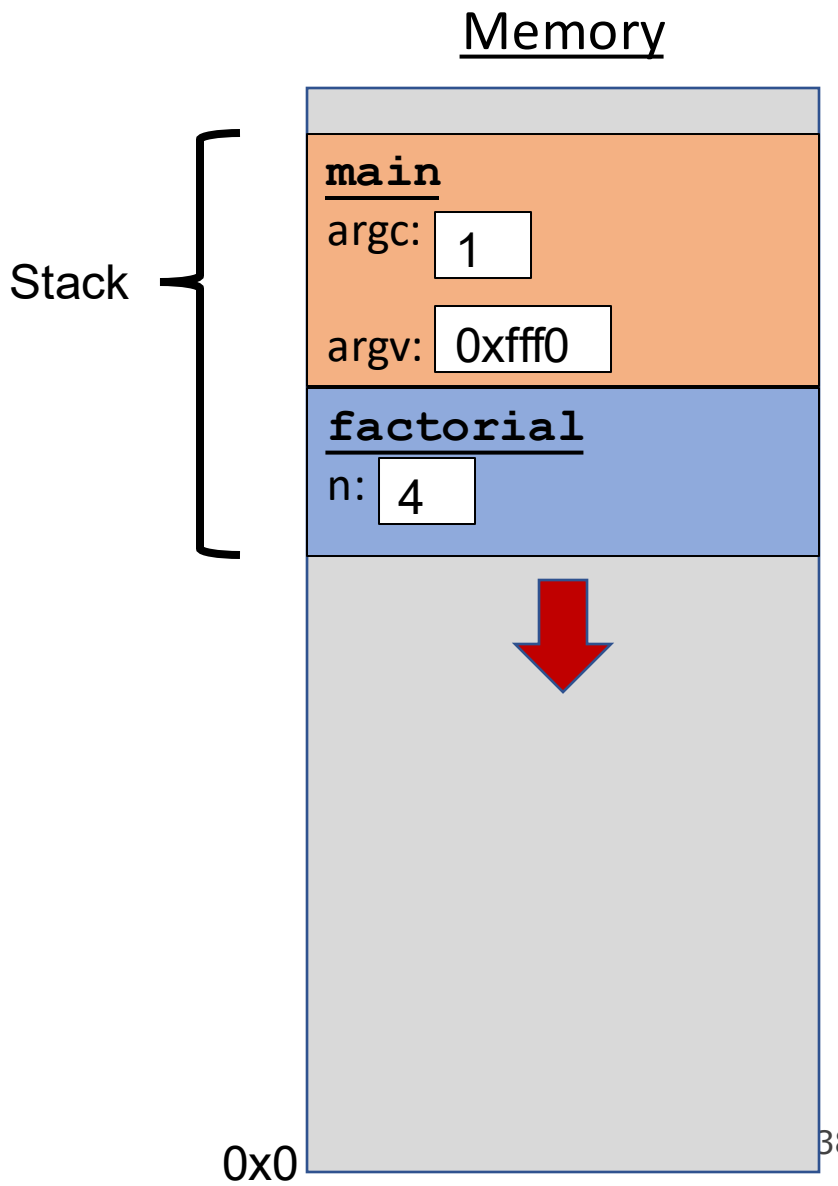

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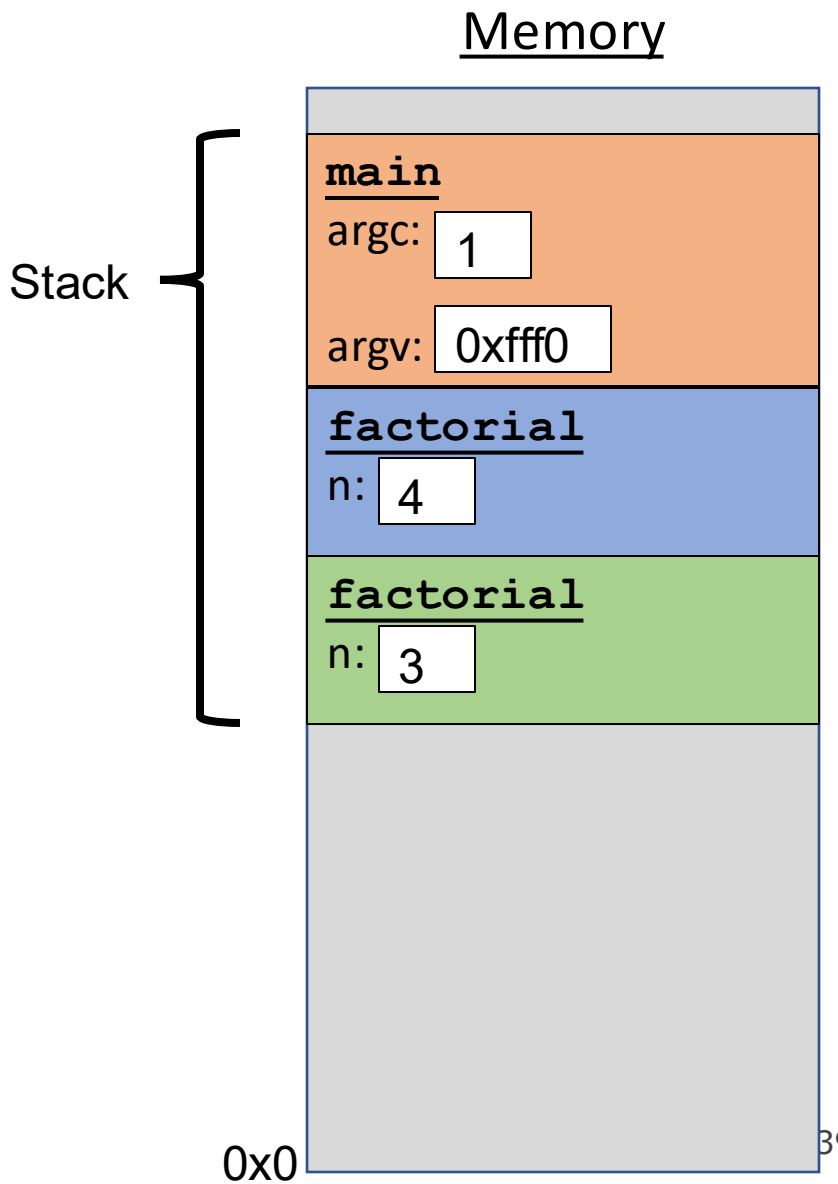

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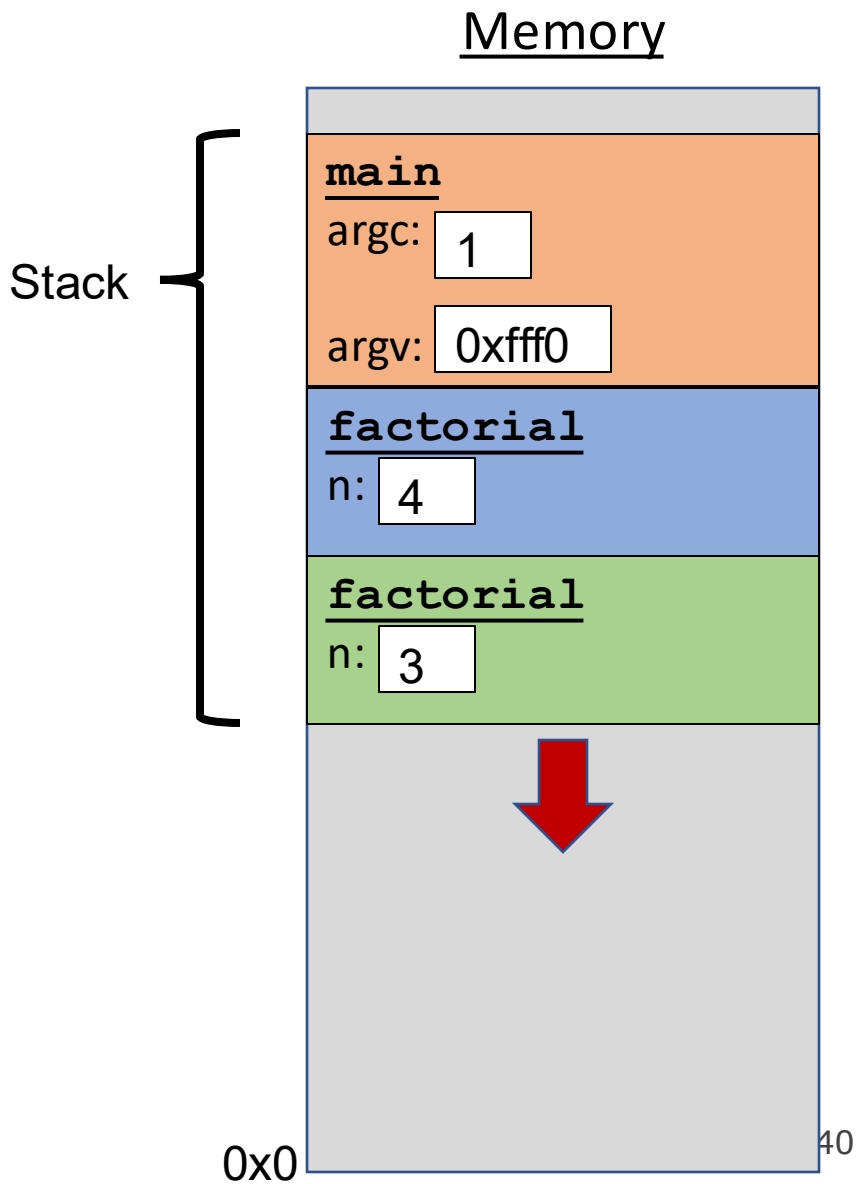

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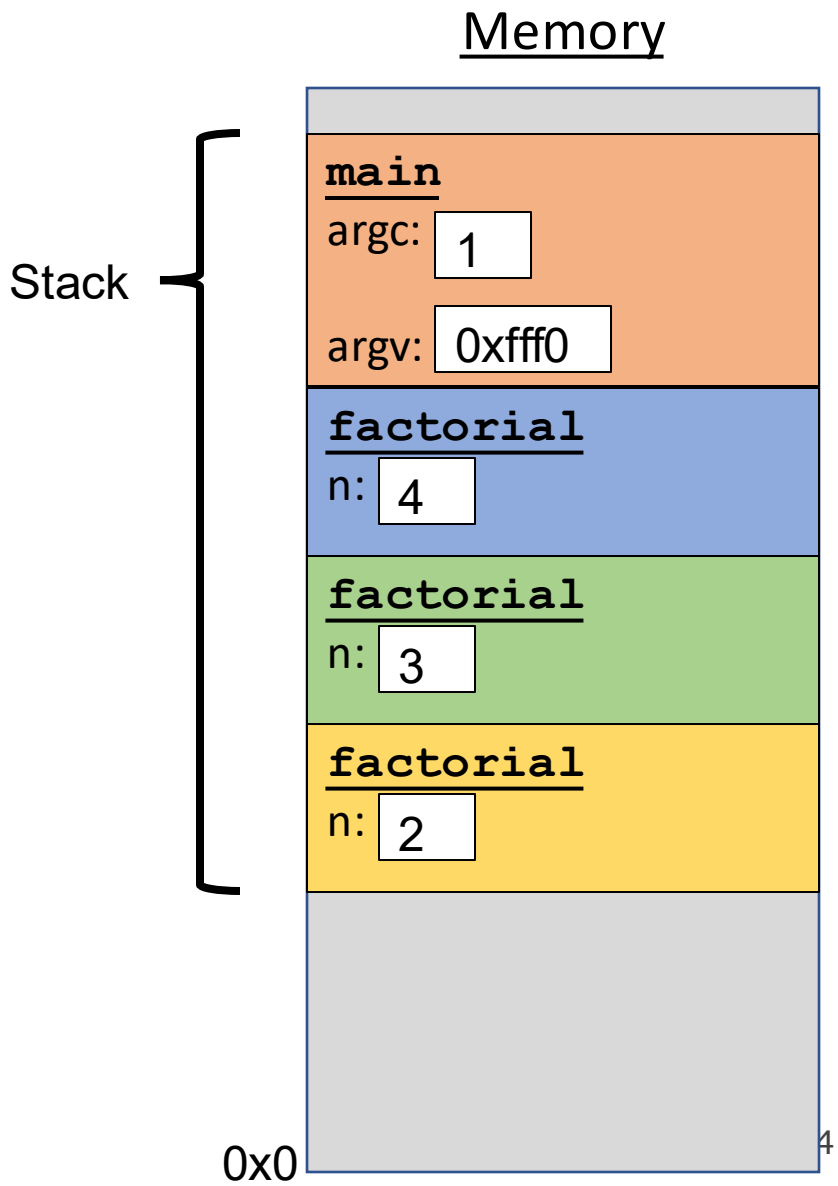
    return 0;
}
```



The Stack

Each function **call** has its own *stack frame* for its own copy of variables.

```
int factorial(int n) {
    if (n == 1) {
        return 1;
    } else {
        return n * factorial(n - 1);
    }
}

int main(int argc, char *argv[]) {
    printf("%d", factorial(4));
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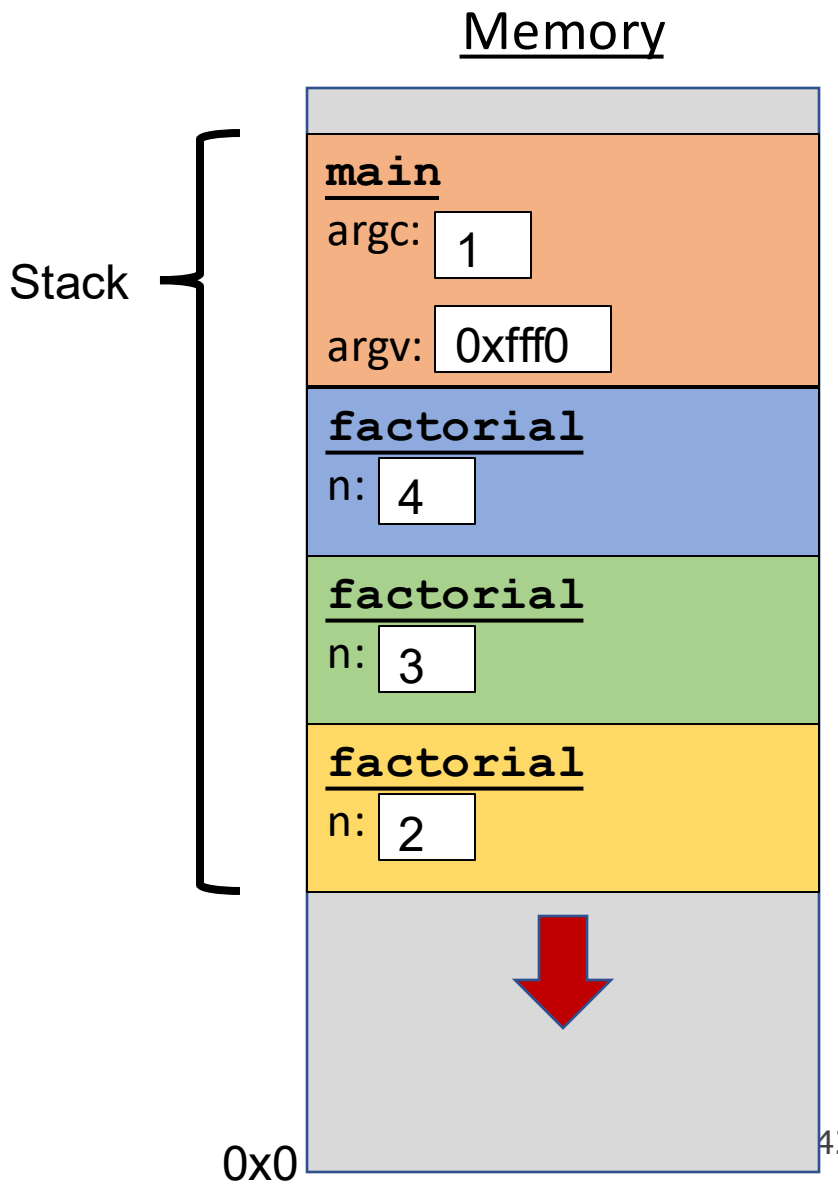

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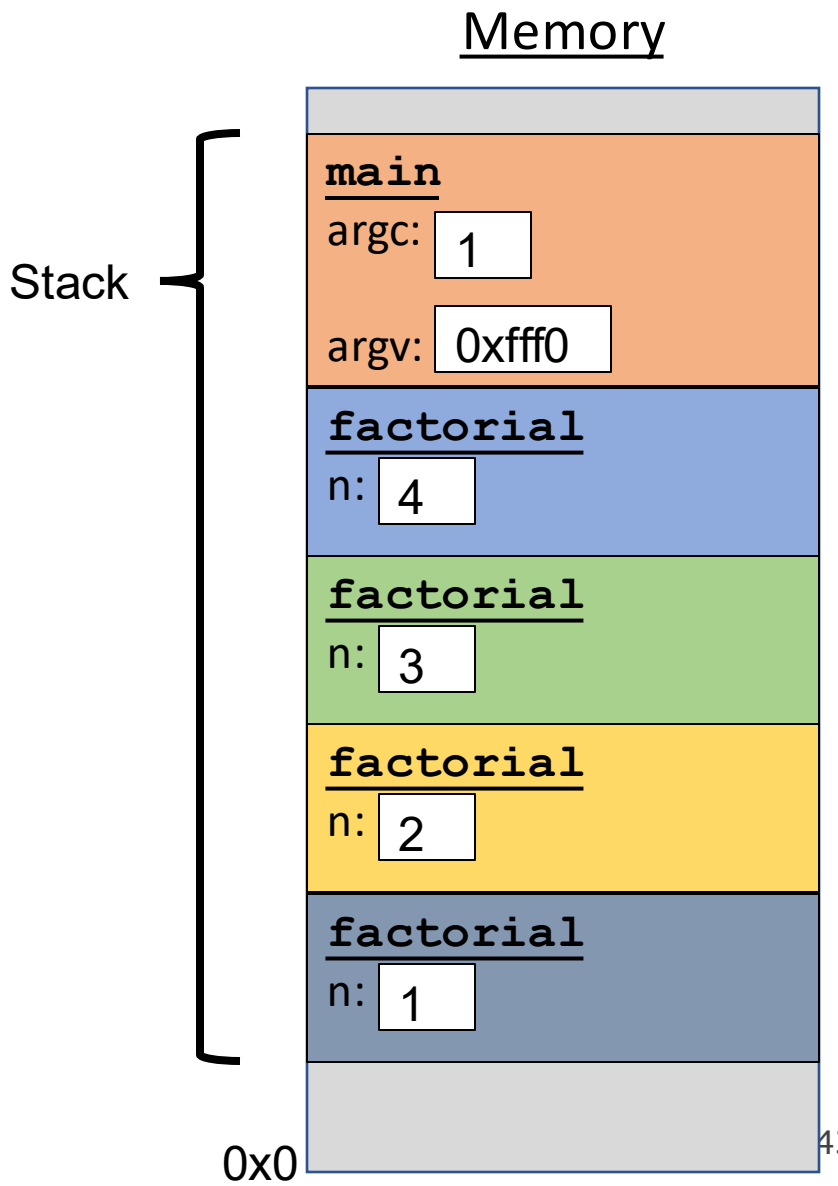

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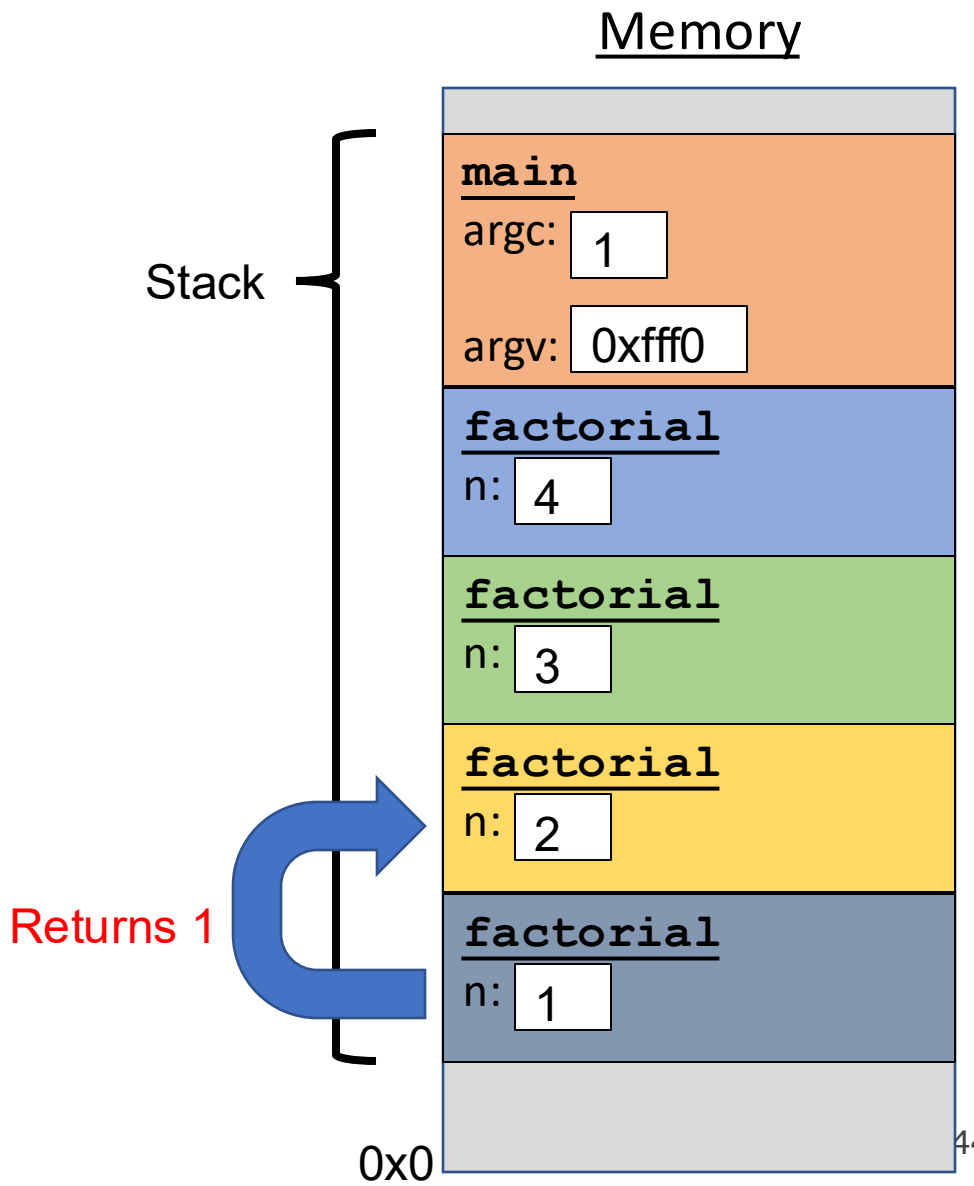

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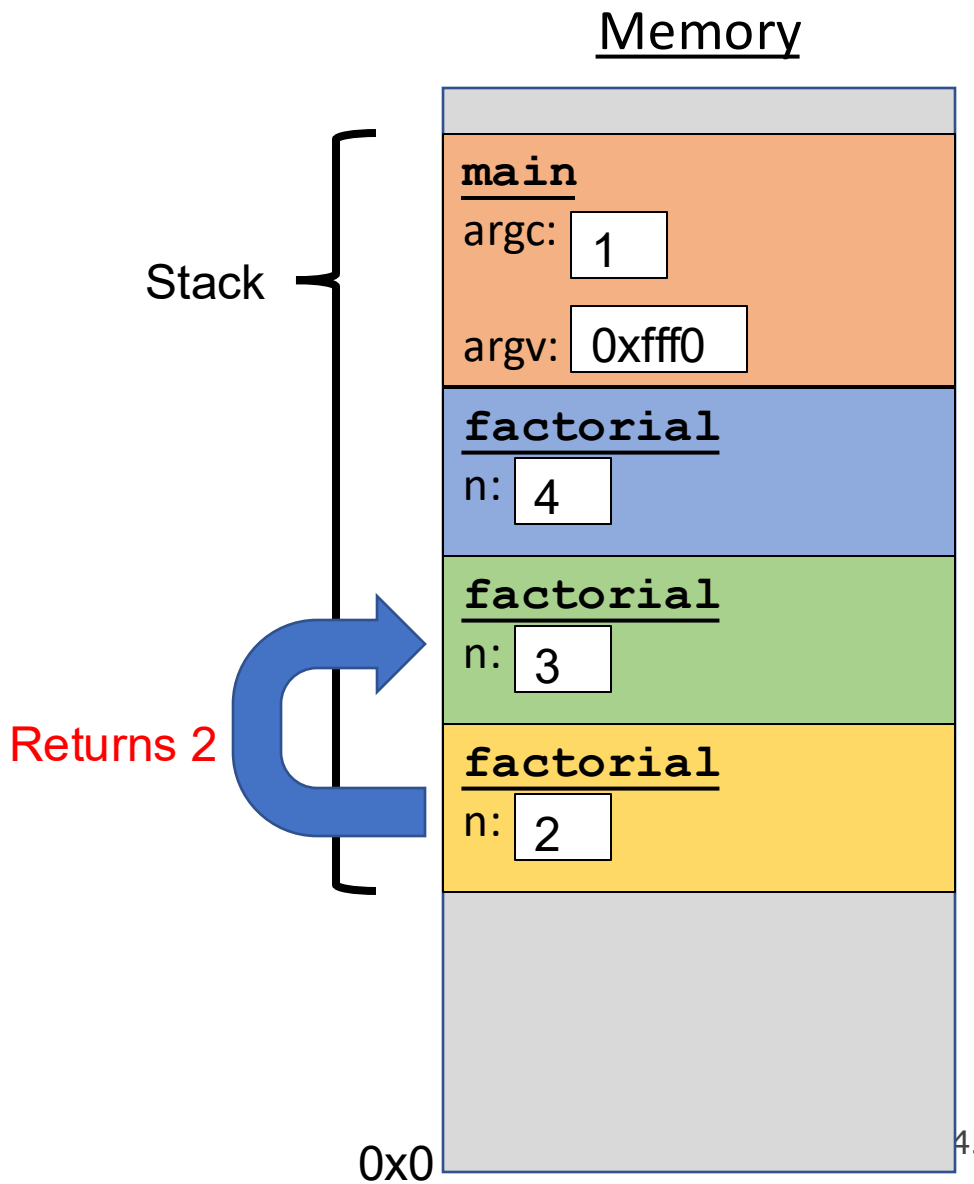

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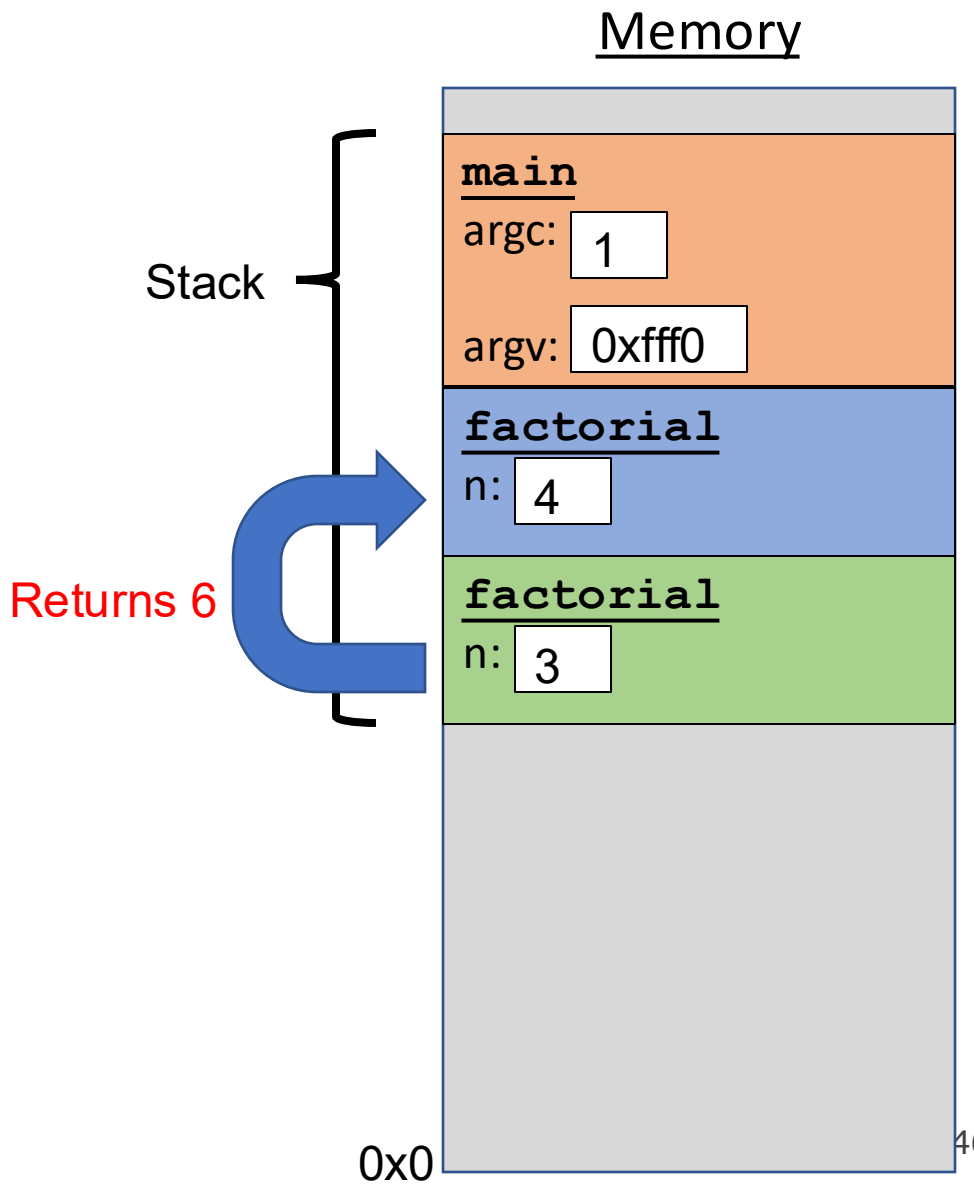

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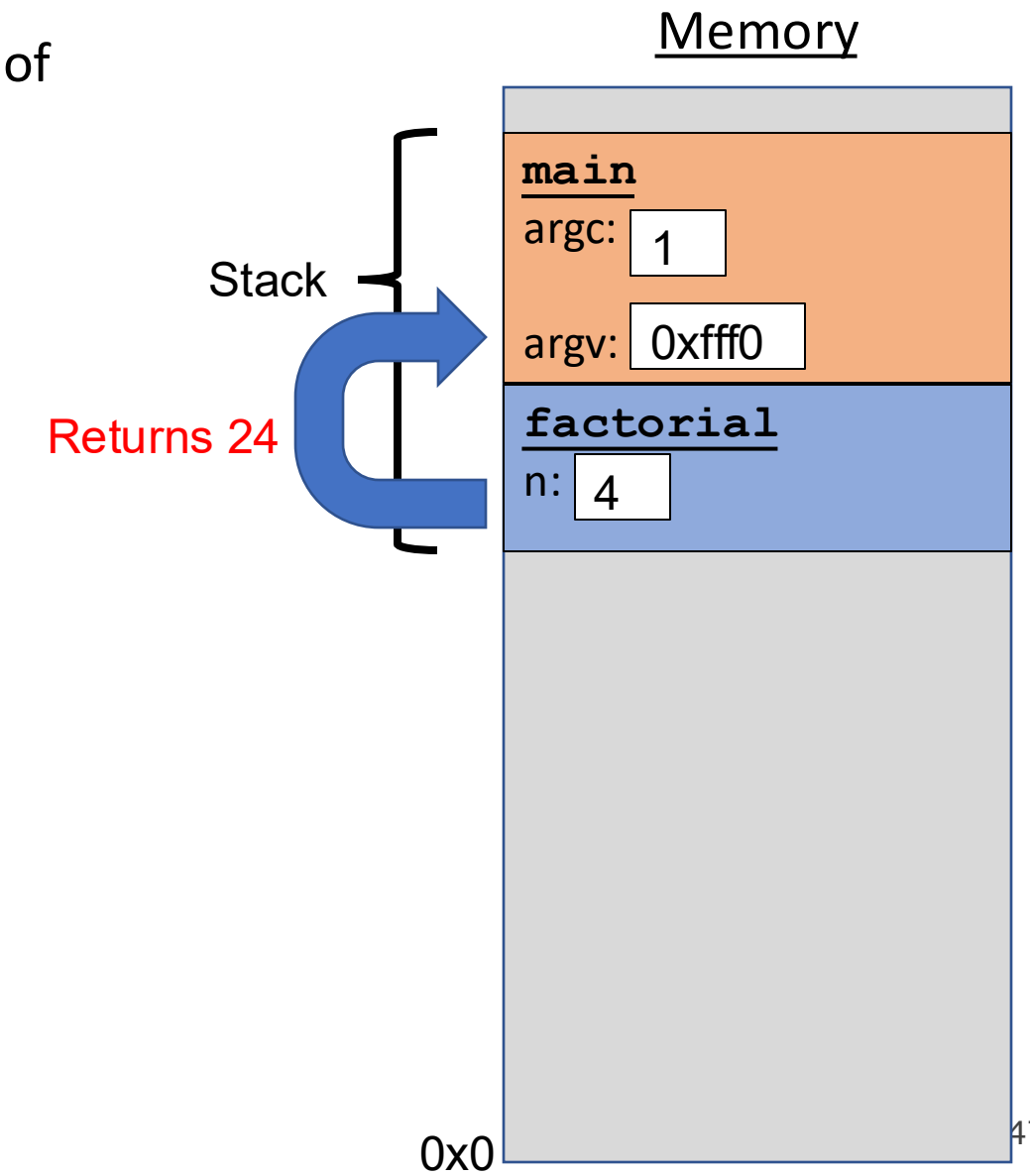

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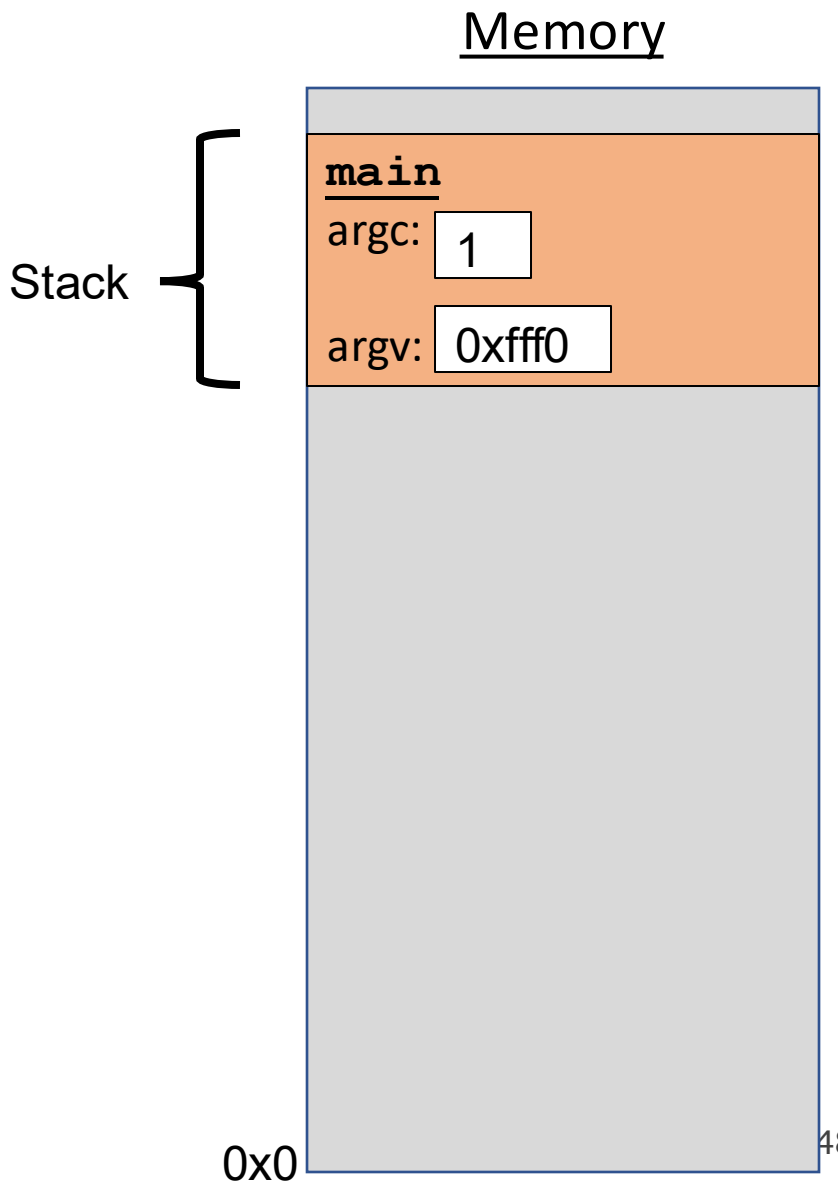

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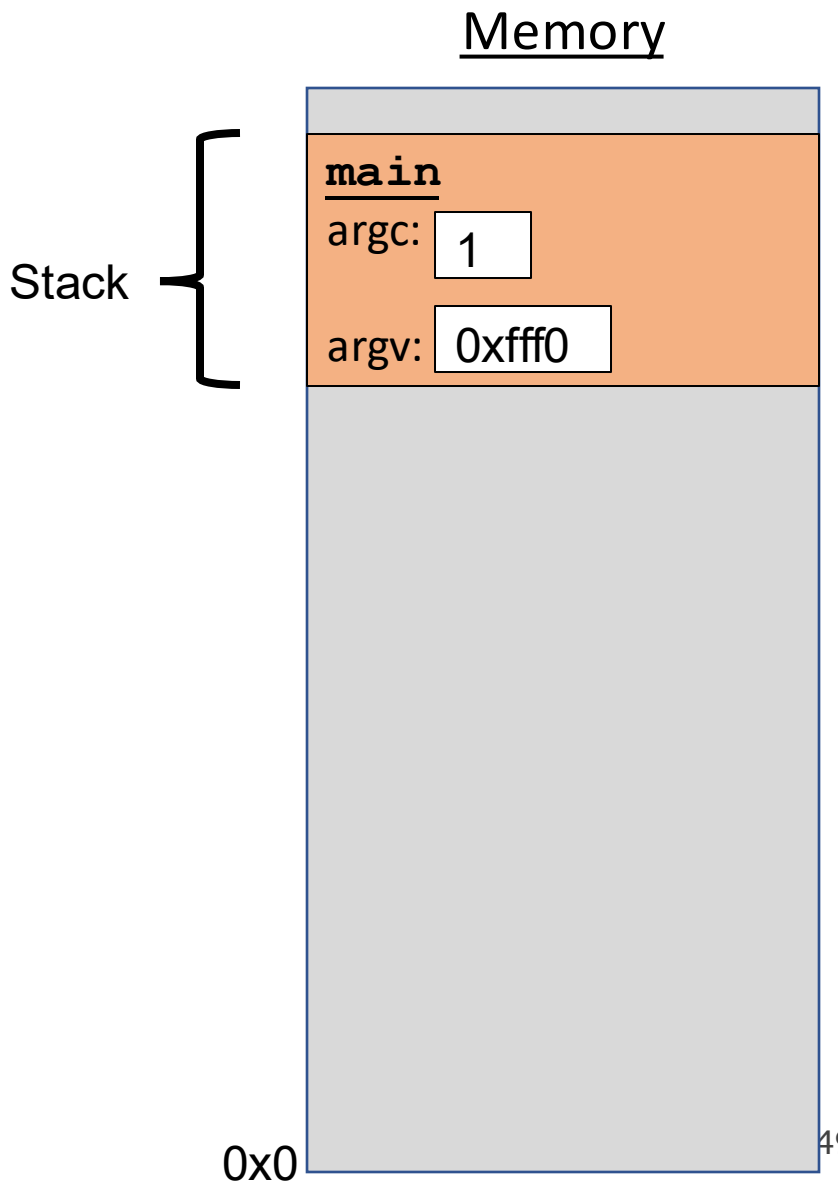


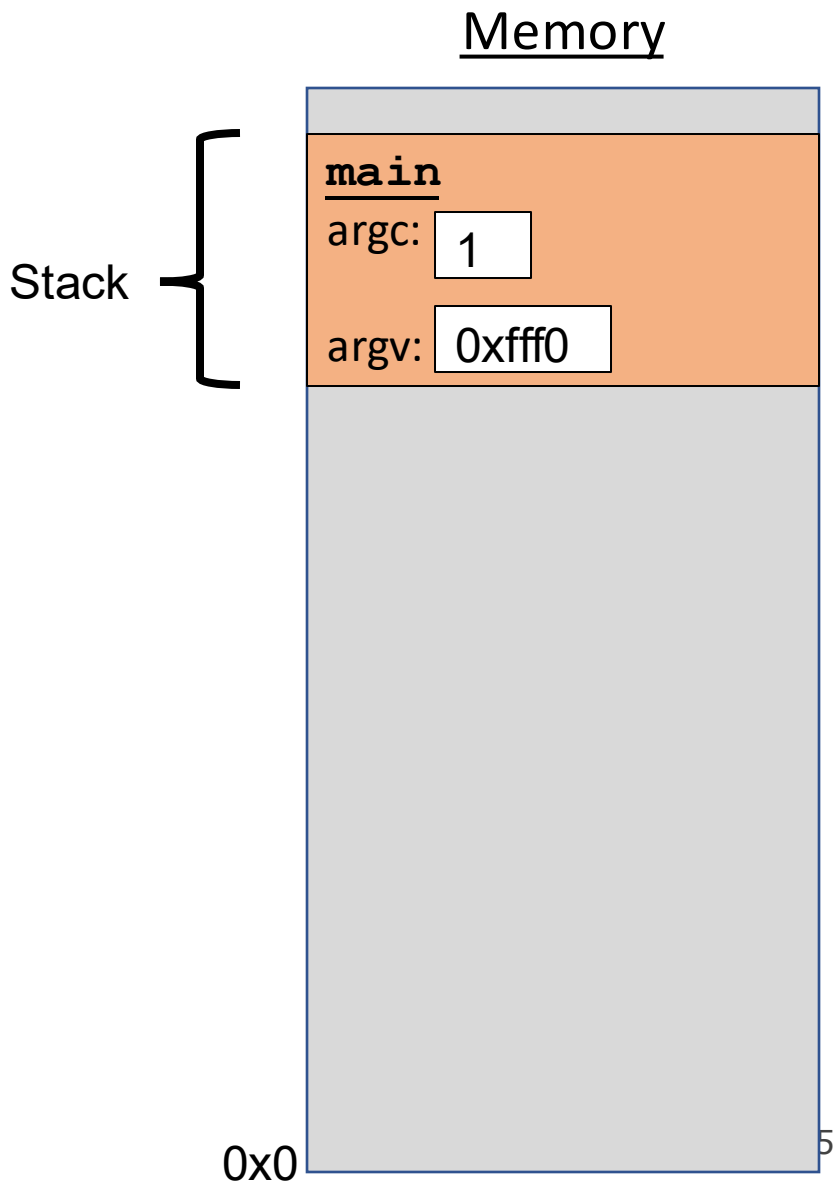
The Stack

- The stack behaves like a…well…stack! A new function call **pushes** on a new frame. A completed function call **pops** off the most recent frame.
- *Interesting fact:* C does not clear out memory when a function's frame is removed. Instead, it just marks that memory as usable for the next function call. This is more efficient!
- A *stack overflow* is when you use up all stack memory. E.g. a recursive call with too many function calls.
- What are the limitations of the stack?

The Stack

```
char *create_string(char ch, int num) {
    char new_str[num + 1];
    for (int i = 0; i < num; i++) {
        new_str[i] = ch;
    }
    new_str[num] = '\0';
    return new_str;
}

int main(int argc, char *argv[]) {
    char *str = create_string('a', 4);
    printf("%s", str);  // want "aaaa"
    return 0;
}
```



The Stack

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    return new_str;
}

int main(int argc, char *argv[]) {
    char *str = create_string('a', 4);
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    return 0;
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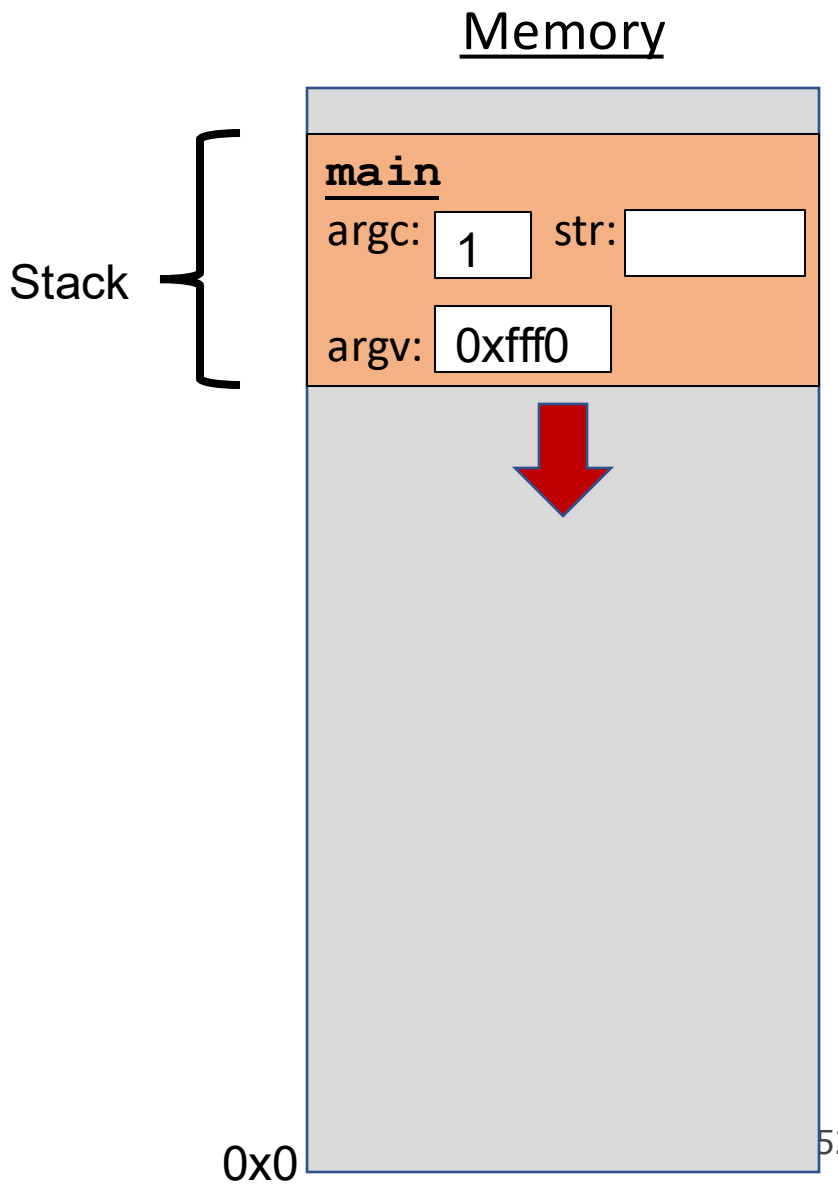

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}

int main(int argc, char *argv[]) {
    char *str = create_string('a', 4);
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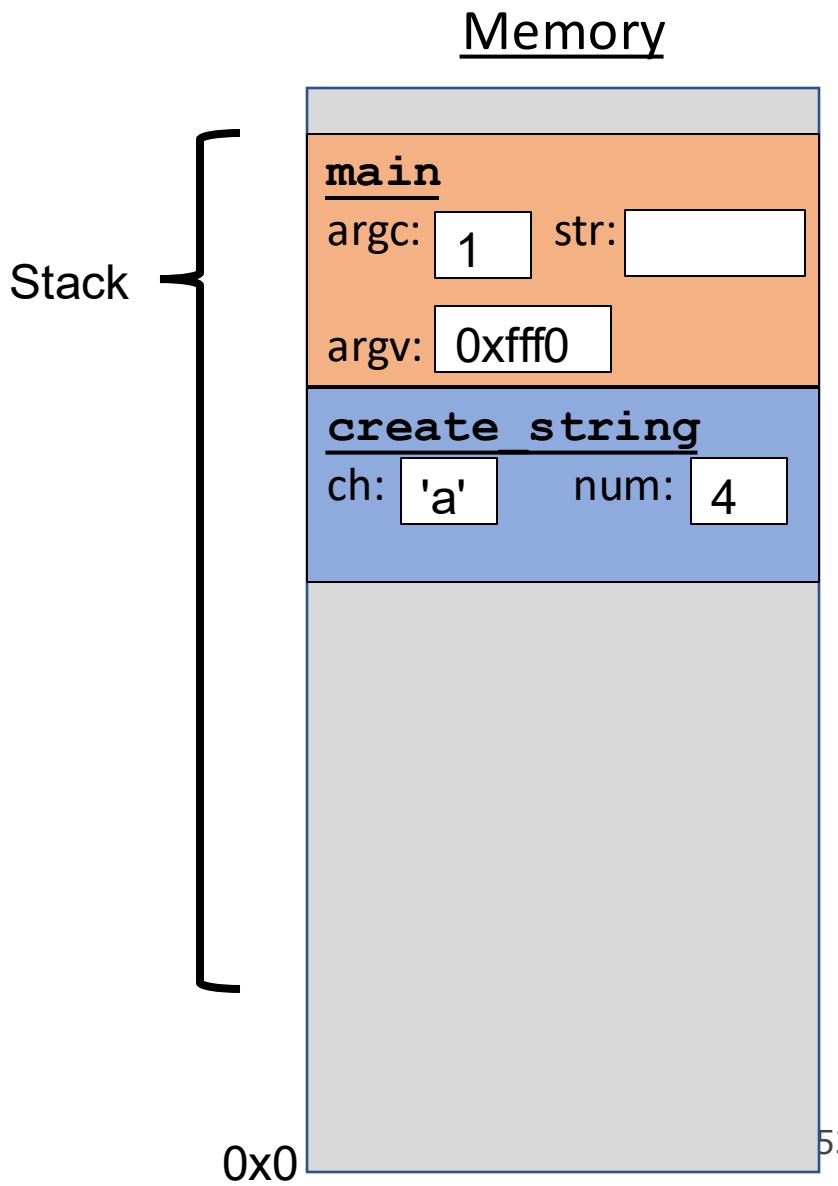

The Stack

```
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    char new_str[num + 1];
    for (int i = 0; i < num; i++) {
        new_str[i] = ch;
    }
    new_str[num] = '\0';
    return new_str;
}

int main(int argc, char *argv[]) {
    char *str = create_string('a', 4);
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    return 0;
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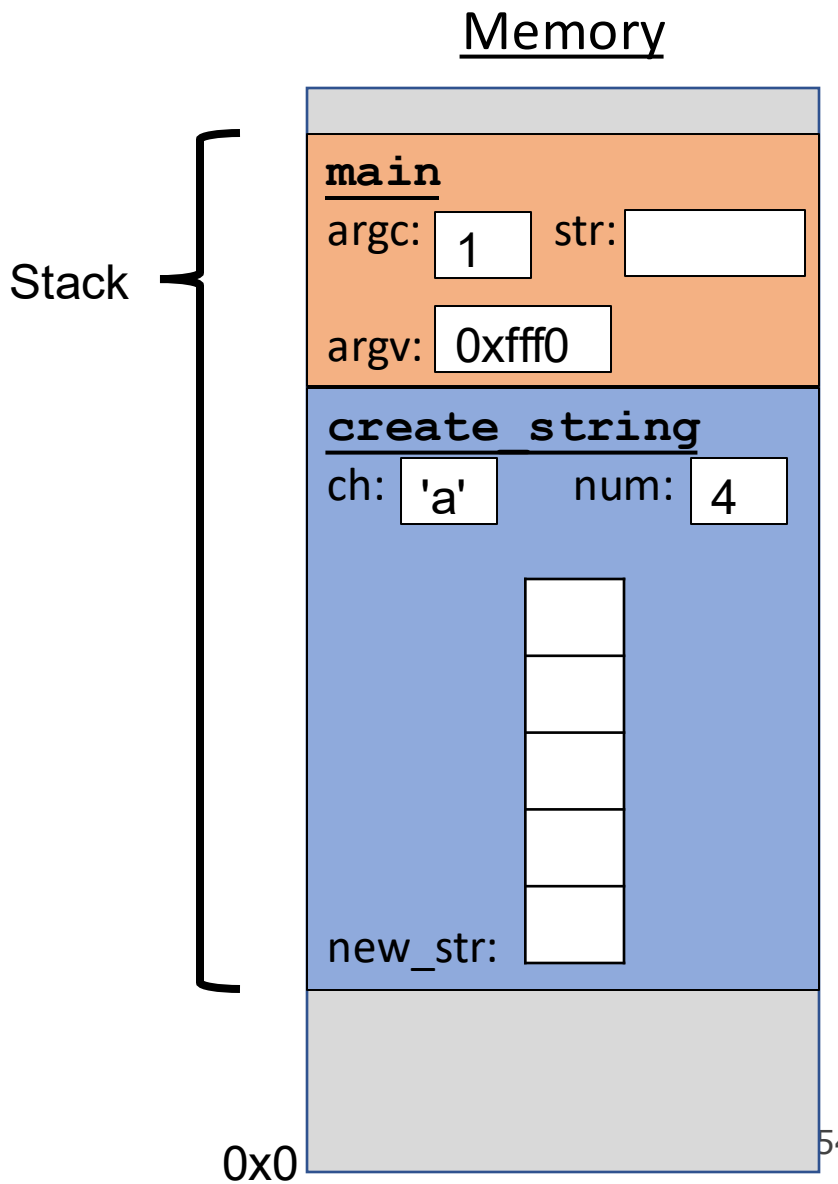

The Stack

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char *create_string(char ch, int num) {
    char new_str[num + 1];
    for (int i = 0; i < num; i++) {
        new_str[i] = ch;
    }
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    return new_str;
}

int main(int argc, char *argv[]) {
    char *str = create_string('a', 4);
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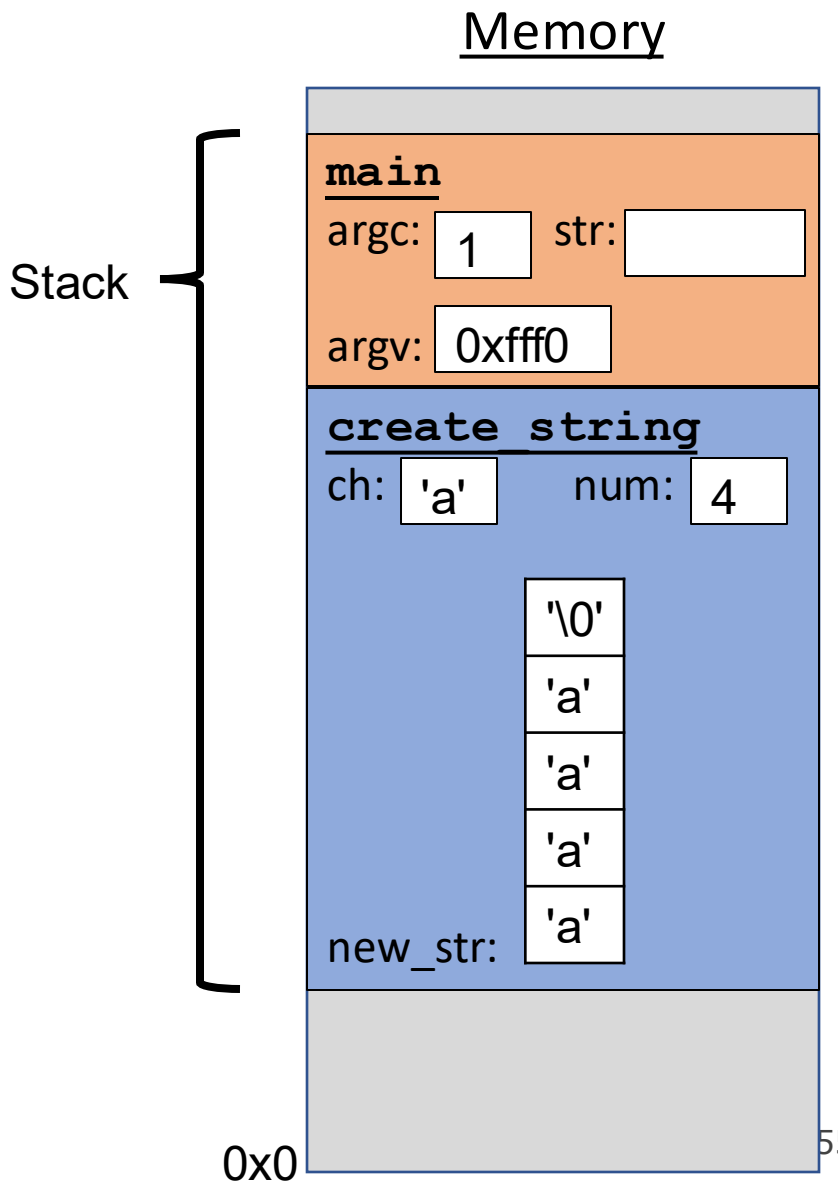
```



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    for (int i = 0; i < num; i++) {
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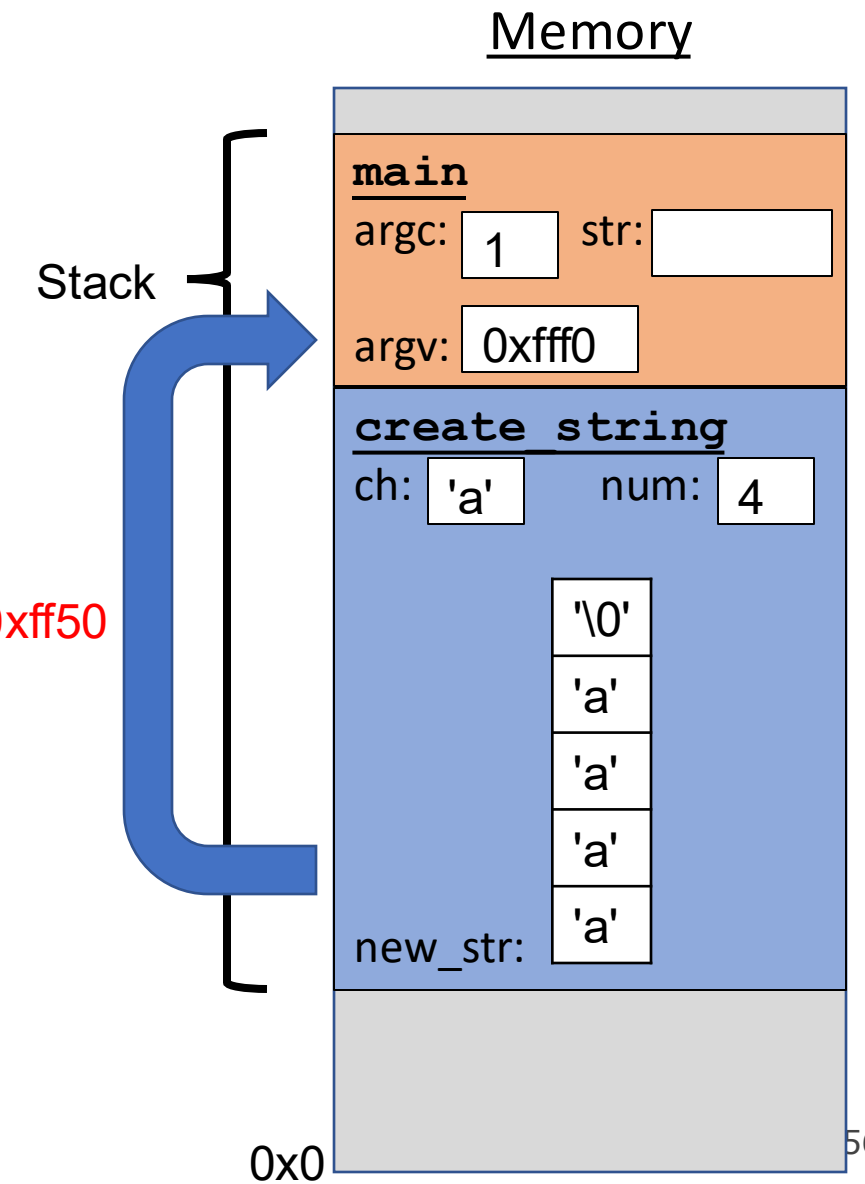
    }
    new_str[num] = '\0';
    return new_str;
}

int main(int argc, char *argv[]) {
    char *str = create_string('a', 4);
    printf("%s", str);  // want "aaaa"
    return 0;
}
```

Returns e.g. 0xff50



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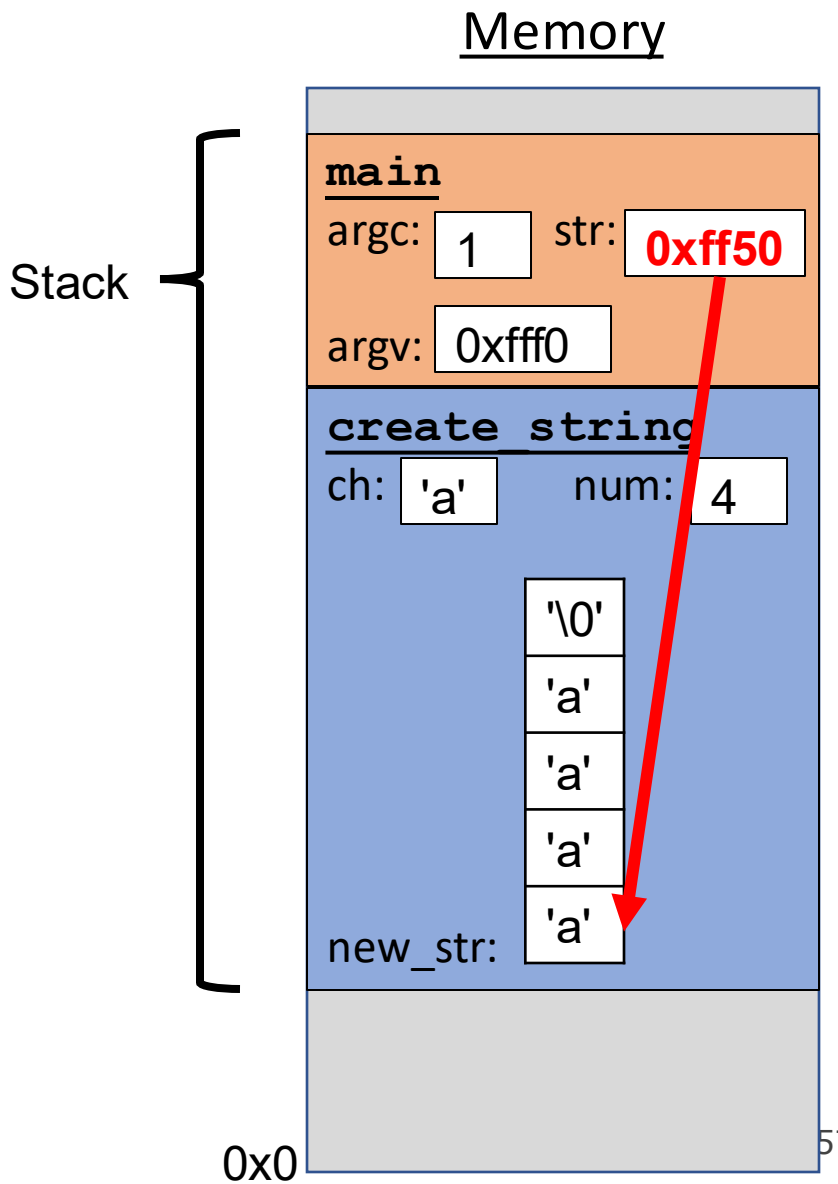
```



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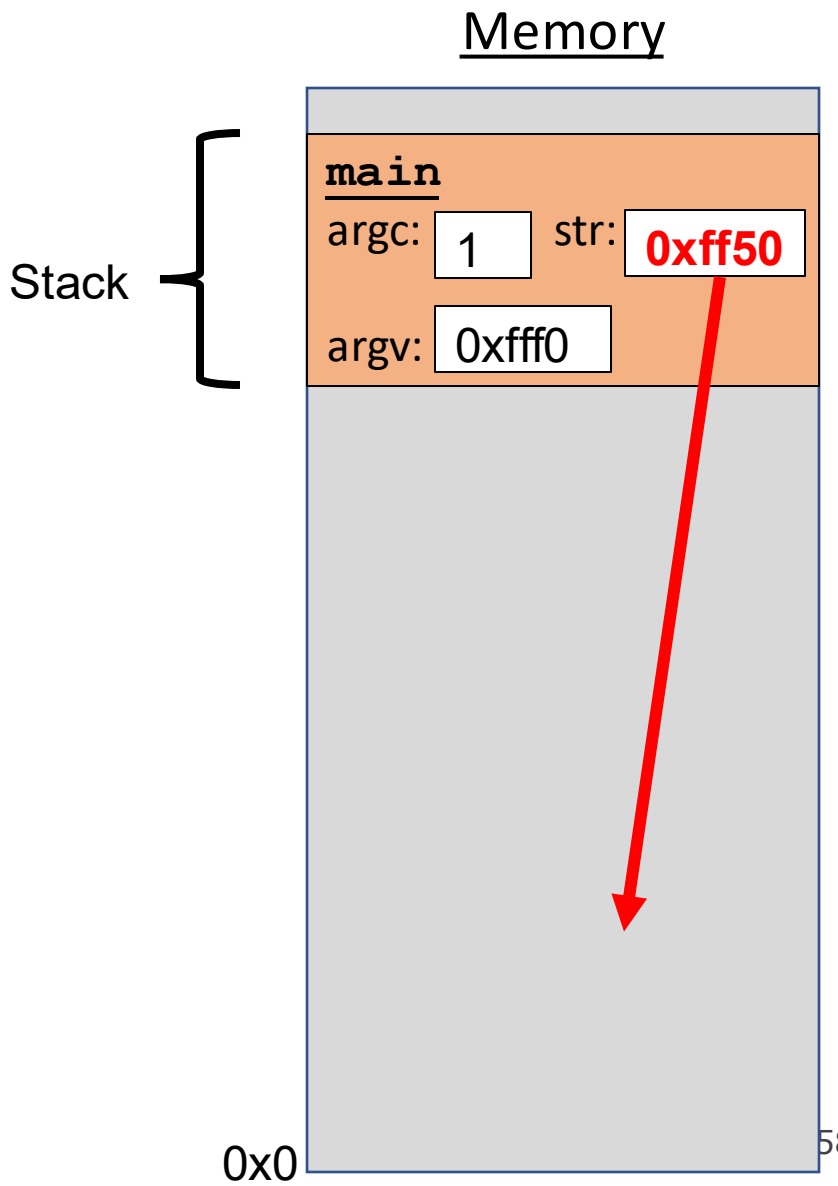

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    for (int i = 0; i < num; i++) {
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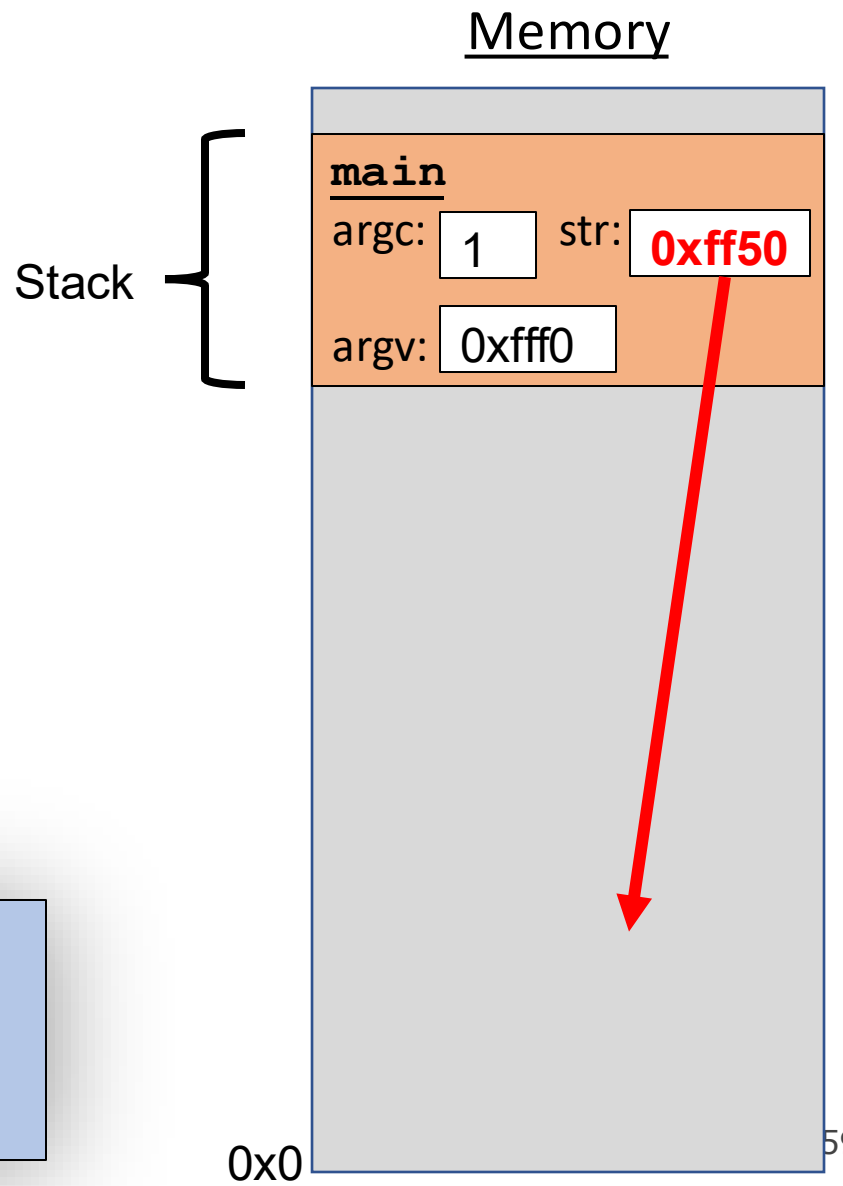
    return new_str;
}

int main(int argc, char *argv[]) {
    char *str = create_string('a', 4);
    printf("%s", str);  // want "aaaa"
    return 0;
}
```

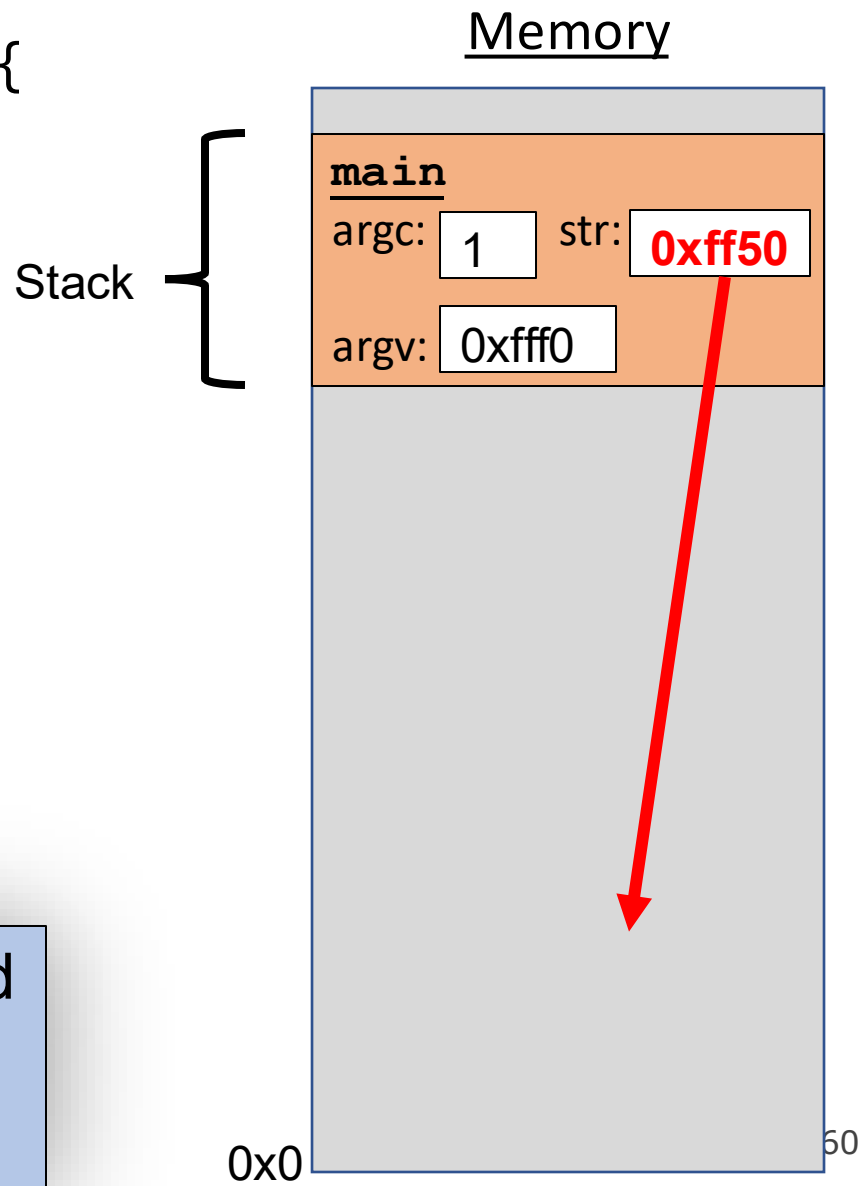


Problem: local variables go away when a function finishes. These characters will thus no longer exist, and the address will be for unknown memory!

The Stack

```
void create_string(char buf[], char ch, int num) {
    char new_str[num + 1];
    for (int i = 0; i < num; i++) {
        buf[i] = ch;
    }
    buf[num] = '\0';
    return new_str;
}

int main(int argc, char *argv[]) {
    char buf[5];
    create_string(buf, 'a', 4);
    printf("%s", str);  // want "aaaa"
    return 0;
}
```



Sometimes, we can make the array in the caller and pass it as a parameter. But this isn't always possible if the size isn't known in advance.

Stacked Against Us

This is a problem! We need a way to have memory that doesn't get cleaned up when a function exits.

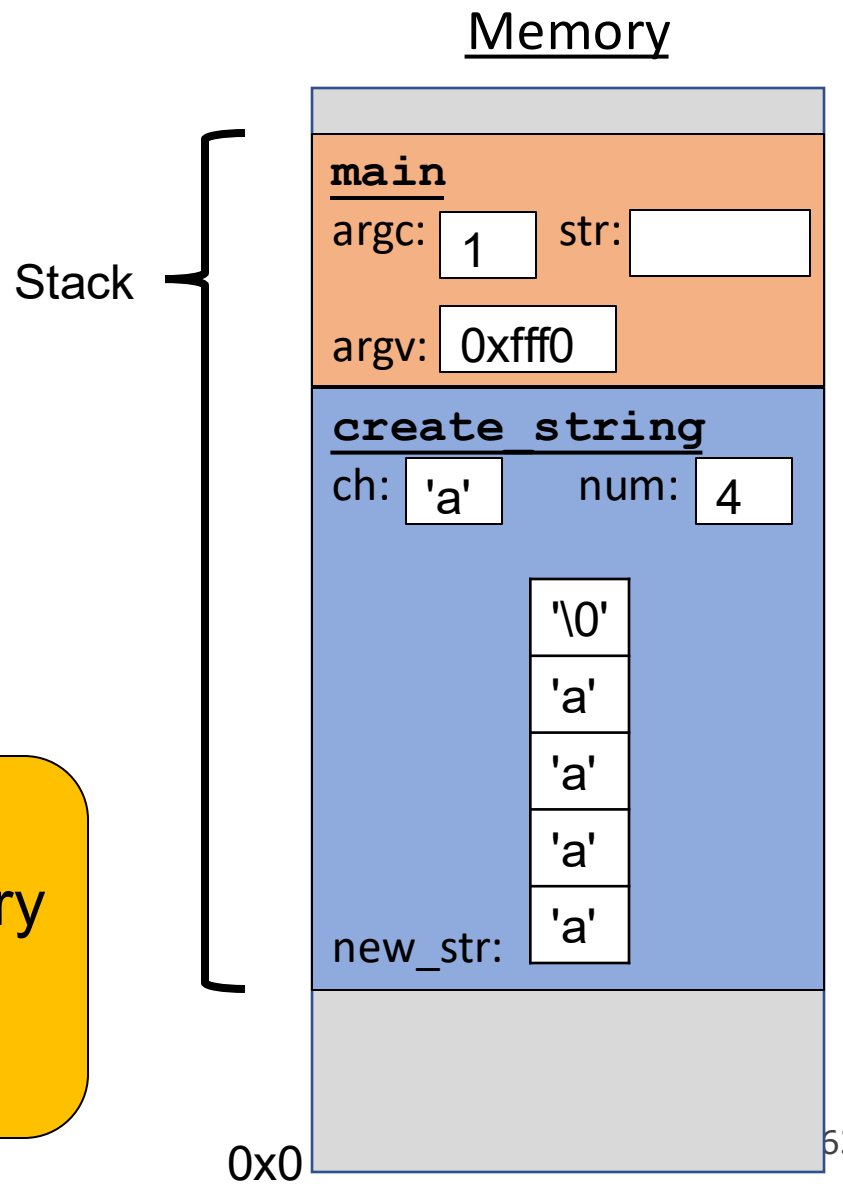
Lecture Plan

- **Recap:** Pointers So Far
- Arrays in Memory
- The Stack
- **The Heap and Dynamic Memory**
- Freeing Memory

The Heap

```
char *create_string(char ch, int num) {
    char new_str[num + 1];
    for (int i = 0; i < num; i++) {
        new_str[i] = ch;
    }
    new_str[num] = '\0';
    return new_str;
}

int main(int argc, char *argv[]) {
    char *str = create_string('a', 4);
    printf("%s", str);
    return 0;
}
```



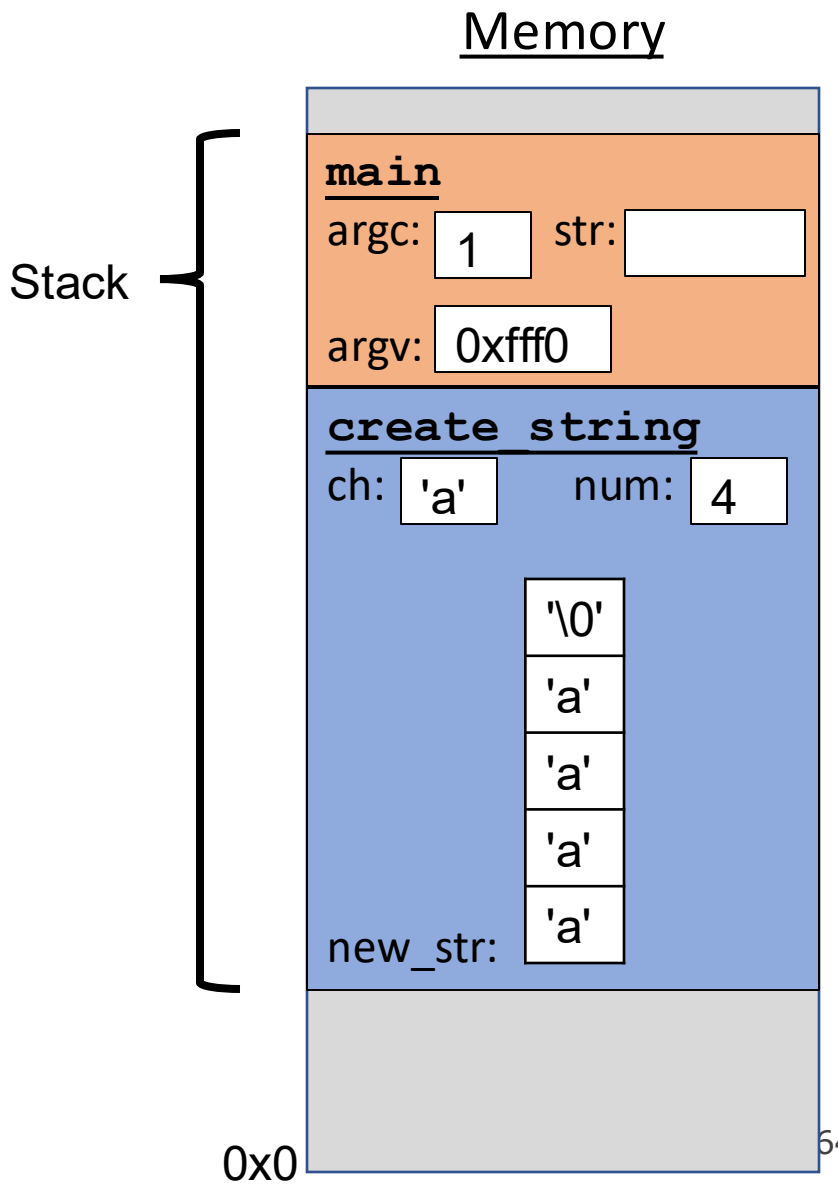
Us: hey C, is there a way to make this variable in memory that isn't automatically cleaned up?

The Heap

```
char *create_string(char ch, int num) {
    char new_str[num + 1];
    for (int i = 0; i < num; i++) {
        new_str[i] = ch;
    }
    new_str[num] = '\0';
    return new_str;
}

int main(int argc, char *argv[]) {
    char *str = create_string('a', 4);
    printf("%s", str);  // want "aaaa"
    return 0;
}
```

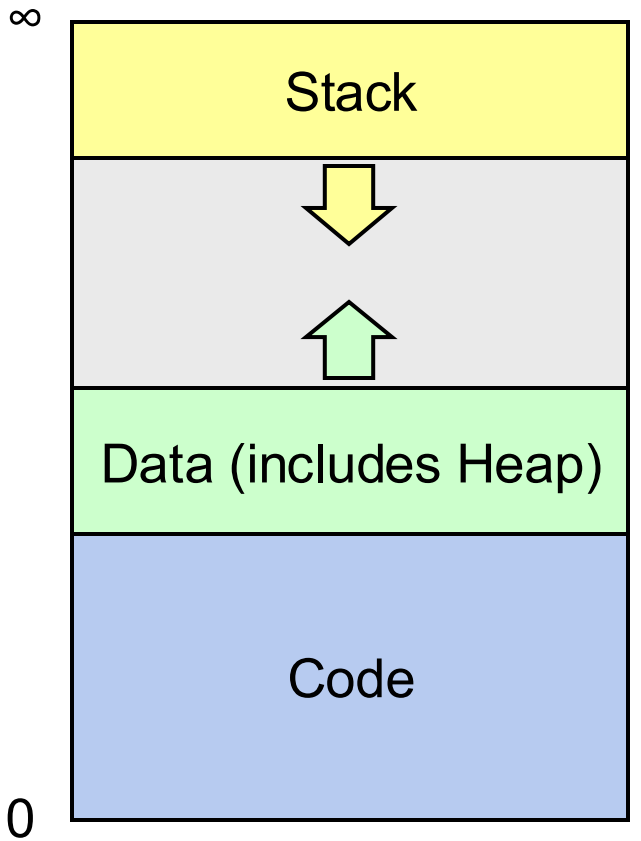
C: sure, but since I don't know when to clean it up anymore, it's your responsibility…



Memory Layout

- The **heap** is a part of memory that you can manage yourself.
- The **heap** is a part of memory below the stack that you can manage yourself. Unlike the stack, the memory only goes away when you delete it yourself.
- Unlike the stack, the heap grows **upwards** as more memory is allocated.

The heap is **dynamic memory** – memory that can be allocated, resized, and freed during **program runtime**.



Working with the heap

Working with the heap consists of 3 core steps:

1. Allocate memory with malloc/realloc/strdup/calloc
2. Assert heap pointer is not NULL (more later)
3. Free when done (more later)

The heap is **dynamic memory**, so you may encounter many **runtime errors**, even if your code compiles!

malloc

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

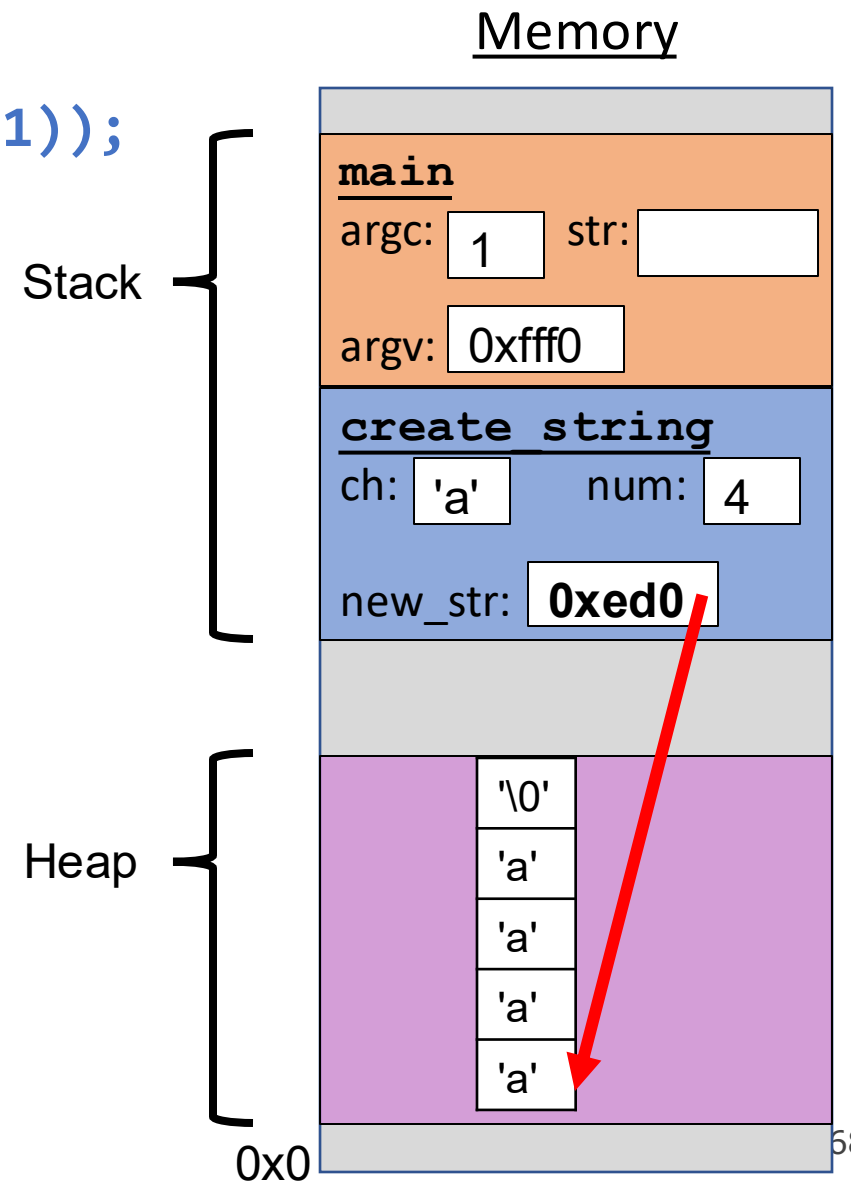
To allocate memory on the heap, use the **`malloc`** function ("memory allocate") and specify the number of bytes you'd like.

- This function returns a pointer to *the **starting address** of the new memory*. It doesn't know or care whether it will be used as an array, a single block of memory, etc.
- **`void *`**means a pointer to generic memory. You can set another pointer equal to it without any casting.
- The memory is *not* cleared out before being allocated to you!
- If `malloc` returns `NULL`, then there wasn't enough memory for this request.

The Heap

```
char *create_string(char ch, int num) {
    char *new_str = malloc(sizeof(char) * (num + 1));
    for (int i = 0; i < num; i++) {
        new_str[i] = ch;
    }
    new_str[num] = '\0';
    return new_str;
}

int main(int argc, char *argv[]) {
    char *str = create_string('a', 4);
    printf("%s", str);  // want "aaaa"
    return 0;
}
```



The Heap

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    char *new_str = malloc(sizeof(char) * (num + 1));
    for (int i = 0; i < num; i++) {
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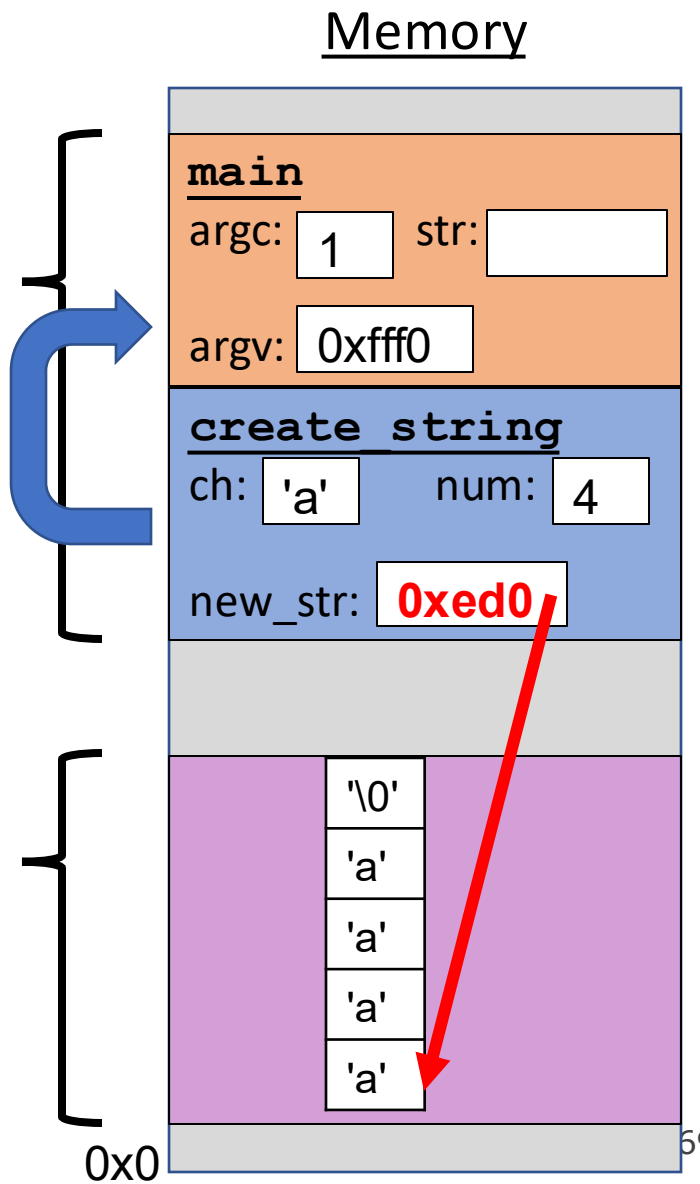
    }
    new_str[num] = '\0';
    return new_str;
}

int main(int argc, char *argv[]) {
    char *str = create_string('a', 4);
    printf("%s", str);  // want "aaaa"
    return 0;
}
```

Returns e.g. 0xed0



The Heap

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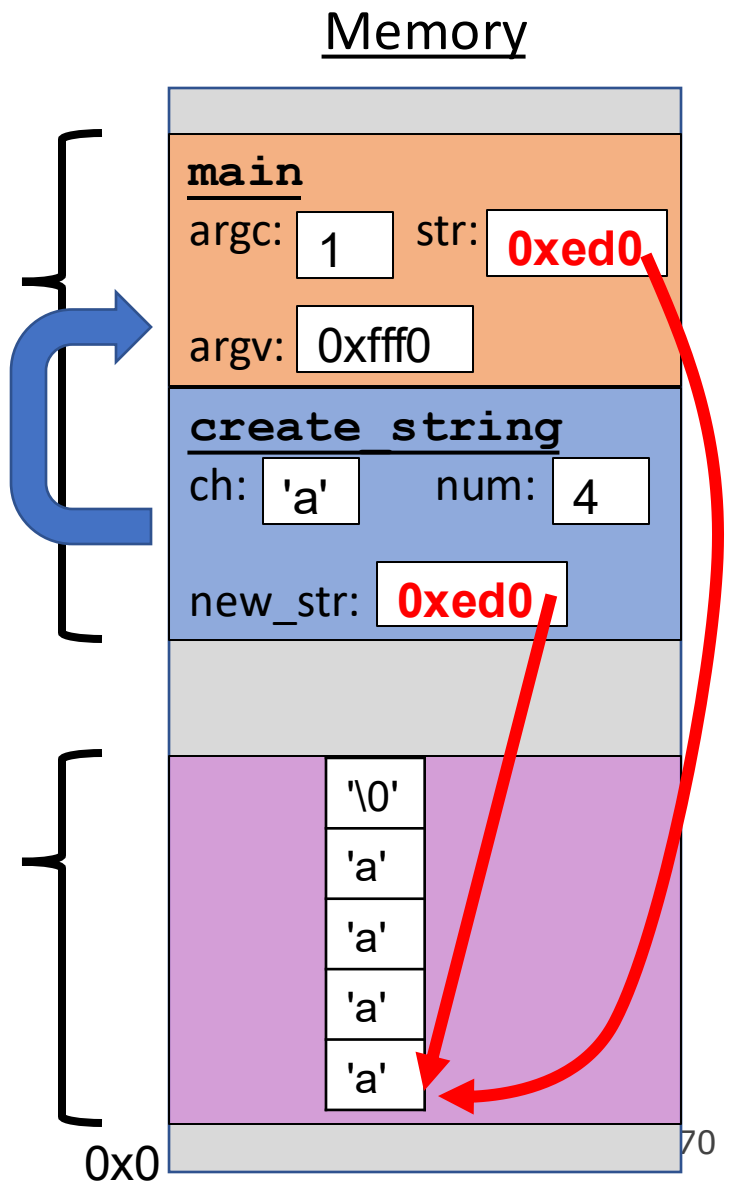

The Heap

```
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    }
    new_str[num] = '\0';
    return new_str;
}

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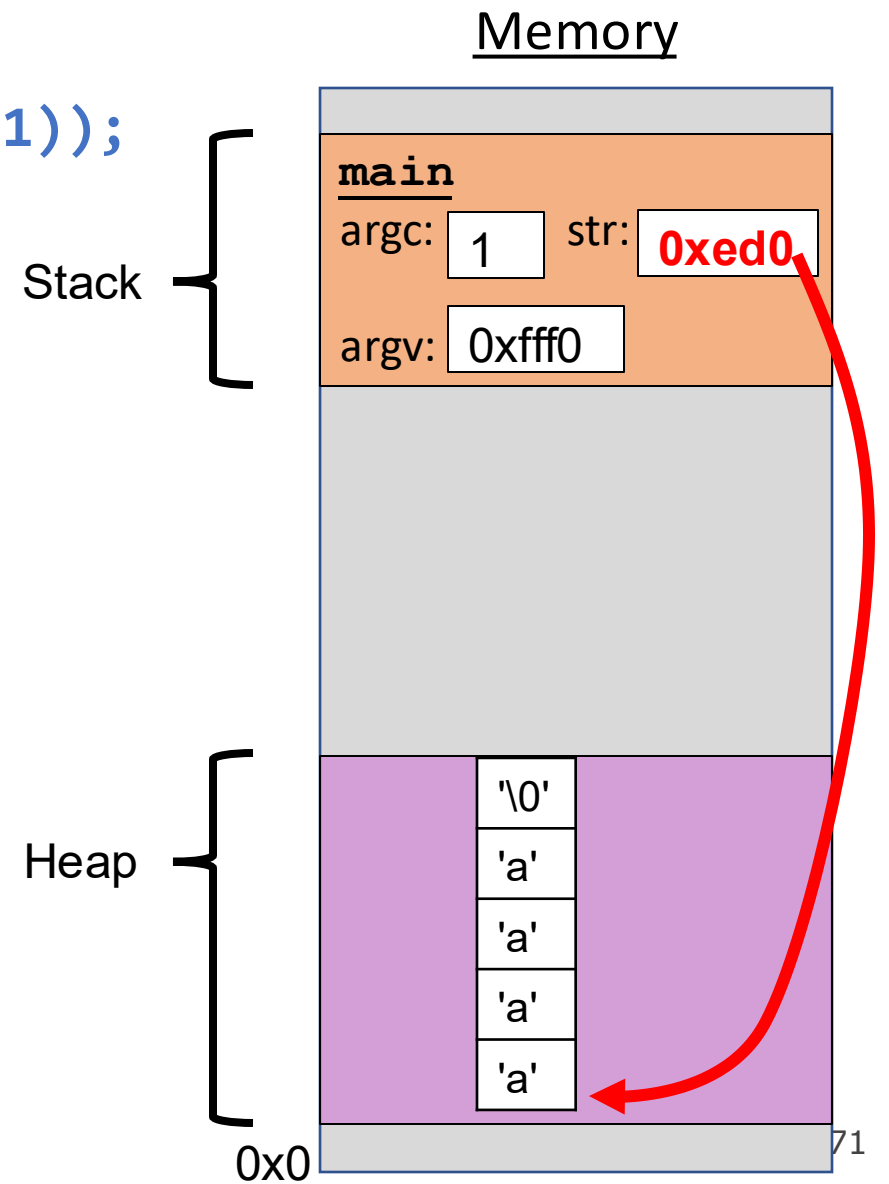
    char *str = create_string('a', 4);
    printf("%s", str);  // want "aaaa"
    return 0;
}
```



The Heap

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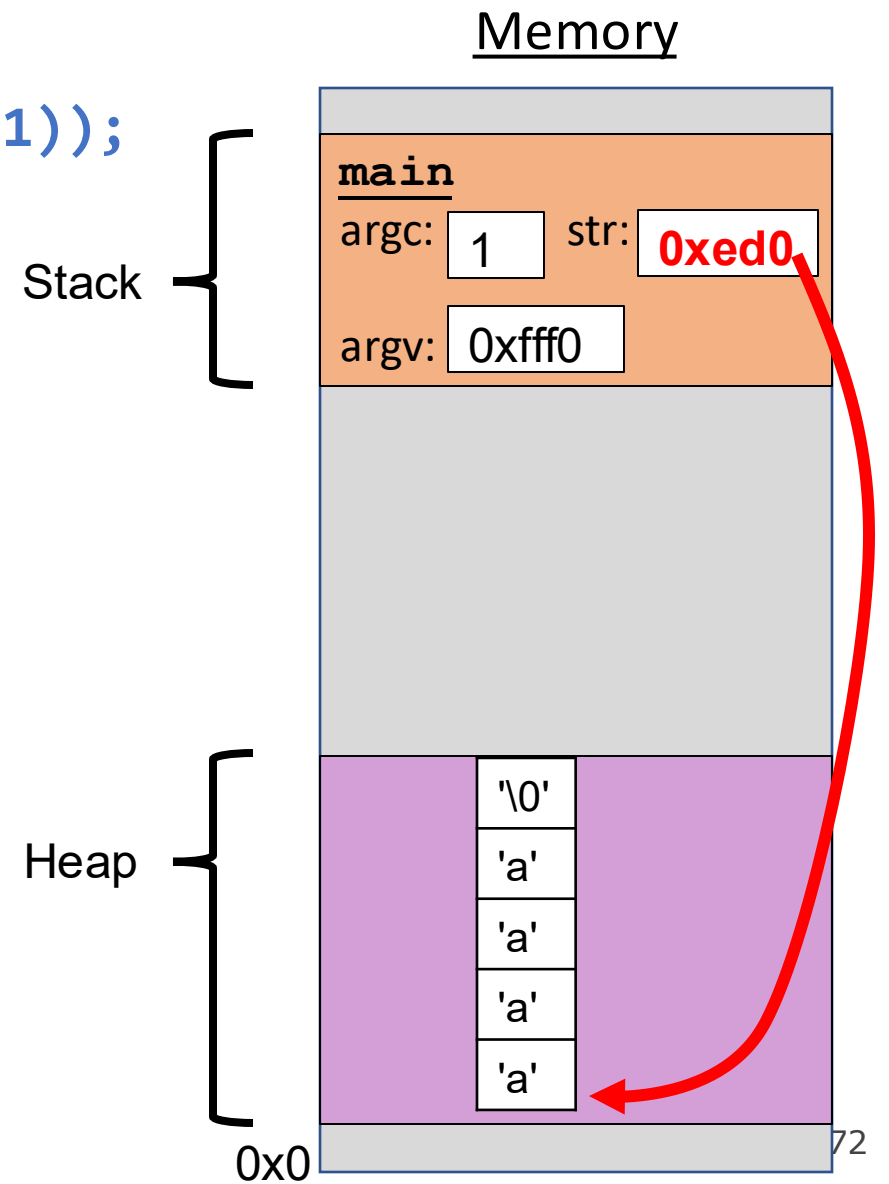

The Heap

```
char *create_string(char ch, int num) {
    char *new_str = malloc(sizeof(char) * (num + 1));
    for (int i = 0; i < num; i++) {
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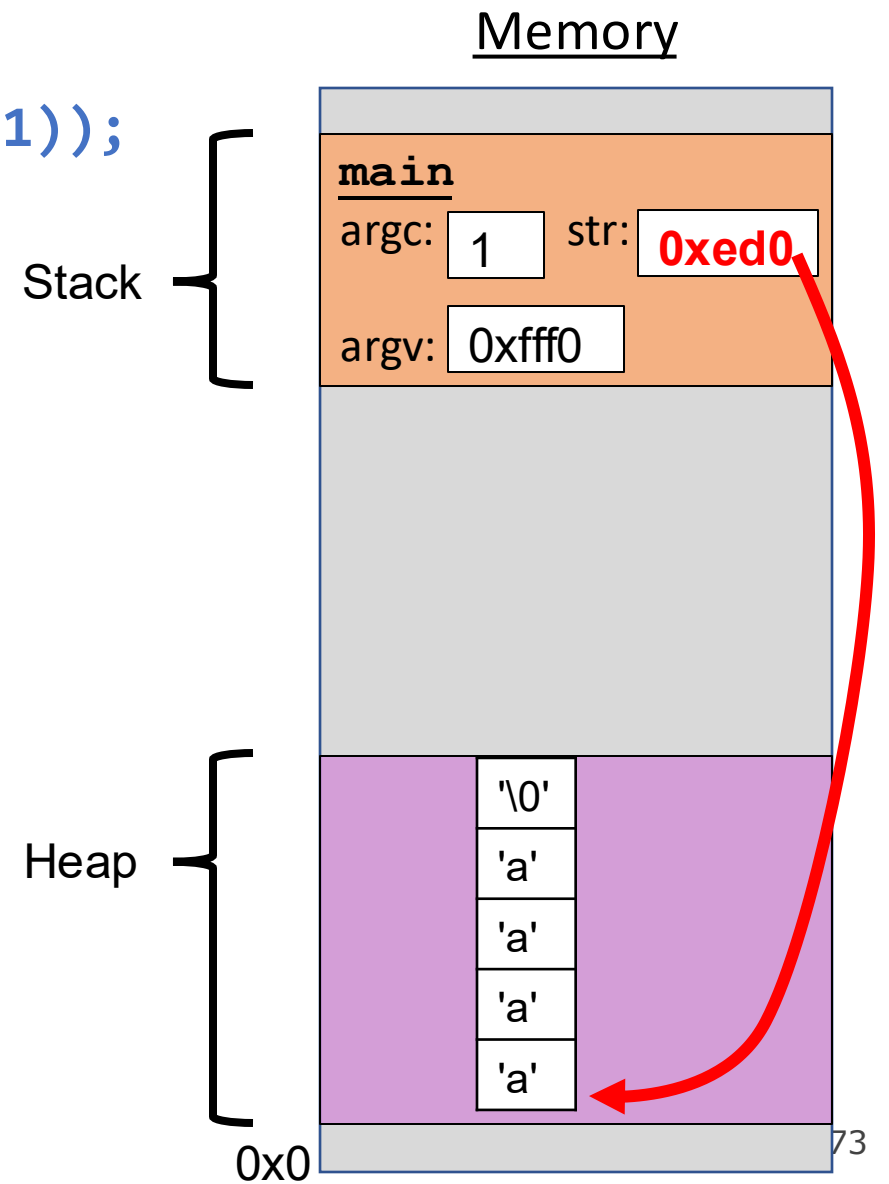


Exercise: `malloc` multiples

Let's write a function that returns an array of the first **len** multiples of **mult**.

```
1 int *array_of_multiples(int mult, int len) {
2     /* TODO: arr declaration here */
3
4     for (int i = 0; i < len; i++) {
5         arr[i] = mult * (i + 1);
6     }
7     return arr;
8 }
```

Respond on PollEv:
pollev.com/cs107

Line 2: How should we declare `arr`?

A. `int arr[len];`
B. `int arr[] = malloc(sizeof(int));`
C. `int *arr = malloc(sizeof(int) * len);`
D. `int *arr = malloc(sizeof(int) * (len + 1));`
E. `int *arr = malloc(len);`

How should we declare *arr*?

int arr[len];

0%

int arr[] = malloc(sizeof(int));

0%

int *arr = malloc(sizeof(int) * len);

0%

int *arr = malloc(sizeof(int) * (len + 1));

0%

int *arr = malloc(len);

0%

Exercise: `malloc` multiples

Let's write a function that returns an array of the first **len** multiples of **mult**.

```
1 int *array_of_multiples(int mult, int len) {
2     /* TODO: arr declaration here */
3
4     for (int i = 0; i < len; i++) {
5         arr[i] = mult * (i + 1);
6     }
7     return arr;
8 }
```

- Use a pointer to store the address returned by malloc.
- Malloc's argument is the **number of bytes** to allocate, not # of elements.
- Arrays other than strings don't have special terminating elements/values.

Line 2: How should we declare `arr`?

A. `int arr[len];`
B. `int arr[] = malloc(sizeof(int));`
C. `int *arr = malloc(sizeof(int) * len);`
D. `int *arr = malloc(sizeof(int) * (len + 1));`
E. `int *arr = malloc(len);`

Working with the heap

Working with the heap consists of 3 core steps:

1. Allocate memory with malloc/realloc/strdup/calloc
2. **Assert heap pointer is not NULL**
3. Free when done (more later)

The heap is **dynamic memory**, so you may encounter many **runtime errors**, even if your code compiles!

Always assert with the heap

Let's write a function that returns an array of the first **len** multiples of **mult**.

```
1 int *array_of_multiples(int mult, int len) {
2     int *arr = malloc(sizeof(int) * len);
3     assert(arr != NULL);
4     for (int i = 0; i < len; i++) {
5         arr[i] = mult * (i + 1);
6     }
7     return arr;
8 }
```

- If an allocation error occurs (e.g. out of heap memory!), malloc will return NULL. This is an important case to check **for robustness**.
- **assert** will crash the program if the provided condition is false. A memory allocation error is significant, and we should terminate the program.

Other heap allocations: `calloc`

```
void *calloc(size_t nmemb, size_t size);
```

`calloc` is like `malloc` that **zeros out** the memory for you—thanks, `calloc`!

- You might notice its interface is also a little different—it takes two parameters, which are multiplied to calculate the number of bytes (`nmemb * size`).

```
// allocate and zero 20 ints
int *scores = calloc(20, sizeof(int));

// alternate (but slower)
int *scores = malloc(20 * sizeof(int));
for (int i = 0; i < 20; i++) scores[i] = 0;
```

- calloc is more expensive than malloc because it zeros out memory. Use only when necessary!

Other heap allocations: `strdup`

```
char *strdup(char *s);
```

`strdup` is a convenience function that returns a **null-terminated**, heap-allocated string with the provided text, instead of you having to **`malloc`** and copy in the string yourself.

```
char *str = strdup("Hello, world!");  // on heap
str[0] = 'h';
```

You could imagine **strdup** might be implemented in terms of **malloc** + **strcpy**.

Lecture Plan

- **Recap:** Pointers So Far
- Arrays in Memory
- The Stack
- The Heap and Dynamic Memory
- **Freeing Memory**

Cleaning Up with `free`

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

- If we allocated memory on the heap and no longer need it, it is our responsibility to **free** it.
- To do this, use the **`free`** command and pass in the *starting address on the heap for the memory you no longer need.*
- Example:

```
char *bytes = malloc(4);
…
free(bytes);
```

Free

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

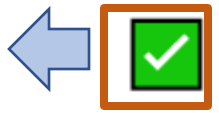
When you free an allocation, you are freeing up what it *points* to. You are not freeing the pointer itself. You can still use the pointer to point to something else.

```
char *str = strdup("hello");
...
free(str);
str = strdup("hi");
```

free details

Even if you have multiple pointers to the same block of memory, each memory block should only be freed **once**.

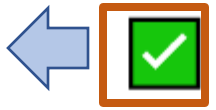
```
char *bytes = malloc(4);
char *ptr = bytes;
…
free(bytes);
…
free(ptr);
```

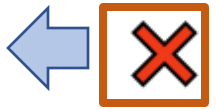


✗ Memory at this address was already freed!

You must free the address you received in the previous allocation call; you cannot free just part of a previous allocation.

```
char *bytes = malloc(4);
char *ptr   = malloc(10);
…
free(bytes);
…
free(ptr + 1);
```





Cleaning Up

You may need to free memory allocated by other functions if that function expects the caller to handle memory cleanup.

```
char *str = strdup("Hello!");
…
free(str);     // our responsibility to free!
```

Cleaning Up

You may need to free memory allocated by other functions if that function expects the caller to handle memory cleanup.

```
char *create_string(char ch, int num) {
    char *new_str = malloc(sizeof(char) * (num + 1));
    for (int i = 0; i < num; i++) {
        new_str[i] = ch;
    }
    new_str[num] = '\0';
    return new_str;  // caller must free
}

int main(int argc, char *argv[]) {
    char *str = create_string('a', 4);
    printf("%s", str);
    free(str);
    return 0;
}
```

Memory Leaks

A **memory leak** is when you do not free memory you previously allocated.

```
char *str = strdup("hello");
str = strdup("hi"); // memory leak!  Lost previous str
```

Memory Leaks

A **memory leak** is when you do not free memory you previously allocated.

- Your program should be responsible for cleaning up any memory it allocates but no longer needs.
- If you never free any memory and allocate an extremely large amount, you may run out of memory in the heap!
- However, memory leaks rarely (if ever) cause crashes.
- We recommend not to worry about freeing memory until your program is written. Then, go back and free memory as appropriate.
- Valgrind is a very helpful tool for finding memory leaks!
- Tip: free as soon as you are done with a block of memory

Recap

- **Recap:** Pointers So Far
- Arrays in Memory
- The Stack
- The Heap and Dynamic Memory
- Freeing Memory

Lecture 10 takeaway: We can allocate memory on the heap to manage it ourselves. We manipulate heap memory via pointers.

Extra Practice

Translating C into English

* If **declaration**: “pointer”
ex: `int *` is "pointer to an int”
If **operation**: "dereference/the value at address”
ex: `*num` is "the value at address num"

& “address of”

`<ptr name>` address

`<arr name>` address (except sizeof)

```
int arr[] = {3, 4, -1, 2};
// initializes stack array
// with 4 ints
```

1. `int *ptr0  = arr;`
2. `int elt0   = *arr;`
3. `int elt    = *(arr + 3);`
4. `int **ptr1 = &ptr0;`

Type check with a diagram!

Translating C into English

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int arr[] = {3, 4, -1, 2};
```

1. `int *ptr0 = arr;`
2. `int elt0 = *arr;`
3. `int elt = *(arr + 3);`
4. `int **ptr1 = &ptr0;`

```
// initializes stack array
// with 4 ints
```

Address arr

Value at address arr

The value at address <3 ints after address arr>

address of ptr0

Type check with a diagram!

Translating C into English

* If **declaration**: “pointer”
ex: `int *` is "pointer to an int”
If **operation**: "dereference/the value at address”
ex: `*num` is "the value at address num"

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`<arr name>` address (except sizeof)

```
int arr[] = {3, 4, -1, 2};
```

1. `int *ptr0 = arr;`
2. `int elt0 = *arr;`
3. `int elt = *(arr + 3);`
4. `int **ptr1 = &ptr0;`

```
// initializes stack array
// with 4 ints
```

Type check with a diagram!

* Wars: Episode I (of 2)

In variable **declaration**, * creates a **pointer**.

```
char ch = 'r';
```

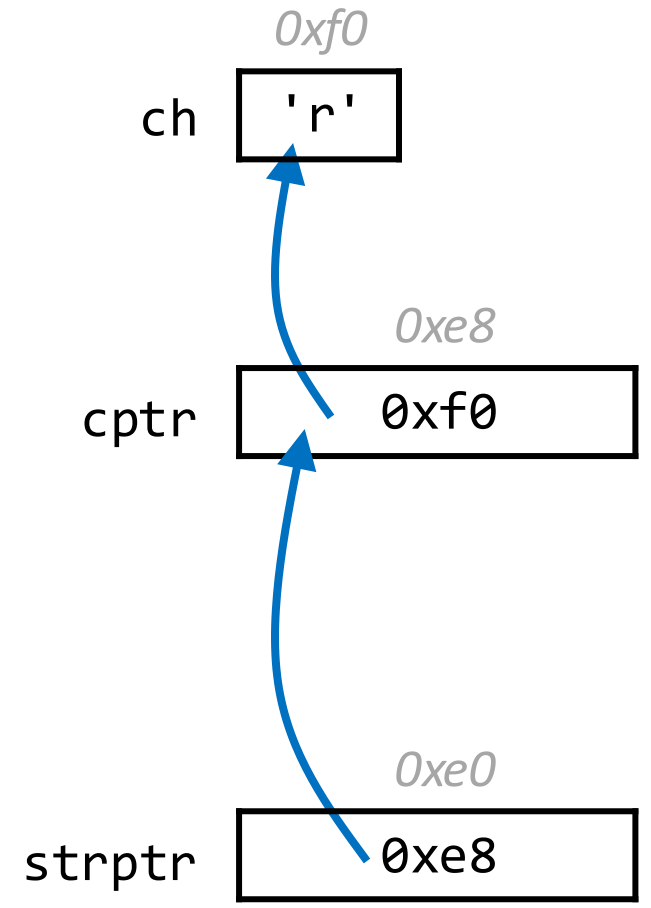
ch stores a char

```
char *cptr = &ch;
```

cptr stores an address of a char
(**points to** a char)

```
char **strptr = &cptr;
```

strptr stores an address of a char *
(**points to** a char *)



* Wars: Episode II (of 2)

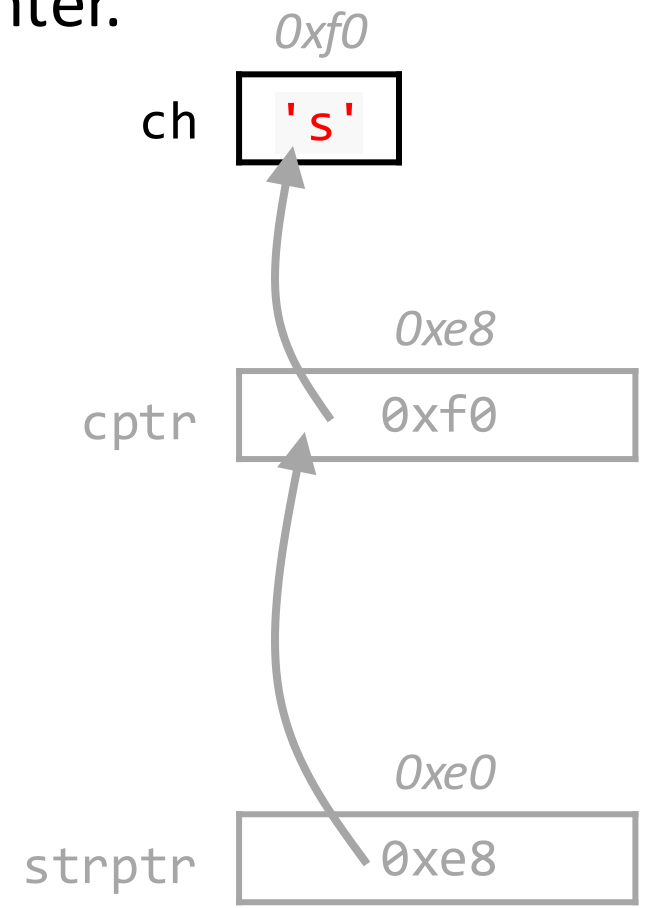
In **reading values from/storing values**, * **dereferences** a pointer.

```
char ch = 'r';
ch = ch + 1;
```

Increment value stored in ch

```
char *cptr = &ch;
```

```
char **strptr = &cptr;
```



* Wars: Episode II (of 2)

In **reading values from/storing values**, * **dereferences** a pointer.

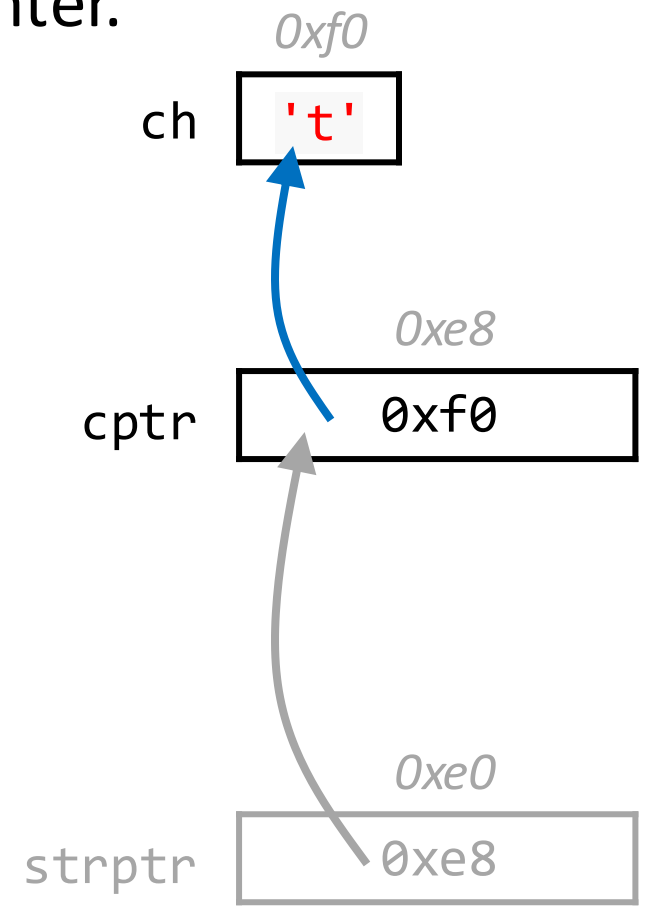
```
char ch = 'r';
ch = ch + 1;
```

Increment value stored in ch

```
char *cptr = &ch;
*cptr = *cptr + 1;
```

Increment value stored at memory address in cptr (increment char **pointed to**)

```
char **strptr = &cptr;
```



* Wars: Episode II (of 2)

In **reading values from/storing values**, * **dereferences** a pointer.

```
char ch = 'r';
ch = ch + 1;
```

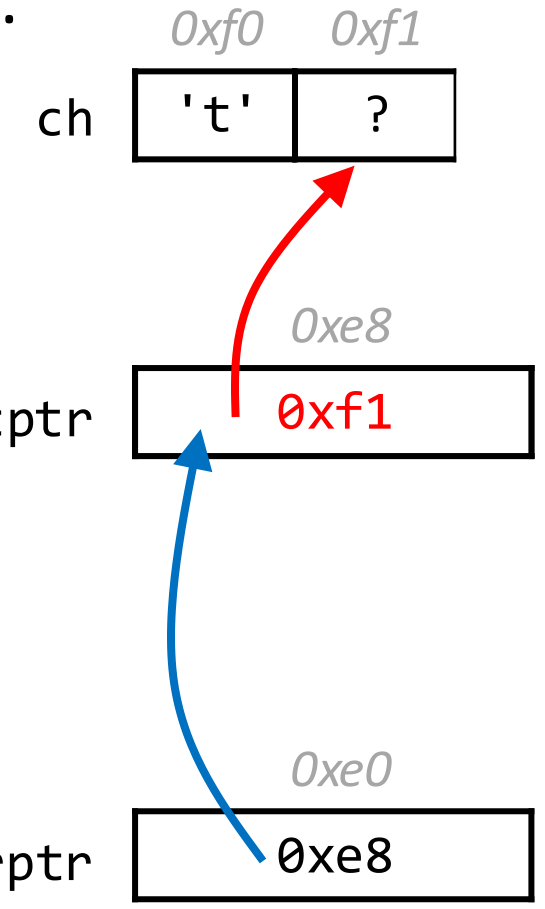
Increment value stored in ch

```
char *cptr = &ch;
*cptr = *cptr + 1;
```

Increment value stored at memory address in cptr (increment char **pointed to**)

```
char **strptr = &cptr;
*strptr = *strptr + 1;
```

Increment value stored at memory address in cptr (increment address **pointed to**)



Exercise: Implementation

The below function sums up the string lengths of the `num` strings in `strs`.

- Try both 1. array [ ] syntax and 2. pointer arithmetic!

```
1 size_t get_total_strlen(char *strs[], size_t num) {
2     size_t total_length = 0;
3     for (int i = 0; i < num; i++) {
4         // fill this in
5     }
6     return total_length;
7 }
```

Exercise: Implementation

The below function sums up the string lengths of the `num` strings in `strs`.

- Try both 1. array [ ] syntax and 2. pointer arithmetic!

```
1 size_t get_total_strlen(char *strs[], size_t num) {
2     size_t total_length = 0;
3     for (int i = 0; i < num; i++) {
4         // TODO: fill this in two ways
5     }
6     return total_length;
7 }
```

Equivalent:

1. `total_length += strlen(strs[i]);`
2. `total_length += strlen(*(strs + i));`

strdup means string duplicate

How can we implement **strdup** using functions we've already seen?

```
1 char *mystrdup(const char *str) {
2     char *heapstr = ____(A)____;
3     ____(B)____;
4     ____(C)____;
5     return heapstr;
6 }
```

[Note] Use library functions:
<stdlib.h>: malloc
<assert.h>: assert
<string.h>: strcpy, strlen

strdup means string duplicate

How can we implement **strdup** using functions we've already seen?

```
1 char *mystrdup(const char *str) {
2     char *heapstr = malloc(strlen(str) + 1);
3     assert(heapstr != NULL);
4     strcpy(heapstr, str);
5     return heapstr;
6 }
```

char arrays differ from other arrays in that valid strings must be null-terminated (i.e., have an extra ending char).

(Note: library strdup doesn't have an assert—it leaves the assert to the callee)