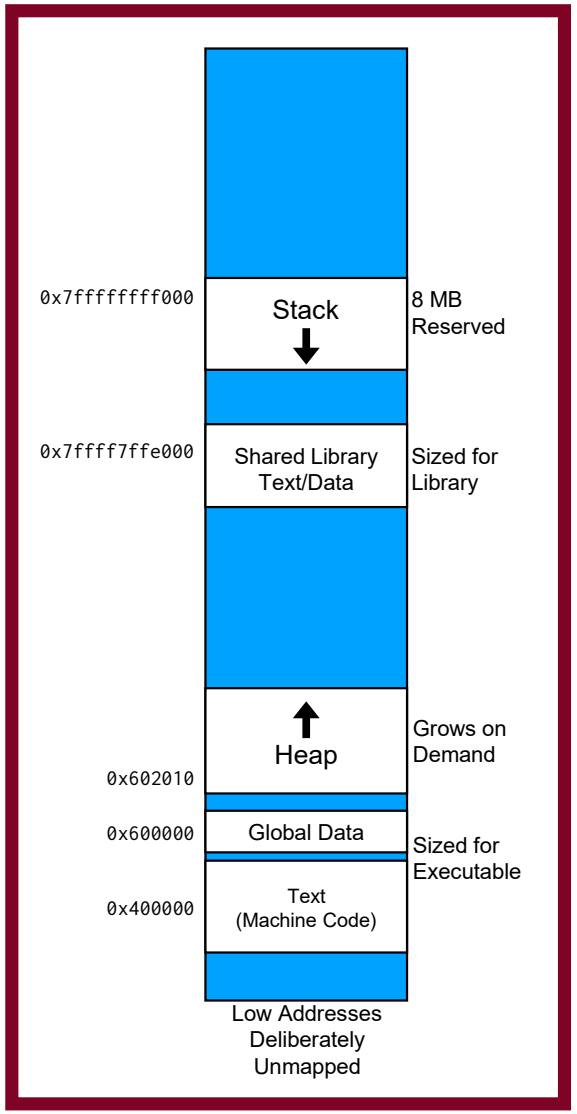
Stack and Heap

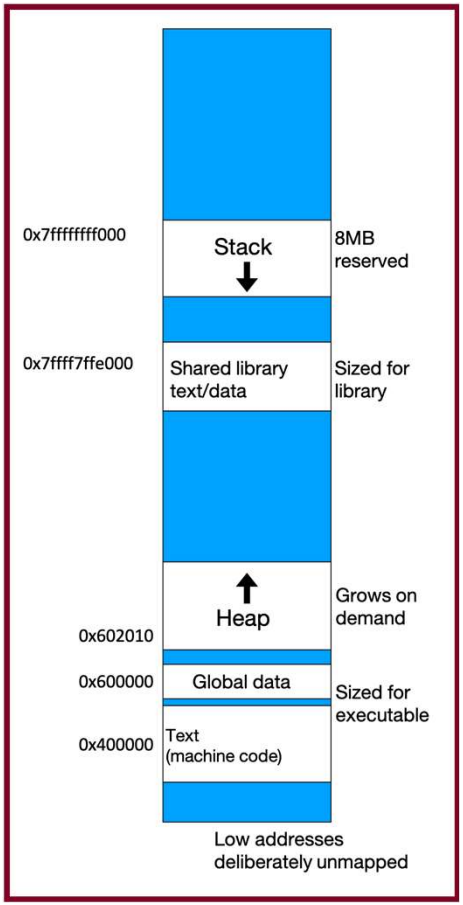


Memory Layout

- We are going to dive deeper into different areas of memory used by our programs.

- The **stack** is the place where all local variables and parameters live for each function. A function's stack "frame" goes away when the function returns.

- The stack grows **downwards** when a new function is called and shrinks **upwards** when the function is finished.



The Stack

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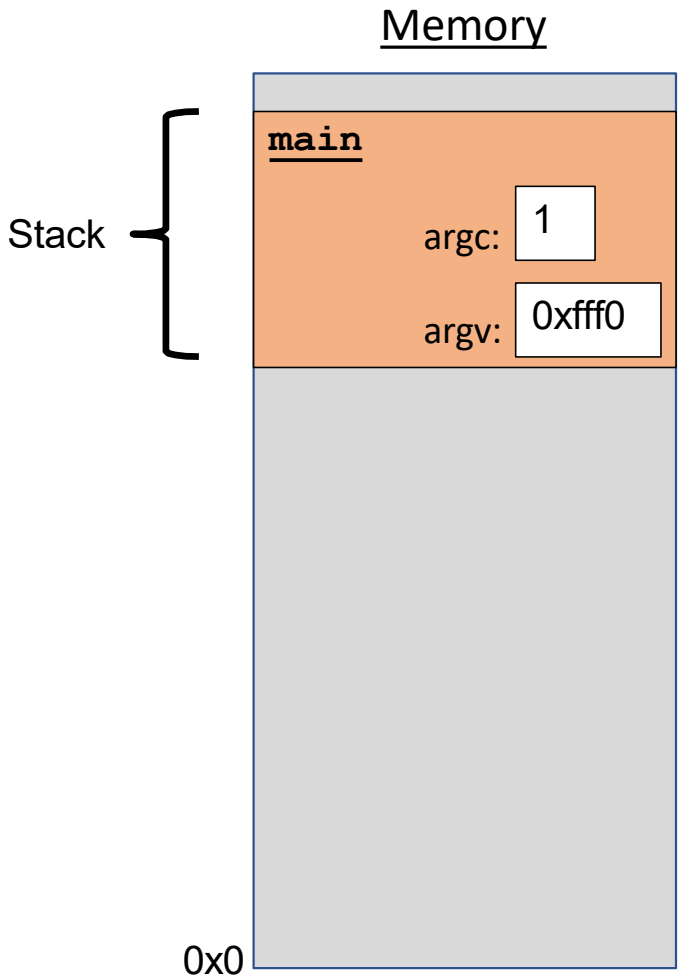

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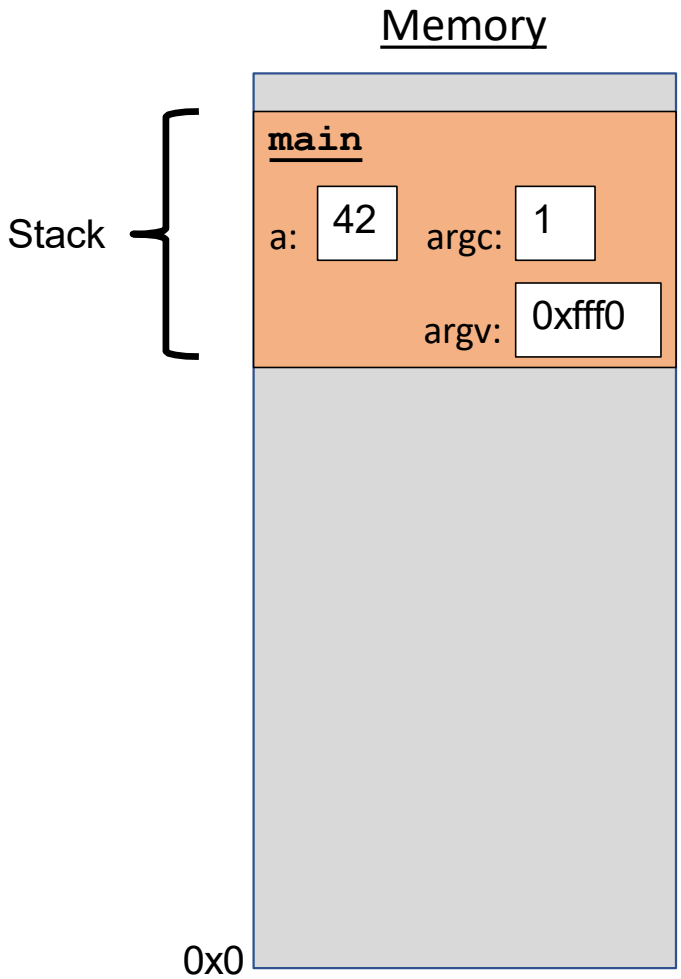

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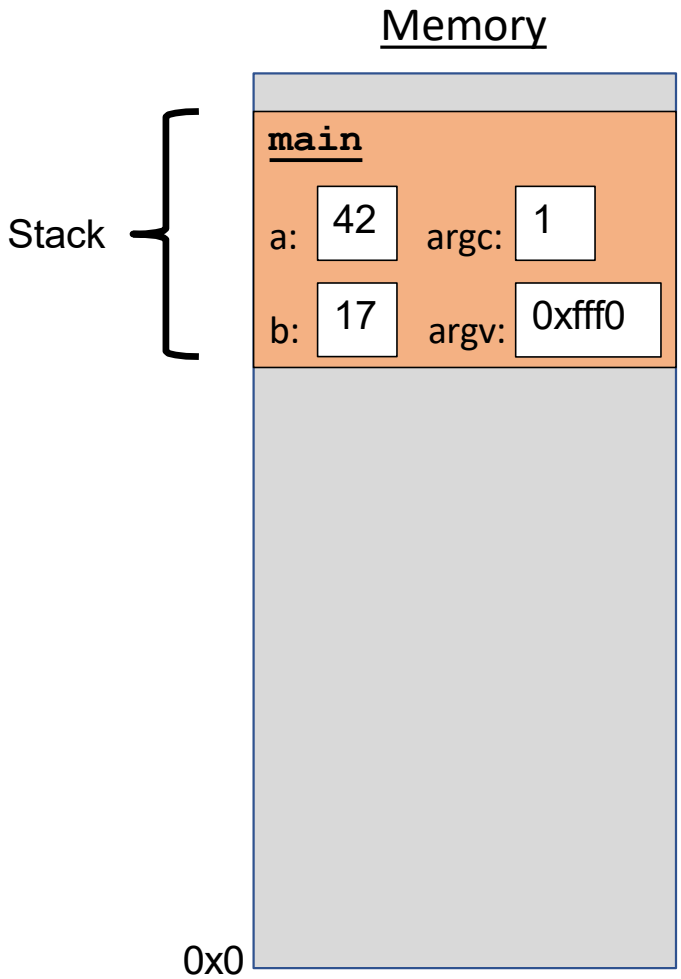

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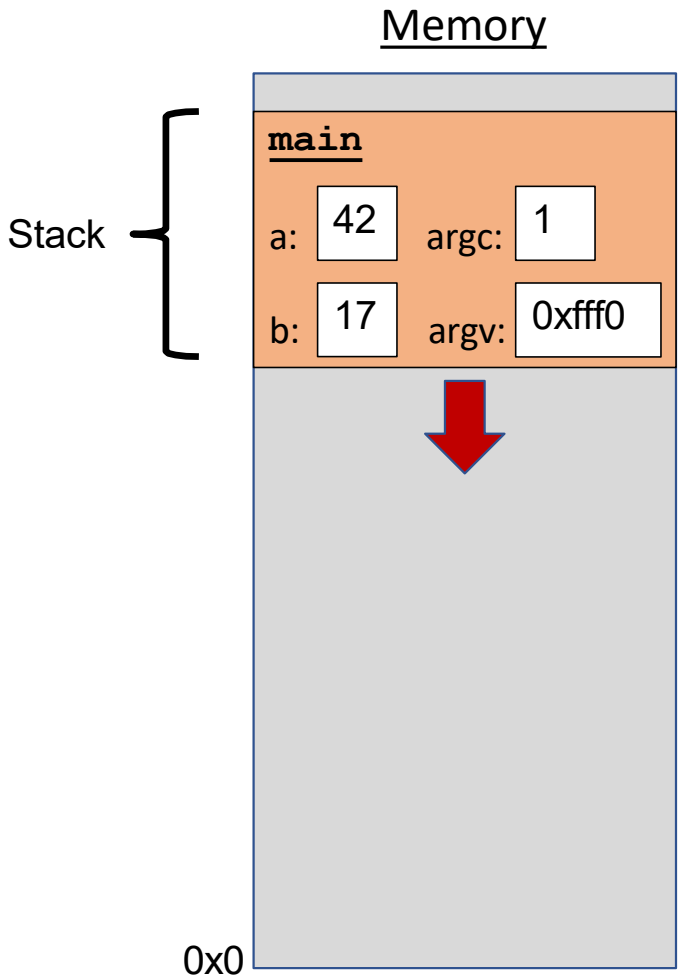

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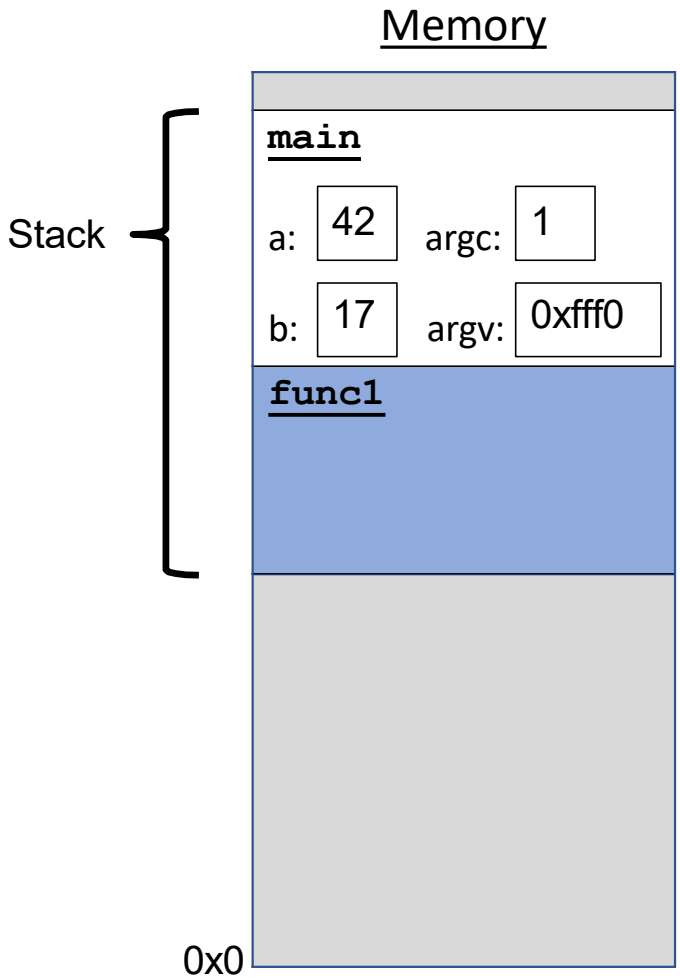

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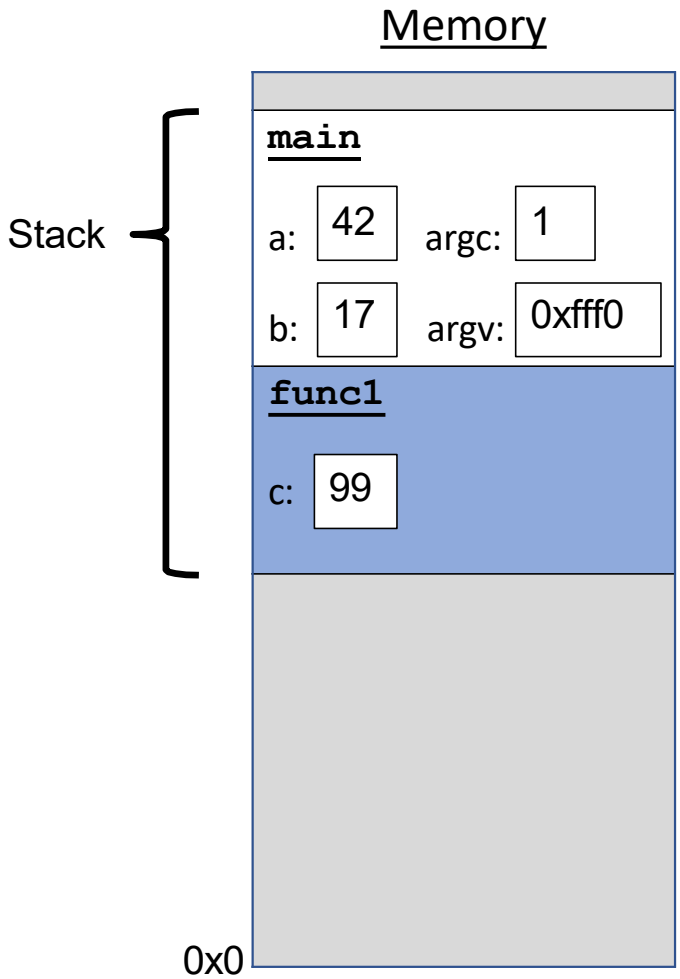

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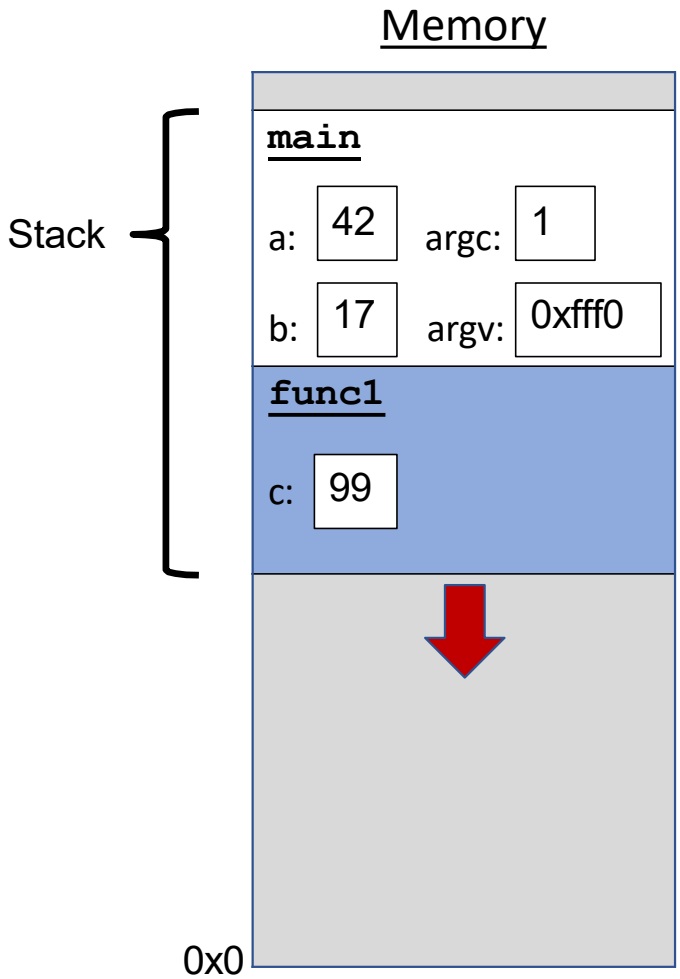

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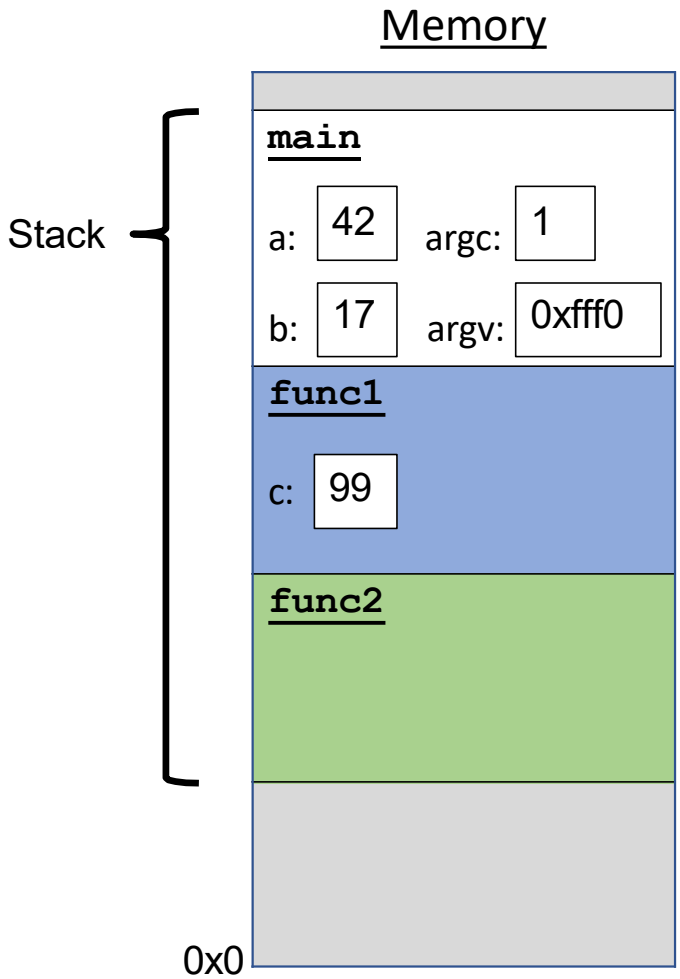

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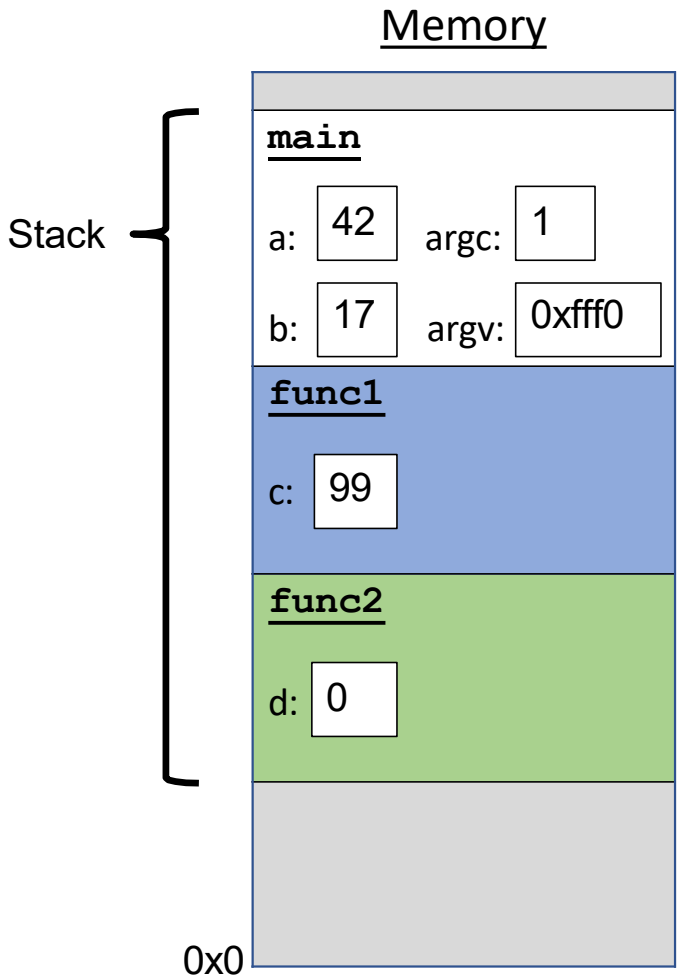

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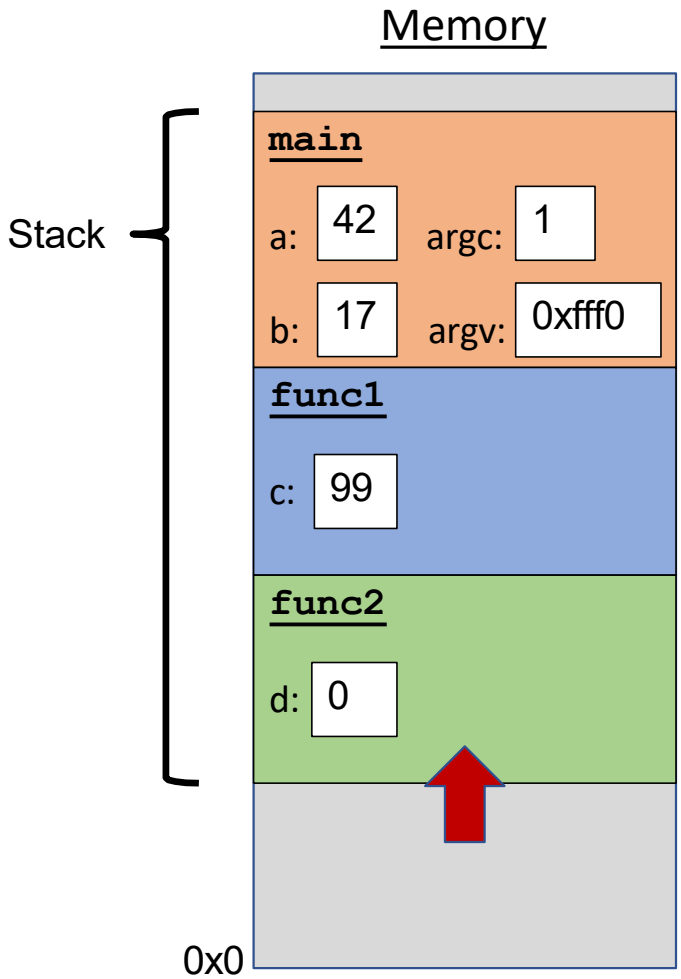

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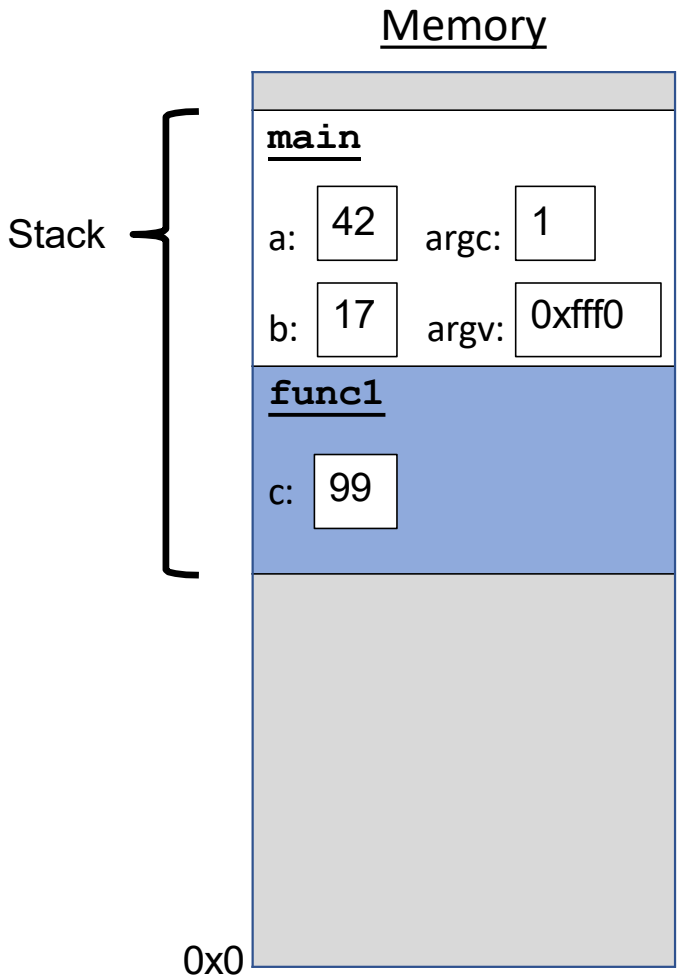

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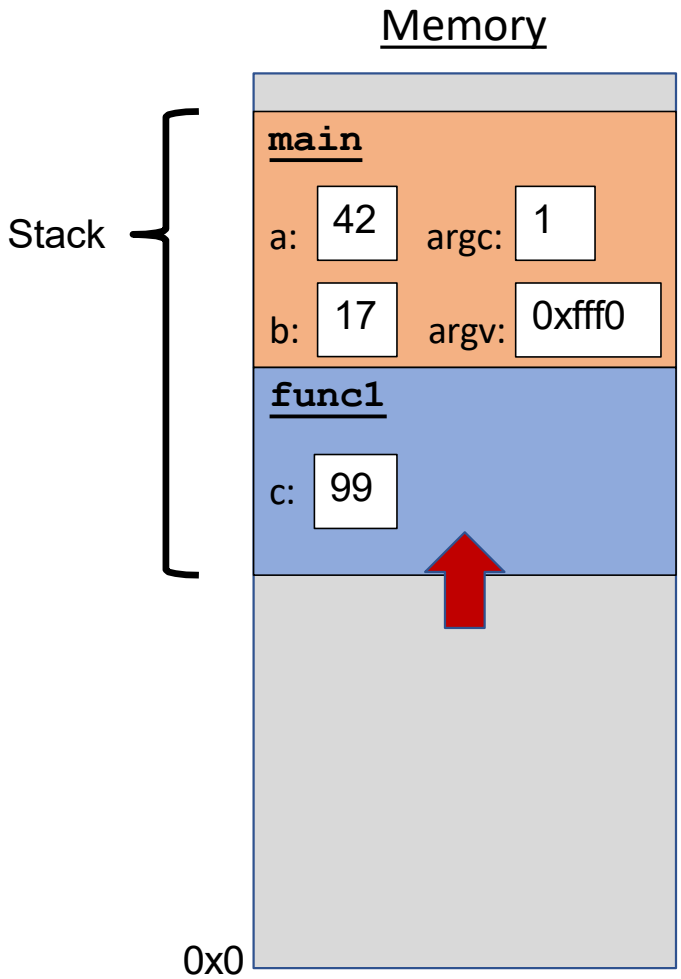

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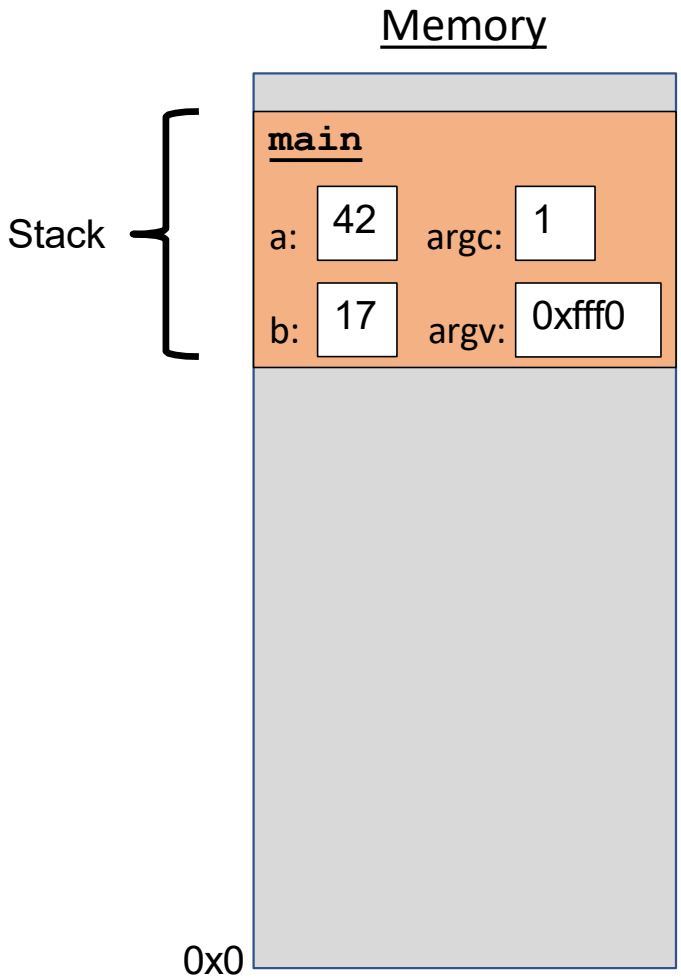

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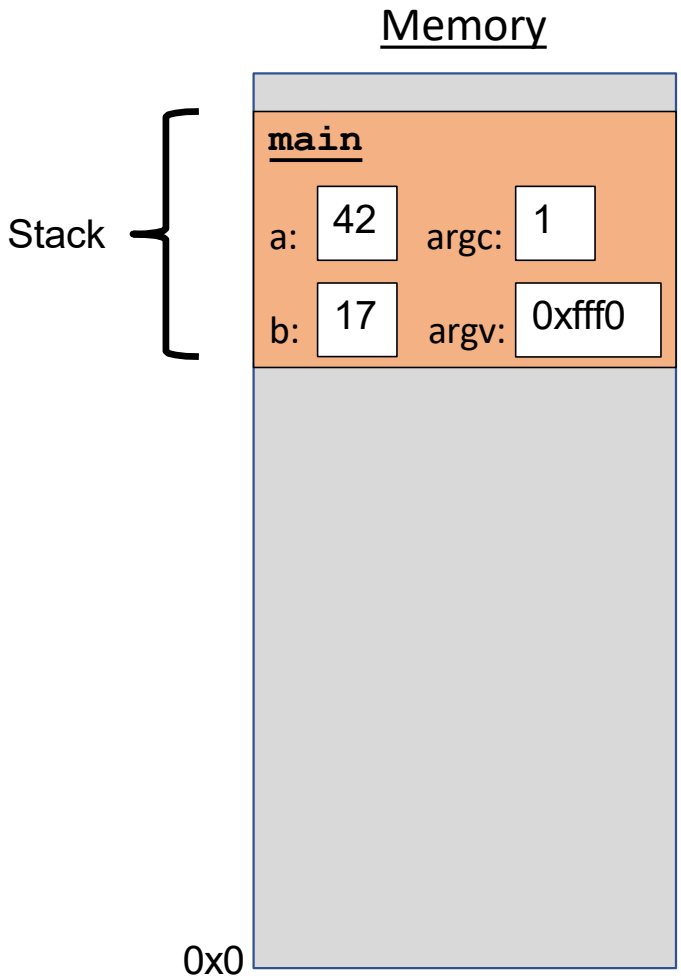

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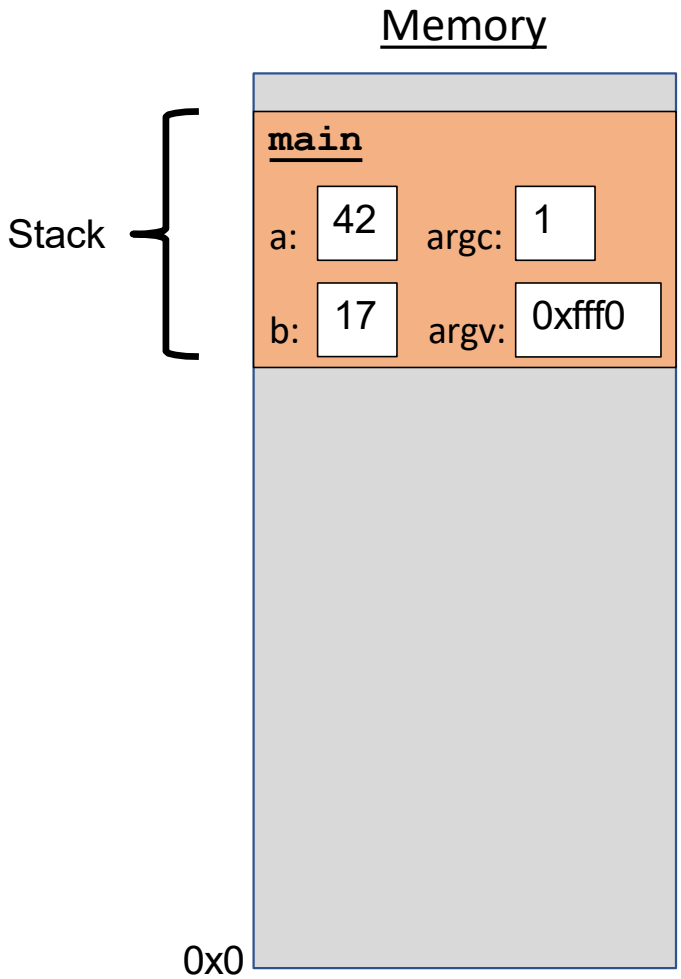

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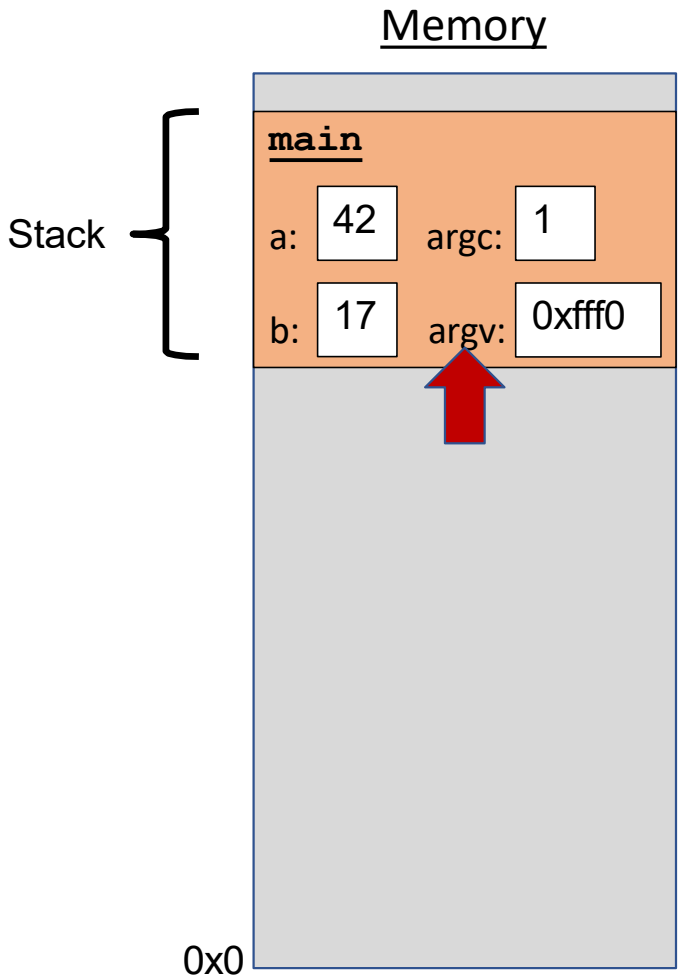

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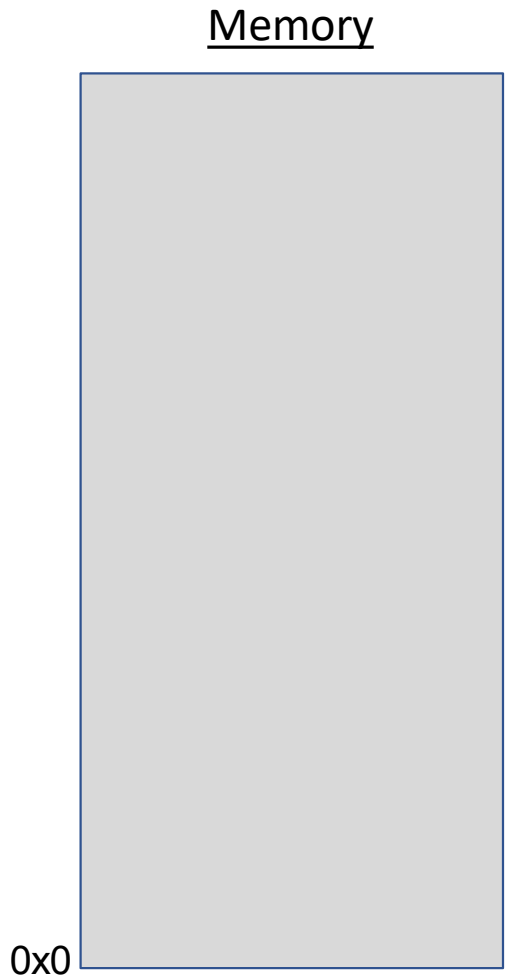

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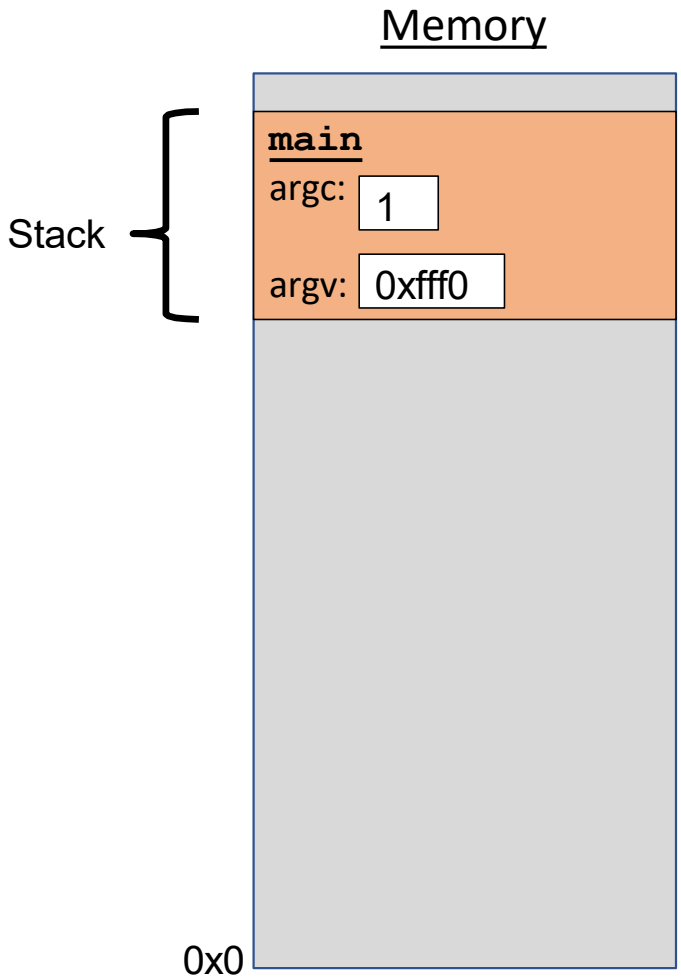

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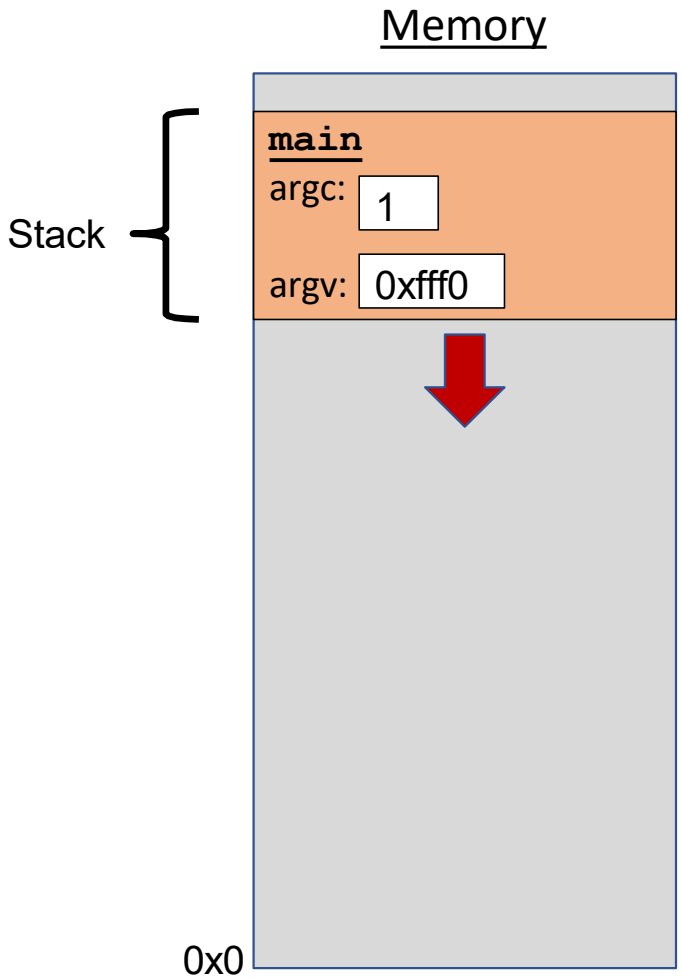

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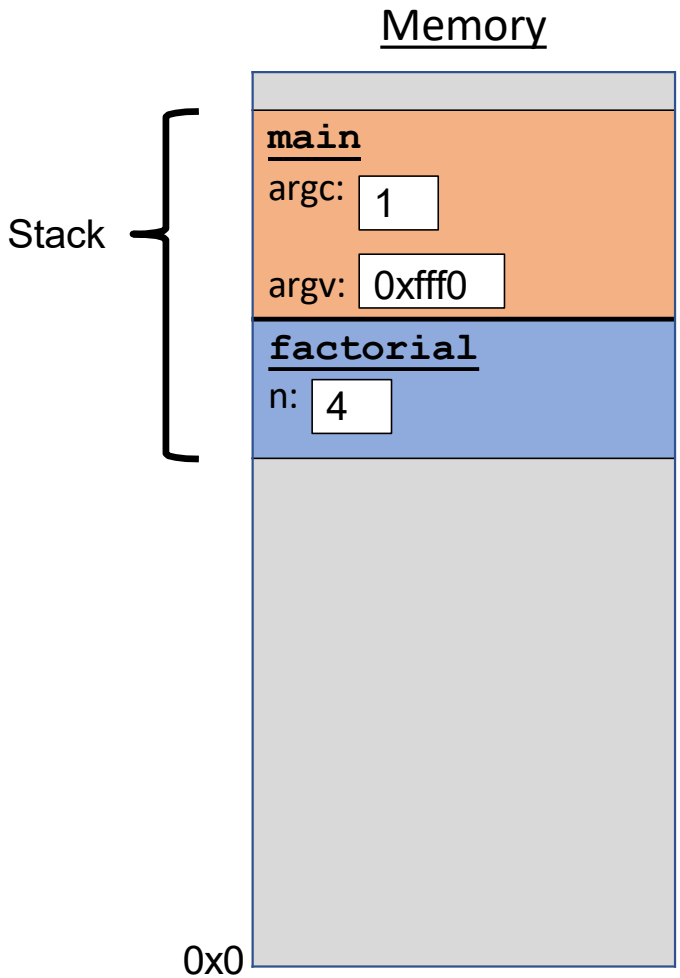

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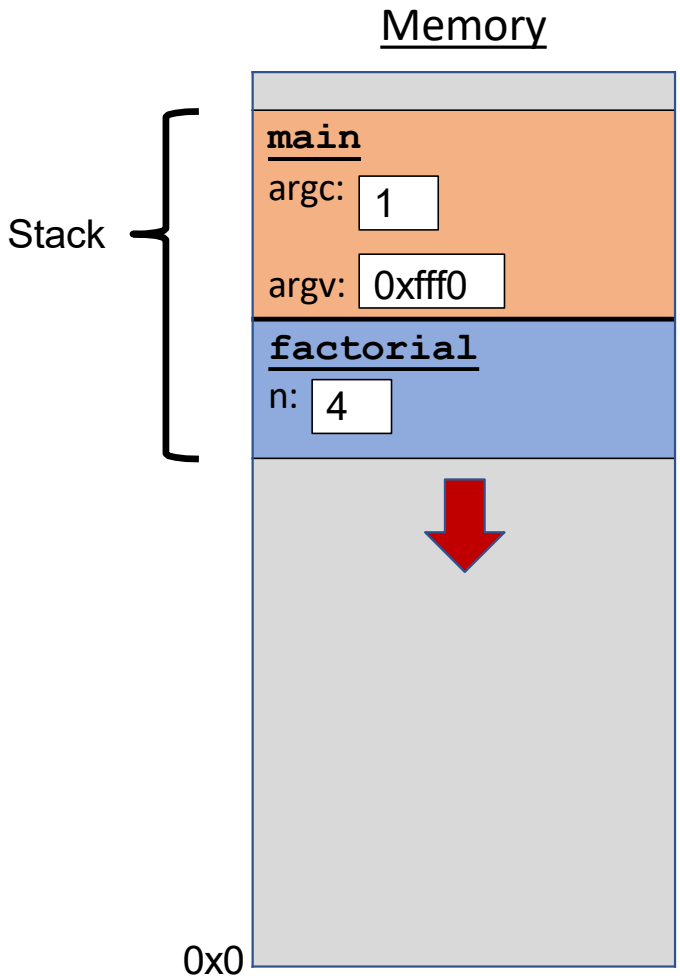

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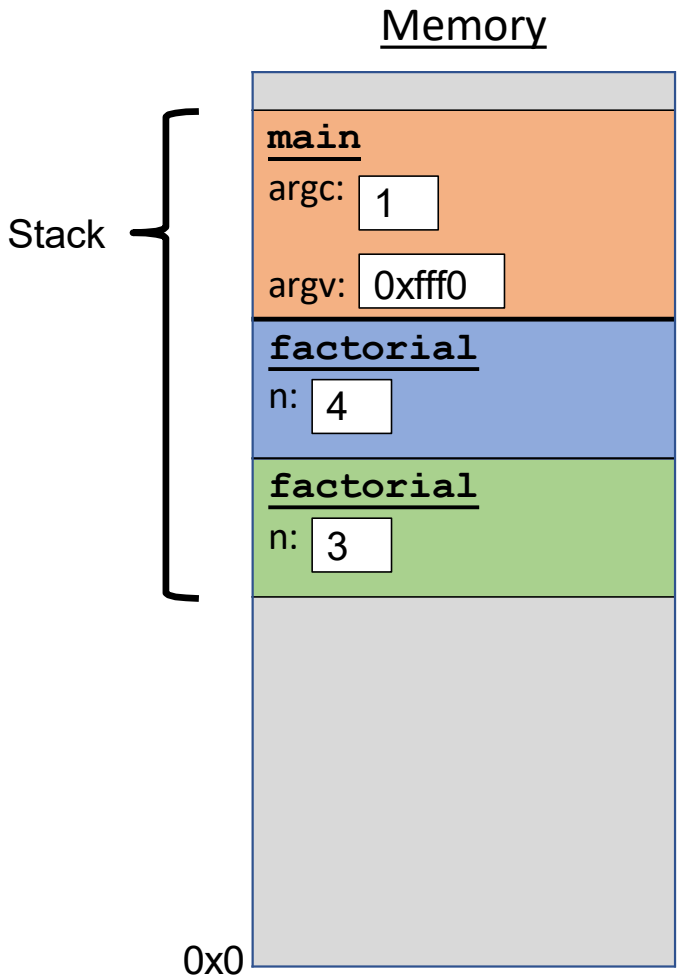

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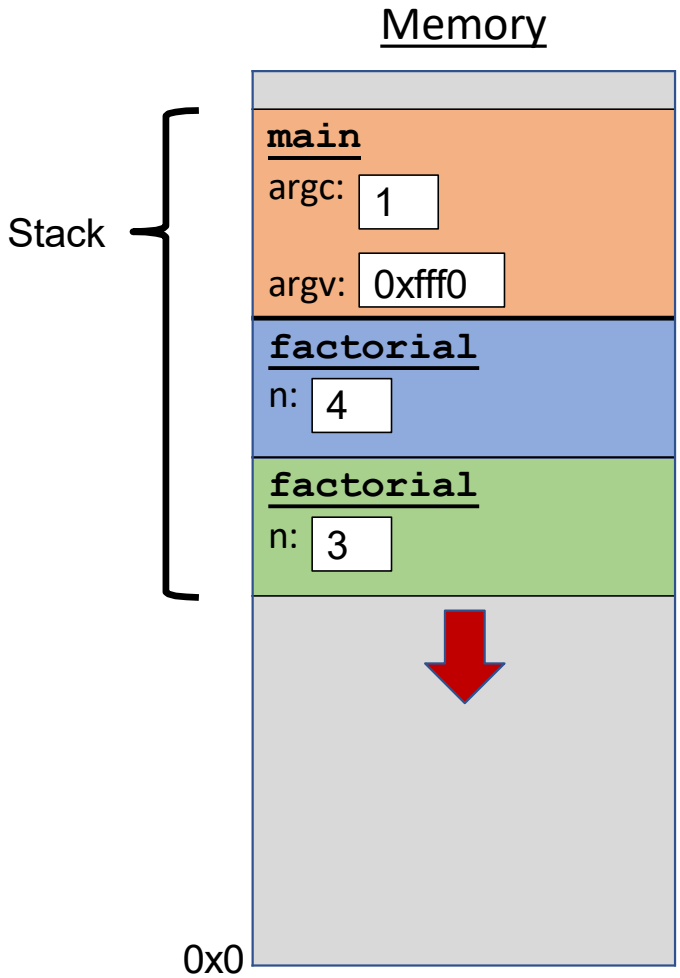

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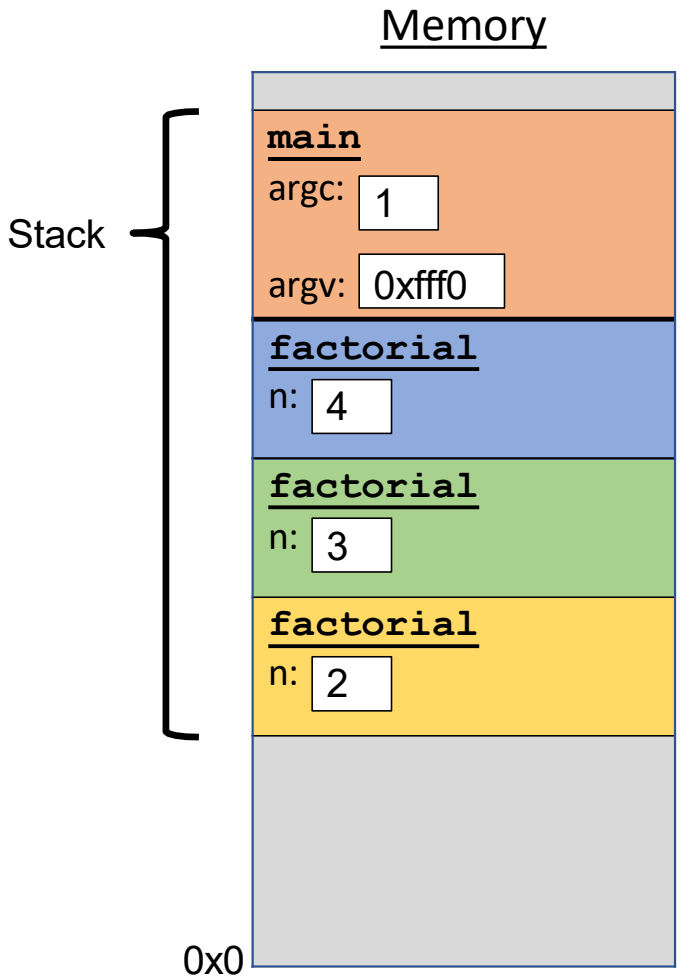

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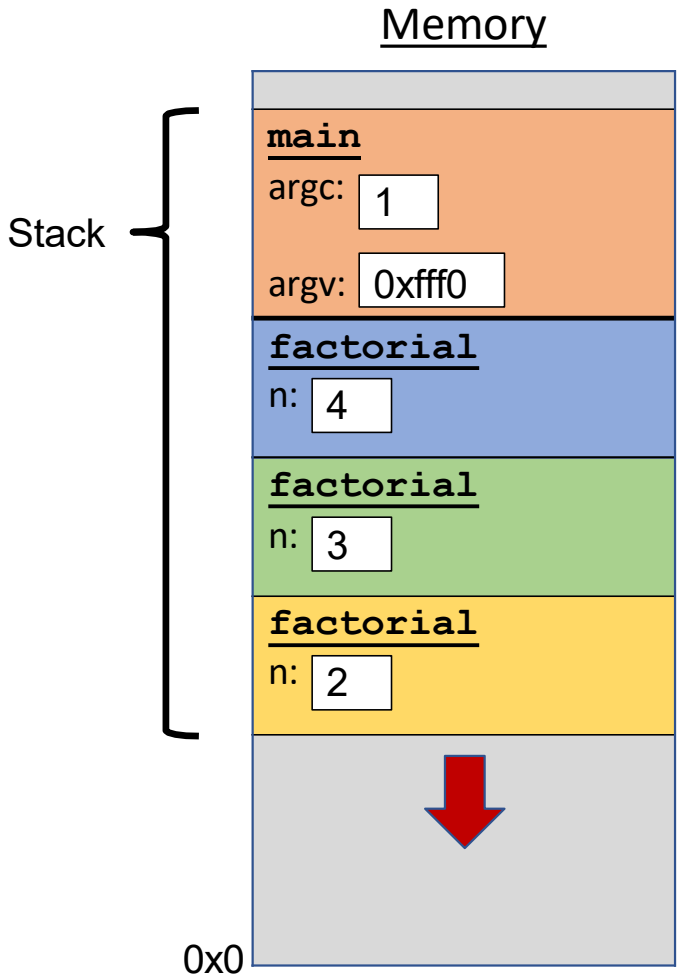

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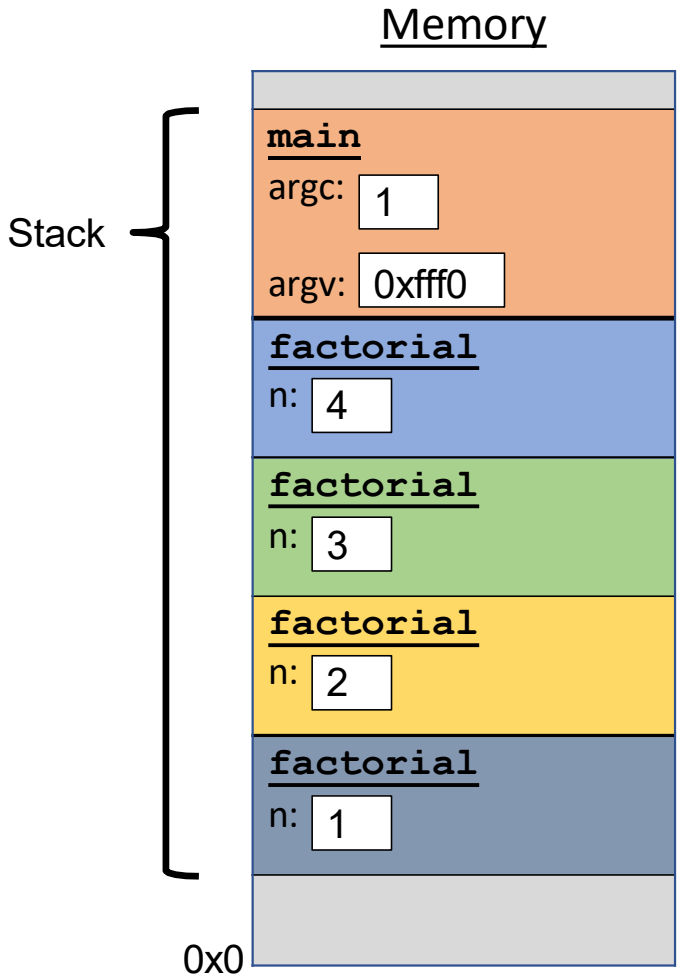

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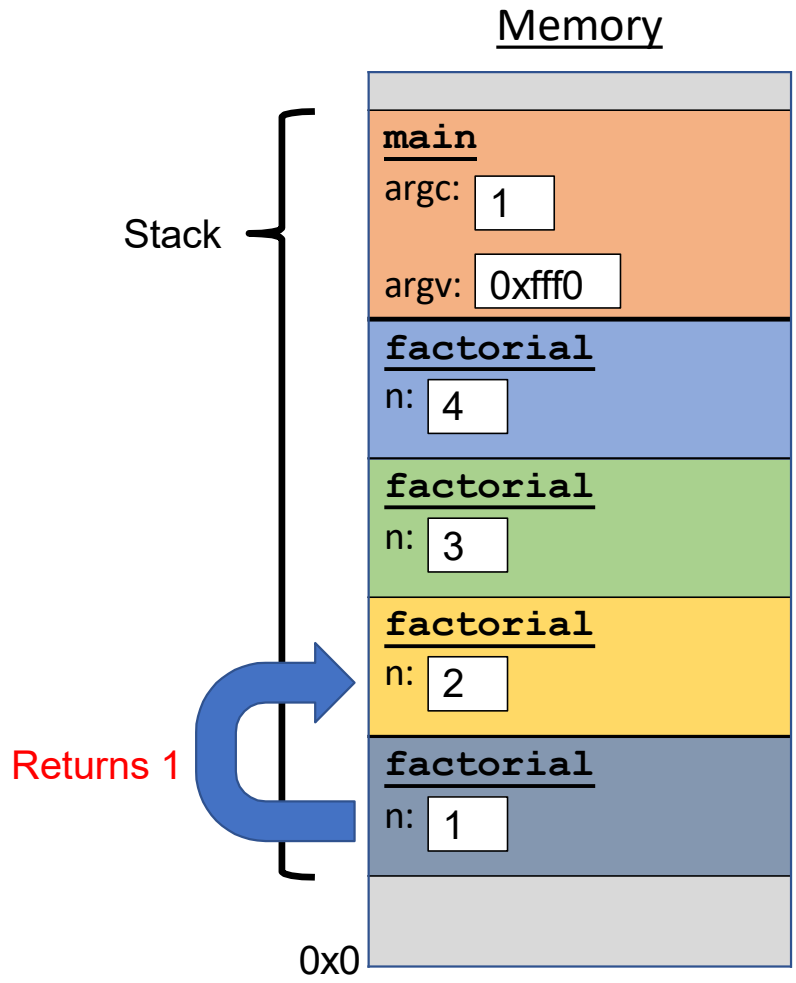

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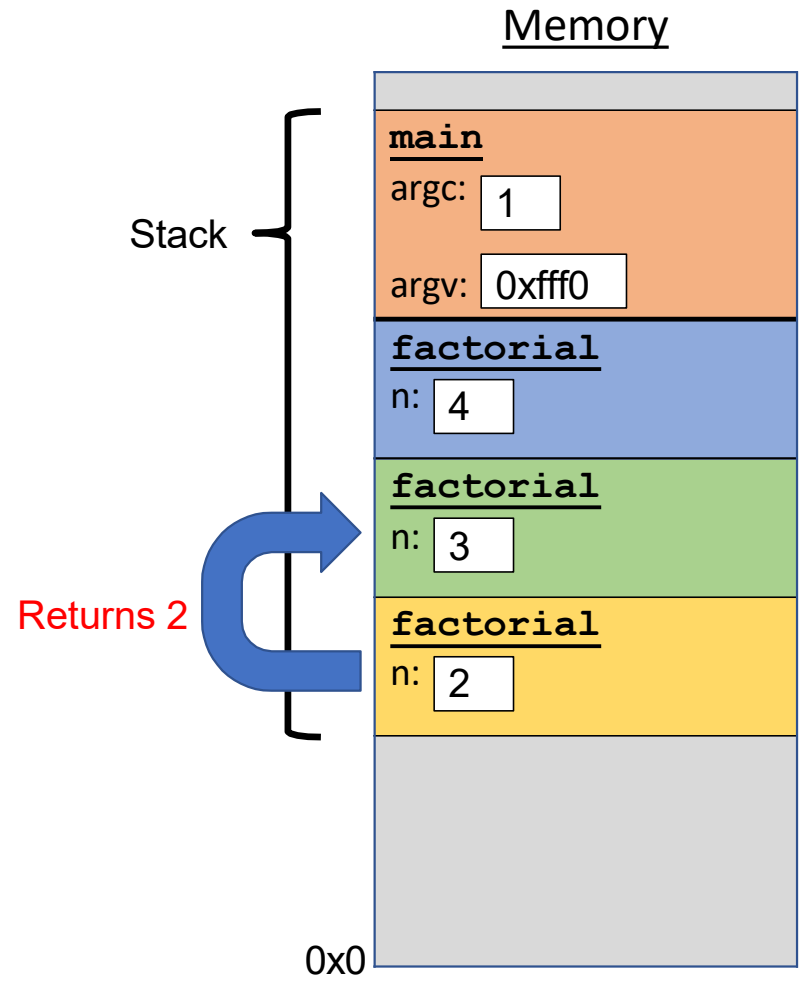

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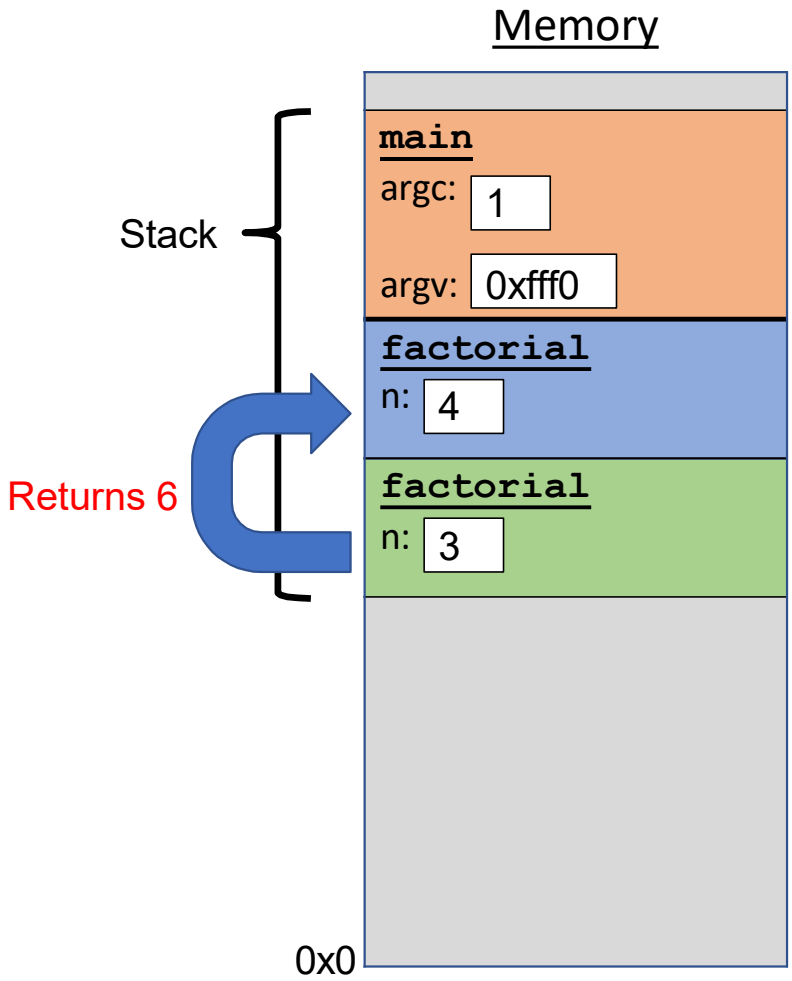

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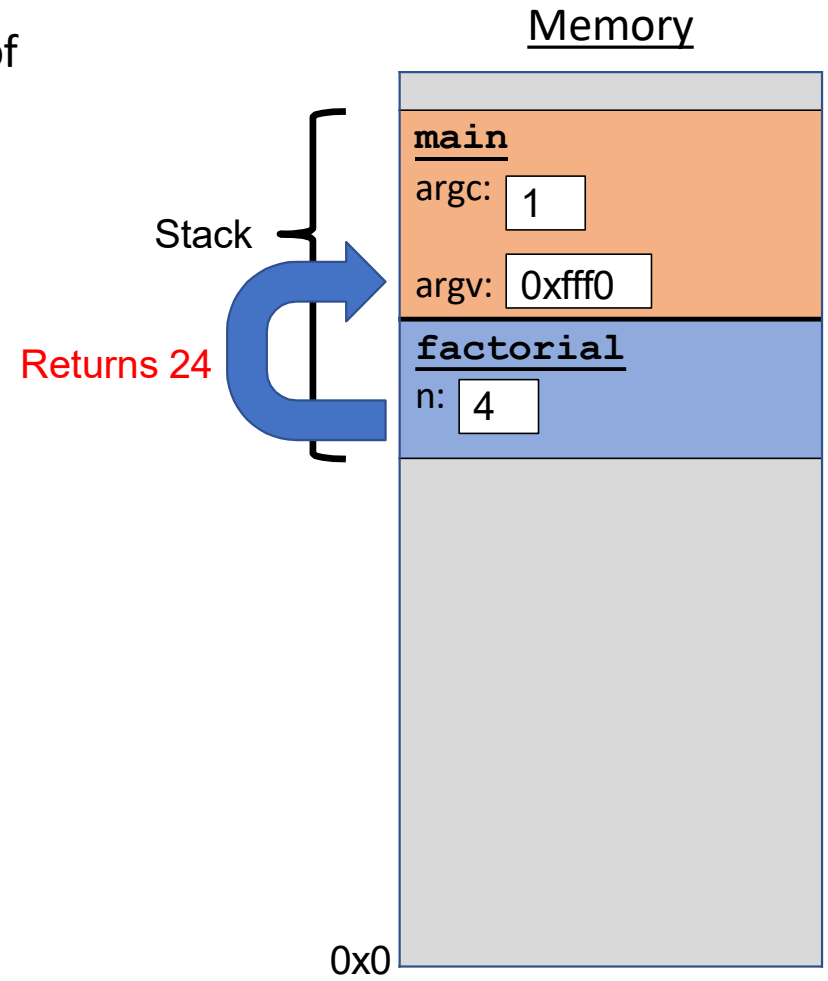

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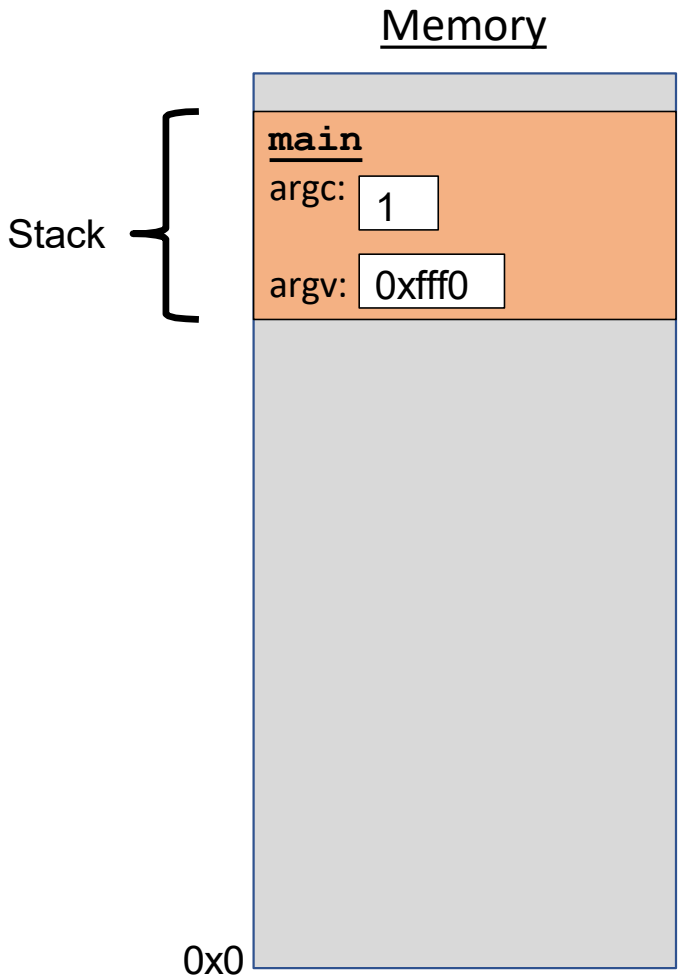

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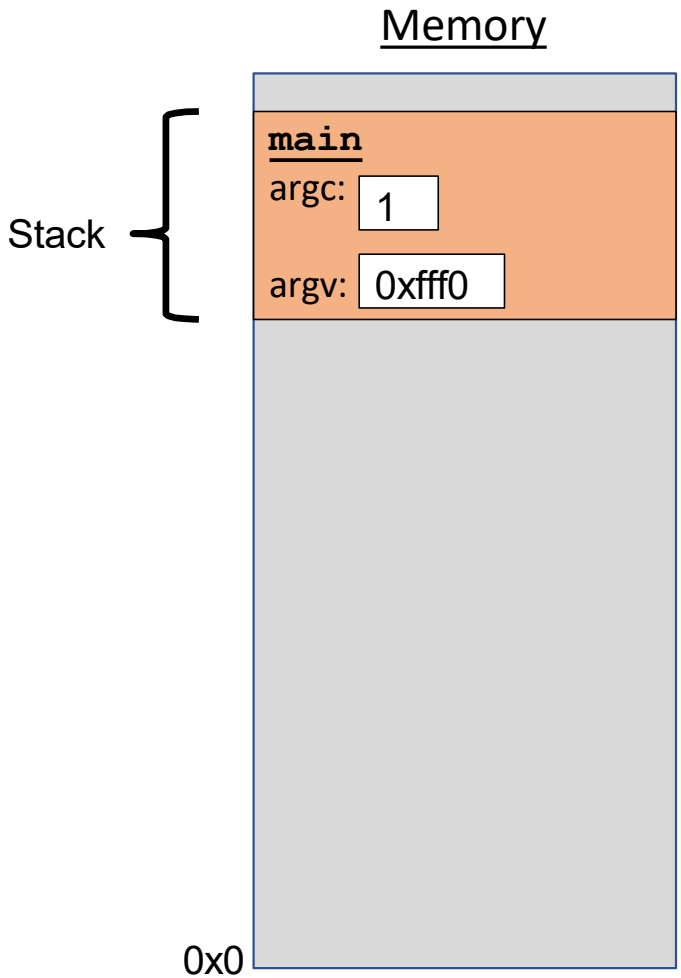


The Stack

- 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!

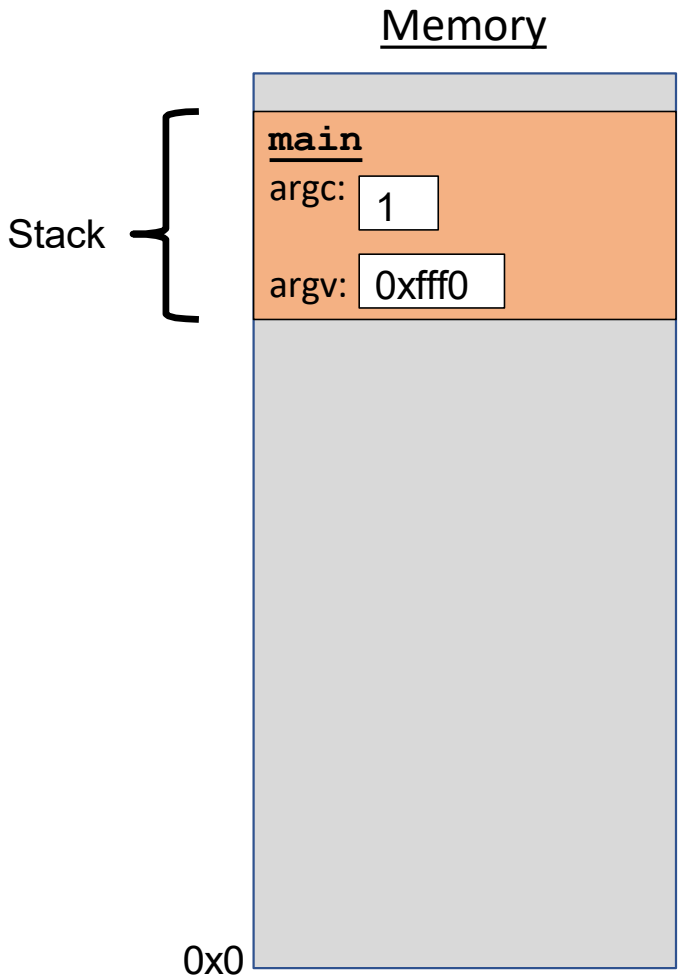
- What are the limitations of the stack?

- A *stack overflow* is when you use up all stack memory. E.g. a recursive call with too many function calls.

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

```
char *create_string(char ch, int num) {
    char new_str[num + 1];
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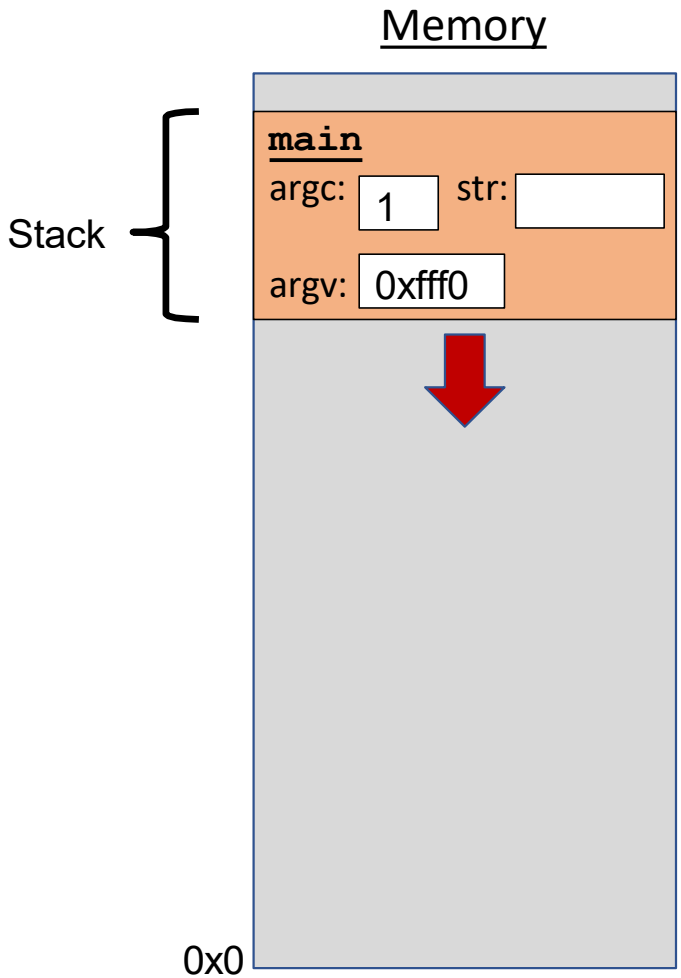

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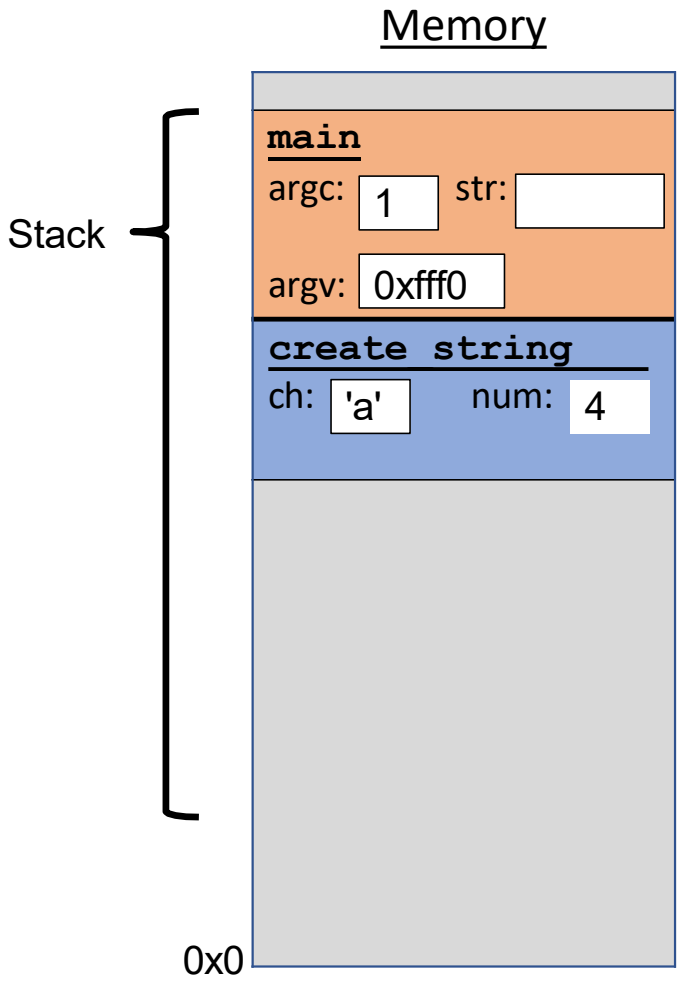

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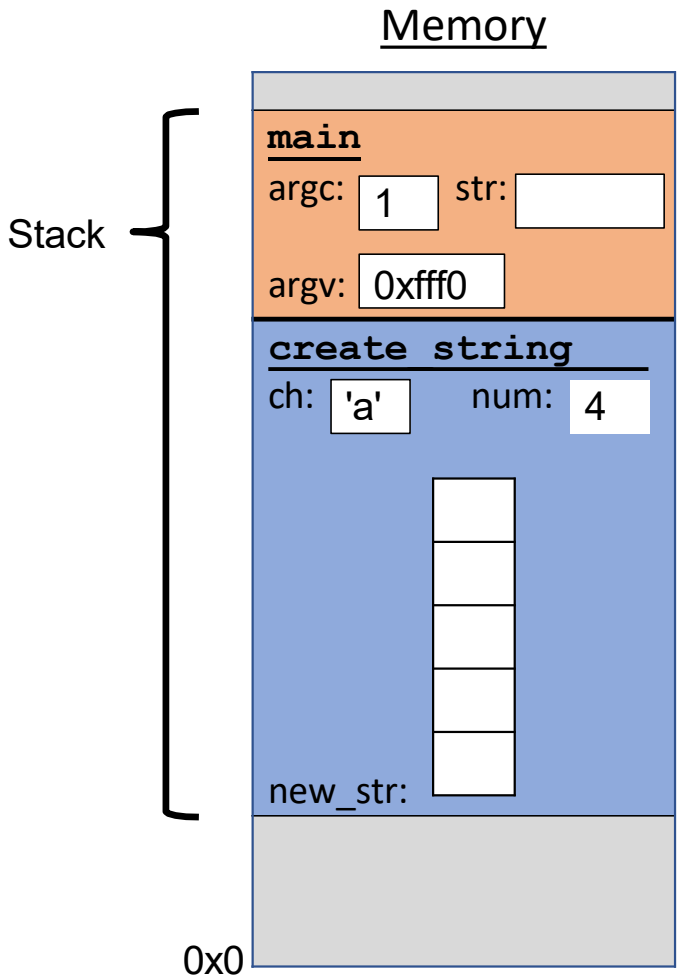

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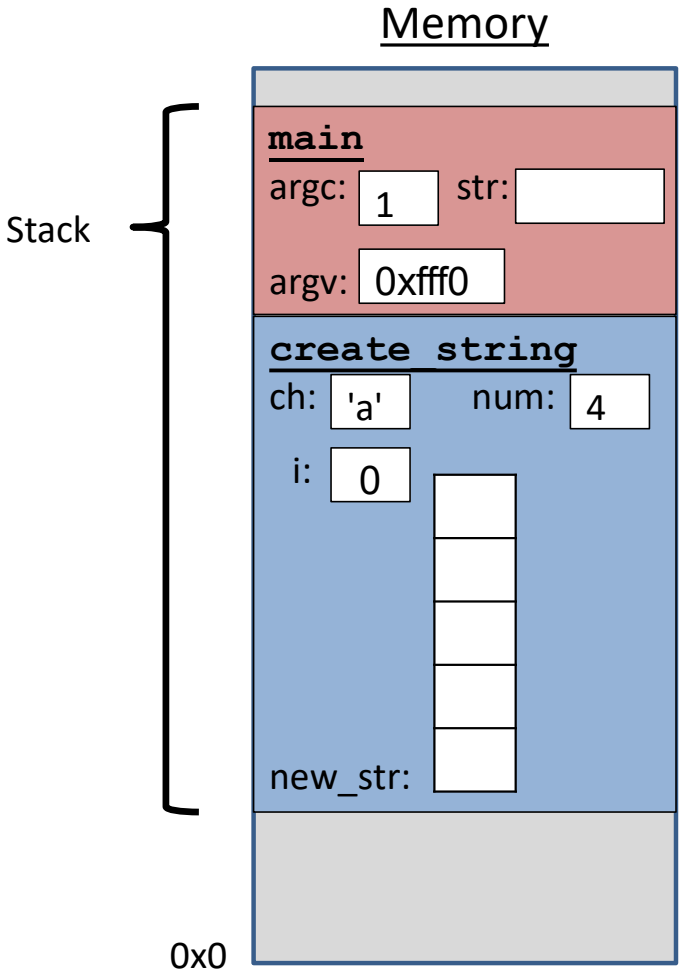

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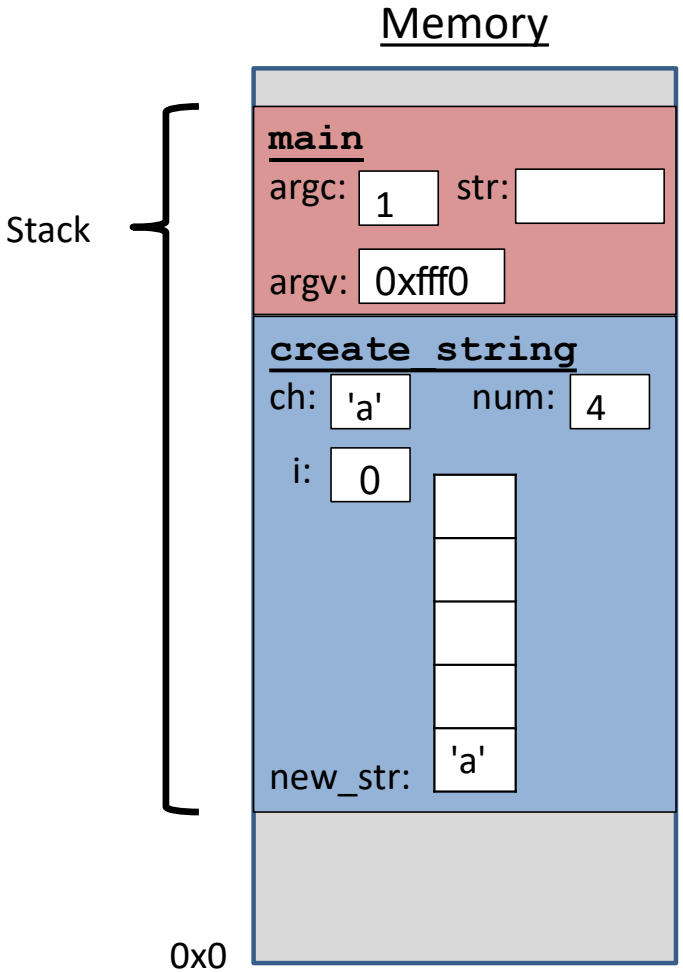

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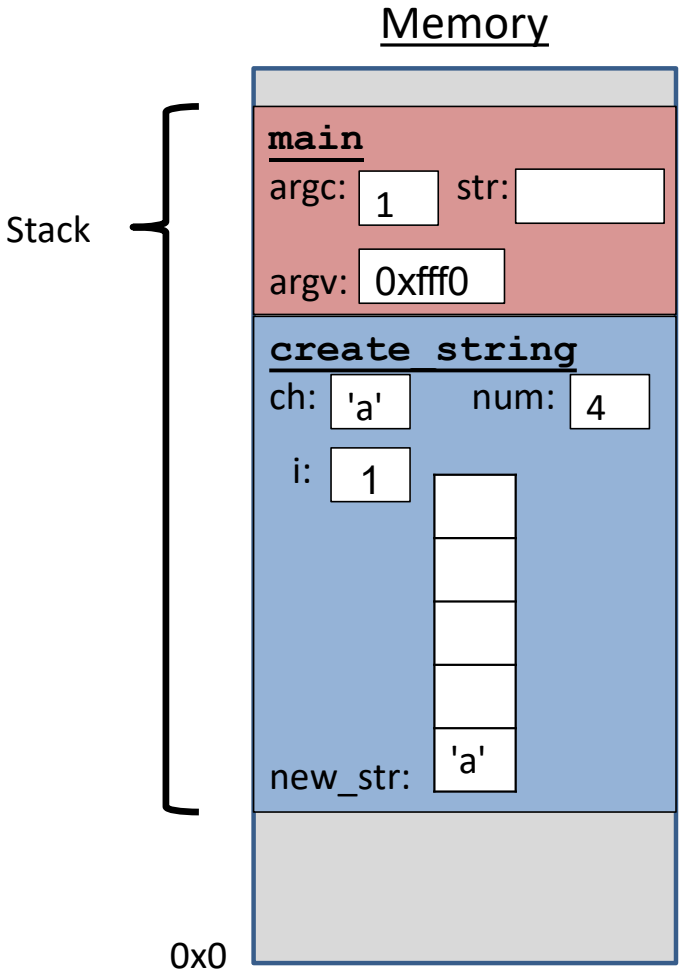

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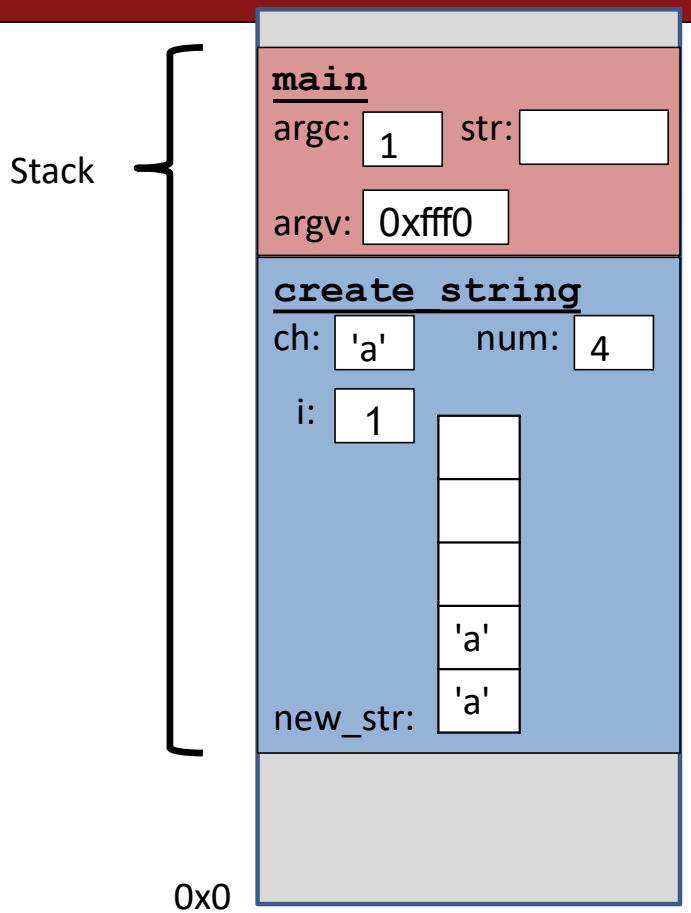

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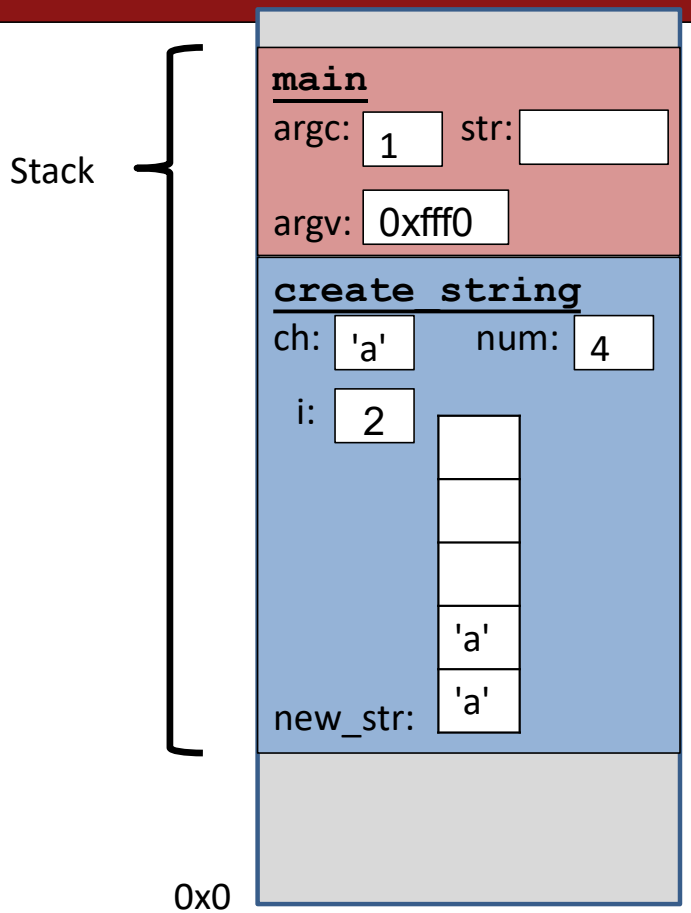

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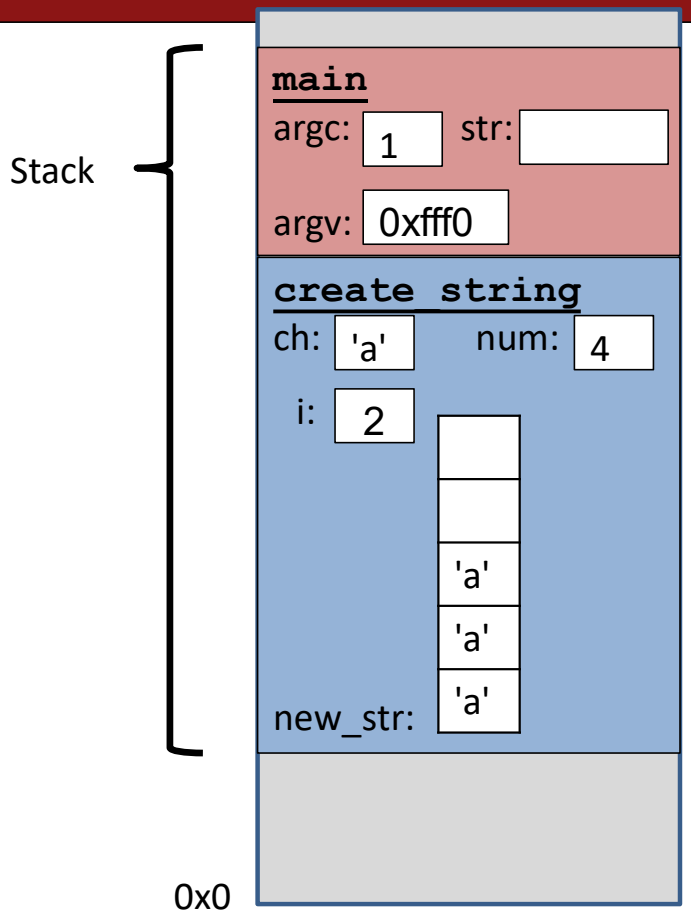

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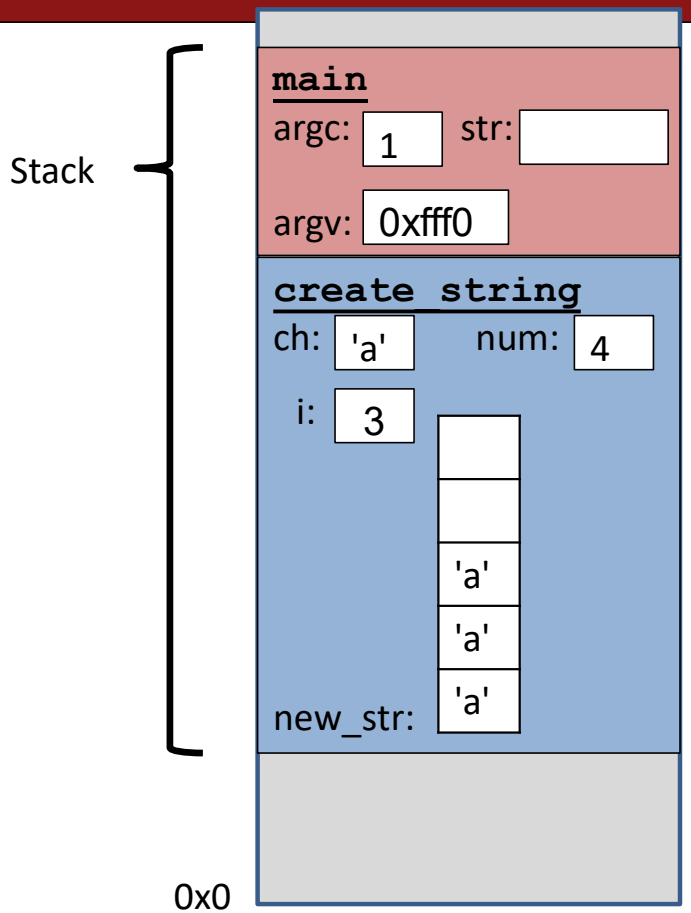

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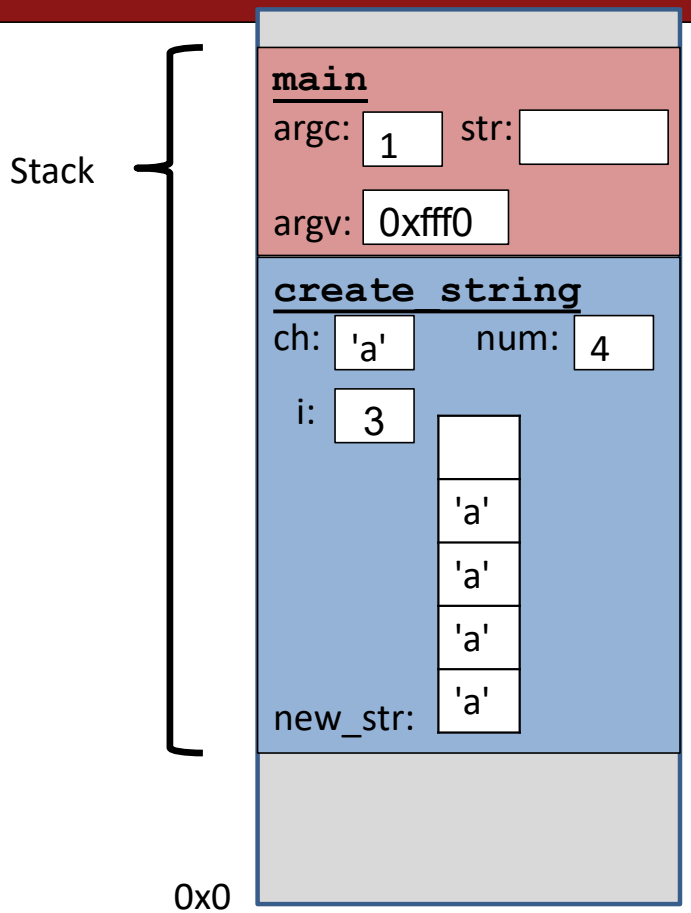

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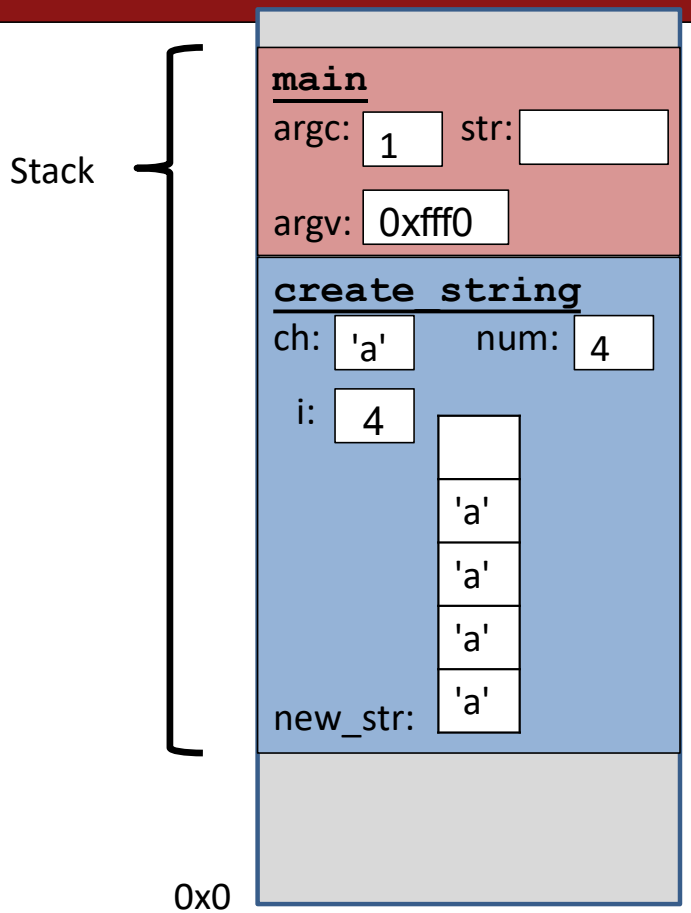

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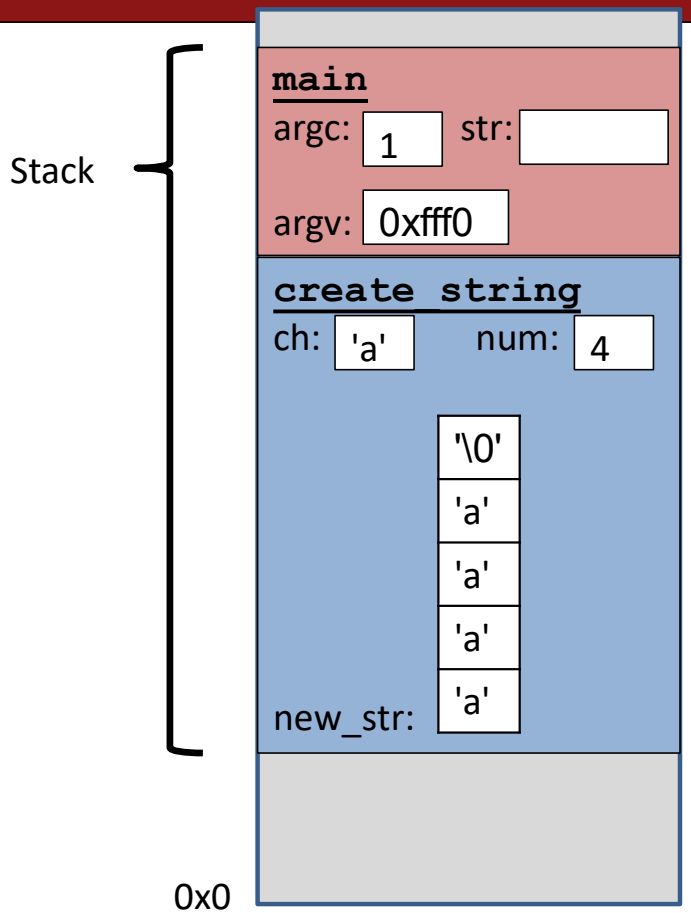

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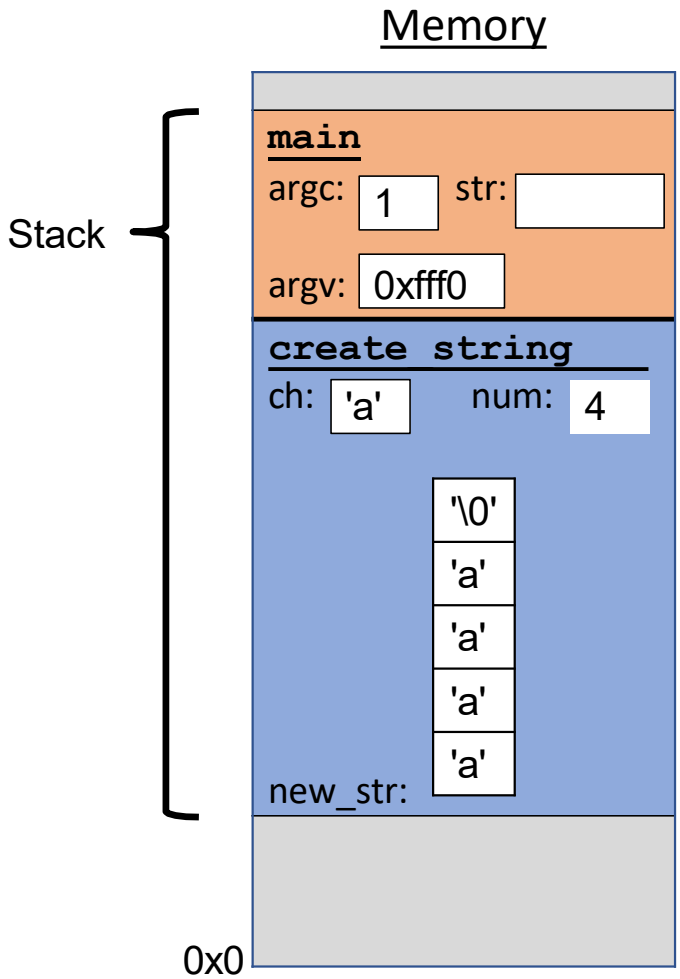

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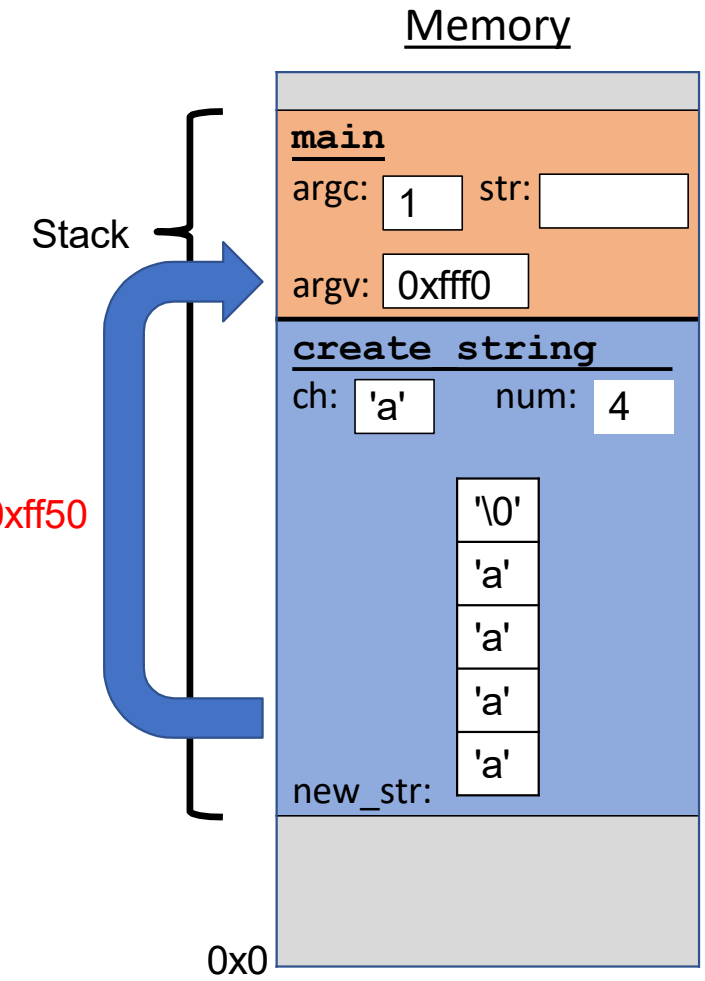

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    return new_str;
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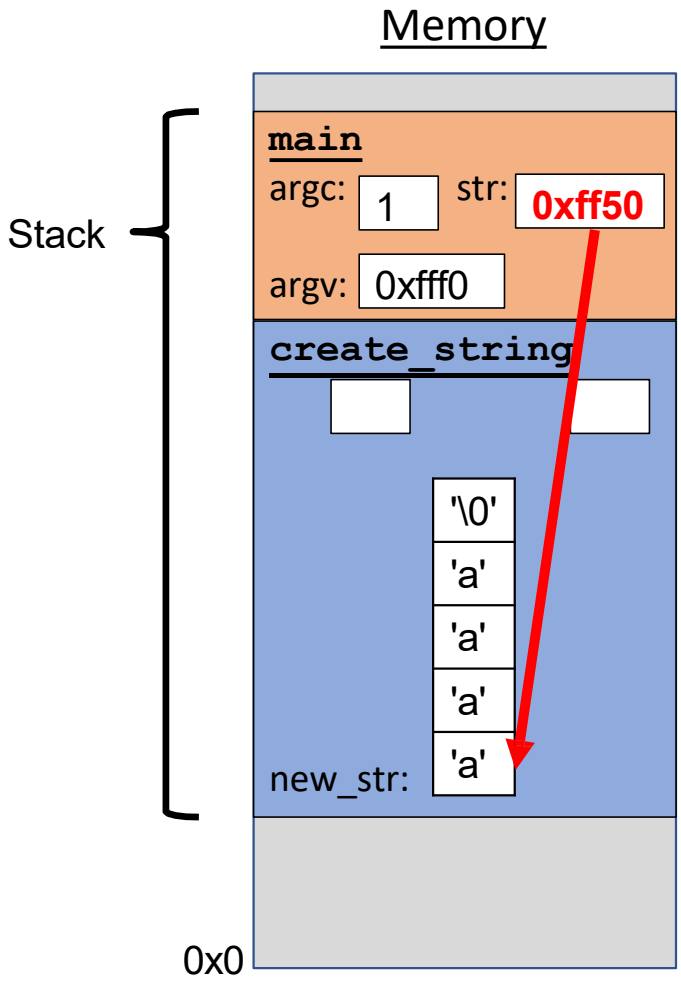

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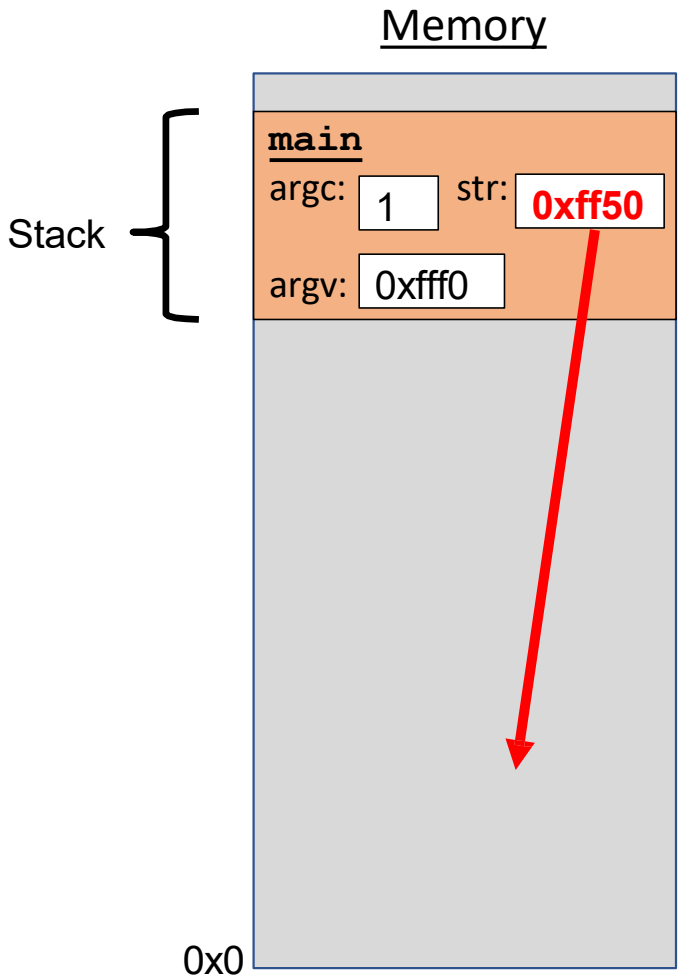

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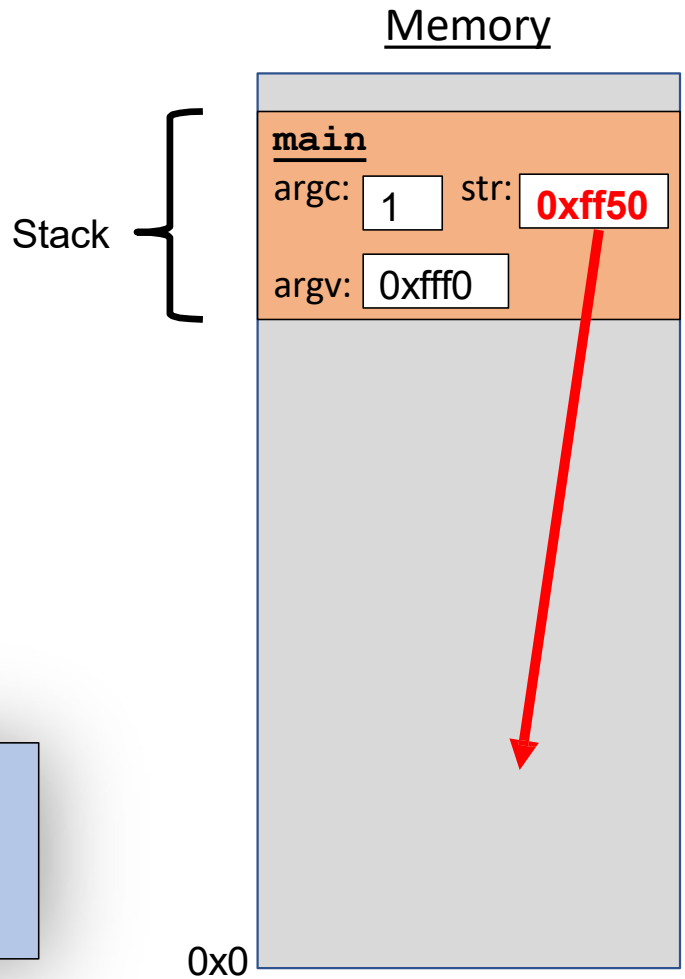
    new_str[num] = '\0';
    return new_str;
}

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

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



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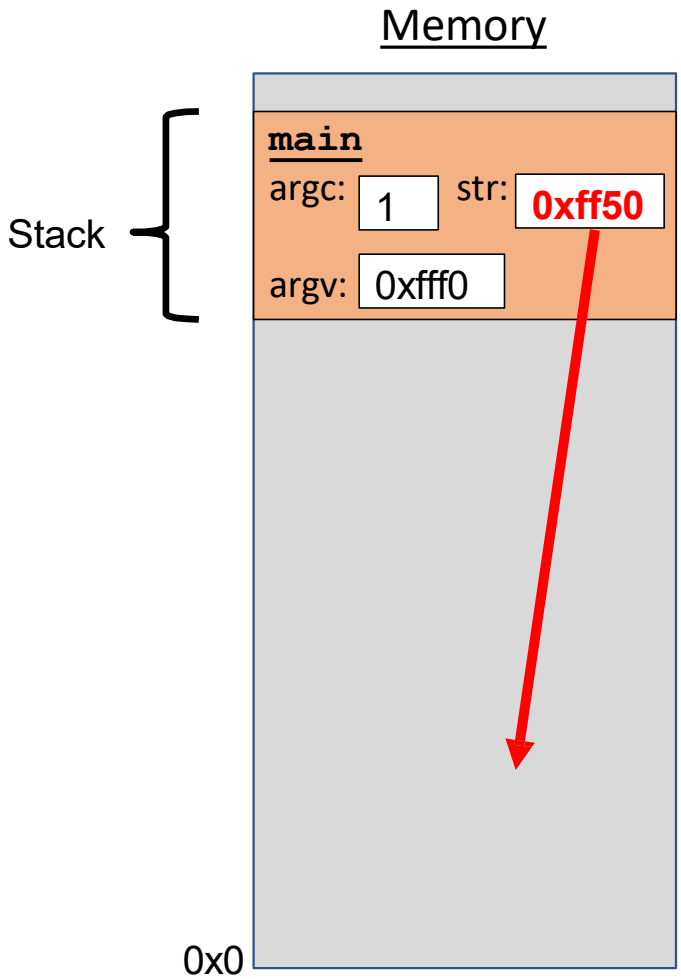

Stacked Against Us

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

Lecture Plan


```
cp -r /afs/ir/class/cs107/lecture-code/lect07 .
```

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);
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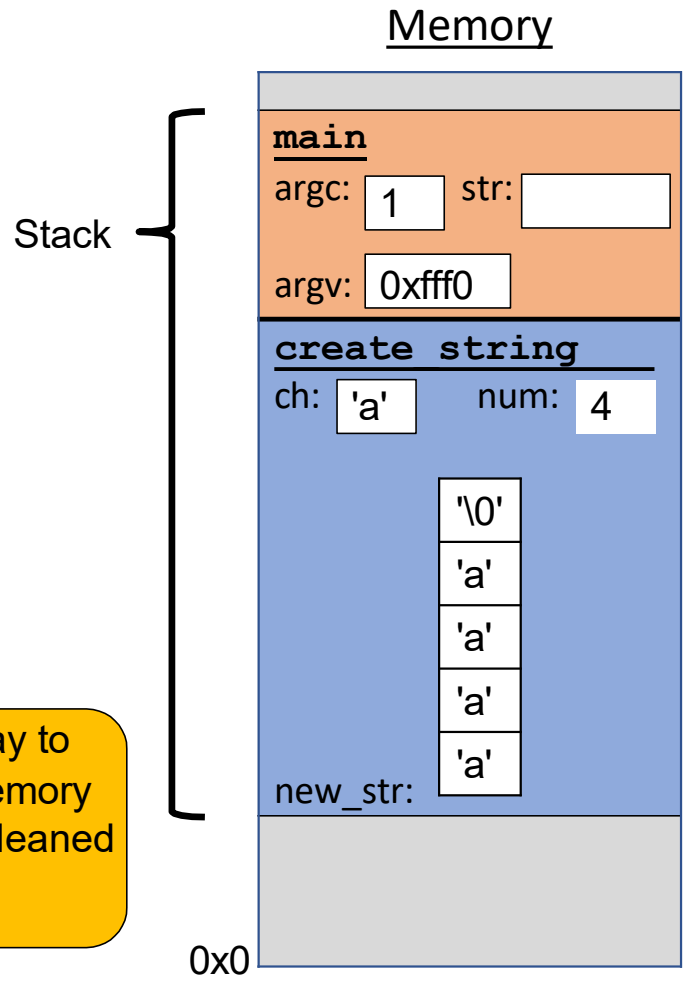
    return 0;
}
```



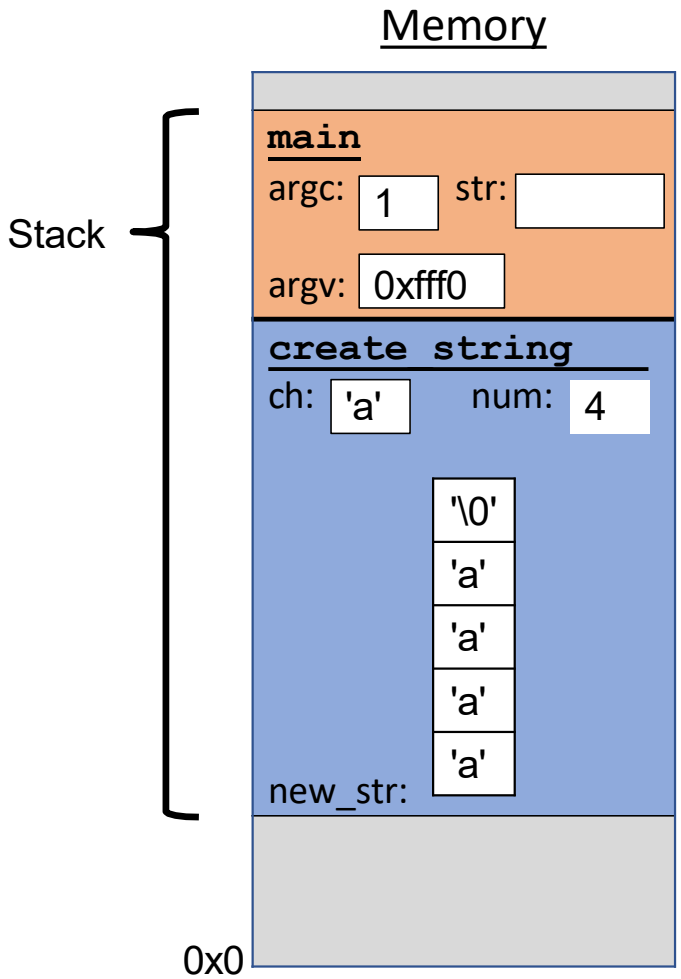
Us: Hey C, is there a way to make this variable in memory that isn't automatically cleaned up?

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;
}

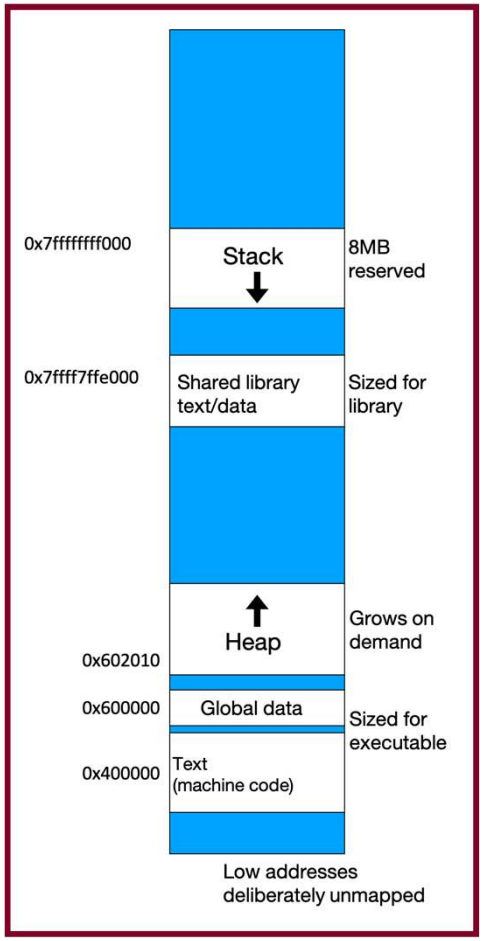
int main(int argc, char *argv[]) {
    char *str = create_string('a', 4);
    printf("%s", str);  // want "aaaa"
    return 0;
}
```

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



The Heap

- 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**.



The Heap

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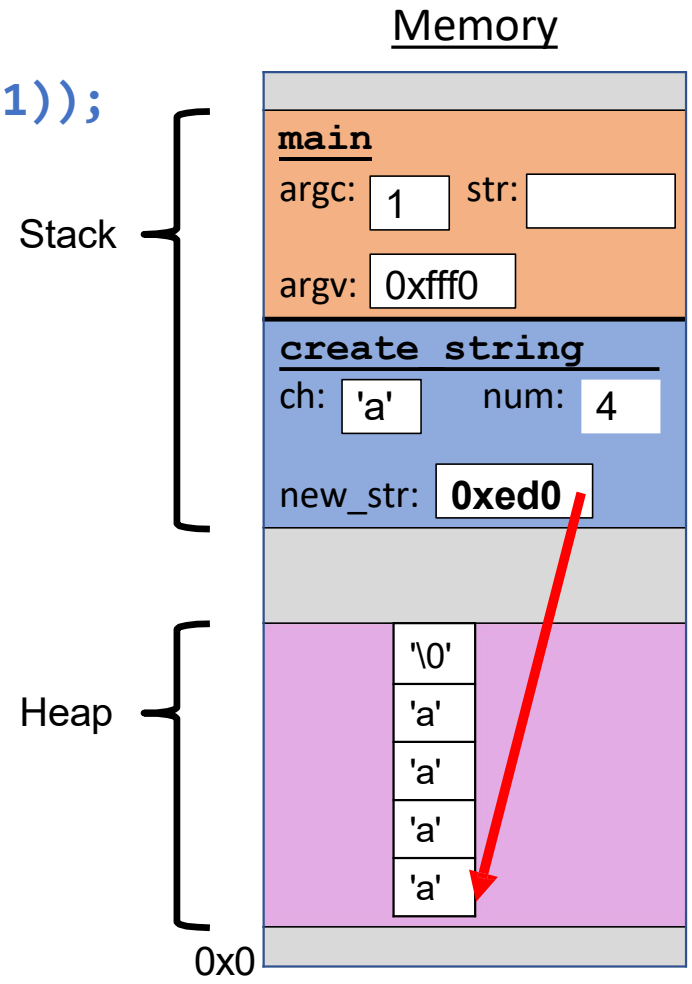

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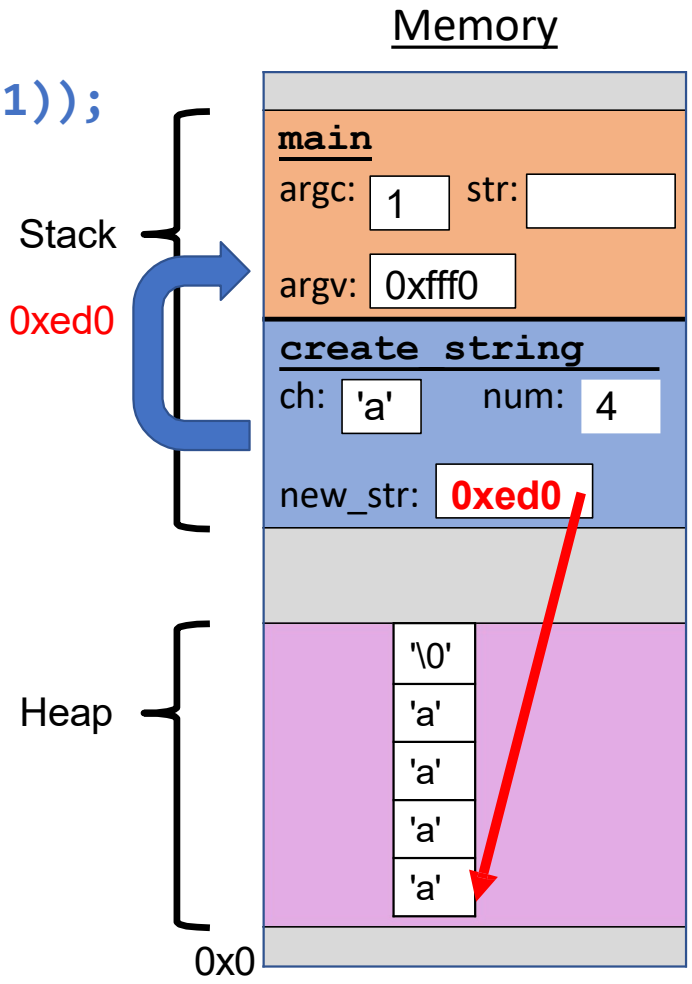

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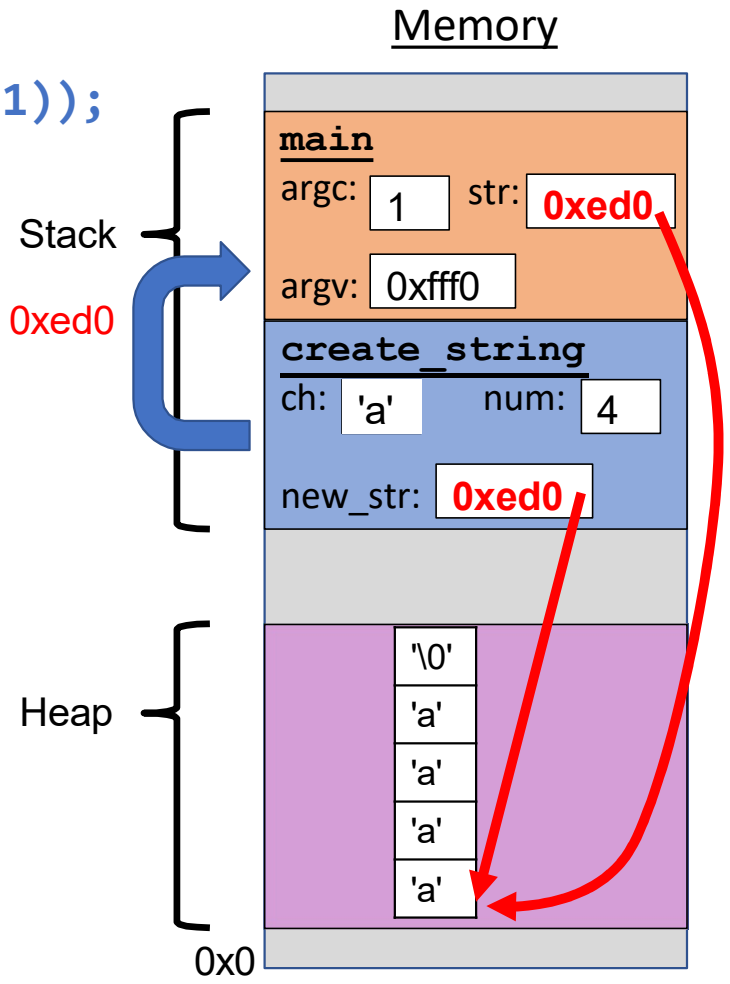

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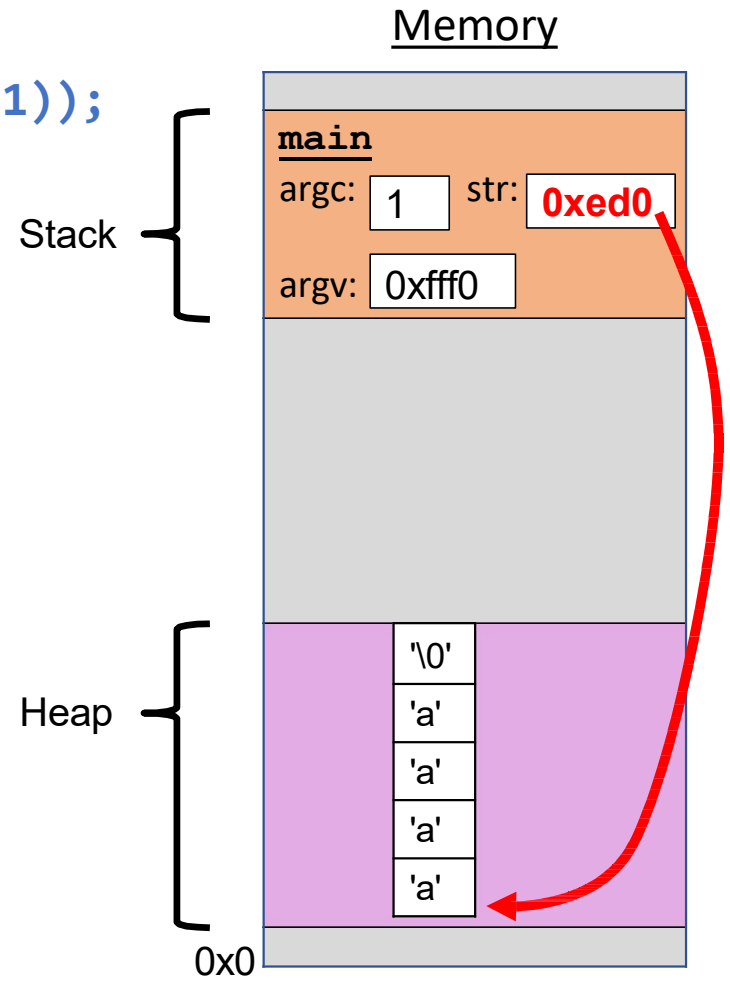

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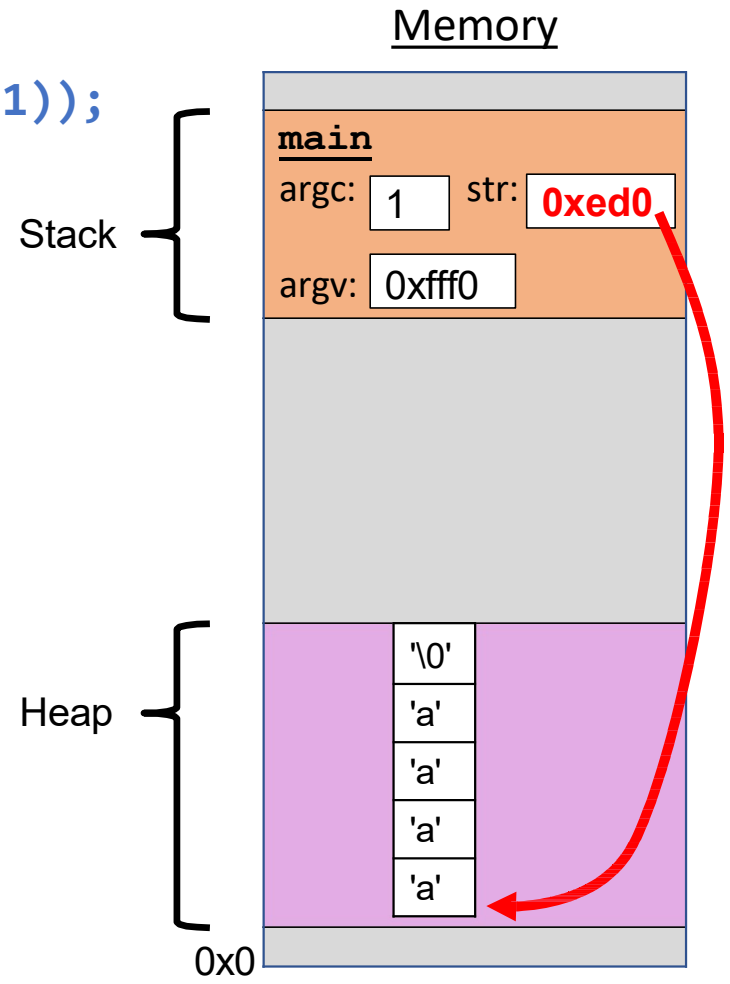

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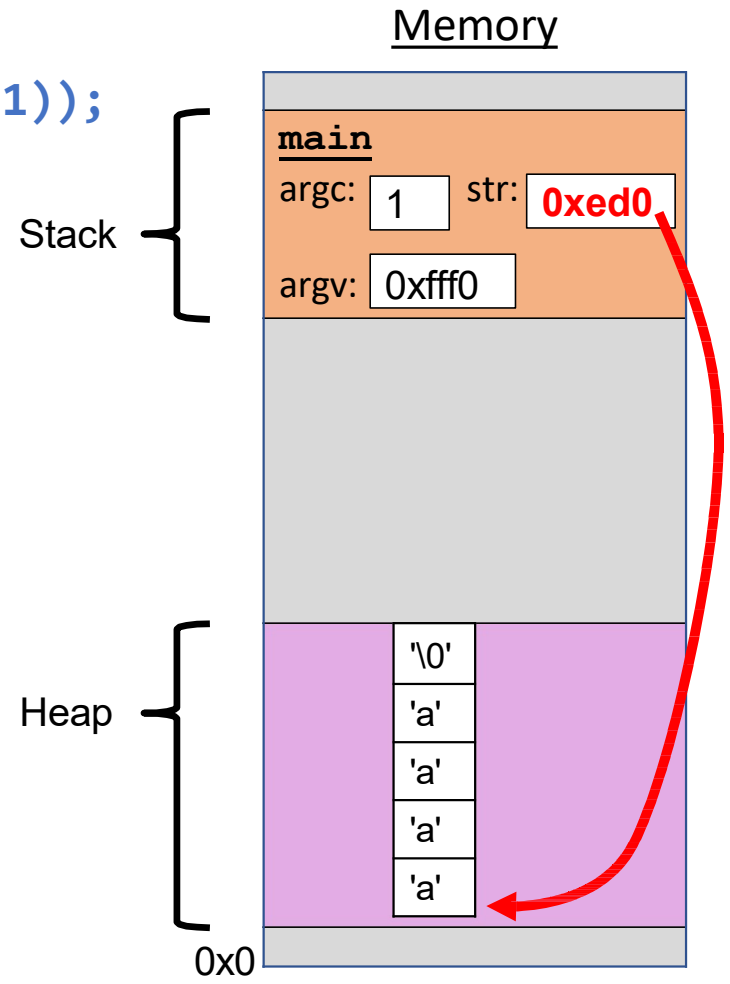

Memory Leaks

- A memory ***leak*** is when you ***allocate*** memory on the heap, ***but*** do ***not free*** it.
- ***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!

Engineering principles: stack vs heap

Stack ("local variables")

- **Fast**
  Fast to allocate/deallocate
- **Convenient**.
  Automatic allocation/ deallocation; declare/initialize in one step
- **Reasonable type safety**
  Thanks to the compiler

⚠ **Not especially plentiful**
Total stack size fixed, default 8MB

⚠ **Somewhat inflexible**
Cannot add/resize at runtime, scope dictated by control flow in/out of functions

Heap (dynamic memory)

Engineering principles: stack vs heap

Stack ("local variables")

- **Fast**
  Fast to allocate/deallocate; okay to oversize
- **Convenient.**
  Automatic allocation/ deallocation; declare/initialize in one step
- **Reasonable type safety**
  Thanks to the compiler
- ⚠ **Not especially plentiful**
  Total stack size fixed, default 8MB
- ⚠ **Somewhat inflexible**
  Cannot add/resize at runtime, scope dictated by control flow in/out of functions

Heap (dynamic memory)

- **Plentiful.**
  Can provide more memory on demand!
- **Very flexible.**
  Runtime decisions about how much/when to allocate, can resize easily with realloc
- **Scope under programmer control**
  Can precisely determine lifetime
- ⚠ **Lots of opportunity for error**
  Low type safety, forget to allocate/free before done, allocate wrong size, etc., Memory leaks (much less critical)

Stack and Heap

- Generally, unless a situation requires dynamic allocation, stack allocation is preferred. Often both techniques are used together in a program.
- Heap allocation is a necessity when:
  - you have a very large allocation that could blow out the stack
  - you need to control the memory lifetime, or memory must persist outside of a function call
  - you need to resize memory after its initial allocation