



CS107 Lecture 09

Stack and Heap

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

Array Trivia: sizeof

When you declare an array, **contiguous memory is allocated on the stack** to store each of its elements.

```
char fruit[6];  
strcpy(fruit, "grape");  
size_t size = sizeof(fruit); // 6
```

The array name (e.g., **fruit**) is not a true pointer. It refers to the entire array.

Here, **sizeof** returns the size of the entire array, in bytes.

That's because the array declaration is in scope at the time the compile-time **sizeof** operation is evaluated.

STACK Address	Value
	...
0x105	'\0'
0x104	'e'
0x103	'p'
0x102	'a'
0x101	'r'
0x100	'g'
	...

fruit {

Array Trivia: sizeof

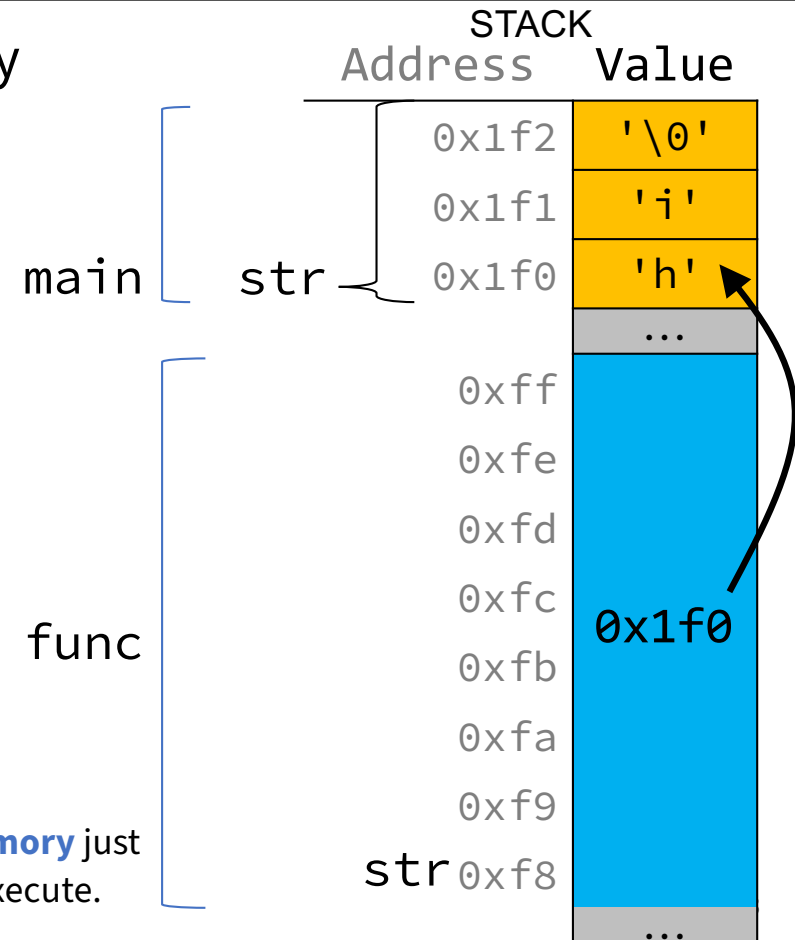
When you pass an **array** as a parameter, C really does pass the address of the first element.

The **amount of memory** set aside for **func's str** is 8 bytes.

```
void func(char *str) {  
    size_t size = sizeof(str); // 8  
    ...  
}  
  
int main(int argc, char *argv[]) {  
    char str[3];  
    size_t size = sizeof(str); // 3  
    strcpy(str, "hi");  
    func(str);  
    ...  
}
```

The **amount of memory** set aside for **main's str** array is 3 bytes.

This is the **state of memory** just as **func** begins to execute.



Array Trivia: Pointer Arithmetic

When applying pointer arithmetic, we **advance a pointer by a certain number of bytes**.

```
char *a = "peach";           // e.g., 0xff0
char *b = str + 1;           // e.g., 0xff1
char *c = str + 3;           // e.g., 0xff3

printf("%s\n", a);           // prints peach
printf("%s\n", b);           // prints each
printf("%s\n", c);           // prints ch
```

READ-ONLY DATA	
Address	Value
	...
0xff5	'\0'
0xff4	'h'
0xff3	'c'
0xff2	'a'
0xff1	'e'
0xff0	'p'
	...

Array Trivia: Pointer Arithmetic

Pointer arithmetic advances a pointer by a **multiple of the pointee type's size**.

The 1, 2, and -1 offsets are **internally scaled** by **sizeof(int)**.

```
int numbers[] = {52, 23, 12, 34, 16, 45};
int *nums0 = numbers;    // shorter name
int *nums1 = nums0 + 1;  // e.g., 0xff4
int *nums3 = nums1 + 2;  // e.g., 0xffc
int *nums2 = nums3 - 1;  // e.g., 0xff8

printf("%d\n", *nums1);    // 23
printf("%d\n", *nums2);    // 12
printf("%d\n", *nums3);    // 34
printf("%zu\n", nums3 - nums1); // 2
```

Because **nums1** and **nums3** are both of type **int ***,
nums3 - nums1 evaluates to the **number of ints that fit in between them**.
Restated, if **nums1 + 2** equals **nums3**, then **nums3 - nums1** better equal 2.

STACK	
Address	Value
	...
0x1004	45
0x1000	16
0xffc	34
0xff8	12
0xff4	23
0xff0	52
	...

CS107 Topic 3: Stack and Heap Memory

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

Why is answering this question useful?

- Illustrates how we can **efficiently pass data around using pointers**
- Illustrates how to construct data structures that **live longer than the function calls that create them**.

Learning goals:

- Understand the differences between **stack and heap memory** and **when to choose one over the other**.
- Become **fluent** in **malloc**, **free**, and **realloc** as standard C language directives used to **manage heap memory**.

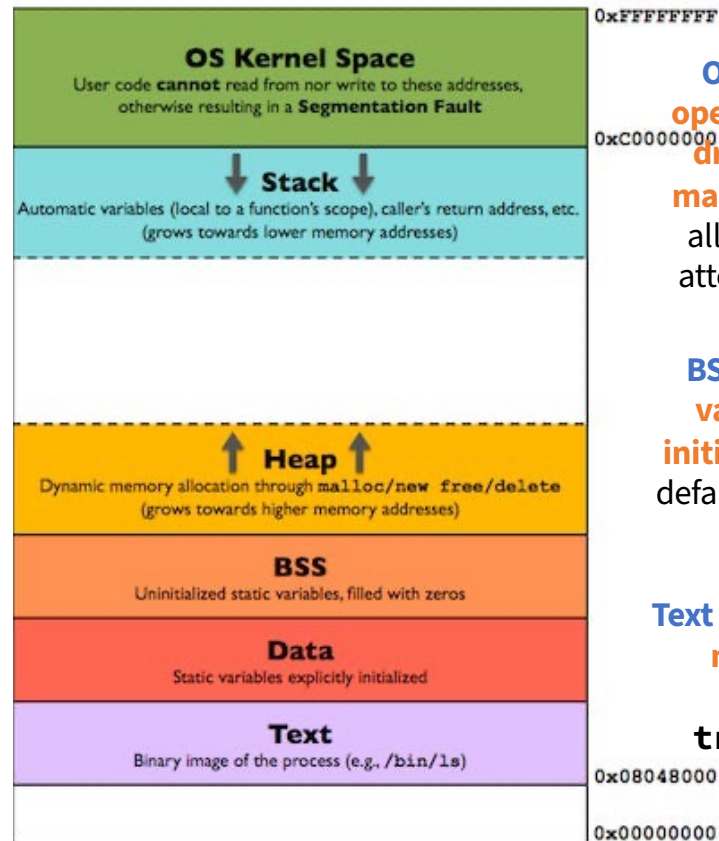
CS107 Topic 3: Stack and Heap Memory

this week's focus

Stack segment: Used for **function calls, local variables, and return addresses**. It typically occupies higher memory addresses and grows downwards towards the heap as it expands.

Heap segment: Used for **dynamic memory allocation** (e.g., via **malloc** in C, **new** in C++) and grows upwards towards higher addresses.

Data segment: Used to **store explicitly initialized global variables and constant**, including the string constants used throughout your code (e.g., **"apple"**, **"peach"**, **"rutabaga"**, **"absquatulation"**).



OS Kernel region: Used for the **operating system's kernel, device drivers, and low-level memory management code**. Your code isn't allowed to access this region and attempts to do so result in a crash.

BSS segment: Used for all **global variables that aren't explicitly initialized** before **main** is called. By default, all bytes in this segment start out as zeroes.

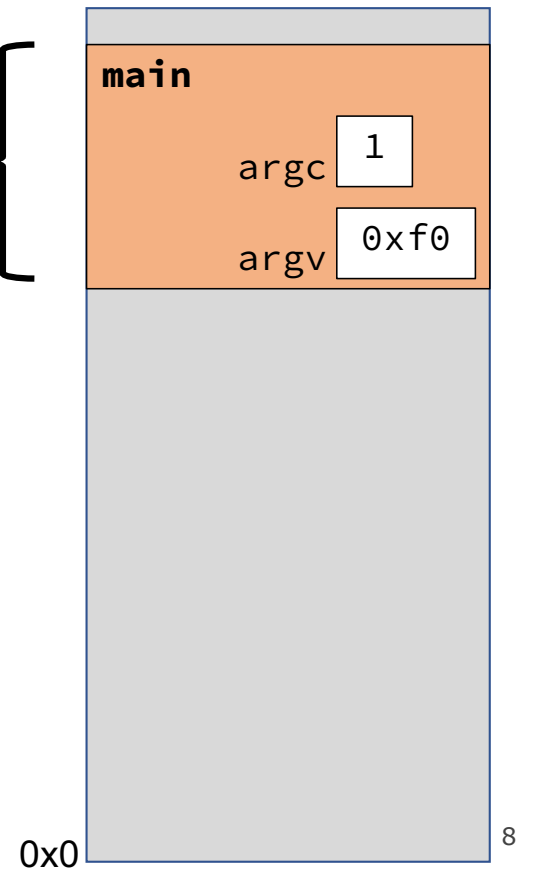
Text segment: Contains the **compiled machine code** of the running executable, like **ls**, **emacs**, **triangle**, **sat**, or **automata**.

Stack Segment Case Study

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stack

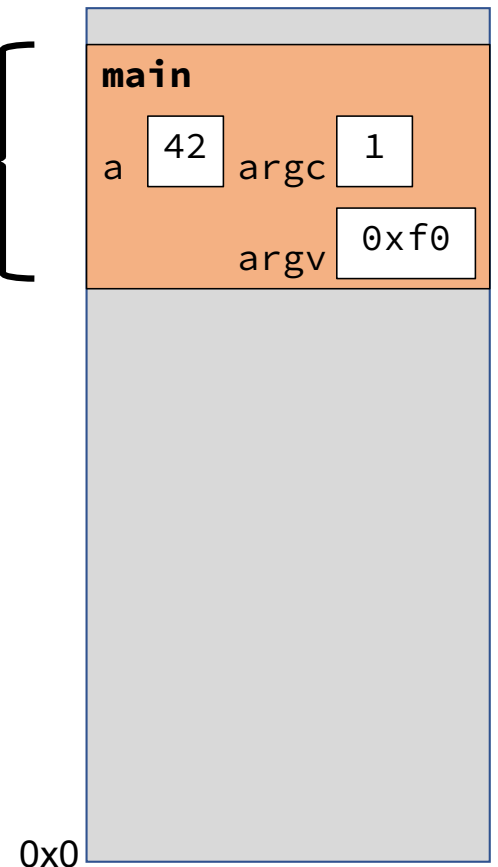


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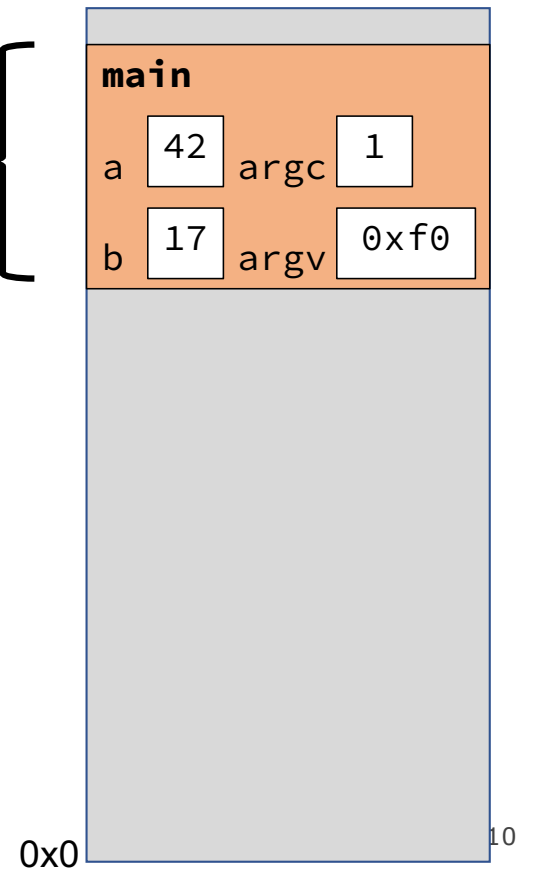


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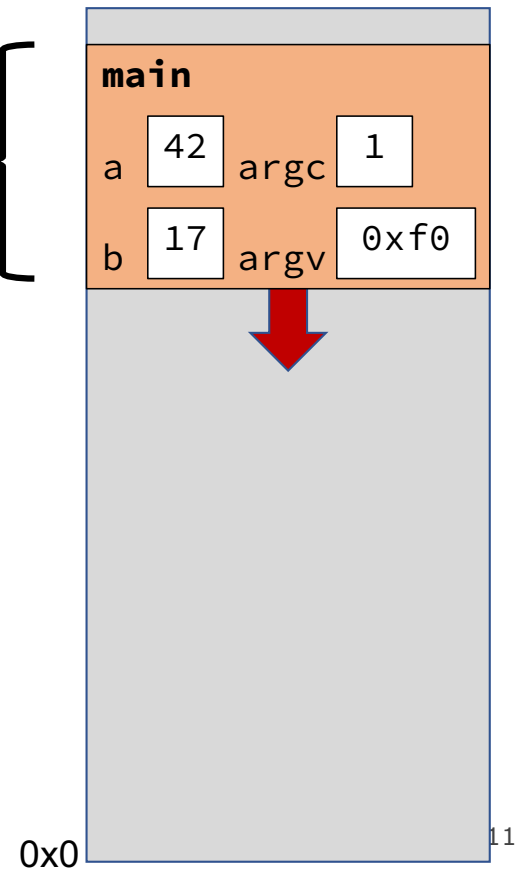


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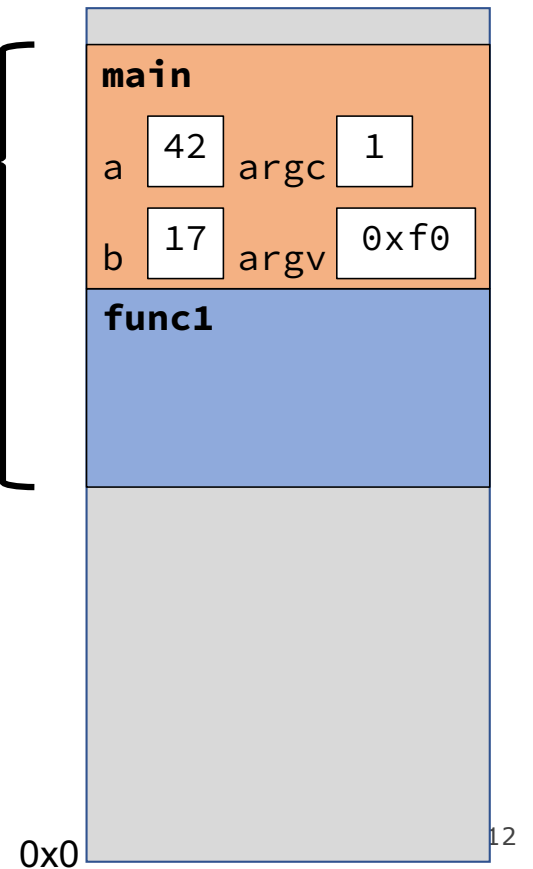


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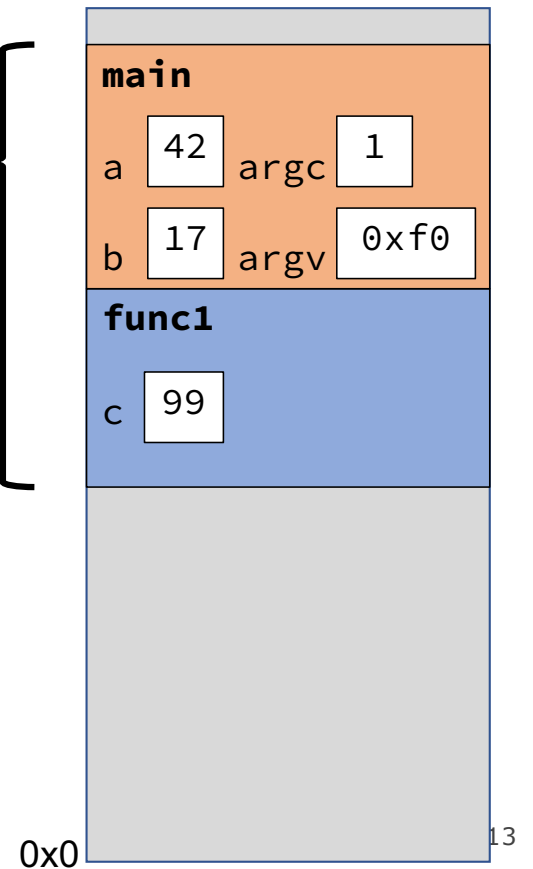


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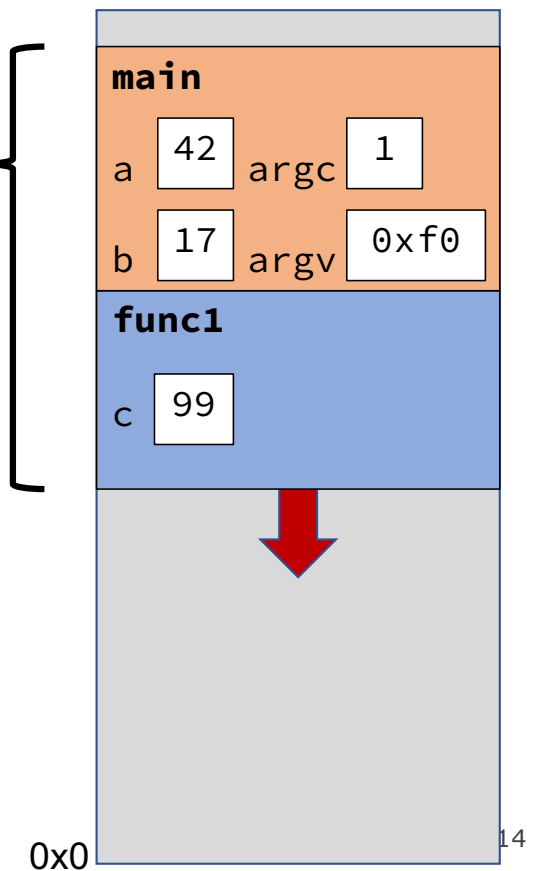


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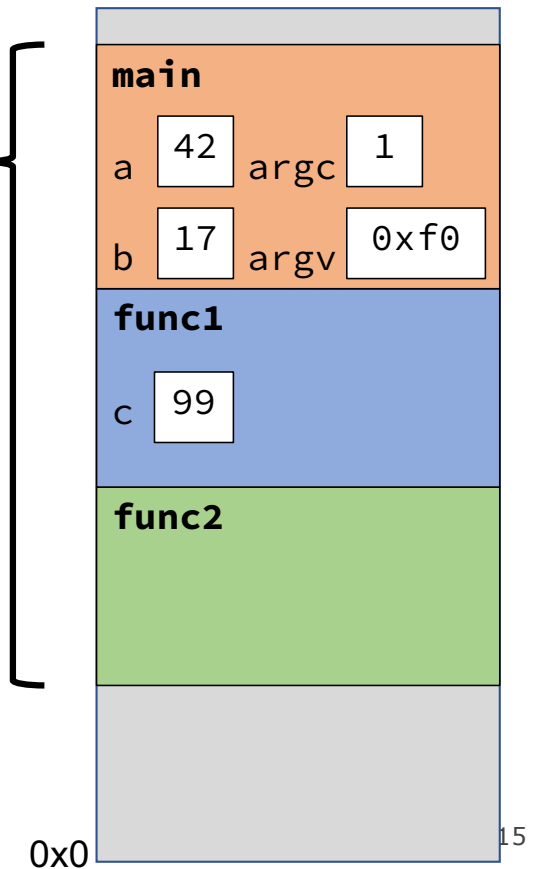


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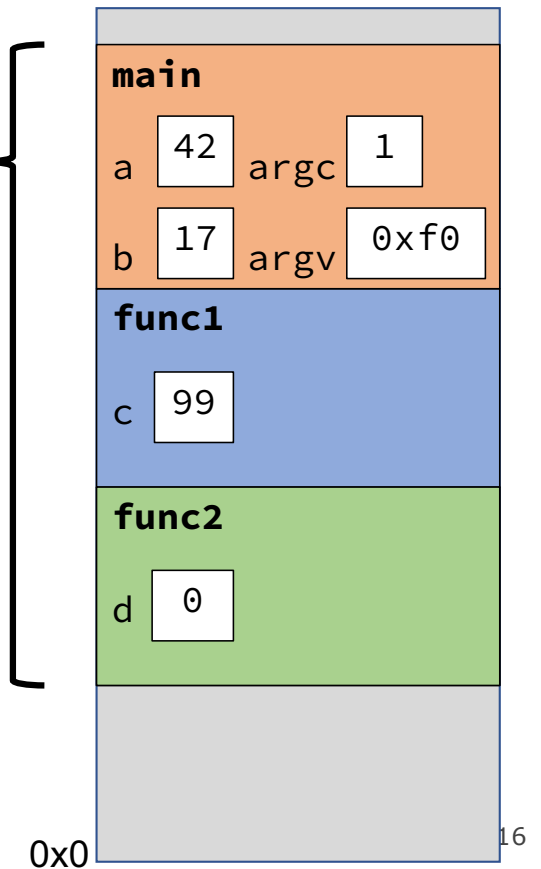


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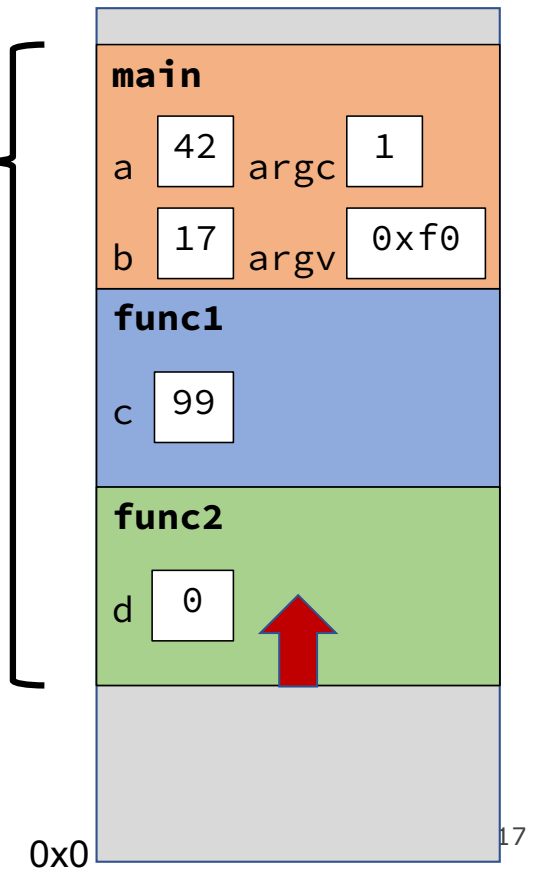


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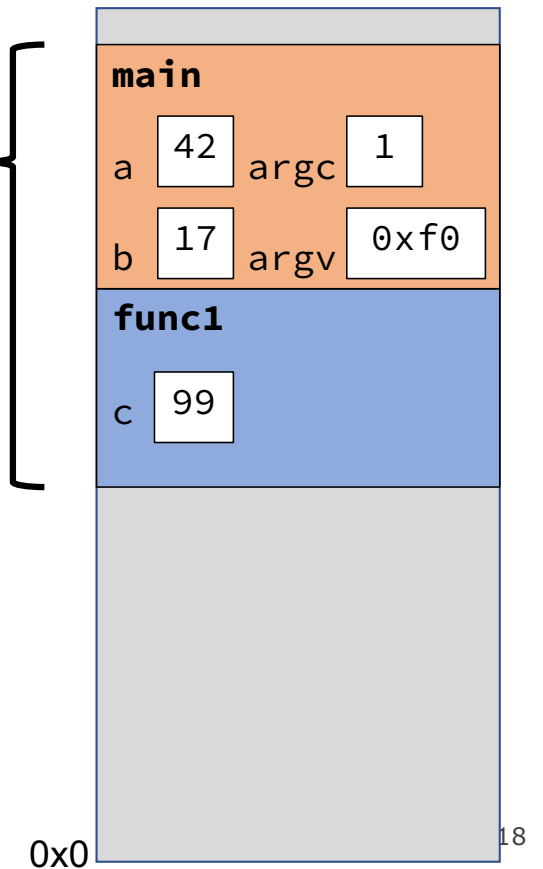


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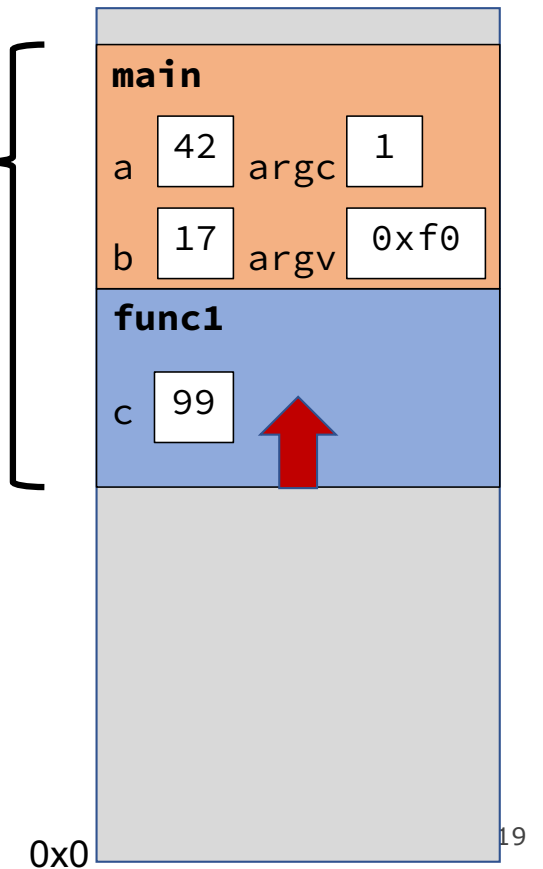


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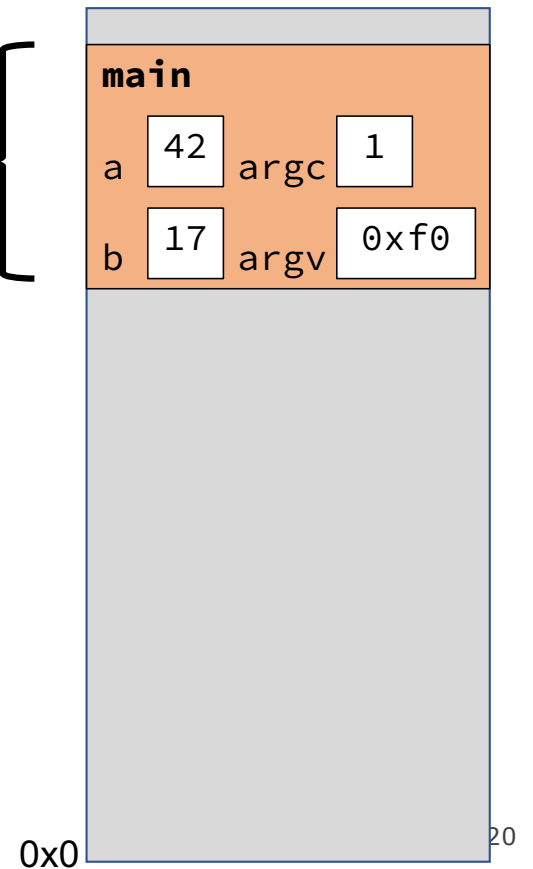


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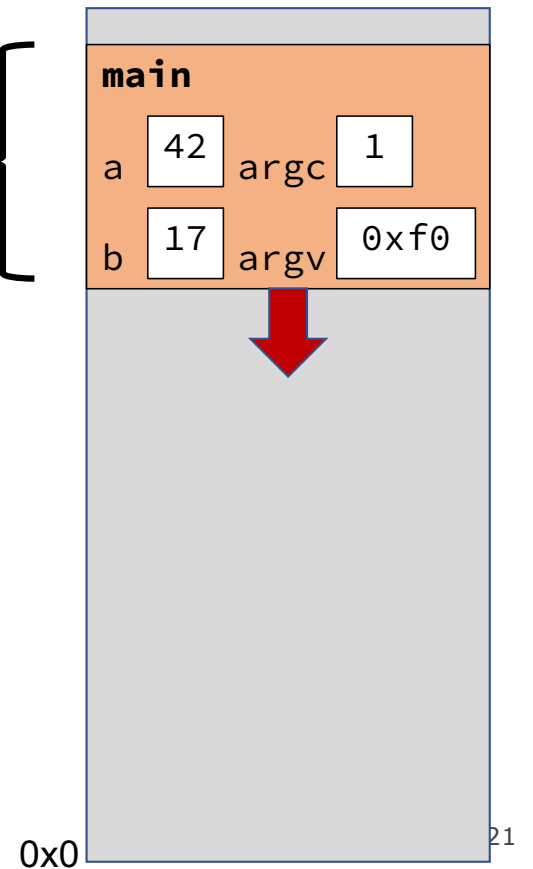


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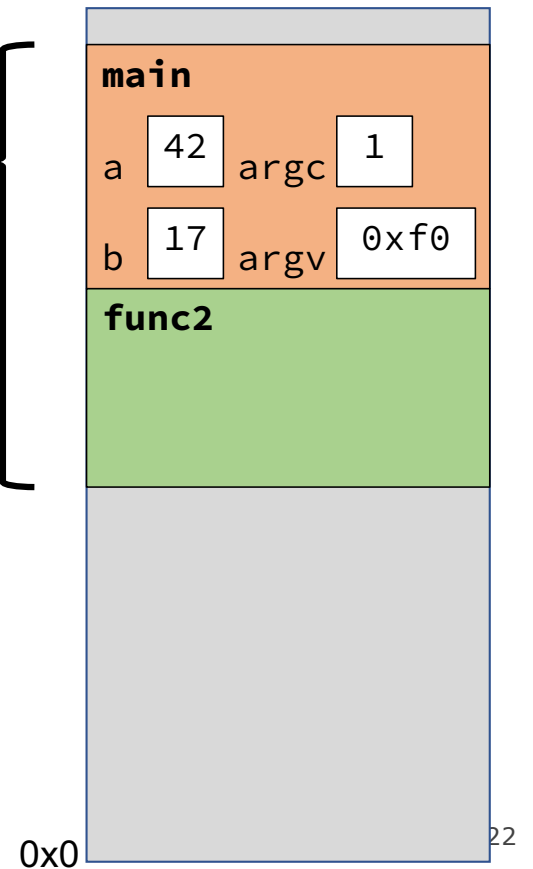
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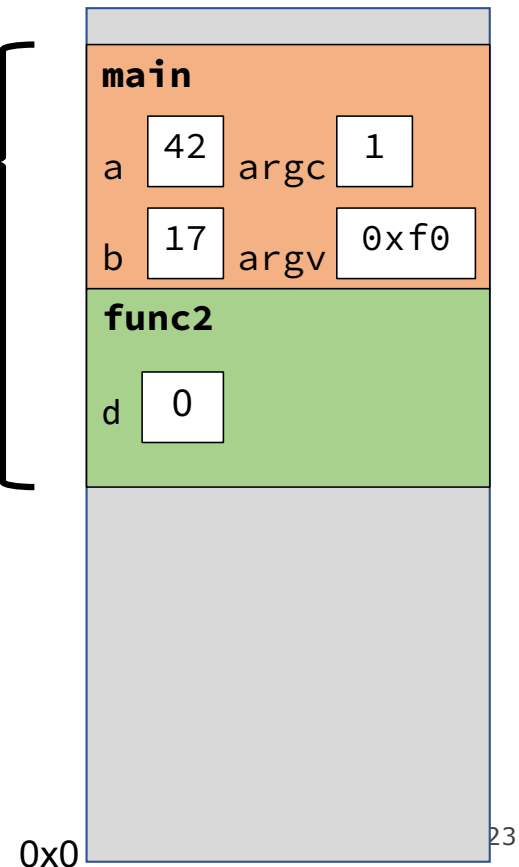
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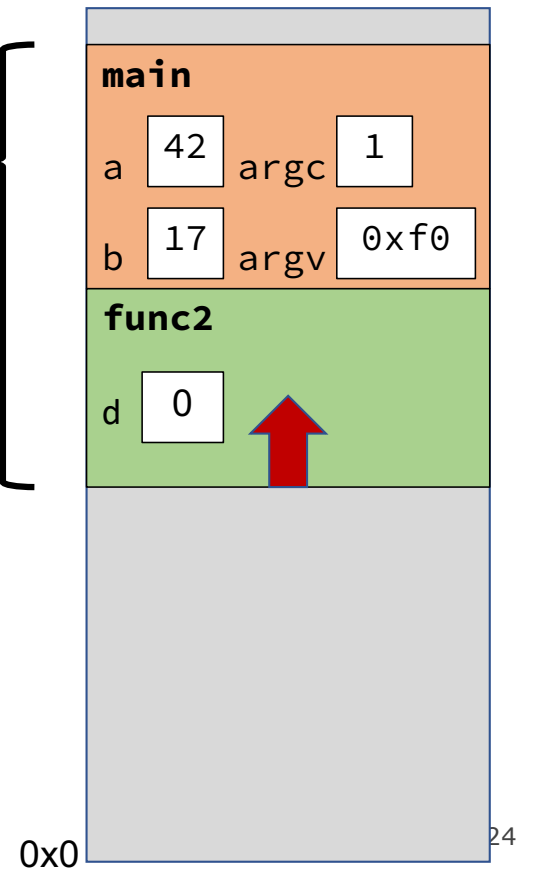
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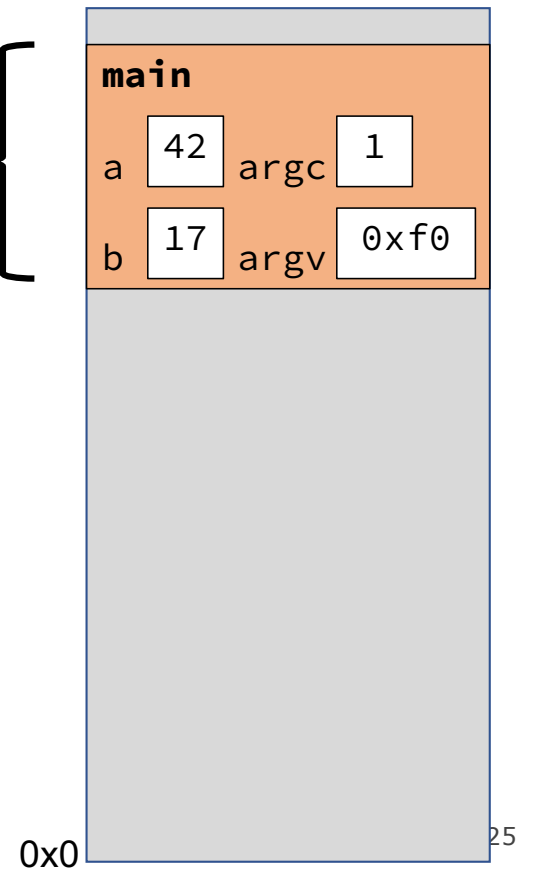


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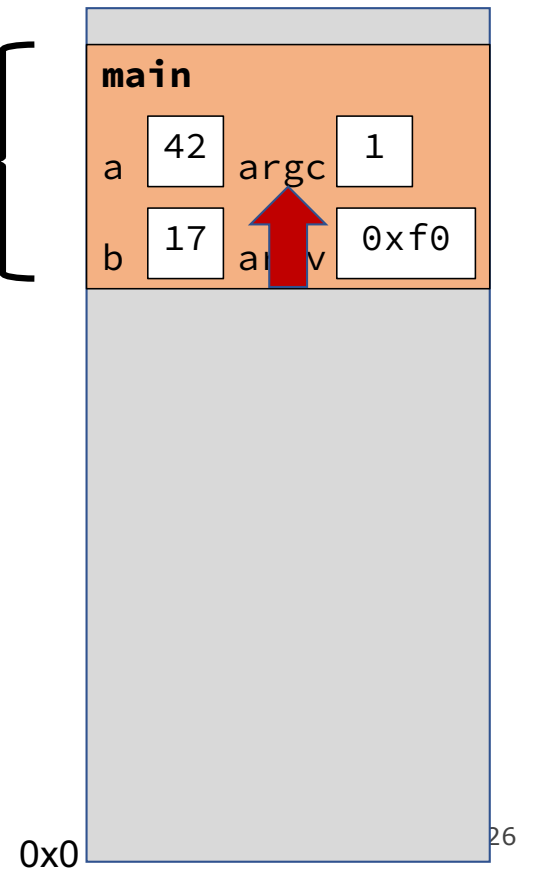


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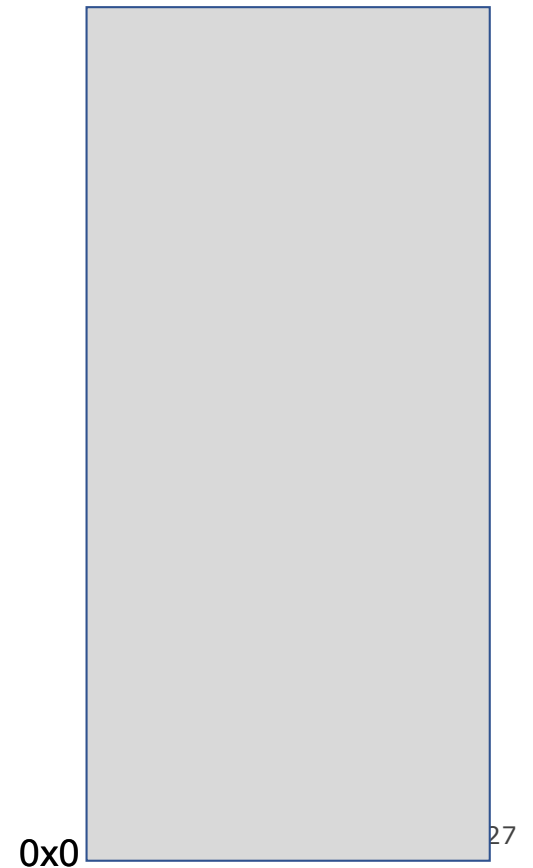
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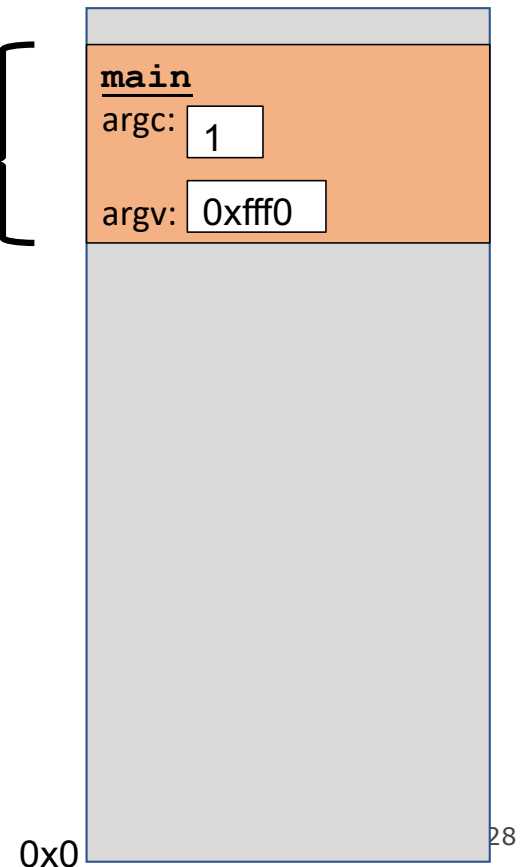


Stack Segment Case Study: Mayday, Mayday

Here's a **well-intentioned** (but **broken**) **program** that relies on a **(broken)** helper function to **create a string of repeated characters**.

```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (size_t 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\\n", str); // want to print aaaa  
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stack

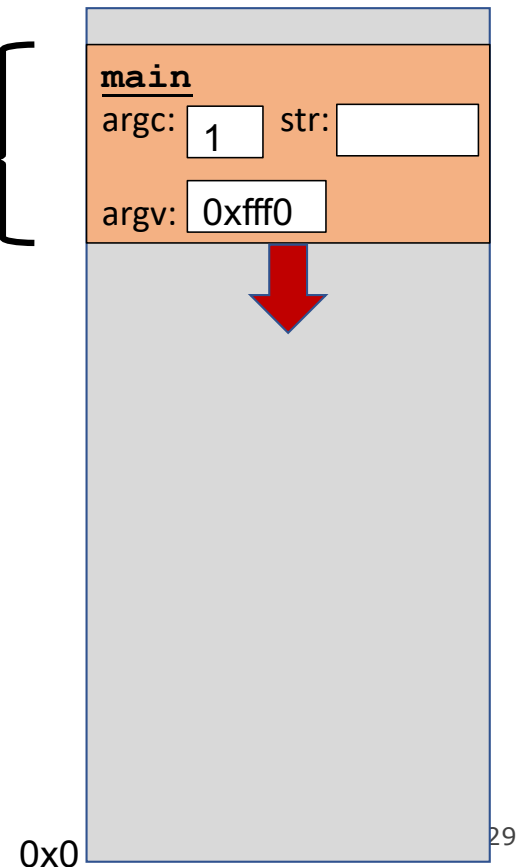


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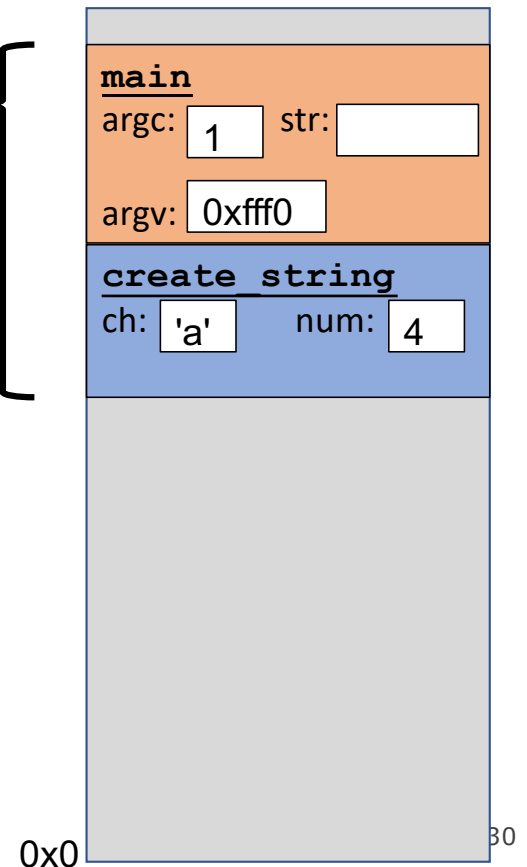


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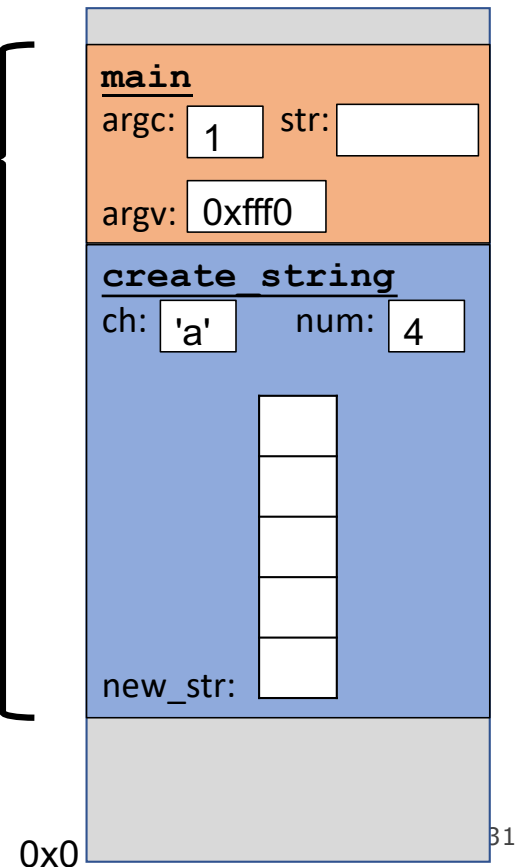


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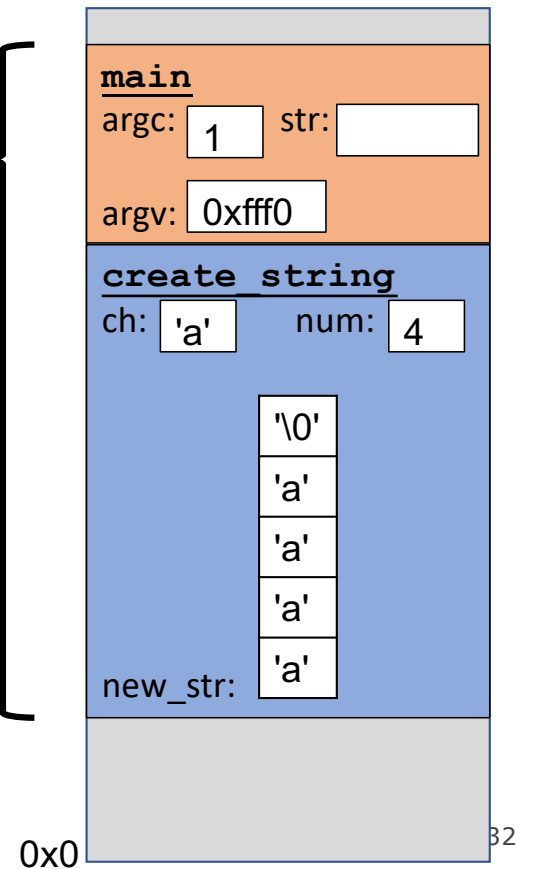


Stack Segment Case Study: Mayday, Mayday

Here's a **well-intentioned** (but **broken**) **program** that relies on a **(broken)** helper function to **create a string of repeated characters**.

```
char *create_string(char ch, int num) {  
    char new_str[num + 1];  
    for (size_t 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\n", str); // want to print aaaa  
    return 0;  
}
```

stack



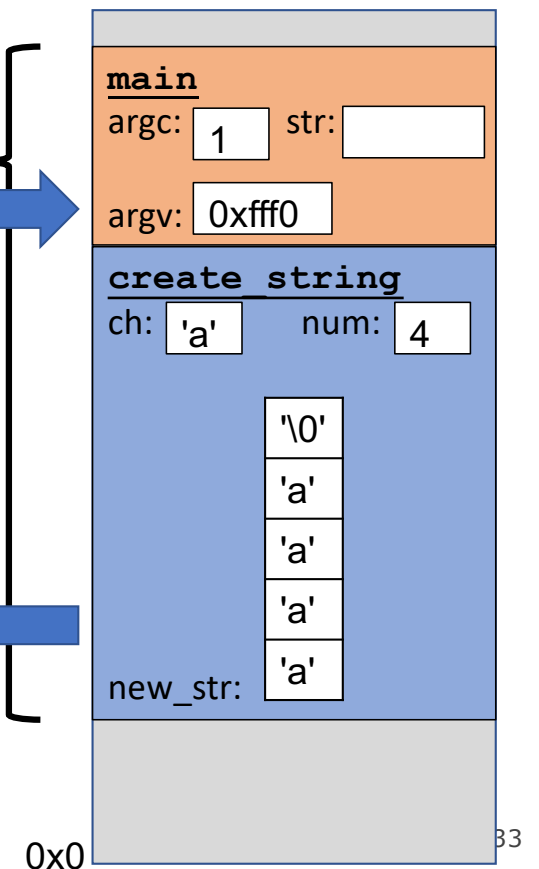
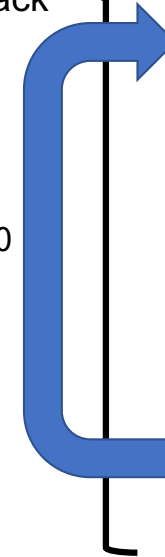
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```

returns e.g., 0xff50

stack

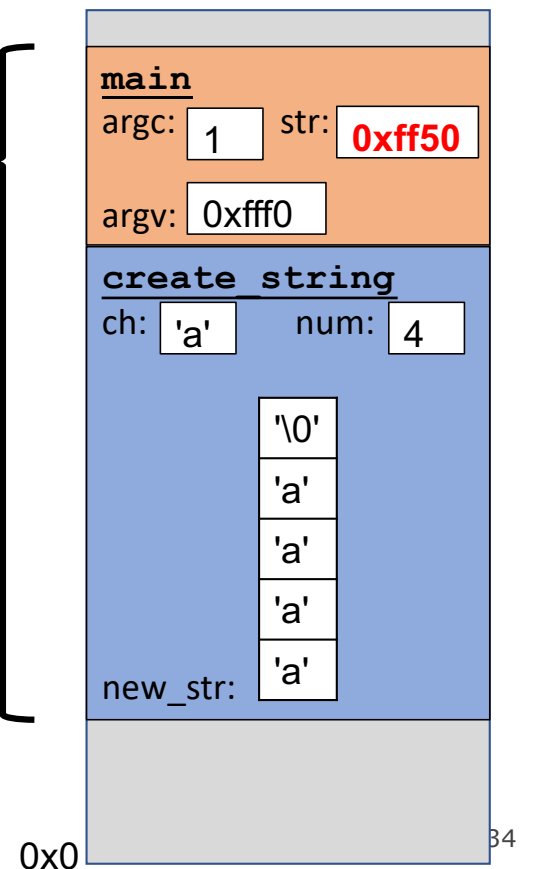


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```

stack



Stack Segment Case Study: Mayday, Mayday

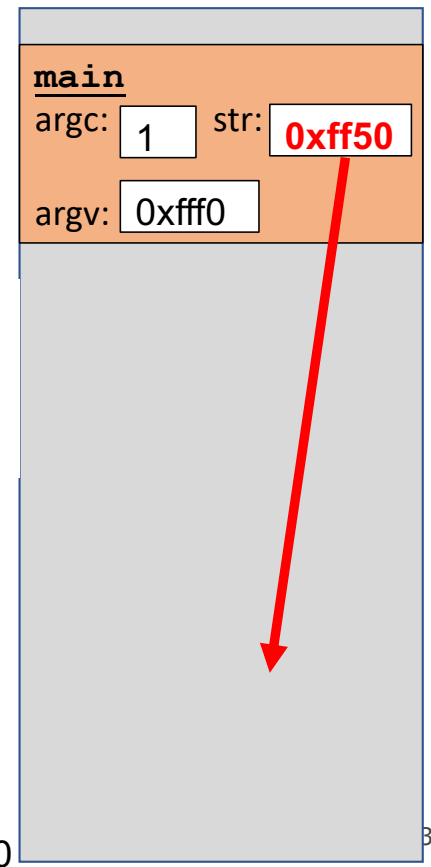
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}
```

Defcon 1: Local variables **disappear** when the function returns. These four **a**'s are **embedded in a local array that no longer exists**, so **str** is **not our address to dereference**.

In some cases, the array can be **pre-allocated on the stack** using **size information computed at runtime**. But that's **not ideal** if it requires an **inelegant restructuring of the code**.



Introducing malloc

Much as C++ allows you to via its **operator new**, C allows you to **dynamically allocate memory** using **operator new**'s equivalent: **malloc**

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

- **malloc** expects the **number of raw bytes** that should be allocated from the heap.
- **malloc** returns the **base address** of the freshly allocated memory.
 - **malloc** doesn't **know or care** if the memory is to be used as an **array**, a record, or something else.
- The return type is a **void *** to denote an address to **generic (i.e., type-less) memory**.
 - You can set another pointer equal to it without casting.

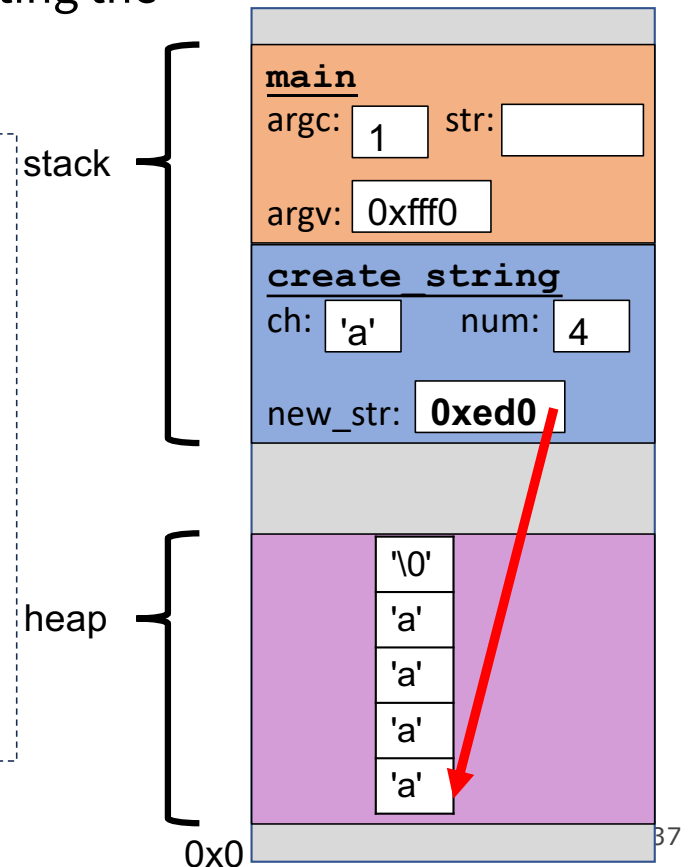
Examples:

```
int *arr = malloc(n * sizeof(int));  
char *t = malloc(strlen(s) + 1);  
node *n = malloc(sizeof(node));
```

Stack Segment Case Study: malloc Heals

Here's a **working version** that repairs the problem by allocating the new string on the heap using **malloc**.

```
char *create_string(char ch, int num) {  
    char *new_str = malloc(num + 1);  
    assert(new_str != NULL);  
    for (size_t i = 0; i < num; i++) {  
        new_str[i] = ch;  
    }  
    new_str[num] = '\0';  
    return new_str;  
}  
  
int main(int argc, char *argv[]) {  
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    return 0; // should free str, will soon  
}
```

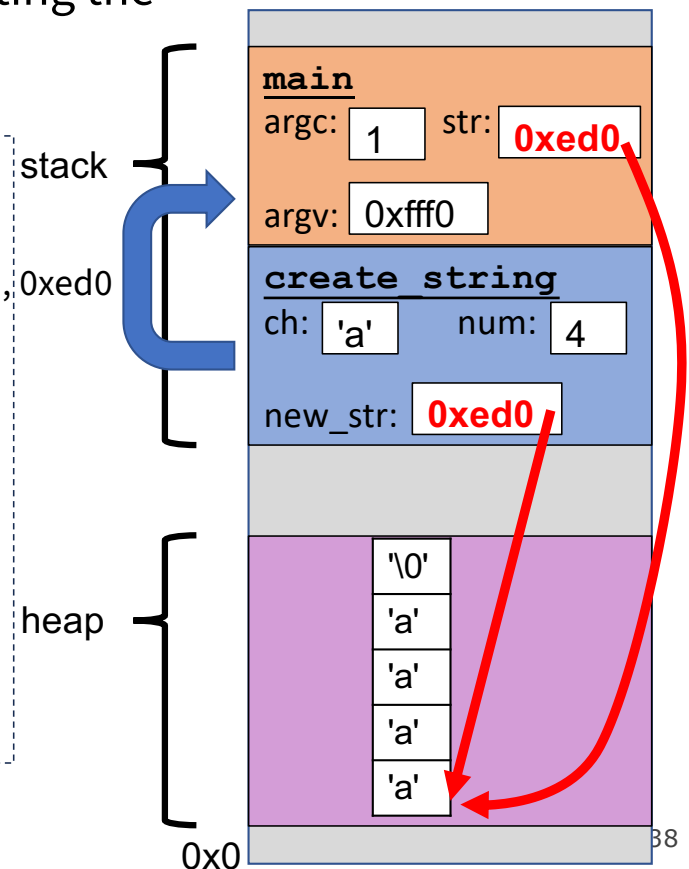


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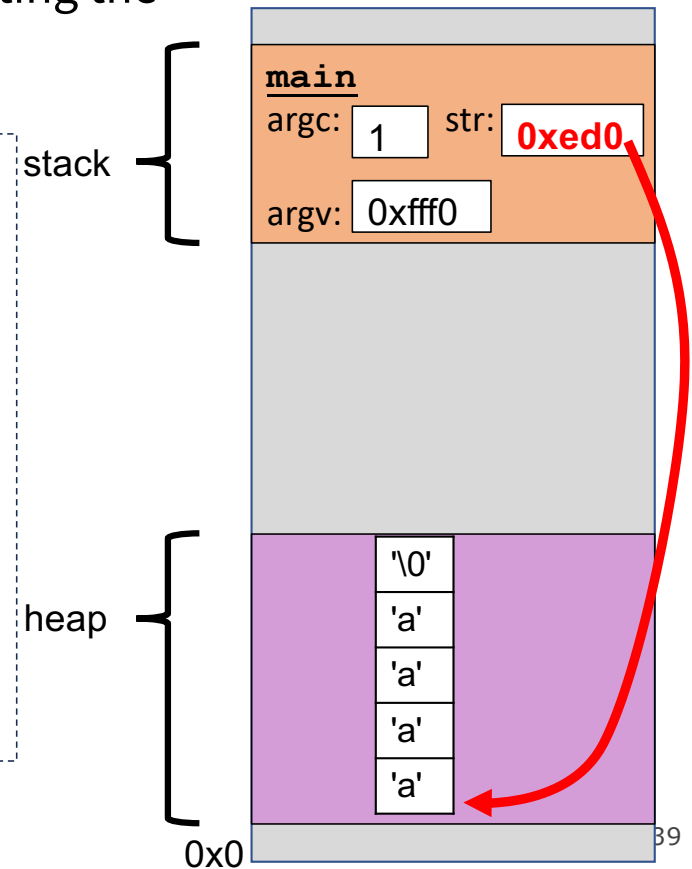
returns e.g., 0xed0



Stack Segment Case Study: malloc Heals

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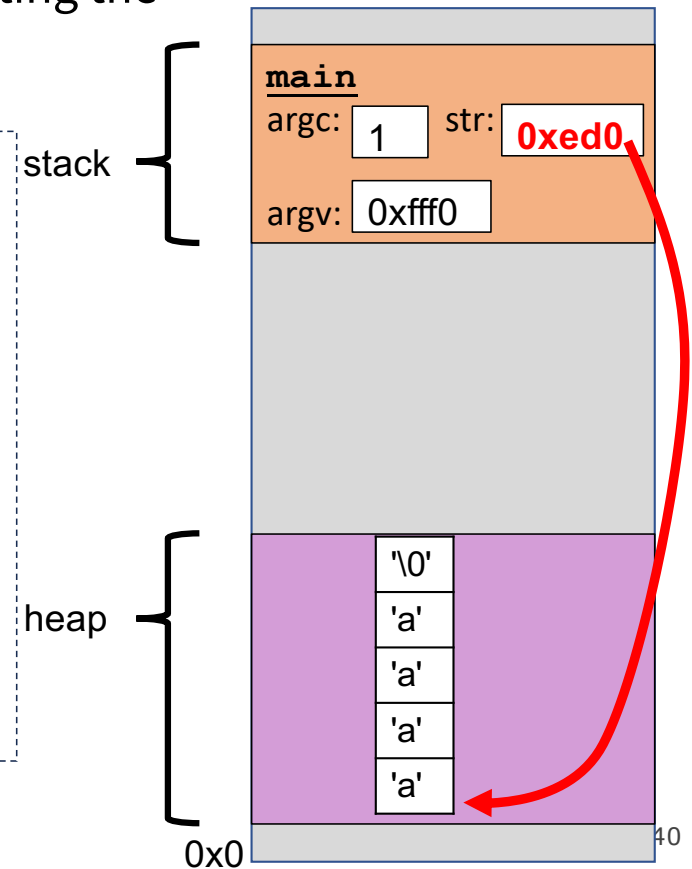
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Stack Segment Case Study: malloc Heals

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}
```



Dynamic Memory Etude

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

```
int *array_of_multiples(int mult, int len) {  
    /* TODO: arr declaration here */  
  
    for (size_t i = 0; i < len; i++) {  
        arr[i] = mult * (i + 1);  
    }  
    return arr;  
}
```

Declare a pointer to **catch the heap-based address returned** by **malloc**.

Ensure **malloc**'s argument is the **number of bytes** needed to fulfill the allocation request.

CS107 policy: assert the address is non-**NULL**.

How should we declare and initialize **arr**?

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



Dynamic Memory Etude

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        arr[i] = mult * (i + 1);  
    }  
    return arr;  
}
```

If an allocation error occurs (e.g., the process is **out of heap memory** or the heap has been **corrupted by flawed heap management**), **malloc** might return **NULL**.

assert will **intentionally terminate the program** if the condition evaluates to **false**. Memory allocation errors are a big deal, and we should end the program the moment we see them. Otherwise, your program will proceed and likely crash in a much more anonymous manner that might not be easily traced back to a failed **malloc** call.

In practice, you **never ship code** with active **assert** statements, but they are used during the development process to **verify that certain expectations are being met** and minimize the chances of runtime surprises. (The **assert** statements can be stripped out of the executable pretty easily during compilation.)

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When Heap-Based Allocation Makes Sense

Here are **four common scenarios** where dynamic memory allocation is preferable to stack allocation:

- **When memory must **outlive** the current function call**
Heap-based memory persists beyond the function call allocating it, unlike stack variables whose lifetime ends when the allocating function returns.
- **When building **flexible or resizable data structures****
Linked lists, trees, hash tables, and dynamically expanding arrays require memory that can be allocated, reallocated, and freed on demand.
- **When the size required is very **large or not easily predicted****
Larger arrays and data structures can exhaust the entire stack segment, whereas the heap segment can manage much larger allocations.
- **When data must be **shared across multiple functions or modules****
Heap memory allows multiple parts of a program to reference and modify the same data without copying, and that data isn't easily allocated in the **main** function.

Other heap allocators: calloc, strdup

void *calloc(size_t count, size_t size);

calloc is a **heap allocation function** just like **malloc**, with one important extra guarantee—it **zeroes out the memory** before it returns.

Examples:

```
int *counts = calloc(26, sizeof(int)); // all zeroes
bool *answers = calloc(n, sizeof(bool)); // all falses
struct node ** = calloc(num_buckets, sizeof(struct node *)); // all NULLs
```

char *strdup(const char *str);

strdup is a convenience function for **duplicating C strings onto the heap**.

Example:

```
char *news = strdup("disinformation");
news[0] = 'm';
char *british = strdup("disorganization");
british[9] = 's';
```

Like anything created using **malloc**, anything created using **calloc** or **strdup** **should be freed** when it's no longer needed. Again, soon!

Cleaning Up with free

void free(void *ptr);

free accepts an address previously returned by **malloc**, **calloc**, **strdup**, or (the soon to be discussed) **realloc** and donates the memory there back to the heap.

Simple Example:

```
char *earth = strdup("earth");
char *quake = strdup("quake");
char *earthquake = malloc(strlen(earth) + strlen(quake) + 1);
strcpy(earthquake, earth);
free(earth);
strcat(earthquake, quake);
free(quake);
printf("%s\n", earthquake);
free(earthquake); // three allocations reverted by three frees
```

When you **fail to free heap memory** you no longer need before letting go of it, you **leak** that memory.