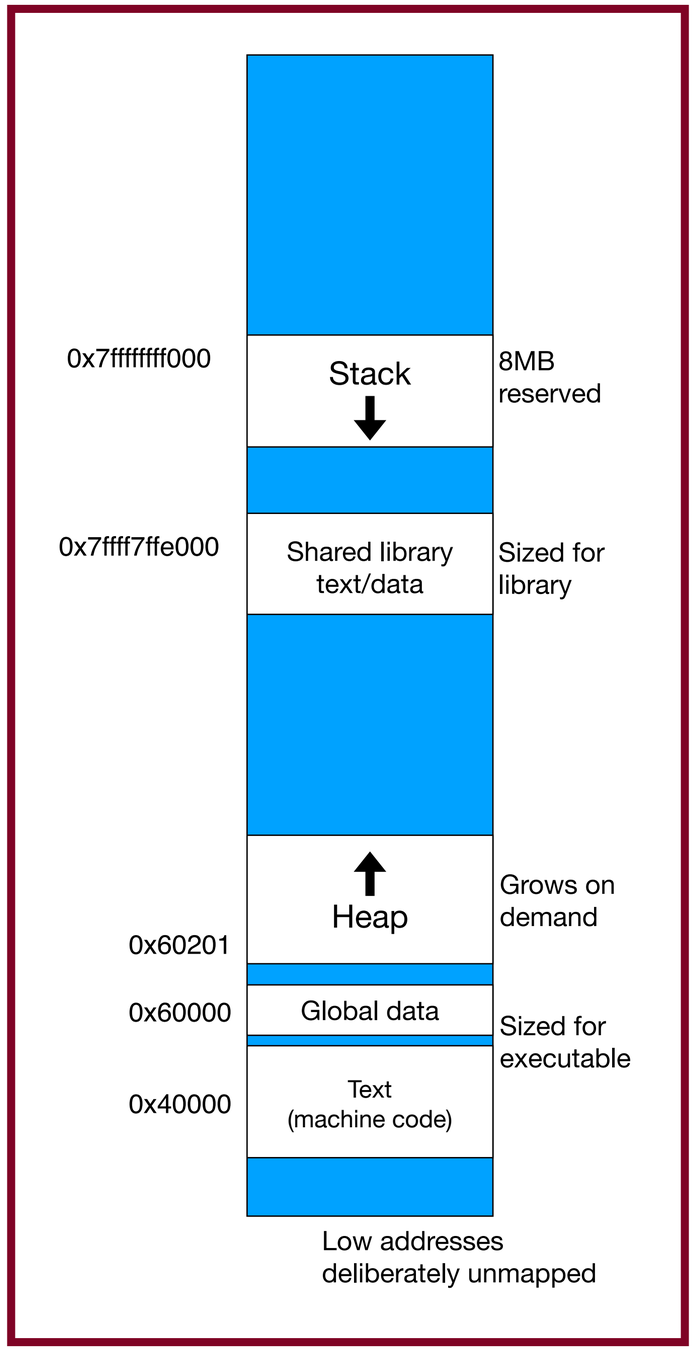
CS 107
Lecture 6: Stack and Heap

Monday, January 24, 2022

Computer Systems
Winter 2022
Stanford University
Computer Science Department

Reading: Reader: Ch 4, *C Primer,* K&R Ch 1.6, 5.1-5.5

Lecturers: Chris Gregg



Today's Topics

- Logistics
  - Assign2 — Due Wednesday Jan 26th at 11:59pm, with a late deadline of Friday Jan 28th.

- Reading: Reader: *C Primer*

- Pointers to Arrays (finish from last time)
- Stack allocation
- Stack frames
- Parameter passing
- Dynamic allocation (malloc/realloc/free).
- More Pointers to pointers

Double pointers — why are they needed?

Here is an example I posted on Ed. Let's take an in-depth look at it:

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

// print the next character in p
// and update the local pointer, p (which does nothing)
char nextCharA(char *p) {
    char next = p[0];
    p++; // this does not do anything except inside this function
    // and, we are returning here, so it really doesn't
    // do anything productive
    return next;
}

// print the next character in the string pointed to by p
// and update the string pointer by one to go to the next character
char nextCharB(char **p) {
    char next = (*p)[0];
    (*p)++; // now the original pointer gets updated!
    // we return here, but the calling function has the
    // details it needs for the next call
    return next;
}
```

```
int main() {
    char *myString = "hello";
    char *pA = myString;
    char *pB = myString;

    for (int i = 0; i < 5; i++) {
        printf("nextCharA(pA): %c ", nextCharA(pA));
        printf("nextCharB(&pB): %c\n",
nextCharB(&pB));
    }
    return 0;
}
```

Pointers to Arrays — char *envp[]

One tricky part of CS 107 for many students is getting comfortable with what the memory looks like for pointers to arrays, particularly when the arrays themselves are filled with pointers. This week's assignment has a good example: **`envp`**.

With arrays:

1. Always draw a picture!!!1! Make up the addresses -- the actual numbers aren't particularly important for understanding.

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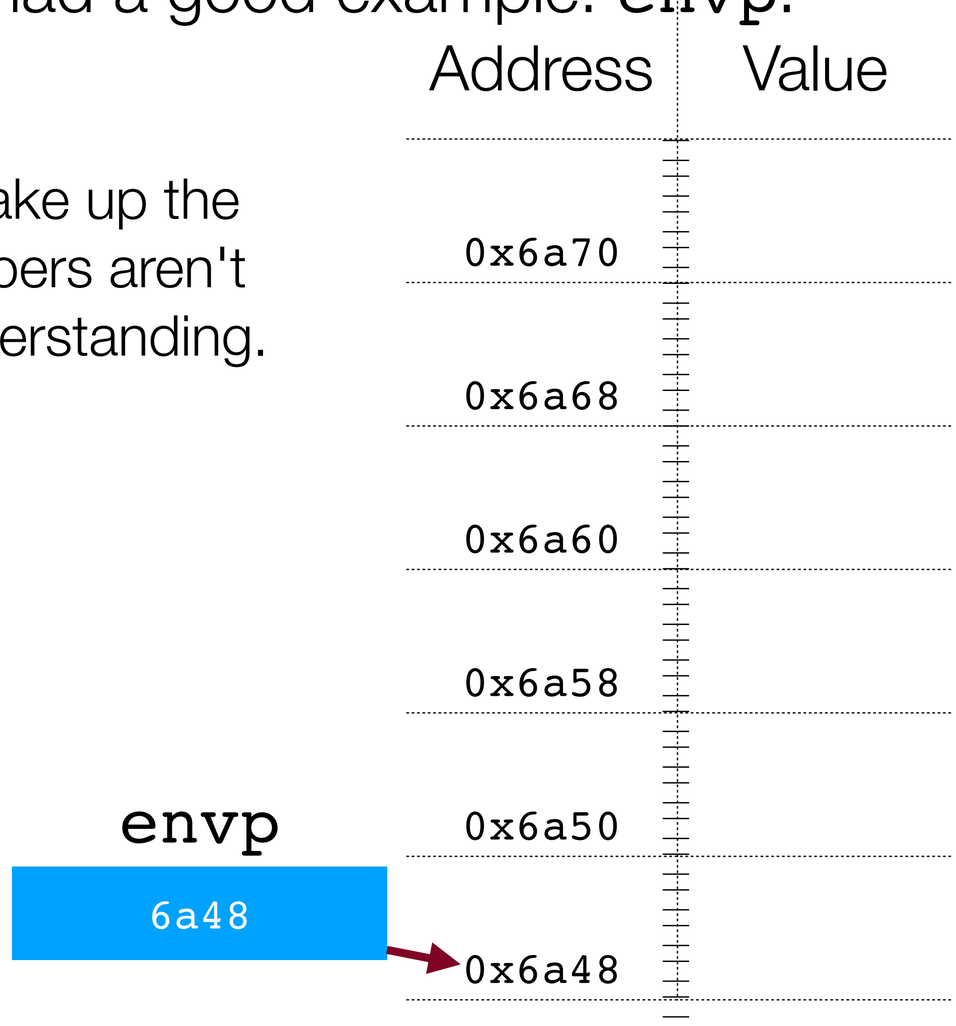

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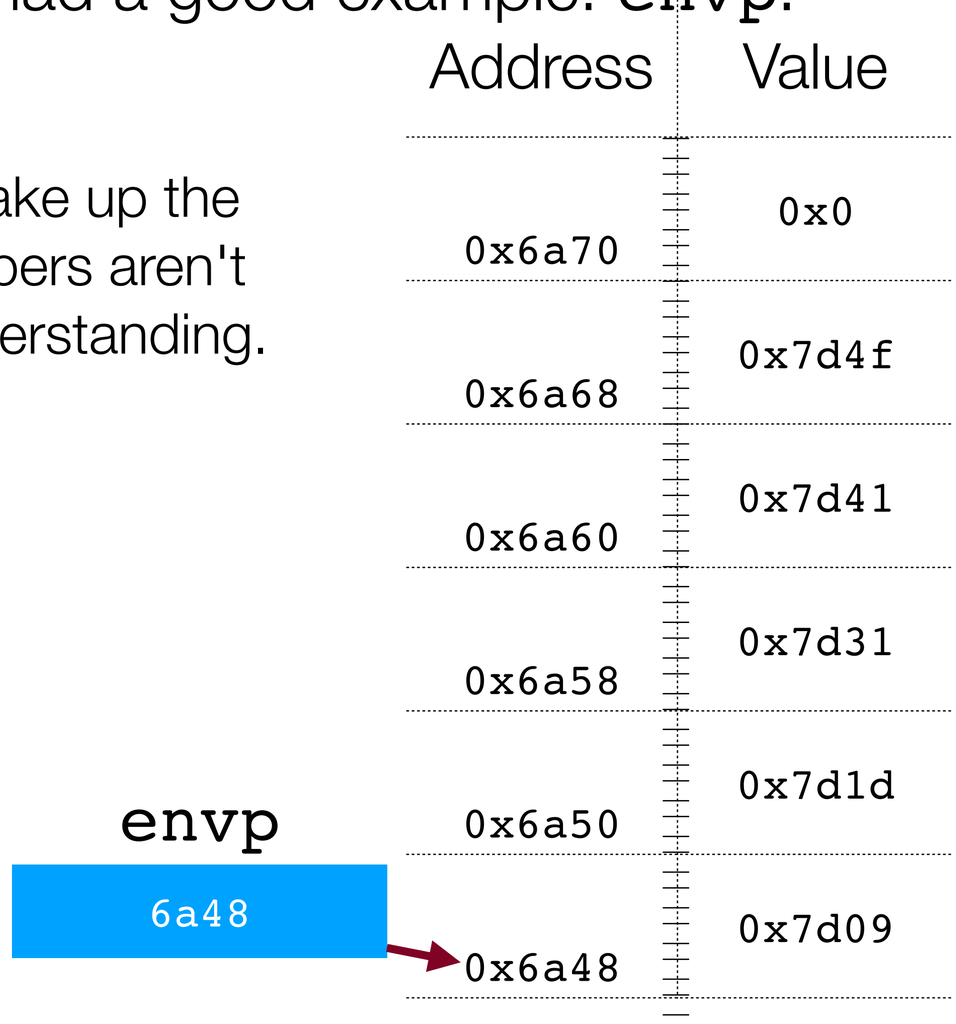

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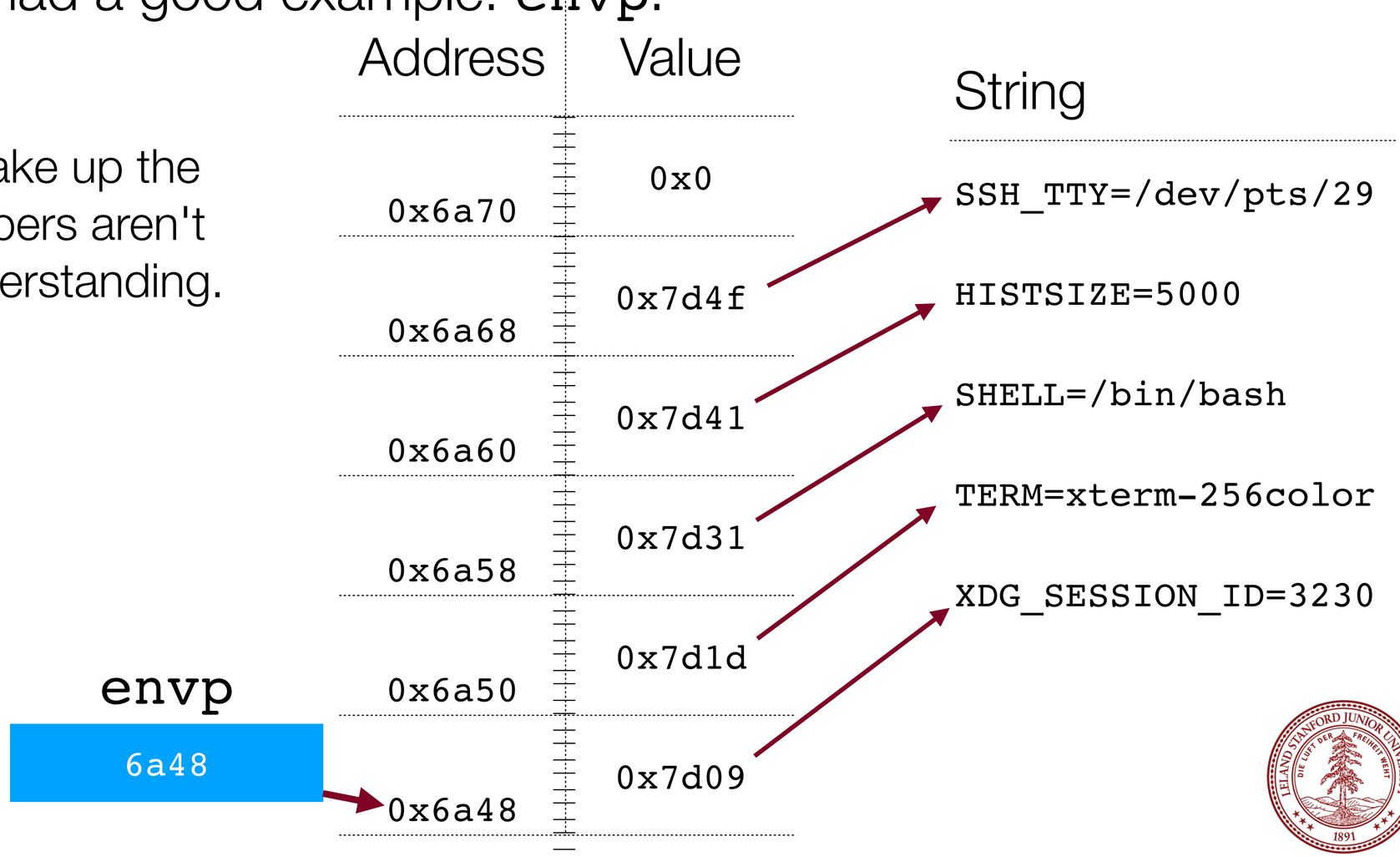

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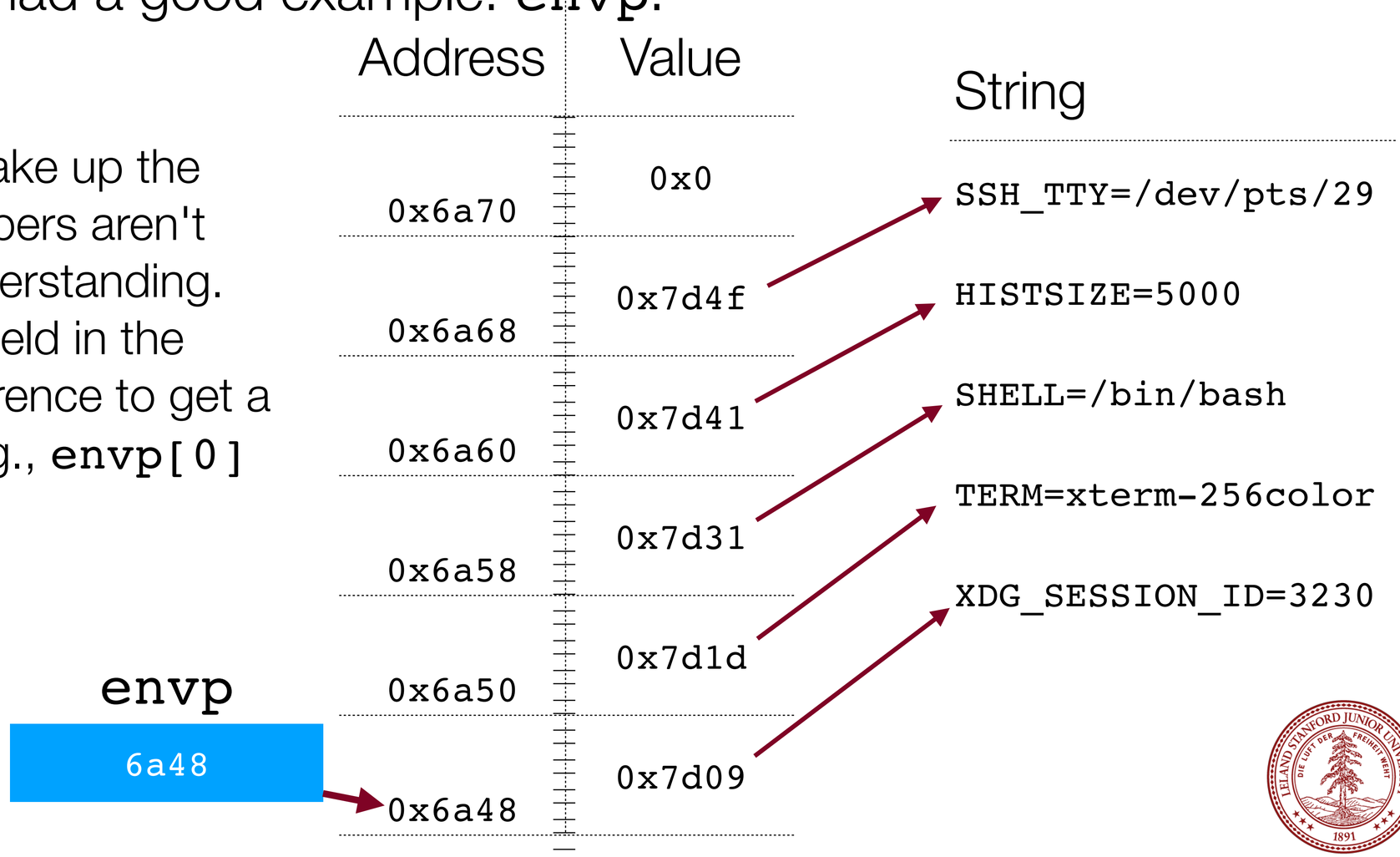
2. If you know the type that is held in the array, you can always dereference to get a single pointer to the type. E.g., **`envp[0]`** is a pointer to the string **`"XDG_SESSION_ID=3230"`**

What is *the value* of **`envp[2]`** for the diagram?



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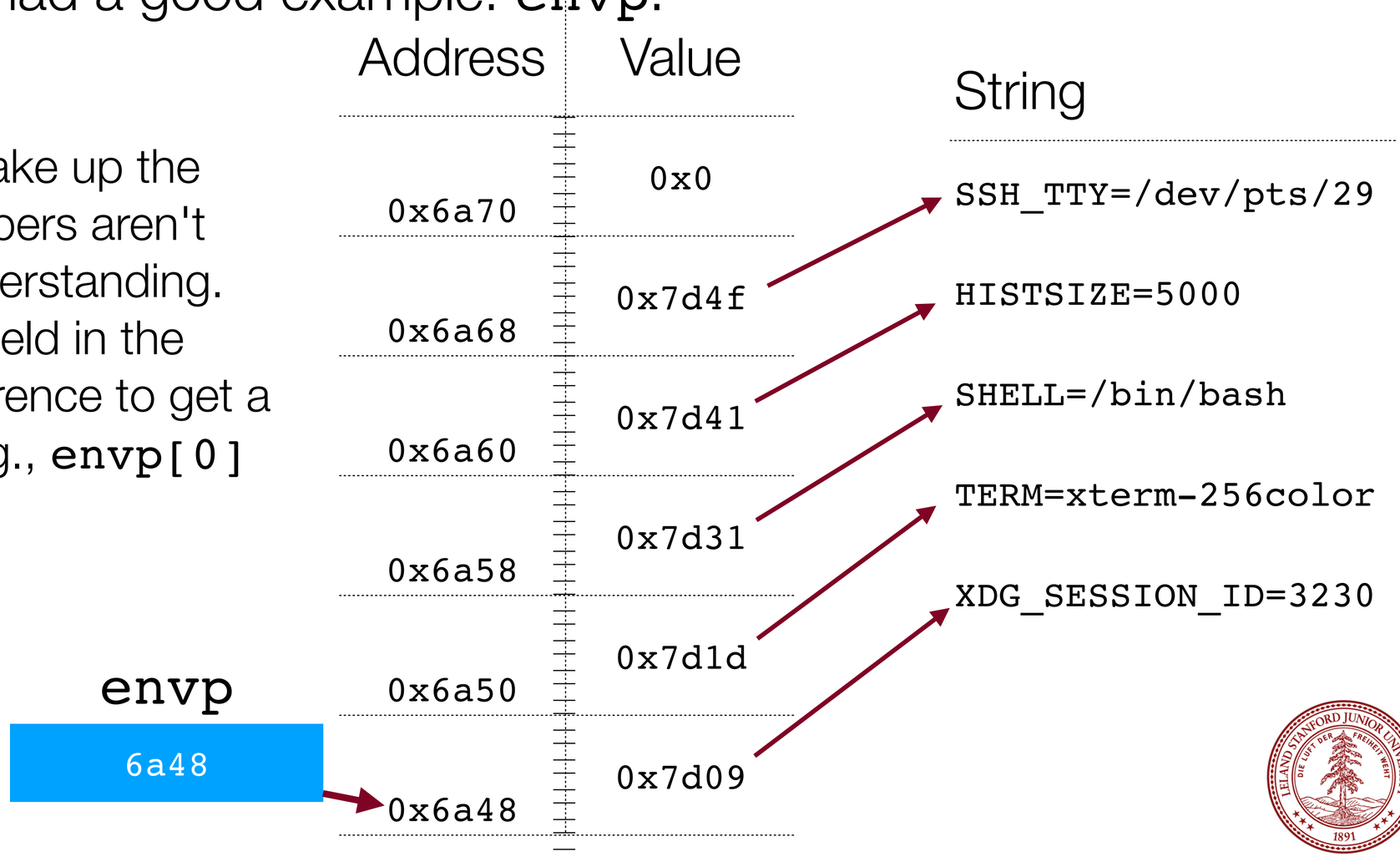
What is *the value* of **`envp[2]`** for the diagram? **`0x7d31`**



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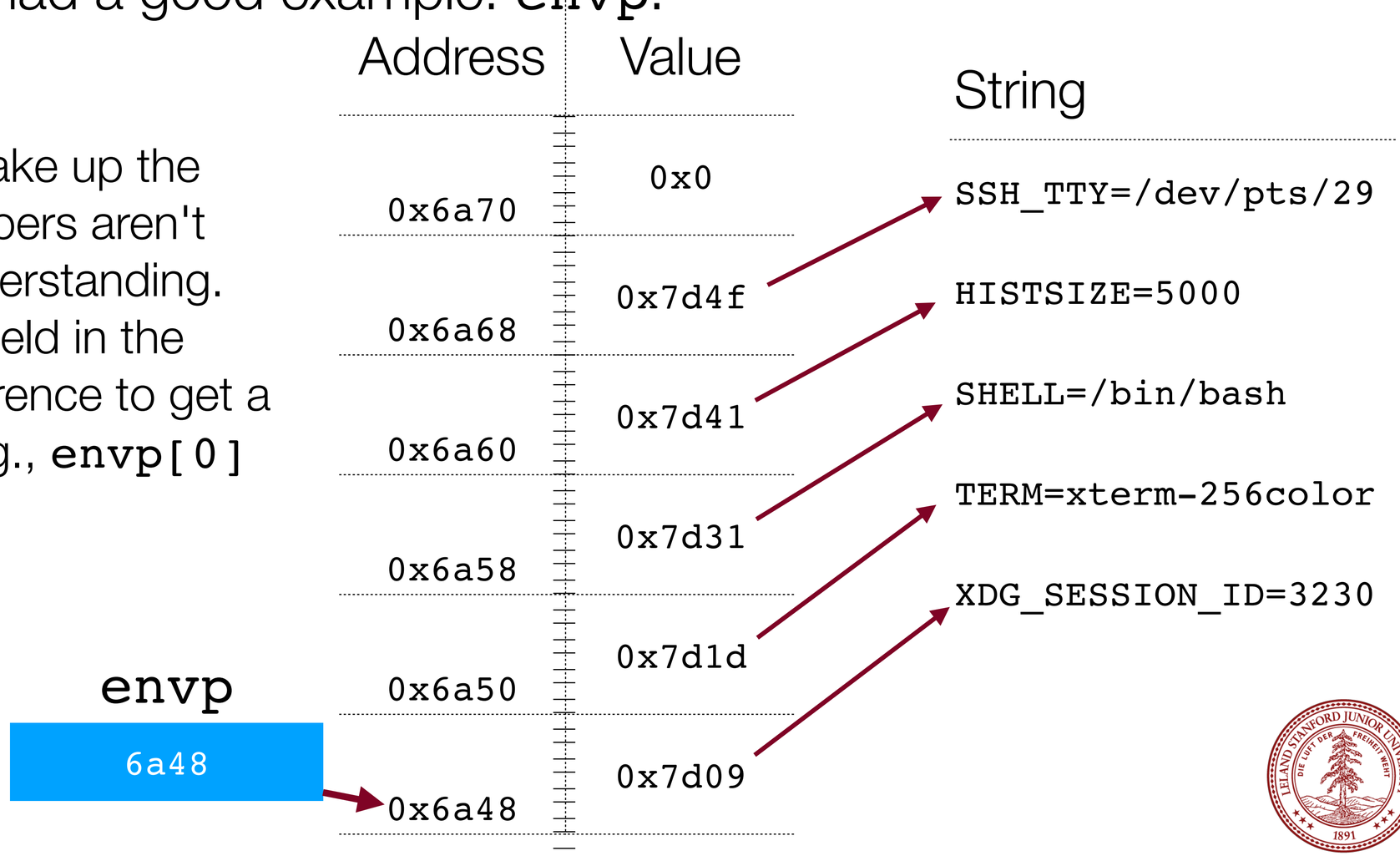

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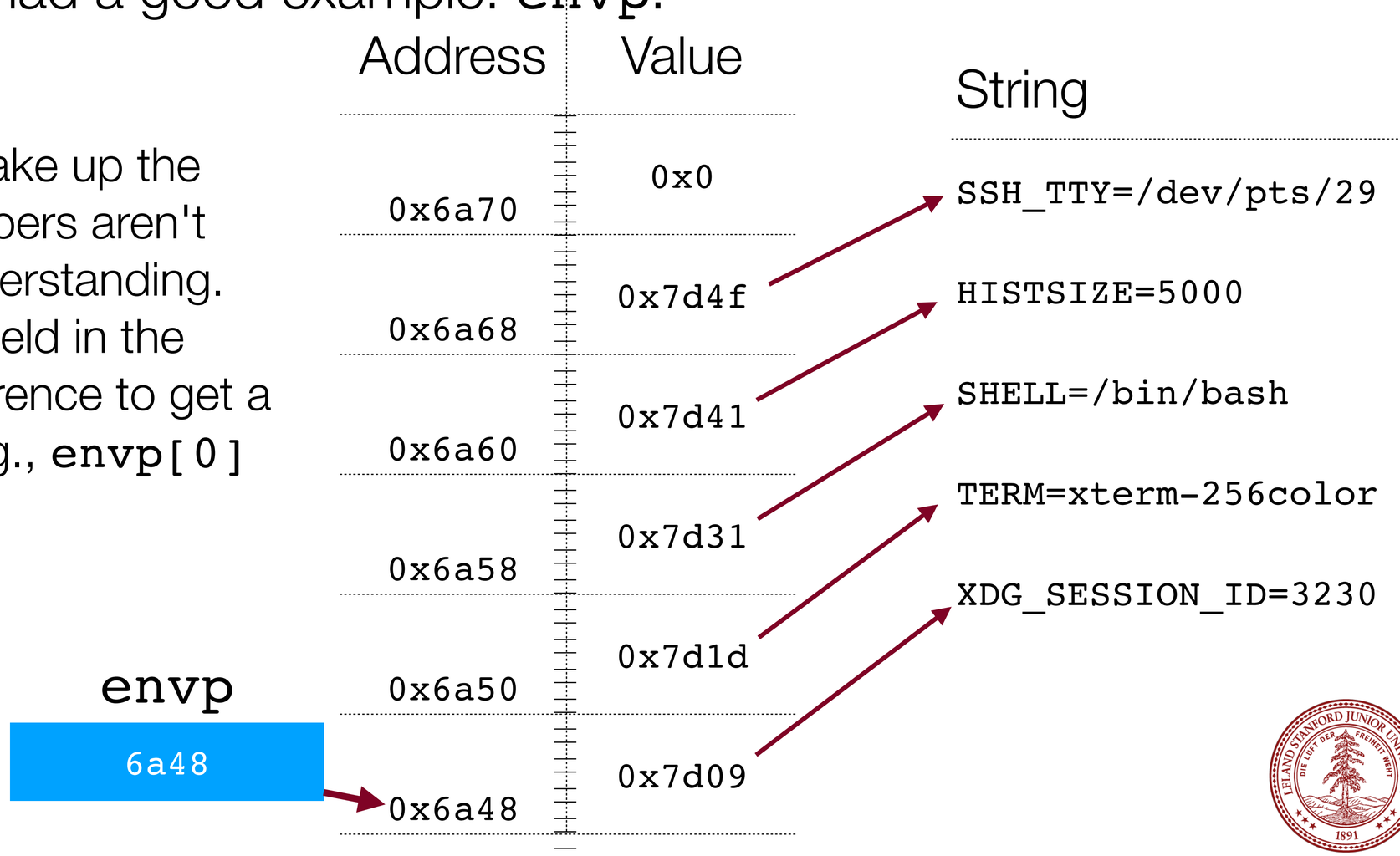
char *

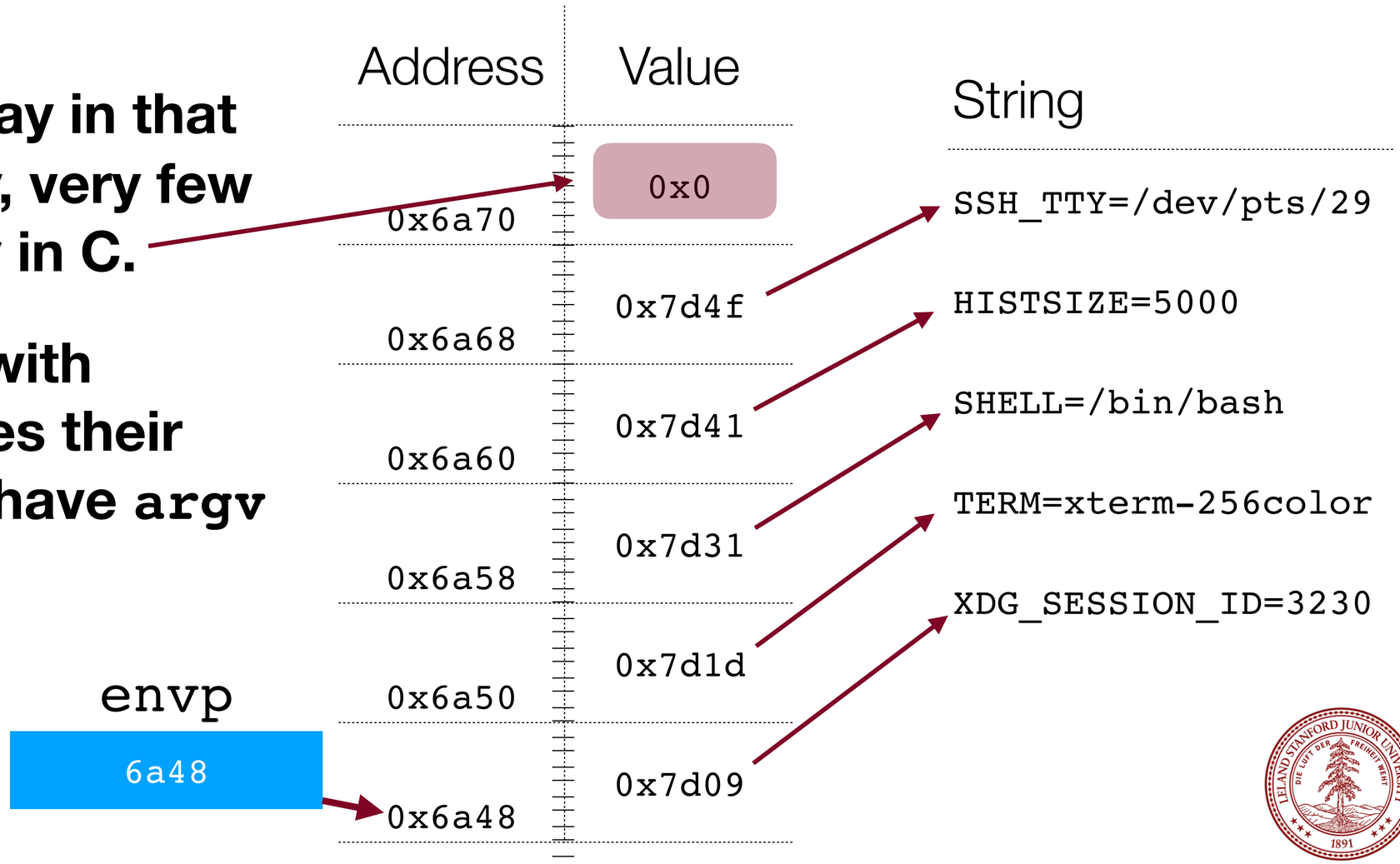


Pointers to Arrays — char *envp[]

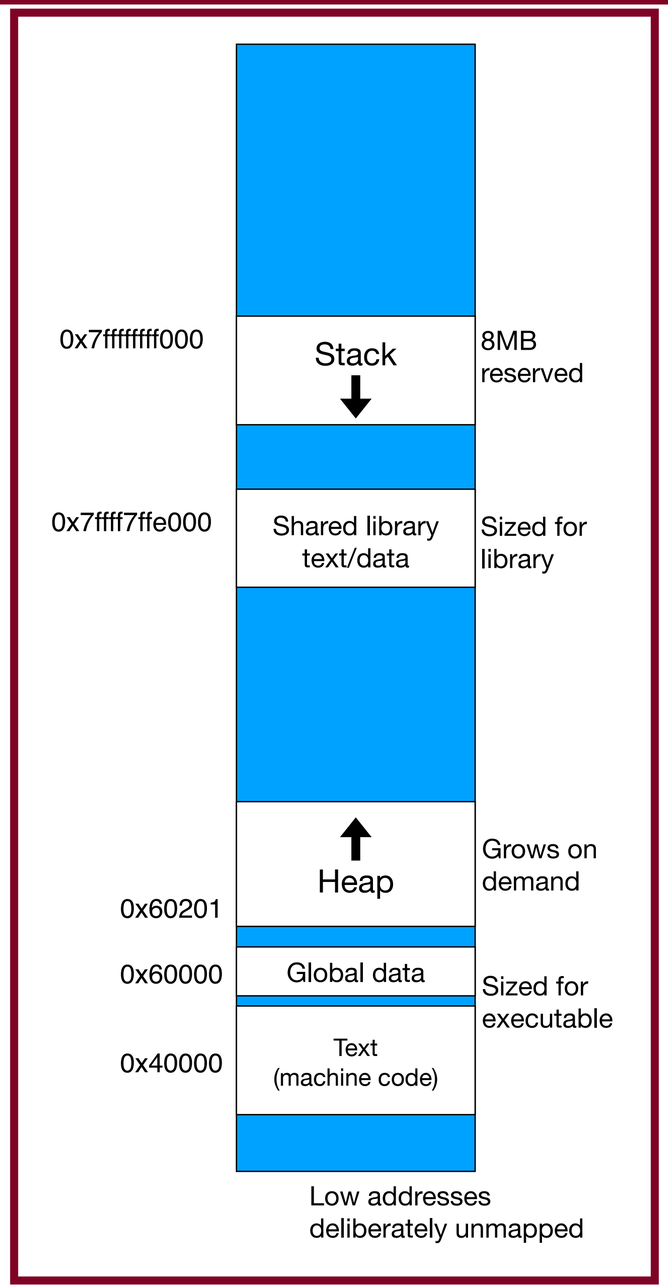
Note: `envp` is a weird array in that it is null-terminated! Very, very few arrays have this property in C.

Most arrays are passed with another variable that gives their length. For example, we have `argv` and `argc`.*

*Note: `argv[argc]` *is* defined to be `NULL`, but that still an anomaly for C arrays in general.



x86-64 Memory Layout

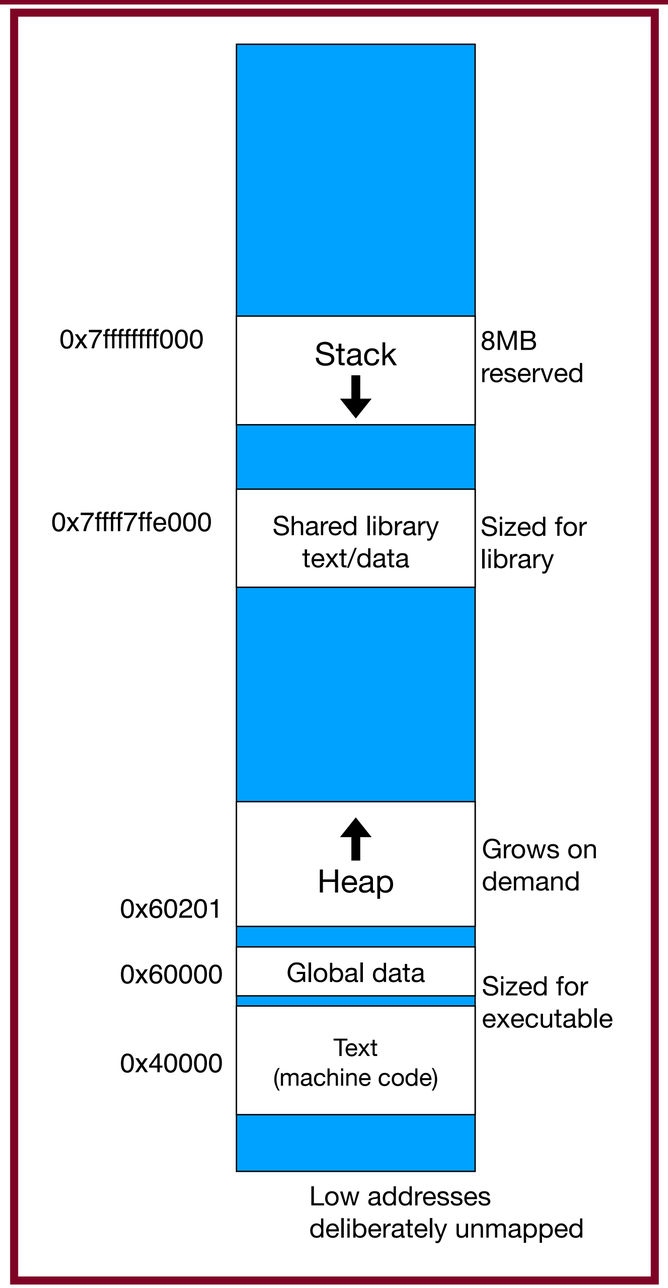


In CS 107, we are going to talk about two different areas of memory that your program will access, called the *stack* and the *heap*.

This diagram shows the overall memory layout in Linux on an x86-64 computer (e.g., the Myth computers).

Every program, by default, has access to an 8MB stack segment in memory. Your program can do anything it wants with that memory, but it is limited. The stack grows *downward* in memory, so your program starts with a location on the stack, and you get the next 8MB *lower* in memory.

x86-64 Memory Layout

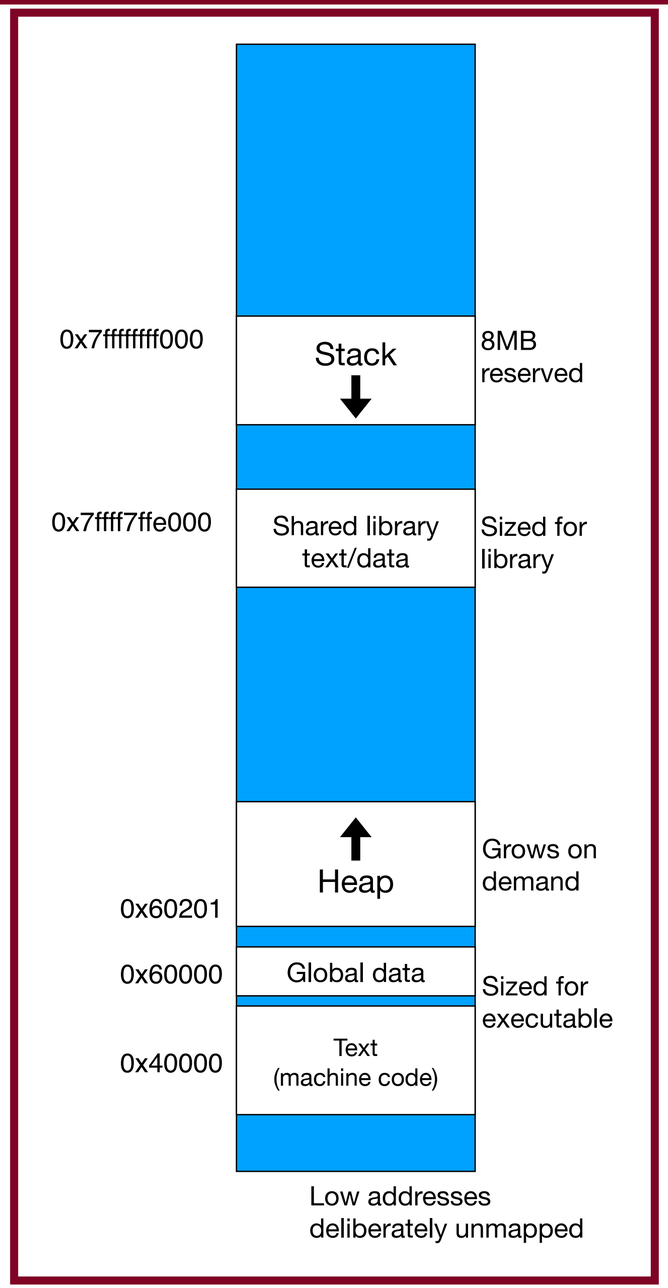


Below the stack is the shared library. This is all of the standard libraries that are used by programs (e.g., stdlib.h, stdio.h, string.h, etc.) Your programs do not have access to these directly, except to call functions that are there.

Below the shared library data is the *heap*, which is managed by the operating system, and comprises the vast majority of the memory in your computer. When a program wants to use heap memory, it requests it from the operating system (using **`malloc`**, **`calloc`**, or **`realloc`** in C).

The heap starts at a low memory address and grows upwards.

x86-64 Memory Layout



Below the heap is global data for your program (i.e., global variables and string literals -- remember that string literals are not modifiable).

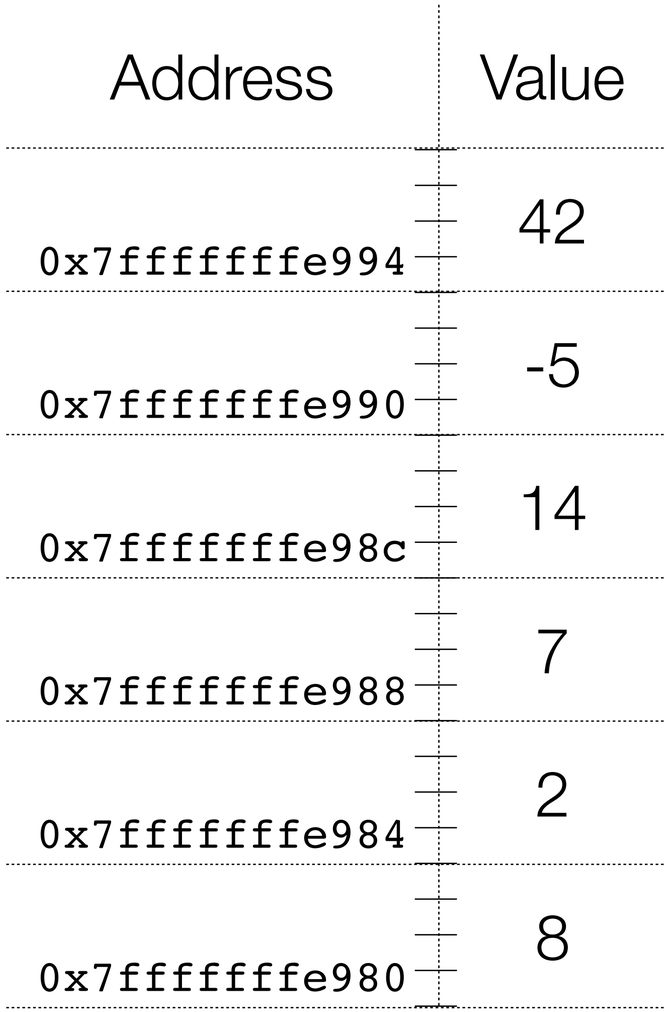
Below the global data is your program code.

Note: When you program references memory, it references *virtual* memory. Virtual memory is a way for every program to *think* it has access to the entire memory system, while hiding the details. The operating system and PC hardware handle all of the details of the translation between virtual memory and physical memory, and for this course you only need to consider the diagram to the left.

Stack Allocation

When a function creates a local variable, or when a function receives parameters, the data is either kept in *registers* or kept on the stack. We will cover registers when we get to assembly language, but for now we will assume that all of our local variables go on the stack (and we will compile with "`-O0`" which forces everything onto the stack.

Arrays are also kept on the stack.



Stack Allocation

Let's look at an example:

```
// file: stack_ex1.c
#include<stdio.h>
#include<stdlib.h>

int main(int argc, char **argv)
{
    int a = 0x12345;
    int b = 0x98765432;
    char str[] = "hello";
    short array[] = {0x2,0x4,0x6,0x8,0xa};

    printf("0x%x\n",a);
    printf("0x%x\n",b);
    printf("%s\n",str);
    for (int i=0; i < sizeof(array) / sizeof(array[0]); i++) {
        printf("0x%x,",array[i]);
    }
    printf("\n");
    return 0;
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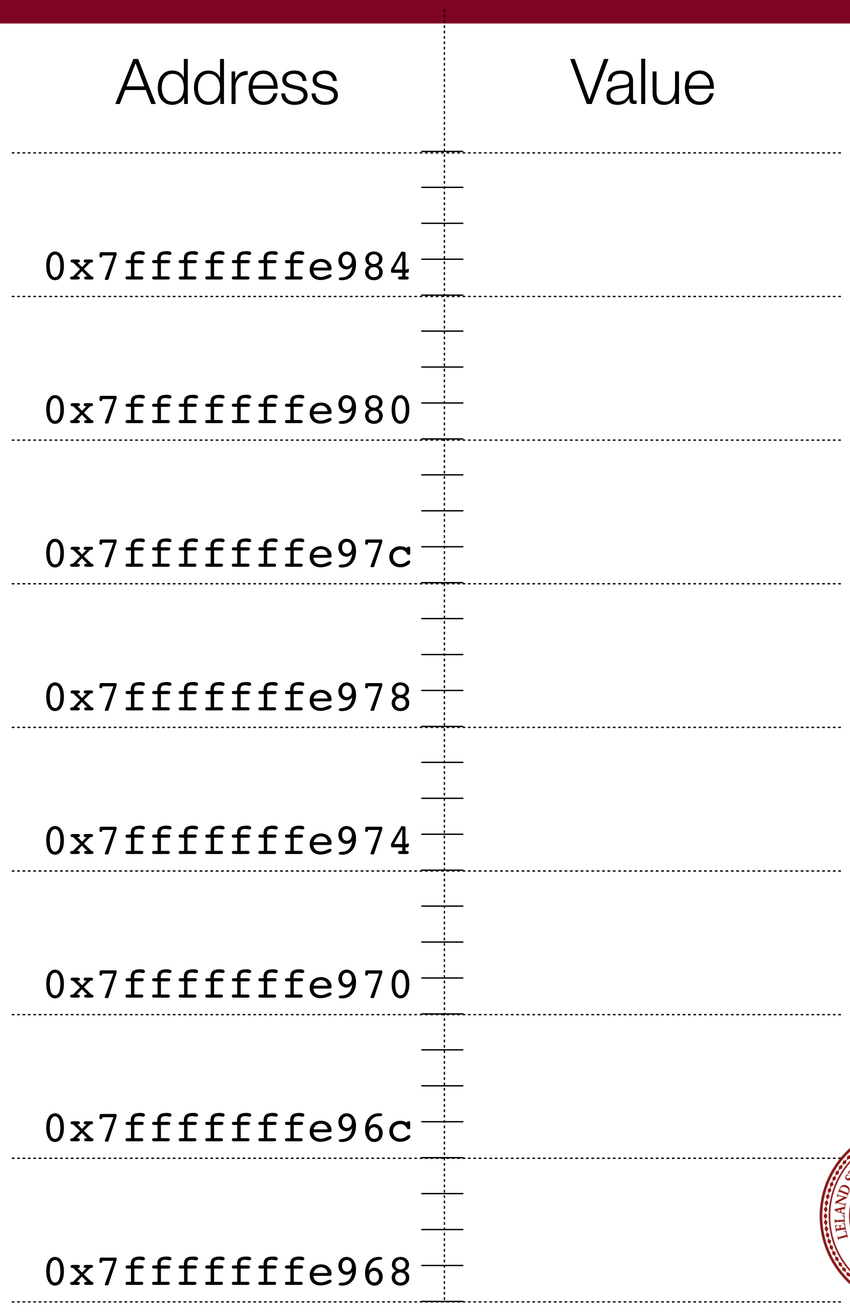

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$ gdb stack_ex1
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stack_ex1.c, line 12.
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```
(gdb) p &a
$16 = (int *) 0x7fffffffe968
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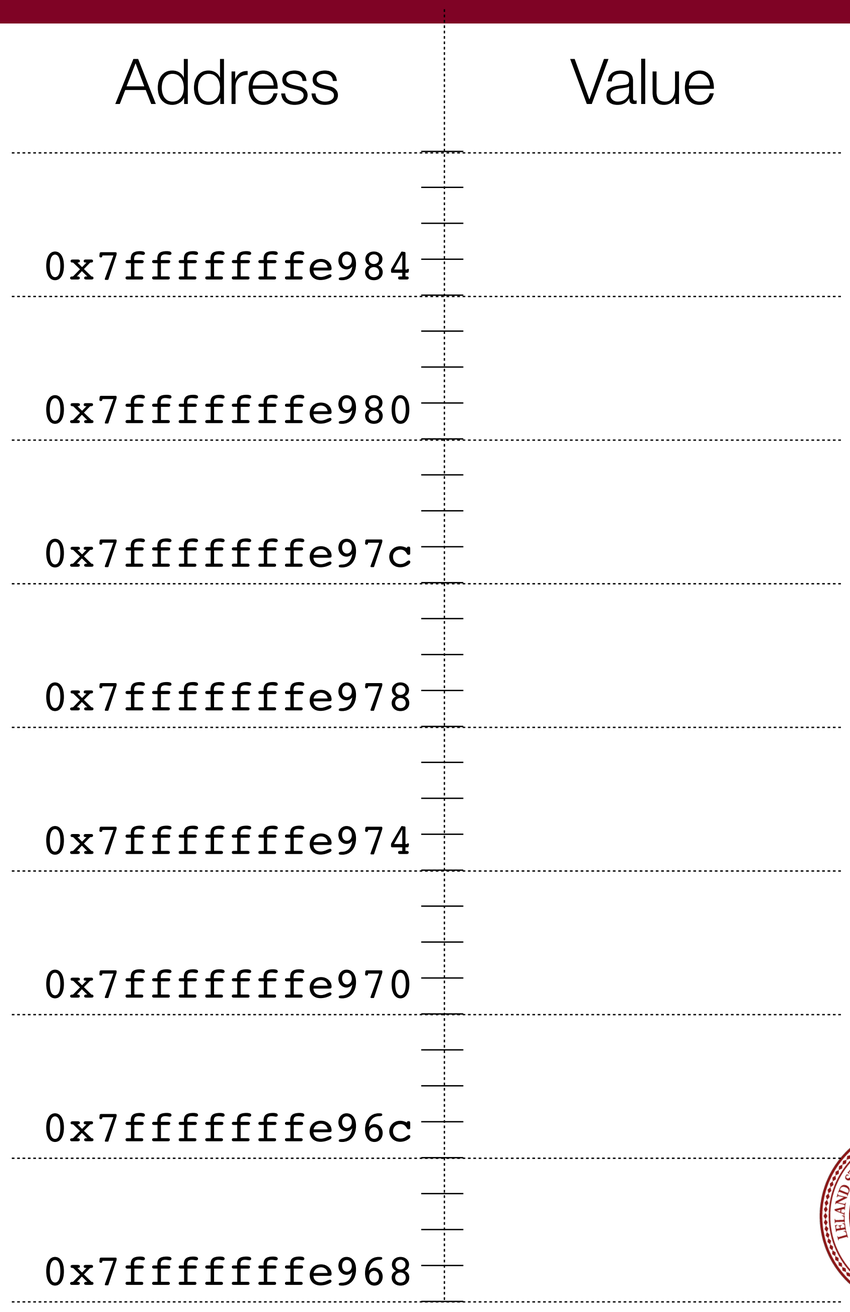

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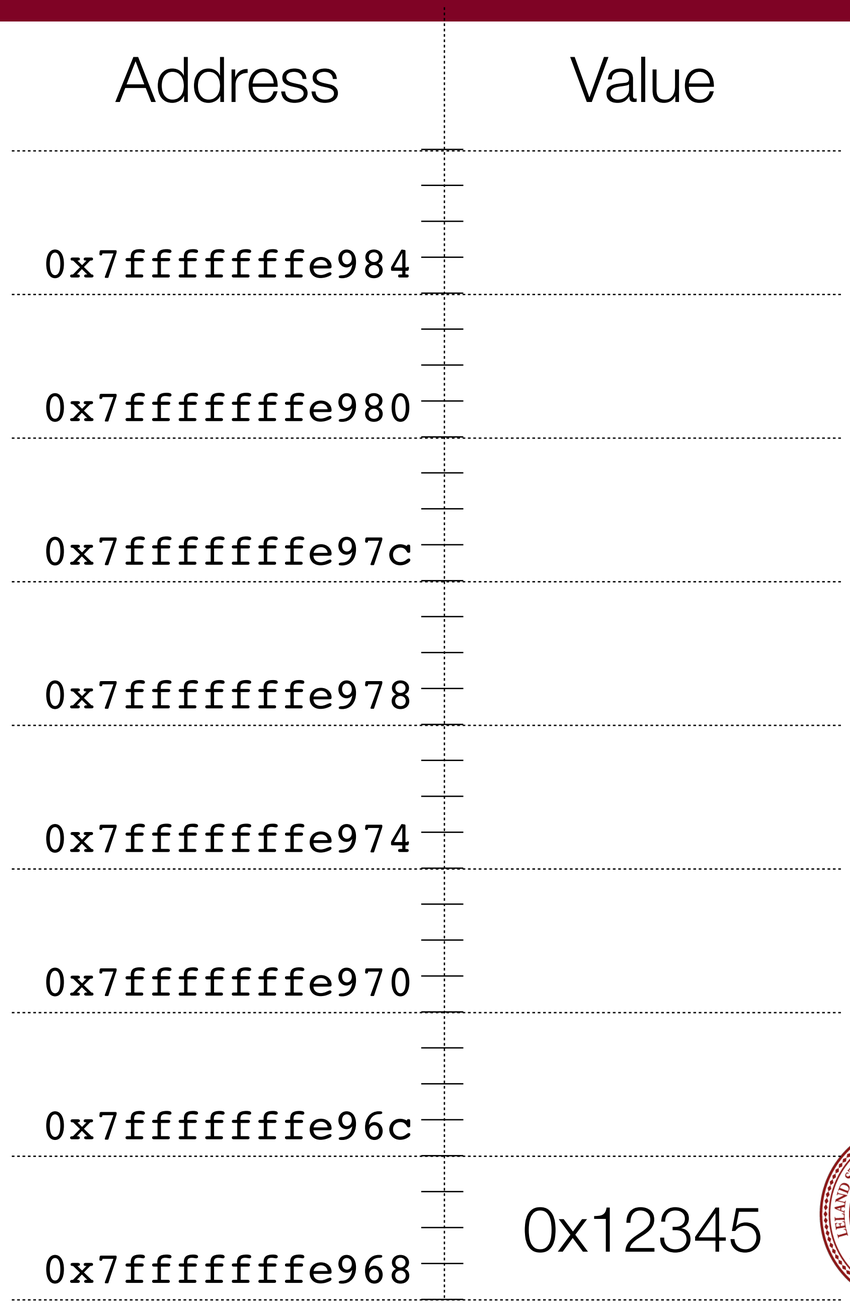

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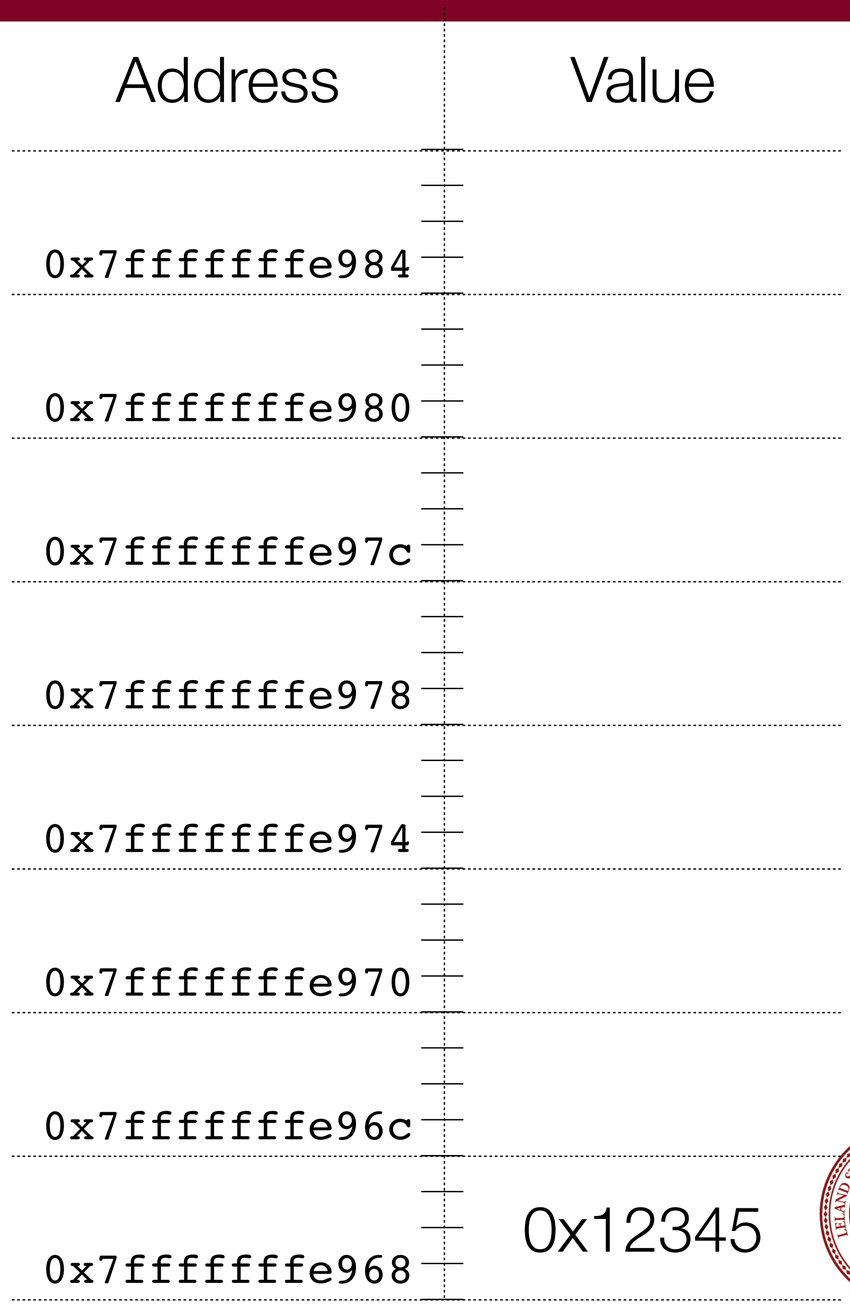

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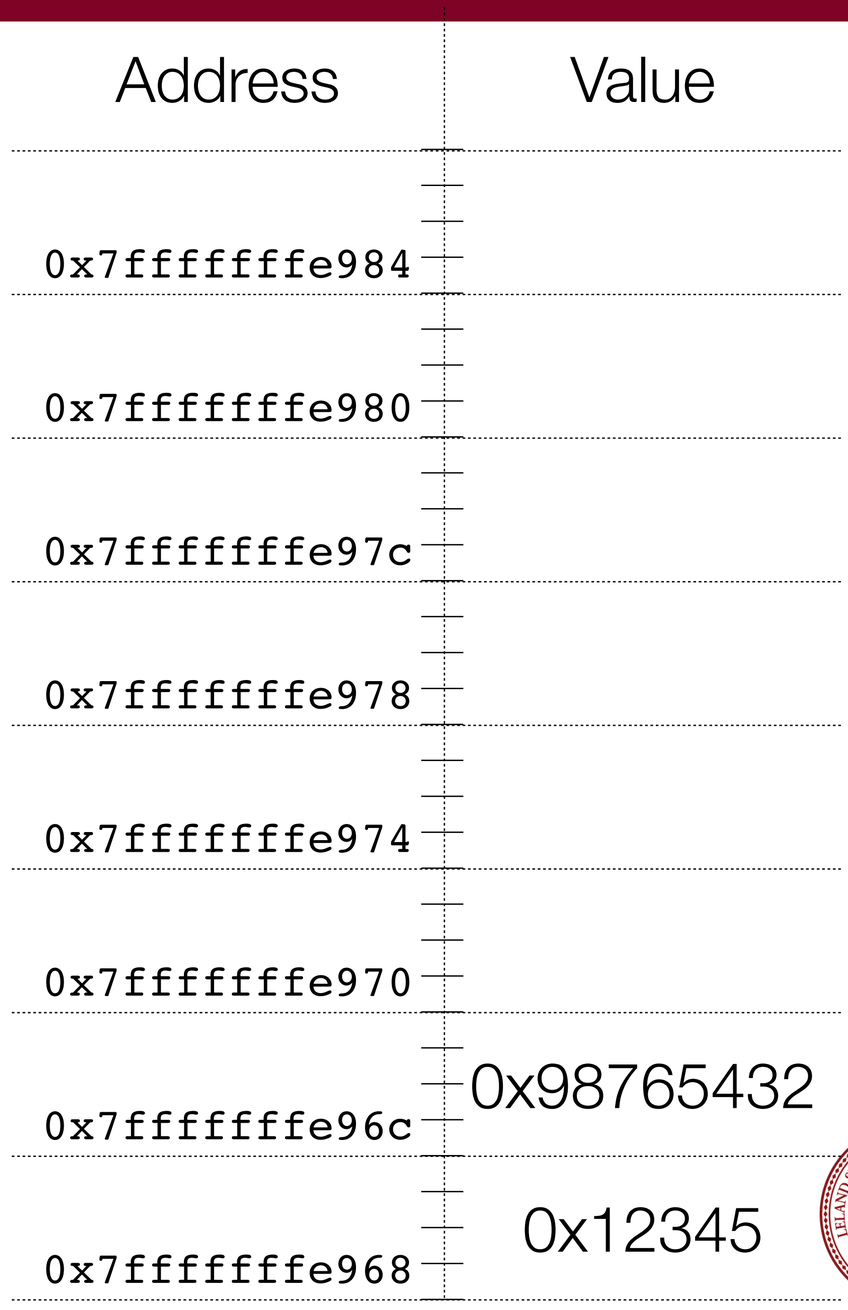

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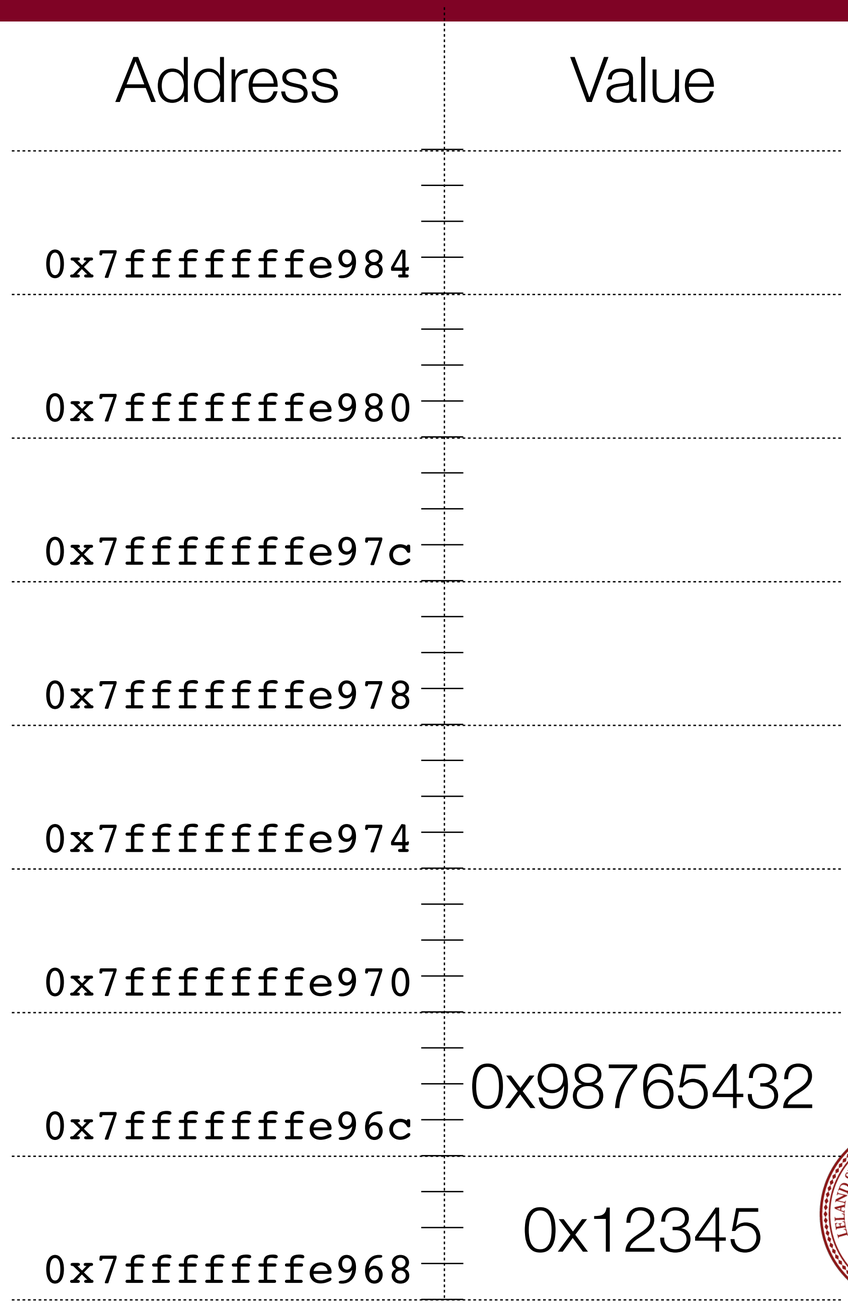

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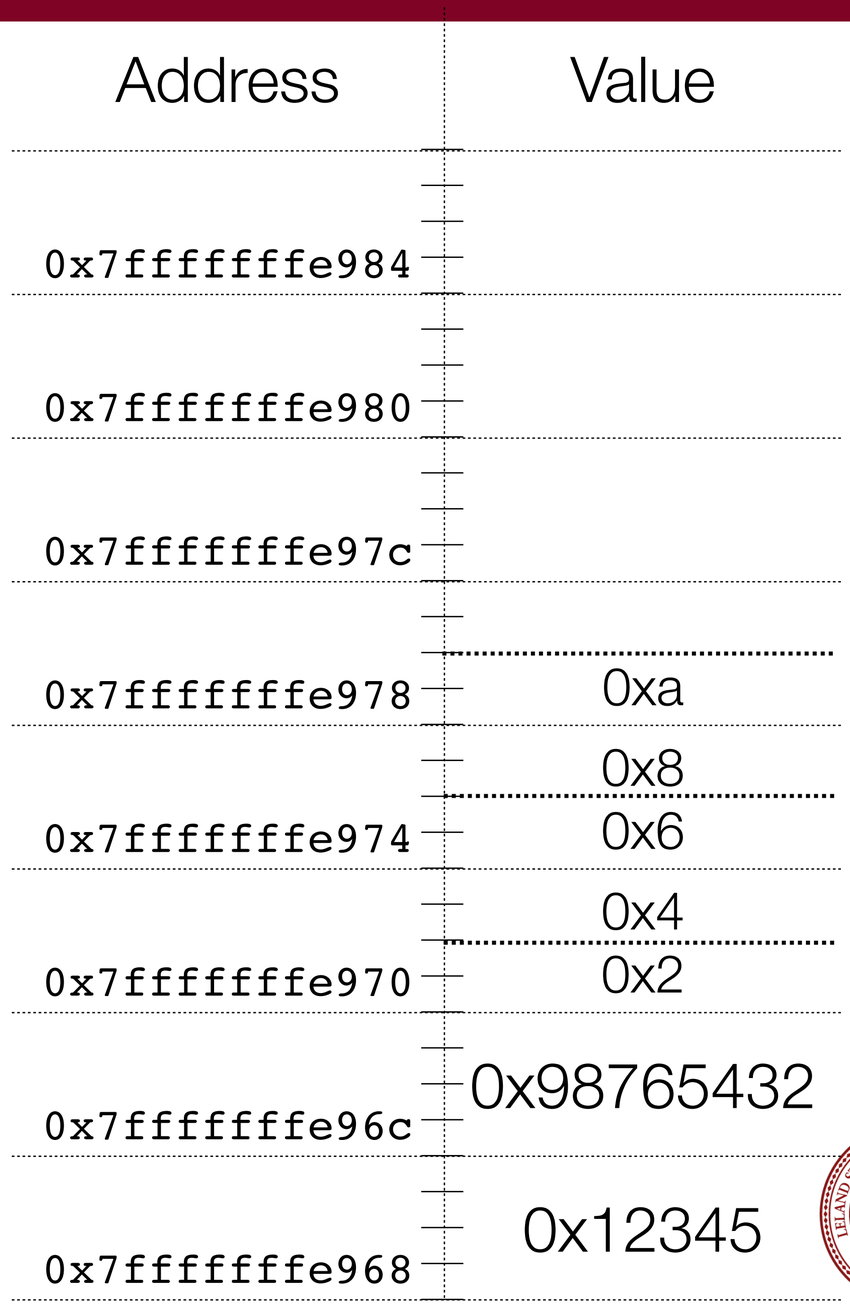
```



Stack Allocation

Let's look at an example:

```
// file: stack_ex1.c
#include<stdio.h>
#include<stdlib.h>

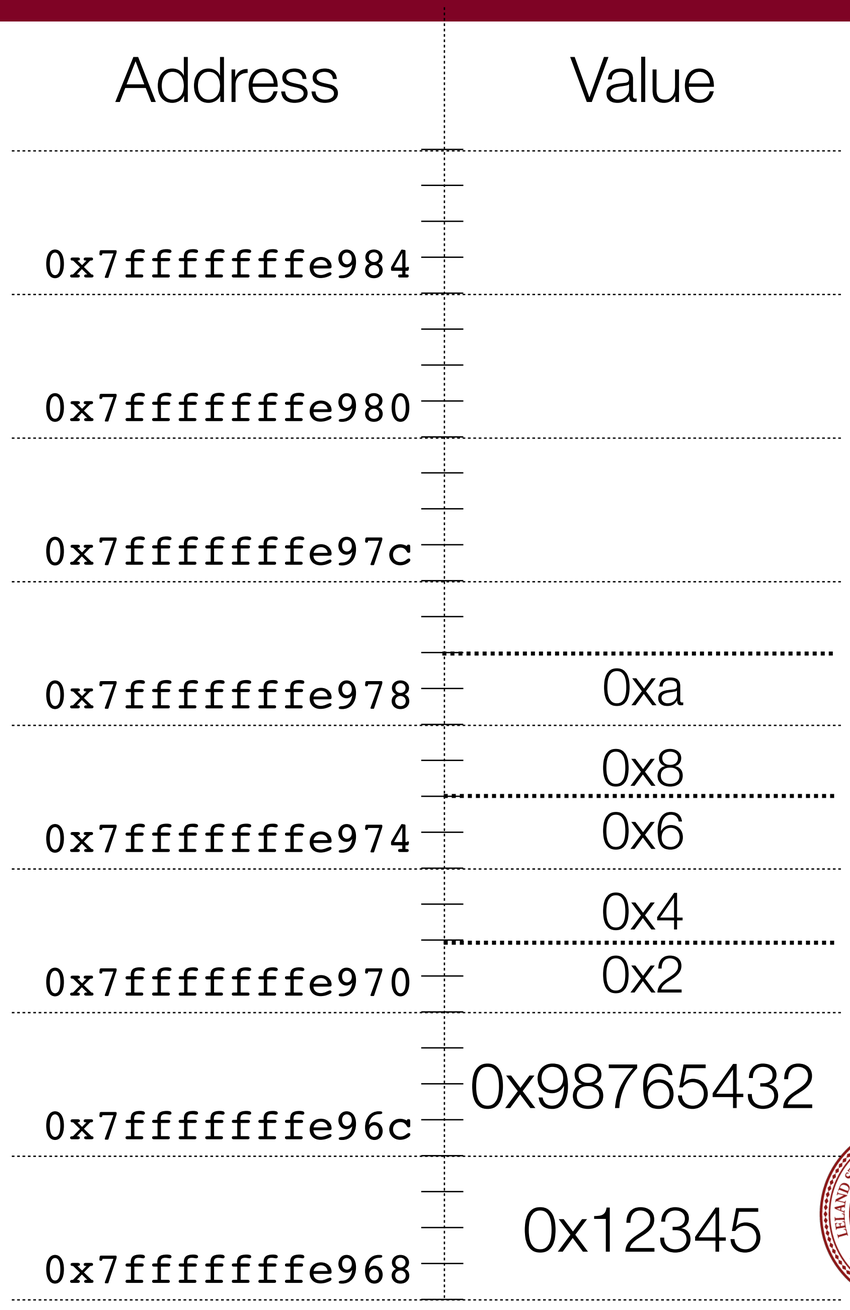
int main(int argc, char **argv)
{
    int a = 0x12345;
    int b = 0x98765432;
    char str[] = "hello";
    short array[] = {0x2,0x4,0x6,0x8,0xa};

    printf("0x%x\n",a);
    printf("0x%x\n",b);
    printf("%s\n",str);
    for (int i=0; i < sizeof(array) / sizeof(array[0]); i++) {
        printf("0x%x,",array[i]);
    }
    printf("\n");
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 -Wall
    stack_ex1.c -o stack_ex1
$ ./stack_ex1
0x12345
0x98765432
hello
0x2,0x4,0x6,0x8,0xa,
$ gdb stack_ex1
(gdb) break 12
Breakpoint 1 at 0x40067d: file
stack_ex1.c, line 12.
(gdb) run
Starting program: stack_ex1

Breakpoint 1, main (argc=1,
argv=0x7fffffffea78) at stack_ex1.c:12
12        printf("0x%x\n",a);
(gdb)
```

```
(gdb) p &a
$16 = (int *) 0x7fffffffe968
(gdb) p &b
$17 = (int *) 0x7fffffffe96c
(gdb) p &array[0]
$18 = (short *) 0x7fffffffe970
(gdb) p &str[0]
$19 = 0x7fffffffe980 "hello"
```



Stack Allocation

Let's look at an example:

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

int main(int argc, char **argv)
{
    int a = 0x12345;
    int b = 0x98765432;
    char str[] = "hello";
    short array[] = {0x2,0x4,0x6,0x8,0xa};

    printf("0x%x\n",a);
    printf("0x%x\n",b);
    printf("%s\n",str);
    for (int i=0; i < sizeof(array) / sizeof(array[0]); i++) {
        printf("0x%x,",array[i]);
    }
    printf("\n");
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 -Wall
    stack_ex1.c -o stack_ex1
$ ./stack_ex1
0x12345
0x98765432
hello
0x2,0x4,0x6,0x8,0xa,
$ gdb stack_ex1
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Breakpoint 1 at 0x40067d: file
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Starting program: stack_ex1

Breakpoint 1, main (argc=1,
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```

```
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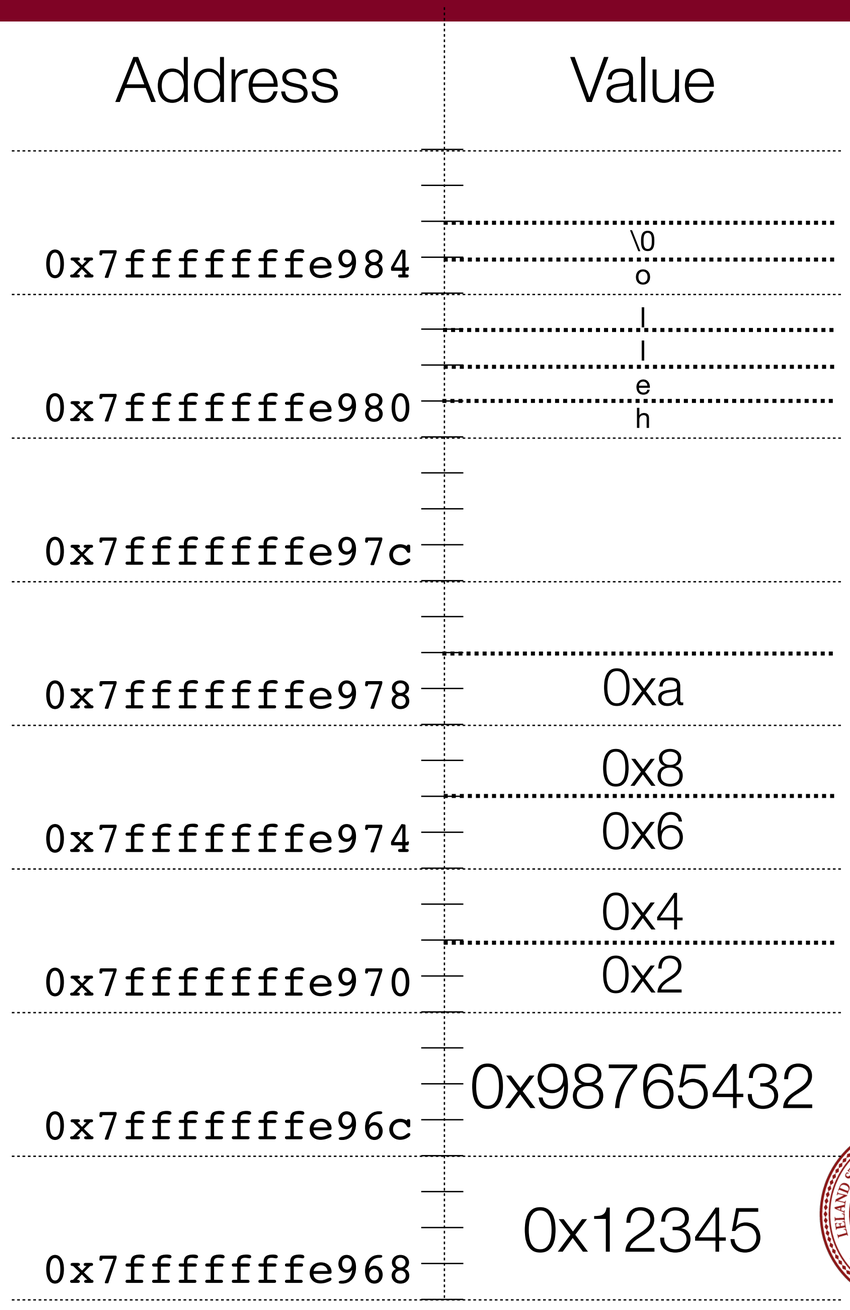
$18 = (short *) 0x7fffffffe970
(gdb) p &str[0]
$19 = 0x7fffffffe980 "hello"
```



Stack Allocation

Let's look at an example:

```
// file: stack_ex1.c
#include<stdio.h>
#include<stdlib.h>

int main(int argc, char **argv)
{
    int a = 0x12345;
    int b = 0x98765432;
    char str[] = "hello";
    short array[] = {0x2,0x4,0x6,0x8,0xa};

    printf("0x%x\n",a);
    printf("0x%x\n",b);
    printf("%s\n",str);
    for (int i=0; i < sizeof(array) / sizeof(array[0]); i++) {
        printf("0x%x,",array[i]);
    }
    printf("\n");
    return 0;
}
```

```
$ gcc -g -O0 -std=gnu99 -Wall
    stack_ex1.c -o stack_ex1
$ ./stack_ex1
0x12345
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hello
0x2,0x4,0x6,0x8,0xa,
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(gdb)
```

```
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$16 = (int *) 0x7fffffffe968
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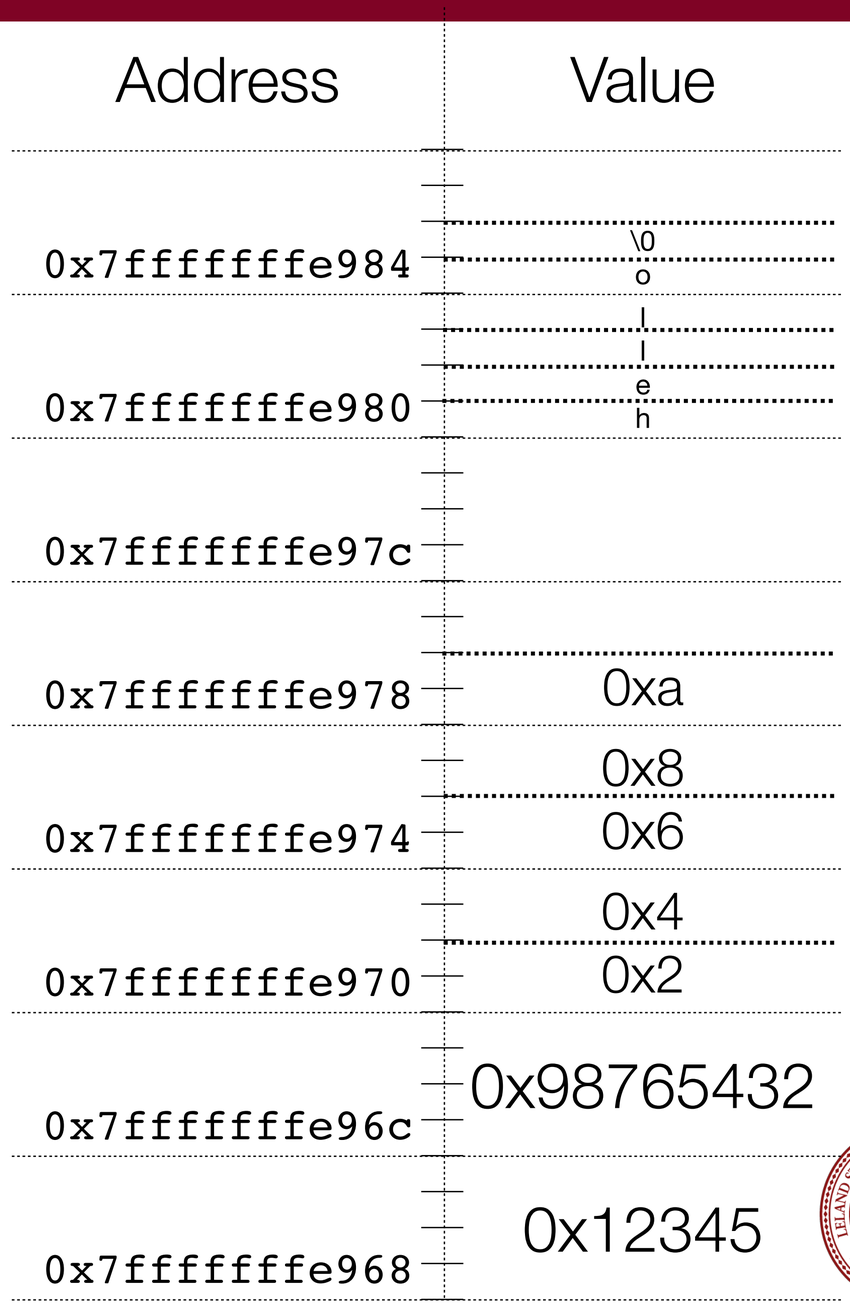
(gdb) p &array[0]
$18 = (short *) 0x7fffffffe970
(gdb) p &str[0]
$19 = 0x7fffffffe980 "hello"
(gdb) x/30bx &a
0x7fffffffe968:   0x45   0x23   0x01   0x00   0x32   0x54   0x76   0x98
0x7fffffffe970:   0x02   0x00   0x04   0x00   0x06   0x00   0x08   0x00
0x7fffffffe978:   0x0a   0x00   0x40   0x00   0x00   0x00   0x00   0x00
0x7fffffffe980:   0x68   0x65   0x6c   0x6c   0x6f   0x00
(gdb)
```



3 minute break

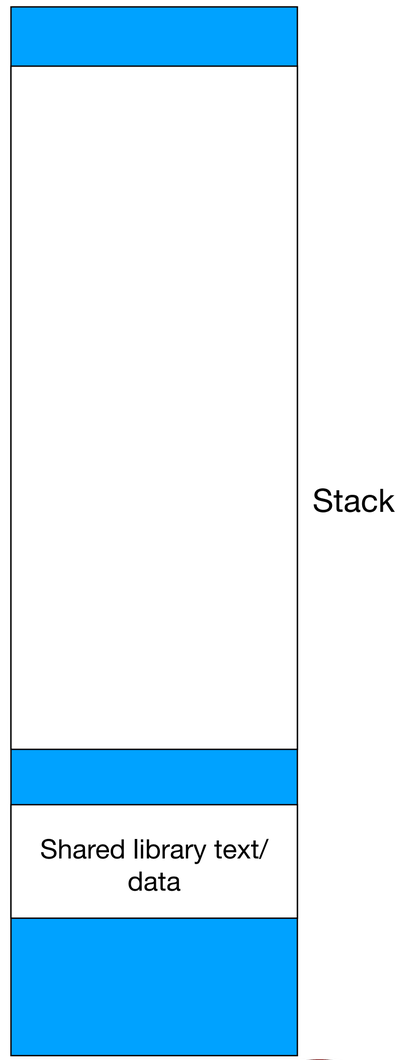
Stack Frames

Every time you call a function, the data for the current function needs to be saved. The x86 operating system handles this in an elegant manner: a function just uses memory farther down in the stack, and leaves the part of the stack that the calling function was using unchanged. Example:

```
int rotate_rgb(int rgb)
{
    // rgb -> brg
    int g = ((rgb & 0xff) << 16);
    return (rgb >> 8) | g;
}

void colorize(int *colors, size_t nelems)
{
    for (int i=0; i < nelems; i++) {
        colors[i] = rotate_rgb(colors[i]);
    }
}

int main(int argc, char **argv)
{
    size_t nelems = argc-1;
    int values[nelems];
    char *err;
    for (int i=0; i < argc-1; i++) {
        values[i] = strtol(argv[i+1],&err,0);
    }
    print_colors(values, nelems);
    colorize(values,sizeof(values)/sizeof(values[0]));
    print_colors(values, nelems);
    return 0;
}
```



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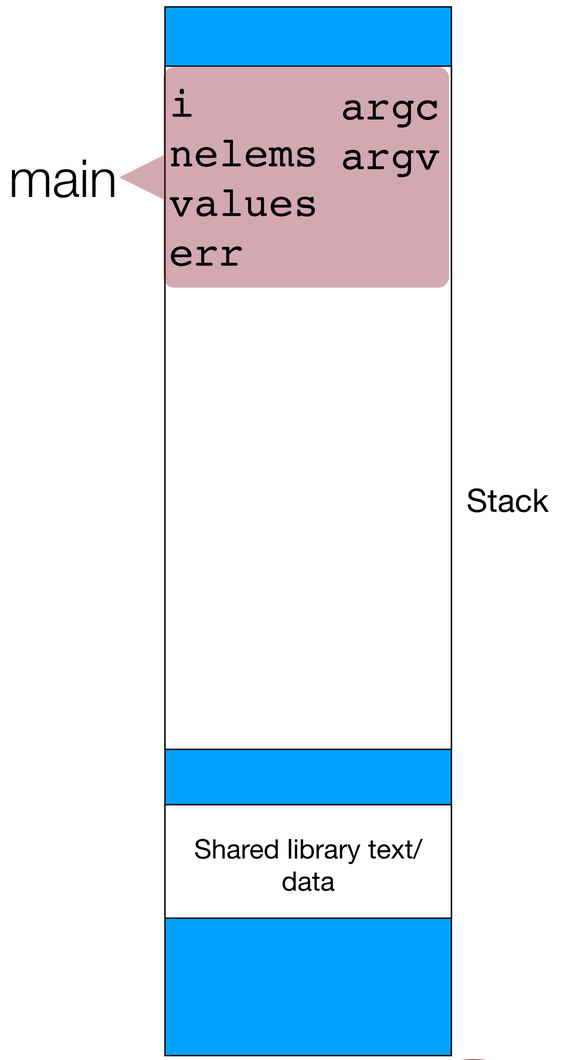
        colors[i] = rotate_rgb(colors[i]);
    }
}

int main(int argc, char **argv)
{
    size_t nelems = argc-1;
    int values[nelems];
    char *err;
    for (int i=0; i < argc-1; i++) {
        values[i] = strtol(argv[i+1],&err,0);
    }
    print_colors(values, nelems);
    colorize(values,sizeof(values)/sizeof(values[0]));
    print_colors(values, nelems);
    return 0;
}
```



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{
    for (int i=0; i < nelems; i++) {
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    }
}

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{
    size_t nelems = argc-1;
    int values[nelems];
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    for (int i=0; i < argc-1; i++) {
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    }
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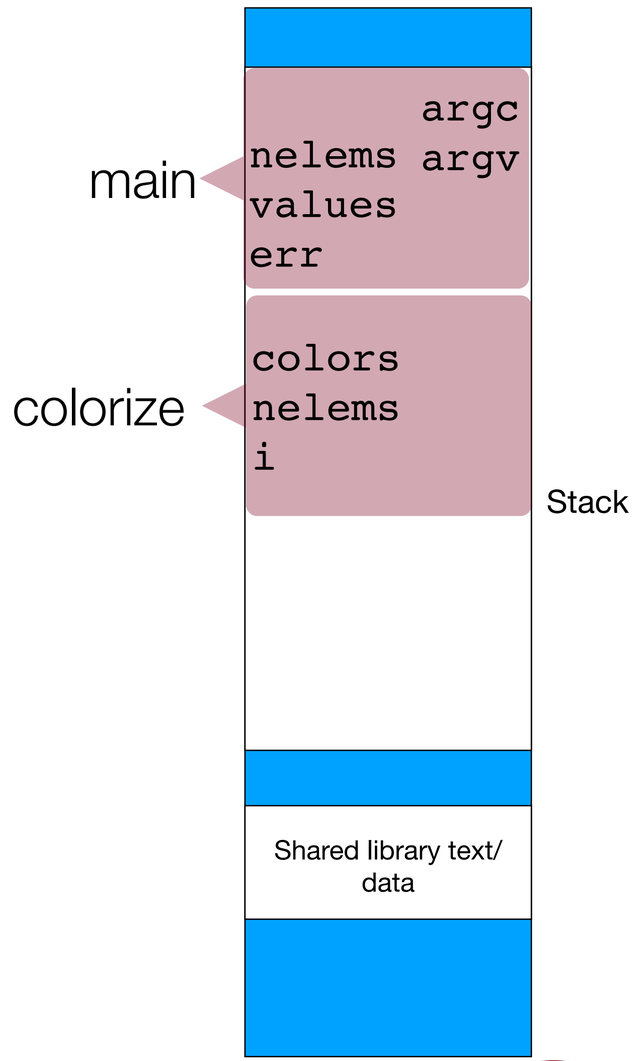
```



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{
    for (int i=0; i < nelems; i++) {
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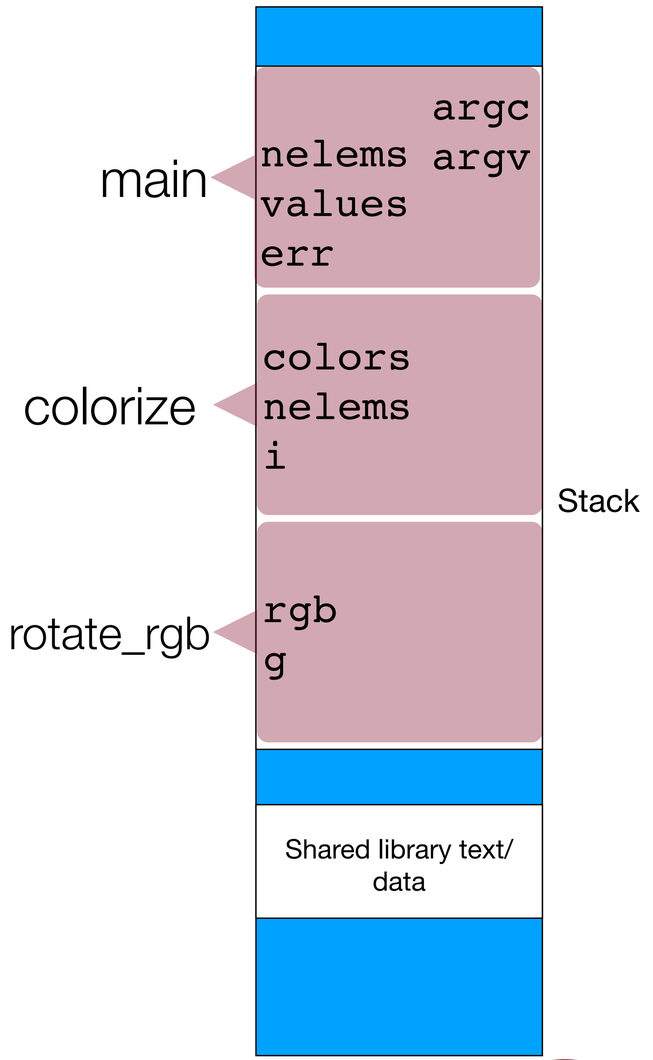
    }
}

int main(int argc, char **argv)
{
    size_t nelems = argc-1;
    int values[nelems];
    char *err;
    for (int i=0; i < argc-1; i++) {
        values[i] = strtol(argv[i+1],&err,0);
    }
    print_colors(values, nelems);
    colorize(values,sizeof(values)/sizeof(values[0]));
    print_colors(values, nelems);
    return 0;
}
```



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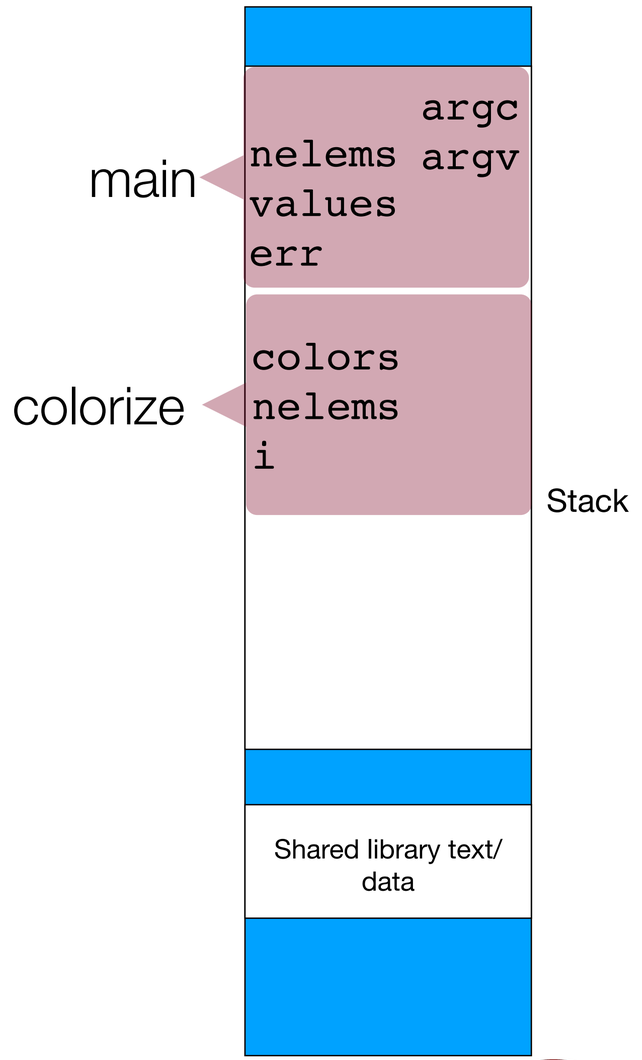
{
    for (int i=0; i < nelems; i++) {
        colors[i] = rotate_rgb(colors[i]);
    }
}

int main(int argc, char **argv)
{
    size_t nelems = argc-1;
    int values[nelems];
    char *err;
    for (int i=0; i < argc-1; i++) {
        values[i] = strtol(argv[i+1],&err,0);
    }
    print_colors(values, nelems);
    colorize(values,sizeof(values)/sizeof(values[0]));
    print_colors(values, nelems);
    return 0;
}
```



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}

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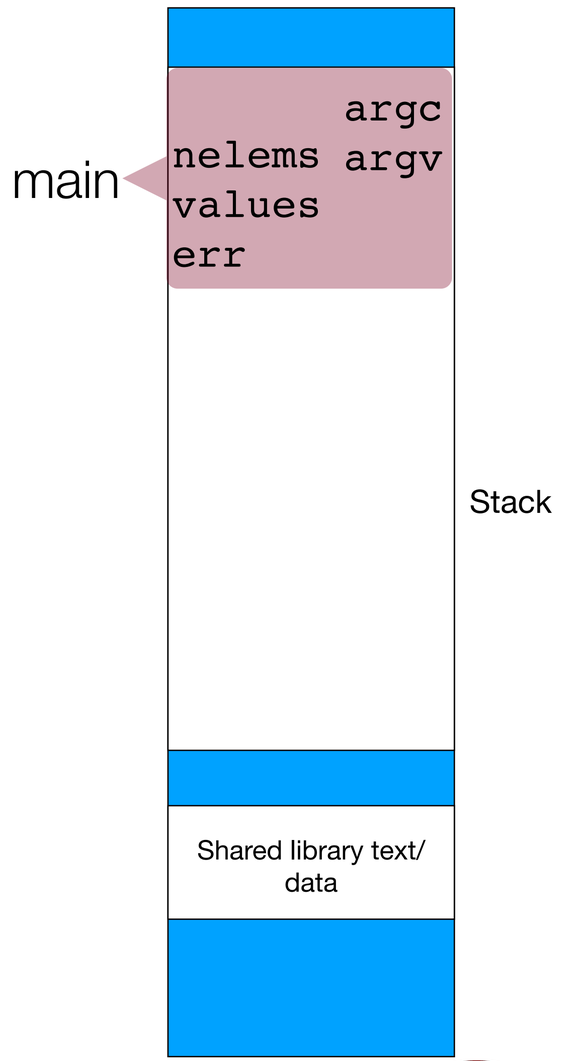
{
    for (int i=0; i < nelems; i++) {
        colors[i] = rotate_rgb(colors[i]);
    }
}

int main(int argc, char **argv)
{
    size_t nelems = argc-1;
    int values[nelems];
    char *err;
    for (int i=0; i < argc-1; i++) {
        values[i] = strtol(argv[i+1],&err,0);
    }
    print_colors(values, nelems);
    colorize(values,sizeof(values)/sizeof(values[0]));
    print_colors(values, nelems);
    return 0;
}
```



Parameter Passing

Parameters can also be put onto the stack, and they just behave like local variables.

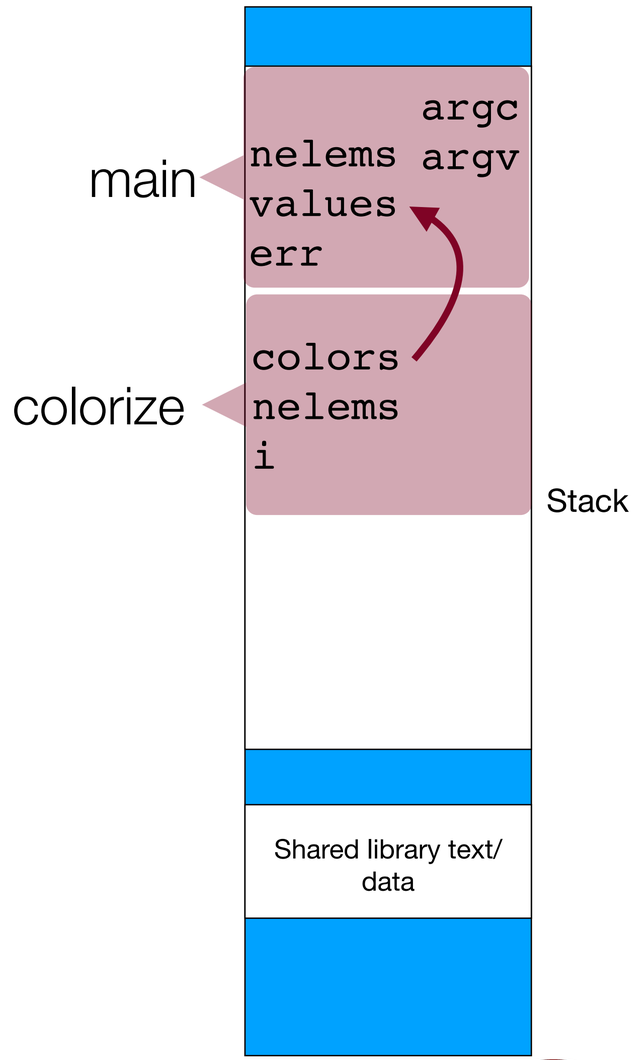
They might actually point to other elements on the stack.

In our example, colors points to the values array. Non-pointers are just copied (e.g., **`nelems`**).

```
int rotate_rgb(int rgb)
{
    // rgb -> brg
    int g = ((rgb & 0xff) << 16);
    return (rgb >> 8) | g;
}

void colorize(int *colors, size_t nelems)
{
    for (int i=0; i < nelems; i++) {
        colors[i] = rotate_rgb(colors[i]);
    }
}

int main(int argc, char **argv)
{
    size_t nelems = argc-1;
    int values[nelems];
    char *err;
    for (int i=0; i < argc-1; i++) {
        values[i] = strtol(argv[i+1],&err,0);
    }
    print_colors(values, nelems);
    colorize(values,sizeof(values)/sizeof(values[0]));
    print_colors(values, nelems);
    return 0;
}
```



Why we like stack allocation

It is fast. Allocating space on the stack is efficient because your program already has access to the memory.

It is convenient. When you leave a function, all your stack-allocated data is left in place, and there isn't anything to clean up. Think of the stack as "scratch space" where your program can jot things down when it needs them inside a function. The scope (lifetime) of the data is inside the function, so it keeps things tidy.

Type safety. You are controlling the type of the variables, and therefore the compiler can do lots of checks on the data. We will see that this isn't always the case with heap memory.

Why we dislike stack allocation

It isn't that plentiful. You're limited to 8MB of data for your program, by default (you can change this before you run the program if you want). This might seem like a good deal of space, but if your program needs more space, you can't get it from the stack!

Size fixed at declaration, with no option to resize. You can't resize an array, and once you allocate it, it is there for the lifetime of your function or block.

Limited scope. Once the function or block is finished, your stack-based memory is gone! You can't return a pointer to a stack array, for instance (well, you can, but your program will be corrupted).

Dynamic Allocation (malloc / realloc / free)

"Dynamic allocation" should be familiar to you if you took CS 106B, where you used the **`new`** and **`delete`** operators to request memory for arrays and objects.

In C, we don't have objects, but we can request memory from the heap, using three functions:

`malloc`

`calloc`

`realloc`

and we return the memory to the operating system using **`free`**.

malloc

The most common method for requesting memory from the heap is by using **`malloc`**. The function is used to allocate a specified number of bytes:

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

Size is always in **bytes**, so often you need to calculate the number of bytes with **`sizeof`** and a multiplication.

malloc returns a "**`void *`**" pointer, which basically means that you can assign the return value to any pointer. Example:

```
int *scores = malloc(20 * sizeof(int)); // allocate an array of 20 ints.
```

(In reality, this is just an allocation of 80 bytes, which the compiler will treat as an **`int`** array)

If malloc returns **`NULL`**, then there wasn't enough memory for the request. :(

calloc

`calloc` is like malloc, except that it takes two parameters which are multiplied to calculate the number of bytes, and it **zeros** the memory for you (`malloc` does not `zero` the memory!*)

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

`nmemb * size` will be bytes, so the following would be functionally equivalent:

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

// alternate (but slower)
int *scores = malloc(20 * sizeof(int)); // allocate an array of 20 ints.
for (int i=0; i < 20; i++) scores[i] = 0;
```

* it's a bit more subtle than that -- new memory that your process hasn't used before will be zeroed for security reasons by `malloc`, but if the OS re-issues you memory, it won't be zeroed.

realloc

`realloc` can be used to (potentially) change the size of the memory block pointed to by its pointer:

```
void *realloc(void *ptr, size_t size);
```

The `realloc` function returns a pointer to the memory block, which will often be the same pointer you pass in as `ptr`. If it needs to move the data, it moves it for you, `free`s the old memory, and then passes back a different pointer. If the request fails, it returns `NULL`, but the original memory is not affected (e.g., your original pointer is still valid). Example:

```
int *values = malloc(10 * sizeof(int)); // allocate space for 10 ints
... // fill up values, etc.
int *new_values = realloc(20 * sizeof(int)); // increase the memory to 20 ints
if (new_values != NULL) values = new_values;
else { ...request failed, deal with gracefully }
```

free

When a function uses **`malloc`**, **`calloc`**, and **`realloc`**, the function is responsible for returning the memory to the operating system when it no longer needs it. Un-returned memory is called a *memory leak*, and wastes memory.

To return memory, the **`free`** function is used:

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

`ptr` must point to a previously allocated block (or it can be **`NULL`**). Once a program frees memory, *it cannot be used again*. The pointer can, of course, be re-used to point elsewhere.

dynamic memory allocation example

```
// file: allocation.c
#include<stdio.h>
#include<stdlib.h>
#include<error.h>

int main(int argc, char **argv)
{
    int nelems = argc - 1;
    int *scores = malloc(nelems * sizeof(int)); // allocate an array for args.
    if (scores == NULL) {
       error(1,0,"Could not allocate memory!");
    }

    for (int i=0; i < nelems; i++) {
        scores[i] = atoi(argv[i+1]);
    }

    // let's add some more scores
    nelems += 2;
    int *new_scores = realloc(scores,nelems * sizeof(int));
    if (new_scores == NULL) {
        error(1,0,"Could not reallocate memory!");
    }
    scores = new_scores;

    scores[nelems-2] = 90;
    scores[nelems-1] = 95;

    for (int i=0; i < nelems; i++) {
        printf("%d",scores[i]);
        i == nelems - 1 ? printf("\n") : printf(",");
    }

    free(scores);

    return 0;
}
```

```
$ ./allocation 90 85 92
90,85,92,90,95
```

We can use valgrind to determine if there are memory leaks:

```
$ valgrind ./allocation 90 85 92
==6038== Memcheck, a memory error detector
==6038== Copyright (C) 2002-2015, and GNU GPL'd, by Julian Seward et al.
==6038== Using Valgrind-3.11.0 and LibVEX; rerun with -h for copyright info
==6038== Command: ./allocation 90 85 92
==6038==
90,85,92,90,95
==6038==
==6038== HEAP SUMMARY:
==6038==     in use at exit: 0 bytes in 0 blocks
==6038==   total heap usage: 3 allocs, 3 frees, 1,056 bytes allocated
==6038==
==6038== All heap blocks were freed -- no leaks are possible
==6038==
==6038== For counts of detected and suppressed errors, rerun with: -v
==6038== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 0 from 0)
```

You want to see the "All heap blocks were freed" message.

References and Advanced Reading

- **References:**
  - K&R C Programming (from our course)
  - Course Reader, C Primer
  - Awesome C book: http://books.goalkicker.com/CBook

- **Advanced Reading:**
  - virtual memory: https://en.wikipedia.org/wiki/Virtual_memory

Extra Slides

Values of variables

```
char arr1[8]; // assume arr1 is at address 0x7ffdf94d7830
char *ptr1; // assume ptr1 is at address 0x7ffdf94d77e0

char *arr2[8]; // assume arr2 is at address 0x7ffdf94d77f0
char **ptr2; // assume ptr2 is at address 0x7ffdf94d77e8
```

What values print out?

```
printf("%p\n",arr1);
printf("%lu\n",sizeof(arr1));
printf("%p\n",ptr1);
printf("%lu\n",sizeof(ptr1));

printf("%p\n",arr2);
printf("%lu\n",sizeof(arr2));
printf("%p\n",ptr2);
printf("%lu\n",sizeof(ptr1));
```

Values of variables

```
char arr1[8]; // assume arr1 is at address 0x7ffdf94d7830
char *ptr1 = 0; // assume ptr1 is at address 0x7ffdf94d77e0

char *arr2[8]; // assume arr2 is at address 0x7ffdf94d77f0
char **ptr2 = 0; // assume ptr2 is at address 0x7ffdf94d77e8
```

What values print out?

```
printf("%p\n",arr1);           // 0x7ffdf84d7830
printf("%lu\n",sizeof(arr1)); // 8
printf("%p\n",ptr1);           // 0 (or (nil))
printf("%lu\n",sizeof(ptr1)); // 8

printf("%p\n",arr2);           // 0x7ffdf94d77f0
printf("%lu\n",sizeof(arr2)); // 64
printf("%p\n",ptr2);           // 0 (or (nil))
printf("%lu\n",sizeof(ptr1)); // 8
```

Values of variables

```
char arr1[8]; // assume arr1 is at address 0x7ffdf94d7830
char *ptr1 = 0; // assume ptr1 is at address 0x7ffdf94d77e0
```

```
char *str = "a string"; // assume str has the value of 0x40073d
                        // assume str's address is 0x7ffecdcbcc38
```

What bytes get moved, and where do they move to?

```
memmove(arr1,&str,8);
memmove(&ptr1,&str,8);
memmove(arr1,str,8);
memmove(ptr1,&str,8);
```

Values of variables

```
char arr1[8]; // assume arr1 is at address 0x7ffdf94d7830
char *ptr1 = 0; // assume ptr1 is at address 0x7ffdf94d77e0
```

```
char *str = "a string"; // assume str has the value of 0x40073d
                        // assume str's address is 0x7ffecdcbcc38
```

What bytes get moved, and where do they move to?

```
memmove(arr1,&str,8);  // "0x40073d" is moved from 0x7ffecdcbcc38 to 0x7ffdf94d7830
memmove(&ptr1,&str,8); // "0x40073d" is moved from 0x7ffecdcbcc38 to 0x7ffdf94d77e0
memmove(arr1,str,8);   // "a string" (without \0) is moved from 0x40073d to
                       //                                              0x7ffdf94d7830
memmove(ptr1,&str,8);  // seg fault!
```