CS 107
Lecture 6: More Heap, and Void *

Monday, January 30, 2023

```
void swap_generic(void *arr, int index_x,
                  int index_y, int width)
{
    char tmp[width];
    void *x_loc = (char *)arr + index_x * width;
    void *y_loc = (char *)arr + index_y * width;

    memmove(tmp, x_loc, width);
    memmove(x_loc, y_loc, width);
    memmove(y_loc, tmp, width);
}
```

Computer Systems
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Stanford University
Computer Science Department

Reading: Reader: Ch 8, *Pointers, Generic functions with void *, and Pointers to Functions,* K&R Ch 1.6, 5.6-5.9

Lecturer: Chris Gregg

Today's Topics

- Logistics
  - Assign3 - out
- Reading: Reader: Ch 8, Pointers, Generic functions with void *, and Pointers to Functions

- More on heap allocation: contractual guarantees, undefined behavior
- Heap allocation, the good, the bad
- How to choose: stack or heap?
- Generic pointers, void *
  - Why we use them
  - How to use them
  - Examples

Assign3:

You will have to write a function called **`read_line`** which improves upon the terrible **`gets`** function, and the better **`fgets`** function.

You will also write two utilities, **`myuniq`** and **`mytail`**, where you will use **`read_line`** (so make it good!). Let's look at **`uniq`** and **`tail`**.

More on Heap Allocation

```
void *malloc(size_t nbytes);
void *calloc(size_t count, size_t size);
void *realloc(void *ptr, size_t nbytes);
void free(void *ptr);
```

`malloc`, **`calloc`**, and **`realloc`** guarantee:

- NULL on failure
- Memory is contiguous; the number of bytes is >= to the requested amount.
- They are not recycled unless you call free
- realloc preserves existing data
- **`calloc`** initializes bytes, **`malloc`** and **`realloc`** do not

Undefined behavior occurs when:

- If overflow (i.e., beyond bytes allocated)
- if use after **`free`**, or if **`free`** is called twice on a location.
- realloc/free non-heap address

Why do we like heap allocation?

Plentiful — you can request lots of heap memory if your program needs it.

Allocation and deallocation are under the program's control — you can precisely determine the lifetime of a block of memory.

Can resize — you can use `realloc` to resize a block.

Why don't we like heap allocation?

Only moderately efficient — The operating system needs to be involved, and it needs to search for available space, update its records, etc.

Low type safety — You get back a `void *` pointer, and that limits the compiler's ability to provide warnings.

Memory management is tricky — you have to remember to initialize, you have to keep track of how many bytes you've requested, you have to remember to `free` but to not `free` twice, etc.

Leaks possible — this is less critical, but causes programs to waste memory.

How do you choose between stack and heap allocation?

Use stack if possible, go to heap only when you must

Stack is safer, more efficient, more convenient

When is heap allocation required?

Very large allocation that could blow out stack

Dynamic construction, not known at compile-time what declarations will be needed

Need to control lifetime — memory must persist outside of function call

Need to resize memory after initial allocation

With heap, comes responsibility

Your responsibility for correct allocation at right time and right size

Your responsibility to manage the pointee type and size

Your responsibility for correct deallocation at right time, once and only once

`valgrind` is your friend!

Generic Pointers

We are now going to go into an area that I like to call "the wild west" of pointers. We are going to discuss the `void *` pointer, which is a pointer that has an unspecified pointee type. In other words, it is a pointer, but does not have a width associated with the underlying data based on some type.

You can pass `void *` pointers to and from functions, and you can assign them values with the `&` operator. E.g.,

```
int arr[] = {2, 4, 6, 8, 10};
void *arr_p1 = arr;
int *arr_p2 = arr_p1;
```


Generic Pointers

You **cannot** dereference a `void *` pointer, nor can you use pointer arithmetic with it. E.g.,

```
int arr[] = {2, 4, 6, 8, 10};

void *arr_p1 = arr;

arr_p1++; // gives compiler warning about incrementing void *

printf("%d\n", arr_p1[0]); // warns, but also causes compiler error
                           // because you cannot dereference void *
```


Generic Pointers

Why would we ever want a type where we *lose* information?

Sometimes, a function needs to be *generic* so it can deal with any type. We have seen this with **`realloc`** and **`free`**:

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

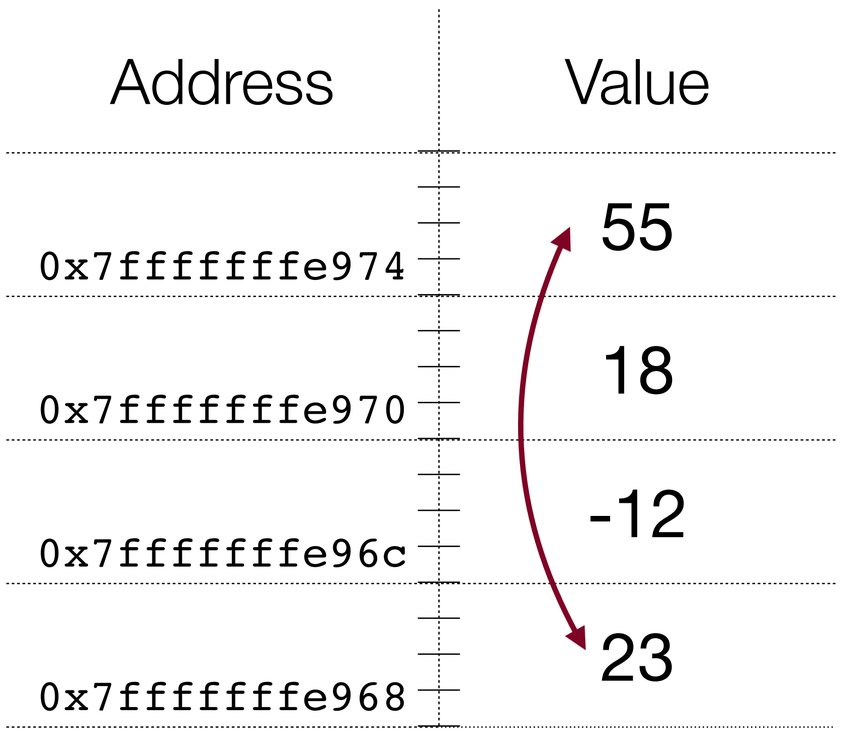
It would not be very nice if we had to have a different **`free`** function for every type of pointer!

Generic Pointers

What if you wanted to write a program to swap the first and last element in an `int` array? You might write something like this:

```
void swap_ends_int(int *arr, size_t nelems)
{
    int tmp = *arr;
    *arr = *(arr + nelems - 1);
    *(arr + nelems - 1) = tmp;
}

int main(int argc, char **argv)
{
    int i_array[]   = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);
    swap_ends_int(i_array, i_nelems);
    return 0;
}
```



Great! But what if you also wanted to swap the first and last element in a `long` array?

Generic Pointers

Great! But what if you also wanted to swap the first and last element in a **`long`** array?

```
void swap_ends_int(int *arr, size_t nelems)
{
    int tmp = *arr;
    *arr = *(arr + nelems - 1);
    *(arr + nelems - 1) = tmp;
}

void swap_ends_long(long *arr, size_t nelems)
{
    long tmp = *arr;
    *arr = *(arr + nelems - 1);
    *(arr + nelems - 1) = tmp;
}

int main(int argc, char **argv)
{
    int i_array[]   = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);
    swap_ends_int(i_array, i_nelems);

    long l_array[]  = {100, 400, 800, 200, -300, 500};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);
    swap_ends_long(l_array, l_nelems);
    return 0;
}
```

Bummer. We have to write a function that is virtually identical, with the only difference being that we handle the type of the array elements differently.

In other words, the type system is getting in the way! We would like to write a single **`swap_ends`** function that handles *any* array, but the type system foils us.

Generic Pointers

`void *` to the rescue! In this case, the pointer type gives us information about the size of the elements being pointed to (either 4-bytes for **`int`**, or 8-bytes for **`long`**, in the previous example).

By using void * and *explicitly including the width of the type*, we can write a function that can take any type as the elements to swap:

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}
```

Remember last time we showed that we can copy bytes using **`memmove`**?

We must pass the width of the elements in the array because the **`void *`** pointer doesn't carry that information.

Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr, (char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}
```

Let's look at this function in more detail. First, we have a **`void *`** pointer passed in as the array.

Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}
```

Let's look at this function in more detail. First, we have a **`void *`** pointer passed in as the array.

Next, we create a **`char`** array to hold the bytes. Remember: **`char`** is the only 1-byte type we have, and using a **`char`** array is how we can create an array that is exactly the number of bytes we want. We will use this almost every time we use **`void *`** pointers, so get used to it!

(we could also use **`malloc`** if we wanted to, but it isn't really necessary here, as the array works just fine*. Regardless, we would still use a **`char *`** pointer)

*not true for C++!

Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}
```

Let's look at this function in more detail. First, we have a **`void *`** pointer passed in as the array.

Next, we create a **`char`** array to hold the bytes. Remember: **`char`** is the only 1-byte type we have, and using a **`char`** array is how we can create an array that is exactly the number of bytes we want. We will use this almost every time we use **`void *`** pointers, so get used to it!

We copy the bytes with **`memmove`**.

Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}
```

This part takes some time to get used to!

Notice that we need a pointer to the element that we are trying to copy into. We already said that we cannot do pointer arithmetic on a **`void *`** pointer, so we first cast the pointer to **`char *`**, and then manually calculate the pointer arithmetic to get us to the correct location. In this case, because we want the last element in the array, the calculation is:

```
(char *)arr + (nelems - 1) * width
```


Generic Pointers

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}
```

In other words, what is the location of the 42?

```
(char *)arr + (nelems - 1) * width
```

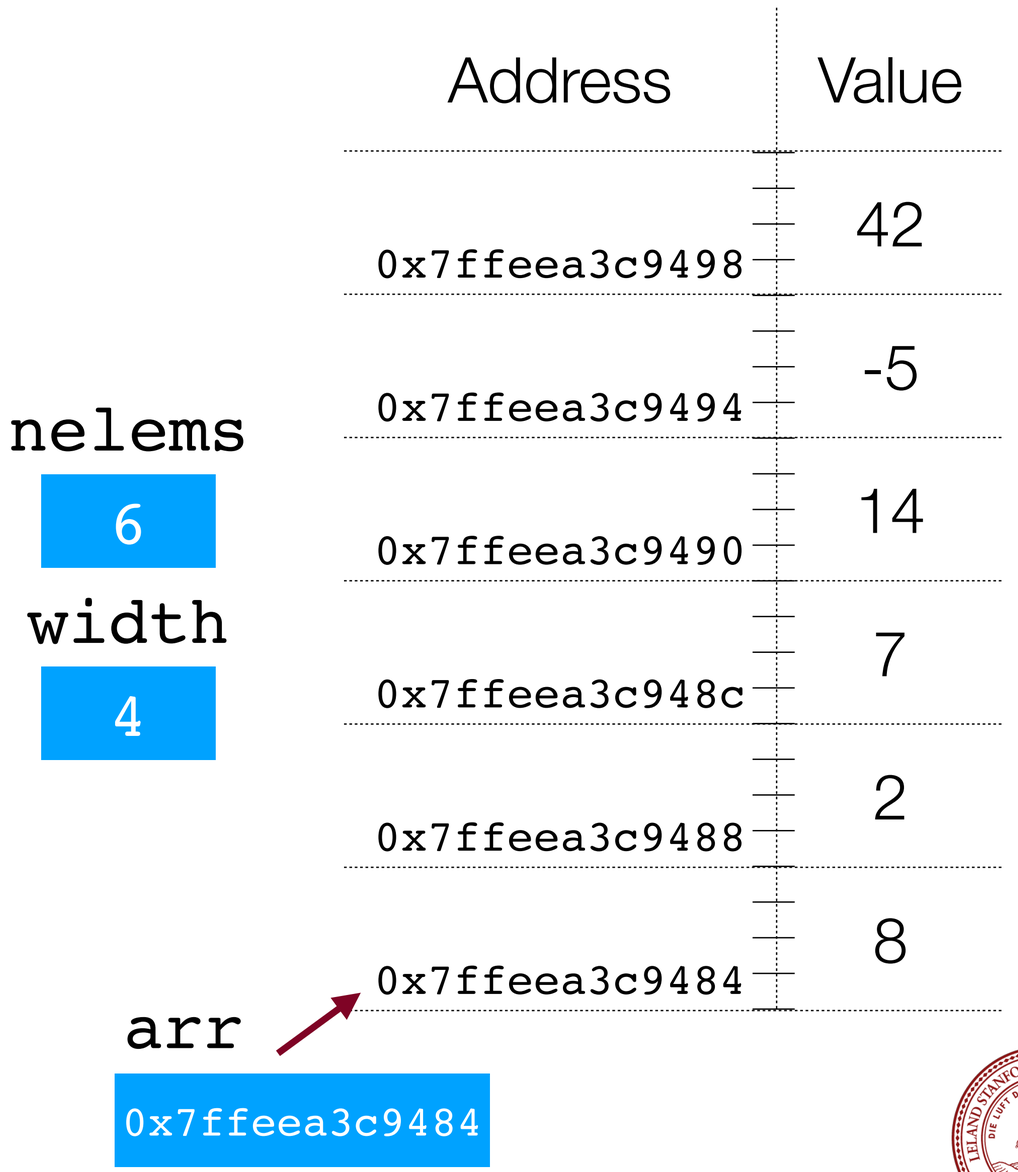
```
0x7ffeea3c9484 + (5 * 4) == 0x7ffeea3c9498
```

A key point to understand is that the pointer arithmetic increases by exactly 20 because of the **`char *`** cast, which means that +1 equals 1 byte.

Generic Pointers

Very often, we will need to find the i^{th} element in an array. You should be **extremely** familiar with the following idiom:

```
for (size_t i=0; i < nelems; i++) {
    // get ith element
    void *ith = (char *)arr + i * width;
}
```

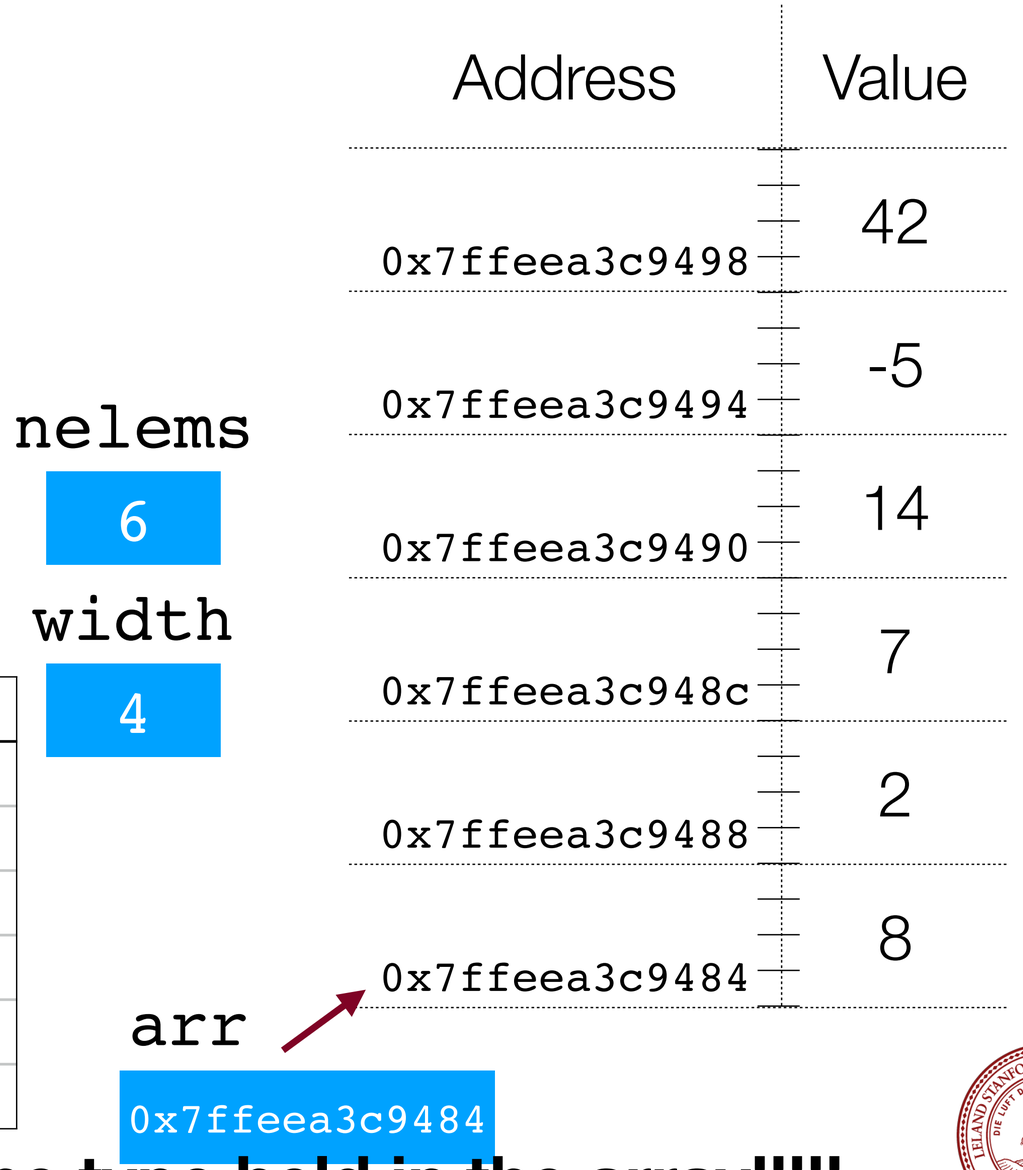


Generic Pointers

Very often, we will need to find the i^{th} element in an array. You should be **extremely** familiar with the following idiom:

```
for (size_t i=0; i < nelems; i++) {
    // get ith element
    void *ith = (char *)arr + i * width;
}
```

i	expression	result
0	(char *)0x7ffeea3c9484 + 0 * 4	0x7ffeea3c9484
1	(char *)0x7ffeea3c9484 + 1 * 4	0x7ffeea3c9488
2	(char *)0x7ffeea3c9484 + 2 * 4	0x7ffeea3c948c
3	(char *)0x7ffeea3c9484 + 3 * 4	0x7ffeea3c9490
4	(char *)0x7ffeea3c9484 + 4 * 4	0x7ffeea3c9494
5	(char *)0x7ffeea3c9484 + 5 * 4	0x7ffeea3c9498



Important! These numbers are pointers to the type held in the array!!!!!

Generic example with two different arrays

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    int i_array[]   = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    long l_array[]  = {100, 400, 800, 200, -300, 500};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(l_array, l_nelems, sizeof(l_array[0]));
  ...
```

Let's walk through this example.

First, we create an **`int`** array, then we find its size.

Generic example with two different arrays

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    int i_array[]   = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    long l_array[]  = {100, 400, 800, 200, -300, 500};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(l_array, l_nelems, sizeof(l_array[0]));
  ...
```

Let's walk through this example.

First, we create an `int` array, then we find its size.

Next, we create a long array, then we find its size.

Generic example with two different arrays

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    int i_array[]   = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    long l_array[]  = {100, 400, 800, 200, -300, 500};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(l_array, l_nelems, sizeof(l_array[0]));
    ...
```

Let's walk through this example.

First, we create an **`int`** array, then we find its size.

Next, we create a long array, then we find its size.

Then, we call swap_ends on the **`int`** array.

Note that we pass in the width, which is 4:

`sizeof(i_array[0])`

Generic example with two different arrays

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    int i_array[]   = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    long l_array[]  = {100, 400, 800, 200, -300, 500};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(l_array, l_nelems, sizeof(l_array[0]));
  ...
```

Create a char array to hold the width of the element we want to swap.

At this point, all information about the int array is gone, so we just have to rely on the **`width`** argument.

Generic example with two different arrays

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    int i_array[]   = {10, 40, 80, 20, -30, 50};
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    long l_array[]  = {100, 400, 800, 200, -300, 500};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(l_array, l_nelems, sizeof(l_array[0]));
    ...
```

Create a char array to hold the width of the element we want to swap.

At this point, all information about the int array is gone, so we just have to rely on the **`width`** argument.

Move 4 bytes from the first element in the array to **`tmp`**.

Generic example with two different arrays

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    int i_array[]   = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    long l_array[]  = {100, 400, 800, 200, -300, 500};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(l_array, l_nelems, sizeof(l_array[0]));
    ...
```

Create a char array to hold the width of the element we want to swap.

At this point, all information about the int array is gone, so we just have to rely on the **`width`** argument.

Move 4 bytes from the first element in the array to **`tmp`**.

Move 4 bytes from the last element in the array to the first element.

Generic example with two different arrays

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    int i_array[]   = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    long l_array[]  = {100, 400, 800, 200, -300, 500};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(l_array, l_nelems, sizeof(l_array[0]));
  ...
```

Create a char array to hold the width of the element we want to swap.

At this point, all information about the int array is gone, so we just have to rely on the **`width`** argument.

Move 4 bytes from the first element in the array to **`tmp`**.

Move 4 bytes from the last element in the array to the first element.

Move 4 bytes from tmp to the last position in the array.

Generic example with two different arrays

```
void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    int i_array[]   = {10, 40, 80, 20, -30, 50};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    long l_array[]  = {100, 400, 800, 200, -300, 500};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    swap_ends(i_array, i_nelems, sizeof(i_array[0]));
    swap_ends(l_array, l_nelems, sizeof(l_array[0]));
  ...
```


Repeat the process for the long array, which will pass in a **`width`** of 8:

```
sizeof(l_array[0]);
```

It's really generic

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

void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    swap_ends(argv, argc, sizeof(argv[0]));
    for (int i=0; i < argc; i++) {
       printf("%s\n",argv[i]);
    }
    return 0;
}
```


We've seen that this function works on elements of an integer type.

The beauty is that it will work on ***any*** array. What about **`char **`** arrays, like **`argv`**? Sure — **`argv`** is a pointer to an array, and we'll be swapping pointers, not moving string **`char`**s.

```
$ gcc -g -O0 -std=gnu99 -Wall
  prog_name_to_end.c  -o
  prog_name_to_end
$ ./prog_name_to_end abc def ghi
ghi
abc
def
./prog_name_to_end
```

It's really generic

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

void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    swap_ends(argv, argc, sizeof(argv[0]));
    for (int i=0; i < argc; i++) {
       printf("%s\n",argv[i]);
    }
    return 0;
}
```

What is the type of `argv[0]`?

It's really generic

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

void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    swap_ends(argv, argc, sizeof(argv[0]));
    for (int i=0; i < argc; i++) {
       printf("%s\n",argv[i]);
    }
    return 0;
}
```

What is the type of `argv[0]`?

`char *`

It's really generic

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

void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    swap_ends(argv, argc, sizeof(argv[0]));
    for (int i=0; i < argc; i++) {
       printf("%s\n",argv[i]);
    }
    return 0;
}
```

What is the type of `argv[0]`?

`char *`

What is `sizeof(argv[0])` ?

It's really generic

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

void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    swap_ends(argv, argc, sizeof(argv[0]));
    for (int i=0; i < argc; i++) {
       printf("%s\n",argv[i]);
    }
    return 0;
}
```

What is the type of `argv[0]`?

`char *`

What is `sizeof(argv[0])` ?

8

It's really generic

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

void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    swap_ends(argv, argc, sizeof(argv[0]));
    for (int i=0; i < argc; i++) {
       printf("%s\n",argv[i]);
    }
    return 0;
}
```

What is the type of `argv[0]`?

`char *`

What is `sizeof(argv[0])` ?

8

What is the type of `argv`?

It's really generic

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

void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    swap_ends(argv, argc, sizeof(argv[0]));
    for (int i=0; i < argc; i++) {
       printf("%s\n",argv[i]);
    }
    return 0;
}
```

What is the type of `argv[0]`?

`char *`

What is `sizeof(argv[0])` ?

8

What is the type of `argv`?

`char **`

It's really generic

```
// file: prog_name_to_end.c
#include<stdio.h>
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void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    swap_ends(argv, argc, sizeof(argv[0]));
    for (int i=0; i < argc; i++) {
       printf("%s\n",argv[i]);
    }
    return 0;
}
```

What is the type of **`argv[0]`**?

`char *`

What is **`sizeof(argv[0])`** ?

8

What is the type of **`argv`**?

`char **`

What is the underlying type (unknown to the function) of **`arr`** in **`swap_ends`**?

It's really generic

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

void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    swap_ends(argv, argc, sizeof(argv[0]));
    for (int i=0; i < argc; i++) {
       printf("%s\n",argv[i]);
    }
    return 0;
}
```

What is the type of **`argv[0]`**?

`char *`

What is **`sizeof(argv[0])`** ?

8

What is the type of **`argv`**?

`char **`

What is the underlying type (unknown to the function) of **`arr`** in **`swap_ends`**?

`char **`

It's really generic

```
// file: prog_name_to_end.c
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#include<stdlib.h>
#include<string.h>

void swap_ends(void *arr, size_t nelems, int width)
{
    // allocate space for the copy
    char tmp[width];

    // copy the first element to tmp
    memmove(tmp, arr, width);

    // copy the last element to the first
    memmove(arr,(char *)arr + (nelems - 1) * width, width);

    // copy tmp to the last element
    memmove((char *)arr + (nelems - 1) * width, tmp, width);
}

int main(int argc, char **argv)
{
    swap_ends(argv, argc, sizeof(argv[0]));
    for (int i=0; i < argc; i++) {
       printf("%s\n", argv[i]);
    }
    return 0;
}
```

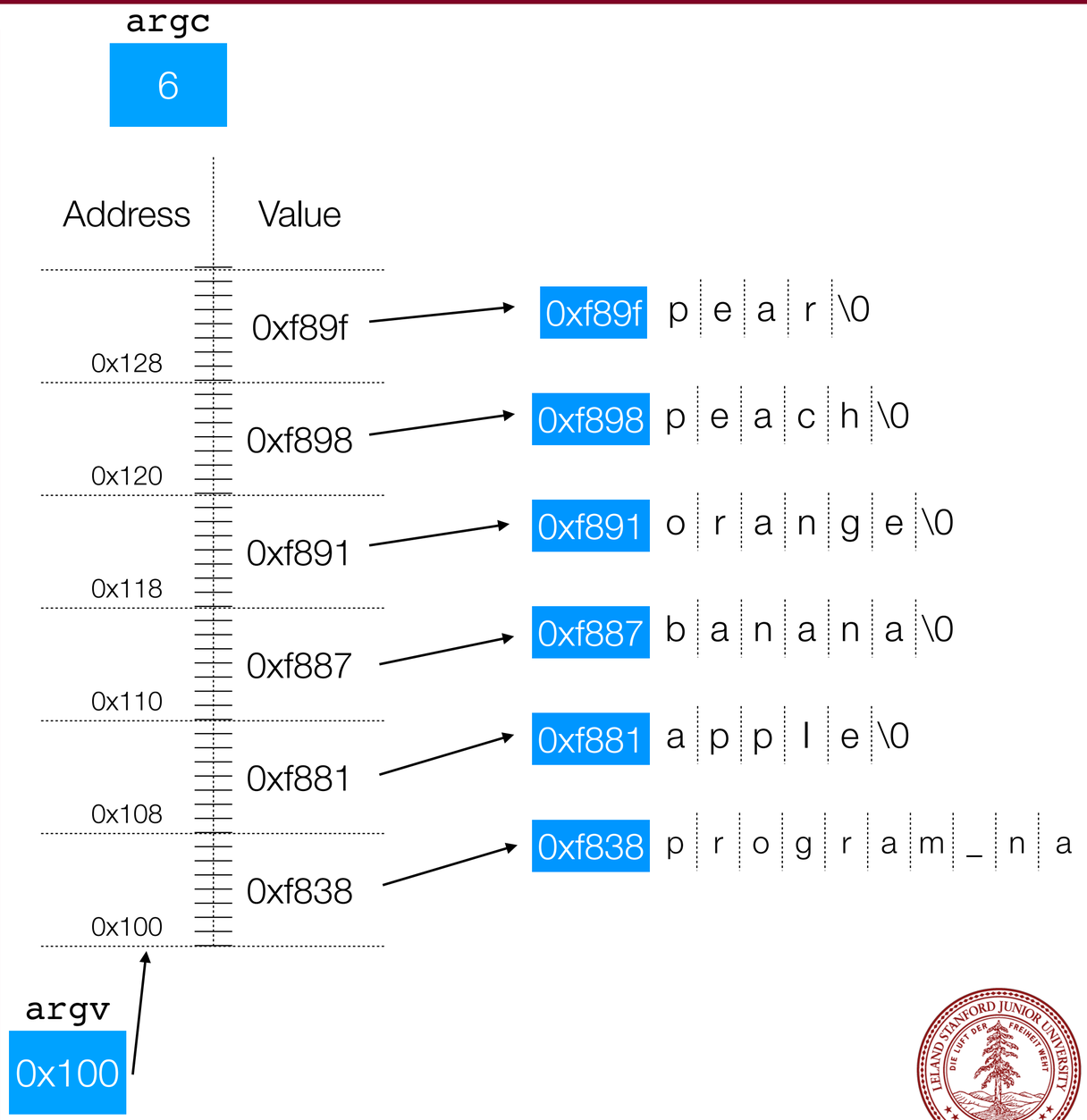

Getting more out of void *

Now it is time to really ramp up the up the generic nature of `void *` pointers.

So far, we've seen how we can manipulate array elements by knowing their width. But we can't do much else with them — sometimes you really do need to know the underlying type to be able to work with a piece of data!

For example, what if we wanted to print arrays generically. In other words, we want a function like this:

```
void print_array(void *arr, size_t nelems, int width)
```

We want the function to print the elements. What challenges are there in this case?

Getting more out of void *

The challenges are that we have no idea how to print something pointed to by a **`void *`**!

Let's make a first attempt at our function:

```
void print_array(void *arr,size_t nelems,int width)
{
    for (int i=0; i < nelems; i++) {
        void *element = (char *)arr + i * width;
        printf("%?", element);
        i == nelems - 1 ? printf("\n") : printf(", ");
    }
}
```

Houston, we have a problem.

Getting more out of void *

The challenges are that we have no idea how to print something pointed to by a **`void *`**!

Let's make a first attempt at our function:

```
void print_array(void *arr,size_t nelems,int width)
{
    for (int i=0; i < nelems; i++) {
        void *element = (char *)arr + i * width;
        printf("%?",element);
        i == nelems - 1 ? printf("\n") : printf(", ");
    }
}
```

Houston, we have a problem. What goes in the format string for the **`printf`** call?

Getting more out of void *

The challenges are that we have no idea how to print something pointed to by a **`void *`**!

Let's make a first attempt at our function:

```
void print_array(void *arr, size_t nelems, int width)
{
    for (int i=0; i < nelems; i++) {
        void *element = (char *)arr + i * width;
        printf("%?",element);
        i == nelems - 1 ? printf("\n") : printf(", ");
    }
}
```

Houston, we have a problem. What goes in the format string for the **`printf`** call?

We have no idea! Because we don't know *what* the elements in **`arr`** are, we have no hope to print them correctly. They could be **`float`**s, **`char`**s, **`int`**s, **`char *`**s, etc…

Function pointers

Wouldn't it be nice if we could have the *calling function* tell us how to print the elements in the array?

Well, we can!

In C, we are allowed to pass *function pointers* as parameters to other functions. A function pointer tells the other function, "Hey, run this function on the element when you get to it!" The other function has no idea what type it will work on, but it just runs the function with the element and gets back the result, which it can use to perform more work.

In this way, we can write a generic function to do something, but when it works on each element, it uses the other function to do the work.

Function pointers

The function pointer syntax is a bit strange. Here is an example:

```
void (*myfunc)(int);
```

This says, there is a function called **`myfunc`** that takes one **`int`** parameter and returns **`void`** (no return value).

Let's look at a more detailed example:

```
void *(*myfunc)(int *);
```

You read this "inside out" — this is a function called **`myfunc`** that takes an **`int *`** parameter, and returns a **`void *`** pointer.

Function pointers

You can use the website cdecl.org (or the program, **`cdecl`** on Myth) to get details about the type if you have trouble figuring it out:

```
$ cdecl explain "void (*myfunc)(int)"
declare myfunc as pointer to function (int) returning void

$ cdecl explain "void *(*myfunc)(int *)"
declare myfunc as pointer to function (pointer to int)
returning pointer to void

$ cdecl explain "long *(*myfunc)(void *, char, char *)"
declare myfunc as pointer to function (pointer to void,
char, pointer to char) returning pointer to long
```


Function pointers

Let's go back to our print array elements example:

```
void print_array(void *arr, size_t nelems, int width)
{
    for (int i=0; i < nelems; i++) {
        void *element = (char *)arr + i * width;
        printf("%?", element);
        i == nelems - 1 ? printf("\n") : printf(", ");
    }
}
```

Instead of **`printf`**, we want to call a function that knows how to print the data. We want a function that takes a **`void *`** element pointer, and then prints it.

Function pointers

Something like this:

```
void print_array(void *arr, size_t nelems, int width, void (*pr_func)(void *))
{
    for (int i=0; i < nelems; i++) {
        void *element = (char *)arr + i * width;
        pr_func(element);
        i == nelems - 1 ? printf("\n") : printf(", ");
    }
}
```

In other words, we need to pass in a function (called **`pr_func`** in this case), that will do the printing for us.

Function pointers

Something like this:

```
void print_array(void *arr, size_t nelems, int width, void (*pr_func)(void *))
{
    for (int i=0; i < nelems; i++) {
        void *element = (char *)arr + i * width;
        pr_func(element);
        i == nelems - 1 ? printf("\n") : printf(", ");
    }
}
```

In other words, we need to pass in a function (called **`pr_func`** in this case), that will do the printing for us.

Function pointers

Something like this:

```
void print_array(void *arr, size_t nelems, int width, void (*pr_func)(void *))
{
    for (int i=0; i < nelems; i++) {
        void *element = (char *)arr + i * width;
        pr_func(element);
        i == nelems - 1 ? printf("\n") : printf(", ");
    }
}
```

In other words, we need to pass in a function (called **`pr_func`** in this case), that will do the printing for us.

The calling function provides the function pointer, and the function pointer is specific to the type of data stored in the array.

Function pointers

Let's write a function pointer that will print **`int`** elements.

```
void print_int(void *arr)
{
    int i = *(int *)arr;
    printf("%d",i);
}
```

When you have a function like this, it does know the type of the data stored in the **`void *`** pointer! We created this function *specifically to print* ***`int`****s*, so it knows that it has an **`int`** pointer, and we can cast it to that pointer.

Function pointers

Let's write a function pointer that will print **`int`** elements.

```
void print_int(void *arr)
{
    int i = *(int *)arr;
    printf("%d",i);
}
```

When you have a function like this, it does know the type of the data stored in the **`void *`** pointer! We created this function *specifically to print* ***`int`****s*, so it knows that it has an int pointer, and we can cast it to that pointer.

If we know it is an int pointer, why can't we just have the following function definition?

```
void print_int(int *arr)
```


We can't, because the print_arr function required a generic function.

Function pointers

Here is our full example:

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

void print_array(void *arr, size_t nelems, int
                 width, void(*pr_func)(void *))
{
    for (int i=0; i < nelems; i++) {
        void *element = (char *)arr + i * width;
        pr_func(element);
        i == nelems - 1 ? printf("\n") : printf(", ");
    }
}

void print_int(void *arr)
{
    int i = *(int *)arr;
    printf("%d", i);
}

void print_long(void *arr)
{
    long l = *(long *)arr;
    printf("%ld", l);
}
```

```
int main(int argc, char **argv)
{
    int i_array[] = {0, 1, 2, 3, 4, 5};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    long l_array[] = {0, 10, 20, 30, 40, 50};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    print_array(i_array, i_nelems,sizeof(i_array[0]), print_int);
    print_array(l_array, l_nelems,sizeof(l_array[0]), print_long);

    return 0;
}
```


Function pointers

Here is our full example:

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

void print_array(void *arr, size_t nelems, int
                  width, void(*pr_func)(void *))
{
    for (int i=0; i < nelems; i++) {
        void *element = (char *)arr + i * width;
        pr_func(element);
        i == nelems - 1 ? printf("\n") : printf(", ");
    }
}

void print_int(void *arr)
{
    int i = *(int *)arr;
    printf("%d", i);
}

void print_long(void *arr)
{
    long l = *(long *)arr;
    printf("%ld", l);
}
```

```
int main(int argc, char **argv)
{
    int i_array[] = {0, 1, 2, 3, 4, 5};
    size_t i_nelems = sizeof(i_array) / sizeof(i_array[0]);

    long l_array[] = {0, 10, 20, 30, 40, 50};
    size_t l_nelems = sizeof(l_array) / sizeof(l_array[0]);

    print_array(i_array, i_nelems,sizeof(i_array[0]), print_int);
    print_array(l_array, l_nelems,sizeof(l_array[0]), print_long);

    return 0;
}
```

Note that when you pass a function pointer, you don't need to use "**&**" because it is implied (though you can if you want).

Function pointers

For our print_array function, we can have the printing do anything we want!

Let's look at the **`printf_coordinates.c`** file from **`/afs/ir/class/cs107/lecture-code/lect6`**

Also available in the course reader: http://stanford.edu/~cgregg/107-Reader/107-Reader-code.zip

Look in **`code/Ch8_C_Low_Level`**

C standard library example: `qsort`

The C standard library has a number of functions that expect function pointers. The `qsort` function is one of them:

```
void qsort(void *base, size_t nmemb, size_t size,
           int (*compar)(const void *, const void *));
```

The `base`, `nmemb`, and `size` variables are just standard pointer-to-array details. The `compar` function is a comparison function that expects two elements from the array, and will perform a comparison on them. This is a standard comparison with the following return `int` value possibilities:

negative: the first element is less than the second element
zero: the elements are equal
positive: the first element is greater than the second element

C standard library example: `qsort`

The C standard library has a number of functions that expect function pointers. The **`qsort`** function is one of them:

```
void qsort(void *base, size_t nmemb, size_t size,
           int (*compar)(const void *, const void *));
```

If you want to use the **`qsort`** function, you need to write a **`compar`** function yourself. Sometimes, we just need to build a function that utilizes another built-in function, like **`strcmp`**, to do the work:

```
int compar_str(const void *s1, const void *s2) {
    return strcmp(*(char **)s1, *(char **)s2);
}
```


C standard library example: `qsort`

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```
void qsort(void *base, size_t nmemb, size_t size,
           int (*compar)(const void *, const void *));
```

If you want to use the **`qsort`** function, you need to write a **`compar`** function yourself. Sometimes, we just need to build a function that utilizes another built-in function, like **`strcmp`**, to do the work:

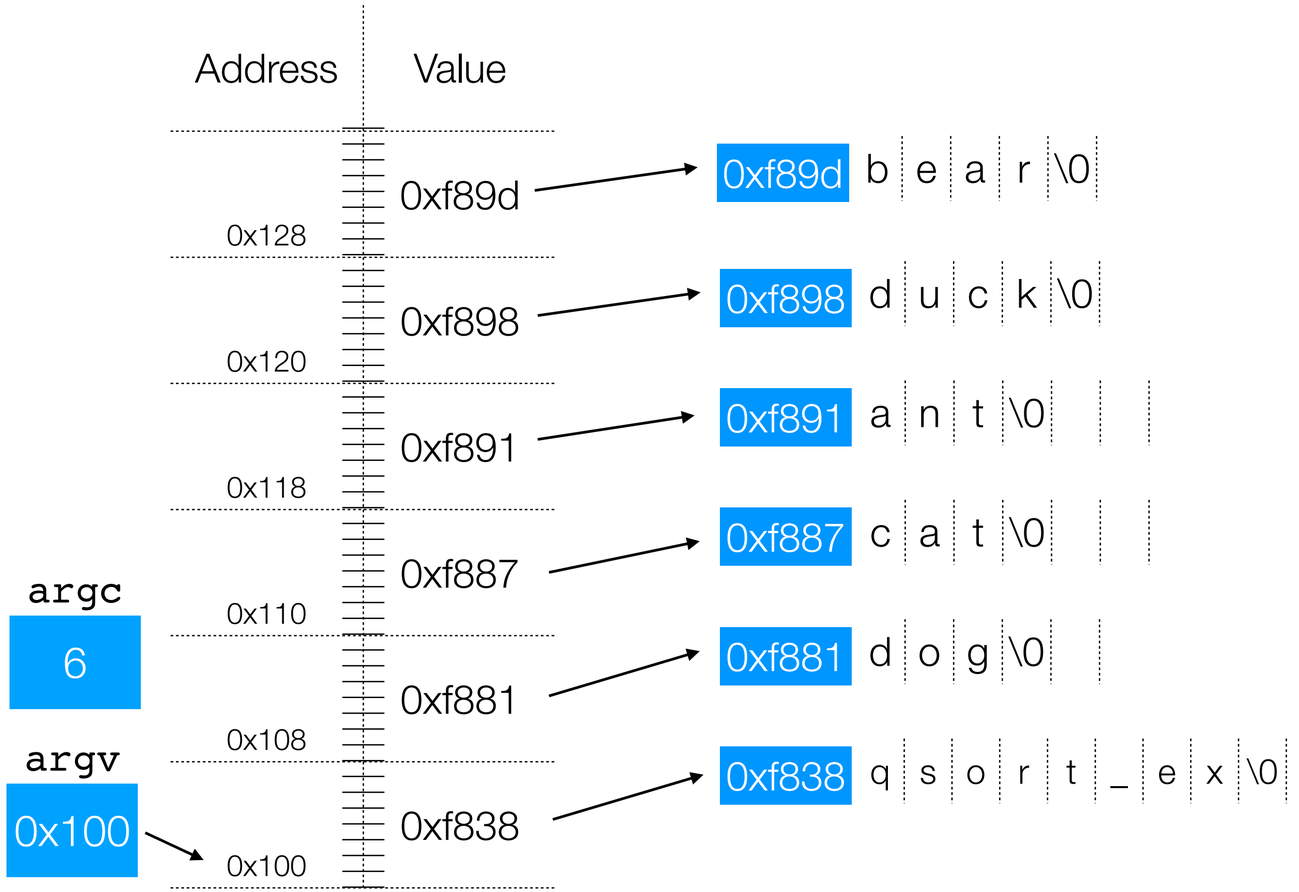
```
int compar_str(const void *s1, const void *s2) {
    return strcmp(*(char **)s1, *(char **)s2);
}
```

Important! Look at the type of **`s1`** and **`s2`** in the comparison function! This is a case where we must draw the situation!

C standard library example: `qsort` full example

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

int compar_str(const void *s1, const void *s2) {
    return strcmp(*(char **)s1, *(char **)s2);
}

int main(int argc, char **argv)
{
    // ignore program name
    argc--;
    argv++;

    qsort(argv, argc, sizeof(argv[0]), compar_str);
    for (int i=0; i < argc; i++) {
        printf("%s", argv[i]);
        i == argc - 1 ? printf("\n") : printf(", ");
    }

    return 0;
}
```

```
$ ./qsort_ex dog cat ant duck bear
ant bear cat dog duck
```

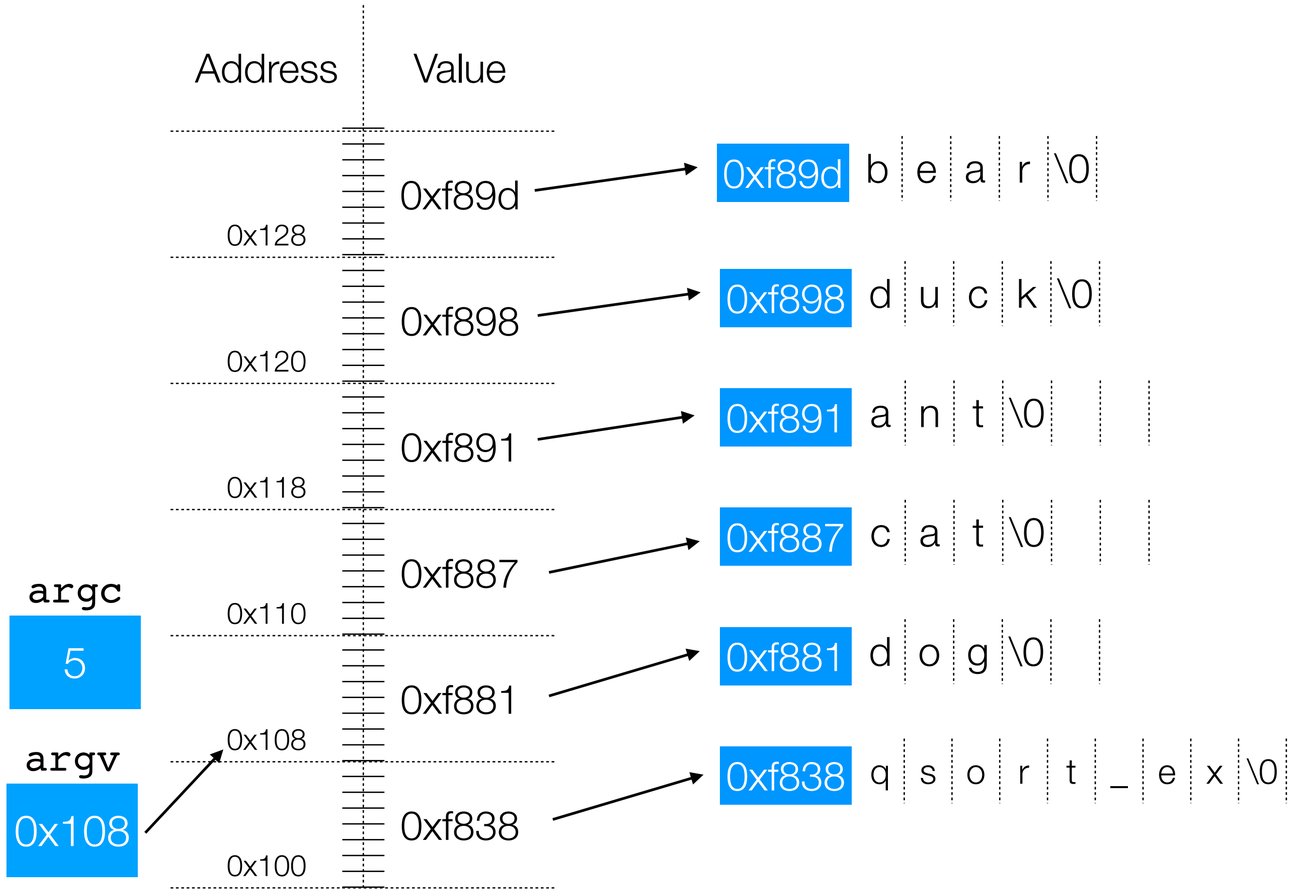



At this point in the program, this is what the situation looks like.

C standard library example: `qsort` full example

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

int compar_str(const void *s1, const void *s2) {
    return strcmp(*(char **)s1, *(char **)s2);
}

int main(int argc, char **argv)
{
    // ignore program name
    argc--;
    argv++;

    qsort(argv, argc, sizeof(argv[0]), compar_str);
    for (int i=0; i < argc; i++) {
        printf("%s", argv[i]);
        i == argc - 1 ? printf("\n") : printf(", ");
    }

    return 0;
}
```

```
$ ./qsort_ex dog cat ant duck bear
ant bear cat dog duck
```

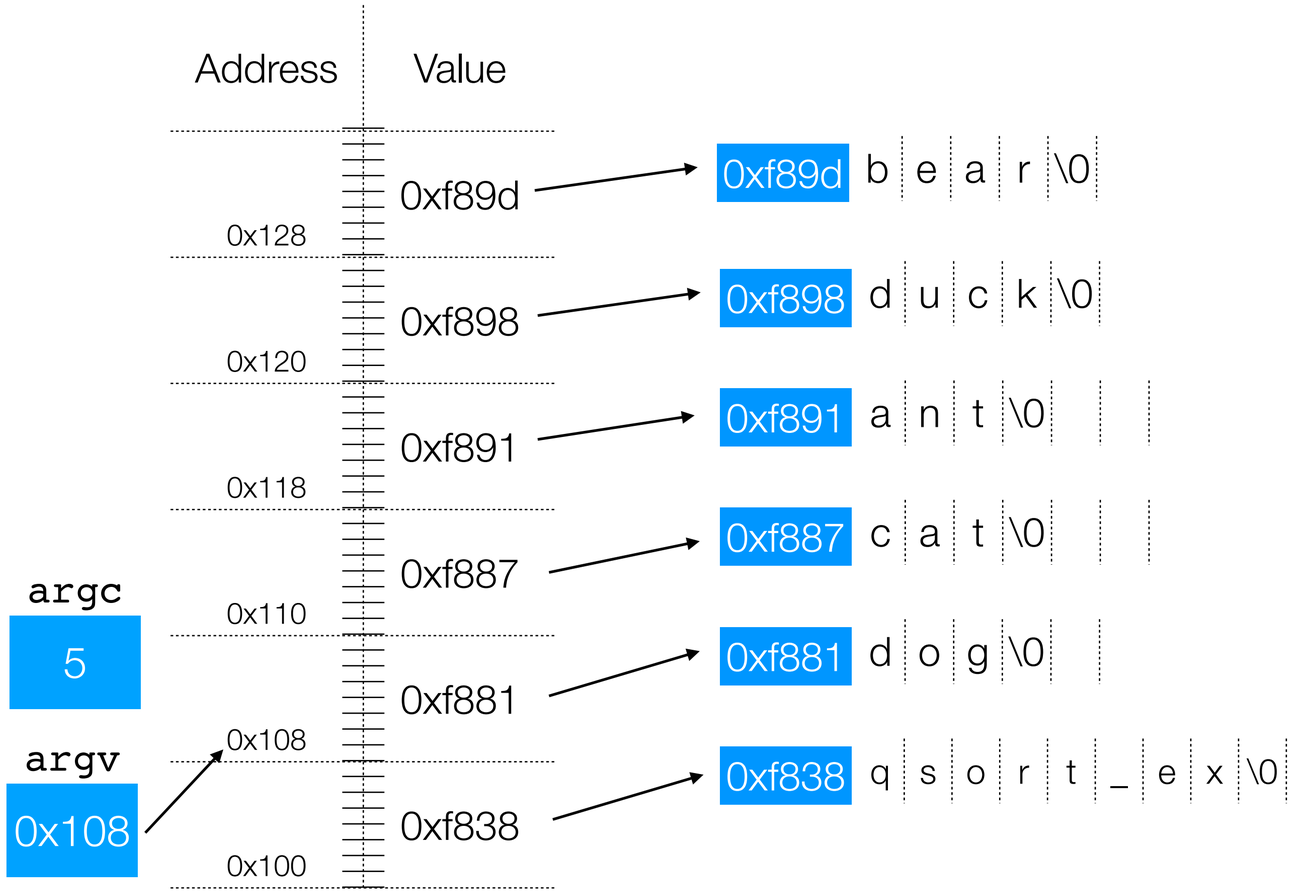



We have updated **`argc`** and **`argv`** to ignore the program name.

C standard library example: `qsort` full example

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

int compar_str(const void *s1, const void *s2) {
    return strcmp(*(char **)s1, *(char **)s2);
}

int main(int argc, char **argv)
{
    // ignore program name
    argc--;
    argv++;

    qsort(argv, argc, sizeof(argv[0]), compar_str);
    for (int i=0; i < argc; i++) {
        printf("%s", argv[i]);
        i == argc - 1 ? printf("\n") : printf(", ");
    }

    return 0;
}
```

```
$ ./qsort_ex dog cat ant duck bear
ant bear cat dog duck
```

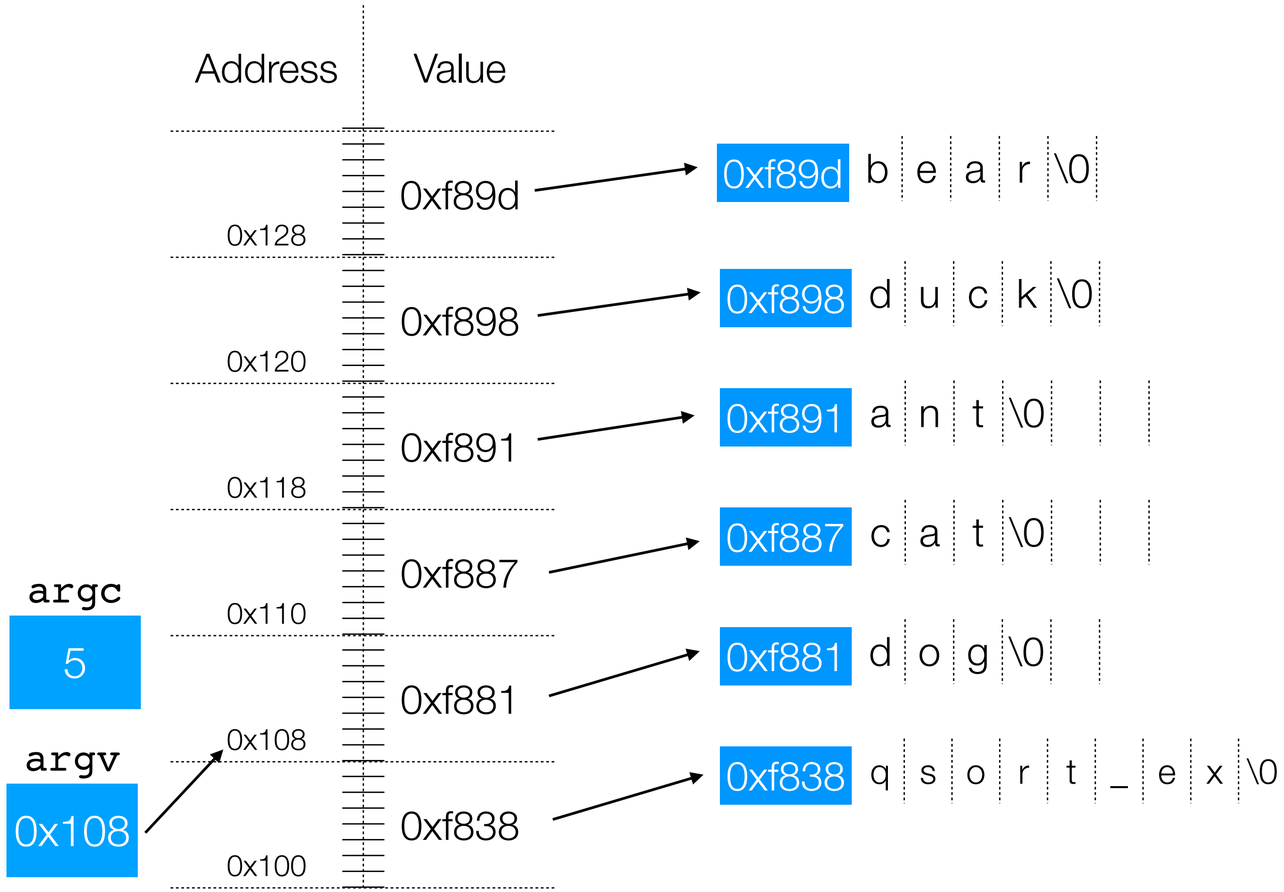



Based on the diagram above, what number gets passed as the first argument of `qsort`?

C standard library example: `qsort` full example

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

int compar_str(const void *s1, const void *s2) {
    return strcmp(*(char **)s1, *(char **)s2);
}

int main(int argc, char **argv)
{
    // ignore program name
    argc--;
    argv++;

    qsort(argv, argc, sizeof(argv[0]), compar_str);
    for (int i=0; i < argc; i++) {
        printf("%s", argv[i]);
        i == argc - 1 ? printf("\n") : printf(", ");
    }

    return 0;
}
```

```
$61./qsort_ex dog cat ant duck bear
ant bear cat dog duck
```

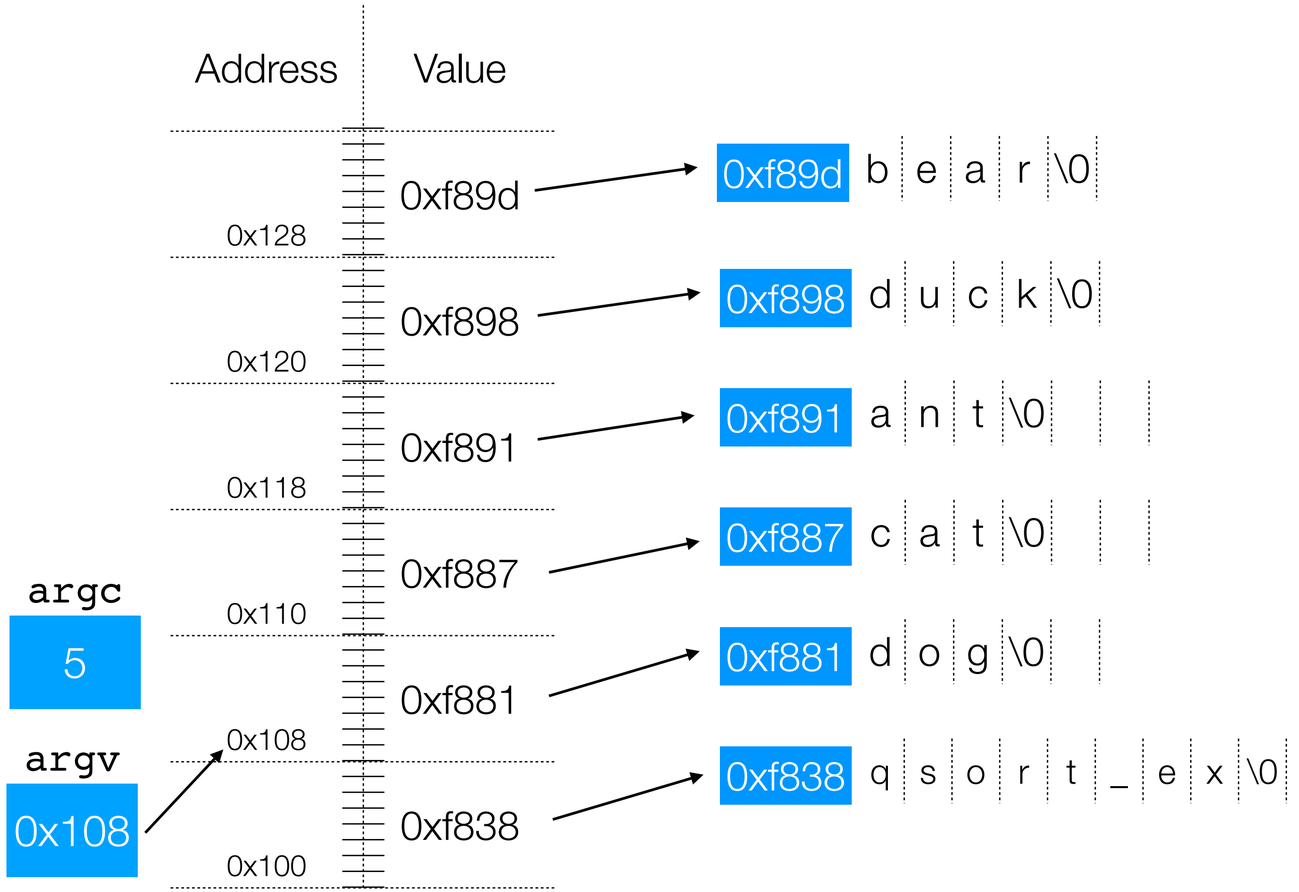


Based on the diagram above, what number gets passed as the first argument of `qsort`? **0x108**

C standard library example: `qsort` full example

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

int compar_str(const void *s1, const void *s2) {
    return strcmp(*(char **)s1, *(char **)s2);
}

int main(int argc, char **argv)
{
    // ignore program name
    argc--;
    argv++;

    qsort(argv, argc, sizeof(argv[0]), compar_str);
    for (int i=0; i < argc; i++) {
        printf("%s", argv[i]);
        i == argc - 1 ? printf("\n") : printf(", ");
    }

    return 0;
}
```

```
$ ./qsort_ex dog cat ant duck bear
ant bear cat dog duck
```

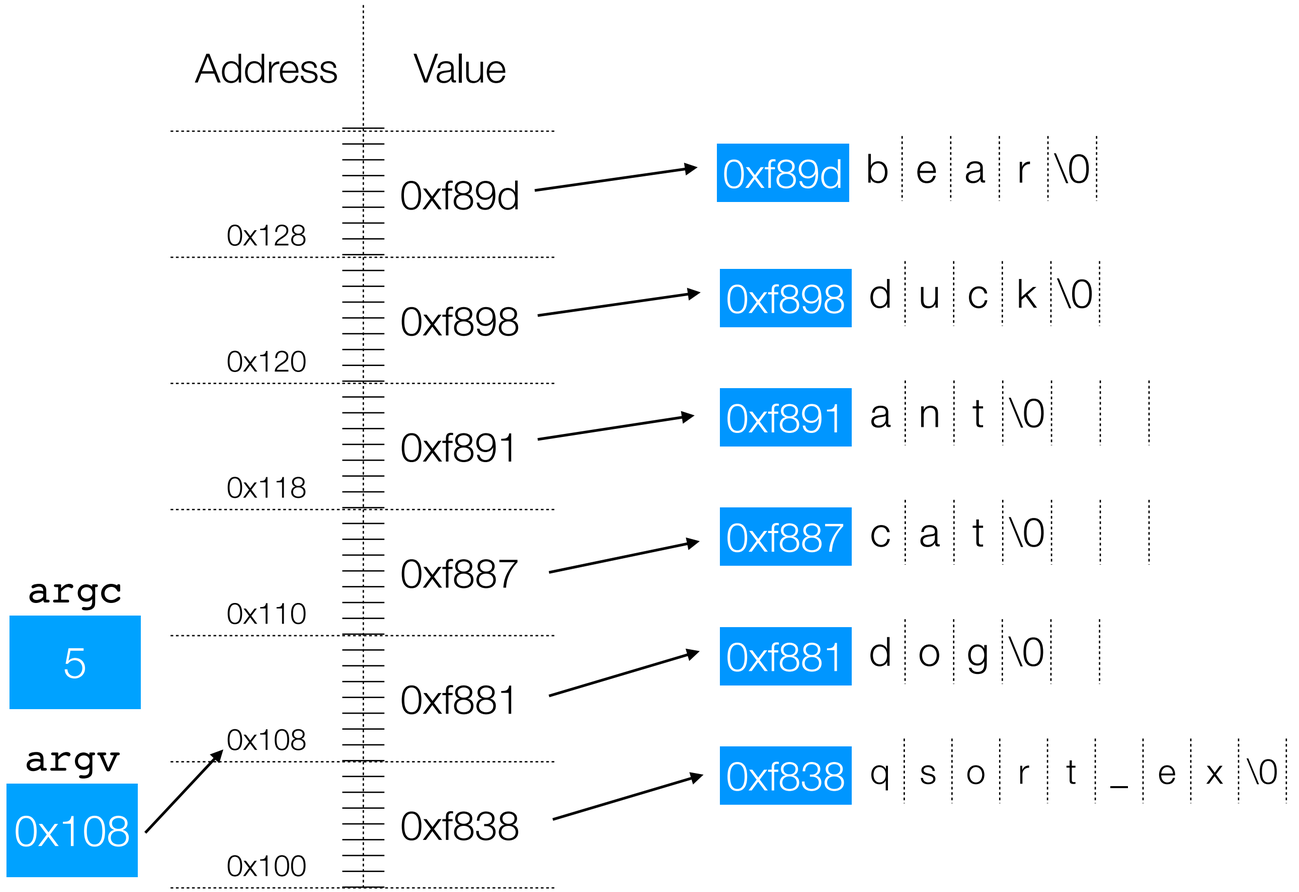



`qsort` has no way to dereference `argv`, so it can **only** pass char ** pointers to sort (e.g., `0x108`, `0x110`)

C standard library example: `qsort` full example

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

int compar_str(const void *s1, const void *s2) {
    return strcmp(*(char **)s1, *(char **)s2);
}

int main(int argc, char **argv)
{
    // ignore program name
    argc--;
    argv++;

    qsort(argv, argc, sizeof(argv[0]), compar_str);
    for (int i=0; i < argc; i++) {
        printf("%s", argv[i]);
        i == argc - 1 ? printf("\n") : printf(", ");
    }

    return 0;
}
```

```
$ ./qsort_ex dog cat ant duck bear
ant bear cat dog duck
```

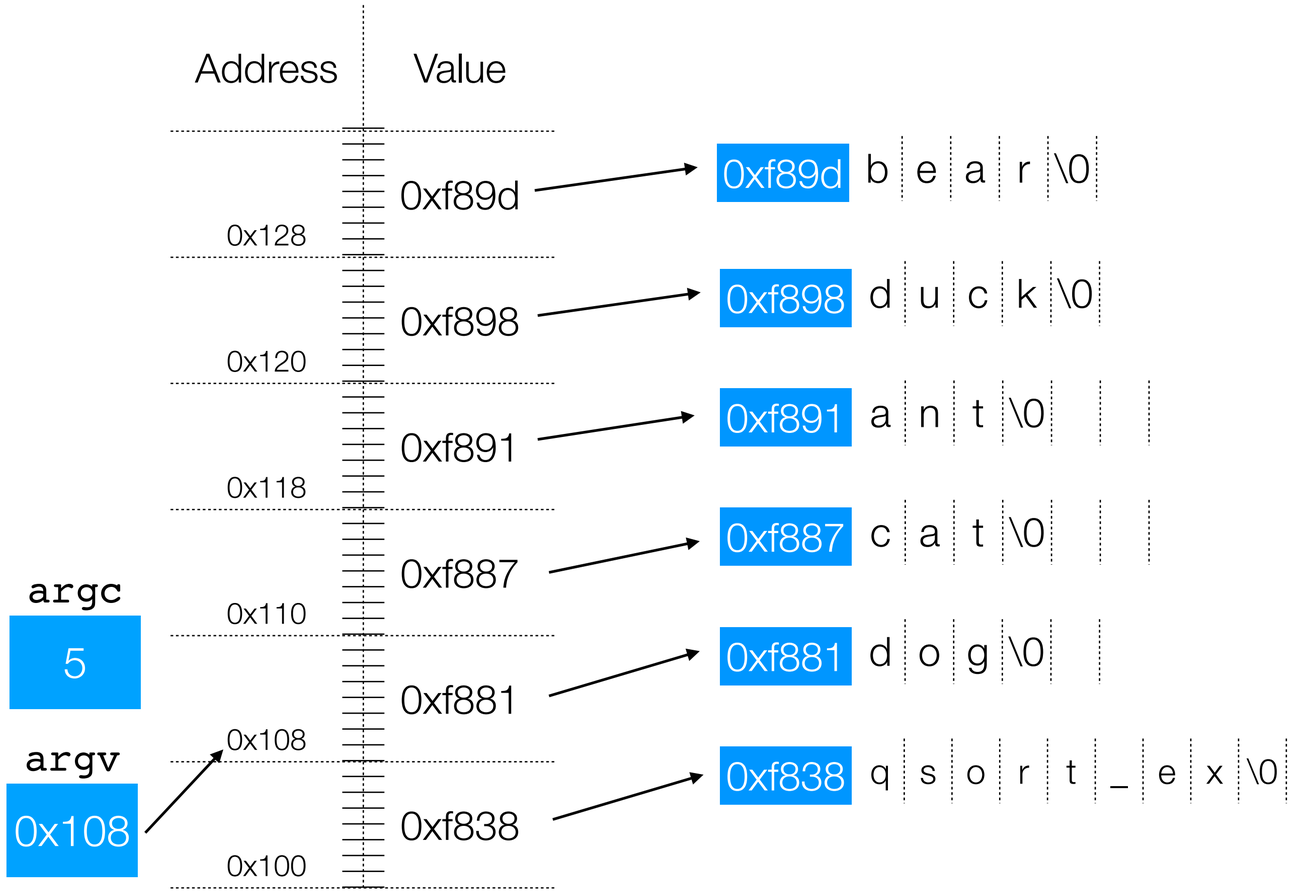


Therefore, the type that gets passed to `compar_str` **must** be char ** pointers. (e.g., `0x108`, `0x110`)

C standard library example: `qsort` full example

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

int compar_str(const void *s1, const void *s2) {
    return strcmp(*(char **)s1, *(char **)s2);
}

int main(int argc, char **argv)
{
    // ignore program name
    argc--;
    argv++;

    qsort(argv, argc, sizeof(argv[0]), compar_str);
    for (int i=0; i < argc; i++) {
        printf("%s", argv[i]);
        i == argc - 1 ? printf("\n") : printf(", ");
    }

    return 0;
}
```

```
$64./qsort_ex dog cat ant duck bear
ant bear cat dog duck
```



So, we are correct to cast **`s1`** and **`s2`** to **`char **`**, and then dereference to get **`char *`** to pass to **`strcmp`**.

Function pointers

Function pointer takeaways:

1. Function pointers allow us to add generic features to our functions, so that even if the function doesn't know what the underlying type of a `void *` is, it can still do something useful with the data.
2. The calling function passes in a function that knows how to deal with the correct type for the elements in the array.
3. Function pointers have some strange syntax, and you read from "inside out"

References and Advanced Reading

- **References:**
  - K&R C Programming (from our course)
  - Course Reader, C Primer
  - Awesome C book: http://books.goalkicker.com/CBook
  - Function Pointer tutorial: https://www.cprogramming.com/tutorial/function-pointers.html

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

Extra Slides