

COMP201

Computer Systems & Programming

Lecture #12 – Other heap allocations, C Generics – Void *




KOÇ
UNIVERSITY

Aykut Erdem // Koç University // Fall 2020

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COMP201 Early Course Feedback For

Questions Responses 19



COMP201 Early Course Feedback Form

Now that the first four weeks of COMP201 is over, I would like to get your feedback so that I continue improving this course and how it is taught and in turn help you improve your learning. Your input is collected ANONYMOUSLY and I will be the only one looking at your responses.

What are the most positive aspects of this course overall? In other words, what contributes most to your learning? *

Long answer text

<https://forms.gle/5d8LDWfH84pC33Fg7>

Recap

- Pointer Arithmetic
- The Stack
- The Heap and Dynamic Memory

Plan for Today

- Other heap allocations
- **Overview:** Generics
- Generic Swap

Disclaimer: Slides for this lecture were borrowed from
—Nick Troccoli's Stanford CS107 class

Lecture Plan

- Other heap allocations
- **Overview:** Generics
- Generic Swap

Recap: malloc

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

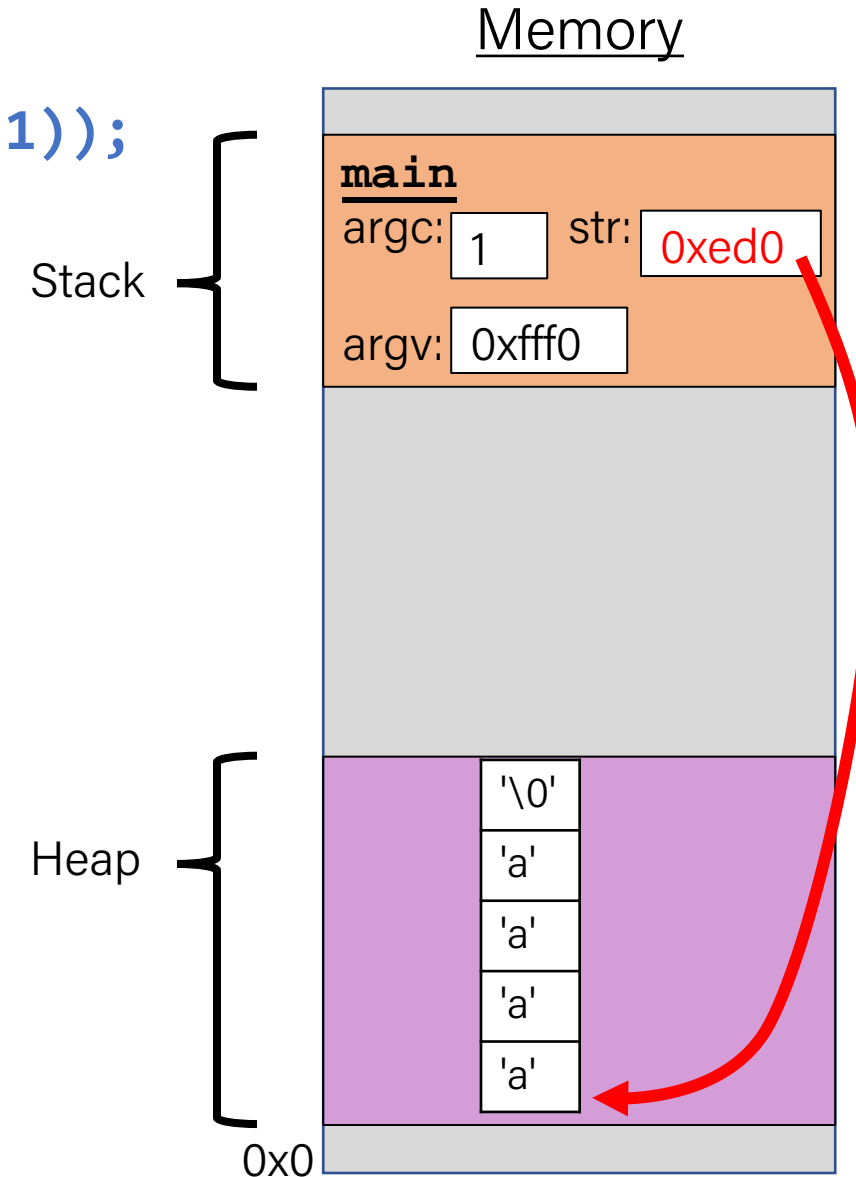
To allocate memory on the heap, use the **malloc** function ("memory allocate") and specify the number of bytes you'd like.

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

Recap: malloc

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

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



Other heap allocations: calloc

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

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

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

```
// allocate and zero 20 ints
```

```
int *scores = calloc(20, sizeof(int));
```

```
// alternate (but slower)
```

```
int *scores = malloc(20 * sizeof(int));
```

```
for (int i = 0; i < 20; i++) scores[i] = 0;
```

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

Other heap allocations: strdup

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

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

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

Implementing strdup

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

```
char *myStrdup(char *str) {  
    char *heapStr = malloc(strlen(str) + 1);  
    assert(heapStr != NULL);  
    strcpy(heapStr, str);  
    return heapStr;  
}
```

Cleaning Up with free

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

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

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

```
...
```



```
free(bytes);
```

free details

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

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

```
...  
free(bytes);
```

```
...  
free(ptr);
```





 Memory at this address was already freed!



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

```
char *bytes = malloc(4);  
char *ptr = malloc(10);
```

```
...  
free(bytes);
```

```
...  
free(ptr + 1);
```

Cleaning Up

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

```
char *str = strdup("Hello!");
```

```
...
```

```
free(str);    // our responsibility to free!
```

Memory Leaks

- A memory leak is when you allocate memory on the heap, but do not free it.
- Your program should be responsible for cleaning up any memory it allocates but no longer needs.
- If you never free any memory and allocate an extremely large amount, you may run out of memory in the heap!

However, memory leaks rarely (if ever) cause crashes.

- We recommend not to worry about freeing memory until your program is written. Then, go back and free memory as appropriate.
- Valgrind is a very helpful tool for finding memory leaks!

Free Practice

Freeing Memory

Where should we free memory below so that all memory is freed properly?

```
1  char *str = strdup("Hello");
2  assert(str != NULL);
3  char *ptr = str + 1;
4  for (int i = 0; i < 5; i++) {
5      int *num = malloc(sizeof(int));
6      assert(num != NULL);
7      *num = i;
8      printf("%s %d\n", ptr, *num);
9  }
10 printf("%s\n", str);
```


Freeing Memory

Where should we free memory below so that all memory is freed properly?

```
1 char *str = strdup("Hello");
2 assert(str != NULL);
3 char *ptr = str + 1;
4 for (int i = 0; i < 5; i++) {
5     int *num = malloc(sizeof(int));
6     assert(num != NULL);
7     *num = i;
8     printf("%s %d\n", ptr, *num);
9 }
10 printf("%s\n", str);
```



Head for
www.slido.com
and enter your
answers using the
event code **#73165**

Freeing Memory

Where should we free memory below so that all memory is freed properly?

```
1  char *str = strdup("Hello");
2  assert(str != NULL);
3  char *ptr = str + 1;
4  for (int i = 0; i < 5; i++) {
5      int *num = malloc(sizeof(int));
6      assert(num != NULL);
7      *num = i;
8      printf("%s %d\n", ptr, *num);
9      free(num);
10 }
11 printf("%s\n", str);
12 free(str);
```

Demo: Pig Latin



```
pig_latin.c
```

realloc

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

- The **realloc** function takes an existing allocation pointer and enlarges to a new requested size. It returns the new pointer.
- If there is enough space after the existing memory block on the heap for the new size, **realloc** simply adds that space to the allocation.
- If there is not enough space, **realloc** *moves the memory to a larger location*, frees the old memory for you, and *returns a pointer to the new location*.

realloc

```
char *str = strdup("Hello");  
assert(str != NULL);
```

...

```
// want to make str longer to hold "Hello world!"
```

```
char *addition = " world!";  
str = realloc(str, strlen(str) + strlen(addition) + 1);  
assert(str != NULL);
```

```
strcat(str, addition);  
printf("%s", str);  
free(str);
```

realloc

- realloc only accepts pointers that were previously returned by malloc/etc.
- Make sure to not pass pointers to the middle of heap-allocated memory.
- Make sure to not pass pointers to stack memory.

Cleaning Up with `free` and `realloc`

You only need to free the new memory coming out of `realloc`—the previous (smaller) one was already reclaimed by `realloc`.

```
char *str = strdup("Hello");
assert(str != NULL);
...
// want to make str longer to hold "Hello world!"
char *addition = " world!";
str = realloc(str, strlen(str) + strlen(addition) + 1);
assert(str != NULL);
strcat(str, addition);
printf("%s", str);
free(str);
```

Heap allocator analogy: A hotel

Request memory by size (`malloc`)

- Receive room key to first of connecting rooms

Need more room? (`realloc`)

- Extend into connecting room if available
- If not, trade for new digs, employee moves your stuff for you

Check out when done (`free`)

- You remember your room number though

Errors! What happens if you...

- Forget to check out?
- Bust through connecting door to neighbor? What if the room is in use? Yikes...
- Return to room after checkout?



Demo: Pig Latin Part 2



pig_latin.c

Heap allocation interface: A summary

```
void *malloc(size_t size);  
void *calloc(size_t nmemb, size_t size);  
void *realloc(void *ptr, size_t size);  
char *strdup(char *s);  
void free(void *ptr);
```

Compare and contrast the heap memory functions we've learned about.



Heap allocation interface: A summary

```
void *malloc(size_t size);  
void *calloc(size_t nmemb, size_t size);  
void *realloc(void *ptr, size_t size);  
char *strdup(char *s);  
void free(void *ptr);
```

Heap **memory allocation** guarantee:

- NULL on failure, so check with `assert`
- Memory is contiguous; it is not recycled unless you call `free`
- `realloc` preserves existing data
- `calloc` zero-initializes bytes, `malloc` and `realloc` do not

Undefined behavior occurs:

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

Engineering principles: stack vs heap

Stack ("local variables")

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

Heap (dynamic memory)

Engineering principles: stack vs heap

Stack ("local variables")

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

Heap (dynamic memory)

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

Stack and Heap

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

Recap: malloc

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

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

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

Lecture Plan

- Heap allocations
- **Overview:** Generics
- Generic Swap

**COMP201 Topic 5: How can we
use our knowledge of memory and
data representation to write code
that works with any data type?**

Learning Goals

- Learn how to write C code that works with any data type.
- Learn about how to use void * and avoid potential pitfalls.

Generics

- We always strive to write code that is as general-purpose as possible.
- Generic code reduces code duplication and means you can make improvements and fix bugs in one place rather than many.
- Generics is used throughout C for functions to sort any array, search any array, free arbitrary memory, and more.
- How can we write generic code in C?

Lecture Plan

- Heap allocations
- **Overview:** Generics
- Generic Swap

Swap

You're asked to write a function that swaps two numbers.

```
void swap_int(int *a, int *b) {  
    int temp = *a;  
    *a = *b;  
    *b = temp;  
}  
  
int main(int argc, char *argv[]) {  
    int x = 2;  
    int y = 5;  
    swap_int(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %d, y = %d\n", x, y);  
    return 0;  
}
```

Swap

You're asked to write a function that swaps two numbers.

```
void swap_int(int *a, int *b) {  
    int temp = *a;  
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}  
  
int main(int argc, char *argv[]) {  
    int x = 2;  
    int y = 5;  
    swap_int(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %d, y = %d\n", x, y);  
    return 0;  
}
```

main()



		Stack	
Address		Value	
		...	
x	0xff14	2	
y	0xff10	5	
		...	

Swap

You're asked to write a function that swaps two numbers.

```
void swap_int(int *a, int *b) {  
    int temp = *a;  
    *a = *b;  
    *b = temp;  
}  
  
int main(int argc, char *argv[]) {  
    int x = 2;  
    int y = 5;  
    swap_int(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %d, y = %d\n", x, y);  
    return 0;  
}
```

main()

swap_int()

		Stack	
		Address	Value
x	0xff14		...
			2
y	0xff10		5
			...
b	0xf18		0xff10
a	0xf10		0xff14
			...

Swap

You're asked to write a function that swaps two numbers.

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void swap_int(int *a, int *b) {  
    int temp = *a;  
    *a = *b;  
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}  
  
int main(int argc, char *argv[]) {  
    int x = 2;  
    int y = 5;  
    swap_int(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %d, y = %d\n", x, y);  
    return 0;  
}
```

main()

swap_int()

		Stack	
		Address	Value
x	0xff14		...
			2
y	0xff10		5
			...
b	0xf18		0xff10
			0xff14
temp	0xf0c		2
			...

Swap

You're asked to write a function that swaps two numbers.

```
void swap_int(int *a, int *b) {  
    int temp = *a;  
    *a = *b;  
    *b = temp;  
}  
  
int main(int argc, char *argv[]) {  
    int x = 2;  
    int y = 5;  
    swap_int(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %d, y = %d\n", x, y);  
    return 0;  
}
```

main()

swap_int()

		Stack	
		Address	Value
main()	x	0xff14	5
	y	0xff10	5
			...
swap_int()	b	0xf18	0xff10
	a	0xf10	0xff14
	temp	0xf0c	2
		...	

Swap

You're asked to write a function that swaps two numbers.

```
void swap_int(int *a, int *b) {  
    int temp = *a;  
    *a = *b;  
    *b = temp;  
}  
  
int main(int argc, char *argv[]) {  
    int x = 2;  
    int y = 5;  
    swap_int(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %d, y = %d\n", x, y);  
    return 0;  
}
```

main()

swap_int()

		Stack
Address		Value
		...
x	0xff14	5
y	0xff10	2
		...
b	0xf18	0xff10
a	0xf10	0xff14
temp	0xf0c	2
		...

Swap

You're asked to write a function that swaps two numbers.

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void swap_int(int *a, int *b) {  
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    *a = *b;  
    *b = temp;  
}  
  
int main(int argc, char *argv[]) {  
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    int y = 5;  
    swap_int(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %d, y = %d\n", x, y);  
    return 0;  
}
```

main()



		Stack	
Address		Value	
		...	
x	0xff14	5	
y	0xff10	2	
		...	

Swap

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    int y = 5;  
    swap_int(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %d, y = %d\n", x, y);  
    return 0;  
}
```

main()



		Stack	
Address		Value	
		...	
x	0xff14	5	
y	0xff10	2	
		...	

Swap

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int main(int argc, char *argv[]) {  
    int x = 2;  
    int y = 5;  
    swap_int(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %d, y = %d\n", x, y);  
    return 0;  
}
```

main()



		Stack	
Address		Value	
		...	
x	0xff14	5	
y	0xff10	2	
		...	

**“Oh, when I said ‘numbers’
I meant shorts, not ints.”**



Swap

```
void swap_short(short *a, short *b) {  
    short temp = *a;  
    *a = *b;  
    *b = temp;  
}
```

```
int main(int argc, char *argv[]) {  
    short x = 2;  
    short y = 5;  
    swap_short(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %d, y = %d\n", x, y);  
    return 0;  
}
```

Swap

```
void swap_short(short *a, short *b) {  
    short temp = *a;  
    *a = *b;  
    *b = temp;  
}
```

```
int main(int argc, char *argv[]) {  
    short x = 2;  
    short y = 5;  
    swap_short(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %d, y = %d\n", x, y);  
    return 0;  
}
```

main()

swap_short()

Stack		
Address		Value
		...
x	0xff12	2
y	0xff10	5
		...
b	0xf18	0xff10
a	0xf10	0xff12
temp	0xf0e	2
		...

**“You know what, I goofed.
We’re going to use strings.
Could you write something to
swap those?”**



Swap

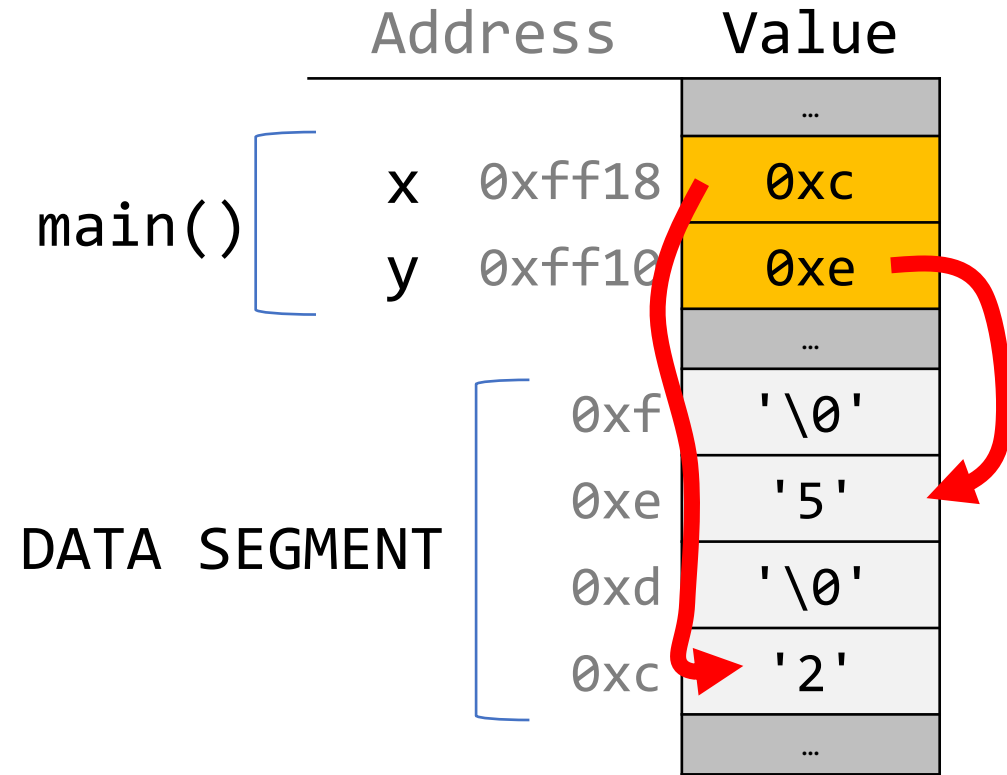
```
void swap_string(char **a, char **b) {  
    char *temp = *a;  
    *a = *b;  
    *b = temp;  
}
```

```
int main(int argc, char *argv[]) {  
    char *x = "2";  
    char *y = "5";  
    swap_string(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %s, y = %s\n", x, y);  
    return 0;  
}
```

Swap

```
void swap_string(char **a, char **b) {  
    char *temp = *a;  
    *a = *b;  
    *b = temp;  
}
```

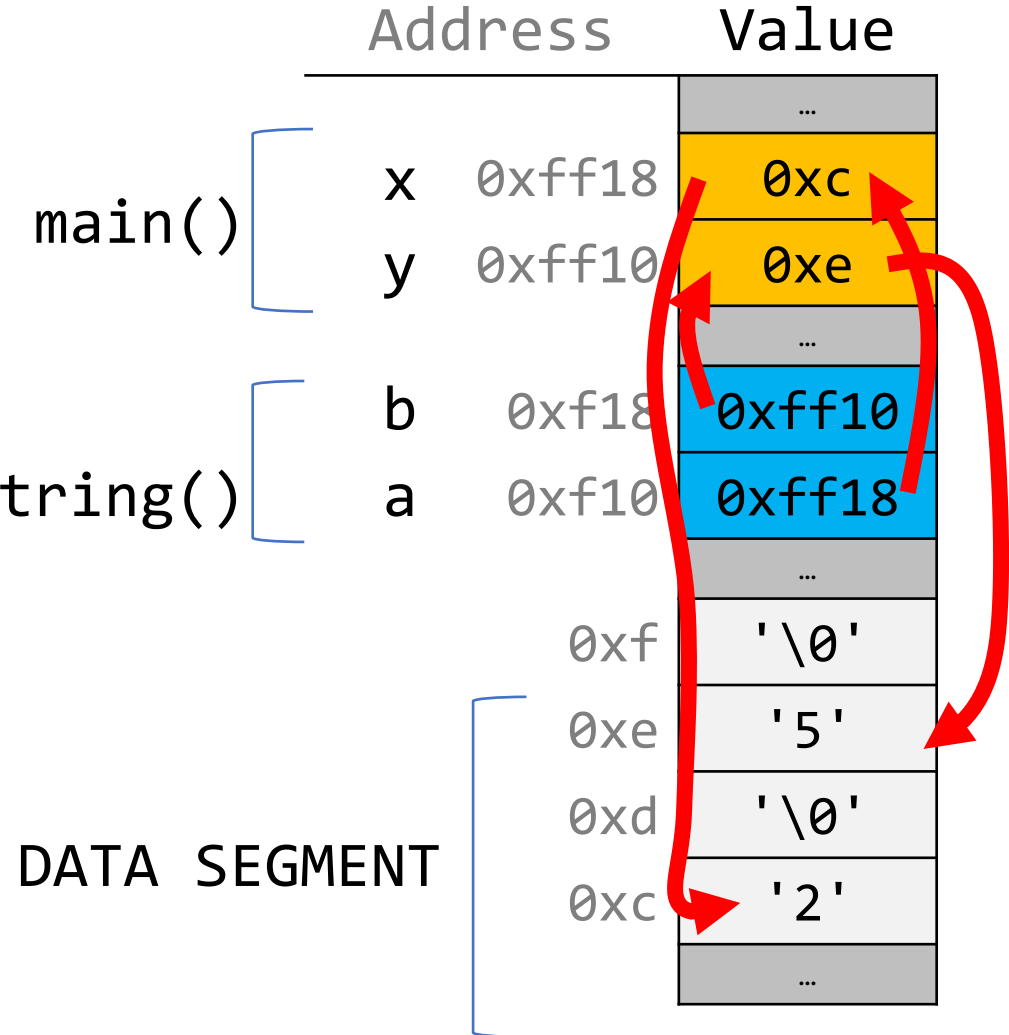
```
int main(int argc, char *argv[]) {  
    char *x = "2";  
    char *y = "5";  
    swap_string(&x, &y);  
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    printf("x = %s, y = %s\n", x, y);  
    return 0;  
}
```



Swap

```
void swap_string(char **a, char **b) {  
    char *temp = *a;  
    *a = *b;  
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}
```

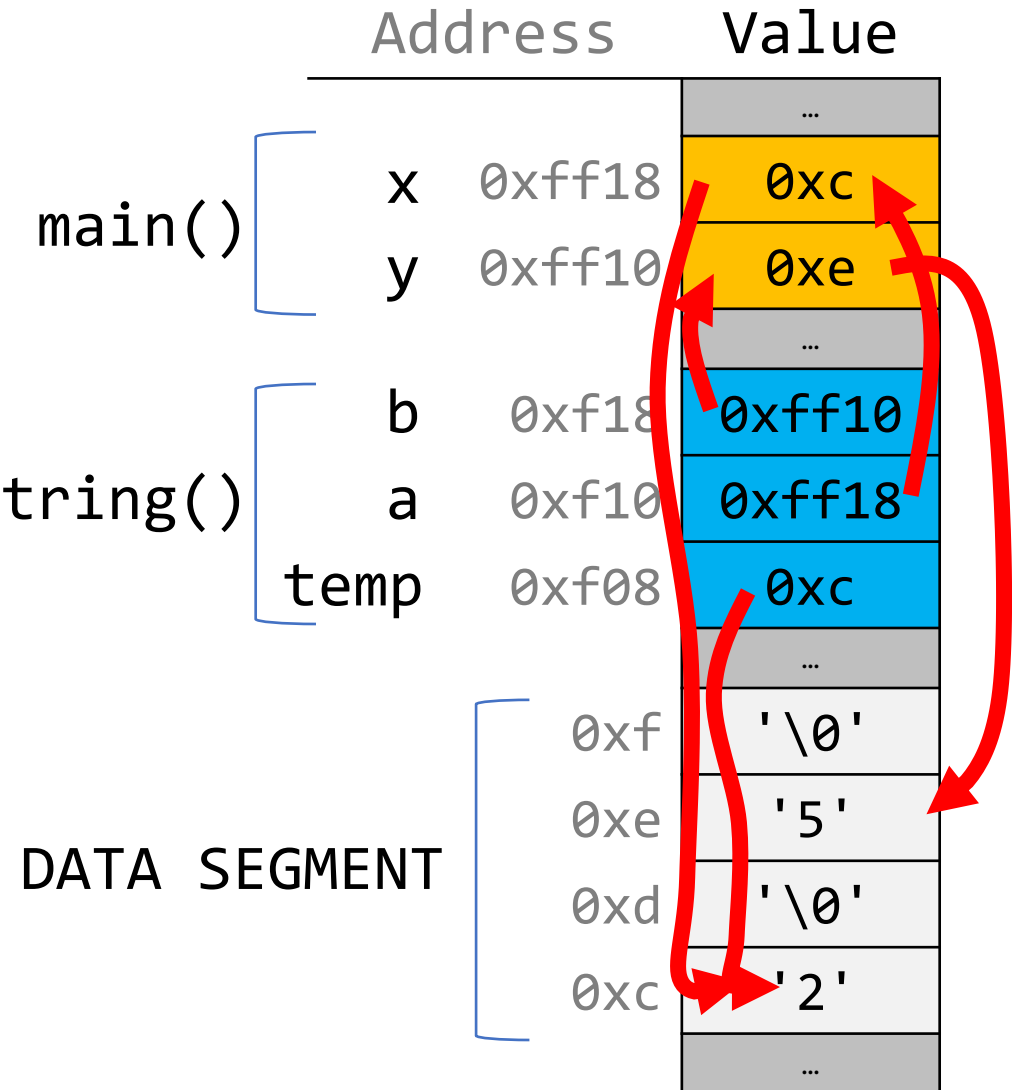
```
int main(int argc, char *argv[]) {  
    char *x = "2";  
    char *y = "5";  
    swap_string(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %s, y = %s\n", x, y);  
    return 0;  
}
```



Swap

```
void swap_string(char **a, char **b) {  
    char *temp = *a;  
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}
```

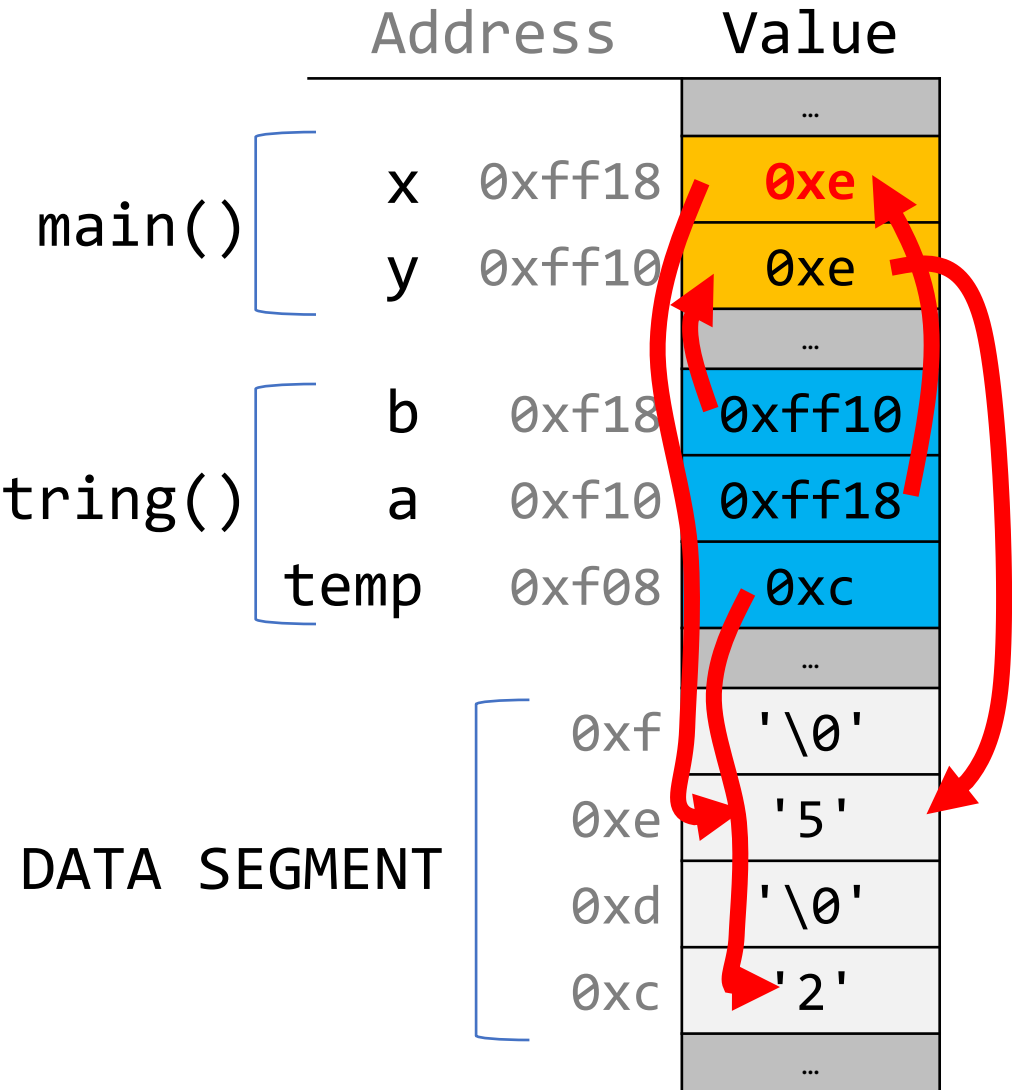
```
int main(int argc, char *argv[]) {  
    char *x = "2";  
    char *y = "5";  
    swap_string(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %s, y = %s\n", x, y);  
    return 0;  
}
```



Swap

```
void swap_string(char **a, char **b) {  
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    *b = temp;  
}
```

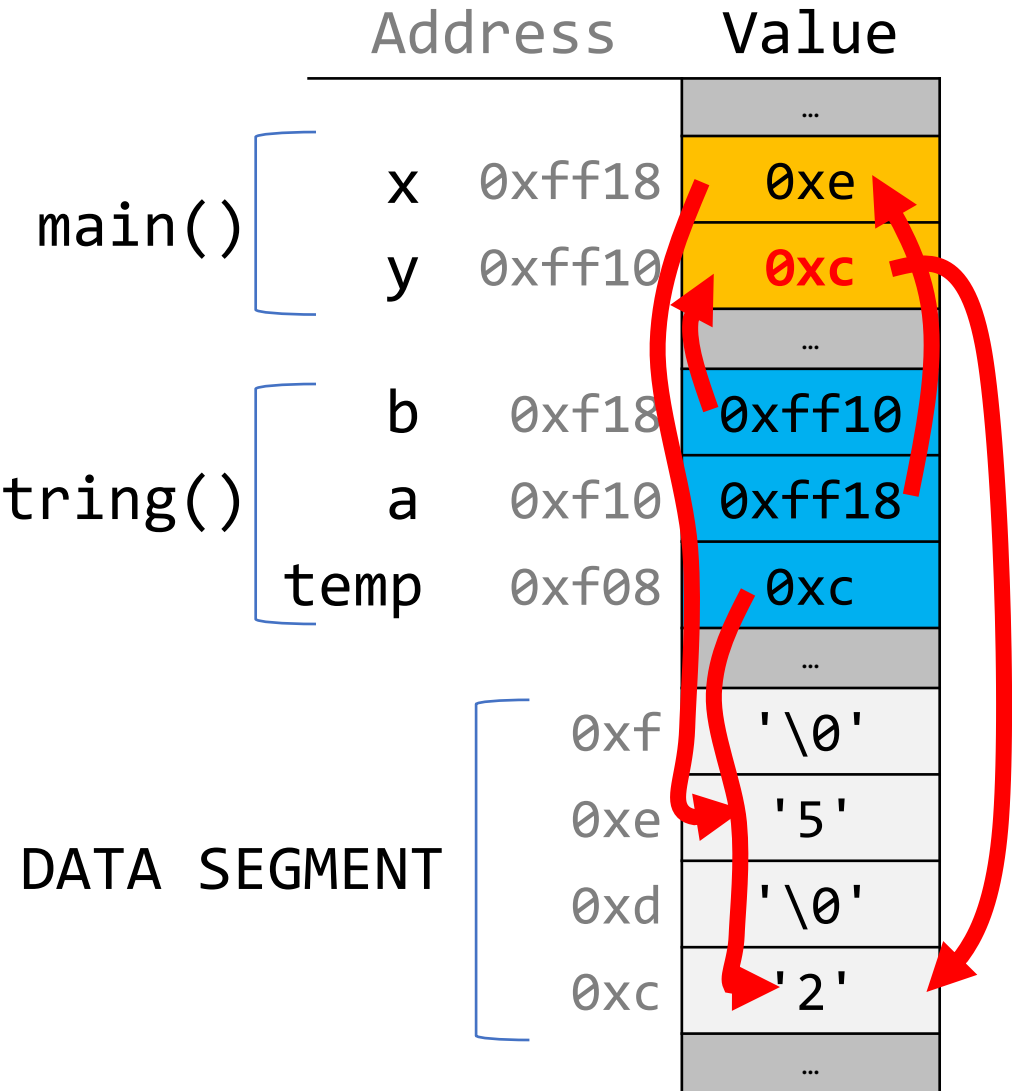
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    swap_string(&x, &y);  
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    return 0;  
}
```



Swap

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    char *temp = *a;  
    *a = *b;  
    *b = temp;  
}
```

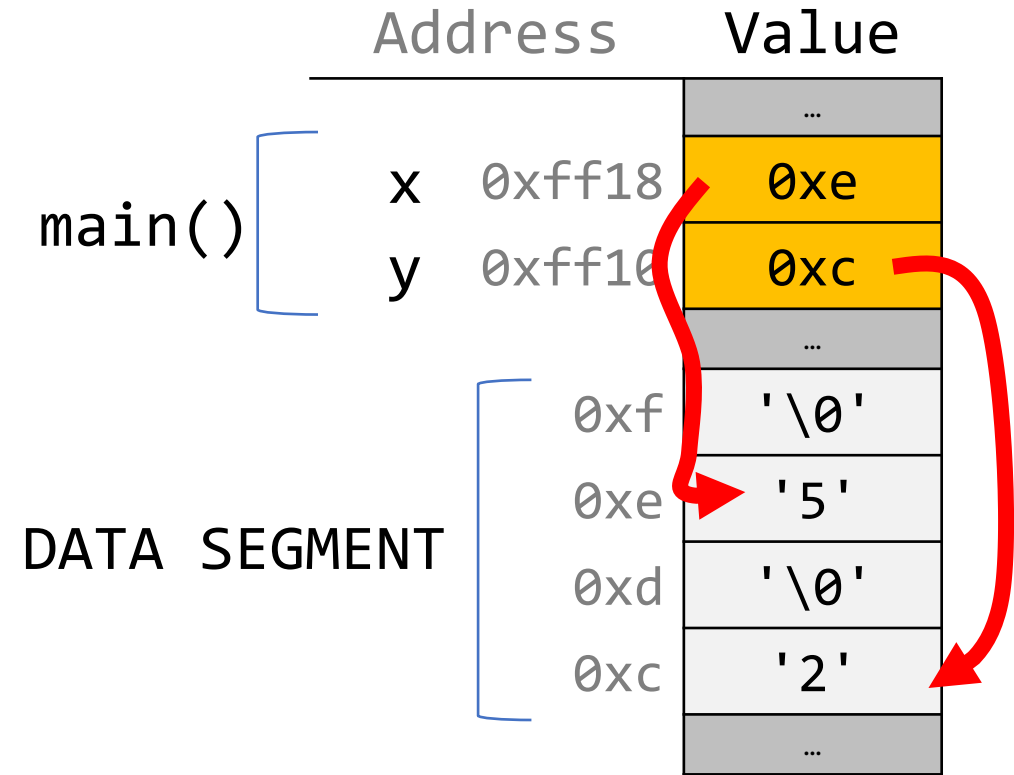
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    char *x = "2";  
    char *y = "5";  
    swap_string(&x, &y);  
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Swap

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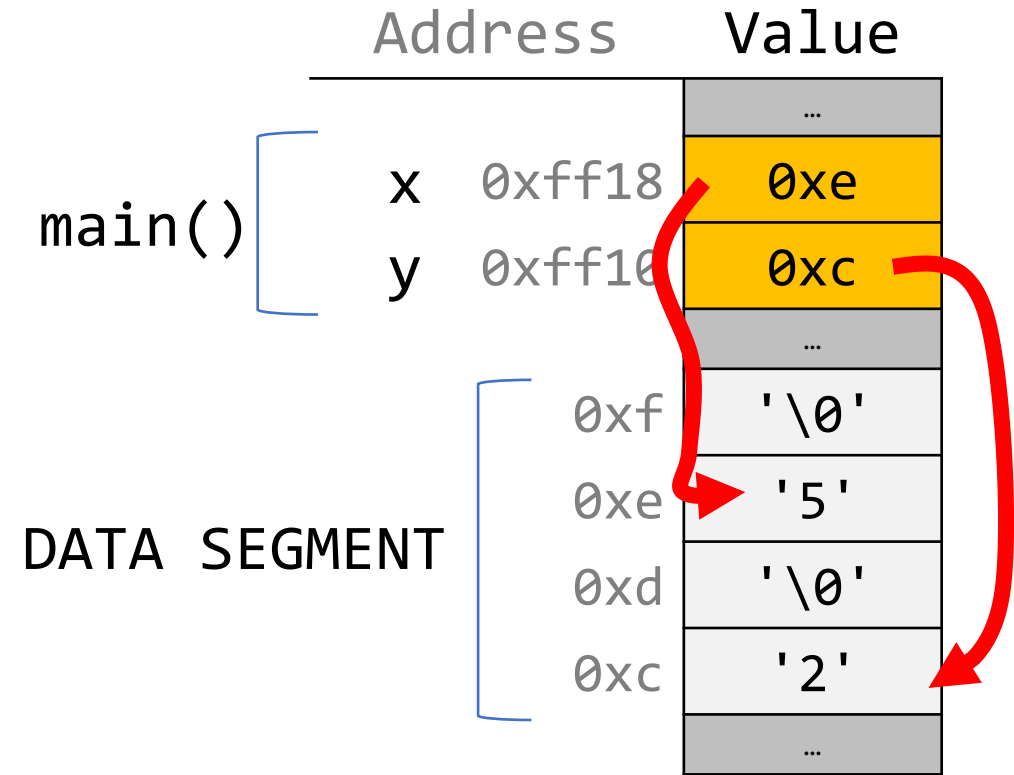
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}
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Swap

```
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    char *temp = *a;  
    *a = *b;  
    *b = temp;  
}
```

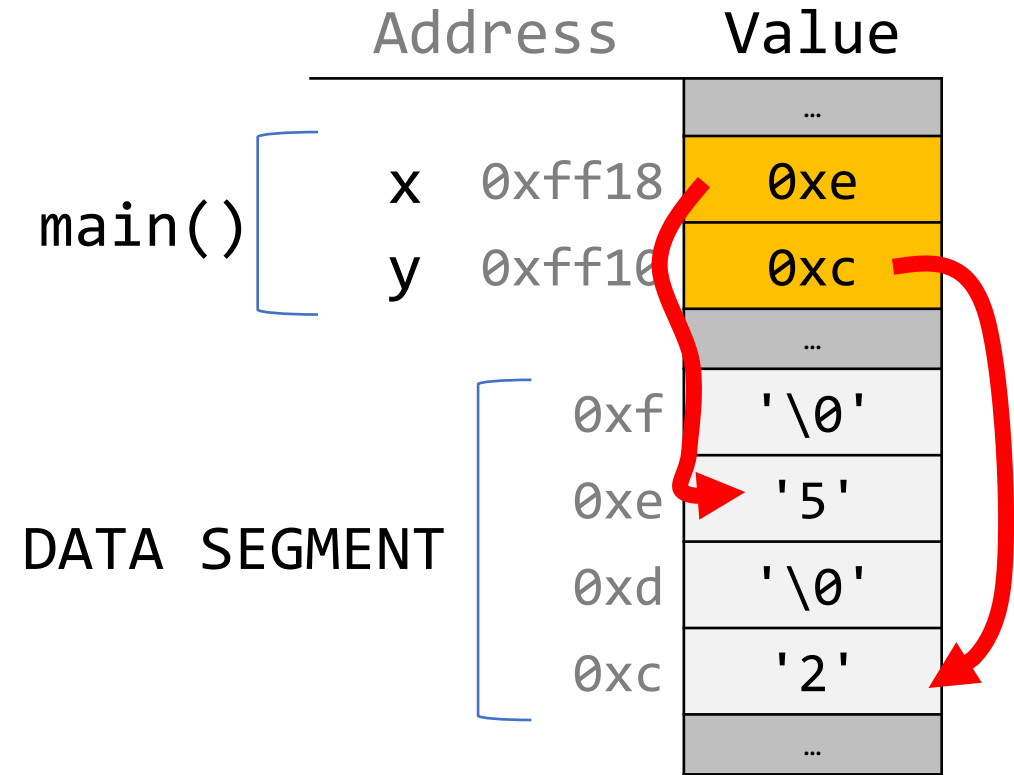
```
int main(int argc, char *argv[]) {  
    char *x = "2";  
    char *y = "5";  
    swap_string(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %s, y = %s\n", x, y);  
    return 0;  
}
```



Swap

```
void swap_string(char **a, char **b) {  
    char *temp = *a;  
    *a = *b;  
    *b = temp;  
}
```

```
int main(int argc, char *argv[]) {  
    char *x = "2";  
    char *y = "5";  
    swap_string(&x, &y);  
    // want x = 5, y = 2  
    printf("x = %s, y = %s\n", x, y);  
    return 0;  
}
```



“Awesome! Thanks.”

**“Awesome! Thanks. We also
have 20 custom struct types.
Could you write swap for
those too?”**



Generic Swap

What if we could write *one* function to swap two values of any single type?

```
void swap_int(int *a, int *b) { ... }
```

```
void swap_float(float *a, float *b) { ... }
```

```
void swap_size_t(size_t *a, size_t *b) { ... }
```

```
void swap_double(double *a, double *b) { ... }
```

```
void swap_string(char **a, char **b) { ... }
```

```
void swap_mystruct(mystruct *a, mystruct *b) { ... }
```

...

Generic Swap

```
void swap_int(int *a, int *b) {  
    int temp = *a;  
    *a = *b;  
    *b = temp;  
}
```

```
void swap_short(short *a, short *b) {  
    short temp = *a;  
    *a = *b;  
    *b = temp;  
}
```

```
void swap_string(char **a, char **b) {  
    char *temp = *a;  
    *a = *b;  
    *b = temp;  
}
```

Generic Swap

```
void swap_int(int *a, int *b) {  
    int temp = *a;  
    *a = *b;  
    *b = temp;  
}
```

```
void swap_short(short *a, short *b) {  
    short temp = *a;  
    *a = *b;  
    *b = temp;  
}
```

```
void swap_string(char **a, char **b) {  
    char *temp = *a;  
    *a = *b;  
    *b = temp;  
}
```

All 3:

- Take pointers to values to swap
- Create temporary storage to store one of the values
- Move data at **b** into where **a** points
- Move data in temporary storage into where **b** points

Generic Swap

```
void swap(pointer to data1, pointer to data2) {  
    store a copy of data1 in temporary storage  
    copy data2 to location of data1  
    copy data in temporary storage to location of data2  
}
```


Generic Swap

```
void swap(pointer to data1, pointer to data2) {  
    store a copy of data1 in temporary storage  
    copy data2 to location of data1  
    copy data in temporary storage to location of data2  
}
```

```
int temp = *data1ptr;
```

4 bytes

```
short temp = *data1ptr;
```

2 bytes

```
char *temp = *data1ptr;
```

8 bytes

Problem: each type may need a different size temp!

Generic Swap

```
void swap(pointer to data1, pointer to data2) {  
    store a copy of data1 in temporary storage  
    copy data2 to location of data1  
    copy data in temporary storage to location of data2  
}
```

`*data1Ptr = *data2ptr;`

4 bytes

`*data1Ptr = *data2ptr;`

2 bytes

`*data1Ptr = *data2ptr;`

8 bytes

Problem: each type needs to copy a different amount of data!

Generic Swap

```
void swap(pointer to data1, pointer to data2) {  
    store a copy of data1 in temporary storage  
    copy data2 to location of data1  
    copy data in temporary storage to location of data2  
}
```

`*data2ptr = temp;`

4 bytes

`*data2ptr = temp;`

2 bytes

`*data2ptr = temp;`

8 bytes

Problem: each type needs to copy a different amount of data!

**C knows the size of temp, and
knows how many bytes to
copy, because of the variable
types.**

**Is there a way to make a
version that doesn't care
about the variable types?**

Recap

- [illegible]