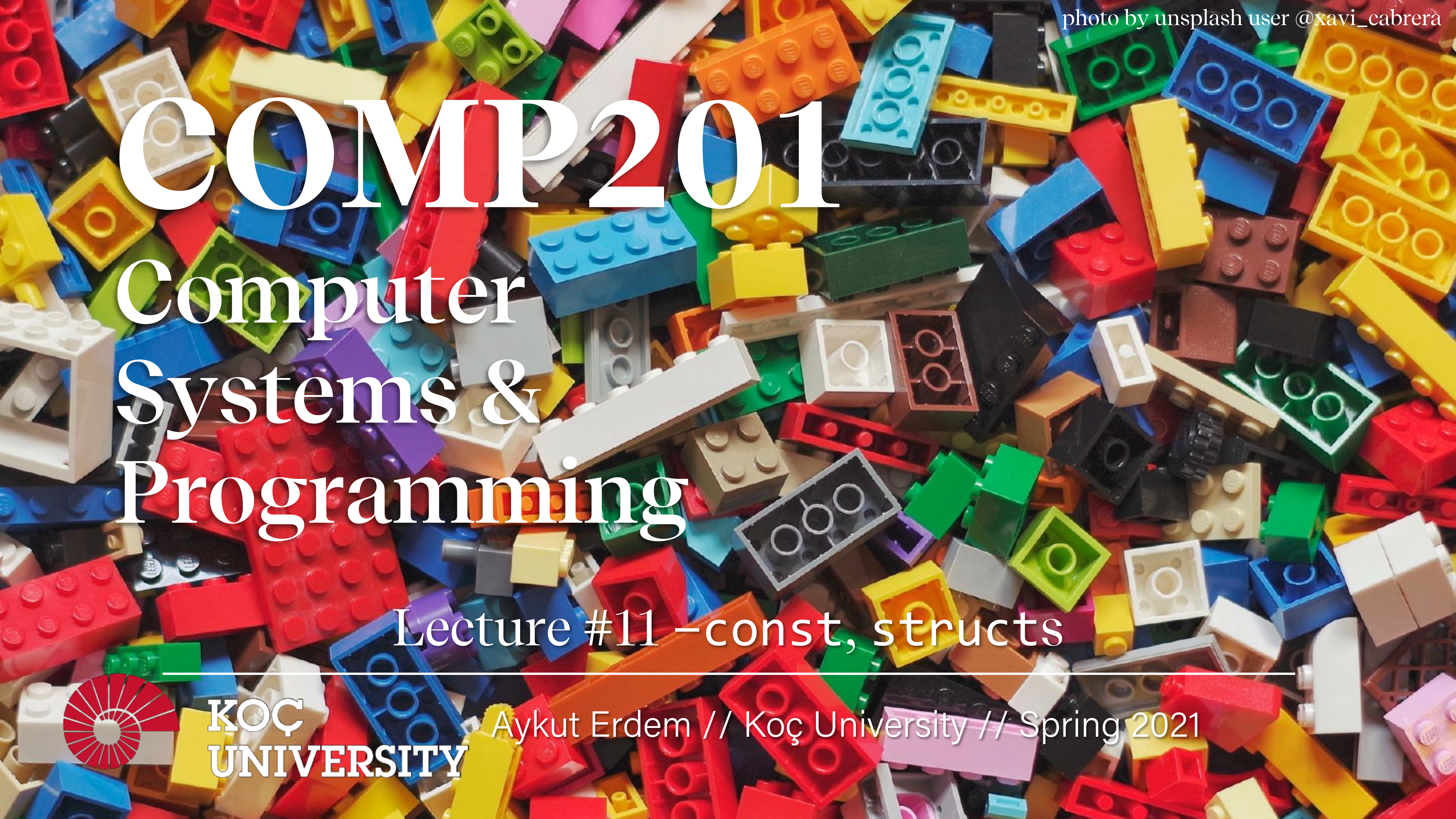

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COMP201 Computer Systems & Programming

Lecture #11 – const, structs

KOÇ UNIVERSITY

Aykut Erdem // Koç University // Spring 2021

Recap

- Generics So Far
- Motivating Example: Bubble Sort
- Function Pointers

Recap: Generics Overview

- We use **`void *`** pointers and memory operations like **`memcpy`** and **`memmove`** to make data operations generic.
- We use **function pointers** to make logic/functionality operations generic.

Recap: Why Are void * Pointers Useful?

- Each parameter and return type must be a *single* type with a *single* size.
- **Problem #1:** for a function parameter to accept multiple data types, it needs to be able to accept data of different sizes.
  - **Key Idea #1:** pointers are all the same size regardless of what they point to. To pass different sizes of data via a single parameter type, make the parameter be a pointer to the data instead.
- **Problem #2:** we still might pass either a `char *`, `int *`, etc. These are the same size, but still different declared types. What should the parameter type be?
  - **Key Idea #2:** A `void *` encompasses all these types – it represents a "pointer to something". A `char *`, `int *`, etc. all implicitly cast to `void *`.
- **Solution:** to pass one of multiple types via a single parameter/return, that parameter/return's type can be **`void *`**, and we can pass a pointer to the data.

Recap: Generic Bubble Sort

```
void bubble_sort(void *arr, int n, int elem_size_bytes,
                 int (*compare_fn)(void *a, void *b)) {
    while (true) {
        bool swapped = false;
        for (int i = 1; i < n; i++) {
            void *p_prev_elem = (char *)arr + (i - 1) * elem_size_bytes;
            void *p_curr_elem = (char *)arr + i * elem_size_bytes;
            if (compare_fn(p_prev_elem, p_curr_elem) > 0) {
                swapped = true;
                swap(p_prev_elem, p_curr_elem, elem_size_bytes);
            }
        }

        if (!swapped) {
            return;
        }
    }
}
```

Recap: Comparison Functions

- Function pointers are used often in cases like this to compare two values of the same type. These are called **comparison functions**.
- The standard comparison function in many C functions provides even more information. It should return:
  - < 0 if first value should come before second value
  - > 0 if first value should come after second value
  - 0 if first value and second value are equivalent
- This is the same return value format as **`strcmp`**!

```
int (*compare_fn)(void *a, void *b)
```

Recap: `integer_compare`

```
int integer_compare(void *ptr1, void *ptr2) {
    return *(int *)ptr1 - *(int *)ptr2;
}

int main(int argc, char *argv[]) {
    int nums[] = {4, 2, -5, 1, 12, 56};
    int nums_count = sizeof(nums) / sizeof(nums[0]);
    bubble_sort(nums, nums_count, sizeof(nums[0]), integer_compare);
    ...
}
```

`bubble_sort` is generic and works for any type. But the **caller** knows the specific type of data being sorted and provides a comparison function specifically for that data type.

Recap: `string_compare`

```
int string_compare(void *ptr1, void *ptr2) {
     return strcmp(*(char **)ptr1, *(char **)ptr2);
}

int main(int argc, char *argv[]) {
    char *classes[] = {"COMP100", "COMP132", "COMP201", "COMP202"};
    int arr_count = sizeof(classes) / sizeof(classes[0]);
    bubble_sort(classes, arr_count, sizeof(classes[0]), string_compare);
    ...
}
```

`bubble_sort` is generic and works for any type. But the **caller** knows the specific type of data being sorted and provides a comparison function specifically for that data type.

Recap: Function Pointers

- We can pass functions as parameters to pass logic around in our programs.
- Comparison functions are one common class of functions passed as parameters to generically compare the elements at two addresses.
- Functions handling generic data must use *pointers to the data they care about*, since any parameters must have *one type* and *one size*.

Plan for Today

- `const`
- `struct`
- Generic stack

Disclaimer: Slides for this lecture were borrowed from

—Nick Troccoli's Stanford CS107 class

Lecture Plan

- `const`
- `struct`
- Generic stack

const

- Use **const** to declare global constants in your program. This indicates the variable cannot change after being created.

```
const double PI = 3.1415;
const int DAYS_IN_WEEK = 7;

int main(int argc, char *argv[]) {
	…
	if (x == DAYS_IN_WEEK) {
		…
	}
	…
}
```

const

- Use **const** with pointers to indicate that the data that is pointed to cannot change.

```
char str[6];
strcpy(str, "Hello");
const char *s = str;

// Cannot use s to change characters it points to
~~s[0] = 'h';~~
```

const

Sometimes we use **const** with pointer parameters to indicate that the function will not / should not change what it points to. The actual pointer can be changed, however.

```
// This function promises to not change str's characters
int countUppercase(const char *str) {
    int count = 0;
    for (int i = 0; i < strlen(str); i++) {
        if (isupper(str[i])) {
            count++;
        }
    }
    return count;
}
```

`memcpy` Revisited

`memcpy` is a function that copies a specified amount of bytes at one address to another address.

```
void *memcpy(void *dest, const void *src, size_t n);
```

It copies the next n bytes that src points to to the location contained in dest. (It also returns **dest**). It does not support regions of memory that overlap.

```
int x = 5;
int y = 4;
memcpy(&x, &y, sizeof(x));  // like x = y
```

const

By definition, C gets upset when you set a **non-const** pointer equal to a **const** pointer. You need to be consistent with **const** to reflect what you cannot modify.

```
// This function promises to not change str’s characters
int countUppercase(const char *str) {
      // compiler warning and error
     char *strToModify = str;
     strToModify[0] = …
}
```

const

By definition, C gets upset when you set a **non-const** pointer equal to a **const** pointer. You need to be consistent with **const** to reflect what you cannot modify. **Think of const as part of the variable type**.

```
// This function promises to not change str's characters
int countUppercase(const char *str) {
     const char *strToModify = str;
     ~~strToModify[0] = …~~
}
```

const

const can be confusing to interpret in some variable types.

```
// cannot modify this char
const char c = 'h';

// cannot modify chars pointed to by str
const char *str = …

// cannot modify chars pointed to by *strPtr
const char **strPtr = …
```

Practice

const

```
1    char buf[6];
2    strcpy(buf, "Hello");
3    const char *str = buf;
4    str[0] = 'M';
5    str = "Mello";
6    buf[0] = 'M';
```

Which lines (if any) above will cause an error due to violating `const`? Remember that `const char *` means that the characters at the location it stores cannot be changed.

const

```
✅ 1    char buf[6];
   2    strcpy(buf, "Hello");
   3    const char *str = buf;
   4    str[0] = 'M';
   5    str = "Mello";
   6    buf[0] = 'M';
```

Line 1 makes a typical modifiable character array of 6 characters.

Which lines (if any) above will cause an error due to violating `const`? Remember that `const char *` means that the characters at the location it stores cannot be changed.

const

```
✅ 1   char buf[6];
✅ 2   strcpy(buf, "Hello");
   3   const char *str = buf;
   4   str[0] = 'M';
   5   str = "Mello";
   6   buf[0] = 'M';
```

Line 2 copies characters into this modifiable character array.

Which lines (if any) above will cause an error due to violating `const`? Remember that `const char *` means that the characters at the location it stores cannot be changed.

const

```
✅ 1    char buf[6];
✅ 2    strcpy(buf, "Hello");
✅ 3    const char *str = buf;
   4    str[0] = 'M';
   5    str = "Mello";
   6    buf[0] = 'M';
```

Line 3 makes a `const` pointer that points to the first element of `buf`. We cannot use `str` to change the characters it points to because it is `const`.

Which lines (if any) above will cause an error due to violating `const`? Remember that `const char *` means that the characters at the location it stores cannot be changed.

const

```
✓ 1    char buf[6];
✓ 2    strcpy(buf, "Hello");
✓ 3    const char *str = buf;
✗ 4    str[0] = 'M';
  5    str = "Mello";
  6    buf[0] = 'M';
```

Line 4 is not allowed – it attempts to use a const pointer to characters to modify those characters.

Which lines (if any) above will cause an error due to violating `const`? Remember that `const char *` means that the characters at the location it stores cannot be changed.

const

```
✓ 1    char buf[6];
✓ 2    strcpy(buf, "Hello");
✓ 3    const char *str = buf;
✗ 4    str[0] = 'M';
✓ 5    str = "Mello";
  6    buf[0] = 'M';
```

Line 5 is ok – `str`'s type means that while you cannot change the characters at which it points, you can change `str` itself to point somewhere else. `str` is not `const` – its characters are.

Which lines (if any) above will cause an error due to violating `const`? Remember that `const char *` means that the characters at the location it stores cannot be changed.

const

```
✅ 1    char buf[6];
✅ 2    strcpy(buf, "Hello");
✅ 3    const char *str = buf;
❌ 4    str[0] = 'M';
✅ 5    str = "Mello";
✅ 6    buf[0] = 'M';
```

Line 6 is ok – **buf** is a modifiable char array, and we can use it to change its characters. Declaring **str** as **const** doesn't mean that place in memory is not modifiable at all – it just means that you cannot modify it using **str**.

Which lines (if any) above will cause an error due to violating **const**? Remember that **const char *** means that the characters at the location it stores cannot be changed.

Lecture Plan

- `const`
- `struct`
- Generic stack

Structs

A **`struct`** is a way to define a new variable type that is a group of other variables.

```
struct date {               // declaring a struct type
    int month;
    int day;                // members of each date structure
};
…

struct date today;                              // construct structure instances
today.month = 1;
today.day = 28;

struct date new_years_eve = {12, 31};  // shorter initializer syntax
```

Structs

Wrap the struct definition in a **`typedef`** to avoid having to include the word **`struct`** every time you make a new variable of that type.

```
typedef struct date {
    int month;
    int day;
} date;
…

date today;
today.month = 1;
today.day = 28;

date new_years_eve = {12, 31};
```

Structs

If you pass a struct as a parameter, like for other parameters, C passes a **copy** of the entire struct.

```
void advance_day(date d) {
     d.day++;
}

int main(int argc, char *argv[]) {
     date my_date = {1, 28};
     advance_day(my_date);
     printf("%d", my_date.day); // 28
     return 0;
}
```

Structs

If you pass a struct as a parameter, like for other parameters, C passes a **copy** of the entire struct. **Use a pointer to modify a specific instance.**

```
void advance_day(date *d) {
     (*d).day++;
}

int main(int argc, char *argv[]) {
     date my_date = {1, 28};
     advance_day(&my_date);
     printf("%d", my_date.day); // 29
     return 0;
}
```

Structs

The **arrow** operator lets you access the field of a struct pointed to by a pointer.

```
void advance_day(date *d) {
     d->day++;       // equivalent to (*d).day++;
}

int main(int argc, char *argv[]) {
     date my_date = {1, 28};
     advance_day(&my_date);
     printf("%d", my_date.day); // 29
     return 0;
}
```

Structs

C allows you to return structs from functions as well. It returns whatever is contained within the struct.

```
date create_new_years_date() {
     date d = {1, 1};
     return d;        // or return (date){1, 1};
}

int main(int argc, char *argv[]) {
     date my_date = create_new_years_date();
     printf("%d", my_date.day); // 1
     return 0;
}
```

Structs

sizeof gives you the entire size of a struct, which is the sum of the sizes of all its contents.

```
typedef struct date {
      int month;
      int day;
  } date;

int main(int argc, char *argv[]) {
      int size = sizeof(date);   // 8
      return 0;
}
```

Arrays of Structs

You can create arrays of structs just like any other variable type.

```
typedef struct my_struct {
     int x;
     char c;
} my_struct;

…

my_struct array_of_structs[5];
```

Arrays of Structs

To initialize an entry of the array, you must use this special syntax to confirm the type to C.

```
typedef struct my_struct {
     int x;
     char c;
} my_struct;

…

my_struct array_of_structs[5];
array_of_structs[0] = (my_struct){0, 'A'};
```

Arrays of Structs

You can also set each field individually.

```
typedef struct my_struct {
     int x;
     char c;
} my_struct;

…
my_struct array_of_structs[5];
array_of_structs[0].x = 2;
array_of_structs[0].c = 'A';
```

Lecture Plan

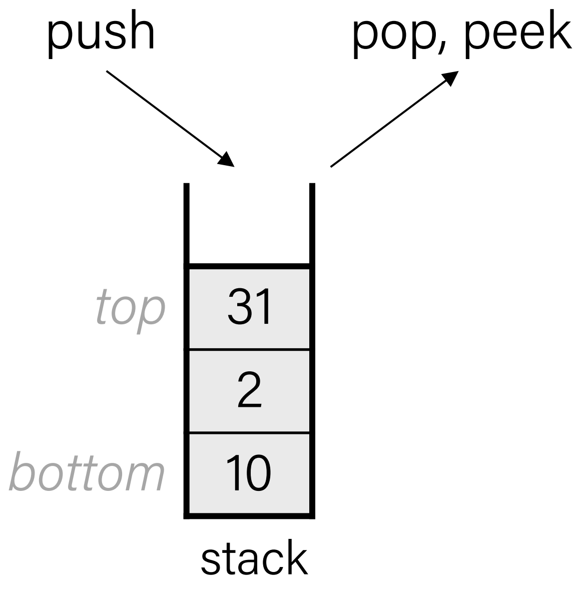
- `const`
- `struct`
- Generic stack

Stacks

- C generics are particularly powerful in helping us create generic data structures.
- Let’s see how we might go about making a Stack in C.

Stacks

- A **Stack** is a data structure representing a stack of things.
- Objects can be ***pushed*** on top of or ***popped*** from the top of the stack.
- Only the top of the stack can be accessed; no other objects in the stack are visible.
- Main operations:
  - **`push(value)`**: add an element to the top of the stack
  - **`pop()`**: remove and return the top element in the stack
  - **`peek()`**: return (but do not remove) the top element in the stack

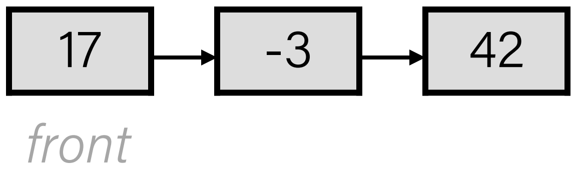


Stacks

A stack is often implemented using a **linked list** internally.

- "bottom" = tail of linked list
- "top" = head of linked list *(why not the other way around?)*

```
Stack<int> s;
s.push(42);
s.push(-3);
s.push(17);
```



Problem: C is not object-oriented! We can't call methods on variables.

Demo: Int Stack

`int_stack.c`

Int Stack Structs

```c
typedef struct int_node {
    struct int_node *next;
    int data;
} int_node;


typedef struct int_stack {
    int nelems;
    int_node *top;
} int_stack;
```

Int Stack Functions

- **`int_stack_create()`**: creates a new stack on the heap and returns a pointer to it
- **`int_stack_push(int_stack *s, int data)`**: pushes data onto the stack
- **`int_stack_pop(int_stack *s)`**: pops and returns topmost stack element

int_stack_create

```
int_stack *int_stack_create() {
    int_stack *s = malloc(sizeof(int_stack));
    s->nelems = 0;
    s->top = NULL;
    return s;
}
```

From previous slide:

```
typedef struct int_stack {
    int nelems;
    int_node *top;
} int_stack;
```

int_stack_push

```
void int_stack_push(int_stack *s, int data) {
    int_node *new_node = malloc(sizeof(int_node));
    new_node->data = data;

    new_node->next = s->top;
    s->top = new_node;
    s->nelems++;
}
```

int_stack_pop

```
int int_stack_pop(int_stack *s) {
    if (s->nelems == 0) {
        error(1, 0, "Cannot pop from empty stack");
    }
    int_node *n = s->top;
    int value = n->data;

    s->top = n->next;

    free(n);
    s->nelems--;

    return value;
}
```

From previous slide:

```
typedef struct int_stack {
    int nelems;
    node *top;
} int_stack;
```

Pushing Elements to Int Stack

```
int_stack *intstack = int_stack_create();
for (int i = 0; i < TEST_STACK_SIZE; i++) {
    int_stack_push(intstack, i);
}
```

Popping Elements from Int Stack

```
// Pop off all elements
while (intstack->nelems > 0) {
    printf("%d\n", int_stack_pop(intstack));
}
```

What modifications are necessary to make a generic stack?

Stack Structs

```
typedef struct int_node {
    struct int_node *next;
    int data;
} int_node;


typedef struct int_stack {
    int nelems;
    int_node *top;
} int_stack;
```

How might we modify the Stack data representation itself to be generic?

Stack Structs

```
typedef struct int_node {
    struct int_node *next;
    int data;
} int_node;


typedef struct int_stack {
    int nelems;
    int_node *top;
} int_stack;
```

Problem: each node can no longer store the data itself, because it could be any size!

Generic Stack Structs

```
typedef struct int_node {
    struct int_node *next;
    void *data;
} int_node;


typedef struct stack {
    int nelems;
    int elem_size_bytes;
    node *top;
} stack;
```

Solution: each node stores a pointer, which is always 8 bytes, to the data somewhere else. We must also store the data size in the Stack struct.

Stack Functions

- **`int_stack_create()`**: creates a new stack on the heap and returns a pointer to it
- **`int_stack_push(int_stack *s, int data)`**: pushes data onto the stack
- **`int_stack_pop(int_stack *s)`**: pops and returns topmost stack element

int_stack_create

```
int_stack *int_stack_create() {
    int_stack *s = malloc(sizeof(int_stack));
    s->nelems = 0;
    s->top = NULL;
    return s;
}
```

How might we modify this function to be generic?

From previous slide:

```
typedef struct stack {
    int nelems;
    int elem_size_bytes;
    node *top;
} stack;
```

Generic stack_create

```
stack *stack_create(int elem_size_bytes) {
    stack *s = malloc(sizeof(stack));
    s->nelems = 0;
    s->top = NULL;
    s->elem_size_bytes = elem_size_bytes;
    return s;
}
```

int_stack_push

```
void int_stack_push(int_stack *s, int data) {
    int_node *new_node = malloc(sizeof(int_node));
    new_node->data = data;

    new_node->next = s->top;
    s->top = new_node;
    s->nelems++;
}
```

How might we modify this function to be generic?

From previous slide:

```
typedef struct stack {
    int nelems;
    int elem_size_bytes;
    node *top;
} stack;
```

```
typedef struct node {
    struct node *next;
    void *data;
} node;
```

Generic stack_push

```
void int_stack_push(int_stack *s, int data) {
    int_node *new_node = malloc(sizeof(int_node));
    new_node->data = data;

    new_node->next = s->top;
    s->top = new_node;
    s->nelems++;
}
```

Problem 1: we can no longer pass the data itself as a parameter, because it could be any size!

Generic `stack_push`

```
void int_stack_push(int_stack *s, const void *data) {
    int_node *new_node = malloc(sizeof(int_node));
    new_node->data = data;

    new_node->next = s->top;
    s->top = new_node;
    s->nelems++;
}
```

Solution 1: pass a pointer to the data as a parameter instead.

Generic stack_push

```
void int_stack_push(int_stack *s, const void *data) {
    int_node *new_node = malloc(sizeof(int_node));
    new_node->data = data;

    new_node->next = s->top;
    s->top = new_node;
    s->nelems++;
}
```

Problem 2: we cannot copy the existing data pointer into **new_node**. The data structure must manage its own copy that exists for its entire lifetime. The provided copy may go away!

Generic stack_push

```
int main() {
    stack *int_stack = stack_create(sizeof(int));
    add_one(int_stack);
    // now stack stores pointer to invalid memory for 7!
}

void add_one(stack *s) {
    int num = 7;
    stack_push(s, &num);
}
```

Generic stack_push

```
void stack_push(stack *s, const void *data) {
    node *new_node = malloc(sizeof(node));
    new_node->data = malloc(s->elem_size_bytes);
    memcpy(new_node->data, data, s->elem_size_bytes);

    new_node->next = s->top;
    s->top = new_node;
    s->nelems++;
}
```

Solution 2: make a heap-allocated copy of the data that the node points to.

int_stack_pop

```
int int_stack_pop(int_stack *s) {
    if (s->nelems == 0) {
        error(1, 0, "Cannot pop from empty stack");
    }
    int_node *n = s->top;
    int value = n->data;

    s->top = n->next;

    free(n);
    s->nelems--;

    return value;
}
```

How might we modify this function to be generic?

From previous slide:

```
typedef struct stack {
    int nelems;
    int elem_size_bytes;
    node *top;
} stack;
```

```
typedef struct node {
    struct node *next;
    void *data;
} node;
```

Generic stack_pop

```
int int_stack_pop(int_stack *s) {
    if (s->nelems == 0) {
        error(1, 0, "Cannot pop from empty stack");
    }
    int_node *n = s->top;
    int value = n->data;

    s->top = n->next;

    free(n);
    s->nelems--;

    return value;
}
```

Problem: we can no longer return the data itself, because it could be any size!

Generic stack_pop

```c
void *int_stack_pop(int_stack *s) {
    if (s->nelems == 0) {
        error(1, 0, "Cannot pop from empty stack");
    }
    int_node *n = s->top;
    void *value = n->data;

    s->top = n->next;

    free(n);
    s->nelems--;

    return value;
}
```

While it's possible to return the heap address of the element, this means the client would be responsible for freeing it. Ideally, the data structure should manage its own memory here.

Generic stack_pop

```
void stack_pop(stack *s, void *addr) {
    if (s->nelems == 0) {
        error(1, 0, "Cannot pop from empty stack");
    }
    node *n = s->top;
    memcpy(addr, n->data, s->elem_size_bytes);
    s->top = n->next;

    free(n->data);
    free(n);
    s->nelems--;
}
```

Solution: have the caller pass a memory location as a parameter and copy the data to that location.

Using Generic Stack

```
int_stack *intstack = int_stack_create();
for (int i = 0; i < TEST_STACK_SIZE; i++) {
    int_stack_push(intstack, i);
}
```

We must now pass the *address* of an element to push onto the stack, rather than the element itself.

Using Generic Stack

```
stack *intstack = stack_create(sizeof(int));
for (int i = 0; i < TEST_STACK_SIZE; i++) {
    stack_push(intstack, &i);
}
```

We must now pass the *address* of an element to push onto the stack, rather than the element itself.

Using Generic Stack

```
int_stack *intstack = int_stack_create();
int_stack_push(intstack, 7);
```

We must now pass the *address* of an element to push onto the stack, rather than the element itself.

Using Generic Stack

```
stack *intstack = stack_create(sizeof(int));
int num = 7;
stack_push(intstack, &num);
```

We must now pass the *address* of an element to push onto the stack, rather than the element itself.

Using Generic Stack

```
// Pop off all elements
while (intstack->nelems > 0) {
    printf("%d\n", int_stack_pop(intstack));
}
```

We must now pass the *address* of where we would like to store the popped element, rather than getting it directly as a return value.

Using Generic Stack

```
// Pop off all elements
int popped_int;
while (intstack->nelems > 0) {
    int_stack_pop(intstack, &popped_int);
    printf("%d\n", popped_int);
}
```

We must now pass the *address* of where we would like to store the popped element, rather than getting it directly as a return value.

Demo: Generic Stack

`generic_stack.c`

Recap

- `const`
- `struct`
- Generic stack

Next Time: Compiling C programs