

# Systems Architecture

## 5. Pointers in C

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# 1. Introduction

- As we know, C is general purpose programming language often classified as **high-level** programming language, since it provides abstractions of the details of the computer using elements close to a natural language
- Nevertheless, C is sometimes called a *middle-level* programming language, since it also provides low-level characteristics (related to memory management)
- This low-level memory management is done through **pointers**, which is one the most powerful features of the C, but at the same time, it can be error-prone
  - The incorrect manipulation of memory in C programs leads to the well-known “**segmentation fault**” problem

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## 2. What are pointers?

- Each variable in a C program is stored in the main memory of the computer executing it
- A **pointer** in C is a variable that stores a memory address
- There are two operators in C to handle pointers:

Operator	Description	Example
&	<i>Reference</i> operator (to get the memory address of a variable)	&b
*	<i>Dereference</i> operator (to declare pointer or get the value of a given pointer)	*b

## 2. What are pointers?

- Pointers, like any other variable in C, need to be declared using a given type and variable name
- The difference from regular variables is that we use the operator `*` before the variable name:

```
type *pointer_name;
```

- For instance:

```
int *ip;    // pointer to an integer
double *dp; // pointer to a double
float *fp;  // pointer to a float
char *cp;   // pointer to a character
```

## 2. What are pointers?

- Consider the following example:

```
int main() {  
    int age = 20;  
    int *p_age = &age;  
  
    // ...  
  
    return 0;  
}
```

This C program defines a regular integer variable (**int**) and a pointer to integer (**int\***)

stack (main)

age

20

p\_age

This box represents the memory handled in the scope of the **main** function

Variable	Memory address	Content
	...	
a	0x7ffe66dd68ac	20
	...	
p_age	0x7ffe8e2379aa	0x7ffe66dd68ac
	...	

This table represents the physical memory of the computer running the C program

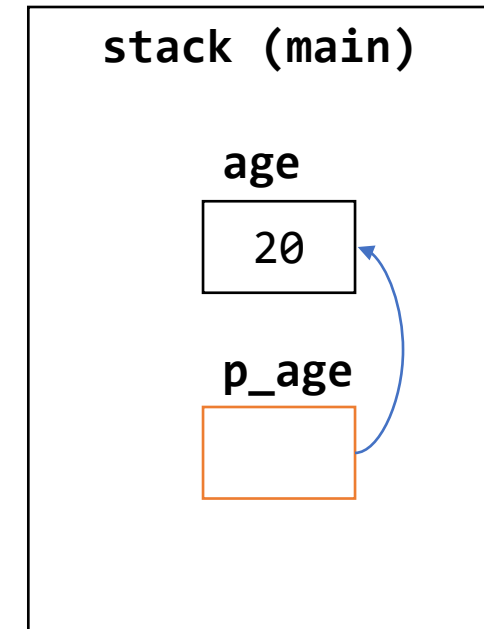
## 2. What are pointers?

- The following example illustrates a very basic declaration and usage of a pointer variable:

```
#include <stdio.h>

int main() {
    int age = 20;
    int *p_age = &age;

    printf("The value of the variable age is %d\n", age);
    printf("The memory address in which age is stored is %p\n", p_age);
    printf("The value pointed by p_age is %d\n", *p_age);
    return 0;
}
```



```
The value of the variable age is 20
The memory address in which age is stored is 0x7ffe66dd68ac
The value pointed by p_age is 20
```



## 2. What are pointers?

```
#include <stdio.h>

int main() {
    int age = 20;
    int *p_age = &age;

    printf("The value of the variable age is %d\n", age);
    printf("The memory address in which age is stored is %p\n", p_age);
    printf("The value pointed by p_age is %d\n", *p_age);

    age = 40;

    printf("The value of the variable age is %d\n", age);
    printf("The value pointed by p_age is %d\n", *p_age);

    return 0;
}
```

What is the value of \*p\_age  
in this example?



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### 3. Passing arguments by value and by reference

- We when invoke a function in C, and their arguments are not pointers, we say that we are passing arguments **by value**. Passing arguments by value implies:
  - Values of caller parameters are copied to the function
  - Changes made inside functions are not reflected in caller parameters
- On the other hand, if the arguments of a function are pointers, we say that the arguments are passed **by reference**. This implies:
  - Both the caller and functional parameters refer to the same location
  - Changes made inside the function are reflected in caller parameters
- To illustrate it, consider the *swap* function, which is a simple function that exchanges the values of two variables

### 3. Passing arguments by value and by reference

```
#include <stdio.h>

void swap(int first, int second) {
    int tmp;

    tmp = first;
    first = second;
    second = tmp;
}

int main() {
    int a = 100;
    int b = 200;

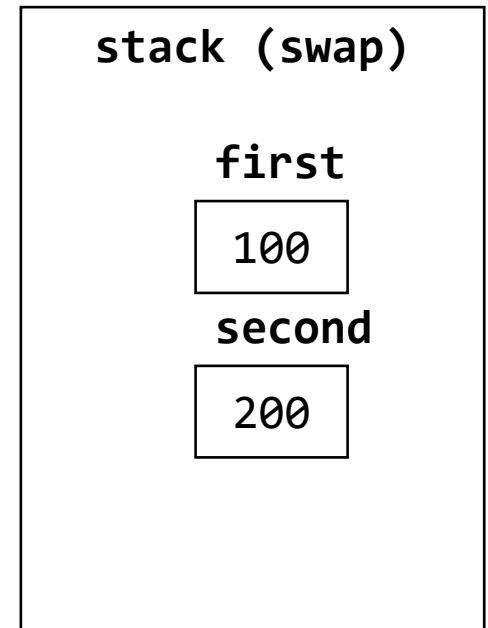
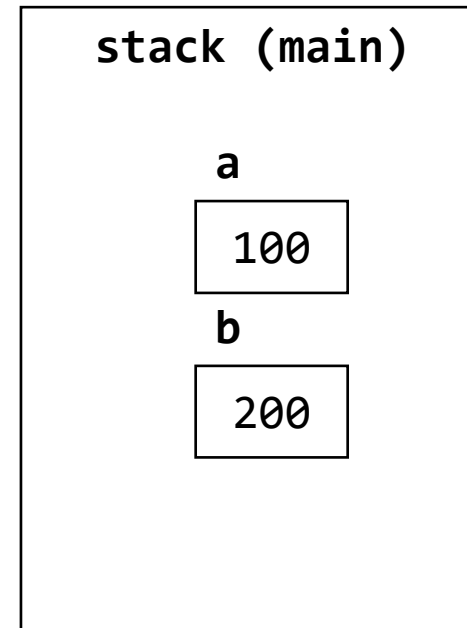
    puts("Before swap:");
    printf("\t a=%d \n", a);
    printf("\t b=%d \n", b);

    swap(a, b);

    puts("After swap:");
    printf("\t a=%d \n", a);
    printf("\t b=%d \n", b);

    return 0;
}
```

This is an example of a function (swap) using pass by value



Before swap:  
a=100  
b=200

### 3. Passing arguments by value and by reference

```
#include <stdio.h>

void swap(int first, int second) {
    int tmp;

    tmp = first;
    first = second;
    second = tmp;
}

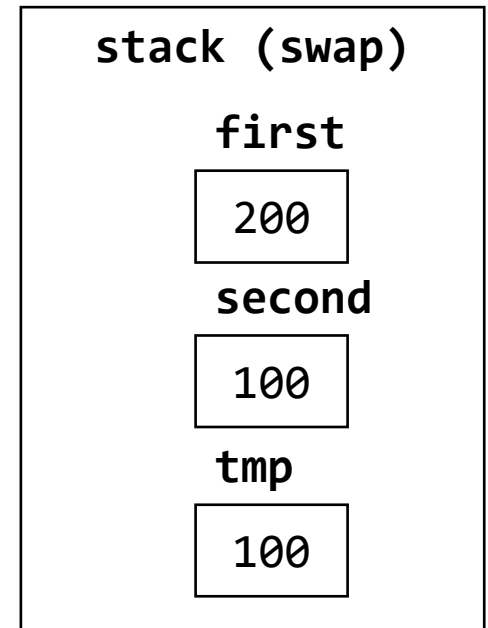
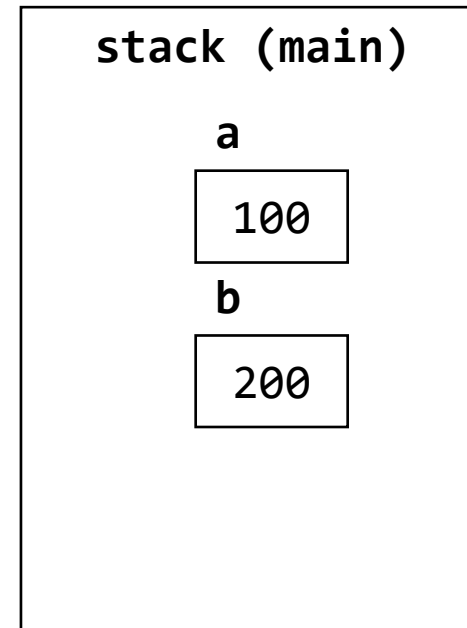
int main() {
    int a = 100;
    int b = 200;

    puts("Before swap:");
    printf("\t a=%d \n", a);
    printf("\t b=%d \n", b);

    swap(a, b);

    puts("After swap:");
    printf("\t a=%d \n", a);
    printf("\t b=%d \n", b);

    return 0;
}
```



Before swap:  
a=100  
b=200

### 3. Passing arguments by value and by reference

```
#include <stdio.h>

void swap(int first, int second) {
    int tmp;

    tmp = first;
    first = second;
    second = tmp;
}

int main() {
    int a = 100;
    int b = 200;

    puts("Before swap:");
    printf("\t a=%d \n", a);
    printf("\t b=%d \n", b);

    swap(a, b);

    puts("After swap:");
    printf("\t a=%d \n", a);
    printf("\t b=%d \n", b);

    return 0;
}
```

stack (main)

a

100

b

200

Before swap:

a=100

b=200

After swap:

a=100

b=200

### 3. Passing arguments by value and by reference

```
#include <stdio.h>

void swap(int *p_first, int *p_second) {
    int tmp;

    tmp = *p_first;
    *p_first = *p_second;
    *p_second = tmp;
}

int main() {
    int a = 100;
    int b = 200;

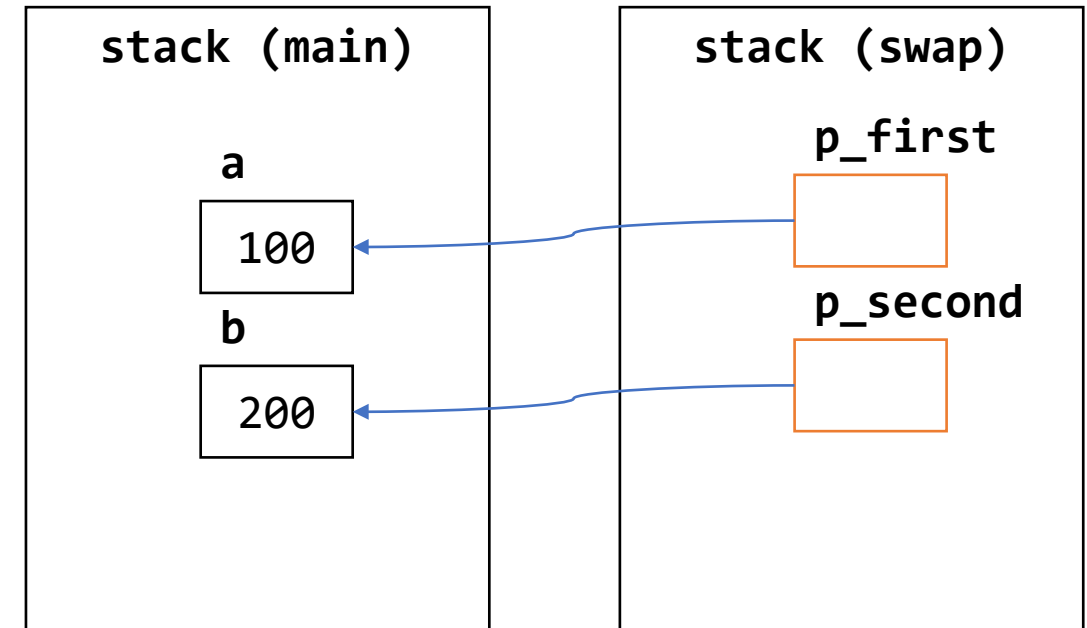
    puts("Before swap:");
    printf("\t a=%d \n", a);
    printf("\t b=%d \n", b);

    swap(&a, &b);

    puts("After swap:");
    printf("\t a=%d \n", a);
    printf("\t b=%d \n", b);

    return 0;
}
```

This is an example of a function (swap) using pass by reference



Before swap:  
a=100  
b=200

# 3. Passing arguments by value and by reference

```
#include <stdio.h>

void swap(int *p_first, int *p_second) {
    int tmp;

    tmp = *p_first;
    *p_first = *p_second;
    *p_second = tmp;
}

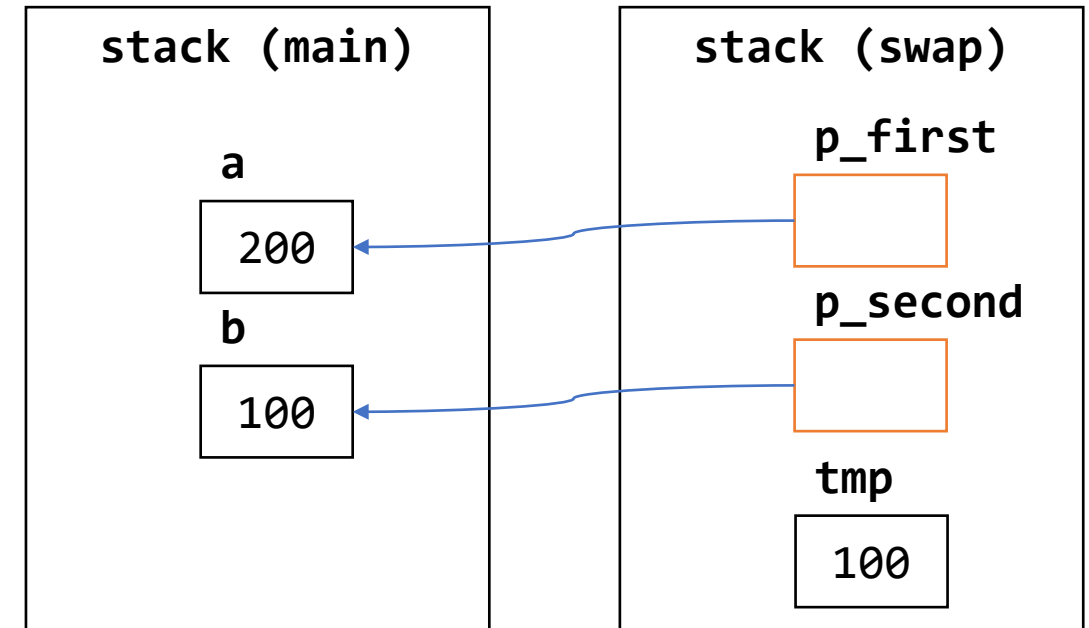
int main() {
    int a = 100;
    int b = 200;

    puts("Before swap:");
    printf("\t a=%d \n", a);
    printf("\t b=%d \n", b);

    swap(&a, &b);

    puts("After swap:");
    printf("\t a=%d \n", a);
    printf("\t b=%d \n", b);

    return 0;
}
```



Before swap:  
a=100  
b=200



### 3. Passing arguments by value and by reference

```
#include <stdio.h>

void swap(int *p_first, int *p_second) {
    int tmp;

    tmp = *p_first;
    *p_first = *p_second;
    *p_second = tmp;
}

int main() {
    int a = 100;
    int b = 200;

    puts("Before swap:");
    printf("\t a=%d \n", a);
    printf("\t b=%d \n", b);

    swap(&a, &b);

    puts("After swap:");
    printf("\t a=%d \n", a);
    printf("\t b=%d \n", b);

    return 0;
}
```

stack (main)

a

200

b

100

Before swap:  
a=100  
b=200  
After swap:  
a=200  
b=100

Arguments passed by reference are sometimes called “output arguments”, since the function can modify the value stored at that address, which will be reflected in the original variable

### 3. Passing arguments by value and by reference

- The **scanf** function works using output arguments (i.e., passed by reference):

```
int scanf(const char *format, ...);
```

The *varargs* parameters in **scanf** need to be pointers, because the changes made inside the function **scanf** are reflected in caller parameters

- For this reason, when we invoke **scanf** for basic types (e.g. **char**, **int**, etc.), we need to use the reference operator (&)

```
int i;  
char str[40];  
  
scanf("%d", &i);  
scanf("%s", str);
```

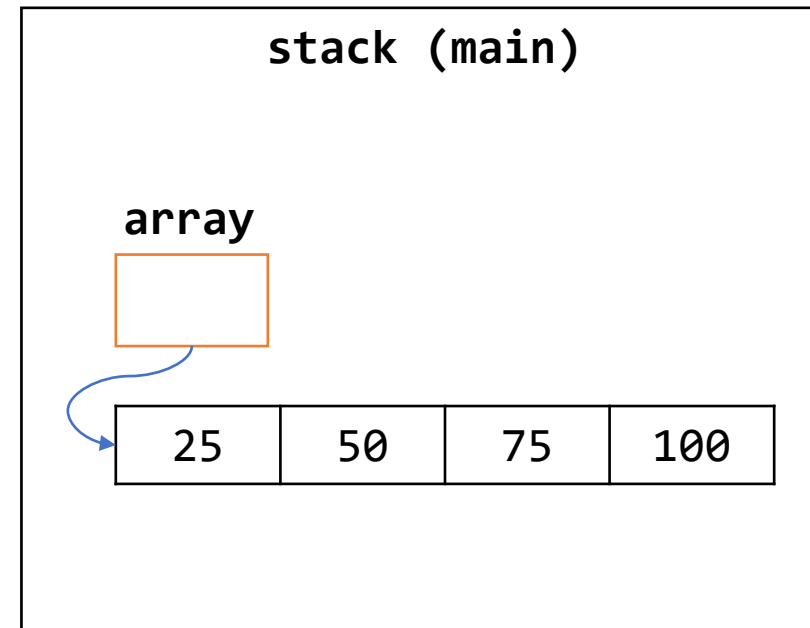
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## 4. Pointers and arrays

- We already know that arrays are collections of data with the same type and stored at contiguous memory
- Arrays behave similarly to pointers, since internally, an array variable is a constant pointer pointing to the first element of the array

```
int main() {  
    int array[] = { 25, 50, 75, 100 };  
  
    // ...  
}
```



## 4. Pointers and arrays

- This fact has relevant implications. For example consider the following program:

```
#include <stdio.h>
#define SIZE 4

void double_array(int array[], int size) {
    for (int i = 0; i < size; i++) {
        array[i] *= 2;
    }
}

int main() {
    int array[SIZE] = { 25, 50, 75, 100 };

    double_array(array, SIZE);

    printf("%d\n", array[0]);

    return 0;
}
```

What can we see in the standard output when this program is executed?



## 4. Pointers and arrays

- A pointer in c is a memory address, which is a numeric value
- We can perform basic arithmetic operations (i.e., **addition** and **subtraction**) on pointers

```
#include <stdio.h>

int main() {
    int array[] = { 25, 50, 75, 100 };

    int *a = array;      // initial address
    int *b = array + 1;  // initial address + (sizeof(int) * 1)
    int *c = array + 2;  // initial address + (sizeof(int) * 2)
    int *d = array + 3;  // initial address + (sizeof(int) * 3)

    printf("*a=%d\n", *a);
    printf("*b=%d\n", *b);
    printf("*c=%d\n", *c);
    printf("*d=%d\n", *d);

    return 0;
}
```

```
*a=25
*b=50
*c=75
*d=100
```

## 4. Pointers and arrays

- One key difference between array and pointers is the size of the memory required
  - When arrays are created, a fixed size of the memory is allocated
  - That size is unknown when using pointers
  - We can check this difference by invoking the operator **sizeof**

```
#include <stdio.h>

int main() {
    int array[8];
    int *pointer = array;

    unsigned int s1 = sizeof(array);
    unsigned int s2 = sizeof(pointer);

    printf("s1=%d\n", s1);
    printf("s2=%d\n", s2);

    return 0;
}
```

```
s1=32
s2=8
```

## 4. Pointers and arrays

- Also, remember that array variables cannot be assigned of another variable (we use the memcpy function instead):

```
#include <stdio.h>
#define SIZE 4

int main() {
    int array_1[SIZE] = { 25, 50, 75, 100 };
    int array_2[SIZE];

    array_2 = array_1; // forbidden

    return 0;
}
```

```
arrays_5_error.c: In function 'main':
arrays_5_error.c:8:13: error: assignment to expression
with array type
```

```
8 |     array_2 = array_1; // forbidden
  |               ^
```



```
#include <stdio.h>
#include <string.h>
#define SIZE 4

void display_array(int array[], int size) {
    for (int i = 0; i < size; i++) {
        printf("array[%d]=%d\n", i, array[i]);
    }
    printf("\n");
}

int main() {
    int array_1[SIZE] = { 25, 50, 75, 100 };
    int array_2[SIZE];

    memcpy(array_2, array_1, sizeof(array_1));

    display_array(array_1, SIZE);
    display_array(array_2, SIZE);

    return 0;
}
```

```
array[0]=25
array[1]=50
array[2]=75
array[3]=100
```

```
array[0]=25
array[1]=50
array[2]=75
array[3]=100
```



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## 5. Pointers and strings

- As we already know, there is no type in C for handling strings
- Instead, we use array of characters
  - For that, we can use arrays or pointers

```
#include <stdio.h>

int main() {
    char *greetings = "Hello";
    printf("%s\n", greetings);

    return 0;
}
```

If we do not assign a string value in the declaration of the variable, we will need to allocate memory later in the program (we will see this in the next lecture about dynamic memory)

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## 6. Pointers and structs

- We can use the arrow operator (`->`) for accessing members of an structure using pointers

```
#include <stdio.h>

#define MAX_STR 80

typedef struct Person {
    char name[MAX_STR];
    int age;
} Person;

int main() {
    Person person = { "Alice", 25 };
    Person *pointer = &person;

    printf("Name: %s -- Age: %d\n", (*pointer).name, (*pointer).age);
    printf("Name: %s -- Age: %d\n", pointer->name, pointer->age);

    return 0;
}
```

```
Name: Alice -- Age: 25
Name: Alice -- Age: 25
```

`(*pointer).name` and `pointer->name` are equivalent, although the use of the arrow operator is more readable

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## 7. Function pointers

- A function pointer in C is a variable that stores the address of a function
  - This allows for dynamic function calls, where the function to be executed is determined at runtime

```
#include <stdio.h>

int add(int a, int b) {
    return a + b;
}

int main() {
    int (*func_ptr)(int, int); // Declare a function pointer
    func_ptr = add; // Assign the address of 'add' function to the pointer

    int result = func_ptr(5, 3); // Call the function using the pointer
    printf("Result: %d\n", result); // Output will be 8

    return 0;
}
```

See a more complex [example](#) in the GitHub repository

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## 8. NULL pointer

- Several programming languages (such as C, Java, JavaScript or Python, among others) has the concept of *null* as a special marker indicating that something has no value
- In C, **NULL** is a special reserved pointer value that does not point to any valid data object
- We can think in **NULL** in C like a memory address (i.e., a pointer) with all its bits put to zero
  - In a 64 bits computer: **NULL** = 0x0000000000000000 (i.e., 0 in decimal)
  - Therefore, **NULL** is interpreted as false in expressions
- Some of the most common use cases for **NULL** are
  - To initialize a pointer variable when that pointer variable hasn't been assigned any valid memory address yet
  - To check for a null pointer before accessing any pointer variable



## 8. NULL pointer

- The following example illustrates a very basic usage of a **NULL** pointer:

```
#include <stdio.h>

int main() {
    int *pointer = NULL;

    /*
     * This equivalent to:
     * if (pointer == 0)
     * if (!pointer)
     */
    if (pointer == NULL) {
        printf("Pointer is NULL\n");
    }

    return 0;
}
```

Pointer is NULL

## 8. NULL pointer

- The following example show how null and non-null references are displayed:

```
#include <stdio.h>

int main() {
    int *null_pointer = NULL;
    char *my_string = "Hello";

    printf("The address of null_pointer is %p\n", null_pointer);
    printf("The address of my_string is %p\n", my_string);

    return 0;
}
```

```
The address of null_pointer is (nil)
The address of my_string is 0x55c366f79008
```

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## 9. Double pointers

- A **double pointer** (also known as *pointer to a pointer*) is a form of multiple indirection, i.e., a chain of pointers
  - We use two stars ( **\*\*** ) to declare a double pointer

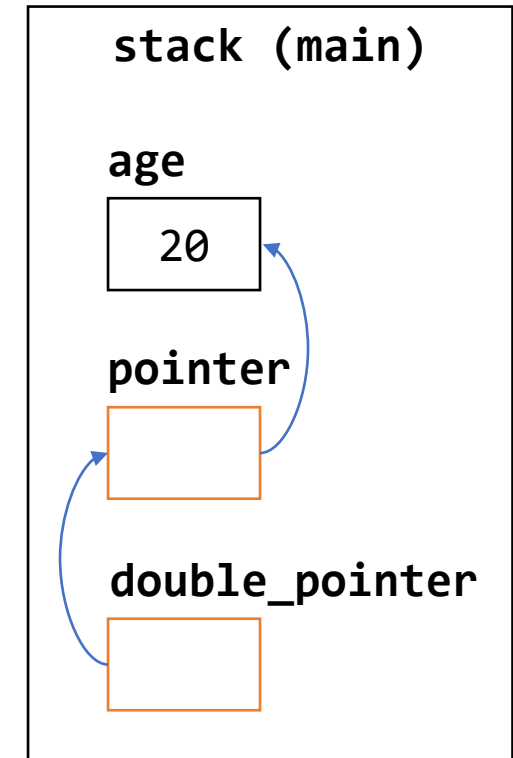
```
#include <stdio.h>

int main() {
    int age = 20;
    int *pointer = &age;
    int **double_pointer = &pointer;

    printf("The value of the variable age is %d\n", age);
    printf("The value pointed by *pointer is %d\n", *pointer);
    printf("The value pointed by **double_pointer is %d\n", **double_pointer);

    return 0;
}
```

```
The value of the variable age is 20
The value pointed by *pointer is 20
The value pointed by **double_pointer is 20
```



## 9. Double pointers

- Here are some common scenarios where double pointers are used:
  - To implement two-dimension arrays (e.g., a arrays of strings)
  - To modify a pointer outside its scope, e.g. for memory allocation (we will see this in the next unit)

```
#include <stdio.h>

int main() {
    char *words[2];
    words[0] = "hello";
    words[1] = "world";

    printf("words[0]=%s\n", words[0]);
    printf("words[1]=%s\n", words[1]);

    return 0;
}
```

```
words[0]=hello
words[1]=world
```

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# 10. Program arguments

- We already know that the entry point of any C program is the main function

```
int main() {  
    // ...  
}
```

- We also know that shell commands can be invoked with a list of arguments (after the command name)

```
$ command <arg1> <arg2>
```

But, how can we handle arguments passed from the command line in our C programs?

# 10. Program arguments

- To pass command line arguments, we typically define **main()** with two arguments:
  - **argc** (*argument count*): it is an integer value that stores the number of command-line arguments passed by the user including the name of the program
  - **argv** (*argument vector*): it is array of character pointers listing all the arguments

```
int main(int argc, char *argv[]) {  
    // ...  
}
```

```
int main(int argc, char **argv) {  
    // ...  
}
```

These two ways to define the main arguments are equivalent



# 10. Program arguments

- This program illustrates the use of program arguments:

```
#include <stdio.h>

int main(int argc, char *argv[]) {
    printf("This program was called with \"%s\\n\"", argv[0]);

    if (argc > 1) {
        for (int i = 1; i < argc; i++) {
            printf("argv[%d] = %s\\n", i, argv[i]);
        }
    } else {
        puts("The command had no other arguments");
    }

    return 0;
}
```

```
$ gcc args.c -o my-program
```

```
$ ./my-program
This program was called with "./my-program"
The command had no other arguments
```

```
$ ./my-program 1 hello 2 world
This program was called with "./my-program"
argv[1] = 1
argv[2] = hello
argv[3] = 2
argv[4] = world
```

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# 11. Takeaways

- A pointer in C is a variable that stores a memory address
- There are two operators in C to handle pointers: & (address-of) and \* (pointer declaration and value-of)
- When the arguments of a function are pointers, we say that the arguments are passed by reference. In this case, changes made inside the function are reflected in caller parameters
- Arrays behave similarly to pointers, since internally, an array variable is a constant pointer pointing to the first element of the array
- We use array of characters (or a pointer to char) to handle strings in C
- We can use the arrow operator (->) for accessing members of an structure using pointers
- Function pointers provide a way to store the address of a function in a variable
- NULL is a special reserved pointer value that does not point to any valid data object
- A double pointer (\*\*) is a chain of pointers (e.g. to allocate memory for a pointer outside its scope)
- To pass command line arguments, we define the main function with argc (argument count) and argv (argument vector)