C Memory Management

Stack and Heap, Memory Management Functions, Memory Leaks, Using Valgrind

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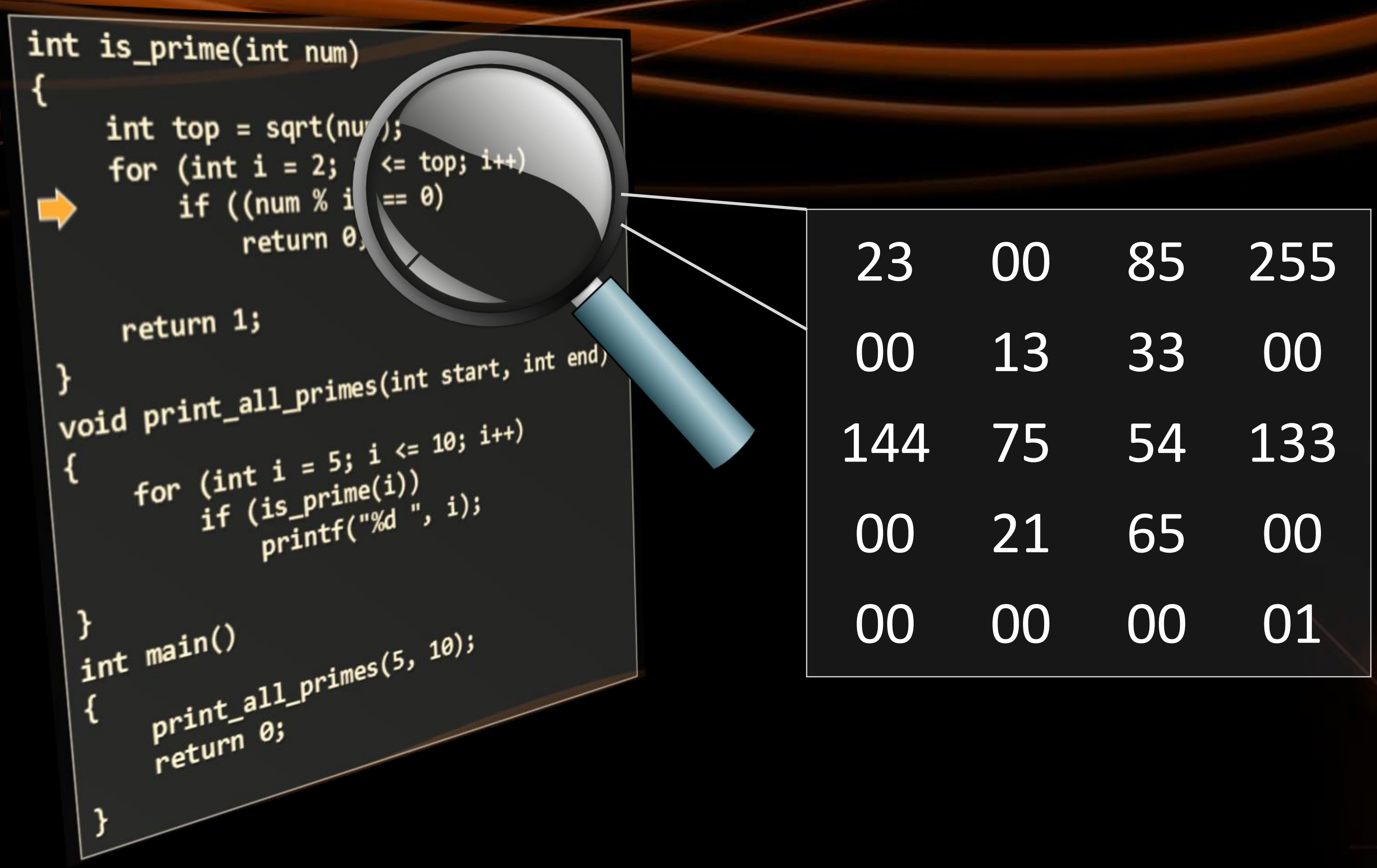


```
int is_prime(int num)
{
    int top = sqrt(nu );
    for (int i = 2;   <= top; i++)
        if ((num % i  == 0)
            return 0;

    return 1;
}
void print_all_primes(int start, int end)
{
    for (int i = 5; i <= 10; i++)
        if (is_prime(i))
            printf("%d ", i);

}
int main()
{
    print_all_primes(5, 10);
    return 0;
}
```

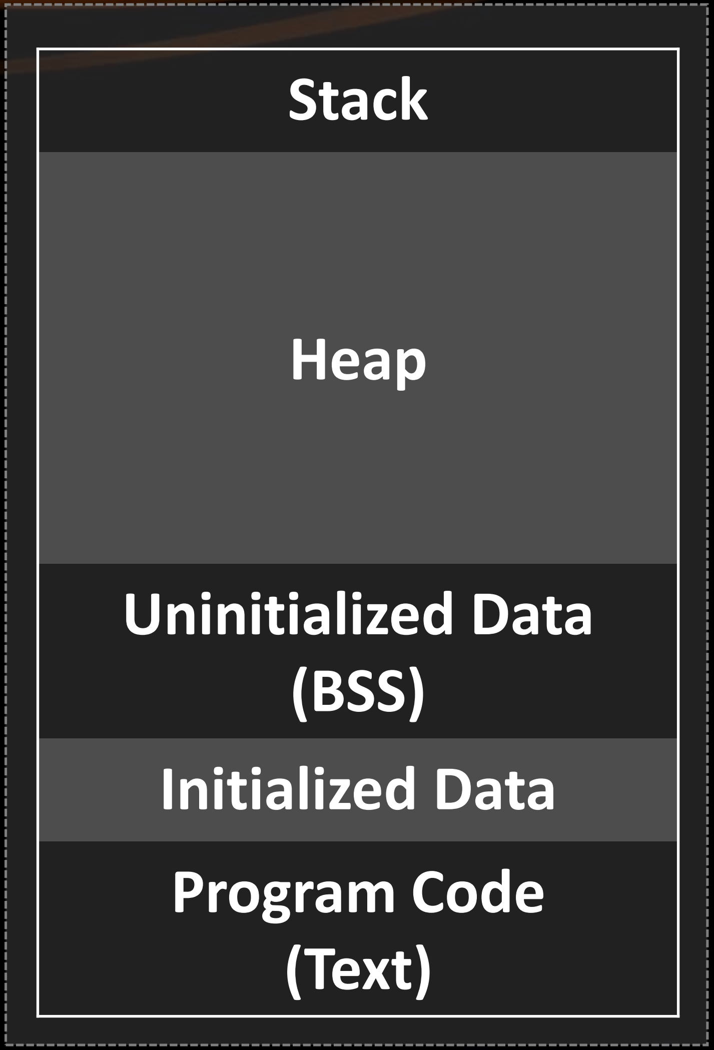
```
 23   00   85   255
 00   13   33   00
144   75   54   133
 00   21   65   00
 00   00   00   01
```

Process Memory

Process Memory

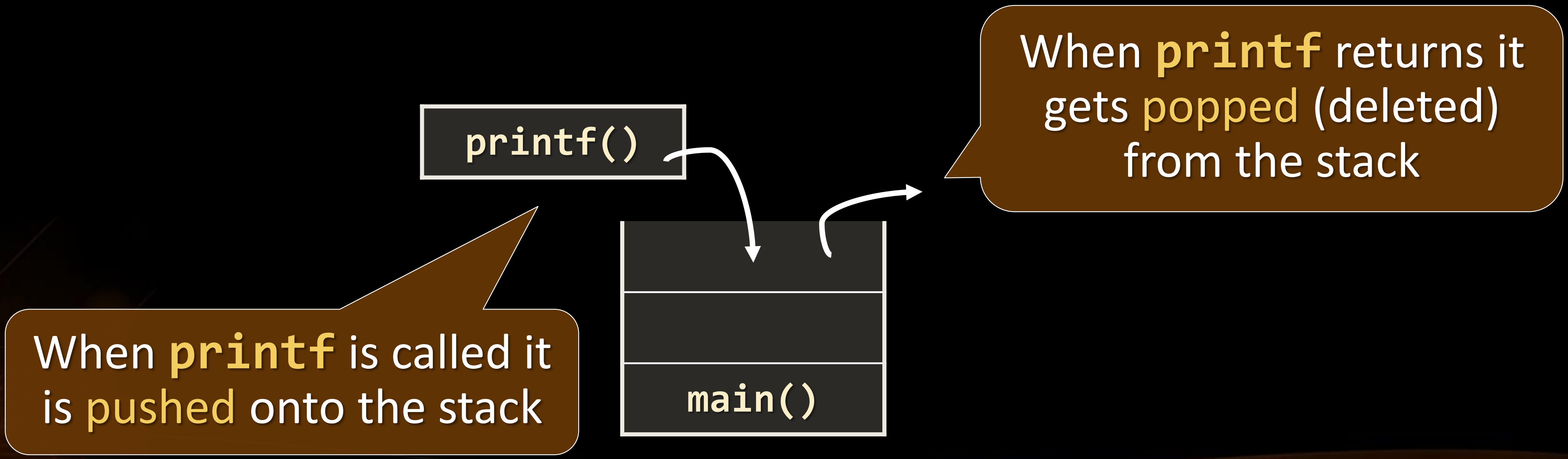
- All Linux processes are granted a memory space to execute on, comprised of:

1. Stack – holds called functions and their local variables
2. Heap – holds dynamically allocated objects
3. Unitialized Data – uninitialized global variables
4. Initialized Data – initialized global variables
5. Program Code (binary)



The Stack

- The stack is a small fixed-size chunk of memory (e.g. 1MB)
  - Keeps the currently called functions in a stack data structure
  - Changes as the program enters / exits a function



printf()

main()

When **printf** is called it is pushed onto the stack

When **printf** returns it gets popped (deleted) from the stack

The Heap

- The heap (dynamic memory) holds dynamically allocated objects during execution
  - Can grow by requesting more memory from the operating system
  - Suitable for keeping large blocks of memory
  - In C, the programmer has to manually allocate and free memory on the heap
    - Functions from `<stdlib.h>` header

Memory Management Functions

malloc

- malloc(size_t size) – allocates size bytes of memory and returns a void* pointer to them
  - E.g. allocating 10 characters on the heap:

```
char *string = malloc(sizeof(char) * 10);
if (string != NULL)
{
    // Use allocated memory
}
```

- Note: malloc() returns NULL if no memory is available
  - Always check if the allocation is successful!

malloc – Example

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

int main()
{
    int n = 5;
    int *numbers = malloc(sizeof(int) * n);
    if (numbers)
    {
        for (int i = 0; i < n; i++)
            scanf("%d", &numbers[i]);
        // ...
        free(numbers);
    }

    return 0;
}
```

Free allocated memory once done using it

malloc – More

- malloc() returns a pointer to uninitialized garbage memory
  - It may contain memory from old data

```
char *str = malloc(100);
size_t length = strlen(str);
```

✗

  - Above code has undefined behavior – *str may point to any data
    - Null terminator '\0' could be anywhere (or even missing)

```
char *str = malloc(100);
str[0] = '\0';
size_t length = strlen(str);
```

✓

calloc

- **calloc(size_t num, size_t size)** – allocates **num** blocks of memory, each **size** bytes long
  - Similar to **malloc()**, but zero-initializes the allocated memory
    - Eliminates the danger of reading garbage memory
  - Returns **NULL** if allocation fails

```
float *xCoords = calloc(10, sizeof(float));
if (xCoords)
{
    // ...
}
```

realloc

- **realloc(void *ptr, size_t newSize)** – copies the memory pointed by ***ptr** to a new block of memory
  - If sucessful, automatically frees the old block of memory
  - Returns **NULL** if the allocation fails

```
int *nums = malloc(sizeof(int) * n);
if (nums)
{
     int *newNums = realloc(nums, sizeof(int) * n * 2);
     if (newNums)
        ...
}
```

free

- free(void *ptr) – marks the memory pointed to by *ptr as free to the operating system
  - After that, that memory should no longer be read/written (can damage data or segfault)

```
char *string = malloc(sizeof(char) * 10);
if (string)
{
    // Use allocated memory
    free(string);
}
```

Using free

- Rules when using **free()**:
  - Use only on pointers obtained with **malloc()**, **calloc()** or **realloc()**
  - Do NOT use the pointer after you have free'd it
  - Do NOT use on stack-allocated or read-only memory pointers, e.g.:

```
char *name = "Gosho";
int nums[] = { 2, 3, 4 };
free(name);  // Segmentation fault, do not free!
free(nums);  // Segmentation fault
```

  - Always free heap-allocated resources once you're done using them

free()

Live Demo

Matrix on the Heap

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

#define ROWS 4
#define COLS 4

void error(char *message)
{
    perror(message);
    exit(1);
}
```

Prints message to the standard error stream

Terminates the program with status code 1

(example continues)

Allocating the Matrix (2)

```
int main()
{
    int **matrix = calloc(ROWS, sizeof(int*));
    if (!matrix)
    {
        error("Error allocating matrix");
    }

    for (int i = 0; i < ROWS; i++)
    {
        matrix[i] = calloc(COLS, sizeof(int));
        if (!matrix[i])
            error("Error allocating matrix row");
    }
```

(example continues)

Using and Disposing the Matrix (3)

```
    matrix[0][1] = 5;
    matrix[3][3] = 16;

    for (int r = 0; r < ROWS; r++)
    {
        for (int c = 0; c < COLS; c++)
        {
            printf("%-5d", matrix[r][c]);
        }
        printf("\n");
    }

    for (int i = 0; i < ROWS; i++)
        free(matrix[i]);
    free(matrix);

    return 0;
}
```

Matrix on the Heap

Live Demo

memset

- **memset(void *ptr, int n, size_t size)** – sets **n** bytes to **size**, starting from the address of ***ptr**
  - Returns a pointer to the memory area

```
int memSize = sizeof(int) * 20;
int *array = malloc(memSize);
if (array)
{
    memset(array, 0, memSize);
    // Use memory...
    free(array);
}
```

calloc() does this internally

memcpy

- **void *memcpy(void *s1, const void *s2, size_t n)** – copies **n** characters from ***s2** to ***s1**

```
int nums[] = { 5, 6, 10, 13, 2 };
int size = sizeof(int) * sizeof(nums);

int *copy = malloc(size);
memcpy(copy, nums, size);

for (int i = 0; i < 5; i++)
{
    printf("%d\n", copy[i]);
}
```

Other Memory Functions

- `void *memmove(void *s1, const void *s2, size_t n)` – copies `n` characters from `*s2` to `*s1`
  - The copy is performed as if the characters from `*s2` were copied into a temporary array first
- `int memcmp(const void *s1, const void *s2, size_t n)` – compares `n` bytes from `*s1` to bytes of `*s2`

Common Errors When Working with Memory

Memory Leak

- A memory leak occurs when the program does not release unused resources, e.g.:
  - Not closing a file or network socket after using it
  - Not freeing allocated heap memory

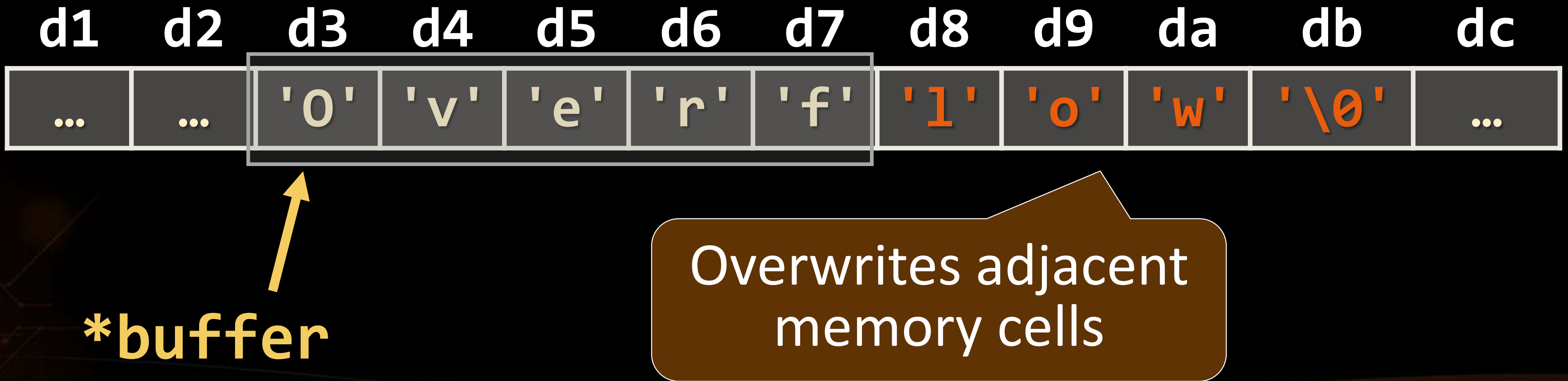
```
int process()
{
    char *bytes = malloc(50);
    ...
    // Does not free
    return 0;
}
```

Allocated memory pointed to by *bytes is lost forever

Buffer Overflow

- A buffer overflow happens when the program overruns a buffer's boundary and writes to adjacent memory

```
char *buffer = malloc(5);
strcpy(buffer, "Overflow");
```



d1	d2	d3	d4	d5	d6	d7	d8	d9	da	db	dc
…	…	'O'	'v'	'e'	'r'	'f'	'l'	'o'	'w'	'\0'	…

Overwrites adjacent memory cells

Dangling Pointer

- Dangling pointers are pointers that no longer point to a valid block of memory, e.g.:
  - Using a pointer after it is freed:

```
char *text = malloc(128);
...
free(text);
...
printf("%s", text);
```

✗

  - Returning a pointer to a local function variable:

```
char *get_string()
{
    char str[100];

    return str;
}
```

✗

Dangling Pointer – Example

```c
#define MIN 5
#define MAX 7

int *get_range(int min, int max)
{
    int nums[max - min + 1];
    for (int i = 0; i <= max – min + 1; i++)
        nums[i] = min++;

    return nums;
}

int main()
{
    int *nums = get_range(MIN, MAX);
    for (int i = 0; i <= MAX - MIN + 1; i++)
        printf("%d ", nums[i]);

    return 0;
}
```

Return pops **get_range()** from the stack (along with **nums**)

Prints garbage memory

Dangling Pointers

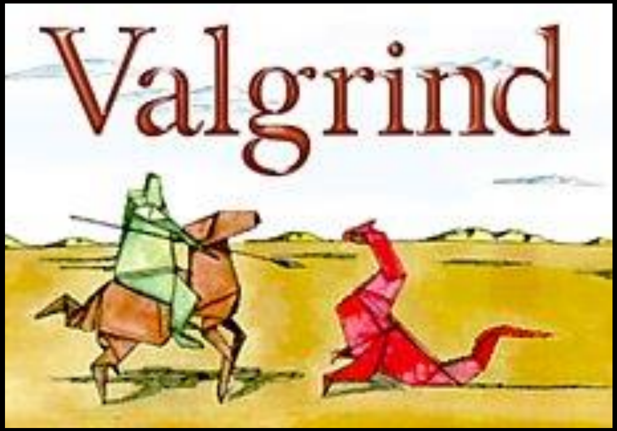
Live Demo

Memory Profilers

Valgrind

Memory Profilers

- Memory profilers analyze the program's memory allocations, reads, writes and deallocations during execution
- Valgrind is a multiplatform C/C++ memory profiler
  - Free and open source (GPL license)
  - Features memory checking tools for finding memory leaks, dangling pointers and buffer overflows
  - http://www.valgrind.org/



Using Valgrind

- Can be installed through the package manager
  - *buntu:

```
sudo apt-get install valgrind
```

- Run command:

```
valgrind [param1 param2 ...] ./{executable}
```

  - Parameters:
    - `--leak-check=yes` – checks for memory leaks
    - `--track-origins=yes` – tracks the source of uninitialized data
    - `--log-file="log.out"` – redirects the output to a file
    - `--track-fds=yes` – displays non-closed files/sockets

Using Valgrind

Live Demo

Stack Smashing

- Valgrind does not offer protection against stack smashing
- GCC adds protection when run when run with the `-fstack-protector-all` flag

```
typedef struct User {
    char name[10];
    int isAdmin;
} User;
```

```
User user;
user.isAdmin = 0;
gets(user.name);
if (user.isAdmin)
{
    // .. Do sensitive stuff
}
```

- Note: NEVER use `gets()`!

Stack Smashing

Live Demo

Summary

- `malloc()`, `calloc()` and `realloc()` allocate a memory block on the heap and return a pointer to it
- `free()` releases the occupied memory block
- Should be used only on pointers obtained by the above functions

- Valgrind is a memory profiling tool that tracks down errors
  - Buffer overflows – writing outside the boundaries of a buffer
  - Memory leaks – unreleased resources
  - Dangling pointers – pointers that point to invalid memory

C Programming – Memory Management

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