Memory (Stack and Heap)
Praktikum „C-Programmierung“

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1 Introduction

2 Heap vs. Stack

3 Memory management in C
   - Library
   - Common techniques

4 Pitfalls

5 Quellen
Virtual address space

- Modern operating systems manage memory allocation
- A page table maps physical memory to virtual address space
- Each process see contiguous memory space
Memory layout of C programs

- **Text segment**
  - Contains executable instructions
  - Often read only and shared by processes

- **DATA:**
  - Data segment, initialized by programmer

- **BSS:**
  - Data segment, uninitialized by programmer
  - Initialized to arithmetic 0
  - Stores global and static variables

- **Stack**
  - Stores automatic variables
  - Typically grows from higher addresses towards zero

- **Heap**
  - Dynamically allocated space
  - Begins at the end of BSS segment

**Abbildung:** Memory Layout [1]
1 Introduction

2 Heap vs. Stack

3 Memory management in C
   - Library
   - Common techniques

4 Pitfalls

5 Quellen
Stack vs. Heap [2]

- **Stack**
  - very fast access
  - don’t have to explicitly de-allocate variables
  - space is managed efficiently by CPU, memory will not become fragmented
  - local variables only
  - limit on stack size (OS-dependent)
  - variables cannot be resized

- **Heap**
  - variables can be accessed globally
  - no limit on memory size
  - (relatively) slower access
  - no guaranteed efficient use of space, memory may become fragmented over time as blocks of memory are allocated, then freed
  - you must manage memory (you’re in charge of allocating and freeing variables)
  - variables can be resized using realloc()
1. Introduction

2. Heap vs. Stack

3. Memory management in C
   - Library
   - Common techniques

4. Pitfalls

5. Quellen
C memory management functions

- `malloc`: allocates memory
- `calloc`: allocates and zeroes memory
- `realloc`: expands previously allocated memory block
- `free`: deallocates previously allocated memory

- The memory management functions
  - allocate and deallocated memory on the heap
  - are defined in header `<stdlib.h>`
malloc

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

- Allocates size bytes and returns a pointer to the allocated memory.
- The memory is not initialized.
- If size is 0, then malloc() returns either NULL, or a unique pointer value that can later be successfully passed to free().
**Library**

**calloc**

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

- Allocates memory for an array of `nmemb` elements of `size` bytes each and returns a pointer to the allocated memory.
- The memory is set to zero.
- If `nmemb` or `size` is 0, then `calloc()` returns either `NULL`, or a unique pointer value that can later be successfully passed to `free()`.
### realloc

1. **void *realloc(void *ptr, size_t size);**

- Changes the size of the memory block pointed to by ptr to size bytes
- The contents will be unchanged in the range from the start of the region up to the minimum of the old and new sizes.
- If the new size is larger than the old size, the added memory will not be initialized.

```
1  p = realloc(NULL, size);
2  // the same as
3  p = malloc(size);
```

```
1  realloc(ptr, 0);
2  // the same as
3  free(ptr)
```
**free**

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

- Frees the memory space pointed to by `ptr`
- `ptr` must have been returned by a previous call to `malloc()`, `calloc()`, or `realloc()`.
- Otherwise, or if `free(ptr)` has already been called before, undefined behavior occurs.
- If `ptr` is `NULL`, no operation is performed.
Usage example

```c
/* Allocate space for an array with ten elements of type int. */
int *ptr = (int *) malloc(10 * sizeof (int));
if (ptr == NULL) {
    /* Memory could not be allocated, the program should
     handle the error here as appropriate. */
} else {
    /* Allocation succeeded. Do something. */
    free(ptr);
    ptr = NULL;
}
```
Allocation idiom

1 int *ptr1 = malloc(10 * sizeof(int));

Listing 1: Straight forward allocation

1 int *ptr2 = malloc(10 * sizeof(*ptr));

Listing 2: Allocation idiom

- Instead of `sizeof(int)` we used `sizeof(*ptr)`
- `sizeof()` automatically determines the correct size of `*ptr`
- If type changes, the malloc still provides right amount of memory
Single dynamic allocation with ownership semantics

```c
{
    struct obj otmp;
    /* do stuff with otmp */
}
```

- User is responsible for memory allocation and deallocation
- Memory is allocated and released in the same scope
Dynamic memory allocation in functions

```c
int *my_func(void) {
    int * x;
    x = (int *) malloc(25);
    return x;
}

int main(int argc, char** argv) {
    int *pi = my_func();
    /* do something with pi */
    free(pi);
    return 0;
}
```

- Memory is allocated by `malloc` in a function
- The user is responsible for deallocation
Introduction

Heap vs. Stack

Memory management in C
  - Library
  - Common techniques

Pitfalls

Quellen
Common pitfalls

Memory management is a source for bugs [4], e.g.

- Memory leaks
- Use after free
- Freeing not dynamically allocated memory
- Accessing not allocated memory
- Multiple free
Memory leaks

```c
int memory_leak() {
    int* ptr = malloc(sizeof(*ptr));
    return 0;
}
```

- Pointer get lost after function returns
- Memory stays allocated, until program exits
Use after free

```c
int *ptr = malloc(sizeof(int));
free(ptr);
*ptr = 7; /* Undefined behavior */
```

- Memory is used after it was freed
- Results in undefined behaviour
Freeing not dynamically allocated memory

1. `char *msg = "Default message";`
2. `int tbl[100];`
3. `free(msg);`
4. `free(tbl);`

- Freeing memory that was not allocated by `malloc`, `calloc` or `realloc`
- Results in undefined behaviour
Accessing not allocated memory

```c
int *my_func(void) {
    int x[25];
    return x;
}

int main(int argc, char** argv) {
    int *pi = my_func();
    *(pi + 1) = 5;
    free(pi);
    return 0;
}
```

- Not allocated memory is used after freed
Multiple free

```c
void main(){
    int *p;
    p = (int *)malloc(10 * sizeof(int));
    f(p);
    free(p);
}

void f(int *g){
    printf("%d", g);
    free(g);
}
```

- The same allocation is freed several times
- Results in undefined behaviour
Summary

- From application’s perspective, memory is a contiguous space partitioned in segments (Text, DATA, BSS, Stack and Heap)

- Memory management
  - On stack memory is managed for you
  - On heap the user is responsible for memory management
  - Memory management functions are defined in `<stdlib.h>`

- Common bugs
  - Memory leaks
  - Use after free
  - Freeing not dynamically allocated memory
  - Accessing not allocated memory
  - Multiple free
# Introduction

# Heap vs. Stack

# Memory management in C
- Library
- Common techniques

# Pitfalls

# Quellen
Quellen I

