Memory Management. Modules. Abstract Data Types.

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Overview

Questions we will answer today

- What is the difference between the stack and the heap?
- How can we allocate and free memory on the heap?
- How do we use pointers to access memory locations?
- How can we create modules in C? How do we separate the interface from the implementation?

Pointers

Recap

- Pointers are variables storing memory addresses.
- They allow us to manipulate data more flexibly.
- *Dereferencing* means accessing the value pointed to by a pointer.
- Dereferencing operator: *.
- Address operator: &.

Null and dangling pointers I

Null pointer

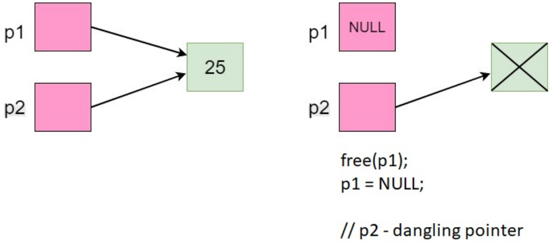
- It is a pointer set to 0 or NULL, an invalid pointer. The null pointer constant is guaranteed not to point to any real object.
- Pointers are often set to 0 (or NULL) to signal that they are not currently valid.
- We should check whether a pointer is null before dereferencing it!

Null and dangling pointers II

Dangling pointer

- It is a pointer that does not point to valid data:
  - the data might have been erased from memory;
  - the memory pointed to has undefined contents.
- Dereferencing such a pointer will lead to undefined behaviour!

Null and dangling pointers III



DEMO

Null and dangling pointers. (*NullDanglingPointers.c*).

Arrays and pointers

- Arrays can be seen as pointers to the first element of the array.
- int arr[10]; **?** What is the difference between arr and &arr[0]?.
- When passed as function parameters, arrays are passed "by reference".
- Check example **Arrays.c** file in **Lecture1_demo**.

Pointers to functions I

- a **function pointer** is a pointer which points to an address of a function (executable code in memory);
- can be used for *dynamic (late)* binding (the function to use is decided at runtime, instead of compile time);
- functions can be used as parameters for other functions;
- do not need memory allocation/deallocation;
- pointer arithmetic cannot be performed on function pointers.

Definition

<return_type> (* <name>)(<parameter_types>)

E.g.

```
double (*operation)(double, double);
```

Pointers to functions II

DEMO

Pointers to functions. (*PointersToFunctions.c*).

Pointers to functions III

C isn't that hard:

void (*(*f[])())()

- declare f as array of pointers to functions returning pointers to functions returning void (https://www.cdecl.org/).

f	f
f[]	is an array
*f[]	of pointers
(*f[])()	to functions
*(*f[])()	returning pointers
(*(*f[])())()	to functions
void (*(*f[])())();	returning void

Const pointers

- *Changeable pointer to constant data* - the pointed value cannot be changed, but the pointer can be changed to point to a different constant value.

```
const int* p;
```

- *Constant pointer to changeable data* - the pointed value can be changed through this pointer, but the pointer cannot be changed to point to a different memory location.

```
int* const p;
```

- *Constant pointer to constant data*.

```
const int* const p;
```

DEMO

Const pointers. (*ConstPointers.c*).

Stack and heap I

The memory used by a program is composed of several segments:

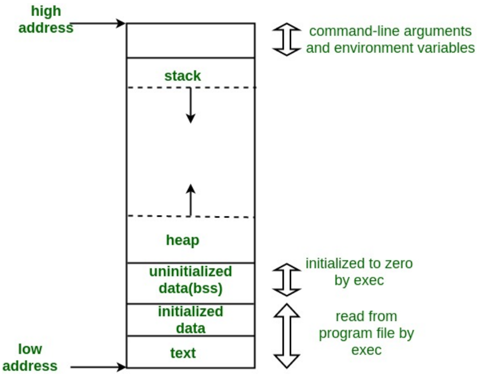


Figure source: Layout of a C program.

Stack and heap II

- *The code (text) segment* - contains the compiled program.
- *The data segment* - used to store global and static variables (uninitialised variables are stored in the BSS (block started by symbol) segment).
- *The stack* - used to store function parameters, local variables and other function-related information.
- *The heap* - used for the dynamically allocated variables.

Stack and heap III

Stack

- Is a continuous block of memory consisting of **stack frames**.
- **Stack frame** - keeps the data associated with one function call: return address, function arguments, local variables (minimum a return address).
- For each function call, a new stack frame is constructed and pushed onto the stack (this is how recursive functions work).
- When a function is terminated, its associated stack frame is popped off the stack, the local variables are destroyed and execution is resumed at the return address.
- The stack has a limited size.
- ? Stack overflow

Stack and heap IV

Heap

- Large pool of memory.
- Used for dynamic memory allocation.
- The data in the heap must be managed by the programmer.
- The size of the heap is only limited by the size of the virtual memory.
- Can be subject to heap fragmentation
  - https://library.softwareverify.com/memory-fragmentation-your-worst-nightmare/
  - https://cpp4arduino.com/2018/11/06/what-is-heap-fragmentation.html

Stack and heap V

Stack	Heap
very fast access	slower access
no need for explicit deallocation	memory must be managed by the programmer
space is managed efficiently	no guaranteed efficient use of space
LIFO system - no fragmentation	memory may become fragmented
local variables only	variables can be accessed "globally"
limit on stack size	"no limit" on memory size
variables cannot be resized	variables can be resized using realloc()

Memory management

- Memory can be allocated in two ways:
  - *Statically* (compile time)
    - by declaring variables;
    - size must be known at compile time;
    - there is no control over variable lifetime.
  - *Dynamically* ("on the fly", during runtime)
    - on the heap;
    - size does not have to be known in advance by the compiler;
    - achieved using pointers;
    - the programmer controls the size and lifetime of the variables.

Dynamic allocation and deallocation I

- **C** - use the functions defined in **stdlib.h**:
  - malloc - finds a specified size of free memory and returns a void pointer to it (memory is uninitialised).
  - calloc - allocates space for an array of elements, initializes them to zero and then returns a void pointer to the memory.
  - realloc - reallocates the given area of memory (either by expanding or contracting or by allocating a new memory block).
  - free - releases previously allocated memory.

DEMO

Dynamic allocation and deallocation in C. (*DynamicMemory-ManagementC.c*).

Dynamic allocation and deallocation II

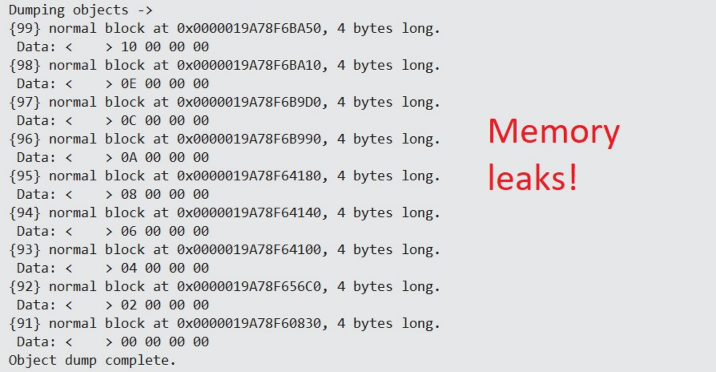
- **C++** - new and delete operators.
- new **T**
  - memory is allocated to store a value of type T;
  - it returns the address of the memory location;
  - the return value has type T*.
- delete p
  - deallocates memory that was previously allocated using new;
  - precondition: p is of type T*;
  - the memory space allocated to the variable p is free.

DEMO

Dynamic allocation and deallocation in C++. (*DynamicMemoryManagement.cpp*).

Memory errors I

- Memory leaks - memory is allocated, but not released (Visual Studio: <**crtdbg.h**> and **_CrtDumpMemoryLeaks();**).



```
Dumping objects ->
{99} normal block at 0x0000019A78F6BA50, 4 bytes long.
 Data: <    > 10 00 00 00
{98} normal block at 0x0000019A78F6BA10, 4 bytes long.
 Data: <    > 0E 00 00 00
{97} normal block at 0x0000019A78F6B9D0, 4 bytes long.
 Data: <    > 0C 00 00 00
{96} normal block at 0x0000019A78F6B990, 4 bytes long.
 Data: <    > 0A 00 00 00
{95} normal block at 0x0000019A78F64180, 4 bytes long.
 Data: <    > 08 00 00 00
{94} normal block at 0x0000019A78F64140, 4 bytes long.
 Data: <    > 06 00 00 00
{93} normal block at 0x0000019A78F64100, 4 bytes long.
 Data: <    > 04 00 00 00
{92} normal block at 0x0000019A78F656C0, 4 bytes long.
 Data: <    > 02 00 00 00
{91} normal block at 0x0000019A78F60830, 4 bytes long.
 Data: <    > 00 00 00 00
Object dump complete.
```

Memory errors II

- Invalid memory access - unallocated or deallocated memory is accessed.
- Mismatched Allocation/Deallocation - deallocation is attempted with a function that is not the logical counterpart of the allocation function used.
- Freeing memory that was never allocated.
- Repeated frees - freeing memory which has already been freed.

So...when should we use pointers?

- When data needs to be allocated on the heap (**?** when is that?).
- When we need "pass by reference".
- When we want to avoid copying data (because of the default "pass by value") - efficiency.
- **?** Where are pointers stored? Where are the objects pointed to by pointers stored?

Modules

A **module** is collection of functions and variables that implements a well defined functionality.

Goals:

- separate the *interface* from the *implementation*;
- hide the implementation details.

Header files. Libraries I

- Function prototypes (function declarations) are grouped into a separate file called *header file*.
- A library is a set of functions, exposed for use by other programs.
- Libraries are generally distributed as:
  - a header file (.h) containing the function prototypes and
  - a binary file (.dll or .lib) containing the compiled implementation.
- The source code (.c/.cpp) does not need to be shared.

Header files. Libraries II

- The library users only need the function prototypes (which are in the header), not the implementation.
- The function specification is separated from the implementation.
- Static linking happens at compile time and the .lib is completely "included" in the executable ($\Rightarrow$ an increase in the size of the resulting executable).
- Dynamic linking (.dll files) includes only the information needed at run time to locate and load the DLL that contains a data item or function.

Preprocessor directives I

- lines in the code preceded by a hash sign (#).
- are executed by the preprocessor, before compilation.

Examples:

- #include *header_file* - tells the proprocessor to open the header file and insert its contents.
    - if the header file is enclosed between angle brackets (<>) - the file is searched in the system directories.
    - if the header in enclosed between double quotes(" ") - the file is first searched in the current directory and then in the system directories.

Preprocessor directives II

- #define *identifier replacement* - any occurence of *identifier* in the code is replaced by *replacement*.
- #ifdef *macro*, ... ,#endif - the section of code between these two directives is compiled only if the specified macro has been defined.
- #ifndef *macro*, ... ,#endif - the section of code between these two directives is compiled only if the specified macro has **not** been defined.

Preprocessor directives III

- #ifndef #define and #endif - can be used as *include guards*.
- *include guards* are used to avoid *multiple inclusion* when using the #include directive. *Multiple inclusion* causes compilation errors (violation of the *One Definition Rule*).
- #pragma - used to specify various options to the compiler. #pragma once (not standard, but widely supported) - the current file will be included only once in a single compilation (same purpose as include guards).

Create modular programs I

The code of a C/C++ program is split into several source files: .h and .c/.cpp:

- .h files - contain the function declarations (the interfaces);
- .c/.cpp files - contain the function implementations.

Advantage: the .c/.cpp files can be compiled separately (for error checking and testing).

- Whenever a header file is changed all the files that include it (directly or indirectly) must be recompiled.

Create modular programs II

- The header file is a **contract** between the developer and the client of the library that describes the data structures and states the arguments and return values for function calls.
- The compiler enforces the contract by requiring the declarations for all structures and functions before they are used (this is why the header file must be included).

Module design guidelines I

- Separate the interface from the implementation:
  - The header file should only contain type declarations and function prototypes.
  - Hide and protect the implementation details.
- Include a short description of the module (comment).
- Cohesion
  - A module should have a single responsibility.
  - The functions inside the module should be related.
- Layered architecture
  - Layers: model, validation, repository, service, ui.
  - Manage dependencies: each layer depends only on the layer immediately below.

Module design guidelines II

- Abstract data types (ADT)
  - Declare operations in the .h file and implement them in the .c/.cpp file.
  - Hide the implementation details, the client should only have access to the interface.
  - Abstract specification (functions' specifications should be independent from the implementation).
- Create self contained headers: they include all the modules on which they depend (no less, no more).
- Protect against multiple inclusion (include guards or #pragma once).

ADT

An ADT is a data type which:

- exports a name (type);
- defines the domain of possible values;
- establishes an interface to work with objects of this type (operations);
- restricts the access to the object components through the operations defined in its interface;
- hides the implementation.

Any program entity that satisfies the requirements from the ADT definition is considered to be an implementation of the ADT.

ADT implementation in C/C++:

- interface - header file (.h);
- implementation - source file (.c/.cpp).

ADT Dynamic Array

Requirement

Create a dynamic array, having a length that can be modified and allowing the insertion and deletion of elements of type *Planet*. Each *Planet* has:

- a name
- a type (Neptune-like, gas giant, terrestrial, super-Earth, unknown)
- the distance to the Earth (measured in light-years)

DEMO

Dynamic array. (*DynamicArray.h, DynamicArray.c*).

Summary I

Memory management

- Memory allocation can be made statically (compile time) or dynamically (run time).
- We are responsible for dynamically allocated memory.
- We must pay attention to memory errors (memory leaks, repeated frees, dangling pointers, accessing memory at the NULL location).

Summary II

Modular programming

- Separate the interface from the implementation.
- Header (.h) files contain function declarations (define the "what").
- .c/cpp files contain function implementations (define the "how").