MEMORY MANAGEMENT PROBLEMS

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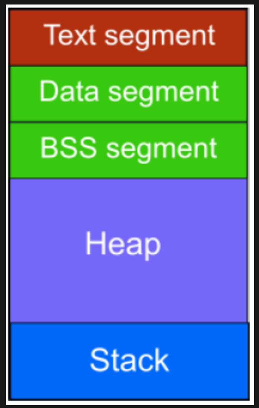
AGENDA

- Process memory allocation
  - process memory map
  - stack vs heap
  - stack allocation
  - heap allocation
  - new expression and operator `new`
  - dynamic array allocation
  - dynamic allocation problems
- RAII
- Memory corruption detection

PROCESS MEMORY MAP

- text - the machine instructions
- data - initialized static and global data
- bss - uninitialized static data
- heap - dynamically allocated memory
- stack - the call stack, which holds return addresses, local variables, temporary data

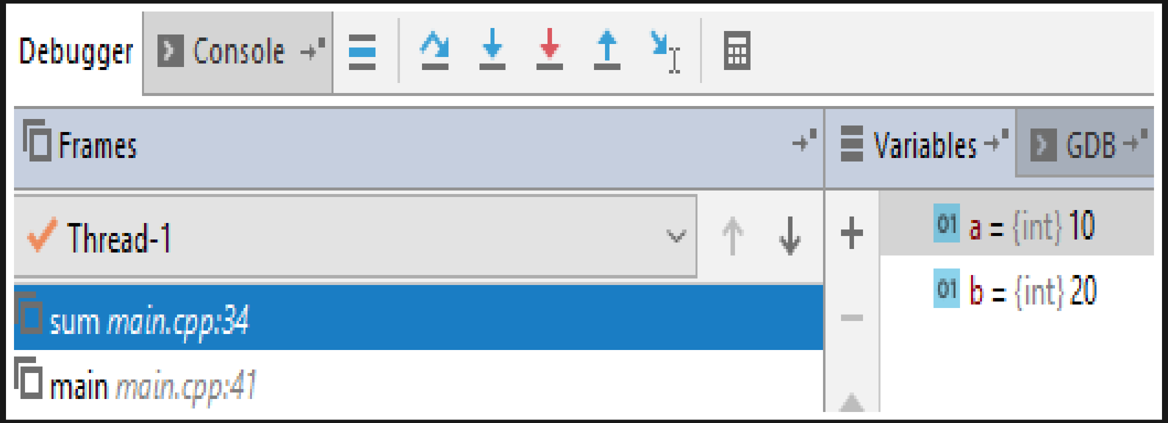


STACK VS HEAP

- Stack
  - very fast access
  - limit on stack size (OS-dependent)
  - not fragmented memory
  - automatic memory management (by CPU via Stack Pointer – SP)
- Heap
  - slower access
  - no limit on memory size (OS-managed)
  - memory may become fragmented
  - manual memory management (allocation and deallocation)

STACK ALLOCATION

- A call stack is composed of stack frames
- A stack frame usually includes at least:
  - arguments passed to a function (if any)
  - the return address back to the caller
  - space for local variables (if any)
- Automatic deallocation when out of scope




```cpp
#include <iostream>

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

int main()
{
    int a = 10;
    int b = 20;

    std::cout << sum(a, b);

    return 0;
}
```

STACK OVERFLOW

- There is a limit on a stack size (OS dependent)

```
int foo()
{
    double x[1048576];
    x[0] = 10;
    return 0;
}

int main()
{
    foo();
    return 0;
}
```

HEAP ALLOCATION

Heap allocation consists of a few steps:

- pointer allocation on a stack
- `sizeof(T)` bytes allocation on a heap
- `T`'s constructor call on allocated memory
- the memory address assignment to the pointer
- manual deallocation using `delete` operator

```
void heap()
{
    int *p = new int(100);
    delete p;
}

void heap()
{
    int *p;
    p = (int*)malloc(sizeof(int));
    *p = 100;
    free(p);
}
```

NEW EXPRESSION AND OPERATOR `new`

new expression does 3 things:

- `sizeof(T)` bytes allocation on a heap (via proper operator `new`)
- `T`'s constructor call on allocated memory
- the memory address assignment to the pointer

```
// replaceable allocation functions
void* operator new ( std::size_t count );
void* operator new[]( std::size_t count );
// replaceable non-throwing allocation functions
void* operator new ( std::size_t count, const std::nothrow_t& tag);
void* operator new[]( std::size_t count, const std::nothrow_t& tag);
// user-defined placement allocation functions
void* operator new ( std::size_t count, user-defined-args... );
void* operator new[]( std::size_t count, user-defined-args... );
// additional param std::align_val_t since C++17, [[nodiscard]] since C++20
// some more versions on https://en.cppreference.com/w/cpp/memory/new/operator_
```

DYNAMIC ARRAY ALLOCATION

- `delete[]` is used to free an array memory

```cpp
#include <iostream>

int main() {
    int staticArray[] = {1, 2, 3, 4, 5, 6};

    constexpr auto size = 10;
    int* dynamicArray = new int[size];
    for (int i = 0; i < size; ++i) {
        *(dynamicArray + i) = i * 10;
    }

    for (int i = 0; i < size; ++i) {
        std::cout << dynamicArray[i] << '\n';
    }

    delete[] dynamicArray;
}
```

DYNAMIC ALLOCATION PROBLEMS

QUIZ

WHAT KIND OF PROBLEM IS HERE? #1

```cpp
#include <iostream>

int main() {
    const auto size = 10;
    int* dynamicArray = new int[size];

    for (int i = 0; i <= size; ++i) {
        *(dynamicArray + i) = i * 10;
    }

    for (int i = 0; i <= size; ++i) {
        std::cout << dynamicArray[i] << '\n';
    }

    delete[] dynamicArray;
}
```

ACCESSING OUT-OF-BOUNDS MEMORY

WHAT KIND OF PROBLEM IS HERE? #2

```cpp
#include <iostream>

struct Msg {
    int value{100};
};

void processMsg(Msg* msg) {
    std::cout << msg->value << '\n';
}

int main() {
    Msg* m = new Msg();
    delete m;
    processMsg(m);
    return 0;
}
```

DANGLING POINTER

A pointer which indicates to something that is not valid

WHAT KIND OF PROBLEM IS HERE? #3

```cpp
class Msg {};

void processMsg(Msg* msg) {
    // ...
    delete msg;
}

int main() {
    Msg* m = new Msg{};
    processMsg(m);
    delete m;
}
```

DOUBLE DELETE

Happens when a dangling pointer is deleted

WHAT KIND OF PROBLEM IS HERE? #4

```cpp
#include <iostream>

int main() {
    int* p = new int{10};
    delete p;
    p = nullptr;

    std::cout << *p << '\n';

    return 0;
}
```

NULL POINTER DEREFERENCE

Happens when a `nullptr` is used

WHAT KIND OF PROBLEM IS HERE? #5

```cpp
class Msg {};

void processMsg(Msg* msg) {
    // ...
    delete msg;
}

int main() {
    Msg m;
    processMsg(&m);

    return 0;
}
```

FREEING STACK ALLOCATED BLOCKS

WHAT KIND OF PROBLEM IS HERE? #6

```
int main() {
    constexpr auto size = 4u;
    int* array = new int[size]{1, 2, 3, 4};
    delete array;

    return 0;
}
```

FREEING A PORTION OF A DYNAMIC BLOCK

Using `delete` instead of `delete[]`

WHAT KIND OF PROBLEM IS HERE? #7

```cpp
#include <iostream>

int main() {
    int* p = new int{10};
    p = new int{20};
    std::cout << *p << '\n';
    delete p;

    return 0;
}
```

MEMORY LEAK

Allocated memory which cannot be freed because there is no pointer that points to it

DYNAMIC ALLOCATION PROBLEMS

- accessing out-of-bounds memory
- dangling pointer
- double deleting
- `null` pointer dereference
- freeing memory blocks that were not dynamically allocated
- freeing a portion of a dynamic block
- memory leak

All allocation problems cause Undefined Behavior.

These problems can be addressed by ASAN (Address Sanitizer) or Valgrind. Unfortunately they do not work on Windows 😕

A SIMPLE QUESTION…

How many possible paths of execution are here?

```
String EvaluateSalaryAndReturnName(Employee e)
{
    if( e.Title() == "CEO" || e.Salary() > 100000 )
    {
        cout << e.First() << " " << e.Last()
             << " is overpaid" << endl;
    }
    return e.First() + " " + e.Last();
}
```

- 23 (twenty three)
- Exceptions are the reason
- Example by Herb Sutter, GotW#20

RAII

- Resource Acquisition Is Initialization
  - idiom / pattern in C++
  - each resource has a handler
  - acquired in constructor
  - released in destructor
- Benefits
  - shorter code (automation)
  - clear responsibility
  - applies to any resources
  - no need for `finally` sections
  - predictable release times
  - language-level guarantee of correctness

	Acquire	**Release**
memory	new, new[]	delete, delete[]
files	fopen	fclose
locks	lock, try_lock	unlock
sockets	socket	close

EXERCISE

Take a look into exercises/FileOperations.cpp file. It is casual file handling in C language. Write a FileHandler class that implements RAII and mimicks the behavior implemented in FileOperations.cpp.

Remember about:

- proper constructor that acquire a file
- proper destructor that release the file
- `operator<<` for displaying file content on the screen
- error handling

MEMORY CORRUPTION DETECTION

- Address Sanitizer (ASAN)
  - add compilation flags:
    - `–fsanitize=address -g`
    - `–fsanitize=leak -g`
  - run a binary
- Valgrind
  - compile a binary
  - run a binary under valgrind:
    - `valgrind /path/to/binary`
  - use additional checks:
    - `valgrind --leak-check=full /path/to/binary`

Neither work on Windows 😕

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