Modern C++ Programming

4. Basic Concepts III

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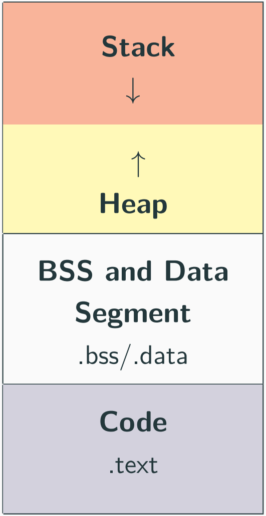
Memory Management: Heap and Stack

Process Address Space

higher memory addresses 0x00FFFFFF



lower memory addresses 0x00FF0000

stack memory	`int data[10]`
dynamic memory	`new int[10]` `malloc(40)`
Static/Global data	`int data[10]` (global scope)

new, delete

`new` /`new[]` and `delete` /`delete[]` are C++ *keywords* that perform dynamic memory allocation/deallocation, and object construction/ destruction at runtime

`malloc` and `free` are C functions and they allocate and free *memory blocks* (expressed in bytes)

Example:

```
int* array = new int[10];  // C: (int*) malloc(10 * sizeof(int))
delete[] array;            // C: free(array)
```

`new`, `delete` Advantages

- **Language keywords**, not functions → *safer*
- **Return type**: `new` returns exact data type, while `malloc()` returns `void*`
- **Failure**: `new` throws an *exception*, while `malloc()` returns a `NULL` pointer → *it cannot be ignored*
- **Allocated bytes**: The size of the allocated memory is calculated by the compiler for `new`, while the user must take care of manually calculate the size for `malloc()`
- **Initialization**: `new` can be used to initialize an object or a set of objects

Dynamic Allocation

- **Allocate a single element**

```
int* value = (int*) malloc(sizeof(int)); // C
int* value = new int;                    // C++
```

- **Allocate N elements**

```
int* array = (int*) malloc(N * sizeof(int)); // C
int* array = new int[N];                     // C++
```

- **Allocate and zero-initialize N elements**

```
int* array = (int*) calloc(N * sizeof(int)); // C
int* array = new int[N]();                   // C++
```

- **Allocate N structures**

```
MyStruct* array = (int*) malloc(N * sizeof(MyStruct)); // C
MyStruct* array = new MyStruct[N];                     // C++
```

Dynamic Deallocation

- **Deallocate a single element**

```
int* value = (int*) malloc(sizeof(int)); // C
free(value);

int* value = new int;                    // C++
delete value;
```

- **Deallocate N elements**

```
int* value = (int*) malloc(N * sizeof(int)); // C
free(value);

int* value = new int[N];                     // C++
delete[] value;
```

Fundamental rules:

- Each object allocated with `new` must be deallocated with `delete`
- Each object allocated with `new[]` must be deallocated with `delete[]`

Mixing `new`, `new[]`, `malloc` with something different from their counterparts leads to *undefined behavior*

`delete` and `delete[]` applied to `NULL`/ `nullptr` pointers do not produce errors (same as `free`)

Memory Leak

A **memory leak** is a dynamically allocated entity in heap memory that is no longer used by the program, but still maintained overall its execution

Problems:

- Illegal memory accesses → segmentation fault
- Undefined values → segmentation fault
- Additional memory consumption

```
int main() {
    int* array = new int[10];
    array      = nullptr; // memory leak!!
} // the memory can no longer be deallocated!!
```

Note: the memory leaks are especially difficult to detect in complex code and when objects are widely used

Wild and Dangling Pointers

Wild pointer:

```
int main() {
    int* ptr;   // wild pointer: Where will this pointer points?
    ...         // solution: always initialize a pointer
}
```

Dangling pointer:

```
int main() {
    int* array = new int[10];
    delete[] array; // ok -> "array" now is a dangling pointer
    delete[] array; // double free or corruption!!
    // program aborted, the value of "array" is not null
}
```

Solution:

```
int main() {
    int* array = new int[10];
    delete[] array;  // ok -> "array" now is a dangling pointer
    array = nullptr; // no more dagling pointer
    delete[] array;  // ok, no side effect
}
```

Stack Allocation

A local variable is either in stack memory or CPU registers

Every object which resides in the stack is not valid outside the current scope!!

```
int* wrongFunction() {
    int A[3] = {1, 2, 3};
    return A;
}
int main() {
   int* ptr = wrongFunction();
   cout << ptr[0]; // Illegal memory access!!
}
```

The organization of stack memory enables much higher performance. On the other hand, this memory space is limited!!
It is $\approx 8MB$ on linux by default

2D Memory Allocation

Easy on stack:

```
int A[3][4];
```

Dynamic Memory 2D allocation/free:

```
int** A = new int*[3];
for (int i = 0; i < 3; i++)
    A[i] = new int[4];

for (int i = 0; i < 3; i++)
    delete[] A[i];
delete[] A;
```

Dynamic memory 2D allocation/free C++11:

```
auto A = new int[3][4];    // allocate 3 objects of size int[4]
int  n = 3;                // dynamic value
auto B = new int[n][4];    // ok
// auto C = new int[n][n]; // compile error!!
delete[] A;                // same for B, C
```

Data and BSS Segment

```c
int data[]             = {1, 2}; // DATA segment memory
int big_data[1000000] = {};     // BSS segment memory
                                // (zero-initialized)

int main() {
    int A[] = {1, 2, 3}; // stack memory
}
```

Data/BSS (Block Started by Symbol) segments are larger than stack memory (max $\approx$ 1GB in general) but slower

Initialization

Variable Initialization

C++03:

```
int a;             // undefined
int a1 = 2;        // copy initialization
int a2(2);         // direct initialization
int a3 = {2};      // copy list initialization
int a4 = int(2);   // copy initialization
int a5 = int();    // copy initialization (zero-initialization)
// int a6();       // a6 is a function
```

C++11 (Uniform Initialization):

```
int b1{2};     // direct list initialization
int b2 = {2};  // copy list initialization

// Zero-initialization / Default-Initialization
int b3 = {};   // copy list initialization, default value
int b4{};      // direct list initialization, default value
```

Stack Array Initialization

One dimension:

```
int  A[3] = {1, 2, 3}; // explicit size
int  B[]  = {1, 2, 3}; // implicit size
char C[]  = "abcd";    // implicit size
int  C[3] = {1, 2};    // C[2] = 0 -> zero/default value

int  D[4] = {0}; // all values of D are initialized to 0
int  E[3] = {};  // all values of E are initialized to 0 (C++11)
int  F[3] {};    // all values of F are initialized to 0 (C++11)
```

Two dimensions:

```
int G[][2] = { {1,2}, {3,4}, {5,6} }; // ok
int H[][2] = { 1, 2, 3, 4 };          // ok
// the type of G and H is an array of type int[]
// int F[][]  = ...;                  // compile error!!
// int G[2][] = ...;                  // compile error!!
```

Default Initialization

Rules for Zero/Default Initialization:

- An object with **dynamic** storage duration (heap) has indeterminate value
- An object whose initializer is an **empty set of parentheses** `{}` is zero or default initialized (C++11)

Dynamic Initialization

C++03:

```
int* a1 = new int;       // undefined
int* a2 = new int();     // zero-initialization
int* a3 = new int(4);    // allocate a single value equal to 4
int* a4 = new int[3];    // allocate 4 elements with undefined values
int* a5 = new int[4](); // allocate 4 elements zero-initialized
```

C++11:

```
int* b1 = new int[4]{};     // allocate 4 elements zero-initialized
int* b2 = new int[4]{1, 2}; // set first, second, zero-initialized
```

Pointers and References

Pointers and Pointer Dereferencing

Pointer

A **pointer** is a value referring to a location in memory

Pointer Dereferencing

Pointer **dereferencing** means obtaining the value stored in at the location refereed to the pointer

```
int* ptr1 = new int;
*ptr1     = 4;      // deferencing (assignment)
int a     = *ptr1; // deferencing (get value)
```

Common error:

```
int *ptr1, ptr2;  // one pointer and one integer!!
int *ptr1, *ptr2; // ok, two pointers
```

`void` Pointer (Generic Pointer)

Instead of declaring different types of pointer variable it is possible to declare single pointer variable which can act as any pointer types

- A `void*` can be assigned to another `void*`
- `void*` can be compared for equality and inequality
- A `void*` can be explicitly converted to another type
- Other operations would be unsafe because the compiler cannot know what kind of object is really pointed to. Consequently, other operations result in compile-time errors

```
cout << (sizeof(void*) == sizeof(int*));  // print true

int array[] = { 2, 3, 4 };
void* ptr = array;
cout << *array;             // print 2
// cout << *ptr;            // compile error!!
cout << *((int*) ptr);      // print 2
// void* ptr2 = ptr + 2;    // compile error!!
```

Address-of operator &

The **address-of operator** (&) returns the address of a variable

```
int  a = 3;
int* b = &a; // address-of operator,
             // 'b' is equal to the address of 'a'
a++;
cout << *b;  // print 4;
```

To not confuse with **Reference syntax:** `T& var = ...`

```
int array[4];
// &array is a pointer to an array of size 4
int size1 = (&array)[1] - array;
int size2 = *(&array + 1) - array;
cout << size1;  // print 4
cout << size2;  // print 4
```

$1 + 1 \neq 2$: Pointer Arithmetic

Pointer syntax:

`ptr[i]` is equal to `*(ptr + i)`

Pointer arithmetic rule:

address(`ptr + i`) $=$ address(`ptr`) $+$ (`sizeof(T) * i`)

where `T` is the type of elements pointed by `ptr`

Example:

```
int array[4] = {1, 2, 3, 4};
cout << array[1];      // print 2
cout << *(array + 1); // print 2
cout << array;         // print 0xFFFAFFF2
cout << array + 1;     // print 0xFFFAFFF6!!
```

`char arr[3] = "abc"`

value	address	
'a'	0x0	←arr[0]
'b'	0x1	←arr[1]
'c'	0x2	←arr[2]

`int arr[3] = {4,5,6}`

value	address	
4	0x0	←arr[0]
	0x1	
	0x2	
	0x3	
5	4	←arr[1]
	0x5	
	0x6	
	0x7	
	0x8	←arr[2]

Reference

A variable **reference** is an **alias**, namely another name for an already existing variable. Both variable and variable reference can be applied to refer the value of the variable

- A pointer has its own memory address and size on the stack, reference shares the **same memory address** (with the original variable)
- References are internally implemented as *pointer*, but the compiler treats them in a very different way

References are safer than pointers:

- References **cannot have NULL** value. You must always be able to assume that a reference is connected to a legitimate storage
- References **cannot be changed**. Once a reference is initialized to an object, it cannot be changed to refer to another object (Pointers can be pointed to another object at any time)
- References must be **initialized** when they are created (Pointers can be initialized at any time)

Reference (Examples)

Reference syntax: `T& var = ...`

```
//int& d;   // reference. compile error!! no initilization
int  c = 2;
int& e = c; // reference. ok valid initialization
e++;        // increment
cout << c;  // print 3
```

```
int  a = 3;
int* b = &a; // pointer
int* c = &a; // pointer
b++;         // change the value of the pointer 'b'
*c++;        // change the value of 'a'

int& c = a;  // reference
c++;         // change the value of 'a'
```

Reference (Function Arguments)

Reference vs. pointer arguments:

```
void f(int* value) {} // value may be a nullptr
void g(int& value) {} // value is never a nullptr

int a = 3;
f(&a);  // ok
g(a);   // ok
//g(3); // compile error!! "3" is not a reference of something
```

References can be use to indicate fixed size arrays:

```
f(int (&array)[3]) {} // accepts only arrays of size 3
                      // f(int array[]) accepts any size
int A[3], B[4];
int* C = A;
//------------------------------------------------------
f(A);    // ok
// f(B); // compile error!! B has size 4
// f(C); // compile error!! C is a pointer
```

Reference (Arrays)

```
int A[4];
int (&B)[4] = A;     // ok, reference to array
int C[10][3];
int (&D)[10][3] = C; // ok, reference to 2D array

auto c = new int[3][4]; // type is int (*)[4]
// read as "pointer to arrays of 4 int"
// int (&d)[3][4] = c;   // compile error!!
// int (*e)[3]     = c;   // complie error!!
int (*f)[4] = c;          // ok
```

Reference:
[1] www3.ntu.edu.sg/home/ehchua/programming/cpp/cp4_
PointerReference.html

Reference and struct

- The dot (.) operator is applied to local objects and references
- The arrow operator (->) is used with a pointer to an object

```
#include <iostream>
struct A {
   int x = 3;
};

int main() {
   A obj;

   A* p = &obj;    // pointer
   p->x;           // arrow syntax

   A& ref = obj;   // reference
   cout << obj.x; // dot syntax
   cout << ref.x; // dot syntax
}
```

`sizeof` Operator

`sizeof` operator

`sizeof`

The `sizeof` is a compile-time operator that determines the size, in bytes, of a variable or data type

- `sizeof` returns a value of type `size_t`
- `sizeof(incomplete type)` produces compile error, e.g. `void`
- `sizeof(bitfield)` produces compile error
- `sizeof(anything)` never returns 0, except for array of size 0
- `sizeof(char)` always returns 1
- When applied to structures, it also takes into account padding
- When applied to a reference, the result is the size of the referenced type

```
sizeof(int);    // 4
sizeof(int*)    // 8 on a 64-bit OS
sizeof(void*)   // 8 on a 64-bit OS
sizeof(size_t)  // 8 on a 64-bit OS
```

```
int f(int[] array) {        // dangerous!!
    cout << sizeof(array);
}

int  array1[10];
int* array2 = new int[10];
cout << sizeof(array1); // print sizeof(int) * 10 = 40
cout << sizeof(array2); // print sizeof(int*) = 8  (64-bit)
f(array1);              // print 8
```

sizeof (struct) 2/3

```
struct B {
    int  x;
    char y;
};

struct C : B { // C extends B
    short z;
};
//-----------------------------------------------------------------
sizeof(B);      //  8 : 4 + 1 (+ 3) (padding)
sizeof(C);      // 12 : sizeof(B) + 2 (+ 2) (padding)

struct A {};
sizeof(A);      // 1 : sizeof never return 0 (except for arrays)
```

```cpp
char  a;
char& b = a;
sizeof(&a);    // 8 in a 64-bit OS (pointer)
sizeof(b);     // 1, i.e. sizeof(char)
               // NOTE: a reference is not a pointer

struct A {};
A array1[10];
sizeof(array1); // 1 : array of empty structures

int array2[0];
sizeof(array2); // 0 : special case
```

`const` and `constexpr`

`const` Keyword

`const` keyword

The `const` keyword indicates objects never changing value after their initialization (they must be initialized when declared)

`const` variables are evaluated at compile-time value if the right expression is also evaluated at compile-time

```
int size = 3;
int A[size] = {1, 2, 3}; // Technically possible (size is dynamic)
                         // But NOT approved by the C++ standard
const int SIZE = 3;
// SIZE = 4;             // compile error!! (SIZE is const)
int B[SIZE] = {1, 2, 3}; // ok

const int size2 = size;
int B[size2] = {1, 2, 3}; // BAD programming!! size is not const
// (some compilers allow variable size stack array -> dangerous!!)
```

Constness rules:

- `int* → const int*`
- `const int* ↛ int*`

```
int f1(const int* array) { // the values of the array cannot be
    ...                    // modified
}

int f2(int* array) {}

int*       ptr   = new int[3];
const int* c_ptr = new int[3];
f1(ptr);      // ok
f2(ptr);      // ok
f1(c_ptr);    // ok
// f2(c_ptr); // compile error!!
```

```
void g(const int) {  // pass-by-value combined with 'const'
    ...              // note: it is not useful because the value
}                    //       is copied
```

- `int*` pointer to `int`
  - The value of the pointer can be modified
  - The elements refereed by the pointer can be modified
- `const int*` pointer to `const int`. Read as `(const int)*`
  - The value of the pointer can be modified
  - The elements refereed by the pointer cannot be modified
- `int *const` const pointer to `int`
  - The value of the pointer cannot be modified
  - The elements refereed by the pointer can be modified
- `const int *const` const pointer to `const int`
  - The value of the pointer cannot be modified
  - The elements refereed by the pointer cannot be modified

Note: `const int*` is equal to `int const*`

Tip: pointer types should be read from right to left

Common error: adding `const` to a pointer is not the same as adding `const` to a type alias of a pointer

```
using ptr_t       = int*;
using const_ptr_t = const int*;

void f1(const int* ptr) {
//  ptr[0] = 0;       // not allowed: pointer to const objects
    ptr    = nullptr; // allowed
}
void f3(const_ptr_t ptr) { // same as before
//  ptr[0] = 0;       // not allowed: pointer to const objects
    ptr    = nullptr; // allowed
}
void f2(const ptr_t ptr) { // warning!!
    ptr[0] = 0;       // allowed
//  ptr    = nullptr; // not allowed: const pointer to
}                     // modifiable objects
```

`constexpr` (function)

C++11/C++14/C++17 guarantees compile-time evaluation of an function as long as **all** its arguments are constant

- C++11: `constexpr` must contain exactly one `return` statement and it must not contain loops or switch
- C++14: `constexpr` has no restrictions

`constexpr` (variable)

C++11/C++14/C++17 `constexpr` variables are evaluated at compile-time

- `const` guarantees the value of a variable to be fixed overall the execution of the program
- `constexpr` tells the compiler that the expression results is at compile-time. `constexpr` value implies `const`

```cpp
const int v1 = 3;      // compile-time evaluation
const int v2 = v1 * 2; // compile-time evaluation

int       a  = 3;      // "a" is dynamic
const int v3 = a;      // run-time evaluation!!

constexpr c1 = v1;     // ok
// constexpr c2 = v3;  // compile error!!
```

```cpp
constexpr int square(int value) {
    return value * value;
}

square(4); // compile-time evaluation

int a = 4; // "a" is dynamic
square(a); // run-time evaluation
```

`if constexpr`

C++17 introduces `if constexpr` feature which allows *conditionally* compiling code based on a *compile-time* value

It is an `if` statement where the branch is chosen at compile-time (similarly to the `#if` preprocessor)

```
void f() {
    if constexpr (true)
        std::cout << "compile!";
    else
        std::cout << "error!"; // never compiled
}
```

`constexpr` example

```cpp
constexpr int fib(int n) {
    return (n == 0 || n == 1) ? 1 : fib(n - 1) + fib(n - 2);
}

int main() {
    if constexpr (sizeof(void*) == 8)
        return fib(5);
    else
        return fib(3);
}
```

Generated assembly code (`x64` OS):

```asm
main:
    mov eax, 8
    ret
```

Explicit Type Conversion

Old style cast `(type) value`

New style cast:

- `static_cast` does compile-time (not run-time) checking of the types involved In many situations, this can make it the safest type of cast, as it provides the least room for accidental/unsafe conversions between various types
- `reinterpret_cast`
  `reinterpret_cast<T*>(v)` equal to `(T*) v`
  `reinterpret_cast<T&>(v)` equal to `*((T*) &v)`
- `const_cast` may be used to cast away (remove) constness or volatility

Static cast vs. old style cast:

```
char a[] = {1, 2, 3, 4};
int* b   = (int*) a;                    // ok
cout << b[0];                           // print 67305985 not 1!!
// int* c = static_cast<int*>(a); // compile error!! unsafe conversion
```

Const cast:

```
const int        a   = 5;
const_cast<int>(a) = 3; // ok
```

Reinterpret cast: (bit-level conversion)

```
float b = 3.0f;
// bit representation of b: 01000000010000000000000000000000
int   c = reinterpret_cast<int&>(b);
// bit representation of c: 01000000010000000000000000000000
int a[3][4];   // array reshaping example
int (&b)[2][6] = reinterpret_cast<int (&)[2][6]>(a);
int (*c)[6]    = reinterpret_cast<int (*)[6]>(a);
```

Type Punning

Pointer Aliasing

One pointer **aliases** another when they both point to the same memory location

Type Punning

Type punning refers to circumvent the type system of a programming language to achieve an effect that would be difficult or impossible to achieve within the bounds of the formal language

```
bool is_negativeA(float x) {
    return x < 0.0;
}
bool is_negativeB(float x) {
    unsigned int* ui = (unsigned int *) &x; // gcc warning:
    return (*ui) & 0x80000000;              // -Wstrict-aliasing
} // this could lead to undefined behavior
```

https://blog.qt.io/blog/2011/06/10/type-punning-and-strict-aliasing/

Brace Initialization

C++11 The **brace initialization** can be also used to *safely* convert arithmetic types, preventing implicit *narrowing*, i.e potential value loss

The syntax is also more concise than modern casts

```
int       x1 = -1;
int64_t   x2 = int64_t{-1};  // ok
//int64_t x3 = uint64_t{-1}; // compile error!! unsafe

int64_t    y1 = int64_t{x1};  // ok (only GCC, not clang)
//uint64_t y2 = uint64_t{x1}; // compile error!! unsafe

uint64_t z1 = static_cast<uint64_t>(-1); // ok
uint64_t z2 = static_cast<uint64_t>(x1); // ok

float   f1 = float{10e30}; // ok
//float f2 = float{10e40}; // compile error!! unsafe
```