

Modern C++ Programming

4. BASIC CONCEPTS III

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Memory Management: Heap and Stack

Process Address Space

higher memory
addresses
0x00FFFFFF

Stack



Heap



**BSS and Data
Segment**

.bss/.data

Code

.text

lower memory
addresses
0x00FF0000

stack memory

`int data[10]`

dynamic memory

`new int[10]`
`malloc(40)`

**Static/Global
data**

`int data[10]`
(global scope)

Stack Memory

A local variable is either in stack memory or CPU registers

```
int x = 3; // not on stack

struct A {
    int k; // depends on where the instance of A is
};

int main() {
    int y = 3; // on stack
    char z[] = "abc"; // on stack
    A a; // on stack (also k)
    int* ptr = new int; // variable "ptr" is on stack
}
```

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

Stack Memory

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

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

```
void g(bool x) {  
    const char* str = "abc";  
    if (x) {  
        char xyz[] = "xyz";  
        str = xyz;  
    }  
    cout << str; // Illegal memory access!! 💀  
}
```

new, delete

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

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

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

```
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 a1;           // default initialization (undefined value)
int a2(2);        // direct (or value) initialization
int a3 = 2;       // copy initialization
int a4 = 2u;      // copy initialization (implicit)
int a5 = int(2);  // copy initialization
int a6 = int();   // copy initialization (zero-initialization)
int a7 = {2};     // copy list initialization
// int a8();      // a8 is a function
```

Uniform Initialization

C++11 provides the **Uniform Initialization** syntax, namely *brace-initialization* or *braced-init-list*, to initialize different entities (variables, objects, structures, etc.) in a consistent way:

```
int b1{2};           // direct list (value) initialization
int b2{};            // direct list (value) initialization (default value)
int b3 = {};         // copy list initialization (default value)
int b4 = int{4};     // copy initialization
```

Brace Initialization

The **C++11 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      b4 = -1; // ok
int      b5{-1};  // ok
//unsigned b5{-1}; // compile error

float    f1 {10e30}; // ok
//float f2{10e40}; // compile error
//-----
// FOR CONVERSION:
int       y1{x1};  // ok (only GCC, not clang)
//unsigned y2{x1}; // compile error (unsafe)

unsigned z1 = (unsigned) -1; // ok, also z1 = -1
unsigned z2 = (unsigned) x1; // ok, also z1 = x1
```

Structure Initialization

```
struct S {  
    unsigned x, y;  
};  
//-----  
// S s0(3, 2);    // compile error  
//               // The compiler searches for a constructor  
S s1 = {3, 2};    // ok  
S s2 = {3, -2};   // ok in C++03, but compile error in C++11  
  
S s3 {3, 2};      // ok, also in C++11  
// S s4 {3, -2}; // compile error in C++11  
  
S f1() { // C++03  
    S s5 = {3, 2};  
    return s5;  
}  
  
S f2() { return {3, 2}; } // C++11
```

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 d[3] = {1, 2};     // d[2] = 0 -> zero/default value

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

Two dimensions:

```
int a[][2] = { {1,2}, {3,4}, {5,6} }; // ok
int b[][2] = { 1, 2, 3, 4 };           // ok
// the type of "a" and "b" is an array of type int[]
// int c[][] = ...;                     // compile error
// int d[2][] = ...;                     // compile error
```

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
// int* a6 = new int[4](3); // not valid
```

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

Pointer

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

Pointer Dereferencing

Pointer **dereferencing** (`*ptr`) means obtaining the value stored in at the location refereed to the pointer

Subscript Operator []

The subscript operator (`ptr[]`) allows accessing to the pointer element at a given position

Deferencing:

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

Array subscript:

```
int* ptr2 = new int[10];  
ptr2[2]   = 3;  
int var   = ptr2[4];
```

Common error:

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

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 0xFFFFAFF2  
cout << array + 1;          // print 0xFFFFAFF6!!
```

```
char arr[3] = "abc"
```

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

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

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

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 = ...`

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 dangling pointer  
    delete[] array; // ok, no side effect  
}
```

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
```

Reference

A variable **reference** `T&` 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 can be internally implemented as *pointers*, 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& a;      // compile error no initialization
//int& b = 3;   // compile error "3" is not a variable
int  c = 2;
int& d = c;    // reference. ok valid initialization
int& e = d;    // ok. the reference of a reference is a reference
d++;          // increment
e++;          // increment
cout << c;    // print 4
```

```
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' (a = 4)

int& d = a;    // reference
d++;          // change the value of 'a' (a = 5)
```


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
f(0);     // dangerous but it works!! (but not with other numbers)
//f(a);  // compile error "a" is not a pointer

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

References can be use to indicate fixed size arrays:

```
void f(int (&array)[3]) { // accepts only arrays of size 3
    cout << sizeof(array);
}

void g(int array[]) {
    cout << sizeof(array); // any surprise?
}

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
g(A);    // ok
g(B);    // ok
g(C);    // ok
```

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;  // compile error  
int (*f)[4] = c;         // ok
```

```
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
```

Reference and struct

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

```
struct A {  
    int x = 3;  
};  
  
A a;  
  
A* ptr = &a;    // pointer  
ptr->x;         // arrow syntax  
  
A& ref = a;     // reference  
cout << a.x;    // dot syntax  
cout << ref.x;  // dot syntax
```

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*`

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

```
void 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 referred 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 referred by the pointer cannot be modified
- `int *const` const pointer to `int`
 - The value of the pointer cannot be modified
 - The elements referred by the pointer can be modified
- `const int *const` const pointer to `const int`
 - The value of the pointer cannot be modified
 - The elements referred 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`

```
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 int c1 = v1;      // ok
// constexpr int c2 = v3; // compile error, "v3" is dynamic
```

```
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)  
        cout << "compile!";  
    else  
        cout << "error!"; // never compiled  
}
```

constexpr example

```
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):

```
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
- `const_cast` can cast away (remove) constness or volatility
- `reinterpret_cast`

`reinterpret_cast<T*>(v)` equal to `(T*) v`

`reinterpret_cast<T&>(v)` equal to `*((T*) &v)`

`const_cast` and `reinterpret_cast` do not compile to any CPU instructions

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, but dangerous
```

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
```


Print the value of a pointer

```
int* ptr = new int;
//int x1 = static_cast<size_t>(ptr);      // compile error unsafe
int x2 = reinterpret_cast<size_t>(ptr); // ok, same size

// but
unsigned v;
//int x3 = reinterpret_cast<int>(v); // compile error
// invalid conversion

int x4 = (int) v; // ok
```

Array reshaping

```
int a[3][4];
int (&b)[2][6] = reinterpret_cast<int (&)[2][6]>(a);
int (*c)[6] = reinterpret_cast<int (*)[6]>(a);
```

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

The compiler assumes that the *strict aliasing rule is never violated*. Accessing a value using a type which is different from the original one is not allowed and it is classified as *undefined behavior*

```
// slow without optimizations. The branch breaks the pipeline
float abs(float x) {
    return (x < 0.0f) ? -x : x;
}

// optimized by hand
float abs(float x) {
    unsigned uvalue = reinterpret_cast<unsigned&>(x);
    unsigned tmp    = uvalue & 0x7FFFFFFF; // clear the last bit
    return reinterpret_cast<float&>(tmp);
}
// this is (potentially) undefined behavior!!
```

GCC warning (not clang): `-Wstrict-aliasing`

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 member)` 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 bytes
sizeof(int*)    // 8 bytes on a 64-bit OS
sizeof(void*)   // 8 bytes on a 64-bit OS
sizeof(size_t)  // 8 bytes 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 bytes
cout << sizeof(array2); // print sizeof(int*) = 8 bytes
f(array1);               // print 8 bytes (64-bit OS)
```

```
struct A {  
    int x;  
    char y; // char is aligned to int  
};  
sizeof(A); // 8 bytes : 4 + 1 (+ 3 padding)
```

```
struct B {  
    int x;  
    char y; // char is aligned to int  
    short z; // short is aligned to int  
};  
sizeof(B); // 8 bytes : 4 + 1 + 2 (+ 1 padding)
```

```
struct C {  
    short z; // short is aligned to int  
    int x;  
    char y; // char is aligned to int  
};  
sizeof(C); // 12 bytes : 2 (+ 2 padding) + 4 + 1 + (+ 3 padding)
```

```
char a;
char& b = a;
sizeof(&a);    // 8 bytes in a 64-bit OS (pointer)
sizeof(b);    // 1 byte, equal to sizeof(char)
              // NOTE: a reference is not a pointer

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

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

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