

Modern C++ Programming

4. BASIC CONCEPTS III - MEMORY MANAGEMENT

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2021, v3.10



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- `constexpr`
- `constexpr`

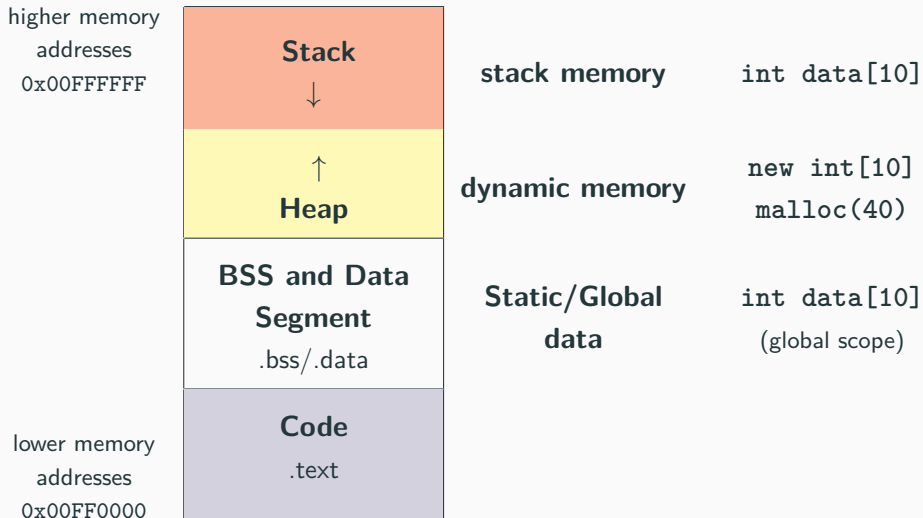
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Heap and Stack

Process Address Space



Stack and Heap Memory Overview

	Stack	Heap
Memory Organization	Contiguous	(block) Fragmented
Max size	Small (~8MB)	Whole system memory
If exceed	Program crash	Exception or <code>nullptr</code>
Allocation	Compile-time	Run-time
Locality	High	Low
Thread View	Each thread in a program has its own stack	Shared among threads

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 Data

Types of data stored in the stack:

Local variables Variable in a local scope

Function arguments Data passed from caller to a function

Return addresses Data passed from a function to a caller

Compiler temporaries Compiler specific instructions

Interrupt contexts

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/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/deallocation:

```
int** A = new int*[3];           // allocation (pointer of pointer)
for (int i = 0; i < 3; i++)
    A[i] = new int[4];           // allocation
for (int i = 0; i < 3; i++)
    delete[] A[i];              // deallocation
delete[] A;                      // deallocation (pointer of pointer)
```

Dynamic memory 2D allocation/deallocation 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 conversion)

int();            // direct (or value) initialization (zero-init)
int(2)            // direct (or value) initialization
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 Uniform Initialization syntax, also called *brace-initialization* or *braced-init-list*, allow to initialize different entities (variables, objects, structures, etc.) in a consistent way:

```
int b1{2};           // direct list (or value) initialization
int b2{};            // direct list (or value) initialization
                     // (zero-initialization)
int b3 = {};          // copy list initialization (zero-initialization)

int{};               // direct list (or value) initialization (zero-init)
int{4};              // direct list (or value) initialization
int b4 = int{};      // copy initialization
int b5 = int{4};     // copy initialization
```

Brace Initialization Advantages

The **uniform 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 b6 = -1; // ok
//unsigned b7{-1}; // compile error

float    f1{10e30}; // ok
float    f2 = 10e40; // ok, "inf" value
//float  f3{10e40}; // compile error
```

```
struct S {  
    unsigned x;  
    unsigned y;  
};  
//-----  
  
// C++03  
S s1;           // default initialization (undefined values)  
S s2 = {};      // copy list initialization (zero-init)  
S s3 = {1, 2};  // copy list initialization  
  
// C++11  
S s4{};         // direct list (or value) initialization (zero-init)  
S s5{1, 2};     // direct list (or value) initialization  
// S s6{1, -2}; // compile error
```

Non-Static Data Member Initialization (NSDMI):

```
struct S {  
    unsigned x = 3; // equal initialization  
    unsigned y = 2; // equal initialization  
}; // also functions are allowed  
  
struct S1 {  
    unsigned x {3}; // brace initialization  
};  
  
//-----  
  
S s1; // call default constructor (x=3, y=2)  
S s2{}; // call default constructor (x=3, y=2)  
S s3{1, 4}; // set x=1, y=4  
  
S f() {  
    return {3, 2};  
}
```


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 Memory 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[4];         // 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 referred 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
```

Subscript operator meaning:

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

Note: subscript operator accepts also negative values

Pointer arithmetic rule:

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

where T is the type of elements pointed by ptr

```
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!!
int* ptr = array + 2;
cout << ptr[-1];      // print 2
```

```
char arr[4] = "abc"
```

value	address	
'a'	0x0	\leftarrow arr[0]
'b'	0x1	\leftarrow arr[1]
'c'	0x2	\leftarrow arr[2]
'\0'	0x3	\leftarrow arr[3]

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

value	address	
4	0x0	\leftarrow arr[0]
	0x1	
	0x2	
	0x3	
5	0x4	\leftarrow arr[1]
	0x5	
	0x6	
	0x7	
6	0x8	\leftarrow arr[2]
	0x9	
	0x10	
	0x11	

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  
}
```

note:

```
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

- `void*` can be compared
- A `void*` can be implicitly converted to another pointer
- Other operations are unsafe because the compiler does not know what kind of object is really pointed to

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

```
int array[] = { 2, 3, 4 };
```

```
void* ptr = array; // implicit conversion
```

```
cout << *array; // print 2
```

```
// *ptr; // compile error
```

```
// 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)
- The compiler can internally implement references as *pointers*, but 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  
a.x;        // dot syntax  
ref.x;       // dot syntax
```

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

- `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* cptr = new int[3];
```

```
f1(ptr);      // ok
```

```
f2(ptr);      // ok
```

```
f1(cptr);     // ok
```

```
// f2(cptr); // 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 Variable (C++11)

`constexpr` specifier declares that the expressions can be evaluated at compile time

- `const` guarantees the value of a variable to be fixed overall the execution of the program
- `constexpr` implies `const`
- `constexpr` helps for performance and memory usage
- `constexpr` could potentially impact on compilation time

constexpr Variable

constexpr variables are evaluated at compile-time

```
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 Function

`constexpr` guarantees compile-time evaluation of a function as long as all its arguments are constant

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

```
constexpr int square(int value) {  
    return value * value;  
}  
  
square(4); // compile-time evaluation  
  
int a = 4; // "a" is dynamic  
square(a); // run-time evaluation
```

constexpr limitations:

- it cannot include run-time only functions
- it cannot include run-time features such as try-catch blocks, and exceptions
- it cannot include `goto` and `asm` statements
- it cannot include `static` storage duration variables
- it must not be virtual
- it cannot use undefined behavior code, e.g. `reinterpret_cast`, unsafe usage of `union`, etc.

constexpr Keyword

constexpr

C++20 `constexpr`, or *immediate functions*, guarantees compile-time evaluation of a function. A non-constant value produces a compilation error

```
constexpr int square(int value) {  
    return value * value;  
}  
  
square(4);    // compile-time evaluation  
  
int v = 4;    // "v" is dynamic  
// square(v); // compile error
```

constexpr Keyword

constexpr (C++20)

`constexpr` guarantees compile-time initialization of a variable. A non-constant value produces a compilation error

- The value of the variable can change during the execution
- `const constexpr` does not imply `constexpr`, while the opposite is true
- `constexpr` requires compile-time evaluation during his entire lifetime

```
constexpr int square(int value) {  
    return value * value;  
}  
  
constexpr int v1 = square(4);    // compile-time evaluation  
v1                = 3;          // ok, v1 can change  
  
int a = 4;                    // "v" is dynamic  
// constexpr int v2 = square(a); // compile error
```

if constexpr

`if constexpr` C++17 feature allows to *conditionally* compile 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)

```
auto f() {  
    if constexpr (true) // if constexpr works very well with templates  
        return "hello"; // const char*  
    else  
        return 3;        // int, 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
```

`std::is_constant_evaluated`

C++20 provides `std::is_constant_evaluated()` utility for evaluating if the current function is evaluated at compile time

```
#include <type_traits> // std::is_constant_evaluated

constexpr int f(int n) {
    if (std::is_constant_evaluated())
        return 0;
    return 4;
}

int x = f(3); // x = 0

int v = 3;
int y = f(v); // y = 4
```

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 add or 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 \\underline{undefined behavior}/
```

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
```

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 undefined behavior!!
```

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

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- blog.qt.io/blog/2011/06/10/type-punning-and-strict-aliasing
 - What is the Strict Aliasing Rule and Why do we care?

memcpy and std::bit_cast

The right way to avoid undefined behavior is using `memcpy`

```
float    v1 = 32.3f;
unsigned v2;
std::memcpy(&v2, &v1, sizeof(float));
// v1, v2 must be trivially copyable
```

C++20 provides `std::bit_cast` safe conversion for replacing `reinterpret_cast`

```
float    v1 = 32.3f;
unsigned v2 = std::bit_cast<unsigned>(v1);
```

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

```
struct B {
    int x; // offset 0
    char y; // offset 4
    short z; // offset 6 -> 2 bytes aligned
};
sizeof(B); // 8 bytes : 4 + 1 (+ 1 padding) + 2
```

```
struct C {
    short z; // offset 0 -> 2 bytes aligned
    int x; // offset 4 -> 4 bytes aligned
    char y; // offset 8
};
```

```
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
```

sizeof and Size of a Byte

Interesting: C++ does not explicitly define the size of a byte (see Exotic architectures the standards committees care about)