Modern C++ Programming

5. Basic Concepts IV

Memory Concepts

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Pointers

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

The **type of a pointer** (e.g. `void*`) is an *unsigned* integer of 32-bit/64-bit depending on the underlying architecture

- It only supports the operators `+, -, ++, --`, comparisons `==, !=, <, <=, >, >=`, subscript `[]`, and dereferencing `*`
- A pointer can be *explicitly* converted to an integer type

```
void*  x;
size_t y = (size_t) x; // ok (explicit conversion)
// size_t y = x;        // compile error (implicit conversion)
```

Dereferencing:

```
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
```

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 = ...`

struct Member Access

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

```
struct A {
    int x;
};

A a;          // local object
a.x;          // dot syntax

A* ptr = &a; // pointer
ptr->x;       // arrow syntax: same of (*ptr).x
```

`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
- Common pointer operations are not allowed because there is no specific type pointed to

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

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

Pointer Conversion

- Any pointer type can be *implicitly* converted to `void*`
- Non- `void` pointers must be explicitly converted
- `static_cast` (see next slides) does not allow pointer conversion for safety reasons, except for `void*`

```
int*  ptr1 = ...;
void* ptr2 = ptr1;         // int* -> void*, implicit conversion

void* ptr3 = ...;
int*  ptr4 = (int*) ptr3;  // void* -> int, explicit conversion required
                           // static_cast allowed
int*  ptr5 = ...;
char* ptr6 = (char*) ptr5; // int* -> char*, explicit conversion required,
                           // static_cast not allowed, dangerous
```

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 0xFFFAFFF2
cout << array + 1;      // print 0xFFFAFFF6!!
int* ptr = array + 2;
cout << ptr[-1];        // print 2
```

`char arr[4] = "abc"`

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

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

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

lib/vsprintf.c of the Linux kernel

```
int vsnprintf(char *buf, size_t size, ...) {
    char *end;
    /* Reject out-of-range values early
       Large positive sizes are used for unknown buffer sizes */
    if (WARN_ON_ONCE((int) size < 0))
        return 0;
    end = buf + size;
    /* Make sure end is always >= buf */
    if (end < buf) { ... } // Even if pointers are represented with unsigned values,
    ...                    // pointer overflow is undefined behavior.
                           // Both GCC and Clang will simplify the overflow check
                           // buf + size < buf to size < 0 by eliminating
}                          // the common term buf
```

Wild and Dangling Pointers

A **wild pointer** is a pointer not initialized

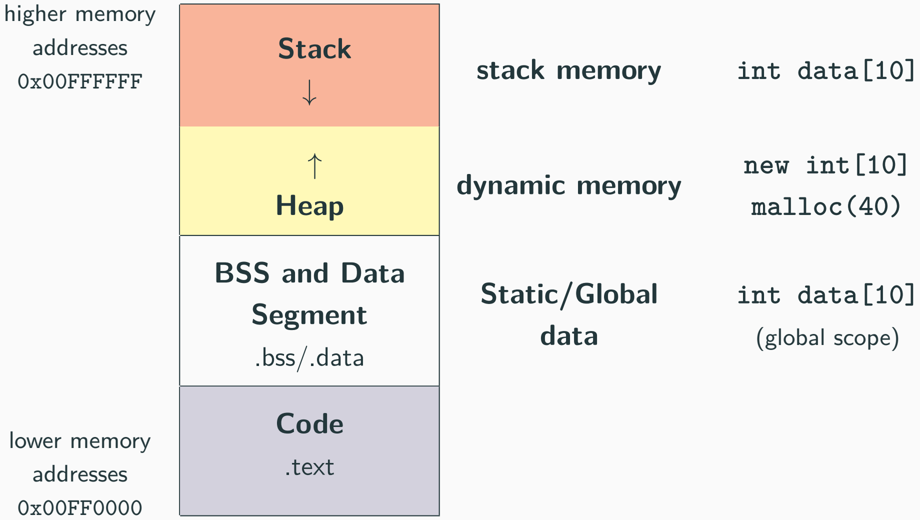
```
int* ptr;    // wild pointer
```

A **dangling pointer** points to a deallocated memory region

```
int* array = new int[10];
delete[] array; // ok -> "array" now is a dangling pointer
*array;         // Potential segmentation fault
delete[] array; // double free or corruption!!
```

Heap and Stack

Process Address Space



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

Stack and Heap Memory Overview

	Stack	Heap
Memory Organization	Contiguous (LIFO)	Contiguous within an allocation, Fragmented between allocations (relies on virtual memory)
Max size	Small (8MB on Linux, 1MB on Windows)	Whole system memory
If exceed	Program crash at function entry (hard to debug)	Exception or `nullptr`
Allocation	Compile-time	Run-time
Locality	High	Low
Thread View	Each thread has its own stack	Shared among threads

Stack Memory

A local variable is either in the stack memory or CPU registers

```
int x = 3; // not on the stack (data segment)

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)
    void* ptr = malloc(4); // variable "ptr" is on the stack
}
```

The organization of the stack memory enables much higher performance. On the other hand, this memory space is limited!!

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; // if "x" is true, then Illegal memory access!! ☠
}
```

Heap Memory - `new`, `delete` Keywords

`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 only allocate and free *memory blocks* (expressed in bytes)

`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*, zero-size allocations do not need special code
- **Allocation size**: The number of bytes is calculated by the compiler with the `new` keyword, while the user must take care of manually calculate the size for `malloc()`
- **Initialization**: `new` can be used to initialize besides allocate
- **Polymorphism**: objects with `virtual` functions must be allocated with `new` to initialize the virtual table pointer

Dynamic Memory 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 N structures**

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

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

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

Dynamic Memory 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;
```

Allocation/Deallocation Properties

Fundamental properties:

- Each object allocated with `malloc()` must be deallocated with `free()`
- Each object allocated with `new` must be deallocated with `delete`
- Each object allocated with `new[]` must be deallocated with `delete[]`
- `malloc()`, `new`, `new[]` never produce `NULL` pointer in the *success* case, except for zero-size allocations (implementation-defined)
- `free()`, `delete`, and `delete[]` applied to `NULL` / `nullptr` pointers do not produce errors

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

Easy on the stack - dimensions known at compile-time:

```
int A[3][4]; // C/C++ uses row-major order: move on row elements, then columns
```

Dynamic Memory 2D allocation/deallocation - dimensions known at run-time:

```
int** A = new int*[3];        // array of pointers allocation
for (int i = 0; i < 3; i++)
    A[i] = new int[4];        // inner array allocations

for (int i = 0; i < 3; i++)
    delete[] A[i];            // inner array deallocations
delete[] A;                   // array of pointers deallocation
```

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

```
auto A = new int[3][4];      // allocate 3 objects of type 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
```

Non-Allocating Placement ★

A **non-allocating placement** `(ptr) type` allows to explicitly specify the memory location (previously allocated) of individual objects

```
// STACK MEMORY
char   buffer[8];
int*   x = new (buffer) int;
short* y = new (x + 1)  short[2];
// no need to deallocate x, y
```

```
// HEAP MEMORY
unsigned* buffer2 = new unsigned[2];
double*   z       = new (buffer2) double;
delete[] buffer2; // ok
// delete[] z;    // ok, but bad practice
```

Placement allocation of *non-trivial objects* requires to explicitly call the object destructor as the runtime is not able to detect when the object is out-of-scope

```
struct A {
    ~A() { cout << "destructor"; }
};

char buffer[10];
auto x = new (buffer) A();
// delete x; // runtime error 'x' is not a valid heap memory pointer
x->~A();     // print "destructor"
```

C++23 introduces a type safe placement allocation function `std::start_lifetime_as()`

Non-Throwing Allocation ⋆

The `new` operator allows a non-throwing allocation by passing the `std::nothrow` object. It returns a `NULL` pointer instead of throwing `std::bad_alloc` exception if the memory allocation fails

```
int* array = new (std::nothrow) int[very_large_size];
```

note: `new` can return `NULL` pointer even if the allocated size is 0

`std::nothrow` doesn't mean that the allocated object(s) cannot throw an exception itself

```
struct A {
    A() { throw std::runtime_error{}; }
};
A* array = new (std::nothrow) A; // throw std::runtime_error
```

Memory Leak

Memory Leak

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

Problems:

- Illegal memory accesses → segmentation fault/wrong results
- Undefined values a their propagation→ segmentation fault/wrong results
- Additional memory consumption (potential segmentation fault)

```
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

Dynamic Memory Allocation and OS

A program does not directly allocate memory itself but, it asks for a chuck of memory to the OS. The OS provides the memory at the granularity of *memory pages* (virtual memory), e.g. 4KB on Linux

Implication: out-of-bound accesses do not always lead to segmentation fault (lucky case). The worst case is an execution with undefined behavior

```
int* x         = new int;
int  num_iters = 4096 / sizeof(int); // 4 KB

for (int i = 0; i < num_iters; i++)
    x[i] = 1; // ok, no segmentation fault
```

Initialization

Variable Initialization

C++03:

```
int a1;           // default initialization (undefined value)

int a2(2);        // direct (or value) initialization
int a3(0);        // direct (or value) initialization (zero-initialization)
// int a4();      // a4 is a function

int a5 = 2;       // copy initialization
int a6 = 2u;      // copy initialization (+ implicit conversion)
int a7 = int(2); // copy initialization
int a8 = int();  // copy initialization (zero-initialization)

int a9 = {2};     // copy list initialization, brace-initialization/braced-init-list syntax
```

Uniform Initialization

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

```
int b1{2};          // direct list (or value) initialization
int b2{};           // direct list (or value) initialization (default constructor/
                    //                                        zero-initialization)
int b3 = int{};     // copy initialization (default constr./zero-initialization)
int b4 = int{4};    // copy initialization


int b5 = {};        // copy list initialization (default constr./zero-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
```

Arrays are *aggregate* types and can be initialized with brace-initialization syntax, also called braced-init-list or aggregate-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 are initialized to 0
int  f[3] = {};        // all values are initialized to 0 (C++11)
int  g[3] {};          // all values are initialized to 0 (C++11)
```

Array Initialization

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
```

Structures are also *aggregate* types and can be initialized with brace-initialization syntax, also called braced-init-list or aggregate-initialization

```
struct S {
    unsigned x;
    unsigned y;
};
S s1;            // default initialization, x,y undefined values
S s2 = {};       // copy list initialization, x,y default constr./zero-init
S s3 = {1, 2};   // copy list initialization, x=1, y=2
S s4 = {1};      // copy list initialization, x=1, y default constr./zero-init
//S s5(3, 5);    // compiler error, constructor not found

S f() {
    S s6 = {1, 2}; // verbose
    return s6;
}
```

```
struct S {
    unsigned x;
    unsigned y;
    void*    ptr;
};

S s1{};         // direct list (or value) initialization
                //     x,y,ptr default constr./zero-initialization

S s2{1, 2};     // direct list (or value) initialization
                //     x=1, y=2, ptr default constr./zero-initialization

// S s3{1, -2}; // compile error, narrowing conversion

S f() { return {3, 2}; } // non-verbose
```

`Non-Static Data Member Initialization (NSDMI)`, also called *brace or equal initialization*:

```
struct S1 {
    unsigned x = 3; // equal initialization
    unsigned y = 2; // equal initialization
//  auto     z = 3; // auto is not allowed for non-static member variables
};
struct S2 {
    unsigned x {3}; // brace initialization
};
//------------------------------------------------------------------------------
S1 s1;        // call the default constructor (x=3, y=2)
S1 s2{};      // call the default constructor (x=3, y=2)
S1 s3{1, 4}; // set x=1, y=4
S2 s4;        // call the default constructor (x=3)
S2 s5{5};     // set x=5
```

C++20 introduces the **`designated initializer list`**

```
struct A {
    int x, y, z;
};
A a1{1, 2, 3};                    // is the same of
A a2{.x = 1, .y = 2, .z = 3}; // designated initializer list
```

Designated initializer list can be very useful for improving code readability

```
void f1(bool a, bool b, bool c, bool d, bool e) {}
// long list of the same data type -> error-prone

struct B {
    bool a, b, c, d, e;
};                                  // f2(B b)
f2({.a = true, .c = true});  // b, d, e = false
```

Structure Binding

Structure Binding declaration C++17 binds the specified names to elements of initializer:

```
struct A {
    int x = 1;
    int y = 2;
} a;
A f() { return A{4, 5}; }
                      // Case (1): struct
auto [x1, y1] = a;    // x1=1, y1=2
auto [x2, y2] = f();  // x2=4, y2=5
int  b[2]     = {1,2}; // Case (2): raw arrays
auto [x3, y3] = b;    // x3=1, y3=2
auto [x4, y4] = std::tuple<float, int>{3.0f, 2}; // Case (3): tuples
// constexpr auto [x1, y1] = a; // constexpr structure binding is not allowed
                               // because it relies on references
```

Dynamic Memory Initialization

Dynamic memory initialization applies the same rules of the object that is allocated

C++03:

```
int* a1 = new int;          // undefined
int* a2 = new int();        // zero-initialization, call "= int()"
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, call "= int()"
// int* a6 = new int[4](3); // not valid
```

C++11:

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

Initialization - Undefined Behavior Example ★

`lib/libc/stdlib/rand.c` of the FreeBSD libc

```
struct timeval tv;
unsigned long junk;                              // not initialized, undefined value

/* XXX left uninitialized on purpose */
gettimeofday(&tv, NULL);
srandom((getpid() << 16) ^ tv.tv_sec ^ tv.tv_usec ^ junk);
  // A compiler can assign any value not only to the variable,
  // but also to expressions derived from the variable

  // GCC assigns junk to a register. Clang further eliminates computation
  // derived from junk completely, and generates code that does not use
  // either gettimeofday or getpid
```

References

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
```

`const` and Constant Expressions

Constants and Literals

A **`constant expression`** is an expression that can be *evaluated at compile-time*

A **`literal`** is a *fixed value* that can be assigned to a *constant*

formally, *"Literals are the tokens of a C++ program that represent constant values embedded in the source code"*

Literal types:

- **Concrete values** of the scalar types `bool`, `char`, `int`, `float`, `double`, e.g. `true`, `'a'`, `3`, `2.0f`
- **String literal** of type `const char[]`, e.g `"literal"`
- `nullptr`
- User-defined literals, e.g. `2s`

const keyword

The `const` keyword declares an object that **never changes** value after the initialization. A `const` variable must be initialized when declared

A `const` variable is evaluated at compile-time value if the right expression is also evaluated at compile-time

```
int size = 3;              // 'size' is dynamic
int A[size] = {1, 2, 3}; // technically possible but, variable size stack array
                           // are considered BAD programming
const int SIZE = 3;
// SIZE = 4;               // compile error, SIZE is const
int B[SIZE] = {1, 2, 3}; // ok

const int size2 = size;  // 'size2' is dynamic
```

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

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

void write(int* array) {}

int*       ptr       = new int;
const int* const_ptr = new int;
read(ptr);             // ok
write(ptr);            // ok
read(const_ptr);       // ok
// write(const_ptr);   // compile error
```

- `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*` (*West notation*) is equal to `int const*` (*East notation*)

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) {   // read as '(const int)*'
//  ptr[0] = 0;             // not allowed: pointer to const objects
    ptr    = nullptr;       // allowed
}

void f2(const_ptr_t ptr) {} // same as before

void f3(const ptr_t ptr) {  // warning!! equal to 'int* const'
    ptr[0] = 0;             // allowed!!
//  ptr    = nullptr;       // not allowed: const pointer to modifiable objects
}
```

`constexpr` Keyword

`constexpr` (C++11)

`constexpr` specifier declares an expression that **can** be evaluated at compile-time

- `constexpr` can improve performance and memory usage
- `constexpr` can potentially impact the compilation time

`constexpr` Variable

`constexpr` Variable

`constexpr` variables are **always** evaluated at compile-time

- `const` guarantees the value of a variable cannot change after the initialization
- `constexpr` 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 a run-time variable
```

`constexpr` Function

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

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

- C++11: must contain exactly one `return` statement, and no loops or `switch`
- C++14: no restrictions

A `constexpr` function is always *evaluated at run-time* if:

- contains run-time arguments with a lifetime that begins with the expression, even if the function doesn't depend on them

```
constexpr int f(int  v) { return 3; }
constexpr int g(int& v) { return 3; }
int v = ...
f(v); // run-time evaluation
g(v); // compile-time evaluation lifetime of 'v' began outside the expression
```

- contains run-time functions, namely non- `constexpr` functions (detected with `-Winvalid-constexpr`)
- contains references to run-time global variables

`constexpr` Function - Limitations ★ 3/4

- cannot contain run-time features such as *exceptions* and *RTTI*
- cannot contain `assert()` until C++14
- cannot be a `virtual` member function or a destructor `~T` until C++20
- cannot contain or `try-catch` blocks or `asm` statements until C++20
- cannot contain `static` variables or `goto` until C++23
- undefined behavior code is not allowed, e.g. `reinterpret_cast`, unsafe usage of `union`, signed integer overflow, etc.

`constexpr` *non-static member functions* of run-time objects cannot be used at compile-time if they contain data members or non-compile-time functions

Note: `static constexpr` *member functions* don't present this issue because they don't depend on a specific instance

```
struct A {
    int v = 3;
    constexpr int        f() const { return v; }
    static constexpr int g()       { return 3; }
};
A a1;
// constexpr int x = a1.f(); // compile error, f() is evaluated at run-time
constexpr    int y = a1.g(); // ok, same as 'A::g()'

constexpr    A   a2;
constexpr    int x = a2.f(); // ok
```

`consteval` Keyword

`consteval` (C++20)

`consteval`, or *immediate function*, guarantees compile-time evaluation.

A run-time value always produces a compile error

```
consteval int square(int value) {
    return value * value;
}

square(4);     // compile-time evaluation

int v = 4;     // "v" is at run-time
// square(v); // compile error
```

`constinit` Keyword

`constinit` (C++20)

`constinit` guarantees compile-time initialization of a variable. A run-time initialization value always produces a compile error

- The value of a variable can change during the execution
- `const constinit` does not imply `constexpr`, while the opposite is true

```
constexpr int square(int value) {
    return value * value;
}
constinit int v1 = square(4);    // compile-time evaluation
v1 = 3;                          // ok, v1 can change

int a = 4;                       // "v" is dynamic
// constinit int v2 = square(a); // compile error
```

`if constexpr` C++17 allows to *conditionally* compile code based on a *compile-time* predicate

The `if constexpr` statement forces the compiler to evaluate the branch at compile-time (similarly to the `#if` preprocessor)

```
auto f() {
    if constexpr (sizeof(void*) == 8)
        return "hello";                  // const char*
    else
        return 3;                        // int, never compiled
}
```

Note: Ternary (conditional) operator does not provide `constexpr` variant

if 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
```

Advanced example: C++17 Compile-time Quick-Sort

`if constexpr` Pitfalls

`if constexpr` only works with *explicit* `if/else` statements

```
auto f1() {
    if constexpr (my_constexpr_fun() == 1)
        return 1;
//  return 2.0; compile error   // this is not part of constexpr
}
```

`else if` branch requires `constexpr`

```
auto f2() {
    if constexpr (my_constexpr_fun() == 1)
        return 1;
    else if (my_constexpr_fun() == 2) // -> else if constexpr
//      return 2.0; compile error     // this is not part of constexpr
    else
        return 3L;
}
```

std::is_constant_evaluated()

C++20 provides `std::is_constant_evaluated()` utility to evaluate 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;
}

f(3); // return 0

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

`std::is_constant_evaluated()` has two problems that `if consteval` C++23 solves:

(1) Calling a `consteval` function cannot be used within a `constexpr` function if it is called with a run-time parameter

```
consteval int g(int n) { return n * 3; }

constexpr int f(int n) {
    if (std::is_constant_evaluated())  // it works with if consteval
        return g(n);
    return 4;
}

// f(3); compiler error
```

(2) `if constexpr (std::is_constant_evaluated())` is a bug because it is always evaluated to `true`

```
constexpr int f(int x) {
    if constexpr (std::is_constant_evaluated())  // if consteval avoids this error
       return 3;
    return 4;
}

constexpr int g(int x) {
    if consteval {
       return 3;
    }
    return 4;
}
```

`volatile` Keyword ★

`volatile` Keyword

`volatile`

`volatile` is a hint to the compiler to avoid aggressive memory optimizations involving a pointer or an object

Use cases:

- *Low-level programming*: driver development, interaction with assembly, etc. (force writing to a specific memory location)
- *Multi-thread program*: variables shared between threads/processes to communicate (don't optimize, delay variable update)
- *Benchmarking*: some operations need to not be optimized away

Note: `volatile` reads/writes can still be reordered with respect to non-volatile ones

volatile Keyword - Example

The following code compiled with `-O3` (full optimization) and without `volatile` could work fine

```
volatile int* ptr = new int[1];                 // actual alloction size is much
int           pos = 128 * 1024 / sizeof(int); // larger, typically 128 KB
ptr[pos]          = 4;                          // ☠ segfault
```

volatile Deprecation

C++20 deprecates `volatile` outside single load and store operations

```
volatile int v  = 3;
auto         v1 = v + 4;  // ok, one load
v              = 4;       // ok, one store
v             += 4;       // deprecated, load + store

volatile int f() {}       // deprecated, volatile return value

void g1(volatile int) {}  // deprecated, volatile argument

void g2(volatile int*) {} // ok

struct A {
    volatile int x = 4;   // deprecated, volatile data member
};
```

Explicit Type Conversion

`static_cast` converts between types and performs compile-time (not run-time) type check

It is equivalent to the **old style cast** `(T) var` or `T(var)` for *value semantic*

```
int   a  = 6;
short b1 = (short) a;           // the compiler can issue a warning without
short b2 = short(a);            // explicit cast
short b3 = static_cast<int>(a);
long  c  = a;                   // not needed
```

`static_cast` prevents accidental/unsafe conversions between pointer types, especially across classes in a hierarchy

```
char* a  = new char[4]{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
```

`static_cast` also prevents accidental/unsafe `const` conversions

```
const char* a = new char;
char*       b = (char*) a;                // ok
//char*     c = static_cast<char*>(a);    // compile error unsafe conversion
```

`static_cast` prevents accidental/unsafe conversions between unrelated classes

```
struct A {};
struct B : A {};
struct C {};

A       a;
B       b;
auto    x1 = (A&) b;               // ok
auto    x2 = (C&) a;               // ok
auto    x3 = (C*) &a;              // ok
auto    x4 = static_cast<A&>(b);   // ok
//auto x5 = static_cast<C&>(a);    // compile error unsafe conversion
//auto x6 = static_cast<C*>(&a);   // compile error unsafe conversion
```

Note: `(T&) v` is equal to `*((T*) &v)`

const_cast

`const_cast` can add or cast away (remove) constness or volatility

```
const int* ptr = new int[4];
auto       x1  = (int*) ptr ;             // ok
auto       x2  = (char*) ptr;             // ok
auto       x3  = const_cast<int*>(ptr);   // ok
//auto     x4  = const_cast<char*>(ptr);  // compile error unsafe conversion

const int       a  = 5;
const_cast<int>(a) = 3; // ok, but undefined behavior

int                         b  = 5;
const_cast<volatile int>(b) = 3; // ok
```

reinterpret_cast

`reinterpret_cast` allows a subset of unsafe conversion:

- between pointers/references of different type with same constness
- between pointers and integer types

```
float b = 3.0f;                         // bits: 01000000010000000000000000000000
int   c = reinterpret_cast<int&>(b); // bits: 01000000010000000000000000000000

const int* ptr     = new int;
//reinterpret_cast<int*>(ptr);          // compile error
uintptr_t  my_int = reinterpret_cast<uintptr_t>(ptr); // 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*

```cpp
// slow without optimizations. The branch breaks the CPU instruction pipeline
float abs(float x) {
    return (x < 0.0f) ? -x : x;
}
// optimized with bitwise operation
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`

- blog.qt.io/blog/2011/06/10/type-punning-and-strict-aliasing
- What is the Strict Aliasing Rule and Why do we care?
- Type Punning In C++17

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

```
#include <cstring> // std::memcpy
float    v1 = 32.3f;
unsigned v2;
std::memcpy(&v2, &v1, sizeof(float));
```

Problems: `memcpy` is unsafe if the variables have not the same size or are not *trivially copyable*. Also, it doesn't work at compile-time (`constexpr`)

C++20 `std::bit_cast` provides a safe alternative to `reinterpret_cast` and `memcpy` that also works at compile-time

```
#include <bit> // std::bit_cast
constexpr float    v1 = 32.3f;
constexpr unsigned v2 = std::bit_cast<unsigned>(v1);
```

Uniform Initialization Conversion

A **narrowing conversion** occurs when the destination type may not be able to represent all the values of the source type

Brace initialization {} C++11 disallows narrowing conversions

```
// RUN-TIME VALUES
int          a = 3;
long long    x1{a};  // ok
//unsigned   x2{a};  // compile error, 'a' could be negative
//float      x3{a};  // compile error, 'a' could not be representable with float

double       b = 3;
//long long x4{b};   // compile error, 'b' could be a number with decimals
//float      x5{b};  // compile error, 'b' could not be representable with float
```

gcc issues a warning instead of a compile error for run-time narrowing conversions

Uniform Initialization Conversion

```
// COMPILE-TIME VALUES
constexpr int c = 3;
unsigned      x6{c};   // ok

constexpr int d = -1;
unsigned      x7{d};   // compile error, 'd' is negative

constexpr float e = 4;
//int           x8{e}; // compile error, 'float' cannot be narrowed to 'int'

constexpr double f = std::numbers::pi_v<double>; // π, C++20 <numbers>
float           x9{f};                           // ok
constexpr double g = 1e+40;
//float          x10{g}; // compile error, too large for 'float'
```

gls::narrow_cast ★

The `Guidelines Support Library (GSL)` contains functions and types that are suggested for use by the `C++ Core Guidelines` maintained by the Standard C++ Foundation

GLS offers `narrow_cast` operation for specifying that narrowing is acceptable and a `narrow` ("narrow if") that throws an exception if a narrowing would throw away legal values

```
#include <gsl/gsl>

double a  = 1.1;
int    x1 = gsl::narrow_cast<int>(d); // ok, explicit narrowing: 'a' becomes 1
int    x2 = gsl::narrow<int>(d);      // ok, throws 'narrowing_error'
```

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

* `gcc` allows array of size 0 (not allowed by the C++ standard)

```
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); // sizeof(int) * 10 = 40 bytes
cout << sizeof(array2); // sizeof(int*) = 8 bytes
f(array1);              // 8 bytes (64-bit OS)
```

```
struct A {
    int  x; // 4-byte alignment
    char y; // offset 4
};
sizeof(A); // 8 bytes: 4 + 1 (+ 3 padding), must be aligned to its largest member

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

struct C {
    short z; // offset 0 -> 2-byte alignment
    int   x; // offset 4 -> 4-byte alignment
    char  y; // offset 8 -> 1-byte alignment
};
sizeof(C); // 12 bytes : 2 (+ 2 padding) + 4 + 1 + (+ 3 padding)
```

```cpp
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
struct S1 {
    void* p;
};
sizeof(S1);      // 8 bytes

struct S2 {
    char& c;
};
sizeof(S2);      // 8 bytes, same as sizeof(void*)
sizeof(S2{}.c); // 1 byte
```

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

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

int array2[0];  // C++ doesn't allow array of size 0, as opposed to C
                // only gcc, compiler error for other compilers
sizeof(array2); // 0 : special case
```

C++20 `[[no_unique_address]]` allows a structure member to be overlapped with other data members of a different type

```
struct Empty {}; // empty class, sizeof(Empty) == 1

struct A {       // sizeof(A) == 5 (4 + 1)
    int   i;
    Empty e;
};

struct B {       // sizeof(B) == 4, 'e' overlaps with 'i'
    int i;
    [[no_unique_address]] Empty e;
};
```

Notes: `[[no_unique_address]]` is ignored by MSVC even in C++20 mode; instead, `[[msvc::no_unique_address]]` is provided

`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`)