

# Modern C++ Programming

## 5. BASIC CONCEPTS IV

### MEMORY CONCEPTS

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# Pointers

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

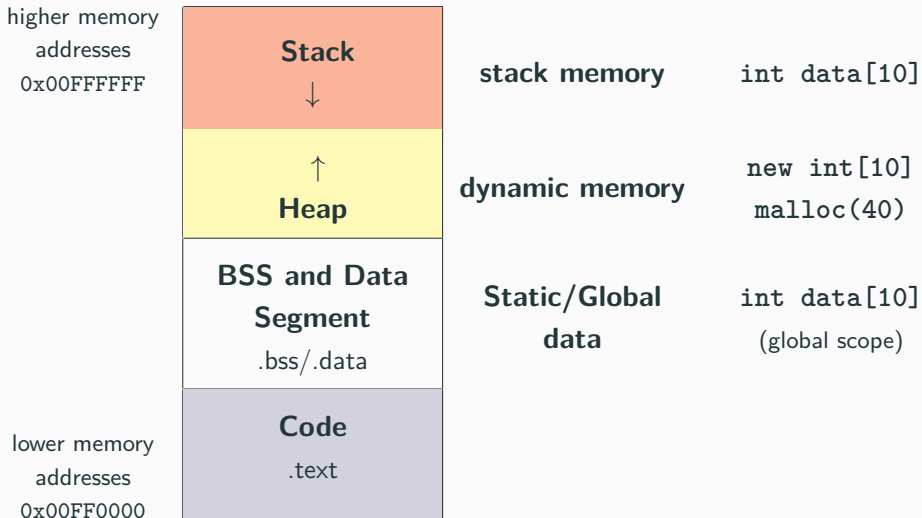
A **dangling pointer** points to a deallocated memory region

```
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

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# 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
<b>Memory Organization</b>	Contiguous (LIFO)	Contiguous within an allocation, Fragmented between allocations (relies on virtual memory)
<b>Max size</b>	Small (8MB on Linux, 1MB on Windows)	Whole system memory
<b>If exceed</b>	Program crash at function entry (hard to debug)	Exception or <code>nullptr</code>
<b>Allocation</b>	Compile-time	Run-time
<b>Locality</b>	High	Low
<b>Thread View</b>	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!!



## 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
```

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

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 and 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 chunk of memory from 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; // potential 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)
```

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({.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**  $\varnothing$  is an expression that can be *evaluated at compile-time*

A **literal**  $\varnothing$  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

## 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 (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` 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

- 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
```

# constexpr Keyword

## constexpr (C++20)

`constexpr` [↗](#), or *immediate function*, guarantees compile-time evaluation.

A run-time value always produces a compile error

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

# constexpr Keyword

## constexpr (C++20)

`constexpr` [↗](#) 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 constexpr` does not imply `constexpr`, while the opposite is true

```
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 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
```

## 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 constexpr` [C++23](#) solves:

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

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

constexpr int f(int n) {
    if (std::is_constant_evaluated()) // it works with if constexpr
        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 allocation 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<short>(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` 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` 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*

```
// 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](http://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

## std::bit\_cast

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

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)
```

```
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) == 8 (4 + 1 + 3 for padding)
    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`)