Modern C++ Programming

3. Basic Concepts I

Type System, Fundamental Types, and Operators

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Table of Contents

Table of Contents

The C++ Type System

The C++ Type System

C++ is a **strongly typed** and **statically typed** language

Every entity has a type and that type never changes

Every variable, function, or expression has a **type** in order to be compiled. Users can introduce new types with `class` or `struct`

The **type** specifies:

- The *amount of memory* allocated for the variable (or expression result)
- The *kinds of values* that may be stored and how the compiler interprets the bit patterns in those values
- The *operations* that are permitted for those entities and provides semantics

Type Categories

C++ organizes the language types in two main categories:

- **Fundamental types** (often called *primitive types*): Types provided by the language itself and don't require additional headers
  - *Arithmetic types*: integer and floating point
  - `void`
  - `nullptr` C++11
- **Compound types**: Composition or references to other types
  - Pointers
  - References
  - Enumerators
  - Arrays
  - `struct`, `class`, `union`
  - Functions

Type Properties ★

C++ types can be also classified based on their properties:

- **Objects**:
  - *size*: `sizeof` is defined
  - *alignment requirement*: `alignof` is defined
  - *storage duration*: describe when an object is allocated and deallocated
  - *lifetime*, bounded by storage duration or temporary
  - *value*, potentially indeterminate
  - optionally, a *name*.

  Types: Arithmetic, Pointers and `nullptr`, Enumerators, Arrays, `struct`, `class`, `union`

- **Scalar**:
  - *Hold a single value* and is not composed of other objects
  - *Trivially Copyable*: can be copied bit for bit
  - *Standard Layout*: compatible with C functions and structs
  - *Implicit Lifetime*: no user-provided constructor or destructor

  Types: Arithmetic, Pointers and `nullptr`, Enumerators

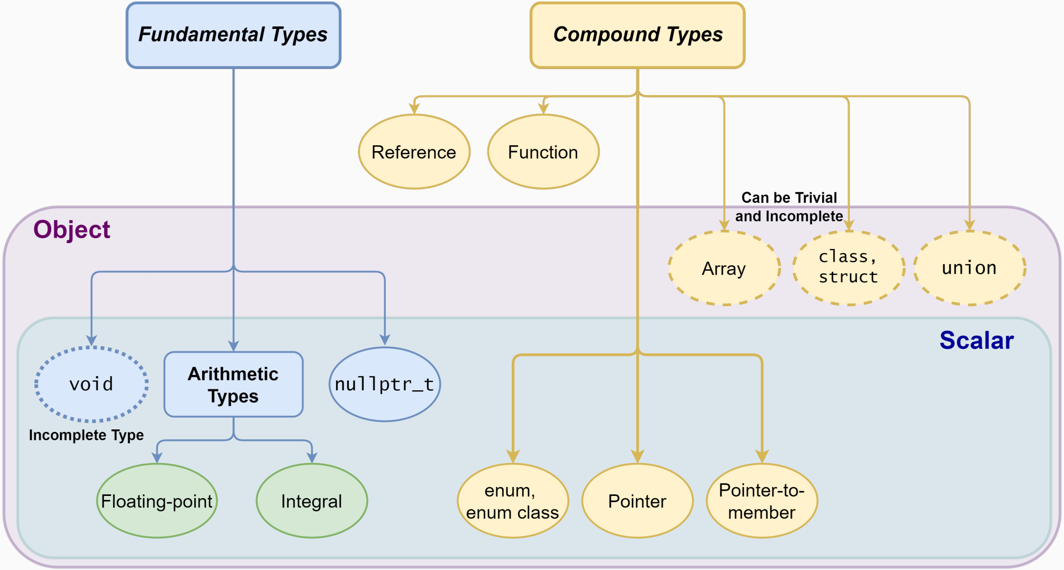
- **Trivial types**: Trivial default/copy constructor, copy assignment operator, and destructor → *Trivially Copyable*

  Types: Scalar, trivial class types, arrays of such types

- **Incomplete types**: A type that has been declared but not yet defined

  Types: `void`, incompletely-defined object types, e.g. `struct A;`, array of elements of incomplete type

C++ Types Summary



Fundamental Types Overview

Arithmetic Types - Integral

Native Type	Bytes	Range	Fixed width types `<cstdint>`
`bool`	1	true, false	
`char` †	1	implementation defined	
`signed char`	1	-128 to 127	int8_t
`unsigned char`	1	0 to 255	uint8_t
`short`	2	-2^{15} to $2^{15}-1$	int16_t
`unsigned short`	2	0 to $2^{16}-1$	uint16_t
`int`	4	-2^{31} to $2^{31}-1$	int32_t
`unsigned int`	4	0 to $2^{32}-1$	uint32_t
`long int`	4/8*		int32_t/int64_t
`long unsigned int`	4/8*		uint32_t/uint64_t
`long long int`	8	-2^{63} to $2^{63}-1$	int64_t
`long long unsigned int`	8	0 to $2^{64}-1$	uint64_t

* 4 bytes on Windows64 systems, † `signed/unsigned`, two-complement from C++11

Arithmetic Types - Floating-Point

Native Type	IEEE	Bytes	Range	Fixed width types C++23 `<stdfloat>`
(bfloat16)	N	2	$\pm 1.18 \times 10^{-38}$ to $\pm 3.4 \times 10^{+38}$	std::bfloat16_t
(float16)	Y	2	0.00006 to $65,536$	std::float16_t
`float`	Y	4	$\pm 1.18 \times 10^{-38}$ to $\pm 3.4 \times 10^{+38}$	std::float32_t
`double`	Y	8	$\pm 2.23 \times 10^{-308}$ to $\pm 1.8 \times 10^{+308}$	std::float64_t

Arithmetic Types - Short Name

Signed Type	short name
`signed char`	/
`signed short int`	`short`
`signed int`	`int`
`signed long int`	`long`
`signed long long int`	`long long`

Unsigned Type	short name
`unsigned char`	/
`unsigned short int`	`unsigned short`
`unsigned int`	`unsigned`
`unsigned long int`	`unsigned long`
`unsigned long long int`	`unsigned long long`

Arithmetic Types - Suffix (Literals)

Type	SUFFIX	Example	Notes
`int`	/	2	
`unsigned int`	u, U	3u	
`long int`	l, L	8L	
`long unsigned`	ul, UL	2ul	
`long long int`	ll, LL	4ll	
`long long unsigned int`	ull, ULL	7ULL	
`float`	f, F	`3.0f`	only decimal numbers
`double`		`3.0`	only decimal numbers

C++23 Type	SUFFIX	Example	Notes
`std::bfloat16_t`	bf16, BF16	`3.0bf16`	only decimal numbers
`std::float16_t`	f16, F16	`3.0f16`	only decimal numbers
`std::float32_t`	f32, F32	`3.0f32`	only decimal numbers
`std::float64_t`	f64, F64	`3.0f64`	only decimal numbers
`std::float128_t`	f128, F128	`3.0f128`	only decimal numbers

Arithmetic Types - Prefix (Literals)

Representation	PREFIX	Example
`Binary` C++14	`0b`	`0b010101`
`Octal`	`0`	`0307`
`Hexadecimal`	`0x` or `0X`	`0xFFA010`

C++14 also allows *digit separators* for improving the readability `1'000'000`

Other Arithmetic Types

- C++ also provides `long double` (no IEEE-754) of size 8/12/16 bytes depending on the implementation

- Reduced precision floating-point supports before C++23:
  - Some compilers provide support for *half* (16-bit floating-point) (GCC for ARM: `__fp16`, LLVM compiler: `half`)
  - Some modern CPUs and GPUs provide *half* instructions
  - Software support: OpenGL, Photoshop, Lightroom, `half.sourceforge.net`

- C++ does not provide **128-bit integers** even if some architectures support it. `clang` and `gcc` allow 128-bit integers as compiler extension (`__int128`)

`void` Type

`void` is an incomplete type (not defined) without a value

- `void` indicates also a function with no return type or no parameters
  e.g. `void f()` , `f(void)`
- In C `sizeof(void) == 1` (GCC), while in C++ `sizeof(void)` does not compile!!

```
int main() {
//  sizeof(void); // compile error
}
```

`nullptr` Keyword

C++11 introduces the keyword `nullptr` to represent a null pointer (`0x0`) and replacing the `NULL` macro

`nullptr` is an object of type `nullptr_t` → safer

```
int* p1 = NULL;      // ok, equal to int* p1 = 0l
int* p2 = nullptr;   // ok, nullptr is convertible to a pointer

int   n1 = NULL;     // ok, we are assigning 0 to n1
//int n2 = nullptr; // compile error nullptr is not convertible to an integer

//int* p2 = true ? 0 : nullptr; // compile error incompatible types
```

Conversion Rules

Conversion Rules

Implicit type conversion rules, applied in order, before any operation:

$\otimes$: any operation (*, +, /, -, %, etc.)

(A) Floating point promotion

`floating_type` $\otimes$ `integer_type` $\rightarrow$ `floating_type`

(B) Implicit integer promotion

`small_integral_type` := any signed/unsigned integral type smaller than `int`

`small_integral_type` $\otimes$ `small_integral_type` $\rightarrow$ `int`

(C) Size promotion

`small_type` $\otimes$ `large_type` $\rightarrow$ `large_type`

(D) Sign promotion

`signed_type` $\otimes$ `unsigned_type` $\rightarrow$ `unsigned_type`

Examples and Common Errors

```
float    f = 1.0f;
unsigned u = 2;
int      i = 3;
short    s = 4;
uint8_t  c = 5; // unsigned char

f * u; // float × unsigned → float: 2.0f
s * c; // short × unsigned char → int: 20
u * i; // unsigned × int → unsigned: 6u
+c;    // unsigned char → int: 5
```

Integers are not floating points!

```
int   b = 7;
float a = b / 2;   // a = 3 not 3.5!!
int   c = b / 2.0; // again c = 3 not 3.5!!
```

Implicit Promotion

Integral data types smaller than 32-bit are *implicitly* promoted to `int`, independently if they are *signed* or *unsigned*

- Unary `+, -, ~` and Binary `+, -, &, etc.` promotion:

```
char a = 48;      // '0'
cout << a;        // print '0'
cout << +a;       // print '48'
cout << (a + 0); // print '48'

uint8_t a1 = 255;
uint8_t b1 = 255;
cout << (a1 + b1);  // print '510' (no overflow)
```

`auto` Keyword

C++11 The `auto` keyword specifies that the type of the variable will be automatically deduced by the compiler (from its initializer)

```
auto a = 1 + 2;   // 1 is int, 2 is int, 1 + 2 is int!
//    -> 'a' is "int"
auto b = 1 + 2.0; // 1 is int, 2.0 is double. 1 + 2.0 is double
//    -> 'b' is "double"
```

`auto` can be very useful for maintainability and for hiding complex type definitions

```
for (auto i = k; i < size; i++)
    ...
```

On the other hand, it may make the code less readable if excessively used because of type hiding

Example: `auto x = 0;` in general makes no sense (`x` is `int`)

In C++11/C++14, `auto` (as well as `decltype`) can be used to define function output types

```
auto g(int x) -> int { return x * 2; } // C++11
// "-> int" is the deduction type
// a better way to express it is:

auto g2(int x) -> decltype(x * 2) { return x * 2; }  // C++11

auto h(int x) { return x * 2; } // C++14

//--------------------------------------------------------------

int x = g(3); // C++11
```

`auto` Keyword - Functions ★

In C++20, `auto` can be also used to define function input

```
void f(auto x) {}
// equivalent to templates

//----------------------------------------------------------------

f(3);    // 'x' is int
f(3.0);  // 'x' is double
```

C++ Operators

Operators Overview

Precedence	Operator	Description	Associativity
1	a++ a-	Suffix/postfix increment and decrement	Left-to-right
2	+a -a ++a -a ! not ∼	Plus/minus, Prefix increment/decrement, Logical/Bitwise Not	Right-to-left
3	a*b a/b a%b	Multiplication, division, and remainder	Left-to-right
4	a+b a-b	Addition and subtraction	Left-to-right
5	$\ll$ $\gg$	Bitwise left shift and right shift	Left-to-right
6	< <= > >=	Relational operators	Left-to-right
7	== !=	Equality operators	Left-to-right
8	&	Bitwise AND	Left-to-right
9	^	Bitwise XOR	Left-to-right
10	|	Bitwise OR	Left-to-right
11	&& and	Logical AND	Left-to-right
12	|| or	Logical OR	Left-to-right
13	= += -= *= /= %= «= »= &= ^= |=	Assignment and Compound operators	Right-to-left

Operators Precedence

`Operators precedence`:

- **Unary** operators have higher precedence than **binary operators**
- **Standard math operators** (`+, *, etc.`) have higher precedence than **comparison**, **bitwise**, and **logic** operators
- **Bitwise** and **logic** operators have higher precedence than **comparison** operators
- **Bitwise** operators have higher precedence than **logic** operators
- **Compound assignment** operators `+=`, `-=`, `*=`, `/=`, `%=`, `^=`, `!=`, `&=`, `>>=`, `<<=` have lower priority
- The **comma** operator has the lowest precedence (see next slides)

Examples:

```
a + b * 4;              // a + (b * 4)

a * b / c % d;          // ((a * b) / c) % d

a + b < 3 >> 4;         // (a + b) < (3 >> 4)

a && b && c || d;       // (a && b && c) || d

a and b and c or d;     // (a && b && c) || d

a | b & c || e && d;    // ((a | (b & c)) || (e && d)
```

Important: sometimes parenthesis can make an expression verbose... but they can help!

Prefix/Postfix Increment Semantic

Prefix Increment/Decrement `++i`, `-i`

(1) Update the value

(2) Return the new (updated) value

Postfix Increment/Decrement `i++`, `i-`

(1) Save the old value (temporary)

(2) Update the value

(3) Return the old (original) value

Prefix/Postfix increment/decrement semantic applies not only to built-in types but also to objects

Operation Ordering Undefined Behavior ★

Expressions with undefined (implementation-defined) behavior:

```
int i = 0;
i = ++i + 2;        // until C++11: undefined behavior
                    // since C++11:  i = 3
i = 0;
i = i++ + 2;        // until C++17: undefined behavior
                    // since C++17: i = 3

f(i = 2, i = 1);    // until C++17: undefined behavior
                    // since C++17:  i = 2
i = 0;
a[i] = ++i;         // until C++17: undefined behavior
                    // since C++17: a[1] = 1

f(++i, ++i);        // undefined behavior
i = ++i + i++;      // undefined behavior
```

Assignment, Compound, and Comma Operators

Assignment and **compound assignment** operators have *right-to-left associativity* and their expressions return the assigned value

```
int y = 2;
int x = y = 3; // y=3, then x=3
               // the same of x = (y = 3)
if (x = 4)     // assign x=4 and evaluate to true
```

The **comma operator**★ has *left-to-right associativity*. It evaluates the left expression, discards its result, and returns the right expression

```
int a = 5, b = 7;
int x = (3, 4); // discards 3, then x=4
int y = 0;
int z;
z = y, x;       // z=y (0), then returns x (4)
```

Spaceship Operator <=> ★

C++20 provides the **three-way comparison operator** `<=>`, also called *spaceship operator*, which allows comparing two objects similarly of `strcmp`. The operator returns an object that can be directly compared with a positive, 0, or negative integer value

```
(3 <=> 5)      == 0; // false
('a' <=> 'a') == 0; // true

(3 <=> 5)      < 0;  // true
(7 <=> 5)      < 0;  // false
```

The semantic of the *spaceship operator* can be extended to any object (see next lectures) and can greatly simplify the comparison operators overloading

Safe Comparison Operators ★

C++20 introduces a set of functions `<utility>` to safely compare integers of different types (`signed`, `unsigned`)

```
bool cmp_equal(T1 a, T2 b)
bool cmp_not_equal(T1 a, T2 b)
bool cmp_less(T1 a, T2 b)
bool cmp_greater(T1 a, T2 b)
bool cmp_less_equal(T1 a, T2 b)
bool cmp_greater_equal(T1 a, T2 b)
```

example:

```
#include <utility>
unsigned a  = 4;
int      b  = -3;
bool     v1 = (a > b);                  // false!!!, see next slides
bool     v2 = std::cmp_greater(a, b); // true
```

How to compare signed and unsigned integers in C++20?