Concepts of C++ Programming

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Tweedback today

The Tweedback session ID today is zb4b, the URL is:

`https://tweedback.de/zb4b`

- I will try prioritizing upvoted questions first!

Contents

Return types

- we already know how to specify a return type:

```
int foo(); // foo returns an int
```

- C++ also allows a trailing return type:

```
auto foo() -> int; // foo returns an int
```

  - the keyword `auto` is fixed, the actual return type follows after the parameter list and the symbols ->

- this really becomes useful with templates (see later), where the return type depends on the arguments:

```
template <typename T, typename U>
auto sum(const T& x, const U& y) -> decltype(x+y);
```

  - but you might also just like the style better

Returning multiple values

- returning more than one value from a function is not supported directly by the syntax
- but we can use structured bindings and `std::pair` or `std::tuple` to do so:

```cpp
std::pair<int, std::string> foo() {
    return std::make_pair(17, "C++");
}

std::tuple<int, int, float> bar() {
    return std::make_tuple(1, 2, 3.0);
}

int main() {
    auto [i, s] = foo(); // i is int with i == 17,
                         // s is std::string with s == "C++"
    auto [a, b, c] = bar(); // a, b are int, c is float,
                            // a == 1, b == 2, c == 3.0
}
```

Structured bindings

- structured bindings allow you to initialize multiple entities by elements / members of an object (such as `std::pair` or `std::tuple`)
- they work nicely with the standard library, for example with associative containers like `std::map`:

```
std::map<std::string, int> myMap; // map with strings as keys
// ... fill the map ...

// iterate over the container using range-for loop
for (const auto& [key, value] : myMap)
    std::println("{}: {}", key, value);
```

Structured bindings (cont.)

- you can also bind `struct` members or `std::array` entries:

```
struct myStruct { int a{1}; int b{2}; };
auto [x, y] = myStruct{}; // x, y are int, x == 1, y == 2

std::array<int, 3> myArray{47, 11, 9};
auto [i, j, k] = myArray; // i == 47, j == 11, k == 9
```

- structured bindings can have qualifiers (references, `const`):

```
myStruct ms;
auto& [u, v] = ms;          // u, v now reference ms.a, ms.b
ms.a = 11;
std::println("{}", u);      // prints 11
u = 22;
std::println("{}", ms.a); // prints 22
```

- you can even provide a `std::tuple`-like API for your own data types to enable structured bindings (see reference)

Returning multiple values revisited

- specifying the return type for multiple values can be annoying:

```
std::tuple<int, int, float> bar() {
    return std::make_tuple(1, 2, 3.0);
}
```

- with auto we can let the compiler deduce the return type automatically (even without trailing return type):

```
auto bar() {
    return std::make_tuple(1, 2, 3.0);
}
```

- this is convenient for the author of the function, but not necessarily great for the user of the function (that might not even be able to see the function body!)

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Parameter passing revisited

We can pass parameters to functions:

- by value:

```
void foo(int value);
```

- by reference:

```
void foo(int& value);
```

- by const reference:

```
void foo(const int& value);
```

How to choose?

Parameter passing

Refer to the C++ Core Guidelines:
`https://isocpp.github.io/CppCoreGuidelines/`

	Cheap or impossible to copy (e.g., int, unique_ptr)	**Cheap to move** (e.g., vector<T>, string) or **Moderate cost to move** (e.g., array<vector>, BigPOD) or **Don't know** (e.g., unfamiliar type, template)	**Expensive to move** (e.g., BigPOD[], array<BigPOD>)
Out	X f()		
In/Out	f(X&)		
In	f(X)	f(const X&)	
In & retain "copy"			

"Cheap" ≈ a handful of hot int copies
"Moderate cost" ≈ memcpy hot/contiguous ~1KB and no allocation

* *or return unique_ptr<X>/make_shared_<X> at the cost of a dynamic allocation*

Parameter passing (cont.)

Summarized guidelines:

- "in" parameters: pass by value (for cheaply-copied types) or pass by const reference

```
void f1(const std::string& s); // OK, pass by const reference
void f2(std::string s);         // potentially expensive
void f3(int x);                 // OK, cheap
void f4(const int& x);          // not good, unnecessary overhead
```

- "in-out" parameters: pass by reference (if you cannot avoid it)

```
void update(Record& r);  // assume that update writes to r
```

- "out" parameters: return them, either as single return type or as `std::pair`, `std::tuple`

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Overloading

Overloaded functions:

- we can declare different functions having the same name but different argument types:

```
void f(int);    // a function called f, taking an int
void f(double); // another function f, taking a double
```

- on a function call, the compiler automatically resolves the overloads in the current scope and calls the best match
  - if there is no best match, it's a compile error

Overload resolution criteria

The following criteria are tried in order:

1. exact match (no or only trivial conversions, e.g. `T` to `const T`)
2. match using promotions (e.g. `bool` to `int`, `char` to `int`, or `float` to `double`)
3. match using standard conversions (e.g. `int` to `double`, `double` to `int`, or `int` to `unsigned int`)
4. match using user-defined conversions (see later)
5. match using ellipsis `...` (see later)

Overloading: examples

```
void print(int);
void print(double);
void print(long);
void print(char);

void f(char c, int i, short s, float f) {
    print(c);   // exact match: print(char)
    print(i);   // exact match: print(int)
    print(s);   // integral promotion: print(int)
    print(f);   // float to double promotion: print(double)

    print('a'); // exact match: print(char)
    print(49);  // exact match: print(int)
    print(0);   // exact match: print(int)
    print(0L);  // exact match: print(long)
}
```

Overloading: examples (cont.)

```cpp
using complex = std::complex<double>;

int pow(int, int);
double pow(double, double);
complex pow(double, complex);
complex pow(complex, int);
complex pow(complex, complex);

void h(complex z) {
    auto i  = pow(2, 2);     // invokes pow(int, int)
    auto d  = pow(2.0, 2.0); // invokes pow(double, double)
    auto z2 = pow(2, z);     // invokes pow(double, complex)
    auto z3 = pow(z, 2);     // invokes pow(complex, int)
    auto z4 = pow(z, z);     // invokes pow(complex, complex)
    auto e  = pow(2.0, 2);   // ERROR: ambiguous
}
```

Overloading and the return type

Caution: return types are **not** considered in overload resolution!

- this is good, so function calls are context-independent:

```
float sqrt(float);
double sqrt(double);

void f(float fla, double da) {
    float fl = sqrt(da);  // invokes sqrt(double)
    auto d = sqrt(da);    // invokes sqrt(double)
    fl = sqrt(fla);       // invokes sqrt(float)
    d = sqrt(fla);        // invokes sqrt(float)
}
```

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Functors

Functions are not objects in C++

- they cannot be passed as parameters
- they cannot have state

However, a type `T` can be a function object (or functor), if:

- `T` is an object
- `T` defines `operator()`

Function objects can be used like functions.

Functor example

Functor storing a state:

```cpp
struct Adder {
    int value{1};

    int operator() (int param) {
        return param + value;
    }
};

int main() {
    Adder myAdder;
    myAdder.value = 5;
    myAdder(1);          // returns 6
    myAdder(4);          // returns 9
    myAdder.value = 7;
    myAdder(1);          // returns 8
}
```

std::function

`std::function` is a wrapper for all callable targets

- defined in `<functional>` header
- stores, copies, and invokes the wrapped target
- caution: can incur a slight overhead in both performance and memory

```
#include <functional>
int addFunc(int a) { return a + 3; }

int main() {
    std::function adder{addFunc};
    int a{adder(5)};   // a == 8

    // alternatively specifying the function type:
    std::function<int(int)> adder2{addFunc};
}
```

- function type is declared as `return_type(argument_list)`
- deduction guides usually makes this unnecessary

std::function example

```cpp
#include <functional>
#include <iostream>

void printNum(int i) { std::println("{}", i); }

struct PrintNum {
    void operator() (int i) { std::println("{}", i); }
};

int main() {
    // store a function
    std::function f_printNum{printNum};
    f_printNum(-47);

    // store the functor
    std::function f_PrintNum{PrintNum{}};
    f_PrintNum(11);

    // fix the function parameter using std::bind
    std::function<void()> f_leet{std::bind(printNum, 31337)};
    f_leet();
}
```

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Lambda expressions

Lambda expressions are a simplified notation for anonymous function objects

- they are an expression and can be used anywhere expressions can be used:

```
std::find_if(container.begin(), container.end(),
    [](int val) { return 1 < val && val < 10; }
);
```

- the function object created by the lambda expression is called closure
- the closure can hold copies or references of captured variables

Lambda expressions: the syntax

```
[ capture_list ] ( param_list ) -> return_type { body }
```

- `capture_list` specifies the variables of the environment to be captured in the closure
- `param_list` are the function parameters
- `return_type` specifies the return type; it is optional! If not specified, the return type is deduced from the return statements in the body

- the `capture_list` can be empty: `[]() {}`
- if the `param_list` is empty, it can be omitted
  - the shortest lambda expression is thus: `[]{}`

Lambda expressions: examples

```
bool isMultipleOf3(int v) { return v % 3 == 0; }

void f() {
    std::vector<int> numbers{ /* ... */ };

    // version with functions:
    std::remove_if(numbers.begin(), numbers.end(), isMultipleOf3);

    // version with lambdas:
    std::remove_if(numbers.begin(), numbers.end(),
        [](int v) { return v % 3 == 0; }
    );
}
```

Storing lambda expressions

Lambda expressions can be stored in variables:

- using `auto`:

```
auto lambda = [](int a, int b) { return a + b; };

std::println("{}", lambda(2, 3)); // outputs 5
```

- using `std::function`:

```
std::function func = [](int a, int b) { return a + b; };

std::println("{}", func(3, 4)); // outputs 7
```

- the signature of the lambda can be stated explicitly:

```
std::function<int(int, int)> func2 =
    [](int a, int b) { return a + b; };

std::println("{}", func2(4, 5)); // outputs 9
```

The type of a lambda expression

- the type of a lambda expression is not defined
- no two lambdas have the same type (even if they are identical otherwise):

```
auto myFunc(bool first) { // ERROR: ambiguous return type
    if (first)
        return []() { return 42; };
    else
        return []() { return 42; };
}
```

- for each lambda, the compiler generates a unique closure class with a constructor and `operator() const`
  - in fact, we could do this ourselves, it's just more effort
  - nevertheless, lambdas turned out to be a game changer

Lambda expression return types

- just like for functions, the return type can be deduced from the return statement:

```
void f() {
    auto x = [] { std::println("Hello"); }; // void return type

    auto y = [] { return 42; }; // int return type

    auto z = [] { if (true) return 1; else return 2.0; };
                  // ERROR: inconsistent types

    auto z2 = [] -> int { if (true) return 1; else return 2.0; };
                  // OK: explicit return type
}
```

Lambda captures

- lambda captures are part of the state of a closure
  - can refer to automatic variables in the surrounding scopes
  - can refer to the `this` pointer in the surrounding scope (see later)

- capture can be done by copy: creates a copy of the captured variable in the closure
- capture can be done by reference: creates a reference to the captured variable in the closure

- captures can be used in the lambda expressions like regular variables or references

Lambda captures: examples

```cpp
void f() {
    int i{0};

    auto lambda1 = [i]() { std::cout << i; }; // i by copy
    auto lambda2 = [i]() { ++i; }; // ERROR: i is read-only!

    auto lambda3 = [&i]() { ++i; }; // OK: i by reference
    lambda3();
    std::cout << i; // outputs 1
}
```

Caution: beware dangling references:

```cpp
auto g() {
    int j{0};
    return [&j]() { ++j; }; // beware: reference to j will dangle!
}
```

Lambda captures: examples (cont.)

Capture by copy vs. by reference:

```
void f() {
    int i{42};

    auto lambda1 = [i]() { return i + 42; };
    auto lambda2 = [&i]() { return i + 42; };

    i = 0;

    int a = lambda1();   // a == 84
    int b = lambda2();   // b == 42
}
```

Lambda default captures

- capture defaults allow you to capture all variables in the surrounding scope
  - by copy: [=]
  - by reference: [&]
- if defaults are used, only diverging capture types can be specified afterwards:

```cpp
void f() {
    int i{0}, j{42};

    auto lambda1 = [&, i]() {};  // j by reference, i by copy
    auto lambda2 = [=, &i]() {}; // j by copy, i by reference

    auto lambda3 = [&, &i]() {}; // ERROR: non-diverging capture
    auto lambda4 = [=, i]() {};  // ERROR: non-diverging capture
}
```

Lambda default captures (cont.)

- default captures can be dangerous
- in particular default by reference `[&]` may have unwanted side effects

- in general: avoid default captures!

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Handling error conditions

What to do in error conditions?

- terminate the program: `if (somethingWrong) exit(1);`
  - quite drastic, very problematic in libraries
- return an error value and let the caller decide
  - often hard to define an error value, e.g. `int getInt();`
- return a legal value and leave program in error state
  - e.g. the C standard library sets global variable `errno`:

```
double d = sqrt(-1.0);  // value of d is meaningless
```

  - need to test `errno` basically everywhere, also issues with concurrency and global `errno` variable
- call an error-handler: `if (wrong) errorHandler();`
  - but how can the handler handle the problem?

Exceptions

The C++ "solution" is exceptions:

- exceptions transfer control and information up the call stack
- see if the caller(s) can handle the exceptional condition

- exceptions are raised via `throw` expressions
  - `dynamic_cast`, `new` and some standard library functions can also raise exceptions
- exceptions are handled in `try`-`catch` blocks
  - handling them is optional
  - however, if an exception is not caught, the program is terminated
  - errors during handling an exception also lead to program termination

Throwing exceptions

- objects of any type may be thrown as exception objects
- syntax: `throw expression;`
- copy initializes the exception object from `expression` and throws it
- the standard library offers `std::exception` and some derived exception types such as `std::invalid_argument` or `std::out_of_range`
  - `std::exception` contains an explanatory string, it can be queried using `what()`
  - your own exceptions should usually derive from the standard library classes

```cpp
#include <stdexcept>

void foo(int i) {
    if (i == 42)
        throw 42;

    throw std::logic_error("What is the meaning of life?");
}
```

Handling exceptions

- when an exception is thrown, C++ performs stack unwinding
  - ensures proper clean up of objects with automatic storage duration
  - there is some slight run-time overhead, so exceptions are sometimes avoided in real-time applications
- the stack is unwound until a `try`-`catch` block is found
  - exceptions that occur in the `try` block can be handled in the `catch` block
  - the parameter of the `catch` block determines the type of exception that causes the block to be entered

Exception handling example

```cpp
#include <exception>
#include <iostream>

void bar() {
    try {
        foo(42);
    } catch (int i) {
        /* handle the exception somehow */
    } catch (const std::exception& e) {
        std::cerr << e.what() << "\n";
        /* handle the exception somehow */
    }
}
```

Noexcept functions

- some functions do not throw (or should not throw)
- you can mark functions as `noexcept`:

```
int myFunction() noexcept; // may not throw an exception
```

- valuable information for the programmer (no need to handle exceptions) and the compiler (optimizations)
- however, the compiler cannot fully check for the compliance of `noexcept` functions
  - if a `noexcept` function throws anyway, the program is terminated immediately
  - this can happen unexpectedly, e.g. using a `std::vector` and not having enough memory (leading to a `std::bad_alloc` exception)

Exception guidelines

- exceptions should be used rarely
    - main use case: establishing class invariants, for example in RAII (see later)
- exceptions should not be used for control flow!

- some functions must not throw exceptions
    - destructors
    - move constructors and assignment operators
    - see reference documentation for details

C++23 and `std::expected`

- C++23 introduces `std::expected`, another way to handle errors
  - this is very similar to Rust
- `std::expected<T, E>` stores either a value of type `T` or an error of type `E`
  - idea: function return value always contains either the valid result, or an error object
  - `has_value()` checks if the expected value is there
  - `value()` or dereferencing `*` accesses the expected value
  - `error()` returns the unexpected value
  - monadic operations are also supported, such as `and_then()` or `or_else()`
- performance guarantee: no dynamic memory allocation takes place

C++23 and std::expected

usage example (omitting the necessary includes to fit slide):

```cpp
enum class parse_error { invalid_input };

auto parse_number(std::string_view str) -> std::expected<double, parse_error> {
    if (str.empty())
        return std::unexpected(parse_error::invalid_input);
    // do actual parsing ...
    return 0.0;
}

int main() {
    auto process = [](std::string_view str) {
        if (const auto num = parse_number(str); num.has_value())
            std::println("value: {}", *num);
        else if (num.error() == parse_error::invalid_input)
            std::println("error: invalid input");
    };

    for (auto s : {"42", ""})
        process(s);
}
```

Error handling in C++

- both error handling mechanisms, exception handling and `std::expected`, have their value
  - exception handling is well suited for the rare failures you cannot do much about at the called function (e.g. out of memory)
  - `std::expected` is well suited for more regular errors, such as errors in parsing
- also used very often still: returning error codes - not very practical, and requires a lot of discipline in querying error values

Summary

1. Concepts of procedural programming
   - Functions and return values
   - Functions and parameters
   - Function overloading
   - Function objects
   - Lambda expressions
   - Error handling