Modern C++ Programming

10. Translation Units

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Basic Concepts

Translation Unit

Header File and Source File

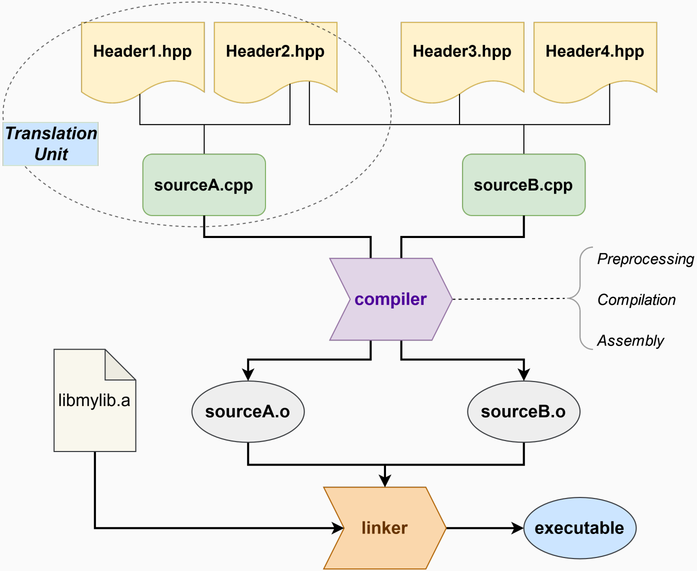
Header files allow to define interfaces (`.h, .hpp, .hxx`), while keeping the implementation in separated **source files** (`.c, .cpp, .cxx`).

Translation Unit

A **translation unit** (or *compilation unit*) is the basic unit of compilation in C++. It consists of the content of a *single* source file, plus the content of *any* header file directly or indirectly included by it

A single translation unit can be compiled into an object file, library, or executable program

Compile Process



Local and Global Scope

Scope

The **scope** of a variable/function/object is the region of the code within the entity can be accessed

Local Scope / Block Scope

Entities that are declared inside a function or a block are called local variables.
Their memory address is not valid outside their scope

Global Scope / File Scope / Namespace Scope

Entities that are defined outside of all functions.
They hold a single memory location throughout the life-time of the program

Local and Global Scope

```cpp
int var1;      // global scope

int f() {
    int var2; // local scope
}

struct A {
    int var3; // depends on where the instance of 'A' is used
};
```

Linkage

Linkage

Linkage refers to the *visibility* of symbols to the linker

No Linkage

No linkage refers to symbols in the local scope of declaration and not visible to the linker

Internal Linkage

Internal linkage refers to symbols visible only in scope of a *single* translation unit. The same symbol name has a different memory address in distinct translation units

External Linkage

External linkage refers to entities that exist *outside* a single translation unit. They are accessible and have the same *identical memory address* through the whole program, which is the combination of all translation units

Storage Class and Duration

Storage Duration

The **storage duration** (or *duration class*) determines the *duration* of a variable, namely when it is created and destroyed

Storage Duration	Allocation	Deallocation
Automatic	Code block start	Code end start
Static	Program start	Program end
Dynamic	Memory allocation	Memory deallocation
Thread	Thread start	Thread end

`en.cppreference.com/w/cpp/language/storage_duration`

- **Automatic storage duration**. Local variables temporary allocated on registers or stack (depending on compiler, architecture, etc.).
  If not explicitly initialized, their value is undefined

- **Static storage duration**. The storage of an object is allocated when the program begins and deallocated when the program ends.
  If not explicitly initialized, it is zero-initialized

- **Dynamic storage duration**. The object is allocated and deallocated by using dynamic memory allocation functions (`new/delete`).
  If not explicitly initialized, its memory content is undefined

- **Thread storage duration** C++11. The object is allocated when the thread begins and deallocated when the thread ends. Each thread has its own instance of the object

Storage Duration Examples

```
int v1; // static duration

void f() {
    int  v2;                    // automatic duration
    auto v3    = 3;             // automatic duration
    auto array = new int[10]; // dynamic duration (allocation)
} // array, v2, v3 variables deallocation (from stack)
  // the memory associated to "array" is not deallocated

int main() {
    f();
}
// main end: v1 is deallocated
```

Storage Class

Storage Class Specifier

The **storage class** for a variable declaration is a **type specifier** that, *together with the scope*, governs its *storage duration* and *linkage*

Storage Class	Notes	Scope	Storage Duration	Linkage
`auto`	local `type` decl.	Local	*automatic*	*No linkage*
no storage class	global `type` decl.	Global	*static*	*External*
`static`		Local	*static*	*No linkage*
`static`		Global	*static*	*Internal*
`extern`		Global	*static*	*External*
`thread_local` C++11		any	*thread local*	*any*

Storage Class Examples

```cpp
int                      v1;     // no storage class
static               int v2 = 2; // static storage class
extern               int v3;     // external storage class
thread_local         int v4;     // thread local storage class
thread_local static int v5;      // thread local and static storage classes

int main() {
    int                 v6;      // auto storage class
    auto                v7 = 3;  // auto storage class
    static int          v8;      // static storage class
    thread_local int v9;         // thread local and auto storage classes
    auto array = new int[10];    // auto storage class ("array" variable)
}
```

Local `static` Variables

`static` *local variables* are allocated when the program begins, *initialized* when the function is called the first time, and deallocated when the program end

```
int f() {
    static int val = 1;
    val++;
    return val;
}

int main() {
    cout << f(); // print 2 ("val" is initialized)
    cout << f(); // print 3
    cout << f(); // print 4
}
```

`static` and `extern` Keywords

`static` /*anonymous namespace-included global variables* or *functions* are visible only within the file (*internal linkage*)

- **Non-** `static` global variables or functions with the same name in different translation units produce *name collision* (or name conflict)

`extern` keyword is used to declare the existence of *global variables* or *functions* in another translation unit (*external linkage*)

- the variable or function must be defined in one and only one translation unit
- it is redundant for functions
- it is necessary for variables to prevent the compiler to associate a memory location in the current translation unit

If the same identifier within a translation unit appears with both *internal* and *external* linkage, the behavior is undefined

Internal/External Linkage Examples

```
int         var1 = 3;  // external linkage
                       // (in conflict with variables in other
                       //  translation units with the same name)
static int var2 = 4;   // internal linkage (visible only in the
                       //                   current translation unit)
extern int var3;       // external linkage
                       // (implemented in another translation unit)
void         f1() {}   // external linkage (could conflict)

static void f2() {}    // internal linkage

namespace {            // anonymous namespace
void         f3() {}   // internal linkage
}
extern void f4();      // external linkage
                       // (implemented in another translation unit)
```

Linkage of `const` and `constexpr`

`const` variables implies *internal linkage* at global scope

`constexpr` implies `const`, which implies *internal linkage*

note: the same variable has different memory addresses on different translation units

```
const     int var1 = 3;        // internal linkage
constexpr int var2 = 2;        // internal linkage

static const     int var3 = 3; // internal linkage (redundant)
static constexpr int var4 = 2; // internal linkage (redundant)

int main() {}
```

Static Initialization Order Fiasco 1/2

In C++, the order in which global variables are initialized at runtime is not defined.

This introduces a subtle problem called *static initialization order fiasco*

source.cpp

```
int f() { return 3; } // run-time function

int x = f();          // run-time evalutation
```

main.cpp

```
extern int x;
int        y = x; // run-time initialized

int main() {
    cout << y;    // print "3" or "0" depending on the linking order
}
```

source.cpp

```cpp
constexpr int f() { return 3; } // compile-time/run-time function

constinit int x = f();          // compile-time initialized (C++20)
```

main.cpp

```cpp
constinit extern int x;     // compile-time initialized (C++20)
int                  y = x; // run-time     initialized

int main() {
    cout << y; // print "3"!!
}
```

Linkage Summary

No Linkage: Local **variables**, **functions**, **classes**

Internal Linkage: (not accessible by other translation units)

- **Global Variables**: `static` or *non-template/non-specialized*, *non-inline* `const` / `constexpr`
- **Functions**: `static` or *non-template/non-specialized*, *non-inline* `constexpr`
- Anonymous `namespace` content (even classes)

External Linkage: (accessible by other translation units)

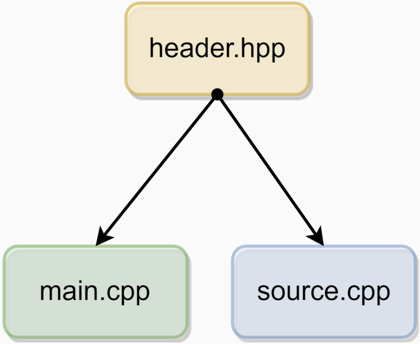
- **Global Variables**: `no specifier`, or `extern`, or `template` (C++14), or `inline` (C++17)
- **Functions**: `no specifier`, or `extern`, or `inline`, or `template`
- **Classes** and their *static*, *non-static* data members

en.cppreference.com/w/cpp/language/storage_duration

Dealing with Multiple Translation Units

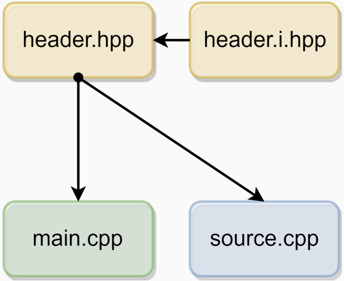
Code Structure 1

- one header, two source files $\rightarrow$ two translation units
- *the header is included in both translation units*



Code Structure 2

- two headers, two source files $\rightarrow$ two translation units
- one header for declarations (`.hpp`), and the other one for implementations (`.i.hpp`)
- *the header and the header implementation are included in both translation units*



* separate header declaration and implementation is not mandatory but it could help to better organize the code

header.hpp:

```
class A {
public:
    void        f();
    static void g();
private:
    int        x;
    static int y;
};
```

main.cpp:

```
#include "header.hpp"
#include <iostream>

int main() {
    A a;
    std::cout << A.x;  // print 1
    std::cout << A::y; // print 2
}
```

source.cpp:

```
#include "header.hpp"

void A::f() {}
void A::g() {}

int A::x = 1;
int A::y = 2;
```

header.hpp:

```cpp
struct A {
    static int y;      // zero-init
//  static int y = 3; // compile error
//            must be initialized out-of-class

    const int z = 3; // only in C++11
//  const int z;      // compile error
//                       must be initialized

    static const int w1;      // zero-init
    static const int w2 = 4; // inline-init
};
```

source.cpp:

```cpp
#include "header.hpp"

int       A::y  = 2;
const int A::w1 = 3;
```

One Definition Rule (ODR)

One Definition Rule (ODR)

(1) In any **(single) translation unit**, a `template`, `type`, `function`, or `object`, *cannot* have more than <u>one definition</u>

- *Compiler error* otherwise
- Any number of declarations are allowed

(2) In the **entire program**, an `object` or `non-inline function` *cannot* have more than <u>one definition</u>

- *Multiple definitions linking error* otherwise
- `Entities` with *internal linkage* in different translation units are allowed, even if their names and types are the same

(3) A `template`, `type`, or `inline functions/variables`, can be defined in <u>more than one</u> translation unit. For a given entity, <u>each definition must be the same</u>

- *Undefined behavior* otherwise
- Common case: same header included in multiple translation units

One Definition Rule - Point (1), (2)

header.hpp:

```cpp
void f(); // DECLARATION
```

main.cpp:

```cpp
#include "header.hpp"
#include <iostream>
int         a = 1; // external linkage
// int      a = 7; // compiler error, Point (1)

extern int b;

static int c = 2; // internal linkage

int main() {
    std::cout << a; // print 1
    std::cout << b; // print 5
    std::cout << c; // print 2
    f();
}
```

source.cpp:

```cpp
#include "header.hpp"
#include <iostream>
// linking error, multiple definitions
// int      a = 2;    // Point (2)

int         b = 5;    // ok
// internal linkage
static int c = 4;    // ok

void f() {            // DEFINITION
//  std::cout << a; // 'a' is not visible
    std::cout << b; // print 5
    std::cout << c; // print 4
}
```

Global Variable Issues

header.hpp:

```cpp
#include <iostream>
struct A {
    A()  { std::cout << "A()";  }
    ~A() { std::cout << '~A()'; }
};
// A           obj;         // linking error multiple definitions
const A        const_obj{}; // "const/constexpr" implies internal linkage
constexpr float PI = 3.14f;
```

source1.cpp:

```cpp
#include "header.hpp"

void f() { std::cout << &PI; }
// address: 0x1234ABCD

// print "A()"  the first time
// print "~A()" the first time
```

source2.cpp:

```cpp
#include "header.hpp"

void f() { std::cout << &PI; }
 // print address: 0x3820FDAC !!

// print "A()"  the second time!!
// print "~A()" the second time!!
```

`inline` Functions/Variables 1/2

`inline`

`inline` specifier allows a function or a variable (in C++17) to be identically defined (not only declared) in multiple translation units

- `inline` is one of the most misunderstood features of C++
- `inline` is a hint for the linker. Without it, the linker can emit "`multiple definitions`" error
- `inline` variables/functions have *external linkage* (unique memory address) as standard variables/functions but cannot be exported, namely, used by other translation units
- It can be applied for optimization purposes only if a function has *internal* linkage (`static` or it is within an `anonymous namespace`)

```cpp
       void f() {}
inline void g() {}
```

`f()` :

- Cannot be defined in a header included in multiple source files
- The linker issues a *"multiple definitions"* error

`g()` :

- Can be defined in a header and included in multiple source files
- The linker removes all definitions except one
- Multiple definitions <u>don't</u> break the ODR rule

One Definition Rule - Point (3)

header.hpp:

```
inline void f() {} // the function is marked 'inline' (no linking error)
inline int  v = 3; // the variable is marked 'inline' (no linking error) (C++17)

template<typename T>
void g(T x) {}     // the function is a template (no linking error)

using var_t = int; // types can be defined multiple times (no linking error)
```

main.cpp:

```
#include "header.hpp"

int main() {
   f();
   g(3); // g<int> generated
}
```

source.cpp:

```
#include "header.hpp"

void h() {
    f();
    g(5); // g<int> generated
}
```

Alternative organization:

header.hpp:

```cpp
inline void f();    // DECLARATION
inline int  v;      // DECLARATION

template<typename T>
void g(T x);        // DECLARATION

using var_t = int; // type
#include "header.i.hpp"
```

header.i.hpp:

```cpp
void f() {}     // DEFINITION
int  v = 3;     // DEFINITION

template<typename T>
void g(T x) {} // DEFINITION
```

main.cpp:

```cpp
#include "header.hpp"

int main() {
    f();
    g(3); // g<int> generated
}
```

source.cpp:

```cpp
#include "header.hpp"

void h() {
    f();
    g(5); // g<int> generated
}
```

ODR Common Class Error

header.hpp:

```cpp
struct A {
    void f() {};   // inline DEFINITION
    void g();      // DECLARATION
    void h();      // DECLARATION
};
void A::g() {}     // DEFINITION
```

main.cpp:

```cpp
#include "header.hpp"
// linking error
// multiple definitions of A::g()

int main() {}
```

source.cpp:

```cpp
#include "header.hpp"
// linking error
// multiple definitions of A::g()

void A::h() {}  // DEFINITION, ok
```

Function Template

Function Template - Case 1

`header.hpp`:

```cpp
template<typename T>
void f(T x) {}; // DECLARATION and DEFINITION
```

`main.cpp`:

```cpp
#include "header.hpp"

int main() {
    f(3);    // call f<int>()
    f(3.3f); // call f<float>()
    f('a');  // call f<char>()
}
```

`source.cpp`:

```cpp
#include "header.hpp"

void h() {
    f(3);    // call f<int>()
    f(3.3f); // call f<float>()
    f('a');  // call f<char>()
}
```

`f<int>()`, `f<float>()`, `f<char>()` are generated two times (in both translation units)

Function Template - Case 2

`header.hpp`:

```cpp
template<typename T>
void f(T x); // DECLARATION
```

`main.cpp`:

```cpp
#include "header.hpp"

int main() {
   f(3);    // call f<int>()
   f(3.3f); // call f<float>()
// f('a');  // linking error
}  // the specialization does not exist
```

`source.cpp`:

```cpp
#include "header.hpp"

template<typename T>
void f(T x) {} // DEFINITION

// template SPECIALIZATION
template void f<int>(int);
template void f<float>(float);
// any explicit instance is also
// fine, e.g. f<int>(3)
```

Function Template and Specialization

header.hpp:

```cpp
template<typename T>
void f() {} // DECLARATION and DEFINITION
```

main.cpp:

```cpp
#include "header.hpp"

int main() {
    f<char>(); // use the generic function
    f<int>();  // use the specialization
}
```

source.cpp:

```cpp
#include "header.hpp"

template<>
void f<int>() {} // SPECIALIZATION
                 // DEFINITION
```

Function Template - extern Keyword

C++11

header.hpp:

```cpp
template<typename T>
void f() {} // DECLARATION and DEFINITION
```

main.cpp:

```cpp
#include "header.hpp"

extern template void f<int>();
// f<int>() is not generated by the
// compiler in this translation unit

int main() {
    f<int>();
}
```

source.cpp:

```cpp
#include "header.hpp"

void g() {
    f<int>();
}
// or 'template void f<int>(int);'
```

ODR Function Template Common Error

header.hpp:

```
template<typename T>
void f();              // DECLARATION

// template<>          // linking error
// void f<int>() {}    // multiple definitions -> included twice
                       // full specializations are like standard functions
                       // it can be solved by adding "inline"
```

main.cpp:

```
#include "header.hpp"

int main() {}
```

source.cpp:

```
#include "header.hpp"

// some code
```

Class Template

Class Template - Case 1

header.hpp:

```cpp
template<typename T>
struct A {
    T    x = 3;  // "inline" DEFINITION
    void f() {}; // "inline" DEFINITION
};
```

main.cpp:

```cpp
#include "header.hpp"

int main() {
   A<int>   a1; // ok
   A<float> a2; // ok
   A<char>  a3; // ok
}
```

source.cpp:

```cpp
#include "header.hpp"

int g() {
   A<int>   a1; // ok
   A<float> a2; // ok
   A<char>  a3; // ok
}
```

Class Template - Case 2

header.hpp:

```
template<typename T>
struct A {
    T    x;
    void f(); // DECLARATION
};
#include "header.i.hpp"
```

header.i.hpp:

```
template<typename T>
T A<T>::x = 3;     // DEFINITION

template<typename T>
void A<T>::f() {} // DEFINITION
```

main.cpp:

```
#include "header.hpp"

int main() {
   A<int>   a1; // ok
   A<float> a2; // ok
   A<char>  a3; // ok
}
```

source.cpp:

```
#include "header.hpp"

int g() {
   A<int>   a1; // ok
   A<float> a2; // ok
   A<char>  a3; // ok
}
```

Class Template - Case 3

header.hpp:

```cpp
template<typename T>
struct A {
    T    x;
    void f(); // DECLARATION
};
```

main.cpp:

```cpp
#include "header.hpp"

int main() {
    A<int>  a1; // ok
//  A<char> a2; // linking error
}               // 'f()' is undefined
                // while 'x' has an undefined
                // value for A<char>
```

source.cpp:

```cpp
#include "header.hpp"

template<typename T>
int A<T>::x = 3;  // initialization

template<typename T>
void A<T>::f() {} // DEFINITION

// generate template specialization
template class A<int>;
```

Class Template - `extern` Keyword

C++11

`header.hpp`:

```cpp
template<typename T>
struct A {
    T    x;
    void f() {}
};
```

`source.cpp`:

```cpp
#include "header.hpp"

extern template class A<int>;
// A<int> is not generated by the
// compiler in this translation unit
int main() {
    A<int> a;
}
```

`source.cpp`:

```cpp
#include "header.hpp"

// template specialization
template class A<int>;

// or any instantiation of A<int>
```

ODR Undefined Behavior and Summary

Undefined Behavior - `inline` Function

`main.cpp`:

```cpp
#include <iostream>
inline int f() { return 3; }

void g();

int main() {
    std::cout << f(); // print 3
    std::cout << g(); // print 3!!
}                     // not 5
```

`source.cpp`:

```cpp
// same signature and inline
inline int f() { return 5; }

int g() { return f(); }
```

The linker can *arbitrary* choose one of the two definitions of `f()`. With `-O3`, the compiler could *inline* `f()` in `g()`, so now `g()` return `5`

This issue is easy to detect in trivial examples but hard to find in large codebase

Solution: `static` or `anonymous namespace`

Undefined Behavior - Member Function

header.hpp:

```cpp
#include <iostream>

struct A {
    int f() { return 3; }
};

int g();
```

main.cpp:

```cpp
#include "header.hpp"

int main() {
    A a;
    std::cout << a.f();// print 3
    std::cout << g();  // print 3!!
}
```

source.cpp:

```cpp
struct A {
    int f() { return 5; }
};

int g() {
    A<int> a;
    return a.f();
}
```

Undefined Behavior - Function Template

header.hpp:

```cpp
template<typename T>
int f() {
    return 3;
}

int g();
```

main.cpp:

```cpp
#include "header.hpp"

int main() {
    std::cout << f<int>(); // print 3
    std::cout << g();      // print 3!!
}
```

source.cpp:

```cpp
template<typename T>
int f() {
    return 5;
}

int g() {
    return f<int>();
}
```

Undefined Behavior

Other ODR violations are even harder (if not impossible) to find, see `Diagnosing Hidden ODR Violations in Visual C++`

Some tools for partially detecting ODR violations:

- `-detect-odr-violations` flag for `gold/llvm linker`
- `-Wodr -flto` flag for GCC
- `Clang address sanitizer` + `ASAN_OPTIONS=detect_odr_violation=2` `(link)`

Another solution could be include all files in a single translation unit

Where Placing Declarations and Implementations

- **Header:** *declaration* of
  - functions, structures, classes, types, alias
  - `template` functions, structs, classes
  - `extern` variables, functions
- **Header implementation:** *definition* of
  - `inline` variables/functions
  - `template` variables/functions/classes
  - global *static, non-static* `const/constexpr` variables and `constexpr` functions
- **Source file:** *definition* of
  - functions, including `template` full specializations
  - classes
  - `extern` and `static` global variables/functions

#include Issues

The **include guard** avoids the problem of multiple inclusions of a header file in a translation unit

header.hpp:

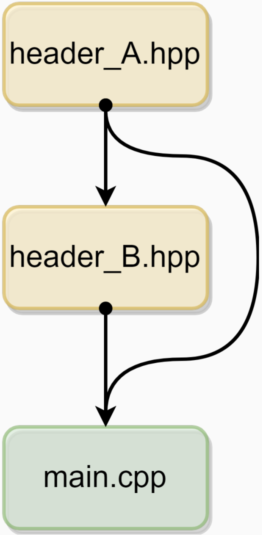
```
#ifndef HEADER_HPP  // include guard
#define HEADER_HPP

... many lines of code ...

#endif // HEADER_HPP
```

`#pragma once` preprocessor directive is an alternative to the the **include guard** to force current file to be included only once in a translation unit

- **#pragma once** is less portable but less verbose and compile faster than the **include guard**

The **include guard**/**#pragma once** should be used in every header file

Common case:



header_A.hpp:

```
#pragma once   // prevent "multiple definitions" linking error

struct A {
};
```

header_B.hpp:

```
#include "header_A.hpp"  // included here

struct B {
    A a;
};
```

main.cpp:

```
#include "header_A.hpp"  // .. and included here
#include "header_B.hpp"
int main() {
    A a;  // ok, here we need "header_A.hpp"
    B b;  // ok, here we need "header_B.hpp"
}
```

Forward Declaration

Forward declaration is a declaration of an identifier for which a complete definition has not yet given. "*forward*" means that an entity is declared before it is defined

main.cpp:

```
void f();  // function forward declaration

class A;   // class    forward declaration

int main() {
    f();   // ok, f() is defined in the translation unit
//  A a;   // compiler error no definition (incomplete type)
           // e.g. the compiler is not able to deduce the size of A
    A* a;  // ok
}

void f() {}  // definition of f()
```

source.cpp:

```
class A  {}; // definition of A()
```

Forward Declaration vs. `#include`

Advantages:

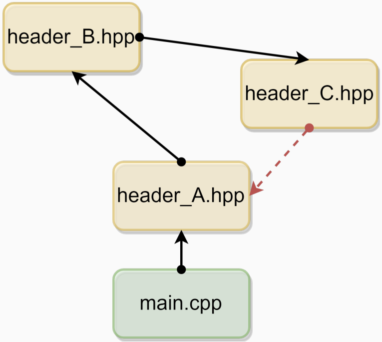
- Forward declarations can save compile time as `#include` forces the compiler to open more files and process more input
- Forward declarations can save on unnecessary recompilation. `#include` can force your code to be recompiled more often, due to unrelated changes in the header

Disadvantages:

- Forward declarations can hide a dependency, allowing user code to skip necessary recompilation when headers change
- A forward declaration may be broken by subsequent changes to the library
- Forward declaring multiple symbols from a header can be more verbose than simply `#including` the header

google.github.io/styleguide/cppguide.html#Forward_Declarations

A **circular dependency** is a relation between two or more modules which either directly or indirectly depend on each other to function properly



Circular dependencies can be solved by using forward declaration, or better, by rethinking the project organization header_A.hpp:

```cpp
#pragma once
#include "header_B.hpp"
class A {
    B* b;
};
```

header_B.hpp:

```cpp
#pragma once
#include "header_C.hpp"
class B {
    C* c;
};
```

header_C.hpp:

```cpp
#pragma once
#include "header_A.hpp"
class C {  // compile error "header_A" already included by "main.cpp"
    A* a;  // the compiler cannot view the "class C"
};
```

Circular Dependencies (fix)

header_A.hpp:

```cpp
#pragma once
class B;    // forward declaration
            // note: does not include "header_B.hpp"
class A {
    B* b;
};
```

header_B.hpp:

```cpp
#pragma once
class C;    // forward declaration
class B {
   C* c;
};
```

header_C.hpp:

```cpp
#pragma once
class A;    // forward declaration
class C {
    A* a;
};
```

Common Linking Errors

Very common *linking* errors:

- `undefined reference`

  Solutions:

  - Check if the right headers and sources are included
  - Break circular dependencies (could be hard to find)

- `multiple definitions`

  Solutions:

  - `inline` function, variable definition or `extern` declaration
  - Add `include guard`/ `#pragma once` to header files
  - Place template definition in header file and full specialization in source files

Namespace

Overview

The problem: Named entities, such as variables, functions, and compound types declared outside any block has *global scope*, meaning that its name is valid anywhere in the code

Namespaces *allow to group named entities that otherwise would have global scope into narrower scopes, giving them* ***namespace scope*** *(where* `std` *stands for "standard")*

Namespaces provide a method for preventing name conflicts in large projects. Symbols declared inside a namespace block are placed in a named scope that prevents them from being mistaken for identically-named symbols in other scopes

Namespace Functions vs. Class + static Methods

Namespace functions:

- Namespace can be extended anywhere (without control)
- Namespace specifier can be avoided with the keyword `using`

Class + `static` methods:

- Can interact only with static data members
- `struct/class` cannot be extended outside their declarations

→ `static` methods should define operations strictly related to an object state (*statefull*)

→ otherwise `namespace` should be preferred (*stateless*)

Defining a Namespace

```cpp
#include <iostream>
namespace ns1 {
void f() {
    std::cout << "ns1" << std::endl;
}
} // namespace ns1

namespace ns2 {
void f() {
    std::cout << "ns2" << std::endl;
}
} // namespace ns2

int main () {
    ns1::f(); // print "ns1"
    ns2::f(); // print "ns2"
//  f();      // compile error f() is not visible
}
```

Namespace Conflits

```
#include <iostream>

void f() { std::cout << "global" << endl; }

namespace ns1 {
    void f() { std::cout << "ns1::f()" << endl; }
    void g() { std::cout << "ns1::g()" << endl; }
}

int main () {
    f();       // ok, print "global"
//  g();       // compile error g() is not visible

    using namespace ns1; // expand "ns1" in this scope (from this line)
//  f();       // compile error ambiguous function name
    ::f();     // ok, print "global"
    ns1::f(); // ok, print "ns1::f()"
    g();       // ok, print "ns1::g()", only one choice
}
```

Nested Namespaces

```cpp
#include <iostream>
using namespace std;
namespace ns1 {
    void f() { cout << "ns1::f()" << endl; }
namespace ns2 {
    void f() { cout << "ns1::ns2::f()" << endl; }
} // namespace ns1
} // namespace ns2

namespace ns1 { // the same namespace can be declared multiple times,
namespace ns2 { // and extended in multiple files
    void g() {}
}
}
```

C++17 allows nested namespace definitions:

```cpp
namespace ns1::ns2 {
    void h()
}
```

Namespace Precedence

```cpp
#include <iostream>

void f()  { std::cout << "global"; }

namespace ns1 {
    void f() { std::cout << "ns1"; }

    void g() { f(); }
}

void g() { f(); }

int main() {
    g();       // "global"
    ns1::g(); // "ns1"
}
```

Namespace Alias

Namespace alias allows declaring an alternate name for an existing namespace

```cpp
namespace very_very_long_namespace {
    void g() {}
}

int main() {
    namespace ns = very_very_long_namespace; // namespace alias
    ns::g();
}
```

Anonymous Namespace

A namespace with no identifier before an opening brace produces an **unnamed/anonymous namespace**

Entities inside an anonymous namespace are used for declaring unique identifiers, visible in the same source file

Anonymous namespaces vs. static global entities

- Anonymous namespaces allow *type declarations*, and they are *less verbose*

main.cpp

```cpp
#include <iostream>
namespace { // anonymous
    void f() { std::cout << "main"; }
}             // internal linkage

int main() {
    f();   // ok, print "main"
}
```

source.cpp

```cpp
#include <iostream>
namespace { // anonymous
    void f() { std::cout << "source"; }
}

int g() {
    f();   // ok, print "source"
}
```

`inline` Namespace

`inline` namespace is a concept similar to library versioning. It is a mechanism that makes a nested namespace look and act as if all its declarations were in the surrounding namespace

```
namespace ns1 {
inline namespace V99 {
    void f(int) {}   // most recent version
}
namespace V98 {
    void f(int) {}
}
}
using namespace ns1;

int main() {
    V98::f(1);  // call V98
    V99::f(1);  // call V99
    f(1);       // call default version (V99)
}
```

How to Compile

Compile Methods

Method 1

Compile all files together (naive):

```
g++ -I include/ main.cpp source.cpp -o main.x
```

`-I` : Specify the **`include` path** for the project headers. `-isystem` : Specify the **`include` path** for system (external) headers (warnings are not emitted).

They can be used multiple times and are evaluated in order from left to right

Method 2

Compile each *translation unit* in a file object:

```
g++ -c -I include/ source.cpp -o source.o
```

```
g++ -c -I include/ main.cpp -o main.o
```

Link all file objects:

```
g++ main.o source.o -o main.x
```

C++ Libraries

A **library** is a package of code that is meant to be reused by many programs

A **static library** is a set of object files (just the concatenation) that are directly linked into the final executable. If a program is compiled with a static library, all the functionality of the static library becomes part of final executable

- A static library cannot be modified without re-link the final executable
- Increase the size of the final executable
- The linker can optimize the final executable (*link time optimization*)

Given the static library `my_lib`, the corresponding file is:

- Linux: `libmy_lib.a`
- Windows: `my_lib.lib`

A **dynamic library**, also called a **shared library**, consists of routines that are loaded into the application at run-time. If a program is compiled with a dynamic library, the library does not become part of final executable. It remains as a separate unit

- A dynamic library can be modified without re-link
- Dynamic library functions are called outside the executable
- Neither the linker, nor the compiler can optimize the code between shared libraries and the final executable
- The environment variables must be set to the right shared library path, otherwise the application crashes at the beginning

Given the shared library `my_lib`, the corresponding file is:

- Linux: `libmy_lib.so`
- Windows: `my_lib.dll` + `my_lib.lib`

Build Static/Dynamic Libraries

Static Library Creation

- Create object files for each translation unit (.cpp)
- Create the static library by using the **archiver** (**ar**) linux utility

```
g++ source1.c -c source1.o
g++ source2.c -c source2.o
ar rvs libmystaticlib.a source1.o source2.o
```

Dynamic Library Creation

- Create object files for each translation unit (.cpp). Since library cannot store code at fixed addresses the compile must generate *position independent code*
- Create the dynamic library

```
g++ source1.c -c source1.o -fPIC
g++ source2.c -c source2.o -fPIC
g++ source1.o source2.o -shared -o libmydynamiclib.so
```

Deal with Libraries

Specify the **library path** (path where search for static/dynamic libraries) to the compiler: `g++ -L<library_path> main.cpp -o main`

`-L` can be used multiple times (`/LIBPATH` on Windows)

Specify the **library name** (e.g. `liblibrary.a`) to the compiler:
`g++ -llibrary main.cpp -o main`

The full path on Windows instead

Deal with Libraries

Linux/Unix environmental variables:

- `LIBRARY_PATH` Specify the directories where search for *static* libraries `.a` at *compile-time*. Used by the compiler in order from left to right
- `LD_LIBRARY_PATH` Specify the directories where search for *dynamic/shared* libraries `.so` at *run-time*. Used by the program in order from left to right

Windows environmental variables:

- `LIBPATH` Specify the directories where search for *static* libraries `.lib` at *compile-time*. Used by the compiler in order from left to right
- `PATH` Specify the directories where search for *dynamic/shared* libraries `.dll` at *run-time*. Used by the program in order from left to right

Find Dynamic Library Dependencies

The `ldd` utility shows the shared objects (shared libraries) required by a program or other shared objects

```
$ ldd /bin/ls
	linux-vdso.so.1 (0x00007ffcc3563000)
	libselinux.so.1 => /lib64/libselinux.so.1 (0x00007f87e5459000)
	libcap.so.2 => /lib64/libcap.so.2 (0x00007f87e5254000)
	libc.so.6 => /lib64/libc.so.6 (0x00007f87e4e92000)
	libpcre.so.1 => /lib64/libpcre.so.1 (0x00007f87e4c22000)
	libdl.so.2 => /lib64/libdl.so.2 (0x00007f87e4a1e000)
	/lib64/ld-linux-x86-64.so.2 (0x00005574bf12e000)
	libattr.so.1 => /lib64/libattr.so.1 (0x00007f87e4817000)
	libpthread.so.0 => /lib64/libpthread.so.0 (0x00007f87e45fa000)
```

Find Object/Executable Symbols

The `nm` utility provides information on the symbols being used in an object file or executable file

```
$ nm -D -C something.so
    w __gmon_start__
    D __libc_start_main
    D free
    D malloc
    D printf

# -C:  Decode low-level symbol names
# -D:  accepts a dynamic library
```

readelf displays information about ELF format object files

```
$ readelf --symbols something.so | c++filt
    ... OBJECT  LOCAL  DEFAULT   17 __frame_dummy_init_array_
    ... FILE    LOCAL  DEFAULT  ABS prog.cpp
    ... OBJECT  LOCAL  DEFAULT   14 CC1
    ... OBJECT  LOCAL  DEFAULT   14 CC2
    ... FUNC    LOCAL  DEFAULT   12 g()

# --symbols: display symbol table
```

Find Object/Executable Symbols

`objdump` displays information about object files

```
$ objdump -t -C something.so | c++filt
... df *ABS*   ...  prog.cpp
...  O .rodata ...  CC1
...  O .rodata ...  CC2
...  F .text   ...  g()
...  O .rodata ...  (anonymous namespace)::CC3
...  O .rodata ...  (anonymous namespace)::CC4
...  F .text   ...  (anonymous namespace)::h()
...  F .text   ...  (anonymous namespace)::B::j1()
...  F .text   ...  (anonymous namespace)::B::j2()

# --t: display symbols
# -C:  Decode low-level symbol names
```

References and Additional Material

- 20 ABI (Application Binary Interface) breaking changes every C++ developer should know
- Policies/Binary Compatibility Issues With C++
- 10 differences between static and dynamic libraries every C++ developer should know