Modern C++ Programming

12. Translation Units

Federico Busato

University of Verona, Dept. of Computer Science
2020, v3.00

Table of Context

Basic Concepts

Translation Unit

Header File and Source File

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

Translation Unit

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

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

Local and Global Scopes

Scope

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

Local Scope

Variables that are declared inside a function or a block are called local variables (**local scope** or **block scope**)

Global Scope

Variables that are defined outside of all the functions and hold their value throughout the life-time of the program are global variables (**global scope** or **file scope**)

Local and Global Scopes

```cpp
int var1;       // global scope

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

struct A {
    int var3;   // local scope
}

int main() {
    int var4;   // local scope
}
```

Linkage

Linkage

Linkage

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

Internal Linkage

Internal linkage refers to every symbol visible only in scope of a *single* translation unit

Multiple definitions of an entity in multiple translation units is a violation of the *One Definition Rule* (see next slides), namely symbol name conflicts in the linking phase

External Linkage

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

`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 a one and only one translation unit

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

`static` Variable Example

To not confuse with symbol visibility

```cpp
#include <iostream>

void f() {
    static int val = 1;  // static
    val++;
}

int main() {
    std::cout << f(); // print 1
    std::cout << f(); // print 2
    std::cout << f(); // print 3
}
```

Internal/External Linkage Example

```cpp
int          var1 = 3;  // external linkage
                        // (in conflict with variable 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 (may conflict)
static f2() {}          // internal linkage
namespace {             // anonymous namespace
void   f3() {}          // internal linkage
}
extern void f4();       // external linkage
                        // (implemented in another translation unit)
int main() {}
```

Linkage of `const` and `constexpr`

`const` variable at global scope implies `static`
→ *internal linkage*

`constexpr` implies `const`, which implies `static`
→ *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() {}
```

Linkage of `inline` Functions/Variables

`inline`-declared functions and variables have *external linkage*. Multiple definitions of the same function do not break the ODR rule (allowed behavior)

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

`static`/*anonymous namespace-included* functions and variables have *internal linkage*

```
inline void f() {}  // external linkage

inline int var = 3; // external linkage (C++17)

static inline void g() {}  // internal linkage

static inline int var = 3; // internal linkage (C++17)
```

Summary

Internal Linkage:

- **Variables**: Local, `static`, `static inline`, `const`, `constexpr`
- **Functions**: `static`, `static inline`, `constexpr`
- Anonymous namespace content
- * Functions on Windows

External Linkage:

- **Variables**: Global, `inline`
- **Functions***: `extern`, `inline`, `template`
- `static` class data member (that are not `inline`)

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* Windows (MSVC) treats function visibility in a different way
`gcc.gnu.org/wiki/Visibility`

Variables Storage

Storage Class

Storage Class Specifier

A **storage class** for a variable declarations is a type **specifier** that governs the lifetime, the linkage, and memory location of objects

- A given object can have only one storage class
- Variables defined within a block have automatic storage unless otherwise specified

Storage Class	Keyword	Lifetime	Visibility	Init value
Automatic	`auto`*/no keyword	Code block	Local	Not defined
Register†	`register`	Code block	Local	Not defined
Static	`static`	Whole program	Local	Zero-initialized
External	`extern`	Whole program	Global	Zero-initialized
Thread Local*	`thread_local`	Thread execution	Thread	Zero-initialized

*C++11 † deprecated

Storage Class Examples

```
int                       v1;     // automatic
static                int v1 = 2; // static (global)
extern                int v3;     // external
thread_local          int v4;     // each thread has its own value
thread_local static int v5;     // each thread has its own value

int main() {
    int                 v6;     // automatic
    auto                v7 = 3; // automatic
    register int        v8;     // automatic (deprecated!)
    static int          v9;     // static (local)
    thread_local int    v10;    // automatic (each thread has its own value)

    auto array = new int[10]; // automatic
}
```

Storage Duration

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

Storage Duration	Keyword	Allocation	Deallocation
Automatic	`auto`/`no keyword`	Code block start	Code end start
Static	`static`, global scope variable, `extern`	Program start	Program end
Dynamic	`new`/`delete`	Memory allocation	Memory deallocation
Thread	`thread_local`	Thread start	Thread end

Full Story:
`http://en.cppreference.com/w/cpp/language/storage_duration`

Automatic storage duration. Scope variables (local variable). register or stack (depending on compiler, architecture, etc.). `register` hints to the compiler to place the object in the processor registers (deprecated in C++11)

Static storage duration. The storage for the object is allocated when the program begins and deallocated when the program ends (`static` keyword at local or global scope)

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. (`thread_local` can appear together with `static` or `extern`)

Dynamic storage duration. The object is allocated and deallocated per request by using dynamic memory allocation functions (`new/delete`)

Storage Duration Examples

```
int        v1;     // static duration
static int v2 = 4; // static duration
extern int v3;     // static duration

void f() {
    int        v4;            // automatic duration
    auto       v5 = 3;        // automatic duration
    static int v6;            // static duration
    auto array = new int[10]; // dynamic duration (allocation)
} // array, v1, v2, v3, v6 variables deallocation (from stack)
  // the memory associeted with "array" is not deallocated!!

int main() {
    auto array = new int[10]; // dynamic duration (allocation)
    delete[] array;           // dynamic duration (deallocation)
}
// main end: v1, v2, v3, v6 deallocation
```

Dealing with Multiple Translation Units

One Definition Rule (ODR)

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

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

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

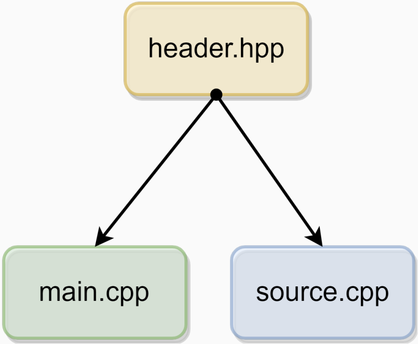
- *Multiple definitions linking error* otherwise
- `Entities` with *internal linkage* in different translation units are allowed, even if their names and types are the same

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

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

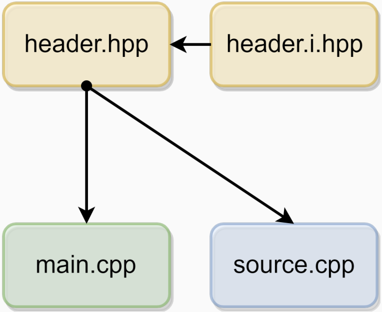
One Definition Rule - Code Structure 1

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



One Definition Rule - Code Structure 2

- two headers, two source files → 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 allows to better organize the code

One Definition Rule (Example, points (1), (2))

header.hpp:

```cpp
void f();
```

main.cpp:

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

// internal linkage
int        a = 1;
static int b = 2;

// external linkage
extern int c;

int main() {
    std::cout << b;  // print 2
    std::cout << c;  // print 4
    f();             // print 5
}
```

source.cpp:

```cpp
#include "header.hpp"
#include <iostream>
// linking error !!
// (multiple definitions)
// int      a = 2;
static int b = 5;  // ok


int c = 4;  // ok

void f() {          // definition
    std::cout << b; // print 5
}
```

One Definition Rule (Example, point (3)) 1/2

header.hpp:

```cpp
inline void f() {} // the function is inline (no linking error)

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:

```cpp
#include "header.hpp"

int main() {
   f();
   g(3);
}
```

source.cpp:

```cpp
#include "header.hpp"

void h() {
    f();
    g(3);
}
```

Correct organization:

header.hpp:

```cpp
inline void f();    // declaration
inline int gvalue; // declar. (C++17)

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 gvalue = 3;     // def. (C++17)

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

main.cpp:

```cpp
#include "header.hpp"

int main() {
    f();
    g(3);
}
```

source.cpp:

```cpp
#include "header.hpp"

void h() {
    f();
    g(3);
}
```

Class in Multiple Translation Units

header.hpp:

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

main.cpp:

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

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

source.cpp:

```cpp
#include "header.hpp"

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

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

Class in Multiple Translation Units 2/2

header.hpp:

```cpp
struct A {
    int x1;
    int x2 = 3;
    int x3 { 4 };

    static int y;
//  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 initilized

    static const int w1;
    static const int w2 = 4; // inline
//                              definition
};
```

source.cpp:

```cpp
#include "header.hpp"

int        A::x1 = 1;
int        A::y  = 2;
const int  A::w1 = 3;
```

ODR Common Errors (Classes)

header.hpp:

```cpp
struct A {
    void f() {};  // declaration/definition inside struct (correct)
    void g();     // declaration
    void h();     // declaration
};

void A::g() {}    // definition (wrong)!! multiple definitions
```

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
}
```

Global Constants

header.hpp:

```
#include <iostream>
struct A {
    A()  { std::cout << "A()";  }
    ~A() { std::cout << "|$\sim$|A()"; }
};

// A            obj;        // linker error!! multiple definitions
const A         const_obj;  // "const" implies static (as "constexpr")
constexpr float PHI = 3.14f;
```

source1.cpp:

```
#include "header.hpp"

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

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

source2.cpp:

```
#include "header.hpp"

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

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

Function Template

Function Template - Case 1

header.hpp:

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

#include "header.i.hpp"
```

header.i.hpp:

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

Function Template Specialization - Case 2

header.hpp:

```
template<typename T>
void f(T x);    // only declaration
```

main.cpp:

```
#include "header.hpp"

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

source.cpp:

```
#include "header.hpp"

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

// template specialization
template void f<int>(int y);
template void f<float>(float y);
```

Function Template Specialization - Case 3

header.hpp:

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

template<>
void f<int>(); // inform the specialization exists in
               // another translation unit (mandatory)

// extern void f<int>(); // alternative form
```

source.cpp:

```cpp
#include "header.hpp"

template<>
void f<int>(int x) {}  // definition
```

ODR Common Errors (Function Templates)

header.hpp:

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

// template<>        // linking error
// void f<int>() {}  //  (multiple definitions) included twice
                     // full specializations are standard functions
```

main.cpp:

```cpp
#include "header.hpp"

int main() {
//  f<int>(); // linking error
}  // f<int>() is not defined here
```

source.cpp:

```cpp
#include "header.hpp"

template<typename T>
void f() {}
// error: valid only in this
// translation unit!!

void g() {
    f<char>();   // ok
}
```

Class Template

Class Template

header.hpp:

```
template<typename T>
strut A {
    T    x;    // declaration
    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() {}
```

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 Specialization

header.hpp:

```
template<typename T>
strut A {
    T    x;    // declaration
    void f();  // declaration
}
```

main.cpp:

```
#include "header.hpp"

int main() {
    A<int>  a1; // ok
//  A<char> a2; // compile error!!
}
```

source.cpp:

```
#include "header.hpp"

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

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

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

Undefined Behavior and Summary

Undefined Behavior - Example 1

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 can *inline* `f()` in `g()`, so now `g()` return 7

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

Solution: `static` functions (or `anonymous namespace`)

Undefined Behavior - Example 2

main.cpp:

```cpp
#include <iostream>
template<typename T>
struct A {
    int f();
};
int g();

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

source1.cpp:

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

template class A<int>;
```

source2.cpp:

```cpp
template<typename T>
struct A {
    int f() { return 5; }
};
int g() {
    A<int> a; return a.f();
}
```

Other ODR violations are even harder (if not impossible) to find, e.g. `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

Summary

- **header:** *declaration* of
  - structs/classes/types/alias
  - functions
  - `template` function/structs/classes
  - `extern` variables/functions
  - global `const`/`constexpr` variables
- **header implementation:** *definition* of
  - `inline` functions/variables
  - `template` functions/classes
- **source file:** *definition* of
  - functions
  - `templates` full specialization (function/class)
  - `static` global variables (+ declaration)
  - `extern` variables/functions

`#include` Issues

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 used

Functions and **Classes** have external linkage by default

main.cpp:

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

class B {
    A* a;   // ok, A* is declared
//  A  b;   // compiler error!! no definition (incomplete type)
};          // e.g. the compiler is not able to deduce the size of A
int main() {
    f();   // ok, f() is a function and not a variable
//  A a;   // compiler error!! no definition (incomplete type)
}
```

source.cpp:

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

Forward Declaration 2/2

Advantages:

- Forward declarations can save compile time, as `#include` force 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

Full Story:
`google.github.io/styleguide/cppguide.html#Forward_Declarations`

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
```

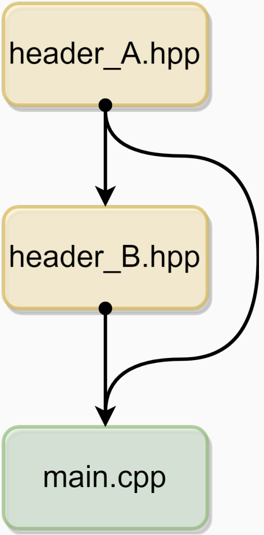
`#pragma once` preprocessor directive is an alternative to the the **include guard** to force current file to be included only once in a translation unit

- **#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

Include Guard

Common case:



header_A.hpp:

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

struct A {
};
```

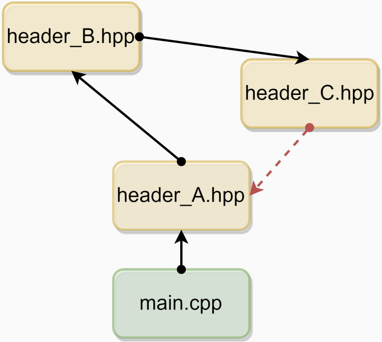
header_B.hpp:

```
#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"
}
```

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:

```
#pragma once
#include "header_B.hpp"

class A {
    B* b;
};
```

header_B.hpp:

```
#pragma once
#include "header_C.hpp"

class B {
    C* c;
};
```

header_C.hpp:

```
#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"
};
```

header_A.hpp:

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

header_B.hpp:

```
#pragma once
class C;   // forward declaration

class B {
   C* c;
};
```

header_C.hpp:

```
#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 are included
  - Break circular dependencies with forward declarations

- `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. Static Methods

Namespace functions:

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

Static methods:

- Can interact with static data members
- Struct/Class cannot be extended outside their declarations

Static methods should define operations strictly related to object definition, otherwise *namespace* should be preferred

Defining a Namespace

```
#include <iostream>

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

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

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

Namespace Conflits

```
#include <iostream>
using namespace std;
void f() {
     cout << "global" << endl;
}

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

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

    using namespace ns1;
//  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

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

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:

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

Namespace Scope

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

namespace ns1 {
    void g() {}     // ok
//  void f() {}     // compile error!! function name conflict with
}                   //                 header.hpp: "ns1::f()"

int main() {
   ns1::f();        // ok, print "ns1::f()"
   ns1::ns2::f();   // ok, print "ns1::ns2::f()"
   using namespace ns1::ns2;
   g();             // ok, print "ns1::ns2::g()"
}
```

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"; }
}           // exteranl linkage, but
            // visible only internally
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` namespaces 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 Strategies

Method 1

Compile all files together (naive):

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

Specify the **`include` path** to the compiler: **`-I`**

`-I` can be used multiple times

Method 2

Compile each *translation unit* in a file object:

```
g++ -c -Iinclude source.cpp -o source.o
```

```
g++ -c -Iinclude main.cpp -o main.o
```

Link all file objects:

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

see CMake in "Debugging and Tools" lecture

C++ Libraries

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

A **static library (`.a`)** consists of routines that are compiled and linked directly into your program. If a program is compiled with a static library, all the functionality of the static library becomes part of your executable

- A static library cannot be modified without re-compile
- Increase the size of the binary

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

- A dynamic library can be modified without re-compile
- Dynamic library functions are called outside the executable

Compile 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

Specify the **library name** (e.g. `liblibrary.a`) to the compiler:

```
g++ -llibrary main.cpp -o main
```

Linux/Unix Environmental variables:

- `LIBRARY_PATH` Specify the directories where search for *static* libraries at *compile-time*. Used by the compiler
- `LD_LIBRARY_PATH` Specify the directories where search for *dynamic/shared* libraries at *run-time*. Used by the program

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
```

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 --defined-only -g -D something.so
    w __gmon_start__
    D __libc_start_main
    D free
    D malloc
    D printf

# --defined-only: only defined symbols
# -g:             only external symbols
# -D:             accepts a dynamic library
```

References and Additional Material

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