Modern C++ Programming

11. Translation Units I

Linkage and One Definition Rule

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Basic Concepts

Translation Unit

Header File and Source File

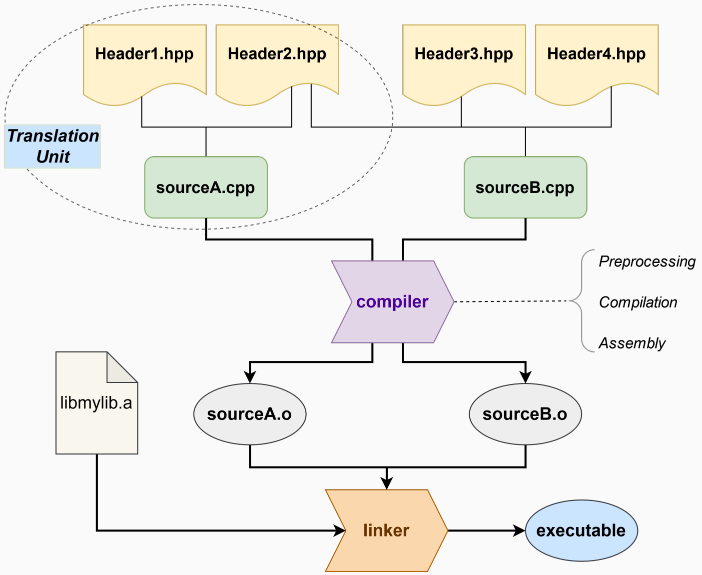
Header files allow to define interfaces (`.h`, `.hpp`, `.hxx`), while keeping the implementation in separated **source files** (`.c`, `.cpp`, `.cxx`).

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 all functions.

They hold a single memory location throughout the life-time of the program

Local and Global Scope

```
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 (visible/accessible) *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 block end
Static	Program start	Program end
Dynamic	Memory allocation	Memory deallocation
Thread	Thread start	Thread end

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

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 `var` decl.	Local	*automatic*	*No linkage*
no storage class	global `var` decl.	Global	*static*	*External*
`static`		Local	*static*	*Function Dependent*
`static`		Global	*static*	*Internal*
`extern`		Global	*static*	*External*
`thread_local`	C++11	any	*thread local*	*any*

Storage Class Examples

```
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 ends

```
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` Variables

Linkage of `const` and `constexpr` Variables

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

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

note: the same variable has different memory addresses on different translation units (code bloat)

```
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

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

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

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

main.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**

- `static` local variable address depends on the linkage of its function

Internal Linkage:

(not accessible by other translation units, no conflicts, different memory addresses)

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

External Linkage:

(accessible by other translation units, potential conflicts, same memory address)

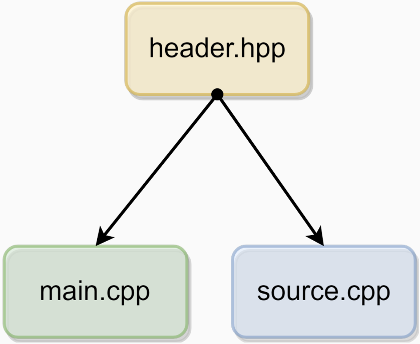
- **Global Variables**:
  - `no specifier`, or `extern`
  - `template/specialized` C++14 (no conflicts for `template`, see ODR)
  - `inline` `const` / `constexpr` C++17 (no conflicts, see ODR)
- **Functions**:
  - `no specifier` (no conflicts with `inline`, see ODR), or `extern`
  - `template/specialized` (no conflicts for `template`, see ODR)

  Note: `inline`, `constexpr` (which implies `inline` for functions) functions are not accessible by other translation units even with *external linkage*
- **Enumerators**, **Classes** and their *static, non-static* members

Dealing with Multiple Translation Units

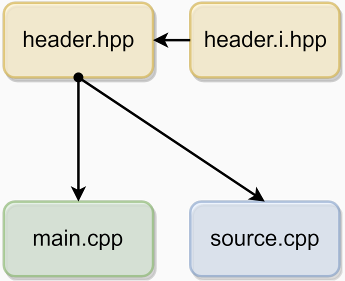
Code Structure 1

- 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:

```
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:

```
#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 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

ODR - 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 - ODR Point (2)

header.hpp:

```cpp
#include <iostream>
struct A {
    A()  { std::cout << "A()";  }
    ~A() { std::cout << "~A()"; }
};
// A           obj;        // linking error multiple definitions, Point (2)
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!!
```

Common Class Error - ODR Point (2)

header.hpp:

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

main.cpp:

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

int main() {}
```

source.cpp:

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

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

ODR - Point (3)

ODR Point (3): A `template`, `type`, or `inline functions/variables`, can be defined in more than one translation unit

- The linker removes all definitions of an `inline` / `template` entity except one
- All definitions must be identical to avoid undefined behavior due to arbitrary linking order
- `inline` / `template` entities have a *unique memory address* across all translation units
- `inline` / `template` entities have the *same linkage* as the corresponding variables/functions without the specifier

`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` entities cannot be *exported*, namely, used by other translation units even if they have *external linkage* (related warning: `-Wundefined-inline`)
- `inline` doesn't mean that the compiler is forced to perform function *inlining*. It just increases the optimization heuristic threshold

```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

constexpr and inline

`constexpr` functions are implicitly `inline`

`constexpr` variables are not implicitly `inline`. C++17 added `inline` variables

```
void                f1() {}  // external linkage
                             // potential multiple definitions error

constexpr void      f2() {}  // external linkage, implicitly inline
                             // multiple definitions allowed

constexpr int       x = 3;   // internal linkage
                             // different files allows distinct definitions
                             // -> different addresses, code bloat

inline constexpr int y = 3;  // external linkage unique memory address
                             // -> potential undefined behavior
int main() {}
```

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:

```
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:

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

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

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
}
```

ODR - 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:

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

main.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:

```
#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:

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

main.cpp:

```
#include "header.hpp"

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

source.cpp:

```
#include "header.hpp"

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

Function Template - extern Keyword

C++11

header.hpp:

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

main.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:

```
#include "header.hpp"

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

ODR Function Template Common Error

header.hpp:

```cpp
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:

```cpp
#include "header.hpp"

int main() {}
```

source.cpp:

```cpp
#include "header.hpp"

// some code
```

ODR - 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:

```
#include <iostream>

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

int g();
```

main.cpp:

```
#include "header.hpp"

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

source.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 included all files in a single translation unit

ODR - Declarations and Definitions Summary

- **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