

Modern C++ Programming

13. TRANSLATION UNITS I

LINKAGE AND ONE DEFINITION RULE

Federico Busato

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Basic Concepts

Translation Unit

Header File and Source File

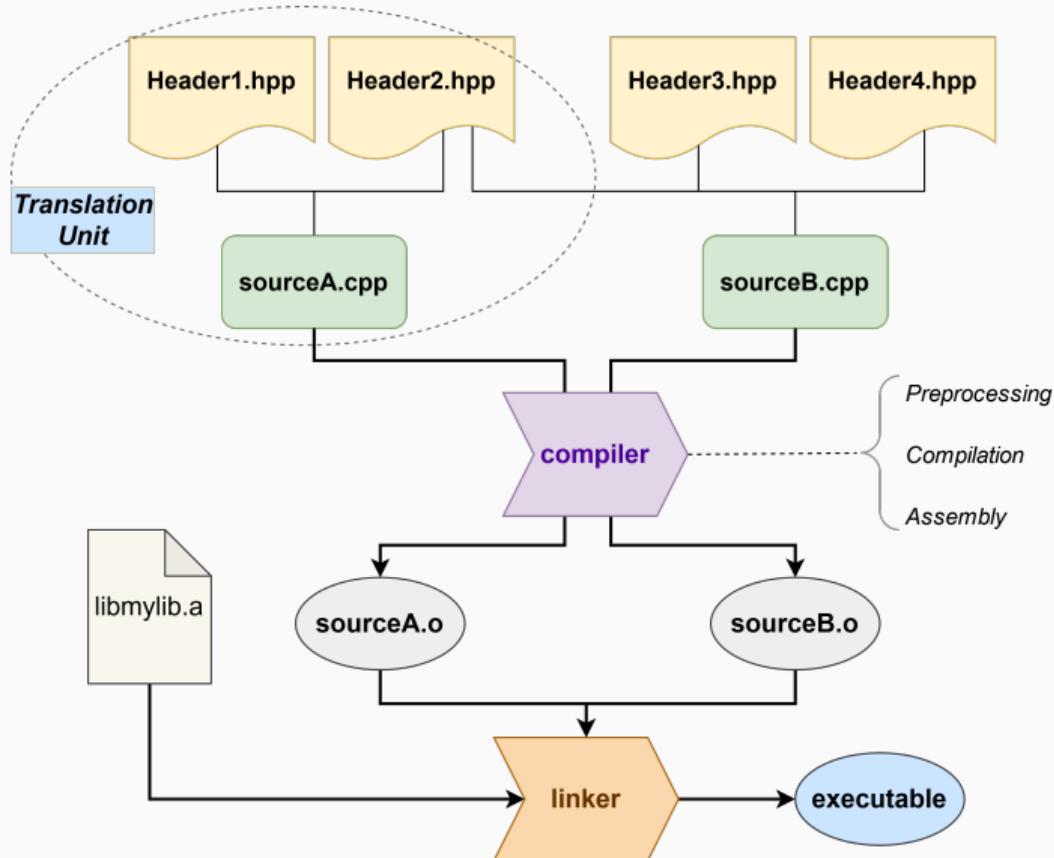
Header files allow defining interfaces (.h, .hpp, .hxx), while keeping the implementation in separated **source files** (.c, .cpp, .cxx).

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. The *final program or library* is the combination of all translation units

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

Symbols

Symbols are named items (identifiers) in a program and they refer to entities such as variables, functions, classes

Linkage

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

There are three ways to link symbols:

- *No linkage*
- *Internal linkage*
- *External linkage*

Linkage

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 accessible 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 symbols that are accessible *outside* a single translation unit. Symbols with external linkage have an *unique memory address* through the whole program. The same name in different translation units causes conflicts.

Visibility

Symbol visibility determines whether a symbol is exported from a shared library or executable, making it available for dynamic linking.

The symbol table holds information about these symbols, including their names, addresses, linkage, and visibility.

Visibility attributes:

default The symbol is visible to external binaries and can be linked against.

hidden The symbol is not visible to external binaries; it is only accessible within the defining component.

Multiple libraries that export symbols with the same name could potentially cause undefined behavior at runtime.

Symbol visibility and *linkage* are related but distinct concepts.

- Symbols with *internal linkage* cannot be exported (*hidden visibility*).
- Symbols with *external linkage* are exported if they have *default visibility*.

GCC/Clang Default visibility: `default`. The compilers allow the opposite behavior with `-fvisibility=hidden`.

MSVC Default visibility: `hidden`.

Additionally, it is possible to control individual symbol visibility:

```
__attribute__((visibility("hidden")))
void internal_function(); // GCC/Clang           __declspec(dllexport) // MSVC
                           void exported_function();

__attribute__((visibility("default")))
int exported_variable = 3;          __declspec(dllimport)
                                     void imported_function();
```

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

- **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
<i>no storage class</i>	local <code>var</code> decl.	Local	<i>automatic</i>	<i>No linkage</i>
<i>no storage class</i>	global <code>var</code> decl.	Global	<i>static</i>	<i>External</i>
<code>static</code>		Local	<i>static</i>	<i>Function Dependent</i>
<code>static</code>		Global	<i>static</i>	<i>Internal</i>
<code>extern</code>		Global	<i>static</i>	<i>External</i>
<code>thread_local</code>	C++11	any	<i>thread local</i>	<i>any</i>

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)
}
```

static Keyword for Local 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 Keyword for Global Variables

static global variables or functions are visible only within the translation unit where they are declared → *internal linkage*

- Non-**static** global variables or functions with the same name in different translation units produce *name collision* (or name conflict) → multiple definitions at link-time

```
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)

void     f1() {} // external linkage (could conflict)

static void f2() {} // internal linkage
```

A namespace with no identifier is called **unnamed/anonymous namespace**

Entities within an anonymous namespace have *internal linkage* and, therefore, are used for declaring unique identifiers, visible only in the same source file

Anonymous namespace vs. global static functions/variables:

- Entities within an *anonymous namespace* have the same properties of `static` declarations at global scope
- In addition, *anonymous namespaces* allow *type declarations* and *class definitions*
- *Anonymous namespaces* are less verbose than `static` variables/functions but, entities within an *anonymous namespace* are less visible if the scope contains many lines

Anonymous Namespace

2/2

```
main.cpp  
#include <iostream>
```

```
namespace { // anonymous, internal linkage
```

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

```
using my_int = int; // not possible  
                  // with 'static'  
} // namespace
```

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

```
source.cpp  
#include <iostream>
```

```
namespace { // anonymous, internal linkage
```

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

```
using my_int = unsigned; // no conflicts  
} // namespace
```

```
int g() {  
    f(); // print "source", no conflicts  
}
```

extern Keyword

`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

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

External Linkage Example

```
int      var1 = 3; // external linkage
           // (in conflict with variables in other
           // translation units with the same name)

extern int var3;    // external linkage
                   // (implemented in another translation unit)

void     f1() {}   // external linkage (could conflict)

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() {}
```

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)

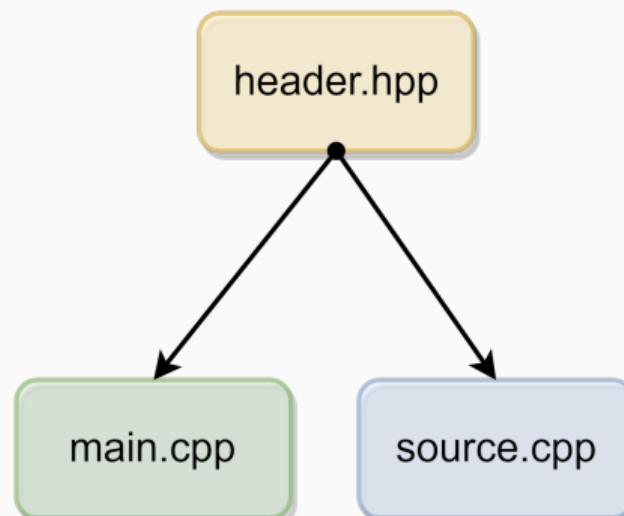
Note: `inline`, `constexpr` (which implies `inline` for functions) functions are not accessible by other translation units even with *external linkage*

- **Enumerators, Classes** and their *static, non-static* members

Dealing with Multiple Translation Units

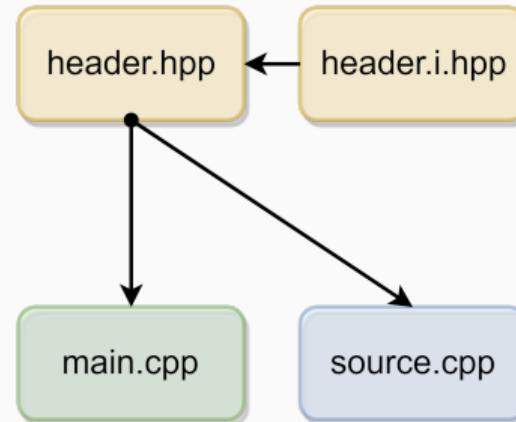
Code Structure 1

- one header, two source files → two translation units
- *the header is included in both translation units*



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 could help to better organize the code

Class in Multiple Translation Units

1/2

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::y = 2;  
// int A::x = 1; // non-static data member  
//                                     cannot be defined out-of-line
```

Class in Multiple Translation Units

2/2

header.hpp:

```
struct A {  
    static int      y1;      // zero-init  
// static int      y2 = 3; // compile error  
//           must be initialized out-of-class  
    inline static int y3 = 4; // inline initialization  
  
    const int z = 3; // C++11 and later  
// 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::y1 = 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:

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

main.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:

```
#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:

```
#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:

```
#include "header.hpp"

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

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

source2.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

`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

```
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)

1/2

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"
```

main.cpp:

```
#include "header.hpp"  
  
int main() {  
    f();  
    g(3); // g<int> generated  
}
```

header.i.hpp:

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

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

source.cpp:

```
#include "header.hpp"  
  
void h() {  
    f();  
    g(5); // g<int> generated  
}
```

ODR - Function Template

Function Template - Case 1

header.hpp:

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

main.cpp:

```
#include "header.hpp"

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

source.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 INSTANTIATION
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>();'
```

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
```

ODR - Class Template

Class Template - Case 1

header.hpp:

```
template<typename T>
struct A {
    T           x = 3; // "inline" DEFINITION
    static inline T y = 3; // "inline" DEFINITION (C++17)
    void         f() {}; // "inline" 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 2

header.hpp:

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

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

main.cpp:

```
#include "header.hpp"

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

header.i.hpp:

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

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

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:

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

main.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:

```
#include "header.hpp"

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

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

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

Class Template - extern Keyword

C++11

header.hpp:

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

source.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:

```
#include "header.hpp"

// template INSTANTIATION
template class A<int>;
// or any instantiation of A<int>
```

ODR Undefined Behavior and Summary

Undefined Behavior - inline Function

main.cpp:

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

void g();

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

source.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 a;
    return a.f();
}
```

Undefined Behavior - Function Template

header.hpp:

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

int g();
```

main.cpp:

```
#include "header.hpp"

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

source.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 -fplt` 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

Declarations and Definitions in Header and Source Files Summary

Declarations

Declarations: entities can be *declared* multiple times as long as all declarations are equivalent

Declarations are typically used in

Header As interface to expose symbols of one or more source files

Source File Directly make available external symbols in the current source file

Definitions in Headers

- ✓ `inline` variables/functions
- ✓ `template` variables/functions/structs/classes
- ✓ `const/constexpr` variables and `constexpr` functions
 - Should be marked `inline` in C++17
- ⚠ `static` or entities in *anonymous namespace* → binary bloating
- ✗ *non-inline, non-template, non-specialized* variables/functions/structs/classes
→ multiple definitions

Entities intended to be **exported**:

- ✓ *non-inline/ extern* functions/variables
- ✓ structs/classes
- ✓ *template , in particular full specialized* functions/variables/structs/classes
- ✗ *inline* variables/functions → potential conflicts/undefined behavior
- ✗ *static /anonymous namespace* variables/functions → not visible externally

Entities that are **internal only**:

- ✓ Any entity marked *static* or in an *anonymous namespace*
- ✓ *const/constexpr* variables and *constexpr* functions
- ✗ Any other entity → multiple definitions/undefined behavior