

Compiling, linking issues

- Inclusion nightmare and compile time
- How to reduce included files
- PIMPL
- Fast PIMPL
- Template code blow
- Linking C and C++ together
- Order of linking issues
- Static initialization/destruction problem

Header files

- Good for defining interface
- Good for breaking circular dependencies
- Necessary for templates
- Increase compile time
- Break OO principles

Header files

```
#include <iostream>
#include <ostream>
#include <list>
// none of A, B, C, D, E are templates
// Only A and C have virtual functions

#include "a.h"      // class A
#include "b.h"      // class B
#include "c.h"      // class C
#include "d.h"      // class D
#include "e.h"      // class E

class X : public A, private B
{
public:
    X( const C&);
    B  f(int, char*);
    C  f(int, C);
    C& g(B);
    E  h(E);
    virtual std::ostream& print(std::ostream&) const;
private:
    std::list<C>    clist_;
    D               d_;
};
```

Header files

- Remove `<iostream>`. People automatically include `<iostream>`, even if input functions never used.
- Replace `<ostream>` with `<iosfwd>`. Parameters and return types only need to be forward declared. Because `ostream` is `basic_ostream<char>` template, it is not enough to declare.
- Replace "e.h" with forward declaration of class E.
- Leave "a.h" and "b.h": we need a full declaration of the base classes in case of inheritance. The compiler must know the size of bases, whether functions are virtual or not.
- Leave "c.h" and "d.h": `list<C>` and D are private data members of X.

Header files v2

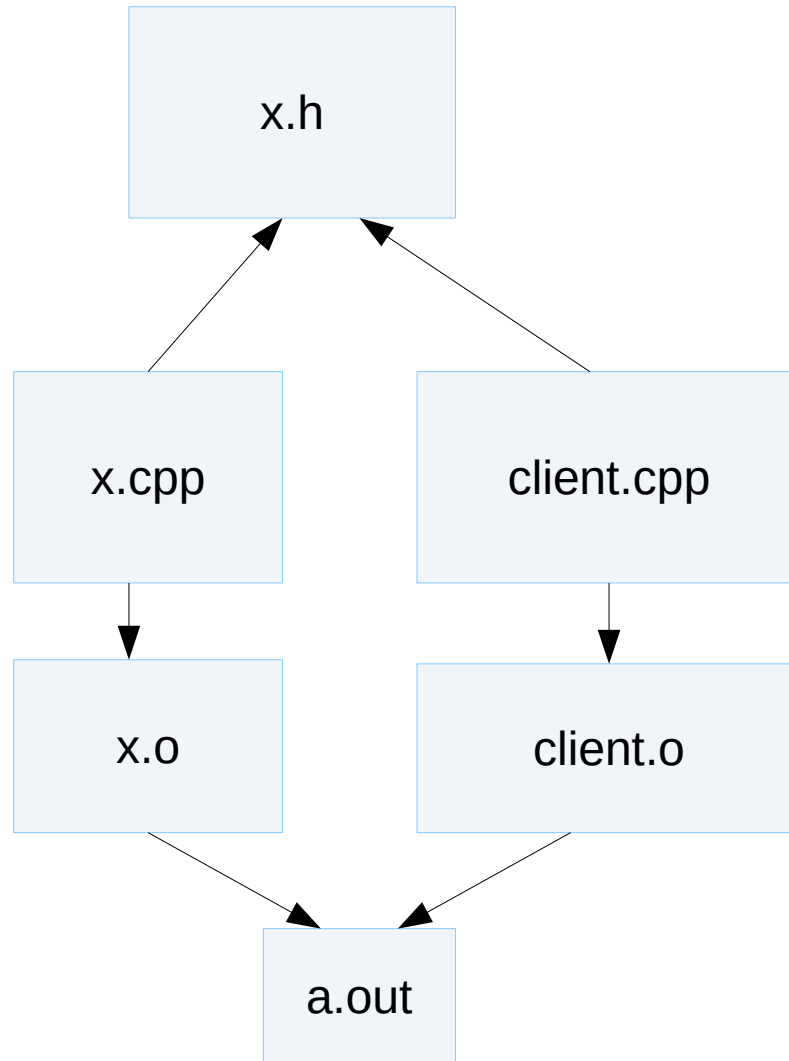
- ```
#include <iosfwd>
#include <list>
// none of A, B, C, D, E are templates
// Only A and C have virtual functions

#include "a.h" // class A
#include "b.h" // class B
// #include "c.h" // class C DEPENDS!
#include "d.h" // class D

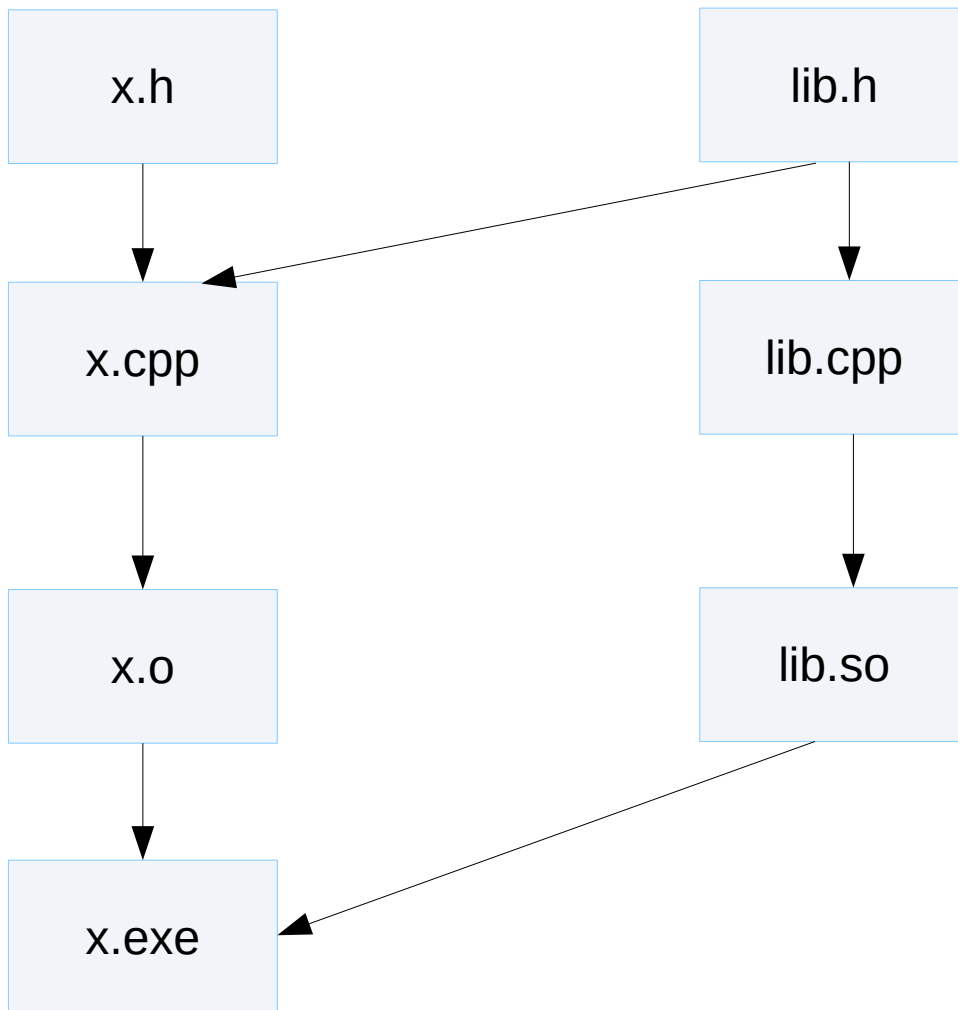
class C; class E; // forward declaration

class X : public A, private B
{
public:
 X(const C&);
 B f(int, char*);
 C f(int, C);
 C& g(B);
 E h(E);
 virtual std::ostream& print(std::ostream&) const;
private:
 std::list<C> clist_;
 D d_;
};
```

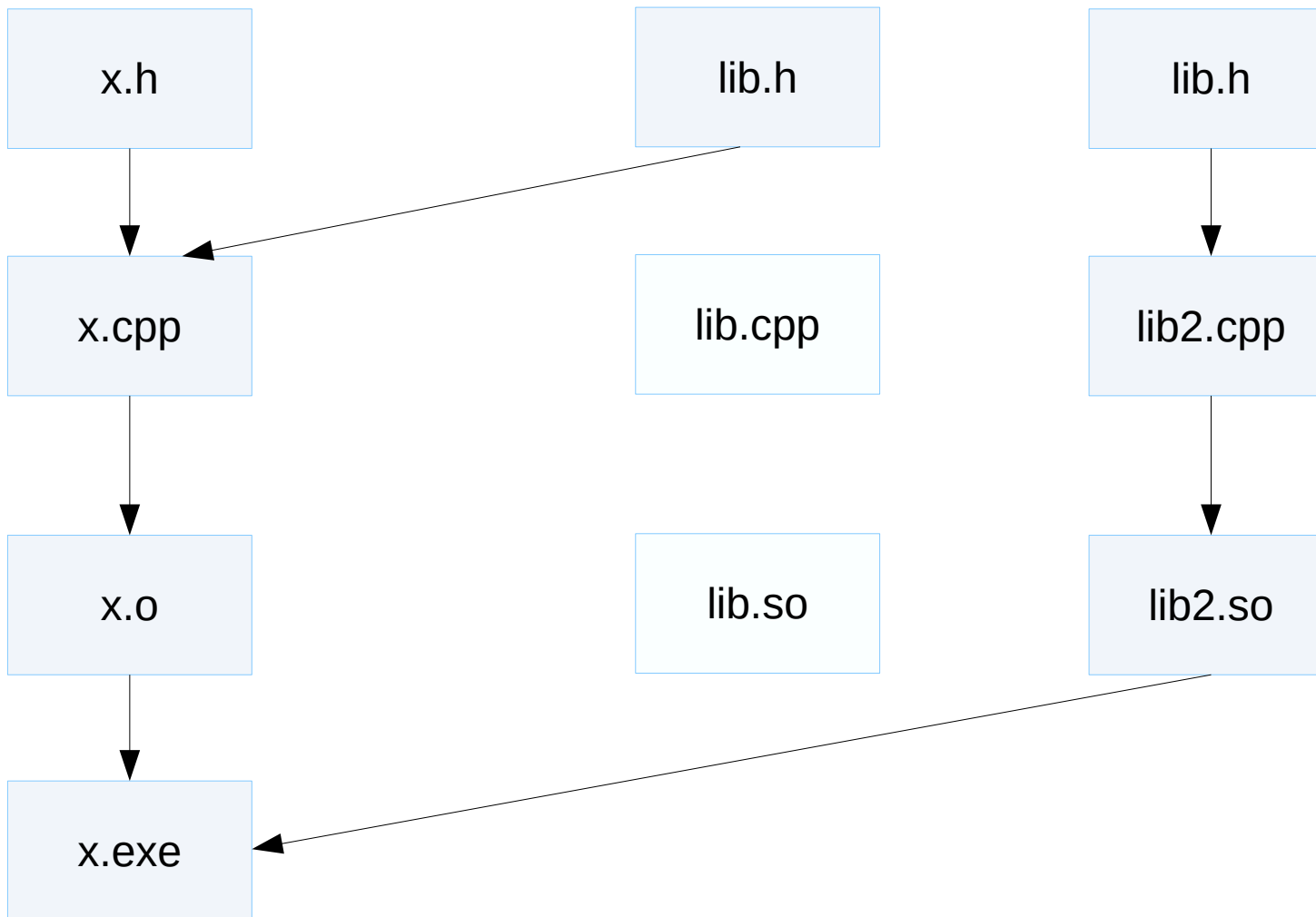
# PIMPL



# Binary compatibility

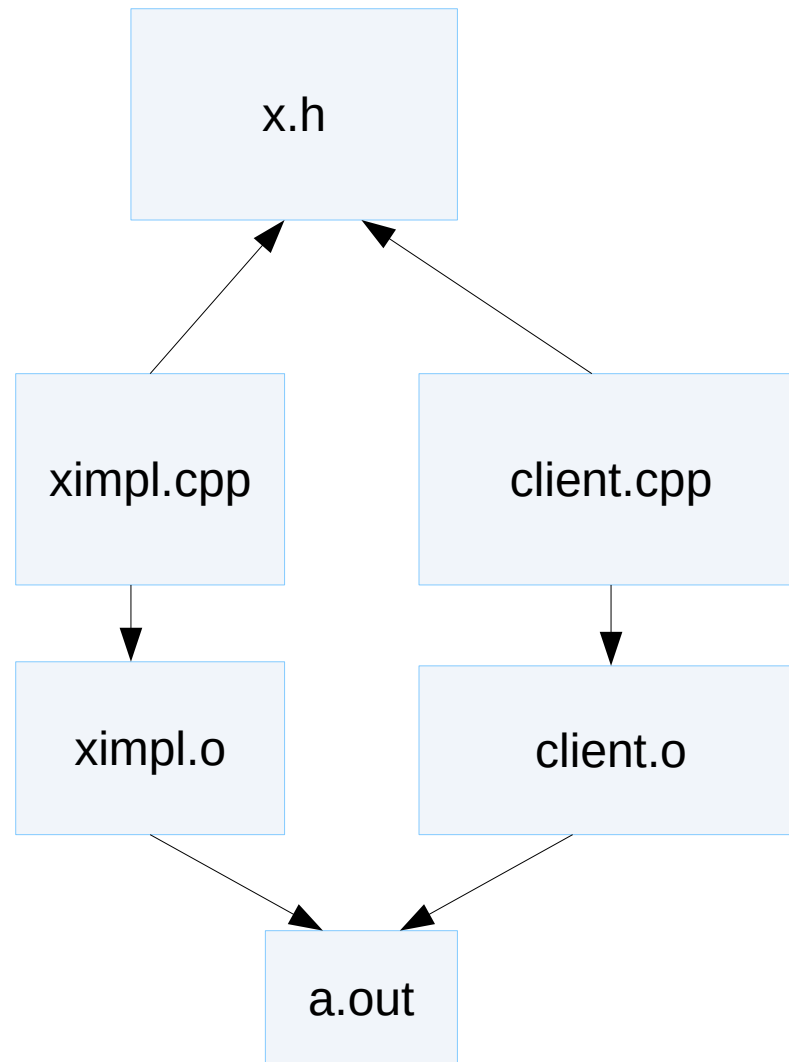


# Binary compatibility





# PIMPL



# PIMPL

```
// file x.h
class X
{
 // public and protected members
private:
 // pointer to forward declared implementation class
 struct XImpl;
 XImpl *pimpl_; // opaque pointer
};
```

```
// file ximpl.cpp
struct XImpl // not necessary to declare as "class"
{
 // private members; fully hidden
 // can be changed without recompiling clients
};
```

# PIMPL

```
#include <iosfwd>
#include "a.h" // class A
#include "b.h" // class B
class C;
class E;
class X : public A, private B
{
public:
 X(const C&);
 B f(int, char*);
 C f(int, C);
 C& g(B);
 E h(E);
 virtual std::ostream& print(std::ostream&) const;
private:
 struct Ximpl;
 Ximpl *pimpl_; // opaque pointer to forward-declared class
};

// file x.cpp
#include "x.h"
#include "c.h" // class C
#include "d.h" // class D
#include <list>
struct Ximpl
{
 std::list<C> clist_; // class list<C> and D is hidden
 D d_;
};
```

# PIMPL with unique\_ptr

```
// file x.h
class X
{
public:
 X();
private:
 // pointer to forward declared class
 struct XImpl;
 std::unique_ptr<XImpl> pimpl_; // opaque pointer
};
```

```
// file ximpl.cpp
struct X::XImpl // not necessary to declare as "class"
{
 XImpl() { ... }
 // can be changed without recompiling clients
};

X::X() : pimpl_(std::make_unique<XImpl>()) {}
```

# PIMPL with unique\_ptr

```
#include "x.h"
```

```
X xObj; // Error: incomplete type!
```

# PIMPL with unique\_ptr

- ```
// file x.h
class X
{
public:
    X();
    // ~X() { } compiler generated
private:
    // pointer to forward declared class
    struct XImpl;
    std::unique_ptr<XImpl> pimpl_; // opaque pointer
};

// file ximpl.cpp
struct X::XImpl // not necessary to declare as "class"
{
    XImpl() { ... }
    // can be changed without recompiling clients
};

X::X() : pimpl_(std::make_unique<XImpl>()) {}
```

PIMPL with unique_ptr

- ```
// file x.h
class X
{
public:
 X();
 ~X(); // declaration only!
private:
 // pointer to forward declared class
 struct XImpl;
 std::unique_ptr<XImpl> pimpl_; // opaque pointer
};

// file ximpl.cpp
struct X::XImpl // not necessary to declare as "class"
{
 XImpl() { ... }
 // can be changed without recompiling clients
};

X::X() : pimpl_(std::make_unique<XImpl>()) {}
X::~~X() {} // definition, also works: X::~~X() = default
```

# PIMPL with unique\_ptr

```
// file x.h
class X
{
public:
 X();
 ~X();
 X(X&& rhs);
 X& operator=(X&& rhs);
private:
 // pointer to forward declared class
 struct XImpl;
 std::unique_ptr<XImpl> pimpl_; // opaque pointer
};

// file ximpl.cpp
X::X() : pimpl_(std::make_unique<XImpl>()) {}
X::~~X() = default;
X::X(X&& rhs) = default;
X& X::operator=(X&& rhs) = default;
```



# PIMPL with unique\_ptr

```
// file x.h
class X
{
public:
 X();
 ~X();
 X(X&& rhs);
 X& operator=(X&& rhs);
 X(const X& rhs);
 X& operator=(const X& rhs);
private:
 // pointer to forward declared class
 struct XImpl;
 std::unique_ptr<XImpl> pimpl_; // opaque pointer
};

// file ximpl.cpp
X::X(const X& rhs) : pimpl_(std::make_unique<XImpl>(*rhs.pImpl_) {}
X& X::operator=(const X& rhs){ *pImpl_ = *rhs.pImpl_; return *this; }
```

# Removing inheritance(?)

```
#include <iosfwd>
#include "a.h" // class A
class B;
class C;
class E;
class X : public A // ,private B
{
public:
 X(const C&);
 B f(int, char*);
 C f(int, C);
 C& g(B);
 E h(E);
 virtual std::ostream& print(std::ostream&) const;
private:
 struct XImpl;
 XImpl *pimpl_; // opaque pointer to forward-declared class
};
// file x.cpp
#include "x.h"
#include "b.h" // class B
#include "c.h" // class C
#include "d.h" // class D
#include <list>
struct Ximpl
{
 B b_; // delegate
 std::list<C> clist_;
 D d_;
};
```

# Fast PIMPL

```
// file x.h
class X
{
 // public and protected members
private:
 static const size_t XImplSize = 128; // estimation
 char ximpl_[XImplSize]; // instead of opaque pointer
};

// file ximpl.cpp
struct XImpl // not necessary to declare as "class"
{
 XImpl(X *tp) : _self(tp) {
 static_assert (XImplSize >= sizeof(XImpl));
 // ...
 };
 X *_self; // might be different than XImpl::this
};
X::X() { new (ximpl_) XImpl(this); }
X::~X() { (reinterpret_cast<XImpl*>(ximpl_)->~XImpl()); }
```

# Fast PIMPL

```
// file x.h
class X
{
 // public and protected members
private:
 static const size_t XImplSize = 128;
 alignas(std::max_align_t) char ximpl_[XImplSize];
};

// file ximpl.cpp
struct XImpl // not necessary to declare as "class"
{
 XImpl(X *tp) : _self(tp) {
 static_assert (XImplSize >= sizeof(XImpl));
 // ...
 };
 X *_self; // might be different than XImpl::this
};
X::X() { new (ximpl_) XImpl(this); }
X::~X() { (reinterpret_cast<XImpl*>(ximpl_)->~XImpl()); }
```

# Template code blow

- Templates are instantiated on request
- Each different template argument type creates new specialization
  - Good: we can specialize for types
  - Bad: Code is generated for all different arguments
  - All template member functions are templates

# Template code blow

```
template <class T>
class matrix
{
public:
 int get_cols() const { return cols_; }
 int get_rows() const { return rows_; }
private:
 int cols_;
 int rows_;
 T *elements_;
};

matrix<int> mi;
matrix<double> md;
matrix<long> ml;
```

# Template code blow

```
class matrix_base
{
public:
 int get_cols() const { return cols_; }
 int get_rows() const { return rows_; }
protected:
 int cols_;
 int rows_;
};

template <class T>
class matrix : public matrix_base
{
private:
 T *elements_;
};
```

# Using C and C++ together

- Object model is (almost) the same
- C++ programs regularly call C libraries
- Issues:
  - Virtual inheritance
  - Virtual functions (pointer to vtbl)
  - Mangled name vs C linkage name



# Using C and C++ together

- ```
//  
// C++ header for C/C++ files:  
//  
#ifdef __cplusplus  
extern "C"  
{  
#endif  
    int    f(int);  
    double g(double, int);  
    // ...  
#ifdef __cplusplus  
}  
#endif
```

Place of instantiation

```
#include <iostream>
#include <algorithm>

// which swap?
template<typename T>
struct Test{
    void operator()(T& lhs,T& rhs){
        std::swap(lhs,rhs);
    }
};
struct MyT { };
namespace std {
    inline void swap(MyT& lhs,MyT& rhs){
        std::cout << "MySwap" << std::endl;
    }
}
```

```
int main()
{
    MyT t1,t2;
    Test<MyT>{}(t1,t2);
}
```

```
$ ./a.out
$
```

Place of instantiation

```
#include <iostream>
#include <algorithm>

// from here
template<typename T>
struct Test{
    void operator()(T& lhs,T& rhs){
        std::swap(lhs,rhs);
    }
};
struct MyT { };
namespace std {
    inline void swap(MyT& lhs,MyT& rhs){
        std::cout << "MySwap" << std::endl;
    }
}
// to here
template<typename T>
struct Test{
    void operator()(T& lhs,T& rhs){
        std::swap(lhs,rhs);
    }
};
int main()
{
    MyT t1,t2;
    Test<MyT>{}(t1,t2);
}

$ ./a.out
MySwap
$
```

Correct use of swap

```
#include <iostream>
#include <algorithm>

struct MyT { };

namespace std { // do not extend std namespace
    inline void swap(MyT& lhs, MyT& rhs) {
        std::cout << "MySwap" << std::endl;
    }
}
// works here
template<typename T>
struct Test {
    void operator()(T& lhs, T& rhs) {
        using std::swap; // introduce std::swap into the sscope
        swap(lhs, rhs); // use ADL to select the better swap
    }
};
```

```
int main()
{
    MyT t1, t2;
    Test<MyT>{}(t1, t2);
}
```

```
$ ./a.out
MySwap
$
```

Correct use of swap

```
#include <iostream>
#include <algorithm>

struct MyT { };

namespace std { // do not extend std namespace
    inline void swap(MyT& lhs, MyT& rhs) {
        std::cout << "MySwap" << std::endl;
    }
}
// works here
template<typename T>
struct Test {
    void operator()(T& lhs, T& rhs) {
        using std::swap; // introduce std::swap into the sscope
        swap(lhs, rhs); // use ADL to select the better swap
    }
};
inline void swap(MyT& lhs, MyT& rhs) {
    std::cout << "MySwap" << std::endl;
}

int main()
{
    MyT t1, t2;
    Test<MyT>{}(t1, t2);
}

$ ./a.out
MySwap
$
```

to_string example

```
#include <string>

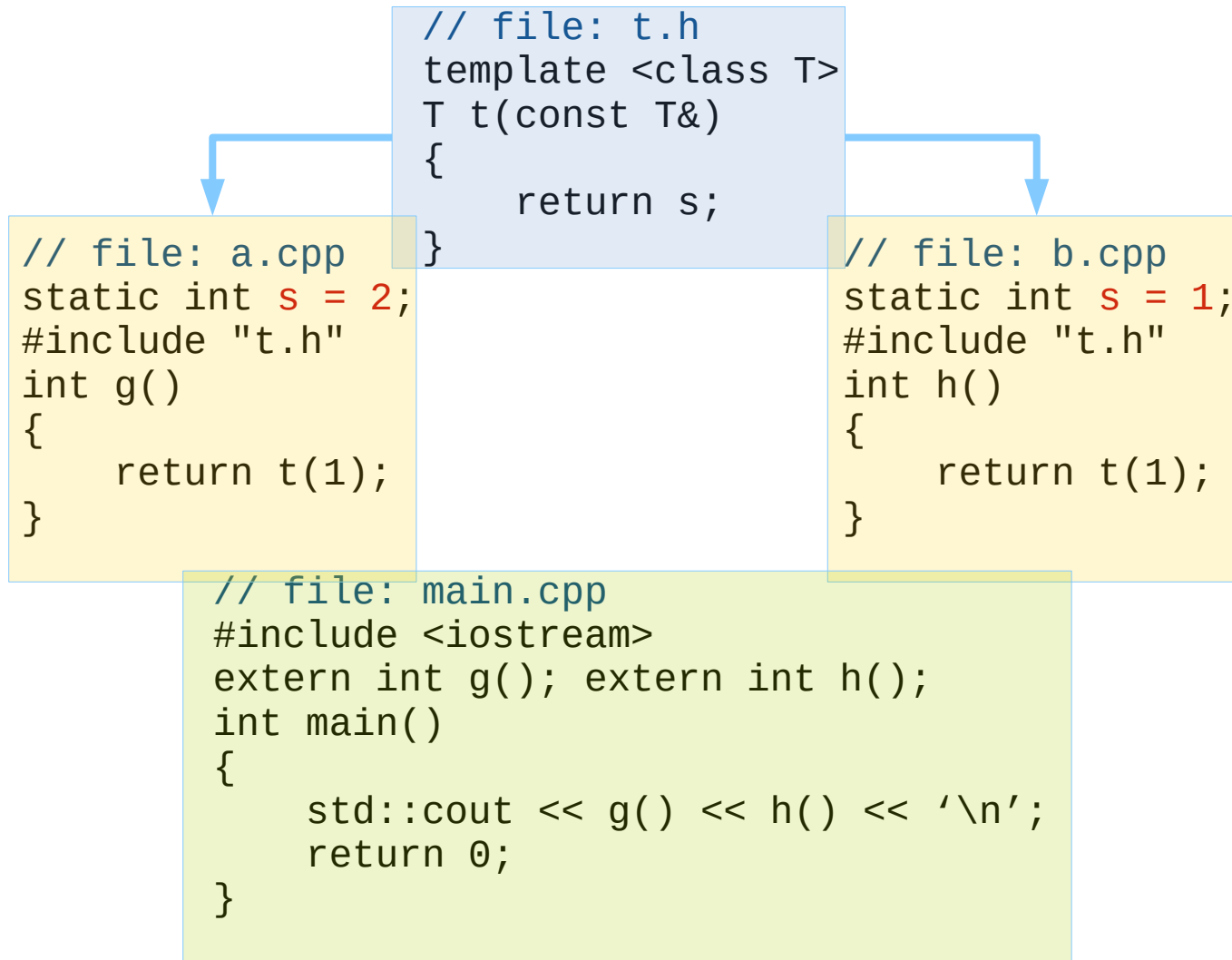
template <typename T>
class MyClass
{
public:
    std::string to_string() const;
private:
    std::string to_string_ads(const T &t) const;
};

template <typename T>
std::string MyClass<T>::to_string_ads(const T &t) const // ADS helper
{
    using std::to_string;
    return to_string(t);
}

int main()
{
    MyClass<double> td;
    MyClass<X> tx;

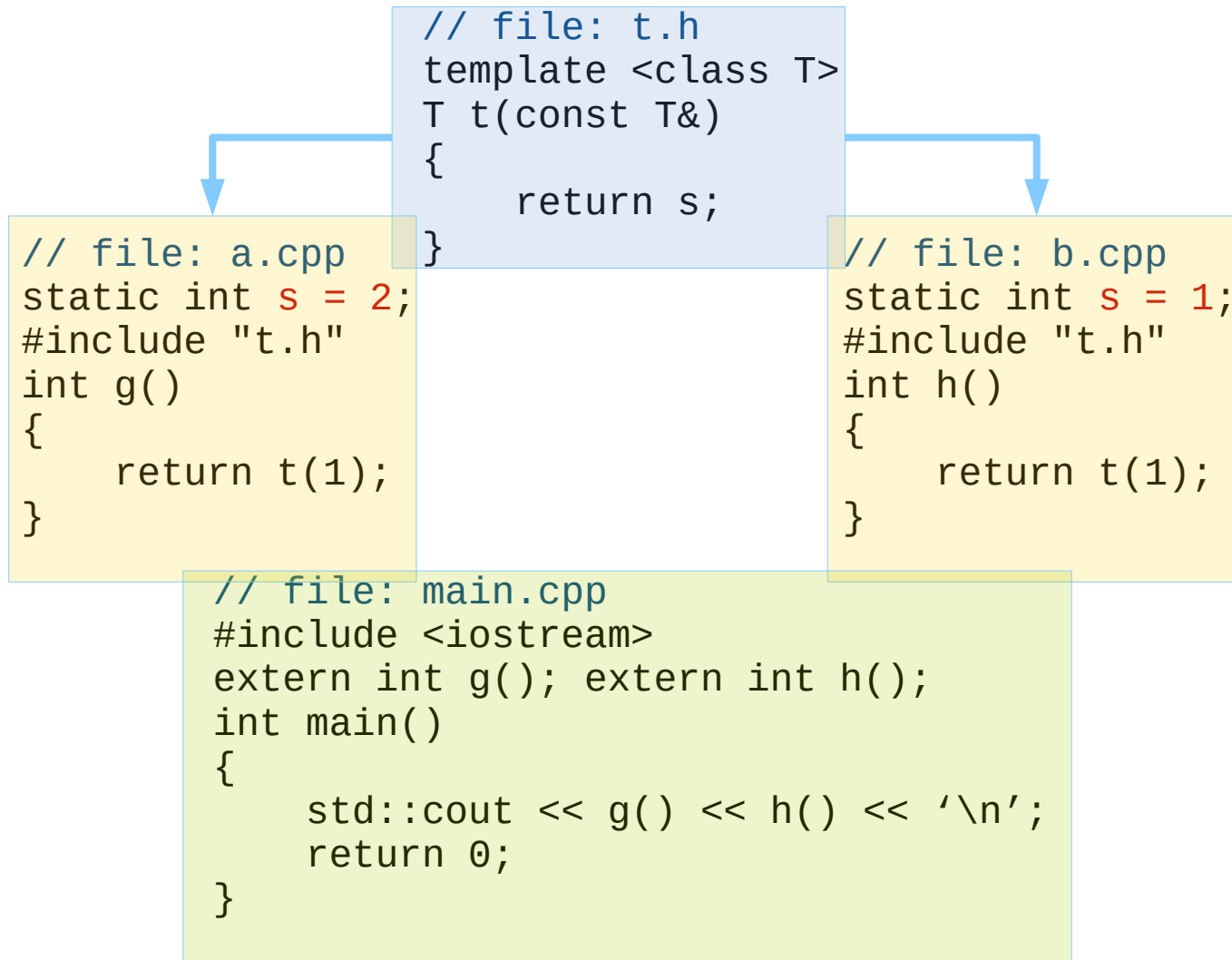
    td.to_string(); // calls std::to_string(double);
    tx.to_string(); // calls to_string(const X&);
}
```

Order of linking?



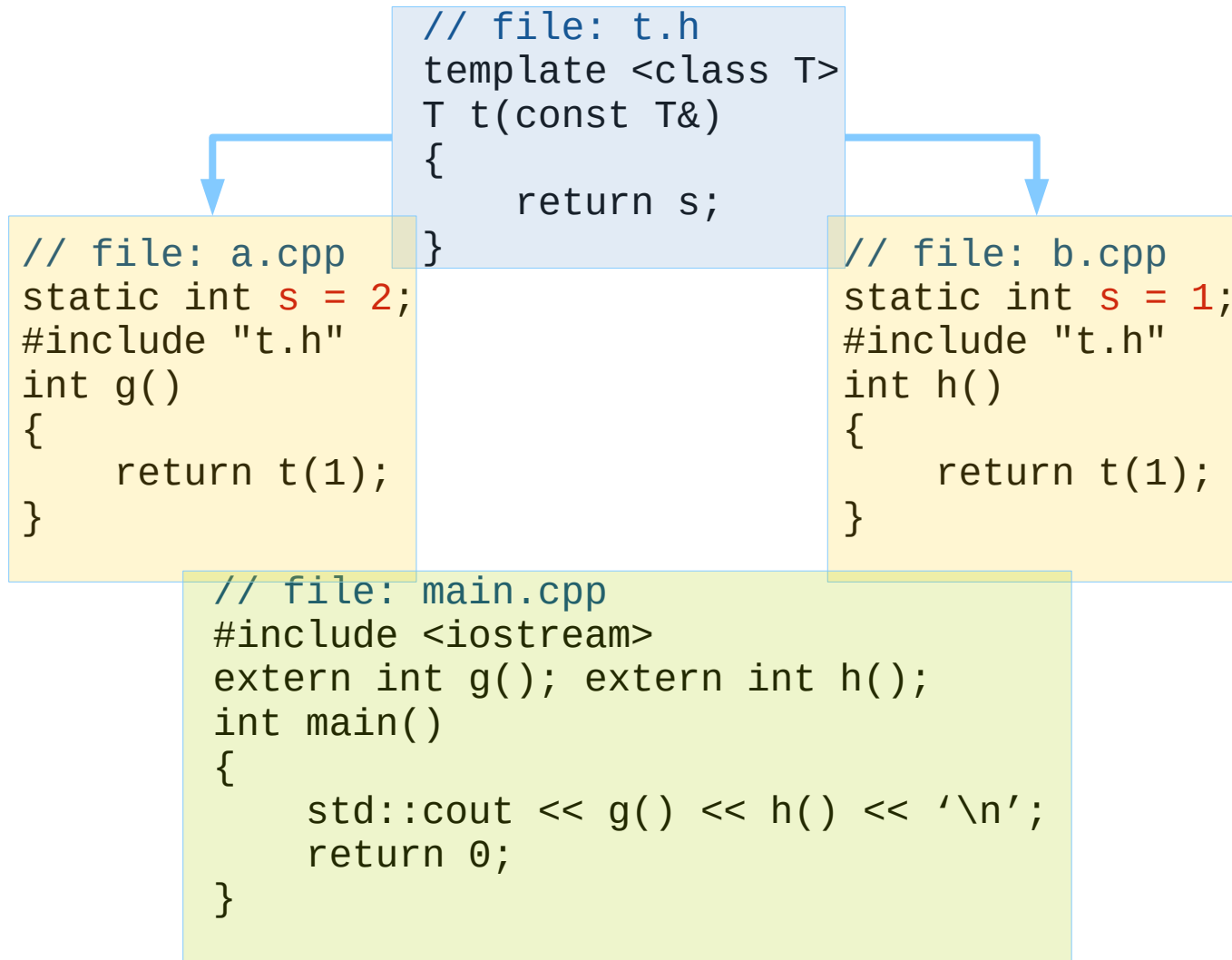
```
$ g++ main.cpp a.cpp b.cpp && ./a.out
```

Order of linking?



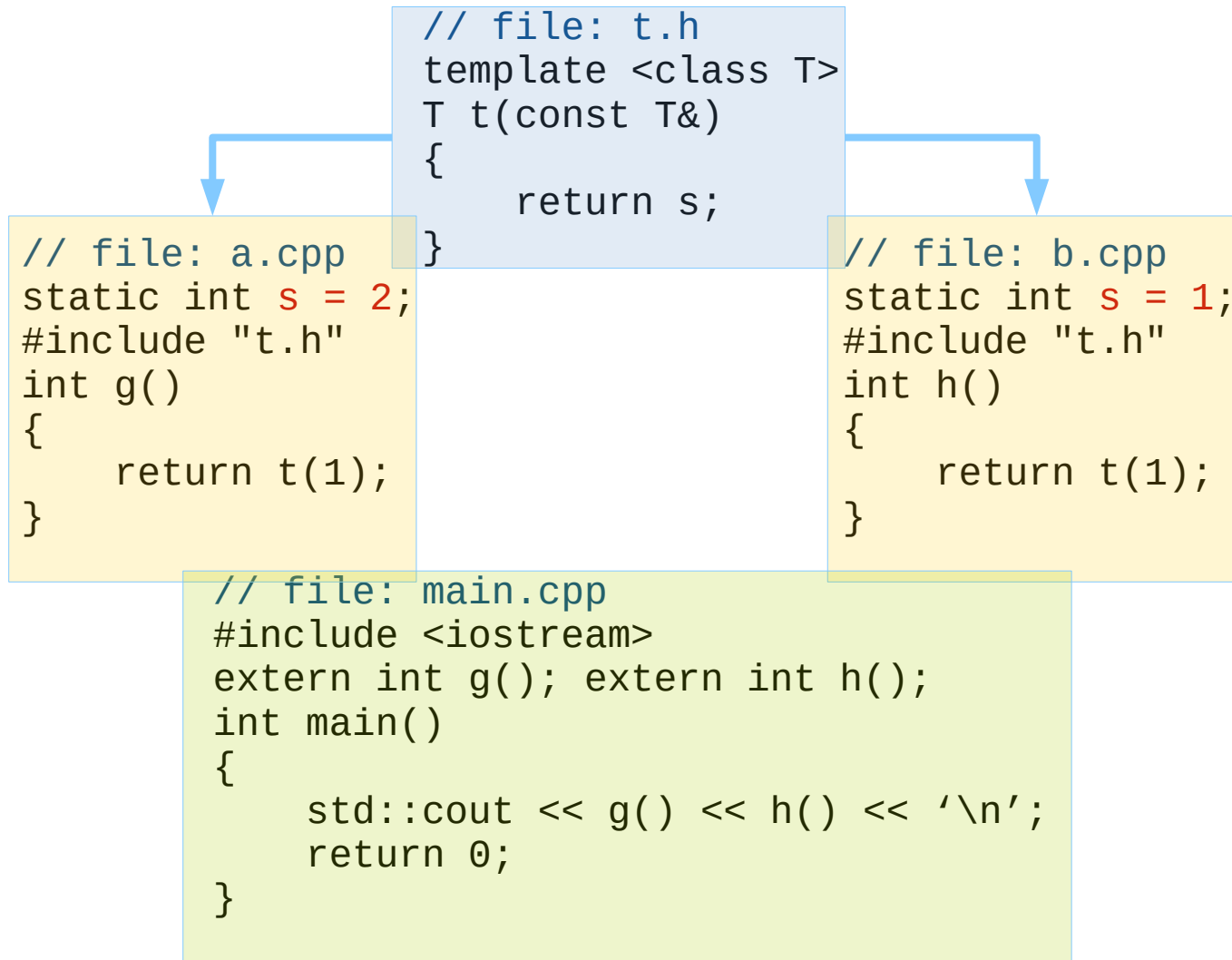
```
$ g++ main.cpp a.cpp b.cpp && ./a.out
2 2
```


Order of linking?



```
$ g++ main.cpp b.cpp a.cpp && ./a.out
```

Order of linking?



```
$ g++ main.cpp b.cpp a.cpp && ./a.out
1 1
```

Inline functions

```
// Date.h
class Date
{
public:
    // ...
private:
    // ...
    int year;
    int month;
    int day;
};

// operators for class Date
inline bool operator<( date d1, date d2) { ... }
inline bool operator==(date d1,date d2) { ... }
inline bool operator!=( date d1, date d2) { ... }
inline bool operator<=( date d1, date d2) { ... }
inline bool operator>=( date d1, date d2) { ... }
inline bool operator>( date d1, date d2) { ... }
```

Inline variables C++17

```
#include <iostream>
void f();
    int g0 = 10;
    inline int g1 = 11;
    static inline int g2 = 12;
    extern inline int g3 = 13;

int main()
{
    std::cout << "&g1 = " << g1 << ", " << &g1 << '\n';
    std::cout << "&g2 = " << g2 << ", " << &g2 << '\n';
    std::cout << "&g3 = " << g3 << ", " << &g3 << '\n';
    f();
    return 0;
}
```

```
#include <iostream>
    int g0 = 20;
    inline int g1 = 21;
    static inline int g2 = 22;
    extern inline int g3 = 23;

void f()
{
    std::cout << "&g1 = " << g1 << ", " << &g1 << '\n';
    std::cout << "&g2 = " << g2 << ", " << &g2 << '\n';
    std::cout << "&g3 = " << g3 << ", " << &g3 << '\n';
}
```

Inline variables C++17

```
#include <iostream>
void f();
```

```
    int g0 = 10;
    inline int g1 = 11;
    static inline int g2 = 12;
    extern inline int g3 = 13;
```

```
int main()
{
    std::cout << "&g1 = " << g1 << ", " << &g1 << '\n';
    std::cout << "&g2 = " << g2 << ", " << &g2 << '\n';
    std::cout << "&g3 = " << g3 << ", " << &g3 << '\n';
    f();
    return 0;
}
```

/usr/bin/ld: inline2.o:(.data+0x0): multiple definition of `g0'; inline1.o:(.data+0x0): first defined here

```
#include <iostream>
```

```
    int g0 = 20;
    inline int g1 = 21;
    static inline int g2 = 22;
    extern inline int g3 = 23;
```

```
void f()
```

```
{
    std::cout << "&g1 = " << g1 << ", " << &g1 << '\n';
    std::cout << "&g2 = " << g2 << ", " << &g2 << '\n';
    std::cout << "&g3 = " << g3 << ", " << &g3 << '\n';
}
```

Inline variables C++17

```
#include <iostream>
void f();
```

```
    int g0 = 10;
    inline int g1 = 11;
    static inline int g2 = 12;
    extern inline int g3 = 13;
```

```
int main()
```

```
{
    std::cout << "&g1 = " << g1 << ", " << &g1 << '\n';
    std::cout << "&g2 = " << g2 << ", " << &g2 << '\n';
    std::cout << "&g3 = " << g3 << ", " << &g3 << '\n';
    f();
    return 0;
}
```

/usr/bin/ld: inline2.o:(.data+0x0): multiple definition of `g0'; inline1.o:(.data+0x0): first defined here

```
#include <iostream>
```

```
    extern int g0 = 20;
    inline int g1 = 21;
    static inline int g2 = 22;
    extern inline int g3 = 23;
```

```
void f()
```

```
{
    std::cout << "&g1 = " << g1 << ", " << &g1 << '\n';
    std::cout << "&g2 = " << g2 << ", " << &g2 << '\n';
    std::cout << "&g3 = " << g3 << ", " << &g3 << '\n';
}
```

Inline variables C++17

```
#include <iostream>
void f();
    int g0 = 10;
    inline int g1 = 11;
    static inline int g2 = 12;
    extern inline int g3 = 13;

int main()
{
    std::cout << "&g1 = " << g1 << ", " << &g1 << '\n';
    std::cout << "&g2 = " << g2 << ", " << &g2 << '\n';
    std::cout << "&g3 = " << g3 << ", " << &g3 << '\n';
    f();
    return 0;
}
```

```
#include <iostream>
    extern int g0;
    inline int g1 = 21;
    static inline int g2 = 22;
    extern inline int g3 = 23;

void f()
{
    std::cout << "&g1 = " << g1 << ", " << &g1 << '\n';
    std::cout << "&g2 = " << g2 << ", " << &g2 << '\n';
    std::cout << "&g3 = " << g3 << ", " << &g3 << '\n';
}
```

Inline variables C++17

```
#include <iostream>
void f();
    int g0 = 10;
    inline int g1 = 11;
    static inline int g2 = 12;
    extern inline int g3 = 13;

int main()
{
    std::cout << "&g1 = " << g1 << ", " << &g1 << '\n';
    std::cout << "&g2 = " << g2 << ", " << &g2 << '\n';
    std::cout << "&g3 = " << g3 << ", " << &g3 << '\n';
    f();
    return 0;
}
```

```
#include <iostream>
    extern int g0;
    inline int g1 = 21;
    static inline int g2 = 22;
    extern inline int g3 = 23;

void f()
{
    std::cout << "&g1 = " << g1 << ", " << &g1 << '\n';
    std::cout << "&g2 = " << g2 << ", " << &g2 << '\n';
    std::cout << "&g3 = " << g3 << ", " << &g3 << '\n';
}
```

```
&g0 = 10, 0x40406c
&g1 = 21, 0x404060
&g2 = 12, 0x404070
&g3 = 23, 0x404068
&g0 = 10, 0x40406c
&g1 = 21, 0x404060
&g2 = 22, 0x404064
&g3 = 23, 0x404068
```


Inline variables C++17

```
#include <iostream>
void f();
    int g0 = 10;
    inline int g1 = 11;
    static inline int g2 = 12;
    extern inline int g3 = 13;

int main()
{
    std::cout << "&g1 = " << g1 << ", " << &g1 << '\n';
    std::cout << "&g2 = " << g2 << ", " << &g2 << '\n';
    std::cout << "&g3 = " << g3 << ", " << &g3 << '\n';
    f();
    return 0;
}
```

```
#include <iostream>
    extern int g0;
    inline int g1 = 21;
    static inline int g2 = 22;
    extern inline int g3 = 23;

void f()
{
    std::cout << "&g1 = " << g1 << ", " << &g1 << '\n';
    std::cout << "&g2 = " << g2 << ", " << &g2 << '\n';
    std::cout << "&g3 = " << g3 << ", " << &g3 << '\n';
}
```

```
&g0 = 10, 0x40406c
&g1 = 11, 0x404060
&g2 = 12, 0x404070
&g3 = 13, 0x404068
&g0 = 10, 0x40406c
&g1 = 11, 0x404060
&g2 = 22, 0x404064
&g3 = 13, 0x404068
```

Linker symbols

```
$ readelf inline1.o
```

Num:	Value	Size	Type	Bind	Vis	Ndx	Name
0:	0000000000000000	0	NOTYPE	LOCAL	DEFAULT	UND	
1:	0000000000000000	0	FILE	LOCAL	DEFAULT	ABS	inline1.cpp
2:	0000000000000040	11	FUNC	LOCAL	DEFAULT	4	__GLOBAL__sub_I_inline1.cp
3:	0000000000000004	4	OBJECT	LOCAL	DEFAULT	7	__ZL2g2
4:	0000000000000000	1	OBJECT	LOCAL	DEFAULT	6	__ZStL8__ioinit
5:	0000000000000000	59	FUNC	LOCAL	DEFAULT	4	__cxx_global_var_init
6:	0000000000000000	0	SECTION	LOCAL	DEFAULT	2	
7:	0000000000000000	0	SECTION	LOCAL	DEFAULT	4	
8:	0000000000000000	0	SECTION	LOCAL	DEFAULT	6	
9:	0000000000000000	0	SECTION	LOCAL	DEFAULT	7	
10:	0000000000000000	0	SECTION	LOCAL	DEFAULT	8	
11:	0000000000000000	0	NOTYPE	GLOBAL	DEFAULT	UND	__Z1fv
12:	0000000000000000	0	NOTYPE	GLOBAL	DEFAULT	UND	__ZNSolsEPKv
13:	0000000000000000	0	NOTYPE	GLOBAL	DEFAULT	UND	__ZNSolsEi
14:	0000000000000000	0	NOTYPE	GLOBAL	DEFAULT	UND	__ZNSt8ios_base4InitC1Ev
15:	0000000000000000	0	NOTYPE	GLOBAL	DEFAULT	UND	__ZNSt8ios_base4InitD1Ev
16:	0000000000000000	0	NOTYPE	GLOBAL	DEFAULT	UND	__ZSt4cout
17:	0000000000000000	0	NOTYPE	GLOBAL	DEFAULT	UND	__ZStlsISt11char_traitsIcE
18:	0000000000000000	0	NOTYPE	GLOBAL	DEFAULT	UND	__ZStlsISt11char_traitsIcE
19:	0000000000000000	0	NOTYPE	GLOBAL	DEFAULT	UND	__cxa_atexit
20:	0000000000000000	0	NOTYPE	GLOBAL	HIDDEN	UND	__dso_handle
21:	0000000000000000	4	OBJECT	GLOBAL	DEFAULT	7	g0
22:	0000000000000000	4	OBJECT	WEAK	DEFAULT	10	g1
23:	0000000000000000	4	OBJECT	WEAK	DEFAULT	12	g3
24:	0000000000000000	316	FUNC	GLOBAL	DEFAULT	2	main

Static initialization/destruction

- Matt Godbolt cppcon 18 The Bits between the Bits
<https://youtu.be/dOfucXtyEsU>

```
typedef void (*init_func)(int, char **, char **);

extern init_func __init_array_start[];
extern init_func __init_array_end[];

int __libc_csu_init(int argc, char **argv, char **envp) {
    const size_t size = __init_array_end - __init_array_start;
    for (size_t i = 0; i < size; i++)
        (*__init_array_start[i])(argc, argv, envp);
}
```

Static initialization/destruction

- Static objects inside translation unit constructed in a well-defined order
- No ordering **between** translation units
- Issues:
 - (1) Constructor of static refers other source's static
 - (2) Destruction order
- Lazy singleton solves (1)
- Schwartz counter solves (1+2)

Schwartz counter

```
// init.h
class InitMngr
{
public:
    InitMngr() { if ( !count_++ ) init(); }
    ~InitMngr() { if (!--count_ ) cleanup(); }
    void init();
    void cleanup();
private:
    static long count_; // one per process
};
namespace { InitMngr initMngr; } // one per file inclusion

// init.cpp
long InitMngr::count_ = 0;
void InitMngr::init() { /* initialization */ }
void InitMngr::cleanup() { /* cleanup */ }
```