Back to Basics: The Structure of a Program

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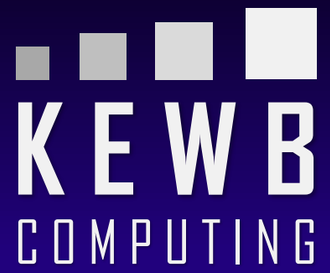
CppCon 2020



Overview

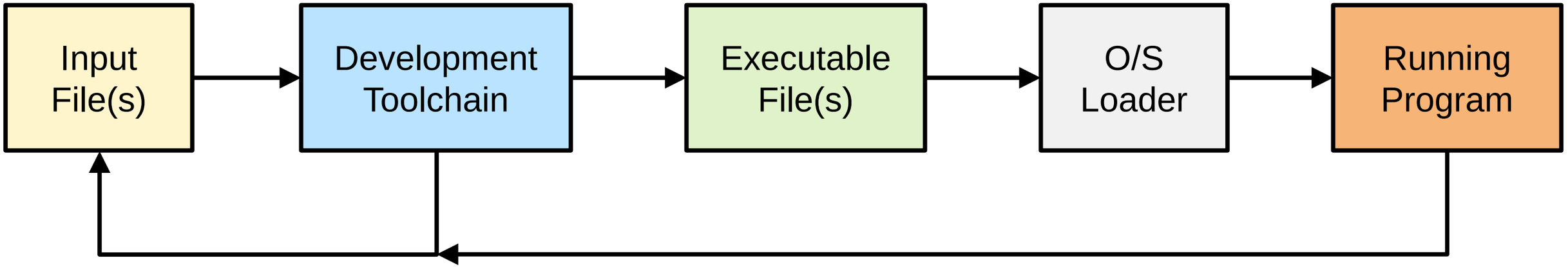
- The process of building a program
- What a translation unit (TU) is, and its relationship to the code you write
- The phases of translation
- Declarations, definitions, and linkage
- The one-definition rule (ODR)
- Storage duration
- ABIs and name-mangling
- Linking and loading

Goals

- Describe a few important "global" concepts
- Clarify terminology that can be confusing
- Shine some light on how C++ compilation works

Building and Running a C++ Program

- 50,000 ft view



Input Files

- User-Defined Code
  - Header files (.h, .hpp, .hh, etc.)
  - Source files (.c, .cpp, .cxx, .C, etc.)
  - Resource files (.res, .qrc, .rcc, etc.)

- Dependencies (libraries)
  - Header files (`<vector>`, `<boost/text/text.hpp>`)
  - Precompiled files (`libstdc++.a`, `libc++.so`, `msvcrt.lib`, `ws2_32.dll`, `crt1.o`)
  - Source files (Boost, Catch2)
  - Resources (icons, images, translations)

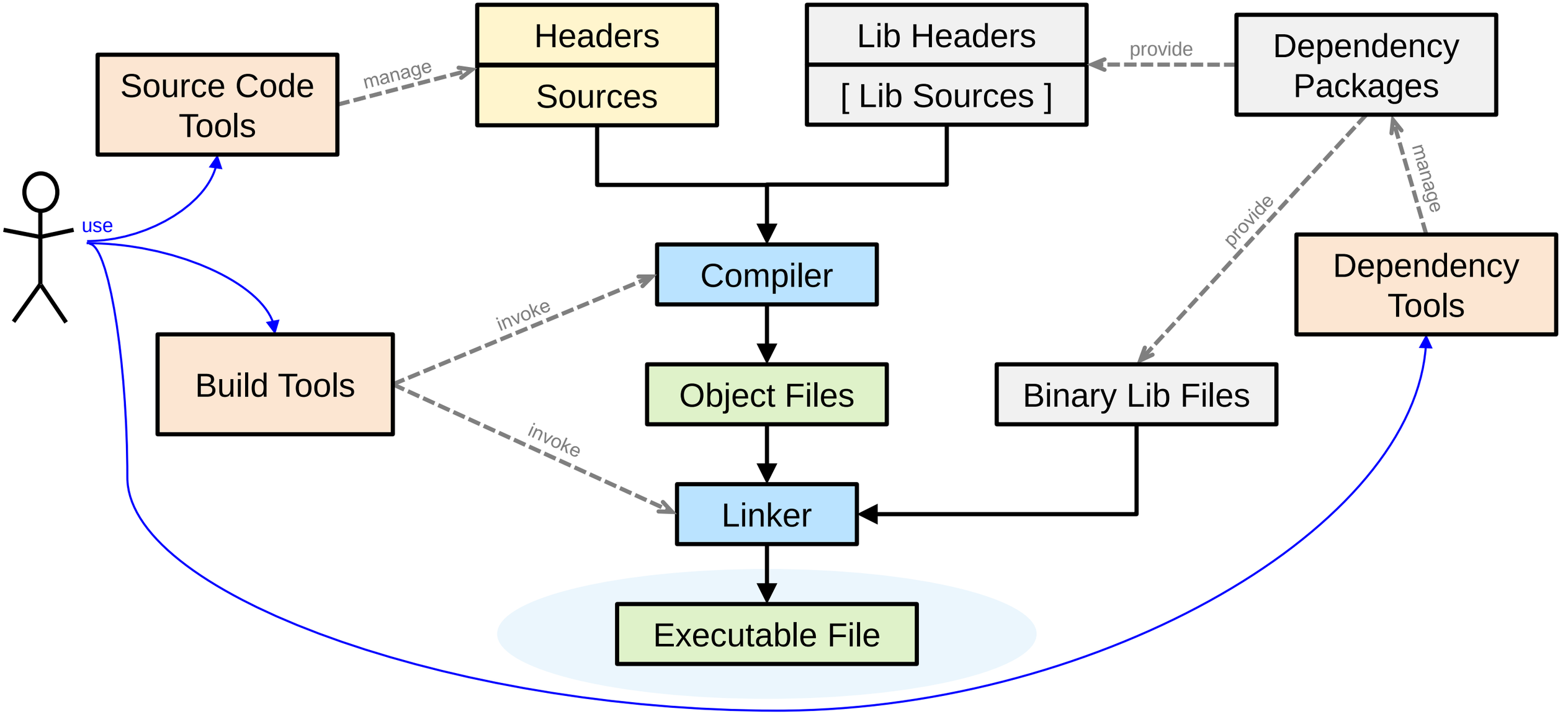
Input Files

- User-Defined Code
  - Header files (.h, .hpp, .hh, etc.)
  - Source files (.c, .cpp, .cxx, .C, etc.)
  - Resource files (.res, .qrc, .rcc, etc.)

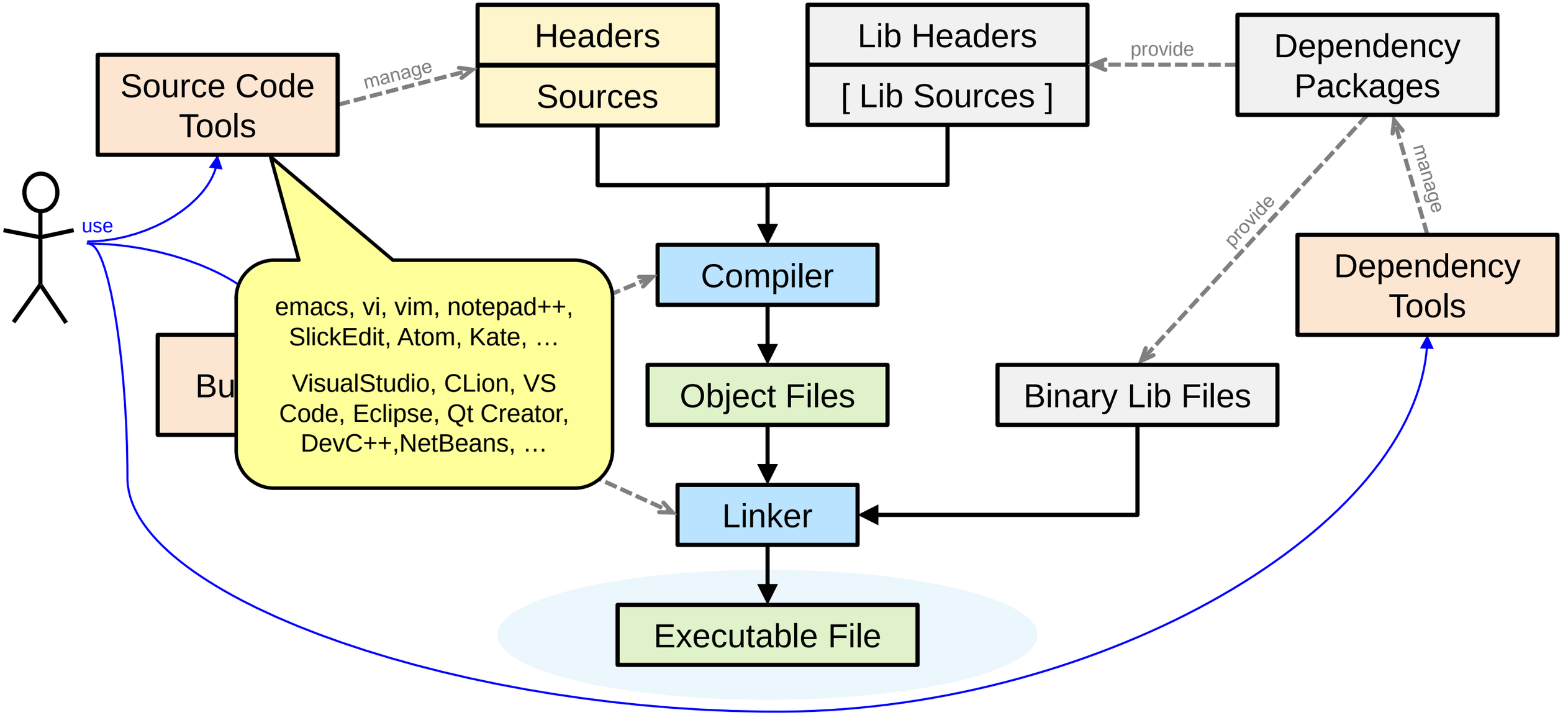
Why do we have this division?

- Dependencies (libraries)
  - Header files (`<vector>`, `<boost/text/text.hpp>`)
  - Precompiled files (`libstdc++.a`, `libc++.so`, `msvcrt.lib`, `ws2_32.dll`, `crt1.o`)
  - Source files (Boost, Catch2)
  - Resources (icons, images, translations for I18N)

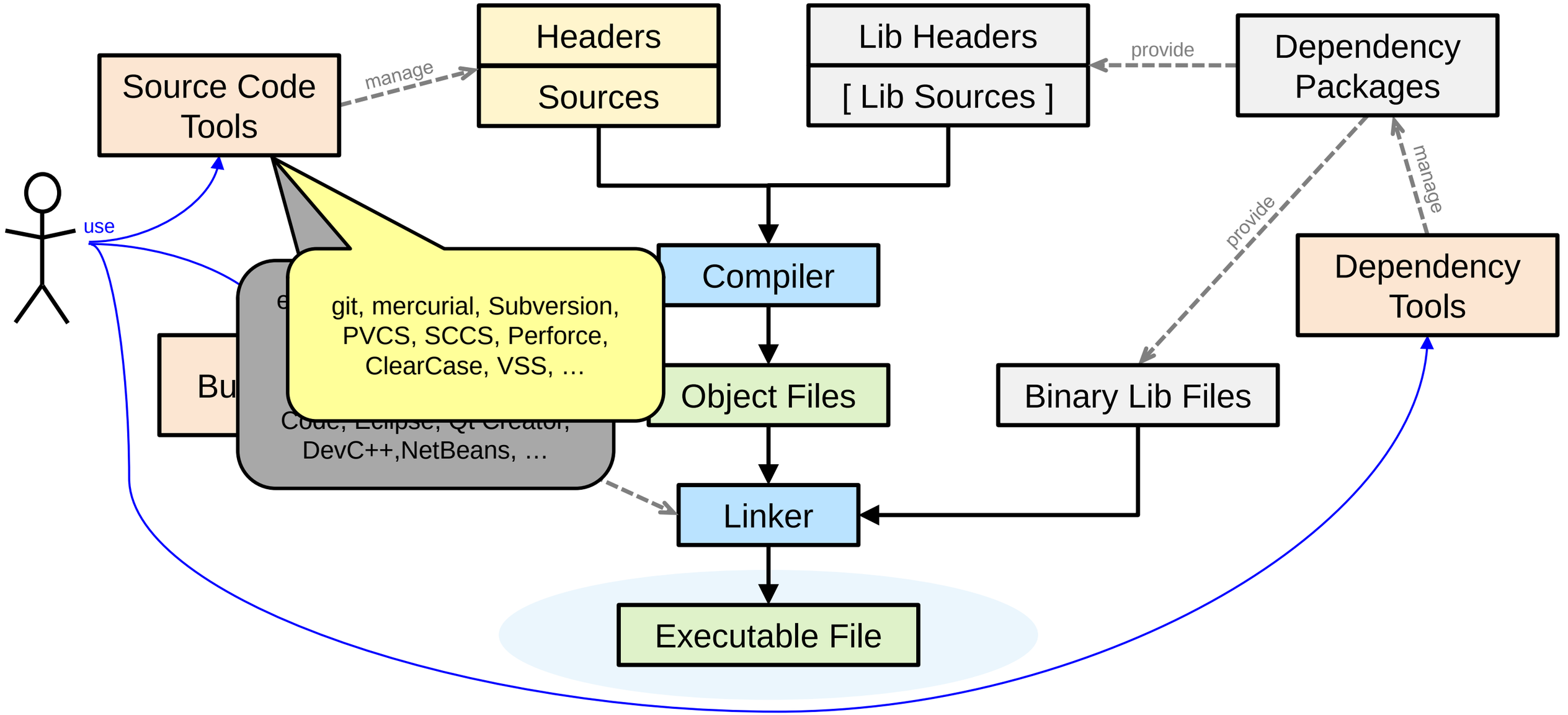
C++ Programming Ecosystem – Building Executables



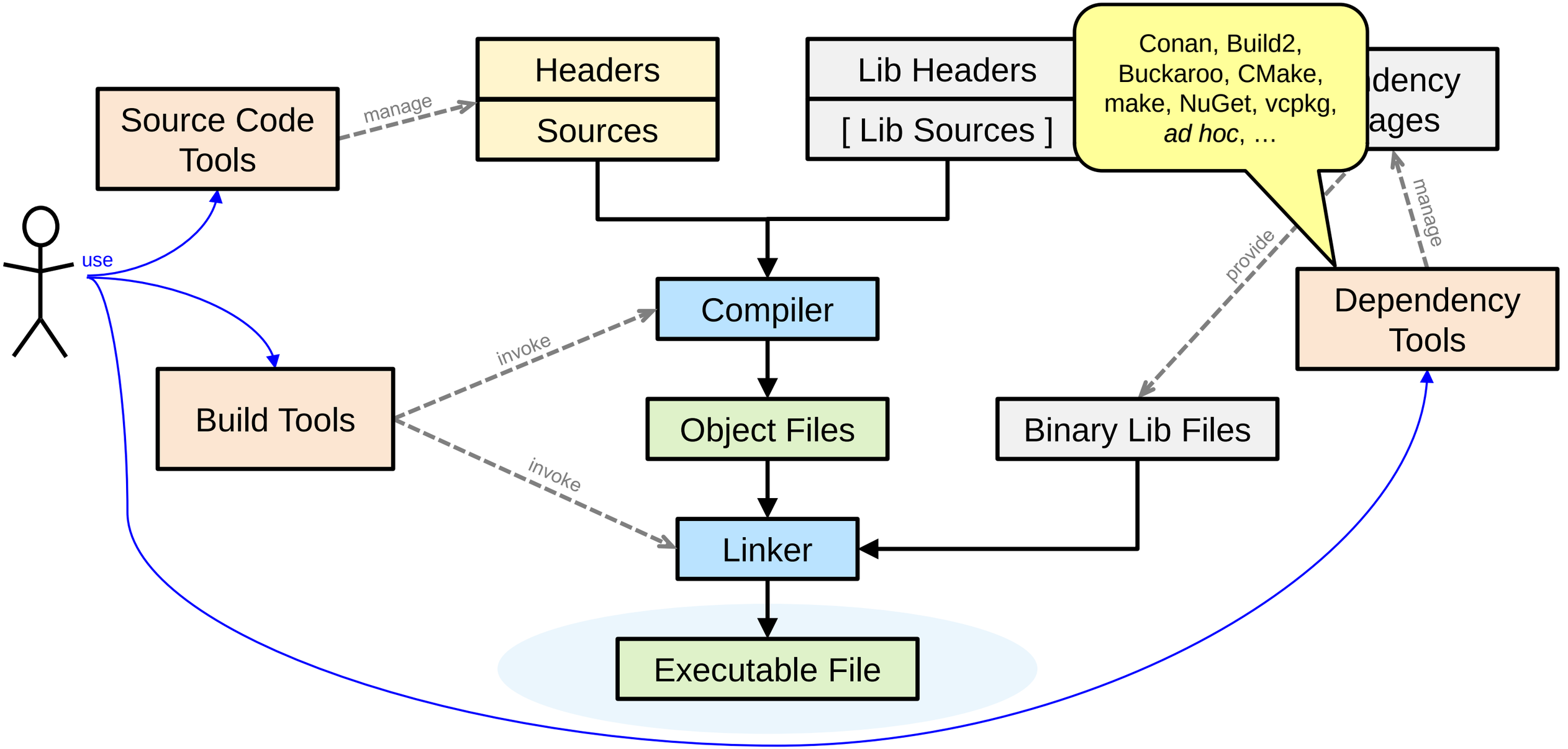
C++ Programming Ecosystem – Building Executables



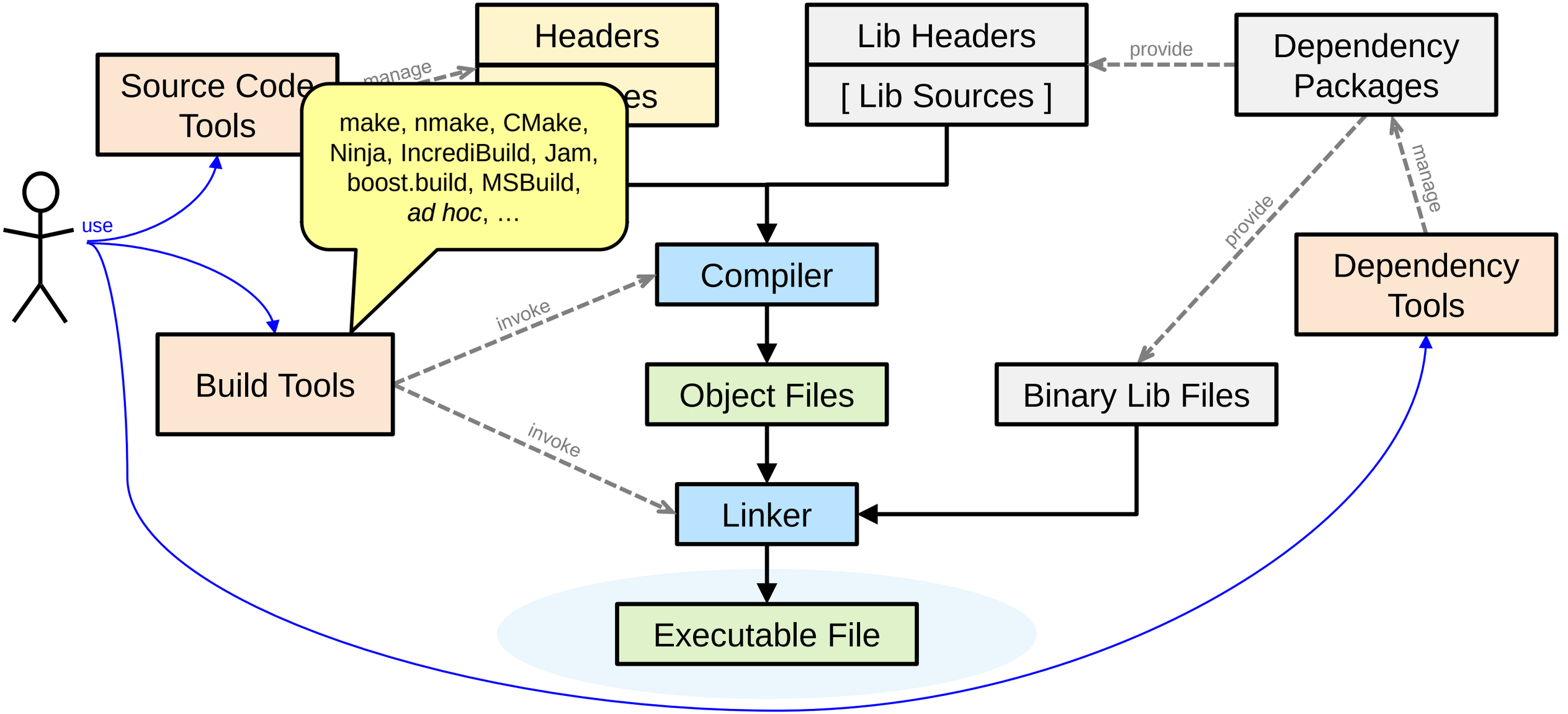
C++ Programming Ecosystem – Building Executables



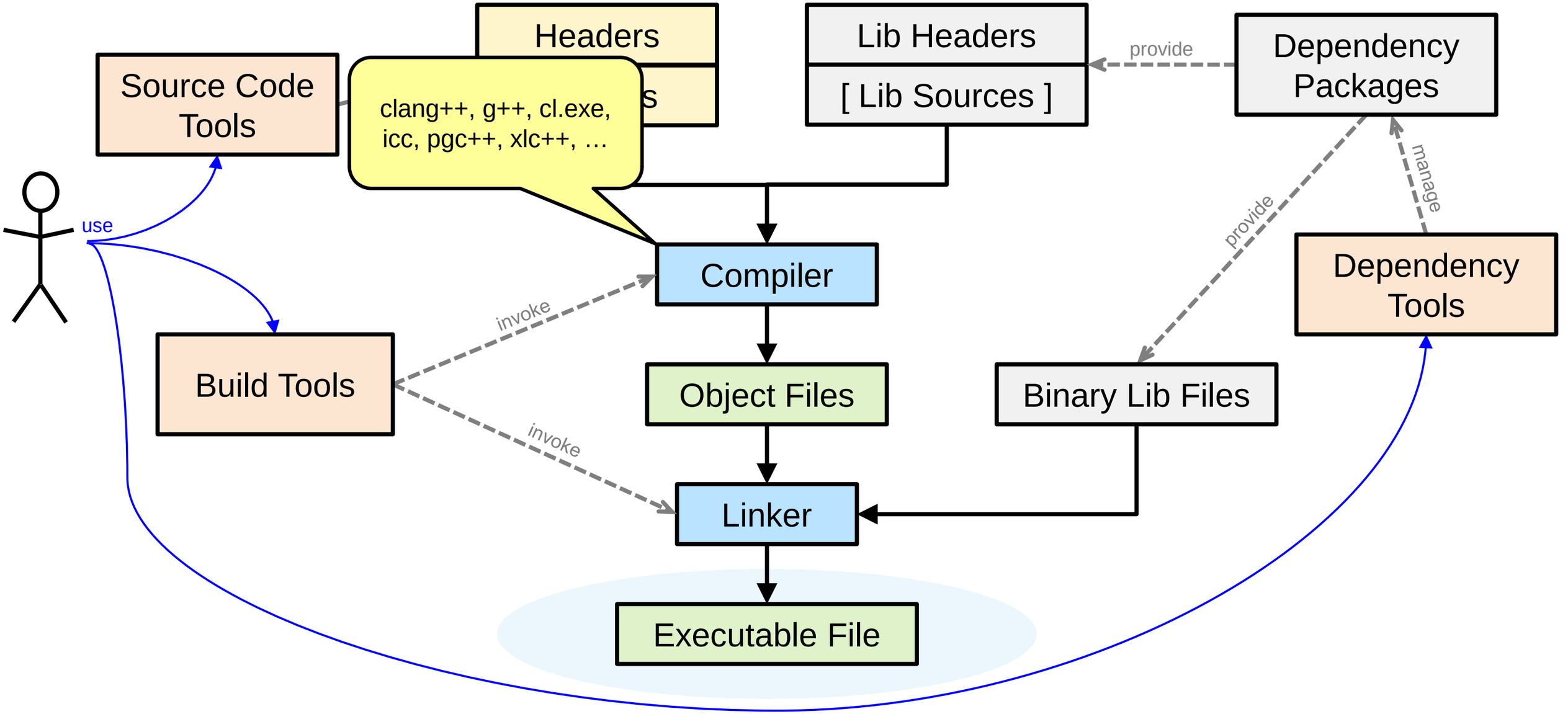
C++ Programming Ecosystem – Building Executables



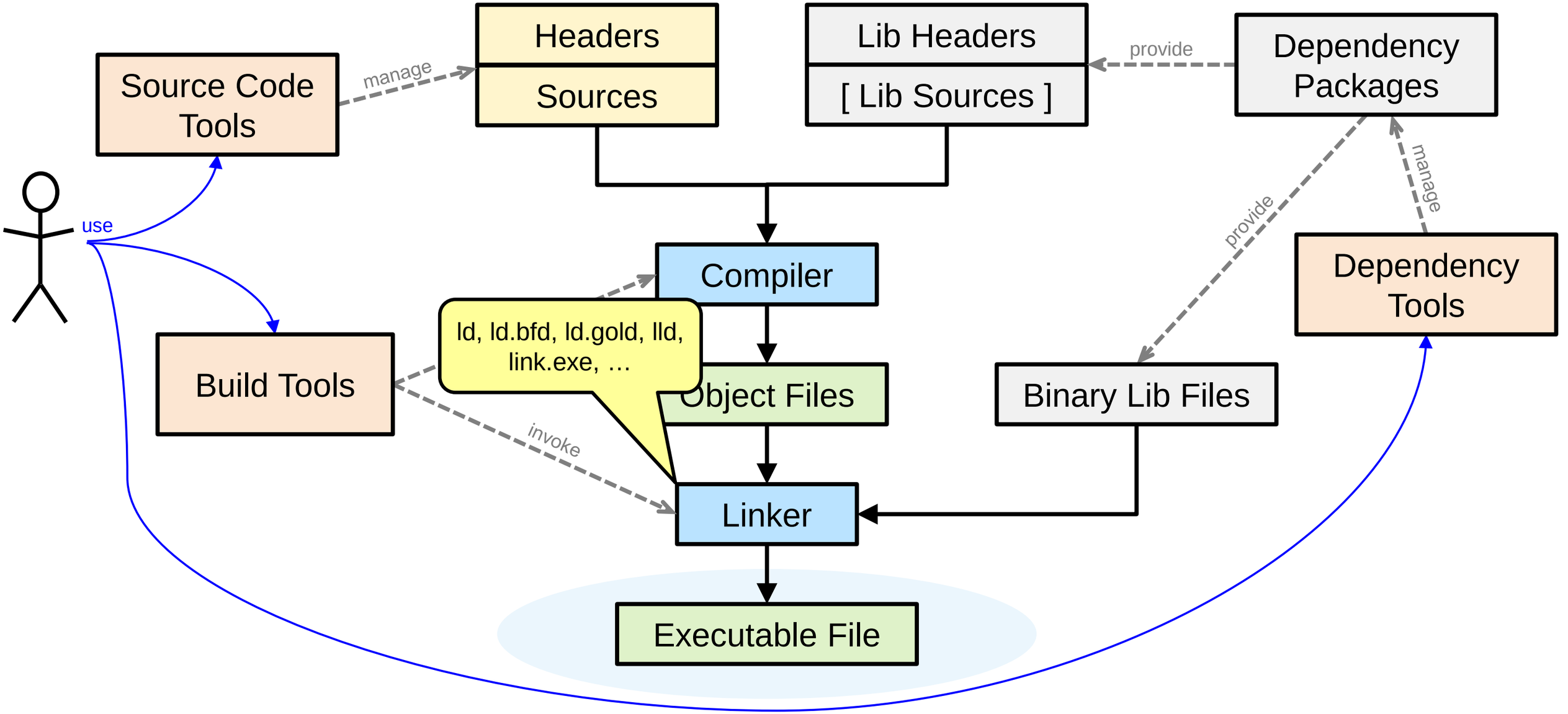
C++ Programming Ecosystem – Building Executables



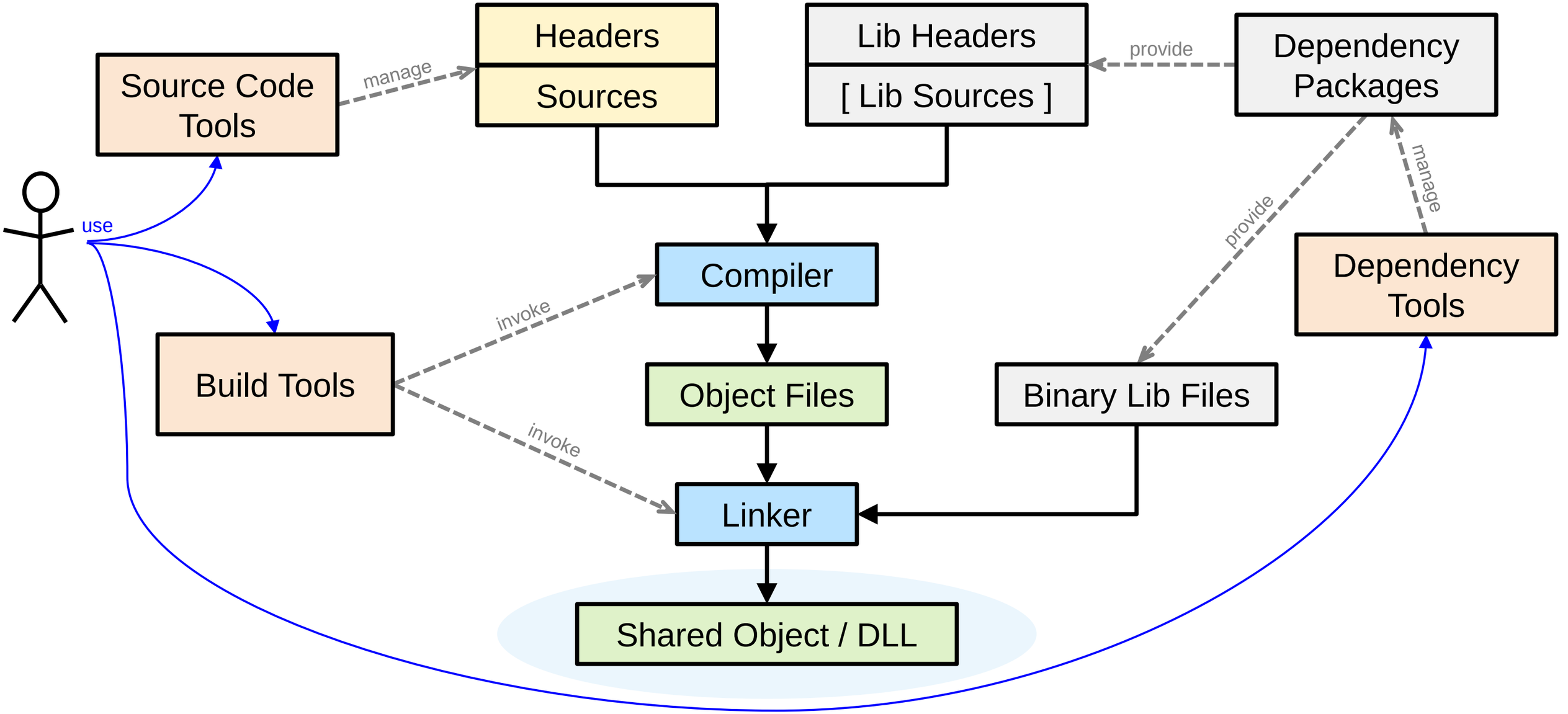
C++ Programming Ecosystem – Building Executables



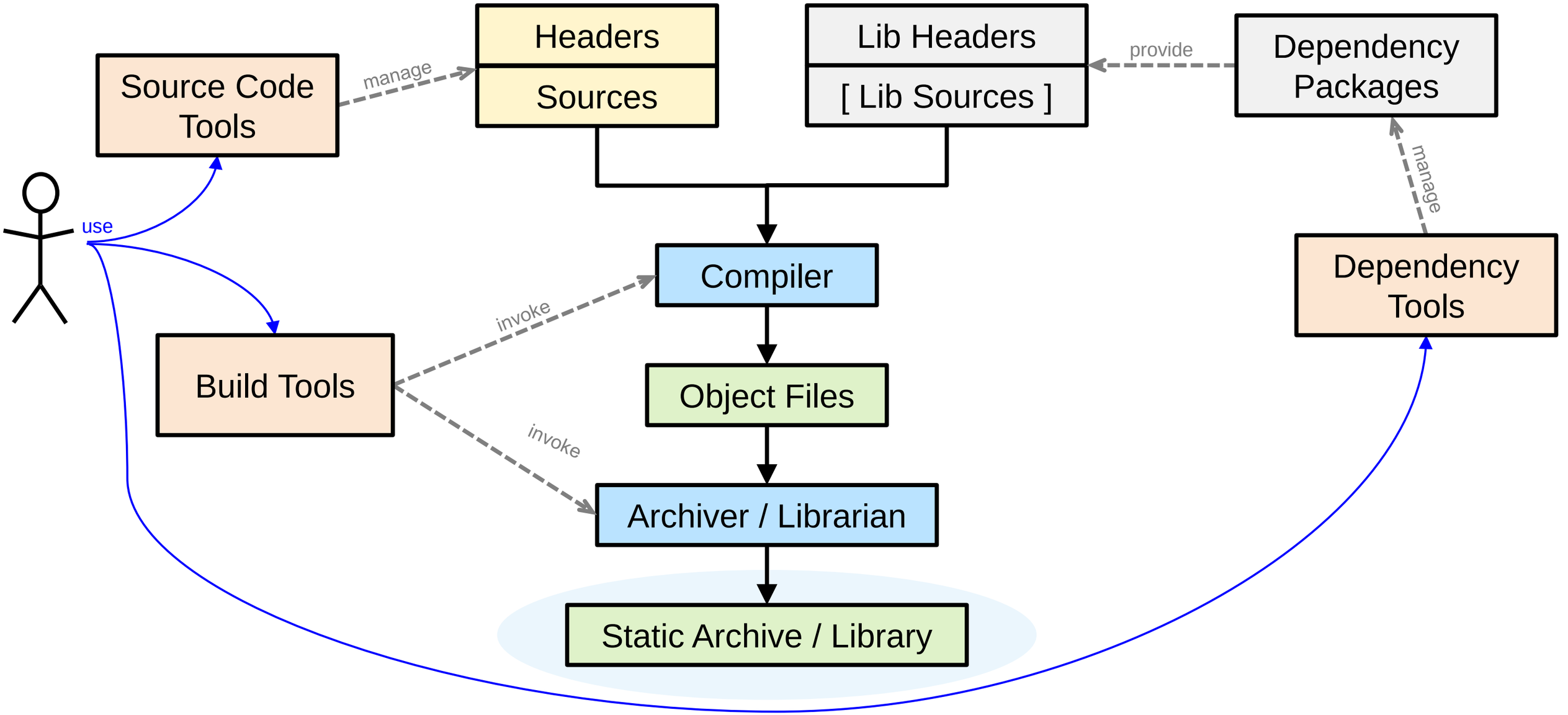
C++ Programming Ecosystem – Building Executables



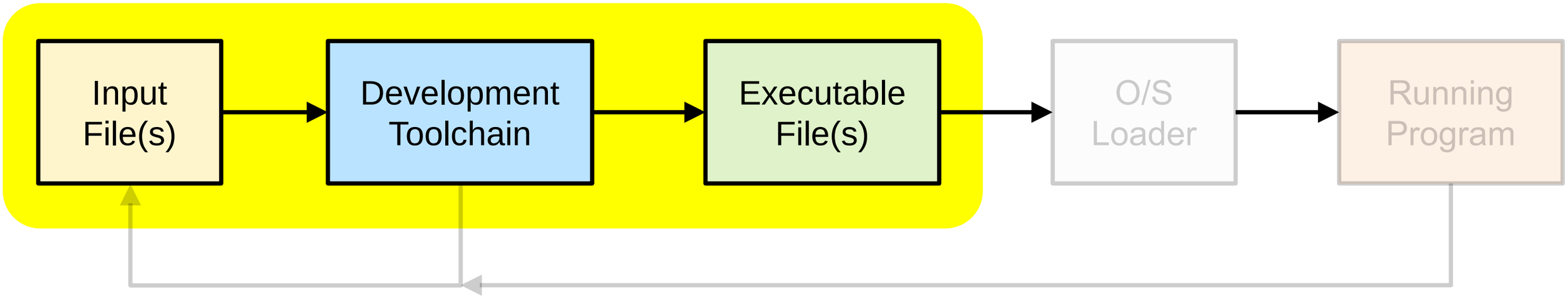
C++ Programming Ecosystem – Building Dynamic Libraries



C++ Programming Ecosystem – Building Static Libraries



Our Focus – Building C++ Executables



How do We Represent C++ Programs?

- Our programs are represented by source code
  - Source code is expressed in human-readable text files

- We typically have three kinds of source code
  - Header files (headers) – generally used more than once when building an executable
  - Source files (source) – generally used only once
  - Resource files (resources) – used only once to represent special non-executable information

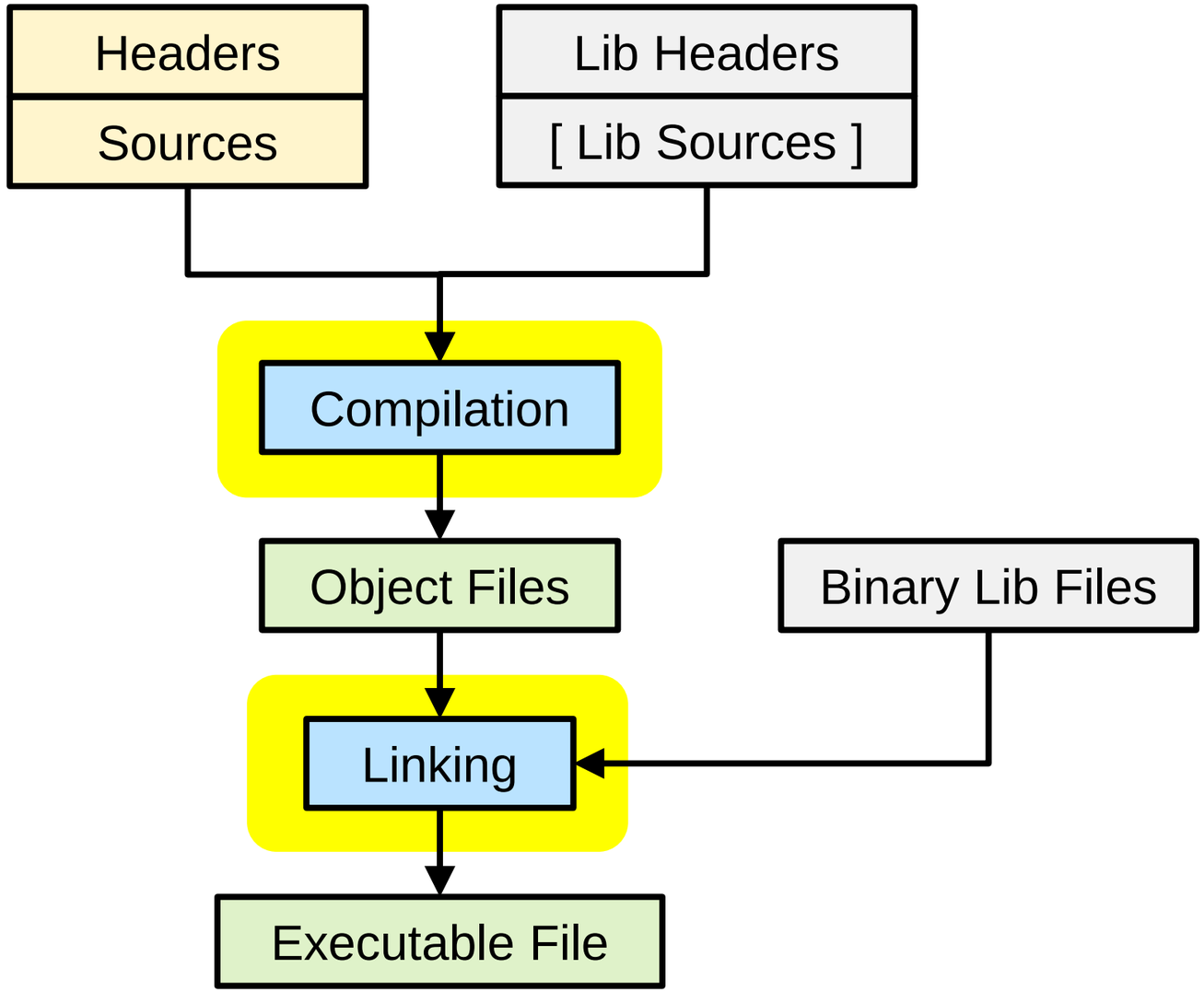
```
//  hello.h
//==========
#ifndef HELLO_H_INC
#define HELLO_H_INC

#include <iostream>

void print_hello();

#endif
```

```
//  hello.cpp
//===========
#include "hello.h"

void print_hello()
{
    std::cout << "Hello!" << std::endl;
}
```

```
//  main.cpp
//==========
#include "hello.h"

int main()
{
    print_hello();
    return 0;
}
```

Building a C++ Executable

- Builds are accomplished by compilation and linking
  - Why?
  - Our human-readable text files must be converted to binary machine language



Building a C++ Executable

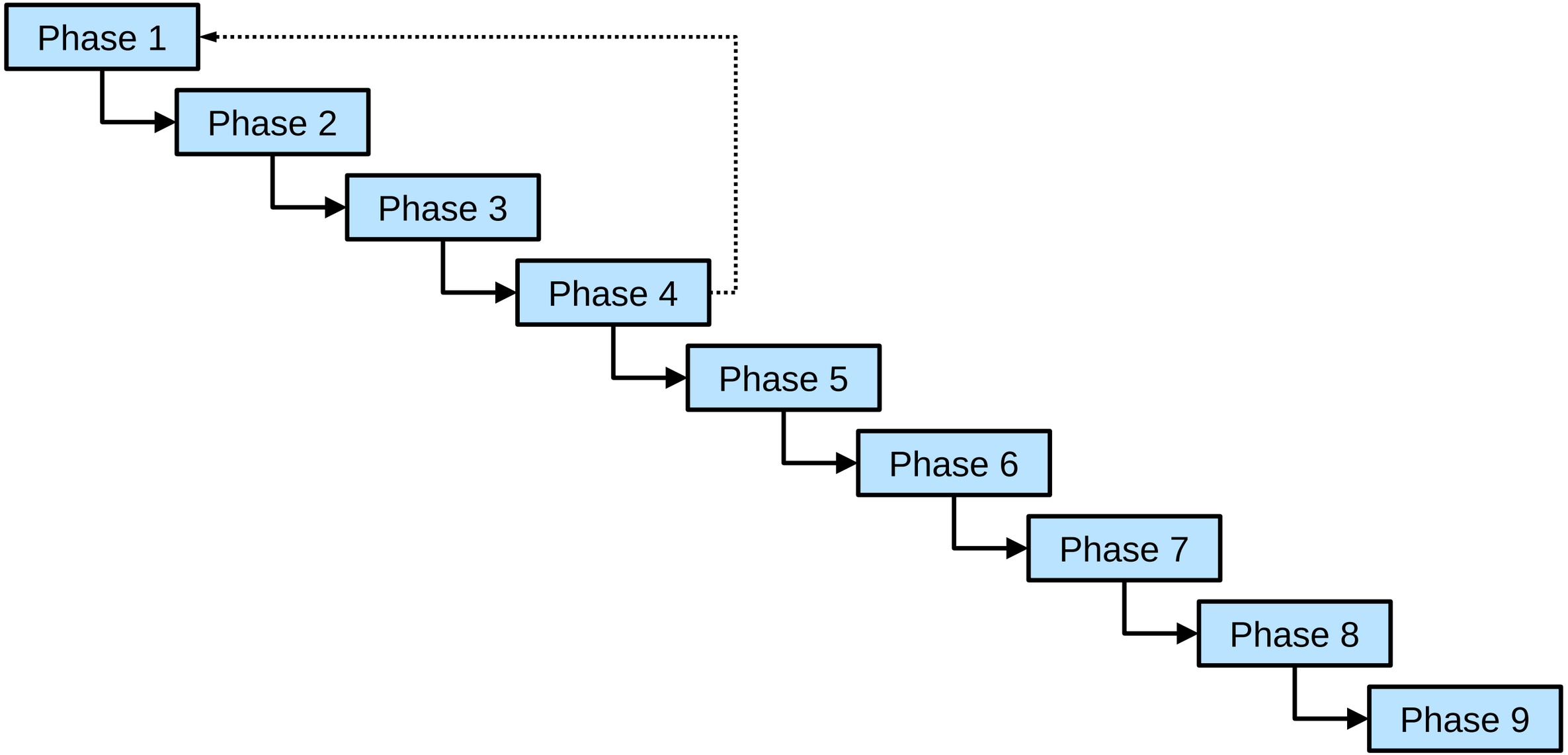
KEWB COMPUTING

- Compilation
  - The process of converting human-readable source code into binary object files
  - From a high-level perspective, there are four stages of compilation:
    - Lexical analysis
    - Syntax analysis
    - Semantic analysis
    - Code generation
  - In C++, we typically generate one object file for each source file
- Linking
  - The process of combining object files and binary libraries to make a working program

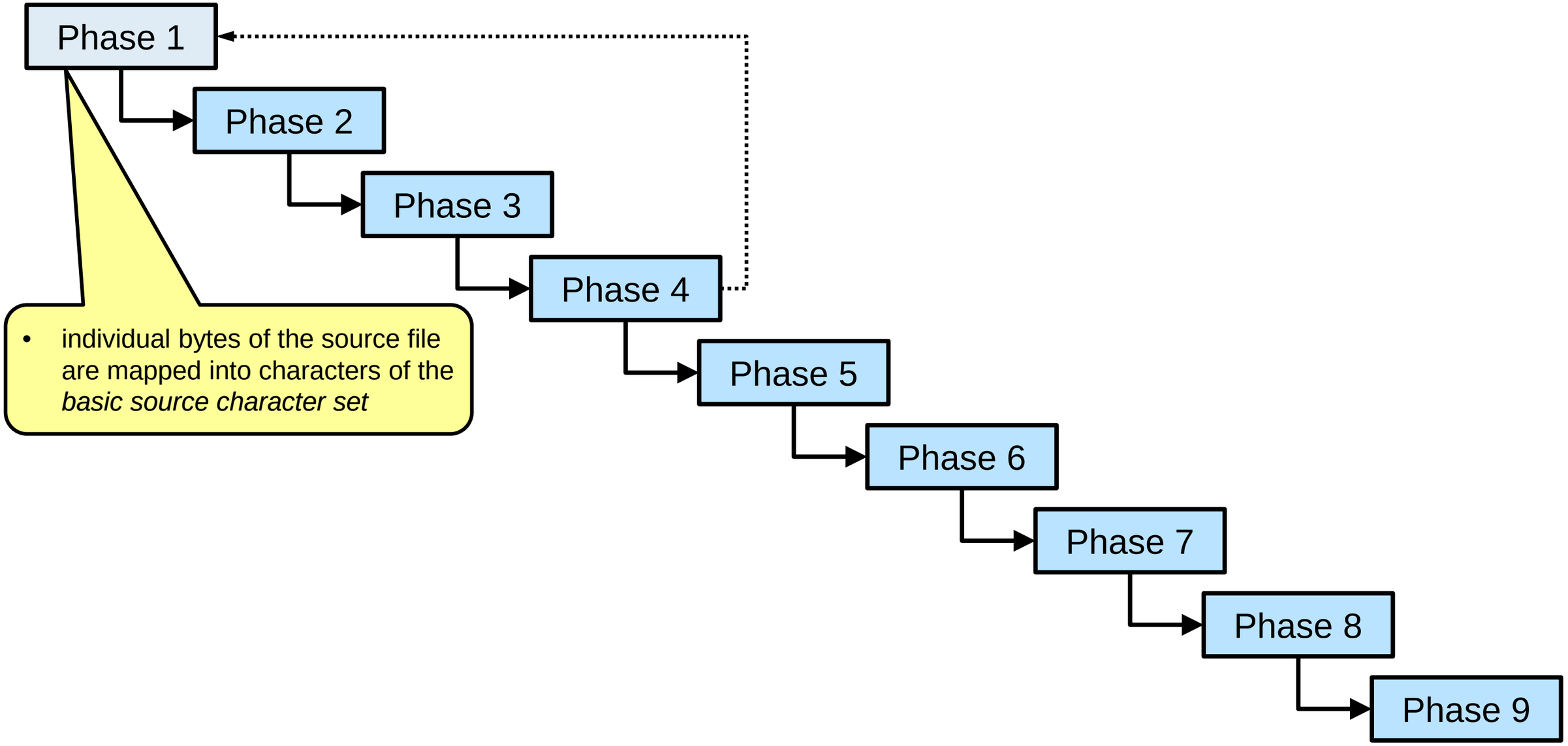
Compilation – From Source File to Object File

- The standard calls the compilation process **translation**
- In C++, translation is performed upon a **translation unit** (**TU**) in nine well-defined stages
  - Evocatively named Phases 1 through 9
- A translation unit is defined (roughly) as
  - A source file,
  - Plus with all the headers and source files included via the `#include` directive,
  - Minus any source lines skipped by conditional inclusion preprocessing directives (#ifdef),
  - And all macros expanded

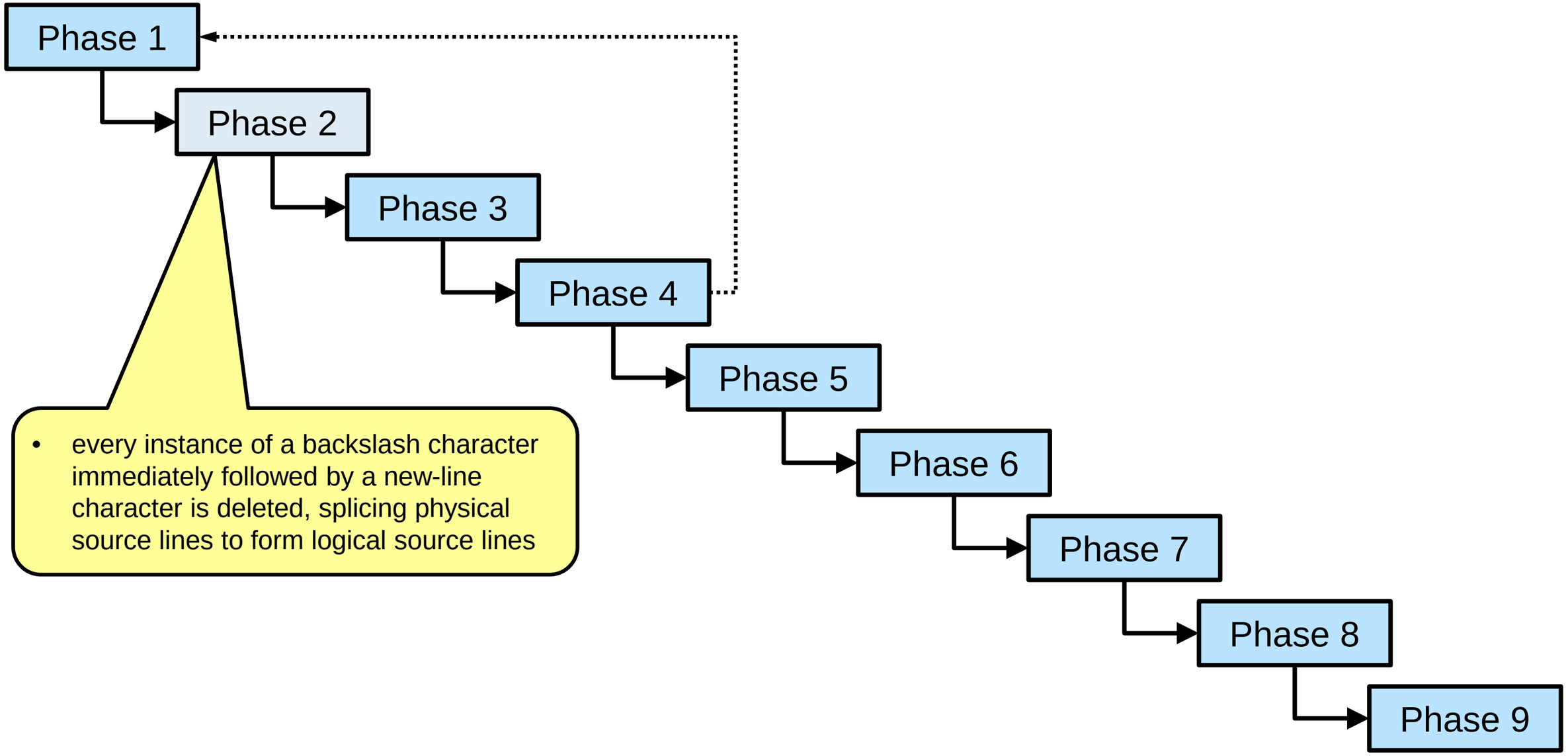
Phases of Translation



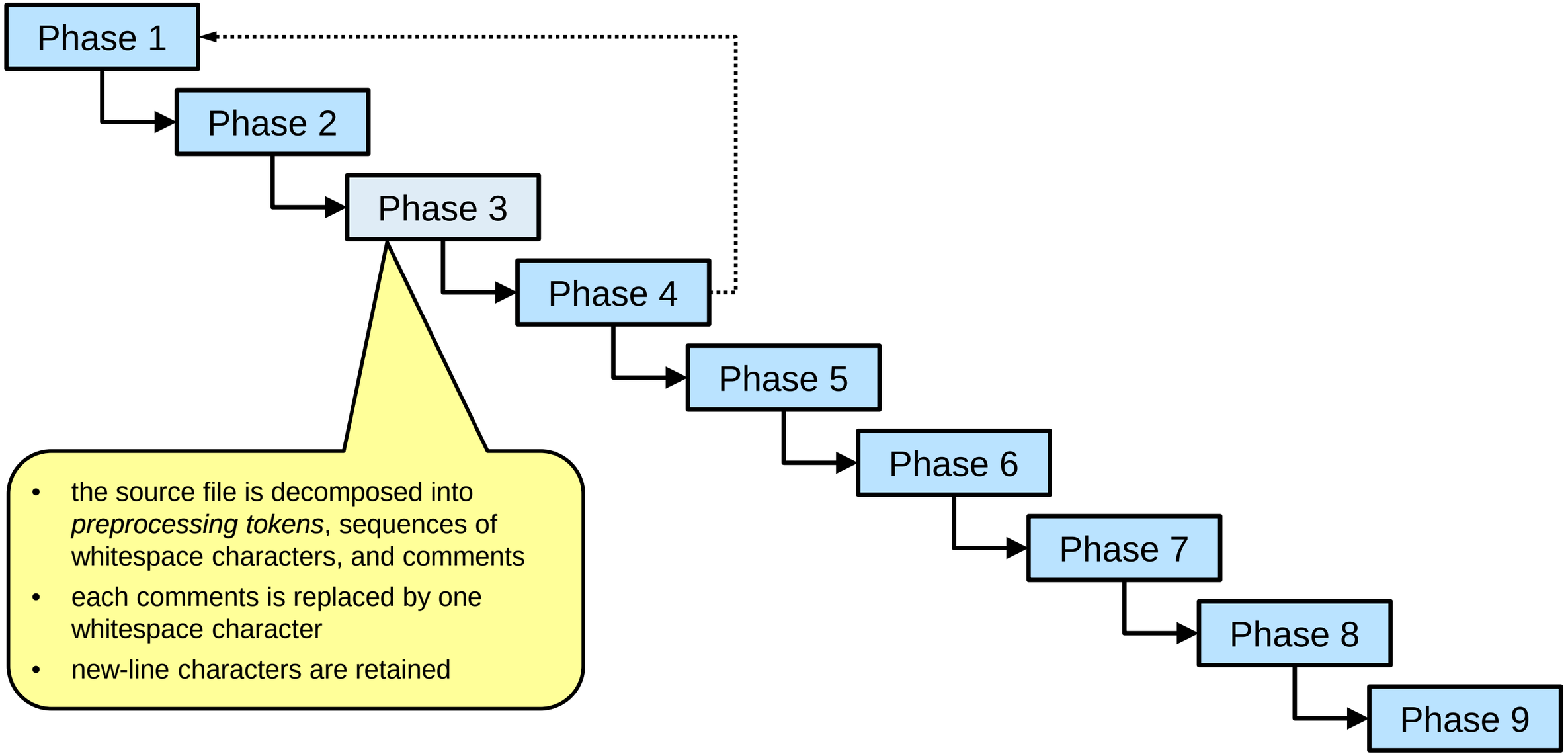
Phases of Translation (1)



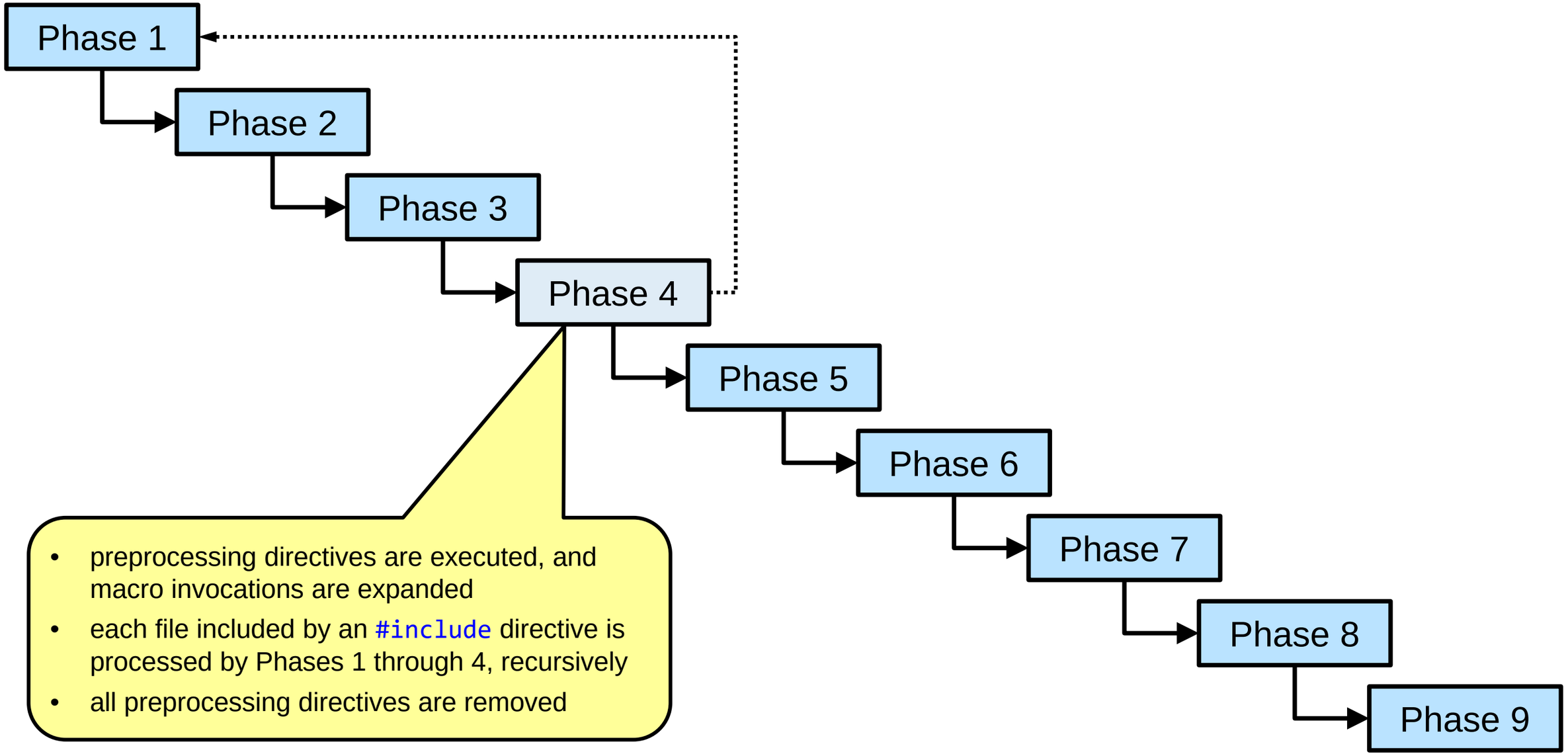
Phases of Translation (2)



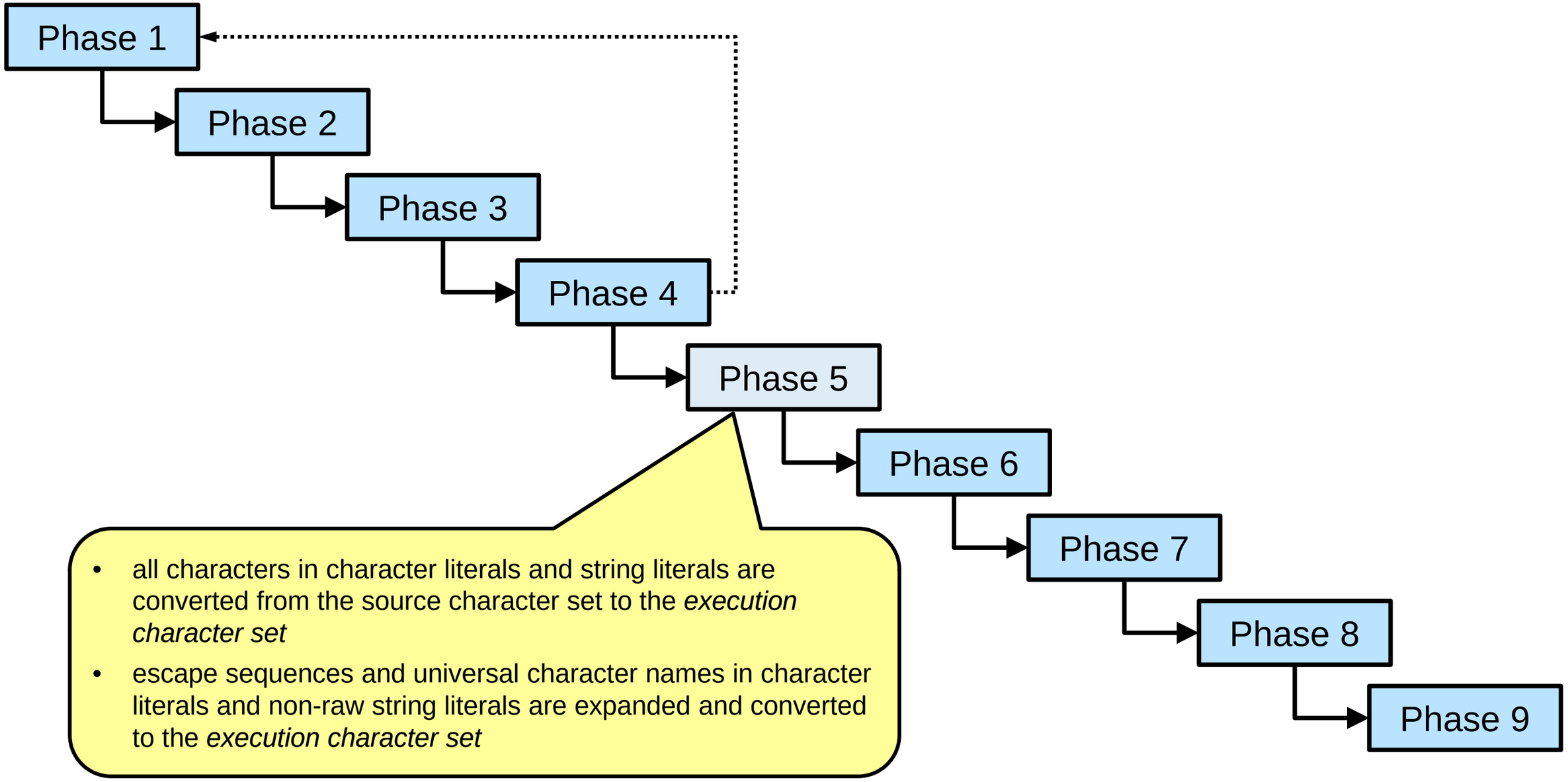
Phases of Translation (3)



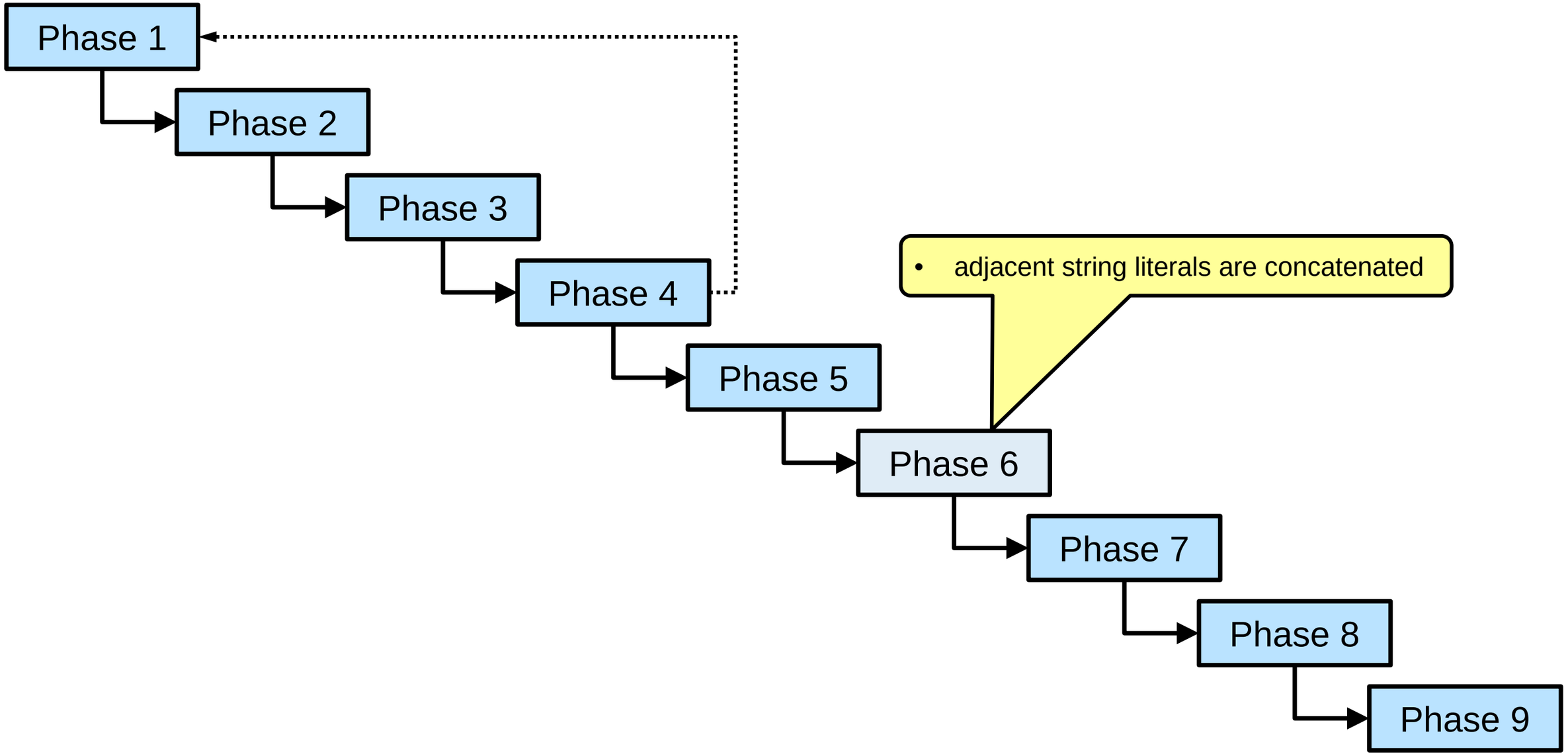
Phases of Translation (4)



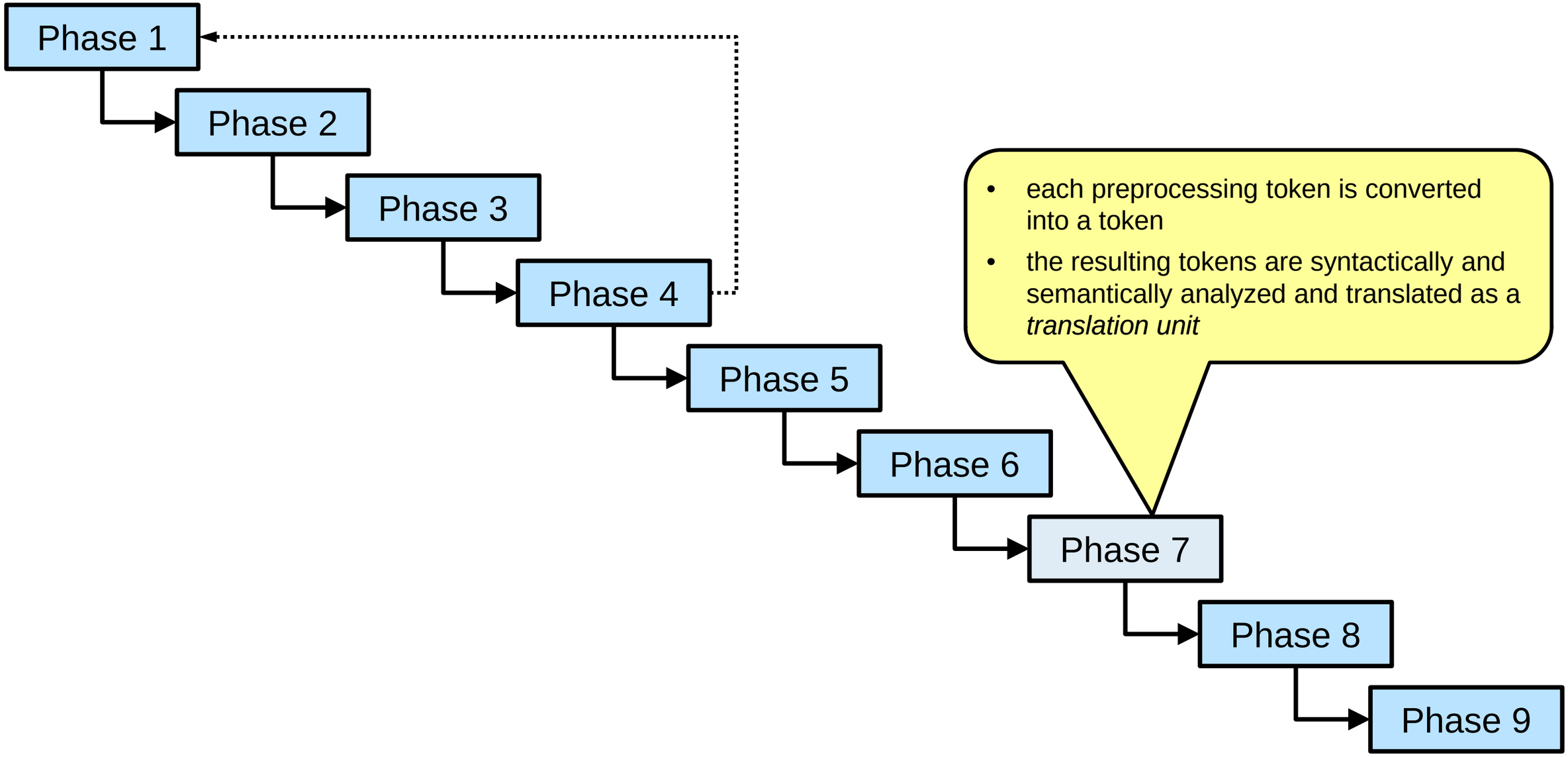
Phases of Translation (5)



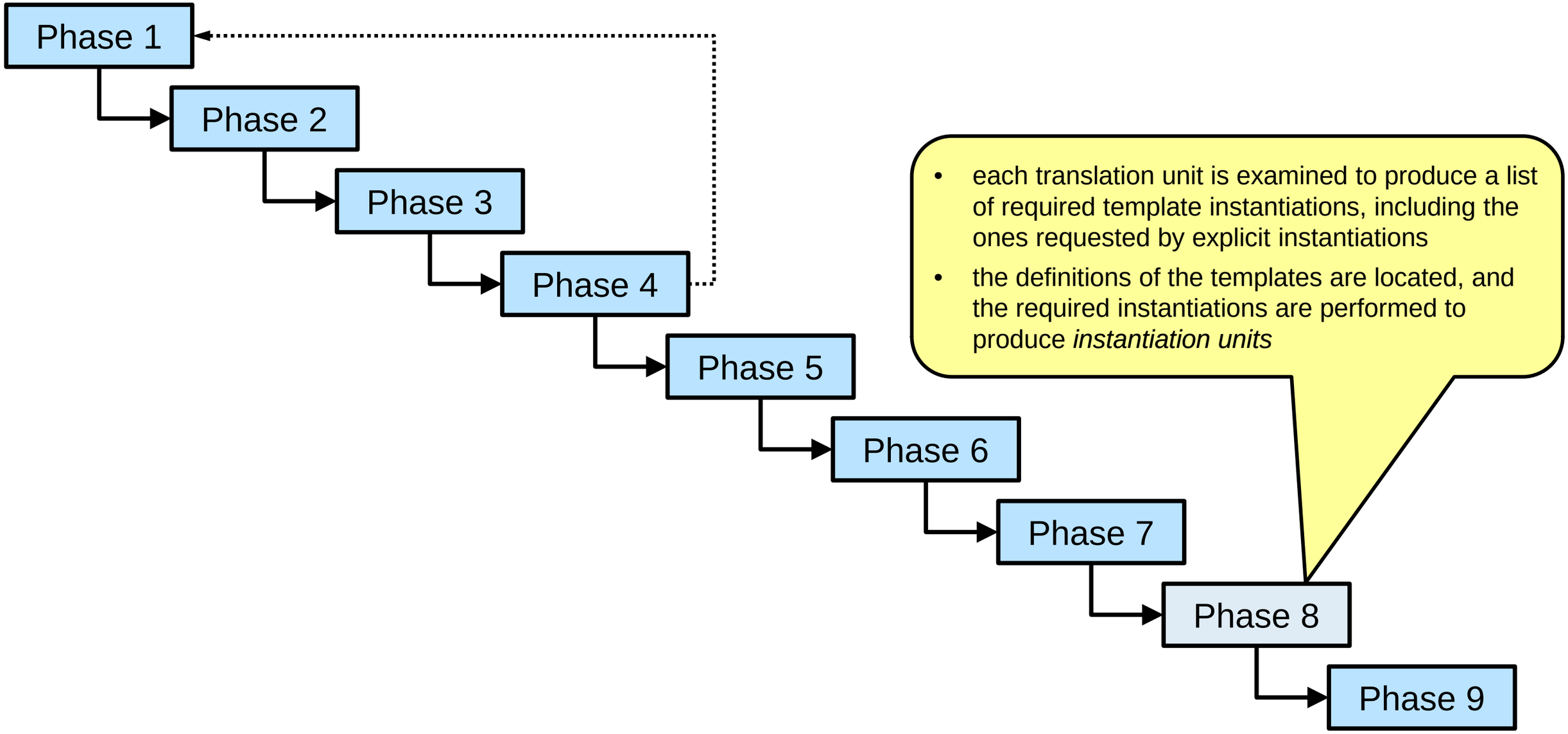
Phases of Translation (6)



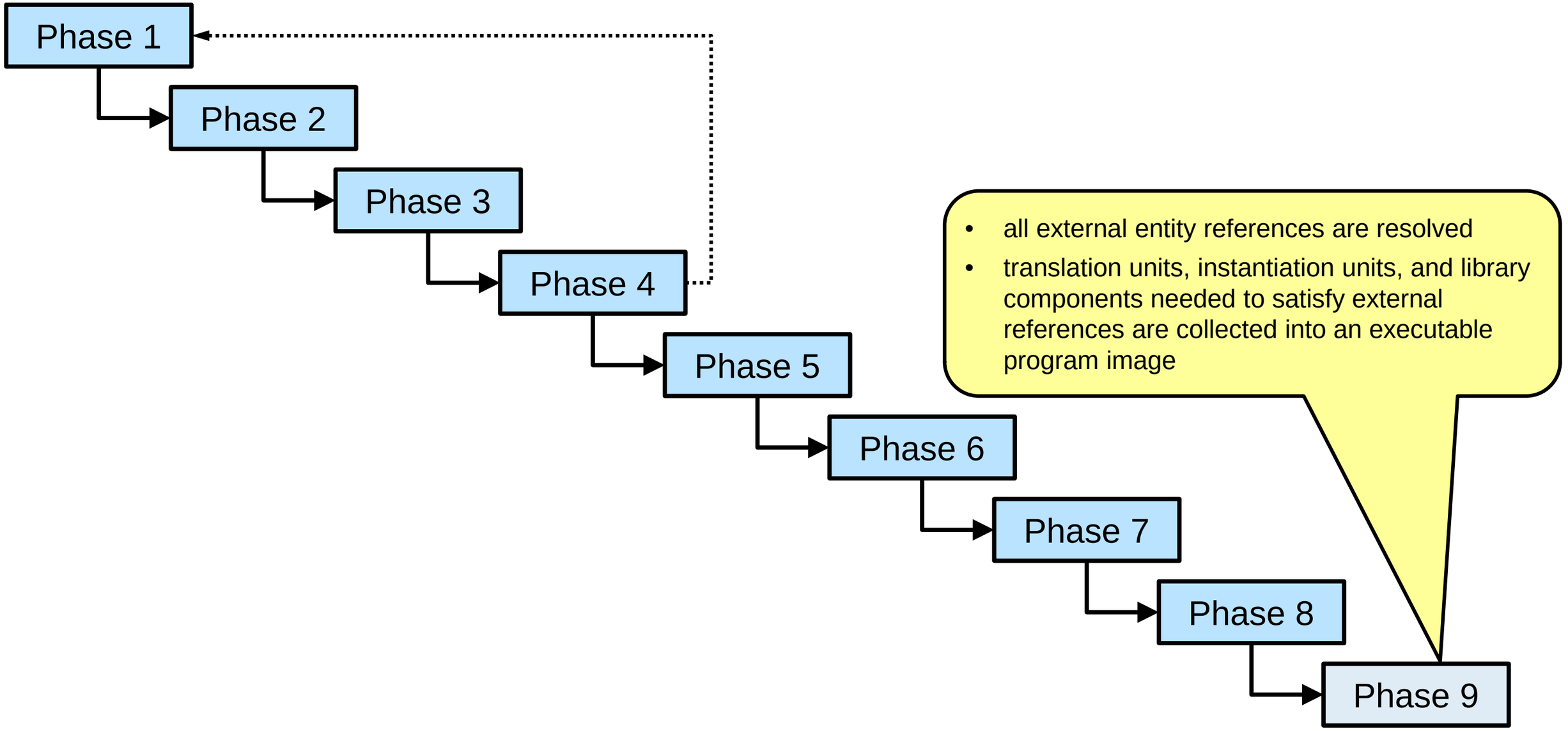
Phases of Translation (7)



Phases of Translation (8)



Phases of Translation (9)



Compilation – From Source File to Object File

- Phases 1 through 6 perform lexical analysis
  - These are what we usually think of as *pre-processing*
  - The output of Phase 6 is a translation unit
- Phases 7 and 8 perform syntax analysis, semantic analysis, and codegen
  - These are what we usually think of as *compilation*
  - The output is called a *translated translation unit* (e.g., object code)
- Phase 9 performs program image creation
  - This is what we normally think of as *linking*
  - The output is an executable image suitable for the intended execution environment

Phases of Translation (6) – a Sample TU For Fun

```
//  hello.h
//==========
#ifndef HELLO_H_INC
#define HELLO_H_INC

#include <iostream>

void print_hello();

#endif
```

```
//  hello.cpp
//===========
#include "hello.h"

void print_hello()
{
    std::cout << "Hello!" << std::endl;
}
```

```
//  main.cpp
//==========
#include "hello.h"

int main()
{
    print_hello();
    return 0;
}
```

- Compilers provide a way to inspect TU contents (or something close to it)
  - With GCC, you can use the `-E` flag:

```
$ g++ -std=c++20 -E main.cpp  | egrep -v '#' | tee main.i
$ g++ -std=c++20 -E hello.cpp | egrep -v '#' | tee hello.i
```

- How many lines in `main.i`? `hello.i`?
  - 41,625 / 41,624 {with GCC 10.2 on Ubuntu 18.04}

Declarations and Definitions

KEWB COMPUTING

- An **entity** is one of these things:
  - value
  - object
  - reference
  - structured binding
  - function
  - enumerator
  - type
  - class member
  - bit-field
  - template
  - template specialization
  - namespace
  - pack

Declarations and Definitions

KEWB COMPUTING

- A **name** is the use of an identifier (several forms are defined) that denotes an entity (or label)
- Every name that denotes an entity is introduced by a **declaration**
- A **declaration** introduces one or more **names** into a translation unit
  - A declaration may also *re-introduce* a name into a translation unit
- A **definition** is a declaration that fully defines the entity being introduced
- A **variable** is an entity introduced by the declaration of an object (or of a reference other than a non-static data member)

Declarations and Definitions

KEWB COMPUTING

- Every declaration *is also a definition*, unless:
  - It declares a function without specifying the function's body
  - It contains the `extern` specifier
  - It is a declaration of a class name without a corresponding definition
  - It is a function declaration without a corresponding definition
  - It is a parameter declaration in a function declaration that is not a definition
  - It is a template parameter
  - It is a `typedef` declaration
  - It is a `using` declaration
  - And several other cases…
- The set of definitions is a subset of the set of declarations

Declarations and Definitions

Declarations

```
extern int       a;
extern const int c;
```

Definitions

```
extern int       a = 0;
extern const int c = 37;
```

Declarations and Definitions

Declarations

```
extern int       a;
extern const int c;

int f(int);
```

Definitions

```
extern int       a = 0;
extern const int c = 37;

int f(int x)
{
    return x + 1;
}
```

Declarations and Definitions

Declarations

```
extern int       a;
extern const int c;

int f(int);




class Foo;
```

Definitions

```
extern int       a = 0;
extern const int c = 37;

int f(int x)
{
    return x + 1;
}

class Foo
{
    int mval;

  public:
    Foo(int x) : mval(x) {}
};
```

Declarations and Definitions

Declarations

```
extern int       a;
extern const int c;

int f(int);




class Foo;









using N::d;
```

Definitions

```
extern int       a = 0;
extern const int c = 37;

int f(int x)
{
    return x + 1;
}

class Foo
{
    int mval;

  public:
    Foo(int x) : mval(x) {}
};

namespace N { int d; }
```

Declarations and Definitions

Declarations

```
extern int       a;
extern const int c;

int f(int);




class Foo;









using N::d;

enum color : int;
```

Definitions

```
extern int       a = 0;
extern const int c = 37;

int f(int x)
{
    return x + 1;
}

class Foo
{
    int mval;

  public:
    Foo(int x) : mval(x) {}
};

namespace N { int d; }

enum color : int { red, green, blue };
```

Declarations and Definitions

Declarations

```
struct Bar
{
    int compute_x(int y, int z);
};


using bar_vec = std::vector<Bar>;

typedef int Int;
```

Definitions

```
int  Bar::compute_x(int y, int z)
{
    return (y + z)*3;
}
```

Linkage

- C++ allows certain declarations of an entity to occur more than once in the same program, translation unit, or scope.

- If a name denotes (refers to) one of these things, it may have **linkage**
  - object
  - reference
  - function
  - type
  - template
  - namespace
  - value

- If a name has linkage, then it refers to the same entity as when that name was introduced by a declaration in a different scope

Linkage

- A name can have one of three kinds of linkage – external, internal, no(ne)

- **External linkage**
  - An entity denoted by a name with external linkage can be referred to by names from scopes of other translation units, or from other scopes of the same translation unit

- **Internal linkage**
  - An entity denoted by a name with internal linkage can be referred to by names from scopes in the same translation unit

- **No linkage**
  - An entity denoted by a name with no linkage can be referred to only by names from the scope where it is declared

External Linkage

```
// my_header.h
//------------
int f(int i);        // declares function f

extern int const x; // declares x

using Int = int;

// my_source.cpp
//--------------
#include "my_header.h"

int f(int i)         // defines f (and i)
{
    return i + x;
}
```

```
// my_other_source.cpp
//--------------------
#include "my_header.h"

extern int const x = 17; // defines x

int g(int i)             // defines g (and i)
{
    return f(i) % 3;
}


// f, x, and Int have external linkage
```

Internal Linkage

```
// my_header.h
//------------
int f(int i);        // declares function f

extern int const x; // declares x

using Int = int;

// my_source.cpp
//--------------
#include "my_header.h"

int f(int i)         // defines f (and i)
{
    return i + x;
}
```

```
// my_other_source.cpp
//--------------------
#include "my_header.h"

extern int const x = 17; // defines x

namespace {
    int const y = 1000;  // defines y
    struct foo {         // defines foo
        int fuzzy();
        ...
    };
    using fubar = foo;
}

int g(int i)           // defines g and i
{
    foo my_foo;
    ...
    return f(i) + y – my_foo.fuzzy();
}

// y, foo, fubar have internal linkage
```

Internal Linkage

```
// my_header.h
//------------
int f(int i);        // declares function f

extern int const x; // declares x

using Int = int;

// my_source.cpp
//--------------
#include "my_header.h"

int f(int i)         // defines f (and i)
{
    return i + x;
}
```

```
// my_other_source.cpp
//--------------------
#include "my_header.h"

extern int const x = 17; // defines x

namespace {
    int const y = 1000;  // defines y
    struct foo {         // defines foo
        int fuzzy();
        ...
    };
    using fubar = foo;
}

int g(int i)             // defines g and i
{
    typedef foo FUBAR;
    foo my_foo;
    int z = 64;          // defines z
    ...
    return f(i) + y - my_foo.fuzzy();
}
// FUBAR, my_foo, and z have no linkage
```

The One-Definition Rule (ODR)

- A given translation unit can contain at most one definition of any:
  - variable
  - function
  - class type
  - enumeration type
  - template
  - default argument for a parameter for a function in a given scope
  - default template argument

- There may be multiple declarations, but there can only be one definition

The One-Definition Rule (ODR)

- A given program must contain exactly one definition of every non-`inline` variable or function that is used in the program
  - Again, multiple declarations are OK, but only one definition

- For an `inline` variable or an `inline` function, a definition is required in every translation unit that uses it
  - `inline` was originally a suggested optimization made to the compiler
  - It has now evolved to mean "multiple definitions are permitted"

- Exactly one definition of a class must appear in any translation unit that uses it in such a way that the class must be complete
  - Like construction or calling a member function

The One-Definition Rule (ODR) - OK

```
// TU-1
//-----

extern int const x;
```

```
// TU-2
//-----

extern int const x = 0;
```

The One-Definition Rule (ODR) - Invalid

```
// TU-1
//-----

extern int const x = 0;
```

```
// TU-2
//-----

extern int const x = 0;
```

The One-Definition Rule (ODR) - OK

```
// TU-1
//-----

void f(int i);
```

```
// TU-2
//-----

void f(int i)
{
   return i+1;
}
```

The One-Definition Rule (ODR) - Invalid

```
// TU-1
//-----

void f(int i)
{
    return i+1;
}
```

```
// TU-2
//-----

void f(int i)
{
   return i+1;
}
```

The One-Definition Rule (ODR) - OK

```
// TU-1
//-----

struct foo
{
    int val;
    foo() : val(-1){}
};
```

```
// TU-2
//-----

struct foo
{
    int val;
    foo() : val(-1){}
};
```

The One-Definition Rule (ODR) - OK

```
// TU-1
//-----

struct foo
{
    int val;
    foo();
};
```

```
// TU-2
//-----

struct foo
{
    int val;
    foo();
};

foo::foo(int i) : val(i) {}
```

The One-Definition Rule (ODR) - Invalid

```
// TU-1
//-----

struct foo
{
    int val;
    foo();
};

foo::foo(int i) : val(i) {}
```

```
// TU-2
//-----

struct foo
{
    int val;
    foo();
};

foo::foo(int i) : val(i) {}
```

The One-Definition Rule (ODR)

- My simple guidelines:

- For an `inline` thing (variable or function) that get used in a translation unit, make sure to define it in at least once somewhere in that translation unit

- For everything else that gets used, make it gets defined exactly once in across all translation units

Storage Duration and Objects

- Every object has a **storage duration**

- **automatic** storage duration
  - Object storage is allocated at the beginning of the enclosing block and deallocated at the end of the block
  - Applies to all local objects except those declared `thread_local`, `static`, or `extern`

- **dynamic** storage duration
  - Object storage is allocated and deallocated by the program using functions that perform dynamic memory allocation
  - Objects with this duration can be created using *new-expressions* and destroyed using *delete-expressions*

Storage Duration and Objects

- **static** storage duration
  - Object storage is allocated at the beginning of the program and deallocated at the end of the program
  - Applies to all objects declared at namespace scope, including the global namespace
  - Applies to all objects declared `static` or `extern`
  - There is only one instance of an object with static duration in the program

- **thread** storage duration
  - Object storage is allocated when the thread creating the object begins and deallocated when that thread ends
  - Applies only to objects declared `thread_local`
  - Each thread has its own instance of an object with thread duration

What is an ABI?

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- ABI (application binary interface) is the platform-specific specification of how entities defined in one TU interact with entities defined in another TU

- For C++, this includes things like
  - Name mangling for functions
  - Name mangling for non-template types
  - Name mangling for template instantiations
  - The size, layout, and alignment of objects of any given type
  - How the bytes in an object's binary representation are interpreted
  - Calling conventions for passing arguments to functions and receiving a returned object
  - Calling conventions for making system calls

- On Linux GCC and Clang use the Itanium ABI; On Windows, MSVC uses its own ABI

Name Mangling

- **Name mangling** refers to the way in which entity names in a TU are transformed into symbol names in object code

- C++ deliberately maintains binary compatibility with C
  - C++ object files can use functions and data in C object files, and vice versa

- The C language does not provide overloading or namespaces
  - Given a C function whose declaration is `void fubar(int)`,
  - The corresponding symbol name in object code is `_fubar`
  - The symbol name will be the same no matter the number of parameters or their types

- Re-using names in C can be tricky, if not impossible

Name Mangling

- C++ **does** support overloading and namespaces, permitting name reuse
  - Map the name of a C++ entity into a name that can co-exist with the names of C entities
  - Transform each overloaded use of a name into a unique symbol name
  - Encode extra information about the entity into the symbol name

```
// From GCC 10.2 on Ubuntu 18.04
namespace wikipedia
{
    class article
    {
      public:
        std::string format();
        // = _ZN9wikipedia7article6formatB5cxx11Ev
    };
}

std::string format(std::string const& fmt, int64_t val);
// _Z6formatRKNSt7__cxx1112basic_stringIcSt11char_traitsIcESaIcEEEl
```

Linking

- **Linking** is the final stage of compilation, performed by the linker

- The linker combines object files and libraries to produce an executable file
  - It examines all the object files and libraries to find their symbols
  - It determines a set of all symbols that are used by the program
  - It resolves references to internal and external symbols
  - It assigns addresses to the symbols representing functions and variables
  - It revises code and data to reflect these addresses
  - It emits executable code

- The compiler and the linker must agree on the ABI
  - Both must understand object code in the same way

Loading and Running

- The operating system loader validates the executable image file
  - Checks permissions and resource requirements
  - Checks that the file is executable and that the instructions in it can be executed

- The operating system loads and runs the image
  - The executable file is copied into memory
    - Relocations and symbol fixups are performed, if needed (e.g., when using shared objects or DLLs)
  - Command-line parameters are copied onto the stack
  - Registers are initialized
    - Stack pointer set to point to the top of the stack; other registers are cleared
  - Control jumps to the start routine, which
    - Performs program initialization
    - Calls `main()` initialization with the command-parameters

Thank You for Attending!

Talk: https://github.com/BobSteagall/CppCon2020

Blog: https://bobsteagall.com