Compilation and Interpretation

COMP 524: Programming Language Concepts
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Based in part on slides and notes by S. Olivier, A. Block, N. Fisher, F. Hernandez-Campos, and D. Stotts.

Executing High-Level Languages

A processor can only execute machine code.

- ➡ Some can execute several “dialects” (e.g., ARM).

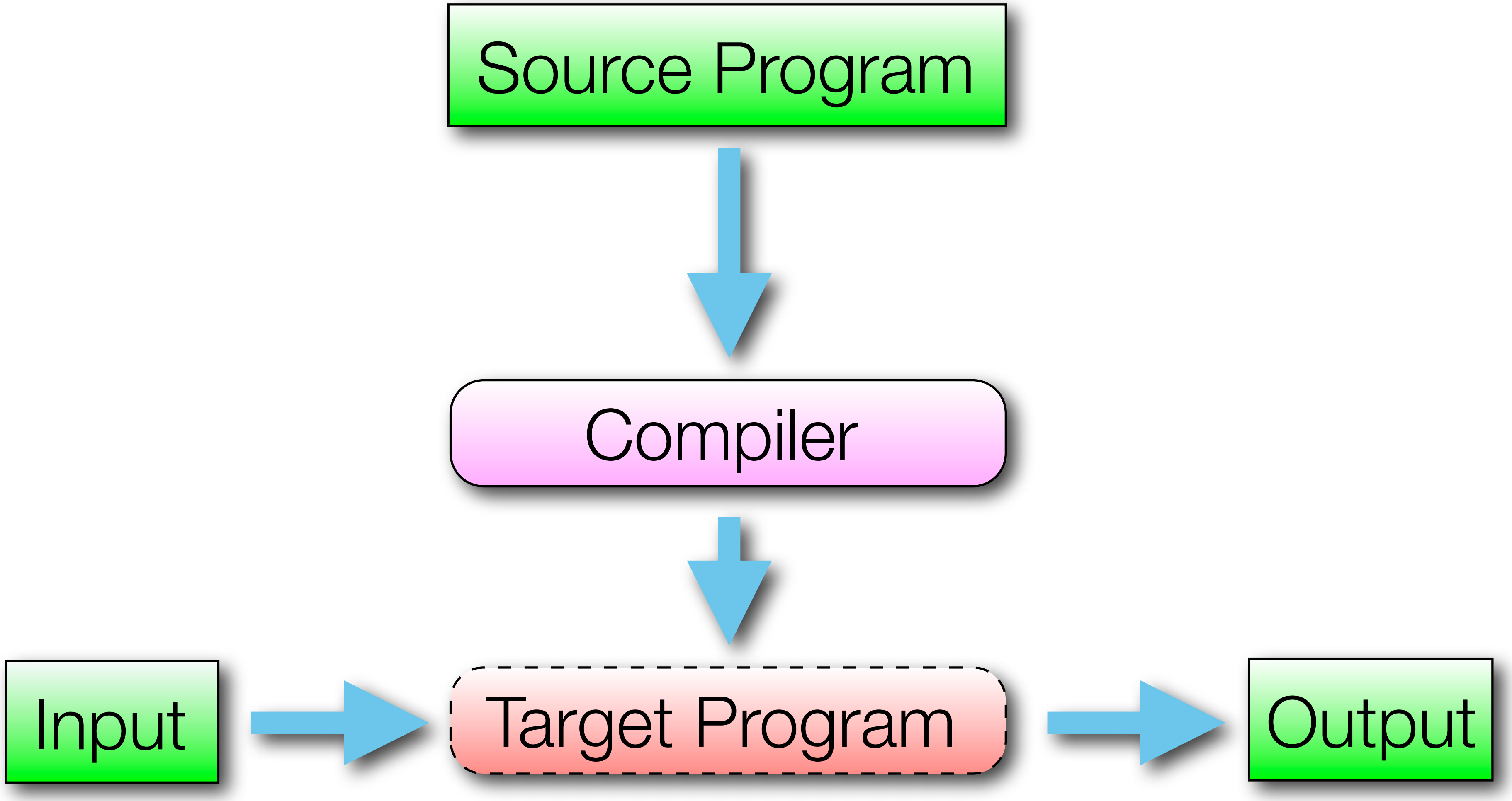
Thus, high-level languages must be translated for execution.

- ➡ Ahead of execution: **compilation**.
- ➡ Piece-wise during execution: **interpretation**.

Compilation

Ahead of time translation.

- From (high-level) **source** language to (lower-level) **target** language.
- **Deep inspection** of source program as a whole.
- Compiler is **unaware of subsequent input**.

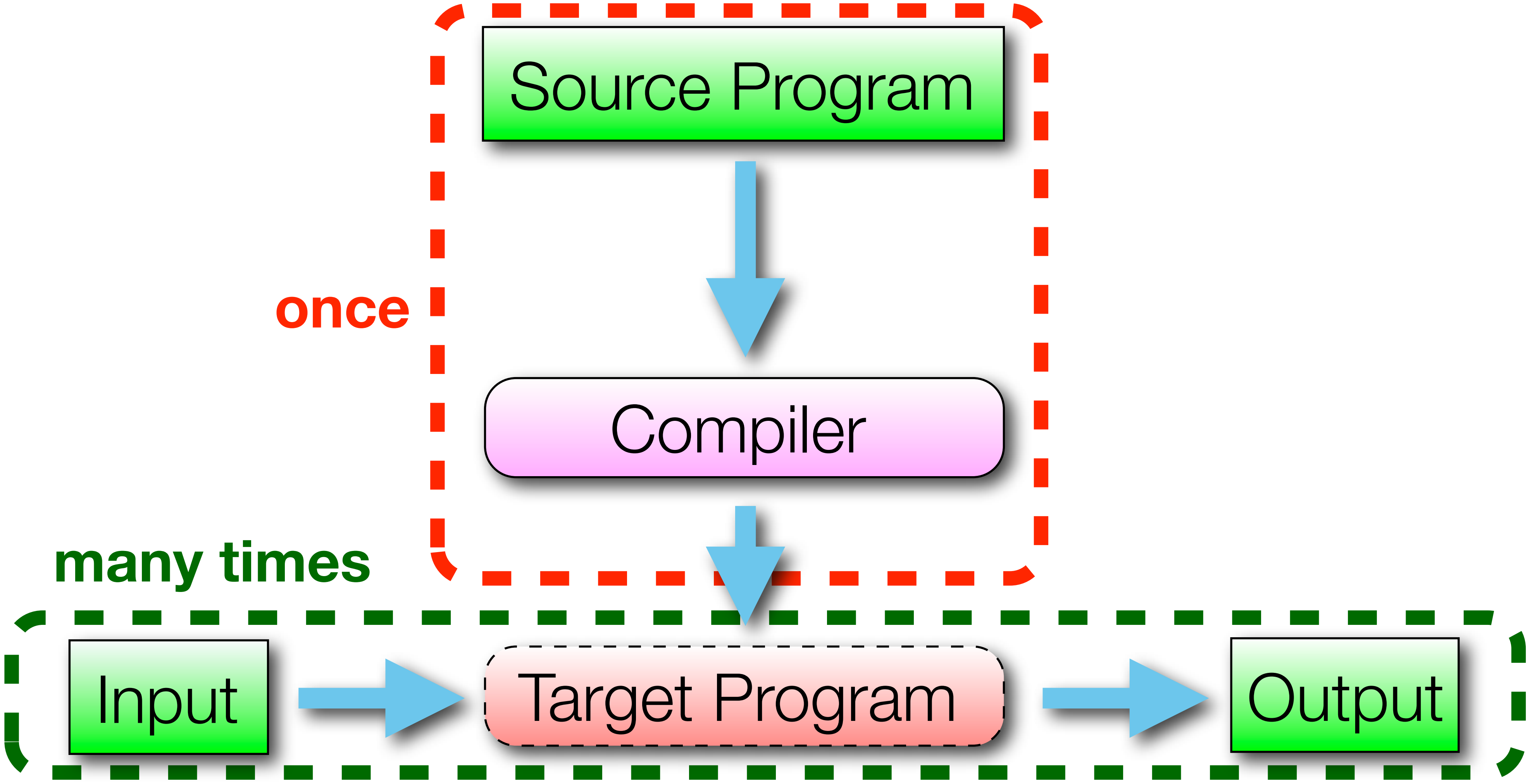


Compilation

Ahead of time tr

- From (high-le uage.
- **Deep inspec**
- Compiler is **u**

Translation occurs only **once**, but program is executed **many times**.



Compilation

Advantages.

- ➡ No translation cost at runtime: **efficient execution**.
- ➡ **Translation cost amortized** over many runs.
- ➡ Can distribute program **without revealing** either **source** or compiler (**commercial software distribution**).
- ➡ Extensive (and slow) **optimizations** possible.

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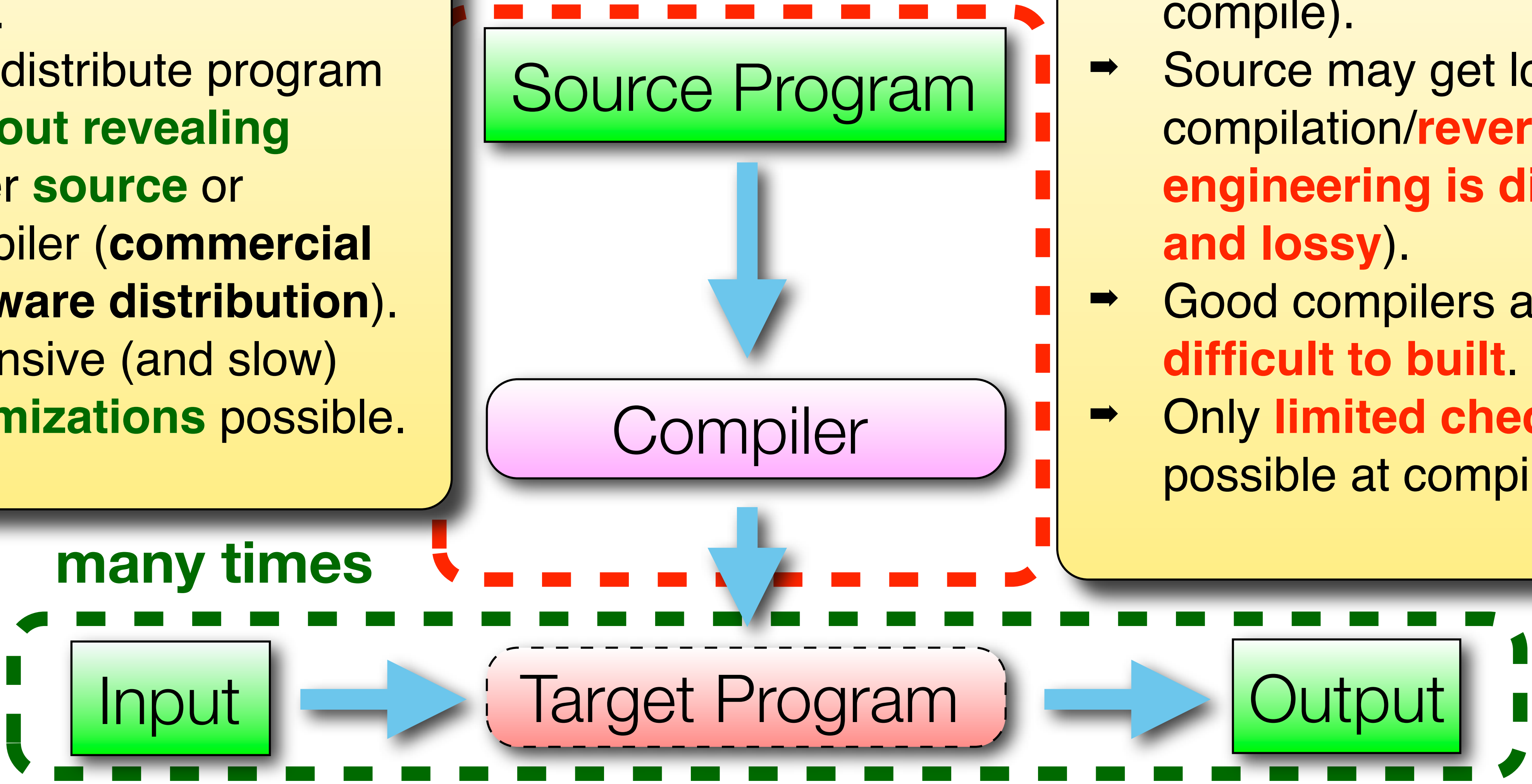
f **subsequent input**.



Disadvantages.

- ➡ Runtime errors hard(er) to **diagnose**.
- ➡ **Slow edit-compile-test cycle** (large systems can take minutes or hours to compile).
- ➡ Source may get lost (de-compilation/**reverse engineering is difficult and lossy**).
- ➡ Good compilers are **difficult to built**.
- ➡ Only **limited checks** possible at compile time

Target Language

Target language.

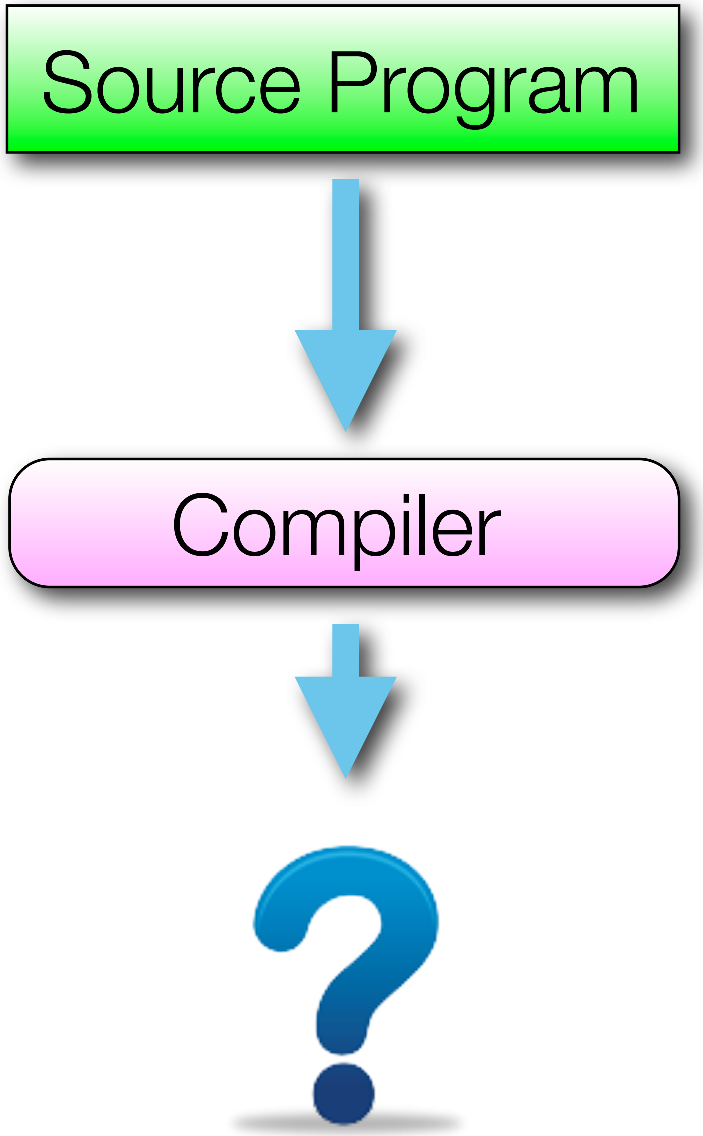
- ➡ Often assembly or machine code.
- ➡ Can be **any** language.

Generating C code.

- ➡ C code generation is a lot easier.
- ➡ C compilers often perform many optimizations.
- ➡ Since C is portable, this makes the higher-language portable “for free.”

Examples.

- ➡ **cfront** (first C++ compiler) produced C code.
- ➡ **ghc** (Glasgow Haskell Compiler) can produce either assembly or C code.


Source Program

Compiler

?

Compilation vs. Assembly

What is the fundamental difference between an assembler and a compiler?

Compiler.

- Deep **inspection** of program **semantics**.
- May **reject** syntactically correct **programs** for many reasons.
- E.g., type checking.
- E.g., “return missing”
- Transforms code.
- Optimization.
- **Complex code generation**.
- **Never produces invalid machine code** (only generates code for valid programs).

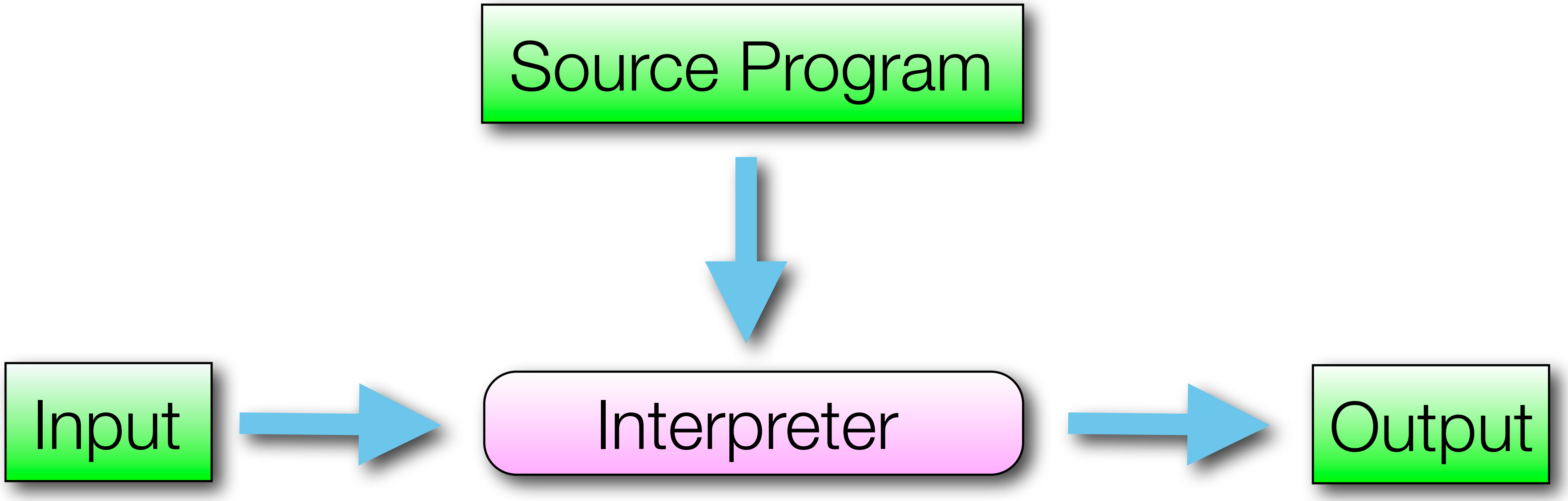
Assembler.

- **Little/no checks** beyond basic syntax correctness.
- Syntactically correct programs are **not rejected**.
- No transformation (beyond macro expansion).
- Simple translation (**table lookup** of instruction encoding).
- Can produce invalid machine code (if fed bad input).

Interpretation

Translation during execution.

- ➡ **Each run** requires on-the-fly translation.
- ➡ Interpreter operates on **two inputs**: program and actual input.
- ➡ Source program is “configuration” for interpreter to transform actual input.
- ➡ Often line/function/instruction interpreted **individually on demand**.



Source Program

Input

Interpreter

Output

Interpretation

Advantages.

- **Excellent debugging** facilities: source code known when error occurs.
- **Excellent checking**: both input and source are known.
- **Easy to implement**.
- Quick feedback due to **rapid edit-test cycle**.
- Can be **embedded** into other applications (for scripting purposes).
- Can **generate and evaluate new code** at runtime (`eval`).

ution.

the-fly translation.

two inputs: program a

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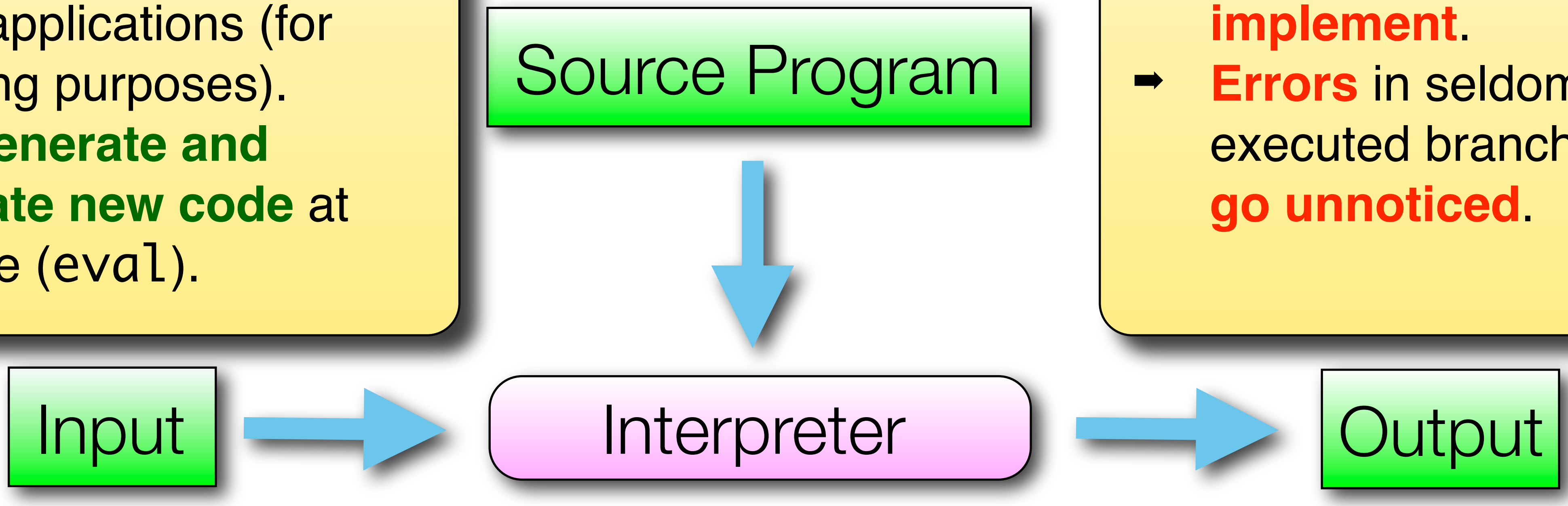
ruction interpreted **indiv**

Disadvantages.

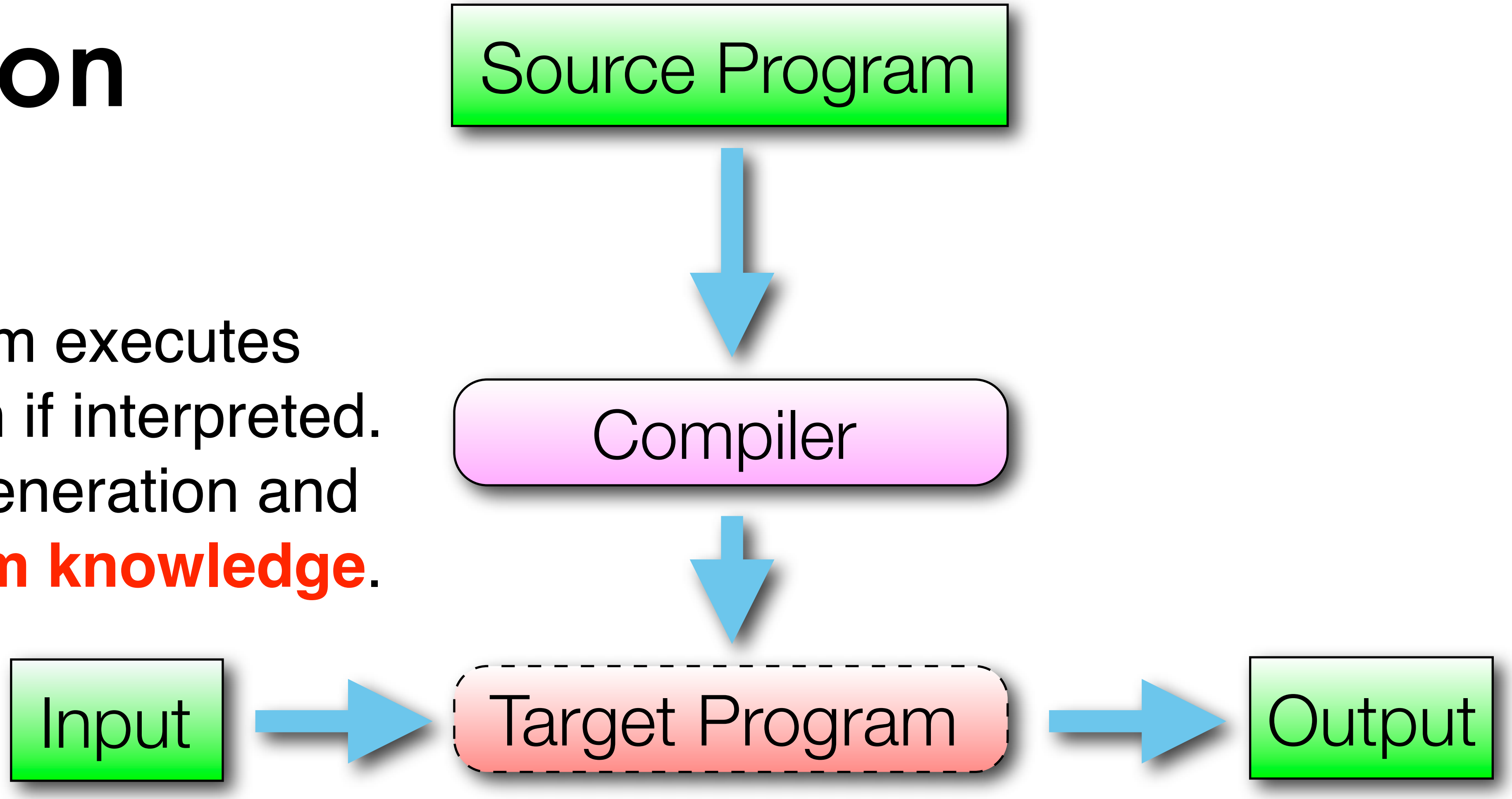
- Translation occurs many times (**redundant work**).
- Translation cost occur at runtime: **inefficient**.
- Protecting intellectual property requires **source code obfuscation** (which can be unreliable).
- Reasonably **fast interpreters** are **hard to implement**.
- **Errors** in seldom-executed branches **may go unnoticed**.



Comparison

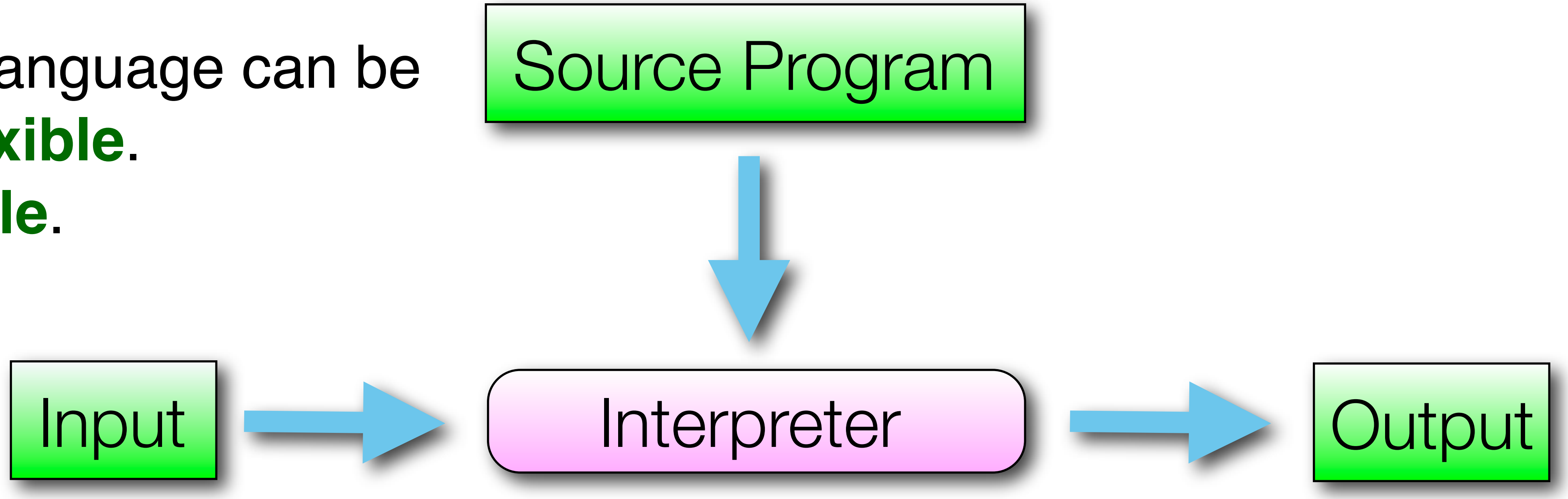
Compilation

- ➡ Resulting program executes much **faster** than if interpreted.
- ➡ Requires code generation and **detailed platform knowledge**.


Source Program
Compiler
Input
Target Program
Output

Interpretation

- ➡ Programming language can be much more **flexible**.
- ➡ Can be **portable**.
- ➡ **Inefficient**.


Source Program
Input
Interpreter
Output

Mixing Compilation and Interpretation

Interpreting high-level languages is usually slow.

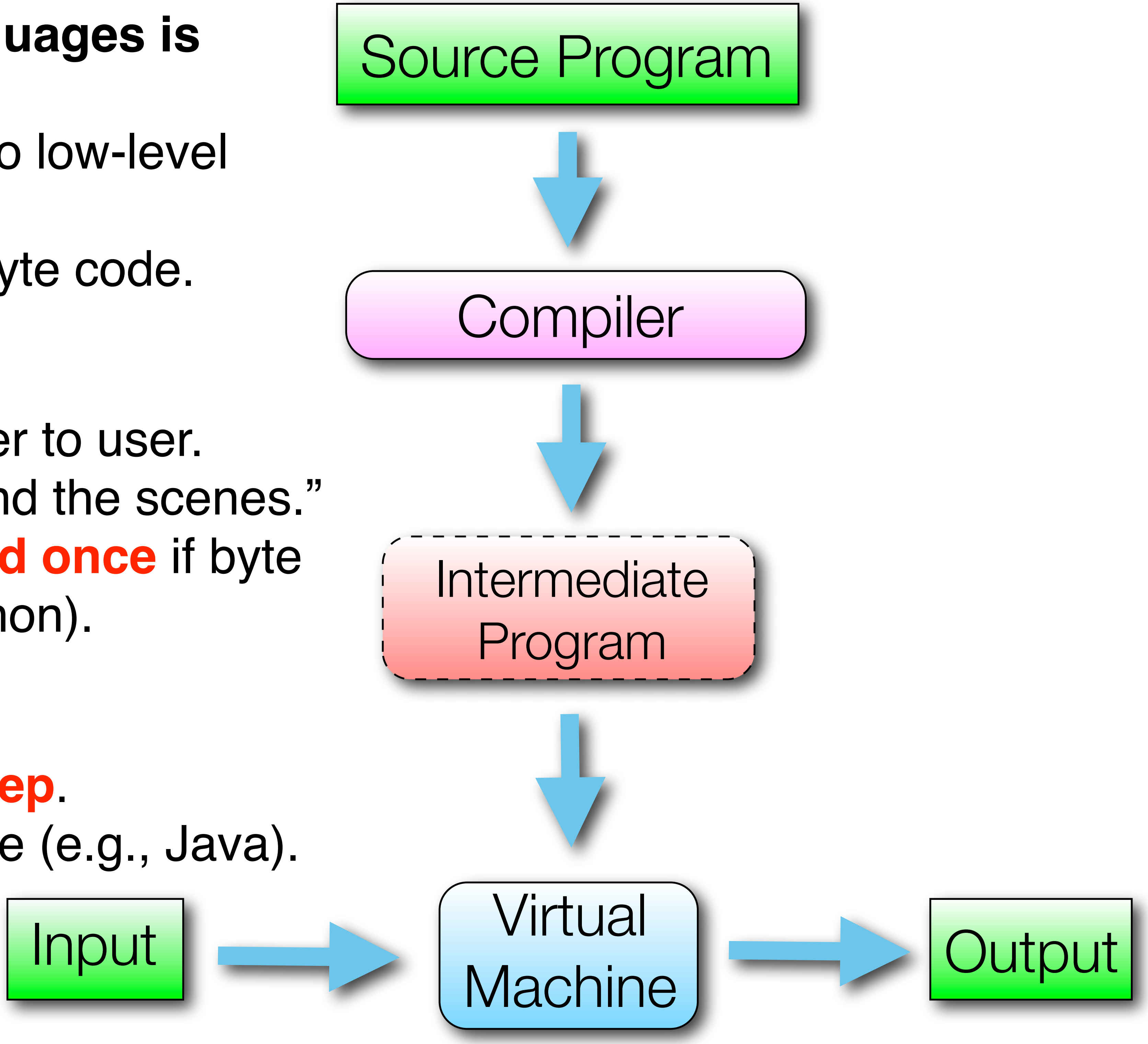
- ➡ First compile high-level to low-level byte code.
- ➡ Interpret much simpler byte code.

Implicit compilation.

- ➡ Tool appears as interpreter to user.
- ➡ Compilation occurs “behind the scenes.”
- ➡ Compilation **only required once** if byte code is cached (e.g., Python).

Explicit compilation.

- ➡ **Separate compilation step**.
- ➡ User is aware of byte code (e.g., Java).



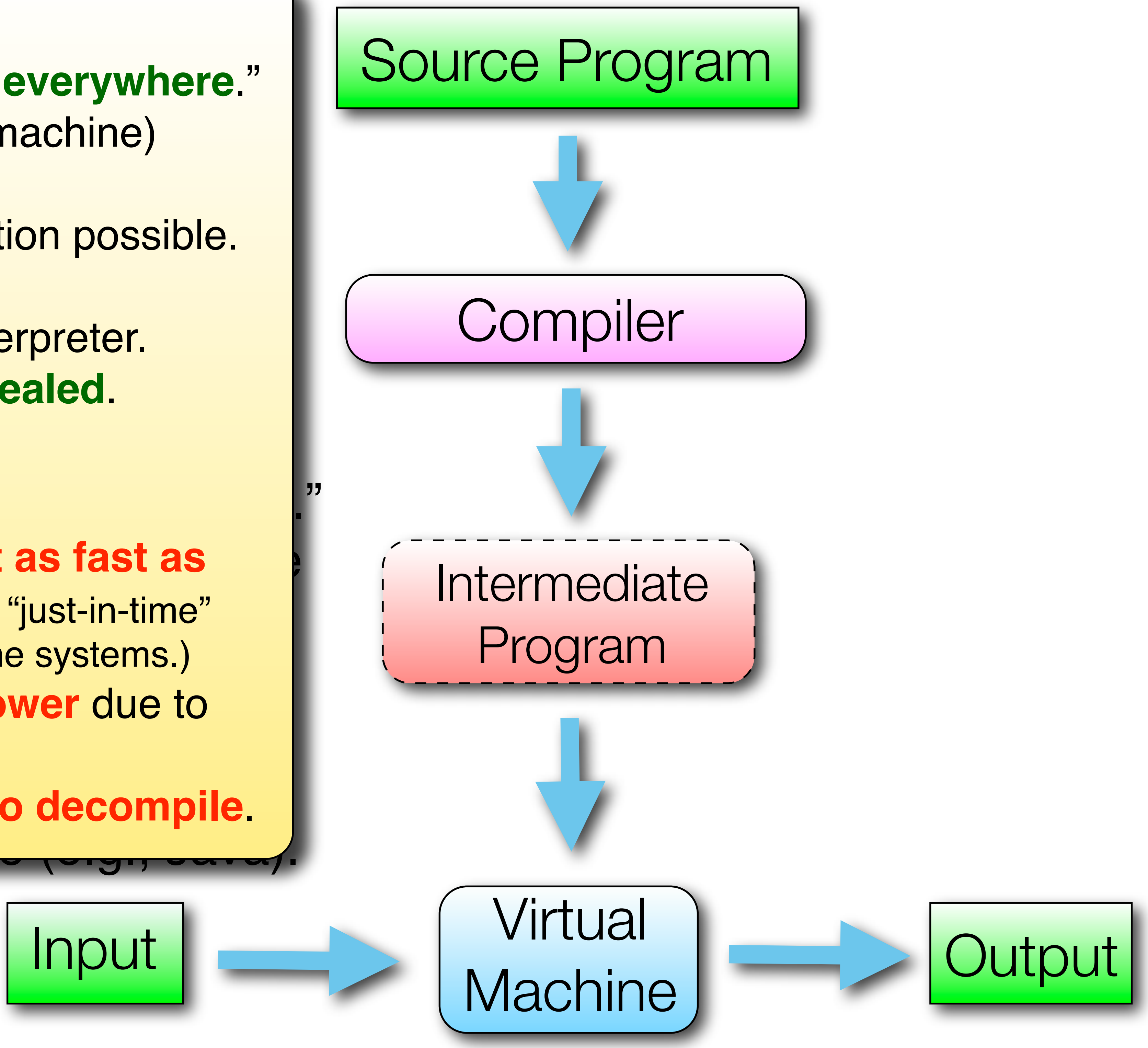
Mixing Compilation and Interpretation

Advantages.

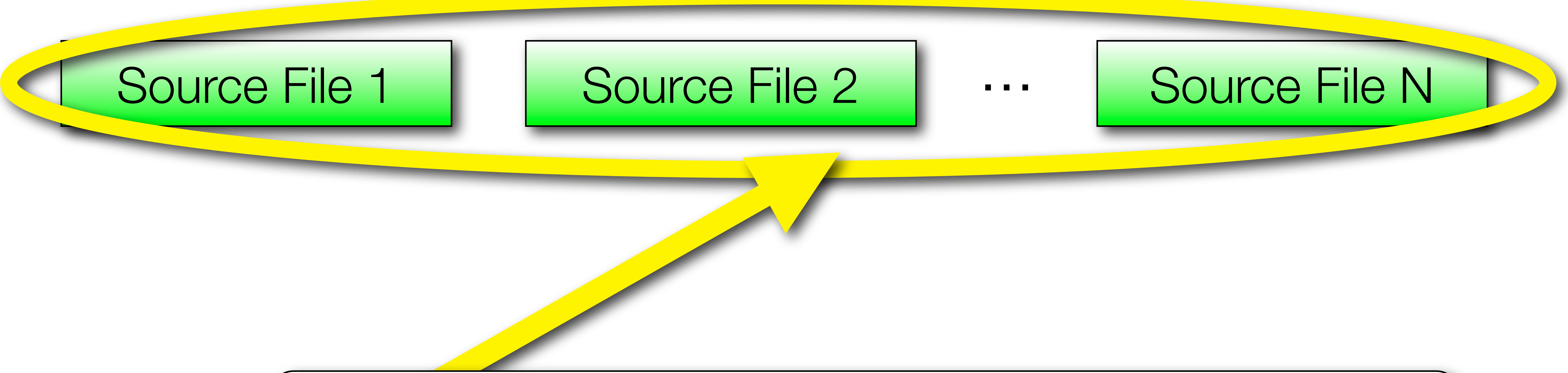
- Enables “**compile once, run everywhere**.”
- Low-level interpreter (virtual machine) **easier to optimize.**
- **Optimization** during compilation possible.
- **Checks** like a compiler.
- Implicit: **Flexibility** like an interpreter.
- Explicit: Source code **not revealed**.

Disadvantages.

- If byte code is interpreted **not as fast as machine code**. (Will talk about “just-in-time” compilation when we cover runtime systems.)
- Implicit: **Program startup slower** due to compilation step.
- Explicit: Byte code is **easier to decompile**.

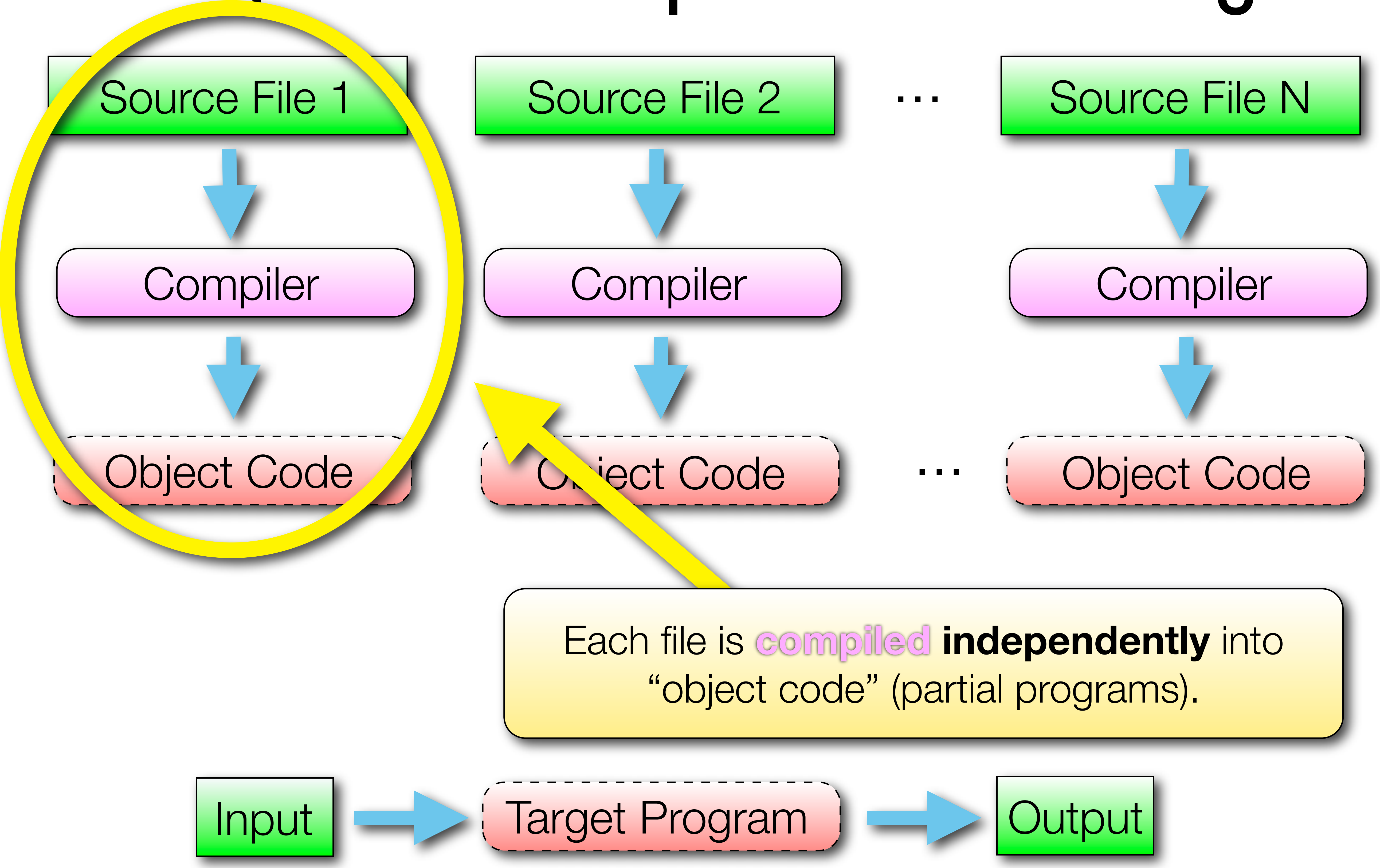


Separate Compilation + Linking



The **source program** is **spread out across several files**.

Separate Compilation + Linking



Source File 1

Source File 2

…

Source File N

Compiler

Compiler

Compiler

Object Code

Object Code

…

Object Code

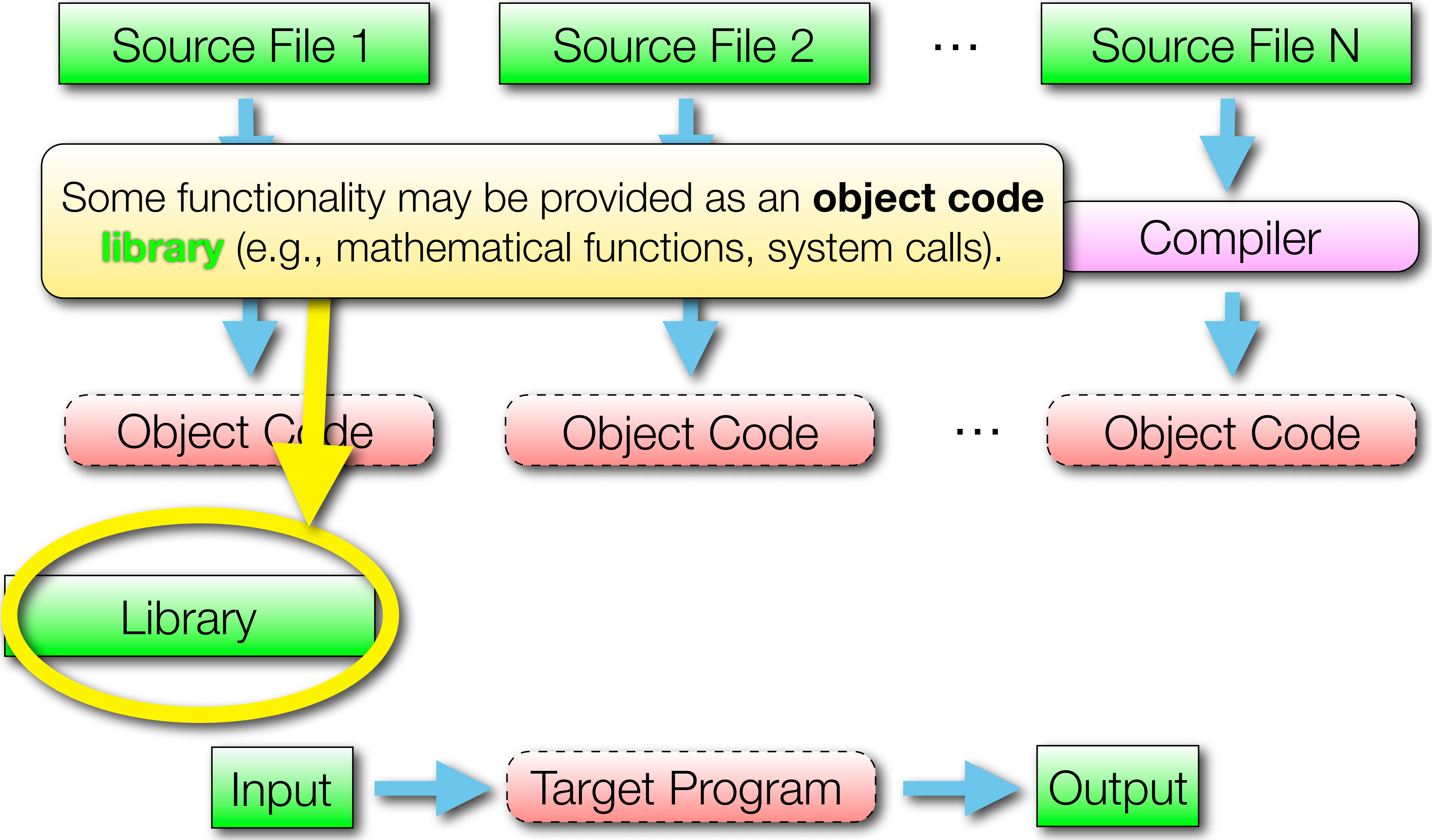
Each file is compiled **independently** into "object code" (partial programs).

Input

Target Program

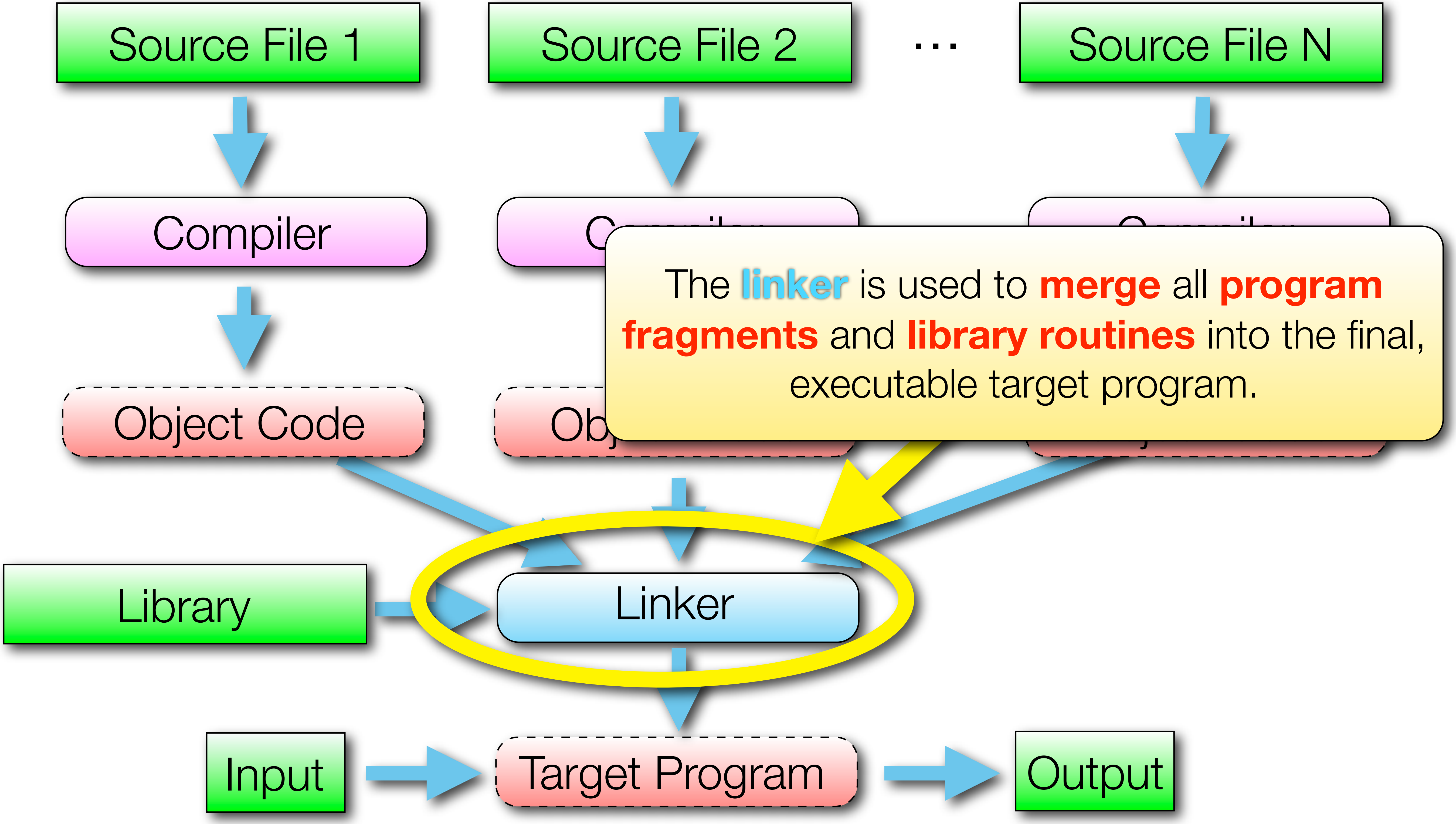
Output

Separate Compilation + Linking



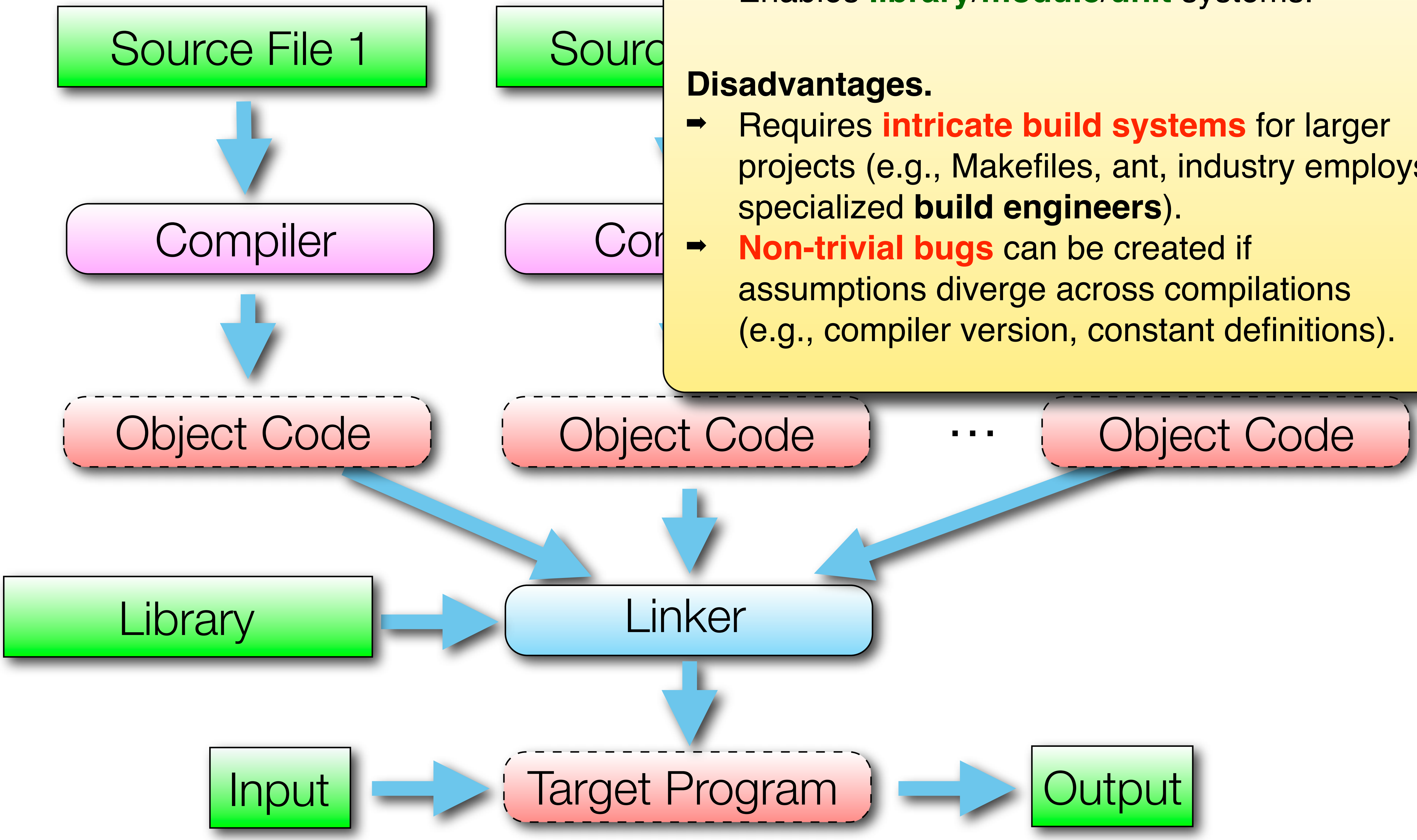
Some functionality may be provided as an **object code library** (e.g., mathematical functions, system calls).

Separate Compilation + Linking



The **linker** is used to **merge** all **program fragments** and **library routines** into the final, executable target program.

Separate Com


Source File 1

Sourc

Compiler

Co

Object Code

Object Code

…

Object Code

Library

Linker

Input

Target Program

Output

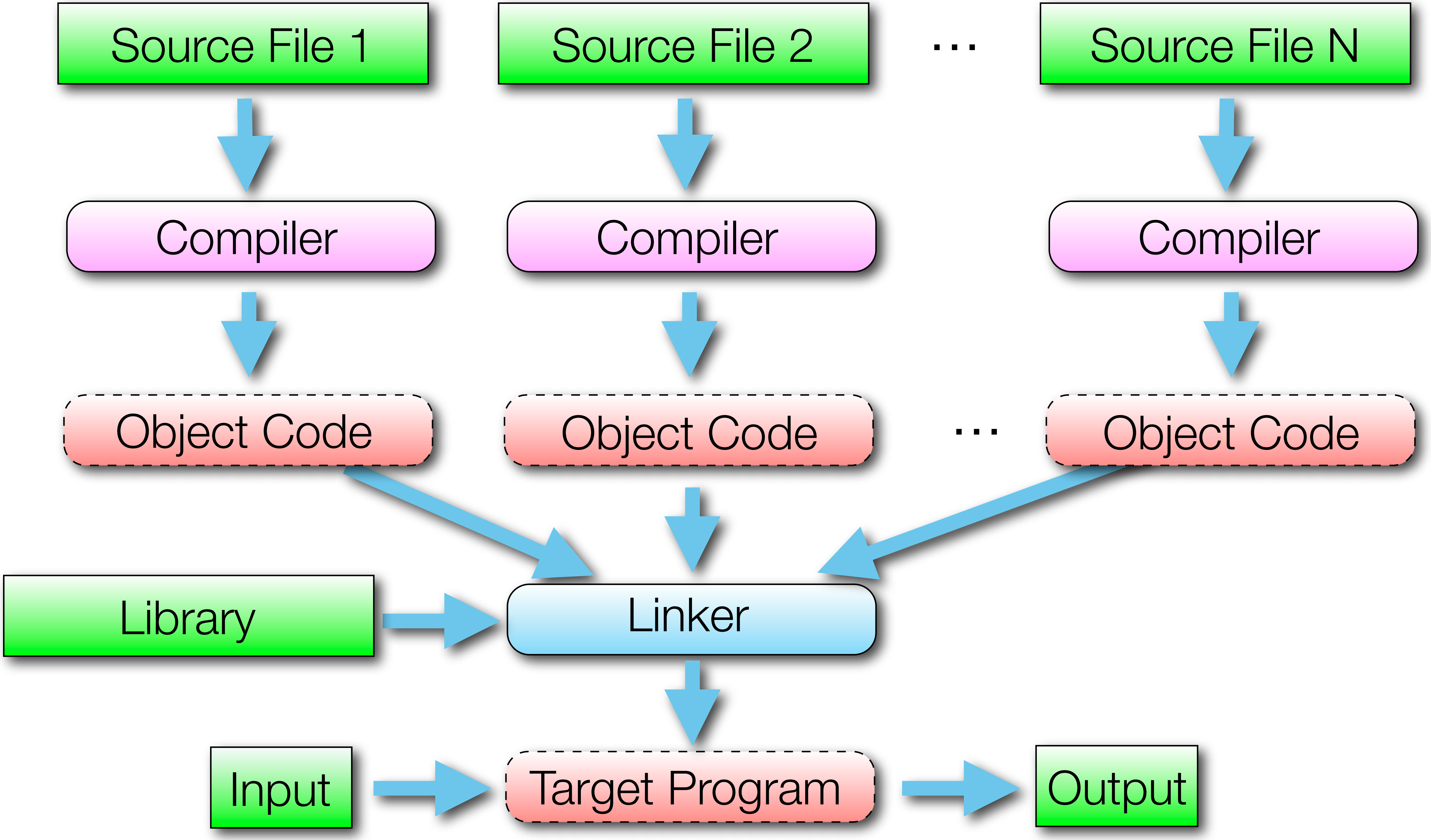
Advantages.

- Enables **collaboration**: teams can work on different files in parallel.
- Enables code reuse.
- Enables **library/module/unit** systems.

Disadvantages.

- Requires **intricate build systems** for larger projects (e.g., Makefiles, ant, industry employs specialized **build engineers**).
- **Non-trivial bugs** can be created if assumptions diverge across compilations (e.g., compiler version, constant definitions).

Separate Compilation + Linking


Source File 1

Source File 2

…

Source File N

Compiler

Compiler

Compiler

Object Code

Object Code

…

Object Code

Library

Linker

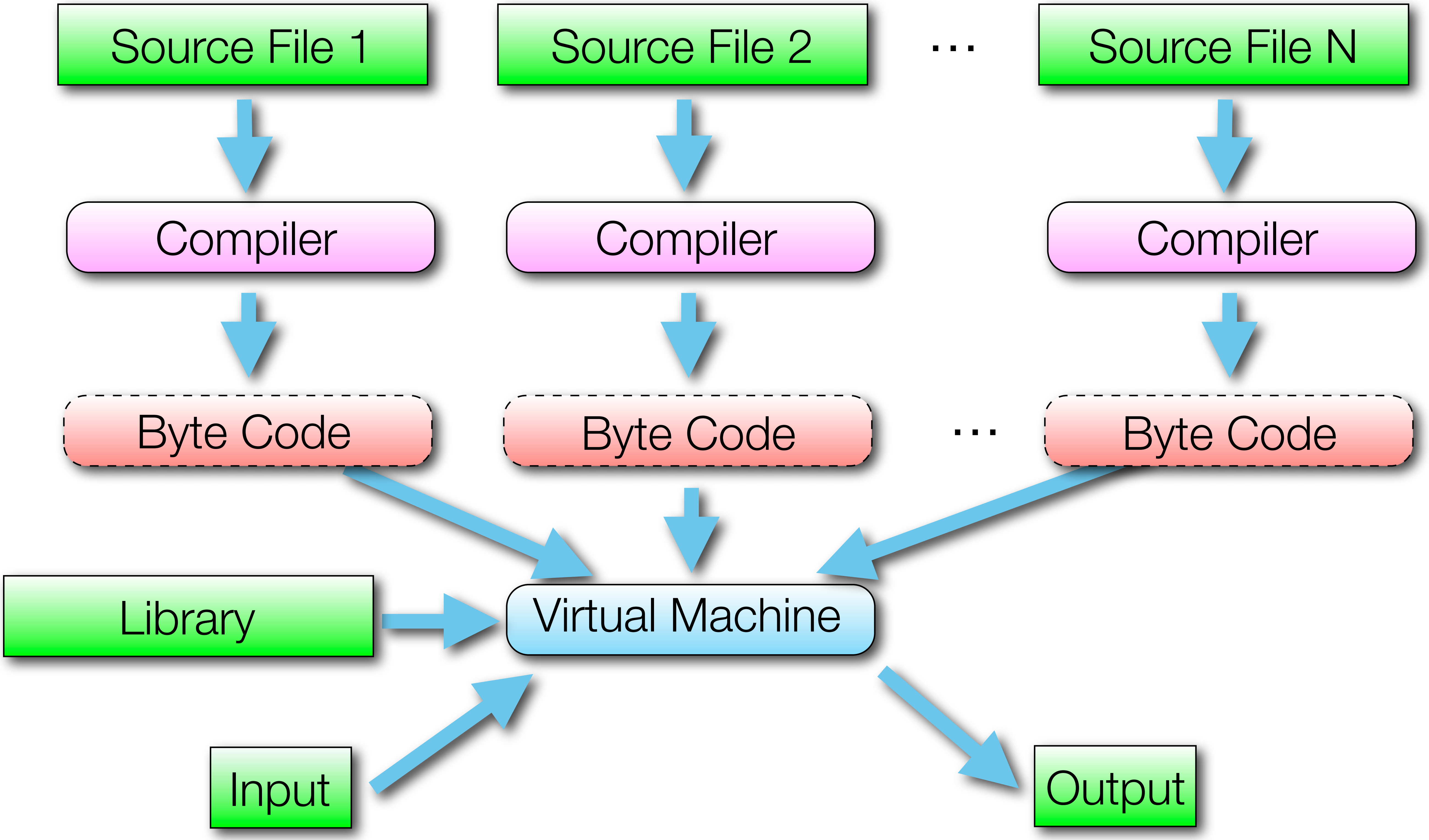
Input

Target Program

Output

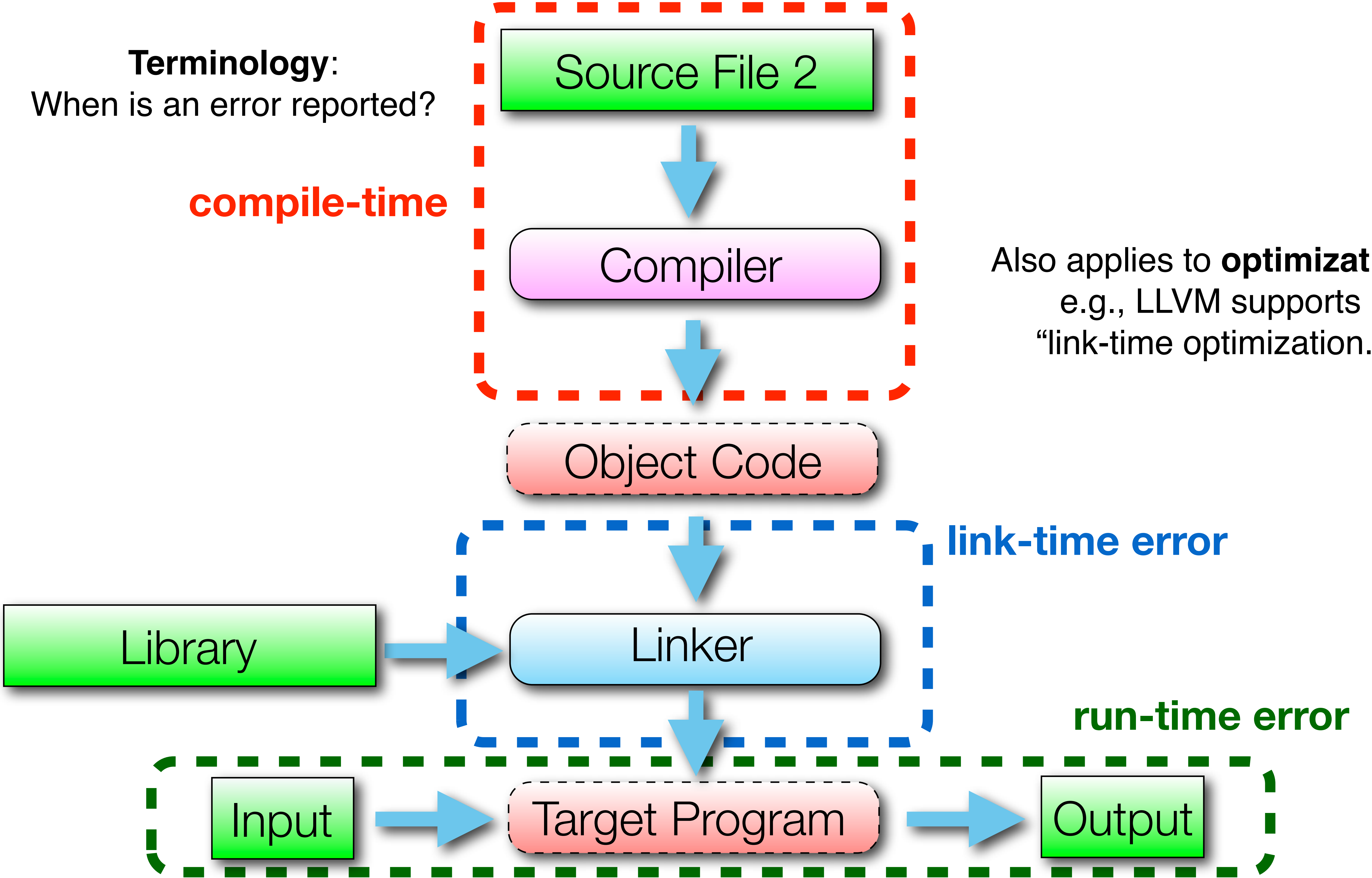
Approach can also be combined with **virtual machines** (e.g., see Java).

Separate Compilation + Interpretation



Time of Error

Terminology:
When is an error reported?



compile-time

Source File 2

Compiler

Object Code

link-time error

Library

Linker

run-time error

Input

Target Program

Output

Also applies to **optimization**,
e.g., LLVM supports
“link-time optimization.”

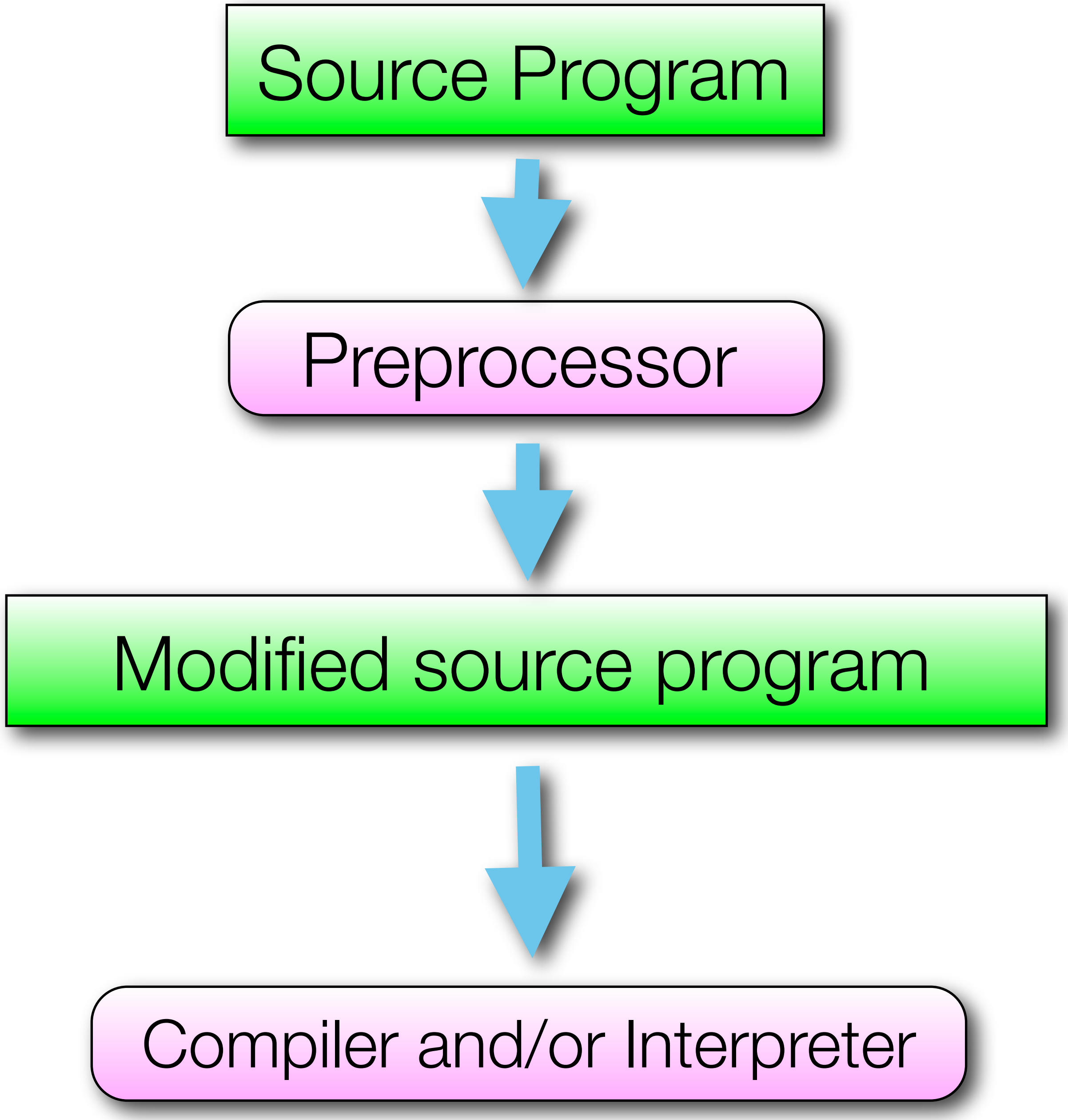
Preprocessing

Source-to-source transformations.

- ➡ **Modify source code** before it is passed to the actual compiler or interpreter.
- ➡ Macro expansion.
- ➡ **Code generation**.
- ➡ Remove comments.
- ➡ **Conditional compilation** (#ifdef).

Examples.

- ➡ Text-based: e.g., `sed`, `perl` (not recommended!)
- ➡ External tool: e.g., `m4`.
- ➡ Integrated: e.g., C preprocessor.


Source Program

Preprocessor

Modified source program

Compiler and/or Interpreter

(rest as before)

C: Preprocessing Example

```
#ifdef ENABLE_INVARIANT_CHECKING
  #define INVARIANT(x) \
    if (!x) {fprintf(stderr, “%s failed!\n”, #x); exit(1);}
#else
  #define INVARIANT(x) /* nothing to do */
#endif
```

Conditional invariant checking.

- Programmer can specify invariants: e.g., `INVARIANT(foo >= 0)`.
- If `ENABLE_INVARIANT_CHECKING` is defined at compile time (using the `-D` switch in `gcc`), the **preprocessor** will replace all invariants with if-statements that verify that the assumption holds.
- Otherwise, the preprocessor will remove all invariants from the code **before passing the code to the compiler**.

Advantages.

- Assumptions made **explicit**.
- **Simplifies debugging**: turn on all checking with one change.
- **No performance penalty in final release**: checking can be turned off.

C: Preprocessing Example

```
#i

#e

#e
```

Co

But keep in mind:

> *“Finally, it is absurd to make elaborate security checks on debugging runs, when no trust is put in the results, and then remove them in production runs, when an erroneous result could be expensive or disastrous. What would we think of a sailing enthusiast who wears his lifejacket when training on dry land, but takes it off as soon as he goes to sea?”*
>
> — C. A. R. Hoare, Hints on Programming Language Design, 1973

- -D switch in gcc), the **preprocessor** will replace all invariants with if-statements that verify that the assumption holds.
- Otherwise, the preprocessor will remove all invariants from the code **before passing the code to the compiler**.

Advantages.

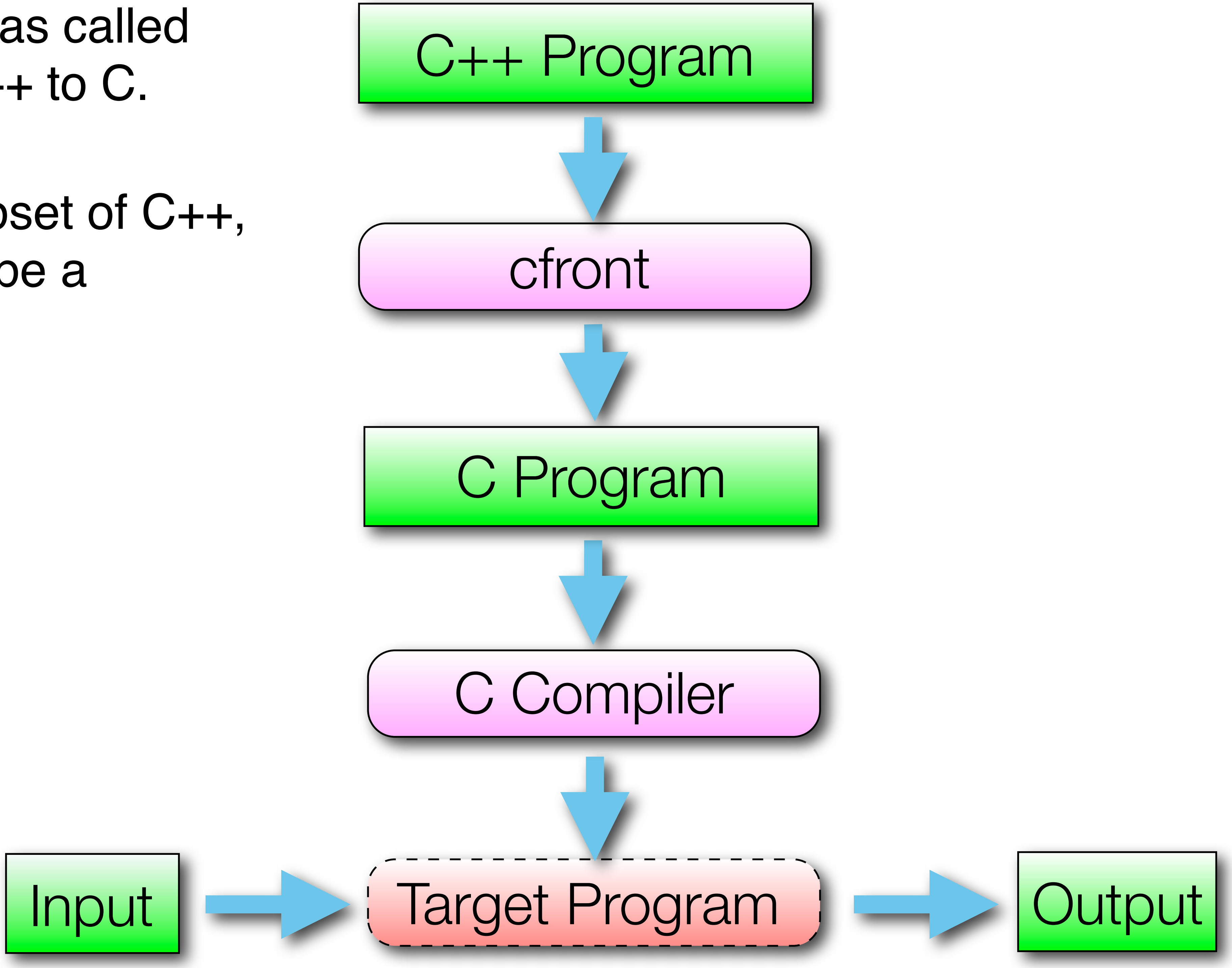
- Assumptions made **explicit**.
- **Simplifies debugging**: turn on all checking with one change.
- **No performance penalty in final release**: checking can be turned off.

Compilation vs. Preprocessing

The first C++ compiler was called “cfront” and compiled C++ to C.

Since C is (mostly) a subset of C++, should we consider it to be a preprocessor?

No!



Compilation vs. Preprocessing

Why is a pre-processor not the same as a source-to-source compiler?

- ➡ Preprocessor: **no inspection** of semantical correctness.
- ➡ A correct compiler does not generate **incorrect code**.
- ➡ Given bad input, most preprocessors will produce code that later **fails compilation**.
- ➡ A preprocessor performs mostly only simple substitutions, without (deeper) understanding of the underlying programming language.

*The C++ compiler **cfront** performs type checking and only generates C programs for C++ programs that pass all semantic tests.*

"Compiled" vs. "Interpreted" Languages

Not a well-defined concept!

Any language can be interpreted.

- ➡ Even machine language (e.g., Qemu, virtualization).
- ➡ For example, the Tiny C Compiler (`tcc`) can be used as an interpreter.

Trivial compilation is always possible.

- ➡ Include source program as string constant when compiling interpreter.
- ➡ Similarly: package byte code and virtual machine together.

However, languages differ in amount of checking that can be done ahead of runtime.

- ➡ A language is compilable if "most" checks can be done at compile time.
- ➡ This requires careful language design and some restrictions.
- ➡ Most languages were designed with either compilation or interpretation in mind.
- ➡ Some languages support both (e.g., Lisp, Haskell).

Bootstrapping and Cross-Compilation

Building the first compiler for a new platform.

Many compilers are written in the language that they implement.

- ➡ Called a "**self-hosting**" compiler.
- ➡ Virtually all C compilers are written in C.
- ➡ The Glasgow Haskell Compiler (ghc) is written in Haskell.
- ➡ Lisp dialects are commonly implemented in Lisp.
- ➡ This creates a "**chicken and egg**" problem.

Given a new hardware platform, how do you obtain a compiler?

- ➡ From scratch: **bootstrapping**.
- ➡ If you already have another working platform: **cross-compilation**.

Bootstrapping

Starting from the spec.

First step.

- ➡ Write a slow, "quick-n-dirty" interpreter for a **subset of the language** (as simple as possible) using machine code, assembly, or some low-level language.
- ➡ **Using the chosen subset**, write compiler prototype (version 0) **for the chosen subset**.
- ➡ Use interpreter to run the **version-0** compiler for the purpose of compiling **itself**: we now have a (very limited) compiler that is self-hosting.

Iterative improvements: given a version-N compiler…

- ➡ Implement a version-(**N+1**) compiler using only language features supported by the version-**N** compiler.
- ➡ Use version-**N** compiler to compile version-(**N+1**) compiler.
- ➡ Repeat, until full language support is complete.

Cross-Compilation

Starting from a host machine.

Notation: (“*runs on*”➜“*generates machine code for*”)

On host machine, given a (host ➜ host) compiler.

- Write portable source code for a (**any** ➜ **target**) compiler.
- Use (**host** ➜ **host**) compiler to compile the (**any** ➜ **target**) compiler, which yields a (**host** ➜ **target**) **cross compiler**.
- Use the (**host** ➜ **target**) cross compiler to compile the (**any** ➜ **target**) a second time.
- This builds a (**target** ➜ **target**) self-hosting compiler.
- Copy (**target** ➜ **target**) compiler to target machine.
- We now have a self-hosting compiler on the target machine.

Example: Cross-Compilation

Going from Intel x86 to Sun's SPARC V9.

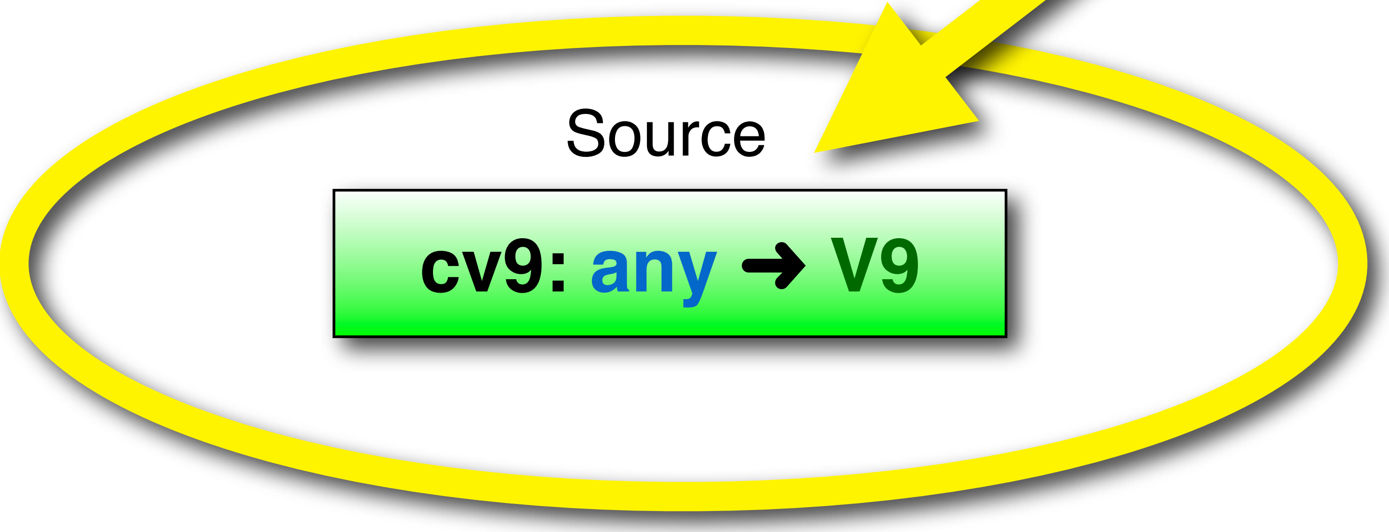
x86 ➜ x86 **V9 ➜ V9**

Example:

Step 1: Write a portable compiler for V9 in C: (any ➜ V9). Name this compiler cv9.

Going from Intel x86 to Sun’s SPARC V9.

x86 ➜ x86 **V9 ➜ V9**



Source

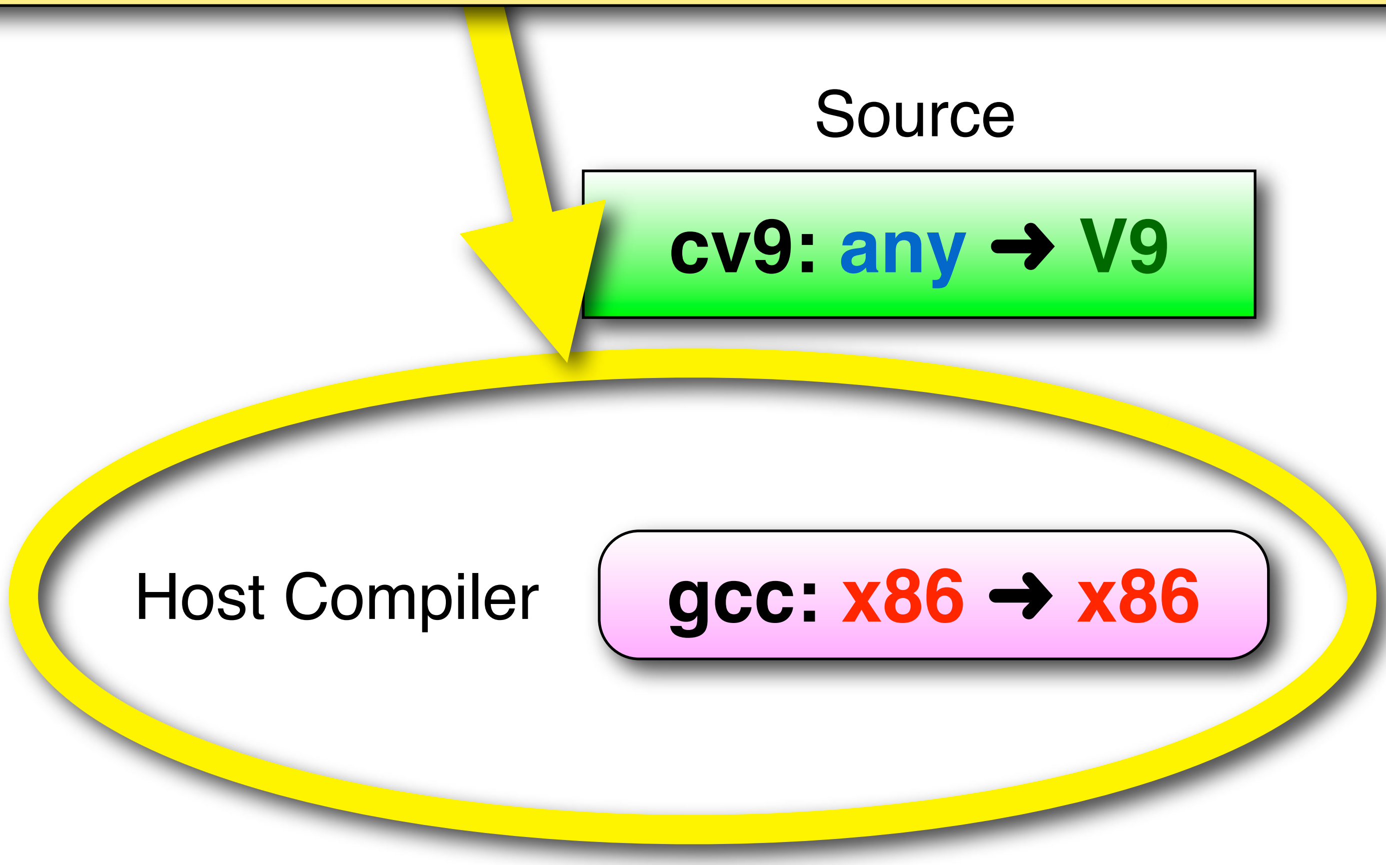
cv9: any ➜ V9

Example: Cross-Compilation

Step 2: Given **Gnu C Compiler (gcc)** on our Intel machine, a (x86 ➜ x86) compiler, …

C V9.

V9



Source

cv9: any ➜ V9

Host Compiler

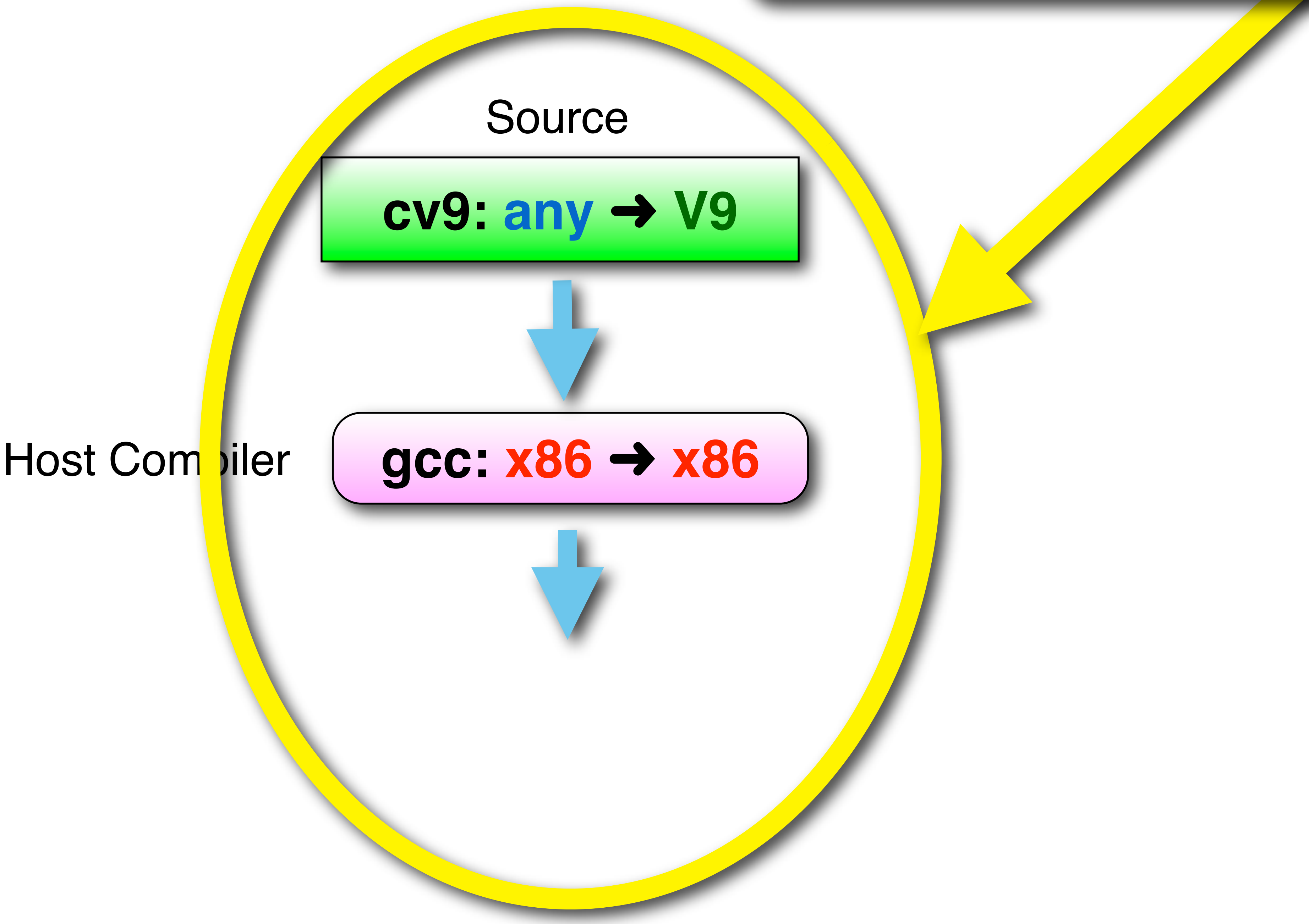
gcc: x86 ➜ x86

Example: Cross-Compilation

Going from Intel x86 to Su

x86 ➜ x86

… use **gcc** to compile **cv9**.



Source

cv9: any ➜ V9

Host Compiler

gcc: x86 ➜ x86

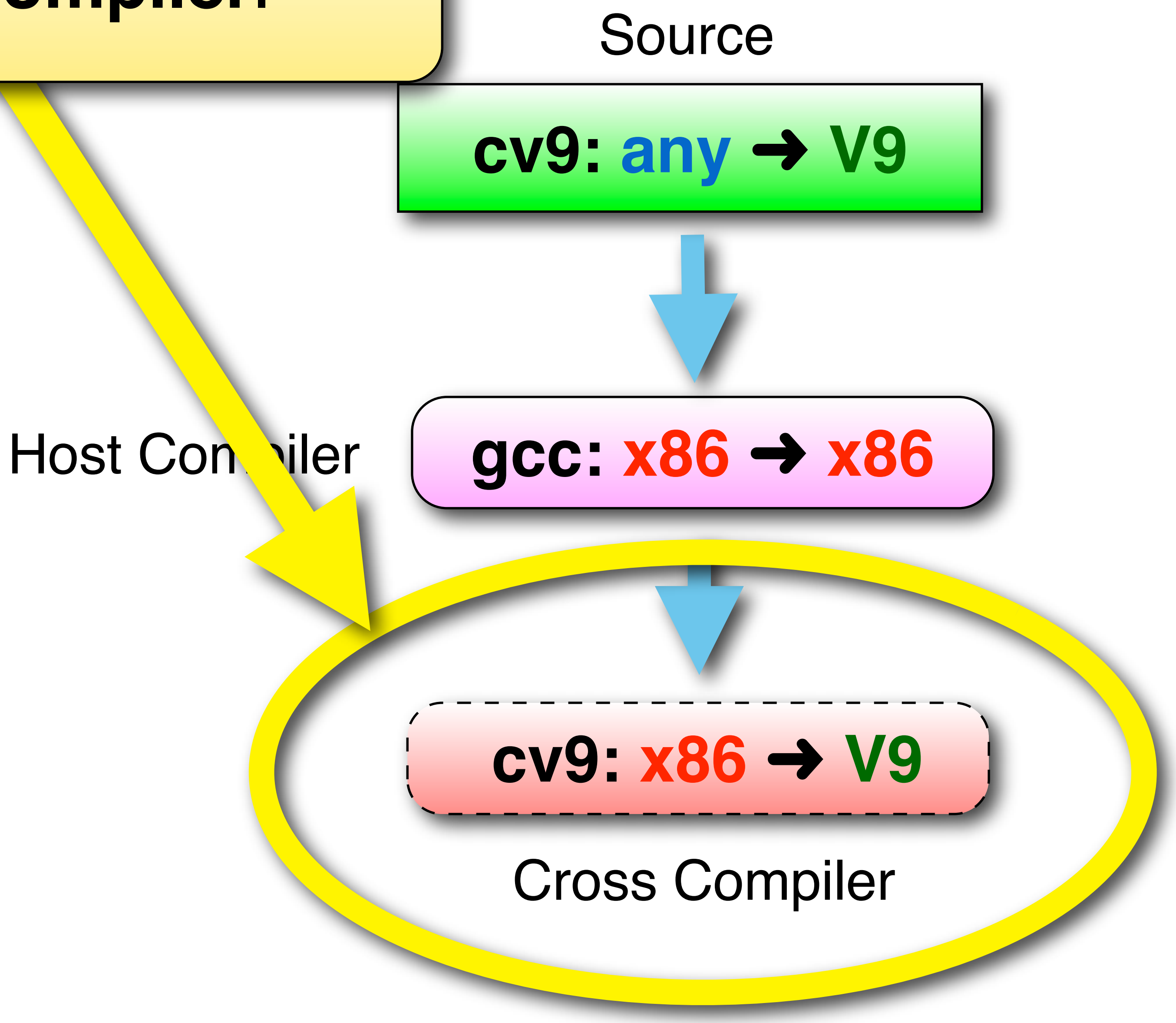
Example: Cross-Compilation

Going from Intel x86 to Sun's SPARC V9.

x86 ➜ x86

V9 ➜ V9

This yields a (**x86 ➜ V9**) **cross compiler**.

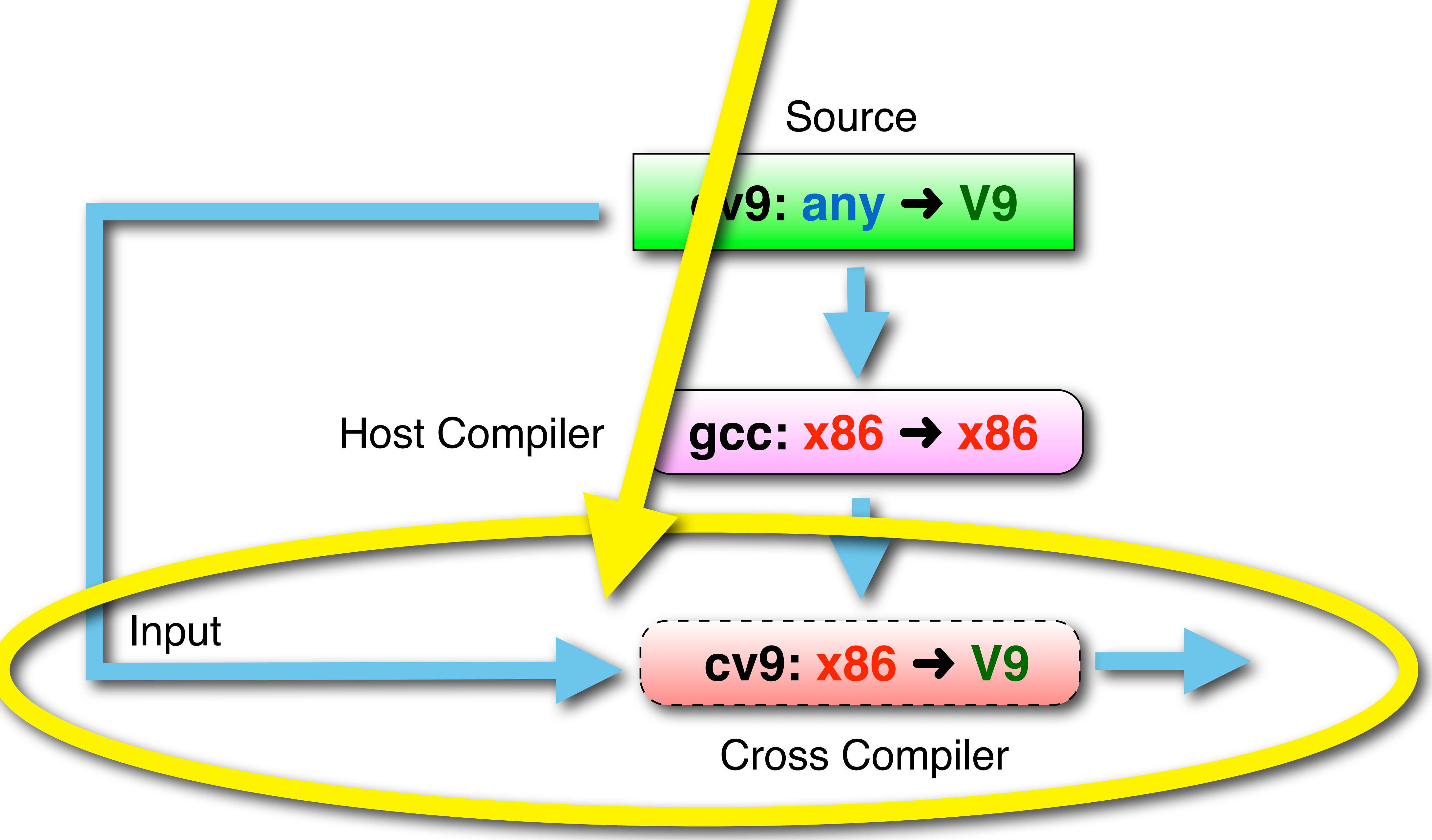


Step 3: Use the (x86 ➜ V9) cross compiler to compile the (any ➜ V9) source code **again**…

pilation

PARC V9.

x86 ➜ x86 V9 ➜ V9

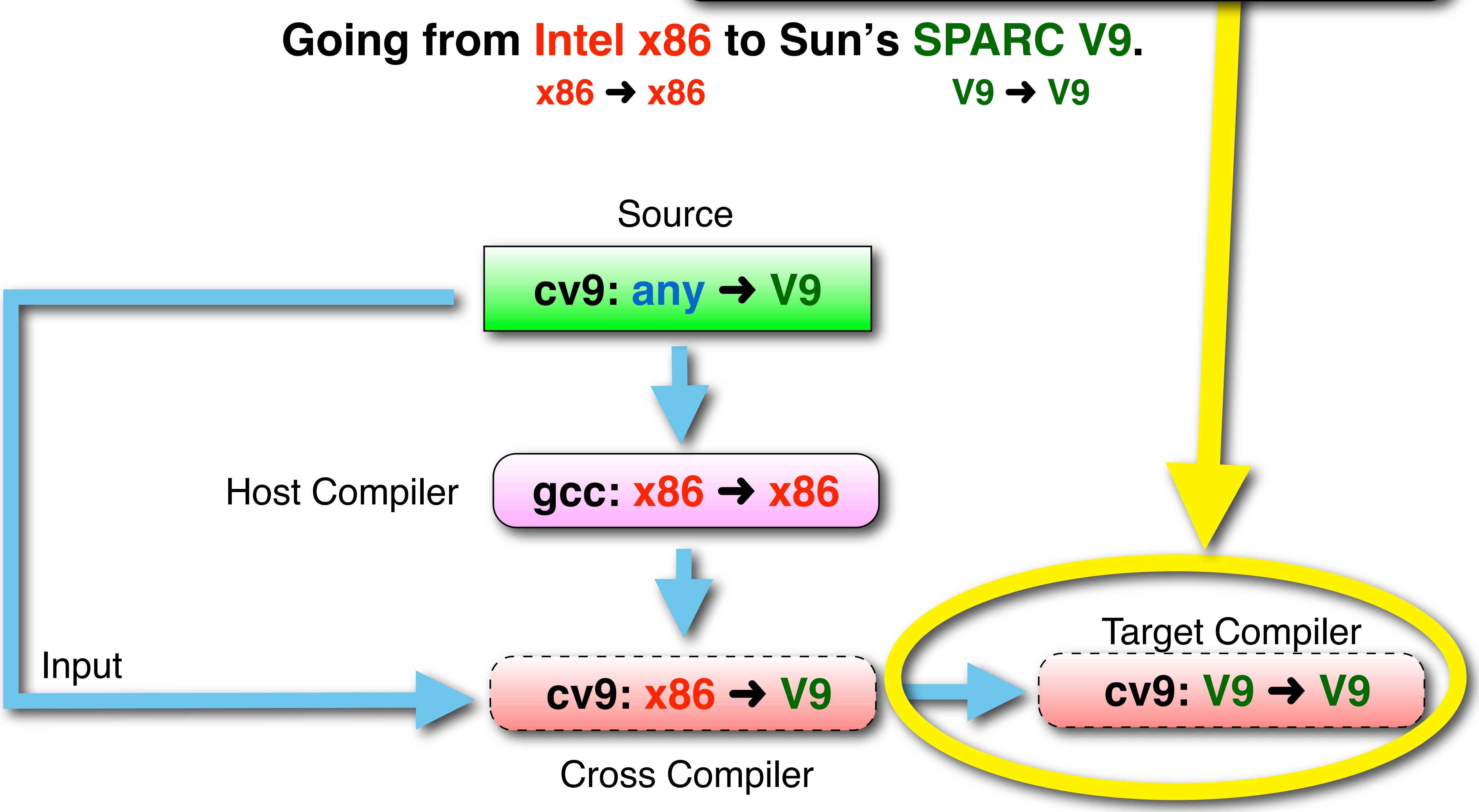


Example: Cr

… this time, we obtain a (**V9 ➜ V9**) self-hosting compiler!

Going from Intel x86 to Sun’s SPARC V9.

x86 ➜ x86 **V9 ➜ V9**



Example: Cross-Compilation

Going from Intel x86 to Sun's SPARC V9.

x86 ➜ x86 **V9 ➜ V9**

Source

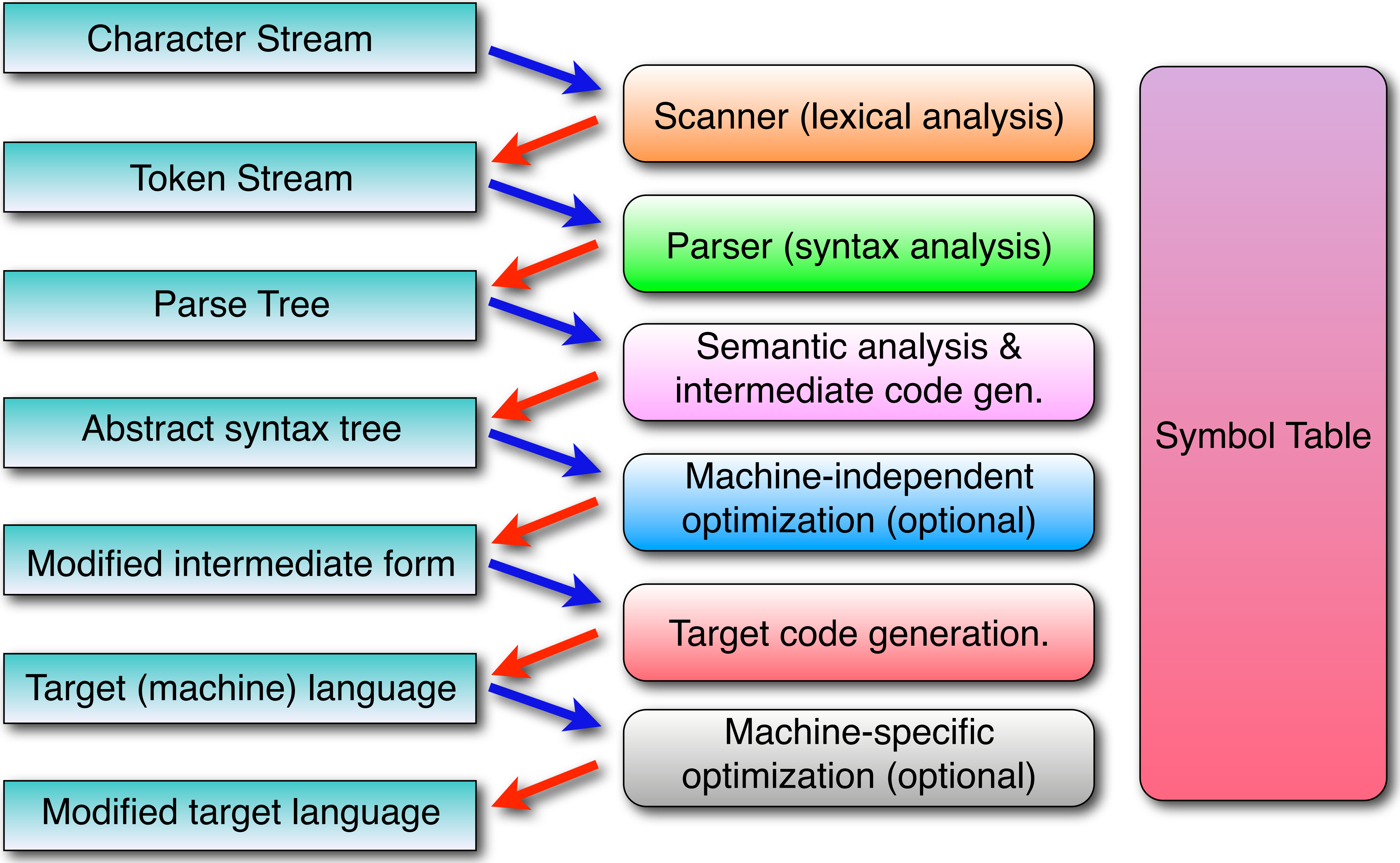
cv9: any ➜ V9

Writing a new **(any ➜ target)** compiler/backend for every target can be **prohibitively expensive**. This can be circumvented by using a **virtual machine + bootstrapping**.

In this case, only one **(any ➜ virtual machine)** backend is required, but a (much simpler) **virtual machine** must be **translated by hand**.

<u>See Pascal P-Code example on page 21 in the textbook.</u>

Compilation Phases



Character Stream

Scanner (lexical analysis)

Token Stream

Parser (syntax analysis)

Parse Tree

Semantic analysis & intermediate code gen.

Abstract syntax tree

Machine-independent optimization (optional)

Modified intermediate form

Target code generation.

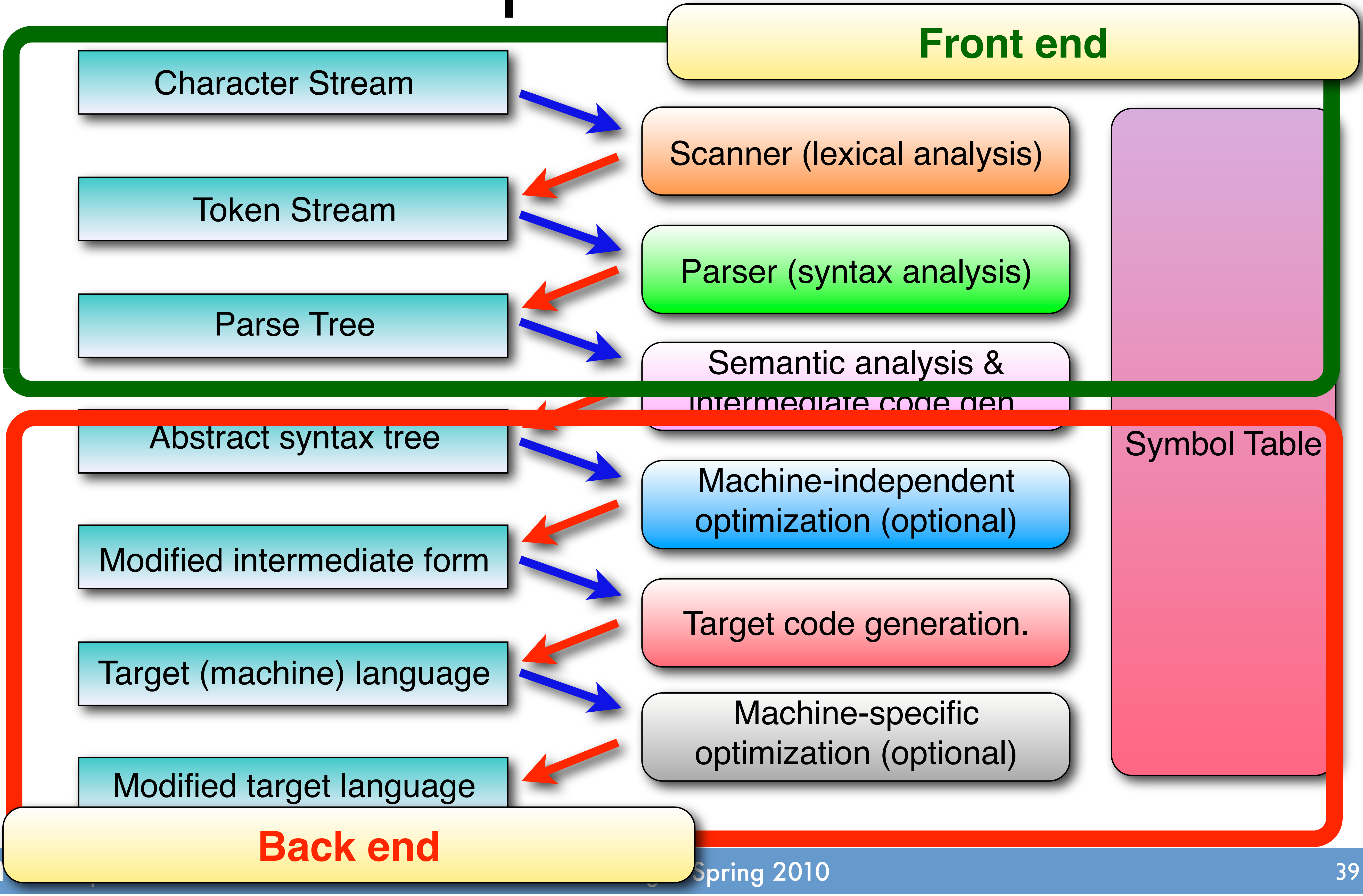
Target (machine) language

Machine-specific optimization (optional)

Modified target language

Symbol Table

Compilation Phases



Front end

Character Stream

Scanner (lexical analysis)

Token Stream

Parser (syntax analysis)

Parse Tree

Semantic analysis & intermediate code gen

Abstract syntax tree

Machine-independent optimization (optional)

Modified intermediate form

Target code generation.

Target (machine) language

Machine-specific optimization (optional)

Modified target language

Symbol Table

Back end

Example Program GCD

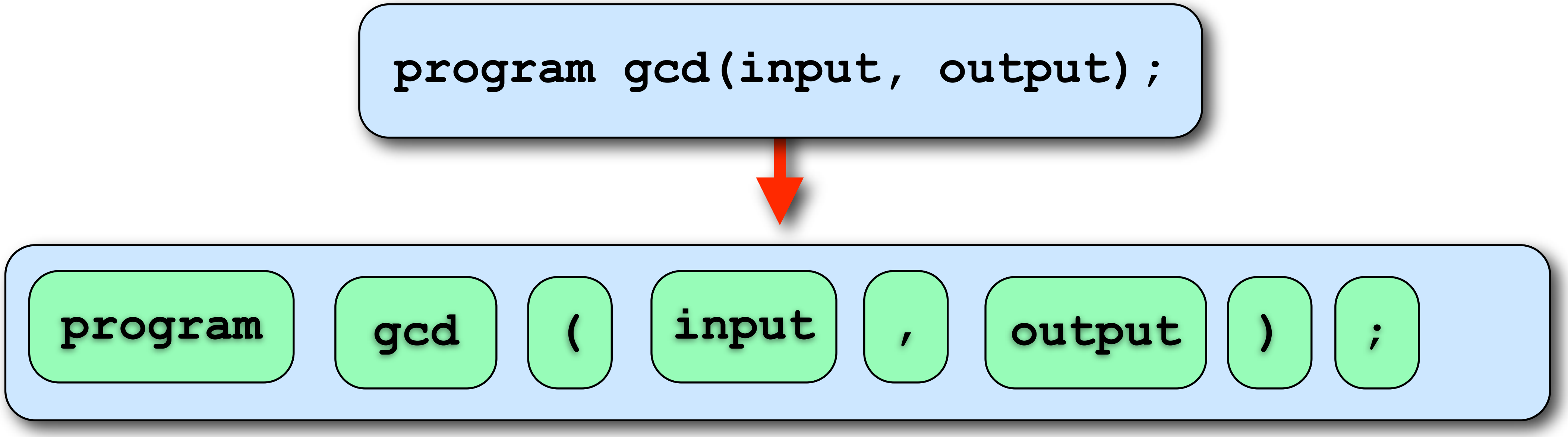
```
program gcd(input, output);
var i, j: integer;
begin
  read(i,j); // get i & j from read
  while i<>j do
    if i>j then i := i-j
    else j := j-1;
  writeln(i)
end.
```

Pascal

Scanner (lexical analysis)

Lexical Analysis

- Recognizes consecutive characters that form a unit and groups them into **tokens**.



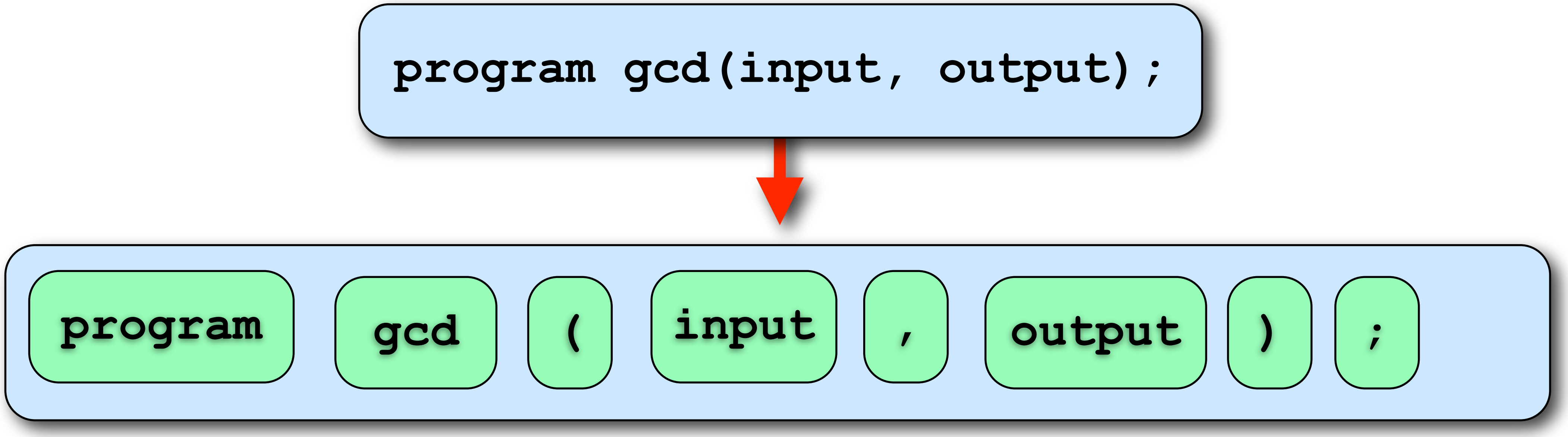
```
program gcd(input, output);
```

- The purpose of the scanner is to simplify the parser by **reducing the size of the input**.

Scanner (lexical analysis)

Token: atomic semantical unit;
the smallest unit of input with individual meaning.

- Recognizes consecutive characters that form a unit and groups them into **tokens**.



`program gcd(input, output);`

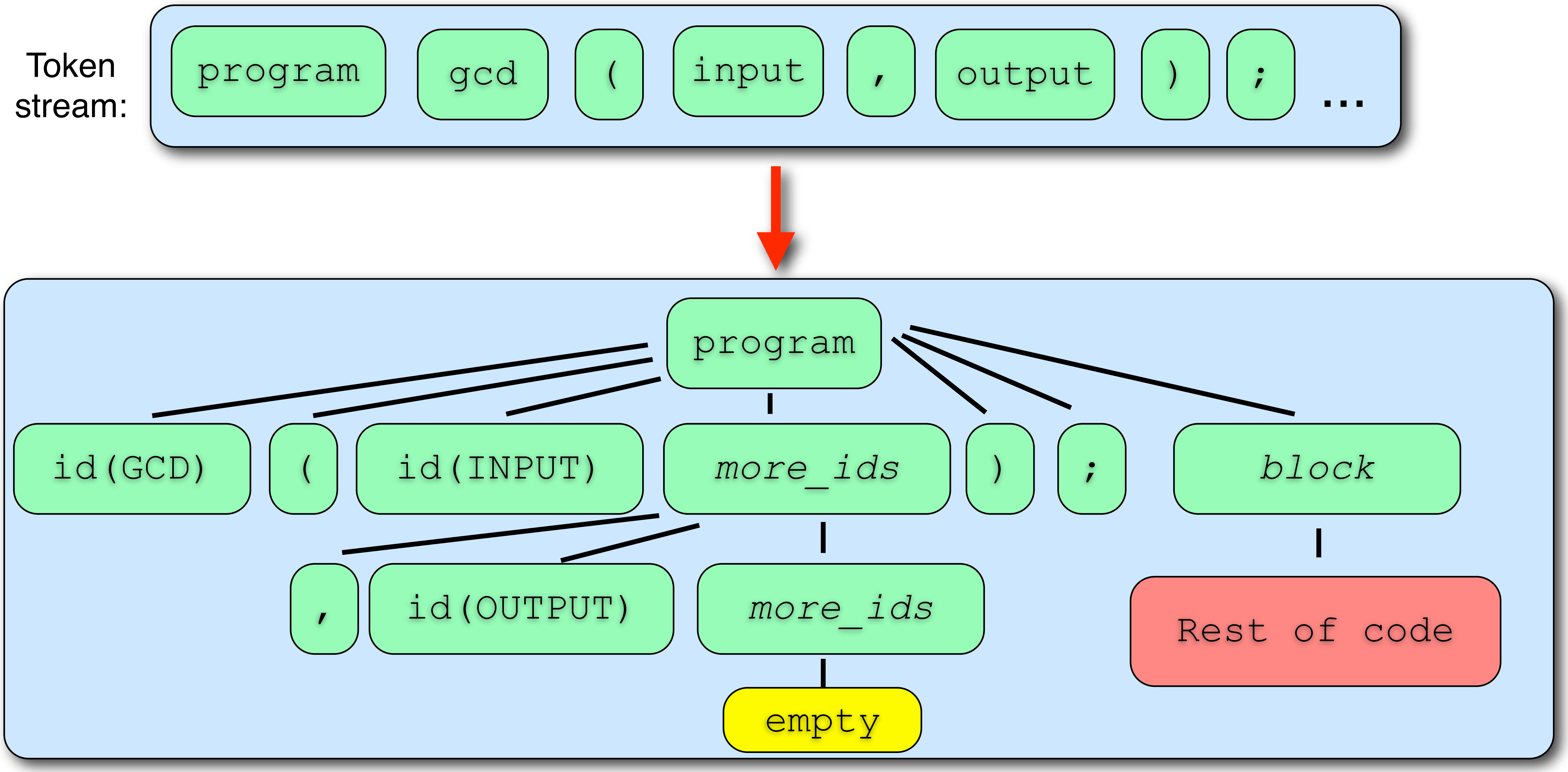
`program` `gcd` `(` `input` `,` `output` `)` `;`

- The purpose of the scanner is to simplify the parser by **reducing the size of the input**.

Parser (syntax analysis)

Syntax Analysis

- Parsing discovers the **structure** in the token stream based on a **a context-free grammar** and yields a **syntax tree**.



Parser (syntax analysis)

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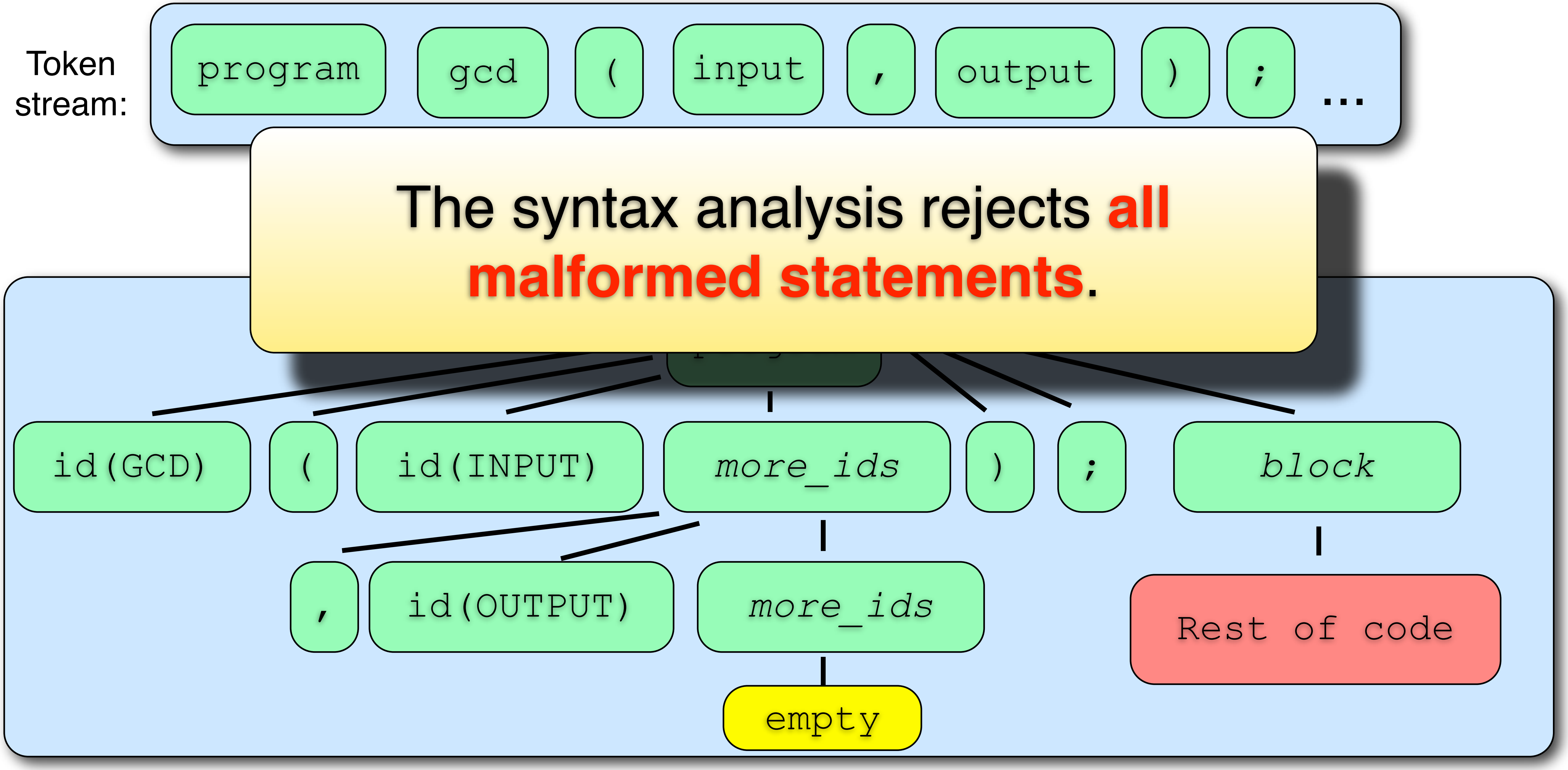

The syntax analysis rejects **all malformed statements**.

Parser (syntax analysis)

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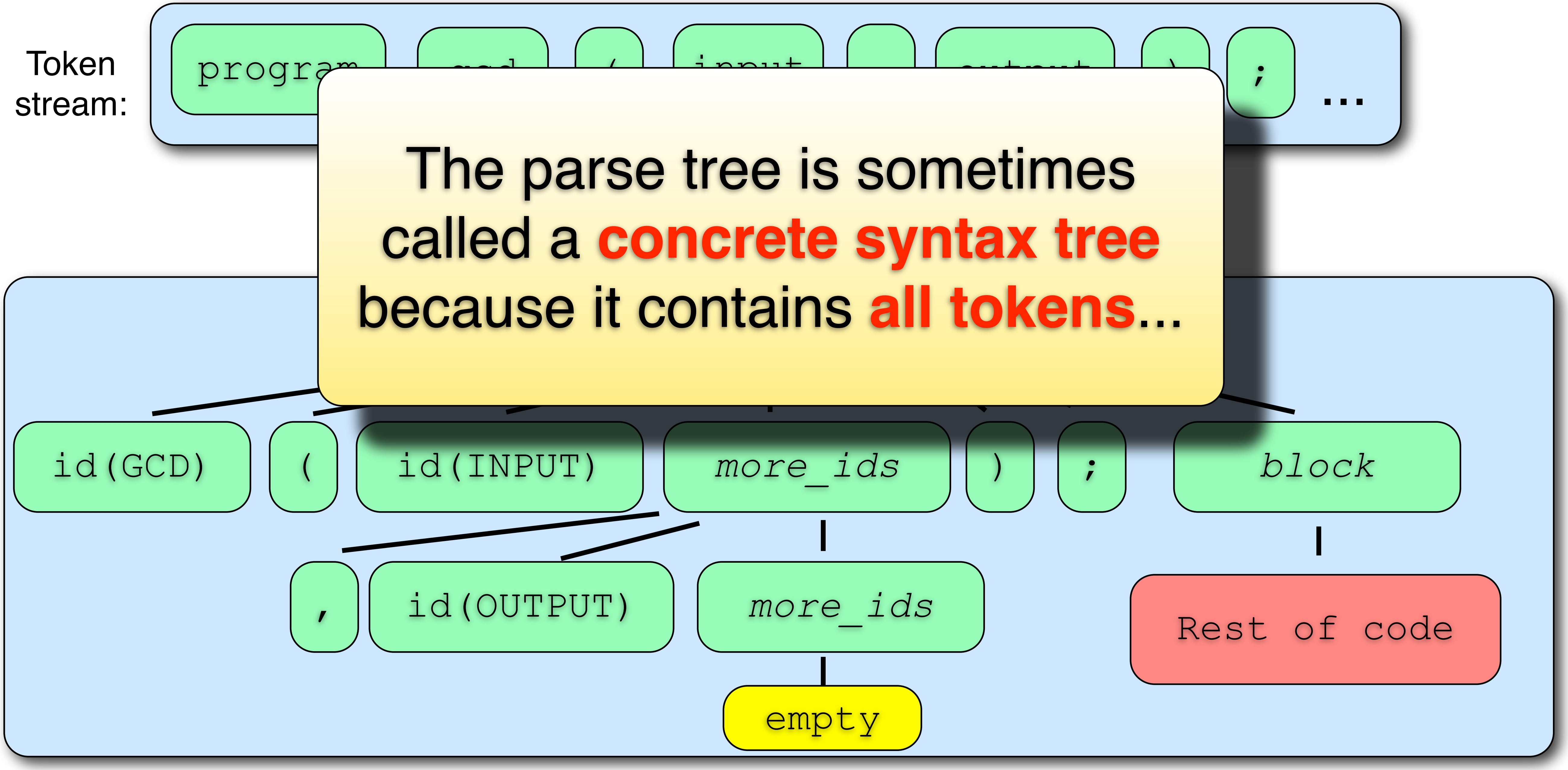
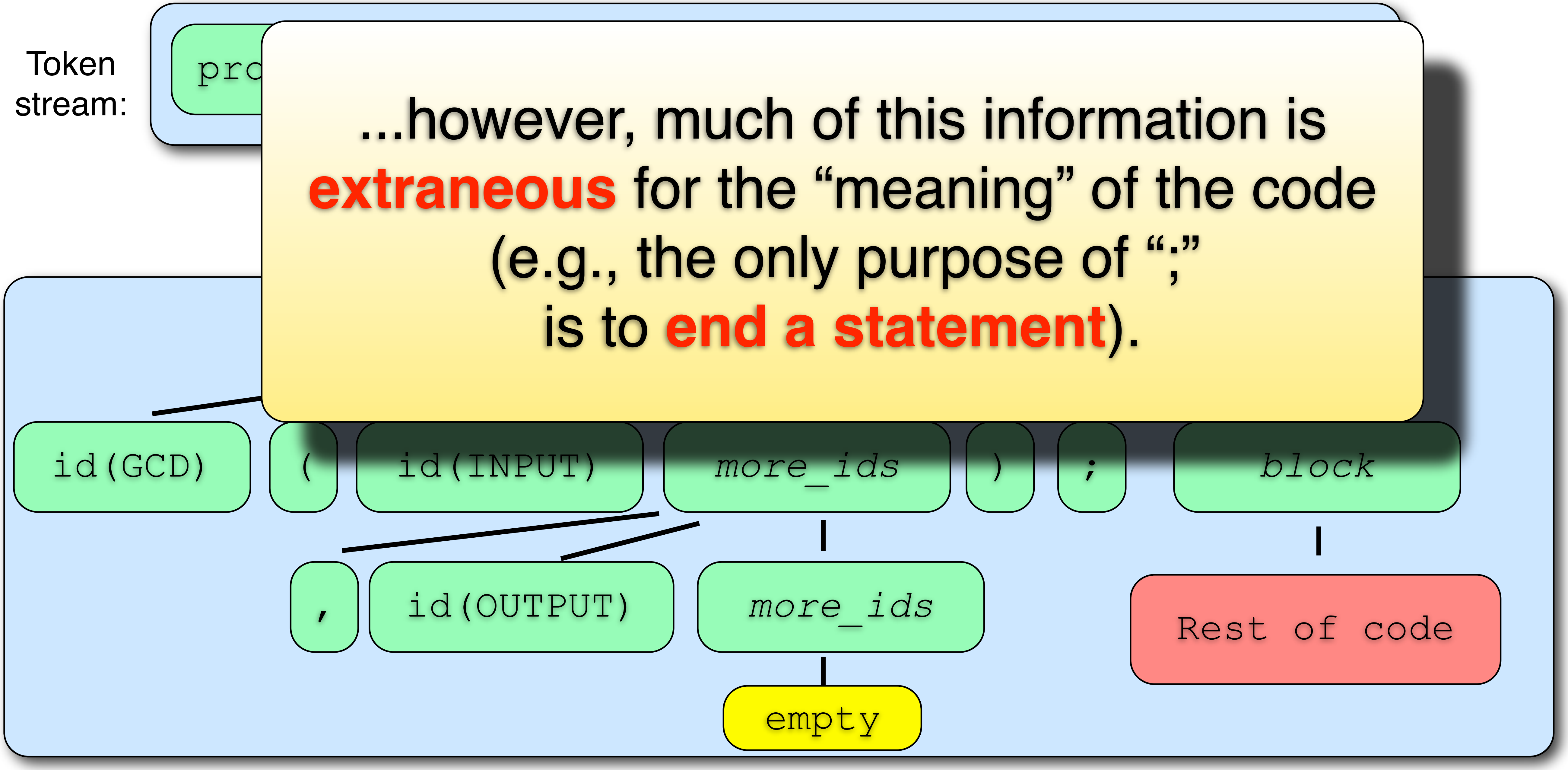


The parse tree is sometimes called a **concrete syntax tree** because it contains **all tokens**...

Parser (syntax analysis)

Syntax Analysis

- Parsing discovers the **structure** in the token stream based on a **a context-free grammar** and yields a **syntax tree**.



...however, much of this information is **extraneous** for the “meaning” of the code (e.g., the only purpose of “;” is to **end a statement**).

Semantic analysis & intermediate code gen.

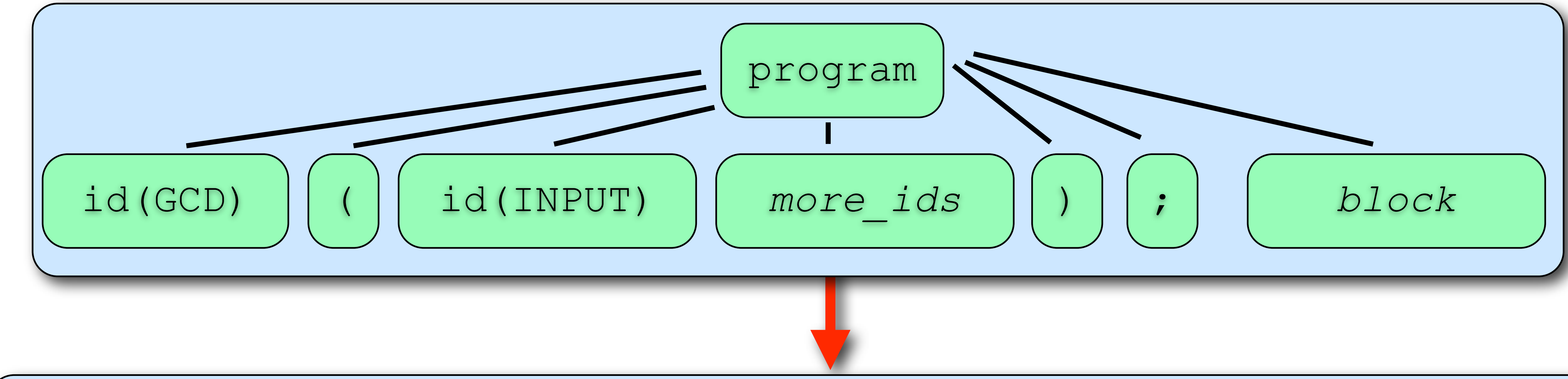
Semantic Analysis

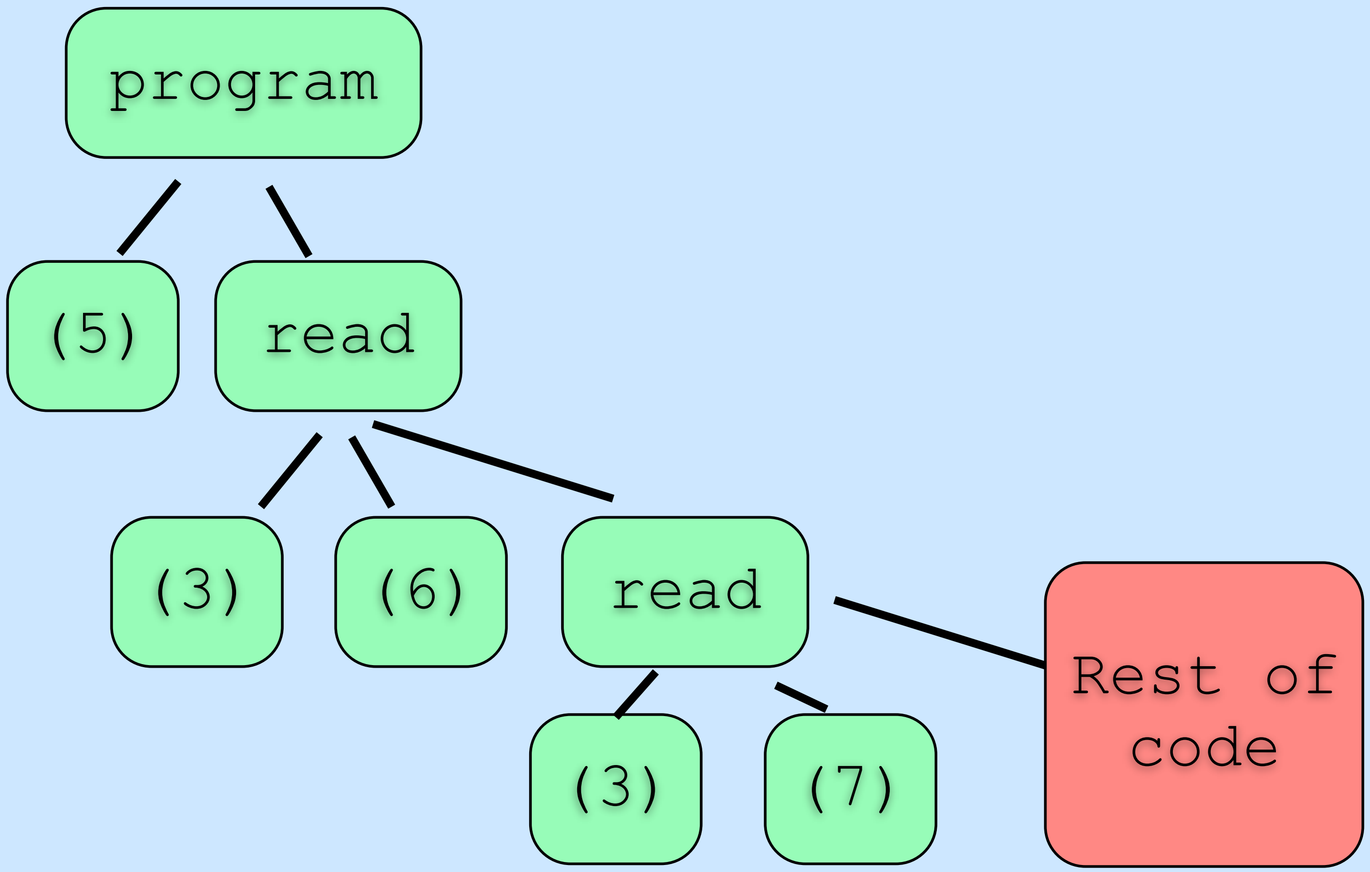
- Semantic analysis discovers the **meaning of a program** by creating an **abstract syntax tree** that removes “extraneous” tokens.
- To do this, the analyzer builds & maintains a **symbol table** to map identifiers to information known about it. (i.e., scope, type, internal structure, etc...)
- By using the symbol table, the semantic analyzer can **catch problems not caught by the parser**. For example, it can enforce that
  - identifiers are declared before use, and that
  - subroutine calls provide correct number and type of arguments.

Semantic analysis & intermediate code gen.

Semantic Analysis

from concrete to abstract syntax tree





Index	Symbol	Type
1	INTEGER	type
2	TEXTFILE	type
3	INPUT	2
4	OUTPUT	2
5	GCD	program
6	I	1
7	J	1

Semantic analysis & intermediate code gen.

Semantic Analysis

Not all semantic rules can be checked at compile time.

- ➡ Those that can are called **static** semantics of the language.
- ➡ Those that cannot are called **dynamic** semantics of the language. For example,
  - Arithmetic operations **do not overflow**.
  - Array subscripts expressions **lie within the bounds of the array**.

Semantic analysis & intermediate code gen.

Intermediate Code Generation

Intermediate form (IF) generation is done after semantic analysis (if the program passes all checks)

- IFs are often chosen for **machine independence**, **ease of optimization**, or **compactness** (these are somewhat contradictory)
- They often resemble **machine code for some imaginary idealized machine**; e.g. a stack machine, or a machine with arbitrarily many registers
- Many compilers actually move the code through more than one IF.

Target code generation.

Target code generation

- Code generation takes the abstract syntax tree and the symbol table to produce machine code.
- **Simple** code follows directly from the abstract syntax tree and symbol table.
- Follows **basic pattern**:
  - Load operands into registers (from **memory**).
  - Compute basic function (e.g., add, div, sub).
  - Store results (to **memory**).
- Other patterns: conditional jumps, subroutine calls.

Machine-independent optimization (optional)

Machine-specific optimization (optional)

Optimization

The process so far will produce correct code, but it may not be fast.

- ➡ Optimization will transform the code to improve performance **without changing its semantics**.
- ➡ In theory… in practice, compiler **bugs often lurk in the optimizer**.
- ➡ It is **easy to overlook corner cases** when coming up with optimizations.
- ➡ Proper program transformations require **rigorous proof** of the claimed equivalences.

First aid in case of compiler trouble:
Remove all intermediate files (`make clean`),
turn off all optimizations (`-O0`), and try again.

Machine-Independent Optimization

Examples.

- Loop unrolling.
  - Enables **hardware parallelism**.
  - Reduces number of times that abort condition is evaluated.
- Inlining of (short) subroutines.
  - E.g., getter/setter methods.
  - Reduces **subroutine call overhead**.
- Store-load pair elimination.
  - Reduces **unnecessary memory accesses**.
- **Jump-coalescing**.
  - Avoid jump to a jump to a jump…
- Escape analysis.
  - Determine which variables are only updated locally.

Common theme:
these overheads are bad on **any** machine.

Mo ion

Examp

- Loop unrolling.
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  - Determine which variables are only updated locally.

Machine-Specific Optimizations

Examples.

- ➡ Instruction **scheduling**
  - ‣ Overlay **memory latency** with computation.
- ➡ Branch-prediction-friendly code layout.
  - ‣ **Move failure cases** out of “hot path.”
- ➡ Instruction **selection**.
  - ‣ Either for **speed** or **size**.
  - ‣ `xorl %eax, %eax` vs. `movl $0, %eax`.
- ➡ **Clever register allocation**.
  - ‣ Avoid spill code (minimize store/loads).
  - ‣ This sub-problem by itself is **NP-complete**.
  - ‣ Uses graph coloring algorithms.

Machine-Specific Optimizations

Examples.

These are all quite **complicated** to do well…

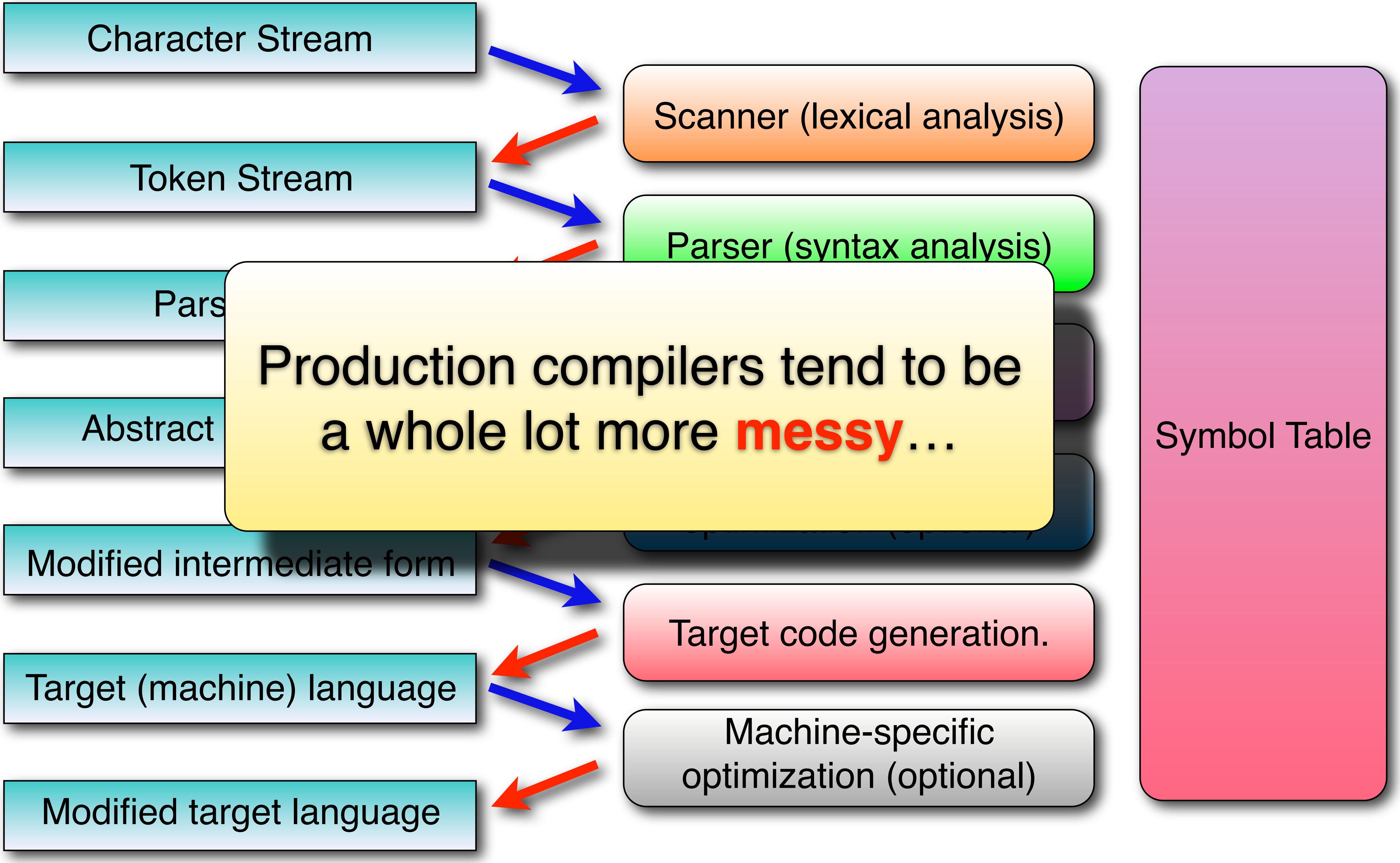
- Branch prediction-friendly code layout.
  - **Move failure cases** out of "hot path."

…and **can be completely avoided**
by compiling to C instead of assembly.

(Unless you are writing a C compiler, that is.)

  - This sub-problem by itself is **NP-complete**.
  - Uses graph coloring algorithms.

Summary: Compilation Phases



Production compilers tend to be a whole lot more **messy**...

Summary: Compilation and Interpretation

Two fundamental approaches.

- Compilation.
  - Resulting program can be efficient.
- Interpretation.
  - Can be very flexible.

Implementation approaches.

- Preprocessing.
  - Macro expansion and code filtering.
- Separate compilation.
  - Divide and conquer…
- Virtual machines
  - Simple interpreters are faster.