603AA - Principles of Programming Languages [PLP-2015]

Andrea Corradini
Department of Computer Science, Pisa

Academic Year 2015/16

- Compilation and interpretation schemes
- Cross compilation
- Bootstrapping
- Compilers

Implementing a Programming Language

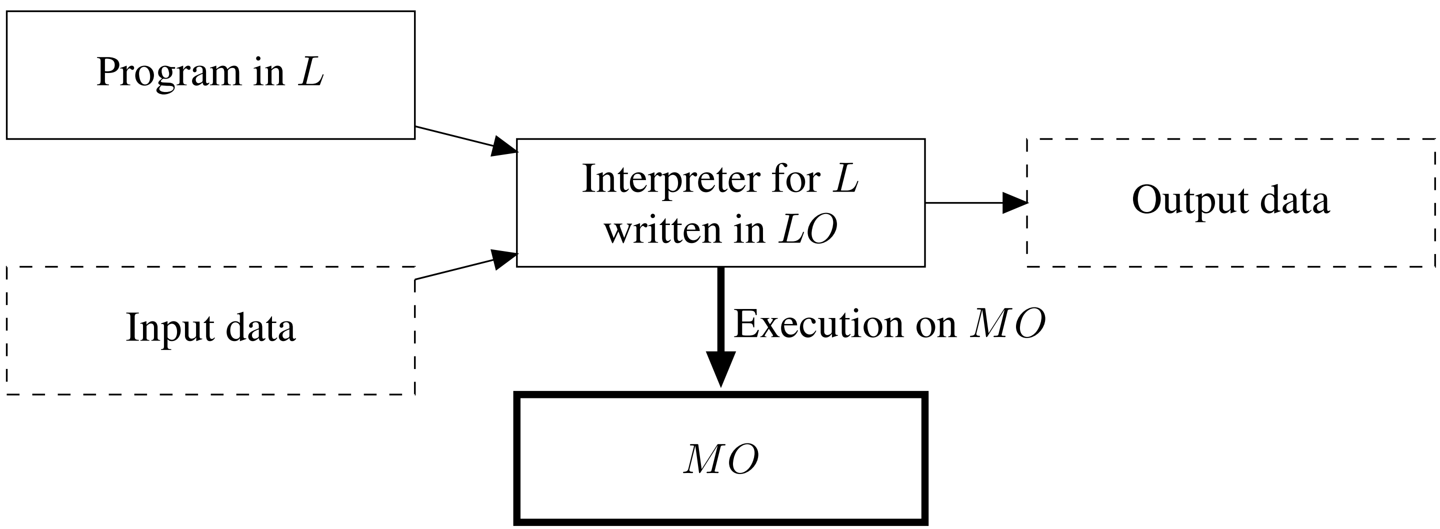
- **L** high level programming language
- **M_L** abstract machine for **L**
- **M_O** host machine
- **Pure Interpretation**
  - **M_L** is interpreted over **M_O**
  - Not very efficient, mainly because of the interpreter (fetch-decode phases)
- **Pure Compilation**
  - Programs written in **L** are translated into equivalent programs written in **L_O**, the machine language of **M_O**
  - The translated programs can be executed directly on **M_O**
    - **M_L** is not realized at all
  - Execution more efficient, but the produced code is larger
- Two limit cases that almost never exist in reality

Pure Interpretation

- Program ***P*** in ***L*** as a partial function on ***D***:

$$\mathscr{P}^{\mathscr{L}} : \mathscr{D} \rightarrow \mathscr{D}$$

- Set of programs in **L**: $\mathscr{P}rog^{\mathscr{L}}$



- The interpreter defines a function

$$\mathscr{I}_{\mathscr{L}}^{\mathscr{L}o} : (\mathscr{P}rog^{\mathscr{L}} \times \mathscr{D}) \rightarrow \mathscr{D} \quad \text{such that } \mathscr{I}_{\mathscr{L}}^{\mathscr{L}o}(\mathscr{P}^{\mathscr{L}}, \mathit{Input}) = \mathscr{P}^{\mathscr{L}}(\mathit{Input})$$

Pure [*cross*] Compilation

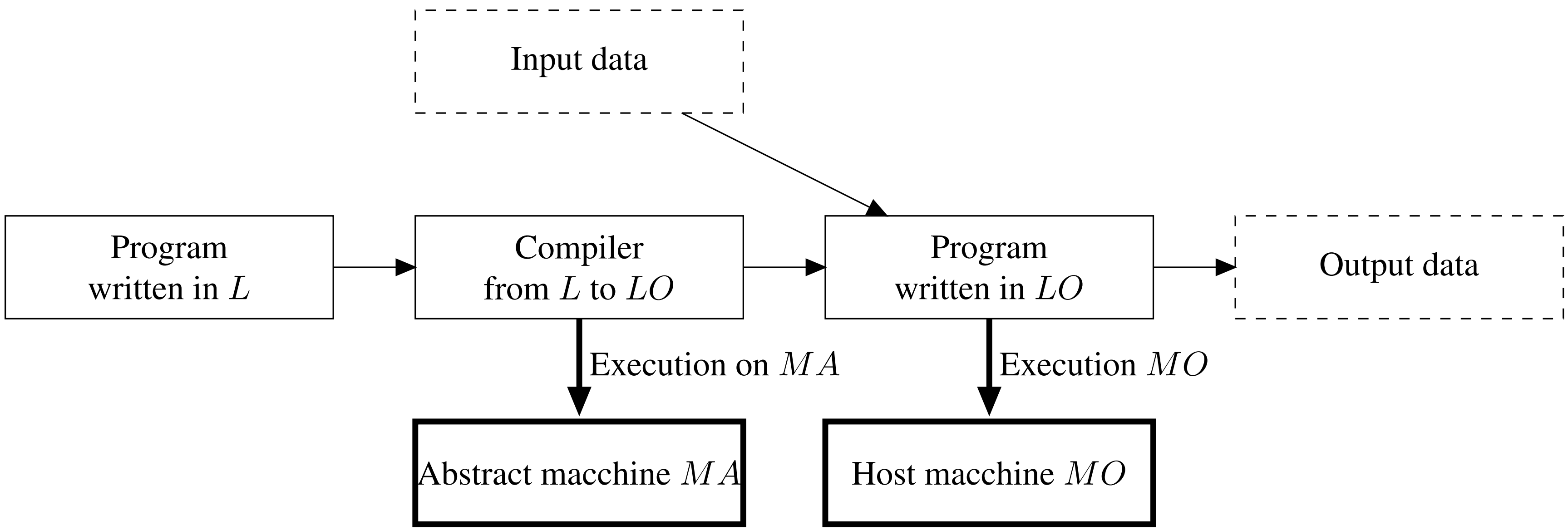
A compiler from ***L*** to ***LO*** defines a function

$$\mathscr{C}_{\mathscr{L},\mathscr{L}o} : \mathscr{P}rog^{\mathscr{L}} \to \mathscr{P}rog^{\mathscr{L}o}$$

such that if

$$\mathscr{C}_{\mathscr{L},\mathscr{L}o}(\mathscr{P}^{\mathscr{L}}) = \mathscr{P}c^{\mathscr{L}o},$$

then for every *Input* we have $\mathscr{P}^{\mathscr{L}}(Input) = \mathscr{P}c^{\mathscr{L}o}(Input)$



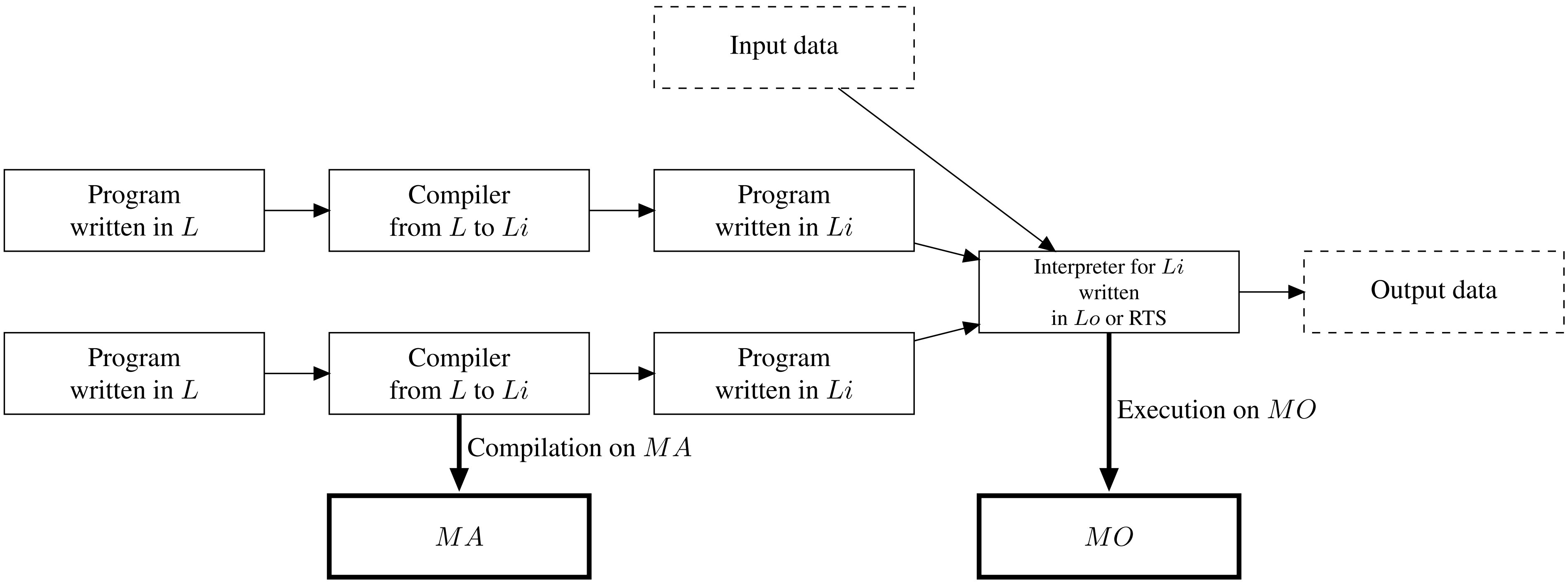
Compilers versus Interpreters

- Compilers efficiently fix decisions that can be taken at compile time to avoid to generate code that makes this decision at run time
  - Type checking at compile time vs. runtime
  - Static allocation
  - Static linking
  - Code optimization
- Compilation leads to better performance in general
  - Allocation of variables without variable lookup at run time
  - Aggressive code optimization to exploit hardware features
- Interpretation facilitates interactive debugging and testing
  - Interpretation leads to better diagnostics of a programming problem
  - Procedures can be invoked from command line by a user
  - Variable values can be inspected and modified by a user

Compilation + Interpretation

- All implementations of programming languages use both. At least:
  - Compilation (= translation) from external to internal representation
  - Interpretation for I/O operations (runtime support)
- Can be modeled by identifying an *Intermediate Abstract Machine* $\boldsymbol{M_I}$ *with language* $\boldsymbol{L_I}$
  - A program in $\boldsymbol{L}$ is compiled to a program in $\boldsymbol{L_I}$
  - The program in $\boldsymbol{L_I}$ is executed by an interpreter for $\boldsymbol{M_I}$

Compilation + Interpretation with Intermediate Abstract Machine



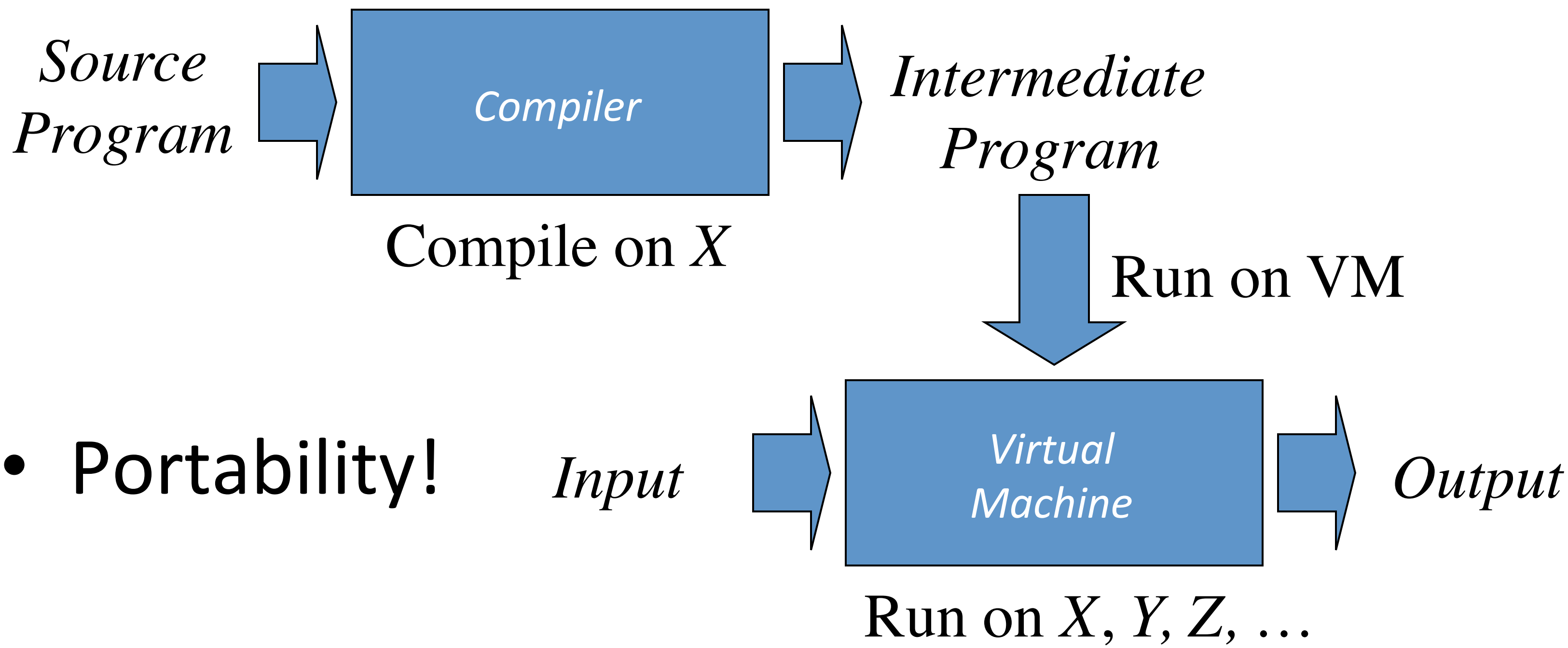
- The "pure" schemes as limit cases
- Let us sketch some typical implementation schemes…

Virtual Machines as Intermediate Abstract Machines

- Several language implementations adopt a compilation + interpretation schema, where the Intermediate Abstract Machine is called Virtual Machine
- Adopted by Pascal, Java, Smalltalk-80, C#, functional and logic languages, and some scripting languages
  - Pascal compilers generate P-code that can be interpreted or compiled into object code
  - Java compilers generate bytecode that is interpreted by the Java virtual machine (JVM)
  - The JVM may translate bytecode into machine code by just-in-time (JIT) compilation

Compilation and Execution on Virtual Machines

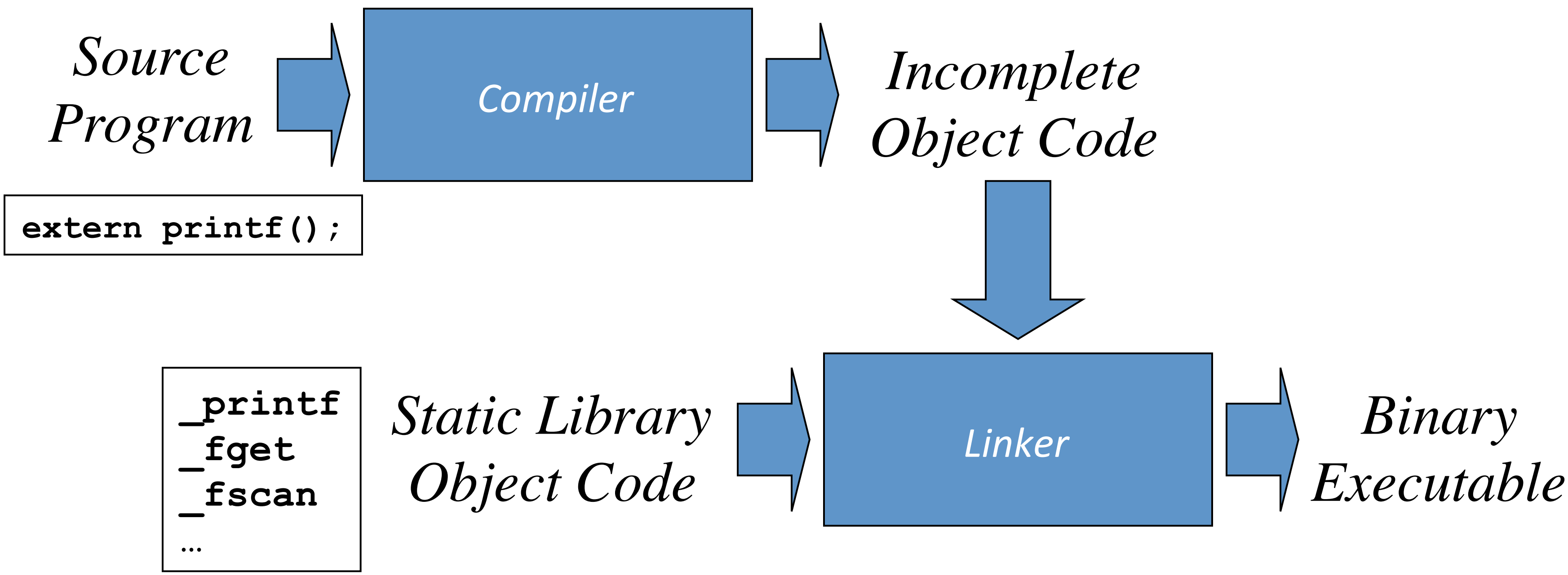
- Compiler generates intermediate program
- Virtual machine interprets the intermediate program



- Portability!

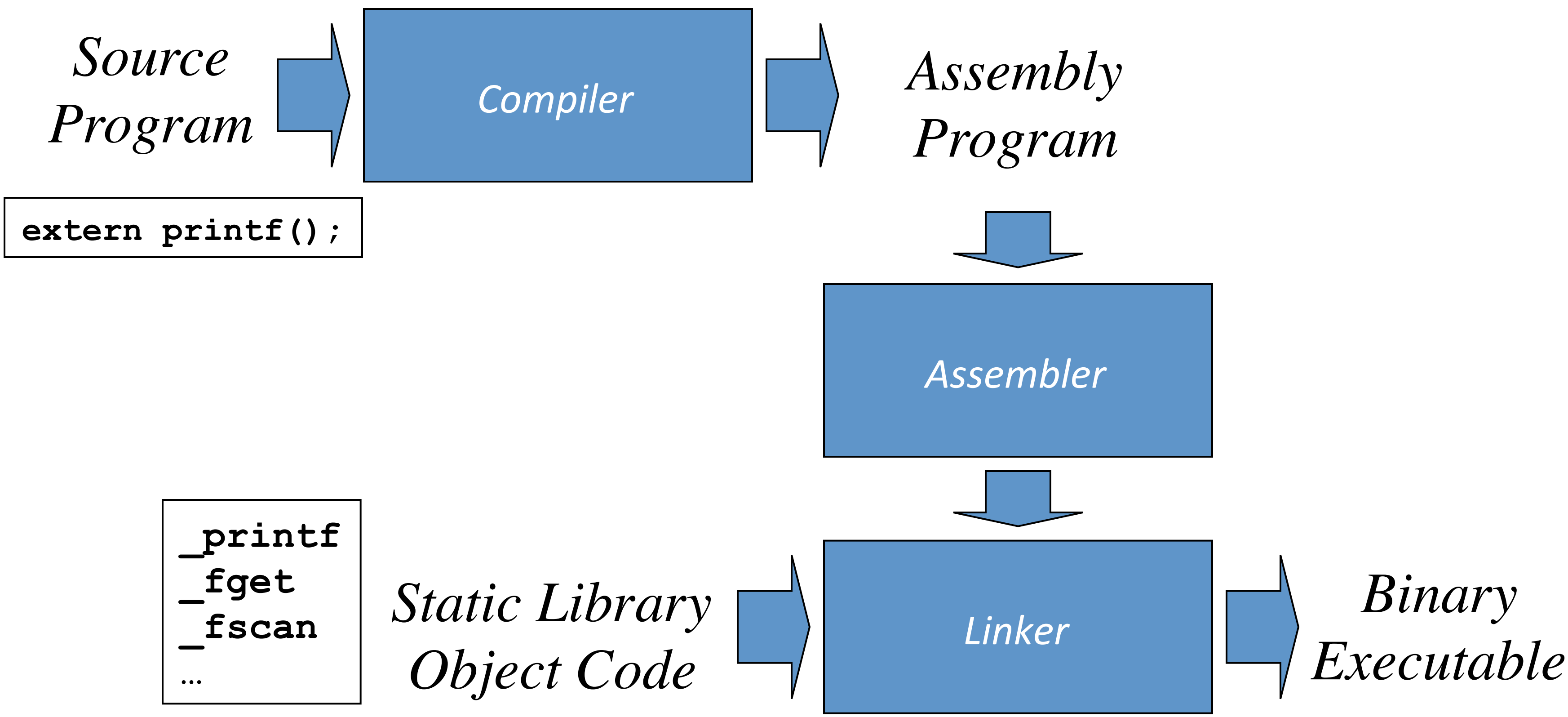
Pure Compilation and Static Linking

- Adopted by the typical Fortran systems
- Library routines are separately linked (merged) with the object code of the program



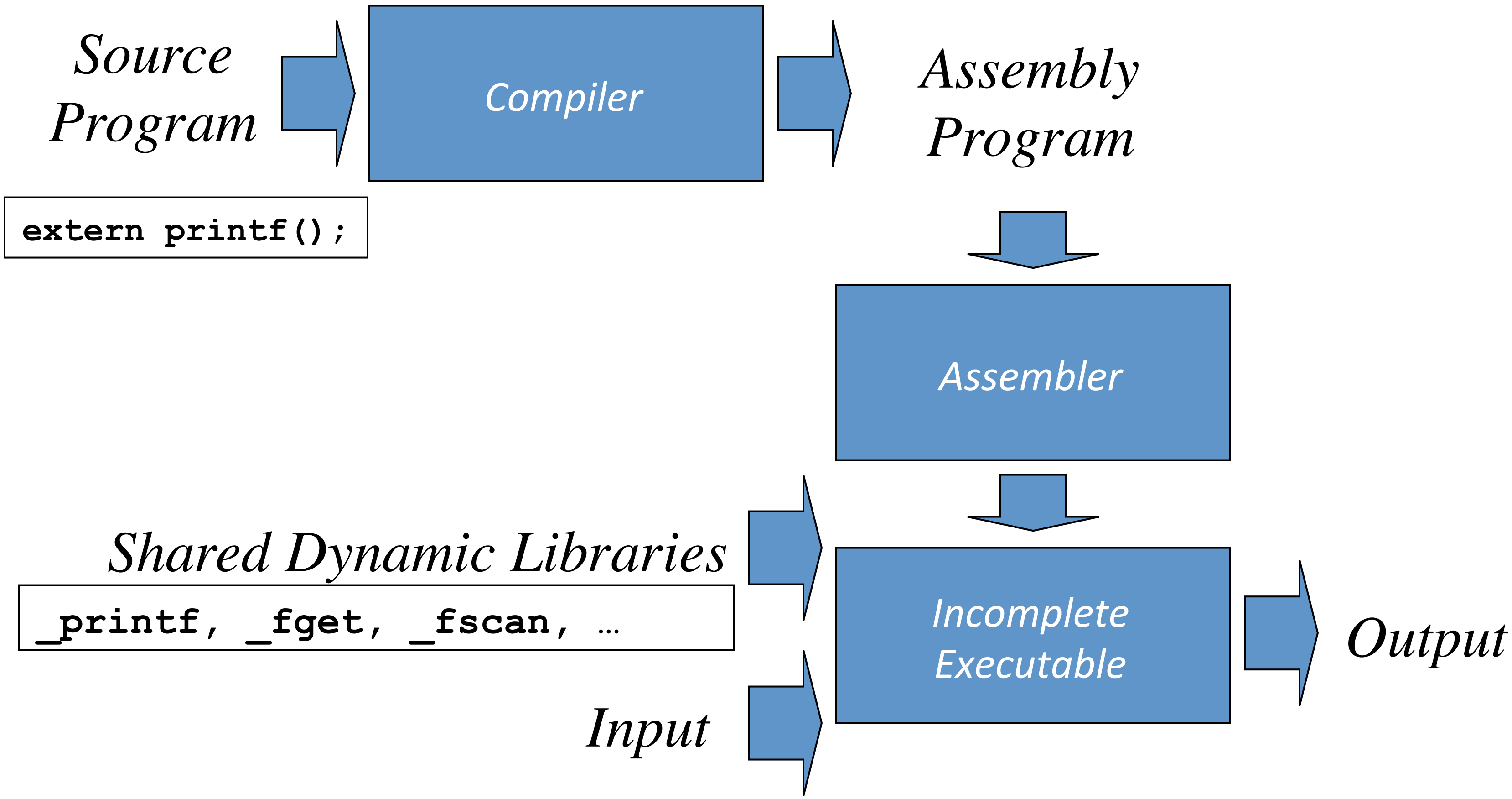
Compilation, Assembly, and Static Linking

- Facilitates debugging of the compiler



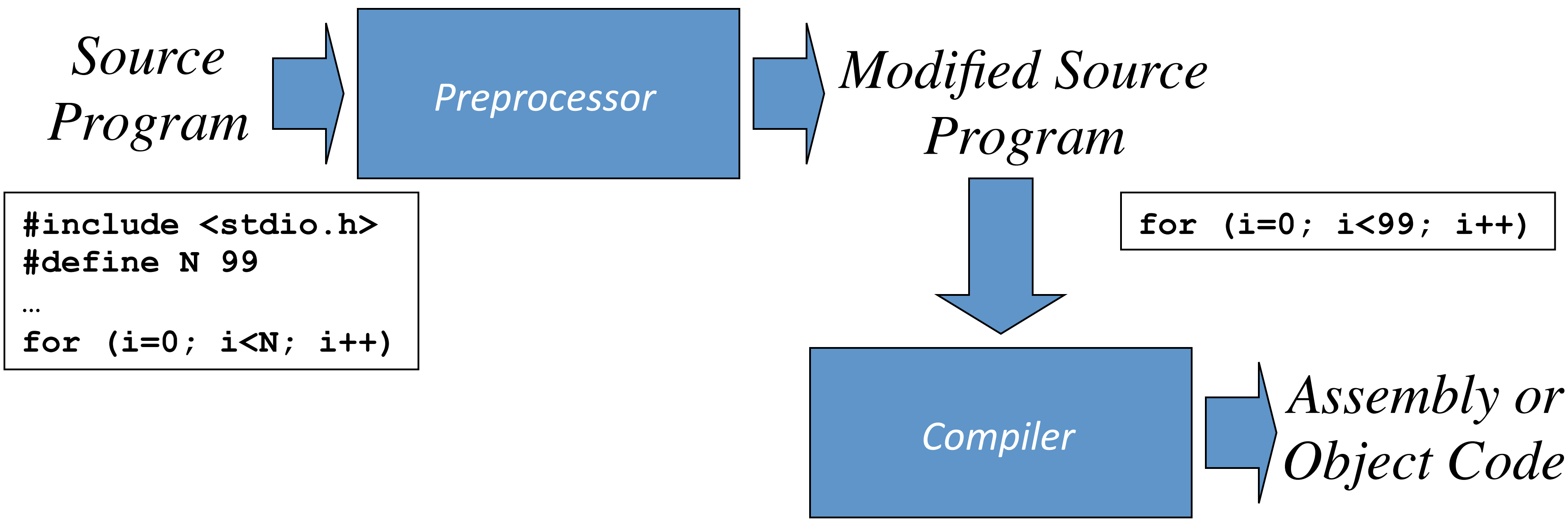
Compilation, Assembly, and Dynamic Linking

- Dynamic libraries (DLL, .so, .dylib) are linked at run-time by the OS (via stubs in the executable)



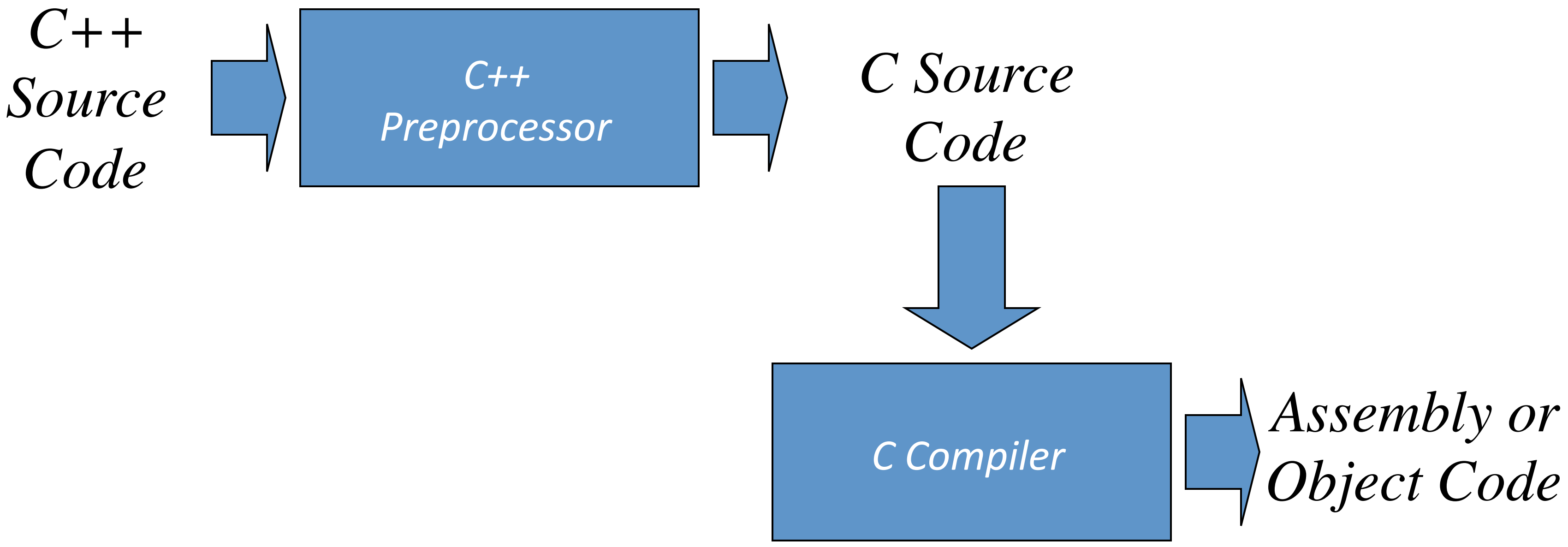
Preprocessing

- Most C and C++ compilers use a preprocessor to import header files and expand macros



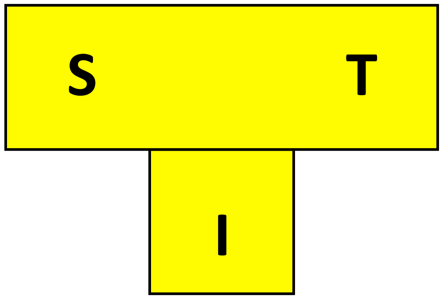
The CPP Preprocessor

- Early C++ compilers used the CPP preprocessor to generated C code for compilation



Compilers, graphically

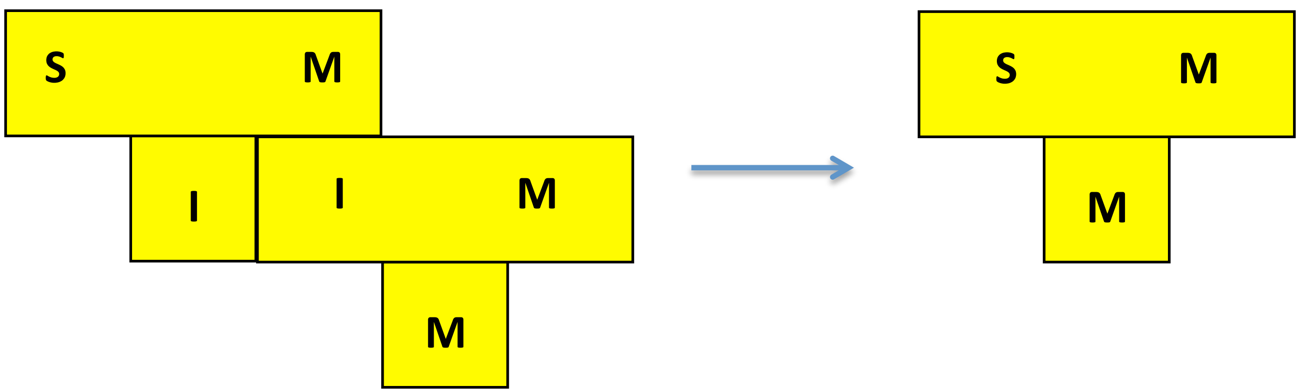
- Three languages involved in writing a compiler
  - Source Language (S)
  - Target Language (T)
  - Implementation Language (I)
- T-Diagram:



- If **I = T** we have a **Host Compiler**
- If **S**, **T**, and **I** are all different, we have a **Cross-Compiler**

Composing compilers

- Compiling a compiler we get a new one: the result is described by composing T-diagrams

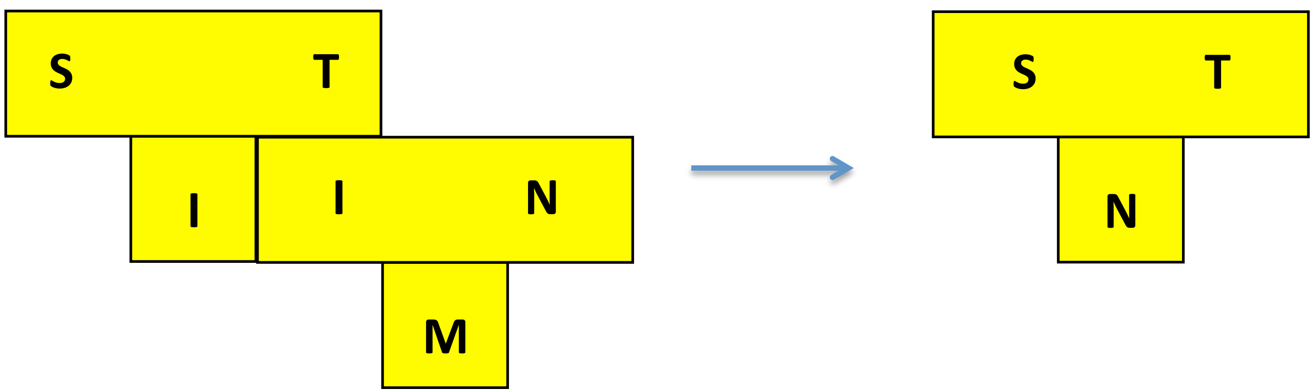


Example:
S **Pascal**
I **C**
M **68000**

- A compiler of **S** to **M** can be written in any language having a host compiler for **M**

Composing compilers

- Compiling a compiler we get a new one: the result is described by composing T-diagrams
- The shape of the basic transformation, in the most general case, is the following:



- Note: by writing this transformation, we implicitly assume that we can execute programs written in **M**

Bootstrapping

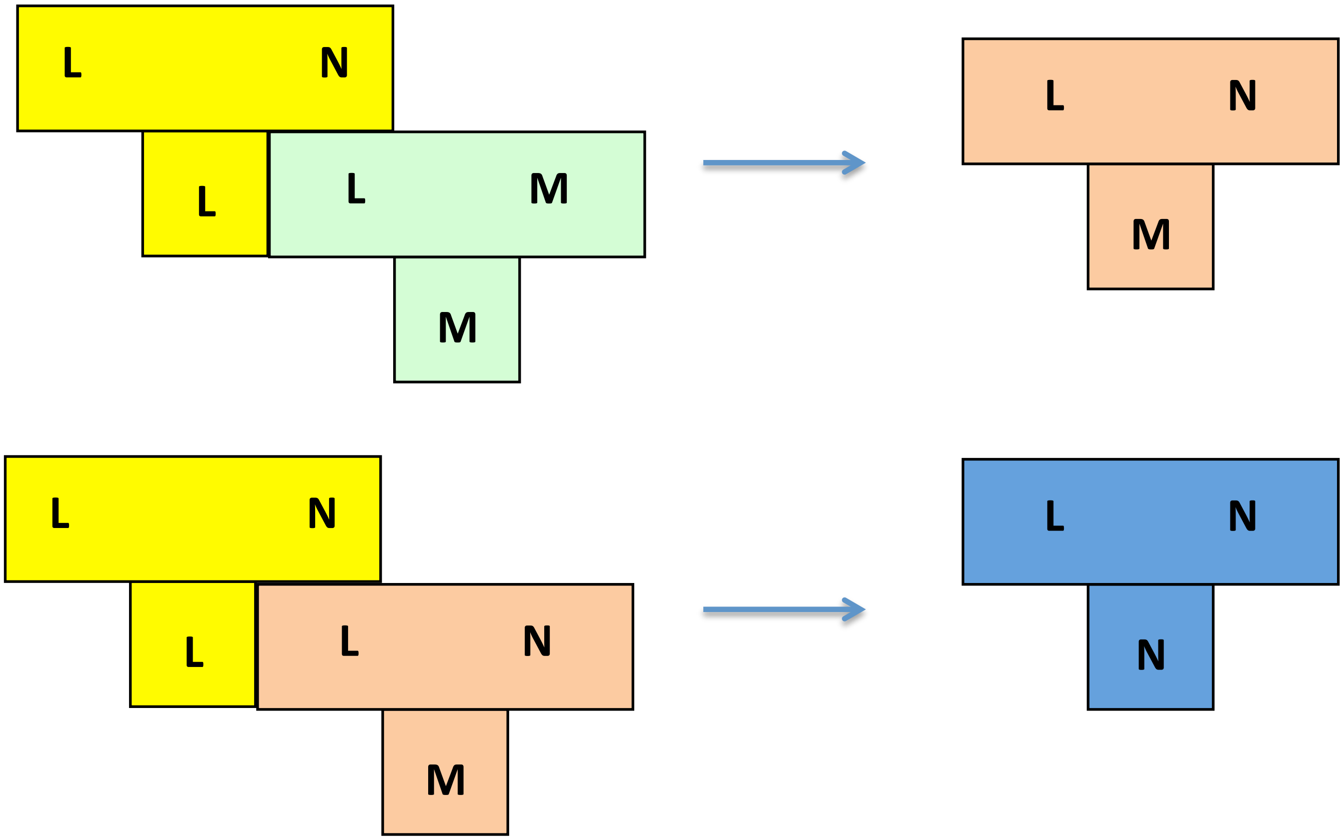
- **Bootstrapping**: techniques which use partial/inefficient compiler versions to generate complete/better ones
- Often compiling a translator programmed in its own language
- Why writing a compiler in its own language?
  - it is a non-trivial test of the language being compiled
  - compiler development can be done in the higher level language being compiled.
  - improvements to the compiler's back-end improve not only general purpose programs but also the compiler itself
  - it is a comprehensive consistency check as it should be able to reproduce its own object code

Compilers: Portability Criteria

- Portability
  - Retargetability
  - Rehostability
- A **retargetable** compiler is one that can be modified easily to generate code for a new target language
- A **rehostable** compiler is one that can be moved easily to run on a new machine
- A portable compiler may not be as efficient as a compiler designed for a specific machine, because we cannot make any specific assumption about the target machine

Using Bootstrapping to port a compiler

- We have a host compiler/interpreter of **L** for **M**
- Write a compiler of **L** to **N** in language **L** itself



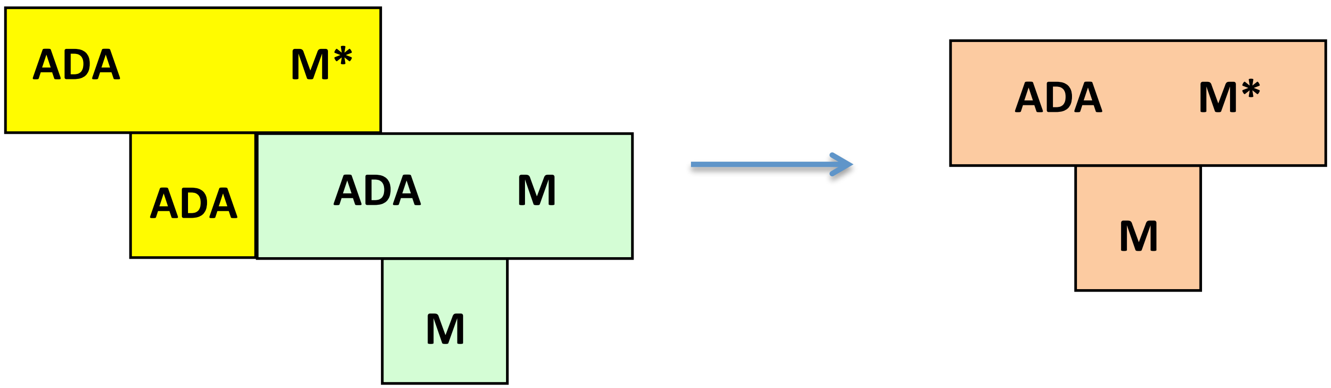
Example:
L **Pascal**
M **P-code**

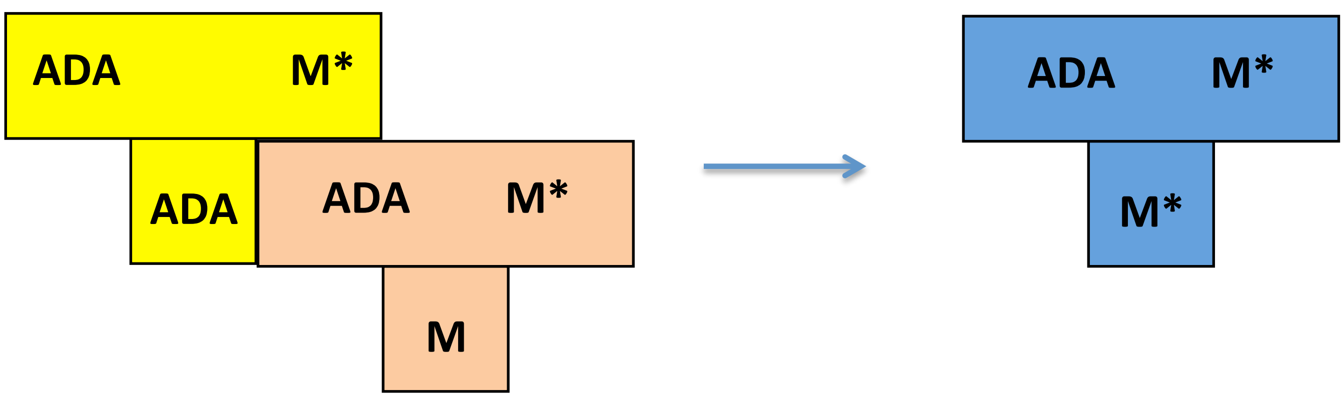
Bootstrapping to optimize a compiler

- The efficiency of programs and compilers:
  - Efficiency of programs:
    - memory usage
    - runtime
  - Efficiency of compilers:
    - Efficiency of the compiler itself
    - Efficiency of the emitted code
- Idea: Start from a simple compiler (generating inefficient code) and develop more sophisticated version of it. We can use bootstrapping to improve performance of the compiler.

Bootstrapping to optimize a compiler

- We have a host compiler of ADA to M
- Write an optimizing compiler of ADA to M in ADA





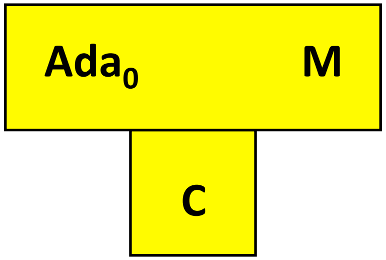
Full Bootstrapping

- A full bootstrap is necessary when building a new compiler from scratch.

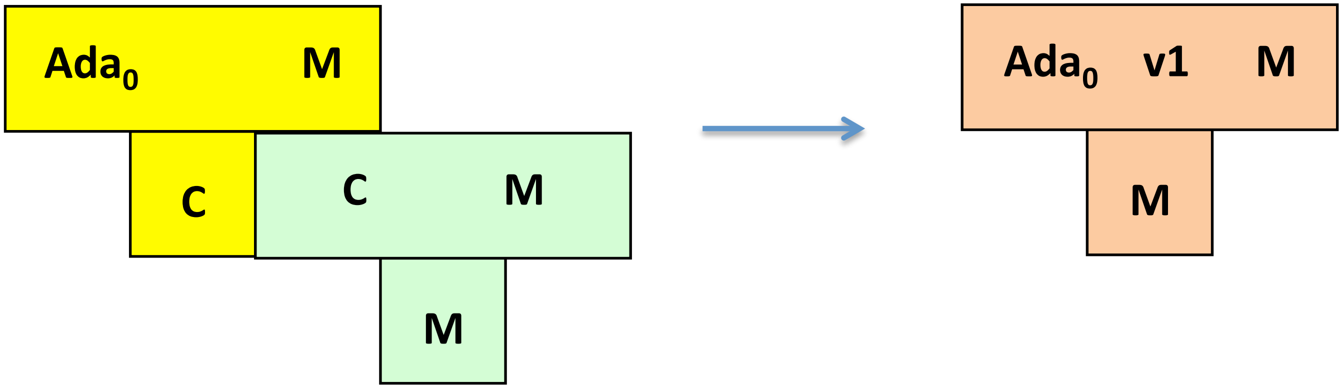
- **Example:**
- We want to implement an **Ada** compiler for machine **M**. We don’t have access to any **Ada** compiler
- Idea: **Ada** is very large, we will implement the compiler in a subset of **Ada** (call it $\mathbf{Ada_0}$) and bootstrap it from a subset of **Ada** compiler in another language (e.g. **C**)

Full Bootstrapping (2)

- **Step 1:** build a compiler of **Ada_0** to **M** in another language, say **C**



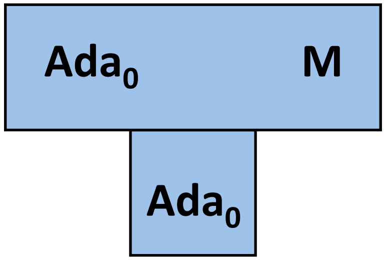
- **Step 2:** compile it using a host compiler of **C** for **M**



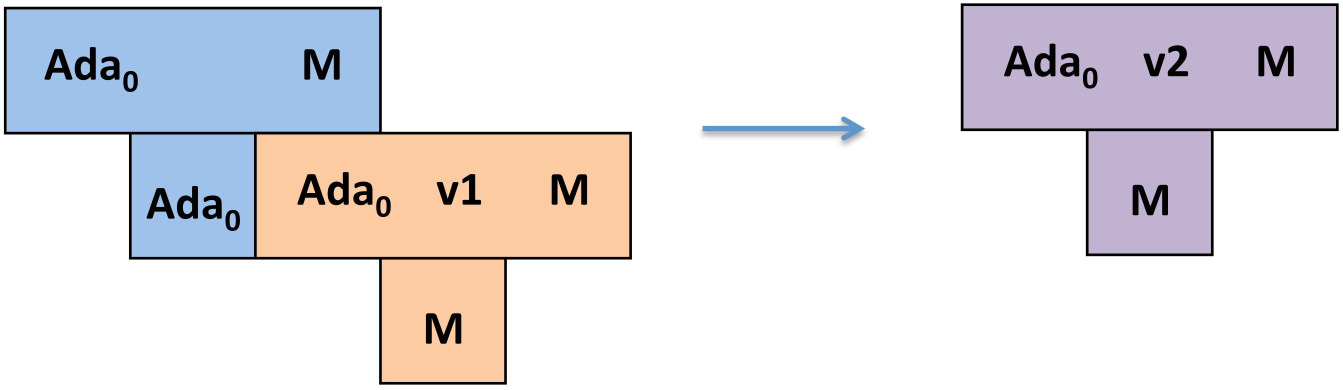
- **Note:** new versions would depend on the **C** compiler for **M**

Full Bootstrapping (3)

- **Step 3:** Build another compiler of **Ada_0** in **Ada_0**



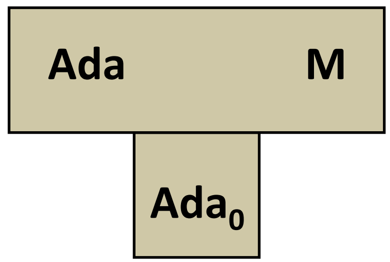
- **Step 4:** compile it using the **Ada_0** compiler for **M**



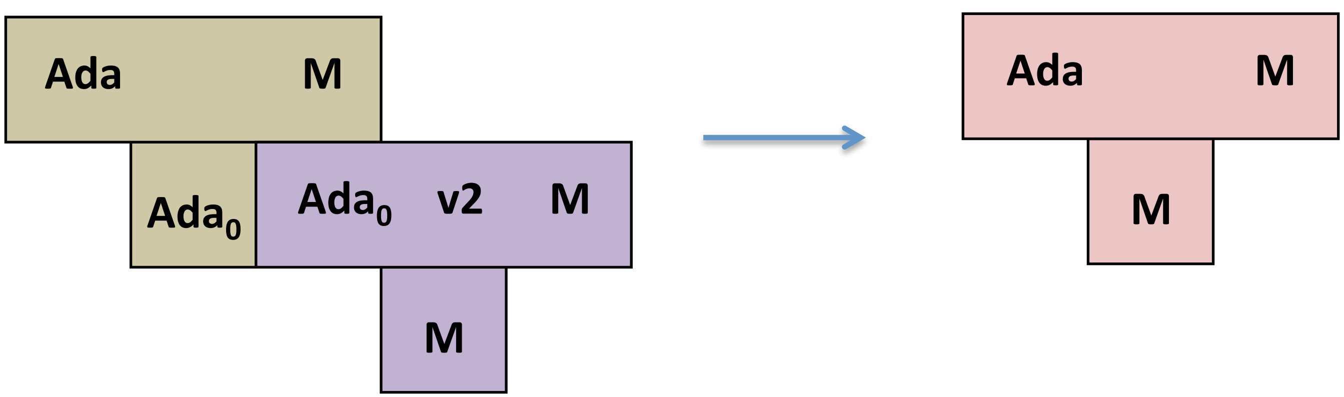
- **Note: C** compiler is no more necessary

Full Bootstrapping (4)

- **Step 5:** Build a full compiler of **Ada** in **Ada_0**



- **Step 4:** compile it using the second **Ada_0** compiler for **M**



- Future versions of the compiler can be written directly in Ada

Compilers

The Analysis-Synthesis Model of Compilation

- Compilers translate programs written in a language into equivalent programs in another language
- There are two parts to compilation:
  – **Analysis** determines the operations implied by the source program which are recorded in a tree structure
  – **Synthesis** takes the tree structure and translates the operations therein into the target program

Other Tools that Use the Analysis-Synthesis Model

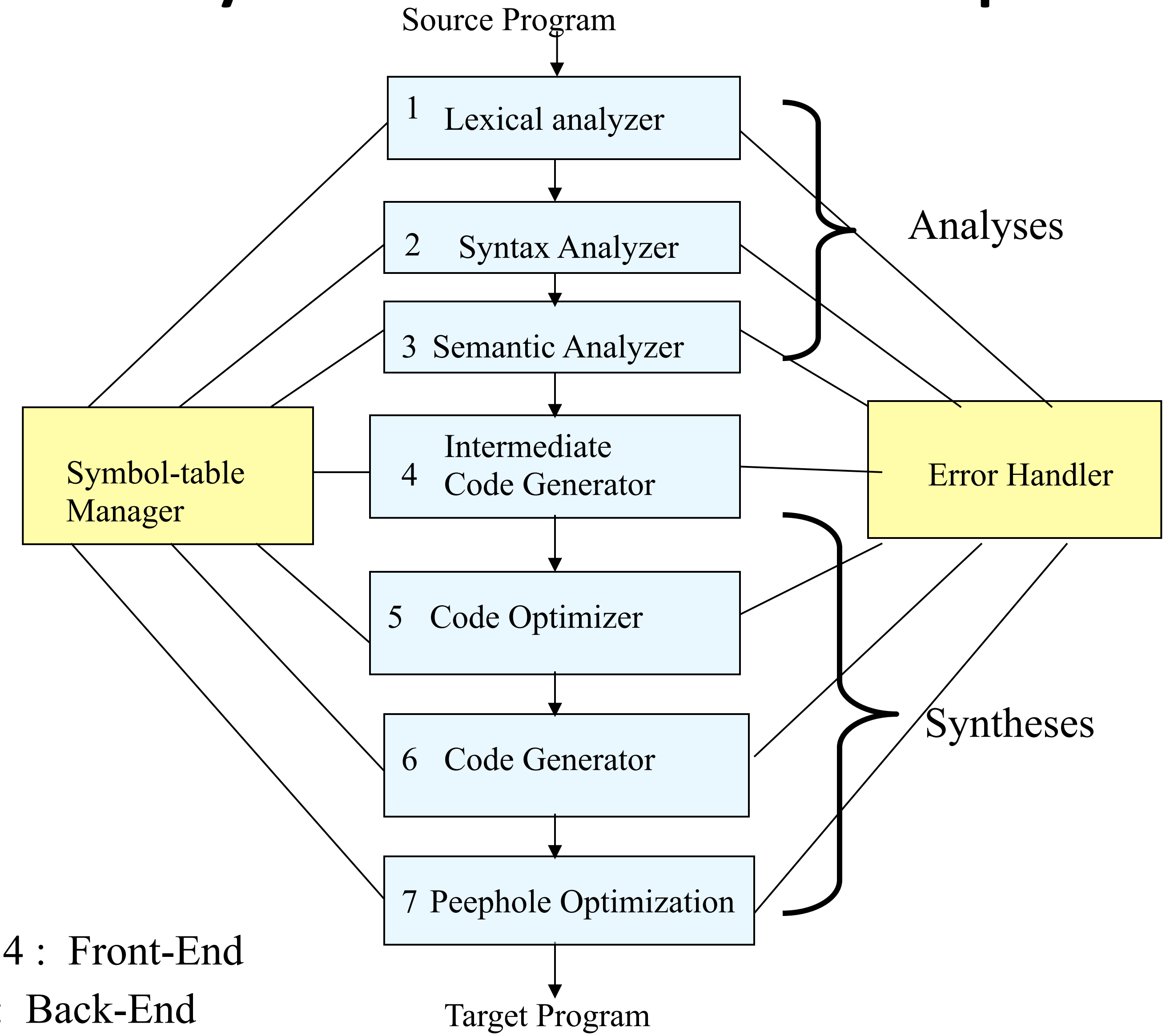
- Editors (syntax highlighting)
- Pretty printers (e.g. Doxygen)
- Static checkers (e.g. Lint and Splint)
- Interpreters
- Text formatters (e.g. TeX and LaTeX)
- Silicon compilers (e.g. VHDL)
- Query interpreters/compilers (Databases)

Several compilation techniques are used in other kinds of systems

Compilation Phases and Passes

- Compilation of a program proceeds through a fixed series of phases
- A **pass** is one phase or a sequence of phases that starts from a representation of the program and produces another representation of it
- Passes can be serialized, phases not necessarily
  - Pascal, FORTRAN, C languages designed for one-pass compilation, which explains the need for function prototypes
  - Single-pass compilers need less memory to operate
  - Java and ADA are multi-pass

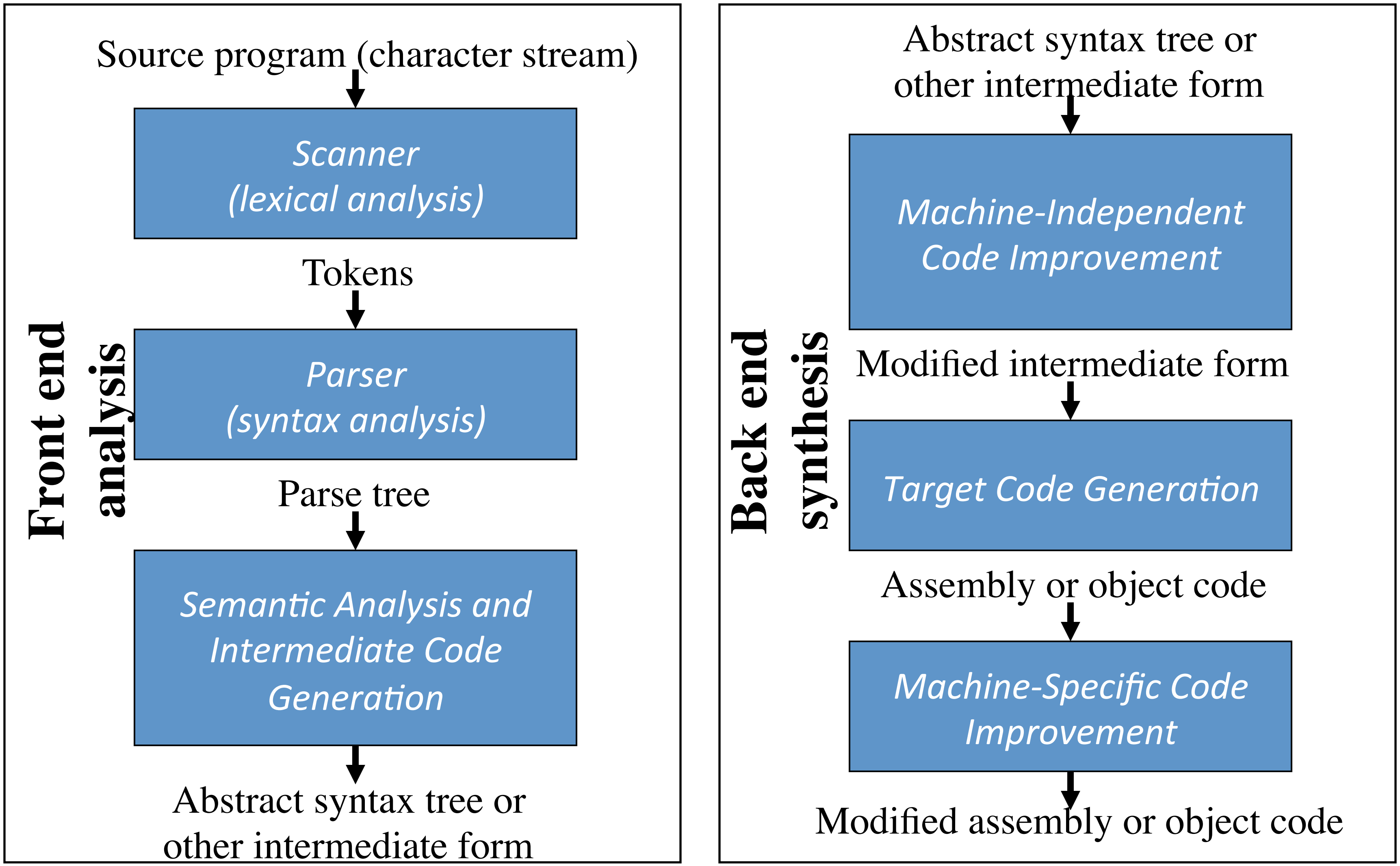
The Many Phases of a Compiler



1, 2, 3, 4 : Front-End

5, 6, 7 : Back-End

Compiler Front- and Back-end



Scanner: Lexical Analysis

- Lexical analysis breaks up a program into tokens

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

program	gcd	(	input	,	output	)	;
var	i	,	j	:	**integer**	;	**begin**
read	(	i	,	j	)	;	**while**
i	<>	j	**do**	**if**	i	>	j
then	i	:=	i	-	j	**else**	j
:=	j	-	i	;	writeln	(	i
)	**end**	.					

Context-Free Grammars

- A context-free grammar defines the syntax of a programming language
- The syntax defines the syntactic categories for language constructs
  - Statements
  - Expressions
  - Declarations
- Categories are subdivided into more detailed categories
  - A Statement is a
    - For-statement
    - If-statement
    - Assignment

<statement> ::= *<for-statement>* | *<if-statement>* | *<assignment>*
<for-statement> ::= **for (** *<expression>* **;** *<expression>* **;** *<expression>* **)** *<statement>*
<assignment> ::= *<identifier>* **:=** *<expression>*

Example: Micro Pascal

<Program> ::= **program** <id> **(** <id> <More_ids> **)** **;** <Block> **.**

<Block> ::= <Variables> **begin** <Stmt> <More_Stmts> **end**

<More_ids> ::= **,** <id> <More_ids>

| ε

<Variables> ::= **var** <id> <More_ids> **:** <Type> **;** <More_Variables>

| ε

<More_Variables> ::= <id> <More_ids> **:** <Type> **;** <More_Variables>

| ε

<Stmt> ::= <id> **:=** <Exp>

| **if** <Exp> **then** <Stmt> **else** <Stmt>

| **while** <Exp> **do** <Stmt>

| **begin** <Stmt> <More_Stmts> **end**

<Exp> ::= <num>

| <id>

| <Exp> + <Exp>

| <Exp> **-** <Exp>

Parser: Syntax Analysis

- Parsing organizes tokens into a hierarchy called a **parse tree**
- Essentially, a grammar of a language defines the structure of the parse tree, which in turn describes the program structure
- A syntax error is produced by a compiler when the parse tree cannot be constructed for a program

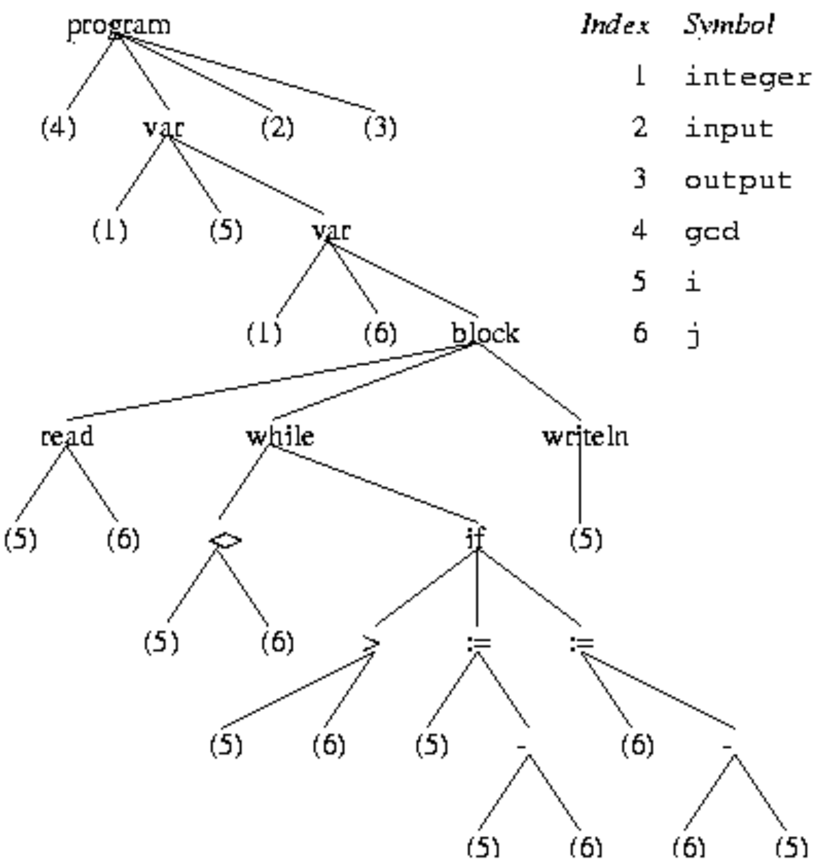
Semantic Analysis

- Semantic analysis is applied by a compiler to discover the meaning of a program by analyzing its parse tree or abstract syntax tree
- Static semantic checks are performed at compile time
  - Type checking
  - Every variable is declared before used
  - Identifiers are used in appropriate contexts
  - Check subroutine call arguments
  - Check labels
- Dynamic semantic checks are performed at run time, and the compiler produces code that performs these checks
  - Array subscript values are within bounds
  - Arithmetic errors, e.g. division by zero
  - Pointers are not dereferenced unless pointing to valid object
  - A variable is used but hasn't been initialized
  - When a check fails at run time, an exception is raised

Semantic Analysis and Strong Typing

- A language is strongly typed "if (type) errors are always detected"
  - Errors are either detected at compile time or at run time
  - Examples of such errors are listed on previous slide
  - Languages that are strongly typed are Ada, Java, ML, Haskell
  - Languages that are not strongly typed are Fortran, Pascal, C/C++, Lisp
- Strong typing makes language safe and easier to use, but potentially slower because of dynamic semantic checks
- In some languages, most (type) errors are detected late at run time which is detrimental to reliability e.g. early Basic, Lisp, Prolog, some script languages

Code Generation and Intermediate Code Forms



Index	*Symbol*
1	`integer`
2	`input`
3	`output`
4	`gcd`
5	`i`
6	`j`

- A typical intermediate form of code produced by the semantic analyzer is an abstract syntax tree (AST)
- The AST is annotated with useful information such as pointers to the symbol table entry of identifiers

Example AST for the gcd program in Pascal

Target Code Generation and Optimization

- The AST with the annotated information is traversed by the compiler to generate a low-level intermediate form of code, close to assembly
- This machine-independent intermediate form is optimized
- From the machine-independent form assembly or object code is generated by the compiler
- This machine-specific code is optimized to exploit specific hardware features

Supporting Phases/ Activities for Analysis

- Symbol Table Creation / Maintenance
  - Contains info (storage, type, scope, args) on each "meaningful" token, typically identifiers
  - Data structure created / initialized during lexical analysis
  - Exploited / updated during later analysis & synthesis
- Error Handling
  - Detection of different errors which correspond to all phases
  - What happens when an error is found?