301AA - Advanced Programming

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***AP-03**: Languages and Abstract machines,*
Compilation and interpretation schemes

Outline

- Programming languages and abstract machines
- Implementation of programming languages
- Compilation and interpretation
- Intermediate virtual machines

Definition of Programming Languages

- A PL is defined via **syntax**, **semantics** and **pragmatics**
- The **syntax** is concerned with the form of programs: how expressions, commands, declarations, and other constructs must be arranged to make a well-formed program.
- The **semantics** is concerned with the meaning of (well-formed) programs: how a program may be expected to behave when executed on a computer.
- The **pragmatics** is concerned with the way in which the PL is intended to be used in practice.

Syntax

- Formally defined, but not always easy to find
  - Java?
  - https://docs.oracle.com/javase/specs/index.html
  - Chapter 19 of Java Language Specification
- Lexical Grammar for tokens
  - A *regular* grammar
- Syntactic Grammar for language constructs
  - A *context free* grammar
- Used by the compiler for *scanning* and *parsing*

Semantics

- Usually described precisely, but informally, in natural language.
  - May leave (subtle) ambiguities
- Formal approaches exist, often they are applied to toy languages or to fractions of real languages
  - Denotational [Scott and Strachey 1971]
  - Operational [Plotkin 1981]
  - Axiomatic [Hoare 1969]
- They rarely scale to fully-fledged programming language

(Almost) Complete Semantics of PLs

- Notable exceptions exist:
  - **Pascal** (part), Hoare Logic [C.A.R. Hoare and N. Wirth, ~1970]
  - **Standard ML**, Natural semantics [R. Milner, M. Tofte and R. Harper, ~1990]
  - **C**, Evolving algebras [Y. Gurevich and J. Huggins, 1993]
  - **Java and JVM**, Abstract State Machines [R. Stärk, J. Schmid, E. Börger, 2001]
  - Executable formal semantics using the **K framework** of several languages (C, Java, JavaScript, PHP, Python, Rust,…) https://runtimeverification.com/blog/k-framework-an-overview/

Pragmatics

- Includes coding conventions, guidelines for elegant structuring of code, etc.
- Examples:
  - Java Code Conventions
    http://www.oracle.com/technetwork/java/codeconventions-150003.pdf
  - Google Java Style Guide
    https://google.github.io/styleguide/javaguide.html
- Also includes the description of the supported *programming paradigms*

Programming Paradigms

A **paradigm** is a style of programming, characterized by a particular selection of key concepts and abstractions

- **Imperative programming**: variables, commands, procedures, …
- **Object-oriented (OO) programming**: objects, methods, classes, …
- **Concurrent programming**: processes, communication..
- **Functional programming**: values, expressions, functions, higher-order functions, …
- **Logic programming**: assertions, relations, …

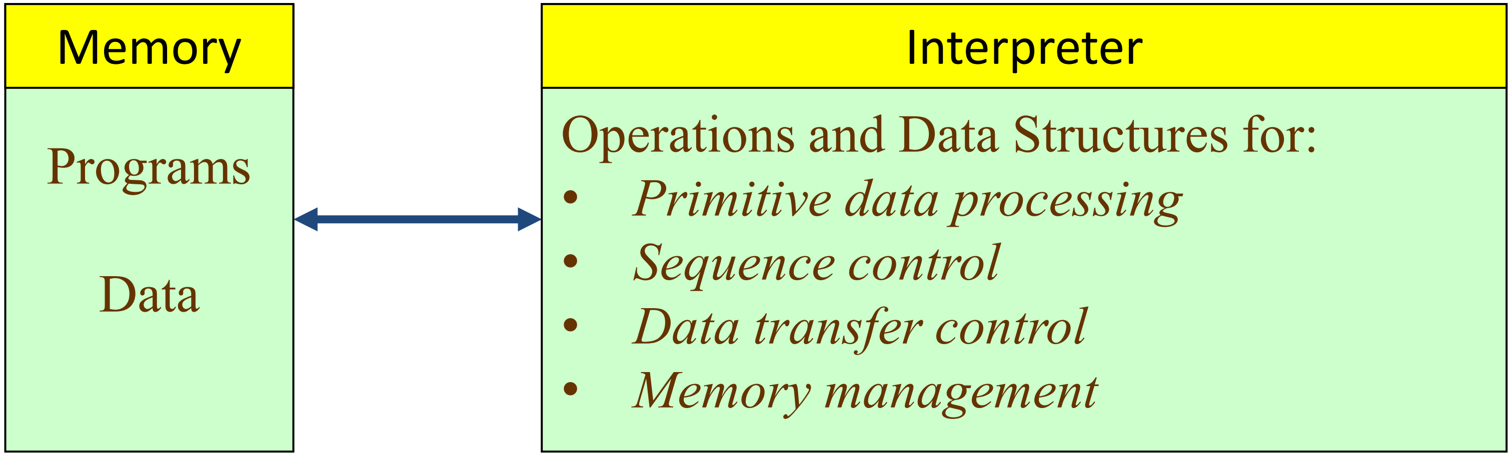
Classification of languages according to paradigms can be misleading

Implementation of a Programming Language *L*

- Programs written in ***L*** must be executable
- Every language ***L*** implicitly defines an ***Abstract Machine*** $\boldsymbol{M_L}$ having ***L*** as machine language
- Implementing $\boldsymbol{M_L}$ on an existing host machine $\boldsymbol{M_O}$ (via ***compilation***, ***interpretation*** or both) makes programs written in ***L*** executable

Programming Languages and Abstract Machines

- Given a programming language **L**, an **Abstract Machine** ***M_L*** **for** ***L*** is *a collection of data structures and algorithms which can perform the storage and execution of programs written in* ***L***
- An abstraction of the concept of hardware machine
- Structure of an abstract machine:



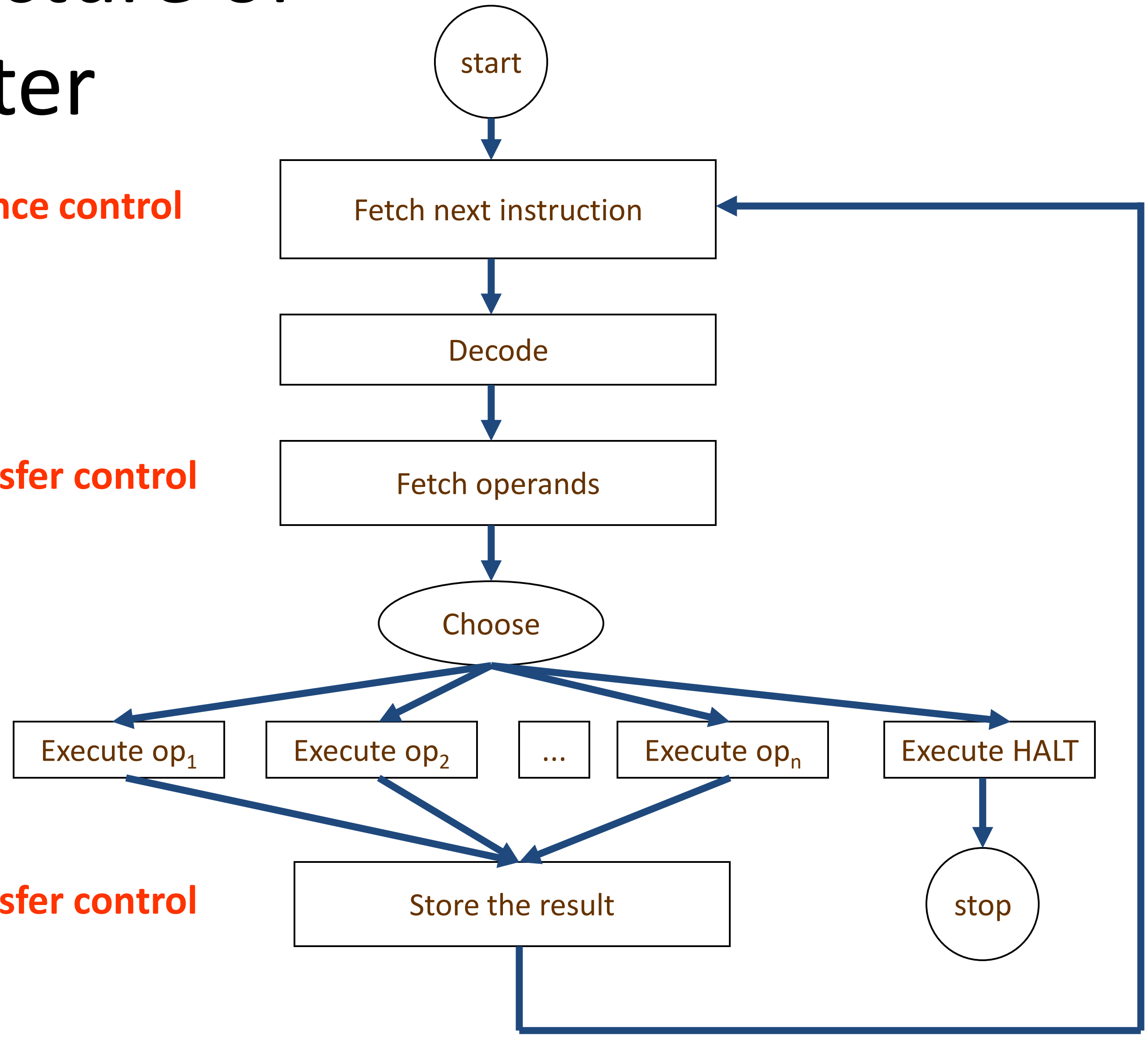
General structure of the Interpreter

Sequence control

Data transfer control

Primitive data processing & Memory management

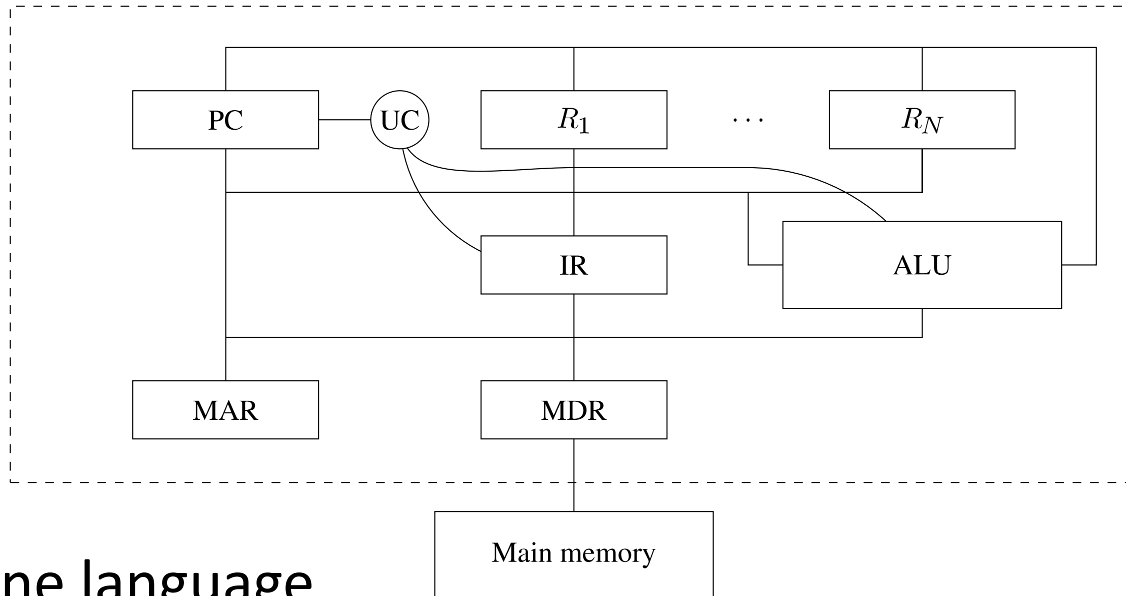
Data transfer control



The Machine Language of an AM

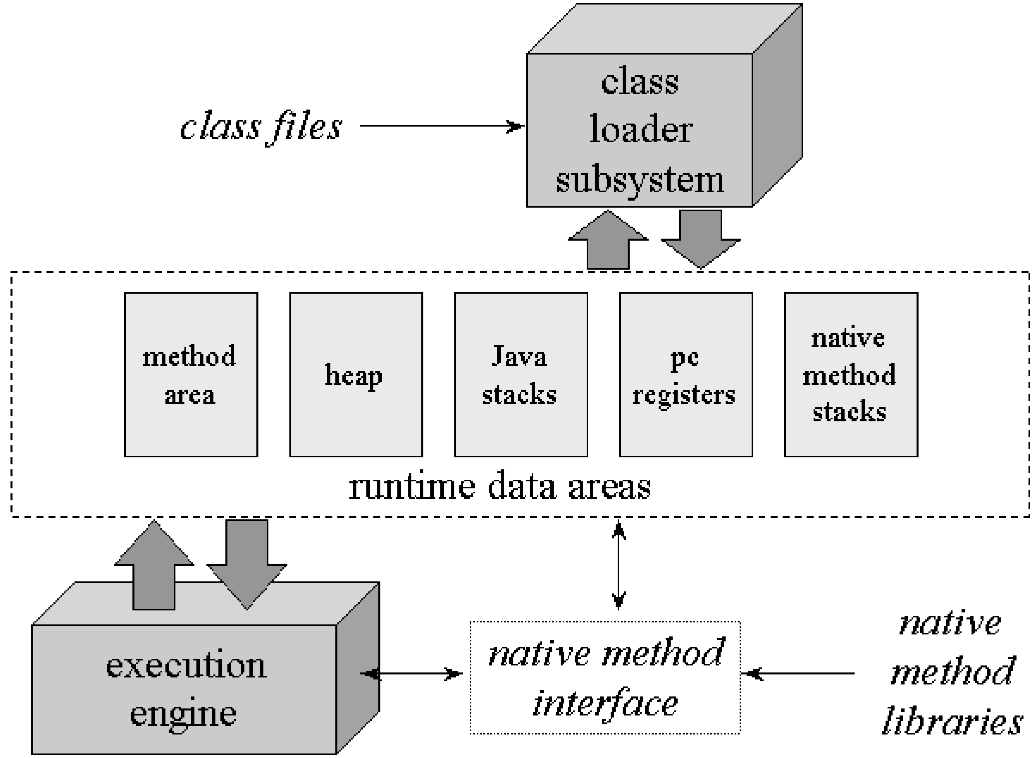
- Viceversa, each abstract machine ***M*** defines a language $\boldsymbol{L_M}$ including all programs which can be executed by the interpreter of ***M***
- Programs are particular data on which the interpreter can act
- Components of ***M*** correspond to components of $\boldsymbol{L_M}$:
  - Primitive data processing ➔ Primitive data types
  - Sequence control ➔ Control structures
  - Data transfer control ➔ Parameter passing and value return
  - Memory management ➔ Memory management

An example: the Hardware Machine



- Language: Machine language
- Memory: Registers + RAM (+ cache)
- Interpreter: fetch, decode, execute loop
- Operations and Data Structures for:
    - Primitive data processing
    - Sequence control
    - Data transfer control
    - Memory management

The Java Virtual Machine



- Language: bytecode
- Memory Heap+Stack+Permanent
- Interpreter

The Java Virtual Machine

The core of a JVM interpreter is basically this:

```
do {
   byte opcode = fetch an opcode;
   switch (opcode) {
     case opCode1 :
         fetch operands for opCode1;
         execute action for opCode1;
         break;
     case opCode2 :
         fetch operands for opCode2;
         execute action for opCode2;
         break;
     case ...
} while (more to do)
```

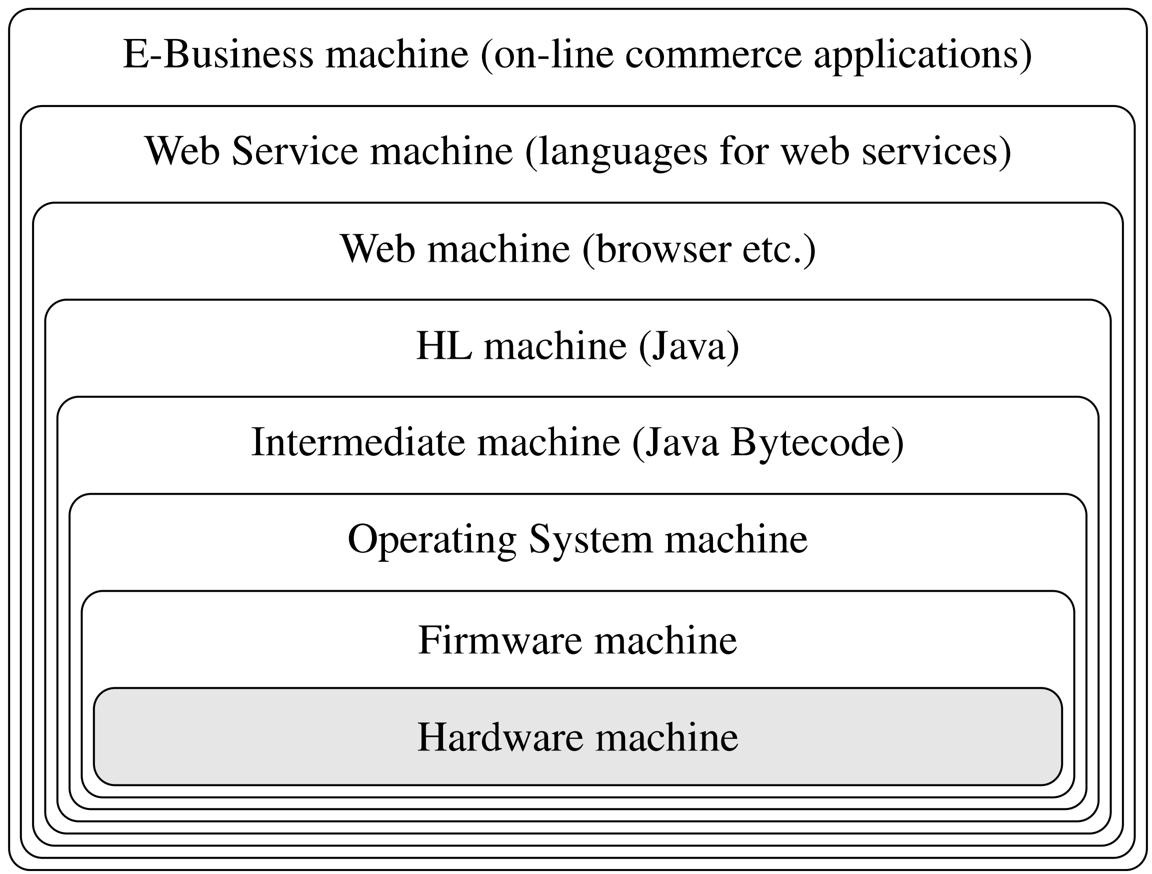
- Language: bytecode
- Memory Heap+Stack+Permanent
- Interpreter
- Operations and Data Structures for:
    - Primitive data processing
    - Sequence control
    - Data transfer control
    - Memory management

Implementing an Abstract Machine

- Each abstract machine can be implemented in **hardware** or in **firmware**, but if high-level this is not convenient in general
  - Exception: Java Processors, …
- Abstract machine **M** can be implemented over a **host machine** $\mathbf{M_O}$, which we assume to be already implemented
- The components of **M** are realized using *data structures* and *algorithms* implemented in the machine language of $\mathbf{M_O}$
- Two main cases:
  - The interpreter of **M** coincides with the interpreter of $\mathbf{M_O}$
    - **M** is an **extension** of $\mathbf{M_O}$
    - other components of the machines can differ
  - The interpreter of **M** is different from the interpreter of $\mathbf{M_O}$
    - **M** is **interpreted** over $\mathbf{M_O}$
    - other components of the machines may coincide

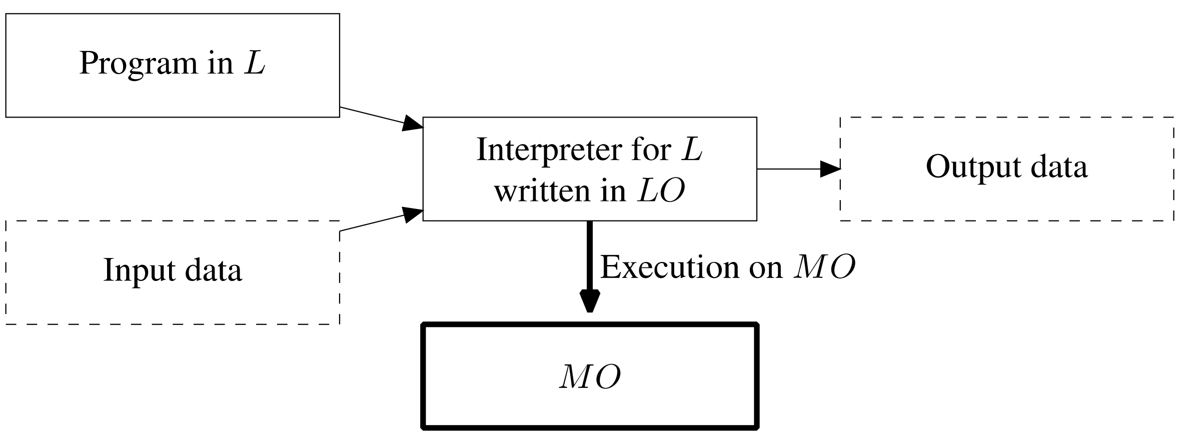
Hierarchies of Abstract Machines

- Implementation of an AM with another can be iterated, leading to a hierarchy (onion skin model)
- Example:



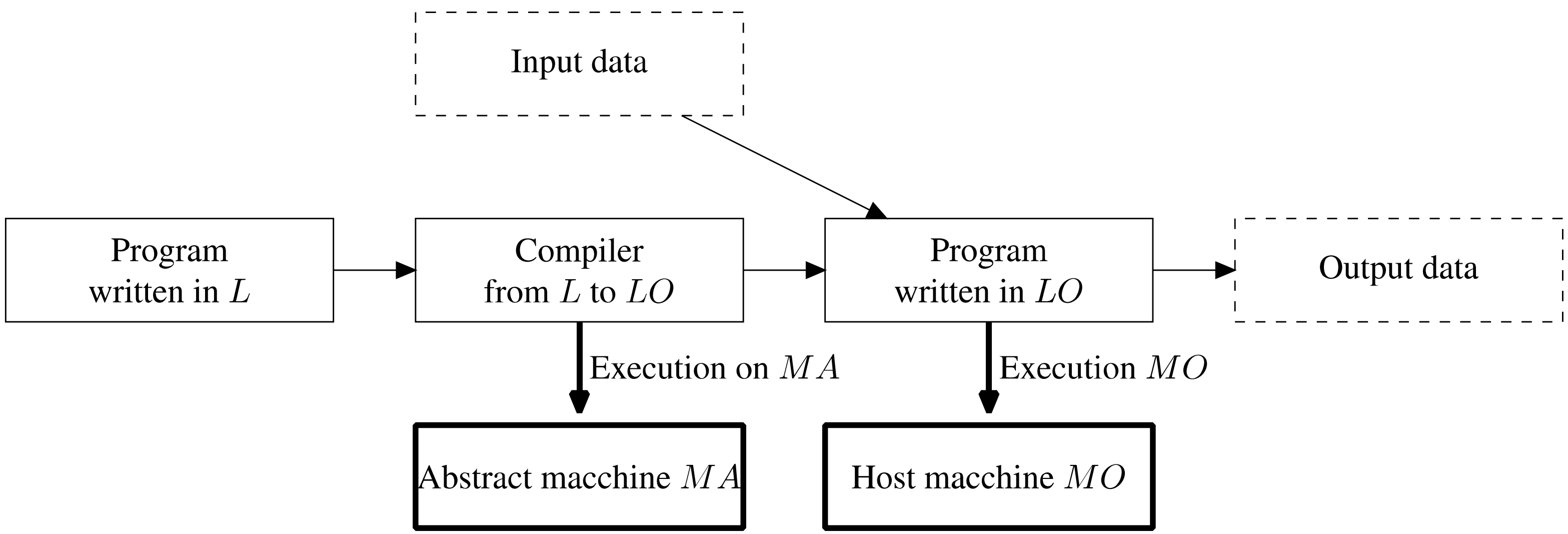
Implementing a Programming Language

- **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)



Implementing a Programming Language

- **Pure Compilation**
  - Programs written in **L** are *translated* into equivalent programs written in $\mathbf{L_O}$, the machine language of $\mathbf{M_O}$
  - The translated programs can be executed directly on $\mathbf{M_O}$
    - $\mathbf{M_L}$ is not realized at all
  - Execution more efficient, but the produced code is larger



- Two limit cases that almost never exist in reality

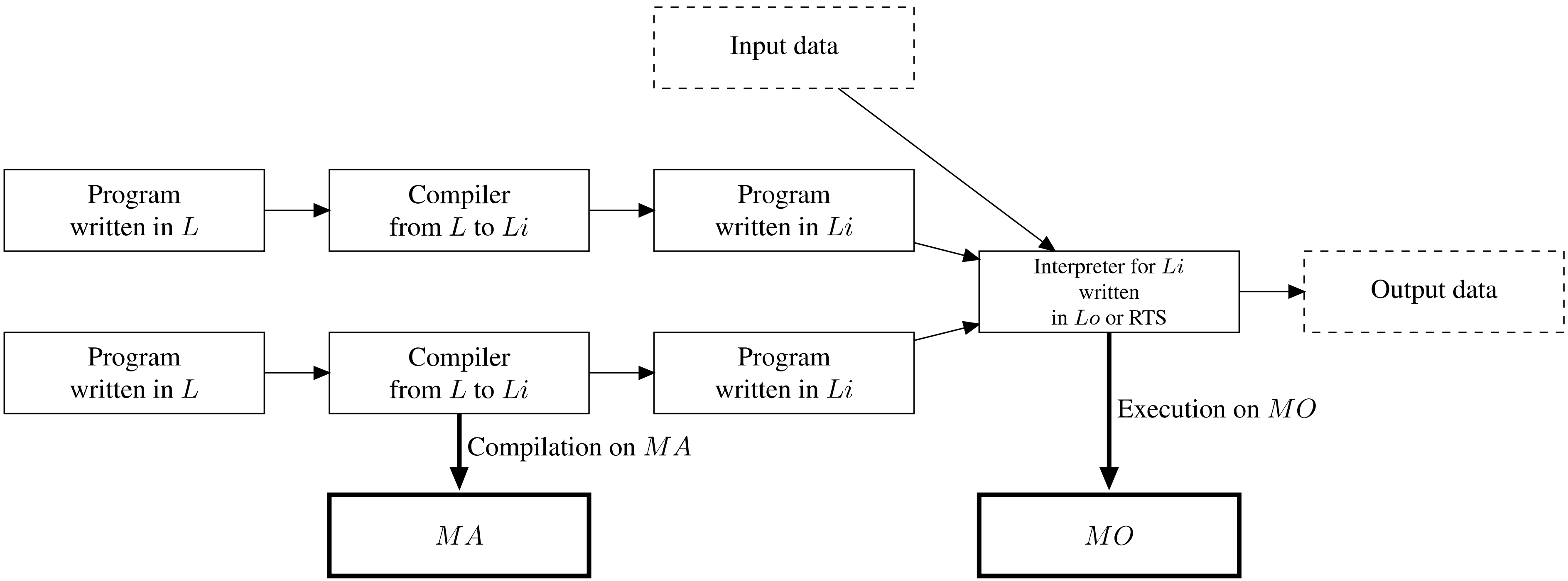
Compilation versus Interpretation

- 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



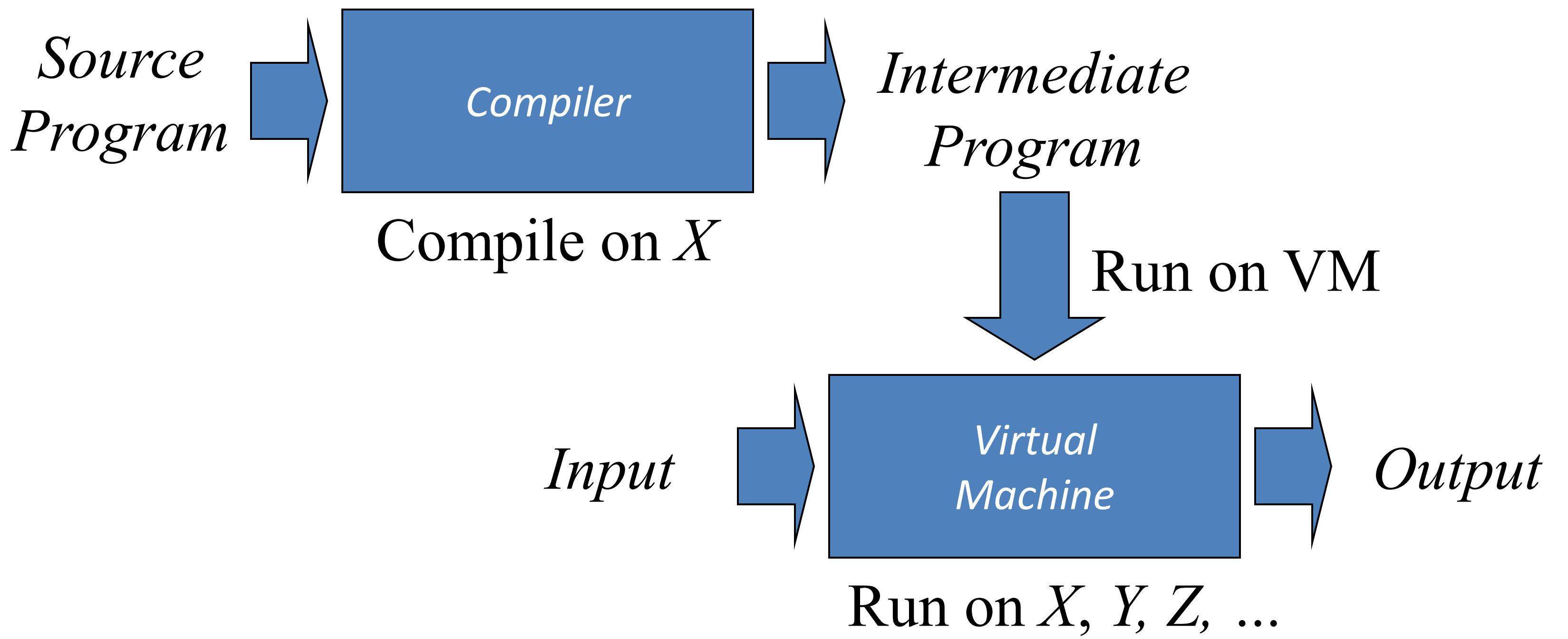
- The “pure” schemes as limit cases

Virtual Machines as Intermediate Abstract Machines

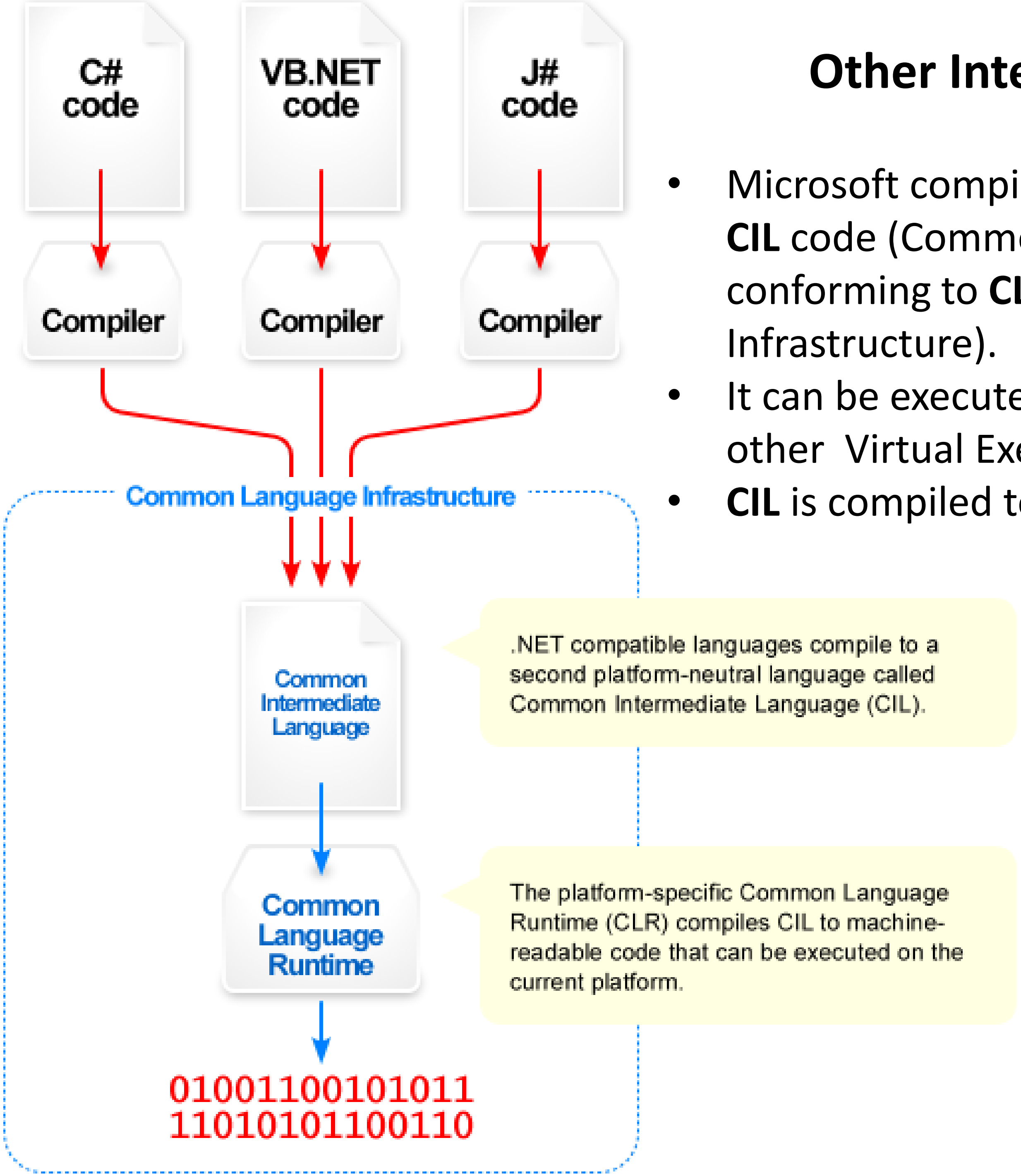
- Several language implementations adopt a compilation + interpretation schema, where the Intermediate Abstract Machine is called **Virtual Machine**
- Adopted by Pascal, Java, Smalltalk-80, C#, functional and logic languages, and some scripting languages
  - Pascal compilers generate **P-code** that 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



Other Intermediate Machines

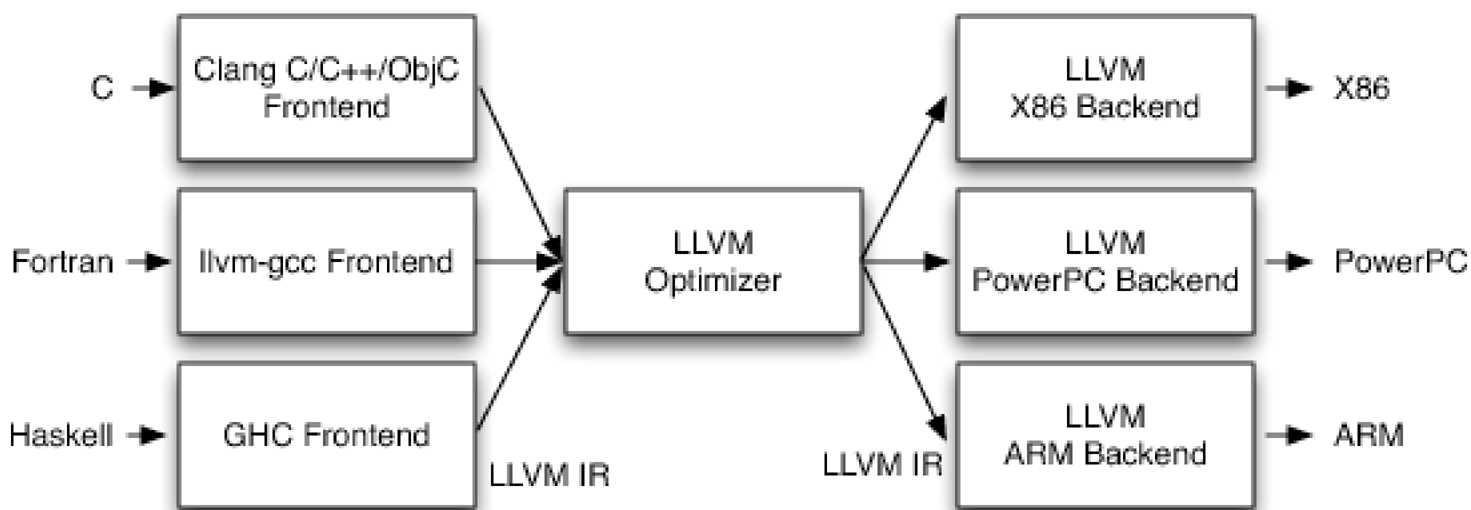


- Microsoft compilers for C#, F#, … generate **CIL** code (Common Intermediate Language) conforming to **CLI** (Common Language Infrastructure).
- It can be executed in **.NET** , **.NET Core**, or other Virtual Execution Systems (like **Mono**)
- **CIL** is compiled to the target machine

LLVM is a **compiler infrastructure** designed as a set of reusable libraries with well-defined interfaces:

- Implemented in C++
- Several front-ends
- Several back-ends
- First release: 2003

- The LLVM IR (Intermediate representation) can also be interpreted
- LLVM IR much lower-level than Java bytecodes or CIL

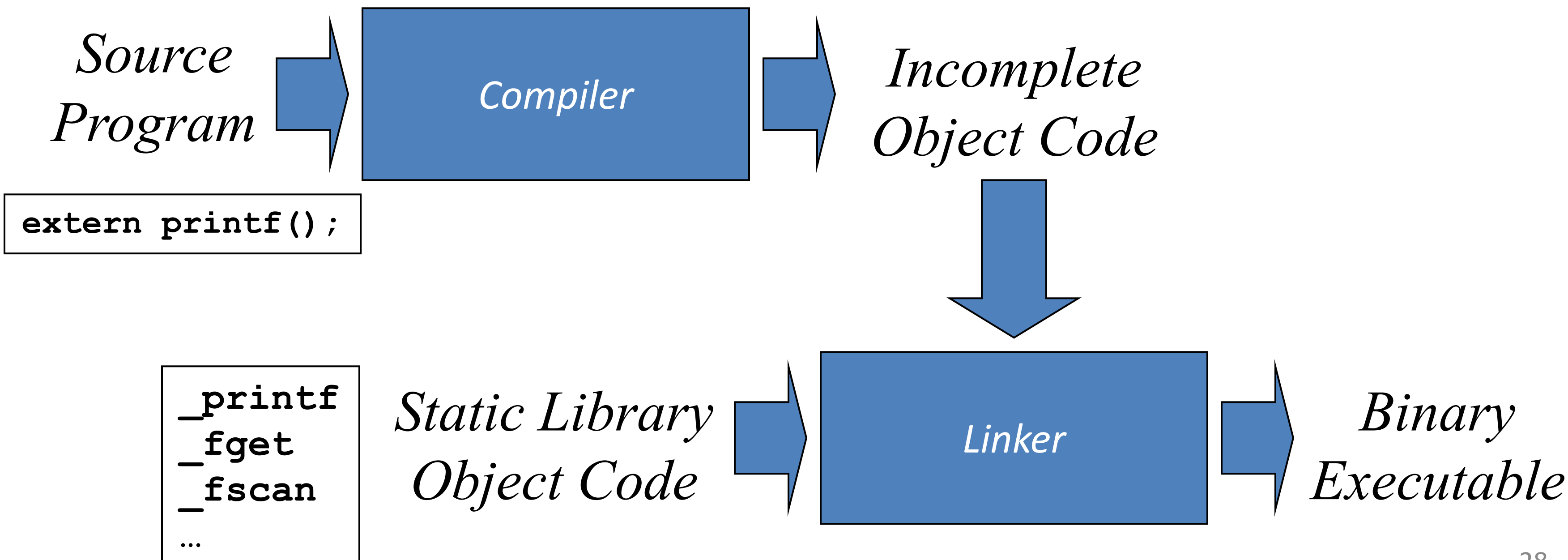


Advantages of intermediate abstract machine (examples for JVM)

- **Portability**: Compile the Java source, distribute the bytecode and execute on any platform equipped with JVM
- **Interoperability**: for a new language **L**, just provide a compiler to JVM bytecode; then it could exploit Java libraries
  - *By design* in Microsoft CLI
  - *De facto* for several languages on JVM

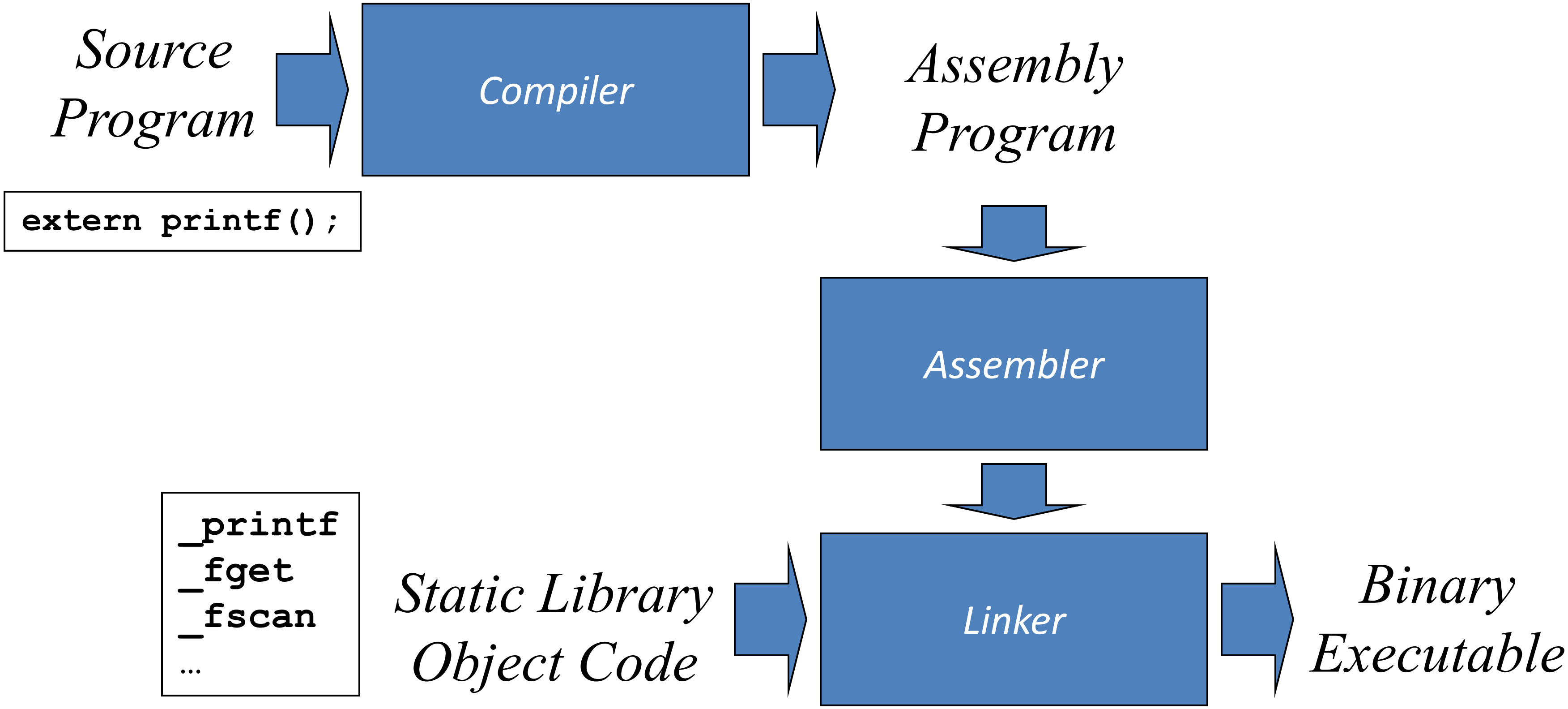
Other Compilation Schemes

- **Pure Compilation and Static Linking**
- Adopted by the typical Fortran systems
- Library routines are separately linked (merged) with the object code of the program



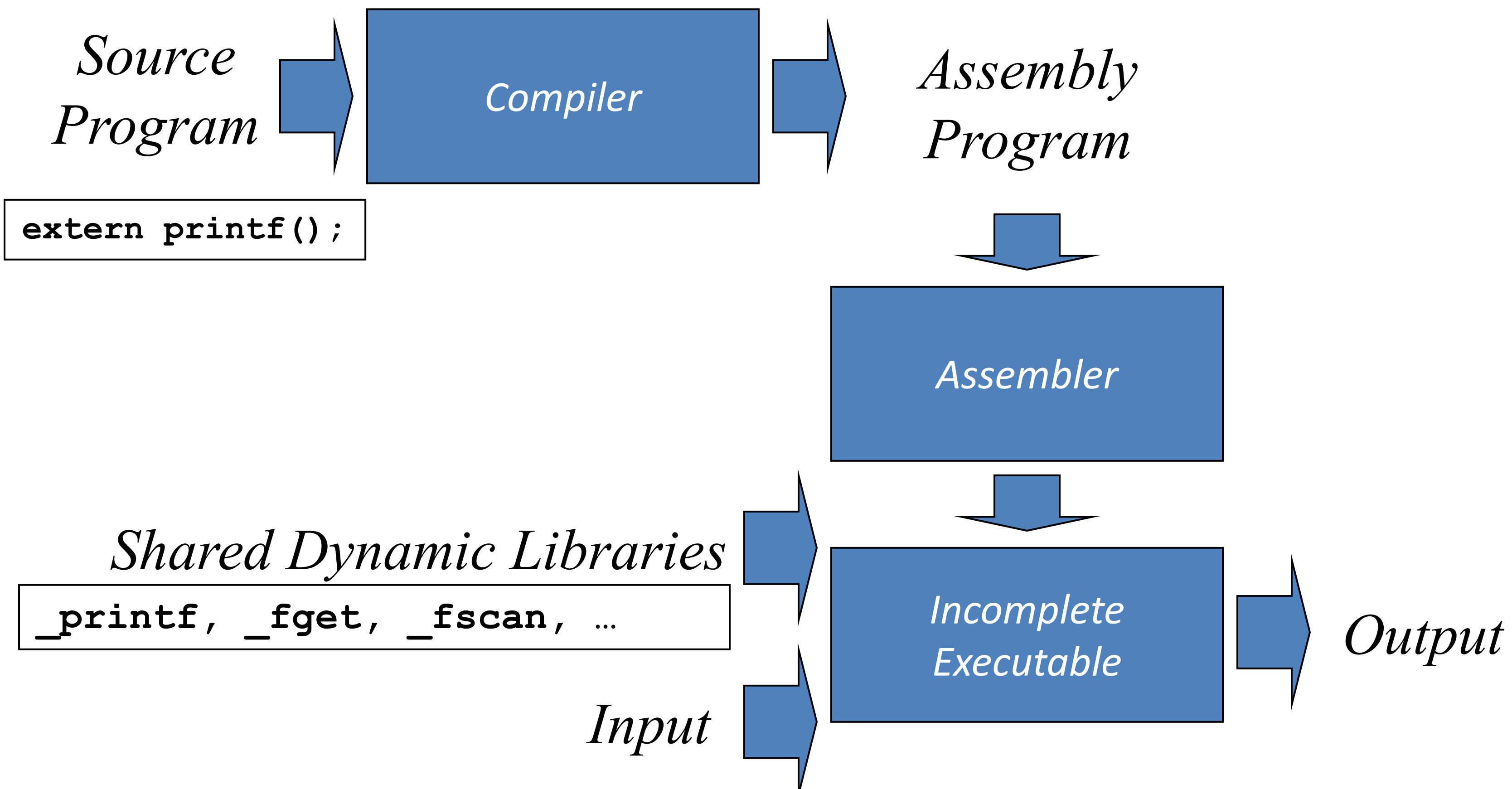
Compilation, Assembly, and Static Linking

- Facilitates debugging of the compiler



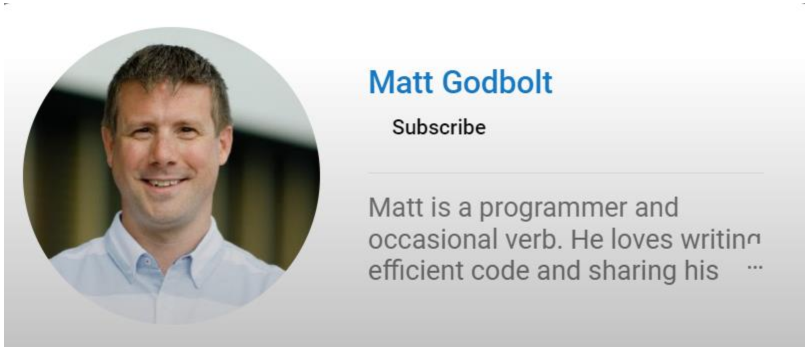
Compilation, Assembly, and Dynamic Linking

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



Exploring the ***Compiler Explorer***

- A very useful tool to test and compare compilers
- Dozens of programming languages
- Hundreds of compilers
- Rich set of functionalities
- https://www.godbolt.org



Summary: **Languages and Abstract Machines Compilation and interpretation schemes**

- **Reading:** Ch. 1 of *Programming Languages: Principles and Paradigms* by M. Gabbrielli and S. Martini
- Syntax, Semantics and Pragmatics of PLs
- Programming languages and Abstract Machines
- Interpretation vs. Compilation vs. Mixed
- Examples of Virtual Machines
- Examples of Compilation Schemes
- Compiler explorer by Matt Godbolt
- → Next topic: **Runtime Support** and the **JVM**