603AA - Principles of Programming Languages [PLP-2016]

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Admins…

- Office hours: **Wednesday, 3-6 pm**
  - **or by appointment <andrea@di.unipi.it>**
- Page on Moodle platform:

https://elearning.di.unipi.it/enrol/index.php?id=52
  - Contains PDFs of relevant chapter
- Tutor: **Lillo Galletta** galletta@di.unipi.it
  - Contact by email, indicating the topics you would like to discuss
  - Based on the requests, Lillo can meet you individually or in group
- No lesson tomorrow, September 23
  - Other possible slot?

- Programming languages and Abstract Machines
- Compilation and interpretation schemes
- Cross compilation
- Bootstrapping
- Compilers

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. Pragmatics include the *paradigm(s)* supported by the PL.

Paradigms

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

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

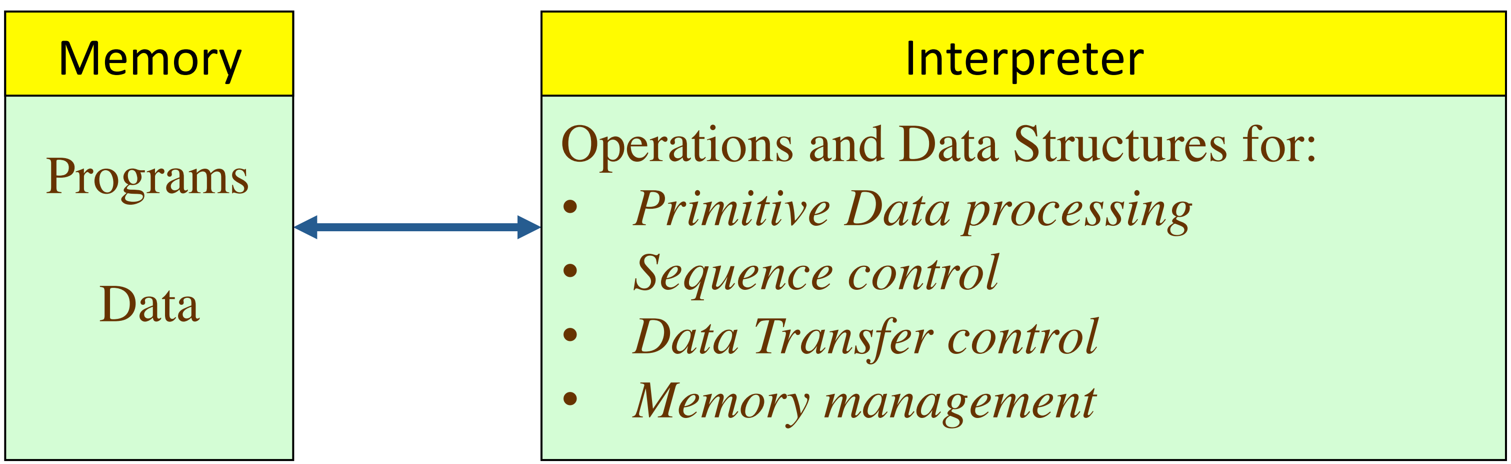
In general, classification of languages according to paradigms is misleading

Implementation of a Programming Language ***L***

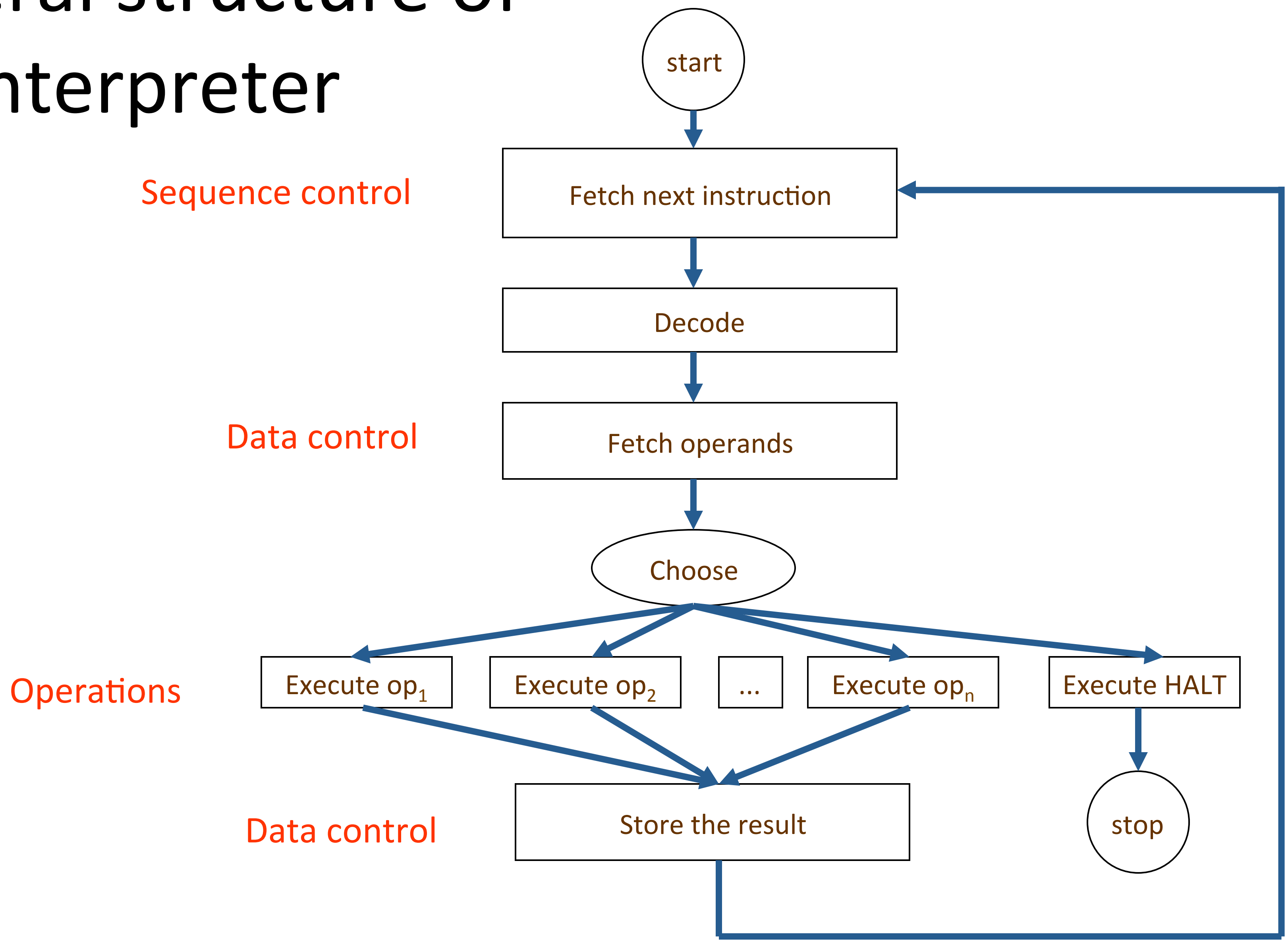
- Programs written in ***L*** must be executable
- Language ***L*** implicitly defines an ***Abstract Machine*** $\boldsymbol{M_L}$ having ***L*** as machine language
- Implementing $\boldsymbol{M_L}$ on an existing host machine $\boldsymbol{M_O}$ (via ***compilation***, ***interpretation*** or both)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

Abstract Machine for a Language **L**

- 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:



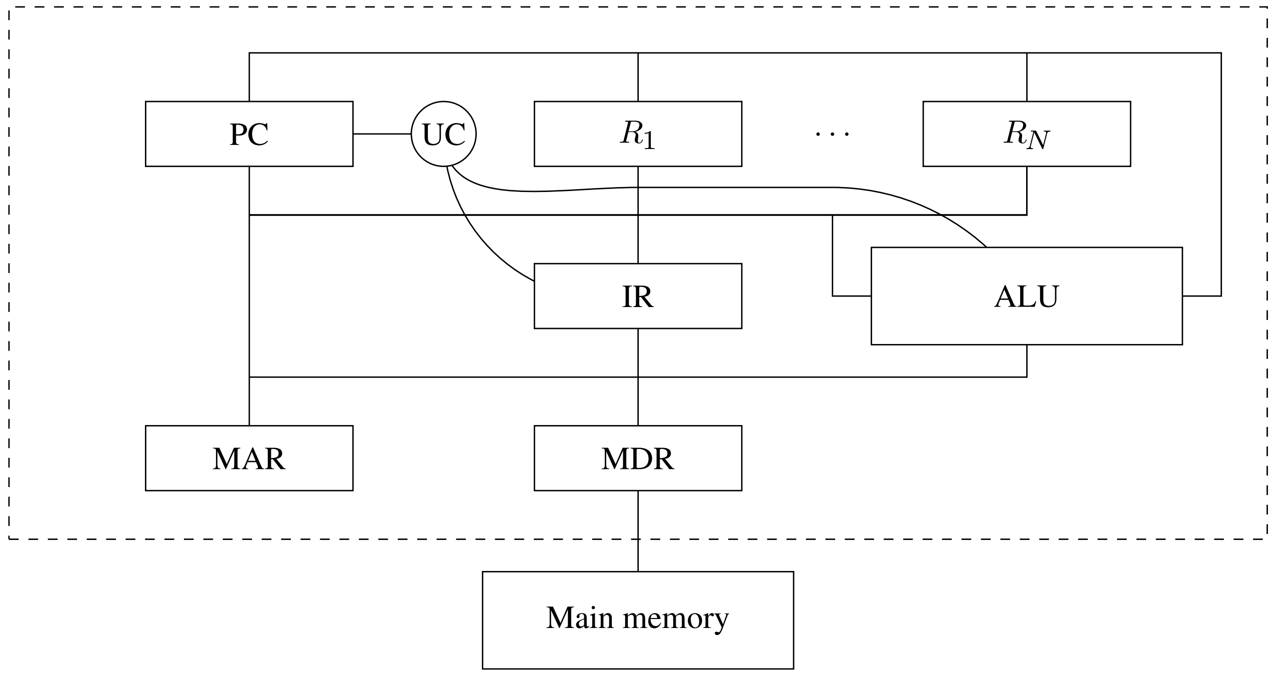
General structure of the Interpreter



The Machine Language of an AM

- Given and Abstract machine **M**, the machine language $\mathbf{L_M}$ of **M**
  - includes all programs which can be executed by the interpreter of M
- Programs are particular data on which the interpreter can act
- The components of **M** correspond to components of $\mathbf{L_M}$, eg:
  - Primitive data types
  - Control structures
  - Parameter passing and value return
  - Memory management
- Every Abstract Machine has a unique Machine Language
- A programming language can have several Abstact Machines

An example: the Hardware Machine

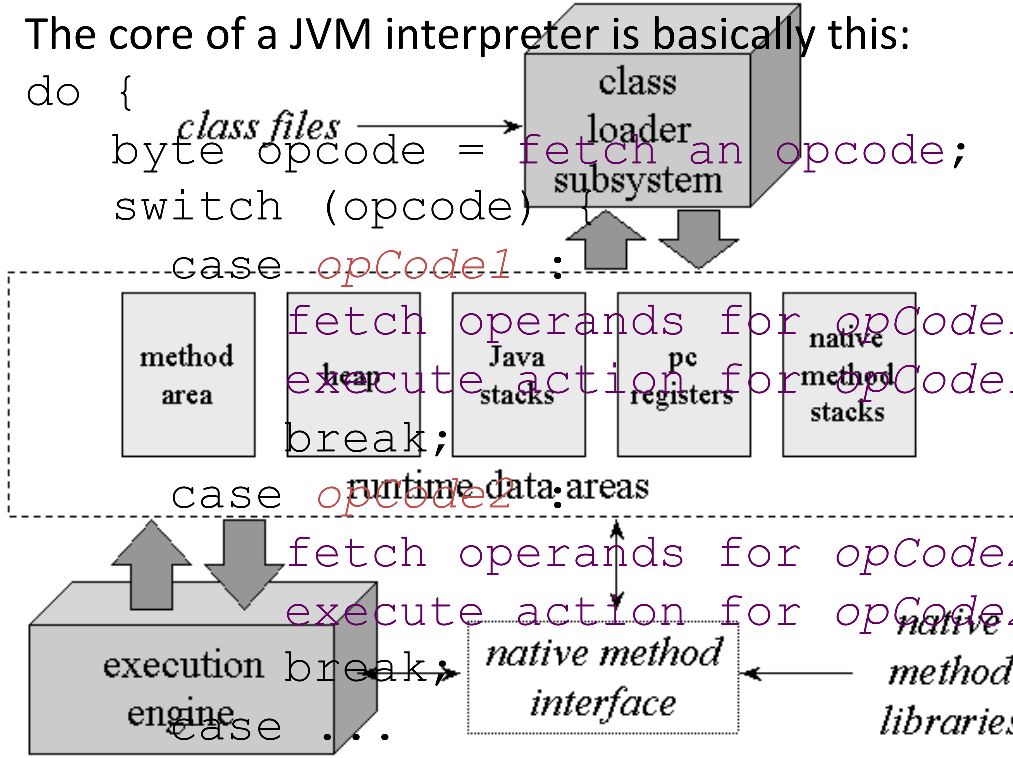


- The language
- The memory
- The interpreter
- Operations and Data Structures for:
  - Primitive Data processing
  - Sequence control
  - Data Transfer control
  - Memory management

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)
```



- The language
- The memory
- The interpreter
- Operations and Data Structures for:
    - Primitive Data processing
    - Sequence control
    - Data Transfer control
    - Memory management

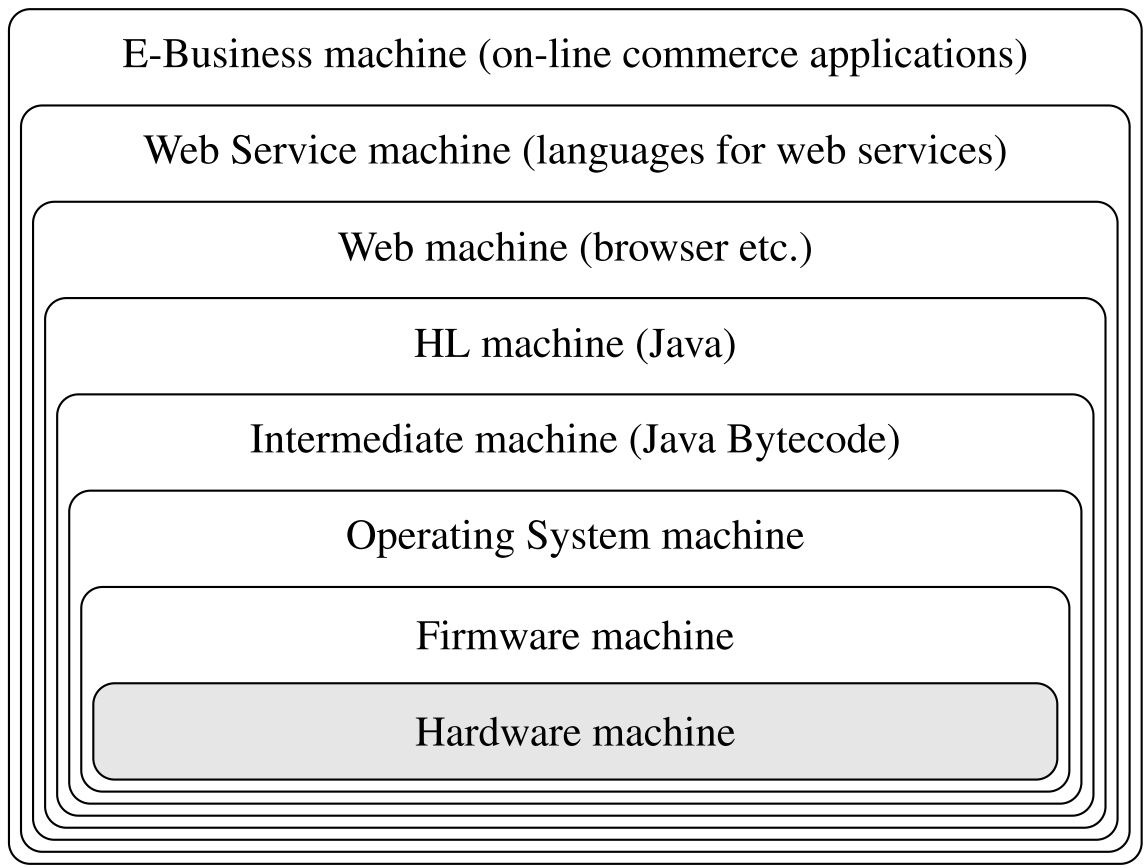
~ 160 opcodes

Implementing an Abstract Machine

- Each abstract machine can be implemented in **hardware** or in **firmware**, but if it is high-level this is not convenient in general
- An abstract machine **M** can be implemented over a **host machine** $\mathbf{M_O}$, which we assume is 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

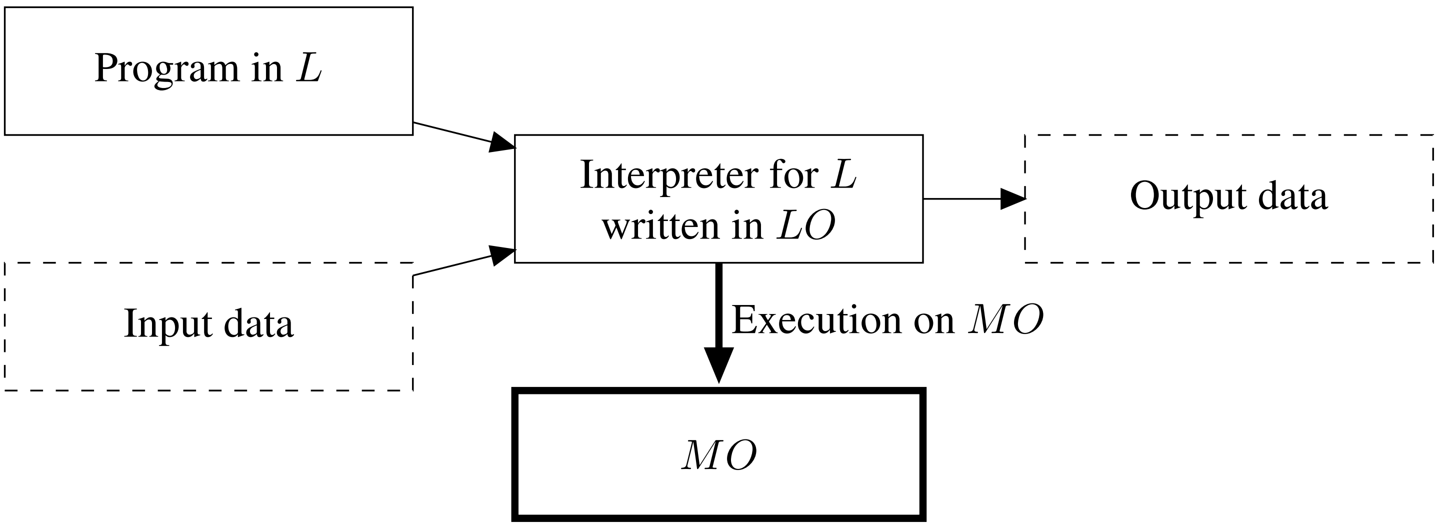
- **L** high level programming language
- $\mathbf{M_L}$ abstract machine for **L**
- $\mathbf{M_O}$ host machine
- **Pure Interpretation**
  - $\mathbf{M_L}$ is interpreted over $\mathbf{M_O}$
  - Not very efficient, mainly because of the interpreter (fetch-decode phases)
- **Pure Compilation**
  - Programs written in **L** are translated into equivalent programs written in $\mathbf{L_O}$, 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

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

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

Pure [*cross*] Compilation

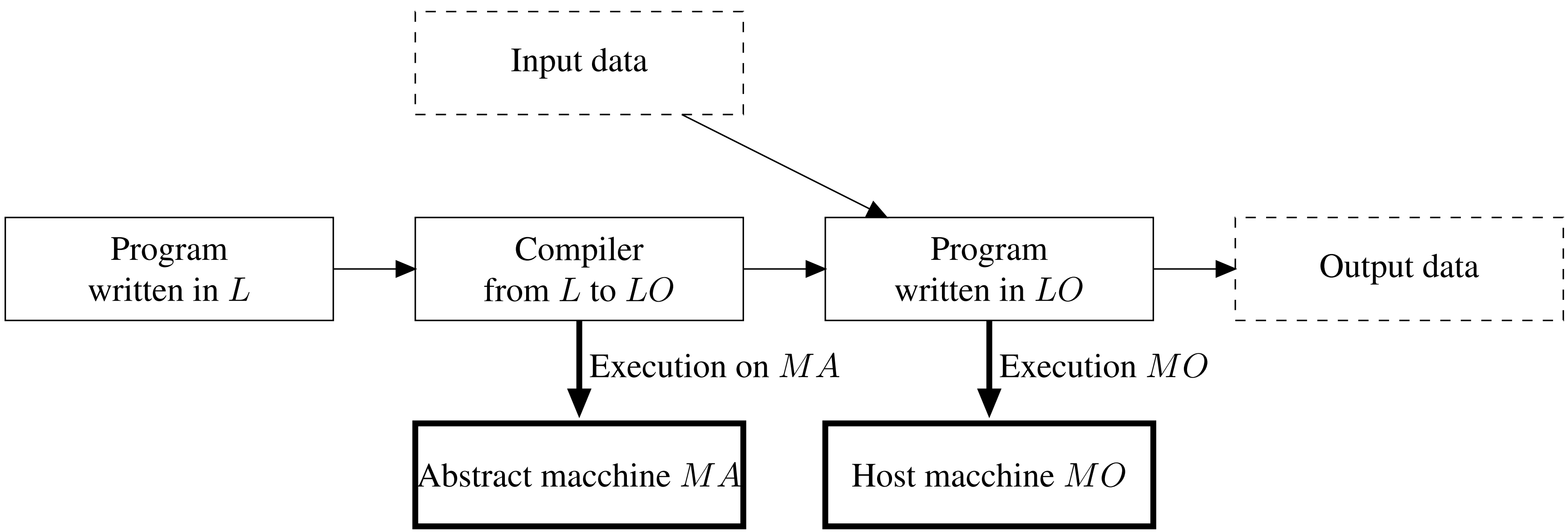
A compiler from ***L*** to ***LO*** defines a function

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

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 $\mathscr{P}^{\mathscr{L}}(\mathit{Input}) = \mathscr{P}c^{\mathscr{L}o}(\mathit{Input})$



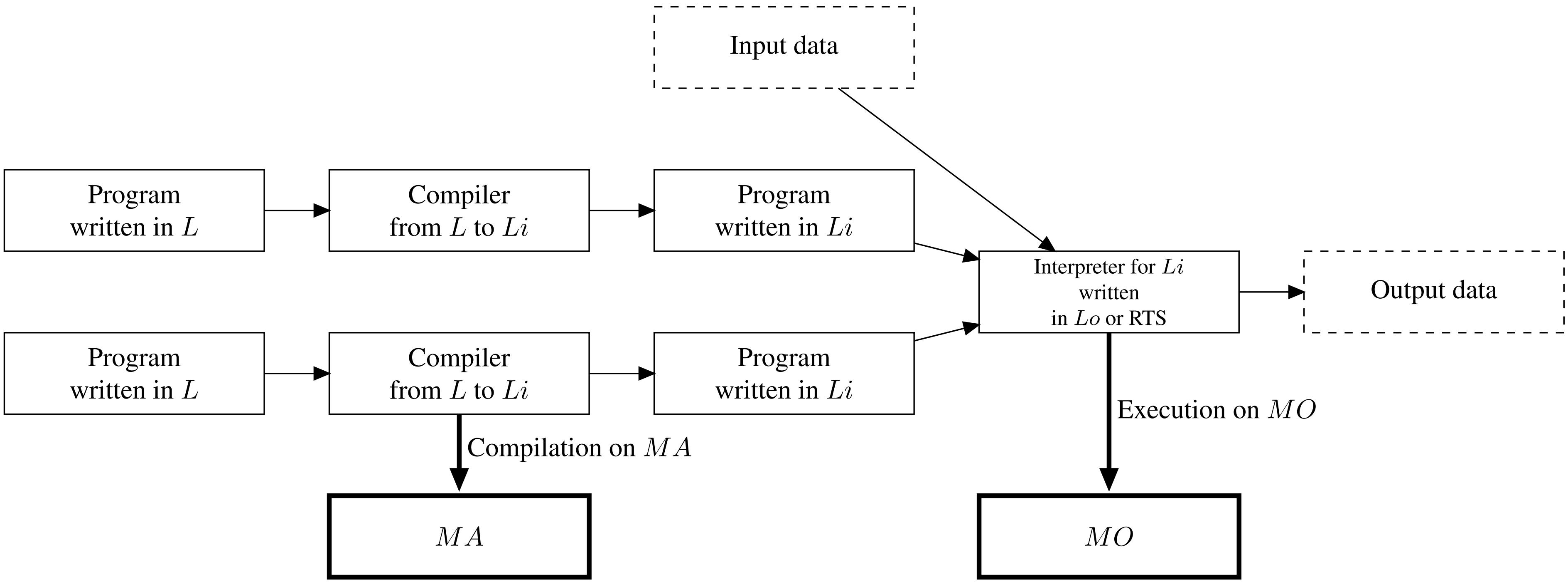
Compilers versus Interpreters

- 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



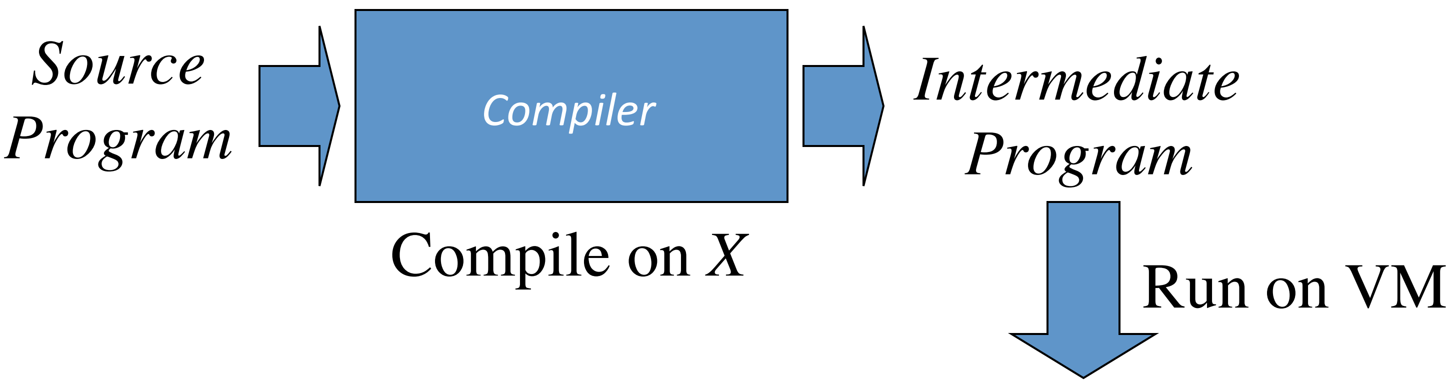
- The "pure" schemes as limit cases
- Let us sketch some typical implementation schemes…

Virtual Machines as Intermediate Abstract Machines

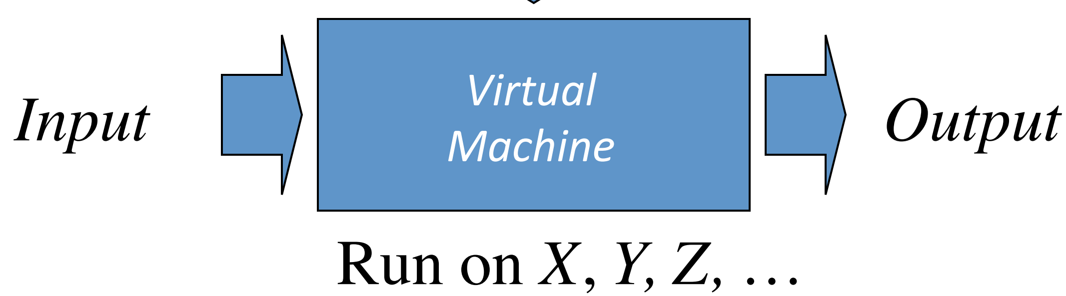
- Several language implementations adopt a compilation + interpretation schema, where the Intermediate Abstract Machine is called Virtual Machine
- Adopted by Pascal, Java, Smalltalk-80, C#, functional and logic languages, and some scripting languages
  - Pascal compilers generate P-code that can be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

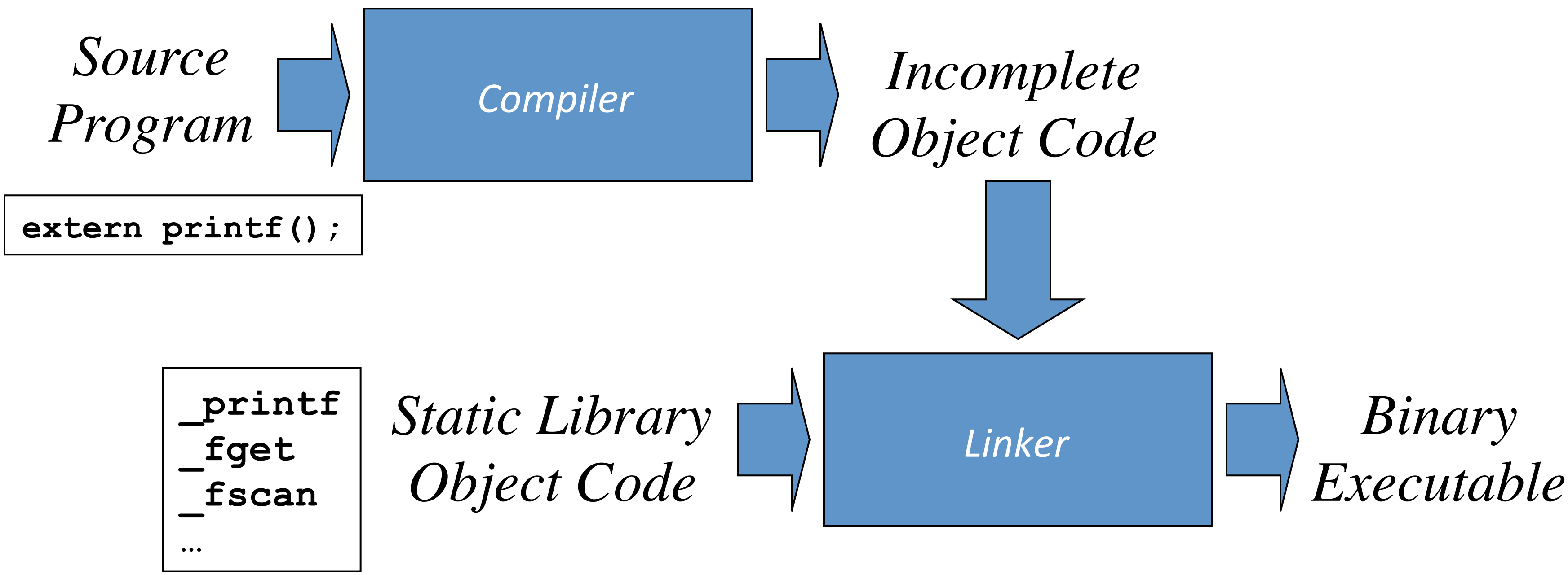


- Portability!



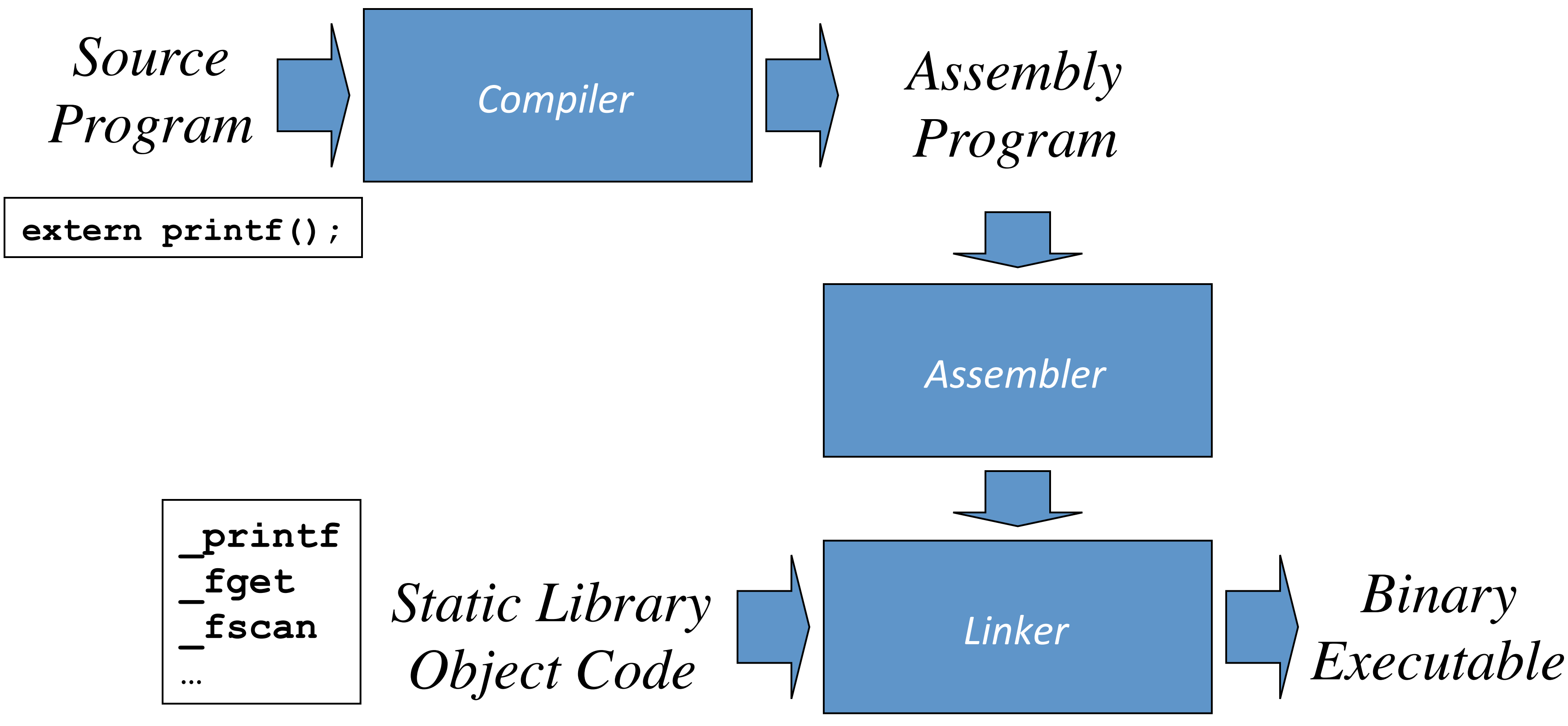
Pure Compilation and Static Linking

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



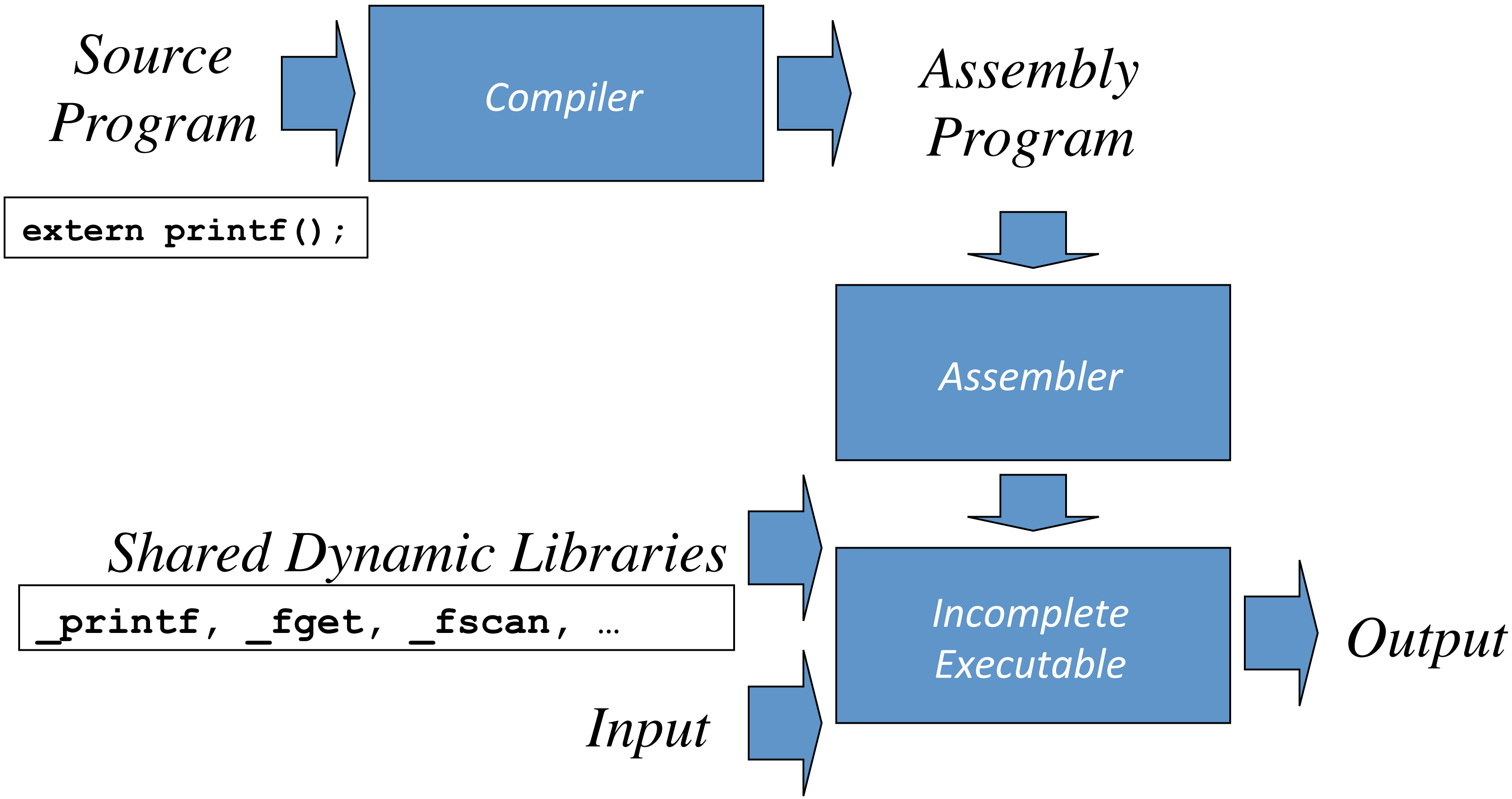
Compilation, Assembly, and Static Linking

- Facilitates debugging of the compiler



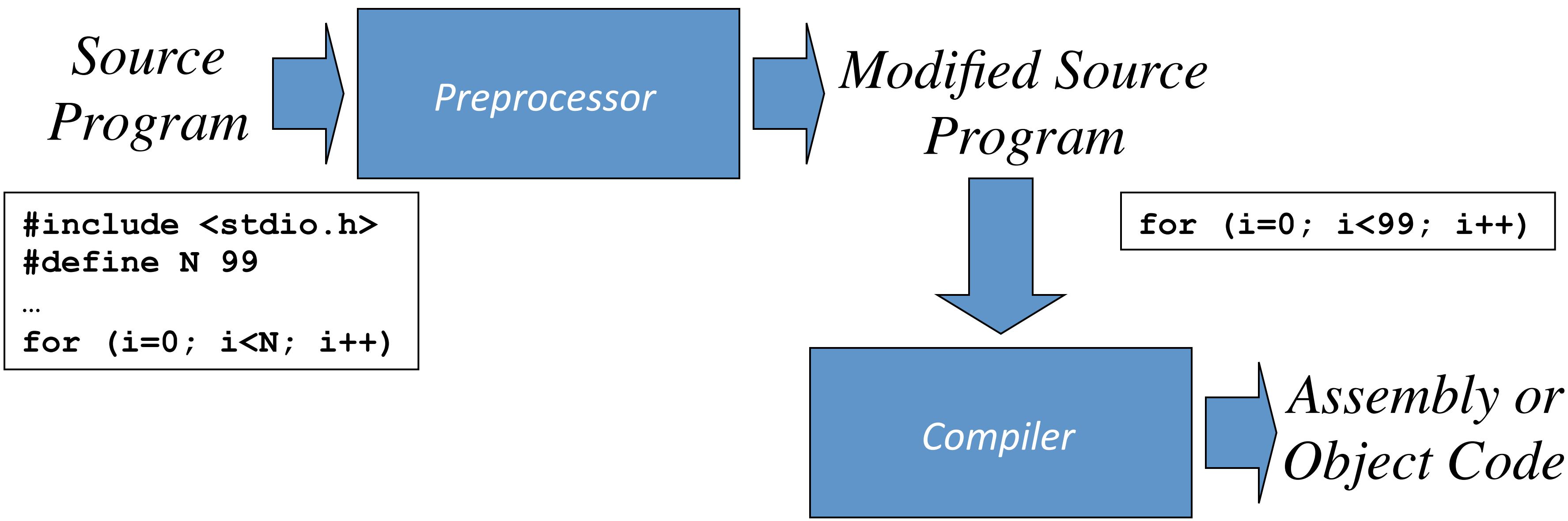
Compilation, Assembly, and Dynamic Linking

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



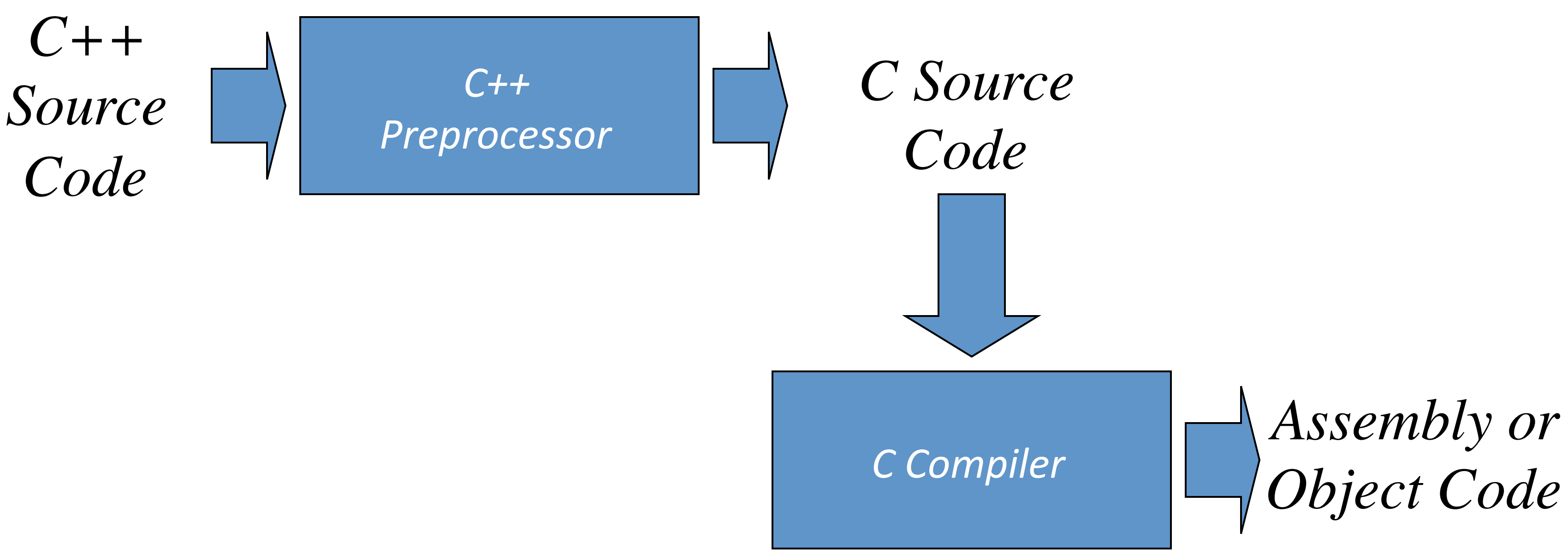
Preprocessing

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



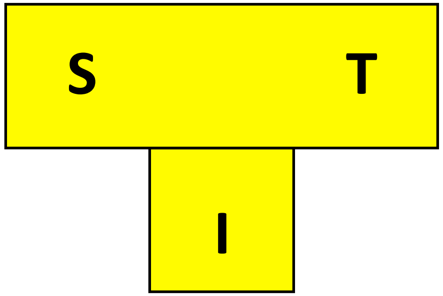
The CPP Preprocessor

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



Compilers, graphically

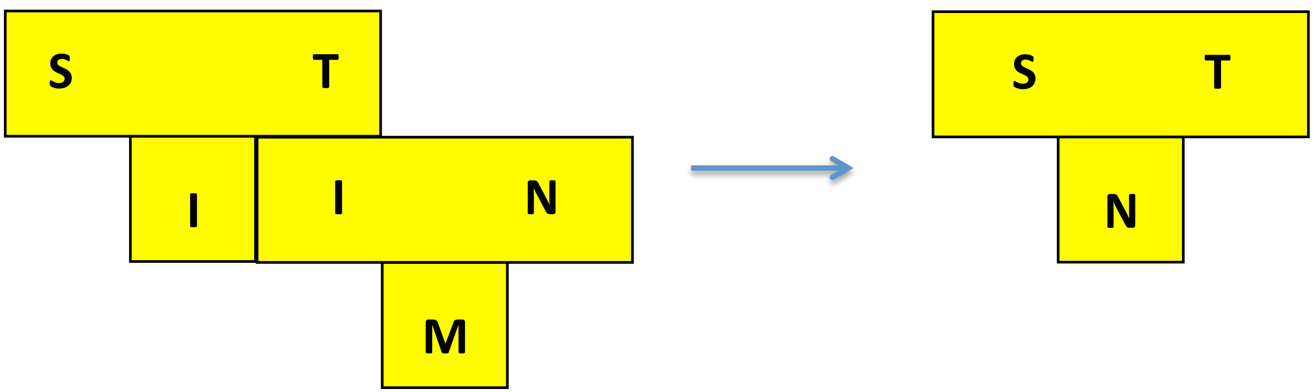
- Three languages involved in writing a compiler
  - Source Language (S)
  - Target Language (T)
  - Implementation Language (I)
- T-Diagram:



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

Composing compilers

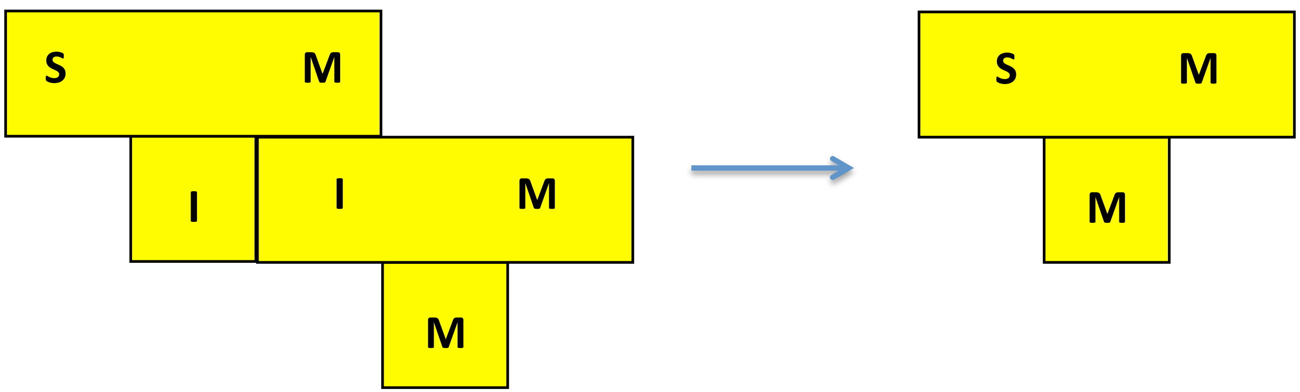
- Compiling a compiler we get a new one: the result is described by composing T-diagrams
- The shape of the basic transformation, in the most general case, is the following:



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

Composing compilers: an example

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



Example:

S	**Pascal**
I	**C**
M	**68000**

- By compiling it we get a host compiler of **S** for **M**.

Bootstrapping

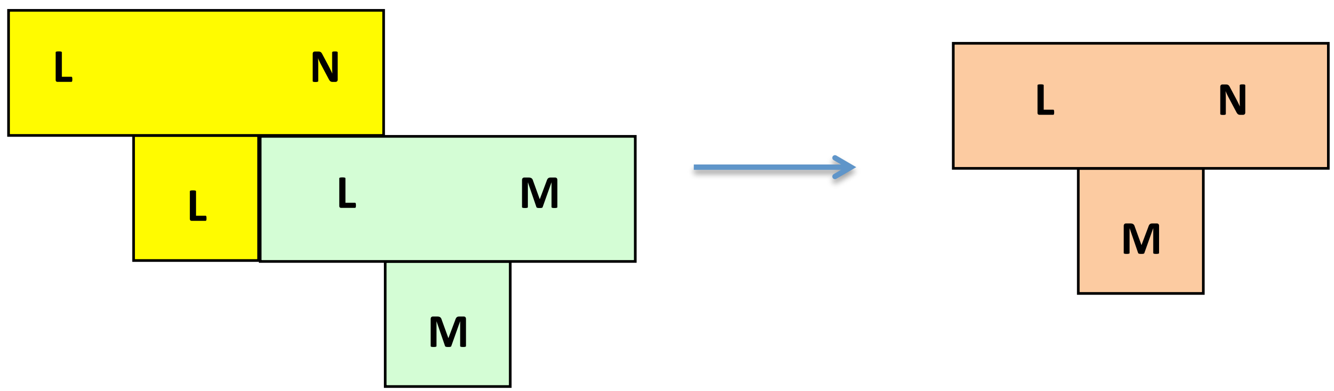
- **Bootstrapping**: techniques which use partial/inefficient compiler versions to generate complete/better ones
- Often compiling a translator programmed in its own language
- Why writing a compiler in its own language?
  - it is a non-trivial test of the language being compiled
  - compiler development 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

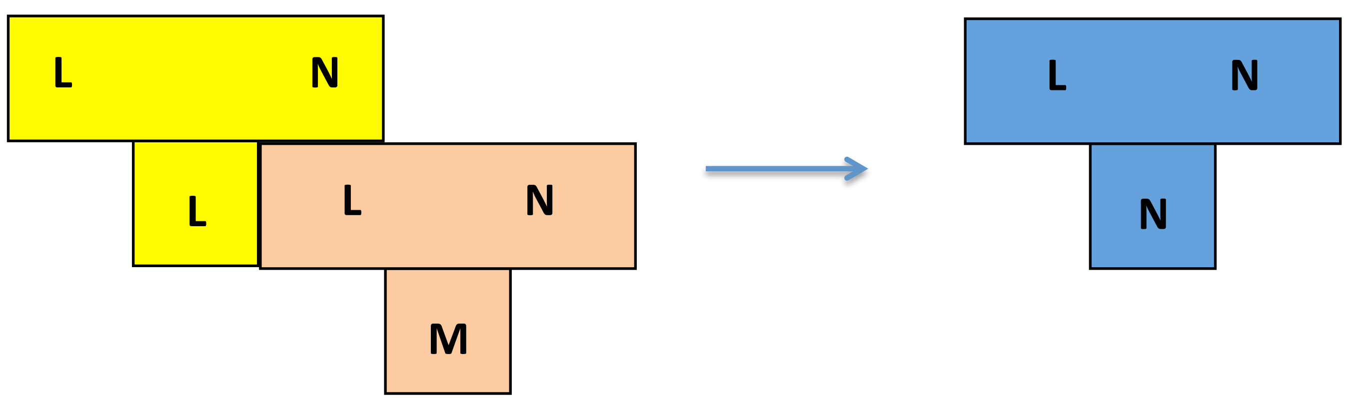
- Portability
  - Retargetability
  - Rehostability
- A **retargetable** compiler is one that can be modified easily to generate code for a new target language
- A **rehostable** compiler is one that can be moved easily to run on a new machine
- A portable compiler may not be as efficient as a compiler 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**

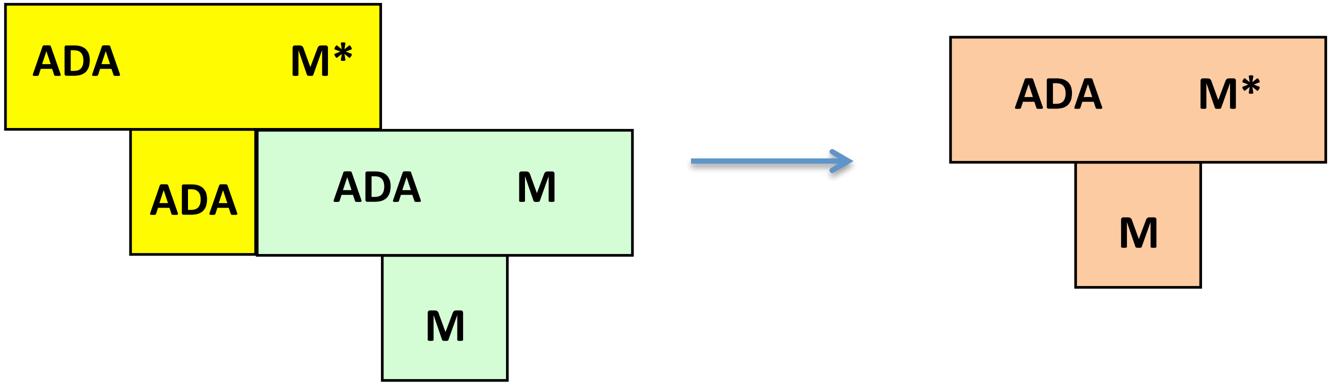


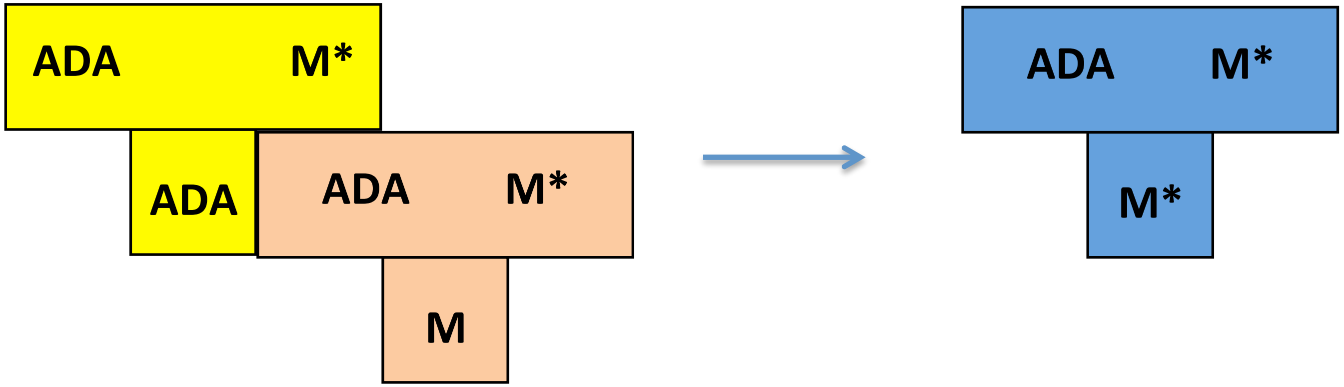
Bootstrapping to optimize a compiler

- 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





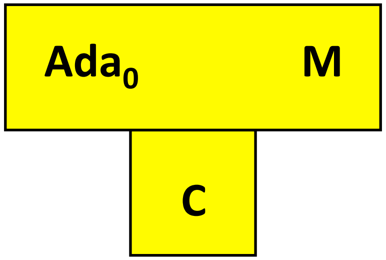
Full Bootstrapping

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

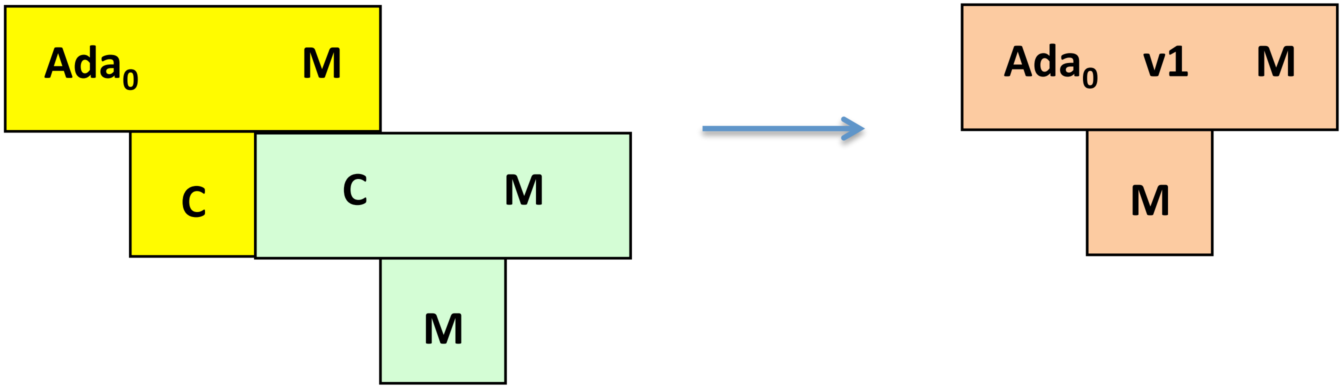
- **Example:**
- We want to implement an **Ada** compiler for machine **M**. We don't have access to any **Ada** compiler
- Idea: **Ada** is very large, we will implement the compiler in a subset of **Ada** (call it $\mathbf{Ada_0}$) and bootstrap it from a subset of **Ada** compiler in another language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

Full Bootstrapping (2)

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



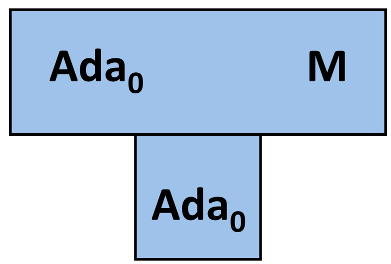
- **Step 2:** compile it using a host compiler of **C** for **M**



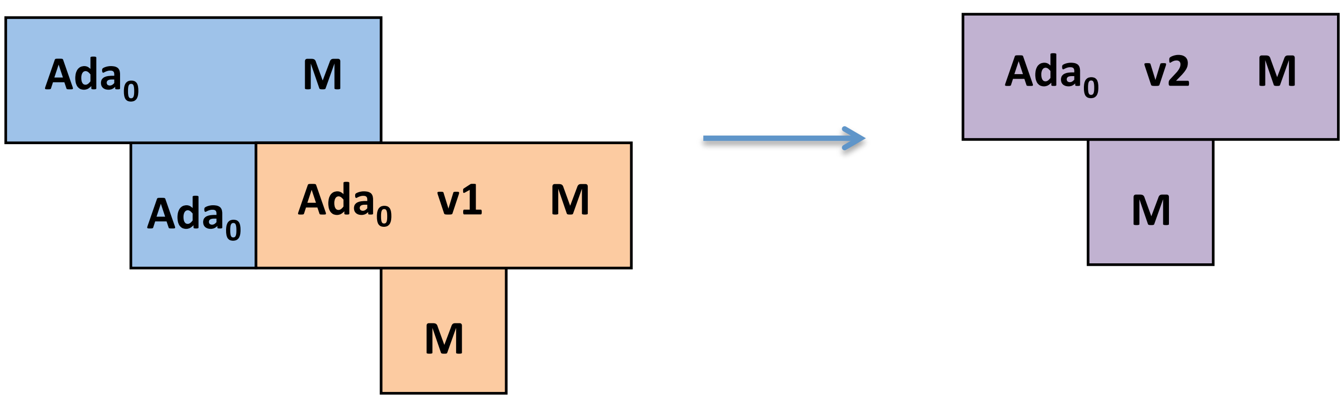
- **Note:** new versions would depend on the **C** compiler for **M**

Full Bootstrapping (3)

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



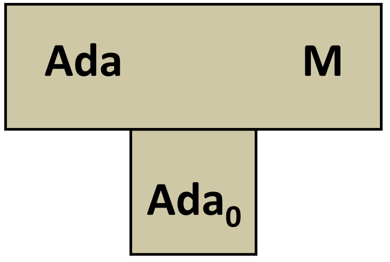
- **Step 4:** compile it using the **Ada_0** compiler for **M**



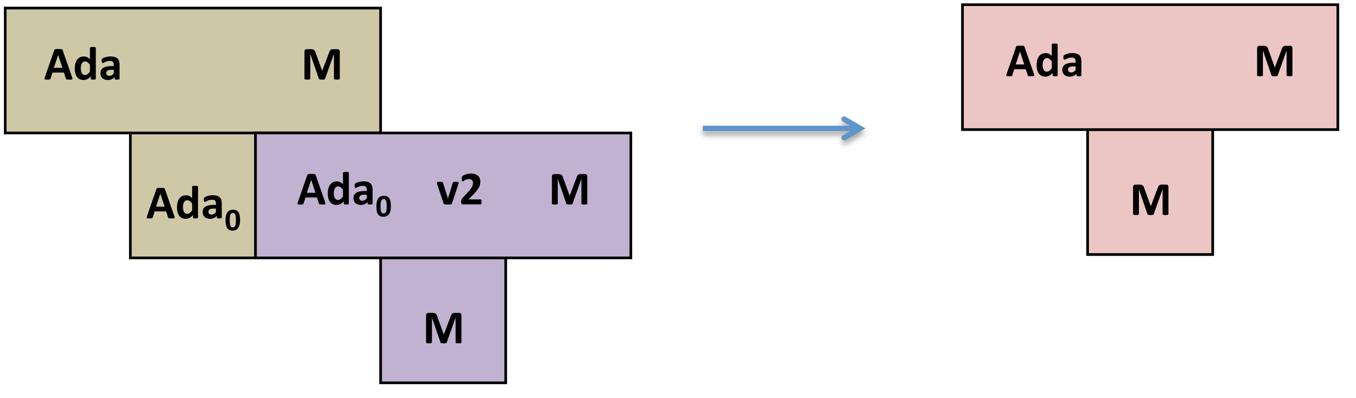
- **Note: C** compiler is no more necessary

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