CS335: An Overview of Compilation

Swarnendu Biswas

Semester 2019-2020-II

CSE, IIT Kanpur

Content influenced by many excellent references, see References slide for acknowledgements.

A Bit of History

- In the early 1950s, most programming was with assembly language
  - Low programmer productivity
  - Cost of software development far exceeded cost of hardware
- In 1954, John Backus proposed a program that translated high level expressions into native machine code for IBM 704 mainframe
- Fortran I project (1954-1957): The first compiler was released

Impact of Fortran

- Fortran I compiler was the first optimizing compiler
  - Programmers were initially reluctant to use a high-level programming language for fear of lack of performance

- The Fortran compiler has had a huge impact on the field of programming languages and computer science
  - Many advances in compilers were motivated by the need to generate efficient Fortran code
  - Modern compilers preserve the basic structure of the Fortran I compiler!

Executing Programs

- Programming languages are an abstraction for describing computations
  - For e.g., control flow constructs and data abstraction
  - Advantages of high-level programming language abstractions
    - Improved productivity, fast prototyping, improved readability, maintainability, and debugging

- The abstraction needs to be transferred to machine-executable form to be executed

What is a Compiler?

- A compiler is a system software that **translates** a program in a source language to an **equivalent** program in a target language

- Typical “source” languages might be C, C++, or Java
- The “target” language is usually the instruction set of some processor

Important Features of a Compiler

- In addition to translation, compilers provide feedback to the user
  - Point out errors and potential mistakes in the program

Source-Source Translators

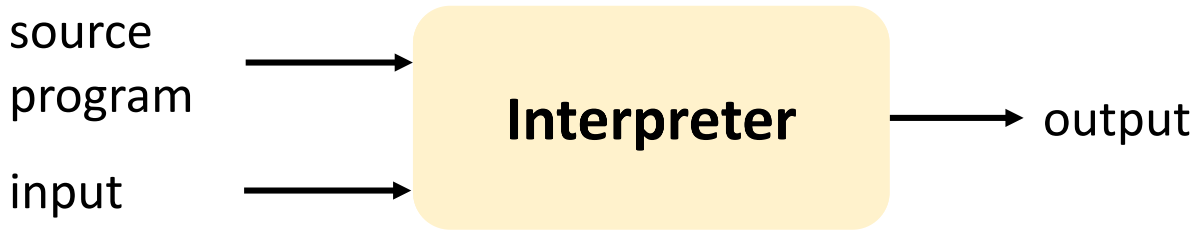
- Produce a target program in another programming language rather than the assembly language of some computer
- The output program require further translation before they can be executed
- Many research compilers produce C programs

More Examples of a Compiler

- A typesetting program that produces PostScript can be considered a compiler
  - Typesetting LaTeX to generate PDF is compilation

Interpreter

- An interpreter takes as input an executable specification and produces as output the result of executing the specification



- Scripting languages are often interpreted
  - For e.g., Perl, Python, and Bash

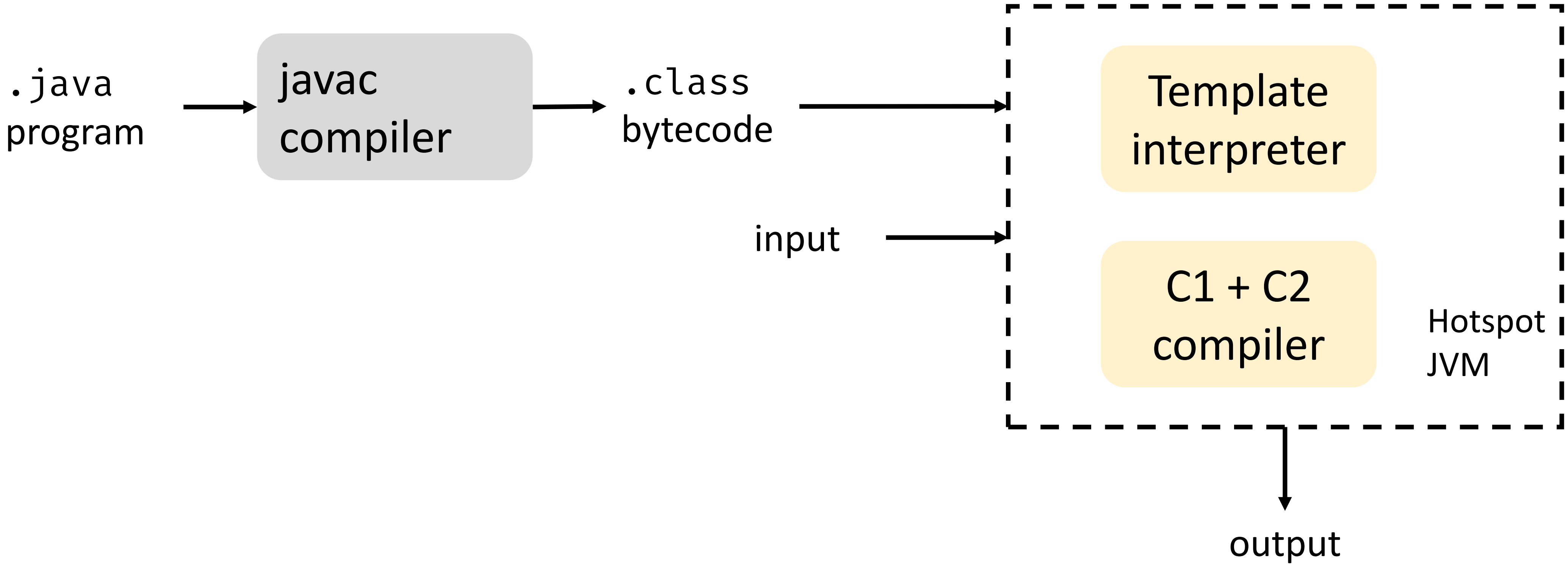
Compilers vs Interpreters

Compilers	Interpreters
• Translates the whole program at once	• Executes the program one line at a time • Compilation and execution happens at the same time
• Memory requirement during compilation is more	• Memory requirement is less, since there is less state to maintain
• Error reports are congregated	• Error reports are per line
• On an error, compilers try to fix the error and proceed past	• Stops translation on an error
• Examples: C, C++, and Java	• Examples: Python, Ruby, PHP

Hybrid Translation Schemes

- Translation process for a few languages include both compilation and interpretation (e.g., Lisp)
- Java is compiled from source code into a form called bytecode (`.class` files)
- Java virtual machines (JVMs) start execution by interpreting the bytecode
- JVMs usually also include a just-in-time compiler that compiles frequently-used bytecode sequences into native code
  - JIT compilation happens at runtime

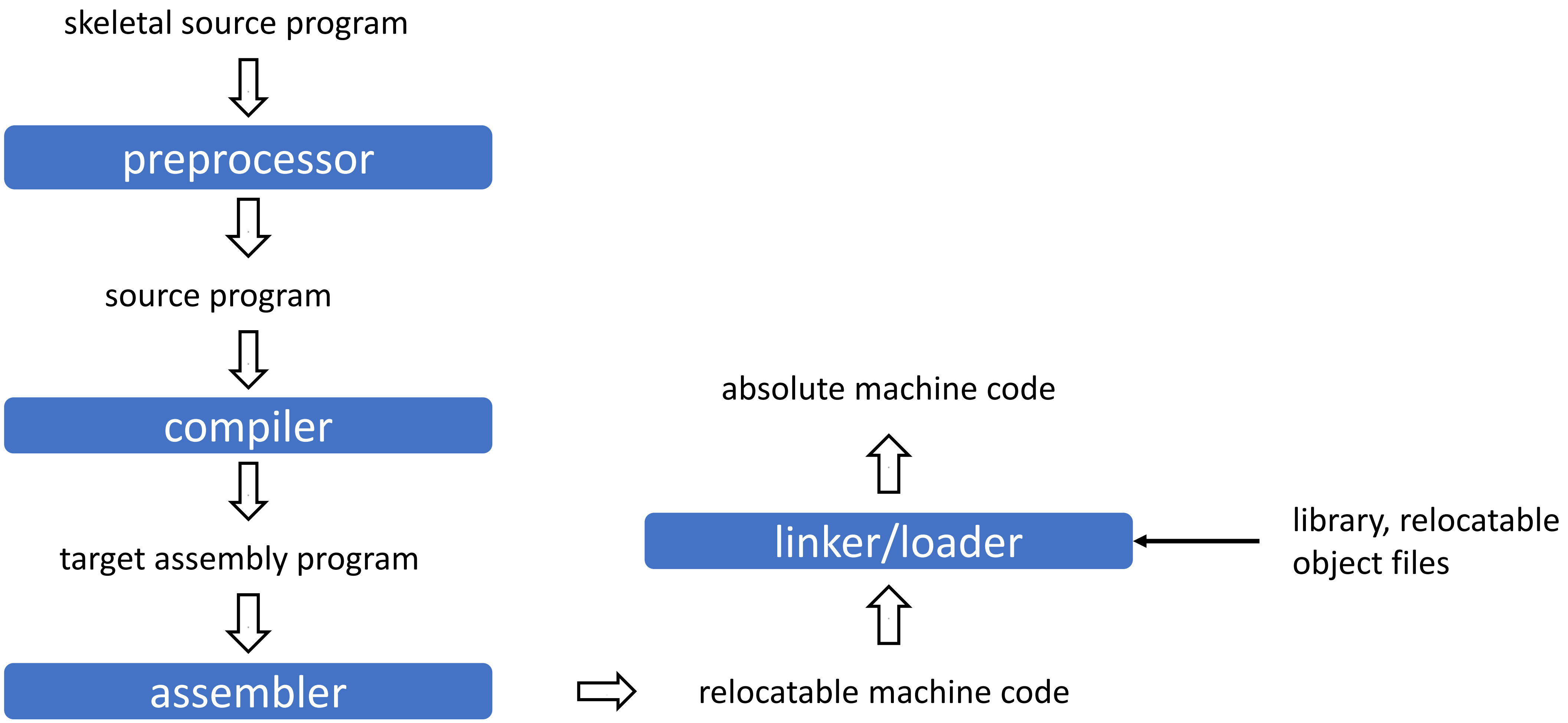
Compilation Flow in Java with Hotspot JVM



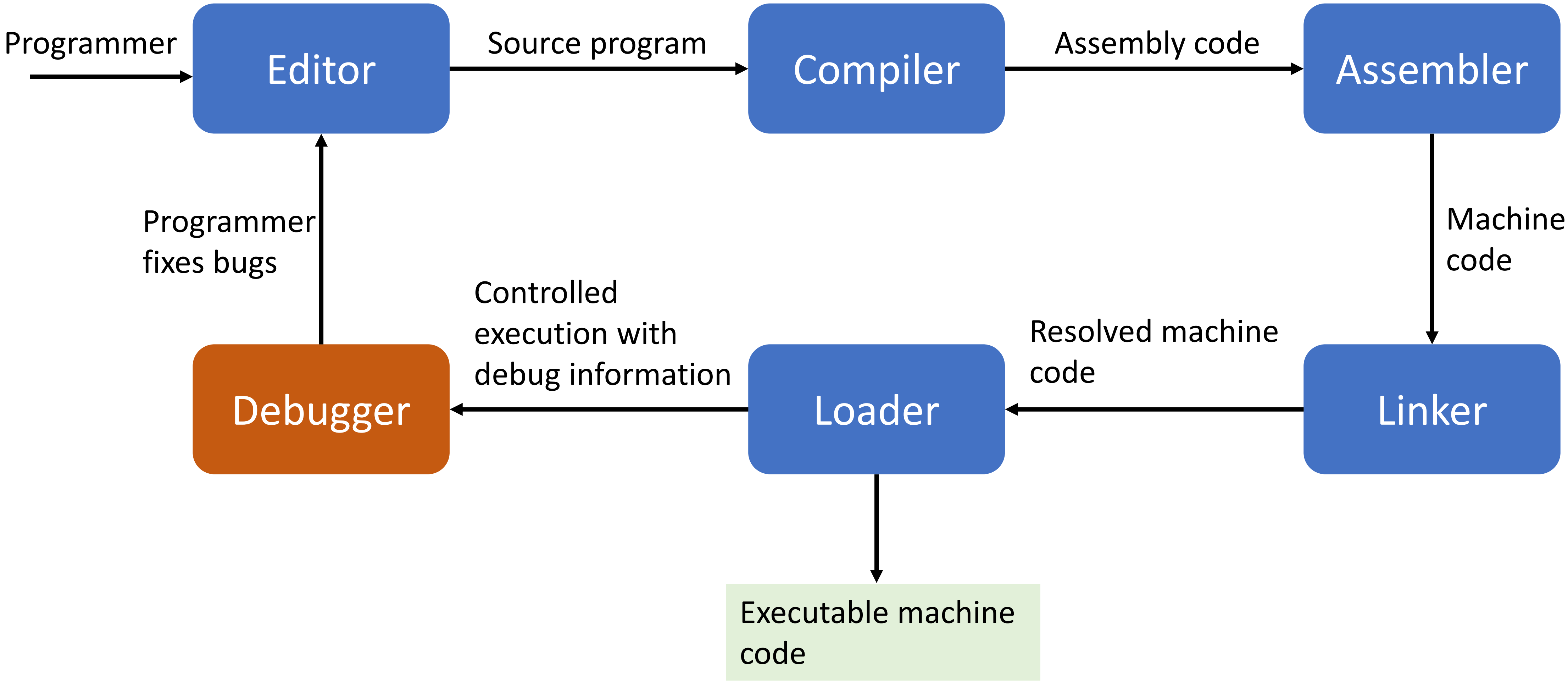
Language Processing

- Language processing is an important component of programming
- A large number of systems software and application programs require structured input
  - Command line interface in Operating Systems
  - Query language processing in Databases
  - Type setting systems like Latex

A Language-Processing System



Development Toolchain



Goals of a Compiler

- A compiler must preserve the meaning of the program being compiled
  - Proving a compiler correct is a challenging problem and an active area of research
- A compiler must improve the input program in some discernible way
- Compilation time and space required must be reasonable
- The engineering effort in building a compiler should be manageable

Applications of a Compiler

```
DO I = 1, N
  DO J = 1, M
    A(I,J+1) = A(I,J) + B
  ENDDO
ENDDO
```

Applications of a Compiler

- Perform loop transformations to help with parallelization

```
DO I = 1, N
  DO J = 1, M
    A(I,J+1) = A(I,J) + B
  ENDDO
ENDDO
```

```
DO J = 1, M
  DO I = 1, N
    A(I,J+1) = A(I,J) + B
  ENDDO
ENDDO
```

Programming Language vs Natural Language

- Natural languages
  - Interpretation of words or phrases evolve over time
    - For e.g., “awful” and “bachelor”
  - Allow ambiguous interpretations
    - “I saw someone on the hill with a telescope.” or “I went to the bank.”
    - “Buffalo buffalo Buffalo buffalo buffalo buffalo Buffalo buffalo”

- Programming languages have well-defined structures and interpretations, and disallow ambiguity

https://en.wikipedia.org/wiki/Buffalo_buffalo_Buffalo_buffalo_buffalo_buffalo_Buffalo_buffalo

Constructing a Compiler

- A compiler is one of the most intricate software systems
  - General-purpose compilers often involve more than a hundred thousand LoC
- Very practical demonstration of integration of theory and engineering

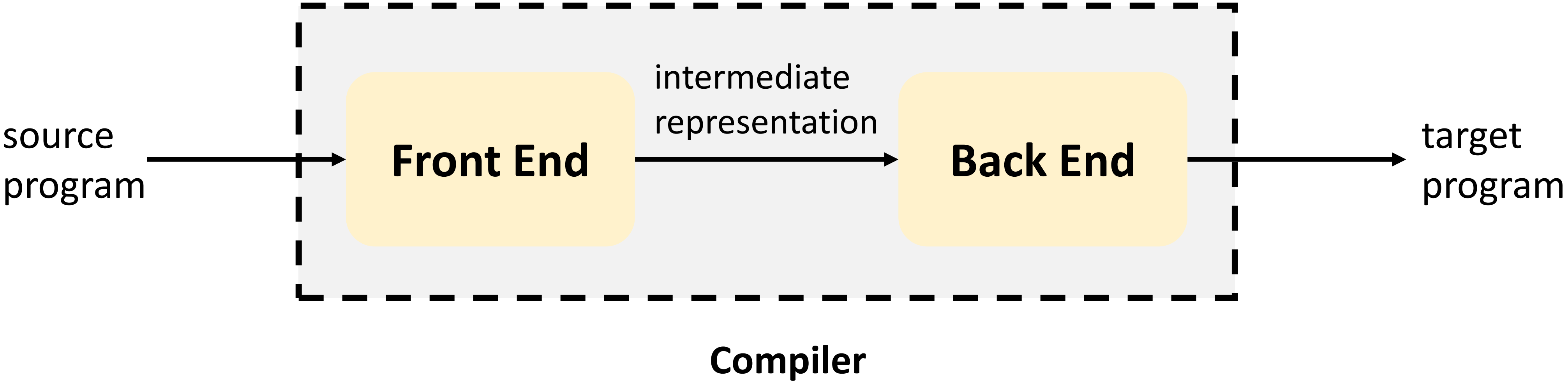
Idea	Implementation
Finite and push-down automata	Lexical and syntax analysis
Greedy algorithms	Register allocation
Fixed-point algorithms	Dataflow analysis

- Other practical issues such as concurrency and synchronization, optimization for memory hierarchy

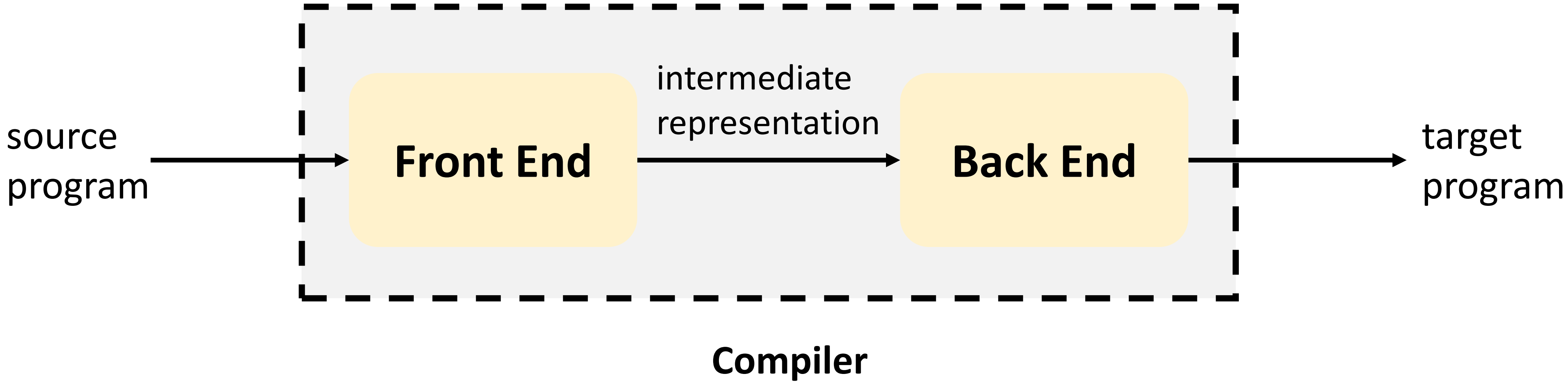
Structure of a Compiler

Compiler Structure

- A compiler interfaces with both the source language and the target architecture



Compiler Structure



- Front end is responsible for understanding the input program in a source language
- Back end is responsible for translating the input program to the target architecture

Intermediate Representation

- An intermediate representation (IR) is a data structure to encode information about the input program
  - For e.g., graphs, three address code
- Different IRs may be used during different phases of compilation

```
int f(int a, int b) {
  return a + 2*b;
}

int main() {
  return f(10, 20);
}
```

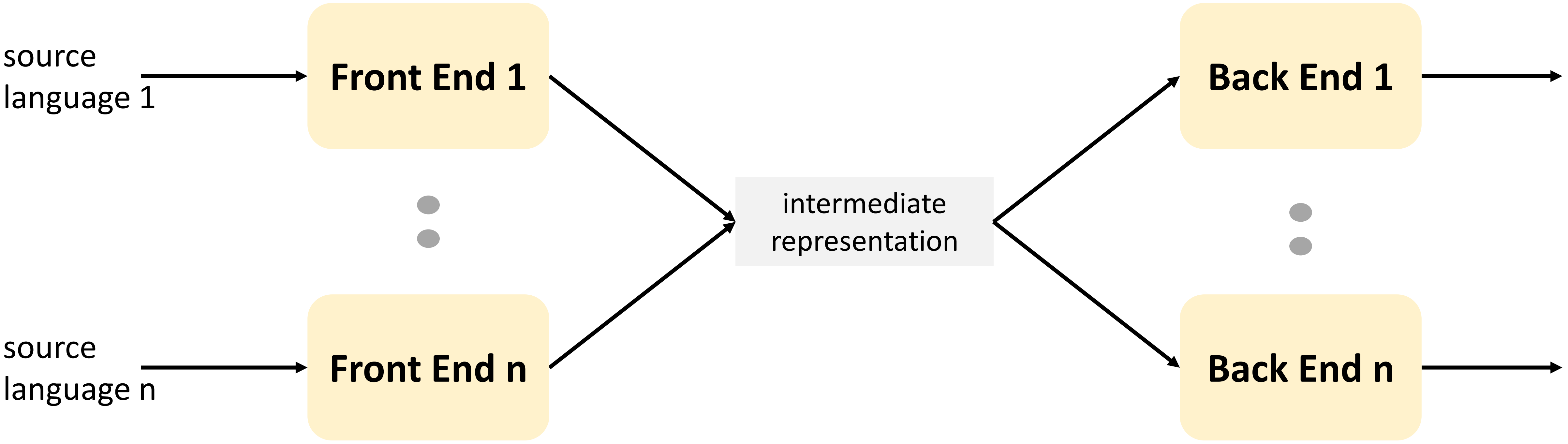
LLVM IR →

```
define i32 @f(i32 %a, i32 %b) {
; <label>:0
    %1 = mul i32 2, %b
    %2 = add i32 %a, %1
    ret i32 %2
}

define i32 @main() {
; <label>:0
    %1 = call i32 @f(i32 10, i32 20)
    ret i32 %1
}
```

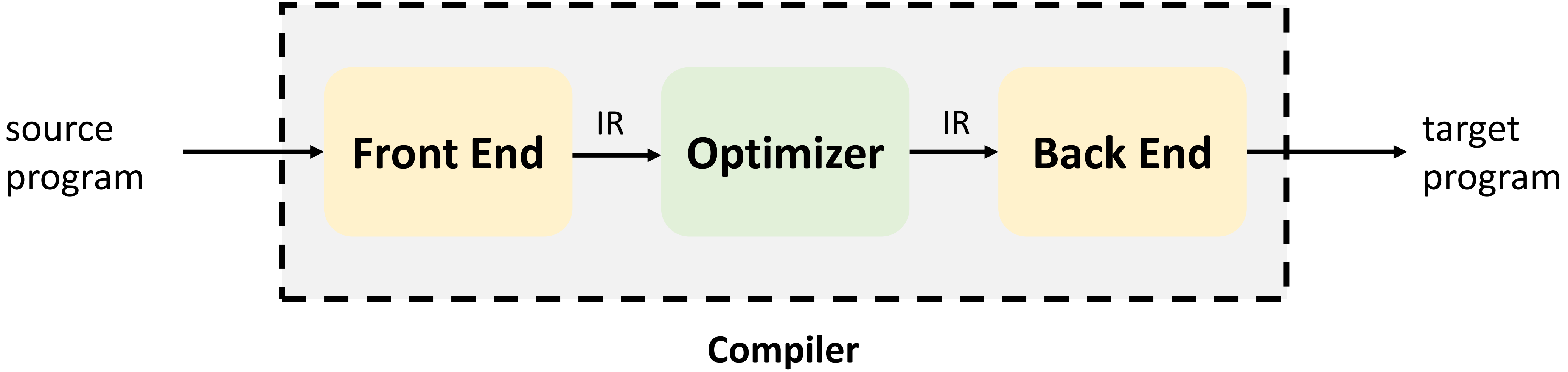
Advantages of Two-Phased Compiler Structure

- Simplifies the process of writing or retargeting a compiler



Three Phased View of a Compiler

- IR makes it possible to add more phases to compilation

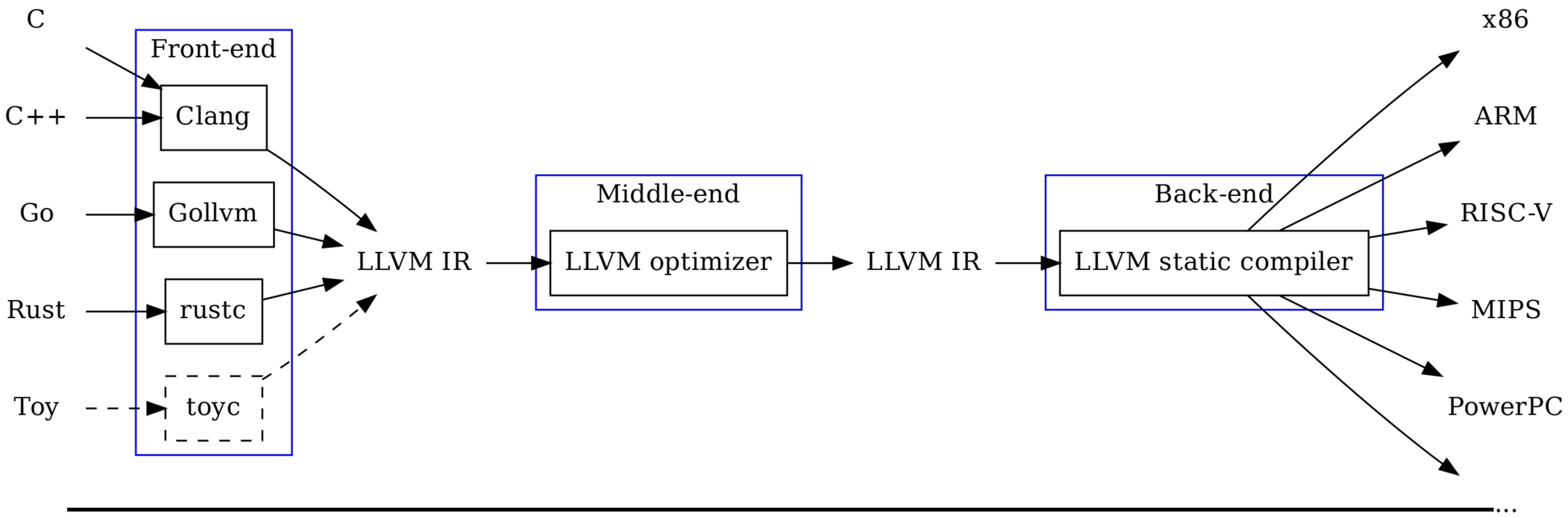


- Optimizer is an IR→IR transformer that tries to improve the IR program in some way

Three Phased View of a Compiler

- Front end consists of two or three passes that handle the details of the input source-language program
- Optimization phase contains passes to perform different optimizations
  - The IR is generated by the front end
  - The number and purpose of these passes vary across compiler implementations
- The back end passes lower the IR representation closer to the target machine's instruction set

Visualizing the LLVM Compiler System



https://blog.gopheracademy.com/advent-2018/llvm-ir-and-go/

Implementation Choices

Monolithic structure	Multipass structure
???	**???**

Implementation Choices

Monolithic structure	Multipass structure
• Can potentially be more efficient, but is less flexible	• Less complex and easier to debug • Can incur compile time performance penalties

Phases in a Compiler

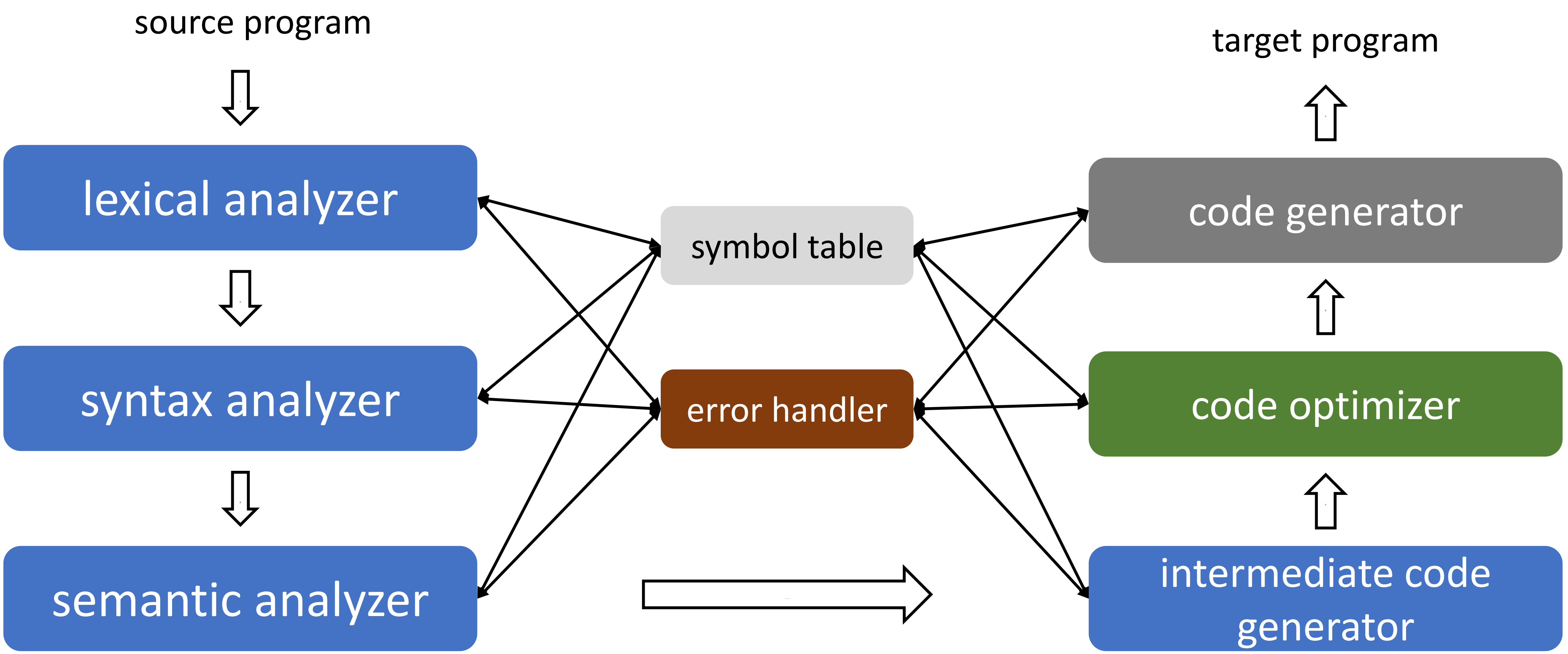
Translation in a Compiler

- Direct translation from a high-level language to machine code is difficult
  - Mismatch in the abstraction level between source code and machine code
    - Abstract data types and variables vs memory locations and registers
    - Control flow constructs vs jump and returns
  - Some languages are farther from machine code than others
    - For example, languages supporting object-oriented paradigm

Translation in a Compiler

- Translate in small steps, where each step handles a reasonably simple, logical, and well defined task
- Design a series of IRs to encode information across steps
  - IR should be amenable to program manipulation of various kinds (for e.g., type checking, optimization, and code generation)
- IR becomes more machine specific and less language specific as translation proceeds

Different Phases in a Compiler



Front End

- First step in translation is to compare the input program structure with the language definition
  - Requires a formal definition of the language, in the form of regular expressions and context-free grammar
  - Two separate passes in the front end, often called the **scanner** and the **parser**, determine whether or not the input code is a valid program defined by the grammar

Lexical Analysis

- Reads characters in the source program and groups them into a stream of **tokens** (or words)
  - Tokens represent a syntactic category
  - Character sequence forming a token is called a **lexeme**
  - Tokens can be augmented with the lexical value

```
position = initial + rate * 60
```

Lexical Analysis

- Reads characters in the source program and groups them into a stream of **tokens** (or words)
  - Tokens represent a syntactic category
  - Character sequence forming a token is called a **lexeme**
  - Tokens can be augmented with the lexical value

```
position = initial + rate * 60
```

- Tokens are ID, “=”, ID, “+”, ID, “*”, CONSTANT

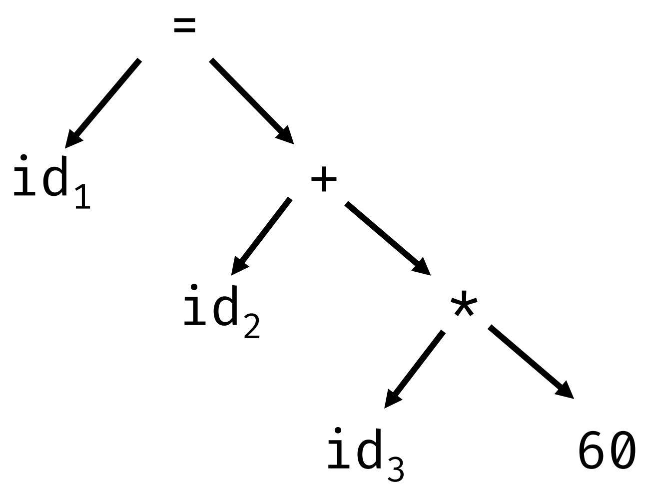
Challenges in Lexical Analysis

- Identify word separators
  - The language must define rules for breaking a sentence into a sequence of words
  - Normally white spaces and punctuations are word separators in languages
  - In programming languages, a character from a different class may also be treated as a word separator

Syntax Analysis

- Once words are formed, the next logical step is to understand the structure of the sentence
  - This is called syntax analysis or parsing
- Syntax analysis imposes a hierarchical structure on the token stream

```
position = initial + rate * 60
```



Semantic Analysis

- Once the sentence is constructed, we need to interpret the meaning of the sentence

X saw someone on the hill with a telescope

JJ said JJ left JJ's assignment at home

- This is a very challenging task for a compiler
  - Programming languages define very strict rules to avoid ambiguities
  - For e.g., scope of variable named JJ

Semantic Analysis

- Compiler performs other checks like type checking

```
position = initial + “rate” * 60
```

Intermediate Representation

- Once all checks pass, the front end generates an IR form of the code
  - IR is a program for an abstract machine

$$id_1 = id_2 + id_3 * 60$$

⇨

$$\begin{aligned} t_1 &= \text{inttofloat}(60) \\ t_2 &= id_3 * t_1 \\ t_3 &= t_2 + id_2 \\ id_1 &= t_3 \end{aligned}$$

Code Optimization

- Attempts to improve the IR code according to some metric
  - For e.g., reduce the execution time, code size, or resource usage
- "Optimizing" compilers spend a significant amount of compilation time in this phase
- Most optimizations consist of an analysis and a transformation
  - Analysis determines where the compiler can safely and profitably apply the technique
    - Data flow analysis tries to statically trace the flow of values at run-time
    - Dependence analysis tries to estimate the possible values of array subscript expressions

Code Optimization

- Some common optimizations
  - Common sub-expression elimination, copy propagation, dead code elimination, loop invariant code motion, strength reduction, constant folding

t_1 = inttofloat(60)
t_2 = id_3 * t_1
t_3 = t_2 + id_2
id_1 = t_3

⇨

t_1 = id_3 * 60.0
id_1 = t_1 + id_2

Challenges with Code Optimization

- All strategies may not work for all applications
- Compiler may need to adapt its strategies to fit specific programs
  - Choice and order of optimizations
  - Parameters that control decisions & transformations
- Active research on “autotuning” or “adaptive runtime”
  - Compiler writer cannot predict a single answer for all possible programs
  - Use learning, models, or search to find good strategies

Code Generation

- Back end traverses the IR code and emits code for the target machine
- First stage is instruction selection
  - Translate IR operations into target machine instructions
  - Can take advantage of the feature set of the target machine
  - Assumes infinite number of registers via virtual registers

```
t1 = id3 * 60.0
id1 = t1 + id2
```

⇨

```
MOVF id3 -> r2
MULF #60.0, r2 -> r2
MOVF id2 -> r1
ADDF r2, r1 -> r1
MOVF r1 -> id1
```

Code Generation

- Register allocation
  - Decide which values should occupy the limited set of architectural registers
- Instruction scheduling
  - Reorder instructions to maximize utilization of hardware resources and minimize cycles

Instruction Scheduling

```
LOAD  @ADDR1, @OFF1 -> R1
ADD    R1, R1 -> R1
LOAD  @ADDR2, @OFF2 -> R2
MUL    R1, R2 -> R1
LOAD  @ADDR3, @OFF3 -> R2
MUL    R1, R2 -> R1
STORE  R1 -> @ADDR1, @OFF1
```

Instruction Scheduling

```
LOAD  @ADDR1, @OFF1 -> R1
ADD    R1, R1 -> R1
LOAD  @ADDR2, @OFF2 -> R2
MUL    R1, R2 -> R1
LOAD  @ADDR3, @OFF3 -> R2
MUL    R1, R2 -> R1
STORE  R1 -> @ADDR1, @OFF1
```

```
LOAD  @ADDR1, @OFF1 -> R1
LOAD  @ADDR2, @OFF2 -> R2
LOAD  @ADDR3, @OFF3 -> R3
ADD    R1, R1 -> R1
MUL    R1, R2 -> R1
MUL    R1, R3 -> R1
STORE  R1 -> @ADDR1, @OFF1
```

References

- A. Aho et al. Compilers: Principles, Techniques, and Tools, 2nd edition.
- K. Cooper and L. Torczon. Engineering a Compiler, 2nd edition.
- A. Karkare. CS 335: Compiler Design, https://www.cse.iitk.ac.in/~karkare/Courses/cs335.