Introduction to Compilation

Lecture 01

What is a compiler?

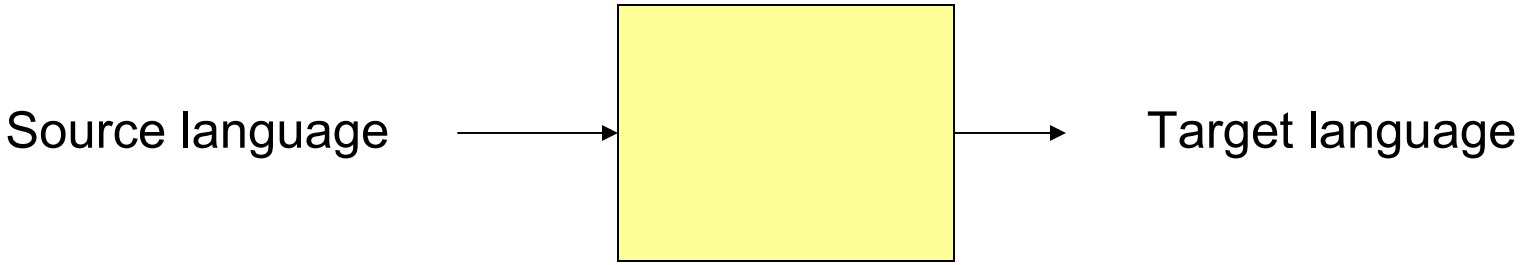
- Programming problems are easier to solve in high-level languages
  - Languages closer to the level of the problem domain, e.g.,
    - SmallTalk: OO programming
    - JavaScript: Web pages

- Solutions are usually more efficient (faster, smaller) when written in machine language
  - Language that reflects to the cycle-by-cycle working of a processor

- Compilers are the bridges:
  - Tools to translate programs written in high-level languages to efficient executable code

What is a compiler?

A program that reads a program written in one language and translates it into another language.



Traditionally, compilers go from high-level languages to low-level languages.

Compilation task is full of variety??

- Thousands of source languages
  - Fortran, Pascal, C, C++, Java, ……
- Thousands of target languages
  - Some other lower level language (assembly language), machine language
- Compilation process has similar variety
  - Single pass, multi-pass, load-and-go, optimizing….
- Variety is overwhelming……

- Good news is:
  - Few basic techniques is sufficient to cover all variety
  - Many efficient tools are available

Requirement

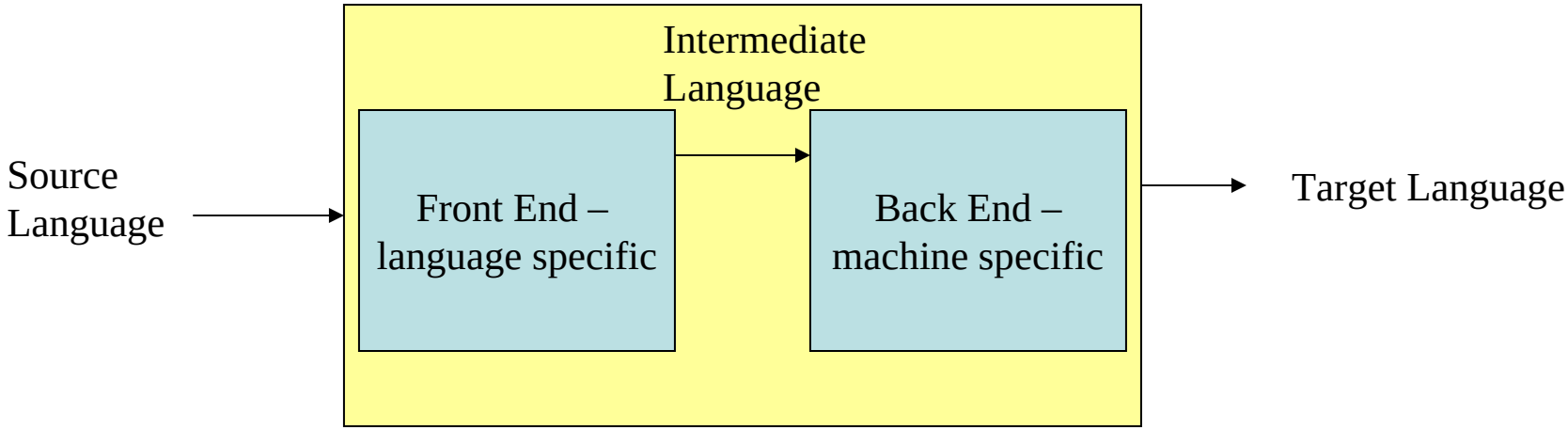
- In order to translate statements in a language, one needs to understand both
  - the structure of the language: the way “sentences" are constructed in the language, and
  - the meaning of the language: what each “sentence" stands for.
- Terminology:

  Structure ≡ Syntax

  Meaning ≡ Semantics

Analysis-Synthesis model of compilation

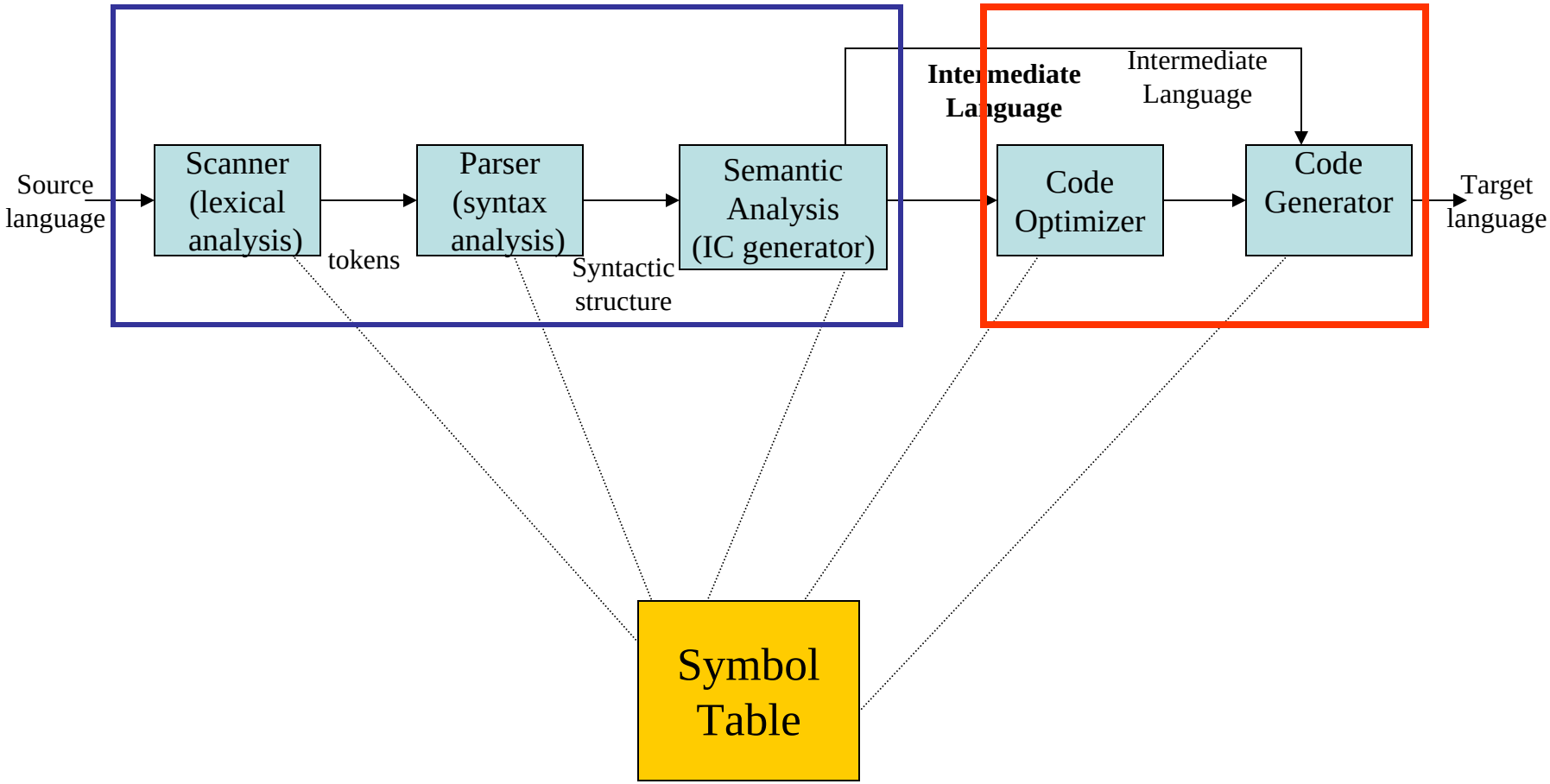
- Two parts
  - **Analysis**
    - Breaks up the source program into constituents
  - **Synthesis**
    - Constructs the target program



Software tools that performs analysis

- Structure Editors
  - Gives hierarchical structure
  - Suggests keywords/structures automatically
- Pretty Printer
  - Provides an organized and structured look to program
  - Different color, font, indentation are used
- Static Checkers
  - Tries to discover potential bugs without running
  - Identify logical errors, type-checking, dead codes identification etc
- Interpreters
  - Does not produce a target program
  - Executes the operations implied by the program

Compilation Steps/Phases



Compilation Steps/Phases

- **Lexical Analysis Phase:** Generates the “tokens” in the source program
- **Syntax Analysis Phase:** Recognizes “sentences" in the program using the syntax of the language
- **Semantic Analysis Phase:** Infers information about the program using the semantics of the language
- **Intermediate Code Generation Phase:** Generates “abstract” code based on the syntactic structure of the program and the semantic information from Phase 2
- **Optimization Phase:** Refines the generated code using a series of optimizing transformations
- **Final Code Generation Phase:** Translates the abstract intermediate code into specific machine instructions

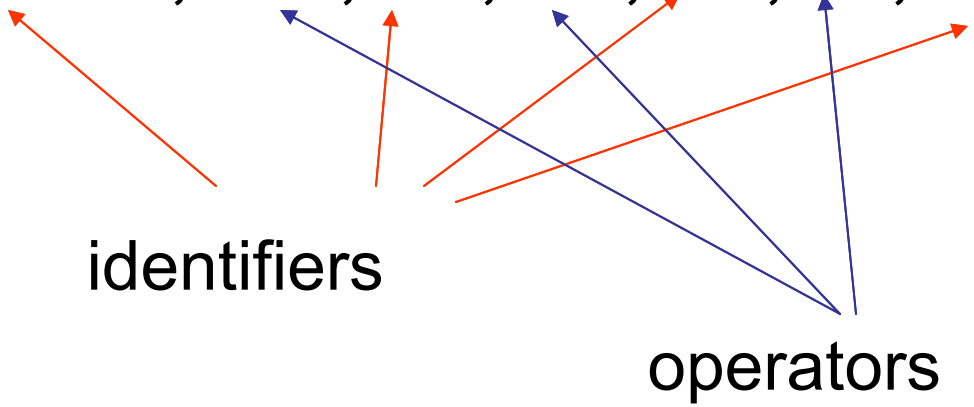
Lexical Analysis

- Convert the stream of characters representing input program into a sequence of tokens
- Tokens are the “words" of the programming language
- Lexeme
  - The characters comprising a token
- For instance, the sequence of characters “static int" is recognized as two tokens, representing the two words “static" and “int"
- The sequence of characters “*x++" is recognized as three tokens, representing “*", “x" and “++“
- Removes the white spaces
- Removes the comments

Lexical Analysis

- Input: result = a + b * 10
- Tokens:

‘result’, ‘=‘, ‘a’, ‘+’, ‘b’, ‘*’, ‘10’



Syntax Analysis (Parsing)

- Uncover the structure of a sentence in the program from a stream of tokens.

- For instance, the phrase “x = +y", which is recognized as four tokens, representing “x", “=“ and “+" and “y", has the structure **=(x,+(y))**, i.e., an assignment expression, that operates on “x" and the expression “+(y)".

- Build a tree called a parse tree that reflects the structure of the input sentence.

Syntax Analysis: Grammars

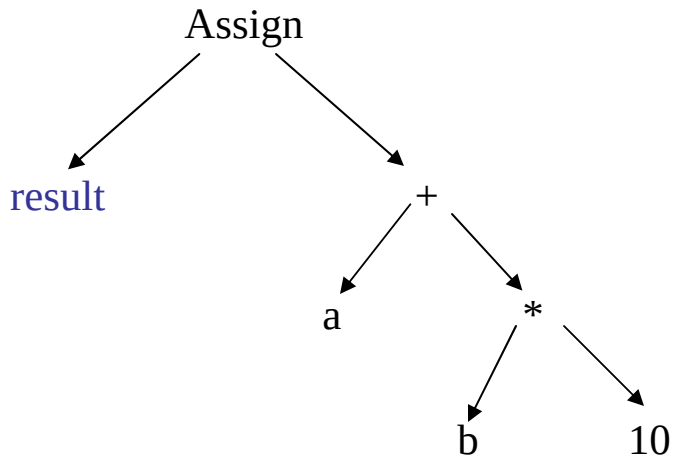
- Expression grammar

```
Exp      ::=  Exp ‘+’ Exp
           |    Exp ‘*’ Exp
           |    ID
           |    NUMBER

Assign  ::=    ID ‘=‘ Exp
```

Syntax Tree

Input: result = a + b * 10



Semantic Analysis

- Concerned with the semantic (meaning) of the program
- Performs type checking
  - Operator operand compitability

Intermediate Code Generation

- Translate each hierarchical structure decorated as tree into intermediate code
- A program translated for an abstract machine
- Properties of intermediate codes
  - Should be easy to generate
  - Should be easy to translate
- Intermediate code hides many machine-level details, but has instruction-level mapping to many assembly languages
- Main motivation: portability
- One commonly used form is “Three-address Code”

Code Optimization

- Apply a series of transformations to improve the time and space efficiency of the generated code.
- Peephole optimizations: generate new instructions by combining/expanding on a small number of consecutive instructions.
- Global optimizations: reorder, remove or add instructions to change the structure of generated code
- Consumes a significant fraction of the compilation time
- Optimization capability varies widely
- Simple optimization techniques can be vary valuable

Code Generation

- Map instructions in the intermediate code to specific machine instructions.
- Memory management, register allocation, instruction selection, instruction scheduling, …
- Generates sufficient information to enable symbolic debugging.

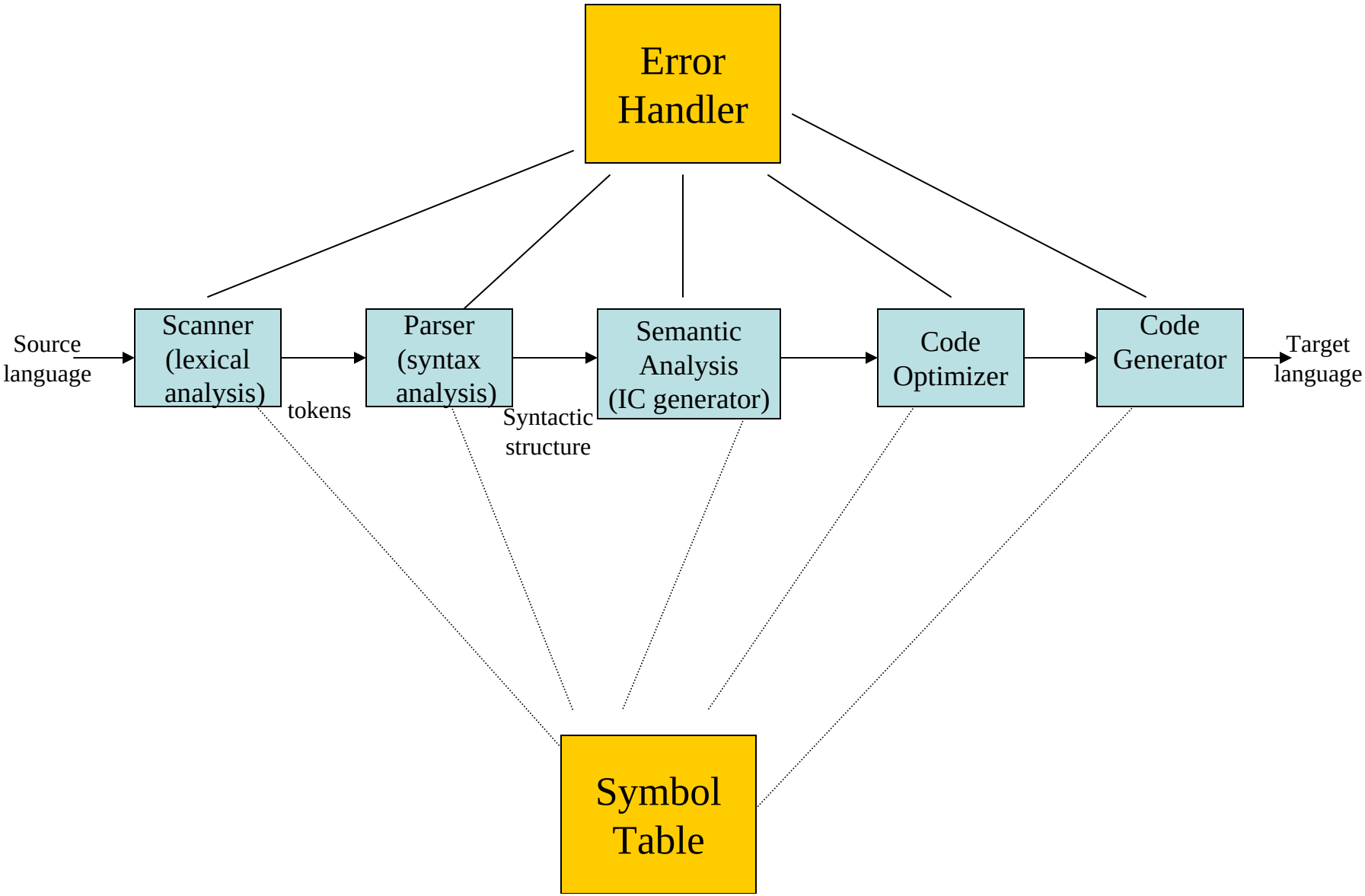
Symbol Table

- Records the identifiers used in the source program
  - Collects various associated information as attributes
    - Variables: type, scope, storage allocation
    - Procedure: number and types of arguments method of argument passing
- It's a data structure with collection of records
  - Different fields are collected and used at different phases of compilation

Error Detection, Recovery and Reporting

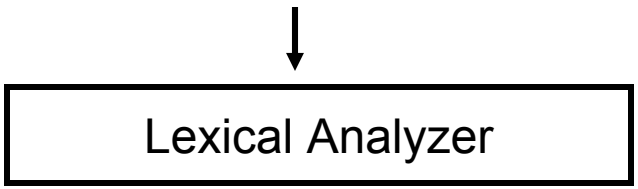
- Each phase can encounter error
- Specific types of error can be detected by specific phases
  - Lexical Error: `int abc, 1num;`
  - Syntax Error: `total = capital + rate  year;`
  - Semantic Error: `value = myarray [realIndex];`
- Should be able to proceed and process the rest of the program after an error detected
- Should be able to link the error with the source program

Error Detection, Recovery and Reporting

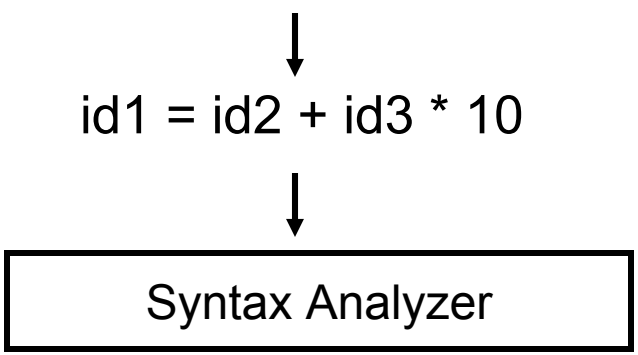


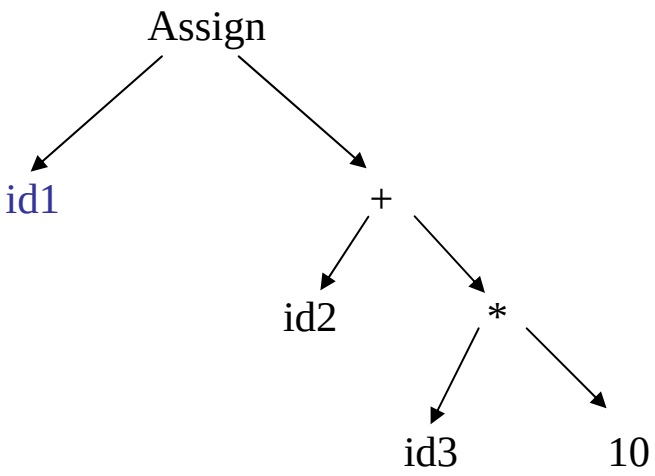
Translation of a statement

result = a + b * 10



id1 = id2 + id3 * 10

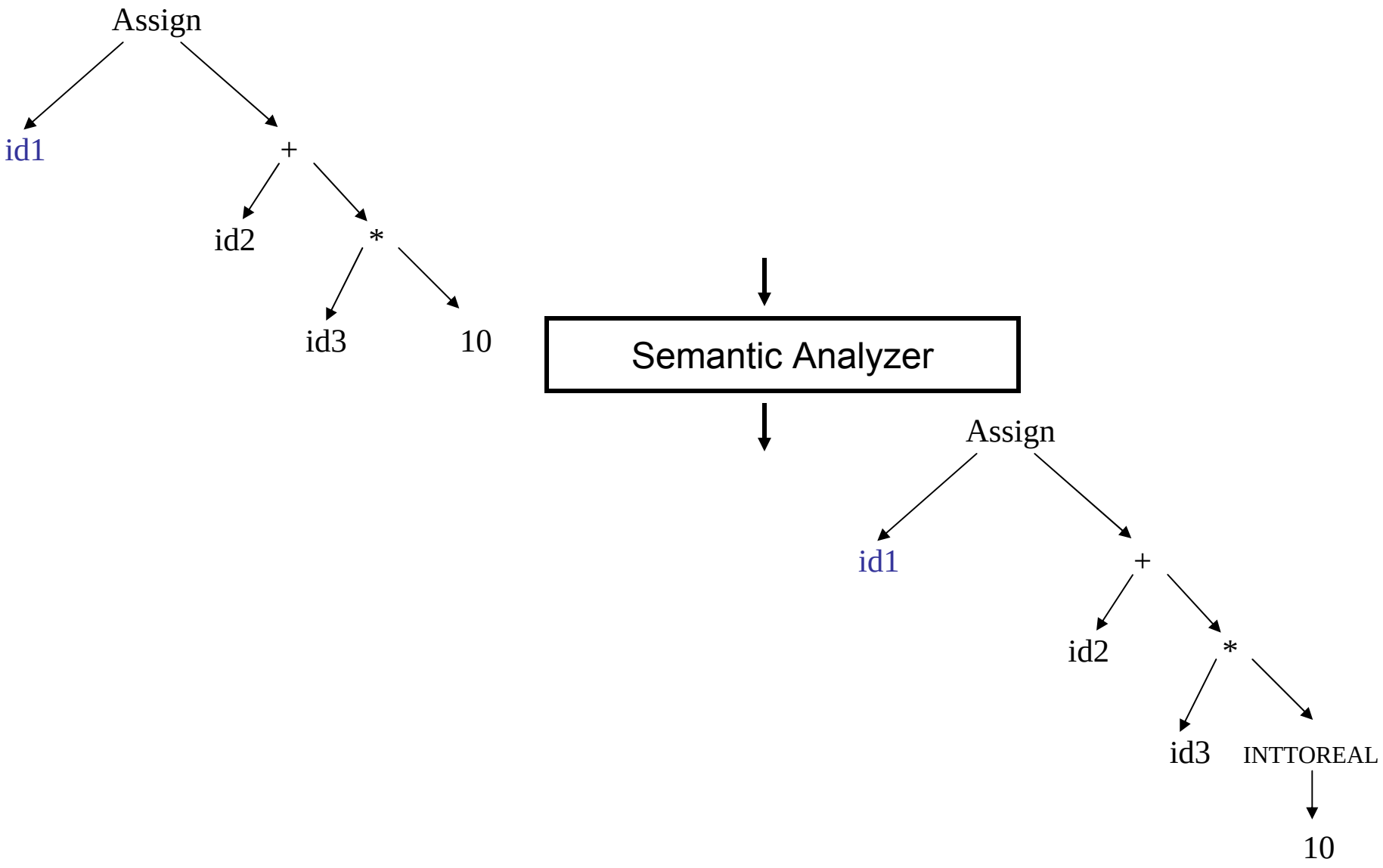




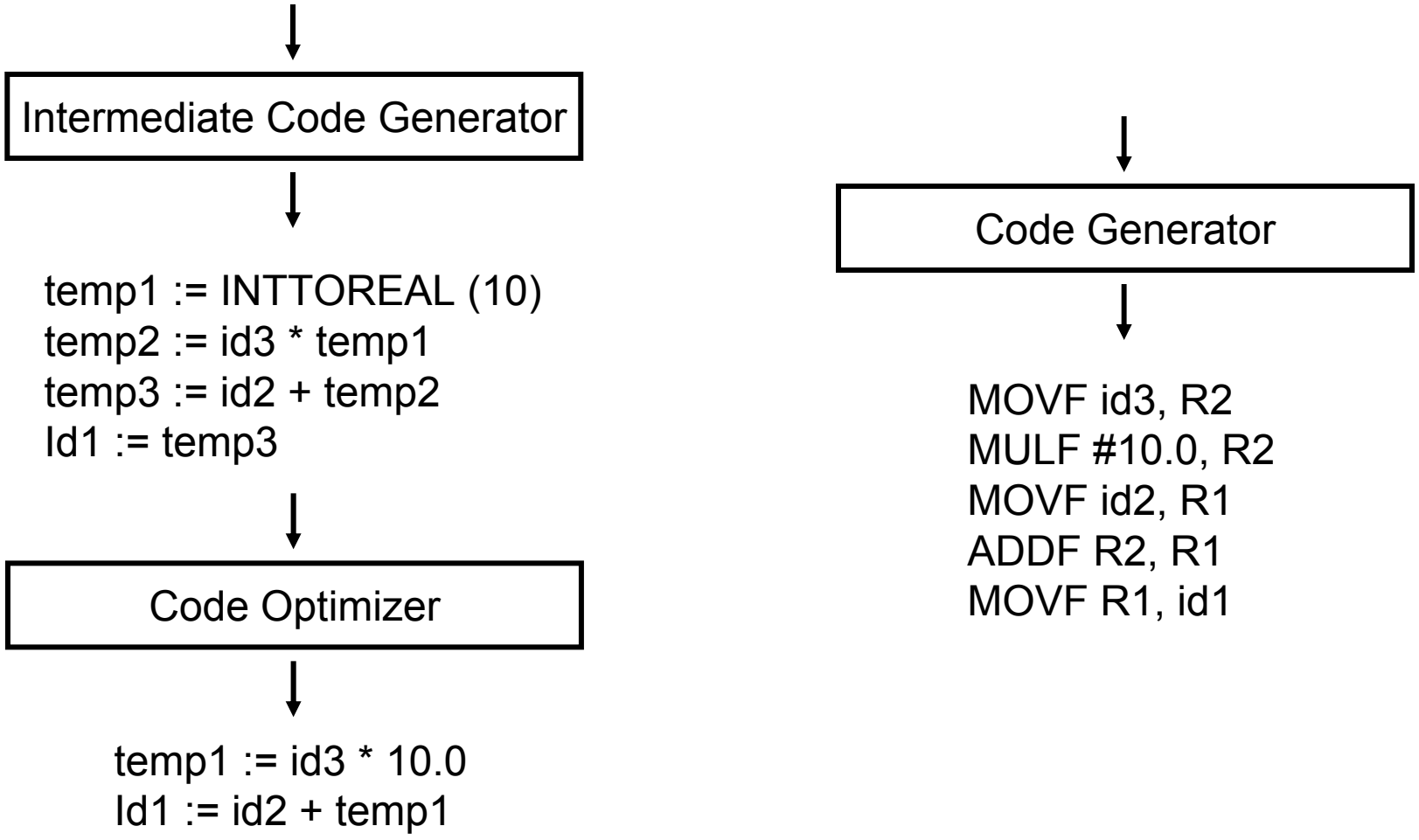
Symbol Table

result	.....
a	.....
b	.....

Translation of a statement



Translation of a statement



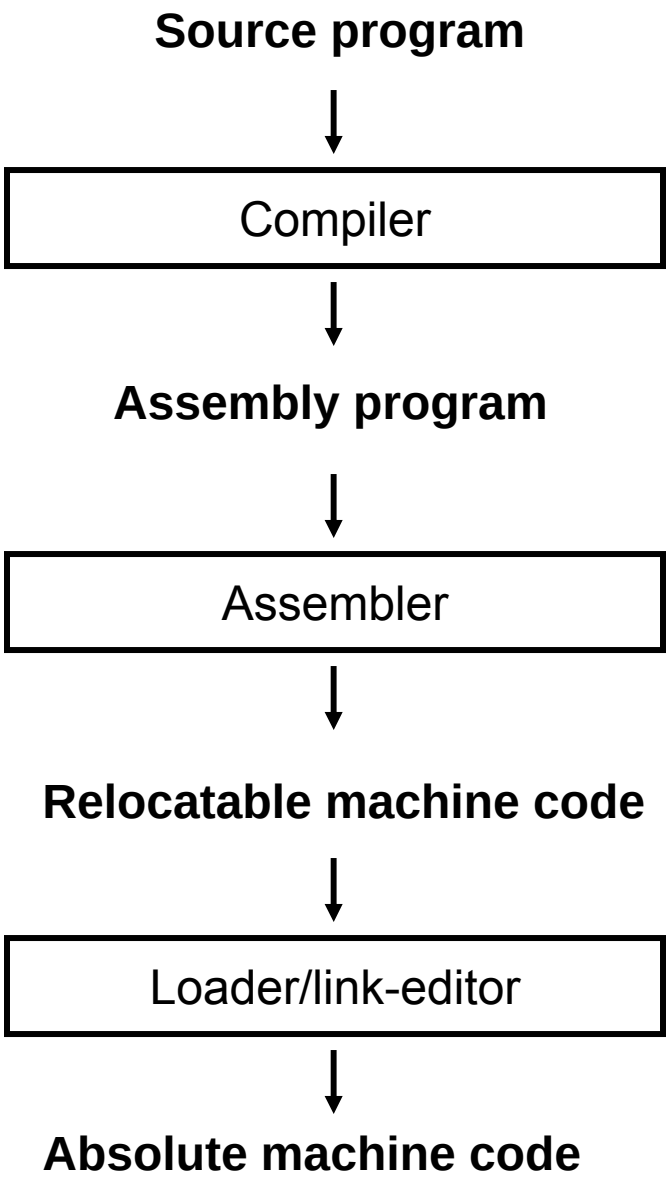
Syntax Analyzer versus Lexical Analyzer

- Which constructs of a program should be recognized by the lexical analyzer, and which ones by the syntax analyzer?
  - Both of them do similar things; But the lexical analyzer deals with simple non-recursive constructs of the language.
  - The syntax analyzer deals with recursive constructs of the language.
  - The lexical analyzer simplifies the job of the syntax analyzer.
  - The lexical analyzer recognizes the smallest meaningful units (tokens) in a source program.
  - The syntax analyzer works on the smallest meaningful units (tokens) in a source program to recognize meaningful structures in our programming language.

Cousins of the Compiler

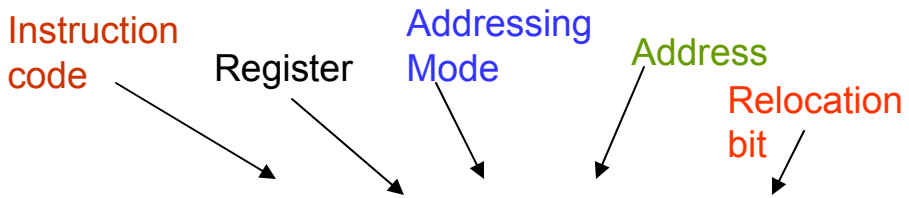
- Preprocessor
  - Macro preprocessing
    - Define and use shorthand for longer constructs
  - File inclusion
    - Include header files
  - “Rational” Preprocessors
    - Augment older languages with modern flow-of-control or data-structures
  - Language Extension
    - Add capabilities to a language
    - Equel: query language embedded in C

Assemblers


Source program
Compiler
Assembly program
Assembler
Relocatable machine code
Loader/link-editor
Absolute machine code

Two-Pass Assembly

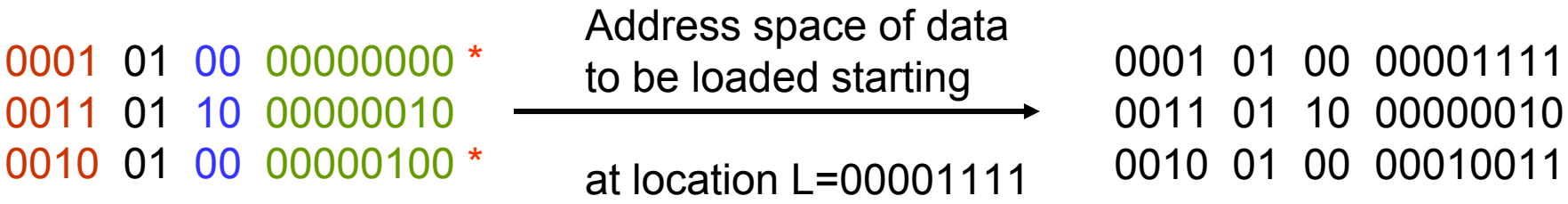
- Simplest form of assembler
- First pass
  - All the identifiers are stored in a symbol table
  - Storage is allocated
- Second pass
  - Translates each operand code in the machine language



Source	After First Pass		After 2nd Pass
MOV a, R1	Identifier	Address	0001 01 00 00000000 *
ADD #2, R1	a	0	0011 01 10 00000010
MOV R1, b	b	4	0010 01 00 00000100 *

Loaders and Link-Editors

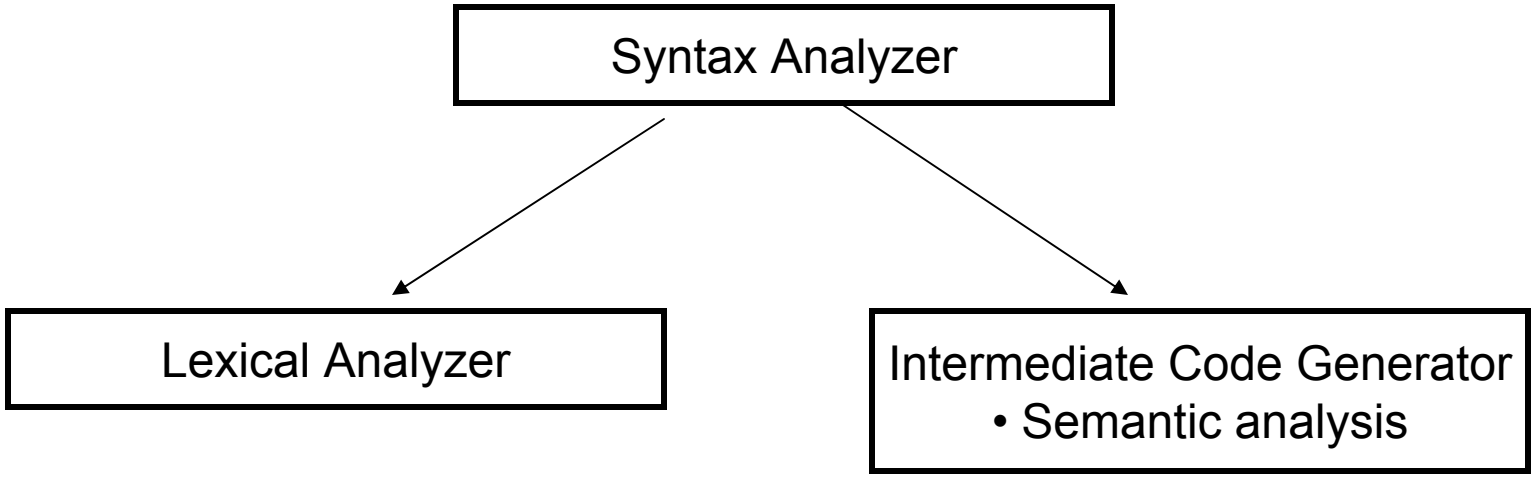
- Convert the relocatable machine code into absolute machine code
  - Map the relocatable address
- Place altered instructions and data in memory



- Make a single program from several files of relocatable machine code
  - Several files of relocatable codes
  - Library files

Multi Pass Compilers

- Passes
  - Several phases of compilers are grouped in to passes
  - Often passes generate an explicit output file
  - In each pass the whole input file/source is processed



How many passes?

- Relatively few passes is desirable
  - Reading and writing intermediate files take time
  - It may require to keep the entire file in memory
    - One phase generate information in different order than that is needed by the next phase
    - Memory space is not trivial in some cases
- Grouping into same pass incurs some problems
  - Intermediate code generation and code generation in the same pass is difficult
    - e.g. Target of '`goto`' that jumps forward is now known
    - 'Backpatching' can be a remedy

Issues Driving Compiler Design

- Correctness
- Speed (runtime and compile time)
  - Degrees of optimization
  - Multiple passes
- Space
- Feedback to user
- Debugging

Other Applications

- In addition to the development of a compiler, the techniques used in compiler design can be applicable to many problems in computer science.
  - Techniques used in a lexical analyzer can be used in text editors, information retrieval system, and pattern recognition programs.
  - Techniques used in a parser can be used in a query processing system such as SQL.
  - Many software having a complex front-end may need techniques used in compiler design.
    - A symbolic equation solver which takes an equation as input. That program should parse the given input equation.
  - Most of the techniques used in compiler design can be used in Natural Language Processing (NLP) systems.