# CS131: Programming Languages and Compilers

Spring 2017

# Course Information

- Instructor: Fu Song
  Office: Room 1A-504C, SIST Building
  Email: songfu@shanghaitech.edu.cn

- Class Hours : Tuesday and Thursday, 8:15--9:55
  Room 1D-106, SIST Building

- TA: Jun Zhang, Zhiming Mei

- Office Hours: Friday 13:30-15:30
  Tuesday 15:00-17:00

- Discussion: PIAZZA
  https://piazza.com/shanghaitech.edu.cn/spring2017/cs131

- Course Information:
  http://sist.shanghaitech.edu.cn/faculty/songfu/course/spring2017/cs131/

Jun Zhang

Zhiming Mei

# Preliminaries Required

## Preliminaries

- data structures and algorithms
- programming languages (C/C++)

## Textbook

Alfred V. Aho, Monica S. Lam, Ravi Sethi, and Jeffrey D. Ullman
"*Compilers: Principles, Techniques, and Tools*" Second Edition
Pearson Addison-Wesley, 2007, ISBN 0-321-48681-1

## Reference book and websites

1. Kenneth C. Louden, *Compiler Construction Principles and Practice*，2002
2. https://courses.engr.illinois.edu/cs426/
3. http://web.stanford.edu/class/cs143/

# Course Structure = Goals

- Theoretical Part

  Basic knowledge of theoretical techniques

- Practical experience

  Design and program an actual compiler using tools, such as LEX/Flex, YACC/Bison

# Grading

- Bonus : 10%
- Homework : 20%
- Projects : 30%
- Midterm : 20%
- Final : 30%

Optional projects (max. 2 students per project)

solution code + report + presentation

# Integrity

You must NOT

- use work from uncited sources
- read or posses solutions written by others
- allow other people to read or possess your solution

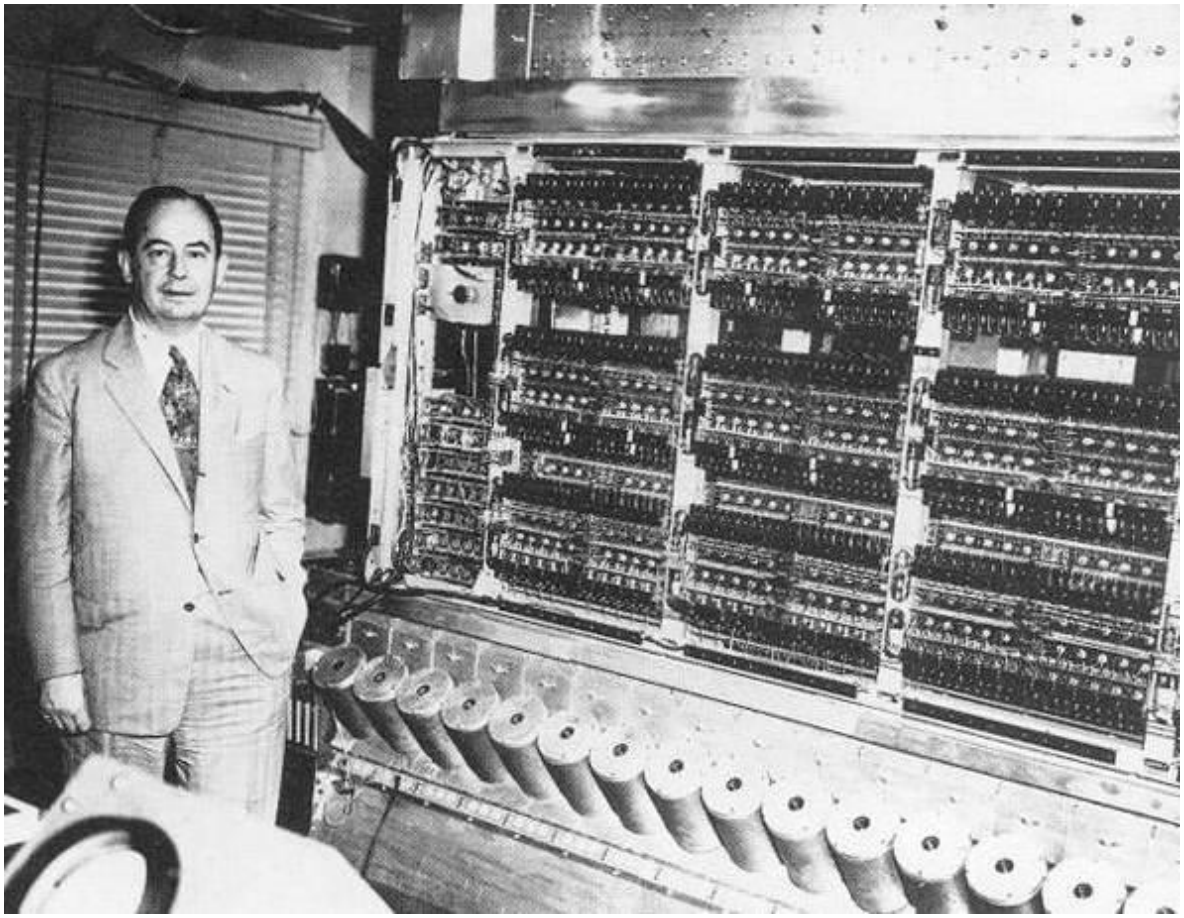
Ask before action when in doubt

# Course Outline

- Introduction to Compiling
- Lexical Analysis
  - Regular expressions, regular definitions
  - NFA, DFA
  - Subset construction, Thompson's construction
- Syntax Analysis
  - Context Free Grammars
  - Top-Down Parsing, LL Parsing
  - Bottom-Up Parsing, LR Parsing
- Syntax-Directed Translation
  - Attribute Definitions
  - Evaluation of Attribute Definitions
- Semantic Analysis, Type Checking
- Intermediate Representations
- Run-Time Environment
- Operational Semantics
- Intermediate Code Generation
- Optimization
- Assembler Code Generation

# A brief history of compiler

- In the late1940s, the stored-program computer invented by John von Neumann， programs were written in machine language, $\{0,1\}^+$

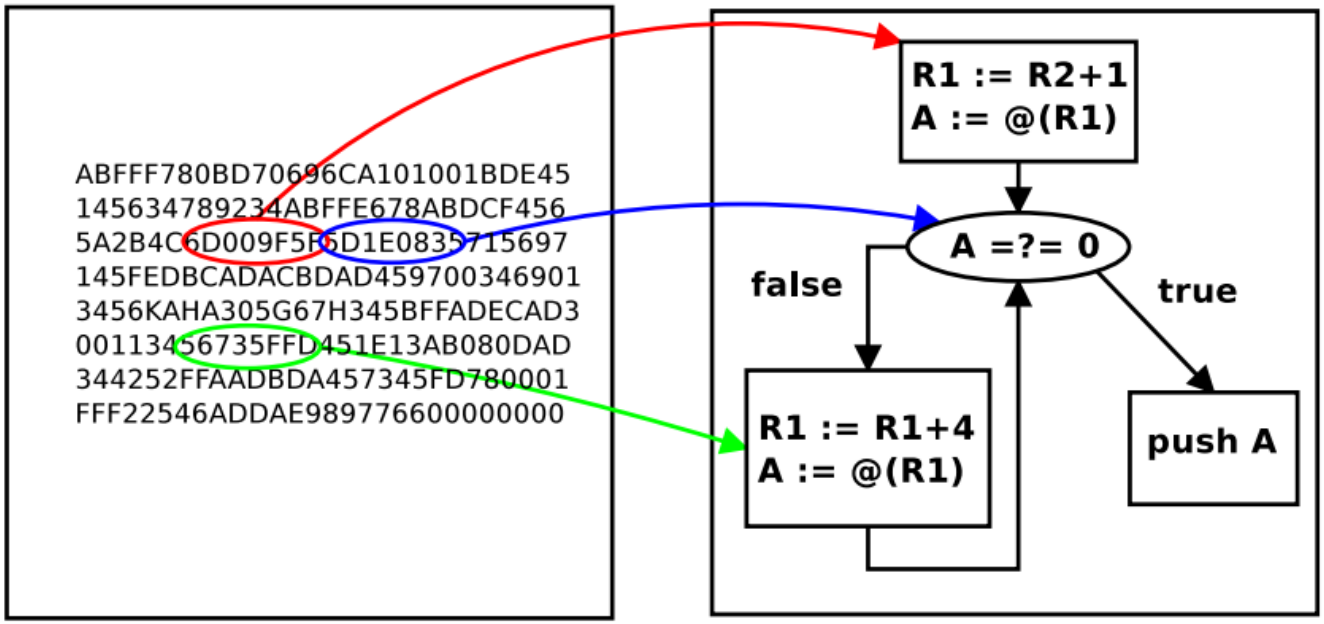


# A brief history of compiler (cont.)

- Mnemonic assembly language: in 1949

  numeric codes were replaced symbolic forms  Mov R, 2 (R=2)
- Assembler: translate the symbolic codes and memory location of assembly  language  into the  corresponding numeric codes.

Macro instructions + assembly language



# A brief history of compiler (cont.)

- FORTRAN language and its compiler: between 1954 and 1957 , developed by the team at IBM , John Backus.

  (1) The structure of natural language studied by **Noam Chomsky**,

  (2) The classification of languages according to the complexity of their grammars and the power of the algorithms needed to recognize them.

  (3) Four levels of grammars: type 0 、 type 1、 type2 and type3 grammars

  Type 0: Turing machine/Recursive enumerable language

  Type 1: context-sensitive grammar/language

  Type 2: context-free grammar/language, the most useful of programming language

  Type 3: right-linear grammar/language, regular expressions

Handbook of Formal Languages Vol 1, 2, 3

# A brief history of compiler (cont.)

(4) parsing problem : studied in 1960s and 1970s

(5) Code improvement techniques (optimization techniques): improve compilers efficiency.

(6) Compiler-compilers (parser generator): only in one part of the compiler process.

YACC: written in 1975 by Steve Johnson for the UNIX system.

LEX: written in 1975 by Mike Lest.

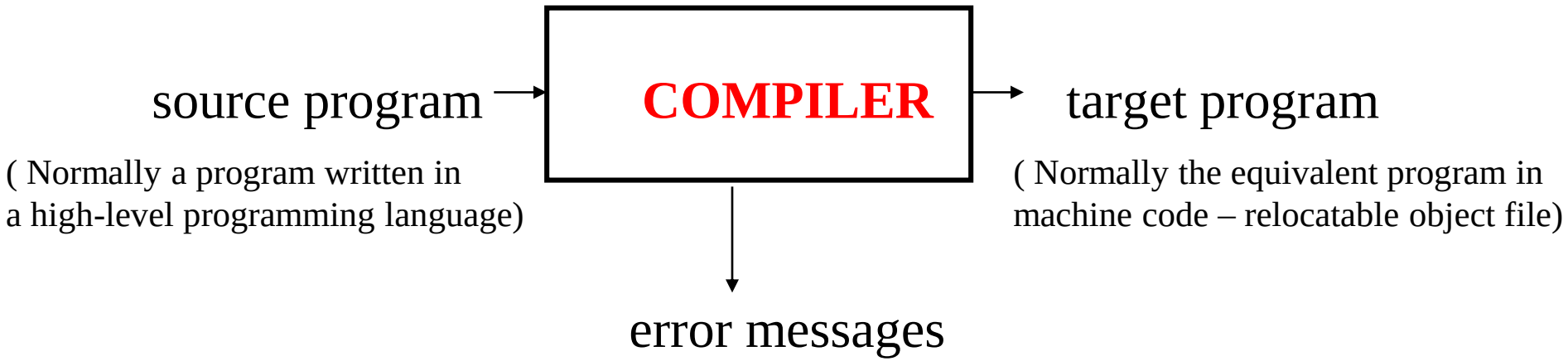
(7) recent advances in compiler design:

(a) application of more sophisticated algorithms for inferring and /or simplifying the information contained in a program. (with the development of more sophisticated programming languages that allow this kind of analysis), e.g. memory safe language Rust

(b) development of standard windowing environments ( interactive development environment IDE)

# Compilers

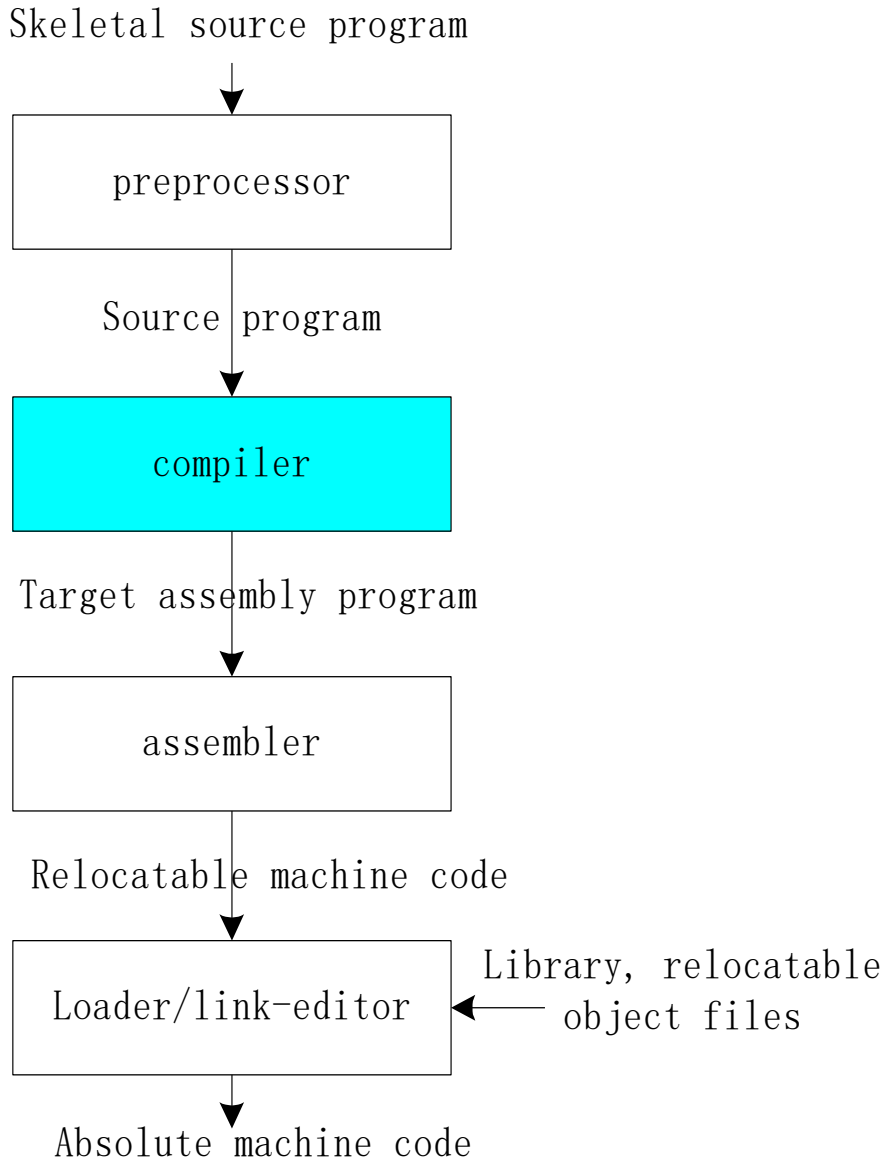
- A **compiler** is a program takes a program written in a source language and translates it into an equivalent program in a target language.



# 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 (Structured Query Language,).
  - 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.

# Compiling system



# Cousins of the compiler

- Preprocessors

  delete comments, include other files, perform macro substitutions.
- Compilers

  A language translator. It executes the source program immediately. Depending on the language in use and the situation
- Assemblers

  A translator translates assembly language into object code
- Linkers

  Collects code separately compiled or assembled in different object files into a file.

  Connects the code for standard library functions.

  Connects resources supplied by the operating system of the computer.

# Cousins of the compiler (cont.)

- Loaders

  Relocatable : the code is not completely fixed .

  Loaders resolve all relocatable address relative to the starting address.
- Editors

  Produce a standard file ( structure based editors)
- Debuggers

  Determine execution errors in a compiled program.

# Major Parts of Compilers

- There are two major parts of a compiler:

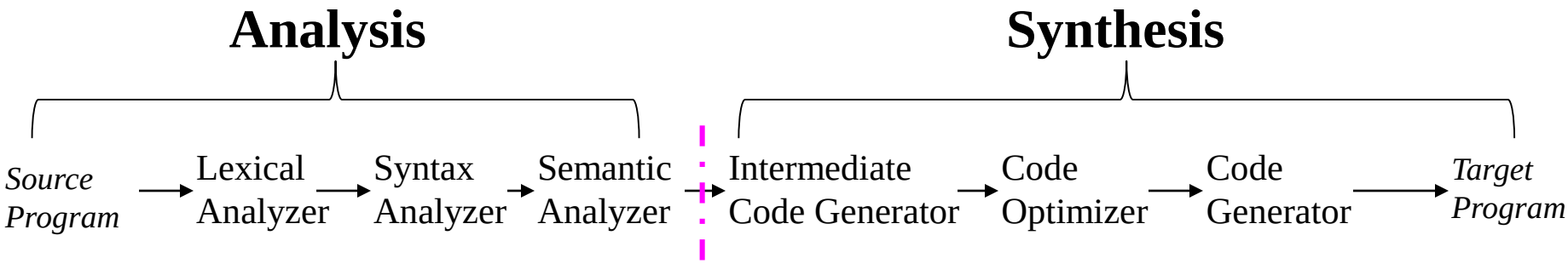
  **Analysis** and **Synthesis**

  **Front-end** and **Back-end**

- In analysis phase, an intermediate representation is created from the given source program.
  - Lexical Analyzer, Syntax Analyzer and Semantic Analyzer are the parts of this phase.
- In synthesis phase, the equivalent target program is created from this intermediate representation.
  - Intermediate Code Generator, Code Generator, and Code Optimizer are the parts of this phase.

# The Phases of a Compiler

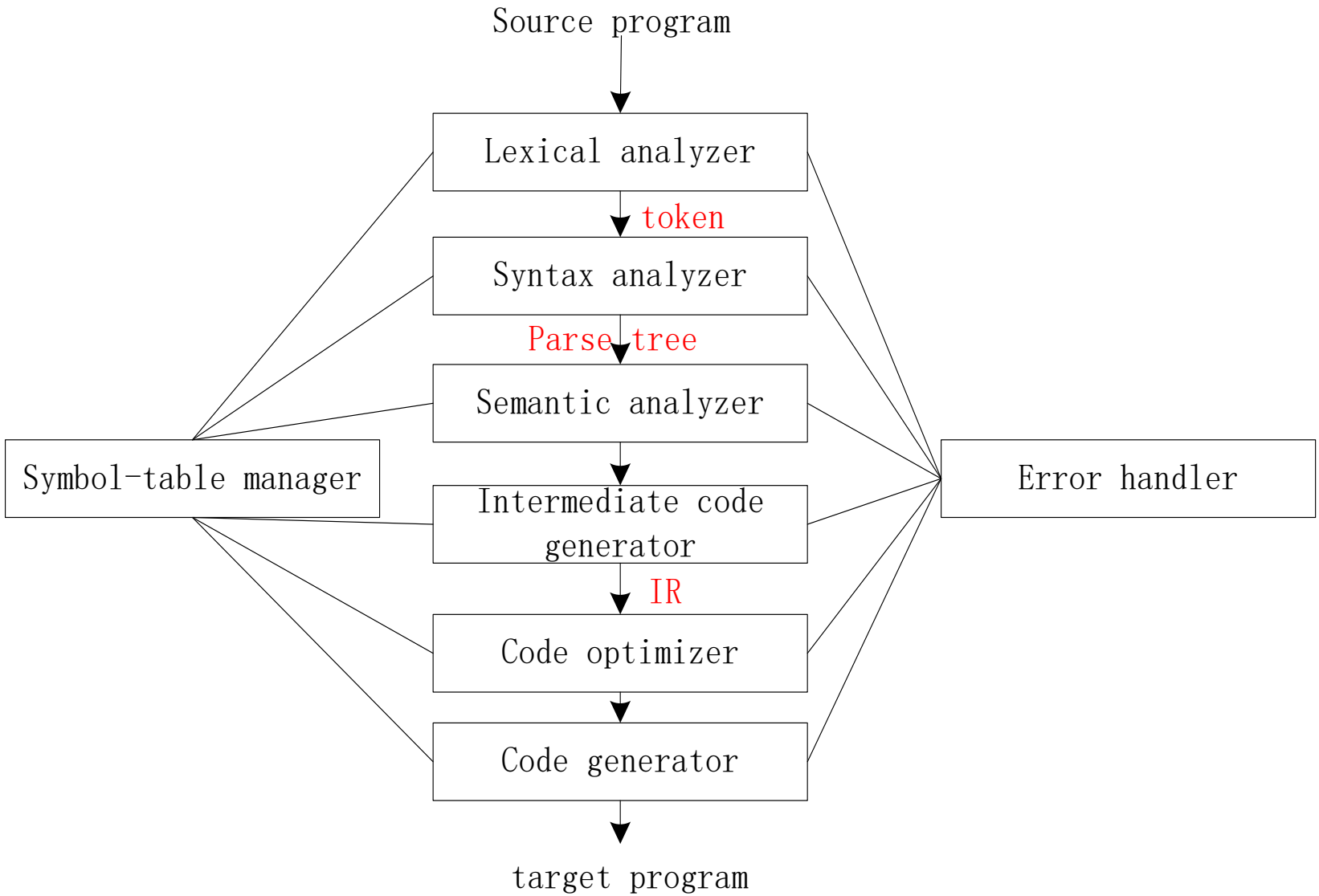



- Each phase transforms the source program from one representation into another representation.

- They communicate with the symbol table

- They communicate with error handlers.

# The Phases of a Compiler (cont.)



# Lexical Analyzer

- First step: recognize words.
  – Smallest unit above letters

This is a sentence.

- Lexical analysis is not trivial.
  Consider:

ist his ase nte nce

# Lexical Analyzer (cont.)

- **Lexical Analyzer:** reads the source program character by character and returns the *tokens* of the source program.
- **Token** describes a pattern of characters having some meaning in the source program (such as identifiers, operators, keywords, numbers, delimiters and so on)

Ex: x = y + 12 ; => tokens: x and y are identifiers
= assignment operator
+ add operator
12 a number
; delimiter

Ex: if x == y then z = 1; else z = 2; => tokens: x, y and z are identifiers
= assignment operator
= = compare operator
1 and 2 are number
; delimiter

# Lexical Analyzer (cont.)

- Puts information about identifiers into the symbol table.
- **Regular expressions** are used to describe tokens (lexical constructs).
- A (Deterministic) **Finite State Automaton** can be used in the implementation of a lexical analyzer.

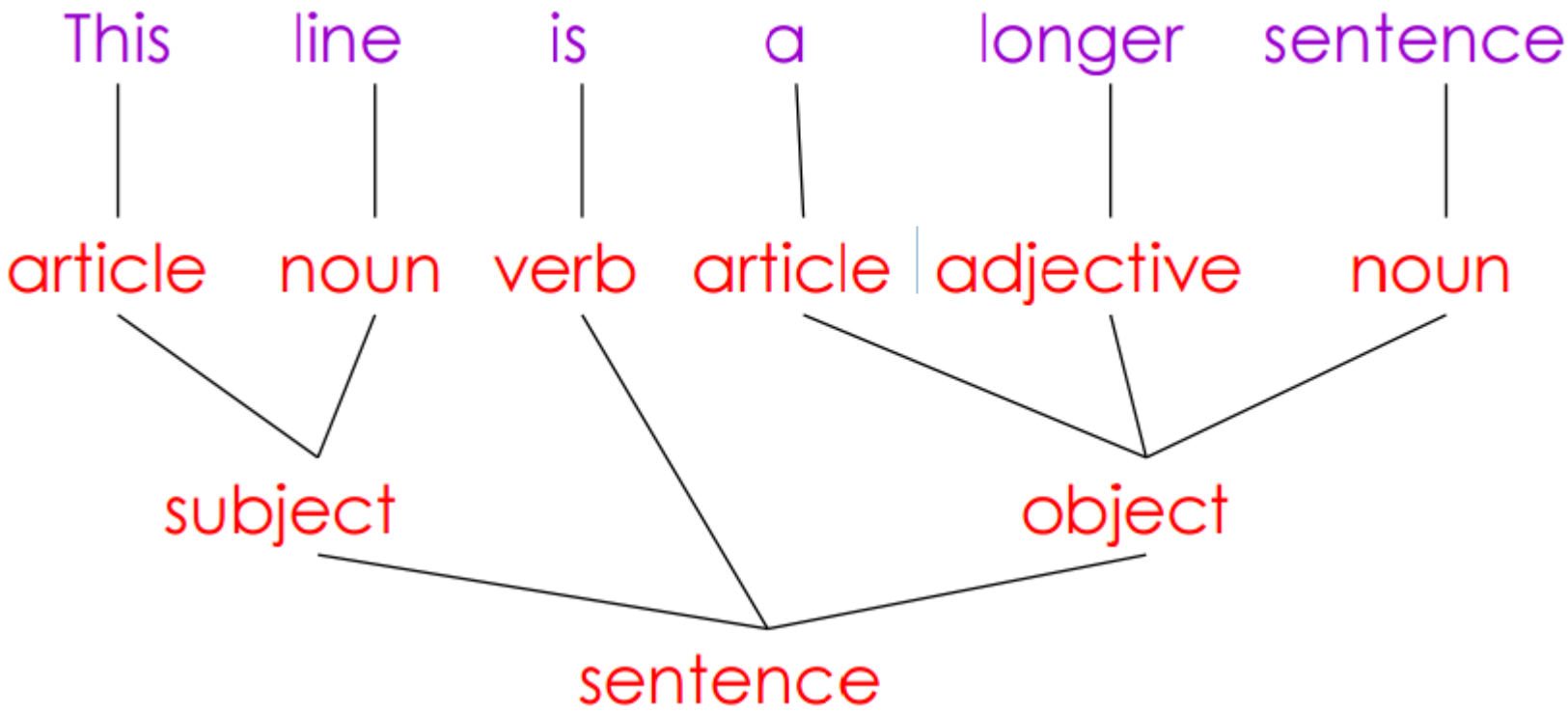
Eg. Identifier: [a-zA-Z] [a-zA-Z0-9]$^{+}$

Good Id: x, y, x1

Bad Id: 1x

# Syntax Analyzer

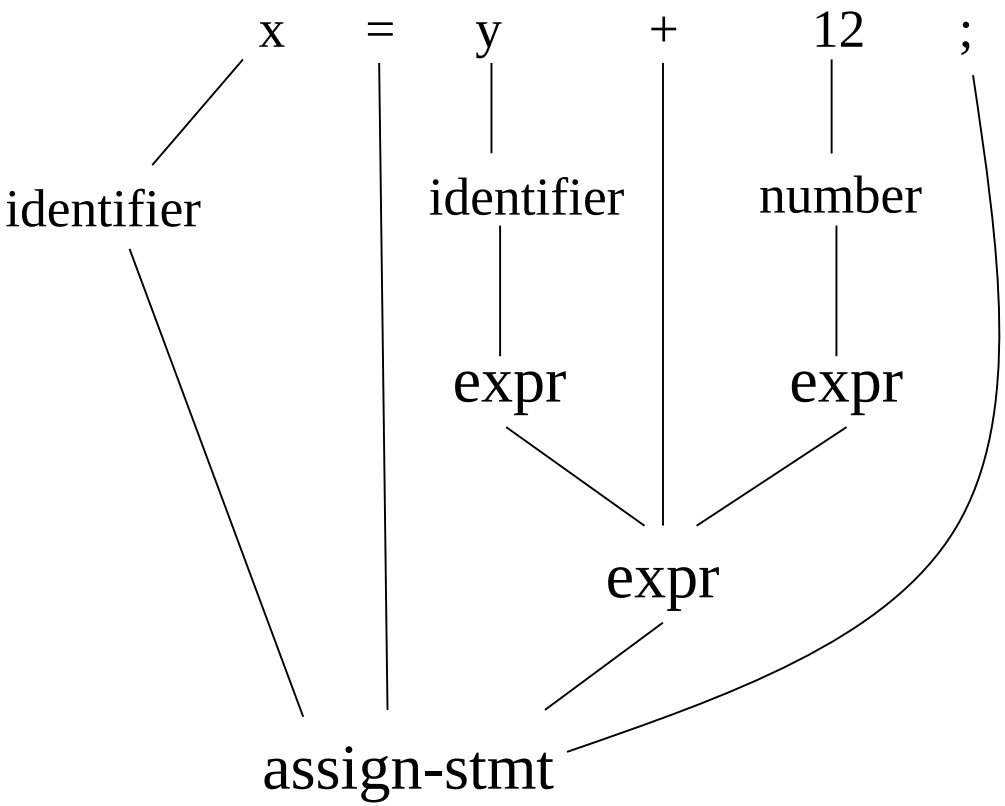
- Lexical Analyzer provides recognized words
- The next step is to understand sentence structure



# Syntax Analyzer (cont.)

- A **Syntax Analyzer (**also known as **parser)** creates the syntactic structure (generally a parse tree) of the given program
- A **parse tree** describes a syntactic structure.

Ex:




- In a parse tree, all terminals are at leaves.
- All inner nodes are non-terminals in a context free grammar.

# Syntax Analyzer (cont.)

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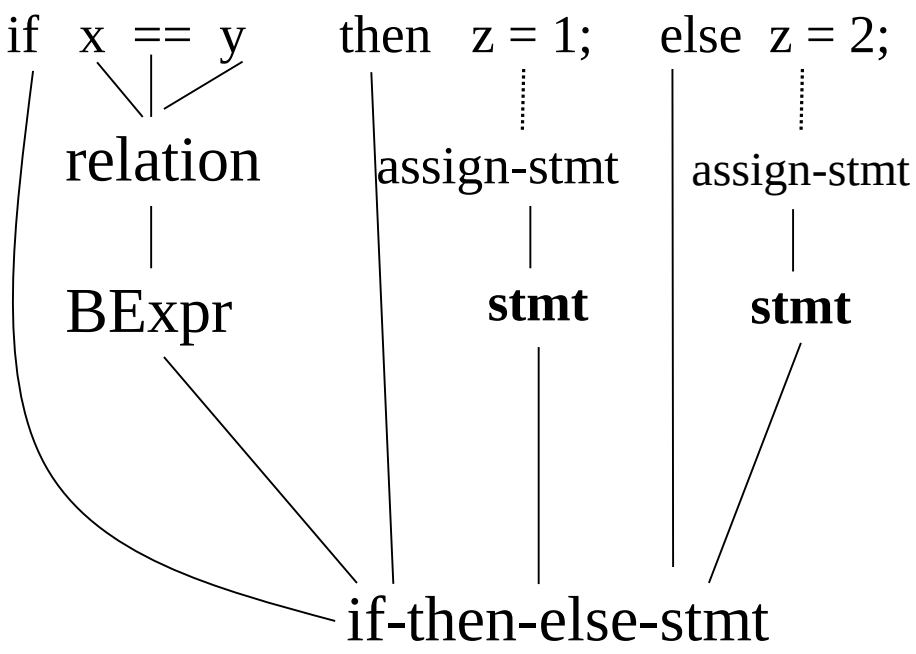



- In a parse tree, all terminals are at leaves.
- All inner nodes are non-terminals in a context free grammar.

# Syntax Analyzer (cont.)

- The syntax of a language is specified by a context free grammar (**CFG**)
- The rules in a CFG are mostly recursive.
- A syntax analyzer checks whether a given program satisfies the rules implied by a CFG or not.
  - If it satisfies, the syntax analyzer creates a parse tree for the given program.

- Ex: We use EBNF (Extended Backus-Naur Form) to specify a CFG

```
assign-stmt ->  identifier  = expr ;
expr        ->  identifier
expr        ->  number
expr        ->  expr  BOP expr
BOP         -> + | - | * | /
```

Good: x = y +1;  Bad:  x = y+1,  x = + y 1

# Syntax Analyzer vs. 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 (**sentences**) in our programming language.

# Parsing Techniques

- Depending on how the parse tree is created, there are different parsing techniques.
- These parsing techniques are categorized into two groups:
  - ***Top-Down Parsing***
  - ***Bottom-Up Parsing***

# Parsing Techniques (cont.)

- **Top-Down Parsing:**
  - Construction of the parse tree starts at the root, and proceeds towards the leaves.
  - Efficient top-down parsers can be easily constructed by hand.
  - Recursive Predictive Parsing,
  - Non-Recursive Predictive Parsing (**LL Parsing**).

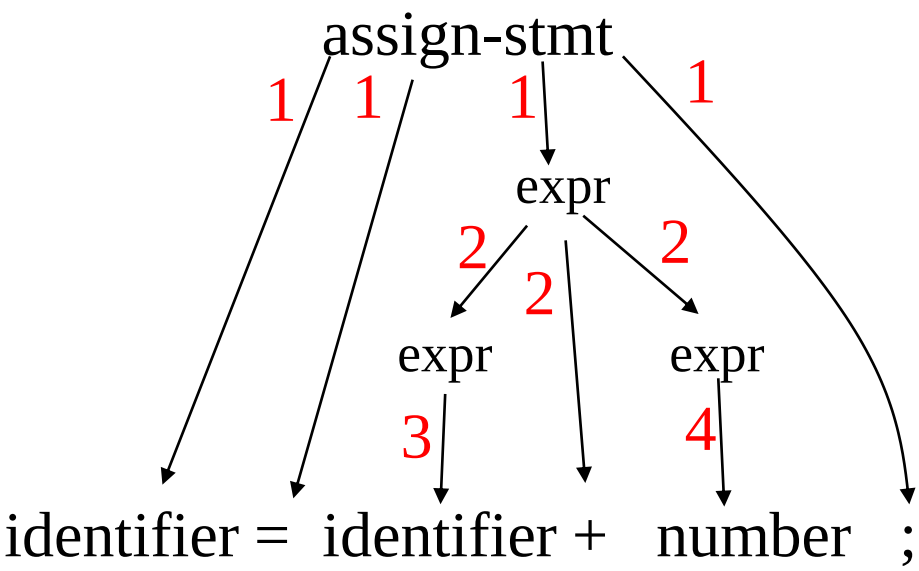
    （**L**-left to right; **L**-leftmost derivation）

# Parsing Techniques (cont.)

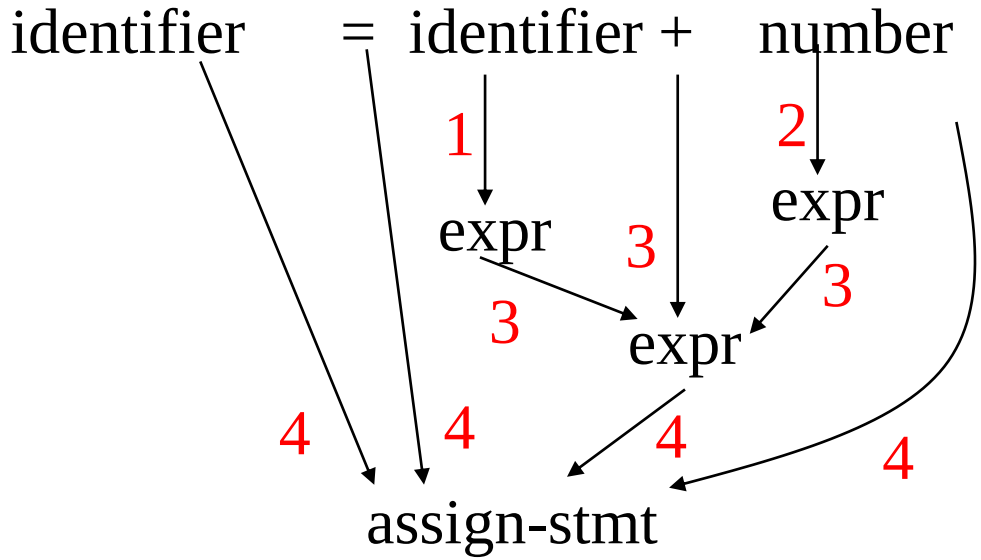
- **Bottom-Up Parsing:**
  - Construction of the parse tree starts at the leaves, and proceeds towards the root.
  - Normally efficient bottom-up parsers are created with the help of some software tools.
  - Bottom-up parsing is also known as shift-reduce parsing
  - LR Parsing – much general form of shift-reduce parsing: LR, SLR, LALR （L-left to right; R-rightmost derivation）

# Top-down vs. Bottom-up

**x = y + 12 ;**




Top-down (preorder )




Bottom-up (postorder)

# Semantic Analyzer

- Once sentence structure is understood, we can try to understand “meaning”
  – But meaning is too hard for compilers
- Compilers perform limited analysis to catch inconsistencies

Eg.

Jack said Jerry left his assignment at home.

What does “his” refer to? Jack or Jerry?

Even worse:

Jack said Jack left his assignment at home.

How many Jacks are there? Which one left the assignment?

# Semantic Analyzer

- Programming languages define strict rules to avoid such ambiguities

```
Jack =1
def f():
    Jack =2
    print(Jack)
print(Jack)
f()
```

Output ?

```
>> 1
>> 2
```

# Semantic Analyzer (cont.)

- A semantic analyzer checks the source program for semantic errors and collects the type information for the code generation.
- Type-checking is an important part of semantic analyzer.
- Normally semantic information cannot be represented by a context-free language used in syntax analyzers.

# Semantic Analyzer (cont.)

Rust programs

```
Let x;
x =1;
```

```
Let x =0;
x =1;
```

```
Let mut x =0;
x =1;
```

Error ? **Type information + uninitialized**

```
Let x = 1
println!("{}", x);
```

```
Let x;
println!("{}", x);
```

Error? **Read uninitialized memory**

cannot be represented by a context-free language

```
Let x;
if true { x = 1;}
println!("{}", x);
```

Error?

```
Let x;
if true { x = 1;}
else {x = 2}
println!("{}", x);
```

Semantic analysis is not panacea

# Semantic Analyzer (cont.)

- Context-free grammars used in the syntax analysis are integrated with attributes (semantic rules)
  - the result is **a syntax-directed translation**
  - **Attribute grammars**
- Ex:

  x = y + 12

  - The type of the identifier *x* must match with type of the expression *(y+12)*

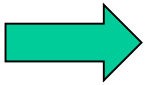
# Optimization

- No strong counterpart in English, but akin to editing
- Automatically modify programs so that they
  - Run faster
  - Use less recourse, e.g. power, memory
  - Small size

Eg. x = y + 0 => x =y

x = y + 1; z = x => z= y + 1

for (x=1; x++; x<=10)
{z=10; y = y + x *z }



for (x=1; x++; x<=10)
{ y = y + x *10 }

The project has no optimization component

# Intermediate Code Generation

- A compiler may produce an explicit intermediate codes representing the source program.
- These intermediate codes are generally machine (architecture) independent (except GCC). But the level of intermediate codes is close to the level of machine codes.

# Intermediate Code Generation (example)

- Ex:

x = y * fact + 1

id1 = id2 * id3 + 1

MULT temp1, id2, id3 ;*Intermediates Codes*
*(Quadraples or three address code)*

ADD temp2, temp1, #1

MOV id1, temp2

# Code Generator

- Produces the target language in a specific architecture.
- The target program is normally is a relocatable object file containing the machine codes.

- Ex: id1 = id2 * id3 + 1

  ( assume that we have an architecture with instructions whose at least one of its operands is a machine register)

ARM:

```
LDR   R1, [id2]
LDR   R2, [id3]
MULT  R1, R2, R1
ADD   R1, R1, #1
MOV   id1, R1
STR   R1, [id1]
```

```
MULT  temp1,  id2,  id3
ADD   id1,  temp1,  #1
```

# Symbol-table management

- A symbol table is a data structure containing a record for each identifier, with fields for the attributes of the identifier
- In lexical analyzer the identifier is entered into the symbol table
- The attributes of an identifier cannot normally be determined during lexical analysis
- Updated and used by syntax analyzer, semantic analyzer, others

# The grouping of phases

- analysis and synthesis

  analysis: lexical analysis , syntax analysis, semantic analysis (optimization)

  synthesis:  code generation (optimization)

- front end and back end

  separation depend on the source language or the target language

  the front end: the scanner, parser, semantic analyzer, intermediate code synthesis

  the back end: the code generator, some optimization

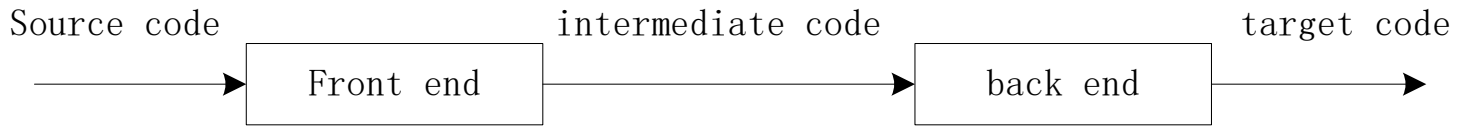
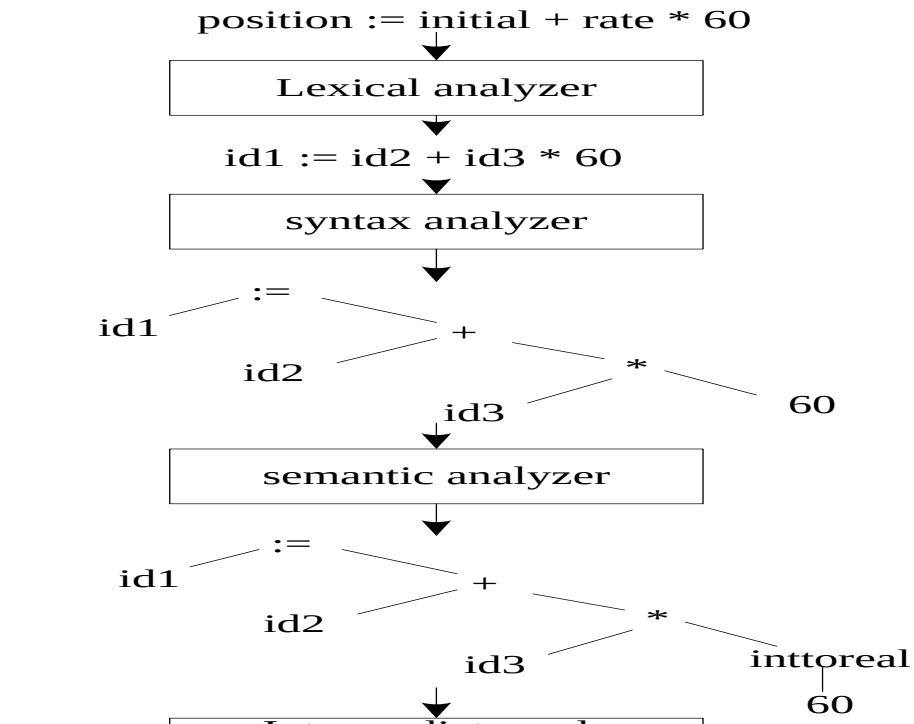



Fig. a. 1. 1

Symbol table

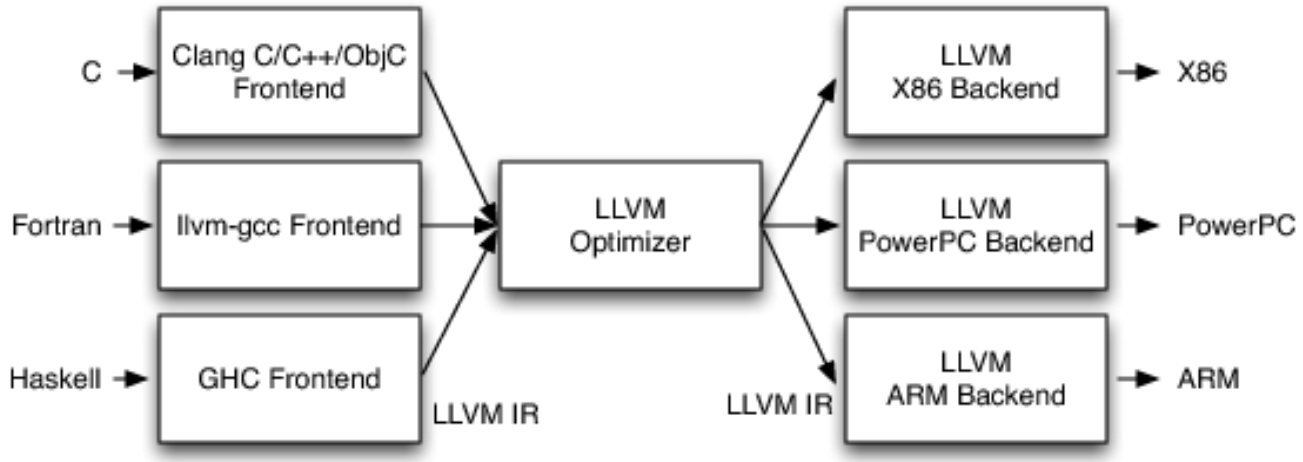
| | |
|---|---|
| position | ... |
| initial | ... |
| rate | ... |
| | |

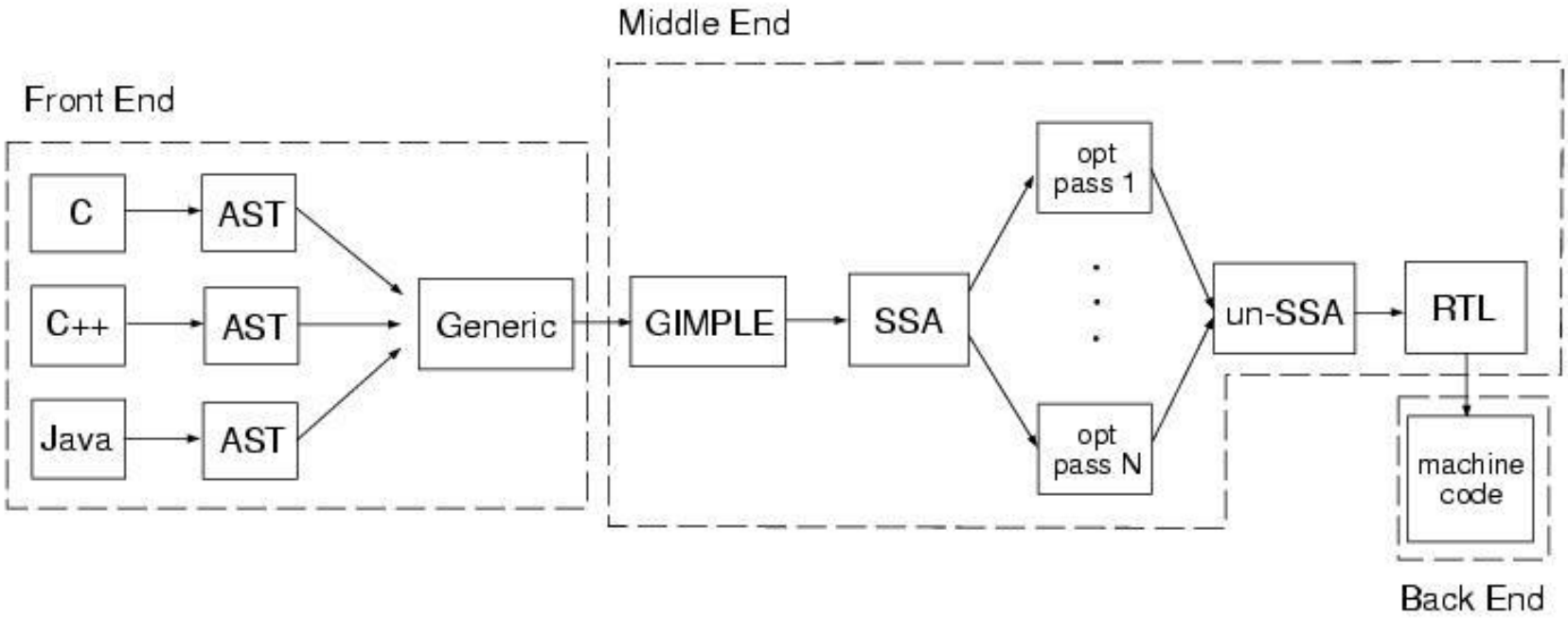



```
MOVF  R2,  id3
MULF  R2,  #60.0
MOVF  R1,  id2
ADDF  R1,  R2
MOVF  id1,  R1
```

```
for MIPS:
lw R2,  id3
mult R2,  R2,   #60.0
lw R1,  id2
add R1,  R1,  R2
sw R1,  id1
```

# LLVM and GCC


C
Clang C/C++/ObjC Frontend
Fortran
llvm-gcc Frontend
Haskell
GHC Frontend
LLVM IR
LLVM Optimizer
LLVM IR
LLVM X86 Backend
X86
LLVM PowerPC Backend
PowerPC
LLVM ARM Backend
ARM


Front End
Middle End
C
C++
Java
AST
AST
AST
Generic
GIMPLE
SSA
opt pass 1
opt pass N
un-SSA
RTL
machine code
Back End

# Issues

- Compiling is almost this simple, but there are many pitfalls.
- Each phase can encounter errors
- A phase must somehow deal with that error, so that compilation can proceed, allowing further errors in the source program to be detected.
- It is very difficult to proceed to analyze program or to correct errors.
- Language design has big impact on compiler
  - Determines what is easy and hard to compile
  - Course theme: many trade-offs in language design

# Summary

- the constitute of compiler and compiling system
- the concept of lexical analyzer, syntax analyzer, semantic analyzer, code generation, symbol table, intermediate representation, parse tree, token and so on.
- Regular expression and regular definition
- Context free grammar (CFG)