CS131: Programming Languages and Compilers

Spring 2021

Course Information

- Instructor: Fu Song
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  Email: songfu@shanghaitech.edu.cn

- Class Hours : Wednesday and Friday, 10:15--11:55
  Room 1D-106, SIST Building

- TA: 季杨彪, 杨易为, 尤存翰(volunteer)

- Office Hours: TBD

- Discussion: PIAZZA
  https://piazza.com/shanghaitech.edu.cn/spring2021/cs131

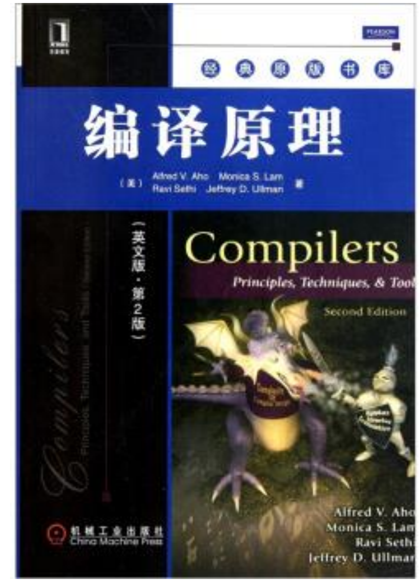
- Writing Assignments: Gradescope, tex/pdf
  https://www.gradescope.com (entry Code:D537GP)

季杨彪

杨易为

尤存翰

Preliminaries Required



Preliminaries

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

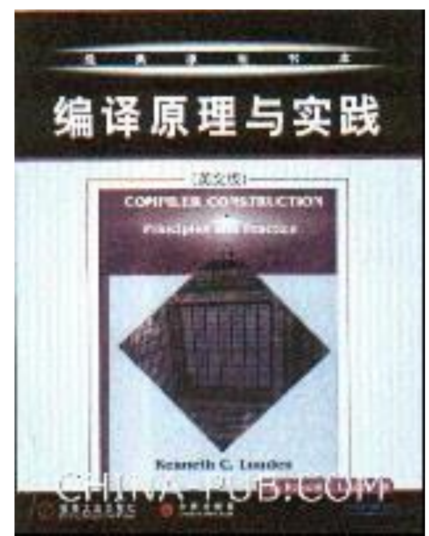
Textbook

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

Kenneth C. Louden,

Compiler Construction: Principles and Practice，2002



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

- Homework : 20% (4)
- Projects : 25% (4)
- Quiz : 10% (random)
- Midterm : 20%
- Final : 25%
- Bonus : 10%
  - optional projects (2-3 students per project)
    solution code + report + presentation + demo
  - discussion and share insight on PIAZZA

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

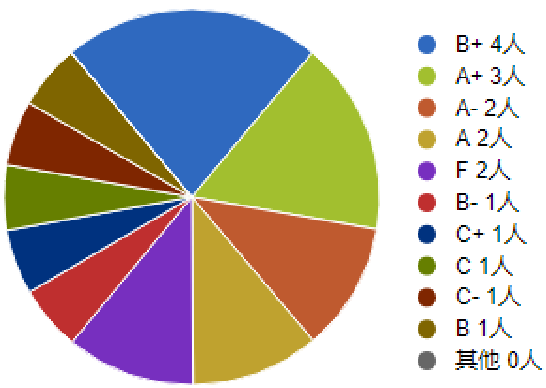
Ask before action when in doubt

Course outline

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

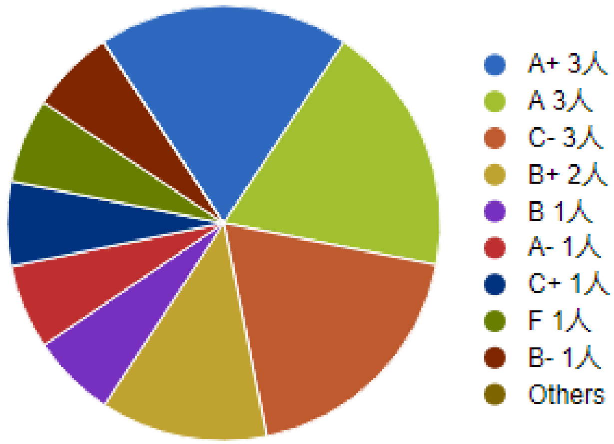
Quit or stay

Spring 2017



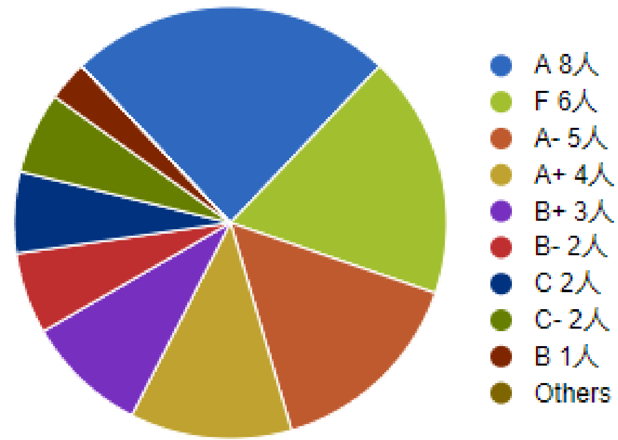
31 → 18 Students

Spring 2018

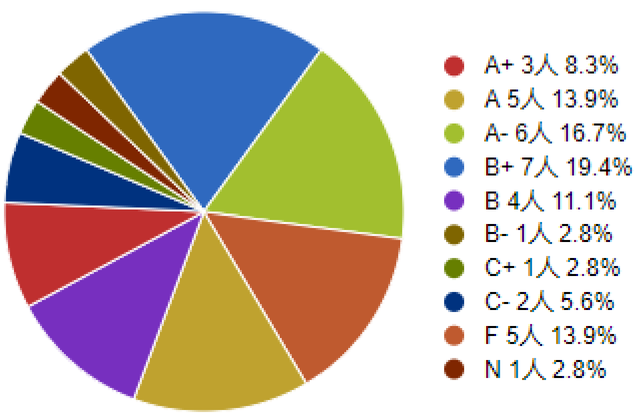


33 → 16 Students

Fall 2018



54→33 Students



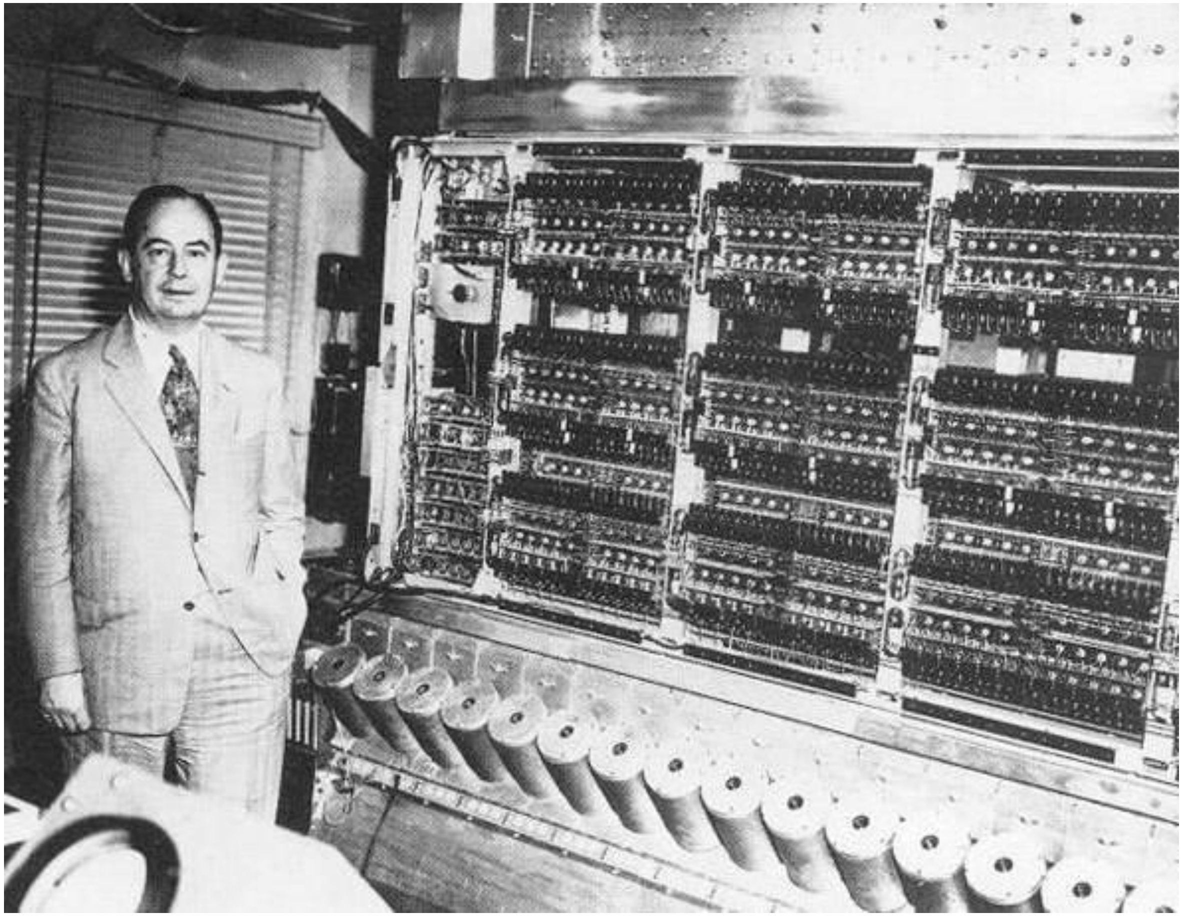
Fall 2019

57→35 Students

56→? Students

A brief history of compiler

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



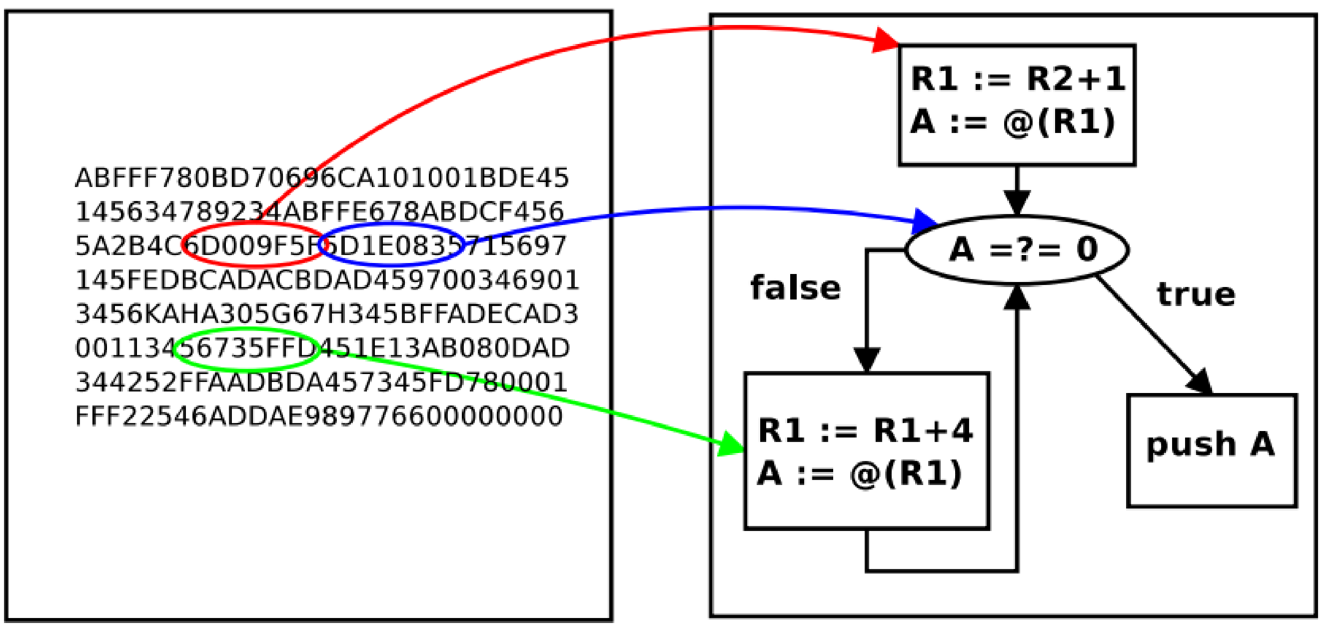
A brief history of compiler (cont.)

- 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、type 2 and type 3 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 (~ 2k pages)

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:

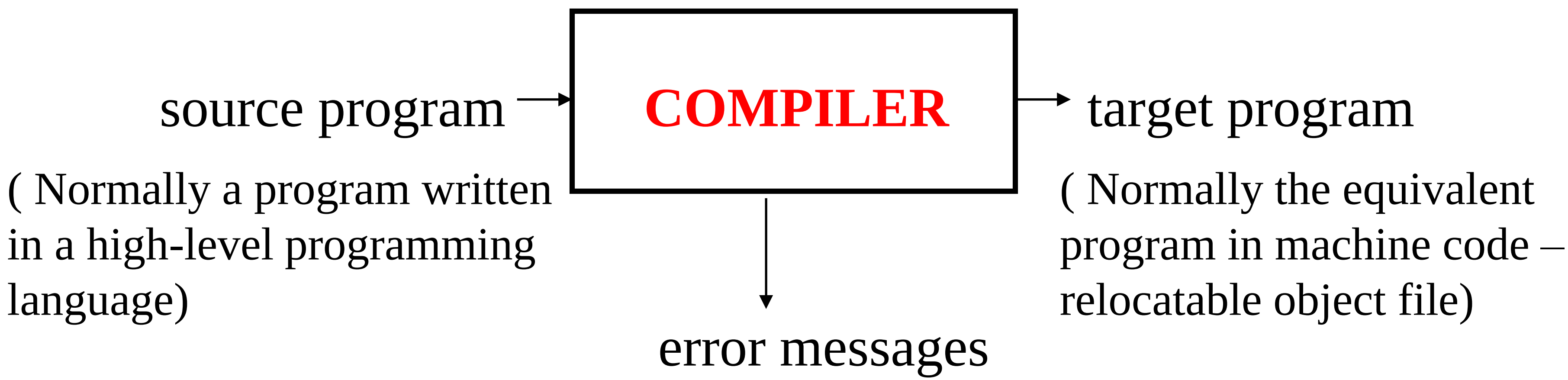
(a) application of more sophisticated algorithms for inferring and /or simplifying the information contained in a program (with the development of more sophisticated programming languages that allow this kind of analysis), e.g. memory safe language Rust

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

(c) just-in-time compiler & secure compilation

Compilers

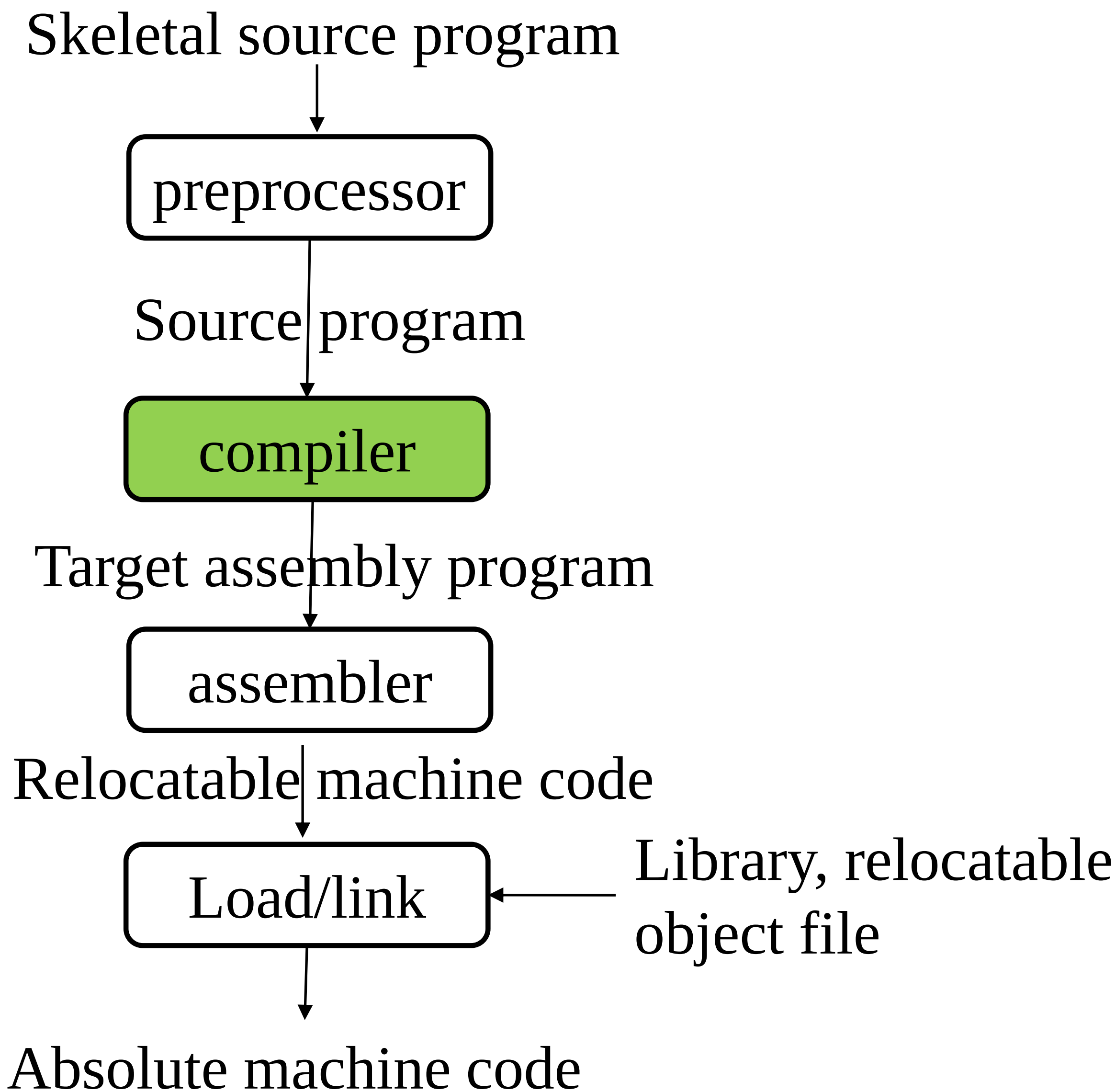
- A **compiler** is a program takes a program written in a source language and translates it into an equivalent program in a target language.



Other Applications

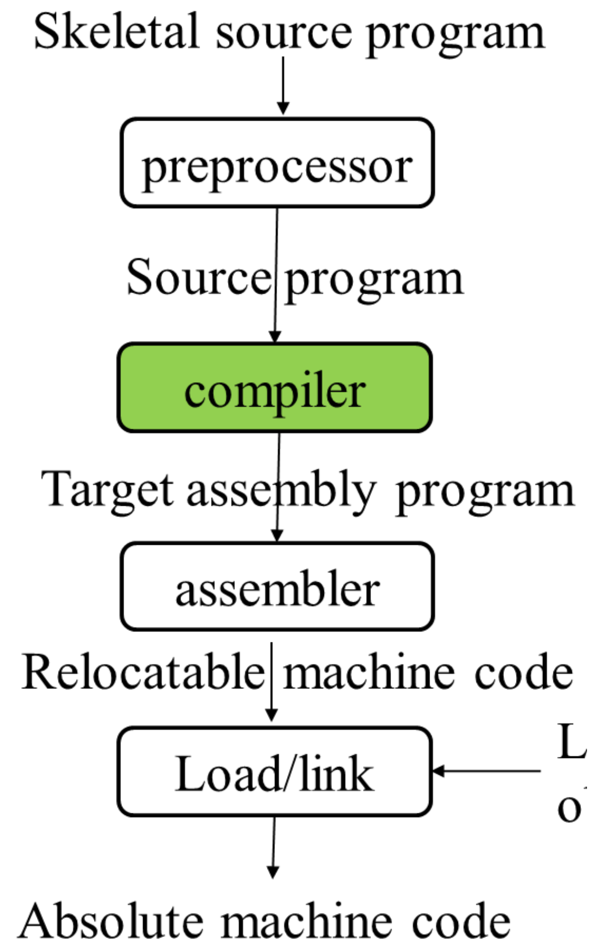
- In addition to the development of a compiler, the techniques used in compiler design can be applicable to many problems in computer science.
  - Techniques used in a lexical analyzer can be used in text editors, information retrieval system, and pattern recognition programs.
  - Techniques used in 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:
  1. Collects code separately compiled or assembled in different object files into a file.
  2. Connects the code for standard library functions.
  3. 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**

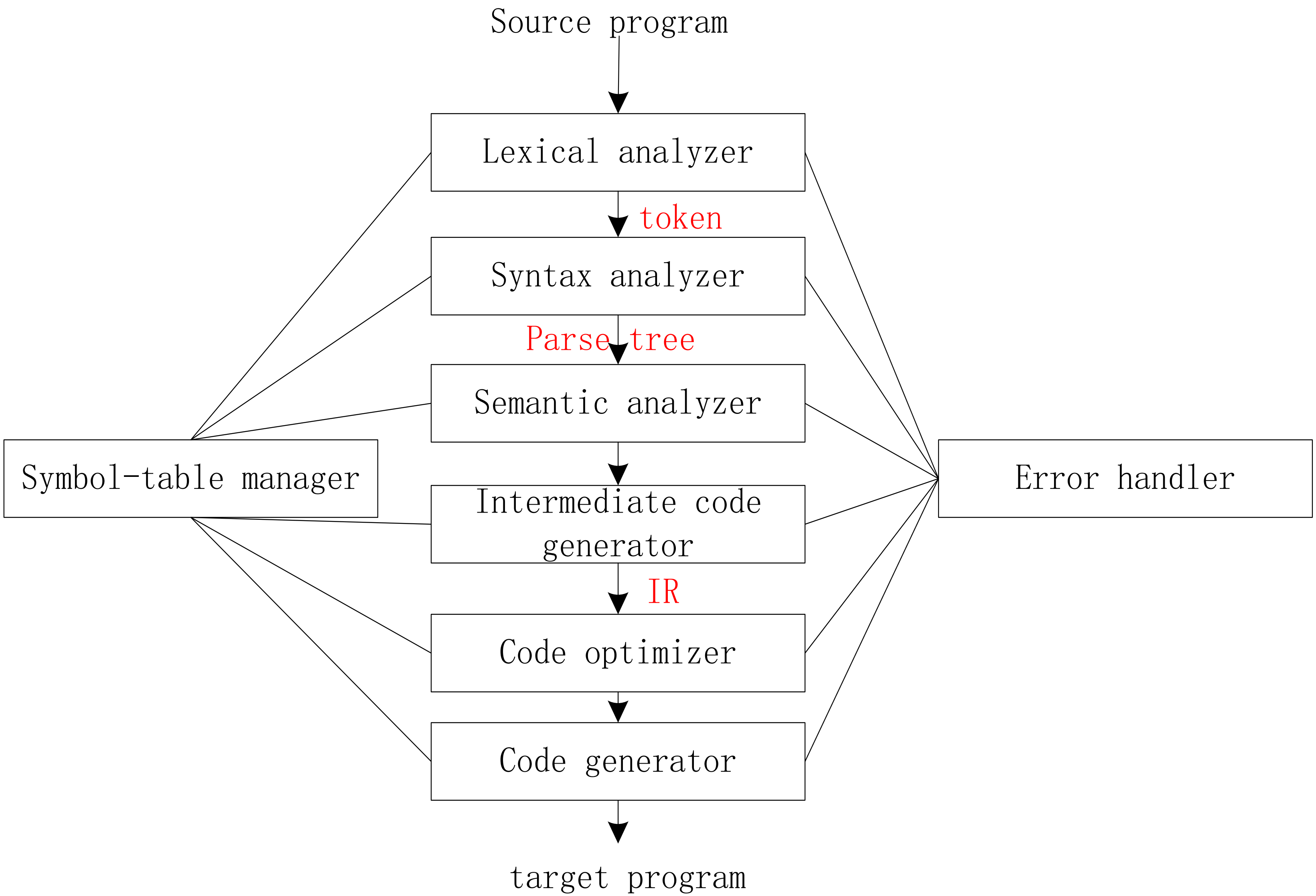
- In analysis phase, an intermediate representation is created from the given source program.
  - Lexical Analyzer, Syntax Analyzer and Semantic Analyzer are the parts of this phase.
- In synthesis phase, the equivalent target program is created from this intermediate representation.
  - Intermediate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

The Phases of a Compiler

$$\underbrace{\textit{Source Program} \rightarrow \text{Lexical Analyzer} \rightarrow \text{Syntax Analyzer} \rightarrow \text{Semantic Analyzer}}_{\textbf{Analysis}} \rightarrow \underbrace{\text{Intermediate Code Generator} \rightarrow \text{Code Optimizer} \rightarrow \text{Code Generator} \rightarrow \textit{Target Program}}_{\textbf{Synthesis}}$$

- 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.

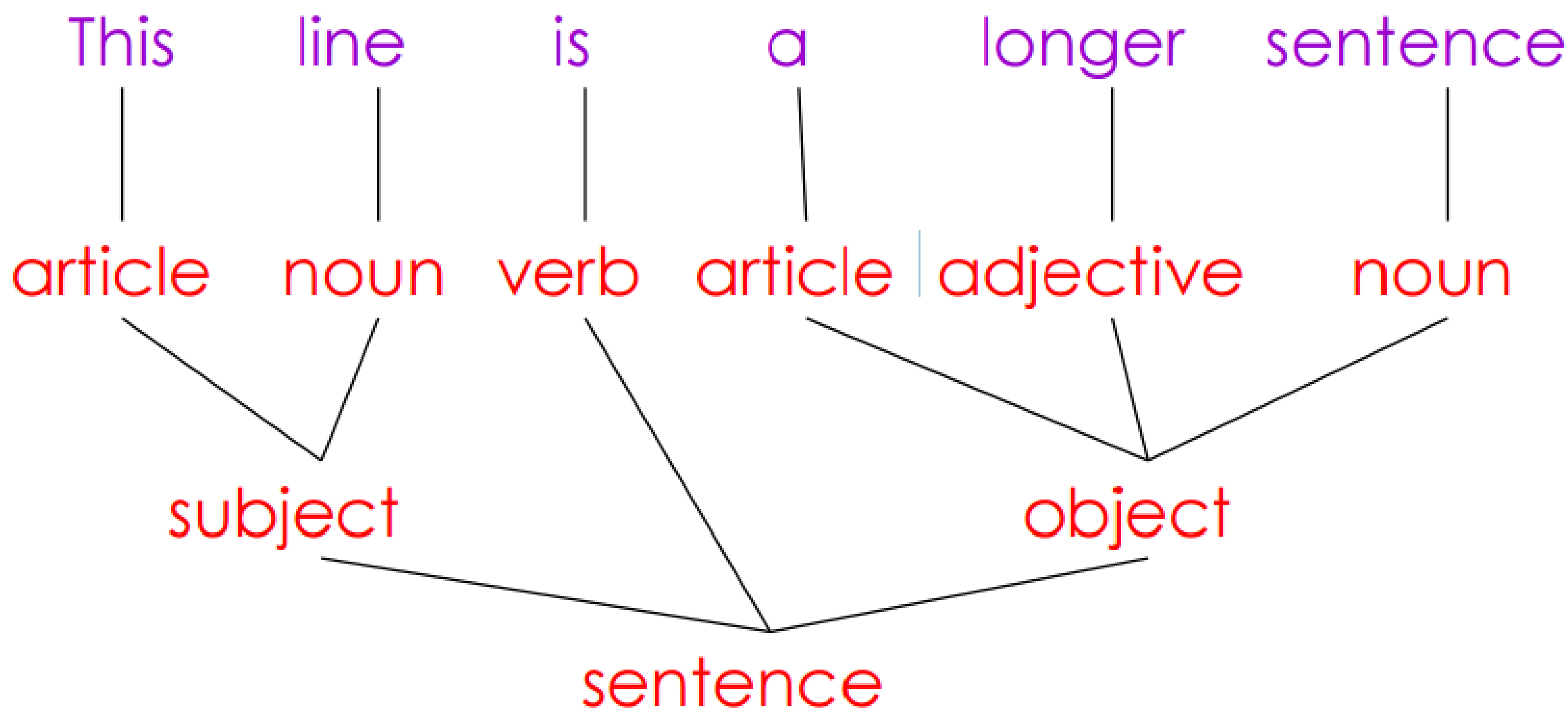
Eg. Identifier: [a-zA-Z] [a-zA-Z0-9]*

Good Id: x, y, x1

Bad Id: 1x

Syntax Analyzer

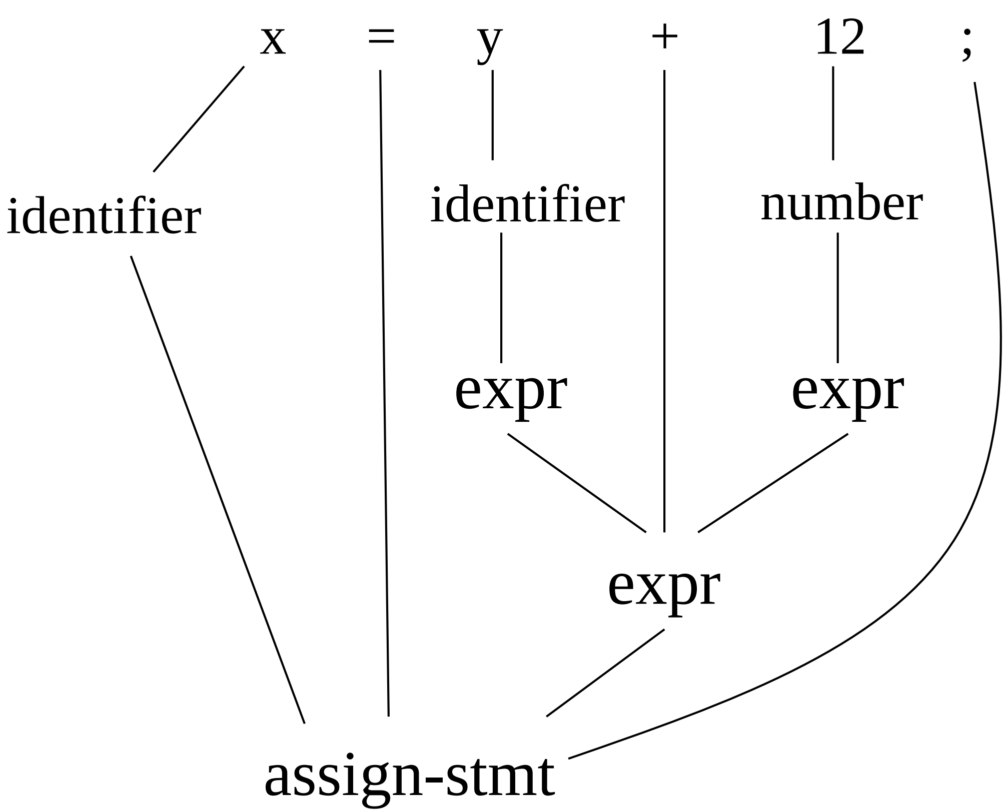
- Lexical Analyzer provides recognized words
- The next step is to understand sentence structure



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 (i.e., tokens) are at leaves.
- All inner nodes are non-terminals (grammar variables) in a context free grammar.

Syntax Analyzer (cont.)

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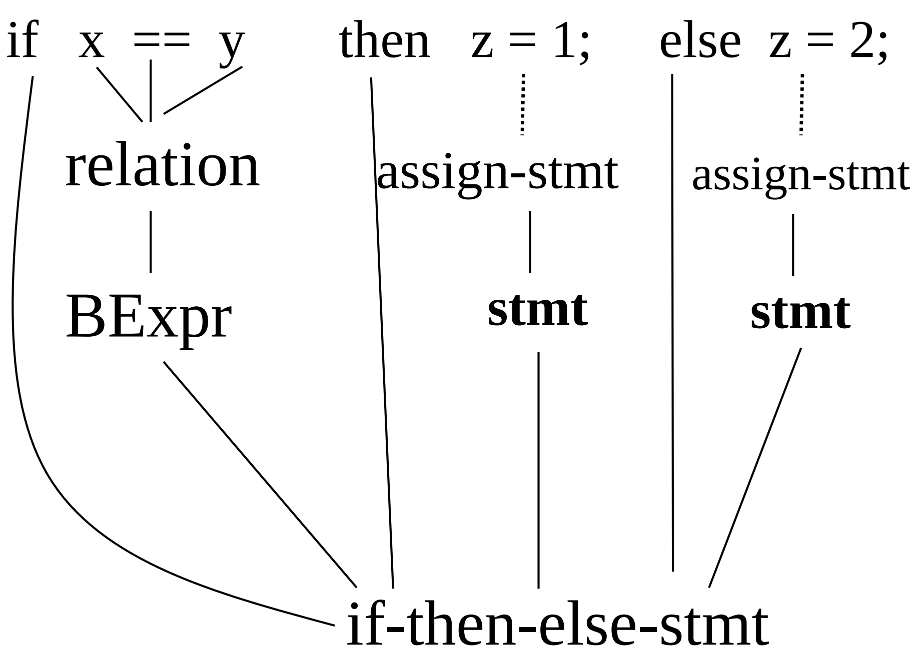

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Syntax Analyzer (cont.)

- 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.

Why not put them together in one analyzer?

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**).

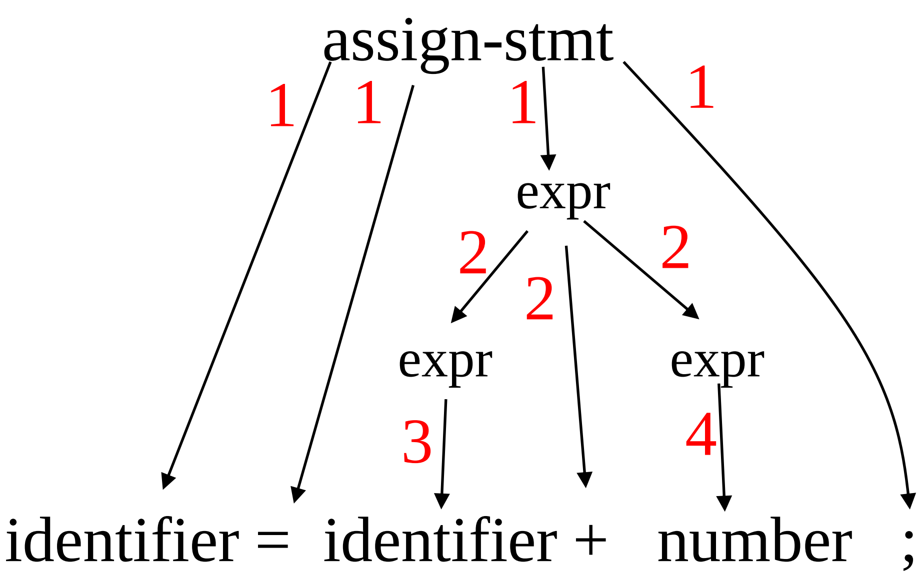
    （**L**-left to right; **L**-leftmost derivation）

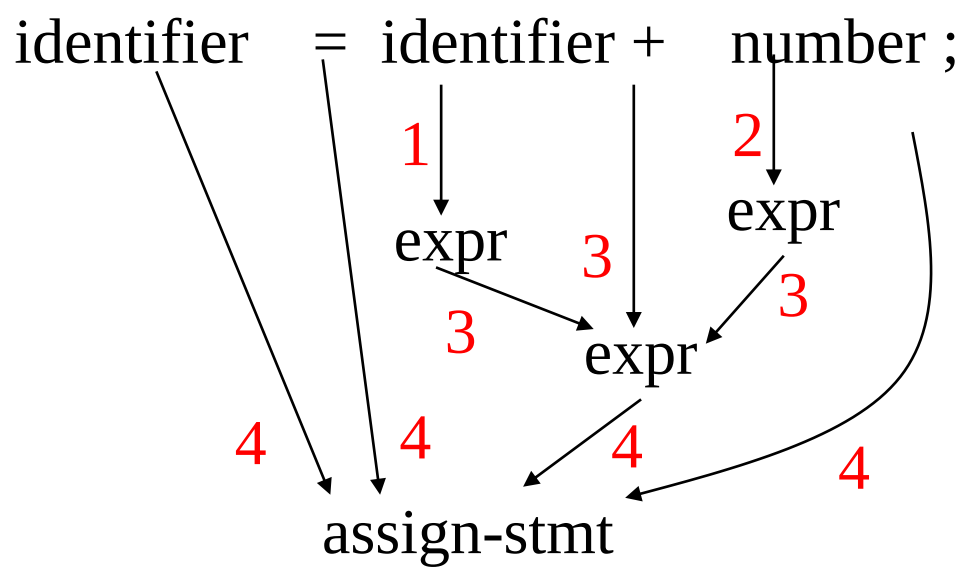
Parsing Techniques (cont.)

- 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.)

- 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
ADD  temp2,  temp1,  #1
MOV id1,  temp2
```

;*Intermediate Codes (Quadraples or three address code)*

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)

```
MOV    R1, id2
MULT   R1, id3
ADD    R1, #1
MOV    id1, R1
```

ARM:

```
LDR    R1, [id2]
LDR    R2, [id3]
MULT   R3, R1, R2
ADD    R1, R3, #1
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

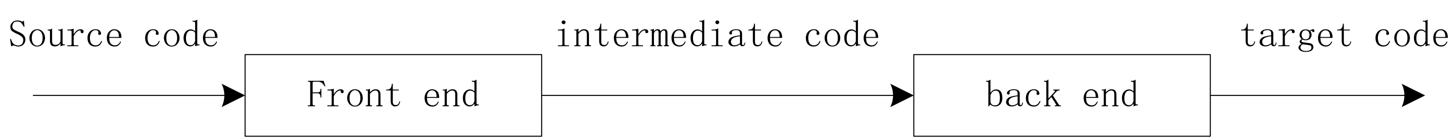


Fig. a. 1. 1

Symbol table

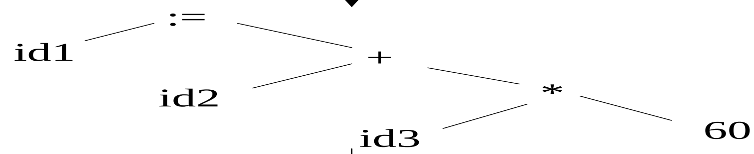
position	...
initial	...
rate	...

position := initial + rate * 60

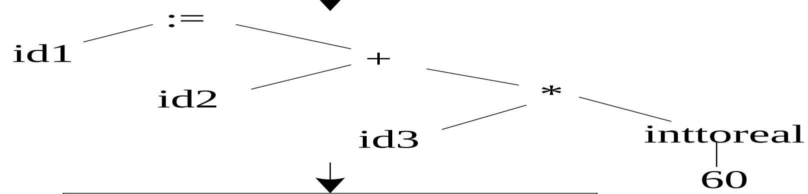
Lexical analyzer

id1 := id2 + id3 * 60

syntax analyzer



semantic analyzer



Intermediate code generator

```
Temp1 := inttoreal(60)
temp2 := id3 * temp1
temp3 := id2 + temp2
id1 := temp3
```

Code optimizer

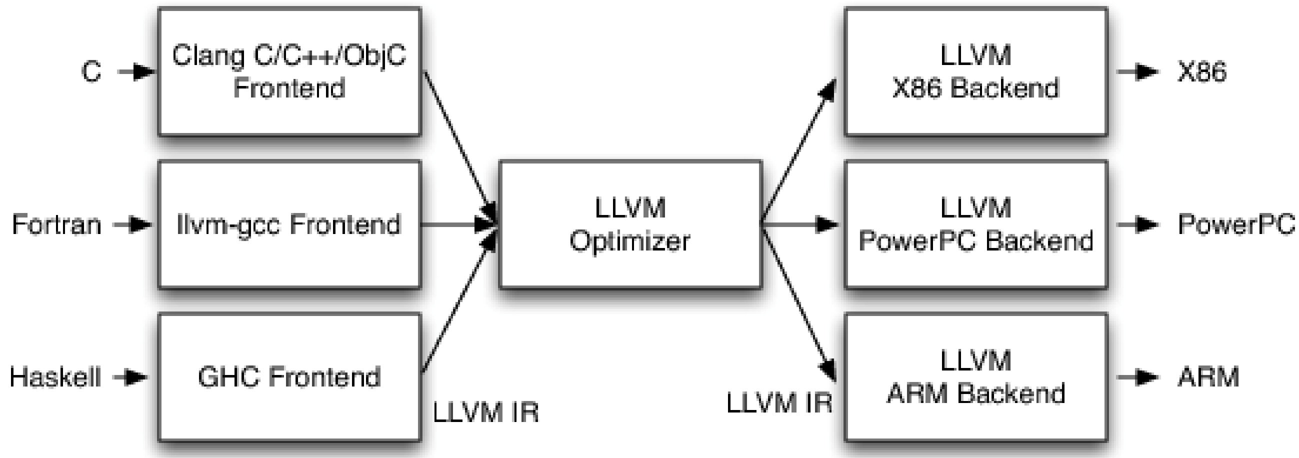
```
temp1 := id3 * 60.0
id1 := id2 + temp1
```

Code generator

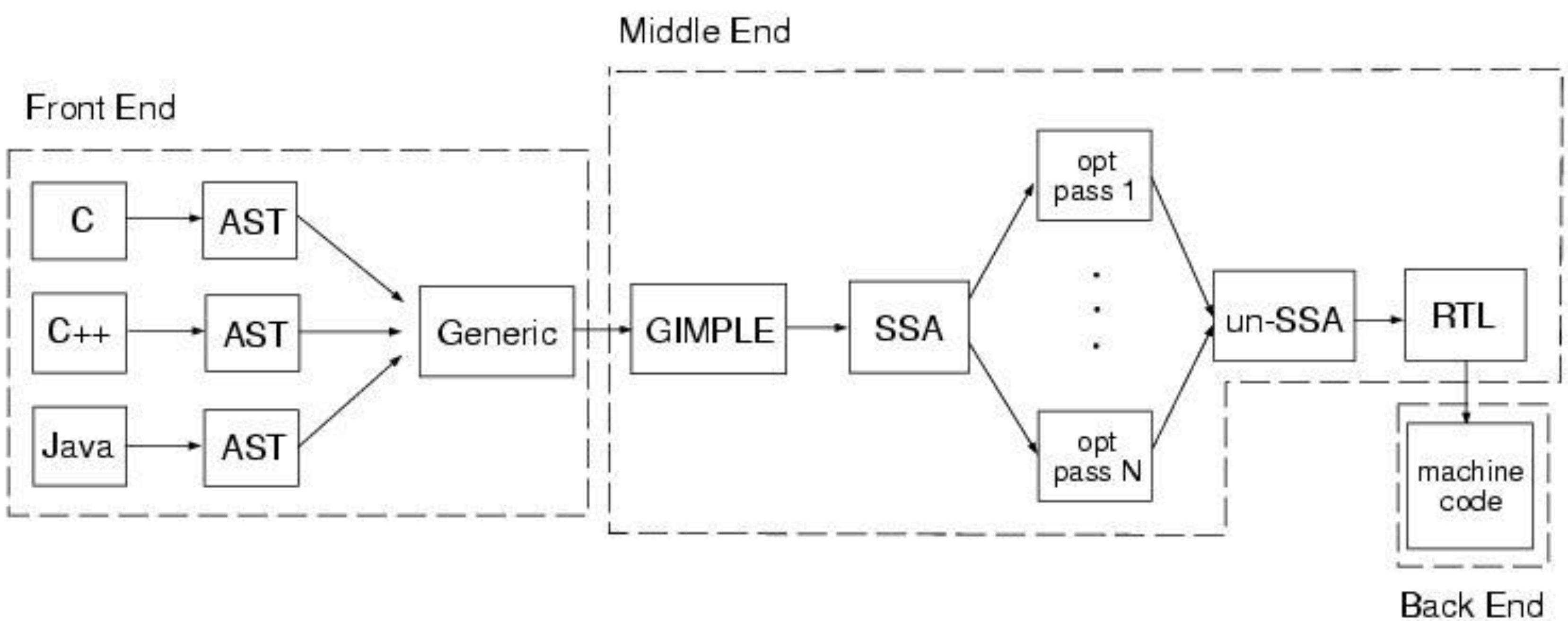
```
MOVF R2, id3
MULF R2, #60.0
MOVF R1, id2
ADDF R1, R2
MOVF id1, R1
```

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

LLVM and GCC

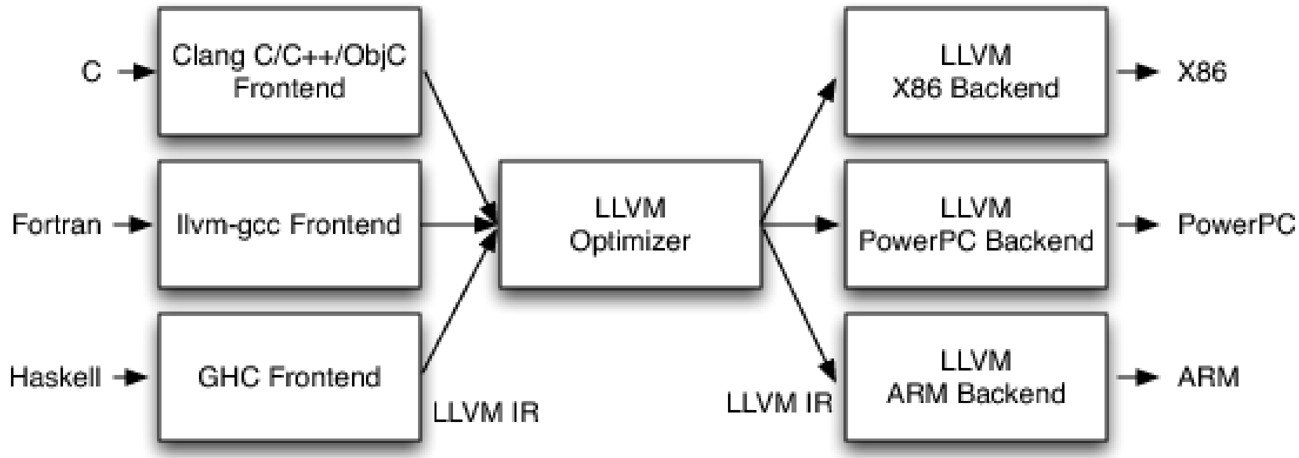


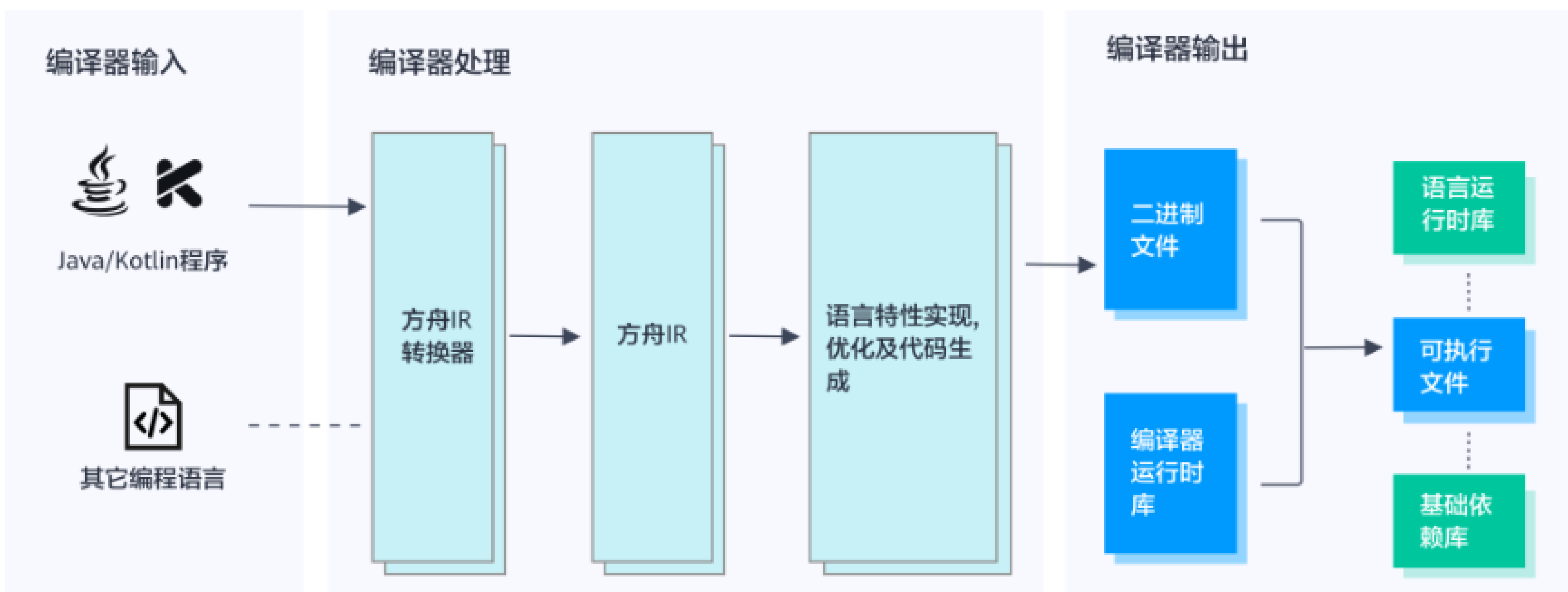
C
Fortran
Haskell
Clang C/C++/ObjC Frontend
llvm-gcc Frontend
GHC Frontend
LLVM IR
LLVM Optimizer
LLVM IR
LLVM X86 Backend
LLVM PowerPC Backend
LLVM ARM Backend
X86
PowerPC
ARM



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

LLVM and Ark


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


编译器输入
Java/Kotlin程序
其它编程语言
编译器处理
方舟IR转换器
方舟IR
语言特性实现,优化及代码生成
编译器输出
二进制文件
编译器运行时库
语言运行时库
可执行文件
基础依赖库

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)