Compiler Design
Unit 1

DR.PARKAVI.A,

ASSOCIATE PROFESSOR

CSE DEPARTMENT

RIT

Course Contents

- Lexical analysis (Scanning)
- Syntax Analysis (Parsing)
- Syntax Directed Translation
- Intermediate Code Generation
- Run-time environments
- Code Generation
- Machine Independent Optimization

Grading policy

- CIE
- 20 mark component
  - Technical paper writing
    - Form team by this week end
    - Download recent compiler research journal papers
      - Elsevier
      - IEEE
      - Springer
    - Literature review – 10 marks - Feb month mid
    - Report writing – 10 marks – March mid

Compiler learning

- Isn't it an old discipline?
  - Yes, it is a well-established discipline
  - Algorithms, methods and techniques are researched and developed in early stages of computer science growth
  - There are many compilers around and many tools to generate them automatically
- So, why we need to learn it?
  - Although you may never write a full compiler
  - But the techniques we learn is useful in many tasks like writing an interpreter for a scripting language, validation checking for forms and so on

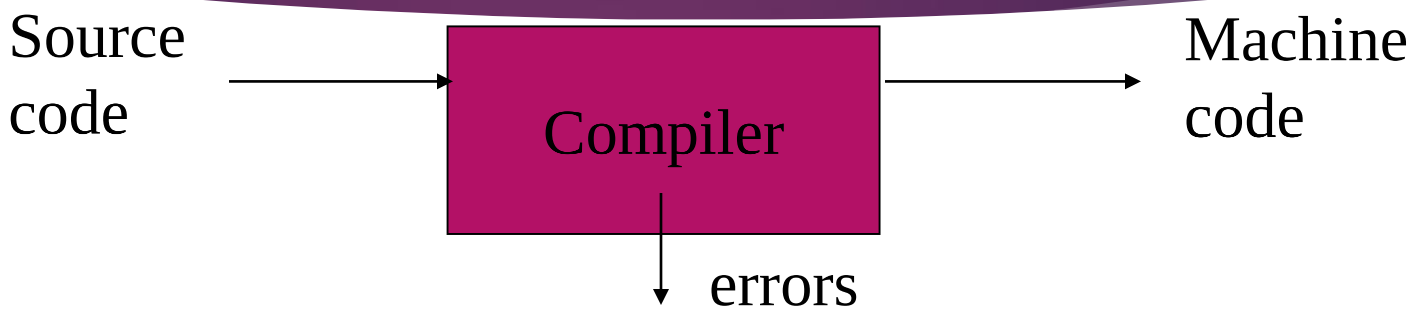
Terminology

- Compiler:
  - a program that translates an *executable* program in one language into an *executable* program in another language
  - we expect the program produced by the compiler to be better, in some way, than the original
- Interpreter:
  - a program that reads an *executable* program and produces the results of running that program
  - usually, this involves executing the source program in some fashion
- Our course is mainly about compilers but many of the same issues arise in interpreters

Disciplines involved

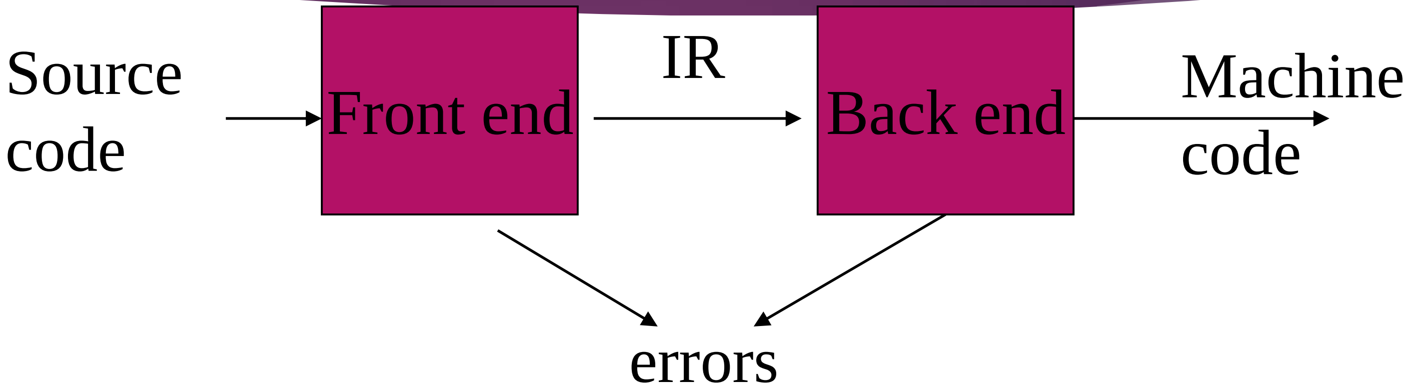
- Algorithms
- Languages and machines
- Operating systems
- Computer architectures

Abstract view



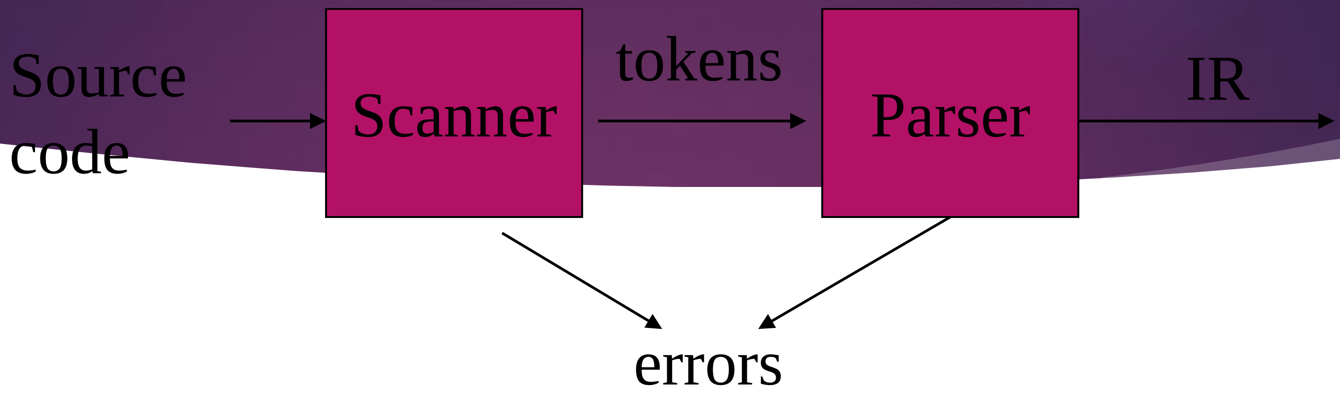
- Recognizes legal (and illegal) programs
- Generate correct code
- Manage storage of all variables and code
- Agreement on format for object (or assembly) code

Front-end, Back-end division



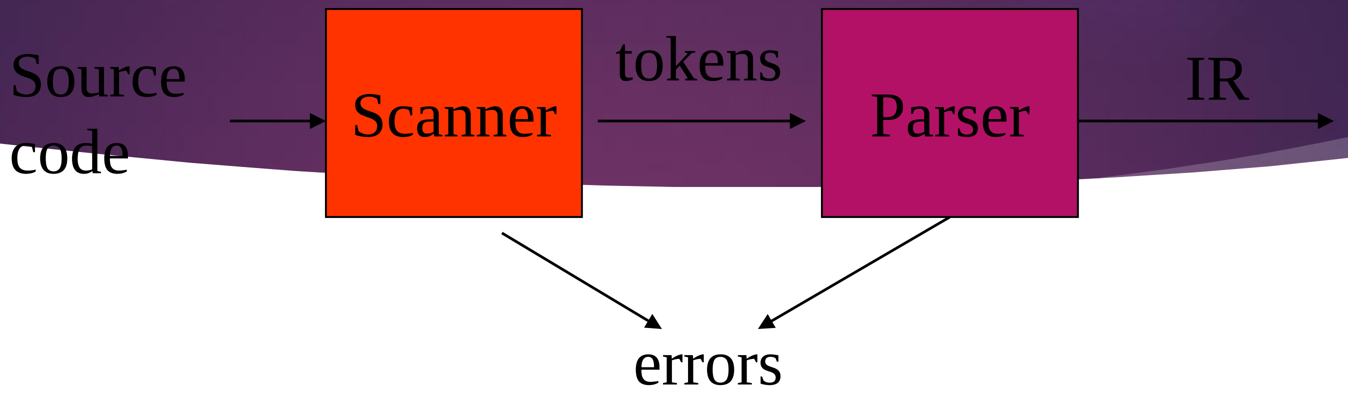
- Front end maps legal code into IR
- Back end maps IR onto target machine
- Simplify retargeting
- Allows multiple front ends
- Multiple passes -> better code

Front end



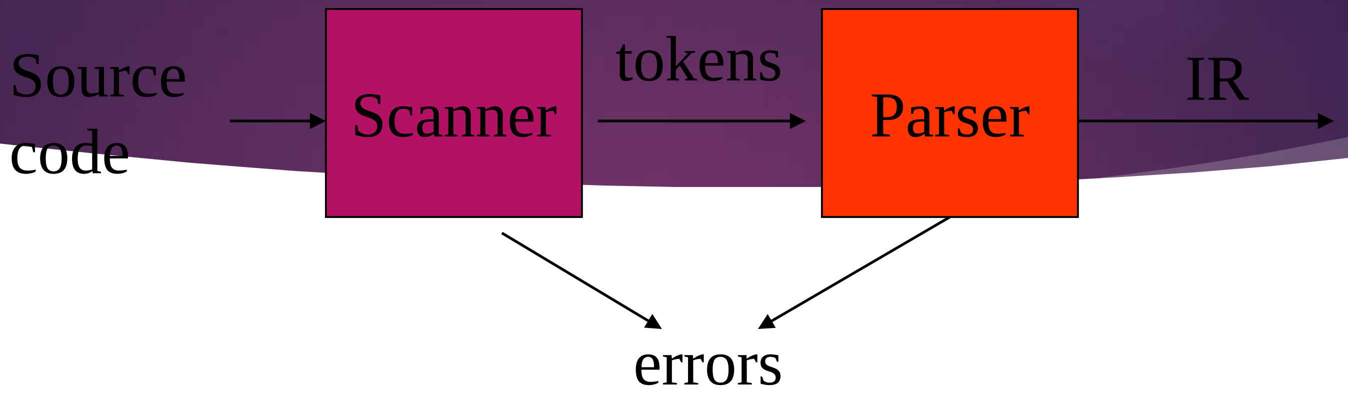
- Recognize legal code
- Report errors
- Produce IR
- Preliminary storage maps

Front end



- Scanner:
  - Maps characters into tokens – the basic unit of syntax
    - x = x + y becomes <id, x> = <id, x> + <id, y>
  - Typical tokens: number, id, +, -, *, /, do, end
  - Eliminate white space (tabs, blanks, comments)
- A key issue is speed so instead of using a tool like LEX it sometimes needed to write your own scanner

Front end



- Parser:
  - Recognize context-free syntax
  - Guide context-sensitive analysis
  - Construct IR
  - Produce meaningful error messages
  - Attempt error correction
- There are parser generators like YACC which automates much of the work

Front end

- Context free grammars are used to represent programming language syntaxes:

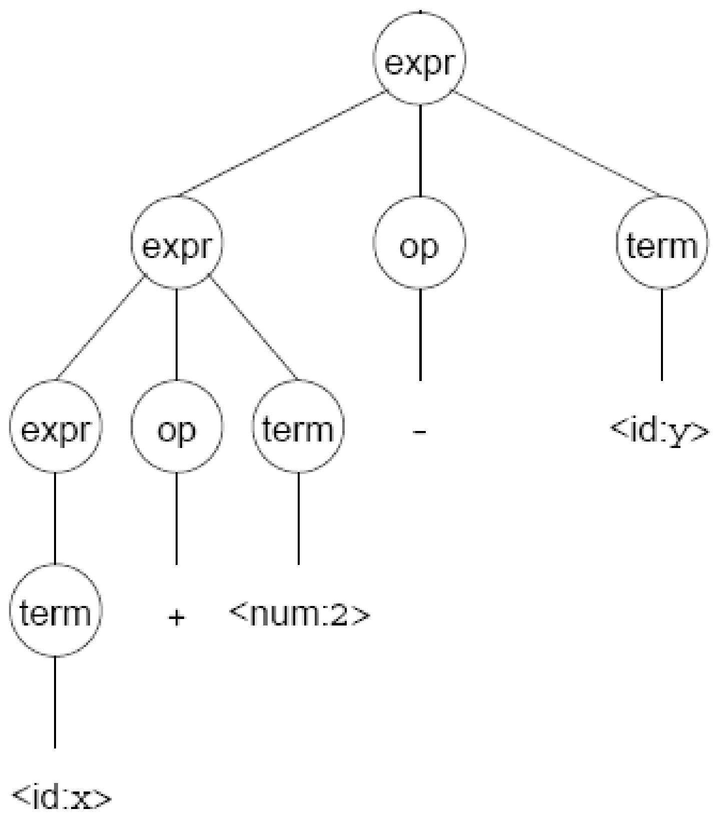
<expr> ::= <expr> <op> <term> | <term>

<term> ::= <number> | <id>

<op> ::= + | -

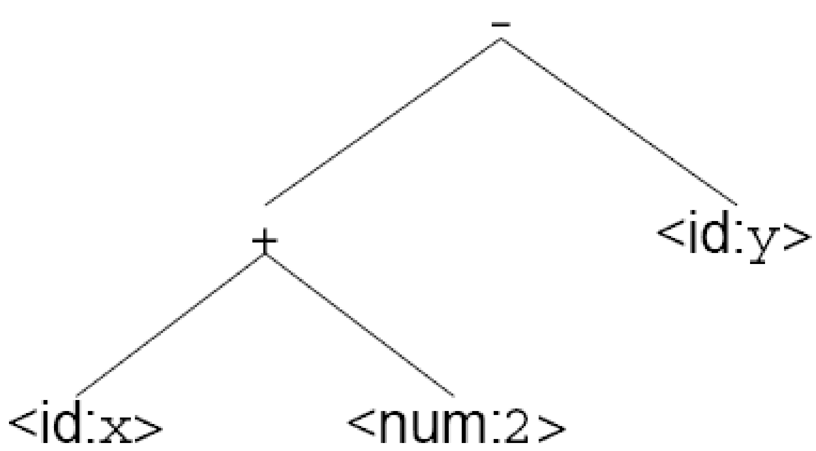
Front end

- A parser tries to map a program to the syntactic elements defined in the grammar
- A parse can be represented by a tree called a parse or syntax tree

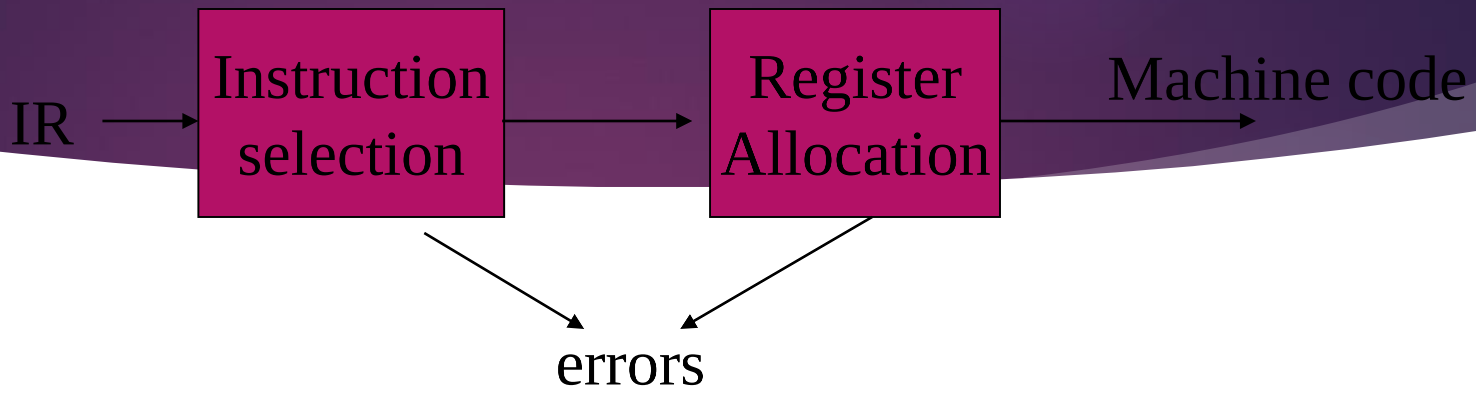


Front end

- A parse tree can be represented more compactly referred to as Abstract Syntax Tree (AST)
- AST is often used as IR between front end and back end

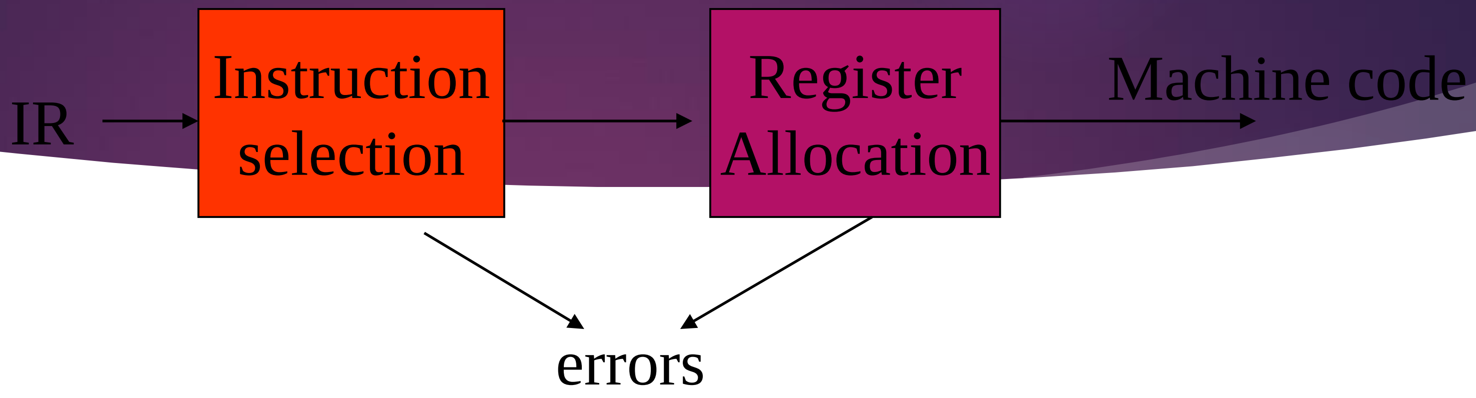


Back end



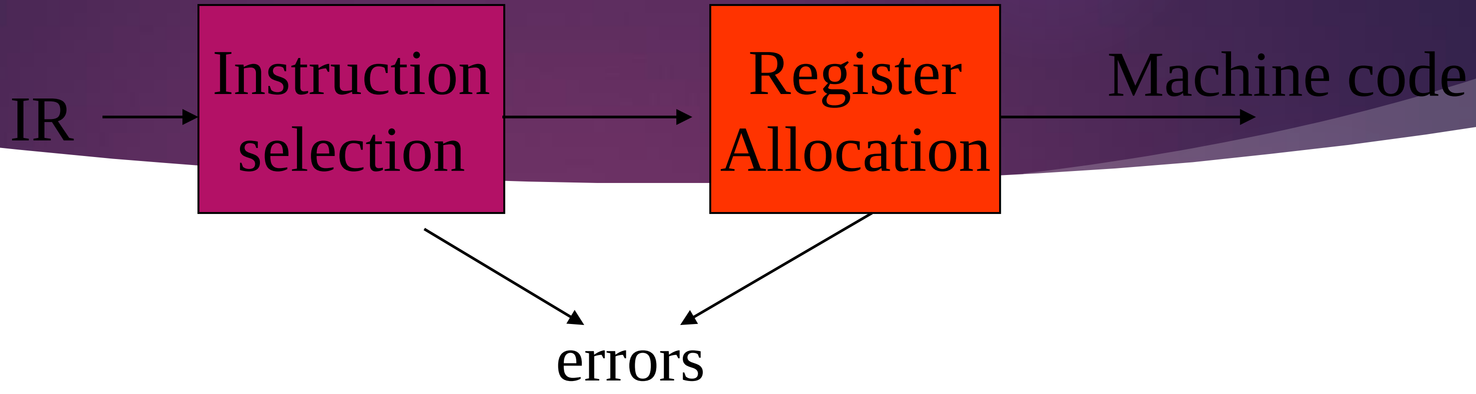
- Translate IR into target machine code
- Choose instructions for each IR operation
- Decide what to keep in registers at each point
- Ensure conformance with system interfaces

Back end



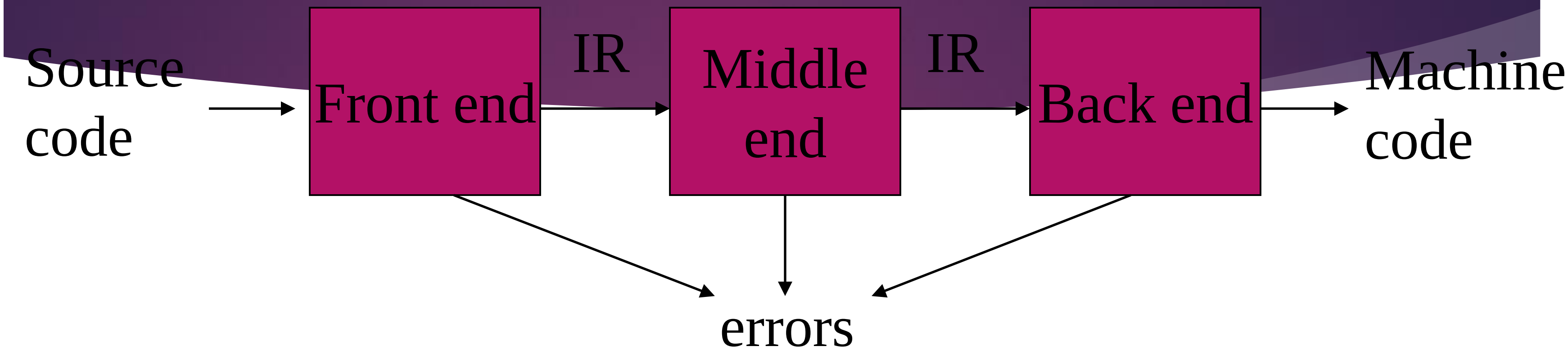
- Produce compact fast code
- Use available addressing modes

Back end



- Have a value in a register when used
- Limited resources
- Optimal allocation is difficult

Traditional three pass compiler



- Code improvement analyzes and change IR
- Goal is to reduce runtime

Middle end (optimizer)

- Modern optimizers are usually built as a set of passes
- Typical passes
  - Constant propagation
  - Common sub-expression elimination
  - Redundant store elimination
  - Dead code elimination

What Do Compilers Do

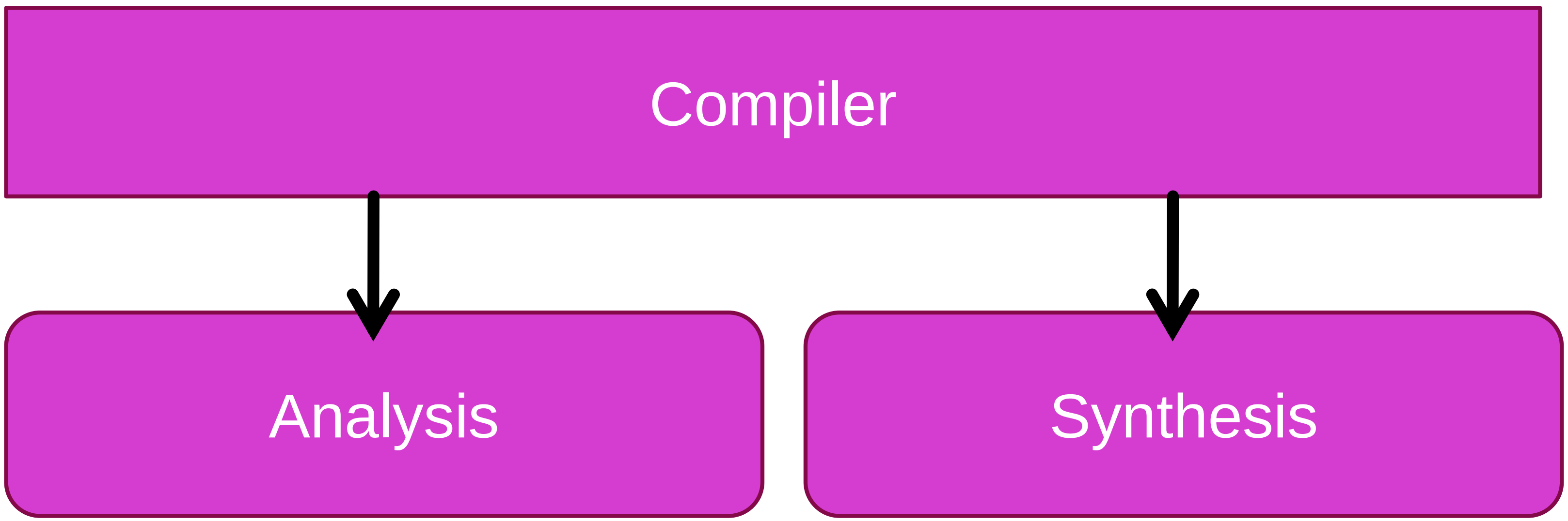
- A compiler acts as a translator, transforming human-oriented programming languages into computer-oriented machine languages.
- Ignore machine-dependent details for programmer

Programming Language (Source) → Compiler → Machine Language (Target)

What Do Compilers Do

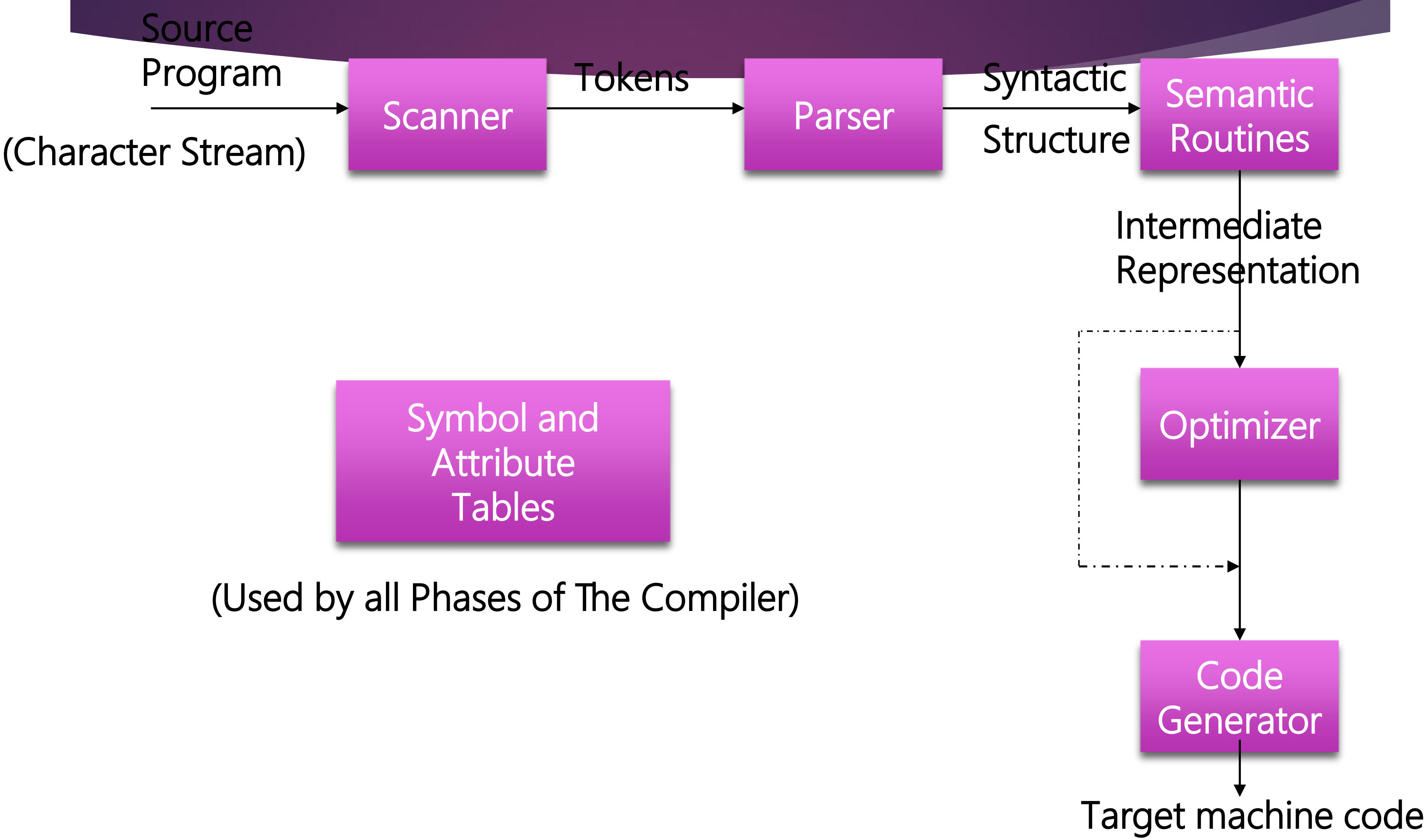
- Another way that compilers
  differ from one another is in the format of the target machine
  code they generate:
  - Assembly or other source format
  - Relocatable binary
    - Relative address
    - A linkage step is required
  - Absolute binary
    - Absolute address
    - Can be executed directly

The Structure of a Compiler

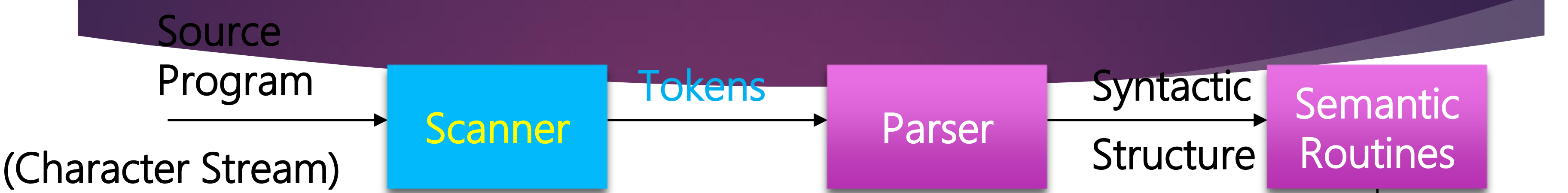


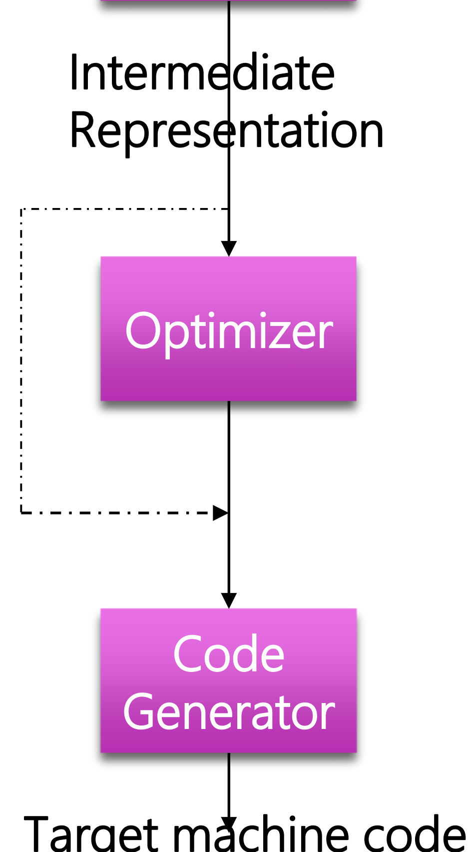
- ***Analysis*** of the source program
- ***Synthesis*** of a machine-language program

The Structure of a Compiler



The Structure of a Compiler



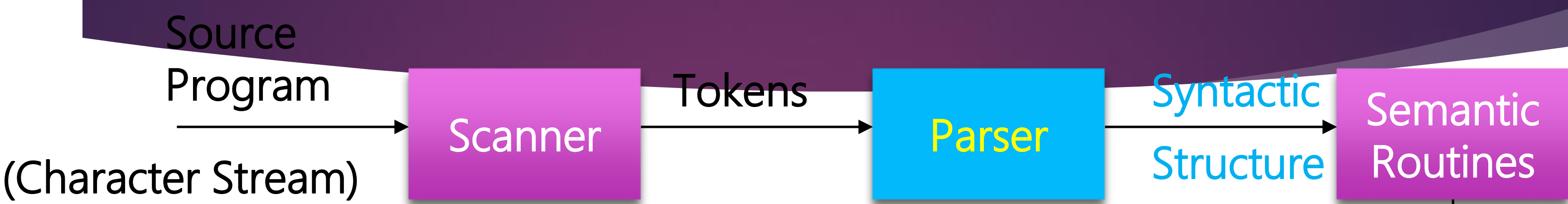


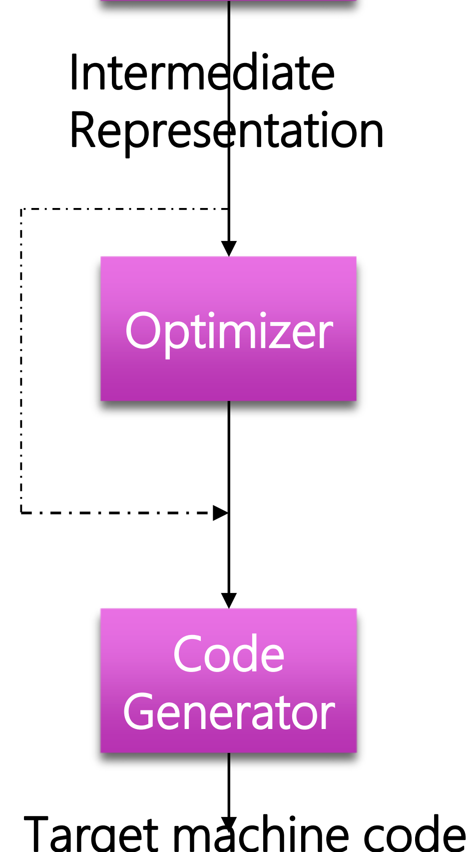
Scanner

- The scanner begins the analysis of the source program by reading the input, character by character, and grouping characters into individual words and symbols (tokens)

- RE (Regular expression)
- NFA (Non-deterministic Finite Automata)
- DFA (Deterministic Finite Automata)
- LEX

The Structure of a Compiler



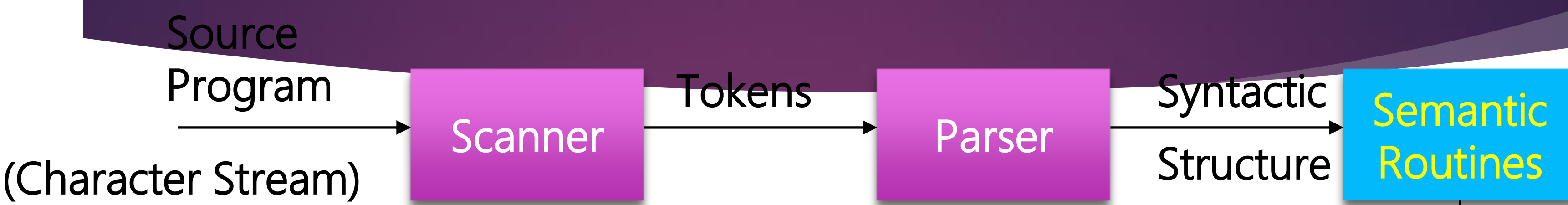


Parser

- Given a formal syntax specification (typically as a context-free grammar [CFG]), the parse reads tokens and groups them into units as specified by the productions of the CFG being used.
- As syntactic structure is recognized, the parser either calls corresponding semantic routines directly or builds a syntax tree.

- CFG (Context-Free Grammar)
- BNF (Backus-Naur Form)
- GAA (Grammar Analysis Algorithms)
- LL, LR, SLR, LALR Parsers
- YACC

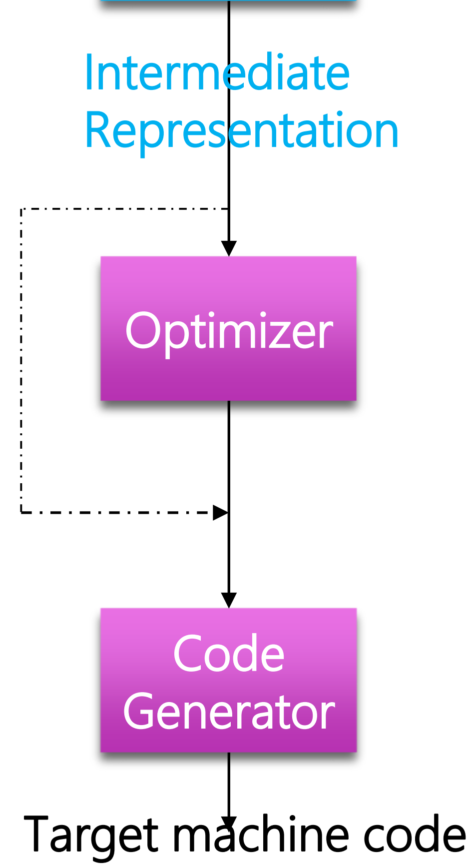
The Structure of a Compiler



Semantic Routines

- Perform two functions
  - Check the static semantics of each construct
  - Do the actual translation
- The heart of a compiler

- Syntax Directed Translation
- Semantic Processing Techniques
- IR (Intermediate Representation)



The Structure of a Compiler

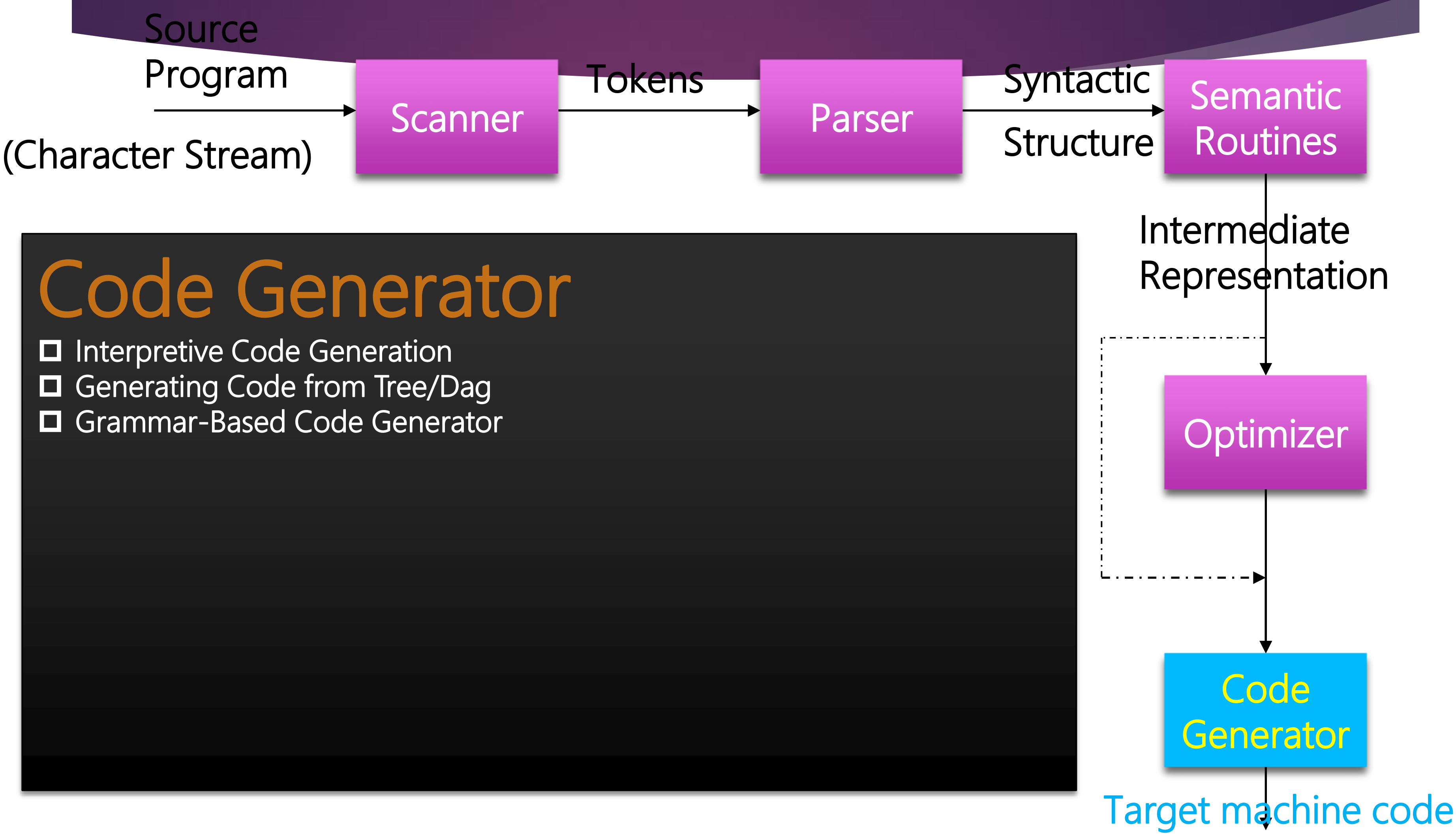
Source Program (Character Stream) → Scanner → Tokens → Parser → Syntactic Structure → Semantic Routines → Intermediate Representation → Optimizer → Code Generator → Target machine code

Optimizer

- ➢ The IR code generated by the semantic routines is analyzed and transformed into functionally equivalent but improved IR code
- ➢ This phase can be very complex and slow
- ➢ Peephole optimization
- ➢ loop optimization, register allocation, code scheduling

- ❑ Register and Temporary Management
- ❑ Peephole Optimization

The Structure of a Compiler



Code Generator

- Interpretive Code Generation
- Generating Code from Tree/Dag
- Grammar-Based Code Generator

The Structure of a Compiler

SYMBOL TABLE

1	position	...
2	initial	...
3	rate	...
4		

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

Scanner
[Lexical Analyzer]

Tokens

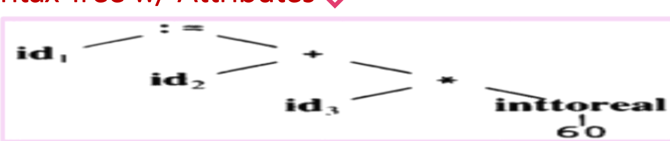
id_1 := id_2 + id_3 * 60

Parser
[Syntax Analyzer]

Parse tree

Semantic Process
[Semantic analyzer]

Abstract Syntax Tree w/ Attributes



Code Generator
[Intermediate Code Generator]

Non-optimized Intermediate Code

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

Code Optimizer

Optimized Intermediate Code

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

Code Optimizer

Target machine code

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

The Structure of a Compiler

- ✓ Compiler writing tools
  - Compiler generators or compiler-compilers
    - E.g. scanner and parser generators
    - Examples : Yacc, Lex

The Syntax and Semantics of Programming Language

- A programming language must include the specification of syntax (structure) and semantics (meaning).
- Syntax typically means the context-free syntax because of the almost universal use of context-free-grammar (CFGs)
- Ex.
  - a = b + c is syntactically legal
  - b + c = a is illegal

The Syntax and Semantics of Programming Language

- The semantics of a programming language are commonly divided into two classes:
  - Static semantics
    - Semantics rules that can be checked at compiled time.
    - Ex. The type and number of a function’s arguments
  - Runtime semantics
    - Semantics rules that can be checked only at run time

Compiler Design and Programming Language Design

- An interesting aspect is how programming language design and compiler design influence one another.
- Programming languages that are easy to compile have many advantages

Computer Architecture and Compiler Design

- Compilers should exploit the hardware-specific feature and computing capability to optimize code.
- The problems encountered in modern computing platforms:
  - Instruction sets for some popular architectures are highly nonuniform.
  - High-level programming language operations are not always easy to support.
    - Ex. exceptions, threads, dynamic heap access …
  - Exploiting architectural features such as cache, distributed processors and memory
  - Effective use of a large number of processors

Compiler Design Considerations

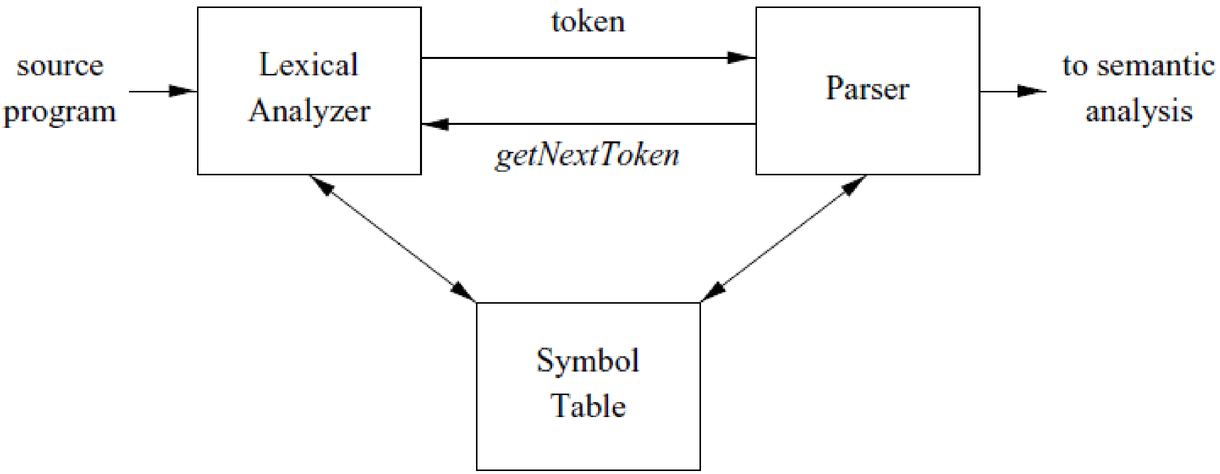
- Debugging Compilers
  - Designed to aid in the development and debugging of programs.
- Optimizing Compilers
  - Designed to produce efficient target code
- Retargetable Compilers
  - A compiler whose target architecture can be changed without its machine-independent components having to be rewritten.

Tools

- Parser generator
  - Yacc
- Scanner generators
  - Lex
- SDT
  - ICG
- Code generator generator
- Data flow analysis engines
  - Code optimization
- Compiler construction toolkits

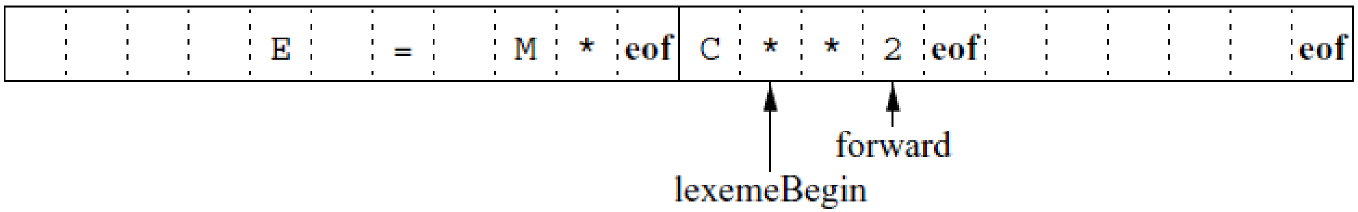
Role of Lexical analysis

- Src program
- Lexical analyzer
  - Token
- Parser
  - Get next token
- Symbol table
- To semantic analyzer



Lexical analysis vs parsing

- Removal of white spaces
- Buffering
- Tokens
- Patterns
- Lexemes



Lookahead buffering

```
switch ( *forward++ ) {
    case eof:
        if (forward is at end of first buffer ) {
            reload second buffer;
            forward = beginning of second buffer;
        }
        else if (forward is at end of second buffer ) {
            reload first buffer;
            forward = beginning of first buffer;
        }
        else /* eof within a buffer marks the end of input */
            terminate lexical analysis;
        break;
    Cases for the other characters
}
```

Attributes for tokens

- Id
- Refers to symtab

Lexical errors

- Panic mode
- Error recovery actions
  - Delete
  - Insert
  - Replace
  - Transpose
  - Examples

Input buffering

- Buffer pairs
- Eof
- Sentinels

Specifications of tokens

- Alphabet
- Binary
- Look ahead code with sentinels
- String
  - Prefix
  - Suffix
  - Substring
  - Proper (ones of above)
  - Subsequence
  - concatenation
- Empty string
- Empty set
- Language

Operations on languages

- Kleene closure
  - L*
- L^+
- L^0
- Union
- Concatenation
- Examples
  - L
  - D
  - LUD
  - L^4
  - L.(LUD)*

RE

Example:

- Letter_(letter_|digit)*
- 2 basic rules
  - Empty set
  - L(a)
- Induction
  - L(r), L(s)
  - (r)|(s)
  - r.s
  - (r)*
  - (r)

Precedence

- Left associative
- *
- .
- |

Example

Example

- Alphabet = {a,b}
- Write example RE

Regular set

- Language defined by RE
- Algebraic laws
  - Commutative over |
  - Associative over .
  - Concatenation associative
  - Concatenation distributive
  - Identity over epsilon and kleene closure

Extensions of RE

- One or more instances
- Zero or more instances
- Character classes

Regular definition

- D1→r1
- D2→r2
- D3→r3
- Di is symbol
- Ri is RE
- Examples
  - Letter → a|b|c….z
  - Digit →0|1|…|9
  - Id→ letter_(letter_|digit)*

Problems

- Write regular definition for Unsigned numbers
- Example inputs
  - 8456
  - 2.345
  - 345.56E-56

Extension of RE

- (L(r))+
- Epcilon
- L(r)
- [a1,a2,….an]
- A1|a2|….an

Recognition of Tokens

$$
\begin{array}{lcl}
stmt & \rightarrow & \textbf{if } expr \textbf{ then } stmt \\
 & | & \textbf{if } expr \textbf{ then } stmt \textbf{ else } stmt \\
 & | & \epsilon \\
expr & \rightarrow & term \textbf{ relop } term \\
 & | & term \\
term & \rightarrow & \textbf{id} \\
 & | & \textbf{number}
\end{array}
$$

A grammar for branching statements

Patterns for recognizing tokens

$$
\begin{array}{rcl}
\mathit{digit} & \rightarrow & \texttt{[0-9]} \\
\mathit{digits} & \rightarrow & \mathit{digit}^{+} \\
\mathit{number} & \rightarrow & \mathit{digits}\ (\texttt{.}\ \mathit{digits})?\ (\ \texttt{E}\ \texttt{[+-]}?\ \mathit{digits}\ )? \\
\mathit{letter} & \rightarrow & \texttt{[A-Za-z]} \\
\mathit{id} & \rightarrow & \mathit{letter}\ (\ \mathit{letter}\ |\ \mathit{digit}\ )^{*} \\
\mathit{if} & \rightarrow & \texttt{if} \\
\mathit{then} & \rightarrow & \texttt{then} \\
\mathit{else} & \rightarrow & \texttt{else} \\
\mathit{relop} & \rightarrow & \texttt{<}\ |\ \texttt{>}\ |\ \texttt{<=}\ |\ \texttt{>=}\ |\ \texttt{=}\ |\ \texttt{<>}
\end{array}
$$

Patterns for tokens

To recognize spaces

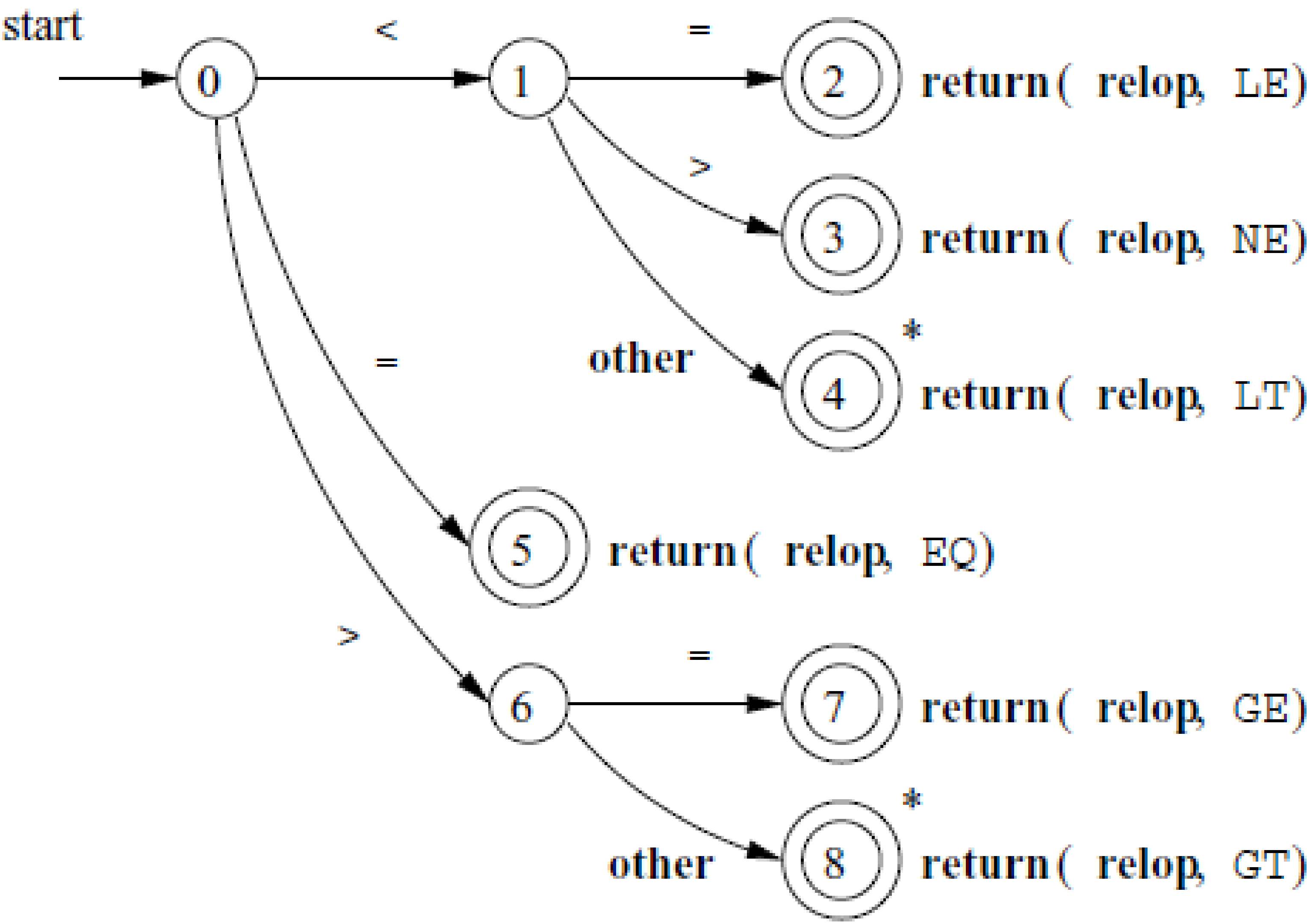
$$ws \rightarrow (\ \mathbf{blank} \mid \mathbf{tab} \mid \mathbf{newline}\ )^{+}$$

Lexemes	Token Name	Attribute Value
Any *ws*	–	–
`if`	**if**	–
`then`	**then**	–
`else`	**else**	–
Any *id*	**id**	Pointer to table entry
Any *number*	**number**	Pointer to table entry
`<`	**relop**	`LT`
`<=`	**relop**	`LE`
`=`	**relop**	`EQ`
`<>`	**relop**	`NE`
`>`	**relop**	`GT`
`>=`	**relop**	`GE`

Tokens, their patterns, and attribute values

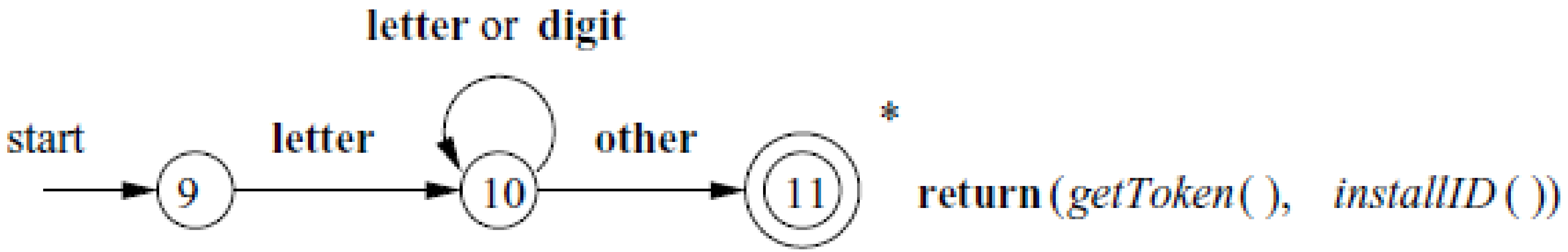
Transition Diagrams

- States
- Lexeme begin
- Forward
- Edges
- Deterministic transition diagrams
- Accepting / Final state
- Start state/ Initial state

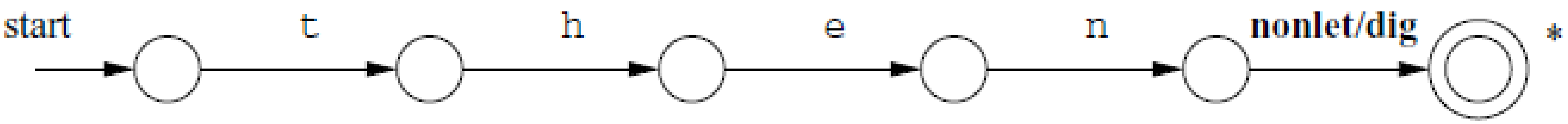


Transition diagram for **relop**

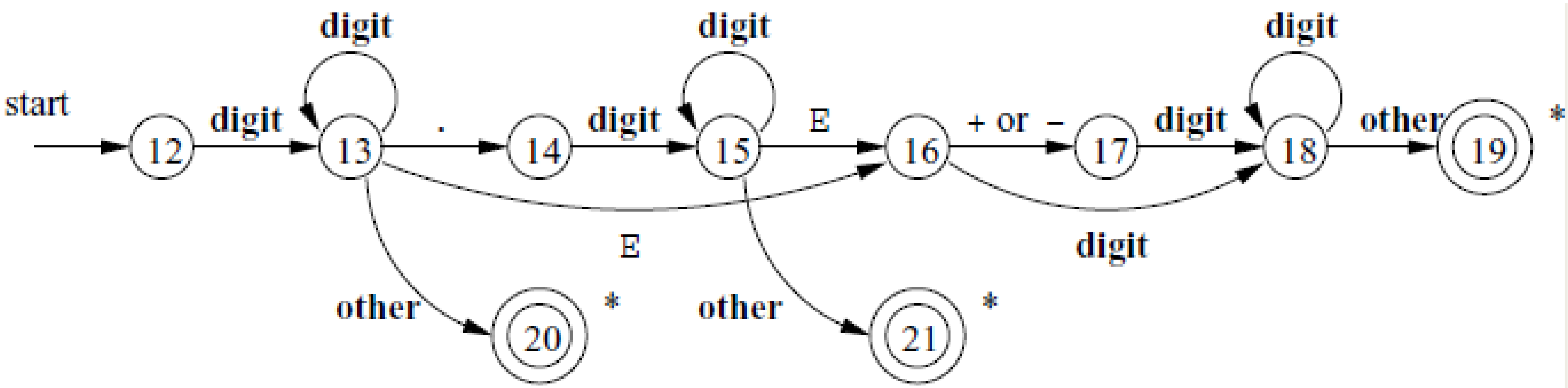
Recognition of reserved words and identifiers



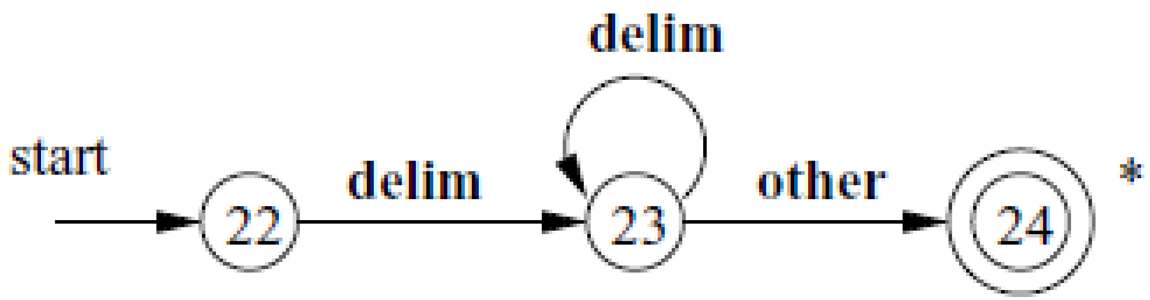
A transition diagram for **id**'s and keywords



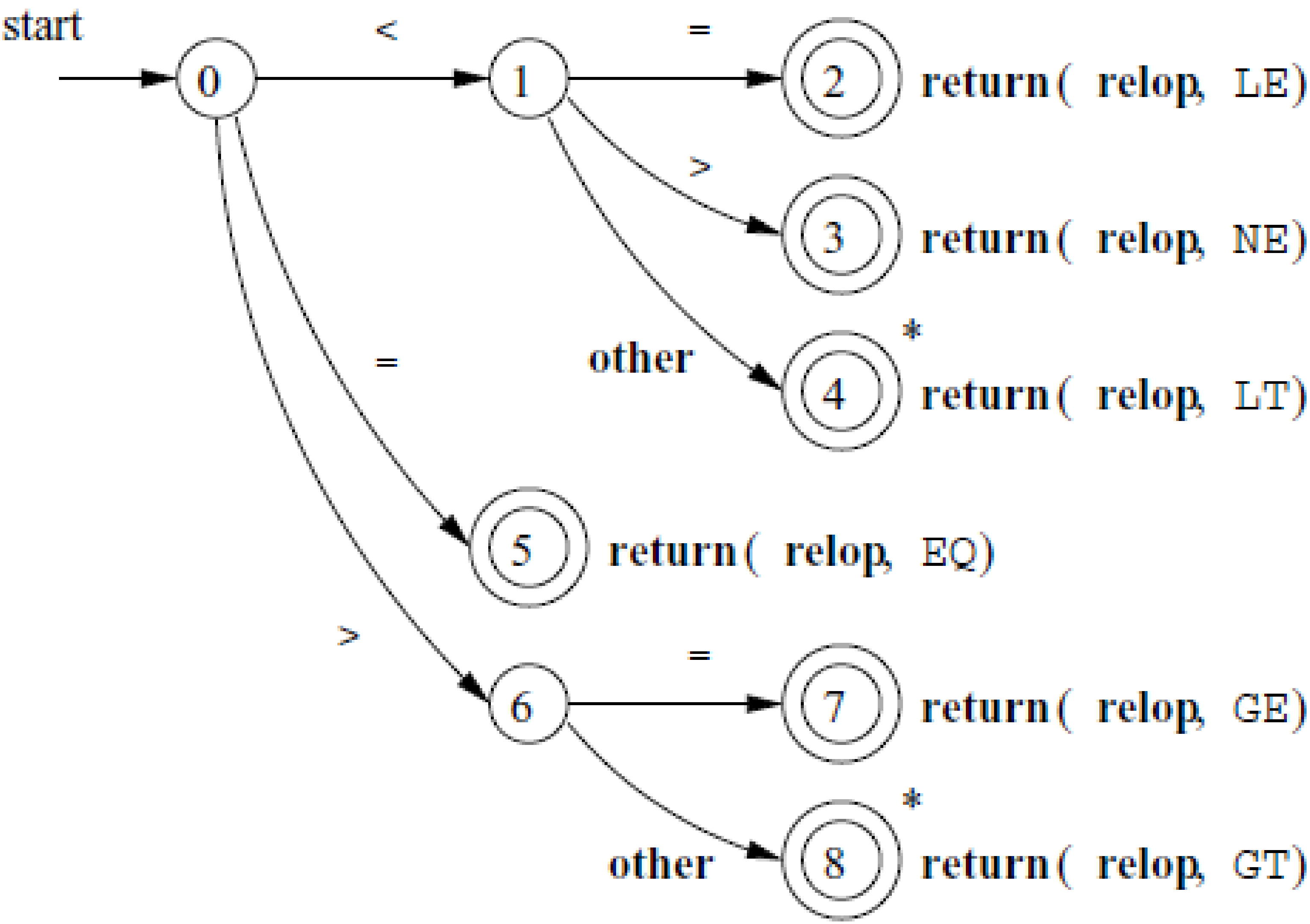
Hypothetical transition diagram for the keyword then



A transition diagram for unsigned numbers



A transition diagram for whitespace

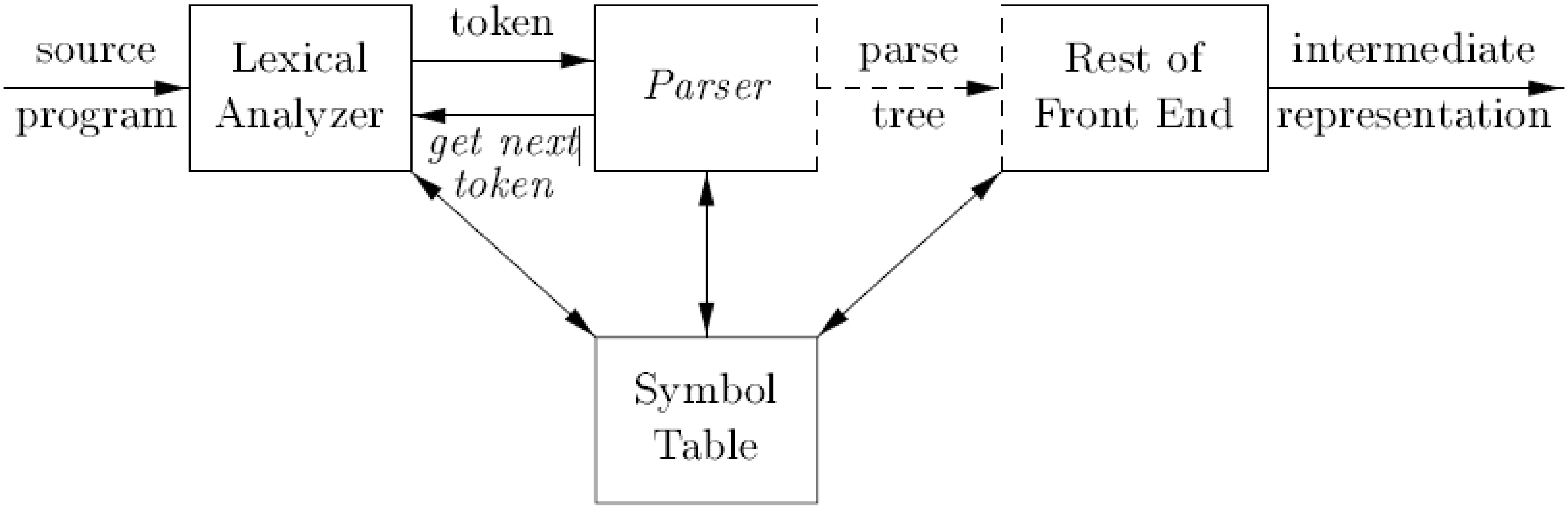


Transition diagram for **relop**

Sketch of Implementation of relop() Transition diagram

```
TOKEN getRelop()
{
    TOKEN retToken = new(RELOP);
    while(1) { /* repeat character processing until a return
                  or failure occurs */
        switch(state) {
            case 0: c = nextChar();
                    if ( c == '<' ) state = 1;
                    else if ( c == '=' ) state = 5;
                    else if ( c == '>' ) state = 6;
                    else fail(); /* lexeme is not a relop */
                    break;
            case 1: ...
            ...
            case 8: retract();
                    retToken.attribute = GT;
                    return(retToken);
        }
    }
}
```

Role of Parser



Position of parser in compiler model

Parsers

- Type of parsers
  - Bottom up
  - Top down
- Input to parser is scanned from left to right, one symbol at a time

Errors in different levels

- Lexical errors
- Syntactic errors
- Semantic errors
- Logical errors
- Error handler works:
  - Report error
  - Correct error

Error recovery strategies

- Panic mode
  - Synchronizing tokens
  - Eg : { , ;
- Phrase level
  - Eg: Insert missing semicolon
- Error productions
  - Production rules
- Global corrections
  - Replace string x by y

Grammar

- Terminal
  - Token name
- Non terminal
  - Set of strings

$$
\begin{aligned}
\mathit{expression} &\rightarrow \mathit{expression} + \mathit{term} \\
\mathit{expression} &\rightarrow \mathit{expression} - \mathit{term} \\
\mathit{expression} &\rightarrow \mathit{term} \\
\mathit{term} &\rightarrow \mathit{term} * \mathit{factor} \\
\mathit{term} &\rightarrow \mathit{term} \; / \; \mathit{factor} \\
\mathit{term} &\rightarrow \mathit{factor} \\
\mathit{factor} &\rightarrow (\; \mathit{expression} \;) \\
\mathit{factor} &\rightarrow \mathbf{id}
\end{aligned}
$$

Grammar for simple arithmetic expressions

Ambiguity

- Grammar
  - More than one parse tree for an input string
- G:

E→ E+E

E→ id | num

Input : a+b+c

Lexical vs syntax analysis

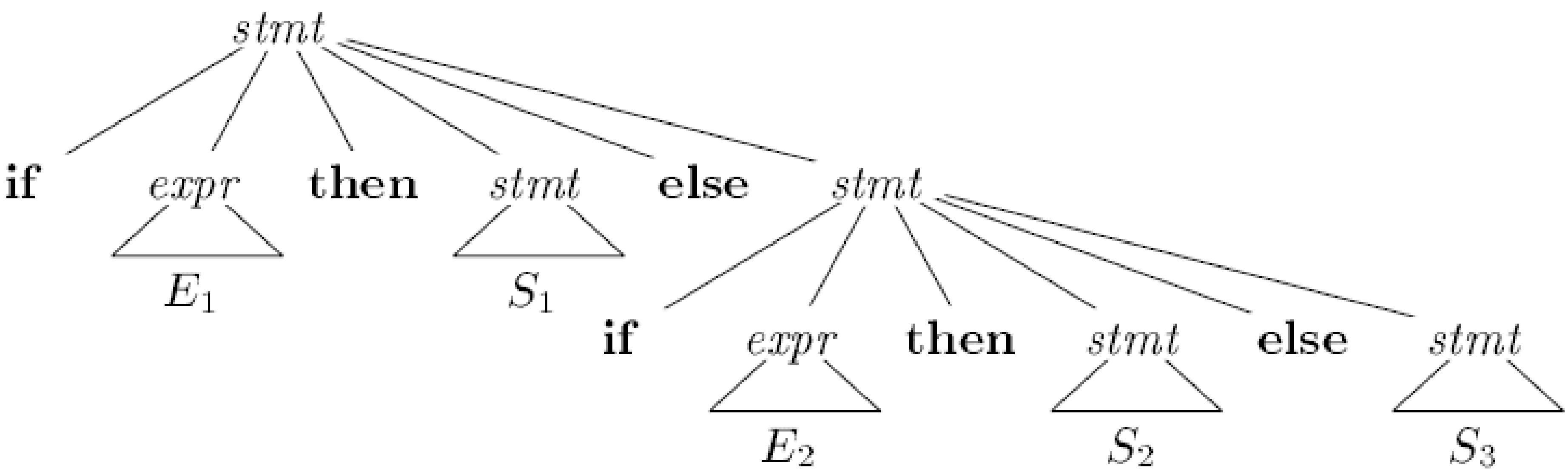
- Lexer
  - RE
- Parser
  - grammar

Eliminating ambiguity

$$
\begin{array}{lcl}
stmt & \rightarrow & \textbf{if } expr \textbf{ then } stmt \\
 & | & \textbf{if } expr \textbf{ then } stmt \textbf{ else } stmt \\
 & | & \textbf{other}
\end{array}
$$

Pbm : Draw parse tree for the given input string

$$\textbf{if } E_1 \textbf{ then } S_1 \textbf{ else if } E_2 \textbf{ then } S_2 \textbf{ else } S_3$$

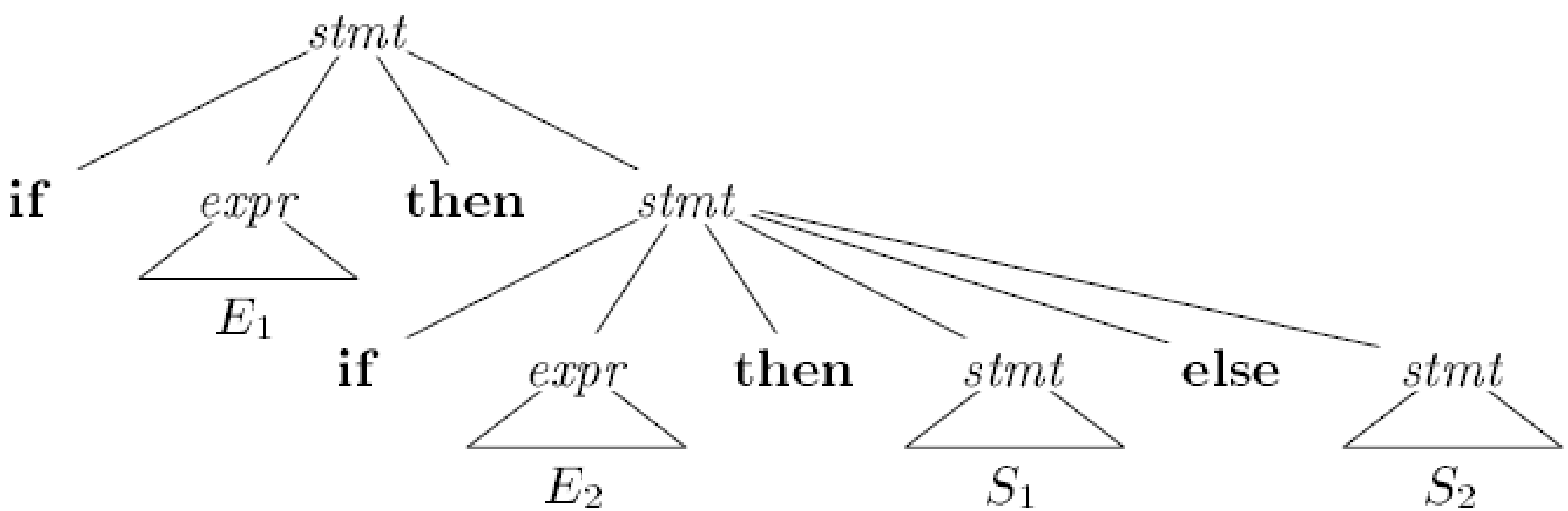


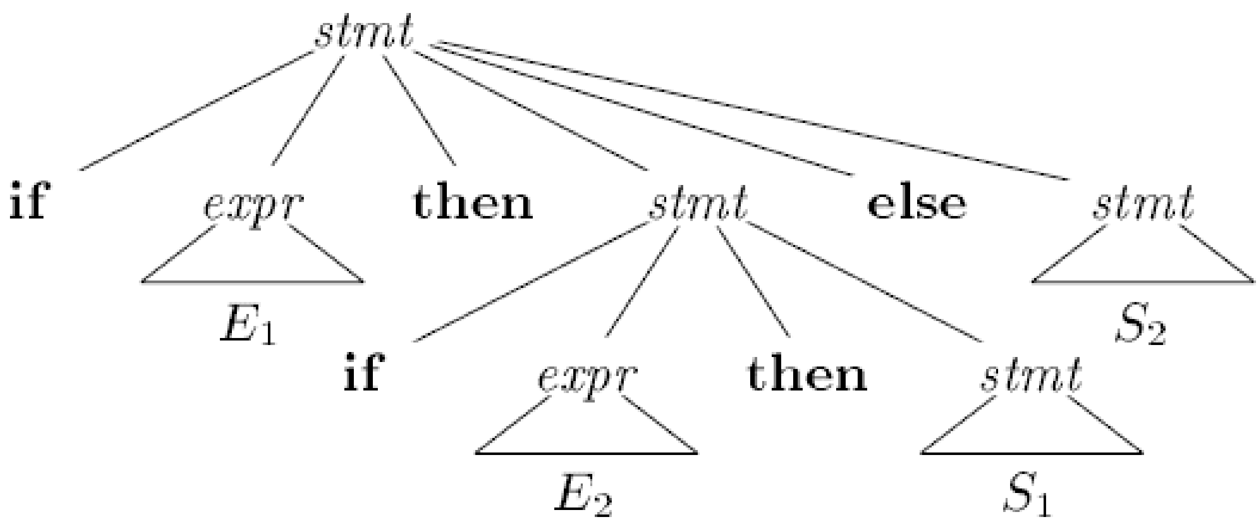
Parse tree for a conditional statement

Draw Parse tree for the given input string

$$\textbf{if } E_1 \textbf{ then if } E_2 \textbf{ then } S_1 \textbf{ else } S_2$$

Parse trees


stmt
if
expr
then
stmt
E_1
if
expr
then
stmt
else
stmt
E_2
S_1
S_2


stmt
if
expr
then
stmt
else
stmt
E_1
S_2
if
expr
then
stmt
E_2
S_1

$$
\begin{array}{rcl}
stmt & \rightarrow & matched\_stmt \\
& | & open\_stmt \\
matched\_stmt & \rightarrow & \textbf{if } expr \textbf{ then } matched\_stmt \textbf{ else } matched\_stmt \\
& | & \textbf{other} \\
open\_stmt & \rightarrow & \textbf{if } expr \textbf{ then } stmt \\
& | & \textbf{if } expr \textbf{ then } matched\_stmt \textbf{ else } open\_stmt
\end{array}
$$

Unambiguous grammar for if-then-else statements

Algorithm Eliminating left recursion.

INPUT: Grammar G with no cycles or ϵ-productions.

OUTPUT: An equivalent grammar with no left recursion.

METHOD: Apply the algorithm to G. Note that the resulting non-left-recursive grammar may have ϵ-productions.

```
arrange the nonterminals in some order A_1, A_2, ..., A_n.
for ( each i from 1 to n ) {
        for ( each j from 1 to i - 1 ) {
                replace each production of the form A_i → A_j γ by the
                    productions A_i → δ_1 γ | δ_2 γ | ··· | δ_k γ, where
                    A_j → δ_1 | δ_2 | ··· | δ_k are all current A_j-productions
        }
        eliminate the immediate left recursion among the A_i-productions
}
```

Left recursion

- **Cases:**

$$A \rightarrow A\alpha$$

$$A \rightarrow A\alpha \mid \beta$$

Left recursion elimination

$$
\begin{aligned}
A &\rightarrow \beta A' \\
A' &\rightarrow \alpha A' \quad | \quad \epsilon
\end{aligned}
$$

Example Grammar : Left recursion

$$
\begin{array}{lcl}
E & \rightarrow & E + T \mid E - T \mid T \\
T & \rightarrow & T * F \mid T \,/\, F \mid F \\
F & \rightarrow & (E) \mid \mathbf{id}
\end{array}
$$

Left recursion

G:

E→ E+ T | T

LRE :

$$E \rightarrow T\ E'$$
$$E' \rightarrow +\ T\ E' \mid \epsilon$$

LRE

T→T*F | F

LRE:

$$T \rightarrow F\ T'$$
$$T' \rightarrow *\ F\ T' \mid \epsilon$$

LRE

$F \rightarrow (E) \mid id$

No LRE needed

Left recursion other cases

$$A \to A\alpha_1 \mid A\alpha_2 \mid \cdots \mid A\alpha_m \mid \beta_1 \mid \beta_2 \mid \cdots \mid \beta_n$$

LRE

$$A \rightarrow \beta_1 A' \mid \beta_2 A' \mid \cdots \mid \beta_n A'$$
$$A' \rightarrow \alpha_1 A' \mid \alpha_2 A' \mid \cdots \mid \alpha_m A' \mid \epsilon$$

Left recursion other cases

$$
\begin{aligned}
S &\rightarrow A\ a \quad | \quad b \\
A &\rightarrow A\ c \quad | \quad S\ d \quad | \quad \epsilon
\end{aligned}
$$

Left recursion

$$S \Rightarrow Aa \Rightarrow Sda$$

Left recursion

$$A \rightarrow A\ c \ \mid \ A\ a\ d \ \mid \ b\ d \ \mid \ \epsilon$$

LRE

$$S \rightarrow A\ a \ \mid\ b$$
$$A \rightarrow b\ d\ A' \ \mid\ A'$$
$$A' \rightarrow c\ A' \ \mid\ a\ d\ A' \ \mid\ \epsilon$$

Need for Left factoring

$$A \rightarrow \alpha\beta_1 \mid \alpha\beta_2$$

Algorithm : Left factoring a grammar.

INPUT: Grammar G.

OUTPUT: An equivalent left-factored grammar.

METHOD: For each nonterminal A, find the longest prefix α common to two or more of its alternatives. If $\alpha \neq \epsilon$ — i.e., there is a nontrivial common prefix — replace all of the A-productions $A \rightarrow \alpha\beta_1 \mid \alpha\beta_2 \mid \cdots \mid \alpha\beta_n \mid \gamma$, where γ represents all alternatives that do not begin with α, by

$$\begin{aligned} A &\rightarrow \alpha A' \mid \gamma \\ A' &\rightarrow \beta_1 \mid \beta_2 \mid \cdots \mid \beta_n \end{aligned}$$

Here A' is a new nonterminal. Repeatedly apply this transformation until no two alternatives for a nonterminal have a common prefix. □

Left factoring

$$A \rightarrow \alpha A'$$
$$A' \rightarrow \beta_1 \quad | \quad \beta_2$$

Example

$$
\begin{array}{lcl}
stmt & \rightarrow & \textbf{if } expr \textbf{ then } stmt \textbf{ else } stmt \\
 & | & \textbf{if } expr \textbf{ then } stmt
\end{array}
$$

Example

$$S \rightarrow i\ E\ t\ S \ \mid\ i\ E\ t\ S\ e\ S \ \mid\ a$$
$$E \rightarrow b$$

Left factoring applied

$$S \rightarrow i\ E\ t\ S\ S' \ \mid\ a$$
$$S' \rightarrow e\ S \ \mid\ \epsilon$$
$$E \rightarrow b$$

Problems to solve

- Pbm 1:

Grammar: Apply LRE

S→ Sa| Sb | c |d

- Pbm 2:

Grammar : Apply LRE

A→Br

B→Cd

C→At

Problems

- Apply left factoring:

S -> 0 S 1 | 0 1