Compilerconstructie

najaar 2012

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Syntax Analysis (1)

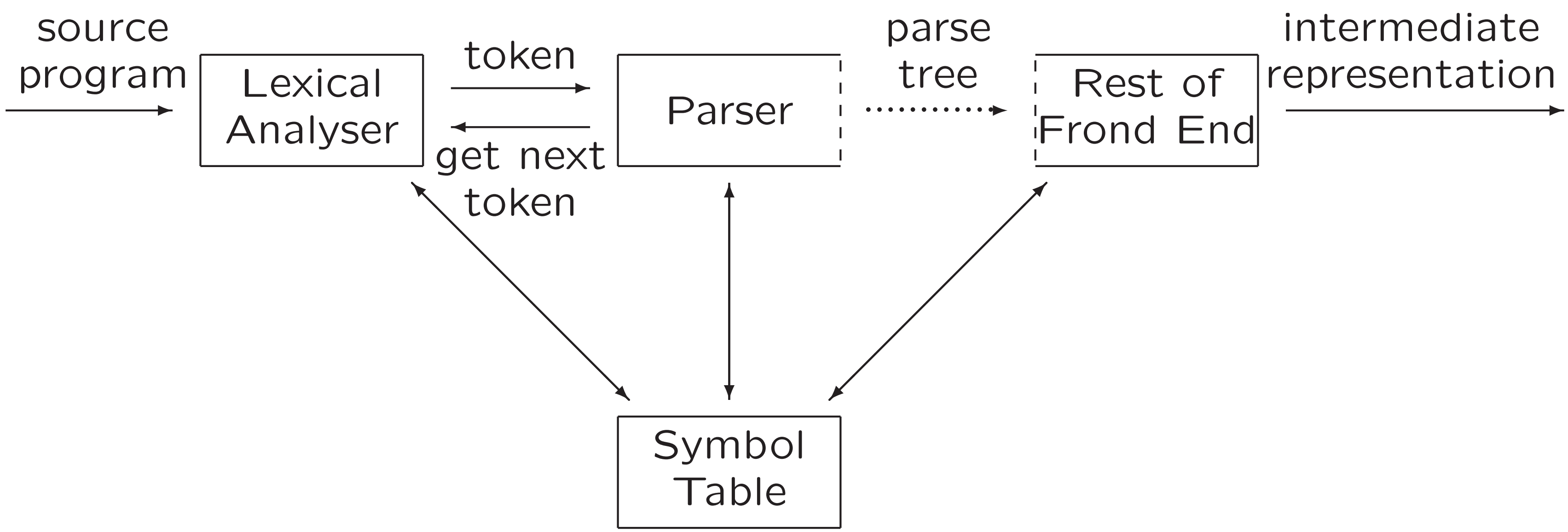
4 Syntax Analysis

- Every language has rules prescribing the syntactic structure of the programs:
  - functions, made up of declarations and statements
  - statements made up of expressions
  - expressions made up of tokens

- Syntax of programming-language constructs can be described by CFG
  - Precise syntactic specification
  - Automatic construction of parsers for certain classes of grammars
  - Structure imparted to language by grammar is useful for translating source programs into object code
  - New language constructs can be added easily

- Syntax analyis is performed by parser

4.1 Parser's Position in a Compiler



Parsing

Finding parse tree for given string

- Universal (any CFG)
  - Cocke-Younger-Kasami
  - Earley

- Top-down (CFG with restrictions)
  - Predictive parsing
  - LL (Left-to-right, Leftmost derivation) methods
  - LL(1): LL parser, needs only one token to look ahead

- Bottom-up (CFG with restrictions)

Today: top-down parsing
Next week: bottom-up parsing

Syntax Error Handling

- Good compiler should assist in identifying and locating errors
  - Lexical errors: compiler can easily detect and continue
  - Syntax errors: compiler can detect and often recover
  - Semantic errors: compiler can sometimes detect
  - Logical errors: hard to detect

- Three goals. The error handler should
  - Report errors clearly and accurately
  - Recover quickly to detect subsequent errors
  - Add minimal overhead to processing of correct programs

Error Detection and Reporting

- Viable-prefix property of LL/LR parsers allow detection of syntax errors as soon as possible,
  i.e., as soon as prefix of input does not match prefix of any string in language (valid program)

- Reporting an error:
  - At least report line number and position
  - Print diagnostic message, e.g.,
    "semicolon missing at this position"

Error-Recovery Strategies

- Continue after error detection,
  restore to state where processing may continue, but. . .
- No universally acceptable strategy,
  but some useful strategies:
  - Panic-mode recovery: discard input until token in designated set of *synchronizing* tokens is found
  - Phrase-level recovery: perform local correction on the input to repair error, e.g., insert missing semicolon
    Has actually been used
  - Error productions: augment grammar with productions for erroneous constructs
  - Global correction: choose minimal sequence of changes to obtain correct string
    Costly, but yardstick for evaluating other strategies

4.2 Context-Free Grammars

Context-free grammar is a 4-tuple with

- A set of *nonterminals* (syntactic variables)
- A set of tokens (*terminal* symbols)
- A designated *start/* symbol (nonterminal)
- A set of *productions*: rules how to decompose nonterminals

Example: CFG for simple arithmetic expressions:

$$G = (\{\textit{expr}, \textit{term}, \textit{factor}\},\ \{\mathbf{id}, +, -, *, /, (,)\},\ \textit{expr},\ P)$$

with productions P:

$$\begin{array}{rcl} \textit{expr} & \rightarrow & \textit{expr} + \textit{term} \mid \textit{expr} - \textit{term} \mid \textit{term} \\ \textit{term} & \rightarrow & \textit{term} * \textit{factor} \mid \textit{term} / \textit{factor} \mid \textit{factor} \\ \textit{factor} & \rightarrow & (\textit{expr}) \mid \mathbf{id} \end{array}$$

Notational Conventions

1. Terminals:
   $a, b, c, \ldots$; specific terminals: $+, *, (,), 0, 1,$ **id**, **if**, ...
2. Nonterminals:
   $A, B, C, \ldots$; specific nonterminals: S, *expr*, *stmt*, ..., $E, \ldots$
3. Grammar symbols: X, Y, Z
4. Strings of terminals: u, v, w, x, y, z
5. Strings of grammar symbols: $\alpha, \beta, \gamma, \ldots$
   Hence, generic production: $A \to \alpha$
6. A-productions:
   $A \to \alpha_1, A \to \alpha_2, \ldots, A \to \alpha_k \quad \Rightarrow \quad A \to \alpha_1 \mid \alpha_2 \mid \ldots \mid \alpha_k$
   Alternatives for A
7. By default, head of first production is start symbol

Notational Conventions (Example)

CFG for simple arithmetic expressions:

$$G = (\{\mathit{expr}, \mathit{term}, \mathit{factor}\},\ \{\mathbf{id}, +, -, *, /, (,)\},\ \mathit{expr},\ P)$$

with productions P:

$$\begin{array}{rcl} \mathit{expr} & \to & \mathit{expr} + \mathit{term} \mid \mathit{expr} - \mathit{term} \mid \mathit{term} \\ \mathit{term} & \to & \mathit{term} * \mathit{factor} \mid \mathit{term} / \mathit{factor} \mid \mathit{factor} \\ \mathit{factor} & \to & (\mathit{expr}) \mid \mathbf{id} \end{array}$$

Can be rewritten concisely as:

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

Derivations

Example grammar:

$$E \to E + E \mid E * E \mid -E \mid (E) \mid \textbf{id}$$

- In each step, a nonterminal is replaced by body of one of its productions, e.g.,

$$E \Rightarrow -E \Rightarrow -(E) \Rightarrow -(\textbf{id})$$

- One-step derivation:
  $\alpha A \beta \Rightarrow \alpha \gamma \beta$, where $A \to \gamma$ is production in grammar
- Derivation in zero or more steps: $\overset{*}{\Rightarrow}$
- Derivation in one or more steps: $\overset{+}{\Rightarrow}$

Derivations

- If $S \stackrel{*}{\Rightarrow} \alpha$, then α is sentential form of G
- If $S \stackrel{*}{\Rightarrow} \alpha$ and α has no nonterminals, then α is sentence of G
- Language generated by G is $L(G) = \{w \mid w$ is sentence of $G\}$
- Leftmost derivation: $wA\gamma \underset{lm}{\Rightarrow} w\delta\gamma$
- If $S \underset{lm}{\stackrel{*}{\Rightarrow}} \alpha$, then α is left sentential form of G
- Rightmost derivation: $\gamma A w \underset{rm}{\Rightarrow} \gamma\delta w$, $\quad \underset{rm}{\stackrel{*}{\Rightarrow}}$

Example of leftmost derivation:

$$E \underset{lm}{\Rightarrow} -E \underset{lm}{\Rightarrow} -(E) \underset{lm}{\Rightarrow} -(E+E) \underset{lm}{\Rightarrow} -(\mathbf{id}+E) \underset{lm}{\Rightarrow} -(\mathbf{id}+\mathbf{id})$$

Parse Tree
(from college 1)

(derivation tree in FI2)

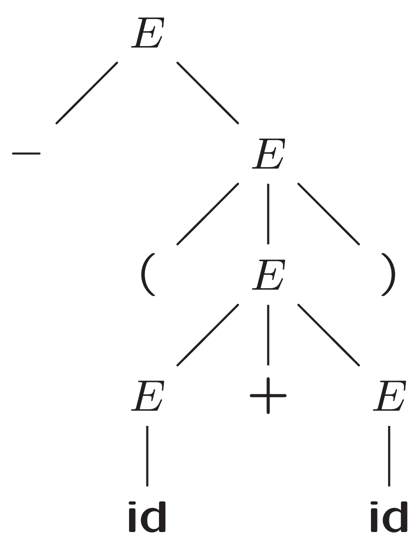
- The root of the tree is labelled by the start symbol
- Each leaf of the tree is labelled by a terminal (=token) or ϵ (=empty)
- Each interior node is labelled by a nonterminal
- If node A has children $X_1, X_2, \ldots, X_n$, then there must be a production $A \rightarrow X_1 X_2 \ldots X_n$

Yield of the parse tree: the sequence of leafs (left to right)

Parse Trees and Derivations

$$E \rightarrow E + E \quad | \quad E * E \quad | \quad -E \quad | \quad (E) \quad | \quad \textbf{id}$$

$$E \underset{lm}{\Rightarrow} -E \underset{lm}{\Rightarrow} -(E) \underset{lm}{\Rightarrow} -(E + E) \underset{lm}{\Rightarrow} -(\textbf{id} + E) \underset{lm}{\Rightarrow} -(\textbf{id} + \textbf{id})$$



Many-to-one relationship between derivations and parse trees. . .

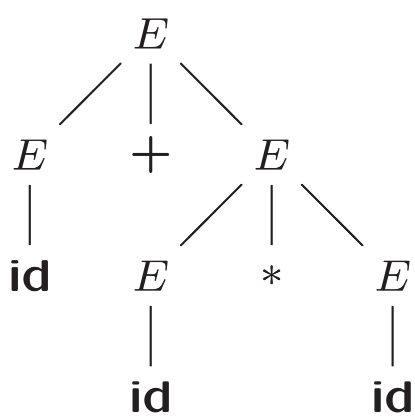
Ambiguity

More than one leftmost/rightmost derivation for same sentence

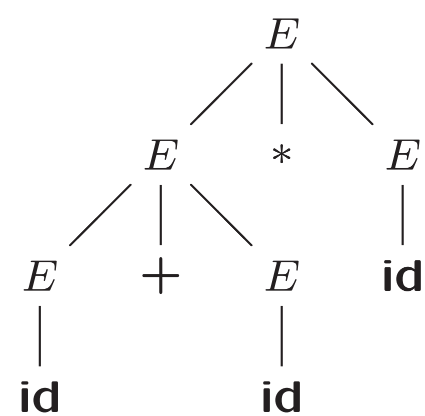
Example: $a + b * c$

$$\begin{aligned} E &\Rightarrow E + E \\ &\Rightarrow \mathbf{id} + E \\ &\Rightarrow \mathbf{id} + E * E \\ &\Rightarrow \mathbf{id} + \mathbf{id} * E \\ &\Rightarrow \mathbf{id} + \mathbf{id} * \mathbf{id} \end{aligned}$$

$$\begin{aligned} E &\Rightarrow E * E \\ &\Rightarrow E + E * E \\ &\Rightarrow \mathbf{id} + E * E \\ &\Rightarrow \mathbf{id} + \mathbf{id} * E \\ &\Rightarrow \mathbf{id} + \mathbf{id} * \mathbf{id} \end{aligned}$$



$a + (b * c)$



$(a + b) * c$

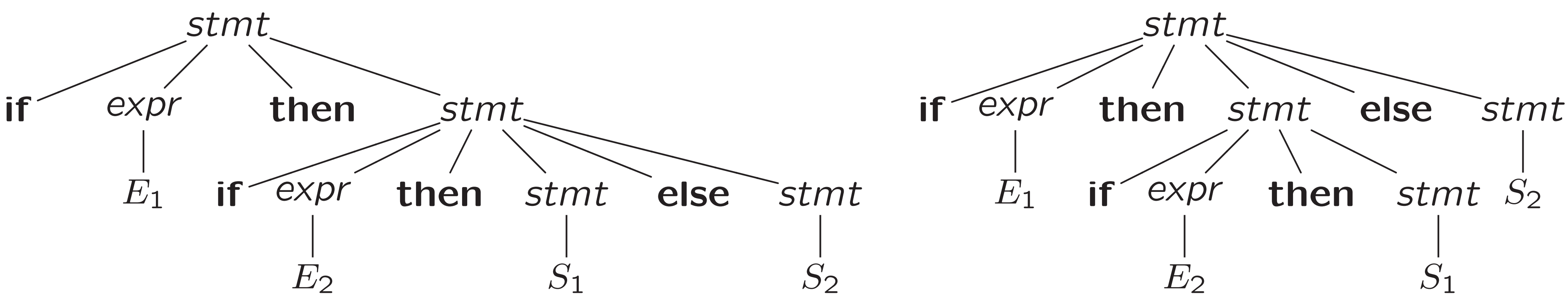
Eliminating ambiguity

- Sometimes ambiguity can be eliminated
- Example: “dangling-else”-grammar

stmt → **if** *expr* **then** *stmt*
  | **if** *expr* **then** *stmt* **else** *stmt*
  | **other**

Here, **other** is any other statement

if E_1 **then if** E_2 **then** S_1 **else** S_2



Eliminating ambiguity

Example: ambiguous "dangling-else"-grammar

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

Equivalent unambiguous grammar

$$\begin{array}{rcl} \textit{stmt} & \rightarrow & \textit{matchedstmt} \\ & | & \textit{openstmt} \\ \textit{matchedstmt} & \rightarrow & \textbf{if } \textit{expr } \textbf{then } \textit{matchedstmt } \textbf{else } \textit{matchedstmt} \\ & | & \textbf{other} \\ \textit{openstmt} & \rightarrow & \textbf{if } \textit{expr } \textbf{then } \textit{stmt} \\ & | & \textbf{if } \textit{expr } \textbf{then } \textit{matchedstmt } \textbf{else } \textit{openstmt} \end{array}$$

Only one parse tree for

if E_1 **then if** E_2 **then** S_1 **else** S_2

Associates each **else** with closest previous unmatched **then**

Left Recursion

- Productions of the form $A \to A\alpha \mid \beta$ are left-recursive
  - β does not start with A
  - Example: $E \to E + T \mid T$
- Top-down parser may loop forever if grammar has left-recursive productions
- Left-recursive productions can be eliminated by rewriting productions

Left Recursion Elimination

Immediate left recursion

- Productions of the form $A \to A\alpha \mid \beta$
- Can be eliminated by replacing the productions by

$$
\begin{array}{lcl}
A & \to & \beta A' \\
A' & \to & \alpha A' \mid \epsilon
\end{array}
$$

(A' is new nonterminal)
($A' \to \alpha A'$ is right recursive)

- Procedure:

1. Group A-productions as

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

2. Replace A-productions by

$$
\begin{array}{lcl}
A & \to & \beta_1 A' \mid \beta_2 A' \mid \ldots \mid \beta_n A' \\
A' & \to & \alpha_1 A' \mid \alpha_2 A' \mid \ldots \mid \alpha_m A' \mid \epsilon
\end{array}
$$

Left Recursion Elimination

General left recursion

- Left recursion involving two or more steps

$$
\begin{aligned}
S &\rightarrow Ba \mid b \\
B &\rightarrow AA \mid a \\
A &\rightarrow Ac \mid Sd
\end{aligned}
$$

- S is left-recursive because

  $S \Rightarrow Ba \Rightarrow AAa \mid SdAa$ (not immediately left-recursive)

General Left Recursion Elimination

- Algorithm for G with no cycles or ϵ-productions

1) arrange nonterminals in some order $A_1, A_2, \ldots, A_n$
2) **for** ($i = 1$ to n)
3) { **for** ($j = 1$ to $i - 1$)
4) { replace each production of form $A_i \rightarrow A_j\gamma$
   by the productions $A_i \rightarrow \delta_1\gamma \mid \delta_2\gamma \mid \ldots \mid \delta_k\gamma$, where
   $A_j \rightarrow \delta_1 \mid \delta_2 \mid \ldots \mid \delta_k$ are all current A_j-productions
5) }
6) eliminate immediate left recursion among A_i-productions
7) }

- Example

$$
\begin{aligned}
S &\rightarrow Ba \mid b \\
B &\rightarrow AA \mid a \\
A &\rightarrow Ac \mid Sd
\end{aligned}
$$

General Left Recursion Elimination

- We order nonterminals: S, B, A ($n = 3$)
- $i = 1$ and $i = 2$: nothing to do
- $i = 3$:
  - substitute $A \to Sd$
  - substitute $A \to Bad$
  - eliminate immediate left-recursion in A-productions
- What would algorithm do for

$$\begin{array}{rcl} S & \to & Ba \mid b \\ B & \to & AA \mid a \\ A & \to & Ac \mid Sd \mid \epsilon \end{array}$$

Left Factoring

Another transformation to produce grammar suitable for predictive parsing

- If $A \rightarrow \alpha\beta_1 \mid \alpha\beta_2$ and input begins with nonempty string derived from α
  How to expand A? To $\alpha\beta_1$ or to $\alpha\beta_2$?

- Solution: left-factoring
  Replace two A-productions by

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

Left Factoring (Example)

- Which production to choose when input token is **if**?

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

- Or abstract:

$$\begin{array}{rcl} S & \rightarrow & iEtS \mid iEtSeS \mid a \\ E & \rightarrow & b \end{array}$$

- Left-factored: ...

Left Factoring (Example)

What is result of left factoring for

$$S \to abS \;\;|\;\; abcA \;\;|\;\; aaa \;\;|\;\; aab \;\;|\;\; aA$$

Non-Context-Free Language Constructs

- Declaration of identifiers before their use

$$L_1 = \{wcw \mid w \in \{a, b\}^*\}$$

- Number of formal parameters in function declaration equals number of actual parameters in function call
  Function call may be specified by

$$\begin{array}{rcl} \textit{stmt} & \rightarrow & \textbf{id}\ (\textit{expr\_list}\ ) \\ \textit{expr\_list} & \rightarrow & \textit{expr\_list},\ \textit{expr} \ \mid\ \textit{expr} \end{array}$$

$$L_2 = \{a^n b^m c^n d^m \mid m, n \geq 1\}$$

Such checks are performed during semantic-analysis phase

4.4 Top-Down Parsing

- Construct parse tree,
  - starting from the root
  - creating nodes in preorder

  Corresponds to finding leftmost derivation

Top-Down Parsing (Example)

- $$E \rightarrow E + T \mid T$$
  $$T \rightarrow T * F \mid F$$
  $$F \rightarrow (E) \mid \textbf{id}$$

- Non-left-recursive variant:

$$E \rightarrow TE'$$
$$E' \rightarrow +TE' \mid \epsilon$$
$$T \rightarrow FT'$$
$$T' \rightarrow *FT' \mid \epsilon$$
$$F \rightarrow (E) \mid \textbf{id}$$

- Top-down parse for input $\textbf{id} + \textbf{id} * \textbf{id}$ ...
- At each step: determine production to be applied

Top-Down Parsing

- Recursive-descent parsing

- Predictive parsing
  - Eliminate left-recursion from grammar
  - Left-factor the grammar
  - Compute FIRST and FOLLOW
  - Two variants:
    - ∗ Recursive (recursive calls)
    - ∗ Non-recursive (explicit stack)

Recursive Descent Parsing

Recursive procedure for each nonterminal

```
void A()
{ Choose an A-production, A → X1 X2 ... Xk;
  for (i = 1 to k)
  { if (Xi is nonterminal)
        call procedure Xi();
    else if (Xi equals current input symbol a)
             advance input to next symbol;
         else /* an error has occurred */;
  }
}
```

Pseudocode is nondeterministic

Recursive Descent

- One may use backtracking:
  - Try each A-production in some order
  - In case of failure at line 7 (or call in line 4), return to line 1 and try another A-production
  - Input pointer must then be reset, so store initial value input pointer in local variable
- Example in book
- Backtracking is rarely needed: predictive parsing

FIRST

- Let α be string of grammar symbols
- FIRST(α) = set of terminals/tokens which begin strings derived from α
- If $\alpha \stackrel{*}{\Rightarrow} \epsilon$, then $\epsilon \in$ FIRST(α)
- Example

$$F \rightarrow (E) \mid \textbf{id}$$

  FIRST(FT') = $\{(, \textbf{id}\}$

- When nonterminal has multiple productions, e.g.,

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

  and FIRST(α) and FIRST(β) are disjoint,
  we can choose between these A-productions by looking at next input symbol

Computing FIRST

Compute FIRST(X) for all grammar symbols X:

- If X is terminal, then FIRST(X) $= \{X\}$
- If $X \rightarrow \epsilon$ is production, then add ϵ to FIRST(X)
- Repeat adding symbols to FIRST(X) by looking at productions

  $$X \rightarrow Y_1 Y_2 \ldots Y_k$$

  (see book) until all FIRST sets are stable

FIRST (Example)

$$\begin{aligned} E &\rightarrow TE' \\ E' &\rightarrow +TE' \mid \epsilon \\ T &\rightarrow FT' \\ T' &\rightarrow *FT' \mid \epsilon \\ F &\rightarrow (E) \mid \textbf{id} \end{aligned}$$

$$\begin{aligned} \text{FIRST}(E) &= \text{FIRST}(T) = \text{FIRST}(F) = \{(, \textbf{id}\} \\ \text{FIRST}(E') &= \{+, \epsilon\} \\ \text{FIRST}(T') &= \{*, \epsilon\} \end{aligned}$$

FOLLOW

- Let A be nonterminal

- FOLLOW(A) is set of terminals/tokens that can appear immediately to the right of A in sentential form:

$$\text{FOLLOW}(A) = \{a \mid S \stackrel{*}{\Rightarrow} \alpha A a \beta\}$$

- Compute FOLLOW(A) for all nonterminals A
  See book

FIRST and FOLLOW (Example)

$$\begin{array}{rcl} E & \rightarrow & TE' \\ E' & \rightarrow & +TE' \mid \epsilon \\ T & \rightarrow & FT' \\ T' & \rightarrow & *FT' \mid \epsilon \\ F & \rightarrow & (E) \mid \textbf{id} \end{array}$$

$$\begin{array}{rcl} \text{FIRST}(E) & = & \text{FIRST}(T) = \text{FIRST}(F) = \{(, \textbf{id}\} \\ \text{FIRST}(E') & = & \{+, \epsilon\} \\ \text{FIRST}(T') & = & \{*, \epsilon\} \\ \text{FOLLOW}(E) & = & \text{FOLLOW}(E') = \{), \$\} \\ \text{FOLLOW}(T) & = & \text{FOLLOW}(T') = \{+,), \$\} \\ \text{FOLLOW}(F) & = & \{*, +,), \$\} \end{array}$$

Parsing Tables

When next input symbol is a (terminal or input endmarker \$), we may choose $A \to \alpha$

- if $a \in \text{FIRST}(\alpha)$
- if ($\alpha = \epsilon$ or $\alpha \overset{*}{\Rightarrow} \epsilon$) and $a \in \text{FOLLOW}(A)$

Algorithm to construct parsing table $M[A, a]$

for (each production $A \to \alpha$)
$\{$ **for** (each $a \in \text{FIRST}(\alpha)$)
    add $A \to \alpha$ to $M[A, a]$;
  if ($\epsilon \in \text{FIRST}(\alpha)$)
  $\{$ **for** (each $b \in \text{FOLLOW}(A)$)
      add $A \to \alpha$ to $M[A, b]$;
  $\}$
$\}$
If $M[A, a]$ is empty, set $M[A, a]$ to **error**.

LL(1) Grammars

- LL(1)
  Left-to-right scanning of input, Leftmost derivation,
  1 token to look ahead suffices for predictive parsing

- Grammar G is LL(1),
  if and only if for two distinct productions $A \rightarrow \alpha \mid \beta$,
  - α and β do not both derive strings beginning with same terminal a
  - at most one of α and β can derive ϵ
  - if $\beta \stackrel{*}{\Rightarrow} \epsilon$, then α does not derive strings beginning with terminal $a \in$ FOLLOW(A)

- In other words, . . .

- Grammar G is LL(1), if and only if parsing table uniquely identifies production or signals error

LL(1) Grammars (Example)

- Not LL(1):

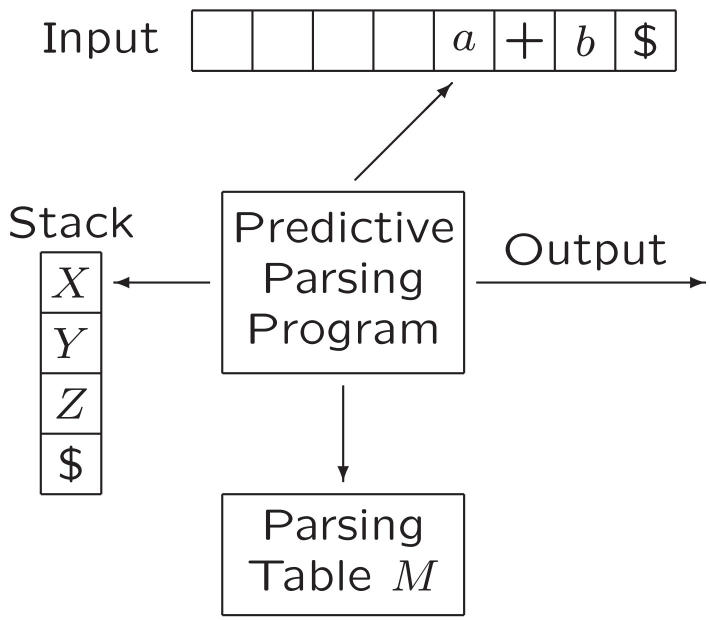
$$
\begin{aligned}
E &\rightarrow E + T \mid T \\
T &\rightarrow T * F \mid F \\
F &\rightarrow (E) \mid \textbf{id}
\end{aligned}
$$

- Non-left-recursive variant, LL(1):

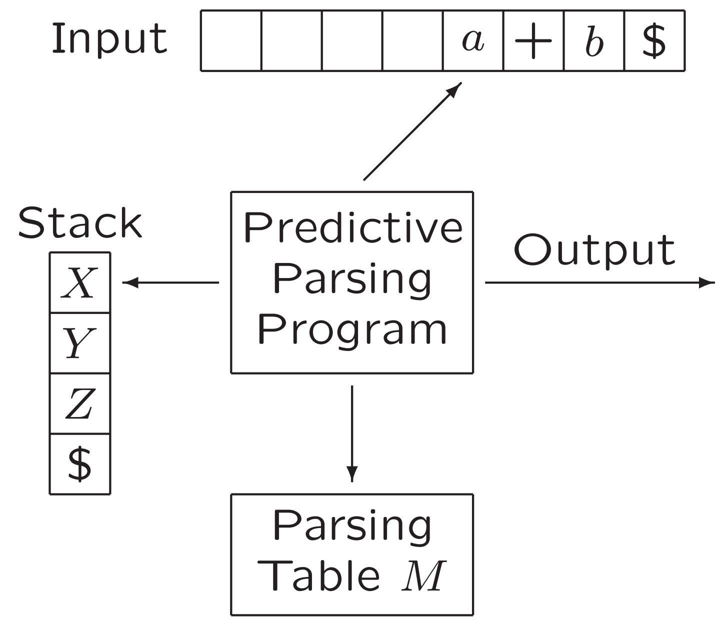
$$
\begin{aligned}
E &\rightarrow TE' \\
E' &\rightarrow +TE' \mid \epsilon \\
T &\rightarrow FT' \\
T' &\rightarrow *FT' \mid \epsilon \\
F &\rightarrow (E) \mid \textbf{id}
\end{aligned}
$$

Nonrecursive Predictive Parsing

Cf. top-down PDA from FI2



Nonrecursive Predictive Parsing



push \$ onto stack;
push S onto stack;
let a be first symbol of input w;
let X be top stack symbol;
while ($X \neq \$$) /* stack is not empty */
{ **if** ($X = a$)
  { pop stack;
    let a be next symbol of w;
  }
  else if (X is terminal)
      error();
    else if ($M[X, a]$ is error entry)
      error();
      else if ($M[X, a] = X \to Y_1 Y_2 \ldots Y_k$)
        { output production $X \to Y_1 Y_2 \ldots Y_k$;
          pop stack;
          push $Y_k, Y_{k-1}, \ldots, Y_1$ onto stack, with Y_1 on top;
        }
  let X be top stack symbol;
}

Error Recovery in Predictive Parsing

Panic-mode recovery

- Discard input until token in set of designated synchronizing tokens is found
- Heuristics
  - Put all symbols in FOLLOW(A) into synchronizing set for A (and remove A from stack)
  - Add symbols based on hierarchical structure of language constructs
  - Add symbols in FIRST(A)
  - If $A \stackrel{*}{\Rightarrow} \epsilon$, use production deriving ϵ as default
  - Add tokens to synchronizing sets of all other tokens

Error Recovery in Predictive Parsing

Phrase-level recovery

- Local correction on remaining input that allows parser to continue

- Pointer to error routines in blank table entries
  - Change symbols
  - Insert symbols
  - Delete symbols
  - Print appropriate message

- Make sure that we do not enter infinite loop

Predictive Parsing Issues

- What to do in case of multiply-defined entries?
  - Transform grammar
    * Left-recursion elimination
    * Left factoring
  - Not always applicable
- Designing grammar suitable for top-down parsing is hard
  - Left-recursion elimination and left factoring make grammar hard to read and to use in translation

Therefore: try to use automatic parser generators

Compiler constructie

college 3

Syntax Analysis (1)

Chapters for reading: 4.1–4.4