Compilers

by
Marwa Yusuf

Lecture 5
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Chapter 4 (4.1 to 4.3)

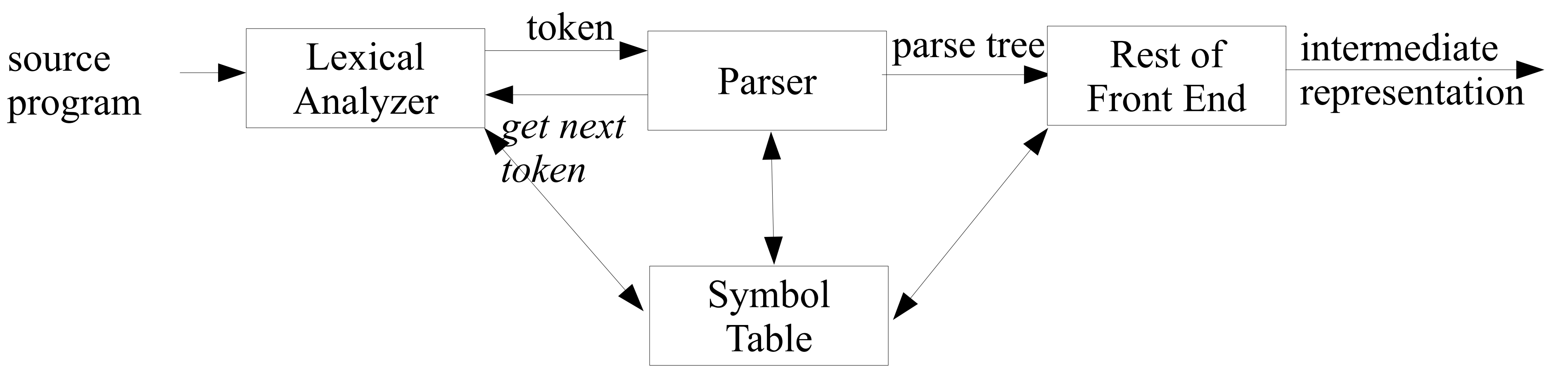
Syntax Analysis

Syntax Analysis

- Every language have rules that define what is a proper program (syntax), in the form of context free grammar or BNF (Backus-Naur Form).
  - In C, a program consists of functions, a function consists of declarations and statements, a statement consists of expressions, ...etc.
- Grammar advantages:
  1) Precise, easy to understand syntactic specification.
  2) From grammar, parser can be constructed automatically, and reveal syntactic ambiguities.
  3) The structure is useful for translating source to object and detecting errors.
  4) Enabling language to evolve iteratively by adding new constructs.

The Role of the Parser

- Gets a string of tokens from lexical analyzer, and verifies that the string of token names can be generated by the grammar.



- Report syntax errors and recover from common errors to continue.
- Parse tree may not be generated explicitly. Parser and the rest of front end may be one mdule.

Parser Types

1) Universal: can parse any grammar, too inefficient to use in a production compiler.

2) Top-down: builds parse tree from the top to the leaves.

3) Bottom-up: vice versa.

- The input in both cases is scanned from left to right, one symbol at a time.
- Both work for only sub-classes of grammar, but they describe most of syntactic constructs in modern languages.

Representative Grammar

- $E \rightarrow E + \mathrm{T} \mid T$ **(If right associative $E \rightarrow T + E \mid T$)**

  $T \rightarrow T * \mathrm{F} \mid F$

  $F \rightarrow (E) \mid \mathbf{id}$ **(Three symbols for 2 levels of precedence)**

  – This grammar is suitable for bottom-up parser, but not for top-down because it is **left-recursive**.
- $E \rightarrow T E'$

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

  $T \rightarrow F T'$

  $T' \rightarrow * \mathrm{F} T' \mid \varepsilon$

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

  – This is modified to be non-left recursive, so it can be used for top-down.
- $L \rightarrow E + E \mid E * E \mid (E) \mid \mathbf{id}$

  – Used to illustrate **ambiguity**. Ex: `a + b * c`

Syntax Error Handling

- Most programming languages leave error handling to the compiler designer.
- Planning from the start simplify compiler structure and improve error handling.
- Common errors:
  1) Lexical: messing quotes, wrong **id** … etc.
  2) Syntactic: missing or extra **;** or **{** or **case** without **switch**.
  3) Semantic: type mismatch, return a value to a void function.
  4) Logical: using = in place of ==, incorrect reasoning.

Syntax Error Handling

- Several parsing methods have *viable-prefix property*, i.e. they detect an error as soon as they see a prefix on input that cannot be completed to form a proper string.
- Error handler goals:
  1) Report errors clearly and accurately.
  2) Recover quickly to detect others.
  3) Add minimal overhead to processing correct programs.
- Common errors are simple.
- Usually reporting error clarifies location of detection.

Error Recovery Strategies

- Simplest: quit with 1st error.
- Usually, parser continues as much as it can (till a threshold) then gives informative message.
- Recovery strategies:
  1) Panic-mode recovery.
  2) Phrase-level recovery.
  3) Error productions.
  4) Global corrections.

Panic-mode recovery

- On finding an error, discard input symbols one by one until finding a *synchronizing token*.
- Synchronizing tokens: usually delimiters (; }), their role is clear and unambiguous, selected by compiler designer.
- -ve: Can skip many input symbols.
- +ve: simple, with no infinite loops.

Phrase-level recovery

- On finding an error, make local correction on the remaining input.
- Ex: replace , with ; or delete or insert ;
- Designed by the compiler designer.
- Must be careful to not enter infinite loop, like inserting symbol ahead of the current.
- +ve: correct errors.
- -ve: difficult to handle cases where the error happens earlier.

Error productions

- Anticipate possible errors, and add productions for them in the grammar.
- When error is "parsed", generate appropriate error diagnostics.

Global corrections

- Given: incorrect input x and grammar G, find a parse tree for a related string y such that the number of insertions, deletions and changes in tokens to transform x into y is as small as possible. (least cost correction)
- -ve: High cost to implement in space and time, might not be what the programmer wants.
- +ve: A reference to evaluate other techniques, finding optimal replacement strings in phrase-level recovery.

Context-Free Grammars

- Systemically describes the syntax of a programming language.
- Ex: $stmt \rightarrow \textbf{if (}\ expr\ \textbf{)}\ stmt\ \textbf{else}\ stmt$
- Consists of:
  - ***Terminals*** (basic symbols, token names);
  - ***Non-terminals*** (syntactic variables denoting sets of strings, defining hierarchical structure);
  - ***Start symbol*** (the language generated by grammar);
  - ***Productions*** (head or left side, → or ::= and body or right side).
- Ex: terminals are:…... non-terminals:…….

$$expression \rightarrow expression + term \mid expression - term \mid term$$

$$term \rightarrow term * factor \mid term\ /\ factor \mid factor$$

$$factor \rightarrow (expression) \mid \textbf{id}$$

Context-Free Grammars (cont.)

- Conventions:
  1) Terminals: early lower case letters (*a*, *b*, *c*), operators (+, *), punctuation(;, parenthesis), digits (0, 1, 2), boldface strings (**id**, **num**).
  2) Non-terminals: early uppercase letters (*A*, *B*, *C*), *S* (start), italic strings (*expr*, *stmt*), uppercase letter when discussing constructs (*E*, *F*).
  3) Uppercase late letters: grammar symbols; terminal or non-terminal (*X*, *Y*, *Z*).
  4) Lowercase late letters: strings of terminals (including ε) (*u*, *v*, *w*).
  5) Lowercase Greek: strings of grammar symbols (α, β, γ). $A \rightarrow \alpha$.
  6) $A \rightarrow \alpha_1$

     $A \rightarrow \alpha_2$

     $A \rightarrow \alpha_3$

     can be transformed to

     $A \rightarrow \alpha_1 \mid \alpha_2 \mid \alpha_3$

     alternatives for a head.
  7) By default, the head of 1st production is the start symbol.

Derivations

- Using rewriting rules.
- Beginning with the start symbol, in each step replace a non-terminal with the body of one of its productions (corresponds to top-down construction of parse tree).
- Ex:

$$E \rightarrow E + E \mid E * E \mid - E \mid (E) \mid \mathbf{id}$$

- If E denotes an expression, then – E also denotes an expression.
- Replacement of E by – E is denoted by

$E \Rightarrow -E$ (E derives $-E$)

Derivations

- $E \Rightarrow -E \Rightarrow -(E) \Rightarrow -(\mathbf{id})$ (derivation of -(**id**) from E, -(**id**) is an instance of expression).
- Derivation definition:
  - given $\alpha A\beta$ and $A \rightarrow \gamma$ then $\alpha A\beta \Rightarrow \alpha\gamma\beta$
- $\Rightarrow$ derives in one step.
- $\Rightarrow^*$ derives in zero or more steps.
- $\Rightarrow^+$ derives in one or more steps.
- If $S \Rightarrow^* \alpha$, then α is called *sentential form of G.*
- A *sentence* of G is a sentential form with no non-terminals.
- The language generated by a grammar is its set of sentences.
- w is in $L(G)$ iff w is a sentence of G (or $S \Rightarrow^* w$).
- A language generated from a grammar is a context free language.
- Equivalent grammars: generate the same language.

Derivations

- Ex: **-(id+id)** is a sentence of grammar

  $E \rightarrow E + E \mid E * E \mid - E \mid (E) \mid \mathbf{id}$

  because :

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

- All these internal strings are sentential forms of G.
- $E \Rightarrow^* -(\boldsymbol{id}+\boldsymbol{id})$
- Alternative derivation:

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

Derivations

1) Leftmost derivations: $\alpha \Rightarrow_{lm} \beta$, the leftmost non-terminal is replaced first.

2) Rightmost derivations: $\alpha \Rightarrow_{rm} \beta$

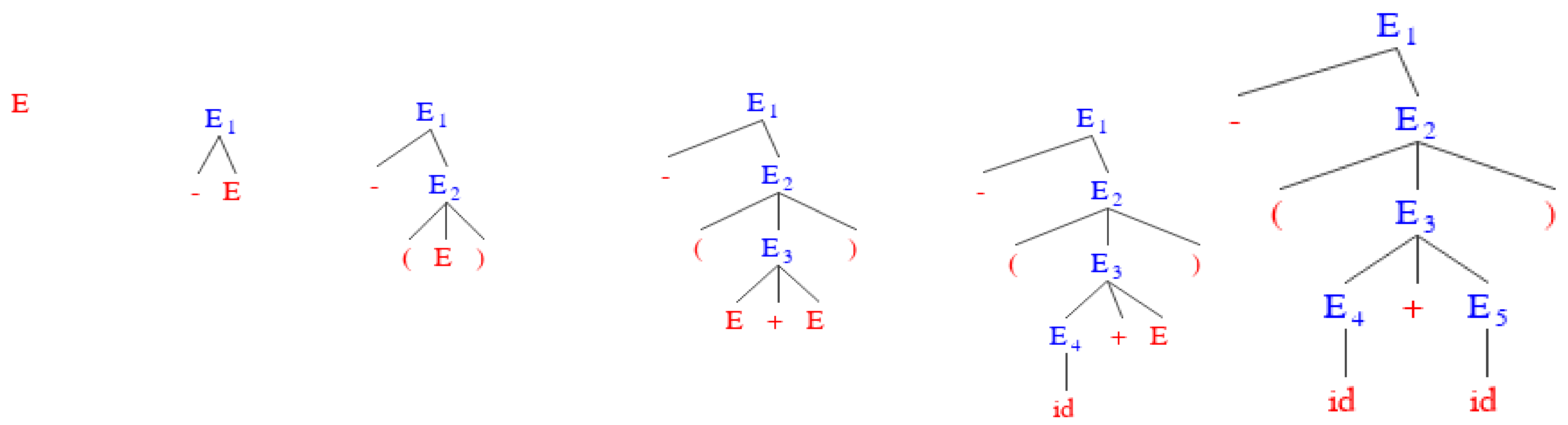
$E \Rightarrow_{lm} -E \Rightarrow_{lm} -(E) \Rightarrow_{lm} -(E+E) \Rightarrow_{lm} -(\mathbf{id}+E) \Rightarrow_{lm} -(\mathbf{id}+\mathbf{id})$

$\mathrm{E} \Rightarrow_{rm} -\mathrm{E} \Rightarrow_{rm} -(\mathrm{E}) \Rightarrow_{rm} -(\mathrm{E}+\mathrm{E}) \Rightarrow_{rm} -(\mathrm{E}+\mathbf{id}) \Rightarrow_{rm} -(\mathbf{id}+\mathbf{id})$

- $S \Rightarrow_{lm}^{*} \alpha$ then α is a leftmost sentential form of G.

Parse Trees and Derivations

- A graphical representation of derivation filtering out ordering of derivations (many to one).
- Leaves read from left or right constitute a sentential form, called yield or frontier of the tree.



Ambiguity

- Grammar that produces more than one parse tree.
- Ex: E $\rightarrow$ $E + E \mid E * E \mid (E) \mid$ **id**

id + id * id

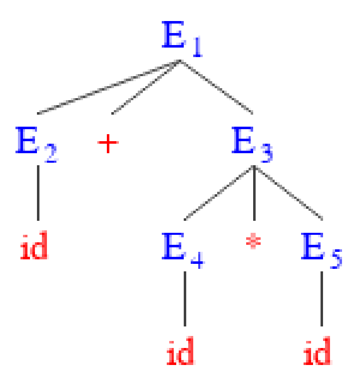
- E $\Rightarrow$ E+E

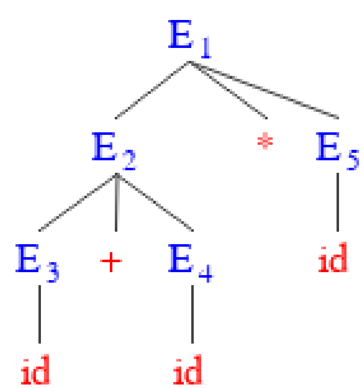
  $\Rightarrow$ id + E

  $\Rightarrow$ id + E * E

  $\Rightarrow$ id + id * E

  $\Rightarrow$ id + id * id





- E $\Rightarrow$ E*E

  $\Rightarrow$ E + E * E

  $\Rightarrow$ id + E * E

  $\Rightarrow$ id + id * E

  $\Rightarrow$ id + id * id

- For most parsers, it is desirable for the grammar to be unambiguous. However, can use carefully chosen ambiguous grammar with disambiguating rules to throw away unwanted parse trees.

Skipped

- Sections 4.2.6 & 4.2.7 are skipped.

Writing a Grammar

- Grammar can describe "most" of the syntax.
- Ex: Condition that **id** declared before use cannot be defined by grammar.
- Later steps after parser deal with such cases.

Lexical vs. Syntactic Analysis

- Section 4.3.1 for reading (MUST).

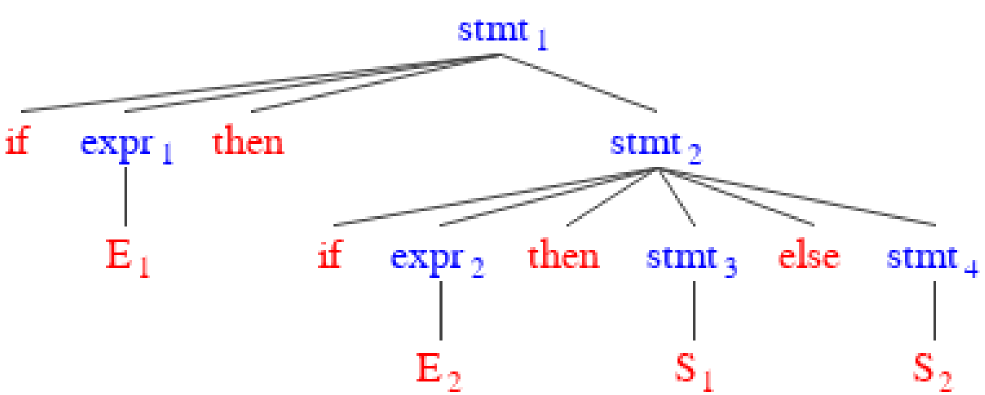
Eliminating Ambiguity

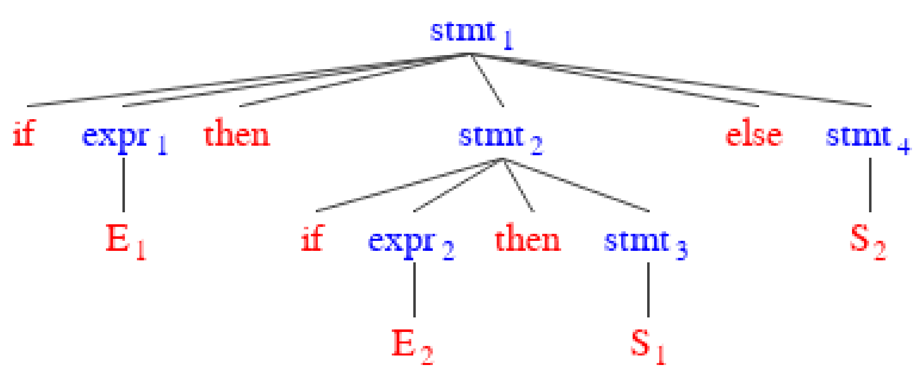
- $stmt \rightarrow$ **if** *expr* **then** *stmt*

  | **if** *expr* **then** *stmt* **else** *stmt*

  | **other**

- if E_1 then if E_2 then S_1 else S_2





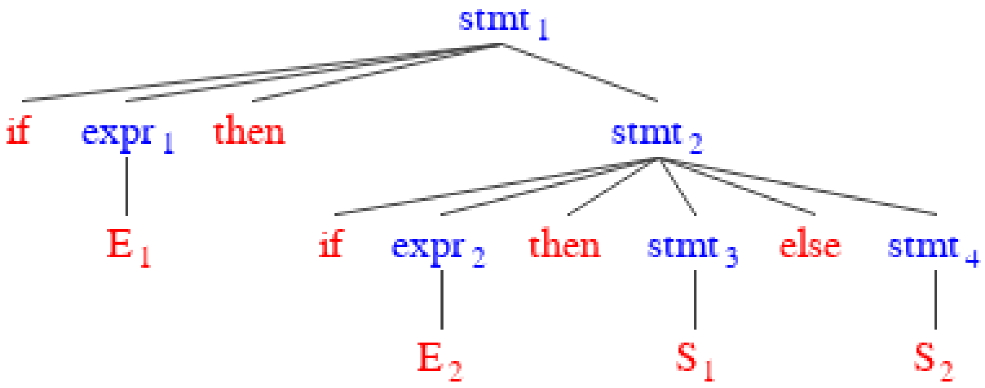
- 1st one is preferred, can be enforced by grammar, but usually not.

Eliminating Ambiguity

- *stmt* → *matched_stmt* | *open_stmt*
- *matched_stmt* → **if** *expr* **then** *matched_stmt* **else** *matched_stmt* | **other**
- *open_stmt* → **if** *expr* **then** *stmt*

  | **if** *expr* **then** *matched_stmt* **else** *open_stmt*

- **The idea is between then and else, there always a matched statement, hence, any else is associated with the closest then.**
- if E_1 then if E_2 then S_1 else S_2



Elimination of Left Recursion

- Left recursive grammar if: $A \Rightarrow^{+} A\alpha$
- Top-down paring cannot handle left recursion.
- Immediate left recursion if $A \rightarrow A\alpha \mid \beta$
- Can be transformed to:

$$A \rightarrow \beta A'$$

$$A' \rightarrow \alpha A' \mid \varepsilon$$

- This rule is sufficient for many grammars.

Look at sec. 2.4.5 page 67

Elimination of Left Recursion

- Ex:

$E \rightarrow E + \mathrm{T}$

$E \rightarrow T$

$T \rightarrow T * \mathrm{F}$

$T \rightarrow F$

$F \rightarrow (E)$

$F \rightarrow \mathbf{id}$

$$\boxed{\begin{array}{l} E \rightarrow T\,E' \\ E' \rightarrow +\,T\,E' \mid \varepsilon \\ T \rightarrow F\,T' \\ T' \rightarrow *\,\mathrm{F}\,T' \mid \varepsilon \\ F \rightarrow (E) \mid \mathbf{id} \end{array}}$$

- **Given:** $A \rightarrow A\alpha_1 \mid A\alpha_2 \mid \ldots \mid A\alpha_m \mid \beta_1 \mid \beta_2 \mid \ldots \mid \beta_n$

  where no β_i begins with A

- **Then:** $A \rightarrow \beta_1 A' \mid \beta_2 A' \mid \ldots \mid \beta_n A'$

  $A' \rightarrow \alpha_1 A' \mid \alpha_2 A' \mid \ldots \mid \alpha_m A' \mid \varepsilon$

Elimination of Left Recursion

- Ex: $S \rightarrow Aa \mid b$

  $A \rightarrow Ac \mid Sd \mid \varepsilon$

  $S \Rightarrow Aa \Rightarrow Sda$

Elimination of Left Recursion Algorithm

- **INPUT:** Grammar G with no cycles($A \Rightarrow + A$) or ε-productions ($A \rightarrow \varepsilon$)
- **OUTPUT:** Equivalent Grammar with no left-recursion
- **METHOD:** Apply the following code to G. Note: resulting grammar may have ε-productions.

Elimination of Left Recursion Code

arrange the non-terminals in some order $A_1, A_2, \ldots, A_n$.

for (each i from 1 to n) {

    for (each j from 1 to $i - 1$) {

        replace each production of the form $A_i \rightarrow A_j \gamma$ 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

    }

    eliminate the immediate left recursion among the A_i-productions

}

Elimination of Left Recursion

- Ex: $S \to Aa \mid b$

  $A \to Ac \mid Sd \mid \varepsilon$ (ε is harmless in this case)
- For $i = 1$, no immediate left recursion, nothing happens.
- For $i = 2$, substitute for $S \to Aa \mid b$ to get

  $A \to Ac \mid Aad \mid bd \mid \varepsilon$
- Then, eliminate the immediate left-recursion

  $S \to Aa \mid b$

  $A \to bdA' \mid A'$

  $A' \to cA' \mid adA' \mid \varepsilon$

Left Factoring

- When it is not clear which to choose directly:
  - $stmt \rightarrow$ **if** $stmt$ **then** $stmt$ **else** $stmt$

    $\quad | \;$ **if** $stmt$ **then** $stmt$
- Rewrite the production to defer the decision

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

$$A \rightarrow \alpha A'$$

$$A' \rightarrow \beta_1 \mid \beta_2$$

Left Factoring Algorithm

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

$$A \rightarrow \alpha A' \mid \gamma$$

$$A' \rightarrow \beta_1 \mid \beta_2 \mid \dots \mid \beta_n$$

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

Left Factoring Example

- For dangling else problem:

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

$$E \rightarrow b$$

becomes:

$$S \rightarrow i\ E\ t\ S\ S' \mid a$$

$$S' \rightarrow e\ S \mid \varepsilon$$

$$E \rightarrow b$$

- Both are ambiguous

Non-Context-Free Language Constructs

- Skipped (Section 4.3.5)