CSE 309 (Compilers)

Basic Concepts of Parsing in Compiler

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Top-Down Parsing

- We introduce top-down parsing by considering a grammar that is well-suited for this class of methods.

Top-Down Parsing — *continued*

$$
\begin{array}{lcl}
stmt & \rightarrow & \textbf{expr} \; \textbf{;} \\
 & | & \textbf{if} \; (\; \textbf{expr} \;) \; stmt \\
 & | & \textbf{for} \; (\; optexpr \; \textbf{;} \; optexpr \; \textbf{;} \; optexpr \;) \; stmt \\
 & | & \textbf{other} \\
 & & \\
optexpr & \rightarrow & \epsilon \\
 & | & \textbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

- The grammar generates a subset of the statements of C or Java.
- We use the boldface terminals **if** and **for** for the keywords "if" and "for", respectively, to emphasize that these character sequences are treated as units, *i.e.*, as single terminal symbols.

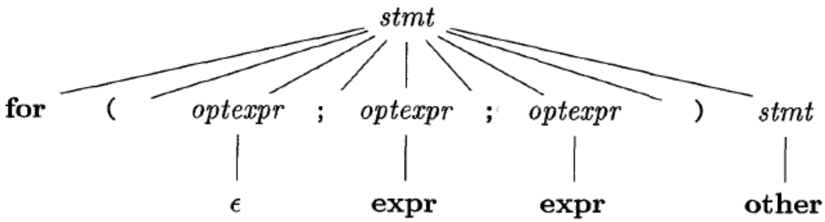
Top-Down Parsing — *continued*

$$
\begin{array}{lcl}
\mathit{stmt} & \rightarrow & \textbf{expr} \; ; \\
 & | & \textbf{if} \; (\; \textbf{expr} \;) \; \mathit{stmt} \\
 & | & \textbf{for} \; (\; \mathit{optexpr} \; ; \; \mathit{optexpr} \; ; \; \mathit{optexpr} \;) \; \mathit{stmt} \\
 & | & \textbf{other} \\
 & & \\
\mathit{optexpr} & \rightarrow & \epsilon \\
 & | & \textbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

- Further, the terminal **expr** represents expressions.
- A more complete grammar would use a nonterminal *expr* and have productions for nonterminal *expr*.
- Similarly, **other** is a terminal representing other statement constructs.

Top-Down Parsing — *continued*



A parse tree according to the grammar

- The top-down construction of a parse tree is done by starting with the root, labeled with the starting nonterminal *stmt*, and repeatedly performing the following two steps.

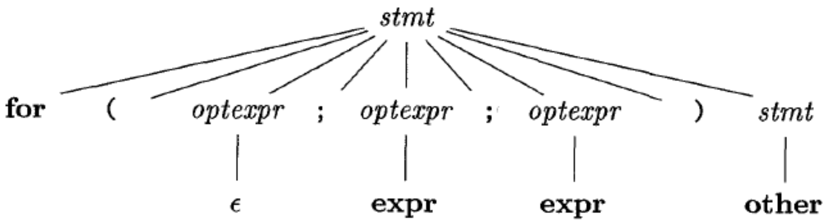
Top-Down Parsing — *continued*

$$
\begin{array}{rcl}
stmt & \rightarrow & \textbf{expr} \; \textbf{;} \\
 & | & \textbf{if} \; (\; \textbf{expr} \;) \; stmt \\
 & | & \textbf{for} \; (\; optexpr \; ; \; optexpr \; ; \; optexpr \;) \; stmt \\
 & | & \textbf{other}
\end{array}
$$

$$
\begin{array}{rcl}
optexpr & \rightarrow & \epsilon \\
 & | & \textbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

- The top-down construction of a parse tree is done by starting with the root, labeled with the starting nonterminal *stmt*, and repeatedly performing the following two steps.



A parse tree according to the grammar

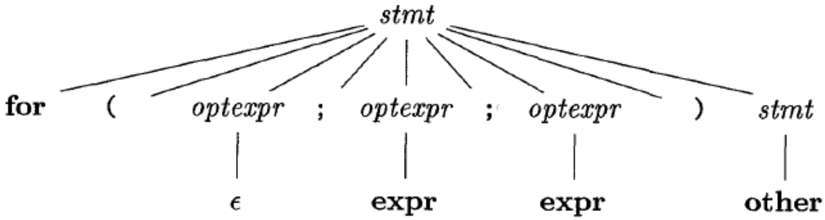
1. At node N, labeled with nonterminal A, select one of the productions for A and construct children at N for the symbols in the production body.

$$
\begin{array}{lcl}
\mathit{stmt} & \rightarrow & \textbf{expr} \ ; \\
 & | & \textbf{if} \ (\ \textbf{expr} \ ) \ \mathit{stmt} \\
 & | & \textbf{for} \ (\ \mathit{optexpr} \ ; \ \mathit{optexpr} \ ; \ \mathit{optexpr} \ ) \ \mathit{stmt} \\
 & | & \textbf{other} \\
\\
\mathit{optexpr} & \rightarrow & \epsilon \\
 & | & \textbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

1. At node N, labeled with nonterminal A, select one of the productions for A and construct children at N for the symbols in the production body.

Top-Down Parsing — *continued*



A parse tree according to the grammar

2. Find the next node at which a subtree is to be constructed, typically the leftmost unexpanded nonterminal of the tree.

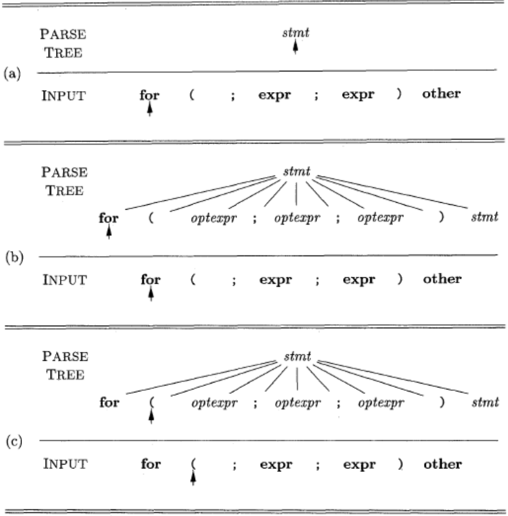
$$
\begin{array}{lcl}
stmt & \rightarrow & \mathbf{expr}\ ; \\
 & | & \mathbf{if}\ (\ \mathbf{expr}\ )\ stmt \\
 & | & \mathbf{for}\ (\ optexpr\ ;\ optexpr\ ;\ optexpr\ )\ stmt \\
 & | & \mathbf{other} \\
 & & \\
optexpr & \rightarrow & \epsilon \\
 & | & \mathbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

2. Find the next node at which a subtree is to be constructed, typically the leftmost unexpanded nonterminal of the tree.

Top-Down Parsing — *continued*

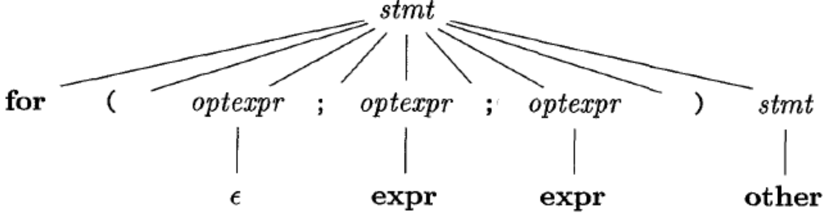
- For some grammars, the above steps can be implemented during a single left-to-right scan of the input string.
- The current terminal being scanned in the input is frequently referred to as the *lookahead* symbol.
- Initially, the lookahead symbol is the first, *i.e.*, leftmost terminal of the input string.



Top-down parsing while scanning the input from left to right

- Figure illustrates the construction of the parse tree in for the input string

  for (; **expr** ; **expr**) **other**

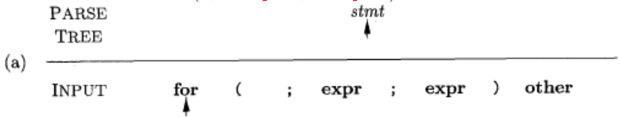


A parse tree according to the grammar

- Figure illustrates the construction of the parse tree in for the input string

  for (; **expr** ; **expr**) **other**

for (; expr ; expr) other

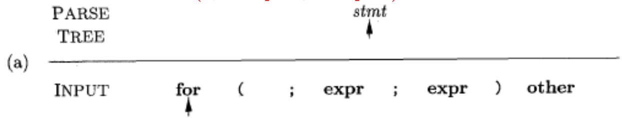


$$
\begin{array}{lcl}
\mathit{stmt} & \rightarrow & \textbf{expr} \; ; \\
 & | & \textbf{if} \; (\; \textbf{expr} \;) \; \mathit{stmt} \\
 & | & \textbf{for} \; (\; \mathit{optexpr} \; ; \; \mathit{optexpr} \; ; \; \mathit{optexpr} \;) \; \mathit{stmt} \\
 & | & \textbf{other} \\
 & & \\
\mathit{optexpr} & \rightarrow & \epsilon \\
 & | & \textbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

- Initially, the terminal **for** is the lookahead symbol, and the known part of the parse tree consists of the root, labeled with the starting nonterminal *stmt*.
- The objective is to construct the remainder of the parse tree in such a way that the string generated by the parse tree matches the input string.

for (; expr ; expr) other

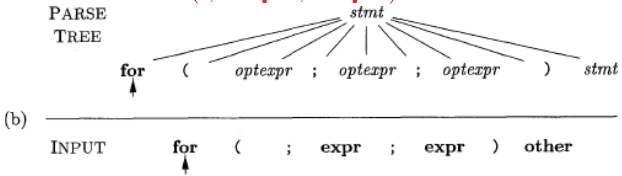


$$
\begin{array}{lcl}
\mathit{stmt} & \rightarrow & \textbf{expr} \; ; \\
& | & \textbf{if} \; (\; \textbf{expr} \;) \; \mathit{stmt} \\
& | & \textbf{for} \; (\; \mathit{optexpr} \; ; \; \mathit{optexpr} \; ; \; \mathit{optexpr} \;) \; \mathit{stmt} \\
& | & \textbf{other} \\
\\
\mathit{optexpr} & \rightarrow & \epsilon \\
& | & \textbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

- For a match to occur, the nonterminal *stmt* in must derive a string that starts with the lookahead symbol **for**.
- In the grammar, there is just one production for *stmt* that can derive such a string, so we select it, and construct the children of the root labeled with the symbols in the production body.
- This expansion of the parse tree is shown in (b).

for (; expr ; expr) other



$$
\begin{array}{lcl}
\textit{stmt} & \rightarrow & \textbf{expr} \; ; \\
& | & \textbf{if} \; (\; \textbf{expr} \;) \; \textit{stmt} \\
& | & \textbf{for} \; (\; \textit{optexpr} \; ; \; \textit{optexpr} \; ; \; \textit{optexpr} \;) \; \textit{stmt} \\
& | & \textbf{other} \\
\\
\textit{optexpr} & \rightarrow & \epsilon \\
& | & \textbf{expr}
\end{array}
$$

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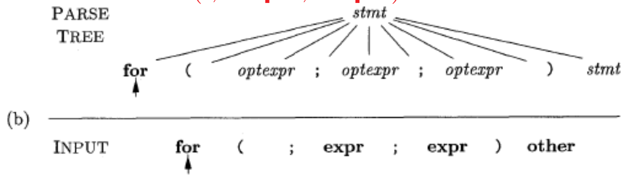


$$
\begin{array}{lcl}
\mathit{stmt} & \rightarrow & \textbf{expr}\ ; \\
 & | & \textbf{if}\ (\ \textbf{expr}\ )\ \mathit{stmt} \\
 & | & \textbf{for}\ (\ \mathit{optexpr}\ ;\ \mathit{optexpr}\ ;\ \mathit{optexpr}\ )\ \mathit{stmt} \\
 & | & \textbf{other} \\
 & & \\
\mathit{optexpr} & \rightarrow & \epsilon \\
 & | & \textbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

- Each of the three snapshots has arrows marking the lookahead symbol in the input and the node in the parse tree that is being considered.
- Once children are constructed at a node, we next consider the leftmost child.
- In (b), children have just been constructed at the root, and the leftmost child labeled with for is being considered.

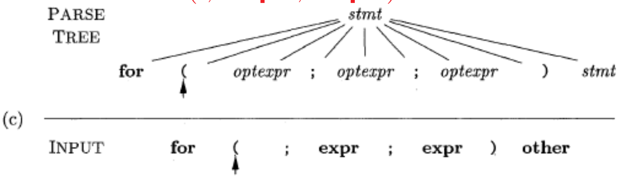
for (; expr ; expr) other

$$
\begin{array}{lcl}
\mathit{stmt} & \rightarrow & \textbf{expr} \ ; \\
 & | & \textbf{if} \ (\ \textbf{expr} \ ) \ \mathit{stmt} \\
 & | & \textbf{for} \ (\ \mathit{optexpr} \ ; \ \mathit{optexpr} \ ; \ \mathit{optexpr} \ ) \ \mathit{stmt} \\
 & | & \textbf{other} \\
 & & \\
\mathit{optexpr} & \rightarrow & \epsilon \\
 & | & \textbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

- When the node being considered in the parse tree is for a terminal, and the terminal matches the lookahead symbol, then we advance in both the parse tree and the input.
- The next terminal in the input becomes the new lookahead symbol, and the next child in the parse tree is considered.

for (; expr ; expr) other

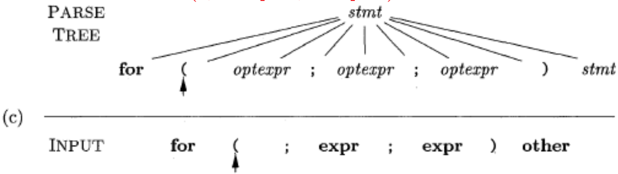


$$
\begin{array}{lcl}
stmt & \rightarrow & \mathbf{expr}\ ; \\
 & | & \mathbf{if}\ (\ \mathbf{expr}\ )\ stmt \\
 & | & \mathbf{for}\ (\ optexpr\ ;\ optexpr\ ;\ optexpr\ )\ stmt \\
 & | & \mathbf{other} \\
 & & \\
optexpr & \rightarrow & \epsilon \\
 & | & \mathbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

- In (c), the arrow in the parse tree has advanced to the next child of the root, and the arrow in the input has advanced to the next terminal, which is (.
- A further advance will take the arrow in the parse tree to the child labeled with nonterminal *optexpr* and take the arrow in the input to the terminal ;.

for (; expr ; expr) other

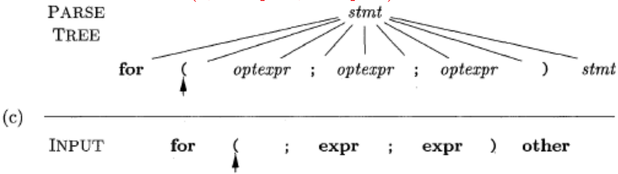


$$
\begin{array}{lcl}
\textit{stmt} & \rightarrow & \textbf{expr} \; ; \\
& | & \textbf{if} \; (\; \textbf{expr} \;) \; \textit{stmt} \\
& | & \textbf{for} \; (\; \textit{optexpr} \; ; \; \textit{optexpr} \; ; \; \textit{optexpr} \;) \; \textit{stmt} \\
& | & \textbf{other} \\
\\
\textit{optexpr} & \rightarrow & \epsilon \\
& | & \textbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

- At the nonterminal node labeled *optexpr*, we repeat the process of selecting a production for a nonterminal.
- Productions with ϵ as the body ("ϵ-productions") require special treatment.
- For the moment, we use them as a default when no other production can be used.

for (; expr ; expr) other



- With nonterminal *optexpr* and lookahead ;, the ϵ-production is used, since ; does not match the only other production for *optexpr*, which has terminal **expr** as its body.

$$
\begin{array}{lcl}
\textit{stmt} & \rightarrow & \textbf{expr} \; ; \\
& | & \textbf{if} \; (\; \textbf{expr} \;) \; \textit{stmt} \\
& | & \textbf{for} \; (\; \textit{optexpr} \; ; \; \textit{optexpr} \; ; \; \textit{optexpr} \;) \; \textit{stmt} \\
& | & \textbf{other} \\
\\
\textit{optexpr} & \rightarrow & \epsilon \\
& | & \textbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

Top-Down Parsing — *continued*

- In general, the selection of a production for a nonterminal may involve trial- and-error.
- That is, we may have to try a production and backtrack to try another production if the first is found to be unsuitable.
- A production is unsuitable if, after using the production, we cannot complete the tree to match the input string.
- Backtracking is not needed, however, in an important special case called predictive parsing.

Predictive Parsing

- Recursive-descent parsing is a top-down method of syntax analysis in which a set of recursive procedures is used to process the input.
- One procedure is associated with each nonterminal of a grammar.
- Here, we consider a simple form of recursive-descent parsing, called predictive parsing, in which the lookahead symbol unambiguously determines the flow of control through the procedure body for each nonterminal.
- The sequence of procedure calls during the analysis of an input string implicitly defines a parse tree for the input, and can be used to build an explicit parse tree, if desired.

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- The sequence of procedure calls during the analysis of an input string implicitly defines a parse tree for the input, and can be used to build an explicit parse tree, if desired.

```
void stmt() {
      switch ( lookahead ) {
      case expr:
            match(expr); match(';'); break;
      case if:
            match(if); match('('); match(expr); match(')'); stmt();
            break;
      case for:
            match(for); match('(');
            optexpr(); match(';'); optexpr(); match(';'); optexpr();
            match(')'); stmt(); break;
      case other;
            match(other); break;
      default:
            report("syntax error");
      }
}

void optexpr() {
      if ( lookahead == expr ) match(expr);
}

void match(terminal t) {
      if ( lookahead == t ) lookahead = nextTerminal;
      else report("syntax error");
}
```

Pseudocode for a predictive parser

- The predictive parser consists of procedures for the nonterminals *stmt* and *optexpr* of the grammar and an additional procedure *match*, used to simplify the code for *stmt* and *optexpr*.

$$
\begin{array}{lcl}
stmt & \rightarrow & \textbf{expr} \; ; \\
 & | & \textbf{if} \; (\; \textbf{expr} \;) \; stmt \\
 & | & \textbf{for} \; (\; optexpr \; ; \; optexpr \; ; \; optexpr \;) \; stmt \\
 & | & \textbf{other} \\
 & & \\
optexpr & \rightarrow & \epsilon \\
 & | & \textbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

- The predictive parser consists of procedures for the nonterminals *stmt* and *optexpr* of the grammar and an additional procedure *match*, used to simplify the code for *stmt* and *optexpr*.

Predictive Parsing — *continued*

```
void match(terminal t) {
        if ( lookahead == t ) lookahead = nextTerminal;
        else report("syntax error");
}
```

- Procedure *match*(t) compares its argument t with the lookahead symbol and advances to the next input terminal if they match.
- Thus match changes the value of variable *lookahead*, a global variable that holds the currently scanned input terminal.

```
void stmt() {
        switch ( lookahead ) {
        case expr:
                match(expr); match(';'); break;
        case if:
                match(if); match('('); match(expr); match(')'); stmt();
                break;
        case for:
                match(for); match('(');
                optexpr(); match(';'); optexpr(); match(';'); optexpr();
                match(')'); stmt(); break;
        case other;
                match(other); break;
        default:
                report("syntax error");
        }
}
```

- Parsing begins with a call of the procedure for the starting nonterminal stmt.

```
void stmt() {
        switch ( lookahead ) {
        case expr:
                match(expr); match(';'); break;
        case if:
                match(if); match('('); match(expr); match(')'); stmt();
                break;
        case for:
                match(for); match('(');
                optexpr(); match(';'); optexpr(); match(';'); optexpr();
                match(')'); stmt(); break;
        case other;
                match(other); break;
        default:
                report("syntax error");
        }
}
```

- With the input **for** (; **expr** ; **expr**) **other**, lookahead is initially the first terminal **for.**

```
void stmt() {
        switch ( lookahead ) {
        case expr:
                match(expr); match(';'); break;
        case if:
                match(if); match('('); match(expr); match(')'); stmt();
                break;
        case for:
                match(for); match('(');
                optexpr(); match(';'); optexpr(); match(';'); optexpr();
                match(')'); stmt(); break;
        case other;
                match(other); break;
        default:
                report("syntax error");
        }
}
```

- Procedure *stmt* executes code corresponding to the production

$$stmt \rightarrow \textbf{for}\ (\ optexpr\ ;\ optexpr\ ;\ optexpr\ )\ stmt$$

```
void stmt() {
    switch ( lookahead ) {
    case expr:
        match(expr); match(';'); break;
    case if:
        match(if); match('('); match(expr); match(')'); stmt();
        break;
    case for:
        match(for); match('(');
        optexpr(); match(';'); optexpr(); match(';'); optexpr();
        match(')'); stmt(); break;
    case other;
        match(other); break;
    default:
        report("syntax error");
    }
}
```

- In the code for the production body — that is, the **for** case of procedure *stmt*— each terminal is matched with the lookahead symbol.

```
void stmt() {
        switch ( lookahead ) {
        case expr:
                match(expr); match(';'); break;
        case if:
                match(if); match('('); match(expr); match(')'); stmt();
                break;
        case for:
                match(for); match('(');
                optexpr(); match(';'); optexpr(); match(';'); optexpr();
                match(')'); stmt(); break;
        case other;
                match(other); break;
        default:
                report("syntax error");
        }
}
```

- Each nonterminal leads to a call of its procedure, in the following sequence of calls:

  match(**for**); *match*('(');
  optexpr(); *match*(';'); *optexpr*(); *match*(';'); *optexpr*();
  match(')'); *stmt*();

Predictive Parsing — *continued*

- Predictive parsing relies on information about the first symbols that can be generated by a production body.
- More precisely, let α be a string of grammar symbols (terminals and/or nonterminals).
- We define FIRST(α) to be the set of terminals that appear as the first symbols of one or more strings of terminals generated from α.
- If α is ϵ or can generate ϵ, then ϵ is also in FIRST(α).

Predictive Parsing — *continued*

- Here, we shall just use ad hoc reasoning to deduce the symbols in FIRST(α).
- Typically, α will either begin with a terminal, which is therefore the only symbol in FIRST(α).
- Or α will begin with a nonterminal whose production bodies begin with terminals, in which case these terminals are the only members of FIRST(α).

Predictive Parsing — *continued*

$$
\begin{array}{lcl}
stmt & \rightarrow & \textbf{expr} \ ; \\
 & | & \textbf{if} \ (\ \textbf{expr} \ ) \ stmt \\
 & | & \textbf{for} \ (\ optexpr \ ; \ optexpr \ ; \ optexpr \ ) \ stmt \\
 & | & \textbf{other} \\
 & & \\
optexpr & \rightarrow & \epsilon \\
 & | & \textbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

- With respect to the grammar, the following are correct calculations of FIRST.
  - FIRST($stmt$) $= \{\textbf{expr}, \textbf{if}, \textbf{for}, \textbf{other}\}$
  - FIRST($\textbf{expr}$;) $= \{\textbf{expr}\}$

Predictive Parsing — *continued*

- The FIRST sets must be considered if there are two productions $A \to \alpha$, and $A \to \beta$.
- Ignoring ϵ-productions for the moment, predictive parsing requires FIRST(α) and FIRST(β) to be disjoint.
- The lookahead symbol can then be used to decide which production to use.
- If the lookahead symbol is in FIRST(α), then α is used.
- Otherwise, if the lookahead symbol is in FIRST(β), then β is used.

When to Use ϵ-Productions

void $optexpr()$ {
    if ($lookahead$ == **expr**) $match$(**expr**);
}

- Our predictive parser uses an ϵ-production as a default when no other production can be used.
- With the input **for** (; **expr** ; **expr**) **other**, after the terminals **for** and (are matched, the lookahead symbol is ;.

When to Use ϵ-Productions

void $optexpr()$ {
  if ($lookahead$ == **expr**) $match$(**expr**);
}

- At this point procedure *optexpr* is called, and the code
  if ($lookahead ==$ **expr**) $match$(**expr**);
  in its body is executed.

When to Use ϵ-Productions

void $optexpr()$ {
    if ($lookahead$ == **expr**) $match$(**expr**);
}

- Nonterminal *optexpr* has two productions, with bodies **expr** and ϵ.
- The lookahead symbol ";" does not match the terminal **expr**, so the production with body **expr** cannot apply.

When to Use ϵ-Productions

void $optexpr$() {
    if ($lookahead$ == **expr**) $match$(**expr**);
}

- In fact, the procedure returns without changing the lookahead symbol or doing anything else.
- Doing nothing corresponds to applying an ϵ-production.

When to Use ϵ-Productions — *continued*

- More generally, consider a variant of the productions where *optexpr* generates an expression nonterminal instead of the terminal **expr**:

$$\begin{array}{rcl} optexpr & \rightarrow & expr \\ & \mid & \epsilon \end{array}$$

- Thus, *optexpr* either generates an expression using nonterminal *expr* or it generates ϵ.
- While parsing *optexpr*, if the lookahead symbol is not in $\text{FIRST}(expr)$ then the ϵ-production is used.

Designing a Predictive Parser

- A predictive parser is a program consisting of a procedure for every nonterminal.
- The procedure for nonterminal A does two things.

1. It decides which A-production to use by examining the lookahead symbol.

   The production with body α (where α is not ϵ, the empty string) is used if the lookahead symbol is in FIRST(α).

   If there is a conflict between two nonempty bodies for any lookahead symbol, then we cannot use this parsing method on this grammar.

   In addition, the ϵ-production for A, if it exists, is used if the lookahead symbol is not in the FIRST set for any other production body for A.

Designing a Predictive Parser

- A predictive parser is a program consisting of a procedure for every nonterminal.
- The procedure for nonterminal A does two things.

2. The procedure then mimics the body of the chosen production.

   That is, the symbols of the body are “executed” in turn, from the left.

   A nonterrninal is “executed” by a call to the procedure for that nonterminal, and a terminal matching the lookahead symbol is “executed” by reading the next input symbol.

   If at some point the terminal in the body does not match the lookahead symbol, a syntax error is reported.

$$
\begin{array}{rcl}
stmt & \rightarrow & \textbf{expr}\ ; \\
 & | & \textbf{if}\ (\ \textbf{expr}\ )\ stmt \\
 & | & \textbf{for}\ (\ optexpr\ ;\ optexpr\ ;\ optexpr\ )\ stmt \\
 & | & \textbf{other}
\end{array}
$$

$$
\begin{array}{rcl}
optexpr & \rightarrow & \epsilon \\
 & | & \textbf{expr}
\end{array}
$$

A grammar for some statements in C and Java

```
void stmt() {
        switch ( lookahead ) {
        case expr:
                match(expr); match(';'); break;
        case if:
                match(if); match('('); match(expr); match(')'); stmt();
                break;
        case for:
                match(for); match('(');
                optexpr(); match(';'); optexpr(); match(';'); optexpr();
                match(')'); stmt(); break;
        case other;
                match(other); break;
        default:
                report("syntax error");
        }
}

void optexpr() {
        if ( lookahead == expr ) match(expr);
}

void match(terminal t) {
        if ( lookahead == t ) lookahead = nextTerminal;
        else report("syntax error");
}
```

Pseudocode for a predictive parser

Designing a Predictive Parser — *continued*

- Just as a translation scheme is formed by extending a grammar, a syntax-directed translator can be formed by extending a predictive parser.
- The following limited construction suffices for the present:
  1. Construct a predictive parser, ignoring the actions in productions.
  2. Copy the actions from the translation scheme into the parser.

     If an action appears after grammar symbol X in production p, then it is copied after the implementation of X in the code for p.

     Otherwise, if it appears at the beginning of the production, then it is copied just before the code for the production body.

Designing a Predictive Parser — *continued*

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Left Recursion

- It is possible for a recursive-descent parser to loop forever.
- A problem arises with “left-recursive” productions like

  $$\textit{expr} \rightarrow \textit{expr} + \textit{term}$$

  where the leftmost symbol of the body is the same as the nonterminal at the head of the production.
- Suppose the procedure for expr decides to apply this production.
- The body begins with *expr* so the procedure for *expr* is called recursively.
- Since the lookahead symbol changes only when a terminal in the body is matched, no change to the input took place between recursive calls of *expr*.
- As a result, the second call to *expr* does exactly what the first call did, which means a third call to *expr*, and so on, forever.

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Left Recursion — *continued*

- A left-recursive production can be eliminated by rewriting the offending production.
- Consider a nonterminal A with two productions

  $$A \to A\alpha \mid \beta$$

  where α and β are sequences of terminals and nonterminals that do not start with A.
- For example, in

  $$\textit{expr} \to \textit{expr} + \textit{term} \mid \textit{term}$$

  nonterminal $A = \textit{expr}$, string $\alpha = +\textit{term}$, and string $\beta = \textit{term}$.

Left Recursion — *continued*

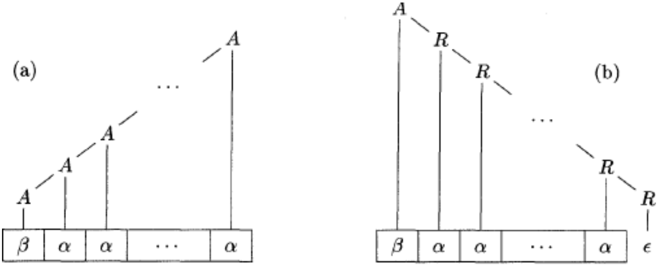
$$A \rightarrow A\alpha \mid \beta$$

- The nonterminal A and its production are said to be left recursive, because the production $A \rightarrow A\alpha$ has A itself as the leftmost symbol on the right side.

Left Recursion — *continued*

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

- Repeated application of this production builds up a sequence of α's to the right of A.



Left- and right-recursive ways of generating a string

- When A is finally replaced by β, we have β followed by a sequence of zero or more α's.

Left Recursion — *continued*

$$A \to A\alpha \mid \beta$$

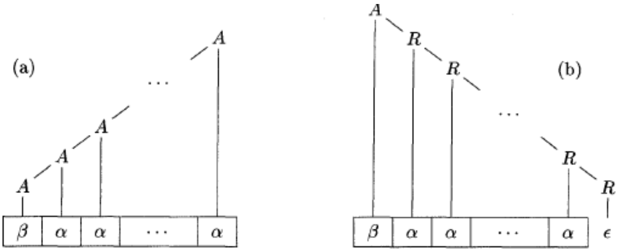
- The same effect can be achieved, by rewriting the productions for A in the following manner, using a new nonterminal R:

$$\begin{aligned} A &\to \beta R \\ R &\to \alpha R \mid \epsilon \end{aligned}$$

Left Recursion — *continued*

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

- Right-recursive productions lead to trees that grow down towards the right.



Left- and right-recursive ways of generating a string

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