TDDD16 Compilers and interpreters
TDDB44 Compiler Construction

# Syntax Analysis, Parsing

Peter Fritzson, Christoph Kessler,
IDA, Linköpings universitet, 2010.

## Parser

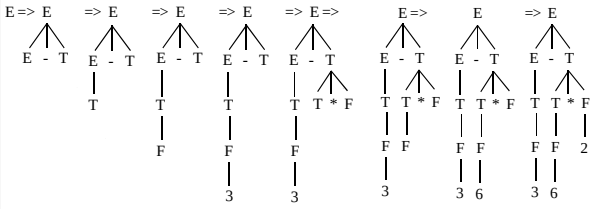
- A parser for a CFG (*Context-Free Grammar*) is a program which determines whether a string w is part of the language L(G).
- **Function**
  - Produces a parse tree if w ∈ L(G).
  - Calls semantic routines.
  - Manages syntax errors, generates error messages.
- **Input:**
  - String (finite sequence of tokens)
  - Input is read from left to right.
- **Output:**
  - Parse tree / error messages



## Top-Down Parsing

- Example: **Top-down** parsing with input: 3 - 6 * 2

  E → E - T | T
  T → T * F | F
  F → Integer | ( E )

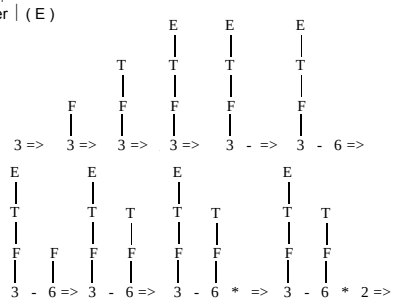





## Bottom-up Parsing

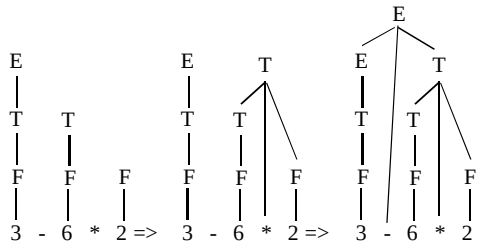
- Example: **Bottom-up** parsing with input: 3 - 6 * 2

  E → E - T | T (same CFG as in previous example)
  T → T * F | F
  F → Integer | ( E )






## Bottom-up Parsing cont.



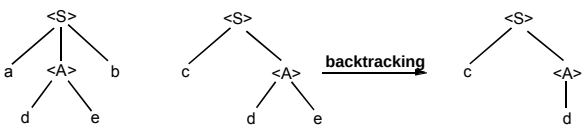



## Top-Down Analysis

- How do we know in which order the string is to be derived?
  - Use one or more tokens lookahead.
- Example: **Top-down analysis with backtracking**

  <S> → a <A> b *1 token lookahead works well*
  | c <A> *1 token lookahead works well*
  <A> → d e *test right side until something*
  | d *fits*

- a) adeb b) cd



## Top-down Analys with Backtracking, cont.

- Top-down analys with backtracking is implemented by writing a **procedure or a function for each nonterminal** whose task is to find one of its right sides:

```
bool A() {  /* A → d e | d */
  char* savep;
  savep = inpptr;

  if (*inpptr == 'd') {
    scan();  /* Get next token, move inpptr a step */
    if (*inpptr == 'e') {
      scan();
      return true;   /* 'de' found */
    }
  }
  inpptr = savep;
  /* 'de' not found, backtrack and try 'd'*/
  if (*inpptr == 'd') {
    scan(); return true;   /* 'd' found, OK */
  }
  return false;
}
```



## Top-down Analys with Backtracking, cont.

```
bool S() {  /* S -> a A b | c A */
  if (*inpptr == 'a') {
    scan();
    if A() {
      if (*inpptr == 'b') {
        scan();
        return true;
      } else return false;
    } else return false;
  }
  else if (*inpptr == 'c') {
    scan();
    if A() return true; else return false;
  }
  else return false;
}
```



## Construction of a top-down parser

- Write a procedure for each nonterminal.
- Call scan directly *after each token is consumed*.
  - Reason: The look-ahead token should be available
- Start by calling the procedure for the start symbol.

At each step check the leftmost non-treated vocabulary symbol.

- If it is a *terminal symbol*
  - Match it with the current token, and read the next token.
- If it is a *nonterminal symbol*
  - Call the routine for this nonterminal.
- In case of error call the error management routine.



## Example: An LL(1) grammar which describes binary numbers

S→ BinaryDigit BinaryNumber

BinaryNumber→ BinaryDigit BinaryNumber

| ε

BinaryDigit→ 0 | 1



## Sketch of a Top-Down Parser (recursive descent)

```
void TopDown(input,output) {

/* main program */
  scan();
  S();
  if not eof then error(...);
}
```

**Grammar:**

S→ BinaryDigit BinaryNumber
BinaryNumber→ BinaryDigit
BinaryNumber
| ε
BinaryDigit→ 0 | 1

```
void BinaryDigit()
{
  if (token==0 || token==1) scan();
  else error(...);
} /* BinaryDigit */

void BinaryNumber()
{
  if (token==0 || token==1)
  {
    BinaryDigit();
    BinaryNumber();
  } /* OK for the case with ε */
} /* B' */

void S()
{
  BinaryDigit();
  BinaryNumber();
} /* S */
```



## A Top-Down Parser that does not Work, Infinite Recursion:

```
void TopDown(input,output)
{

/* main program */
  scan();
  S();
  if not eof then error(...);
}
```

**Grammar:**

S→ BinaryDigit BinaryNumber
BinaryNumber→ BinaryNumber
BinaryDigit
| ε
BinaryDigit→ 0 | 1

```
void BinaryDigit()
{
  if (token==0 || token==1) scan();
  else error(...);
} /* BinaryDigit */

void BinaryNumber()
{
  if (token==0 || token==1)
  {
    BinaryNumber(); /*Infinite Recursion here */
    BinaryDigit();
  } /* OK for the case with ε */
} /* B' */

void S()
{
  BinaryDigit();
  BinaryNumber();
} /* S */
```

## Non-LL(1) Structures in a Grammar:

- Left recursion, example:

  E → E - T
  | T

- Productions for a nonterminal with the same prefix in two or more right-hand sides, example:

  arglist → ( )
  | ( args )

  *or*

  A → a b
  | a c

- The problem can be solved in most cases by rewriting the grammar to an LL(1) grammar



## Convert a grammar for top-down parsing?
### 1. Eliminate left recursion
### a) Transform the grammar to iterative form

EBNF (*Extended BNF) Notation:*

- {β} same as the regular expression: β*
- [β] same as the regular expression: β | ε
- ( ) left factoring, e.g. A → ab | ac in EBNF is rewritten: A → a (b | c)

**Transform the grammar to be iterative using EBNF**

- A → A α | β (where β may not be preceded by A)

in EBNF is rewritten:

- A → β {α}



## 1b) Transform the Grammar to Right Recursive Form Using a Rewrite Rule:

- A → A α | β (where β may not be preceded by A)

is rewritten to

A → β A'
A' → α A' | ε

Generally:

- A → A α1 | A α2 | ... | A αm | β1 | β2 | ... | βn (where β1, β2, ... may not be preceded by A)

is rewritten to:

A → β1 A' | β2 A' | ... | βn A'
A'→ α1 A' | α2 A' | ... | αm A' | ε



## 2. Left Factoring Using ( ) or [ ]

*Original Grammar:*

<stmt> → if <expr> then <stmt>
| if <expr> then <stmt> else <stmt>

*Solution using EBNF:*

<stmt> → if <expr> then <stmt>
[ else <stmt> ]

*Solution using rewriting:*

<stmt> → if <expr> then <stmt> <rest-if>
<rest_if> → else <stmt> | ε

*Original Grammar*

- A → ab | ac

*Solution using EBNF:*

- A → a (b | c)



## Summary LL(1) and Recursive Descent

**Summary of the LL(1) grammar:**

- Many CFGs are not LL(1)
- Some can be rewritten to LL(1)
- - The underlying structure is lost (because of rewriting).

**Two main methods for writing a top-down parser**

- Table-driven, LL(1)
- Recursive descent

| LL(1) | Recursive Descent |
|---|---|
| Table-driven | Hand-written |
| + fast | - Much coding, + fast |
| + Good error management and restart | + Easy to include semantic actions; good error mgmt |



## Small Rewriting Grammar Exercise

## Example: A recursive Descent Parser for Pascal Declarations, Orig. Grammar

<declarations> → <constdecl> <vardecl>
<constdecl> → CONST <consdeflist>
| ε
<consdeflist> → <consdeflist> <constdef>
| <constdef>
<constdef> → id = number ;
<vardecl> → VAR <vardeflist>
| ε
<vardeflist> → <vardeflist> <idlist> : <type> ;
| <idlist> : <type> ;
<idlist> → <idlist> , id
| id
<type> → integer
| real



## Rewrite in EBNF so that a Recursive Descent Parser can be Written

<declarations> → <constdecl> <vardecl>
<constdecl> → CONST <consdef> { <consdef> }
| ε
<constdef> → id = number ;
<vardecl> → VAR <vardef> { <vardef> }
| ε
<vardef> → id { , id } : ( integer | real ) ;



## A Recursive Descent Parser for the New Pascal Declarations Grammar in EBNF

- We have one character lookahead.
- scan should be called when we have consumed a character.

```
void declarations()
/*<declarations>→<constdecl><vardecl> */
{
  constdecl();
  vardecl();
} /* declarations */
```

```
void constdecl()
/* <constdecl> → CONST <consdef>
{ <consdef> }
| ε */
{
   if (token == CONST) {
     scan();
     If (token == id)
       constdef();
     else
       error("Missing id after CONST");

     while (token == id) constdef();
   }
} /* constdecl */
```



## Pascal Declarations Parser cont 1

```
void constdef()
/* <constdef> → id = number ; */
{
  scan(); /* consume ID, get next token */
  if (token == '=')
    scan();
  else
    error("Missing '=' after id");
  if (token == NUMBER) then
    scan();
  else
    error("Missing number");

  if (token == ';')
    scan(); /* consume ';', get next token */
  else
    error("Missing ';' after const decl");
} /* constdef */
```

```
void vardecl()
/* <vardecl> → VAR <vardef> { <vardef> }
|ε */
{
  If (token == VAR) {
    scan();

    if (token == ID)
      vardef();
    else
      error("Missing id after VAR");

   while (token == ID) {
      vardef();
    }

  }
} /* vardecl */
```



## Pascal Declarations Parser cont 2

```
void vardef() /* <vardef> → id { , id } : ( integer | real ) ; */
{
  scan();
  while (token == ',') {
    scan();
  if (token == ID)
    scan();
  else error("id expected after ',' ");
  } /* while */

  if (token == ':') {
    scan();
    if ((token == INTEGER) || (token == REAL))
      scan();
    else error("Incorrect type of variable");
    if (token ==';')
      scan();
    else error("Missing ';' in variable decl.");

  } else error("Missing ':' in var. decl.");
} /* vardef */
```

```
{ /* main */
  scan(); /* lookahead token */
  declarations();
  if (token!=eof_token) then error(...);
} /* main */
```



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# LL Parsing Issues Beyond Recursive Descent

**LL(*k*)**
**LL items**
**Finite pushdown automaton**
**FIRST and FOLLOW**
**Table-driven Predictive Parser**

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## LL(*k*)

- Given:
  - Context-free grammar G = ( N, Σ, P, S )
  - Integer $k > 0$
- G is (in) **LL(*k*)** if:
  for any two leftmost derivations
  - $S \Rightarrow^*_{lm} uY\alpha \Rightarrow u\beta\alpha \Rightarrow^* ux$ and
  - $S \Rightarrow^*_{lm} uY\alpha \Rightarrow u\gamma\alpha \Rightarrow^* uy$

  with $x[1{:}k] = y[1{:}k]$ — the *k* first tokens of *x* and *y* are equal

  it holds $\beta = \gamma$.
- That is, for fixed left context *u*, the choice for the "right" production to apply to Y is uniquely determined by the next *k* input tokens.



## Example

- The following grammar is LL(1)
  (terminals are bold-face):

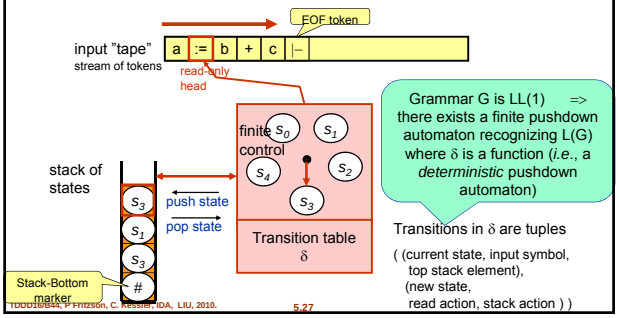
S -> **if ident then** S **else** S **fi**
| **while ident do** S **od**
| **begin** S **end**
| **ident** := **ident**



## Automaton Model for Parsing Context-Free Languages

**Finite pushdown automaton (FPA)**

- a finite automaton with a stack of states






## Context-Free Items

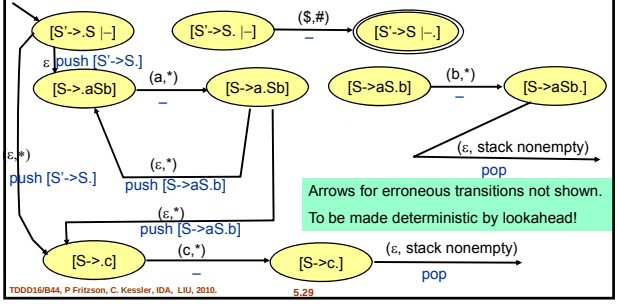
Given CFG G, construct states of the finite pushdown automaton:

- Add new start symbol S' with S' –> S |– (|– means End-of-Input)
- For each production A -> $\alpha_1 \ldots \alpha_k$ e.g. A -> aBc
  create k+1 **context-free items** (= states)
  - e.g., [A->.aBc], [A->a.Bc], [A->aB.c], [A->aBc.]
- Construct a **predictive parser** as finite pushdown automaton:
  - start in state [S'->.S |–] with empty stack (#)
  - halt and accept in state [S'->S |–.] with empty stack (#)
  - at [A->α.bγ]: read input symbol, i.e., [A->α.bγ] –> [A->αb.γ]
  - at [A->α.Bγ]: push [A->αB.γ],
    determine new production B–>β and start from [B->.β] — Prediction!
  - at [B->β.]: pop state [A->αB.γ] to restore context (if #, error)



## Example

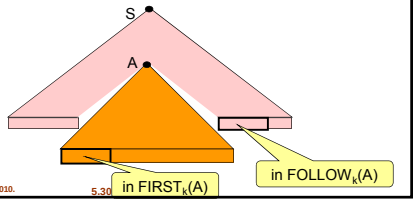
- Grammar with productions { S –> aSb | c }
- Add new start symbol S': { S' –> S; S –> aSb; S–>c }
- Transition diagram (showing stack actions below arrows):






## FIRST and FOLLOW

- For a sentential form α in $(N \cup S)^+$,
  FIRST(α) denotes the set of all terminals with can be ***first*** in a string derived from α.
- For a nonterminal A in N,
  FOLLOW(A) denotes the set of all terminals (e.g. a) that could appear immediately ***after*** A in a sentential form
  i.e., there exists $S \Rightarrow^* \alpha A a \beta$ for arbitrary α, β



## Small FIRST and FOLLOW Exercise



## Computing FIRST = FIRST$_1$

**For all grammar symbols X:**

- If X is a terminal, then FIRST(X) = { X }.
- If X → ε is a production, then add ε to FIRST(X).
- If X is a nonterminal and X → $Y_1$ $Y_2$ ... $Y_q$ is a production,
  - then place all those a of Σ in FIRST(X) where for some i, a is in FIRST($Y_i$) and ε is in all of FIRST($Y_1$), ..., FIRST($Y_{i-1}$) (that is, $Y_1$, ..., $Y_{i-1}$ all may derive ε).
  - If ε is in FIRST($Y_j$) for *all* j=1,2,...,q then add ε to FIRST(X).

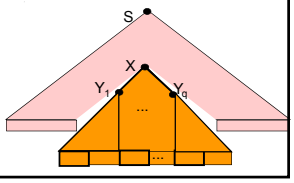
Apply these rules until no more terminals or ε can be added to any FIRST set.

For the example grammar
S' -> S; S -> aSb; S->c

FIRST(a) = {a}, FIRST(b) = {b}, FIRST(c) = {c}

FIRST(S') = FIRST(S)

FIRST(S) = { a, c }






## Computing FIRST (cont.)

**For any string $X_1$ $X_2$ ... $X_n$ of grammar symbols:**

- Add to FIRST( $X_1$ $X_2$ ... $X_n$ ) all non-ε symbols of FIRST($X_1$).
- If ε in FIRST(X1), add also all non-ε symbols of FIRST($X_2$), otherwise done.
- If ε also in FIRST($X_2$), add also all non-ε symbols of FIRST($X_3$), otherwise done.
- ...
- If ε also in FIRST($X_n$), add ε to FIRST($X_1$ $X_2$ ... $X_n$ )

For the example grammar
S' -> S; S -> aSb; S->c

FIRST(abc) = {a}

FIRST(Sb) = FIRST(S) = {a,c}



## Computing FOLLOW

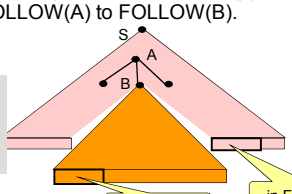
Compute FOLLOW(B) for each nonterminal B:

- Add |– to FOLLOW(S)
- If there is a production A –>* αBβ for arbitrary α, β then add all of FIRST(β) except ε to FOLLOW(B)
- If there is a production A –> αB, or a production A –> αBβ where ε in FIRST(β), i.e. β =>* ε, then add all of FOLLOW(A) to FOLLOW(B).

Apply these rules until no more terminals or ε can be added to any FOLLOW set.

For the example grammar
S -> aSb; S->c

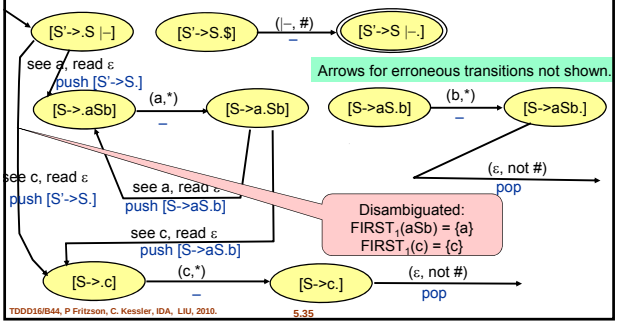
FOLLOW(S) = {|–, b}






## Example Cont.: Finite Pushdown Automaton (FPA) Made Deterministic

- Grammar with productions { S –> aSb | c }
- Added new start symbol S': { S' -> S |–; S -> aSb; S->c }






## Example (cont.): Transition table (*k*=1)

| state | final ? | lookahead a | lookahead b | lookahead c | lookahead |– |
|---|---|---|---|---|---|
| [S'->.S \|–] | no | push [S'->S.$]; [S->.aSb] | [Error] | push [S'->S.$]; [S->.c] | [Error] |
| [S'->S. \|–] | no | [Error] | [Error] | [Error] | read \|–; [S'->S \|–.] |
| [S'->S \|–.] | yes | | | | |
| [S->.aSb] | no | read a; [S->a.Sb] | [Error] | [Error] | [Error] |
| [S->a.Sb] | no | push [S->aS.b]; [S->.aSb] | [Error] | push [S->aS.b]; [S->.c] | [Error] |
| [S->aS.b] | no | [Error] | read b; [S->aSb.] | [Error] | [Error] |
| [S->aSb.] | no | [Error] | pop state | [Error] | pop state |
| [S->.c] | no | [Error] | [Error] | read c; [S->c.] | [Error] |
| [S->c.] | no | [Error] | pop state | [Error] | pop state |

## General Approach: Predictive Parsing

At any production A -> α

- If ε is not in FIRST(α)):
  - Parser expands by production A -> α
    if current lookahead input symbol is in FIRST(α).
- otherwise (i.e., ε in FIRST(α)):
  - Expand by production A -> α
    if current lookahead symbol is in FOLLOW(A)
    or if it is |– and |– is in FOLLOW(A).

Use these rules to fill the transition table.
(pseudocode: see [ASU86] p. 190, [ALSU06] p. 224)



## Summary: Parsing LL(*k*) Languages

- **Predictive LL parser**
  - iterative, based on finite pushdown automaton
  - transition-table-driven
  - can be generated automatically
- **Recursive-descent parser**
  - recursive
  - manually coded
  - easier to fix intermediate code generation, error handling
- **Both require lookahead** (or backtracking)
  to predict the next production to apply
  - Removes nondeterminism
  - Necessary checks derived from FIRST and FOLLOW sets
  - FIRST and FOLLOW are also useful for syntax error recovery



## Homework

- Now, read again the part on recursive descent parsers
  and find the equivalent of
  - Context-free items (Pushdown automaton (PDA) states)
  - The stack of states
  - Pushing a state to stack
  - Popping a state from stack
  - Start state, final state

  in a recursive descent parser.