



3. Parsing

3.1 Context-Free Grammars

3.2 Recursive Descent Parsing

3.3 LL(1) Property

3.4 Error Handling



Context-Free Grammars

Problem

Regular Grammars cannot handle central recursion

$$E = x \mid (" E ") .$$

For such cases we need context-free grammars

Definition

A grammar is called *context-free* (CFG) if all its productions have the following form:

$$X = \alpha. \quad X \in \text{NTS}, \alpha \text{ sequence of TS and NTS}$$

In EBNF, α can also contain the meta symbols |, (), [] and {}

Example

Expr = Term {("+" | "-") Term}.

Term = Factor {("*" | "/") Factor}.

Factor = id | "(" Expr ")".

indirect central recursion

Limitations of Context-Free Grammars



CFGs cannot express *context conditions*

For example:

- ***Each name must be declared before it is used***

The declaration belongs to the context of the use; the statement

`x = 3;`

may be right or wrong, depending on its context

- ***The operands of an expression must have compatible types***

Types are specified in the declarations, which belong to the context of the use

Possible solutions

- ***Use context-sensitive grammars***

too complicated

- ***Check context conditions later during semantic analysis***

i.e. the syntax allows sentences for which the context conditions do not hold:

`int x; ... x = "three";` syntactically correct, semantically wrong

The error is detected during semantic analysis (not during syntax analysis).



Context Conditions

Semantic conditions that are specified for every production

For example in MicroJava

Statement = Designator "=" Expr ";".

- *Designator* must be a variable, an array element or an object field.
- The type of *Expr* must be assignment compatible with the type of *Designator*.

Factor = "new" ident "[" Expr "]".

- *ident* must denote a type.
- The type of *Expr* must be *int*.

Designator₁ = Designator₂ "[" Expr "]".

- *Designator₂* must be a variable, an array element or an object field.
- The type of *Designator₂* must be an array type.
- The type of *Expr* must be *int*.



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Recursive Descent Parsing

- Top-down parsing technique
- The syntax tree is build from the start symbol down to the sentence (top-down)

Example

grammar

$$X = a X c \mid b .$$

input

a b b c

start symbol

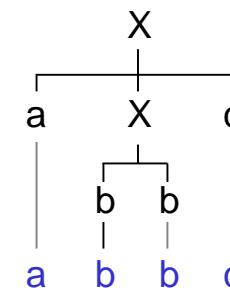
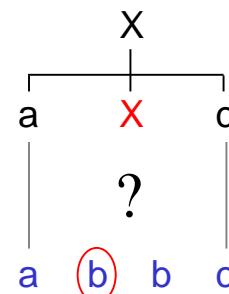
X

?

which
alternative
fits?

input

(a) b b c



The correct alternative is selected using ...

- the **lookahead token** from the input stream
- the **terminal start symbols** of the alternatives



Static Variables of the Parser

The parser is a class with static fields and methods

Lookahead token

At any moment the parser knows the next input token

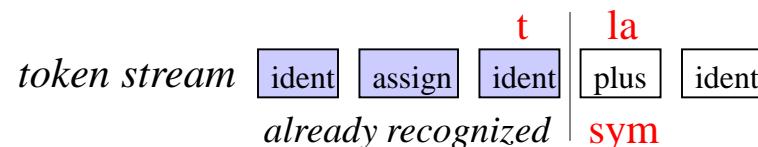
```
private static int sym; // token number of the lookahead token
```

The parser remembers two input tokens (for semantic processing)

```
private static Token t; // most recently recognized token  
private static Token la; // lookahead token (still unrecognized)
```

These variables are set by the method *scan()*

```
private static void scan() {  
    t = la;  
    la = Scanner.next();  
    sym = la.kind;  
}
```



scan() is called at the beginning of parsing \Rightarrow first token is in *sym*

How to Parse Terminal Symbols



Pattern

symbol to be parsed: a
parsing action: **check(a);**

Needs the following auxiliary methods

```
private static void check (int expected) {  
    if (sym == expected) scan(); // recognized => read ahead  
    else error( name[expected] + " expected" );  
}
```

```
private static void error (String msg) {  
    System.out.println("line " + la.line + ", col " + la.col + ": " + msg);  
    System.exit(1); // for a better solution see later  
}
```

```
private static String[] name = {"?", "identifier", "number", ..., "+", "-", ...};
```

ordered by
token codes

The names of the terminal symbols are declared as constants

```
static final int  
none = 0,  
ident = 1,  
...;
```

How to Parse Nonterminal Symbols



Pattern

symbol to be parsed: X
parsing action: **X();** // call the parsing method of X

Each nonterminal symbol is recognized by a parsing method with the same name

```
private static void X() {  
    ... parsing actions for the right-hand side of X ...  
}
```

Initialization of the MicroJava parser

```
public static void parse() {  
    scan();      // initializes la and sym  
    MicroJava(); // calls the parsing method of the start symbol  
    check.eof(); // at the end the input must be empty  
}
```

How to Parse Sequences

Pattern

production: $X = a \ Y \ c.$

parsing method:

```
private static void X() {  
    // sym contains a terminal start symbol of X  
    check(a);  
    Y();  
    check(c);  
    // sym contains a successor of X  
}
```

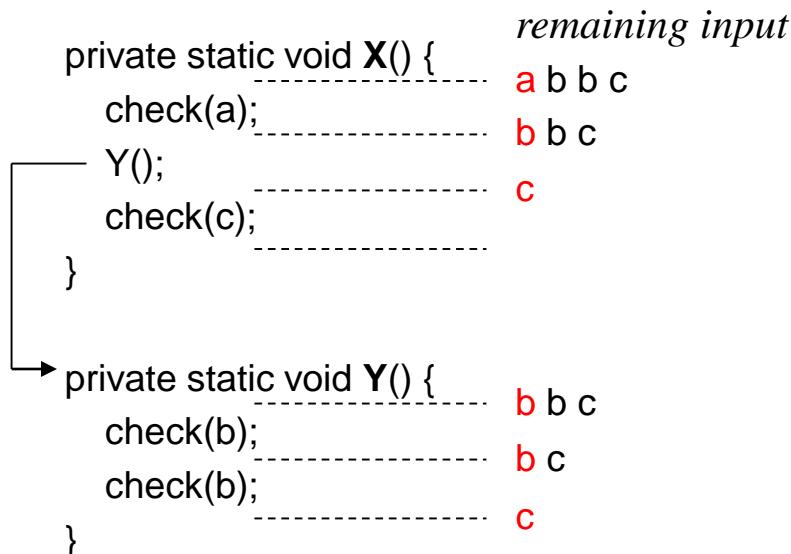
Simulation

$X = a \ Y \ c.$

$Y = b \ b.$

remaining input

```
private static void X() {  
    check(a);  
    Y();  
    check(c);  
}  
  
→ private static void Y() {  
    check(b);  
    check(b);  
}
```



How to Parse Alternatives



Pattern $\alpha \mid \beta \mid \gamma$ α, β, γ are arbitrary EBNF expressions

Parsing action

```
if (sym ∈ First(α)) { ... parse α ... }
else if (sym ∈ First(β)) { ... parse β ... }
else if (sym ∈ First(γ)) { ... parse γ ... }
else error("..."); // find a meaningful error message
```

Example

X = a Y | Y b.
Y = c | d.

First(aY) = {a}
First(Yb) = First(Y) = {c, d}

```
private static void X() {
    if (sym == a) {
        check(a);
        Y();
    } else if (sym == c || sym == d) {
        Y();
        check(b);
    } else error ("invalid start of X");
}
```

How to Parse EBNF Options



Pattern $[\alpha]$ α is an arbitrary EBNF expression

Parsing action $\text{if } (\text{sym} \in \text{First}(\alpha)) \{ \dots \text{parse } \alpha \dots \} // \text{no error branch!}$

Example

$X = [a\ b]\ c.$

```
private static void X() {  
    if (sym == a) {  
        check(a);  
        check(b);  
    }  
    check(c);  
}
```

Example: parse a b c
 parse c

How to Parse EBNF Iterations



Pattern $\{\alpha\}$ α is an arbitrary EBNF expression

Parsing action $\text{while } (\text{sym} \in \text{First}(\alpha)) \{ \dots \text{parse } \alpha \dots \}$

Example

```
X = a {Y} b.  
Y = c | d.
```

```
private static void X() {  
    check(a);  
    while (sym == c || sym == d) Y();  
    check(b);  
}
```

alternatively ...

```
private static void X() {  
    check(a);  
    while (sym != b) Y();  
    check(b);  
}
```

Example: parse a c d c b
parse a b

... but there is the danger of an endless loop,
if *b* is missing in the input

How to Deal with Large First Sets



If the set has 5 or more elements: use class *BitSet*

e.g.: $\text{First}(X) = \{a, b, c, d, e\}$
 $\text{First}(Y) = \{f, g, h, i, j\}$

First sets are initialized at the beginning of the parser

```
import java.util.BitSet;  
  
private static BitSet firstX = new BitSet();  
firstX.set(a); firstX.set(b); firstX.set(c); firstX.set(d); firstX.set(e);  
  
private static BitSet firstY = new BitSet();  
firstY.set(f); firstY.set(g); firstY.set(h); firstY.set(i); firstY.set(j);
```

Usage

$Z = X \mid Y$

```
private static void Z() {  
    if (firstX.get(sym)) X();  
    else if (firstY.get(sym)) Y();  
    else error("invalid Z");  
}
```

If the set has less than 5 elements: use explicit checks (which is faster)

e.g.: $\text{First}(X) = \{a, b, c\}$

```
if (sym == a || sym == b || sym == c) ...
```



Optimizations

Avoiding multiple checks

X = a | b.

unoptimized

```
private static void X() {  
    if (sym == a) check(a);  
    else if (sym == b) check(b);  
    else error("invalid X");  
}
```

optimized

```
private static void X() {  
    if (sym == a) scan(); // no check(a);  
    else if (sym == b) scan();  
    else error("invalid X");  
}
```

X = {a | Y d}.
Y = b | c.

unoptimized

```
private static void X() {  
    while (sym == a || sym == b || sym == c) {  
        if (sym == a) check(a);  
        else if (sym == b || sym == c) {  
            Y(); check(d);  
        } else error("invalid X");  
    }  
}
```

optimized

```
private static void X() {  
    while (sym == a || sym == b || sym == c) {  
        if (sym == a) scan();  
        else { // no check any more  
            Y(); check(d);  
        } // no error case  
    }  
}
```



Optimizations

More efficient scheme for parsing alternatives in an iteration

X = {a | Y d}.

like before

```
private static void X() {
    while (sym == a || sym == b || sym == c) {
        if (sym == a) scan();
        else {
            Y(); check(d);
        }
    }
}
```

optimized

```
private static void X() {
    for (;;) {
        if (sym == a) scan();
        else if (sym == b || sym == c) {
            Y(); check(d);
        } else break;
    }
}
```

no multiple checks on a

Computing Terminal Start Symbols Correctly



Grammar

```
X = Y a.  
Y = {b} c  
| [d]  
| e.
```

terminal start symbols
of alternatives

b and *c*

d and *a* (!)

e

```
Z = U e  
| f.  
U = {d}.
```

d and *e* (*U* is deletable!)

f

Parsing methods

```
private static void X() {  
    Y(); check(a);  
}
```

```
private static void Y() {  
    if (sym == b || sym == c) {  
        while (sym == b) scan();  
        check(c);  
    } else if (sym == d || sym == a) {  
        if (sym == d) scan();  
    } else if (sym == e) {  
        scan();  
    } else error("invalid Y");  
}
```

```
private static void Z() {  
    if (sym == d || sym == e) {  
        U(); check(e);  
    } else if (sym == f) {  
        scan();  
    } else error("invalid Z");  
}
```

```
private static void U() {  
    while (sym == d) scan();  
}
```



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LL(1) Property

Precondition for recursive descent parsing

LL(1) ... can be analyzed from Left to right
with Left-canonical derivations (leftmost NTS is derived first)
and 1 lookahead symbol

Definition

1. A grammar is LL(1) if all its productions are LL(1).
2. A production is LL(1) if for every list of alternatives in it

$$\alpha_1 \mid \alpha_2 \mid \dots \mid \alpha_n$$

the following condition holds:

$$\text{First}(\alpha_i) \cap \text{First}(\alpha_j) = \{ \} \quad (\text{for any } i \neq j)$$

In other words

- The terminal start symbols of all alternatives in a production must be pairwise disjoint.
- The parser must always be able to select one of the alternatives by looking at the lookahead token.



How to Remove LL(1) Conflicts

Factorization

```
IfStatement = "if" "(" Expr ")" Statement  
           | "if" "(" Expr ")" Statement "else" Statement.
```

Extract common start sequences

```
IfStatement = "if" "(" Expr ")" Statement (  
                           | "else" Statement  
                           ).
```

... or in EBNF

```
IfStatement = "if" "(" Expr ")" Statement ["else" Statement].
```

Sometimes nonterminal symbols must be inlined before factorization

```
Statement = Designator "=" Expr ";"  
           | ident "(" [ActualParameters] ")" ";".  
Designator = ident {"." ident}.
```

Inline *Designator* in *Statement*

```
Statement = ident {"." ident} "=" Expr ";"  
           | ident "(" [ActualParameters] ")" ";".
```

then factorize

```
Statement = ident ( {"." ident} "=" Expr ";"  
                     | "(" [ActualParameters] ")" ";"  
                     ).
```



How to Remove Left Recursion

Left recursion is always an LL(1) conflict

For example

```
IdentList = ident | IdentList "," ident.
```

generates the following phrases

```
ident  
ident "," ident  
ident "," ident "," ident  
...  
can always be replaced by iteration
```

```
IdentList = ident {" , " ident}.
```

Hidden LL(1) Conflicts



EBNF options and iterations are hidden alternatives

$X = [\alpha] \beta.$ \equiv $X = \alpha \beta \mid \beta.$ α and β are arbitrary EBNF expressions

Rules

$X = [\alpha] \beta.$ First(α) \cap First(β) must be $\{ \}$
 $X = \{\alpha\} \beta.$ First(α) \cap First(β) must be $\{ \}$

$X = \alpha [\beta].$ First(β) \cap Follow(X) must be $\{ \}$
 $X = \alpha \{\beta\}.$ First(β) \cap Follow(X) must be $\{ \}$

$X = \alpha \mid .$ First(α) \cap Follow(X) must be $\{ \}$

Removing Hidden LL(1) Conflicts



Name = [ident "."] ident.

Where is the conflict and how can it be removed?

Prog = Declarations ";" Statements.
Declarations = D {";" D}.

Where is the conflict and how can it be removed?

Dangling Else

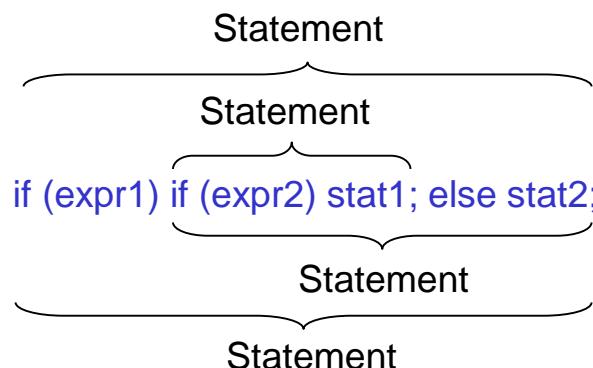
If statement in Java

```
Statement = "if" "(" Expr ")" Statement ["else" Statement]
          | ... .
```

This is an LL(1) conflict!

$$\text{First}(\text{"else" Statement}) \cap \text{Follow}(\text{Statement}) = \{ \text{"else"} \}$$

It is even an ambiguity which cannot be removed



We can build 2 different syntax trees!

LL(1) Conflicts are only warnings



What if we ignore them?

The parser will select the first matching alternative

$X = a \ b \ c$ ← if the lookahead token is an a the parser will select this alternative
| $a \ d.$ ← this alternative will never be entered!
this is an error that must be removed by transforming the grammar

Example: Dangling Else

Statement = "if" "(" Expr ")" Statement ["else" Statement]
|

If the lookahead token is "else" here
the parser starts parsing the option;
i.e. the "else" belongs to the innermost "if"

Luckily this is what we want here.



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Goals of Syntax Error Handling

Requirements

1. The parser should detect as many errors as possible in a single compilation
2. The parser should never crash (even in the case of abstruse errors)
3. Error handling should not slow down error-free parsing
4. Error handling should not inflate the parser code

Error handling techniques for recursive descent parsing

- Error handling with "panic mode"
- Error handling with "dynamically computed recovery sets"
- Error handling with "synchronization points"

Panic Mode



The parser gives up after the first error

```
private static void error (String msg) {  
    System.out.println("line " + la.line + ", col " + la.col + ": " + msg);  
    System.exit(1);  
}
```

Advantages

- cheap
- sufficient for small command languages or for interpreters

Disadvantages

- inappropriate for production-quality compilers

Recovery At Synchronization Points



Error recovery is only done at particularly "safe" positions

i.e. at positions where keywords are expected which do not occur at other positions in the grammar

For example

- start of Statement: `if, while, do, ...`
- start of Declaration: `public, static, void, ...`

anchors

Problem: *ident* can occur at both positions!

ident is not a safe anchor \Rightarrow omit it from the anchor set

Code that has to be inserted at synchronization points

```
...                                anchors at this synchronization point
if (sym  $\notin$  expectedSymbols) {
    error("... ");
    while (sym  $\notin$  (expectedSymbols  $\cup$  {eof})) scan();
}
...                                in order not to get into an endless loop
```

- Anchors (i.e. `expectedSymbols`) can be computed at compile time
- After an error the parser "stumbles ahead" until it reaches the next synchronization point



Example

Synchronization at the start of Statement

```
private static void Statement() {  
    if (!firstStat.get(sym)) {  
        error("invalid start of statement");  
        while (!syncStat.get(sym)) scan();  
    }  
    if (sym == if_) {  
        scan();  
        check(lpar); Expr(); check(rpar);  
        Statement();  
        if (sym == else_) { scan(); Statement(); }  
    } else if (sym == while_) {  
        ...  
    }  
}
```

`x = ...; y = ...; if; while; z = ...;`
 ▲▲▲▲
 synchronization points

}

the rest of the parser remains unchanged
(as if there were no error handling)

```
public static int errors = 0;  
public static void error (String msg) {  
    System.out.println(...);  
    errors++;  
}
```

```
static BitSet firstStat = new BitSet();  
firstStat.set(while_);  
firstStat.set(if_);  
...  
static BitSet syncStat = ...; // firstStat without ident  
// but with eof and rbrace
```

Suppressing Spurious Error Messages



While the parser moves from the error position to the next synchronization point it produces spurious error messages

Solved by a simple heuristics

An error is only reported if at least 3 tokens have been parsed correctly since the last error.

```
private static int errDist = 3; // no. of correctly parsed tokens since last error
```

```
private static void scan() {  
    ...  
    errDist++; // another token was recognized  
}
```

```
public static void error (String msg) {  
    if (errDist >= 3) {  
        System.out.println("line " + la.line + " col " + la.col + ": " + msg);  
        errors++;  
    }  
    errDist = 0; // counting is restarted  
}
```

Example of a Recovery

```

private static void Statement() {
    if (!firstStat.get(sym)) {
        error("invalid start of statement");
        while (!syncStat.get(sym)) scan();
        errDist = 0;
    }
    if (sym == if_) {
        scan();
        check(lpar); Condition(); check(rpar);
        Statement();
        if (sym == else_) { scan(); Statement(); }
        ...
    }
}

```

```

private static void check (int expected) {
    if (sym == expected) scan();
    else error(...);
}

```

```

private static void error (String msg) {
    if (errDist >= 3) {
        System.out.println(...);
        errors++;
    }
    errDist = 0;
}

```

erroneous input: if a > b , max = a; while ...

↑ (expected) ↑ expected recovery

<i>sym</i>	<i>action</i>
if	scan(); <i>if</i> ∈ <i>firstStat</i> ⇒ ok
ident _a	check(lpar); error: "(expected"
	Condition(); parses a > b
comma	check(rpar); error: ") expected"
	Statement(); <i>comma</i> does not match ⇒ error, but no error message
semicolon	skips ", max = a" and synchronizes with <i>semicolon</i> recovery successful!

Synchronization at the Start of an Iteration



For example

Block = "{" {Statement} "}".

Standard pattern in this case

```
private static void Block() {  
    check(lbrace);  
    while (sym ∈ First(Statement))  
        Statement();  
    check(rbrace);  
}
```

If the token after *lbrace* does not match *Statement* the loop is not entered. Synchronization point in *Statement* is not reached.

Thus

```
private static void Block() {  
    check(lbrace);  
    while (sym != rbrace && sym != eof)  
        Statement();  
    check(rbrace);  
}
```

← syncStat should include *rbrace*

Assessment



Error handling at synchronization points

Advantages

- + does not slow down error-free parsing
- + does not inflate the parser code
- + simple

Disadvantage

- needs experience and "tuning"



What you should do in the lab

1. Download *Parser.java* into the package *MJ* and see what it does.
2. Complete *Parser.java* according to the slides of the course.
Write a recursive descent parsing method for every production of the MicroJava grammar.
Compile *Parser.java*.
3. Download *TestParser.java*, compile it, and run it on *sample.mj*.
4. Extend *Parser.java* with an error recovery according to the slides of the course.
Add synchronisation points at the beginning of statements and declarations.
5. Download the MicroJava source program *BuggyParserInput.mj* and run *TestParser* on it.