Generating Compilers with Coco/R

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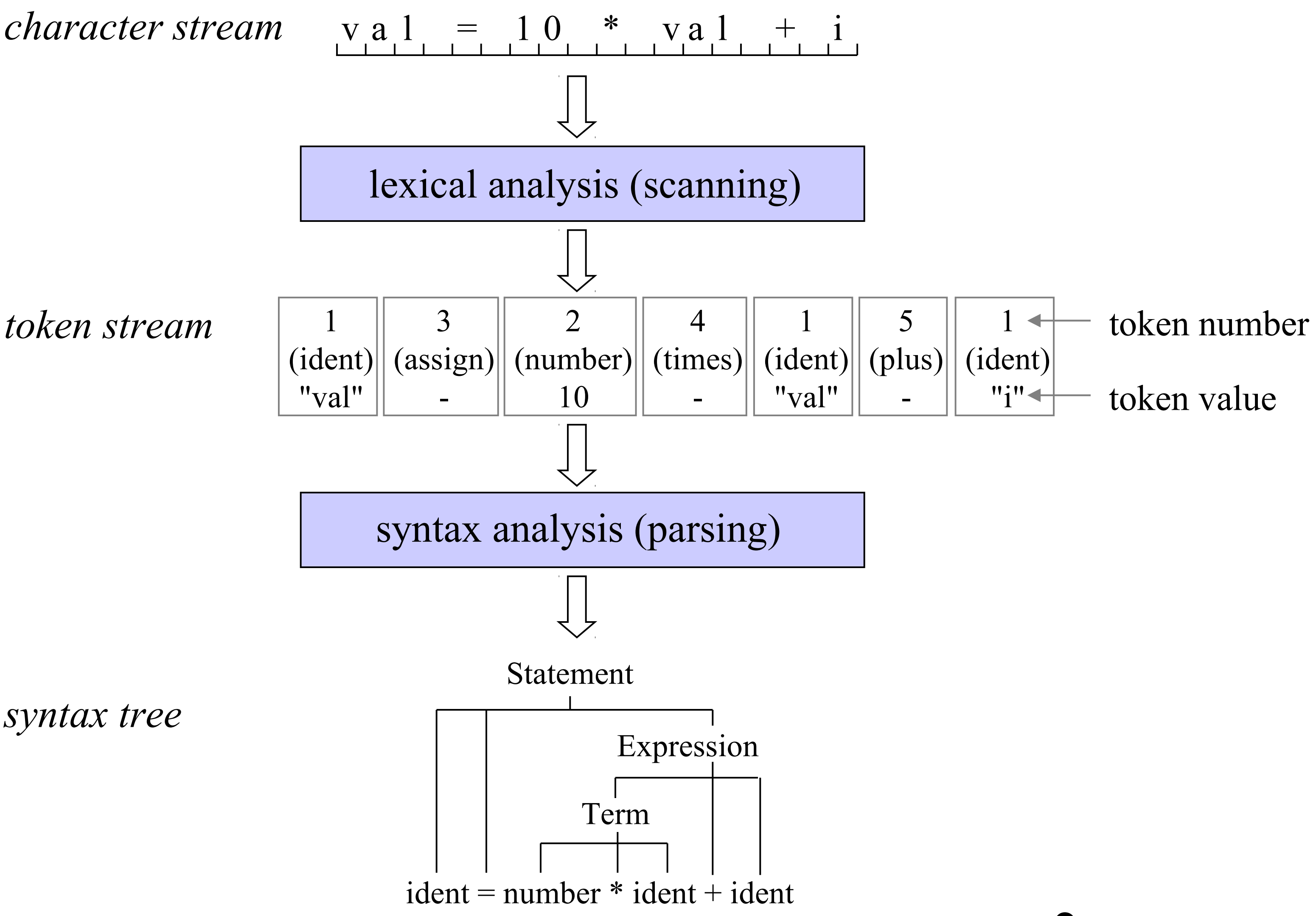
1. Compilers
2. Grammars
3. Coco/R Overview
4. Scanner Specification
5. Parser Specification
6. Error Handling
7. LL(1) Conflicts
8. Case Study

Compilation Phases



character stream

v a l = 1 0 * v a l + i

lexical analysis (scanning)

token stream

1	3	2	4	1	5	1	token number
(ident)	(assign)	(number)	(times)	(ident)	(plus)	(ident)	
"val"	-	10	-	"val"	-	"i"	token value

syntax analysis (parsing)

syntax tree

Statement

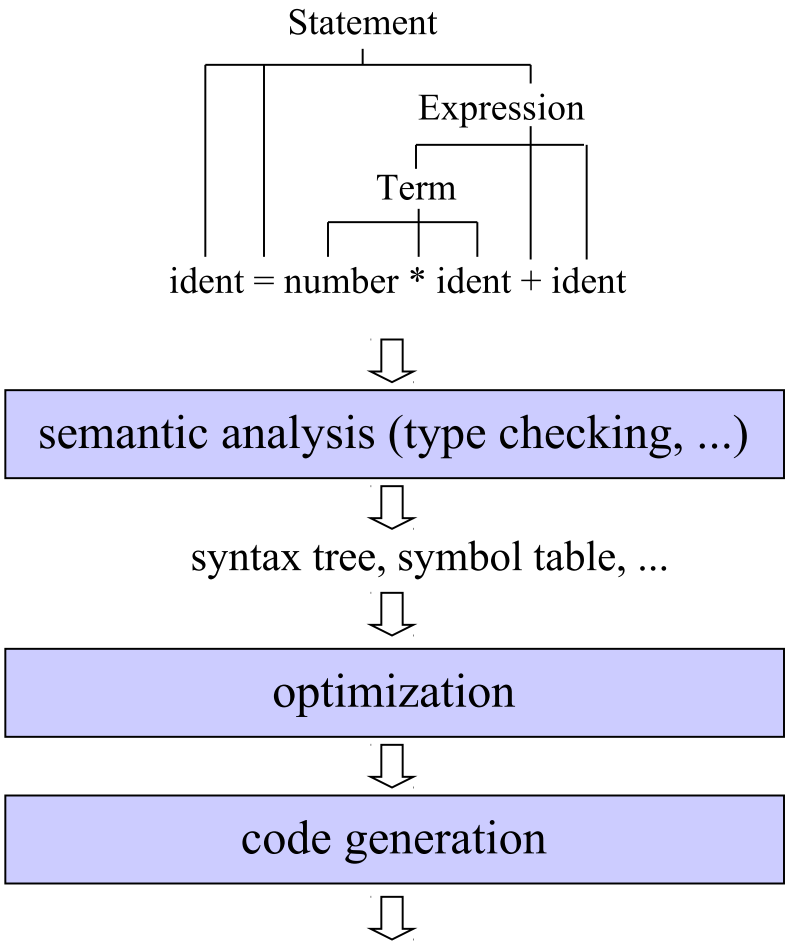
Expression

Term

ident = number * ident + ident

Compilation Phases

syntax tree

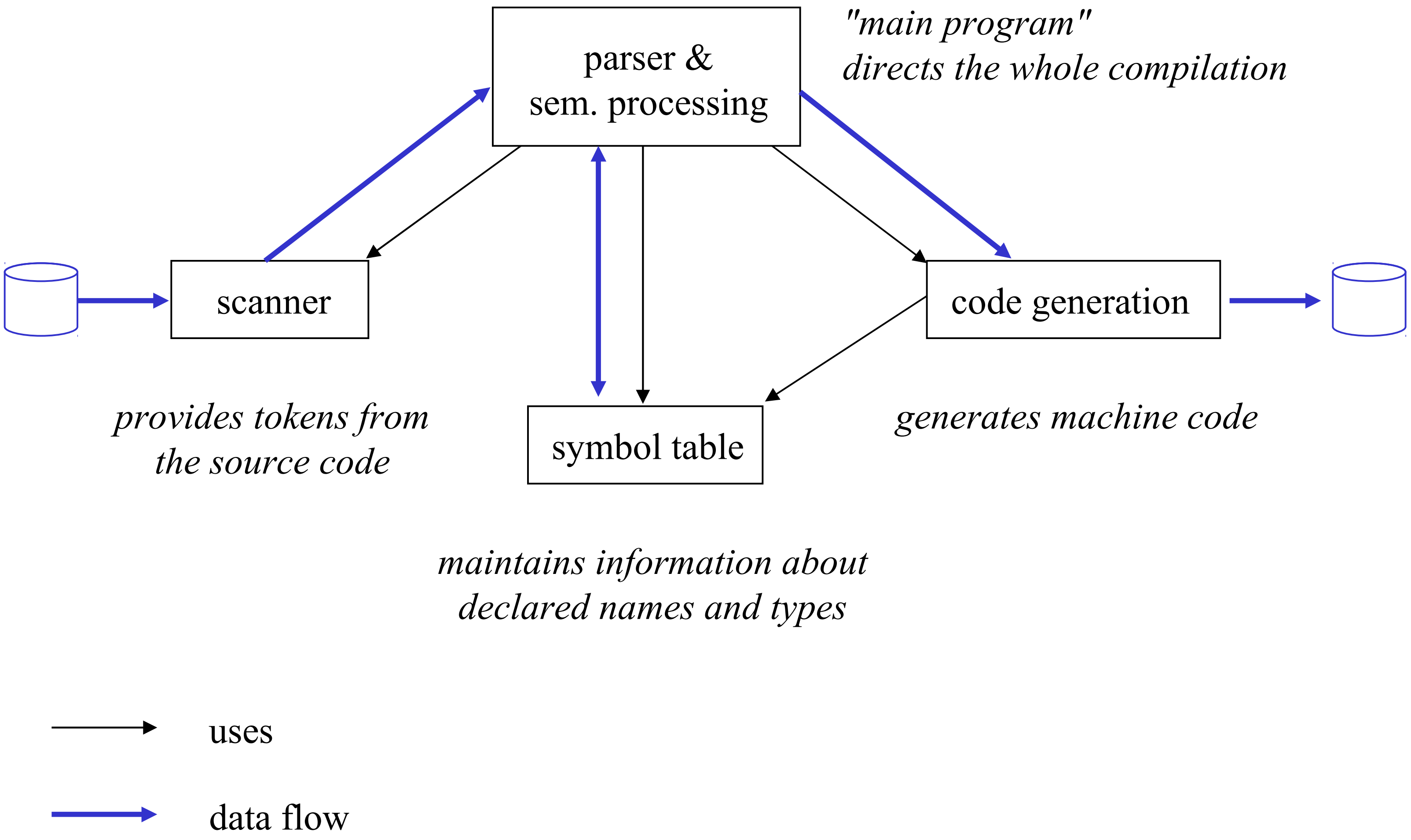

Statement
Expression
Term
ident = number * ident + ident
semantic analysis (type checking, ...)
syntax tree, symbol table, ...
optimization
code generation

intermediate representation

machine code

```
const 10
load  1
mul
...
```

Structure of a Compiler



parser & sem. processing

"main program" directs the whole compilation

scanner

provides tokens from the source code

symbol table

maintains information about declared names and types

code generation

generates machine code

uses

data flow

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What is a grammar?

Example Statement = "if" "(" Condition ")" Statement ["else" Statement].

Four components

terminal symbols	are atomic	"if", ">=", ident, number, ...
nonterminal symbols	are decomposed into smaller units	Statement, Condition, Type, ...

productions	rules how to decompose nonterminals	Statement = Designator "=" Expr ";".
		Designator = ident ["." ident].
		...

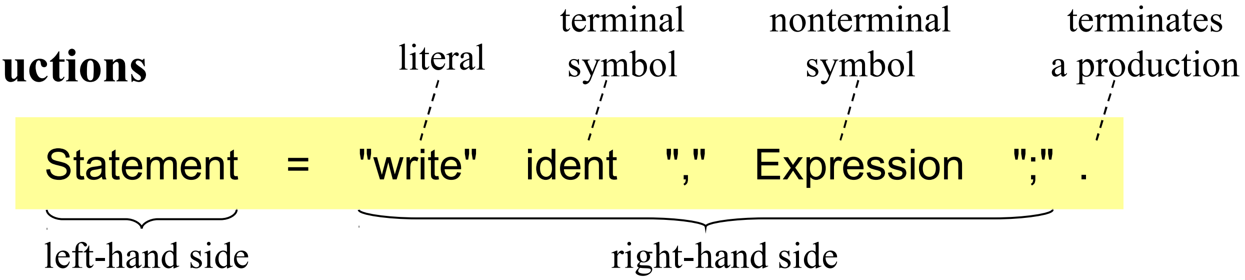
start symbol	topmost nonterminal	CSharp

EBNF Notation

Extended Backus-Naur form for writing grammars

John Backus: developed the first Fortran compiler
Peter Naur: edited the Algol60 report

Productions



Statement = "write" ident "," Expression ";" .

by convention

- terminal symbols start with lower-case letters
- nonterminal symbols start with upper-case letters

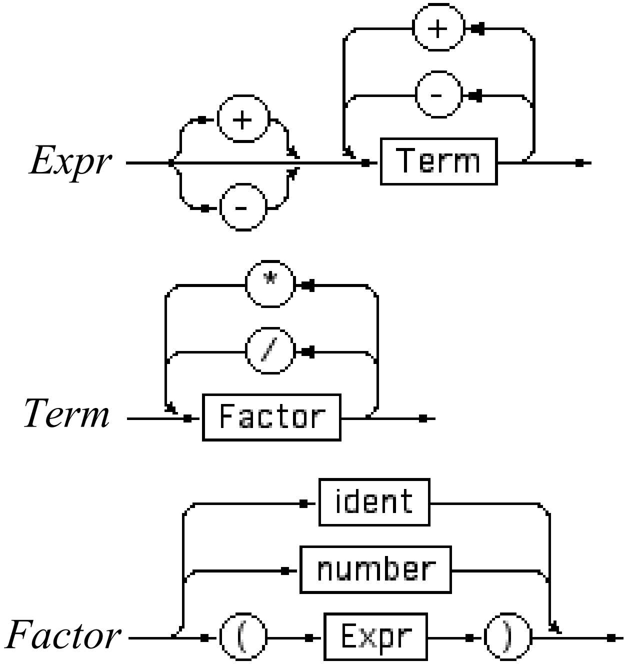
Metasymbols

|	separates alternatives	a | b | c	≡ a or b or c
(...)	groups alternatives	a (b | c)	≡ ab | ac
[...]	optional part	[a] b	≡ ab | b
{...}	iterative part	{a}b	≡ b | ab | aab | aaab | ...

Example: Grammar for Arithmetic Expressions

Productions

```
Expr   = ["+" | "-"] Term {("+" | "-") Term}.
Term   = Factor {("*" | "/") Factor}.
Factor = ident | number | "(" Expr ")".
```



Terminal symbols

simple TS: "+", "-", "*", "/", "(", ")"
(just 1 instance)

terminal classes: ident, number
(multiple instances)

Nonterminal symbols

Expr, Term, Factor

Start symbol

Expr

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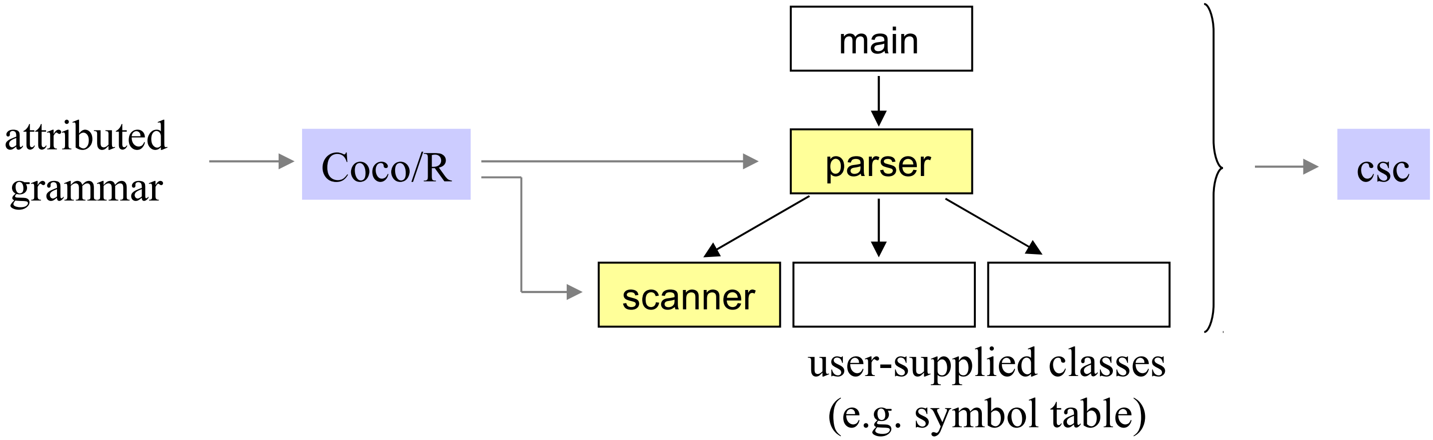
Coco/R - Compiler Compiler / Recursive Descent

Facts

- Generates a scanner and a parser from an attributed grammar
  - scanner as a deterministic finite automaton (DFA)
  - recursive descent parser
- Developed at the University of Linz (Austria)
- There are versions for C#, Java, C/C++, VB.NET, Delphi, Modula-2, Oberon, ...
- Gnu GPL open source: http://ssw.jku.at/Coco/

How it works



A Very Simple Example

Assume that we want to parse one of the following two alternatives

```
red apple
```

```
orange
```

We write a grammar ... and embed it into a Coco/R compiler description

```
COMPILER Sample
PRODUCTIONS
   Sample = "red" "apple" | "orange".
END Sample.
```

file *Sample.atg*

We invoke Coco/R to generate a scanner and a parser

```
>coco Sample.atg
Coco/R (Aug 22, 2006)
checking
parser + scanner generated
0 errors detected
```

A Very Simple Example

We write a main program

```
using System;
class Compile {
    static void Main(string[] arg)
        Scanner scanner = new Scanner(arg[0]);
        Parser parser = new Parser(scanner);
        parser.Parse();
        Console.Write(parser.errors.count + " errors detected");
    }
}
```

must

- create the scanner
- create the parser
- start the parser
- report number of errors

We compile everything ...

```
>csc Compile.cs Scanner.cs Parser.cs
```

... and run it

```
>Compile Input.txt
0 errors detected
```

file *Input.txt*

```
red apple
```

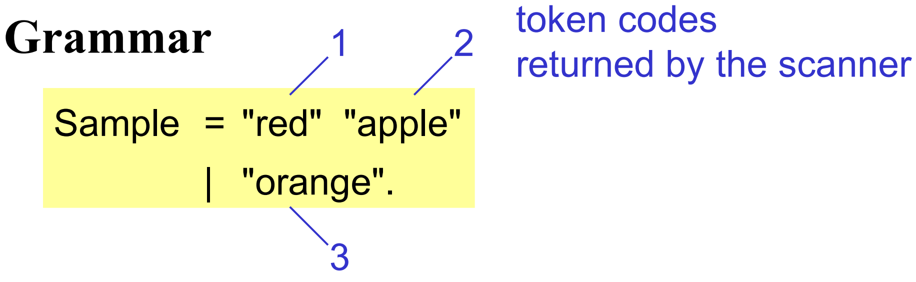
Generated Parser

```
class Parser {
    ...
    void Sample() {
        if (la.kind == 1) {
            Get();
            Expect(2);
        } else if (la.kind == 3) {
            Get();
        } else SynErr(5);
    }
    ...
    Token la;  // lookahead token

    void Get () {
        la = Scanner.Scan(); ...
    }

    void Expect (int n) {
        if (la.kind == n) Get(); else SynErr(n);
    }

    public void Parse() {
        Get();
        Sample();
    }
    ...
}
```



Grammar

```
Sample  =  "red"  "apple"
        |  "orange".
```

token codes returned by the scanner

A Slightly Larger Example

Parse simple arithmetic expressions

```
calc  34 + 2 + 5
calc  2 + 10 + 123 + 3
```

Coco/R compiler description

```
COMPILER Sample

CHARACTERS
   digit = '0'..'9'.

TOKENS
   number = digit {digit}.

IGNORE '\r' + '\n'

PRODUCTIONS
   Sample = {"calc" Expr}.
   Expr = Term {'+' Term}.
   Term = number.
END Sample.
```

file *Sample.atg*

```
>coco Sample.atg
>csc Compile.cs Scanner.cs Parser.cs
>Compile Input.txt
```

The generated scanner and parser will check the syntactic correctness of the input

Now we add Semantic Processing

```
COMPILER Sample
...
PRODUCTIONS

  Sample                     (. int n; .)
  = {  "calc"
       Expr<out n>           (. Console.WriteLine(n); .)
    }.
  /*----------------------------------------------------------*/
  Expr<out int n>            (. int n1; .)
  = Term<out n>
    {  '+'
       Term<out n1>          (. n = n + n1; .)
    }.
  /*----------------------------------------------------------*/
  Term<out int n>
  = number                   (. n = Convert.Int32(t.val); .)
    .
END Sample.
```

This is called an "attributed grammar"

Attributes
similar to parameters
of the symbols

Semantic Actions
ordinary C# code
executed during parsing

Generated Parser

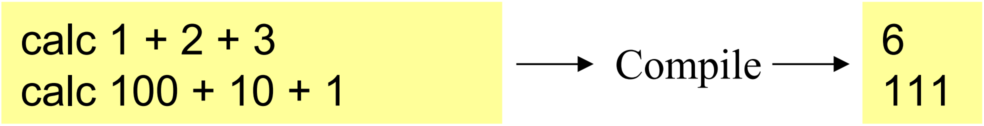
```
class Parser {
    ...
    void Sample() {
        int n;
        while (la.kind == 2) {
            Get();
            Expr(out n);
            Console.WriteLine(n);
        }
    }
    void Expr(out int n) {
        int n1;
        Term(out n);
        while (la.kind == 3) {
            Get();
            Term(out n1);
            n = n + n1;
        }
    }
    void Term(out int n) {
        Expect(1);
        n = Convert.ToInt32(t.val);
    }
    ...
}
```

```
Sample                (. int n; .)
= {   "calc"
      Expr<out n>     (. Console.WriteLine(n); .)
  }.
...
```

Token codes

1 ... number
2 ... "calc"
3 ... '+'

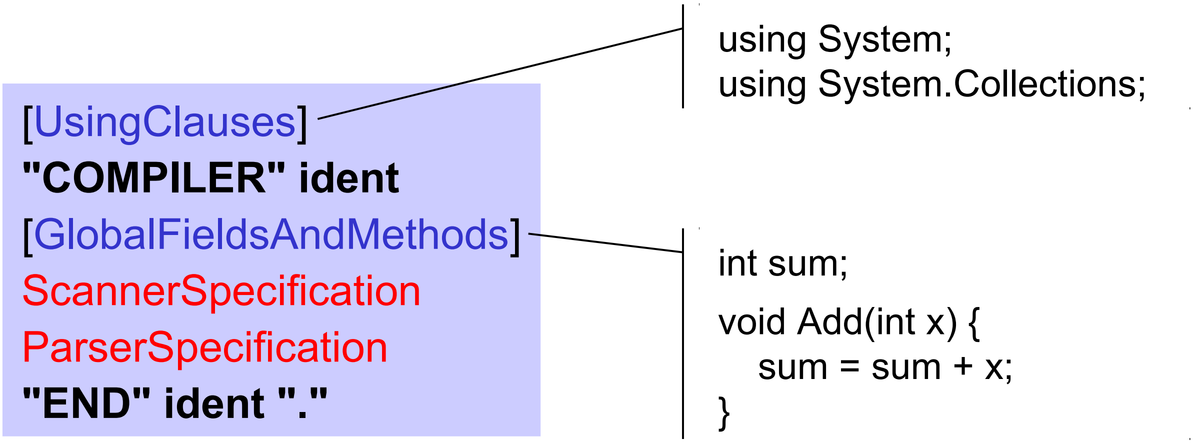
```
>coco Sample.atg
>csc Compile.cs Scanner.cs Parser.cs
>Compile Input.txt
```



```
calc 1 + 2 + 3
calc 100 + 10 + 1
```

```
6
111
```

Structure of a Compiler Description



```
[UsingClauses]
"COMPILER" ident
[GlobalFieldsAndMethods]
ScannerSpecification
ParserSpecification
"END" ident "."
```

```
using System;
using System.Collections;
```

```
int sum;

void Add(int x) {
    sum = sum + x;
}
```

ident denotes the start symbol of the grammar (i.e. the topmost nonterminal symbol)

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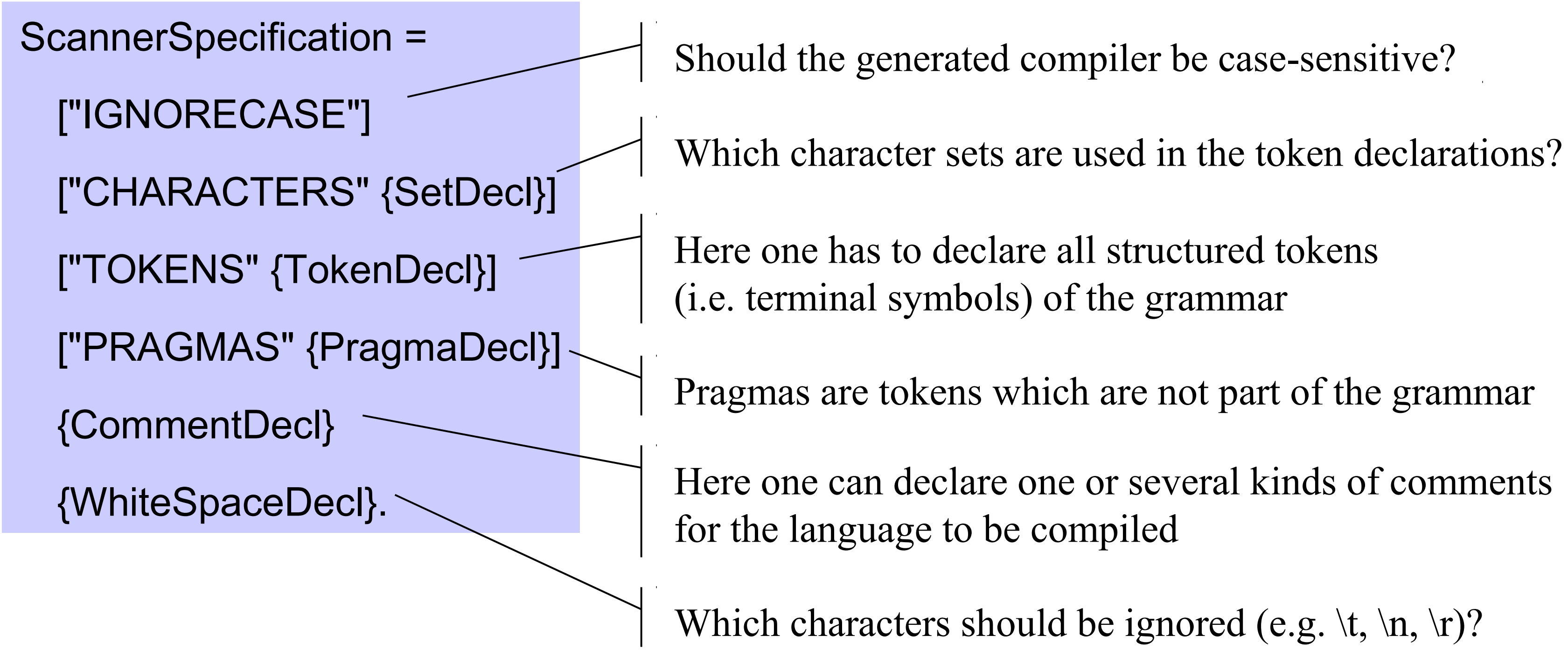
Structure of a Scanner Specification



```
ScannerSpecification =
    ["IGNORECASE"]
    ["CHARACTERS" {SetDecl}]
    ["TOKENS" {TokenDecl}]
    ["PRAGMAS" {PragmaDecl}]
    {CommentDecl}
    {WhiteSpaceDecl}.
```

Should the generated compiler be case-sensitive?

Which character sets are used in the token declarations?

Here one has to declare all structured tokens
(i.e. terminal symbols) of the grammar

Pragmas are tokens which are not part of the grammar

Here one can declare one or several kinds of comments
for the language to be compiled

Which characters should be ignored (e.g. \t, \n, \r)?

Character Sets

Example

```
CHARACTERS
   digit     = "0123456789".
   hexDigit = digit + "ABCDEF".
   letter    = 'A' .. 'Z'.
   eol        = '\r'.
   noDigit   = ANY - digit.
```

digit = "0123456789".	the set of all digits
hexDigit = digit + "ABCDEF".	the set of all hexadecimal digits
letter = 'A' .. 'Z'.	the set of all upper-case letters
eol = '\r'.	the end-of-line character
noDigit = ANY - digit.	any character that is not a digit

Valid escape sequences in character constants and strings

\\	backslash	\r	carriage return	\f	form feed
\'	apostrophe	\n	new line	\a	bell
\"	quote	\t	horizontal tab	\b	backspace
\0	null character	\v	vertical tab	\uxxxx	hex character value

Token Declarations

Define the structure of *token classes* (e.g. ident, number, ...)
Literals such as "while" or ">=" don't have to be declared

Example

```
TOKENS
   ident      =  letter {letter | digit | '_'}.
   number     =  digit {digit}
              |  "0x" hexDigit hexDigit hexDigit hexDigit.
   float      =  digit {digit} '.' digit {digit} ['E' ['+' | '-'] digit {digit}].
```

no problem if alternatives start
with the same character

- Right-hand side must be a regular EBNF expression
- Names on the right-hand side denote character sets

Literal Tokens

Literal tokens can be used without declaration

```
TOKENS
   ...
PRODUCTIONS
   ...
   Statement = "while" ... .
```

... but one can also declare them

```
TOKENS
   while = "while".
   ...
PRODUCTIONS
   ...
   Statement = while ... .
```

Sometimes useful because Coco/R generates constant names for the token numbers of all declared tokens

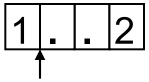
```
const int _while = 17;
```

Context-dependent Tokens

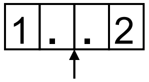
Problem

floating point number	1.23
integer range	1..2

Scanner tries to recognize the longest possible token



decides to
scan a float



got stuck;
no way to continue
in float

CONTEXT clause

```
TOKENS
   intCon    =  digit {digit}
             |  digit {digit} CONTEXT ("..").
   floatCon  =  digit {digit} "." digit {digit}.
```

Recognize a digit sequence as an *intCon* if its right-hand context is ".."

Pragmas

Special tokens (e.g. compiler options)

- can occur anywhere in the input
- are not part of the grammar
- must be semantically processed

Example

```
PRAGMAS
   option = '$' {letter}.  (.  foreach (char ch in t.val)
                                  if (ch == 'A') ...
                                  else if (ch == 'B') ...
                                  ... .)
```

whenever an *option* (e.g. $ABC) occurs
in the input, this semantic action
is executed

Typical applications

- compiler options
- preprocessor commands
- comment processing
- end-of-line processing

Comments

Described in a special section because

- nested comments cannot be described with regular expressions
- must be ignored by the parser

Example

```
COMMENTS FROM "/*" TO "*/" NESTED
COMMENTS FROM "//" TO "\r\n"
```

If comments are not nested they can also be described as pragmas
Advantage: can be semantically processed

White Space and Case Sensitivity

White space

$$\texttt{IGNORE}\quad \underbrace{\texttt{'\textbackslash t' + '\textbackslash r' + '\textbackslash n'}}_{\text{character set}}$$

blanks are ignored by default

Case sensitivity

Compilers generated by Coco/R are case-sensitive by default

Can be made case-insensitive by the keyword `IGNORECASE`

```
COMPILER Sample
IGNORECASE
CHARACTERS
   hexDigit = digit + 'a'..'f'.
   ...
TOKENS
   number = "0x" hexDigit hexDigit hexDigit hexDigit.
   ...
PRODUCTIONS
   WhileStat = "while" '(' Expr ')' Stat.
   ...
END Sample.
```

Will recognize

- 0x00ff, 0X00ff, 0X00FF as a *number*
- while, While, WHILE as a keyword

Token value returned to the parser retains original casing

Interface of the Generated Scanner

```
public class Scanner {
    public Buffer buffer;

    public Scanner (string fileName);
    public Scanner (Stream s);

    public Token        Scan();
    public Token        Peek();
    public void         ResetPeek();
}
```

Scan(): main method: returns a token upon every call

Peek(): reads ahead from the current scanner position without removing tokens from the input stream

ResetPeek(): resets peeking to the current scanner position

```
public class Token {
    public int      kind;   // token kind (i.e. token number)
    public int      pos;    // token position in the source text (starting at 0)
    public int      col;    // token column (starting at 1)
    public int      line;   // token line (starting at 1)
    public string   val;    // token value
}
```

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Structure of a Parser Specification

```
ParserSpecification = "PRODUCTION" {Production}.

Production  =  ident [FormalAttributes] '=' EbnfExpr '.'.
```

```
EbnfExpr    =  Alternative { '|' Alternative}.
Alternative =  [Resolver] {Element}.
Element     =  Symbol [ActualAttributes]
            |  '(' EbnfExpr ')'
            |  '[' EbnfExpr ']'
            |  '{' EbnfExpr '}'
            |  "ANY"
            |  "SYNC"
            |  SemAction.
Symbol      =  ident
            |  string | char.
```

```
SemAction  =  "(." ArbitraryCSharpStatements ".)".

Resolver   =  "IF" '(' ArbitraryCSharpPredicate ')'.
```

```
FormalAttributes   =  '<' ArbitraryText '>'.
ActualAttributes   =  '<' ArbitraryText '>'.
```

Productions

- Can occur in any order
- There must be exactly 1 production for every nonterminal
- There must be a production for the start symbol (the grammar name)

Example

```
COMPILER Expr
   ...
PRODUCTIONS
   Expr      =  SimExpr [RelOp SimExpr].
   SimExpr   =  Term {AddOp Term}.
   Term      =  Factor {Mulop Factor}.
   Factor    =  ident | number | "-" Factor | "true" | "false".
   RelOp     =  "==" | "<" | ">".
   AddOp     =  "+" | "-".
   MulOp     =  "*" | "/".
END Expr.
```

Arbitrary context-free grammar
in EBNF

Semantic Actions

Arbitrary C# code between (. and .)

```
IdentList          (. int n; .)
= ident            (. n = 1; .)
  { ',' ident      (. n++; .)
  }                (. Console.WriteLine(n); .)
  .
```

local semantic declaration

semantic action

Semantic actions are copied to the generated parser without being checked by Coco/R

Global semantic declarations

```
using System.IO;
COMPILER Sample
   Stream s;
   void OpenStream(string path) {
      s = File.OpenRead(path);
      ...
   }
...
PRODUCTIONS
   Sample = ...        (. OpenStream("in.txt"); .)
   ...
END Sample.
```

import of namespaces

global semantic declarations
(become fields and methods of the parser)

semantic actions can access global declarations
as well as imported classes

Attributes

For nonterminal symbols

	actual attributes	*formal attributes*
input attributes pass values from the "caller" to a production	... = ... IdentLIst<type> ...	IdentList<Type t> = ...
output attributes pass results of a production to the "caller"	... = ... Expr<out n> ... ... = ... List<ref b> ...	Expr<out int val> = ... List<ref StringBuilder buf> = ...

For terminal symbols

no explicit attributes;
values are returned
by the scanner

adapter nonterminals necessary

```
Number<out int n> =
   number   (. n = Convert.ToInt32(t.val); .) .
```

```
Ident<out string name> =
   ident      (. name = t.val; .) .
```

Parser has two global token variables

```
Token t;     // most recently recognized token
Token la;    // lookahead token (not yet recognized)
```

The symbol ANY

Denotes any token that is not an alternative of this ANY symbol

Example: counting the number of occurrences of *int*

```
Type
= "int"         (. intCounter++; .)
|  ANY.
```

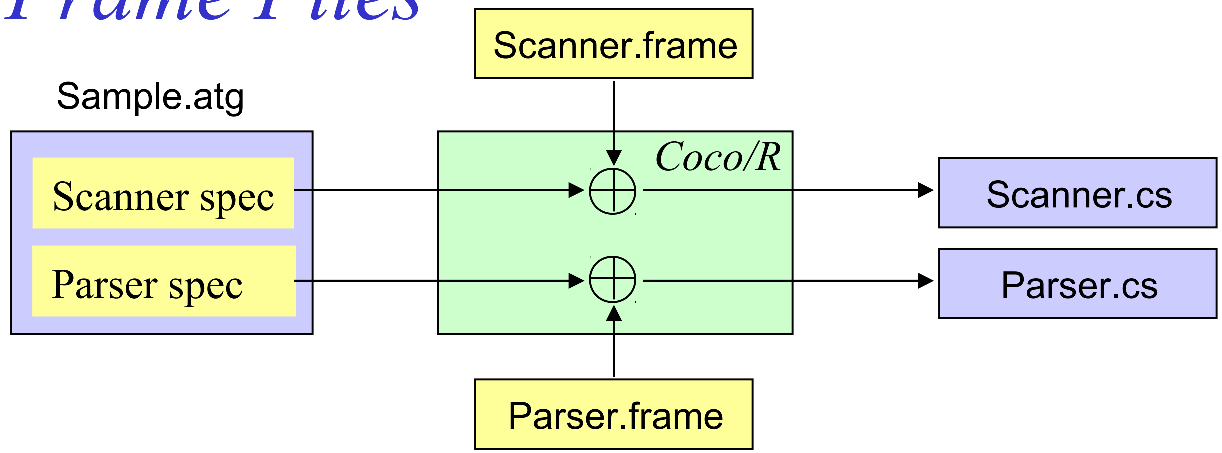
any token except "int"

Example: computing the length of a semantic action

```
SemAction<out int len>
= "(."          (. int beg = t.pos + 2; .)
  { ANY }
  ".)"          (. len = t.pos - beg; .) .
```

any token except ".)"

Frame Files



Scanner.frame snippet

```
public class Scanner {
    const char EOL = '\n';
    const int eofSym = 0;
-->declarations
    ...
    public Scanner (Stream s) {
        buffer = new Buffer(s, true);
        Init();
    }
    void Init () {
        pos = -1; line = 1; …
-->initialization
    ...
}
```

- Coco/R inserts generated parts at positions marked by "-->..."
- Users can edit the frame files for adapting the generated scanner and parser to their needs
- Frame files are expected to be in the same directory as the compiler specification (e.g. *Sample.atg*)

Interface of the Generated Parser

```
public class Parser {
    public Scanner scanner;   // the scanner of this parser
    public Errors  errors;    // the error message stream

    public Token t;           // most recently recognized token
    public Token la;          // lookahead token

    public Parser (Scanner scanner);

    public void Parse ();
    public void SemErr (string msg);
}
```

Parser invocation in the main program

```
public class MyCompiler {

    public static void Main(string[] arg) {
        Scanner scanner = new Scanner(arg[0]);
        Parser parser = new Parser(scanner);
        parser.Parse();
        Console.WriteLine(parser.errors.count + " errors detected");
    }
}
```

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Syntax Error Handling

Syntax error messages are generated automatically

For invalid terminal symbols

production	S = a b c.
input	a x c
error message	-- line ... col ...: b expected

For invalid alternative lists

production	S = a (b | c | d) e.
input	a x e
error message	-- line ... col ...: invalid S

Error message can be improved by rewriting the production

productions	S = a T e.
	T = b | c | d.

input	a x e
error message	-- line ... col ...: invalid T

Syntax Error Recovery

The user must specify synchronization points where the parser should recover

synchronization points

```
Statement
= SYNC
  (  Designator "=" Expr SYNC ';'
  |  "if" '(' Expression ')' Statement ["else" Statement]
  |  "while" '(' Expression ')' Statement
  |  '{' {Statement} '}'
  |  ...
  ).
```

What happens if an error is detected?

- parser reports the error
- parser continues to the next synchronization point
- parser skips input symbols until it finds one that is expected at the synchronization point

```
while (la.kind is not accepted here) {
   la = scanner.Scan();
}
```

What are good synchronization points?

Locations in the grammar where particularly "safe" tokens are expected

- start of a statement: if, while, do, ...
- start of a declaration: public, static, void, ...
- in front of a semicolon

Semantic Error Handling

Must be done in semantic actions

```
Expr<out Type type>          (.  Type type1; .)
=  Term<out type>
   {  '+' Term<out type1>    (.  if (type != type1) SemErr("incompatible types"); .)
   } .
```

***SemErr* method in the parser**

```
void SemErr (string msg) {
    ...
    errors.SemErr(t.line, t.col, msg);
    ...
}
```

Errors Class

Coco/R generates a class for error message reporting

```
public class Errors {
    public int count = 0;                                        // number of errors detected
    public TextWriter errorStream = Console.Out;                 // error message stream
    public string errMsgFormat = "-- line {0} col {1}: {2}";     // 0=line, 1=column, 2=text

    // called by the programmer (via Parser.SemErr) to report semantic errors
    public void SemErr (int line, int col, string msg) {
        errorStream.WriteLine(errMsgFormat, line, col, msg);
        count++;
    }

    // called automatically by the parser to report syntax errors
    public void SynErr (int line, int col, int n) {
        string msg;
        switch (n) {
            case 0: msg = "..."; break;
            case 1: msg = "..."; break;
            ...
        }
        errorStream.WriteLine(errMsgFormat, line, col, msg);
        count++;
    }
}
```

syntax error messages generated by Coco/R

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Terminal Start Symbols of Nonterminals

Those terminal symbols with which a nonterminal symbol can start

```
Expr   = ["+" | "-"] Term {("+" | "-") Term}.
Term   = Factor {("*" | "/") Factor}.
Factor = ident | number | "(" Expr ")".
```

First(Factor) = ident, number, "("

First(Term) = First(Factor)
= ident, number, "("

First(Expr) = "+", "-", First(Term)
= "+", "-", ident, number, "("

Terminal Successors of Nonterminals

Those terminal symbols that can follow a nonterminal in the grammar

```
Expr   = ["+" | "-"] Term {("+" | "-") Term}.
Term   = Factor {("*" | "/") Factor}.
Factor = ident | number | "(" Expr ")".
```

Follow(Expr) = ")", eof

Follow(Term) = "+", "-", Follow(Expr)
= "+", "-", ")", eof

Follow(Factor) = "*", "/", Follow(Term)
= "*", "/", "+", "-", ")", eof

Where does *Expr* occur on the right-hand side of a production? What terminal symbols can follow there?

LL(1) Condition

For recursive descent parsing a grammar must be LL(1)
(parseable from **L**eft to right with **L**eftcanonical derivations 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 all its alternatives start with different terminal symbols

```
S = a b | c.
```

LL(1)

First(a b) = {a}
First(c) = {c}

```
S = a b | T.
T = [a] c.
```

not LL(1)

First(a b) = {a}
First(T) = {a, c}

In other words

The parser must always be able to select one of the alternatives by looking at the lookahead token.

```
S = (a b | T).
```

if the parser sees an "a" here it cannot decide which alternative to select

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

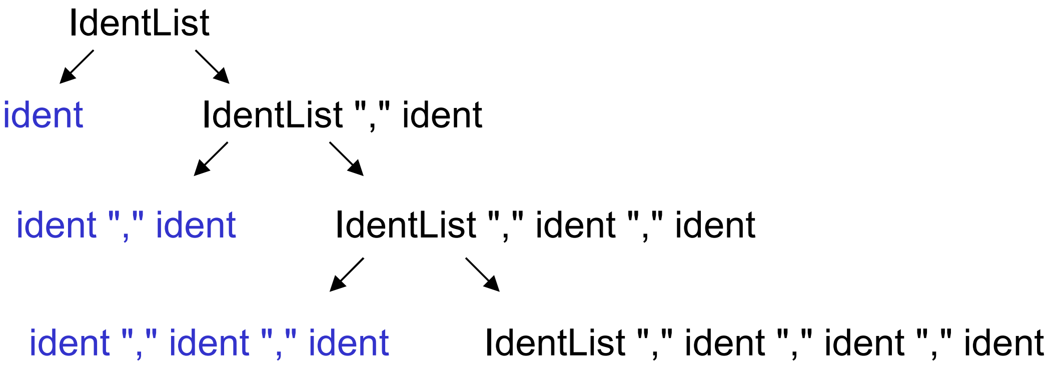
Left recursion is always an LL(1) conflict and must be eliminated

For example

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

(both alternatives start with *ident*)

generates the following phrases



IdentList

ident

IdentList "," ident

ident "," ident

IdentList "," ident "," ident

ident "," ident "," ident

IdentList "," ident "," ident "," ident

can always be replaced by iteration

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

Hidden LL(1) Conflicts

EBNF options and iterations are hidden alternatives

$S = [\alpha]\ \beta.$ ⇔ $S = \alpha\ \beta\ |\ \beta.$ α and β are arbitrary EBNF expressions

$S = \{\alpha\}\ \beta.$ ⇔ $S = \beta\ |\ \alpha\ \beta\ |\ \alpha\ \alpha\ \beta\ |\ \ldots\ .$

Rules

$S = [\alpha]\ \beta.$	$\mathrm{First}(\alpha) \cap \mathrm{First}(\beta)$ must be $\{\}$
$S = \{\alpha\}\ \beta.$	$\mathrm{First}(\alpha) \cap \mathrm{First}(\beta)$ must be $\{\}$

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

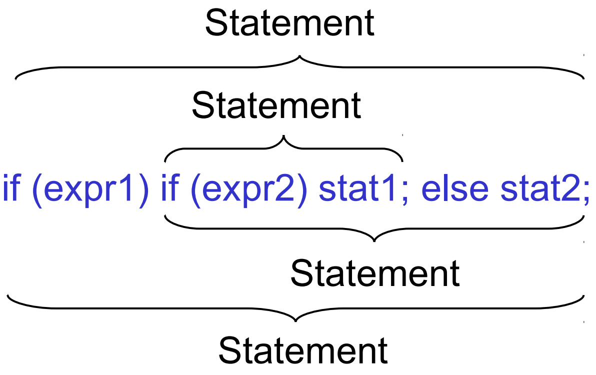
If statement in C# or Java

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

This is an LL(1) conflict!

First("else" Statement) ∩ Follow(Statement) = {"else"}

It is even an ambiguity which cannot be removed



Statement

Statement

if (expr1) if (expr2) stat1; else stat2;

Statement

Statement

We can build 2 different syntax trees!

Can We Ignore LL(1) Conflicts?

An LL(1) conflict is only a warning

The parser selects the first matching alternative

```
S = a b c
  |  a d.
```

if the lookahead token is *a* the parser selects this alternative

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"

$$\underbrace{\text{if (expr1) }\underbrace{\text{if (expr2) stat1; else stat2;}}_{\text{Statement}}}_{\text{Statement}}$$

Luckily this is what we want here.

Coco/R finds LL(1) Conflicts automatically

Example

```
...
PRODUCTIONS
   Sample     = {Statement}.
   Statement =  Qualident '=' number ';'
              |  Call
              |  "if" '(' ident ')' Statement ["else" Statement].
   Call       =  ident '(' ')' ';'.
   Qualident  =  [ident '.'] ident.
   ...
```

Coco/R produces the following warnings

```
>coco Sample.atg
Coco/R (Aug 22, 2006)
checking
   Sample deletable
   LL1 warning in Statement: ident is start of several alternatives
   LL1 warning in Statement: "else" is start & successor of deletable structure
   LL1 warning in Qualident: ident is start & successor of deletable structure
parser + scanner generated
0 errors detected
```

Problems with LL(1) Conflicts

Some conflicts are hard to remove by grammar transformations

```
Expr   =  Factor {'+' Factor}.
Factor =  '(' ident ')' Factor       /* type cast */
       |  '(' Expr ')'               /* nested expression */
       |  ident | number.
```

both alternatives can start with '(' ident ')'

Transformations can corrupt readability

```
Using  =  "using" [ident '='] Qualid ';'.
Qualid =  ident {'.' ident}.
```

⇒

```
Using  =  "using" ident (  {'.' ident} ';'
                        |  '=' Qualid ';'.
                        ).
```

Semantic actions may prevent factorization

```
S  =  ident (. x = 1; .) {',' ident (. x++; .) } ':'
   |  ident (. Foo(); .) {',' ident (. Bar(); .) } ';'.
```

=> Coco/R offers a special mechanism to resolve LL(1) conflicts

LL(1) Conflict Resolvers

Syntax

```
EBNFexpr    =  Alternative { '|' Alternative}.
Alternative =  [Resolver] Element {Element}.
Resolver    =  "IF" '(' ArbitraryCSharpPredicate ')'.
```

Example

```
Using = "using" [ IF (IsAlias()) ident '='] Qualident ';'.
```

We have to write the following method (in the global semantic declarations)

```
bool IsAlias() {
    Token next = scanner.Peek();
    return la.kind == _ident && next.kind == _assign;
}
```

returns *true* if the input is
ident = ...
and *false* if the input is
ident . ident ...

Token names

```
TOKENS
    ident    = letter {letter | digit}.
    number = digit {digit}.
    assign   = '='.
    ...
```

Coco/R generates the following declarations for tokens names

```
const int _EOF      = 0;
const int _ident    = 1;
const int _number = 2;
const int _assign   = 3;
...
```

Example

Conflict resolution by a multi-symbol lookahead

```
A = ident (. x = 1; .) {',' ident (. x++; .) } ':'
  | ident (. Foo(); .) {',' ident (. Bar(); .) } ';'.
```

LL(1) conflict

Resolution

```
A = IF (FollowedByColon())
    ident (. x = 1; .) {',' ident (. x++; .) } ':'
  | ident (. Foo(); .) {',' ident (. Bar(); .) } ';'.
```

Resolution method

```
bool FollowedByColon() {
    Token x = la;
    while (x.kind == _ident || x.kind == _comma) {
        x = scanner.Peek();
    }
    return x.kind == _colon;
}
```

Example

Conflict resolution by exploiting semantic information

```
Factor = '(' ident ')' Factor       /* type cast */
       | '(' Expr ')'               /* nested expression */
       | ident | number.
```

LL(1) conflict

Resolution

```
Factor = IF (IsCast())
         '(' ident ')' Factor       /* type cast */
       | '(' Expr ')'               /* nested expression */
       | ident | number.
```

Resolution method

```
bool IsCast() {
    Token next = scanner.Peek();
    if (la.kind == _lpar && next.kind == _ident) {
        Obj obj = SymTab.Find(next.val);
        return obj != null && obj.kind == TYPE;
    } else return false;
}
```

returns true if '(' is followed by a declared type name

Generating Compilers with Coco/R

1. Compilers
2. Grammars
3. Coco/R Overview
4. Scanner Specification
5. Parser Specification
6. Error Handling
7. LL(1) Conflicts
8. Case Study -- The Programming Language *Taste*

A Simple Taste Program

```
program Test {

    int i;

    // compute the sum of 1..i
    void SumUp() {
        int sum;
        sum = 0;
        while (i > 0) { sum = sum + i; i = i - 1; }
        write sum;
    }

    // the program starts here
    void Main() {
        read i;
        while (i > 0) {
            SumUp();
            read i;
        }
    }
}
```

a single main program

global variables

methods without parameters

Main method

Syntax of Taste

Programs and Declarations

```
Taste     = "program" ident "{"  {VarDecl} {ProcDecl} "}".
ProcDecl  = "void" ident "(" ")" "{" { VarDecl | Stat} "}".
VarDecl   = Type ident {"," ident} ";".
Type      = "int" | "bool".
```

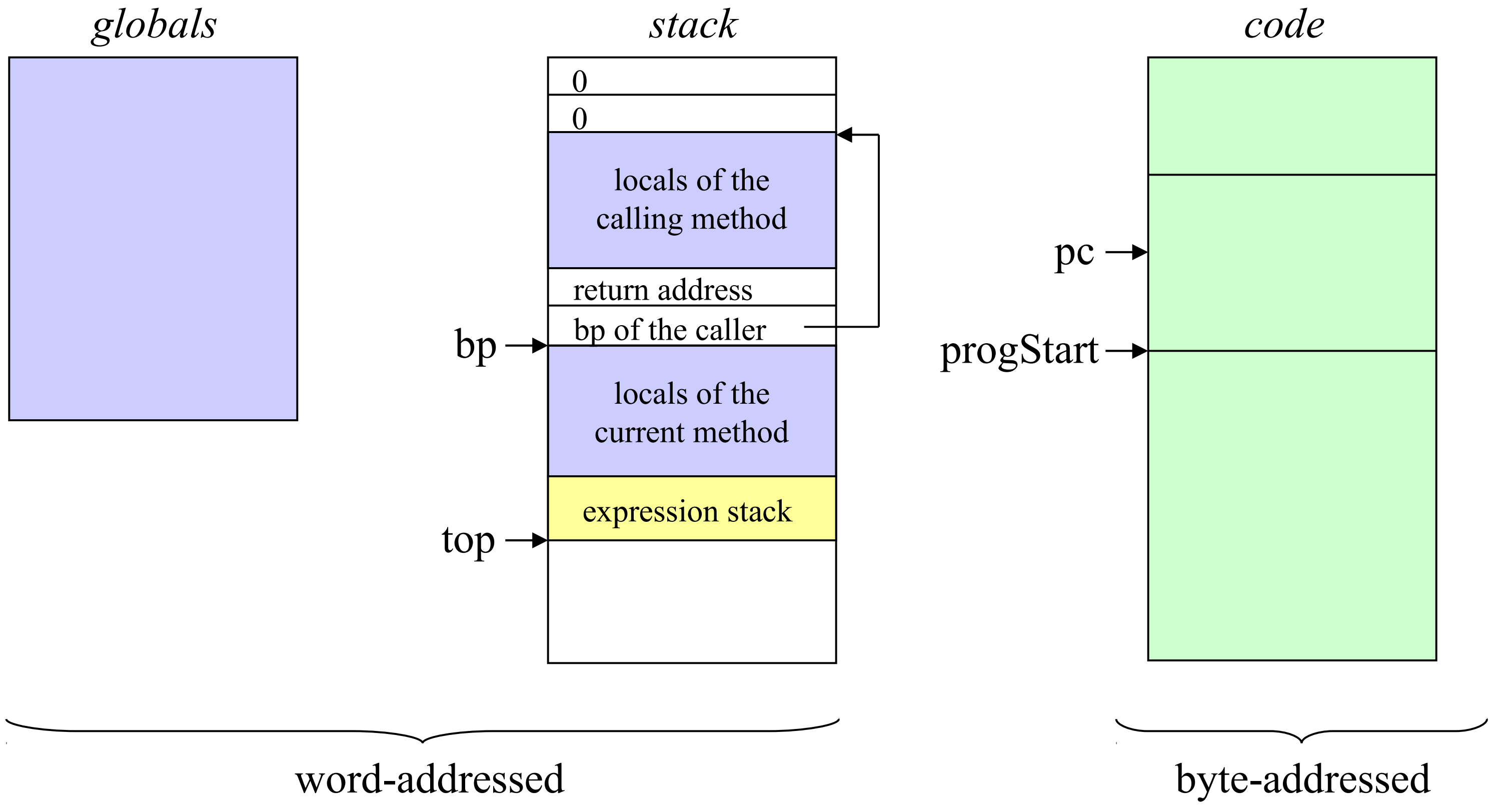
Statements

```
Stat      = ident "=" Expr ";"
          | ident "(" ")" ";"
          | "if" "(" Expr ")" Stat ["else" Stat].
          | "while" "(" Expr ")" Stat
          | "read" ident ";"
          | "write" Expr ";"
          | "{" { Stat | VarDecl } "}".
```

Expressions

```
Expr      = SimExpr [RelOp SimExpr].
SimExpr   = Term {AddOp Term}.
Term      = Factor {Mulop Factor}.
Factor    = ident | number | "-" Factor | "true" | "false".
RelOp     = "==" | "<" | ">".
AddOp     = "+" | "-".
MulOp     = "*" | "/".
```

Architecture or the Taste VM



Instructions of the Taste VM

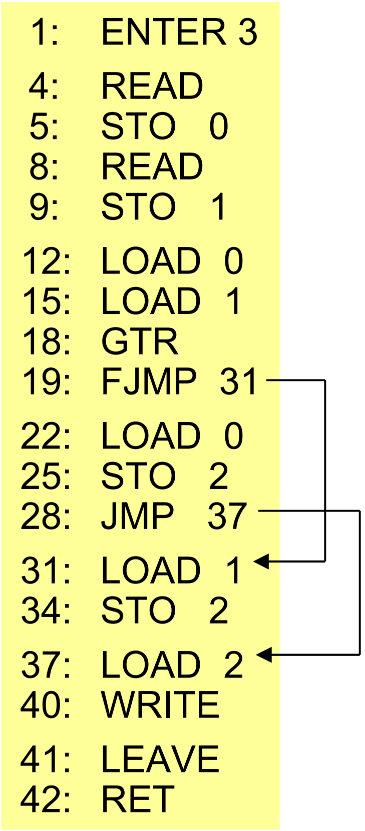
CONST	n	Load constant	Push(n);
LOAD	a	Load local variable	Push(stack[bp+a]);
LOADG	a	Load global variable	Push(globals[a]);
STO	a	Store local variable	stack[bp+a] = Pop();
STOG	a	Store global variable	globals[a] = Pop();
ADD		Add	Push(Pop() + Pop());
SUB		Subtract	Push(-Pop() + Pop());
MUL		Multiply	Push(Pop() * Pop());
DIV		Divide	x = Pop(); Push(Pop() / x);
NEG		Negate	Push(-Pop());
EQL		Check if equal	if (Pop()==Pop()) Push(1); else Push(0);
LSS		Check if less	if (Pop()>Pop()) Push(1); else Push(0);
GTR		Check if greater	if (Pop()<Pop()) Push(1); else Push(0);
JMP	a	Jump	pc = a;
FJMP	a	Jump if false	if (Pop() == 0) pc = a;
READ		Read integer	x = ReadInt(); Push(x);
WRITE		Write integer	WriteInt(Pop());
CALL	a	Call method	Push(pc+2); pc = a;
RET		Return from method	pc = Pop(); if (pc == 0) return;
ENTER	n	Enter method	Push(bp); bp = top; top += n;
LEAVE		Leave method	top = bp; bp = Pop();

Sample Translation

Source code

```
void Foo() {
    int a, b, max;
    read a; read b;
    if (a > b) max = a; else max = b;
    write max;
}
```

Object code



```
 1:   ENTER 3
 4:   READ
 5:   STO   0
 8:   READ
 9:   STO   1
12:   LOAD  0
15:   LOAD  1
18:   GTR
19:   FJMP  31
22:   LOAD  0
25:   STO   2
28:   JMP   37
31:   LOAD  1
34:   STO   2
37:   LOAD  2
40:   WRITE
41:   LEAVE
42:   RET
```

Scanner Specification

```
COMPILER Taste

CHARACTERS
    letter = 'A'..'Z' + 'a'..'z'.
    digit = '0'..'9'.

TOKENS
    ident  = letter {letter | digit}.
    number = digit {digit}.

COMMENTS FROM "/*" TO "*/" NESTED
COMMENTS FROM "//" TO '\r' '\n'

IGNORE '\r' + '\n' + '\t'

PRODUCTIONS
    ...
END Taste.
```

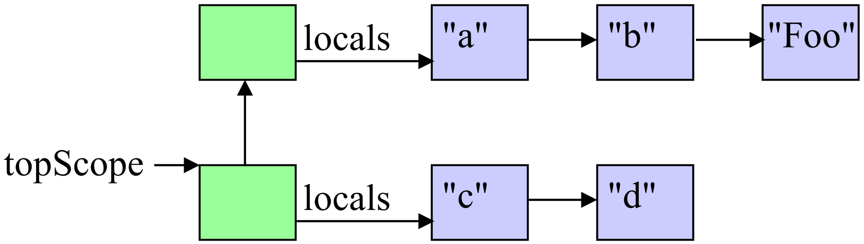
Symbol Table Class

```
public class SymbolTable {
   public Obj   topScope;

   public       SymbolTable(Parser parser) {...}

   public Obj   Insert(string name, int kind, int type) {...}
   public Obj   Find(string name) {...}

   public void  OpenScope() {...}
   public void  CloseScope() {...}
}
```

```
public class Obj {
   public string  name;
   public int     kind;
   public int     type;
   public int     adr;
   public int     level;
   public Obj     locals;
   public Obj     next;
}
```

Sample symbol table

```
program P {
   int a;
   bool b;

   void Foo() {
      int c, d;
      ...
   }
   ...
}
```



Code Generator Class

```
public class CodeGenerator {
    public int     pc;
    public int     progStart;

    public         CodeGenerator() {...}

    public void  Emit(int op) {...}
    public void  Emit(int op, int val) {...}
    public void  Patch(int adr, int val) {...}

    ...
}
```

Parser Specification -- Declarations

```
PRODUCTIONS
  Taste                  (. string name; .)
  = "program"
    Ident<out name>      (. tab.OpenScope(); .)
    '{'
    { VarDecl }
    { ProcDecl }
    '}'                  (. tab.CloseScope(); .).
```

```
public SymbolTable     tab;
public CodeGenerator  gen;
```

```
  VarDecl                (. string name; int type; .)
  = Type<out type>
    Ident<out name>      (. tab.Insert(name, VAR, type); .)
    { ',' Ident<out name> (. tab.Insert(name, VAR, type); .)
    } ';'.
```

```
  Type<out int type>
  =              (. type = UNDEF; .)
    ( "int"      (. type = INT; .)
    | "bool"     (. type = BOOL; .)
    ).
```

```
  ProcDecl               (.  string name; Obj obj; int adr; .)
  = "void"
    Ident<out name>      (.  obj = tab.Insert(name, PROC, UNDEF); obj.adr = gen.pc;
                             if (name == "Main") gen.progStart = gen.pc;
                             tab.OpenScope(); .)
    '(' ')'
    '{'                  (.  gen.Emit(ENTER, 0); adr = gen.pc - 2; .)
    { VarDecl | Stat }
    '}'                  (.  gen.Emit(LEAVE); gen.Emit(RET);
                             gen.Patch(adr, tab.topScope.adr);
                             tab.CloseScope(); .).
```

Parser Specification -- Expressions

```
Expr<out int type>          (. int type1, op; .)
= SimExpr<out type>
  [ RelOp<out op>
    SimExpr<out type1>      (. if (type != type1) SemErr("incompatible types");
                               gen.Emit(op); type = BOOL; .)
  ].
```

```
SimExpr<out int type>       (. int type1, op; .)
= Term<out type>
  { AddOp<out op>
    Term<out type1>         (. if (type != INT || type1 != INT)
                                 SemErr("integer type expected");
                               gen.Emit(op); .)
  }.
```

```
Term<out int type>          (. int type1, op; .)
= Factor<out type>
  { MulOp<out op>
    Factor<out type1>       (. if (type != INT || type1 != INT)
                                 SemErr("integer type expected");
                               gen.Emit(op); .)
  }.
```

```
RelOp<out int op>
=           (. op = UNDEF; .)
  ( "=="    (. op = EQU; .)
  | '<'     (. op = LSS; .)
  | '>'     (. op = GTR; .)
  ).
```

```
AddOp<out int op>
=           (. op = UNDEF; .)
  ( '+'     (. op = PLUS; .)
  | '-'     (. op = MINUS; .)
  ).
```

```
MulOp<out int op>
=           (. op = UNDEF; .)
  ( '*'     (. op = TIMES; .)
  | '/'     (. op = SLASH; .)
  ).
```

Parser Specification -- Factor

```
Factor<out int type>        (. int n; Obj obj; string name; .)
=                           (. type = UNDEF; .)
  (  Ident<out name>        (. obj = tab.Find(name); type = obj.type;
                               if (obj.kind == VAR) {
                                 if (obj.level == 0) gen.Emit(LOADG, obj.adr);
                                 else gen.Emit(LOAD, obj.adr);
                               } else SemErr("variable expected"); .)

  |  number                 (. n = Convert.ToInt32(t.val);
                               gen.Emit(CONST, n); type = INT; .)

  |  '-'
     Factor<out type>       (. if (type != INT) {
                                 SemErr("integer type expected");
                                 type = INT;
                               }
                               gen.Emit(NEG); .)

  |  "true"                 (. gen.Emit(CONST, 1); type = BOOL; .)
  |  "false"                (. gen.Emit(CONST, 0); type = BOOL; .)
  ).
```

```
Ident<out string name>
=  ident                    (. name = t.val; .).
```

Parser Specification -- Statements

```
Stat                    (. int type; string name; Obj obj; int adr, adr2, loopstart; .)
= Ident<out name>       (. obj = tab.Find(name); .)
  ( '='                 (. if (obj.kind != VAR) SemErr("can only assign to variables"); .)
    Expr<out type> ';'  (. if (type != obj.type) SemErr("incompatible types");
                           if (obj.level == 0) gen.Emit(STOG, obj.adr);
                           else gen.Emit(STO, obj.adr); .)
  | '(' ')' ';'         (. if (obj.kind != PROC) SemErr("object is not a procedure");
                           gen.Emit(CALL, obj.adr); .)
  )

| "read"
  Ident<out name> ';'   (. obj = tab.Find(name);
                           if (obj.type != INT) SemErr("integer type expected");
                           gen.Emit(READ);
                           if (obj.level == 0) gen.Emit(STOG, obj.adr);
                           else gen.Emit(STO, obj.adr); .)

| "write"
  Expr<out type> ';'    (. if (type != INT) SemErr("integer type expected");
                           gen.Emit(WRITE); .)

| '{' { Stat | VarDecl } '}'

| ... .
```

Parser Specification -- Statements

```
Stat                         (. int type; string name; Obj obj; int adr, adr2, loopstart; .)
= ...
|  "if"
   '(' Expr<out type> ')'    (. if (type != BOOL) SemErr("boolean type expected");
                                gen.Emit(FJMP, 0); adr = gen.pc - 2; .)
   Stat
   [  "else"                 (. gen.Emit(JMP, 0); adr2 = gen.pc - 2;
                                gen.Patch(adr, gen.pc);
                                adr = adr2; .)
      Stat
   ]                         (. gen.Patch(adr, gen.pc); .)



|  "while"                   (. loopstart = gen.pc; .)
   '(' Expr<out type> ')'    (. if (type != BOOL) SemErr("boolean type expected");
                                gen.Emit(FJMP, 0); adr = gen.pc - 2; .)
   Stat                      (. gen.Emit(JMP, loopstart);
                                gen.Patch(adr, gen.pc); .) .
```

Main Program of Taste

```
using System;

public class Taste {

    public static void Main (string[] arg) {
        if (arg.Length > 0) {
            Scanner scanner = new Scanner(arg[0]);
            Parser parser = new Parser(scanner);
            parser.tab = new SymbolTable(parser);
            parser.gen = new CodeGenerator();
            parser.Parse();
            if (parser.errors.count == 0) parser.gen.Interpret("Taste.IN");
        } else
            Console.WriteLine("-- No source file specified");
    }

}
```

Building the whole thing

```
c:> coco Taste.atg
c:> csc Taste.cs Scanner.cs Parser.cs SymbolTable.cs CodeGenerator.cs
c:> Taste Sample.tas
```

Summary

- Coco/R generates a scanner and a recursive descent parser from an attributed grammar
- LL(1) conflicts can be handled with resolvers
  Grammars for C# and Java are available in Coco/R format
- Coco/R is open source software (Gnu GPL)
  http://ssw.jku.at/Coco/
- Coco/R has been used by us to build
  - a white-box test tool for C#
  - a profiler for C#
  - a static program analyzer for C#
  - a metrics tool for Java
  - compilers for domain-specific languages
  - a log file analyzer
  - ...
- Many companies and projects use Coco/R

- SharpDevelop: a C# IDE	www.icsharpcode.net
- Software Tomography: Static Analysis Tool	www.software-tomography.com
- CSharp2Html: HTML viewer for C# sources	www.charp2html.net
- currently 39000 hits for Coco/R in Google	