Principles of Programming Languages

http://www.di.unipi.it/~andrea/Didattica/PLP-16/
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Lesson 9

- LR parsing with ambiguous grammars
- Error recovery in LR parsing
- Parser generators: yacc/bison
- Handgling ambiguos grammars in yacc/bison

Using Ambiguous Grammars

- All grammars used in the construction of LR-parsing tables must be un-ambiguous
- Can we create LR-parsing tables for ambiguous grammars ?
  - Yes, but they will have conflicts
  - We can resolve these conflicts in favor of one of them to disambiguate the grammar
  - At the end, we will have again an unambiguous grammar

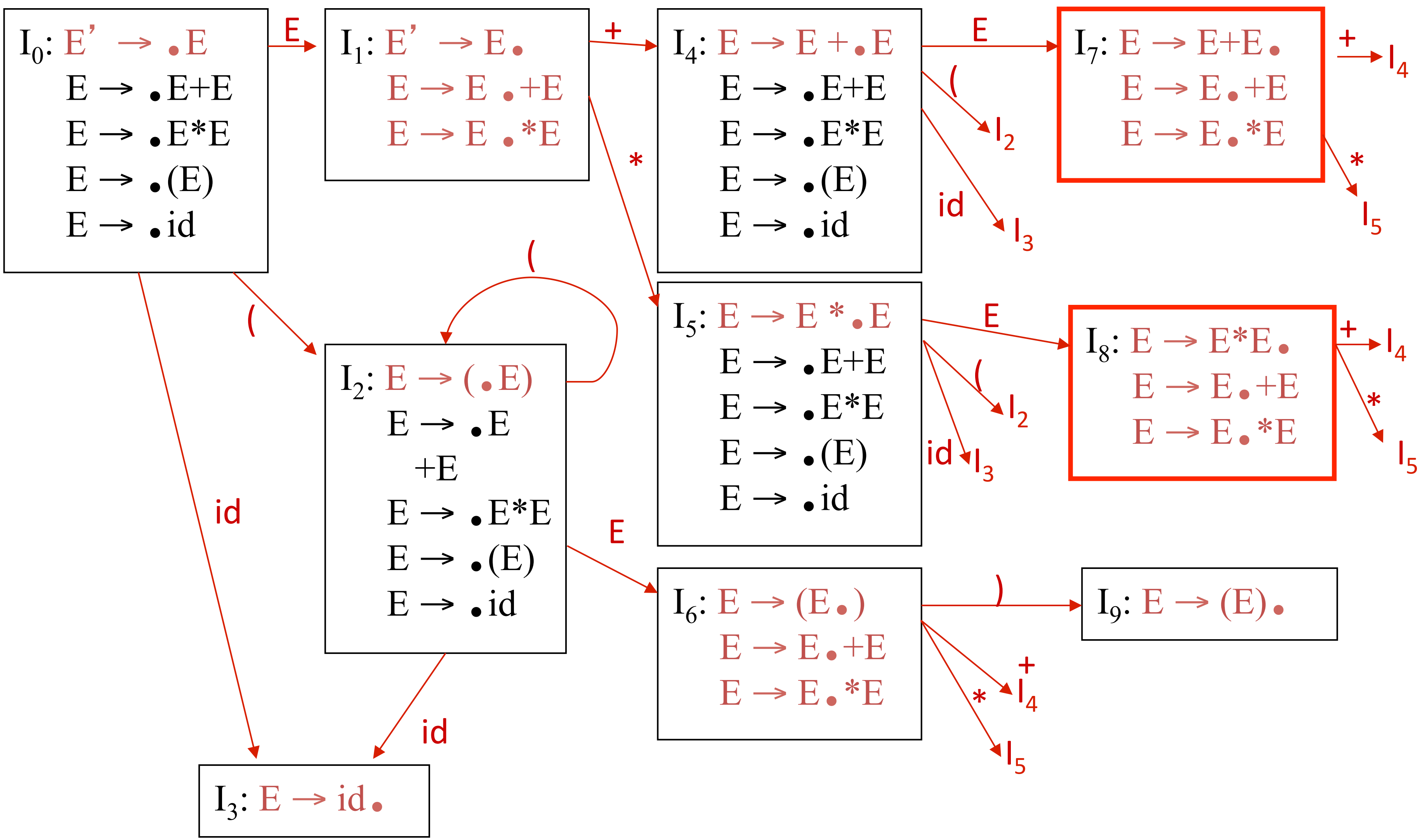
Using Ambiguous Grammars

- Why we want to use an ambiguous grammar?
  - Some of the ambiguous grammars are **much natural**, and a corresponding unambiguous grammar can be very complex
  - Usage of an ambiguous grammar may **eliminate unnecessary reductions** (*single* productions)
  - We may want to postpone/possibly change decisions about associativity/precedence of operators
- Example grammar:

$E \rightarrow E+E \mid E*E \mid (E) \mid id$ →

$E \rightarrow E+T \mid T$
$T \rightarrow T*F \mid F$
$F \rightarrow (E) \mid id$

Sets of LR(0) Items for Ambiguous Grammar



SLR-Parsing Tables for Ambiguous Grammar

	Action							Goto
	id	**+**	*****	**(**	**)**	**$**		**E**
0	s3			s2				1
1		s4	s5			acc		
2	s3			s2				6
3		r4	r4		r4	r4		
4	s3			s2				7
5	s3			s2				8
6		s4	s5		s9			
7		r1/s4	r1/s5		r1	r1		
8		r2/s4	r2/s5		r2	r2		
9		r3	r3		r3	r3		

1. E → E+E
2. E → E*E
3. E → (E)
4. E → id

FOLLOW(E) = { $, + , * ,) }

Resolving conflicts

State I_7 has shift/reduce conflicts for symbols $+$ and $*$.

After reading **id + id**:

$$I_0 \xrightarrow{E} I_1 \xrightarrow{+} I_4 \xrightarrow{E} I_7$$

when current token is +

shift ➔ + is right-associative

reduce ➔ + is left-associative

when current token is *

shift ➔ * has higher precedence than +

reduce ➔ + has higher precedence than *

Resolving conflicts

Also state I_8 has shift/reduce conflicts for symbols + and $*$.
After reading **id * id**:

$$I_0 \xrightarrow{E} I_1 \xrightarrow{*} I_5 \xrightarrow{E} I_8$$

when current token is *
- shift ➔ * is right-associative
- reduce ➔ * is left-associative

when current token is +
- shift ➔ + has higher precedence than *
- reduce ➔ * has higher precedence than +

Disambiguated SLR-Parsing Tables

Action **Goto**

	id	+	*	(	)	$		E
0	s3			s2				1
1		s4	s5			acc		
2	s3			s2				6
3		r4	r4		r4	r4		
4	s3			s2				7
5	s3			s2				8
6		s4	s5		s9			
7		**r1**	**s5**		r1	r1		
8		**r2**	**r2**		r2	r2		
9		r3	r3		r3	r3		

1. E → E+E
2. E → E*E
3. E → (E)
4. E → id

FOLLOW(E) = { $, + , * ,) }

Error Recovery in LR Parsing

- An LR parser will detect an error when it consults the parsing action table and finds an error entry. All empty entries in the action table are error entries.
- Errors are never detected by consulting the **goto** table.
- An LR parser will announce error as soon as there is no valid continuation for the scanned portion of the input.
- A canonical LR parser (LR(1) parser) will never make even a single reduction before announcing an error.
- The SLR and LALR parsers may make several reductions before announcing an error.
- But, all LR parsers (LR(1), LALR and SLR parsers) will never shift an erroneous input symbol onto the stack.

Panic Mode Error Recovery in LR Parsing

- Scan down the stack until a state **s** with a goto on a particular nonterminal **A** is found. (Get rid of everything from the stack before this state s).
- Discard zero or more input symbols until a symbol **a** is found that can "legitimately follow" **A**.
  - The symbol **a** is simply in FOLLOW(A), but this may not work for all situations.
- The parser stacks the nonterminal **A** and the state **goto[s,A]**, and it resumes the normal parsing.
- This nonterminal **A** is normally is a basic programming block (there can be more than one choice for **A**).
  - *stmt*, *expr*, *block*, ...
- Symbol a can be typically '**;**', '**}**'

Phrase-Level Error Recovery in LR Parsing

- Each empty entry in the action table is marked with a specific error routine.
- An error routine reflects the error that the user most likely will make in that case.
- An error routine inserts the symbols into the stack or the input (or it deletes the symbols from the stack and the input, or it can do both insertion and deletion).
  - missing operand
  - unbalanced right parenthesis

Phrase-Level Error Recovery: intuition

- Suppose *abEc* is poped and there is no production right hand side that matches *abEc*
- If there were a rhs *aEc* , we might issue message
  "illegal *b* on line *x*"
- If the rhs is *abEdc*, we might issue message
  "missing *d* on line *x*"
- If the found rhs is *abc*, we might issue message
  "illegal *E* on line *x*"
  where *E* stands for an appropriate syntactic category represented by non-terminal *E*

Disambiguated SLR-Parsing Tables

Action **Goto**

	id	+	*	(	)	$		E
0	s3			s2				1
1		s4	s5			acc		
2	s3			s2				6
3		r4	r4		r4	r4		
4	s3			s2				7
5	s3			s2				8
6		s4	s5		s9			
7		**r1**	**s5**		r1	r1		
8		**r2**	**r2**		r2	r2		
9		r3	r3		r3	r3		

1. E → E+E
2. E → E*E
3. E → (E)
4. E → id

FOLLOW(E) = { $, + , * ,) }

Disambiguated SLR-Parsing Tables with error routines

	Action							Goto
	id	+	*	(	)	$		E
0	s3	**E1**	**E1**	s2	**E2**	**E1**		1
1	**E3**	s4	s5	**E3**	**E2**	acc		
2	s3	**E1**	**E1**	s2	**E2**	**E1**		6
3	**r4**	r4	r4	**r4**	r4	r4		
4	s3	**E1**	**E1**	s2	**E2**	**E1**		7
5	s3	**E1**	**E1**	s2	**E2**	**E1**		8
6	**E3**	s4	s5	**E3**	s9	**E4**		
7	**r1**	**r1**	**s5**	**r1**	r1	r1		
8	**r2**	**r2**	**r2**	**r2**	r2	r2		
9	**r3**	r3	r3	**r3**	r3	r3		

1. E → E+E
2. E → E*E
3. E → (E)
4. E → id

FOLLOW(E) = { $, +, *,) }

Phrase-Level Error Recovery: example

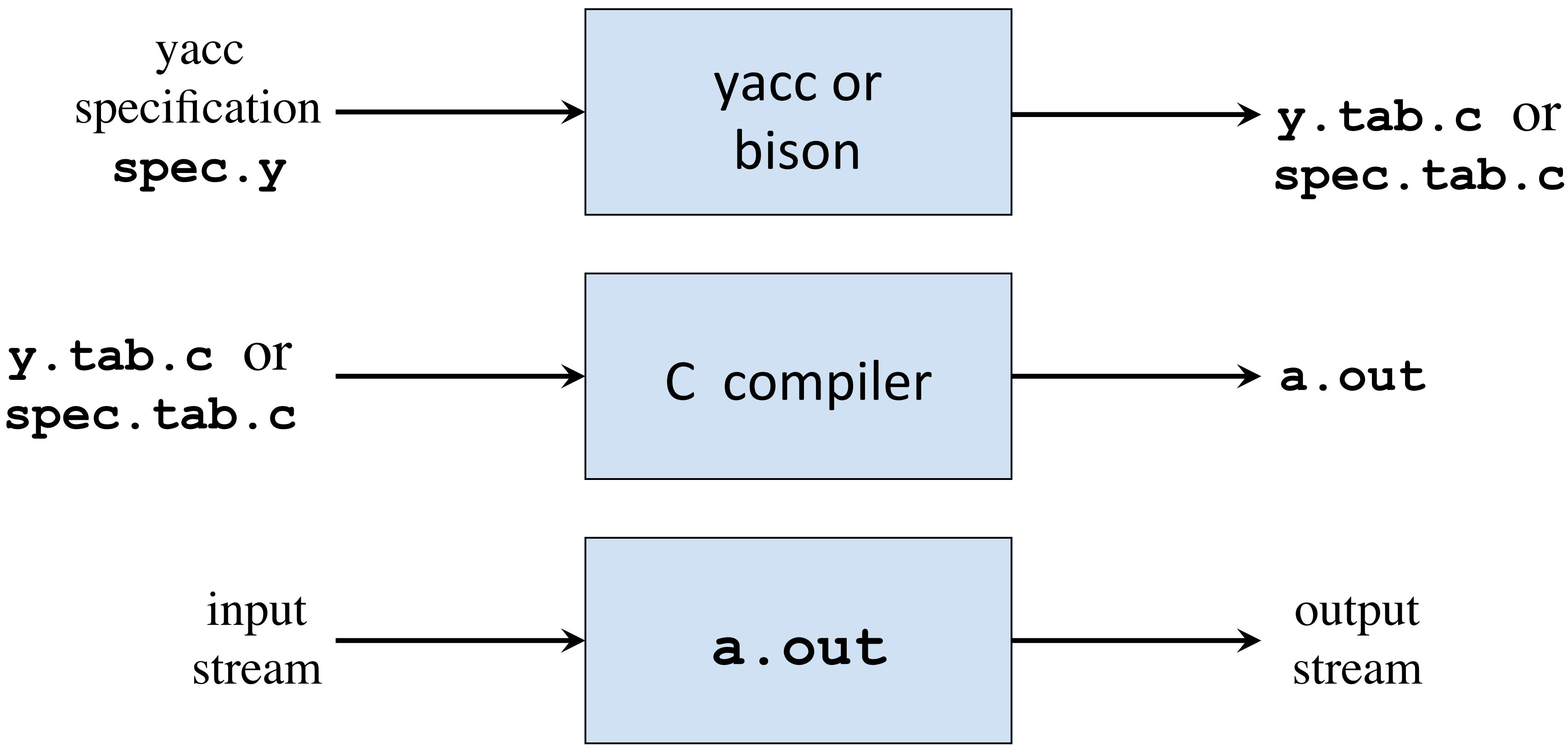
- **E1**: /* called when operand expected: '(' or 'id', but '+', '*' or '$' found */
  - push 'id' (state 3) onto the stack
  - print "missing operand"
- **E2**: /* called when unexpected ')' is found */
  - delete ')' from the input
  - print "unbalanced right parenthesis"
- **E3**: /* called when expecting an operator, but 'id' or '(' found/
  - push '+' (state 4) onto the stack
  - print "missing operator"
- **E4**: /* called from state 6 when end of input is found */
  - print "missing right parenthesis"

PARSER GENERATORS

Parser Generators: ANTLR, Yacc, and Bison

- *ANTLR* tool
  - Generates LL(*k*) parsers
- *Yacc* (Yet Another Compiler Compiler)
  - Generates LALR parsers
- *Bison*
  - Improved version of Yacc (GNU project)

Creating an LALR(1) Parser with Yacc/Bison



Yacc Specification

- A **yacc specification** consists of three parts:

- ***yacc declarations****, and C declarations within* **%{ %}**
  %%
  translation rules *(productions + semantic actions)*
  %%
  user-defined ***auxiliary procedures***

- The *translation rules* are productions with actions:
  $production_1$ { $semantic\ action_1$ }
  $production_2$ { $semantic\ action_2$ }
  …
  $production_n$ { $semantic\ action_n$ }

Writing a Grammar in Yacc

- Productions $\quad head \text{ -> } body_1 \mid body_2 \mid \ldots \mid body_n \mid \varepsilon$
  becomes in Yacc

```
head :  body1  { semantic action1 }
     |  body2  { semantic action2 }
     …
     |  /* empty */
     ;
```

- Tokens (terminals) can be:
  - Quoted single characters, e.g. `'+'`, with corresponding ASCII code
  - Identifiers declared as tokens in the declaration part using
    `%token` *TokenName*
- Nonterminals:
  - Arbitrary strings of letters and digits (not declared as tokens)

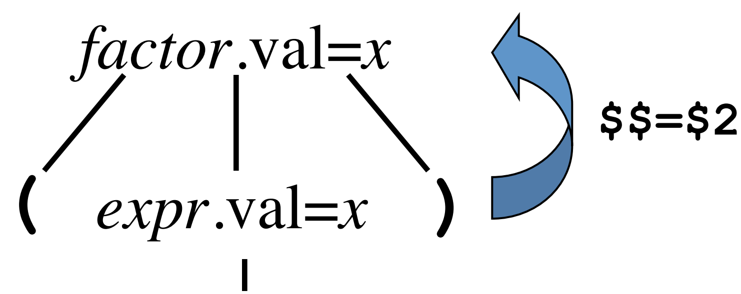
Semantic Actions and Synthesized Attributes

- **Semantic actions** are sequences of C statements, and may refer to values of the *synthesized attributes* of terminals and nonterminals in a production:

  ```
  X : Y1 Y2 Y3 … Yn { action }
  ```

  - `$$` refers to the value of the attribute of X
  - `$`i refers to the value of the attribute of Y_i
- For example

  ```
  factor : '(' expr ')' { $$=$2; }
  ```



- The values associated with tokens (terminals) are those returned by the lexer

An S-attributed Grammar for a simple desk calculator

The grammar

line → expr '\n'

expr → expr + term | term

term → term * factor | factor

factor → (expr) | **DIGIT**

```
%token DIGIT
%%
line    : expr '\n'      { printf("= %d\n", $1); }
    ;
expr    : expr '+' term      { $$ = $1 + $3; }
    | term           { $$ = $1; }
    ;
term    : term '*' factor    { $$ = $1 * $3; }
    | factor         { $$ = $1; }
    ;
factor  : '(' expr ')'       { $$ = $2; }
    | DIGIT          { $$ = $1; }
    ;
%%
```

Also results in definition of **`#define DIGIT xxx`**

Attribute of **`term`** (parent)

Attribute of **`term`** (child)

Attribute of token

A simple desk calculator

```
%{ #include <ctype.h> %}
%token DIGIT
%%
line    : expr '\n'      { printf("= %d\n", $1); }
    ;
expr    : expr '+' term     { $$ = $1 + $3; }
    | term           { $$ = $1; }
    ;
term    : term '*' factor  { $$ = $1 * $3; }
    | factor         { $$ = $1; }
    ;
factor  : '(' expr ')'      { $$ = $2; }
    | DIGIT          { $$ = $1; }
    ;
%%
int yylex()
{ int c = getchar();
  if (isdigit(c))
  { yylval = c-'0';
    return DIGIT;
  }
  return c;
}
```

Attribute of token (stored in **`yylval`**)

Very simple lexical analyzer invoked by the parser

The grammar
line → expr '\n'
expr → expr + term | term
term → term * factor | factor
factor → (expr) | **DIGIT**

Bottom-up Evaluation of S-Attributed Definitions in Yacc

Stack	val	Input	Action	Semantic Rule
$	_	**3*5+4n$**	shift	
$ 3	*3*	***5+4n$**	reduce $F \rightarrow$ **digit**	$$ = $1
$ *F*	*3*	***5+4n$**	reduce $T \rightarrow F$	$$ = $1
$ *T*	*3*	***5+4n$**	shift	
$ *T* *	*3 _*	**5+4n$**	shift	
$ *T* * **5**	*3 _ 5*	**+4n$**	reduce $F \rightarrow$ **digit**	$$ = $1
$ *T* * *F*	*3 _ 5*	**+4n$**	reduce $T \rightarrow T * F$	$$ = $1 * $3
$ *T*	*15*	**+4n$**	reduce $E \rightarrow T$	$$ = $1
$ *E*	*15*	**+4n$**	shift	
$ *E* **+**	*15 _*	**4n$**	shift	
$ *E* **+ 4**	*15 _ 4*	**n$**	reduce $F \rightarrow$ **digit**	$$ = $1
$ *E* **+** *F*	*15 _ 4*	**n$**	reduce $T \rightarrow F$	$$ = $1
$ *E* **+** *T*	*15 _ 4*	**n$**	reduce $E \rightarrow E$ **+** T	$$ = $1 + $3
$ *E*	*19*	**n$**	shift	
$ *E* **n**	*19 _*	**$**	reduce $L \rightarrow E$ **n**	*print* $1
$ *L*	*19*	**$**	accept	

Dealing With Ambiguous Grammars

- By defining operator precedence levels and left/ right associativity of the operators, we can specify ambiguous grammars in Yacc, such as

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

- Yacc resolves conflicts, by default, as follows:
  - **Reduce/reduce** conflict: precedence to first production in the specification
  - **Shift/reduce** conflict: precedence to shift
    - ok for *if-then-else*
    - infix binary operators are handled as **right-associative!**

Example: PlusTimesCalculator-flat

```
%token NUMBER
%%
lines : expr '\n'     { printf("= %g\n", $1); }
expr  : expr '+' expr          { $$ = $1 + $3; }
      | expr '*' expr          { $$ = $1 * $3; }
      | NUMBER
      ;
%%
```

- bison's warning:
  conflicts: 4 shift/reduce

```
> ./PlusTimesCalculator-flat
1+2*3+4*5
= ?
= ?  /* right associate, no precedence */
= 47  (!)
```

```
State 8 conflicts: 2 shift/reduce
State 9 conflicts: 2 shift/reduce
…
state 8
   2 expr: expr . '+' expr
   2     | expr '+' expr .
   3     | expr . '*' expr

   '+'  shift, and go to state 6
   '*'  shift, and go to state 7

   '+'      [reduce using rule 2 (expr)]
   '*'      [reduce using rule 2 (expr)]
   $default  reduce using rule 2 (expr)
```

Ambiguous Grammars in bison

- To define precedence levels and associativity in Yacc's declaration part, list tokens in order of increasing precedence, prefixed by **`%left`** or **`%right`**:

```
%left '+' '-'  //same precedence, associate left
%left '*' '/'
%right UMINUS
```

- If tokens have precedence, productions also have, equal to that of the rightmost terminal in the body. In this case:
  - **Shift/reduce** conflict are resolved with **reduce** if the production has higher precedence than the input symbol, or if they are equal and are left-associative.

Example: PlusTimesCalculator

```
%token NUMBER  /* tokens listed in increasing order of precedence */
%left '+'
%left '*'
%%
lines : expr '\n'      { printf("= %g\n", $1); }
expr  : expr '+' expr          { $$ = $1 + $3; }
      | expr '*' expr          { $$ = $1 * $3; }
      | NUMBER
      ;
%%
```

- No warnings by bison

```
> ./PlusTimesCalculator-flat
1+2*3+4*5
= 27   /* correct  precedence */
```

```
state 8

   2 expr: expr . '+' expr
   2     | expr '+' expr .
   3     | expr . '*' expr

   '*'  shift, and go to state 6

   $default  reduce using rule 2 (expr)
```

A more advanced calculator

Double type for attributes and **yylval**

```
%{
#include <ctype.h>
#include <stdio.h>
#define YYSTYPE double
%}
%token NUMBER   /*  tokens listed in increasing order of precedence  */
%left '+' '-'
%left '*' '/'
%right UMINUS   /*  fake token with highest precedence, used below  */
 %%
lines   : lines expr '\n'        { printf("= %g\n", $2); }
    | lines '\n'
    | /* empty */
    ;
expr: expr '+' expr            { $$ = $1 + $3; }
    | expr '-' expr            { $$ = $1 - $3; }
    | expr '*' expr            { $$ = $1 * $3; }
    | expr '/' expr            { $$ = $1 / $3; }
    | '(' expr ')'             { $$ = $2; }
    | '-' expr %prec UMINUS { $$ = -$2;} /*  rule with highest precedence  */
    | NUMBER
    ;
%%
```

A more advanced calculator (cont’d)

```
%%
int yylex()
{ int c;
  while ((c = getchar()) == ‘ ‘)
    ;
  if ((c == ‘.’) || isdigit(c))
  { ungetc(c, stdin);
    scanf(“%lf”, &yylval);
    return NUMBER;
  }
  return c;
}
int main()
{ if (yyparse() != 0)
    fprintf(stderr, “Abnormal exit\n”);
  return 0;
}
int yyerror(char *s)
{ fprintf(stderr, “Error: %s\n”, s);
}
```

Crude lexical analyzer for fp doubles and arithmetic operators

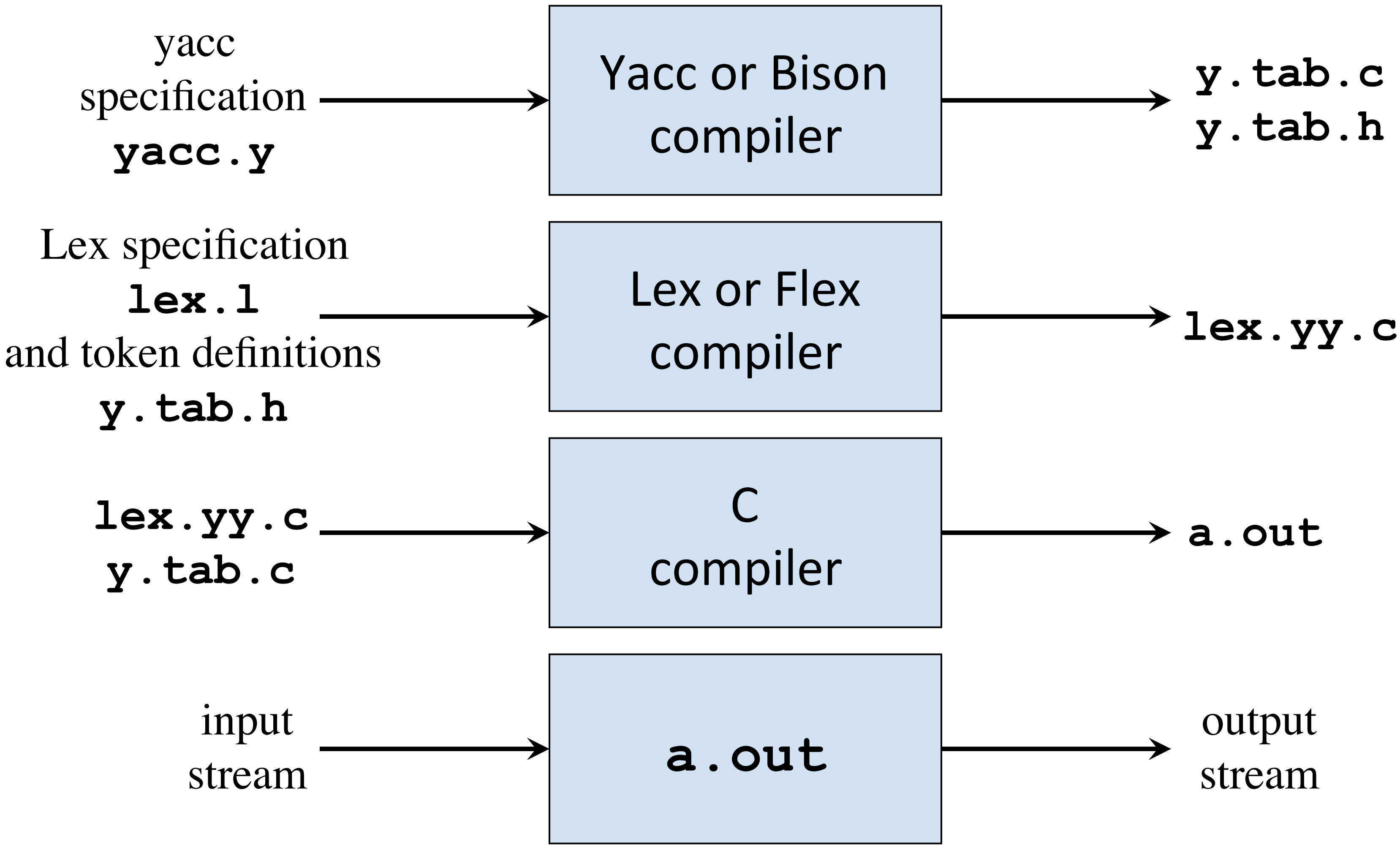
Run the parser

Invoked by parser to report parse errors

Dealing With Ambiguous Grammars (summary)

- Yacc does not report about conflicts that are solved using user-defined precedences
- It reports conflicts that are resolved with default rules
- To visit the automaton and the LALR parsing table generated, execute Bison/Yacc with option **–v**, and read the **<filename>.output** file
- This allows to see where conflicts were generated, and if the parser resolved them correctly
- Graphical representation of the automaton using Bison/Yacc with option **–g**. Output should be in **dot** format

Combining Lex/Flex with Yacc/Bison



Lex Specification for Advanced Calculator

```
%option noyywrap
%{
#define YYSTYPE double
#include "y.tab.h"

extern double yylval;
%}
number  [0-9]+\.?|[0-9]*\.[0-9]+
%%
[ ]     { /* skip blanks */ }
{number}   { sscanf(yytext, "%lf", &yylval);
             return NUMBER;
           }
\n|.       { return yytext[0]; }
```

Generated by Yacc, contains **`#define NUMBER xxx`**

Defined in **`y.tab.c`**

```
yacc -d example2.y
lex example2.l
gcc y.tab.c lex.yy.c
./a.out
```

```
bison -d -y example2.y
flex example2.l
gcc y.tab.c lex.yy.c
./a.out
```

Error Recovery in Yacc

- Based on error productions of the form   ***A* → *error α***

```
%{
…
%}
…
%%
lines   : lines expr ‘\n’  { printf(“%g\n”, $2; }
    | lines ‘\n’
    | /* empty */
    | error ‘\n’       { yyerror(“reenter last line: ”);
                                 yyerrok;
                  }
    ;
…
```

Error production: set error mode and skip input until newline

Reset parser to normal mode