Syntax-Directed Translation

ASU Textbook Chapter 5.1–5.6, 4.9

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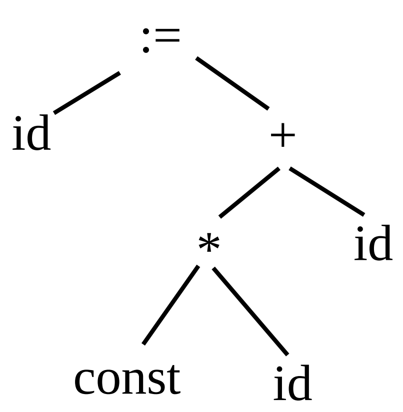
What is syntax-directed translation?

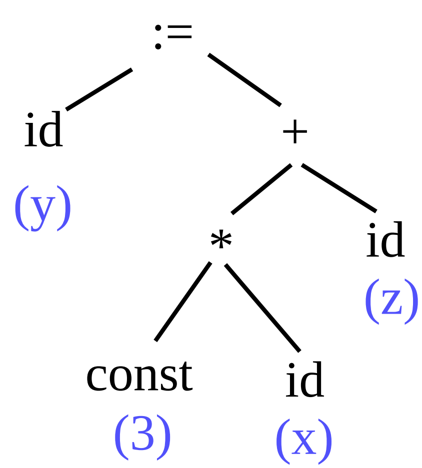
- **Definition:**
  - **The compilation process is driven by the syntax.**
  - **The semantic routines perform interpretation based on the syntax structure.**
  - **Attaching attributes to the grammar symbols.**
  - **Values for attributes are computed by semantic actions associated with the grammar productions.**

Example: Syntax-directed translation

- **Example in a parse tree:**
  - **Annotate the parse tree by attaching semantic attributes to the nodes of the parse tree.**
  - **Generate code by visiting nodes in the parse tree in a given order.**
  - **Input:** $y := 3 * x + z$



parse tree



annotated parse tree

Syntax-directed definitions

- **Each grammar symbol is associated with a set of attributes.**
  - **Synthesized attribute : value computed from its children or associated with the meaning of the tokens.**
  - **Inherited attribute : value computed from parent and/or siblings.**
  - **General attribute : value can be depended on the attributes of any nodes.**

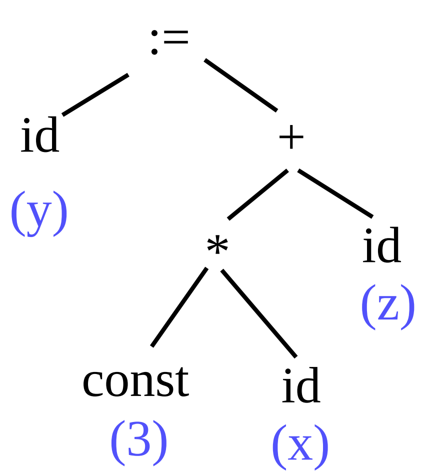
Format for writing syntax-directed definitions

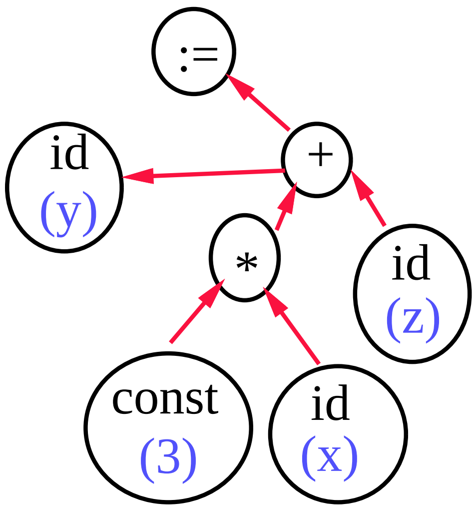
Production	Semantic actions
$L \rightarrow E$	print($E.val$)
$E \rightarrow E_1 + T$	$E.val := E_1.val + T.val$
$E \rightarrow T$	$E.val := T.val$
$T \rightarrow T_1 * F$	$T.val := T_1.val * F.val$
$T \rightarrow F$	$T.val := F.val$
$F \rightarrow (E)$	$F.val := E.val$
$F \rightarrow digit$	$F.val := digit.lexval$

- **$E.val$ is one of the attributes of E.**
- **To avoid confusion, recursively defined nonterminals are numbered on the LHS.**
- **Semantic actions are performed when this production is "used".**

Order of evaluation (1/2)

- **Order of evaluating attributes is important.**
- **General rule for ordering:**
  - **Dependency graph** :
    - ▷ ***If attribute b needs attributes a and c, then a and c must be evaluated before b.***
    - ▷ ***Represented as a directed graph without cycles.***
    - ▷ ***Topologically order nodes in the dependency graph as n_1, n_2, ..., n_k such that there is no path from n_i to n_j with $i > j$.***

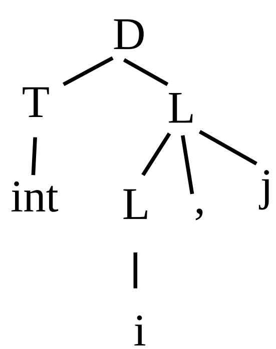


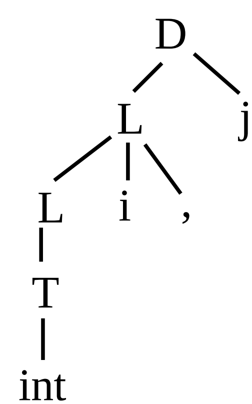


Order of evaluation (2/2)

- **It is always possible to rewrite syntax-directed definitions using only synthesized attributes, but the one with inherited attributes is easier to understand.**
  - **Use inherited attributes to keep track of the type of a list of variable declarations.**
    - ***Example:*** $int\ i, j$

- **Grammar 1: using inherited attributes**
  - $D \rightarrow T L$
  - $T \rightarrow int \mid char$
  - $L \rightarrow L, id \mid id$
- **Grammar 2: using only synthesized attributes**
  - $D \rightarrow L\ id$
  - $L \rightarrow L\ id, \mid T$
  - $T \rightarrow int \mid char$



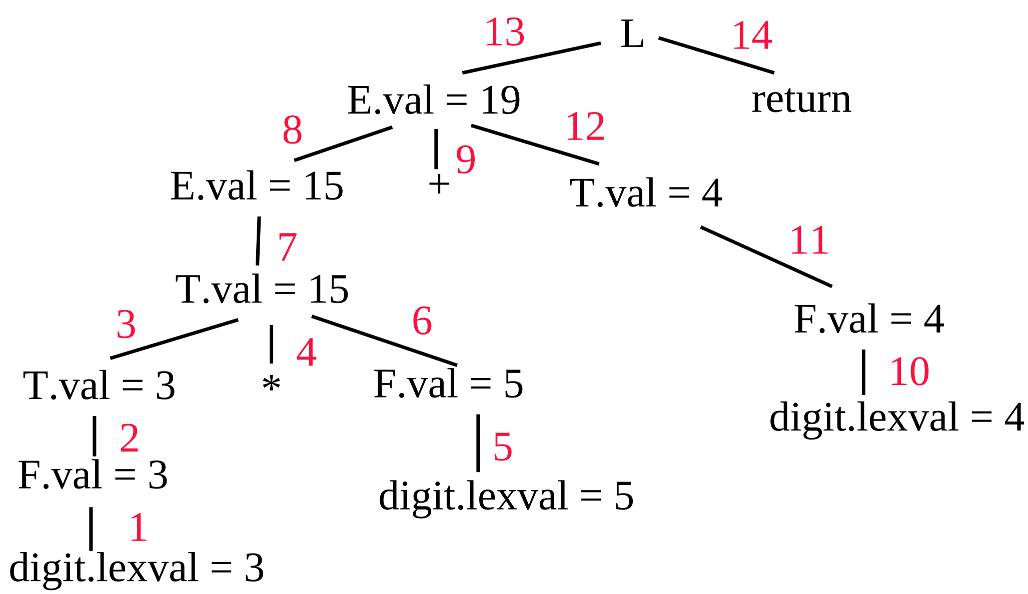


Attribute grammars

- **Attribute grammar: a grammar with syntax-directed definitions and having no side effects.**
  - **Side effect: change values of others not related to the return values of functions themselves.**
- **Tradeoffs:**
  - **Synthesized attributes are easy to compute, but are sometimes difficult to be used to express semantics.**
  - **Inherited and general attributes are difficult to compute, but are sometimes easy to express the semantics.**
  - **The dependence graph for computing some inherited and general attributes may contain cycles and thus not-computable.**
  - **A restricted form of inherited attributes is invented.**
    - ▷ ***L-attributes.***

S-attributed definition

- **Definition: a syntax-directed definition that uses synthesized attributed only.**
  - **A parse tree can be represented using a directed graph.**
  - **A post-order traverse of the parse tree can properly evaluate grammars with S-attributed definitions.**
  - **Bottom-up evaluation.**
- **Example of an S-attributed definition: $3 * 5 + 4$ return**



L-attributed definition

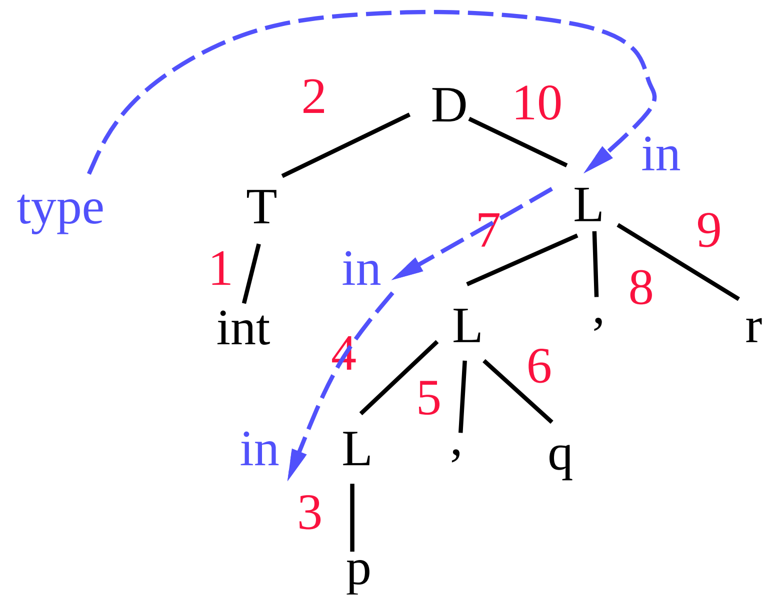
- **Definition:**
  - **Each attribute in each semantic rule for the production $A \rightarrow X_1, \ldots, X_n$ is either a synthesized attribute or an inherited attribute X_j depends only on the inherited attribute of A and/or the attributes of $X_1, \ldots, X_{j-1}$.**
  - **Every S-attributed definition is an L-attributed definition.**
- **For grammars with L-attributed definitions, special evaluation algorithms must be designed.**
- **Bottom-up evaluation of L-attributed grammars.**
  - **Can handle all $LL(1)$ grammars and most $LR(1)$ grammars.**
  - **All translation actions are taken at the right end of the production.**
- **Key observation:**
  - **L-attributes are always computable.**
    - ▷ ***Same argument as the one used in discussing Algorithm 4.1.***
  - **When a bottom-up parser reduces by the production $A \rightarrow XY$, by removing X and Y from the top of the stack and replacing them by A,**
    - ▷ ***$X.s$ (the synthesized attribute of X) is on the top of the stack and thus can be used to compute $Y.in$ (the inherited attribute of Y).***

Example for L-attributed definitions

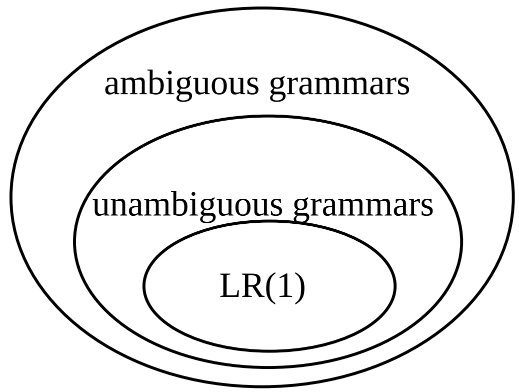
- $D \rightarrow T\ \{L.in := T.type\}\ L$
- $T \rightarrow int\ \{T.type := integer\}$
- $T \rightarrow real\ \{T.type := real\}$
- $L \rightarrow\ \{L_1.in := L.in\}\ L_1, id\ \{addtype(id.entry, L.in)\}$
- $L \rightarrow id\ \{addtype(id.entry, L.in)\}$

Parsing and dependency graph:

STACK	input	production used
	int p, q, r	
int	p, q, r	
T	p, q, r	$T \rightarrow int$
$T\ p$	$, q, r$	
$T\ L$	$, q, r$	$L \rightarrow id$
$T\ L\ ,$	q, r	
$T\ L\ ,\ q$	$, r$	
$T\ L$	$, r$	$L \rightarrow L, id$
$T\ L\ ,$	r	
$T\ L\ ,\ r$		
$T\ L$		$L \rightarrow L, id$
D		$D \rightarrow TL$



Using ambiguous grammars



- **Ambiguous grammars often provide a shorter, more natural specification than their equivalent unambiguous grammars.**
- **Sometimes need ambiguous grammars to specify important language constructs.**
- **For example: declare a variable before its usage.**

```
var xyz : integer
begin
    ...
    xyz := 3;
    ...
```

Ambiguity from precedence and associativity

- **Use precedence and associativity to resolve conflicts.**
- **Example:**
  - G_1:
    - ▷ $E \rightarrow E + E \mid E * E \mid (E) \mid id$
    - ▷ ***Ambiguous, but easy to understand and maintain!***
  - G_2:
    - ▷ $E \rightarrow E + T \mid T$
    - ▷ $T \rightarrow T * F \mid F$
    - ▷ $F \rightarrow (E) \mid id$
    - ▷ ***Unambiguous, but difficult to understand and maintain!***
    - ▷ ***Parse tree is larger for G_2, and thus takes more time to parse.***
- **When parsing the following input for G_1: $id + id * id$.**
  - **Assume the input parsed so far is $id + id$.**
  - **We now see "*".**
  - **We can either shift or perform "reduce by $E \rightarrow E + E$".**
  - **When there is a conflict, say in $LALR(1)$ parsing, we use precedence and associativity information to resolve conflicts.**
    - ▷ ***Here we need to shift because of seeing a higher precedence operator.***

Ambiguity from dangling-else

- **Grammar:**
  - **Statement** $\rightarrow$ **Other_Statement**
    $\mid$ if **Condition** $then$ **Statement**
    $\mid$ if **Condition** $then$ **Statement** $else$ **Statement**
- **When seeing**

$$\underline{if\ \mathbf{C}\ then\ \mathbf{S}}\ else\ \mathbf{S}$$

  - **there is a shift or reduce conflict,**
  - **we always favor a shift.**
  - **Intuition: favor a longer match.**

Special cases

- **Ambiguity from special-case productions:**
  - **Sometime a very rare happened special case causes ambiguity.**
  - **It is too costly to revise the grammar. We can resolve the conflicts by using special rules.**
  - **Example:**
    - ▷ $E \rightarrow E\ sub\ E\ sup\ E$
    - ▷ $E \rightarrow E\ sub\ E$
    - ▷ $E \rightarrow E\ sup\ E$
    - ▷ $E \rightarrow \{E\} \mid character$
  - **Meanings:**
    - ▷ $W\ sub\ U$: W_U.
    - ▷ $W\ sup\ U$: W^U.
    - ▷ $W\ sub\ U\ sup\ V$ is W_U^V, not ${W_U}^V$
  - **Resolve by semantic and special rules.**
  - **Pick the right one when there is a reduce/reduce conflict.**
    - ▷ ***Reduce the production listed earlier.***
  - **Similar to the dangling-else case!**

Implementation

- **Passing of synthesized attributes is best.**
  - Without using global variables.
- **Cannot use information from its younger siblings because of the limitation of LR parsing.**
  - During parsing, the STACK contains information about the older siblings.
- **It is difficult and usually impossible to use information passing from its parent node.**
  - It may be possible to use the state information to pass some information.
- **Choices:**
  - Build a parse tree first, then evaluate its semantics.
  - Parse and evaluate the semantic actions on the fly.
- **YACC can be used to implement L-attributed definitions.**
  - Use top of STACK information to pass synthesized attributes.
  - Use global variables and internal STACK information to pass the inherited values from its older siblings, i.e., L-attributes.

YACC

- Yet Another Compiler Compiler:
  - A UNIX utility for generating $LALR(1)$ parsing tables.
  - Convert your YACC code into C programs.
  - file.y $\longrightarrow$ [yacc file.y] $\longrightarrow$ y.tab.c
  - y.tab.c $\longrightarrow$ [cc y.tab.c -ly -ll] $\longrightarrow$ a.out
- Format:
  - declarations
  - %%
  - grammars and semantic actions.
  - %%
  - supporting C-routines.
- Assume the Lexical analyzer routine is $yylex()$.
  - Need to include the scanner routines.

YACC code example (1/2)

```
%{
#include <stdio.h>
#include <ctype.h>
#include <math.h>
#define YYSTYPE int /* integer type for YACC stack */

%}

%token NUMBER ERROR '(' ')'
%left '+' '-'
%left '*' '/'
%right UMINUS

%%
```

YACC code example (2/2)

```
lines   :  lines expr '\n'        {printf("%d\n", $2);}
        |  lines '\n'
        |  /* empty, i.e., epsilon */
        |  lines error '\n' {yyerror("Please reenter:");yyerrok;}
        ;
expr    :  expr '+' expr    { $$ = $1 + $3; }
        |  expr '-' expr    { $$ = $1 - $3; }
        |  expr '*' expr    { $$ = $1 * $3; }
        |  expr '/' expr    { $$ = $1 / $3; }
        |  '(' expr ')'     { $$ = $2; }
        |  '-' expr  %prec UMINUS  { $$ = - $2; }
        |  NUMBER      { $$ = atoi(yytext);}
        ;

%%
#include "lex.yy.c"
```

Included LEX program

```
%{
%}
Digit         [0-9]
IntLit        {Digit}+
%%
[ \t] {/* skip white spaces */}
[\n] {return('\n');}
{IntLit}                                {return(NUMBER);}
"+"                                     {return('+');}
"-"                                     {return('-');}
"*"                                     {return('*');}
"/"                                     {return('/');}
"("                                     {return('(');}
")"                                     {return(')');}
.          {printf("error token <%s>\n",yytext); return(ERROR);}
%%
```

YACC rules (1/3)

- **Declarations:**
  - **System used and C language declarations.**
    - ▷ *%{ · · · %} to enclose C declarations.*
    - ▷ *Type of attributes associated with each grammar symbol on the stack: YYSTYPE declaration.*
    - ▷ *This area will not be translated by YACC.*
  - **Tokens with associativity and precedence assignments.**
    - ▷ *In increasing precedence from top to the bottom.*
    - ▷ *%left, %right or %token (non-associativity): e.g., dot products of vectors has no associativity.*
  - **Other declarations.**
    - ▷ *%type*
    - ▷ *%union*
    - ▷ · · ·

YACC rules (2/3)

- **Productions and semantic actions:**
  - **Format: for productions P with a common LHS**
    - ▷ *<LHS of P>: <RHS$_1$ of P> { semantic actions # 1}*
    - ▷ *|<RHS$_2$ of P> { semantic actions # 2}*
    - ▷ $\cdots$
  - **The semantic actions are performed, i.e., C routines are executed, when this production is reduced.**
  - **Accessing attributes associated with grammar symbols:**
    - ▷ *$$: the return value of this production if it is reduced.*
    - ▷ *$$i$: the returned value of the ith symbol in the RHS production.*
  - **%prec declaration.**
- **When there are ambiguities:**
  - **reduce/reduce conflict: favor the one listed first.**
  - **shift/reduce conflict: favor shift, i.e., longer match.**
  - **Q: How to implement this?**

YACC rules (3/3)

- **Error handling:**
  - **Example:** `lines: error '\n' {...}`
    - ▷ ***When there is an error, skip until newline is seen.***
  - $error$: **special nonterminal.**
    - ▷ ***A production with*** $error$ ***is "inserted" or "processed" only when it is in the reject state.***
    - ▷ ***It matches any sequence on the stack as if the handle "***$error \rightarrow \cdots$***" is seen.***
    - ▷ ***Use a special token to immediately follow*** $error$ ***for the purpose of skpping until something special is seen.***
    - ▷ ***One of the reasons to use statement terminators, instead of statement separators, in language designs.***
    - ▷ ***Q: How to implement this?***
  - $yyerrok$: **a macro to reset error flags and make** $error$ **invisible again.**
  - $yyerror(string)$: **pre-defined routine for printing error messages.**

In-production actions

- **Actions can be inserted in the middle of a production, each such action is treated as a nonterminal.**
  - **Example:**
    ```
    expr    :  expr { perform some semantic actions} '+' expr
               {$$ = $1 + $4; }
    ```
    is equivalent to
    ```
    expr  :  expr $ACT '+' expr {$$ = $1 + $4;}
    $ACT  : { perform some semantic actions}
    ```
  - **Note: $ACT is a nonterminal created automated for this production.**
- **Avoid in-production actions.**
  - ϵ**-productions can easily generate conflicts.**
    - ▷ *Generate a reduce operation for states including this LR(0)-item.*
  - **Split the production.**
    ```
    expr    :  exprhead exptail {$$ = $1 + $2;}
    exphead :  expr { perform some semantic actions; $$ = $1;}
    exptail : '+'  expr {$$ = $2;}
    ```
    - ▷ *May generate some conflicts.*
    - ▷ *May be difficult to specify precedence and associativity.*
    - ▷ *May change the parse tree and thus the semantic.*

Some useful YACC programming styles

- **Keep the right hand side of a production short.**
  - **Better to have less than 4 symbols.**
- **Language issues.**
  - **Avoiding using names starting with "$".**
  - **Watch out C-language rules.**
    - ▷ *goto*
  - **Some C-language reserved words are used by YACC.**
    - ▷ *union*
  - **Some YACC pre-defined routines are macros, not procedures.**
    - ▷ *yyerrok*
- **Rewrite the productions for S-attributed or L-attributed definitions.**
  - **Grammar 1: Array → id [Elist]**
  - **Grammar 2:**
    - ▷ *Array → Aelist]*
    - ▷ *Aelist → Aelist, id | Ahead*
    - ▷ *Ahead → id [id*

Limitations of syntax-directed translation

- **Limitation of syntax-directed definitions: Without using global data to create side effects, some of the semantic actions cannot be performed.**
- **Examples:**
  - **Checking whether a variable is defined before its usage.**
  - **Checking the type and storage address of a variable.**
  - **Checking whether a variable is used or not.**
  - **Need to use a symbol table : global data to show side effects of semantic actions.**
- **Common approach in using global variables:**
  - **A program with too many global variables is difficult to understand and maintain.**
  - **Restrict the usage of global variables to essential ones and use them as objects.**
    - ▷ ***Symbol table.***
    - ▷ ***Labels for GOTO's.***
    - ▷ ***Forwarded declarations.***
  - **Tradeoff between ease of coding and ease of maintaining.**