CS3300 - Compiler Design

Syntax Directed Translation

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Syntax-Directed Translation

- Attach rules or program fragments to productions in a grammar.
- Syntax directed definition (SDD)
- $E_1 \to E_2 + T \qquad E_1.code = E_2.code || T.code ||' +'$
- Syntax directed translation Scheme (SDT)
- $E \to E + T \qquad$ {print '+'} // semantic action
- $F \to id \qquad$ {print id.val}

SDD and SDT scheme

- SDD: Specifies the values of attributes by associating semantic rules with the productions.
- SDT scheme: embeds program fragments (also called semantic actions) within production bodies.
  - The position of the action defines the order in which the action is executed (in the middle of production or end).
- SDD is easier to read; easy for specification.
- SDT scheme – can be more efficient; easy for implementation.

Example: SDD vs SDT scheme – infix to postfix trans

SDTScheme		*SDD*	
$E \to E + T$	$\{print' +'\}$	$E \to E + T$	$E.code = E.code \| \| T.code \| \|' +'$
$E \to E - T$	$\{print' -'\}$	$E \to E - T$	$E.code = E.code \| \| T.code \| \|' -'$
$E \to T$		$E \to T$	$E.code = T.code$
$T \to 0$	$\{print'0'\}$	$T \to 0$	$T.code =' 0'$
$T \to 1$	$\{print'1'\}$	$T \to 1$	$T.code =' 1'$
$\cdots$		$\cdots$	
$T \to 9$	$\{print'9'\}$	$T \to 9$	$T.code =' 9'$

Syntax directed translation - overview

1. Construct a parse tree
2. Compute the values of the attributes at the nodes of the tree by visiting the tree

Key: We don't need to build a parse tree all the time.

- Translation can be done during parsing.
  - class of SDTs called "L-attributed translations".
  - class of SDTs called "S-attributed translations".

Syntax directed definition

- SDD is a CFG along with attributes and rules.
- An attribute is associated with grammar symbols (attribute grammar).
- Rules are are associated with productions.

Attributes

- Attribute is any quantity associated with a programming construct.
- Example: data types, line numbers, instruction details

Two kinds of attributes: for a non-terminal A, at a parse tree node N

- A synthesized attribute: defined by a semantic rule associated with the production at N.

  defined only in terms of attribute values at the children of N and at N itself.
- An inherited attribute: defined by a semantic rule associated with the parent production of N.

  defined only in terms of attribute values at the parent of N siblings of N and at N itself.

Specifying the actions: Attribute grammars

Idea: attribute the syntax tree

- can add attributes (*fields*) to each node
- specify equations to define values (*unique*)
- can use attributes from parent and children

Example: to ensure that constants are immutable:

- add *type* and *class* attributes to expression nodes
- rules for production on $:=$ that
  1. check that LHS.*class* is *variable*
  2. check that LHS.*type* and RHS.*type* are consistent or conform

Attribute grammars

To formalize such systems Knuth introduced *attribute grammars*:

- grammar-based specification of tree attributes
- value assignments associated with productions
- each attribute uniquely, locally defined
- label identical terms uniquely

Can specify context-sensitive actions with attribute grammars

Example

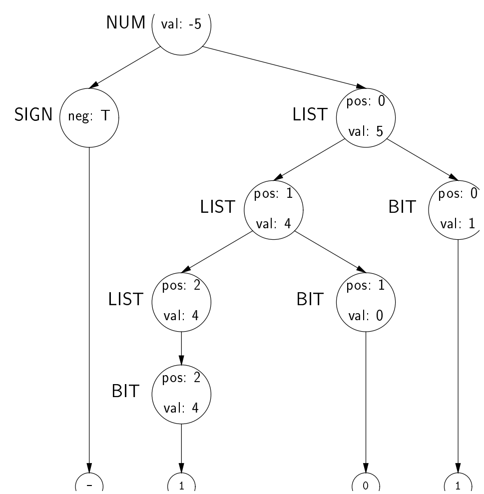
PRODUCTION	SEMANTIC RULES
$D \rightarrow T\ L$	$L.\text{in} := T.\text{type}$
$T \rightarrow$ **int**	$T.\text{type} := \text{integer}$
$T \rightarrow$ **real**	$T.\text{type} := \text{real}$
$L \rightarrow L_1$, **id**	$L_1.\text{in} := L.\text{in}$
	addtype(**id**.entry, L.in)
$L \rightarrow$ **id**	addtype(**id**.entry, L.in)

Example: Evaluate signed binary numbers

PRODUCTION	SEMANTIC RULES
NUM $\rightarrow$ SIGN LIST	LIST.pos := 0
	if SIGN.neg
	NUM.val := -LIST.val
	else
	NUM.val := LIST.val
SIGN $\rightarrow$ +	SIGN.neg := false
SIGN $\rightarrow$ –	SIGN.neg := true
LIST $\rightarrow$ BIT	BIT.pos := LIST.pos
	LIST.val := BIT.val
LIST $\rightarrow$ LIST$_1$ BIT	LIST$_1$.pos := LIST.pos + 1
	BIT.pos := LIST.pos
	LIST.val := LIST$_1$.val + BIT.val
BIT $\rightarrow$ 0	BIT.val := 0
BIT $\rightarrow$ 1	BIT.val := $2^{\text{BIT}.pos}$

Example (continued)

The attributed parse tree for `-101`:



- *val* and *neg* are *synthesized* attributes
- *pos* is an *inherited* attribute

Dependences between attributes

- values are computed from constants & other attributes
- *synthesized attribute* – value computed from children
- *inherited attribute* – value computed from siblings & parent
- *key notion*: induced dependency graph

The attribute dependency graph

- nodes represent attributes
- edges represent flow of values
- graph is specific to parse tree
- size is related to parse tree's size
- can be built alongside parse tree

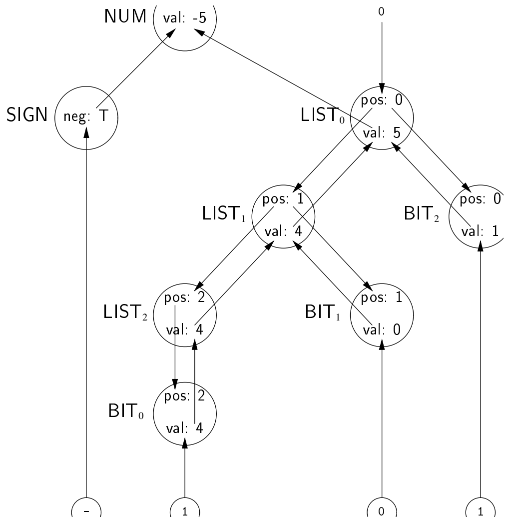
The dependency graph must be acyclic
Evaluation order:

- topological sort the dependency graph to order attributes
- using this order, evaluate the rules

The order depends on both the grammar and the input string

Example (continued)

The attribute dependency graph:



Example: A topological order

1. SIGN.neg
2. LIST_0.pos
3. LIST_1.pos
4. LIST_2.pos
5. BIT_0.pos
6. BIT_1.pos
7. BIT_2.pos
8. BIT_0.val
9. LIST_2.val
10. BIT_1.val
11. LIST_1.val
12. BIT_2.val
13. LIST_0.val
14. NUM.val

Evaluating in this order yields NUM.val: -5

Evaluation strategies

- *Parse-tree methods* (*dynamic*)
  1. build the parse tree
  2. build the dependency graph
  3. topological sort the graph
  4. evaluate it (*cyclic graph fails*)

What if there are cycles?

Avoiding cycles

- Hard to tell, for a given grammar, whether there exists any parse tree whoe depdency graphs have cycles.
- Focus on classes of SDD's that guarantee an evaluation order – do not permit dependency graphs with cycles.
  - L-attributed – class of SDTs called "L-attributed translations".
  - S-attributed – class of SDTs called "S-attributed translations".

Top-down (LL) on-the-fly one-pass evaluation

L-attributed grammar:
Informally – dependency-graph edges may go from left to right, not other way around.
given production $A \to X_1 X_2 \cdots X_n$

- inherited attributes of X_j depend only on:
  1. inherited attributes of A
  2. arbitrary attributes of $X_1, X_2, \cdots X_{j-1}$
- synthesized attributes of A depend only on its inherited attributes and arbitrary RHS attributes
- synthesized attributes of an action depends only on its inherited attributes

i.e., evaluation order:
Inh(A), Inh(X_1), Syn(X_1), . . . , Inh(X_n), Syn(X_n), Syn(A)
This is precisely the order of evaluation for an LL parser

Bottom-up (LR) on-the-fly one-pass evaluation

S-attributed grammar:

- L-attributed
- only synthesized attributes for non-terminals
- actions at far right of a RHS

Can evaluate S-attributed in one bottom-up (LR) pass.

Evaluate S-attributed grammar in bottom-up parsing

- Evaluate it in any bottom-up order of the nodes in the parse tree.
- (One option:) Apply *postorder* to the root of the parse tree:

```
void  postorder (N) {
     for (each child C of N)
      do
        postorder(C);
      done
     evaluate the attributes associated with N;
}
```

- post order traversal of the parse tree corresponds to the exact order in which the bottom-up parsing builds the parse tree.
- Thus, we can evaluate S-attributed in one bottom-up (LR) pass.

Inherited Vs Synthesised attributes

Synthesized attributes are limited

Inherited attributes (are good): derive values from constants, parents, siblings

- used to express context (*context-sensitive checking*)
- inherited attributes are more "natural"

We want to use both kinds of attributes

- can *always* rewrite L-attributed LL grammars (using markers and copying) to avoid inherited attribute problems with LR

Self reading (if interested) – Dragon book Section 5.5.4.

LL parsers and actions

How does an LL parser handle (aka - execute) actions?
Expand productions *before* scanning RHS symbols, so:

- push actions onto parse stack like other grammar symbols
- pop and perform action when it comes to top of parse stack

LL parsers and actions

push EOF
push *Start Symbol*
token $\leftarrow$ next_token()
repeat
    pop X
    if X is a terminal or EOF then
        if X = token then
            token $\leftarrow$ next_token()
        else error()
    else if X is an action
        perform X
    else /* X is a non-terminal */
        if M[X,token] = $X \rightarrow Y_1 Y_2 \cdots Y_k$ then
            push $Y_k, Y_{k-1}, \cdots, Y_1$
        else error()
until X = EOF

LR parsers and action symbols

What about LR parsers?
Scan entire RHS before applying production, so:

- cannot perform actions until entire RHS scanned
- can only place actions at very end of RHS of production
- introduce new marker non-terminals and corresponding productions to get around this restriction†

$$A \rightarrow w \textit{ action } \beta$$

becomes

$$A \rightarrow M\beta$$

$$M \rightarrow w \textit{ action}$$

†yacc, bison, CUP do this automatically

Action-controlled semantic stacks

- Approach:
  - stack is managed explicitly by action routines
  - actions take arguments from top of stack
  - actions place results back on stack
- Advantages:
  - actions can directly access entries in stack without popping (efficient)
- Disadvantages:
  - implementation is exposed
  - action routines must include explicit code to manage stack (or use `stack` abstract data type).

LR parser-controlled semantic stacks

Idea: let parser manage the semantic stack
LR parser-controlled semantic stacks:

- parse stack contains already parsed symbols
- maintain semantic values in parallel with their symbols
- add space in parse stack or parallel stack for semantic values
- every matched grammar symbol has semantic value
- pop semantic values along with symbols

$\Rightarrow$ LR parsers have a very nice fit with semantic processing

LL parser-controlled semantic stacks

Problems:

- parse stack contains predicted symbols, not yet matched
- often need semantic value after its corresponding symbol is popped

Solution:

- use separate semantic stack
- push entries on semantic stack along with their symbols
- on completion of production, pop its RHS's semantic values

Attribute Grammars

Advantages

- clean formalism
- automatic generation of evaluator
- high-level specification

Disadvantages

- evaluation strategy determines efficiency
- increased space requirements
- parse tree evaluators need dependency graph
- results distributed over tree
- circularity testing

Intel's 80286 Pascal compiler used an attribute grammar evaluator to perform context-sensitive analysis.
Historically, attribute grammar evaluators have been deemed too large and expensive for commercial-quality compilers.