Principle of Compilers

Lecture V. Semantic Analysis Formalism: Syntax Directed Translation

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Summary of Lecture V

- **Syntax Directed Definitions**
- Implementing Syntax Directed Translations
  - Dependency Graphs
  - S-Attributed Definitions
  - L-Attributed Definitions
    - Translation Schemes

Semantic Analysis

- **Semantic Analysis** computes additional information once the syntactic structure is known.
- The information to be computed is beyond the capabilities of standard parsing techniques, therefore is not regarded as syntax.
- The information is also related to the meaning of the program.
- In typed languages as C, semantic analysis involves building the symbol table and performing type checking.
- As for Lexical and Syntax analysis, also for Semantic Analysis we need both a *Representation Formalism* and an *Implementation Mechanism*.
- As representation formalism this lecture illustrates what are called *Syntax Directed Translations* (also known as *Attribute Grammars*).

Syntax Directed Translation: Intro

- The **Principle of Syntax Directed Translation** states that the meaning of an input sentence is related to its syntactic structure, i.e. to its Parse-Tree.
- By **Syntax Directed Translations** we indicate those formalisms for specifying translations for programming language constructs guided by context-free grammars.
  - We associate **Attributes** to the grammar symbols representing the language constructs.
  - Values for attributes are computed by **Semantic Rules** associated with grammar productions.
- Evaluation of Semantic Rules may:
  - Generate Code;
  - Insert information into the Symbol Table;
  - Perform Semantic Check;
  - Issue error messages; etc.

Syntax Directed Translation: Intro (Cont.)

- There are two notations for attaching semantic rules:

  1. **Syntax Directed Definitions.** High-level specification hiding many implementation details (also called **Attribute Grammars**).
  2. **Translation Schemes.** More implementation oriented: Indicate the order in which semantic rules are to be evaluated.

Syntax Directed Definitions

- **Syntax Directed Definitions** are a generalization of context-free grammars in which:
  1. Grammar symbols have an associated set of **Attributes**;
  2. Productions are associated with **Semantic Rules** for computing the values of attributes.
- Such formalism generates **Annotated Parse-Trees** where each node is of type record with a field for each attribute (e.g., $X.a$ indicates the attribute a of the grammar symbol X).

Syntax Directed Definitions (Cont.)

- The value of an attribute of a grammar symbol at a given parse-tree node is defined by a semantic rule associated with the production used at that node.
- We distinguish between two kinds of attributes:
  1. **Synthesized Attributes.** They are computed from the values of the attributes of the children nodes.
  2. **Inherited Attributes.** They are computed from the values of the attributes of both the siblings and the parent nodes.

Form of Syntax Directed Definitions

- Each production, $A \rightarrow \alpha$, is associated with a set of semantic rules: $b := f(c_1, c_2, \ldots, c_k)$, where f is a function and either
  1. b is a *synthesized* attribute of A, and $c_1, c_2, \ldots, c_k$ are attributes of the grammar symbols of the production, or
  2. b is an *inherited* attribute of a grammar symbol in α, and $c_1, c_2, \ldots, c_k$ are attributes of grammar symbols in α or attributes of A.
- Terminal symbols are assumed to have synthesized attributes supplied by the lexical analyzer.
- Procedure calls (e.g. *addtype* in the grammar for declarations) define values of *Dummy* synthesized attributes of the non terminal on the left-hand side of the production.

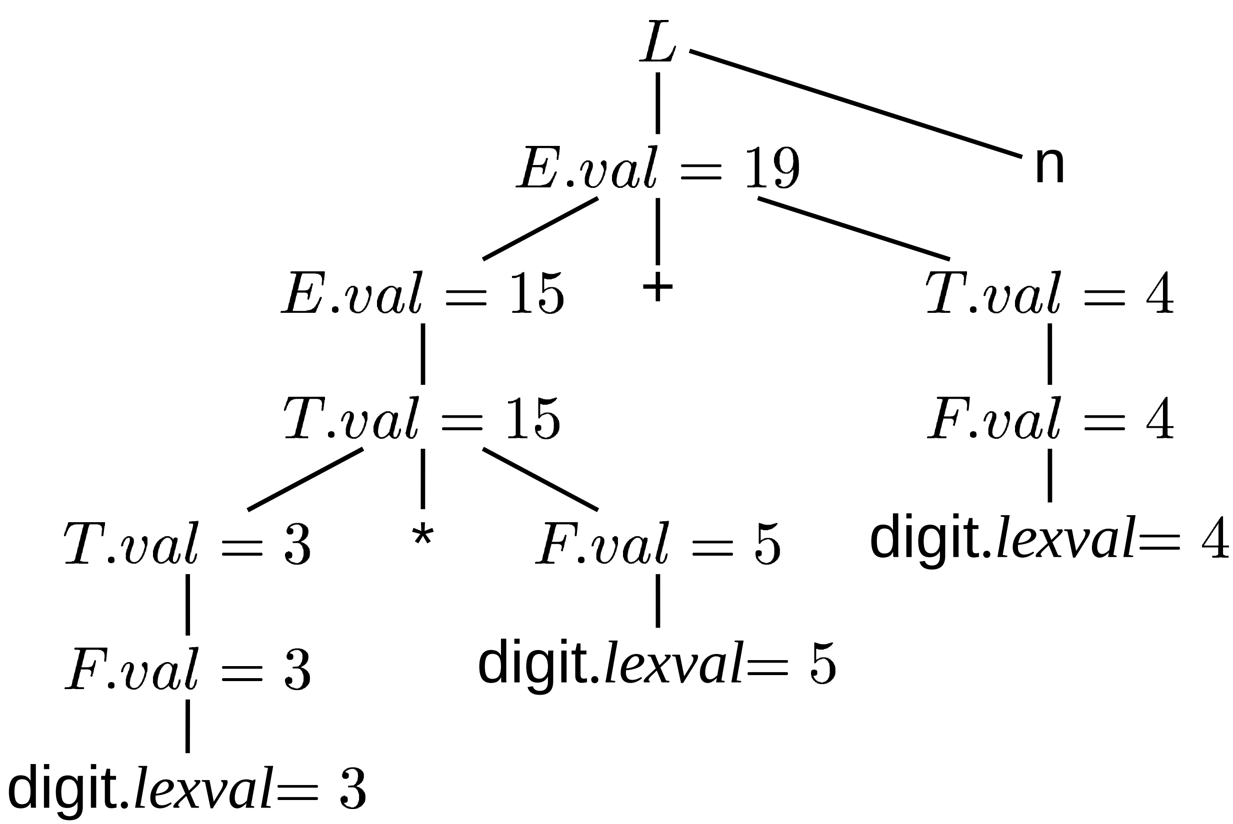
Syntax Directed Definitions: An Example

- **Example.** Let us consider the Grammar for arithmetic expressions. The Syntax Directed Translation associate to each non terminal a synthesized attribute called *val*.

PRODUCTION	SEMANTIC RULE
$L \to E\mathsf{n}$	$print(E.val)$
$E \to E_1 + T$	$E.val := E_1.val + T.val$
$E \to T$	$E.val := T.val$
$T \to T_1 * F$	$T.val := T_1.val * F.val$
$T \to F$	$T.val := F.val$
$F \to (E)$	$F.val := E.val$
$F \to \mathsf{digit}$	$F.val := \mathsf{digit}.lexval$

S-Attributed Definitions

- An **S-Attributed Definition** is a Syntax Directed Definition that uses only synthesized attributes.
- **Evaluation Order.** Semantic rules in a S-Attributed Definition can be evaluated by a bottom-up, or PostOrder, traversal of the parse-tree.
- **Example.** The above arithmetic grammar is an example of an S-Attributed Definition. The annotated parse-tree for the input 3*5+4n is:



Inherited Attributes

- **Inherited Attributes** are useful for expressing the dependence of a construct on the context in which it appears.
- It is always possible to rewrite a syntax directed definition to use only synthesized attributes, but it is often more natural to use both synthesized and inherited attributes.
- **Evaluation Order.** Inherited attributes can be evaluated by a PreOrder traversal of the parse-tree, but
  - Unlike synthesized attributes, the order in which the inherited attributes of the children are computed is important!!! Indeed:
  - Inherited attributes of the children can depend from both left and right siblings!

Inherited Attributes: An Example

- **Example.** Let us consider the syntax directed definition with both inherited and synthesized attributes for the grammar for "type declarations":

PRODUCTION	SEMANTIC RULE
$D \rightarrow TL$	$L.in := T.type$
$T \rightarrow$int	$T.type$:=*integer*
$T \rightarrow$real	$T.type$:=*real*
$L \rightarrow L_1$, id	$L_1.in := L.in$; *addtype(*id.*entry, L.in)*
$L \rightarrow$ id	*addtype(*id.*entry, L.in)*

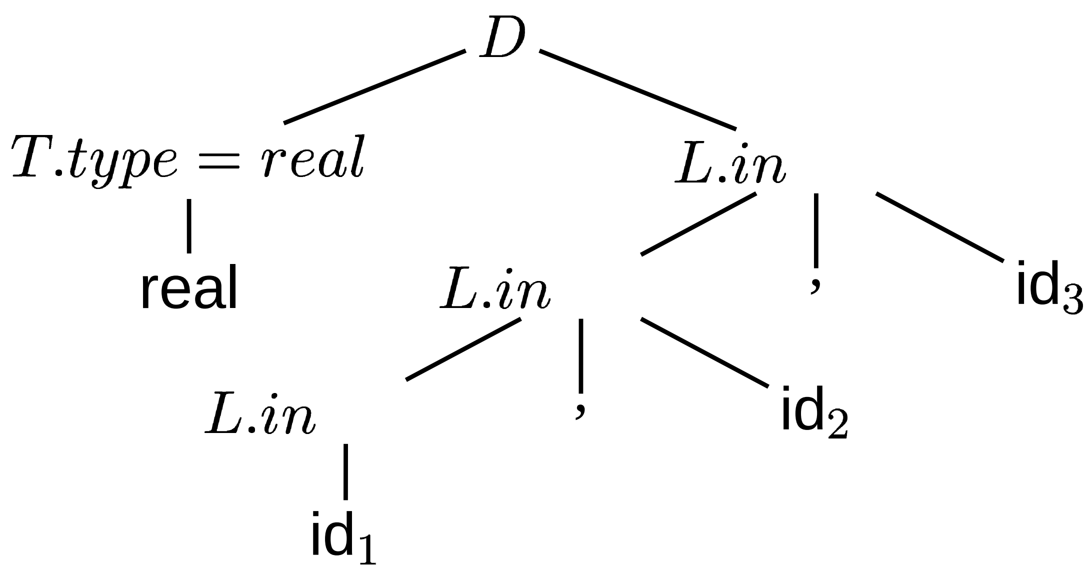
- The non terminal T has a synthesized attribute, *type*, determined by the keyword in the declaration.

- The production $D \rightarrow TL$ is associated with the semantic rule $L.in := T.type$ which set the *inherited* attribute $L.in$.

- The production $L \rightarrow L_1$, id distinguishes the two occurrences of L.

Inherited Attributes: An Example (Cont.)

- Synthesized attributes can be evaluated by a PostOrder traversal.
- Inherited attributes do not depend from right children: They can be evaluated by a classical PreOrder traversal.
- The annotated parse-tree for the input real id_1, id_2, id_3 is:



- $L.in$ is then inherited top-down the tree by the other L-nodes.
- At each L-node the procedure *addtype* inserts into the symbol table the type of the identifier.

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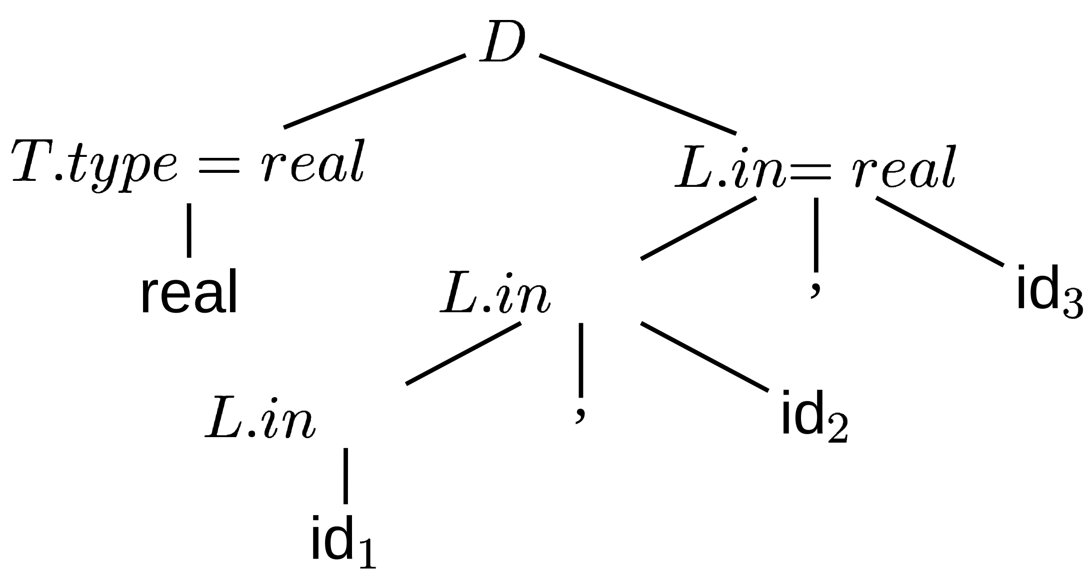

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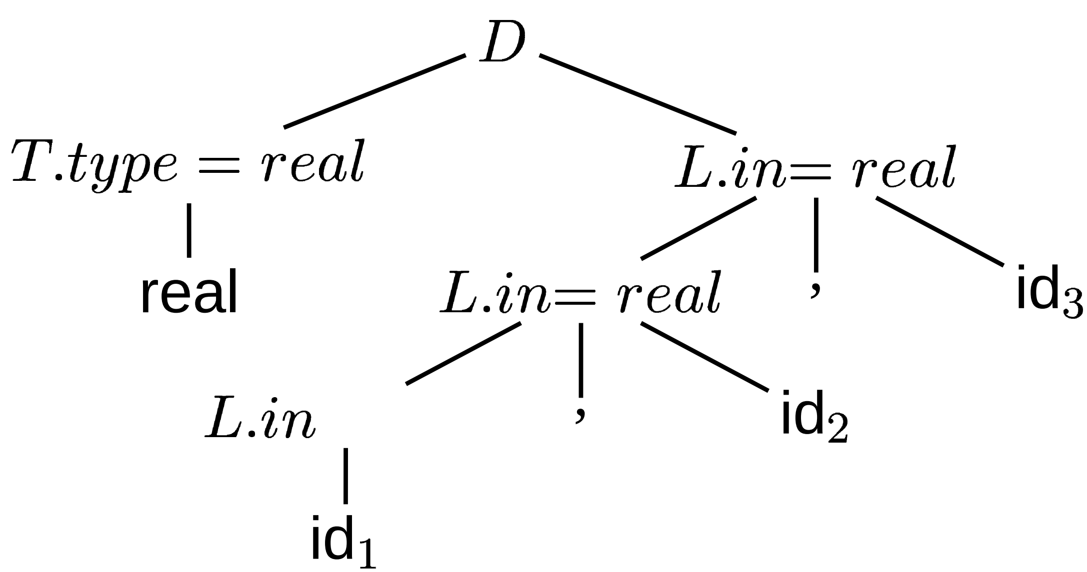

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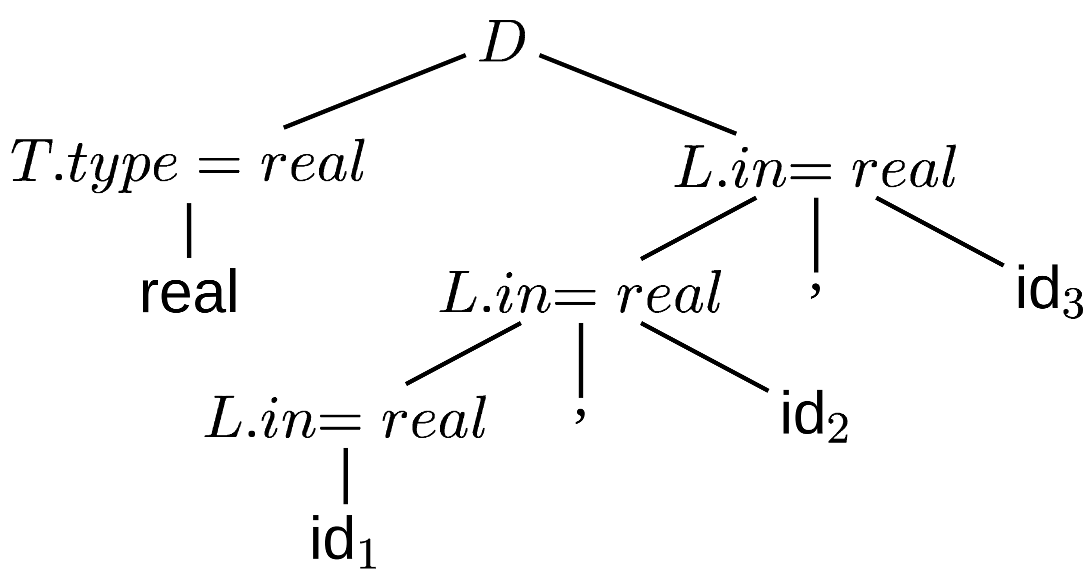

- $L.in$ is then inherited top-down the tree by the other L-nodes.
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- **Implementing Syntax Directed Translations**
  - **Dependency Graphs**
  - S-Attributed Definitions
  - L-Attributed Definitions
    - Translation Schemes

Dependency Graphs

- Implementing a Syntax Directed Definition consists primarily in finding an order for the evaluation of attributes
  - Each attribute value must be available when a computation is performed.
- **Dependency Graphs** are the most general procedure to evaluate syntax directed translations with both synthesized and inherited attributes.
- A Dependency Graph shows the interdependencies among the attributes of the various nodes of a parse-tree.
  - There is a node for each attribute;
  - If attribute b depends on an attribute c there is a link from the node for c to the node for b ($b \leftarrow c$).
- If an attribute b depends from another attribute c then we need to fire the semantic rule for c first and then the semantic rule for b.

Dependency Graphs: An Example

- **Example.** Build the dependency graph for the parse-tree of real id_1, id_2, id_3.

Evaluation Order

- The evaluation order of semantic rules depends from a *Topological Sort* derived from the dependency graph.
- *Topological Sort.* Is any ordering $m_1, m_2, \ldots, m_k$ such that if $m_i \rightarrow m_j$ is a link in the dependency graph then $m_i < m_j$.
- Any topological sort of a dependency graph gives a valid order to evaluate the semantic rules.

Implementing Attribute Evaluation: General Remarks

- Attributes can be evaluated by building a dependency graph at compile-time and then finding a topological sort.
- **Disavantages**
  1. This method fails if the dependency graph has a cycle: We need a test for non-circularity;
  2. This method is time consuming due to the construction of the dependency graph.
- **Alternative Approach.** Design the syntax directed definition in such a way that attributes can be evaluated with a *fixed order* (method followed by many compilers).

Strongly Non-Circular Syntax Directed Definitions

- **Strongly Non-Circular Syntax Directed Definitions.** Formalisms for which an attribute evaluation order can be fixed at compiler construction time.
  - They form a class that is less general than the class of non-circular definitions.
  - In the following we illustrate two kinds of strictly non-circular definitions: *S-Attributed* and *L-Attributed Definitions*.

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Evaluation of S-Attributed Definitions

- Synthesized Attributes can be evaluated by a bottom-up parser as the input is being analyzed avoiding the construction of a dependency graph.
- The parser keeps the values of the synthesized attributes in its stack.
- Whenever a reduction $A \to \alpha$ is made, the attribute for A is computed from the attributes of α which appear on the stack.
- Thus, a translator for an S-Attributed Definition can be implemented by extending the stack of an LR-Parser.

Extending a Parser Stack

- Extra fields are added to the stack to hold the values of synthesized attributes.
- In the simple case of just one attribute per grammar symbol the stack has two fields: *state* and *val*

state	*val*
Z	$Z.x$
Y	$Y.x$
X	$X.x$
$\dots$	$\dots$

- The current top of the stack is indicated by the pointer *top*.
- Synthesized attributes are computed just before each reduction:
  - Before the reduction $A \to XYZ$ is made, the attribute for A is computed: $A.a := f(val[top], val[top-1], val[top-2])$.

Extending a Parser Stack: An Example

- **Example.** Consider the S-attributed definitions for the arithmetic expressions. To evaluate attributes the parser executes the following code

PRODUCTION	CODE
$L \to E\mathsf{n}$	$print(val[top-1])$
$E \to E_1 + T$	$val[ntop] := val[top] + val[top-2]$
$E \to T$	
$T \to T_1 * F$	$val[ntop] := val[top] * val[top-2]$
$T \to F$	
$F \to (E)$	$val[ntop] := val[top-1]$
$F \to \mathsf{digit}$	

- The variable $ntop$ is set to the *new top of the stack*. After a reduction is done *top* is set to *ntop*.
  - When a reduction $A \to \alpha$ is done with $\mid \alpha \mid = r$, then $ntop = top - r + 1$.

Extending a Parser Stack: An Example (Cont.)

- The following Figure shows the moves made by the parser on input 3*5+4n.
  - Stack states are replaced by their corresponding grammar symbol;
  - Instead of the token digit the actual value is shown.

INPUT	*state*	*val*	PRODUCTION USED
3*5+4n	–	–	
*5+4n	3	3	
*5+4n	F	3	$F \rightarrow$ **digit**
*5+4n	T	3	$T \rightarrow F$
5+4n	T *	3 _	
+4n	T * 5	3 _ 5	
+4n	$T * F$	3 _ 5	$F \rightarrow$ **digit**
+4n	T	15	$T \rightarrow T * F$
+4n	E	15	$E \rightarrow T$
4n	E +	15 _	
n	E + 4	15 _ 4	
n	$E + F$	15 _ 4	$F \rightarrow$ **digit**
n	$E + T$	15 _ 4	$T \rightarrow F$
n	E	19	$E \rightarrow E + T$
	E **n**	19 _	
	L	19	$L \rightarrow E$ **n**

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L-Attributed Definitions

- **L-Attributed Definitions** contain both synthesized and inherited attributes but do not need to build a dependency graph to evaluate them.
- **Definition.** A syntax directed definition is *L-Attributed* if each *inherited attribute* of X_j in a production $A \rightarrow X_1 \dots X_j \dots X_n$, depends only on:
  1. The attributes of the symbols to the **left** (this is what L in *L-Attributed* stands for) of X_j, i.e., $X_1 X_2 \dots X_{j-1}$, and
  2. The inherited attributes of A.
- **Note.** An S-Attributed definition is also L-Attributed since the restrictions only apply to inherited attributes.

Evaluating L-Attributed Definitions

- L-Attributed Definitions are a class of syntax directed definitions whose attributes can always be evaluated by single traversal of the parse-tree.
- The following procedure evaluate L-Attributed Definitions by mixing PostOrder (synthesized) and PreOrder (inherited) traversal.

  Algorithm L-Eval(n: Node). *Input:* Parse-Tree node from an L-Attribute Definition. *Output:* Attribute evaluation.

  Begin

      For each child m of n, from left-to-right Do Begin;

          evaluate inherited attributes of m;

          L-Eval(m)

      End;

      evaluate synthesized attributes of n

  End.

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Translation Schemes

- **Translation Schemes** are more implementation oriented than syntax directed definitions since they indicate the order in which semantic rules and attributes are to be evaluated.
- **Definition.** A Translation Scheme is a context-free grammar in which
  1. Attributes are associated with grammar symbols;
  2. Semantic Actions are enclosed between braces {} and are inserted within the right-hand side of productions.

Translation Schemes (Cont.)

- Translation Schemes can have both synthesized and inherited attributes.
- Semantic Actions are treated as terminal symbols: Annotated parse-trees contain semantic actions as children of the node standing for the corresponding production.
- Translation Schemes are useful to evaluate L-Attributed definitions (even if they are a general mechanism).

Translation Schemes: An Example

- Consider the Translation Scheme for the L-Attributed Definition for “type declarations”:

$$D \rightarrow \quad T \ \{L.in := T.type\} \ L$$

$$T \rightarrow \quad \textsf{int} \ \ \{T.type := \textit{integer}\}$$

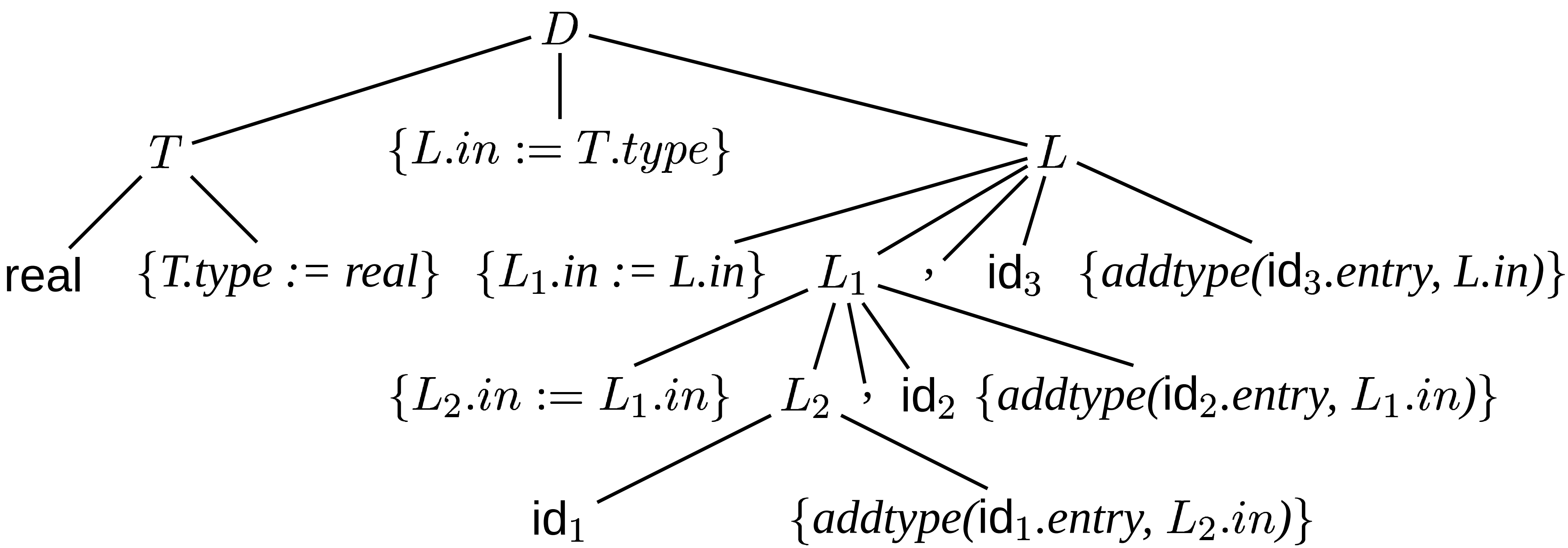
$$T \rightarrow \quad \textsf{real} \ \ \{T.type := \textit{real}\}$$

$$L \rightarrow \quad \{L_1.in := L.in\} \ L_1, \textsf{id} \ \ \{\textit{addtype}(\textsf{id}.\textit{entry}, L.in)\}$$

$$L \rightarrow \quad \textsf{id} \ \ \{\textit{addtype}(\textsf{id}.\textit{entry}, L.in)\}$$

Translation Schemes: An Example (Cont.)

- **Example (Cont).** The parse-tree with semantic actions for the input real id_1, id_2, id_3 is:



- Traversing the Parse-Tree in depth-first order we can evaluate the attributes.

Design of Translation Schemes

- When designing a Translation Scheme we must be sure that an attribute value is available when an action is executed.

- A particular case is when the semantic action involves only synthesized attributes: The action can be put at the end of the production.

  – **Example.** The following Production and Semantic Rule:

  $$T \rightarrow T_1 * F \quad T.val := T_1.val * F.val$$

  yield the translation scheme:

  $$T \rightarrow T_1 * F \ \{T.val := T_1.val * F.val\}$$

Design of Translation Schemes (Cont.)

- If we have both synthesized and inherited attributes we must enforce the following restrictions:
  1. An inherited attribute for a symbol in the right-hand side of a production must be computed in an action before the symbol;
  2. An action must not refer to a synthesized attribute of a symbol to the right of the action;
  3. A synthesized attribute for the non terminal on the left-hand side can only be computed when all the attributes it references have been computed: The action is usually put at the end of the production.
- It is always possible to start with an L-Attributed Definition and build a Translation Scheme that satisfies the above properties.

Compile-Time Evaluation of Translation Schemes

- Attributes in a Translation Scheme can be computed at compile time similarly to the evaluation of S-Attributed Definitions.
- **Main Idea.** Starting from a Translation Scheme with embedded actions, we introduce a transformation that makes all the actions occur at the right ends of their productions.
  - We introduce a new *Marker* (i.e. a non terminal, say M) with an empty reduction for each embedded semantic rule;
  - The semantic rule is attached at the end of the production $M \to \epsilon$.

Compile-Time Evaluation of Translation Schemes (Cont.)

- **Example.** Consider the following translation scheme:

  $S \to aA\{C.i = f(A.s)\}C$

  $S \to bAB\{C.i = f(A.s)\}C$

  $C \to c\{C.s = g(C.i)\}$

  Then, we add new markers M_1, M_2 with:

  $S \to aAM_1C$

  $S \to bABM_2C$

  $M_1 \to \epsilon \qquad \{M_1.s := f(val[top])\}$

  $M_2 \to \epsilon \qquad \{M_2.s := f(val[top-1])\}$

  $C \to c \qquad \{C.s := g(val[top-1])\}$

  The inherited attribute of C is the synthesized attribute of either M_1 or M_2:
  The value of C_i is *always* in *val*[*top -1*] when $C \to c$ is applied.

Compile-Time Evaluation of Translation Schemes (Cont.)

General rules to compute translations during bottom-up parsing assuming an L-attributed grammar.

- For every production $A \to X_1 \dots X_n$ introduce n new markers $M_1, \dots, M_n$ and replace the production by $A \to M_1 X_1 \dots M_n X_n$.
- Thus, we know the position of every synthesized and inherited attribute of X_j and A:
  1. $X_j.s$ is stored in the *val* entry in the parser stack associated with X_j;
  2. $X_j.i$ is stored in the *val* entry in the parser stack associated with M_j;
  3. $A.i$ is stored in the *val* entry in the parser stack immediately before the position storing M_1.
- **Remark 1.** An LL(1) Grammar with marker is also an LR(1) Grammar.
- **Remark 2.** An LR(1) Grammar with marker can contain conflicts!!!

Compile-Time Evaluation of Translation Schemes (Cont.)

Example. Computing the inherited attribute $X_j.i$ after reducing with $M_j \to \epsilon$.

	M_j	$X_j.i$
top$\to$	X_{j-1}	$X_{j-1}.s$
	M_{j-1}	$X_{j-1}.i$
	$\dots$	$\dots$
	X_1	$X_1.s$
	M_1	$X_1.i$
(*top*-2*j*+2)$\to$	M_A	$A.i$
(*top*-2*j*)$\to$		

- $A.i$ is in $val[top - 2j + 2]$;
- $X_1.i$ is in $val[top - 2j + 3]$;
- $X_1.s$ is in $val[top - 2j + 4]$;
- $X_2.i$ is in $val[top - 2j + 5]$;
- and so on.

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