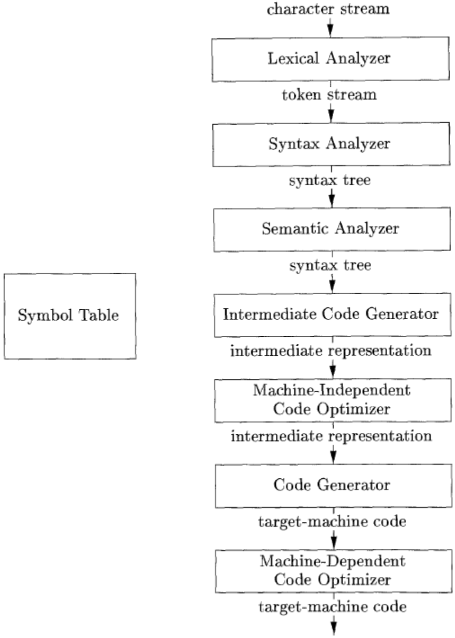
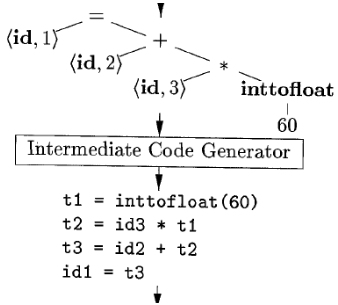
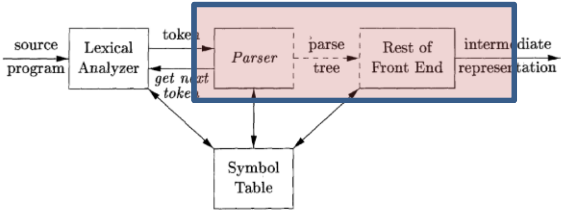
Syntax-Directed Translation

The Phases of a Compiler



Syntax-Directed Translation





- **Semantic analysis** and **translation** actions can be **interlinked** with parsing
- Implemented as a **single module**.

Syntax-Directed Translation

- **Translation** of languages **guided** by **context-free grammars**.

- Attach ***attributes*** to the **grammar symbol**

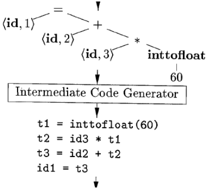
- **Syntax-directed definition** specifies the **values of attributes**
  - By associating **semantic rules** with the **grammar productions**

Syntax-Directed Translation

- *Syntax-directed definition* (SDD) is a **context-free grammar** together with **attributes and rules**
    - Attributes are associated with grammar symbols
    - Rules are associated with productions.

- If ***X*** is a **grammar symbol** and ***a*** is one of its **attributes**,
    - ***X.a*** denotes the value of the attribute *X.*

- Attributes may be
    - numbers, types, table references, or strings,
    - Strings may even be code in the intermediate language.



Attributes

Synthesized attribute:

- *Synthesized attribute* for a **nonterminal *A*** at a parse-tree node *N* is defined by
- **Semantic rule** associated with the **production at *N*.**
- The production must have ***A* as its head**.

- A synthesized attribute at node *N* is defined only in terms of attribute values at the **children of *N* and at *N* itself**.

PRODUCTION	SEMANTIC RULE
$E \rightarrow E_1 + T$	$E.code = E_1.code \parallel T.code \parallel '+'$

Attributes

Inherited attribute:

- Inherited attribute for a **nonterminal B** at a parse-tree node N is defined by

- **Semantic rule** associated with the **production at the parent of N**

- Note that the production must have **B as a symbol in its body**.

- An inherited attribute at node N is defined only in terms of **attribute values at N's parent, N itself, and N's siblings**

$T \rightarrow F\, T'$	$T'.inh = F.val$
$T' \rightarrow *\, F\, T_1'$	$T_1'.inh = T'.inh \times F.val$

Attributes

- **Synthesized attribute** at node N to be **defined** in terms of **inherited attribute** values at node **N itself**.

$$T' \to \epsilon \qquad \Big|\; T'.syn = T'.inh$$

- **Do not allow** an **inherited attribute** at node *N* to be defined in terms of attribute values at the **children of node *N***

- **Terminals** can have **synthesized attributes**, but not inherited attributes.
- **Attributes for terminals** have **lexical values** that are supplied by the **lexical analyzer**

$$F \to \mathbf{digit} \qquad \Big|\; F.val = \mathbf{digit}.\mathrm{lexval}$$

Example of SDD

Each of the Non-terminals has a **single synthesized attribute**, called ***val***

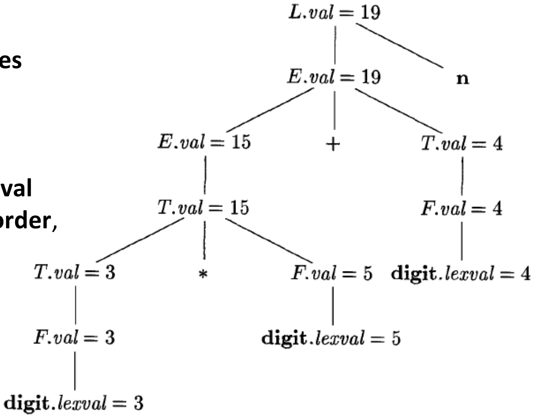
	Production	Semantic Rules
1)	$L \rightarrow E\ \mathbf{n}$	$L.val = E.val$
2)	$E \rightarrow E_1\ +\ T$	$E.val = E_1.val + T.val$
3)	$E \rightarrow T$	$E.val = T.val$
4)	$T \rightarrow T_1\ *\ F$	$T.val = T_1.val \times F.val$
5)	$T \rightarrow F$	$T.val = F.val$
6)	$F \rightarrow (\ E\ )$	$F.val = E.val$
7)	$F \rightarrow \mathbf{digit}$	$F.val = \mathbf{digit}.\text{lexval}$

Annotated parse tree.

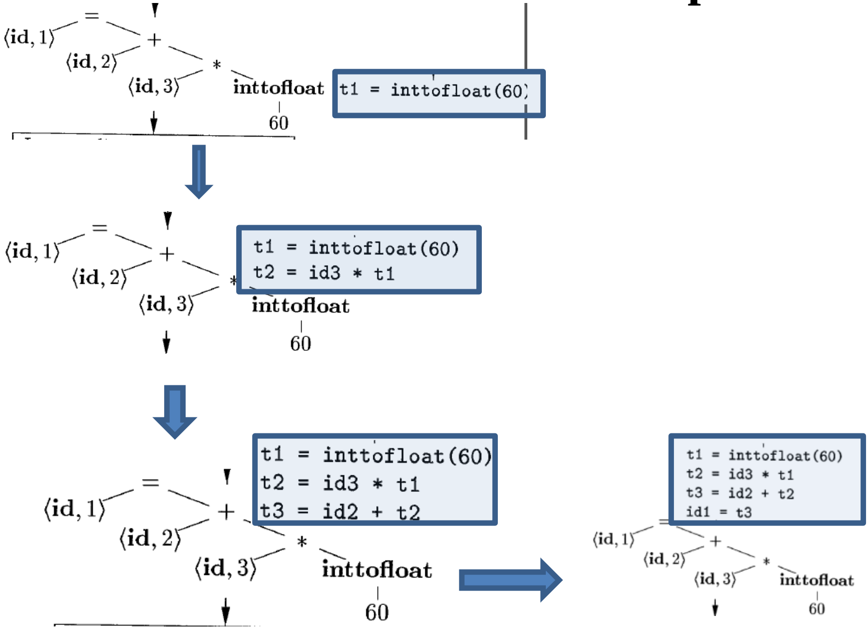
A **parse tree**, showing the **value(s) of its attribute(s)** is called an ***annotated*** *parse tree.*

Input string: **3 * 5 + 4 n**

- We show the resulting **values associated** with **each node**.
- Each of the nodes for the nonterminals has **attribute val** computed in a **bottom-up order**,



Annotation and Evaluation of parse tree

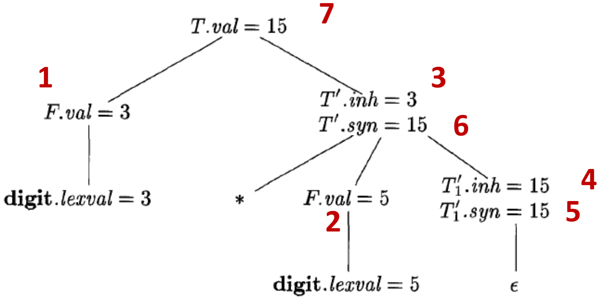


Annotated parse tree.

PRODUCTION	SEMANTIC RULES
1) $T \to F\ T'$	$T'.inh = F.val$ $T.val = T'.syn$
2) $T' \to *\ F\ T'_1$	$T'_1.inh = T'.inh \times F.val$ $T'.syn = T'_1.syn$
3) $T' \to \epsilon$	$T'.syn = T'.inh$
4) $F \to \textbf{digit}$	$F.val = \textbf{digit}.lexval$

val and **syn**: Synthesized
inh: Inherited

Annotated parse tree for 3 * 5



Evaluation Orders of SDD

- "**Dependency graphs**" are a useful tool for determining an **evaluation order** for the **attribute** instances in a given parse tree.
  - Depicts the **flow of information** among the attribute instances in a particular parse tree
  - **Directed edges**

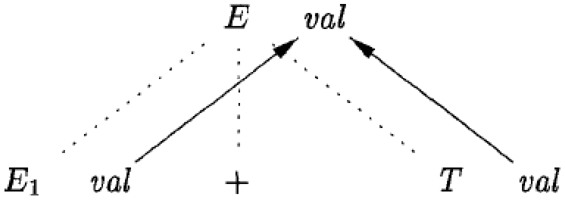
- For a **node A in parse tree** -> **node A in dependency graph**

A has a **synthesized** attribute **b**

Production	**Semantic Rule**
A->…X..	A.b=f(.., X.c, ..)

- **Edge** from X.c to A.b
  - Edge from **child attribute** to **parent attribute**

Production	Semantic Rule
$E \rightarrow E_1 + T$	$E.val = E_1.val + T.val$



Evaluation Orders of SDD

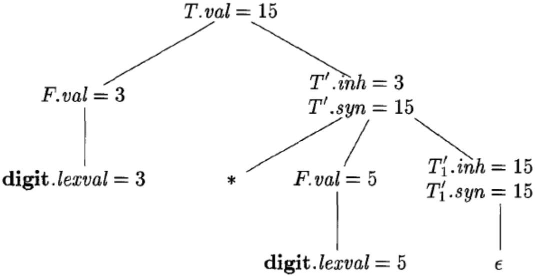
- "Dependency graphs" are a useful tool for determining an **evaluation order** for the attribute instances in a given parse tree.
    - Depicts the flow of information among the attribute instances in a particular parse tree
    - Directed edges
- For a **node A in parse tree** -> **node A in dependency graph**

B has an inherited attribute **c**

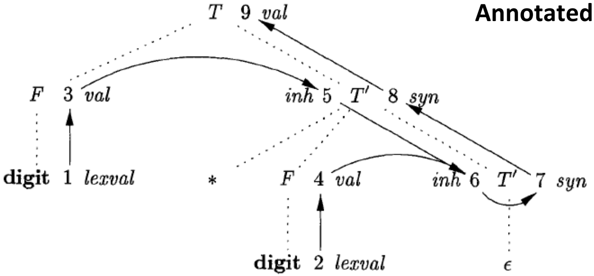
Production	**Semantic Rule**
A->…B..X..	B.c=f(.., X.a, ..)

- **Edge** from **X.a to B.c**
    - Edge from **attribute a of X** (parent or sibling of B) to **attribute c of B** (body of the production)

	Production	Semantic Rules
1)	$T \to F\,T'$	$T'.inh = F.val$ $T.val = T'.syn$
2)	$T' \to *\,F\,T'_1$	$T'_1.inh = T'.inh \times F.val$ $T'.syn = T'_1.syn$
3)	$T' \to \epsilon$	$T'.syn = T'.inh$
4)	$F \to \mathbf{digit}$	$F.val = \mathbf{digit}.lexval$



Annotated parse tree for 3 * 5



Ordering the Evaluation of Attributes

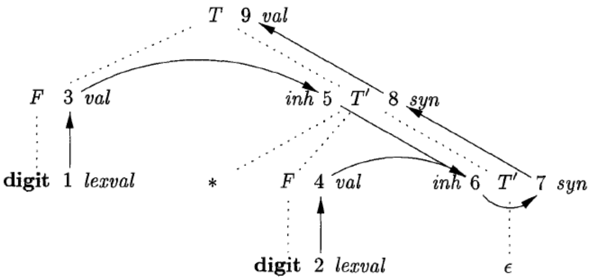
- The **dependency graph** characterizes the possible **evaluation orders**
  - In which we can **evaluate the attributes** at the various nodes of a parse tree.

- If the dependency graph has an **edge from node M to node N**,
  - Attribute corresponding to **M must be evaluated before** the attribute of N.

- If there is an edge of the dependency graph from **Ni to Nj, such that i < j**
  - the only allowable orders of evaluation are those sequences of nodes **N1, N2,... ,Nk**

- Embeds a directed graph into a linear order, and is called a **topological sort** of the graph

Topological Sort- Ordering the Evaluation



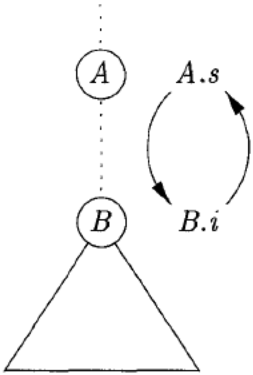
- One **topological sort** is the order in which the nodes have already been numbered: 1,2,... ,9.

- There are other topological sorts as well, such as 1,3,5,2,4,6,7,8,9.

Ordering the Evaluation – Cycles

PRODUCTION	SEMANTIC RULES
$A \rightarrow B$	$A.s = B.i;$ $B.i = A.s + 1$

These rules are circular; it is impossible to evaluate either *A.s* or *B.i*



Classes of SDD

(a) S-Attributed Definitions
(b) L-Attributed Definitions

Guarantee an evaluation order

S-Attributed SDD

An SDD is *S-attributed* if **every attribute is synthesized**.

	Production	Semantic Rules
1)	$L \rightarrow E\ \mathbf{n}$	$L.val = E.val$
2)	$E \rightarrow E_1\ +\ T$	$E.val = E_1.val + T.val$
3)	$E \rightarrow T$	$E.val = T.val$
4)	$T \rightarrow T_1\ *\ F$	$T.val = T_1.val \times F.val$
5)	$T \rightarrow F$	$T.val = F.val$
6)	$F \rightarrow (\ E\ )$	$F.val = E.val$
7)	$F \rightarrow \mathbf{digit}$	$F.val = \mathbf{digit}.\mathrm{lexval}$

L-Attributed SDD

- The idea behind L-attributed SDD class is that,
  - **Between the attributes** associated with a **production body**, **dependency-graph edges can go from left to right**,
  - But not from right to left (hence "L-attributed")

1. Synthesized, or

2. Inherited, but with the rules limited as follows. Suppose that there is a production $A \to X_1 X_2 \cdots X_n$, and that there is an inherited attribute $X_i.a$ computed by a rule associated with this production. Then the rule may use only:

   (a) Inherited attributes associated with the head A.

   (b) Either inherited or synthesized attributes associated with the occurrences of symbols $X_1, X_2, \ldots, X_{i-1}$ located to the left of X_i.

   (c) Inherited or synthesized attributes associated with this occurrence of X_i itself, but only in such a way that there are no cycles in a dependency graph formed by the attributes of this X_i.

L-Attributed SDD

	Production	Semantic Rules
1)	$T \rightarrow F\ T'$	$T'.inh = F.val$ $T.val = T'.syn$
2)	$T' \rightarrow *\ F\ T'_1$	$T'_1.inh = T'.inh \times F.val$ $T'.syn = T'_1.syn$
3)	$T' \rightarrow \epsilon$	$T'.syn = T'.inh$
4)	$F \rightarrow \textbf{digit}$	$F.val = \textbf{digit}.lexval$

Production	Semantic Rules
$A \rightarrow B\ C$	$A.s = B.b;$ $B.i = f(C.c, A.s)$

Side Effects

- Print a result,
- Enter the type of an identifier into a symbol table.

	PRODUCTION	SEMANTIC RULES
1)	$L \rightarrow E\ \mathbf{n}$	$L.val = E.val$
2)	$E \rightarrow E_1\ +\ T$	$E.val = E_1.val + T.val$
3)	$E \rightarrow T$	$E.val = T.val$
4)	$T \rightarrow T_1\ *\ F$	$T.val = T_1.val \times F.val$
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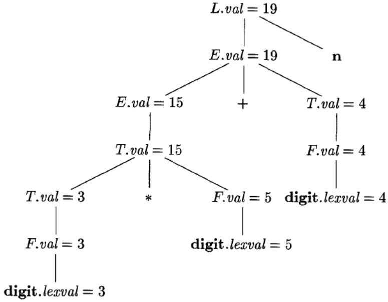
	PRODUCTION	SEMANTIC RULE
1)	$L \rightarrow E\ \mathbf{n}$	$print(E.val)$



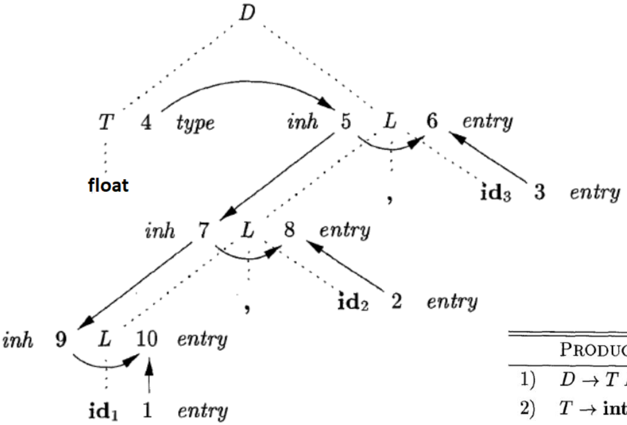
Side Effects – examples

- The SDD takes a **simple declaration** D consisting of a **basic type T** followed by a **list L of identifiers**.
- T can be **int or float**.
- For each identifier on the list, the **type is entered into the symbol-table** entry for the identifier.

	PRODUCTION	SEMANTIC RULES	
1)	$D \rightarrow T\ L$	$L.inh = T.type$	**The type is passed to the attribute L.inh**
2)	$T \rightarrow \textbf{int}$	$T.type = \text{integer}$	**Evaluate the synthesized attribute T.type, giving it the appropriate value, integer or float.**
3)	$T \rightarrow \textbf{float}$	$T.type = \text{float}$	
4)	$L \rightarrow L_1\ ,\ \textbf{id}$	$L_1.inh = L.inh$	**Passes L.inh down the parse tree**
		$addType(\textbf{id}.entry, L.inh)$	**Function addType() properly installs the type L.inh as the type of the identifier.**
5)	$L \rightarrow \textbf{id}$	$addType(\textbf{id}.entry, L.inh)$	

Side Effects

float id$_1$, id$_2$, id$_3$



	Production	Semantic Rules
1)	$D \to T\ L$	$L.inh = T.type$
2)	$T \to$ **int**	$T.type =$ integer
3)	$T \to$ **float**	$T.type =$ float
4)	$L \to L_1$, **id**	$L_1.inh = L.inh$ $addType($**id**$.entry, L.inh)$
5)	$L \to$ **id**	$addType($**id**$.entry, L.inh)$

Declaration statement

Representing data types: **Type Expressions**

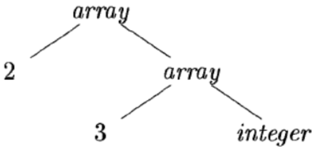
Types have structure, which we shall represent using type expressions.

- A **type expression is either a basic type** (*boolean, char, integer, float,* and *void*)

  or
- is formed by **applying an operator** called a **type constructor** to a type expression.
- A **type expression** can be formed by applying the **array type constructor** to a **number and a type expression**.

Declaration statement

- The array type int [2] [3] can be read as "array of 2 arrays of 3 integers each"
- Can be represented as a **type expression** array(2, array(3, integer)).
- This type is represented by the tree.



- The **operator array** takes **two parameters**, a number and a type.
  - Here the **type expression** can be formed by applying the **array type constructor** to a number and a type expression.

Declaration statement Example SDD

PRODUCTION	SEMANTIC RULES
$T \rightarrow B\ C$	$T.t = C.t$ $C.b = B.t$
$B \rightarrow \textbf{int}$	$B.t = integer$
$B \rightarrow \textbf{float}$	$B.t = float$
$C \rightarrow [\ \textbf{num}\ ]\ C_1$	$C.t = array(\textbf{num}.val,\ C_1.t)$ $C_1.b = C.b$
$C \rightarrow \epsilon$	$C.t = C.b$

Type Expressions

- Nonterminal T generates either a **basic type** or an **array type**.
- Nonterminal B generates one of the basic types int and float.
- T generates a basic type when C derives €.
- Otherwise, C generates array components consisting of a sequence of integers, each integer surrounded by brackets.

Declaration statement Example SDD

PRODUCTION	SEMANTIC RULES
$T \rightarrow B\ C$	$T.t = C.t$ $C.b = B.t$
$B \rightarrow \textbf{int}$	$B.t = integer$
$B \rightarrow \textbf{float}$	$B.t = float$
$C \rightarrow [\ \textbf{num}\ ]\ C_1$	$C.t = array(\textbf{num}.val,\ C_1.t)$ $C_1.b = C.b$
$C \rightarrow \epsilon$	$C.t = C.b$

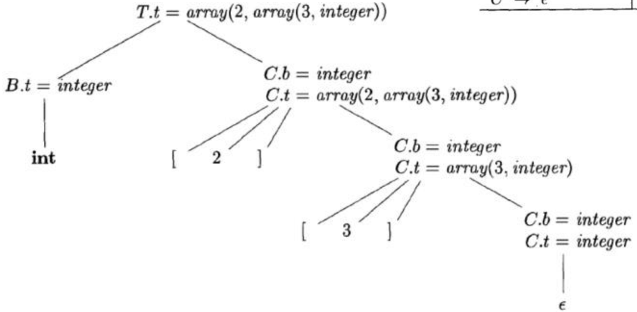
Type Expressions

- The nonterminals *B* and *T* have a synthesized attribute *t* representing a type.
- The nonterminal *C* has two attributes: an inherited attribute *b* and a synthesized attribute *t*.

Declaration statement Example SDD

PRODUCTION	SEMANTIC RULES
$T \rightarrow B\ C$	$T.t = C.t$ $C.b = B.t$
$B \rightarrow$ **int**	$B.t = integer$
$B \rightarrow$ **float**	$B.t = float$
$C \rightarrow$ [**num**] C_1	$C.t = array(\textbf{num}.val,\ C_1.t)$ $C_1.b = C.b$
$C \rightarrow \epsilon$	$C.t = C.b$

input string int [2][3]



- The nonterminal *C* has two attributes: an inherited attribute *b* and a synthesized attribute *t.*
- The inherited *b* attributes pass a basic type down the tree, and the synthesized *t* attributes accumulate the result.

Application of SDD – Syntax tree construction

- **Each node** in a syntax tree represents **a construct**; the children of the node represent the meaningful components of the construct.

- A syntax-tree node representing an expression E1 + E2 has label + and two children representing the subexpressions E1 and E2

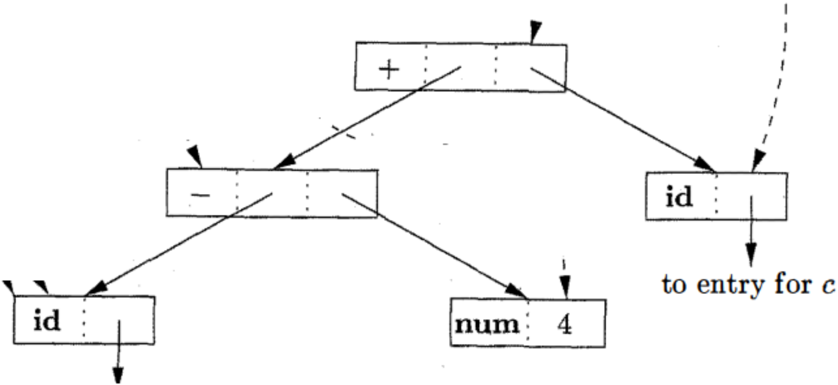
We shall implement the nodes of a syntax tree by objects with a suitable number of fields. Each object will have an *op* field that is the label of the node. The objects will have additional fields as follows:

- If the node is a leaf, an additional field holds the lexical value for the leaf. A constructor function *Leaf*(*op*, *val*) creates a leaf object.

- If the node is an interior node, there are as many additional fields as the node has children in the syntax tree. A constructor function *Node* takes two or more arguments: $Node(op, c_1, c_2, \ldots, c_k)$ creates an object with first field *op* and k additional fields for the k children $c_1, \ldots, c_k$.

Application of SDD – Syntax tree construction

Syntax tree for $a - 4 + c$



Application of SDD – Syntax tree construction

- Each node in a syntax tree represents a construct; the children of the node represent the meaningful components of the construct.

- A syntax-tree node representing an expression E1 + E2 has label + and two children representing the subexpressions E1 and E2

	Production	Semantic Rules
1)	$E \rightarrow E_1 + T$	$E.node = \textbf{new } Node('+', E_1.node, T.node)$
2)	$E \rightarrow E_1 - T$	$E.node = \textbf{new } Node('-', E_1.node, T.node)$
3)	$E \rightarrow T$	$E.node = T.node$
4)	$T \rightarrow (E)$	$T.node = E.node$
5)	$T \rightarrow \textbf{id}$	$T.node = \textbf{new } Leaf(\textbf{id}, \textbf{id}.entry)$
6)	$T \rightarrow \textbf{num}$	$T.node = \textbf{new } Leaf(\textbf{num}, \textbf{num}.val)$

Application of SDD – Syntax tree construction

	PRODUCTION	SEMANTIC RULES
1)	$E \to E_1 + T$	$E.node = \textbf{new } Node('+', E_1.node, T.node)$
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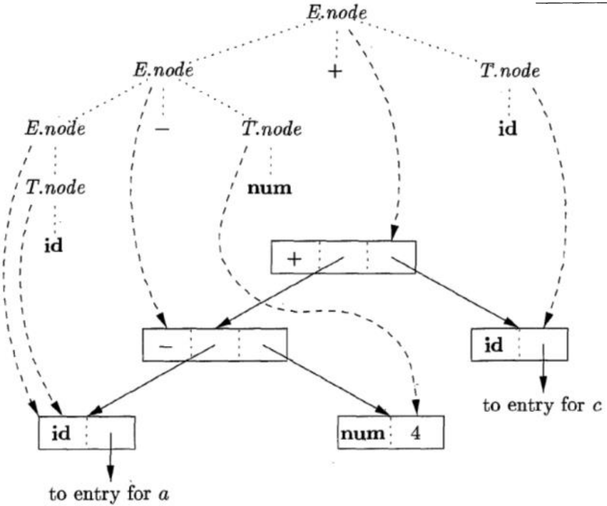
Syntax tree for $a - 4 + c$



Application of SDD – Syntax tree construction

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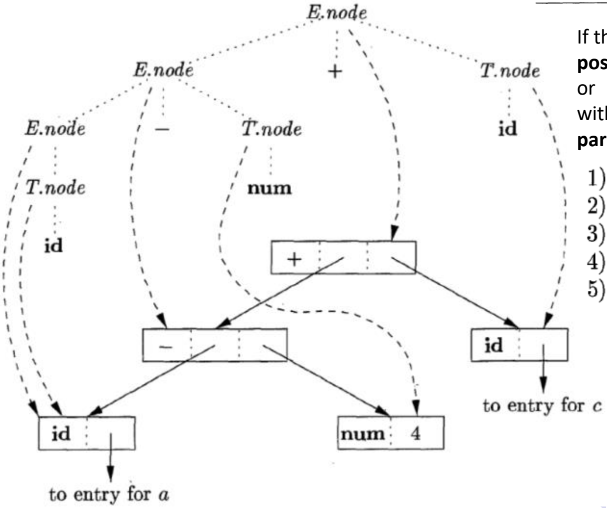
Syntax tree for $a - 4 + c$

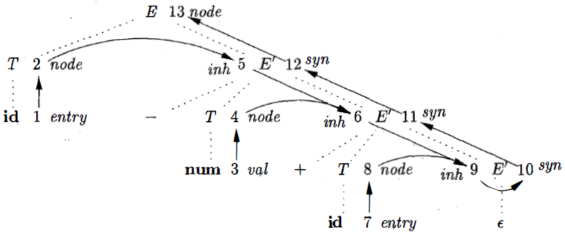


If the rules are **evaluated** during a **postorder traversal** of the parse tree, or
with reductions during a **bottom-up parse**, then the sequence of steps

1) $p_1 = \textbf{new } Leaf(\textbf{id}, entry\text{-}a);$
2) $p_2 = \textbf{new } Leaf(\textbf{num}, 4);$
3) $p_3 = \textbf{new } Node('-', p_1, p_2);$
4) $p_4 = \textbf{new } Leaf(\textbf{id}, entry\text{-}c);$
5) $p_5 = \textbf{new } Node('+', p_3, p_4);$

	Production	Semantic Rules
1)	$E \rightarrow T\ E'$	$E.node = E'.syn$ $E'.inh = T.node$
2)	$E' \rightarrow +\ T\ E'_1$	$E'_1.inh = \textbf{new}\ Node('+', E'.inh, T.node)$ $E'.syn = E'_1.syn$
3)	$E' \rightarrow -\ T\ E'_1$	$E'_1.inh = \textbf{new}\ Node('-', E'.inh, T.node)$ $E'.syn = E'_1.syn$
4)	$E' \rightarrow \epsilon$	$E'.syn = E'.inh$
5)	$T \rightarrow (\ E\ )$	$T.node = E.node$
6)	$T \rightarrow \textbf{id}$	$T.node = \textbf{new}\ Leaf(\textbf{id}, \textbf{id}.entry)$
7)	$T \rightarrow \textbf{num}$	$T.node = \textbf{new}\ Leaf(\textbf{num}, \textbf{num}.val)$

Syntax tree for $a - 4 + c$



Dependency graph for $a - 4 + c$,

Syntax-Directed Translation Schemes

- **Syntax-directed translation schemes** are a **complementary** notation to syntax directed definitions.

- All of the applications of syntax-directed definitions can be implemented using syntax-directed translation schemes.

- Syntax-directed translation scheme (SDT) is a **context free grammar** with **program fragments embedded** within **production bodies**.

- The program fragments are called **semantic actions** and can appear at any position within a production body.

Syntax-Directed Translation Schemes

$$
\begin{array}{lcll}
L & \rightarrow & E\ \mathbf{n} & \{\ \text{print}(E.val);\ \} \\
E & \rightarrow & E_1 + T & \{\ E.val = E_1.val + T.val;\ \} \\
E & \rightarrow & T & \{\ E.val = T.val;\ \} \\
T & \rightarrow & T_1 * F & \{\ T.val = T_1.val \times F.val;\ \} \\
T & \rightarrow & F & \{\ T.val = F.val;\ \} \\
F & \rightarrow & (\ E\ ) & \{\ F.val = E.val;\ \} \\
F & \rightarrow & \mathbf{digit} & \{\ F.val = \mathbf{digit}.lexval;\ \}
\end{array}
$$

- The **simplest SDD implementation** occurs when we can parse the grammar **bottom-up** and the SDD is **S-attributed**.
- In that case, we can **construct an SDT** in which each **action** is placed at the **end of the production**
    - **Executed** along with the **reduction of the body** to the head of that production.
- SDT's with all actions at the right ends of the production bodies are called **postfix SDT's.**

Syntax-Directed Translation Schemes

$$
\begin{array}{llll}
L & \rightarrow & E\ \mathbf{n} & \{\ \text{print}(E.val);\ \} \\
E & \rightarrow & E_1 + T & \{\ E.val = E_1.val + T.val;\ \} \\
E & \rightarrow & T & \{\ E.val = T.val;\ \} \\
T & \rightarrow & T_1 * F & \{\ T.val = T_1.val \times F.val;\ \} \\
T & \rightarrow & F & \{\ T.val = F.val;\ \} \\
F & \rightarrow & (\ E\ ) & \{\ F.val = E.val;\ \} \\
F & \rightarrow & \mathbf{digit} & \{\ F.val = \mathbf{digit}.lexval;\ \}
\end{array}
$$

SDT's that can be implemented during parsing can be characterized by introducing distinct *marker nonterminals* in place of each embedded action; each marker M has only one production, $M \rightarrow \epsilon$. If the grammar with marker nonterminals can be parsed by a given method, then the SDT can be implemented during parsing.

Parser Implementation of Postfix SDT's

- Postfix SDT's can be implemented during **LR parsing** by executing the **actions when reductions** occur.
- The **attribute(s)** of each grammar symbol can be put **on the stack** in a place where they can be found during the reduction.
- The parser stack contains **records** with a field for a **grammar symbol (or parser state)** and, below it, **a field for an attribute**

	X	Y	Z	State/grammar symbol
	$X.x$	$Y.y$	$Z.z$	Synthesized attribute(s)
			top	

The three grammar symbols X Y Z are on top of the stack.

Perhaps they are about to be **reduced** according to a production like **A->X Y Z**

Parser Implementation of Postfix SDT's

	X	Y	Z	State/grammar symbol
	$X.x$	$Y.y$	$Z.z$	Synthesized attribute(s)

top

A->X Y Z

- If the attributes are **all synthesized**, and the **actions occur at the ends** of the productions
    - then we can **compute the attributes** for the **head** when we **reduce the body** to the head.

- If we **reduce by a production** such as A -> X Y Z, then
    - we have all the **attributes** of X, Y, and Z available, at **known positions** on the stack.

- **After the action**, **A and its attributes are pushed** at the top of the stack, in the position of the **record for X**

Actions of the desk-calculator SDT so that they manipulate the parser stack explicitly

L	$\rightarrow$	E **n**	$\{ \text{print}(E.val); \}$
E	$\rightarrow$	$E_1 + T$	$\{ E.val = E_1.val + T.val; \}$
E	$\rightarrow$	T	$\{ E.val = T.val; \}$
T	$\rightarrow$	$T_1 * F$	$\{ T.val = T_1.val \times F.val; \}$
T	$\rightarrow$	F	$\{ T.val = F.val; \}$
F	$\rightarrow$	(E)	$\{ F.val = E.val; \}$
F	$\rightarrow$	**digit**	$\{ F.val = \textbf{digit}.lexval; \}$

PRODUCTION	ACTIONS
$L \rightarrow E\ \mathbf{n}$	$\{ \text{print}(stack[top-1].val);$ $top = top - 1; \}$
$E \rightarrow E_1 + T$	$\{ stack[top-2].val = stack[top-2].val + stack[top].val;$ $top = top - 2; \}$
$E \rightarrow T$	
$T \rightarrow T_1 * F$	$\{ stack[top-2].val = stack[top-2].val \times stack[top].val;$ $top = top - 2; \}$
$T \rightarrow F$	
$F \rightarrow (E)$	$\{ stack[top-2].val = stack[top-1].val;$ $top = top - 2; \}$
$F \rightarrow \mathbf{digit}$	

SDT's With Actions Inside Productions

An action may be placed at any position within the body of a production. It is performed immediately after all symbols to its left are processed. Thus, if we have a production $B \to X \ \{a\} \ Y$, the action a is done after we have recognized X (if X is a terminal) or all the terminals derived from X (if X is a nonterminal). More precisely,

- If the parse is bottom-up, then we perform action a as soon as this occurrence of X appears on the top of the parsing stack.

- If the parse is top-down, we perform a just before we attempt to expand this occurrence of Y (if Y a nonterminal) or check for Y on the input (if Y is a terminal).

SDT for infix-to-prefix translation during parsing

$3 * 5 + 4$ $\qquad\qquad + * 3\ 5\ 4.$

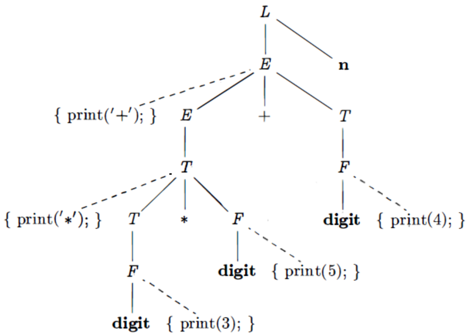
$$
\begin{array}{llll}
1) & L & \rightarrow & E \; \mathbf{n} \\
2) & E & \rightarrow & \{ \, \text{print}('+'); \, \} \;\; E_1 + T \\
3) & E & \rightarrow & T \\
4) & T & \rightarrow & \{ \, \text{print}('*'); \, \} \;\; T_1 * F \\
5) & T & \rightarrow & F \\
6) & F & \rightarrow & (\; E \;) \\
7) & F & \rightarrow & \mathbf{digit} \;\; \{ \, \text{print}(\mathbf{digit}.\mathit{lexval}); \, \}
\end{array}
$$

- It is impossible to implement this SDT during either topdown or bottom-up parsing,
    - because the parser would have to perform semantic actions, like printing instances of * or +,
    - long before it knows whether these symbols will appear in its input .

Any SDT can be implemented as follows:

1. Ignoring the actions, parse the input and produce a parse tree as a result.
2. Then, examine each interior node N, say one for production $A \to \alpha$. Add additional children to N for the actions in α, so the children of N from left to right have exactly the symbols and actions of α.
3. Perform a preorder traversal of the tree, and as soon as a node labeled by an action is visited, perform that action.

parse tree for expression $3 * 5 + 4$



If we visit the nodes in preorder, we get the prefix form of the expression: **+ * 3 5 4**