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SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY

Chapter 3:

Syntax-Directed Translation

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Why Do We Learn This Chapter?

- When implementing your compiler using Bison or Antlr, you write semantic actions to construct parse trees, manage symbol tables, and perform type checking, etc.
- Did you ever have the following questions?
 - What are the theories behind the semantic actions?
 - What computations can be done?
 - What is the order of executing the code snippets? ...

Outline

- Syntax-Directed Definitions
- Evaluation Orders for SDD's
- Applications of Syntax-Directed Translation
- Syntax-Directed Translation Schemes
- Uses of SDTs ([Self-Study](#))
- Implementing L-Attributed SDD's ([Self-Study](#))

A Brief Introduction

- **Syntax-directed translation** (语法制导的翻译) is the process of language translation guided by context-free grammars
 - Here, “language translation” is in a broad sense
 - Transforming infix expressions (中缀表达式) to postfix expressions (后缀表达式) is also viewed as “translation”
 - A language construct is typically made of smaller constructs
 - The **semantics** of a construct can be **synthesized** from its constituent constructs’ semantics
 - The type of the expression $x + y$ is determined by the type of x and y , and the operator $+$
 - Or **inherited** from other constructs (e.g., siblings in the parse tree)
 - In “int x ”, the type of x is determined by the type specifier to the left of x

Syntax-Directed Definitions

- A *syntax-directed definition* (语法制导定义, SDD) is a context-free grammar together with *attributes* and *rules*
 - A set of **attributes** (属性) is associated with each grammar symbol^{*}
 - Can be anything, e.g., data type of expressions, # instructions in the generated code
 - A **semantic rule** (语义规则) is associated with a production and describes how attributes are computed

$$E \rightarrow E_1 + T$$

$$E.\text{code} = E_1.\text{code} \parallel T.\text{code} \parallel '+'$$

The attribute **code** represents the **postfix notation** of the construct

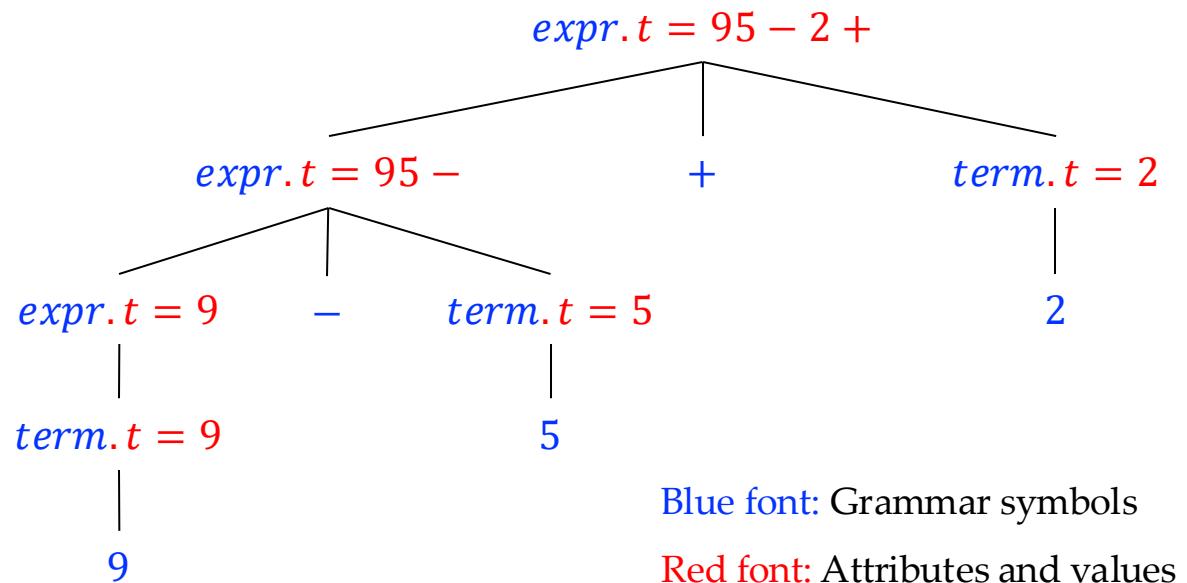
|| is the operator for **string concatenation**

^{*}Grammar symbols represent language constructs. Nonterminal nodes and subtrees rooted at these nodes correspond to productions.

Annotated Parse Tree

- An annotated parse tree for infix expression $9 - 5 + 2$
- The attribute t represents postfix notation

```
expr → expr + term
expr → expr - term
expr → term
term → 0
...
term → 9
```

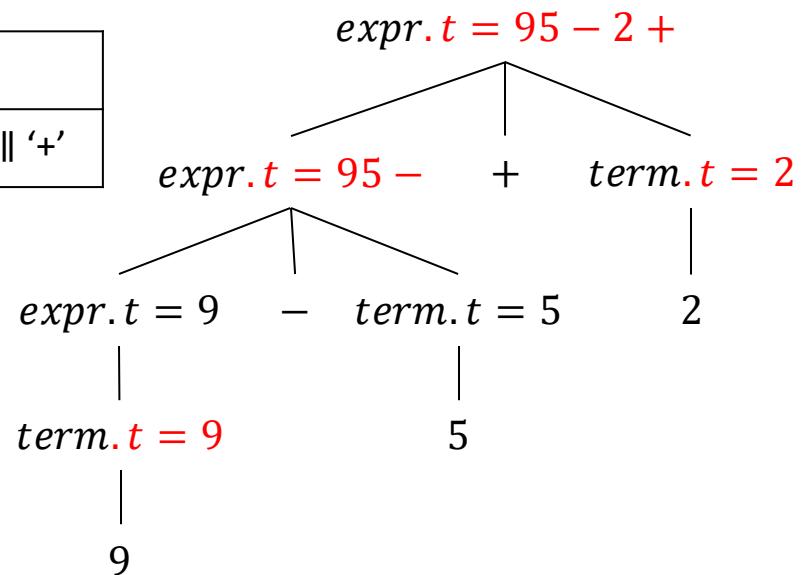


Synthesized Attributes (合成属性)

- An attribute is said to be *synthesized* if its value at a parse-tree node N is only determined from attribute values at the children of N and at N itself (defined by a semantic rule associated with the production at N)

Production	$expr \rightarrow expr_1 + term$
Rule	$expr.t = expr_1.t \parallel term.t \parallel '+'$

Production	$term \rightarrow 9$
Rule	$term.t = '9'$

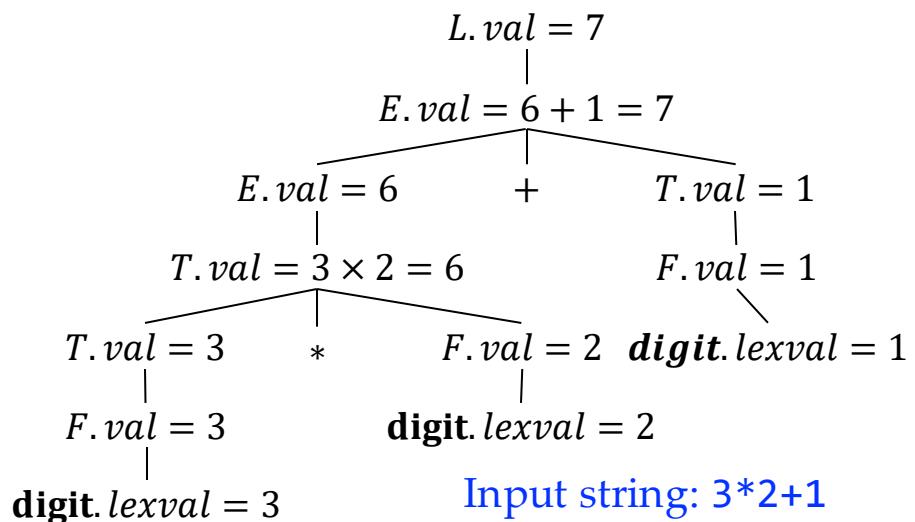


Terminals can also have synthesized attributes (lexical values), but there are no rules for computing the value of an attribute for a terminal.

A Complete Example of SDD

- The SDD below helps compute the value of an expression L
- SDD's do not specify the evaluation order** of attributes on a parse tree
 - Any order that computes an attribute a after all other attributes that a depends on is fine
 - Synthesized attributes have a nice property** that they can be evaluated during a single bottom-up traversal of a parse tree (it is often unnecessary to explicitly create the tree)

PRODUCTION	SEMANTIC RULES
1) $L \rightarrow E \ n$	$L.val = E.val$
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) $F \rightarrow \text{digit}$	$F.val = \text{digit}.lexval$



Inherited Attributes (继承属性)

- *Inherited attributes* have their value at a parse-tree node determined from attribute values at **the node itself, its parent**, and its **siblings** in the parse tree

We already have synthesized attributes. When are inherited attributes useful???



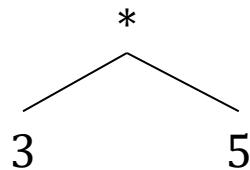
Top-Down Parse of $3 * 5$

$$T \rightarrow FT'$$

$$T' \rightarrow^* FT'$$

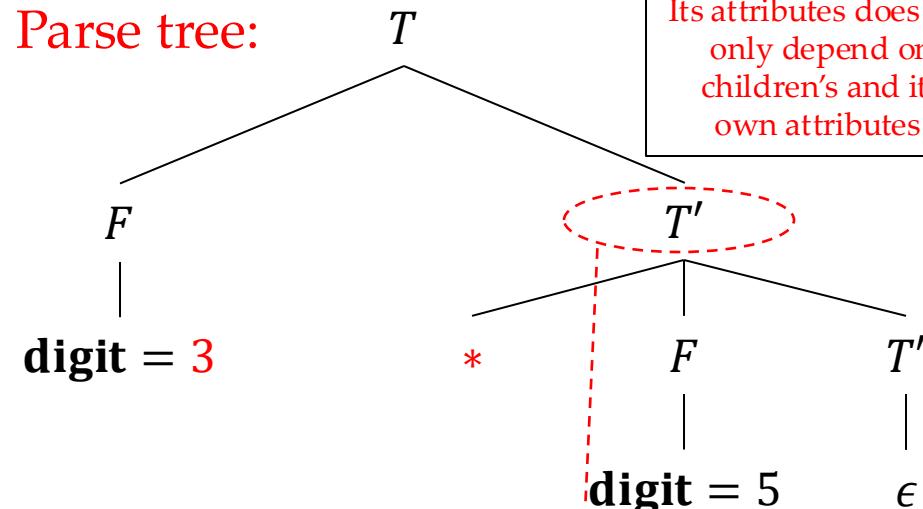
$$T' \rightarrow \epsilon$$

$$F \rightarrow \text{digit}$$



Abstract syntax tree

Parse tree:



Does not represent a valid subexpression;

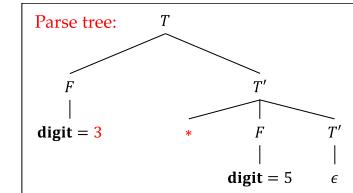
Its attributes does not only depend on children's and its own attributes.

For some grammars, the structure of the parse tree does not **match** the abstract syntax of the code (**3** and ***** are in different subtrees)

Not all non-terminals in a parse tree correspond to proper language constructs, e.g., T' above.

SDD with Inherited Attributes

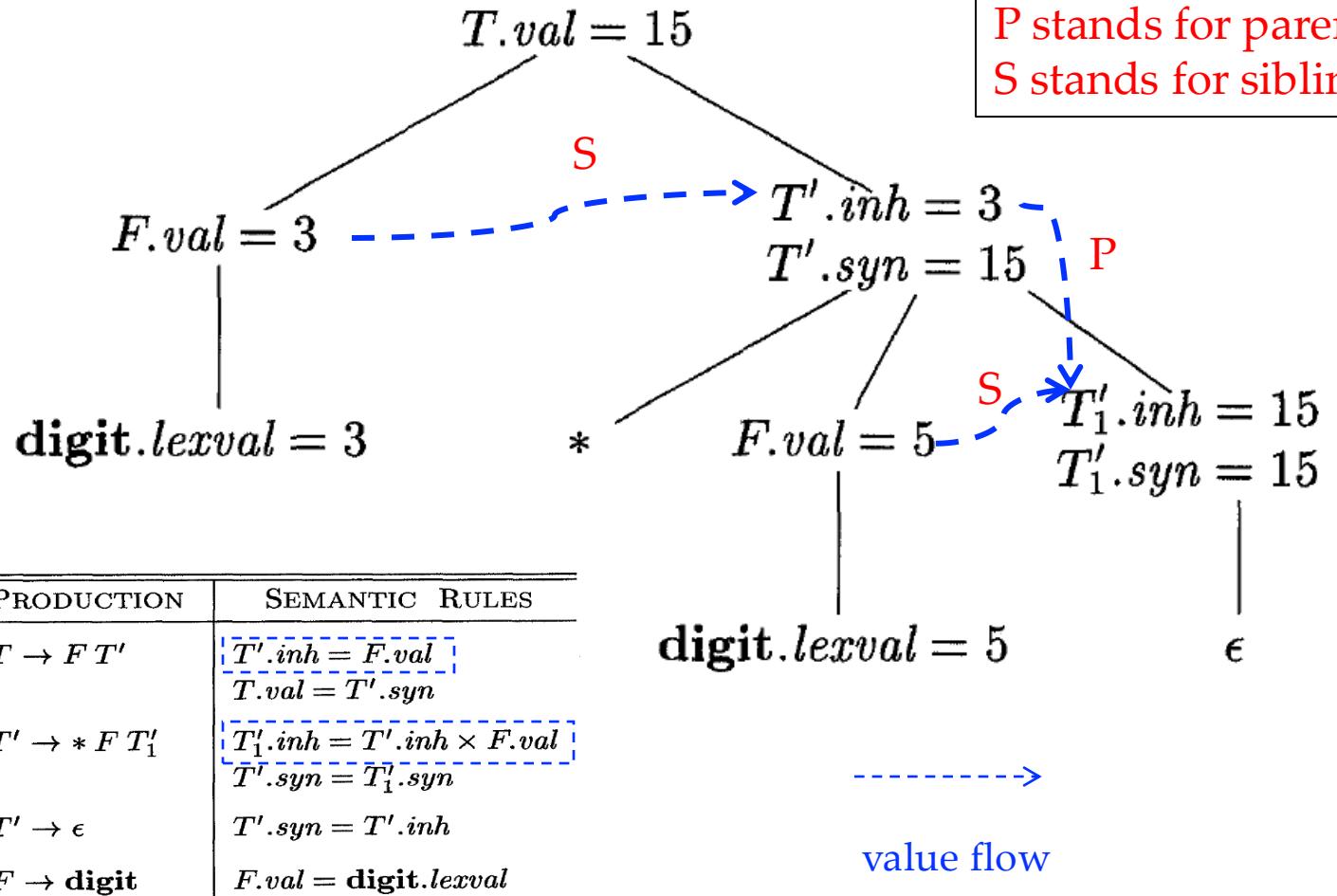
PRODUCTION	SEMANTIC RULES
1) $T \rightarrow F T'$	$T'.inh = F.val$ $T.val = T'.syn$
2) $T' \rightarrow * F T'_1$	$T'_1.inh = T'.inh \times F.val$ $T'.syn = T'_1.syn$
3) $T' \rightarrow \epsilon$	$T'.syn = T'.inh$
4) $F \rightarrow \text{digit}$	$F.val = \text{digit}.lexval$



The left operand of the operator $*$ is inherited by T' and kept for later computation when T' further gets replaced

The inherited attribute of T' is not defined by a rule associated with the production (2) or (3), whose head is T'

Annotated Parse Tree for $3 * 5$



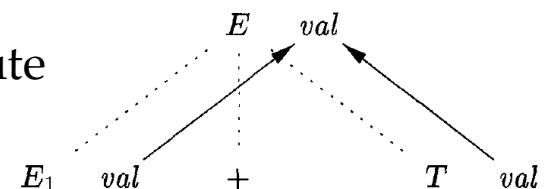
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- Implementing L-Attributed SDD's (Self-Study)

Evaluation Orders for SDD's

- Given parse tree nodes N, M_1, M_2, \dots, M_k , if the attribute a of N is defined as $N.a = f(M_1.a_1, M_2.a_2, \dots, M_k.a_k)$, then in order to compute $N.a$, we must first compute $M_i.a_i$ ($1 \leq i \leq k$)
- Dependency graphs* (依赖图) are a useful tool for determining evaluation orders

- Depict the **information flow** among the attribute instances in **a particular parse tree**
- Model the **partial order** among attribute instances
(Why partial? Not every pair of elements has an order)



Dependency Graph

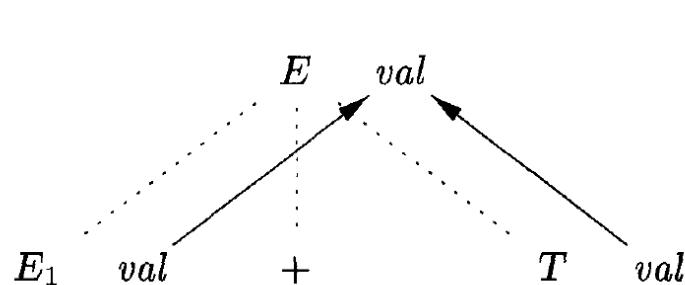
- An **edge** from one **attribute instance** (a_1) to another (a_2) means that the value of a_1 is needed to compute the value of a_2
- If there is any **cycle** in a dependency graph, we cannot find an order to compute the value of all attribute instances

PRODUCTION

$$E \rightarrow E_1 + T$$

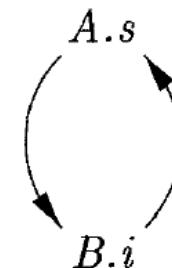
SEMANTIC RULE

$$E.val = E_1.val + T.val$$



Dotted lines: parse tree edges

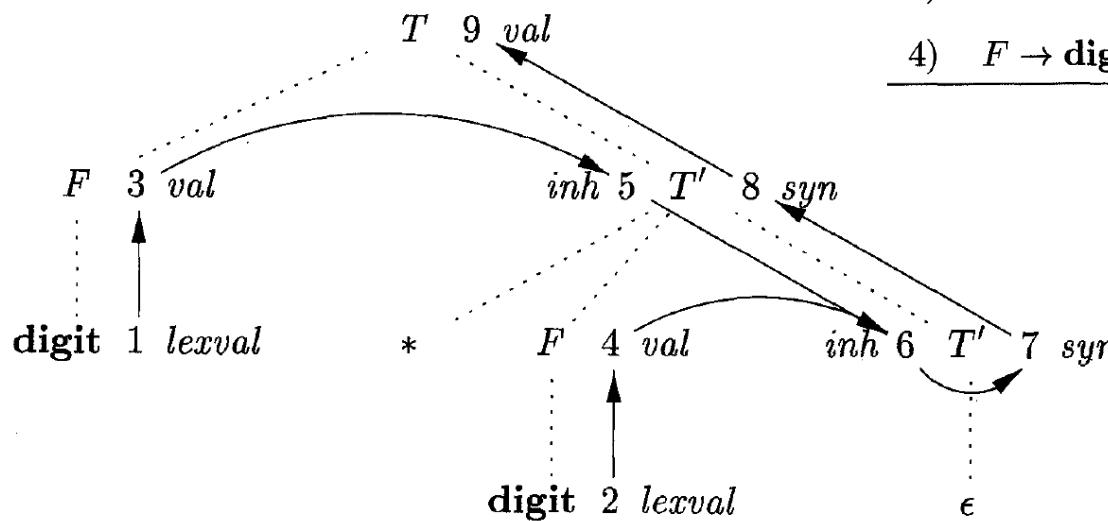
Solid lines: dependency graph edges



Example: Parsing $3 * 2$

Attribute values can be computed according to any *topological sort* (拓扑排序)* of the graph, e.g., 1, 2, 3, ..., 9 in the example below

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) $F \rightarrow \text{digit}$	$F.val = \text{digit}.lexval$



1–9: Evaluation order

* Topological sorting for a directed acyclic graph is a linear ordering of vertices such that for every directed edge $u \rightarrow v$, vertex u comes before v in the ordering. Topological sorting is not possible for graphs with cycles.

Ordering the Evaluation of Attributes

- Given an arbitrary SDD, it is hard to tell whether there exist any parse trees (annotated) whose dependency graphs have cycles (i.e., whether the SDD is computable)
- In practice, translations can be implemented using classes of SDD's that guarantee an evaluation order^{*}
 - *S-attributed* SDD's
 - *L-attributed* SDD's

^{*}The dependency graphs for such SDDs are directed acyclic graphs

S-Attributed SDDs

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

PRODUCTION		SEMANTIC RULES
1)	$L \rightarrow E \text{ n}$	$L.val = E.val$
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)	$F \rightarrow \text{digit}$	$F.val = \text{digit.lexval}$

Intuitively, there cannot be cycles in the dependency graph of any parse tree, since edges always go from children nodes to parent nodes, never the other way around.

S-Attributed SDDs Cont.

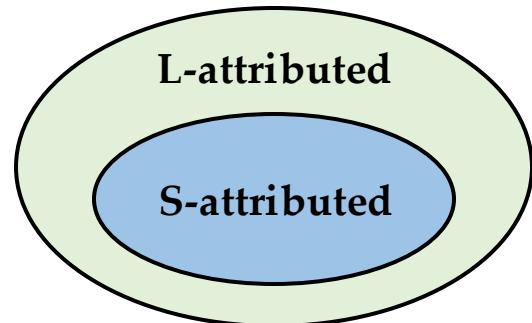
- When an SDD is S-attributed, we can evaluate its attributes in any **bottom up order** of the parse-tree nodes
 - e.g., **postorder traversal** (后序遍历) of the parse tree
- So, S-attributed SDDs can be easily implemented during **bottom-up parsing** (the parsing process corresponds to a postorder traversal)

```
postorder( $N$ ) {  
    for ( each child  $C$  of  $N$ , from the left ) postorder( $C$ );  
    evaluate the attributes associated with node  $N$ ;  
}
```

L-Attributed SDDs

- An SDD is *L-attributed* if for each production $A \rightarrow X_1X_2 \dots X_n$, for each $j = 1 \dots n$, each inherited attribute of X_j depends on only:
 - the attributes of X_1, \dots, X_{j-1} (either synthesized or inherited), or
 - the inherited attributes of A
- Or each attribute is synthesized

- Dependency-graph edges can go from left to right (on an annotated parse tree), but not right to left (hence the SDD is named “L-attributed”)
- There cannot be cycles in the graph, as edges only go from left to right or from parents to children



L-Attributed SDD Example

PRODUCTION	SEMANTIC RULES
1) $T \rightarrow F T'$	$T'.inh = F.val$ Left sibling's attribute $T.val = T'.syn$
2) $T' \rightarrow * F T'_1$	$T'_1.inh = T'.inh \times F.val$ $T'.syn = T'_1.syn$ <ul style="list-style-type: none"> • Parent's inherited attribute • Left sibling's attribute
3) $T' \rightarrow \epsilon$	$T'.syn = T'.inh$
4) $F \rightarrow \text{digit}$	$F.val = \text{digit}.lexval$

Synthesized attributes: val, syn, lexval. Inherited attributes: inh

Attribute Evaluation for L-Attributed SDD's

Input: A node n in a parse tree T

Output: An evaluation order for the attributes of the subtree rooted at n

procedure $\text{depth_first}(n)^*$



begin

for every child m of n from left to right **do begin**

evaluate the inherited attributes of m ;

$\text{depth_first}(m)$; // here m 's synthesized attributes will be evaluated

end

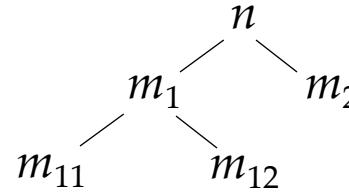
evaluate the synthesized attributes of n ;

end

Imagine the directions of the dependency graph edges, then it is easy to understand why DFS works here. Is the evaluation order a topological sort of parse tree nodes?

* The inherited attributes of x (non-root) are computed before calling $\text{depth_first}(x)$, as indicated by the for body

Example



```
procedure depth_first( $n$ )  
begin  
    for every child  $m$  of  $n$  from left to right do begin  
        evaluate the inherited attributes of  $m$ ;  
        depth_first( $m$ );  
    end  
    evaluate the synthesized attributes of  $n$ ;  
end
```

1. Compute m_1 's inherited attribute depth_first(n)
2. Compute m_{11} 's inherited attribute depth_first(m_1)
3. Compute m_{11} 's synthesized attribute depth_first(m_{11})
4. Compute m_{12} 's inherited attribute
5. Compute m_{12} 's synthesized attribute depth_first(m_{12})
6. Compute m_1 's synthesized attribute
7. Compute m_2 's inherited attribute
8. Compute m_2 's synthesized attribute depth_first(m_2)
9. Compute n 's synthesized attribute

Attribute Evaluation for L-Attributed Definitions

Input: A node n in a parse tree T

Output: An evaluation order for the attributes of the subtree rooted at n

procedure $\text{depth_first}(n)^*$

begin

for every child m of n from left to right do begin

 evaluate the inherited attributes of m ;

$\text{depth_first}(m)$; // here m 's synthesized attributes will be evaluated

end

 evaluate the synthesized attributes of n ;

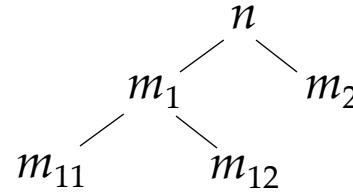
end

When evaluating the inherited attributes of a node, the attributes of nodes to its left have been evaluated

↑ Guarantee

* The inherited attributes of x (non-root) are computed before calling $\text{depth_first}(x)$, as indicated by the for body

Example



```
procedure depth_first( $n$ )  
begin  
    for every child  $m$  of  $n$  from left to right do begin  
        evaluate the inherited attributes of  $m$ ;  
        depth_first( $m$ );  
    end  
    evaluate the synthesized attributes of  $n$ ;  
end
```

1. Compute m_1 's inherited attribute

depth_first(n)

2. Compute m_{11} 's inherited attribute

depth_first(m_1)

3. Compute m_{11} 's synthesized attribute

depth_first(m_{11})

4. Compute m_{12} 's inherited attribute

5. Compute m_{12} 's synthesized attribute

depth_first(m_{12})

6. Compute m_1 's synthesized attribute

7. Compute m_2 's inherited attribute

8. Compute m_2 's synthesized attribute

depth_first(m_2)

9. Compute n 's synthesized attribute

Attribute Evaluation for L-Attributed Definitions

Input: A node n in a parse tree T

Output: An evaluation order for the attributes of the subtree rooted at n

procedure $\text{depth_first}(n)^*$

When evaluating the inherited attributes of a node (m), the inherited attributes of its parent node (n) have been evaluated

begin

for every child m of n from left to right do begin

 evaluate the inherited attributes of m ;

$\text{depth_first}(m)$; // here m 's synthesized attributes will be evaluated

end

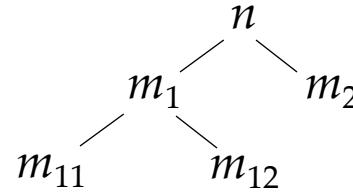
 evaluate the synthesized attributes of n ;

end

Guarantee

* The inherited attributes of n are computed before calling $\text{depth_first}(n)$, as indicated by the for body

Example



```
procedure depth_first( $n$ )  
begin  
    for every child  $m$  of  $n$  from left to right do begin  
        evaluate the inherited attributes of  $m$ ;  
        depth_first( $m$ );  
    end  
    evaluate the synthesized attributes of  $n$ ;  
end
```

1. Compute m_1 's inherited attribute

depth_first(n)

2. Compute m_{11} 's inherited attribute

depth_first(m_1)

3. Compute m_{11} 's synthesized attribute

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4. Compute m_{12} 's inherited attribute

5. Compute m_{12} 's synthesized attribute

depth_first(m_{12})

6. Compute m_1 's synthesized attribute

7. Compute m_2 's inherited attribute

8. Compute m_2 's synthesized attribute

depth_first(m_2)

9. Compute n 's synthesized attribute

Attribute Evaluation for L-Attributed Definitions

Input: A node n in a parse tree T

Output: An evaluation order for the attributes of the subtree rooted at n

procedure $\text{depth_first}(n)^*$

begin

for every child m of n from left to right do begin

 evaluate the inherited attributes of m ;

$\text{depth_first}(m)$; // here m 's synthesized attributes will be evaluated

end

 evaluate the synthesized attributes of n ;

end

Can be implemented in
top-down parsing
(will be introduced later)

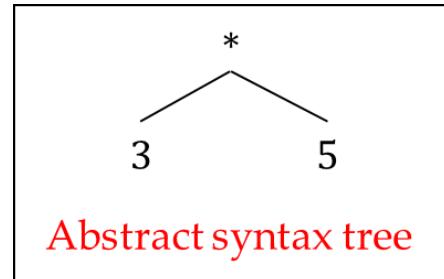
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- Constructing Syntax tree
 - The Structure of a Type
- 

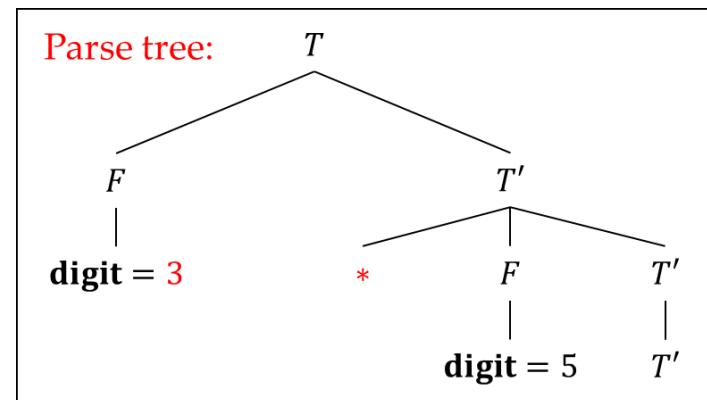
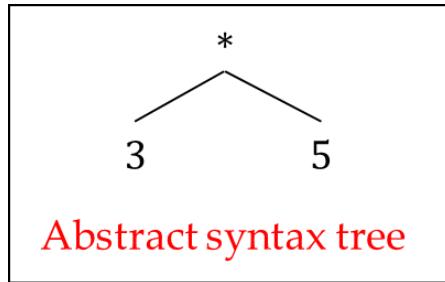
Construction of Syntax Tree

- Abstract syntax tree (or syntax tree for short) revisited:
 - Each interior node N represents a construct (corresponding to an operator)
 - The children of N represent the meaningful components of the construct represented by N (corresponding to operands)



Construction of Syntax Tree

- **Syntax tree vs. parse tree**
 - In a syntax tree, interior nodes represent **programming constructs**, while in a parse tree, interior nodes represent **nonterminals**^{*}
 - A parse tree is also called a ***concrete syntax tree***, and the underlying grammar is called a ***concrete syntax*** for the language

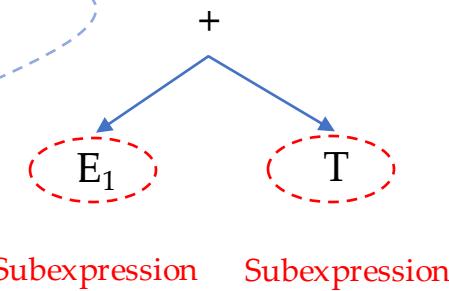


*Not all nonterminals represent programming constructs, e.g., those introduced to eliminate left recursions (T' in the earlier L-attributed SDD example)

Construction of Syntax Tree

- An S-attributed SDD for building syntax trees for simple expressions
 - Each node of the syntax tree is implemented as an **object** with a field *op*, representing the label of the node, and some additional fields
 - **Leaf node:** one additional field holding the lexical value
 - **Interior node:** # additional fields = # of children

PRODUCTION	SEMANTIC RULES
1) $E \rightarrow E_1 + T$	$E.\text{node} = \text{new Node}(' + ', E_1.\text{node}, T.\text{node})$
2) $E \rightarrow E_1 - T$	$E.\text{node} = \text{new Node}(' - ', E_1.\text{node}, T.\text{node})$
3) $E \rightarrow T$	$E.\text{node} = T.\text{node}$
4) $T \rightarrow (E)$	$T.\text{node} = E.\text{node}$
5) $T \rightarrow \text{id}$	$T.\text{node} = \text{new Leaf}(\text{id}, \text{id}.entry)$
6) $T \rightarrow \text{num}$	$T.\text{node} = \text{new Leaf}(\text{num}, \text{num}.val)$

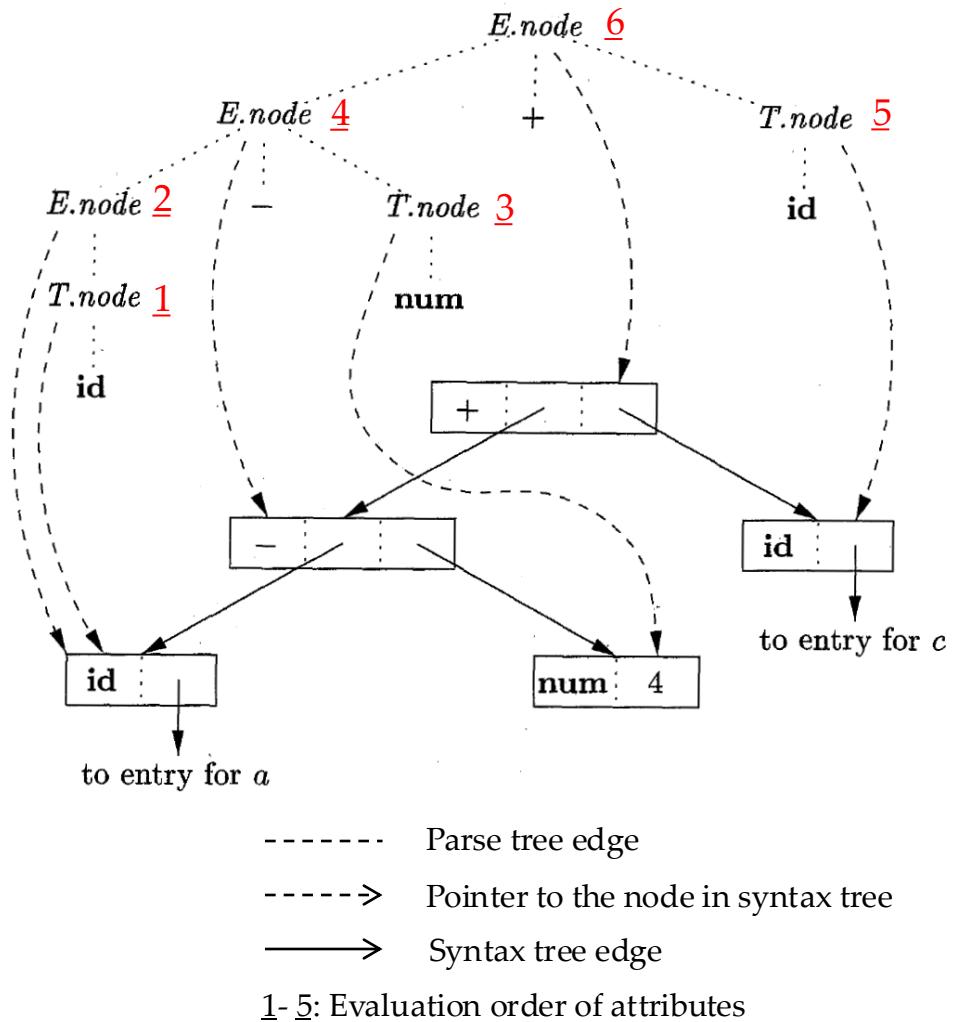


Construction of Syntax Tree

Input expression: $a - 4 + c$

Steps (object creations only;
bottom-up evaluation):

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



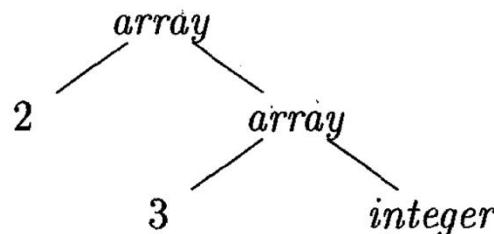
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- Constructing Syntax tree
 - The Structure of a Type
- 

Computing the Structure of a Type

```
int[2][3] a = ...;
```

What is the type of **a**?



The diagram shows the declaration of an allocatable array:

```
array( 2, array( 3, integer ) )
```

The first dimension has a size of 2, indicated by the label "# elements" pointing to the first element of the outermost array. The second dimension has a size of 3, indicated by the label "Element type" pointing to the inner array.

That is: array of 2 arrays of 3 integers

Computing the Structure of a Type

PRODUCTION	
$T \rightarrow B C$	
$B \rightarrow \text{int}$	
$B \rightarrow \text{float}$	
$C \rightarrow [\text{num}] C_1$	
$C \rightarrow \epsilon$	

The grammar generates type specifiers:

- `int`
 - `float`
 - `int[2]`
 - `int[2][3]`
 - `int[4][5][6]`
 - `...`
- }
- Basic types
- }
- Array types

Computing the Structure of a Type

- $\text{int}[2][3]$

PRODUCTION

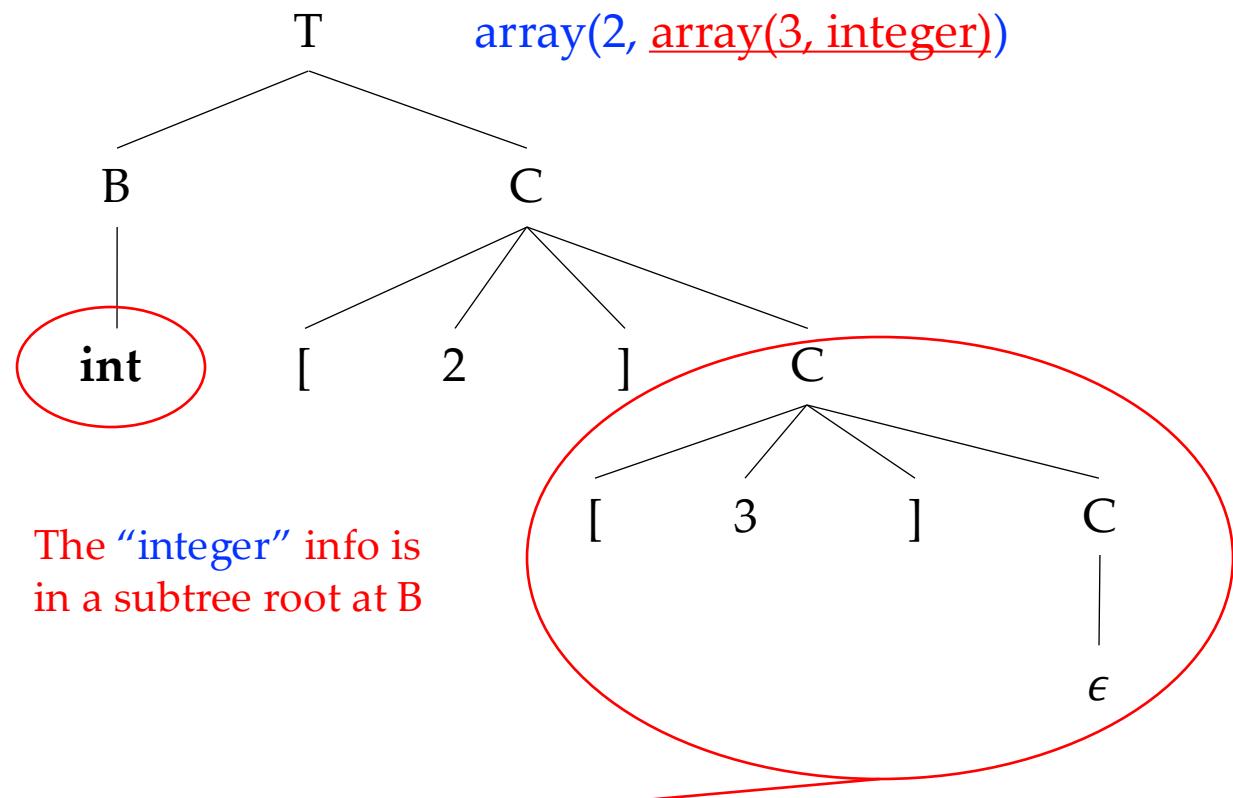
$$T \rightarrow B\ C$$

$B \rightarrow \text{int}$

$B \rightarrow \text{float}$

$C \rightarrow [\text{num}]C_1$

$C \rightarrow \epsilon$



How can we obtain the type expression $\text{array}(3, \text{integer})$ from this subtree?

Computing the Structure of a Type

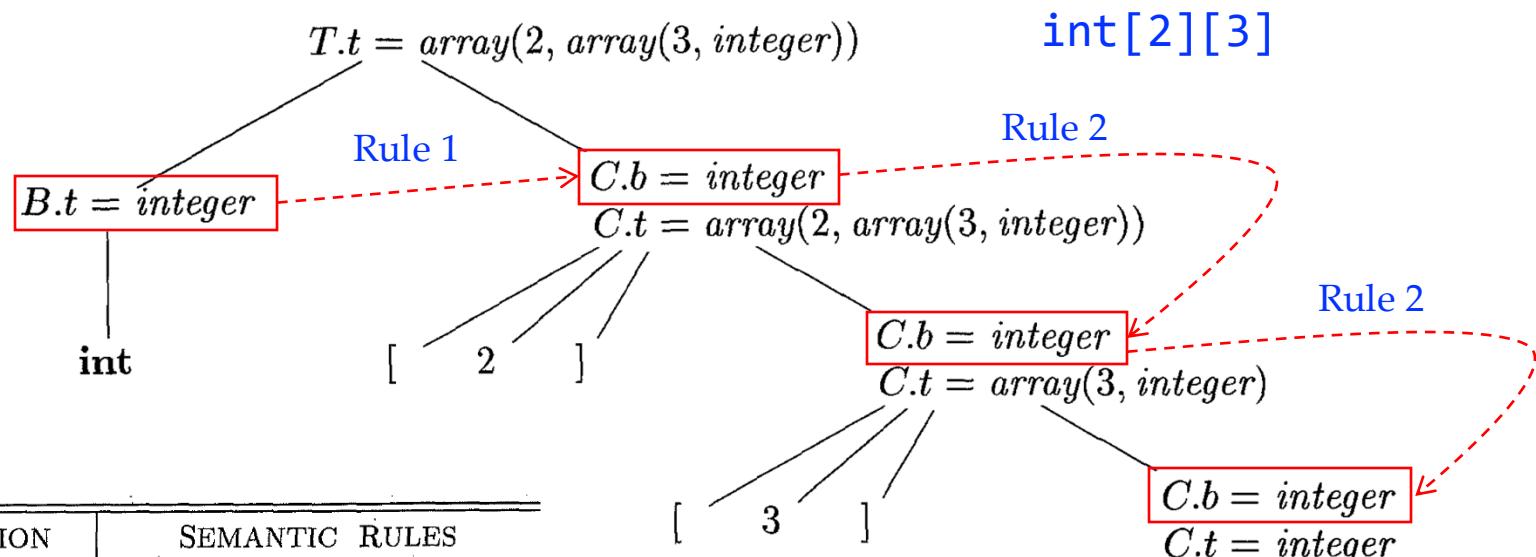
PRODUCTION	SEMANTIC RULES	
$T \rightarrow B C$	$T.t = C.t$ $C.b = B.t$	
$B \rightarrow \text{int}$	$B.t = \text{integer}$	L-attributed SDD
$B \rightarrow \text{float}$	$B.t = \text{float}$	
$C \rightarrow [\text{num}] C_1$	$C.t = \text{array}(\text{num}.val, C_1.t)$ $C_1.b = C.b$	
$C \rightarrow \epsilon$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

Synthesized attribute t represents a type

Inherited attribute b passes the basic type down the parse tree

Computing the Structure of a Type

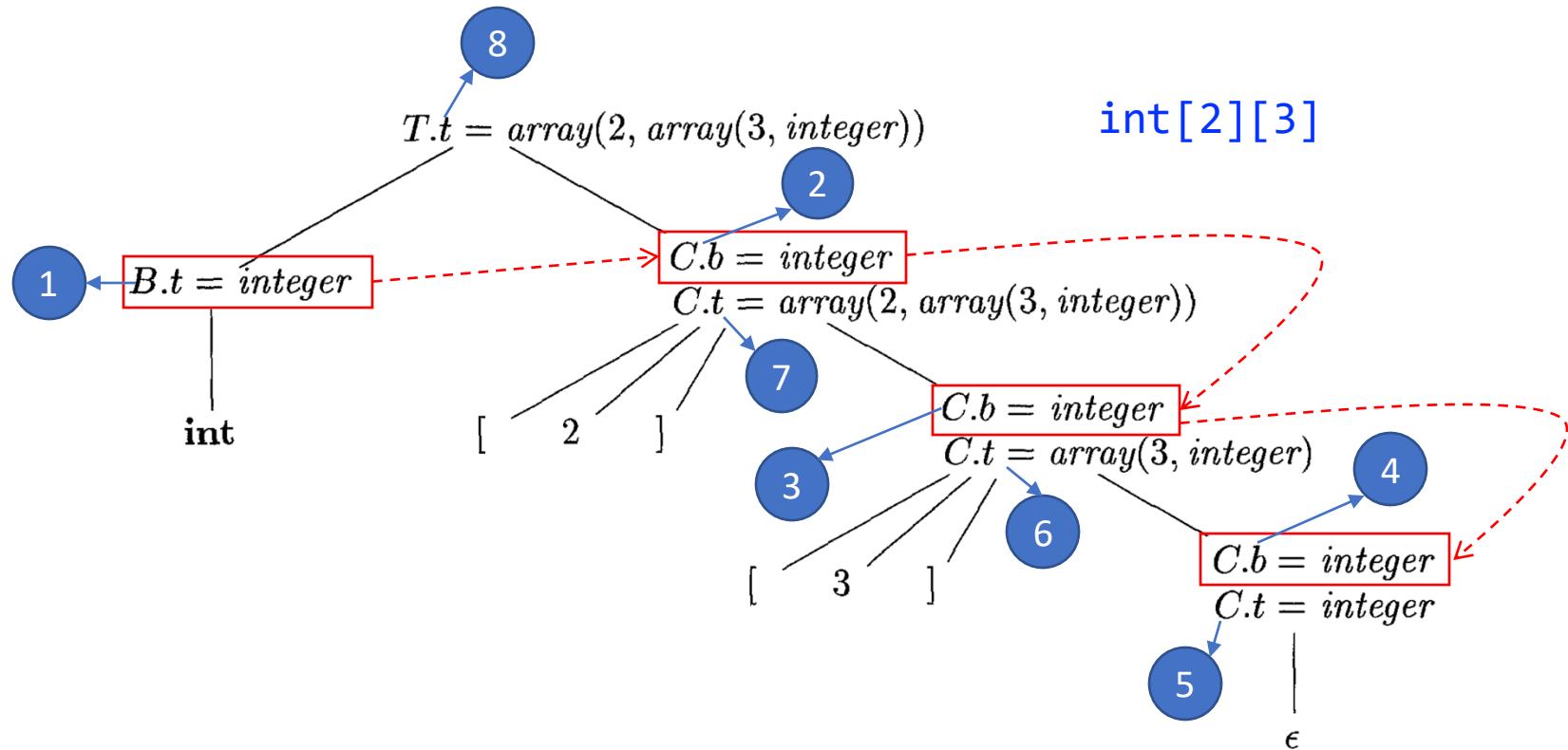
Dependency
----->



PRODUCTION	SEMANTIC RULES
$T \rightarrow B\ C$	$T.t = C.t$ $C.b = B.t$ Rule 1
$B \rightarrow \text{int}$	$B.t = \text{integer}$
$B \rightarrow \text{float}$	$B.t = \text{float}$
$C \rightarrow [\text{num}] C_1$	$C.t = \text{array}(\text{num}.val, C_1.t)$ $C_1.b = C.b$ Rule 2
$C \rightarrow \epsilon$	$C.t = C.b$

Computing the Structure of a Type

Dependency
----->



1 ... 8 : evaluation order (according to the algorithm on #22)

Outline

- Syntax-Directed Definitions
- Evaluation Orders for SDD's
- Applications of Syntax-Directed Translation
- Syntax-Directed Translation Schemes
- Uses of SDTs (Self-Study)
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Syntax-Directed Translation Schemes

- SDD's tell us what to do (**high-level specifications**) in the translation task, but not how to do
- Syntax-directed translation schemes (SDT's, 语法制导的翻译方案) specify more details on how to do the translation
- An SDT* is a context-free grammar with semantic actions (program fragments) embedded within production bodies
 - Differ from the semantic rules in SDD's (specification vs. implementation)
 - Semantic actions can appear anywhere within a production body

*In this course, we are only interested in SDT's for computing L-attributed SDD's.

An Example SDT (1)

- The SDT below implements a simple calculator

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

Semantic actions:
Real code in {}

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

Semantic rules:
Mathematical definitions

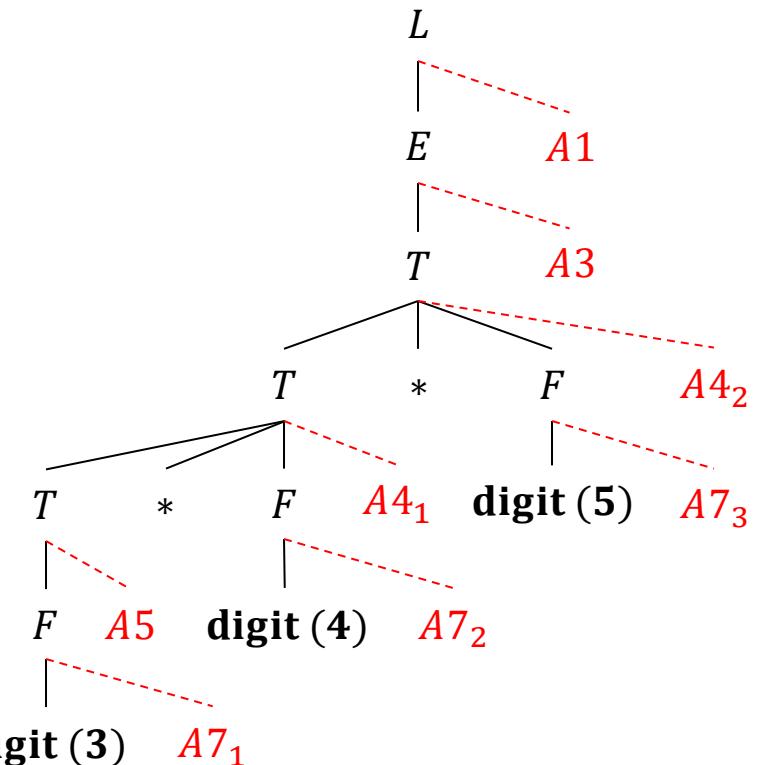
An Example SDT (2)

- Parse and calculate $3 * 4 * 5$

$L \rightarrow E \ n$	$\{ \text{print}(E.\text{val}); \}$	A1
$E \rightarrow E_1 + T$	$\{ E.\text{val} = E_1.\text{val} + T.\text{val}; \}$	A2
$E \rightarrow T$	$\{ E.\text{val} = T.\text{val}; \}$	A3
$T \rightarrow T_1 * F$	$\{ T.\text{val} = T_1.\text{val} \times F.\text{val}; \}$	A4
$T \rightarrow F$	$\{ T.\text{val} = F.\text{val}; \}$	A5
$F \rightarrow (E)$	$\{ F.\text{val} = E.\text{val}; \}$	A6
$F \rightarrow \text{digit}$	$\{ F.\text{val} = \text{digit}.lexval; \}$	A7

Order of actions:

A7₁, A5, A7₂, A4₁, A7₃, A4₂, A3, A1



All SDT's for computing **L-attributed** SDD's can be implemented by: 1) first building the parse tree, 2) treating semantic actions as "virtual" parse-tree nodes, and 3) performing preorder traversal

SDT's With Actions Inside Productions

$$B \rightarrow X\{a\}Y$$

- The action a should be done after we have recognized X (if X is a terminal) or all the terminals derived from X (if X is a nonterminal)
 - If the parse is **bottom-up**, we perform the **action a** as soon as X appears on the top of the parsing stack
 - If the parse is **top-down**, we perform the **action a** before attempting to expand Y (if Y is a nonterminal) or check for Y on the input (if Y is a terminal)

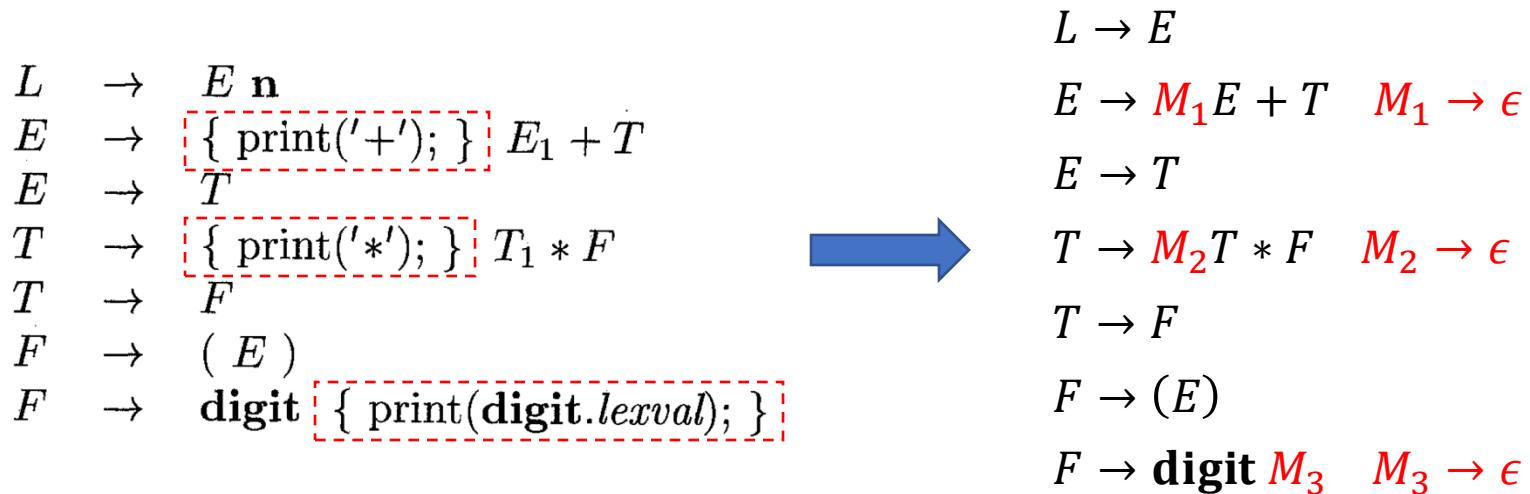
SDT's Implementable During Parsing

- In practice, SDT's are often implemented during parsing, **without first building a parse tree**
- Not all SDT's can be implemented during parsing^{*}
 - Even if the underlying grammar is parsable by a method (e.g., LL, LR), after introducing semantic actions, the parsing method may become inapplicable
- Determine if an SDT can be implemented during parsing
 - Introduce distinct *marker nonterminals* to replace 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

^{*}Note that all SDT's for computing L-attributed SDD's can be implemented after building the parse tree, as earlier mentioned

A Problematic SDT

- This SDT translates infix expression to prefix expressions



It is impossible to build parsing tables without conflicts using top-down or bottom-up parsing methods. This SDT cannot be implemented during parsing.
It can be implemented after parsing according to earlier mentioned steps.

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Uses of SDT's

- We can use SDT's to implement two important classes of SDD's:
 - The underlying grammar is LR, and the SDD is S-attributed
 - The underlying grammar is LL, and the SDD is L-attributed

Postfix Translation Schemes

- If the grammar of an SDD is LR, and the SDD is S-attributed, then we can construct a *postfix SDT* (后缀SDT) to implement the SDD in bottom-up parsing
 - Semantic actions always appear at the end of productions (hence “postfix”)

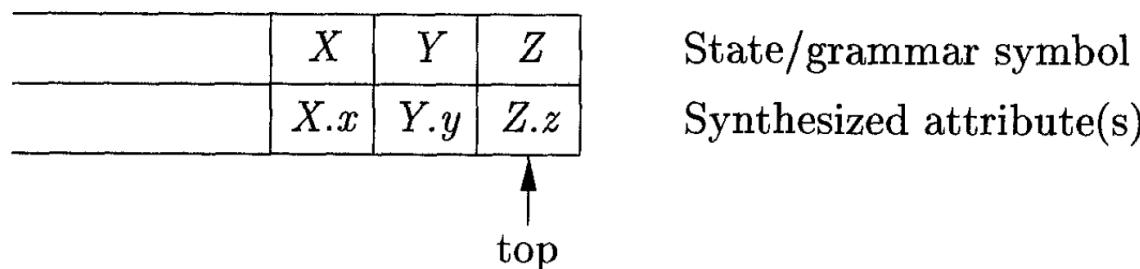
$L \rightarrow E \text{ n}$	$L.val = E.val$	SDD
$E \rightarrow E_1 + T$	$E.val = E_1.val + T.val$	
$E \rightarrow T$	$E.val = T.val$	
$T \rightarrow T_1 * F$	$T.val = T_1.val \times F.val$	
$T \rightarrow F$	$T.val = F.val$	
$F \rightarrow (E)$	$F.val = E.val$	
$F \rightarrow \text{digit}$	$F.val = \text{digit}.lexval$	

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

This is possible because in bottom-up parsing, before reducing to a production head, the grammar symbols in the production body have been visited and their synthesized attributes have been computed (both non-terminals and terminals).

Parser-Stack Implementation of Postfix SDT's

- Postfix SDT's can be implemented during LR parsing by executing the actions when reductions occur
- The synthesized attributes can be placed along with the grammar symbols on the stack



If we do reduction using $A \rightarrow XYZ$, then the attributes of A can be calculated based on the attributes of X , Y , and Z , which are already on the stack.

The Calculator Example

PRODUCTION

$L \rightarrow E \ n$ { print($stack[top - 1].val$);
 $top = top - 1;$ }

$E \rightarrow E_1 + T$ { $stack[top - 2].val = stack[top - 2].val + stack[top].val$;
 $top = top - 2;$ }

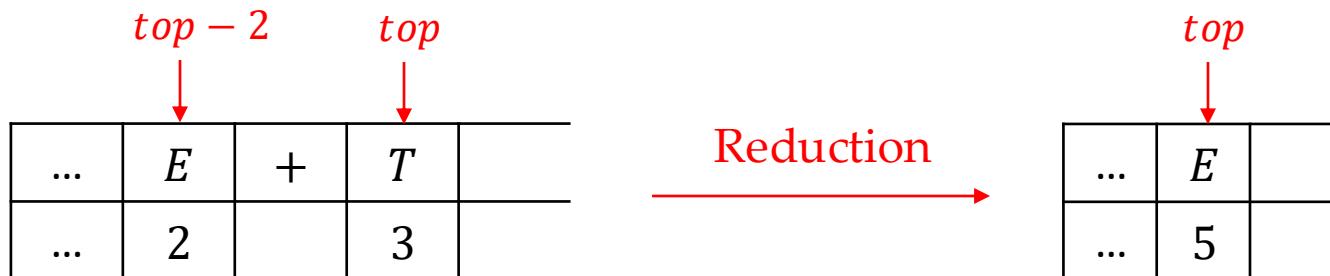
$E \rightarrow T$

$T \rightarrow T_1 * F$ { $stack[top - 2].val = stack[top - 2].val \times stack[top].val$;
 $top = top - 2;$ }

$T \rightarrow F$

$F \rightarrow (E)$ { $stack[top - 2].val = stack[top - 1].val$;
 $top = top - 2;$ }

$F \rightarrow \text{digit}$



Uses of SDT's

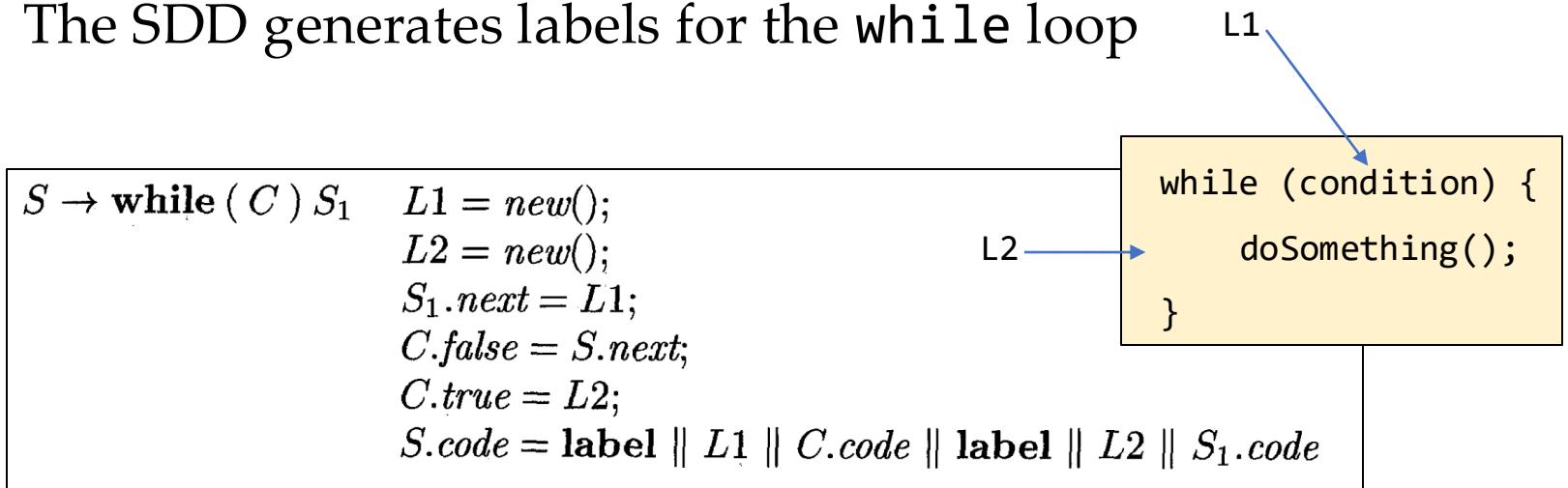
- We can use SDT's to implement two important classes of SDD's:
 - The underlying grammar is LR, and the SDD is S-attributed
 - The underlying grammar is LL, and the SDD is L-attributed

SDT's for L-Attributed SDD's

- L-attributed SDD's can be implemented during top-down parsing, if the underlying grammar is LL
- The way of turning an L-attributed SDD into an SDT is to **place semantic actions at appropriate positions** in the concerned production $A \rightarrow X_1 X_2 \dots X_n$
 - Embed the action that computes the **inherited attributes** for a nonterminal X_i immediately **before X_i** in the production body
 - Place the actions that compute a **synthesized attribute** for the production head **at the end** of the production body

An L-Attributed SDD

- The SDD generates labels for the `while` loop



Inherited attributes: $S.\text{next}$, $C.\text{true}$, $C.\text{false}$

* There will be jump instructions with the

labels as targets in $C.\text{code}$ and $S_1.\text{code}$.

Synthesized attribute: $S.\text{code}$

Turning into an SDT

- Semantic actions:
 - $L1 = new(); L2 = new();$
 - $C.false = S.next; C.true = L2;$
 - $S_1.next = L1;$
 - $S.code = \dots;$
 - According to the rules of action placement:
 - b) should be placed before C , c) should be placed before S_1 , and d) should be placed at the end of the production body
 - a) can be placed at the very beginning; there is no constraint

$$S \rightarrow \mathbf{while} (\quad \{ L1 = new(); L2 = new(); C.false = S.next; C.true = L2; \} \\ C) \quad \{ S_1.next = L1; \} \\ S_1 \quad \{ S.code = \text{label} \parallel L1 \parallel C.code \parallel \text{label} \parallel L2 \parallel S_1.code; \}$$

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Translation During Recursive-Descent Parsing

- Many translation applications can be addressed using L-attributed SDD's. It is possible to **extend a recursive-descent parser to implement L-attributed SDD's.**
 - A recursive-decent parser has a function A for each nonterminal A

```
void A() {
    1)     Choose an  $A$ -production,  $A \rightarrow X_1 X_2 \cdots X_k$ ;
    2)     for (  $i = 1$  to  $k$  ) {
    3)         if (  $X_i$  is a nonterminal )
    4)             call procedure  $X_i()$ ;
    5)         else if (  $X_i$  equals the current input symbol  $a$  )
    6)             advance the input to the next symbol;
    7)         else /* an error has occurred */;
    }
}
```

Translation During Recursive-Descent Parsing

- Extend a recursive-descent parser to implement L-attributed SDD's as follows:
 - A recursive-decent parser has a function A for each nonterminal A
 - Use the arguments of function A to pass A 's **inherited attributes** so that children nodes on the parse tree can use the attributes
 - Return the **synthesized attributes** of A when the function A completes so that parent node on the parse three can use the attributes
- With the above extension, in the body of the function A , we need to both **parse** and **handle attributes**

The While-Loop Example

$$S \rightarrow \text{while} (C) S_1$$

```
string S(label next) {
    string Scode, Ccode; /* local variables holding code fragments */
    label L1, L2; /* the local labels */
    if ( current input == token while ) {
        advance input;
        check '(' is next on the input, and advance;
        L1 = new();  C.false  C.true
        L2 = new();
        Ccode = C(next, L2);
        check ')' is next on the input, and advance;
        Scode = S(L1);  S1.next (the label of the condition evaluating statement)
        return("label" || L1 || Ccode || "label" || L2 || Scode);
    }
    else /* other statement types */
}
```

Pass inherited attributes
(the label of the statement after while)

Save attributes in
local variables

Pass inherited attributes
when further handling
other nonterminals

Compute synthesized attributes
and return

We mainly put code that handles attributes here, the code is not complete.

Reading Tasks

- Chapter 5 of the dragon book
 - 5.1 Syntax-Directed Definitions
 - 5.2 Evaluation Orders for SDD's (5.2.1-5.2.4)
 - 5.3 Applications of Syntax-Directed Translation
 - 5.4 Syntax-Directed Translation Schemes
 - 5.5 Implementing L-Attributed SDD's (5.5.1)