# Syntax Directed Translation

Akshaya Arunan, Govt. Engg College, Trivandrum

# Syntax-directed translation



- Syntax-directed translation (SDT) refers to a method of compiler implementation where the source language translation is completely driven by the parser.
- The parsing process and parse trees are used to direct semantic analysis and the translation of the source program.
- We can augment grammar with information to control the semantic analysis and translation. Such grammars are called **attribute grammars.**

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# Syntax-directed translation



- Associate attributes with each grammar symbol that describes its properties.
- An attribute has a name and an associated value.
- With each production in a grammar, give semantic rules or actions.
- The general approach to syntax-directed translation is to construct a parse tree or syntax tree and compute the values of attributes at the nodes of the tree by visiting them in some order.

# Syntax-directed translation



- There are two ways to represent the semantic rules associated with grammar symbols.
  - Syntax-Directed Definitions (SDD)
  - Syntax-Directed Translation Schemes (SDT)

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# Syntax-Directed Definitions



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

| PRODUCTION | SEMANTIC RULE |
|---|---|
| $E \rightarrow E1 + T$ | E.code = E1.code \|\| T.code \|\| ‘+’ |

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# Syntax-Directed Definitions



- SDDs are highly readable and give high-level specifications for translations.
- But they hide many implementation details.
- For example, they do not specify order of evaluation of semantic actions.
- Syntax-Directed Translation Schemes (SDT) embeds program fragments called semantic actions within production bodies
- SDTs are more efficient than SDDs as they indicate the order of evaluation of semantic actions associated with a production rule.

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# Inherited Attributes



- An INHERITED ATTRIBUTE for a non-terminal B at a parse-tree node N is defined by a semantic rule associated with the production at the parent of N. 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.

# Synthesized Attributes



| 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) $F \rightarrow$ **digit** | $F.val =$ **digit**.$lexval$ |

- Each of the non-terminals has a single synthesized attribute, called val.
- An SDD that involves only synthesized attributes is called **S-attributed**
- Each rule computes an attribute for the non-terminal at the head of a production from attributes taken from the body of the production.

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# Evaluating an SDD at the Nodes of a Parse Tree



- A parse tree, showing the value(s) of its attribute(s) is called an **annotated parse tree.**
- With synthesized attributes, evaluate attributes in bottom-up order.

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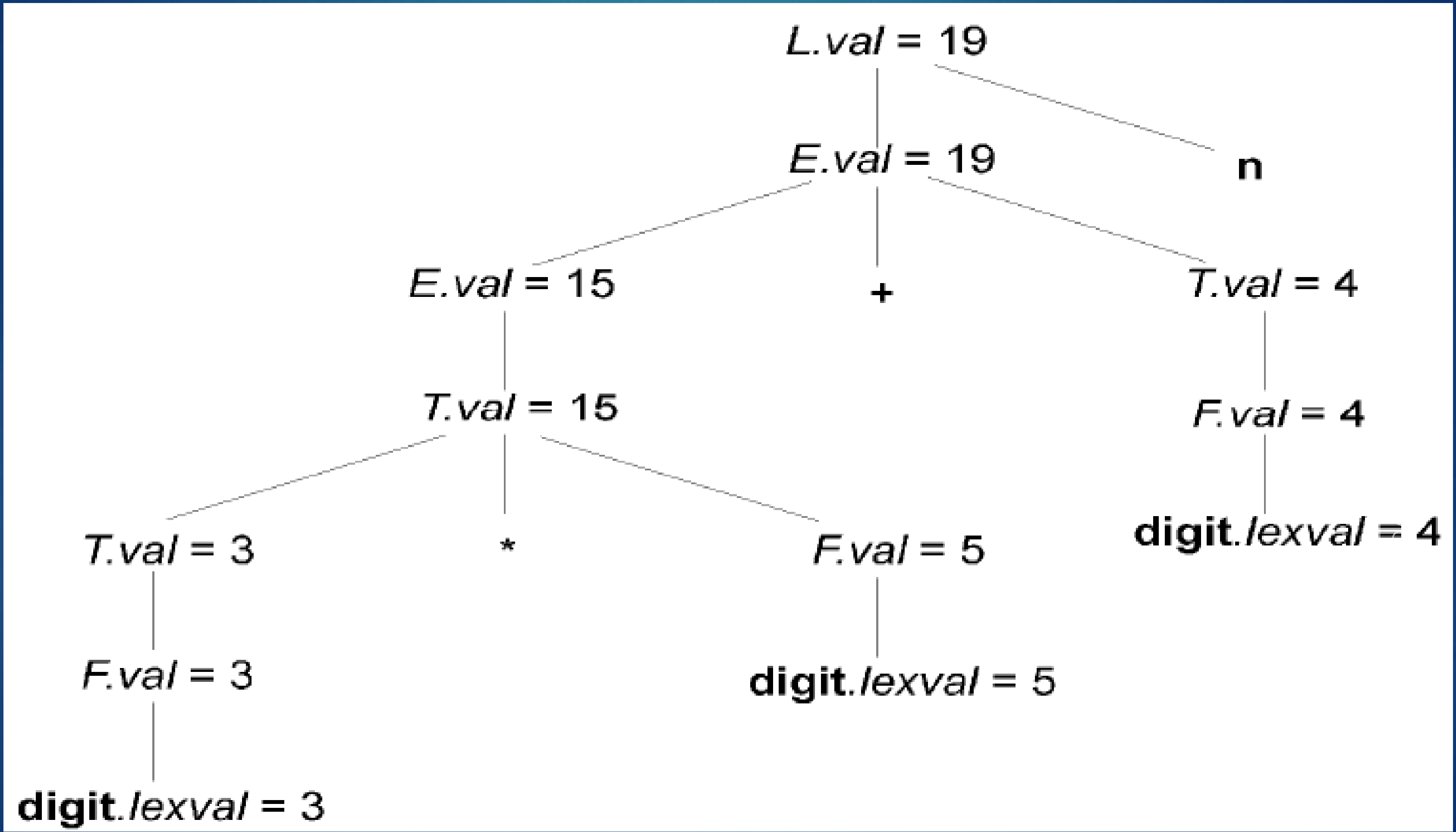
# Annotated Parse Tree for 3*5+4n





□give annotated parse trees for the following expressions:

$(3 + 4) * (5 + 6)\ \mathbf{n}.$

$1 * 2 * 3 * (4 + 5)\ \mathbf{n}.$

$(9 + 8 * (7 + 6) + 5) * 4\ \mathbf{n}.$

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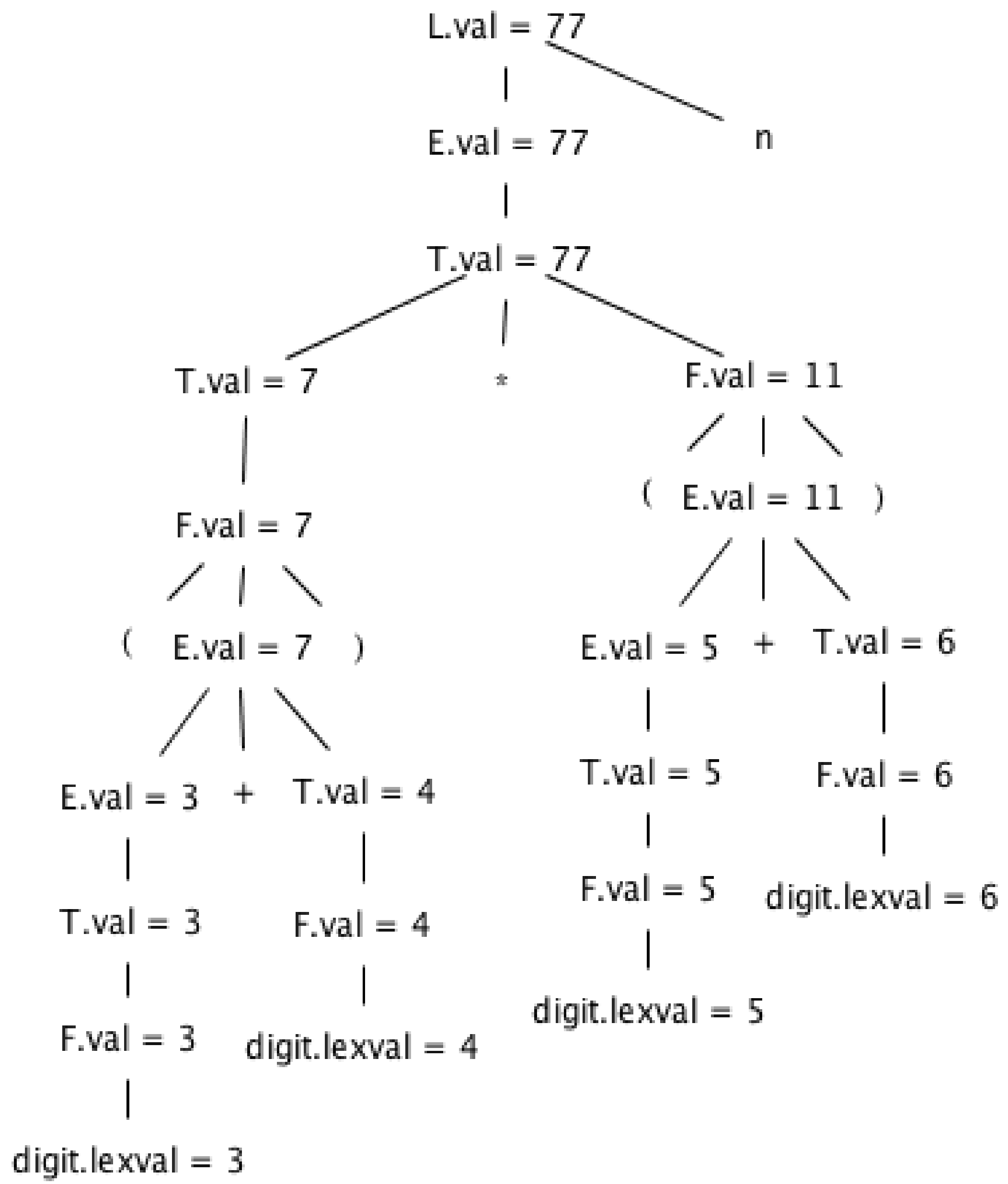
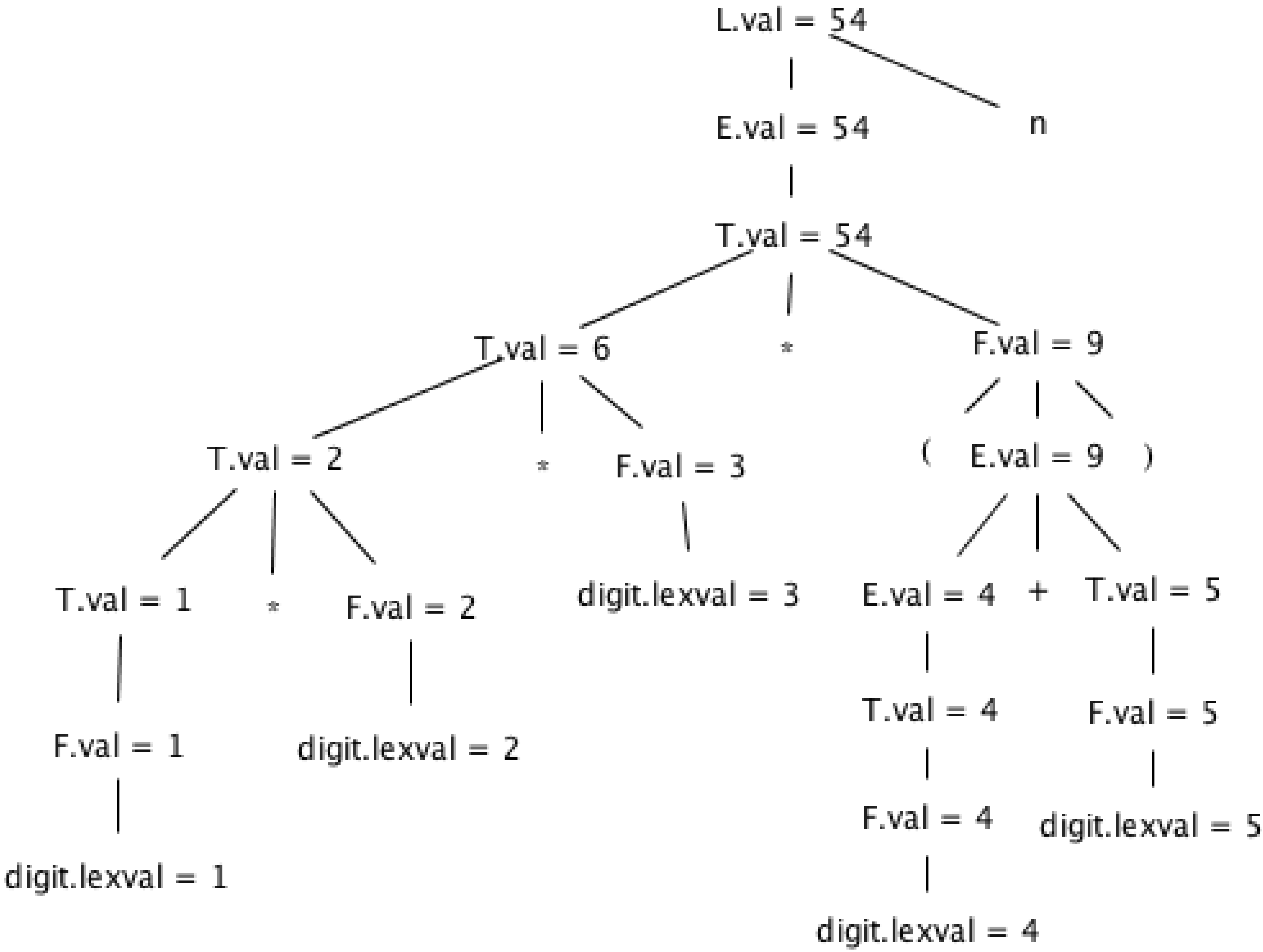

L.val = 77
E.val = 77
n
T.val = 77
T.val = 7
*
F.val = 11
( E.val = 11 )
F.val = 7
( E.val = 7 )
E.val = 5
+
T.val = 6
E.val = 3
+
T.val = 4
T.val = 5
F.val = 6
T.val = 3
F.val = 4
F.val = 5
digit.lexval = 6
F.val = 3
digit.lexval = 4
digit.lexval = 5
digit.lexval = 3



L.val = 54
n
E.val = 54
T.val = 54
T.val = 6
*
F.val = 9
T.val = 2
*
F.val = 3
(
E.val = 9
)
T.val = 1
*
F.val = 2
digit.lexval = 3
E.val = 4
+
T.val = 5
F.val = 1
digit.lexval = 2
T.val = 4
F.val = 5
digit.lexval = 1
F.val = 4
digit.lexval = 5
digit.lexval = 4

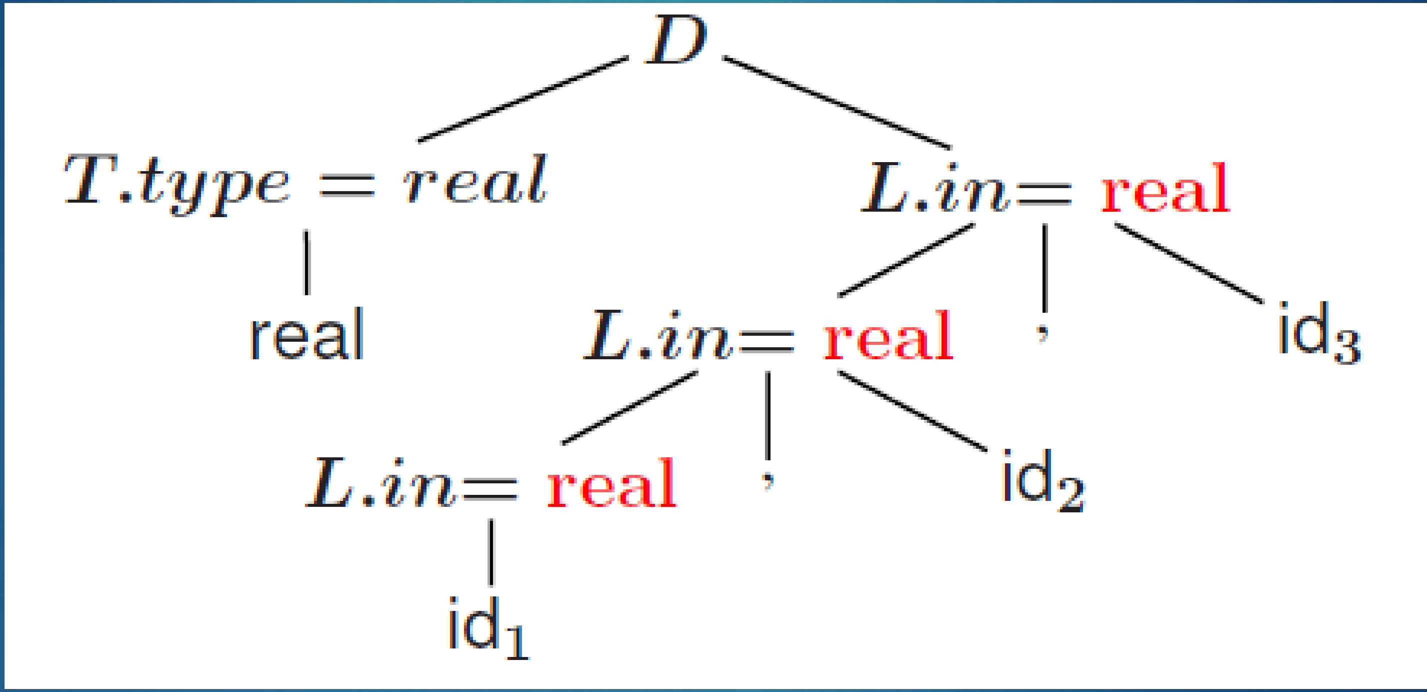
# SDD for expression grammar with inherited attributes



| 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$.entry, L.in)$ |

# Annotated parse-tree for the input real id1, id2, id3



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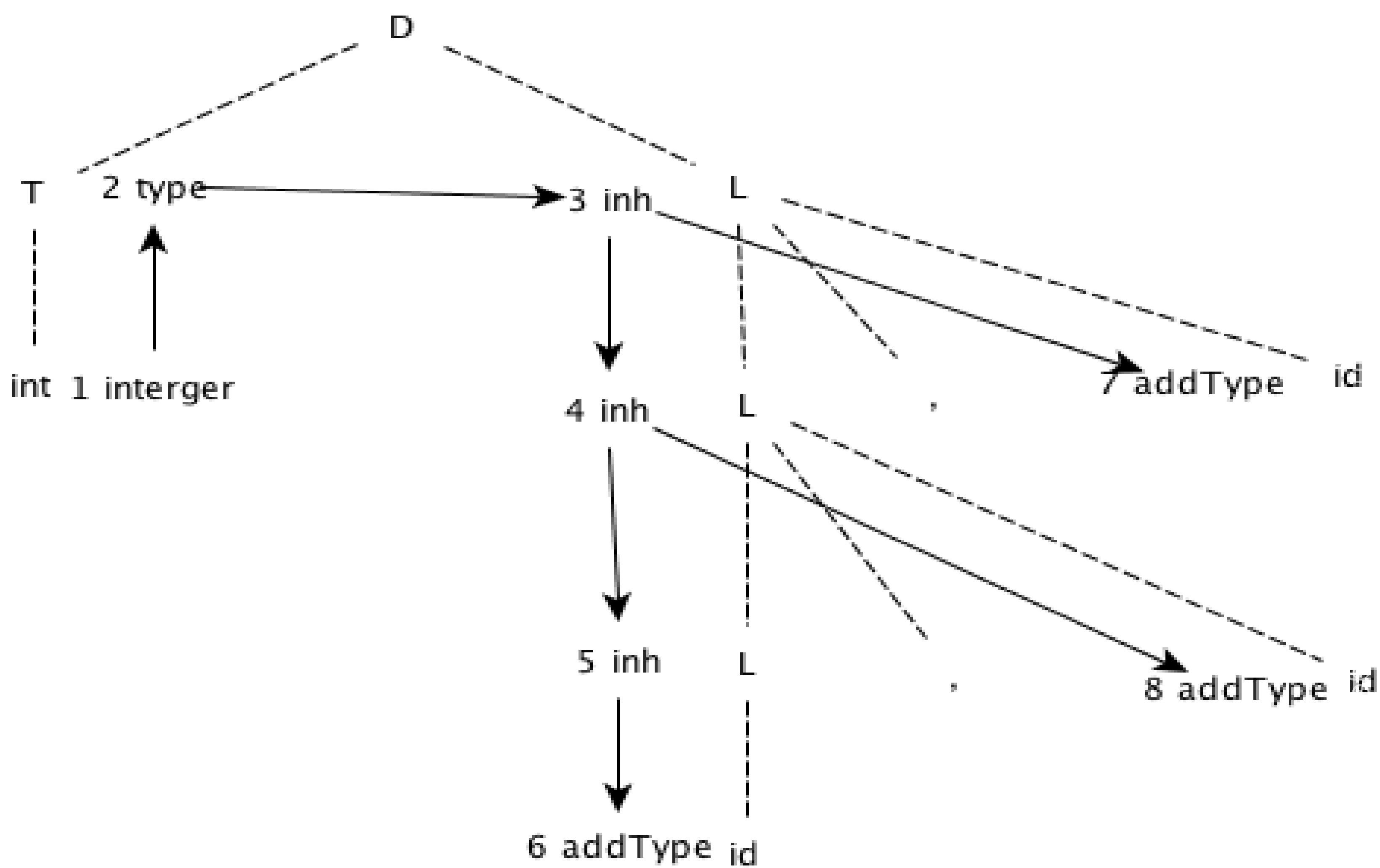

D
T
2 type
3 inh
L
int
1 interger
4 inh
L
,
7 addType
id
5 inh
L
,
8 addType
id
6 addType
id

# SDD for expression grammar with inherited attributes

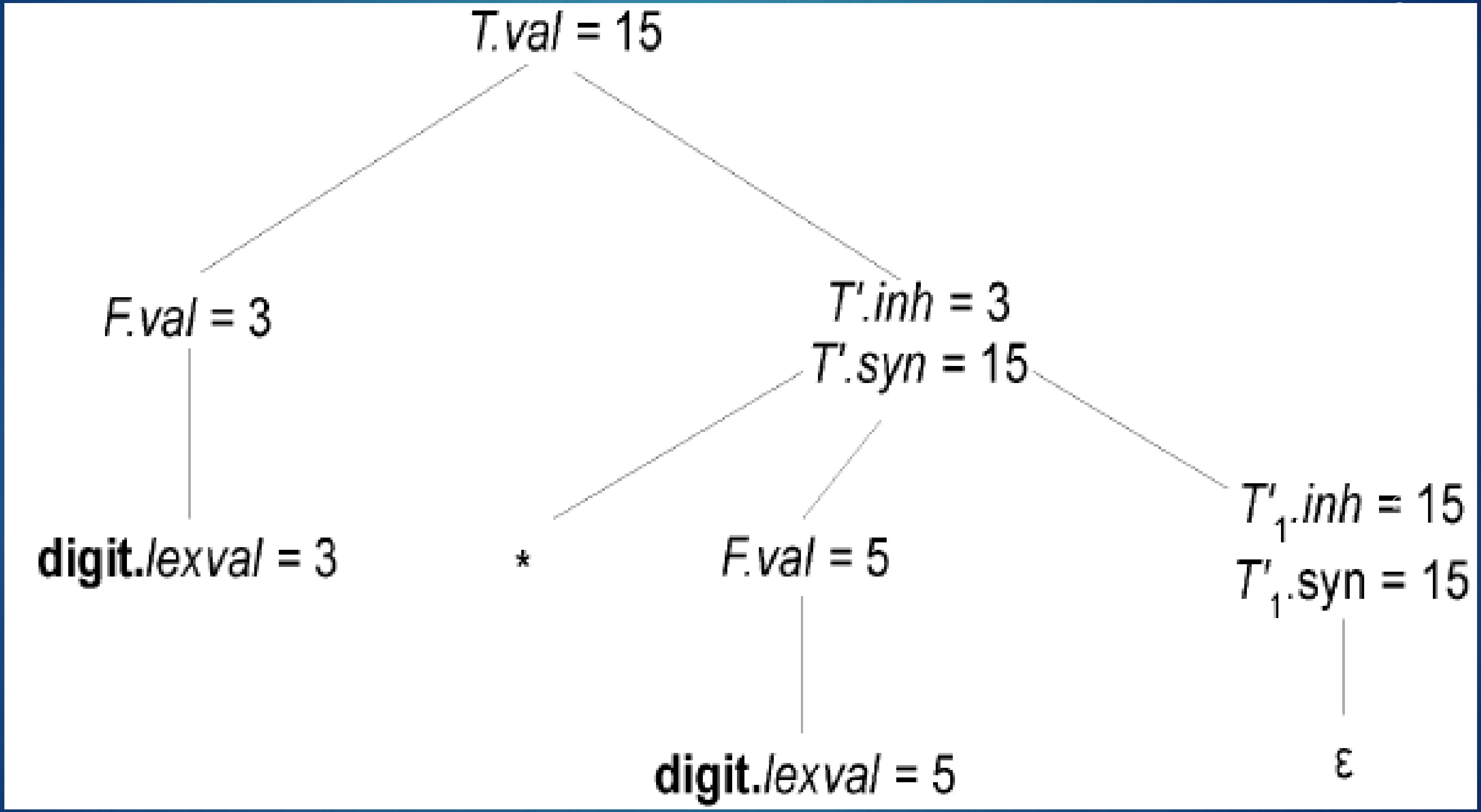




| Production | Semantic Rules |
|---|---|
| $T \rightarrow F\ T'$ | $T'.inh = F.val$<br>$T.val = T'.syn$ |
| $T' \rightarrow {}^*F\ T'_1$ | $T'_1.inh = T'.inh \times F.val$<br>$T'.syn = T'_1.syn$ |
| $T' \rightarrow \varepsilon$ | $T'.syn = T'.inh$ |
| $F \rightarrow \textbf{digit}$ | $F.val = \textbf{digit}.lexval$ |

# Annotated Parse Tree for 3*5





| | | |
|---|---|---|
| 1) | L -> En | L.val = E.val |
| 2) | E -> TE' | E'.inh = T.val<br>E.val = E'.syn |
| 3) | E' -> +TE_1' | E_1'.inh = E'.inh + T.val<br>E'.syn = E_1'.syn |
| 4) | E' -> ε | E'.syn = E'.inh |
| 5) | T -> FT' | T'.inh = F.val<br>T.val = T'.syn |
| 6) | T' -> *FT_1' | T_1'.inh = T'.inh * F.val<br>T'.syn = T_1'.syn |
| 7) | T' -> ε | T'.syn = T'.inh |
| 8) | F -> (E) | F.val = E.val |
| 9) | F -> digit | F.val = digit.lexval |

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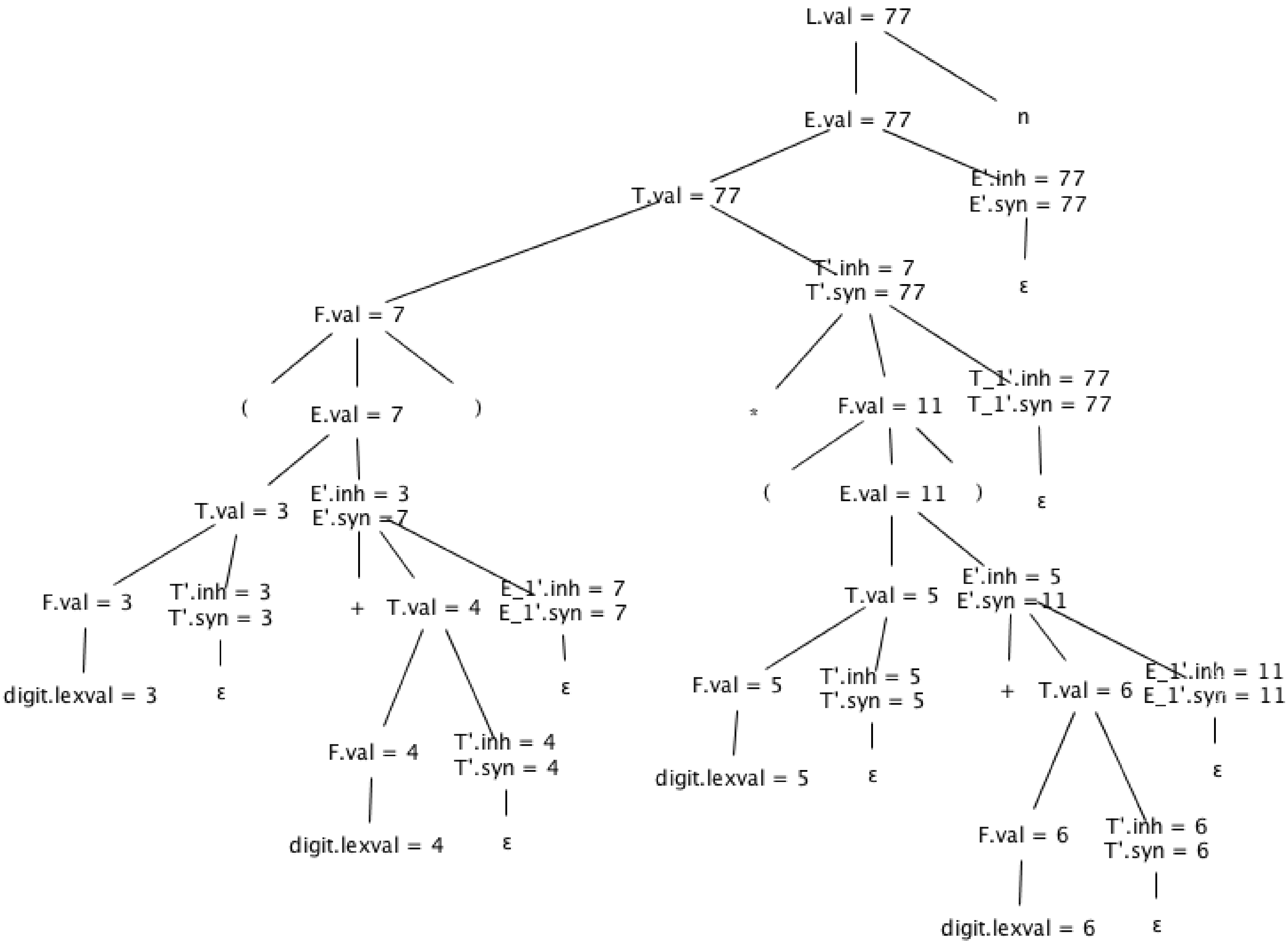
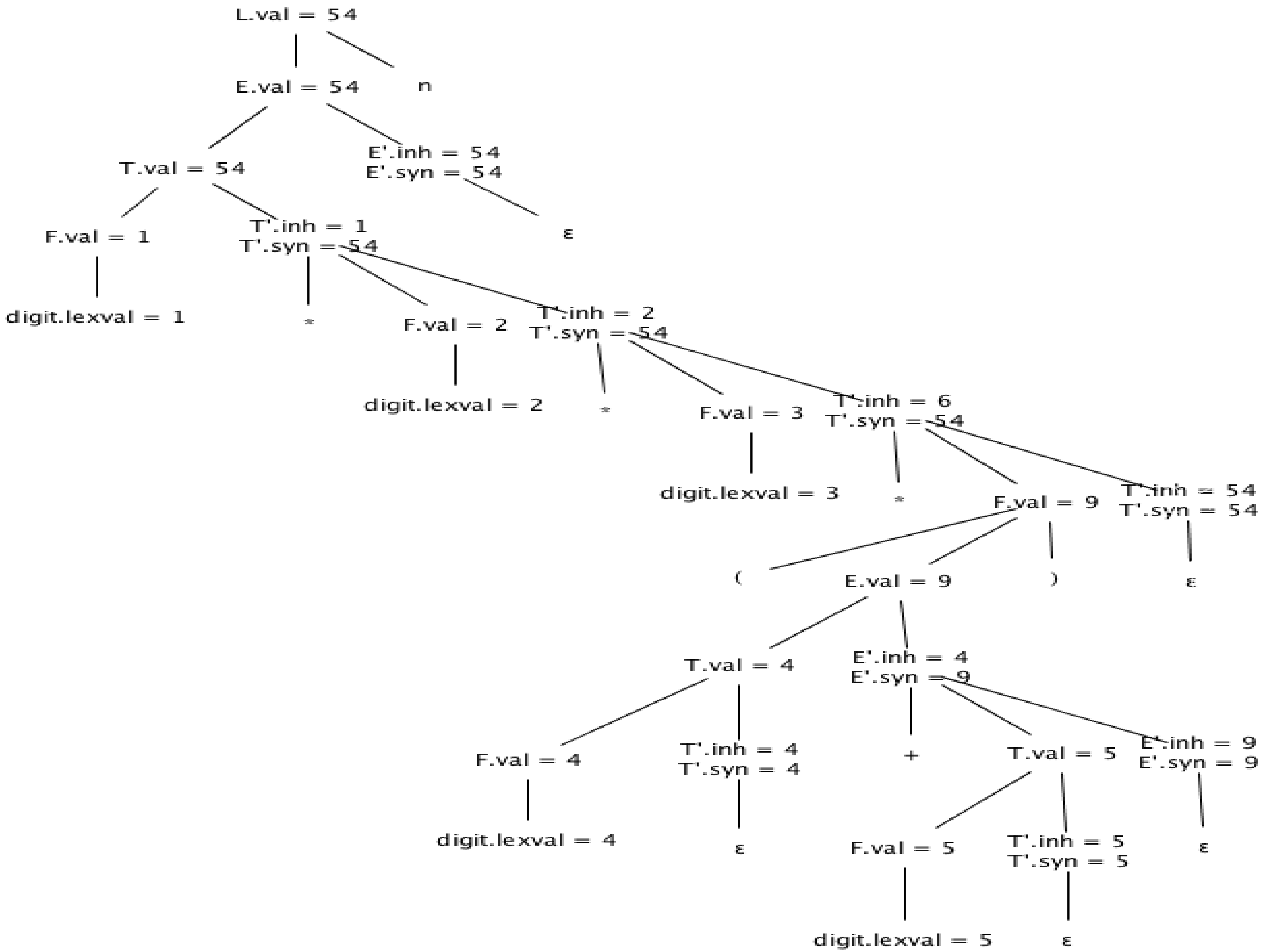


L.val = 77
E.val = 77
n
T.val = 77
E'.inh = 77
E'.syn = 77
ε
F.val = 7
T'.inh = 7
T'.syn = 77
(
E.val = 7
)
*
F.val = 11
T_1'.inh = 77
T_1'.syn = 77
T.val = 3
E'.inh = 3
E'.syn = 7
(
E.val = 11
)
ε
F.val = 3
T'.inh = 3
T'.syn = 3
+
T.val = 4
E_1'.inh = 7
E_1'.syn = 7
T.val = 5
E'.inh = 5
E'.syn = 11
digit.lexval = 3
ε
ε
F.val = 5
T'.inh = 5
T'.syn = 5
+
T.val = 6
E_1'.inh = 11
E_1'.syn = 11
F.val = 4
T'.inh = 4
T'.syn = 4
digit.lexval = 5
ε
ε
digit.lexval = 4
ε
F.val = 6
T'.inh = 6
T'.syn = 6
digit.lexval = 6
ε



L.val = 54
E.val = 54
n
T.val = 54
E'.inh = 54
E'.syn = 54
F.val = 1
T'.inh = 1
T'.syn = 54
ε
digit.lexval = 1
*
F.val = 2
T'.inh = 2
T'.syn = 54
digit.lexval = 2
*
F.val = 3
T'.inh = 6
T'.syn = 54
digit.lexval = 3
*
F.val = 9
T'.inh = 54
T'.syn = 54
(
E.val = 9
)
ε
T.val = 4
E'.inh = 4
E'.syn = 9
F.val = 4
T'.inh = 4
T'.syn = 4
+
T.val = 5
E'.inh = 9
E'.syn = 9
digit.lexval = 4
ε
F.val = 5
T'.inh = 5
T'.syn = 5
ε
digit.lexval = 5
ε

- SDD with circular dependencies no guarantee in the order of evaluation.

e.g.

| Production | Semantic Rules |
|---|---|
| $A \rightarrow B$ | $A.s = B.i$ |
| | $B.i = A.s + 1$ |

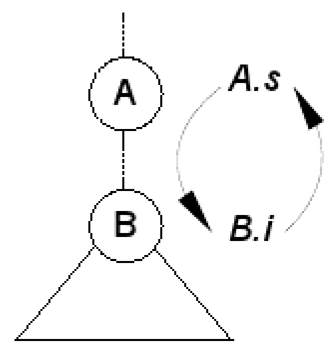



Fig 5.2: The circular dependency of *A.s* and *B.i* on one another

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# Evaluation Orders for SDD's



□**"Dependency graphs" tool for determining an evaluation order for the** attribute instances in a given parse tree.

□annotated parse tree shows the values of attributes, a dependency graph helps to determine how those values can be computed.

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# Dependency graphs



- Edges express constraints implied by the semantic rules.
- Each attribute is associated to a node
- If a semantic rule associated with a production *p defines the value of synthesized* attribute *A.b in terms of the value of X.c, then graph has an edge from X.c to A.b*
- If a semantic rule associated with a production *p defines the value of inherited* attribute *B.c in terms of value of X.a, then graph has an edge from X.a to B.c*

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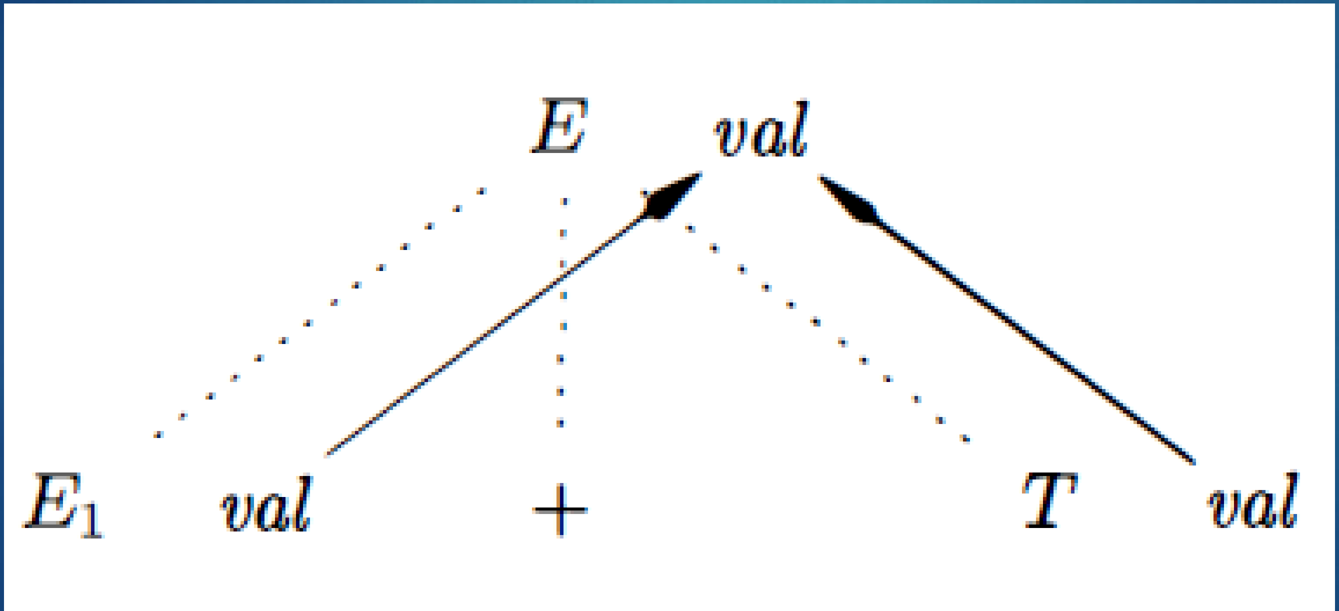
| PRODUCTION | SEMANTIC RULE |
|---|---|
| $E \to E_1 + T$ | $E.val = E_1.val + T.val$ |

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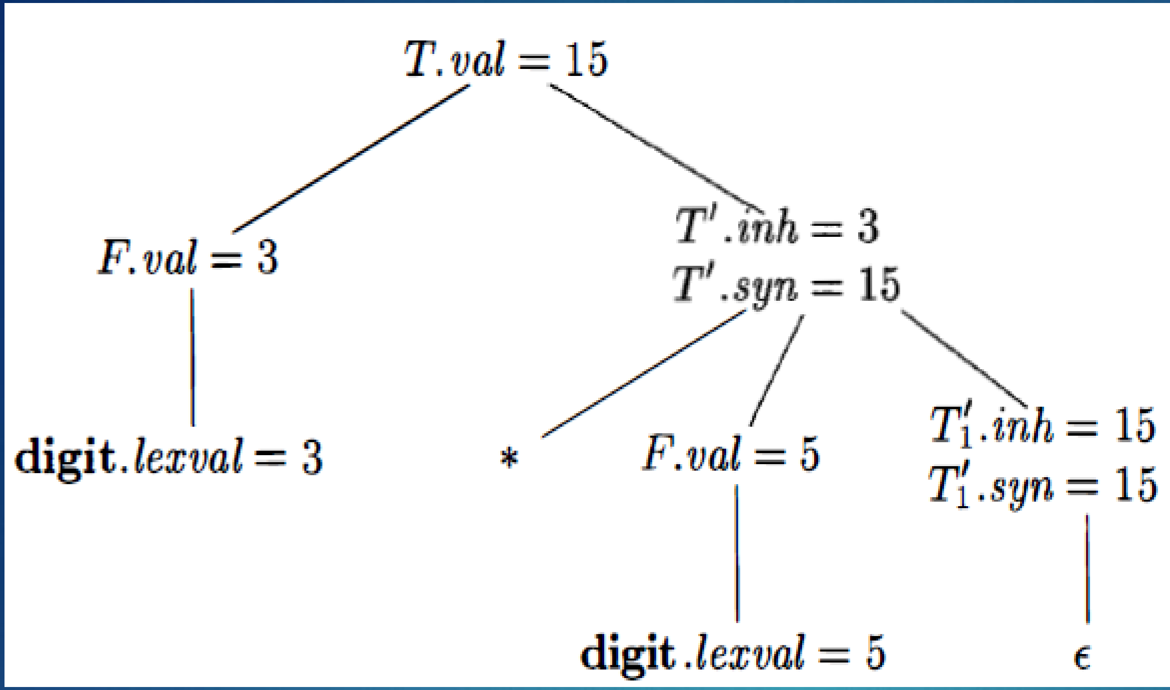


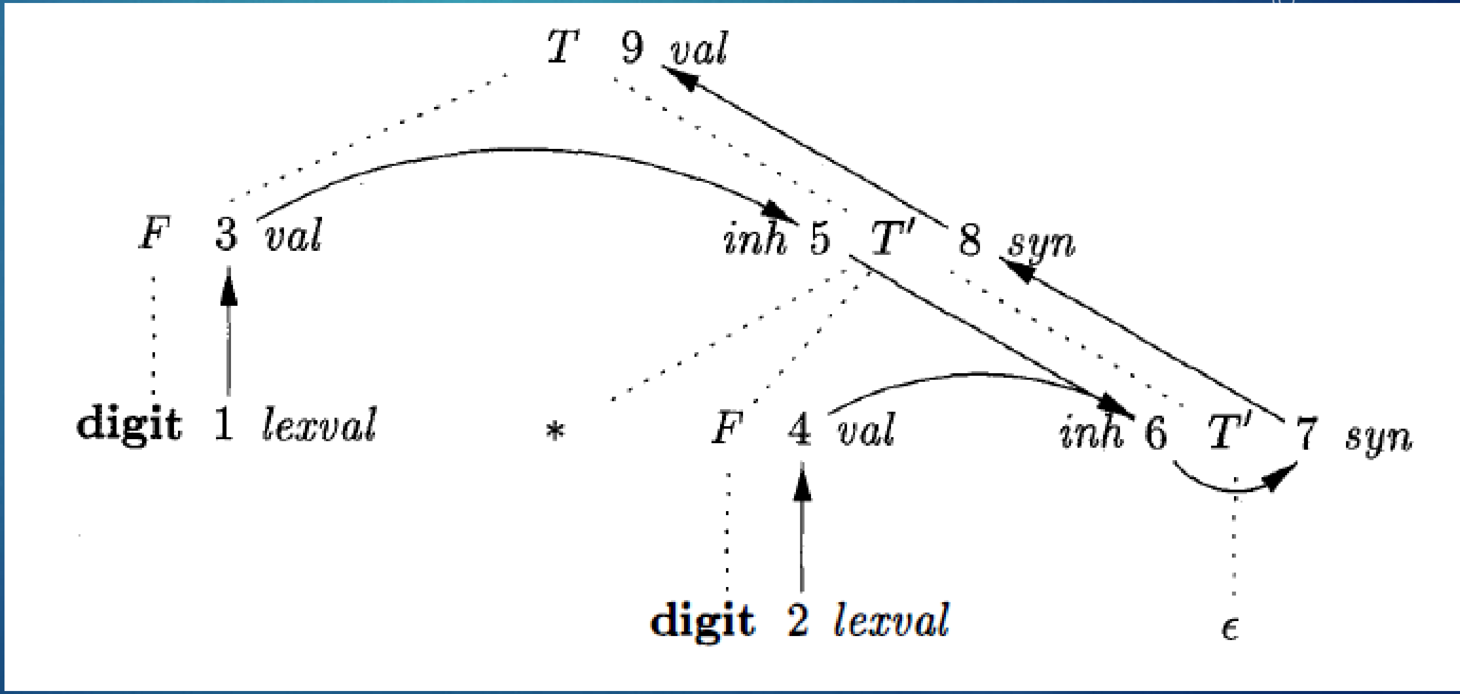


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# Topological Sort



- A dependency graph characterizes the possible order in which we can evaluate the attributes at various nodes of a parse tree.
- If there is an edge from node M to N, then attribute corresponding to M first be evaluated before evaluating N.
- Thus the allowable orders of evaluation are N1, N2, ..., Nk such that if there is an edge from Ni to Nj then i < j.
- Such an ordering embeds a directed graph into a linear order, and is called a ***topological sort*** *of the graph.*
- If there is any cycle in the graph, then there are no topological sorts.

# S-Attributed



- If every attribute is synthesized.
- S-attributed SDD can be evaluated in bottom up order of the nodes of the parse tree.

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# L-attributed definitions



- Synthesized, or
- Inherited, but with the rules limited as follows . Suppose that there is a production A -> XIX2 · . . Xn , and that there is an inherited attribute Xi·a computed by a rule associated with this production. Then the rule may use only:

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# L-attributed definitions



- Inherited attributes associated with the head A.
- Either inherited or synthesized attributes associated with the occurrences of symbols Xl , X2 , ••• ,Xi-l located to the left of Xi.
- Inherited or synthesized attributes associated with this occurrence of Xi itself, but only in such a way that there are no cycles in a dependency graph formed by the attributes of this Xi .

# Semantic Rules with Controlled Side Effects



- Permit incidental side effects that do not disturb attribute evaluation.
- Impose restriction on allowable evaluation orders, so that the same translation is produced for any allowable order.

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# Applications of Syntax-Directed Translations



- Construction of Syntax Trees
- Syntax trees are useful for representing programming language constructs like expressions and statements.
- Each node of a syntax tree represents a construct; the children of the node represent the meaningful components of the construct.
  - e.g. a syntax-tree node representing an expression E1 + E2 has label + and two children representing the sub expressions E1 and E2

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# Applications of Syntax-Directed Translations

- Each node is implemented by objects with suitable number of fields; each object will have an op field that is the label of the node with additional fields as follows:
  - If the node is a leaf, an additional field holds the lexical value for the leaf . This is created by function Leaf(op, val)
  - If the node is an interior node, there are as many fields as the node has children in the syntax tree. This is created by function Node(op, c1, 2,...,ck) .

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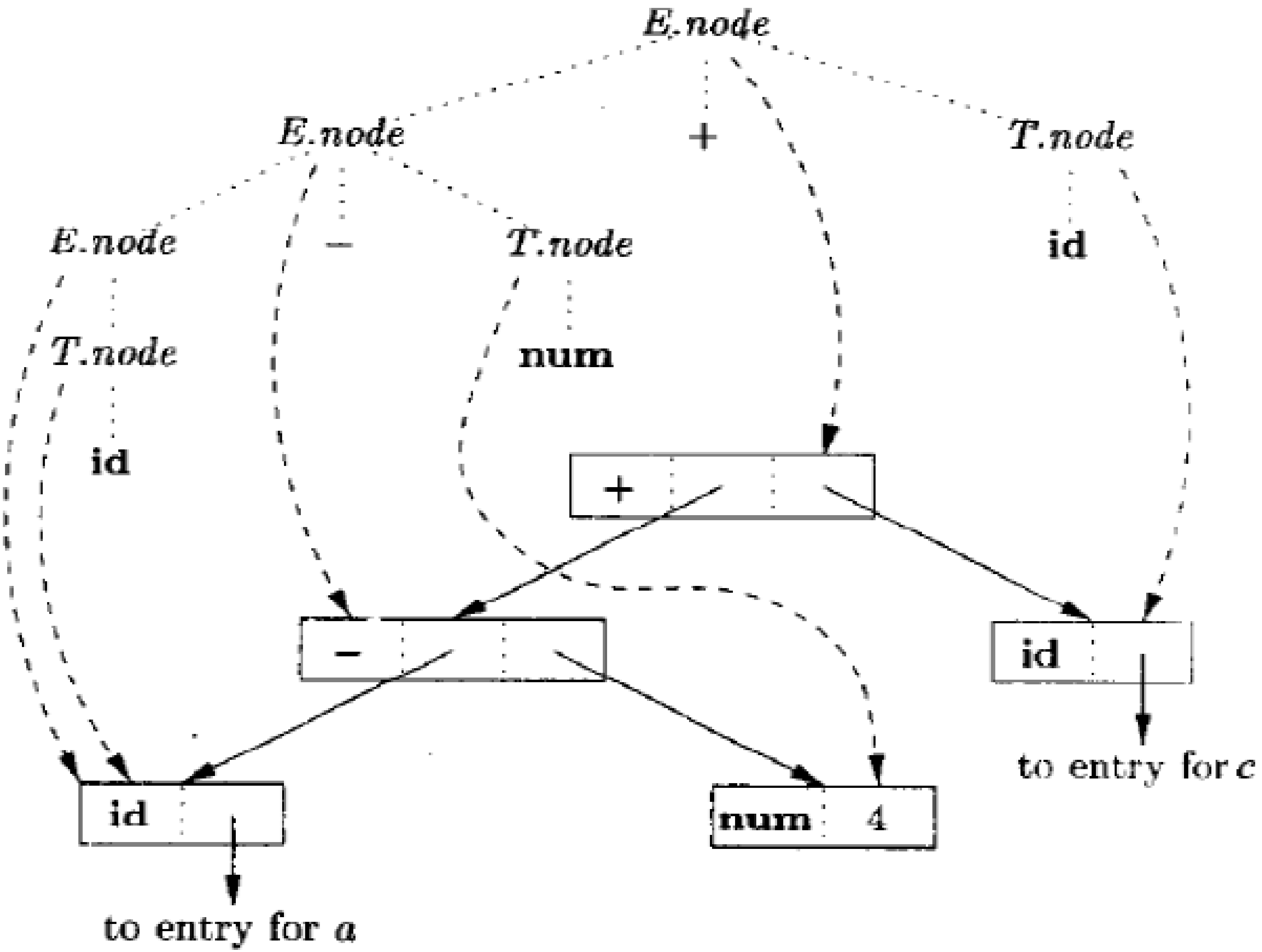
| Production | Semantic Rules |
| --- | --- |
| 1) $E \rightarrow E_1 + T$ | $E.node$ = **new** $Node$ ( '+', $E_1.node$, $T.node$ ) |
| 2) $E \rightarrow E_1 - T$ | $E.node$ = **new** $Node$ ( '−', $E_1.node$, $T.node$ ) |
| 3) $E \rightarrow T$ | $E.node = T.node$ |
| 4) $T \rightarrow ( E )$ | $E.node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



E.node
E.node
+
T.node
E.node
−
T.node
id
T.node
num
id
+
−
id
id
num 4
to entry for c
to entry for a

# Syntax Directed Translation Schemes



- SDT can be implemented by first building a parse tree and then performing the actions in a left-to-right depth-first order
- Postfix Translation Schemes:each semantic action can be placed at the end of production and executed along with the reduction of body to the head of the production.

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| Production | Semantic Rules |
| --- | --- |
| $L \rightarrow E\ \mathbf{n}$ | { print ( $E.val$ ); } |
| $E \rightarrow E_1 + T$ | { $E.val = E_1.val + T.val$; } |
| $E \rightarrow T$ | { $E.val = T.val$; } |
| $T \rightarrow T_1 * F$ | { $T.val = T_1.val \times F.val$; } |
| $T \rightarrow F$ | { $T.val = F.val$; } |
| $F \rightarrow ( E )$ | { $F.val = E.val$; } |
| $F \rightarrow \mathbf{digit}$ | { $F.val = \mathbf{digit}.lexval$; } |

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# Parser-Stack Implementation of Postfix SDTs

| | | | | |
|---|---|---|---|---|
| | $X$ | $Y$ | $Z$ | state/grammar symbol |
| | $X.a$ | $Y.b$ | $Z.c$ | synthesized attribute |

top

# Semantic Actions during Parsing



- when shifting
  - push the value of the terminal on the semantic stack
- when reducing
  - pop k values from the semantic stack, where k is the number of symbols on production's RHS
  - push the production's value on the semantic stack

# SDTs with Actions inside Productions

- Action can be placed at any position in the production body.
- Action is performed immediately after all symbols left to it are processed.
- Given B —> X { a } Y , an action a is done after
  - we have recognized X (if X is a terminal), or
  - all terminals derived from X (if X is a nonterminal).

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# SDTs with Actions inside Productions



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- If bottom-up parser is used, then action a is performed as soon as X appears on top of the stack.
- If top-down parser is used, then action a is performed
  - just before Y is expanded (if Y is nonterminal), or
  - check Y on input (if Y is a terminal).
- Any SDT can be implemented as follows:
  - Ignoring actions, parse input and produce parse tree.
  - Add additional children to node N for action in α, where A → α.
  - Perform preorder traversal of the tree, and as soon as a node labeled by an action is visited, perform that action.

# Semantic Actions during Parsing



| Production | Actions |
|---|---|
| $L \rightarrow E$ **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* x *stack*[*top*].*val*; *top* = *top* - 2; } |
| $T \rightarrow F$ | |
| $F \rightarrow ( E )$ | { *stack* [*top* - 2].*val* = *stack*[*top* - 1].*val*; *top* = *top* - 1; } |
| $F \rightarrow$ **digit** | |

# Type checking

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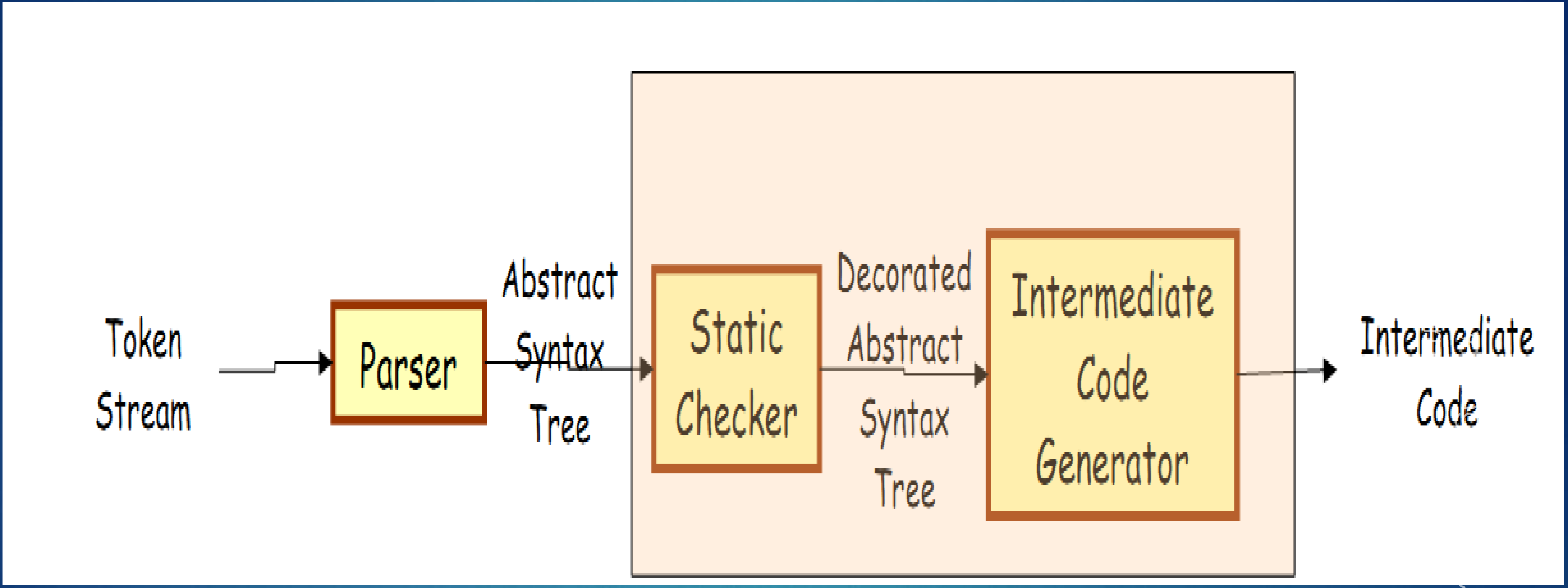
# Type Checking?



- Type checking is the process of verifying that each operation executed in a program respects the type system of the language.
- This generally means that all operands in any

  expression are of appropriate types and number.
- Much of what we do in the semantic analysis phase is type checking.


Token
Stream
Parser
Abstract
Syntax
Tree
Static
Checker
Decorated
Abstract
Syntax
Tree
Intermediate
Code
Generator
Intermediate
Code

# Static checks





- *Type checks.* A compiler should report an error if an operator is applied to an incompatible operand.
- *Flow-of-control checks.* Statements that cause flow of control to leave a construct must have some place to which to transfer flow of control. For example, branching to non-existent labels.
- *Uniqueness checks.* Objects should be defined only once. This is true in many languages.
- *Name-related checks.* Sometimes, the same name must appear two or more times.

# type system



- The compiler must then determine that these type expressions conform to a collection of logic al rules that is called the type system for the source language

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# Type Expression

Informally, a type expression is either a basic type or is formed by applying an operator called a *type constructor* to other type expressions.

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# Type Expression



1. A basic type is a type expression. A special basic type, *type_error*, will signal an error during type checking. Finally, a basic type *void* denoting the absence of a value allows statements to be checked.

2. Since type expressions may be named, a type name is a type expression.

3. A type constructor applied to type expressions is a type expression. Constructors include:

   (a) *Arrays.* If $T$ is a type expression, then $array(I, T)$ is a type expression denoting the type of an array with elements of type $T$ and index set $I$.

   (b) *Products.* If $T_1$ and $T_2$ are type expressions, then their Cartesian product $T_1 \times T_2$ is a type expression.

# Type Expression



(c) *Records.* The type of a record is in a sense the product of the types of its fields. The difference between a record and a product is that the fields of a record have names. Type checking of records can be done using the type expression formed by applying the constructor *record* to a tuple formed from field names and their associated types.

(d) *Pointers.* If $T$ is a type expression, then $pointer(T)$ is a type expression denoting the type pointer to an object of type $T$.

(e) *Functions.* Functions take values in some domain and map them into value in some range. This is denoted *domain values* $\rightarrow$ *range values.*

4. Type expressions may contain variables whose values are type expressions.

# Type System



- A *type system* is a collection of rules for assigning type expressions to the various parts of a program.
- A type checker implements a type system.

# Static and Dynamic checking



- Checking done by the compiler is static, while if it done at run–time, it is dynamic.
- A *sound* type system eliminates the need for dynamic checking for type errors because it allows us to determine statically that these errors cannot occur when the target program runs.
- A language is *strongly typed* if its compiler can guarantee that the programs it accepts will execute without type errors.

# Error Recovery



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- It is important for a type checker to do something reasonable when an error is discovered.
- At the very least, the compiler must report the nature and location of the error.
- It is desirable for the type checker to recover from errors, so it can check the rest of the input.

# Coercions





- Conversion from one type to another is said to be *implicit* if it is to be done automatically by the compiler.

- Implicit type conversions are also called *coercions*.

- Conversion is said to be *explicit* if the programmer must write something to cause the conversion.