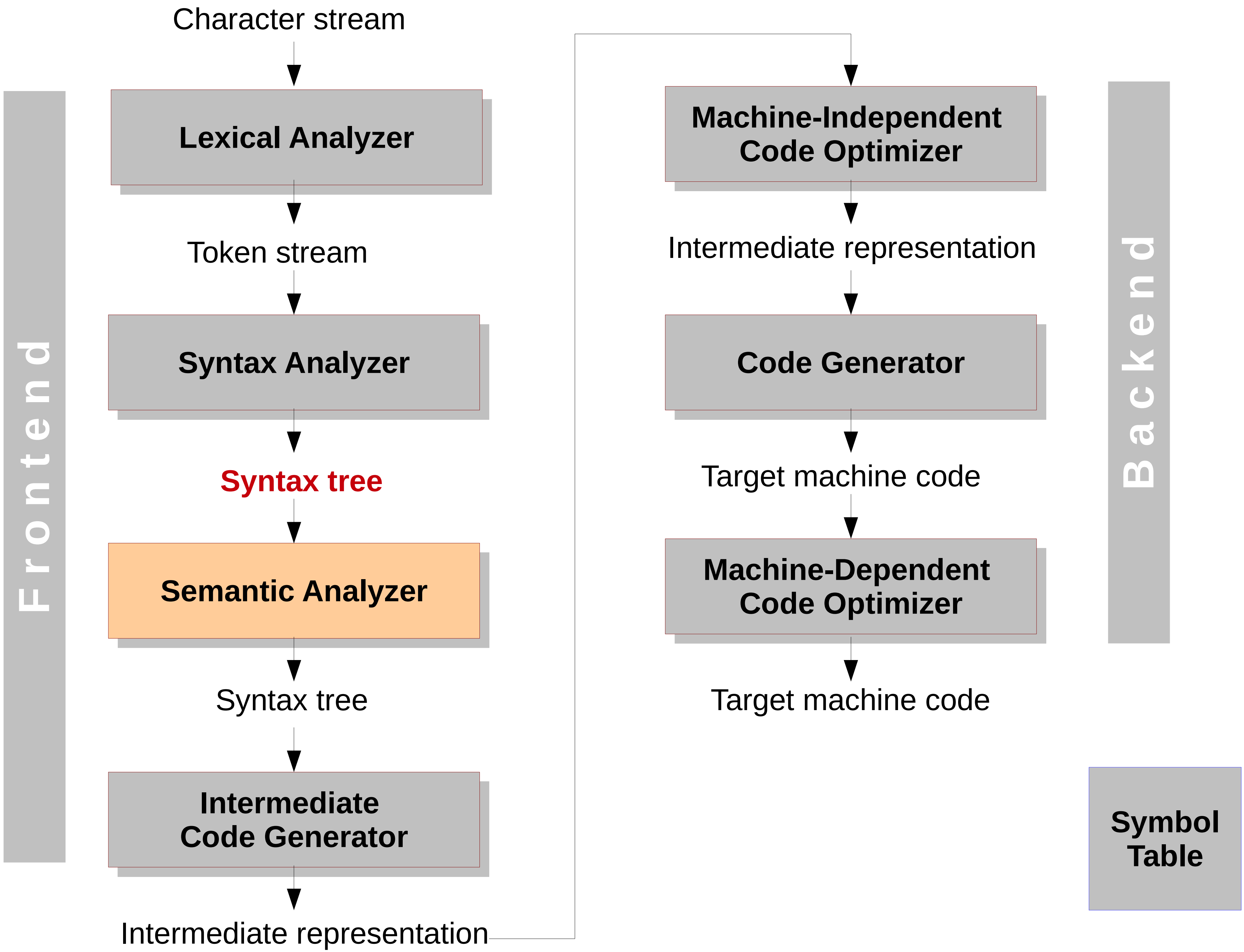
Syntax Directed Translation

Rupesh Nasre.

CS3300 Compiler Design
IIT Madras
July 2018


Character stream
Lexical Analyzer
Token stream
Syntax Analyzer
Syntax tree
Semantic Analyzer
Syntax tree
Intermediate Code Generator
Intermediate representation
Frontend
Machine-Independent Code Optimizer
Intermediate representation
Code Generator
Target machine code
Machine-Dependent Code Optimizer
Target machine code
Backend
Symbol Table

Role of SDT

- To associate actions with productions
- To associate attributes with non-terminals
- To create implicit or explicit syntax tree
- To perform semantic analysis

- … essentially, to add life to the skeleton.

Example

E → E + T $$.code = “”;
strcat($$.code, $1.code);
strcat($$.code, $3.code);
strcat($$.code, “+”);

SDD

Attributes

E → E + T   { printf(“+”); }

SDT

SDTs may be viewed as implementations of SDDs and are important from efficiency perspective.

Productions   **Actions**

Syntax Directed Definition

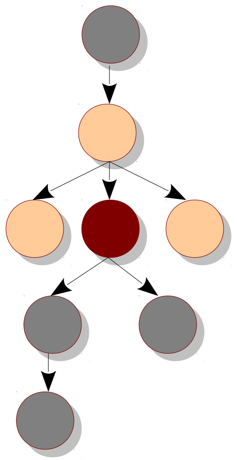
- An SDD is a CFG with attributes and rules.
  - Attributes are associated with grammar symbols.
  - Rules are associated with productions.
- An SDD specifies the semantics of productions.
  - It does not enforce a specific way of achieving the semantics.

Syntax Directed Translation

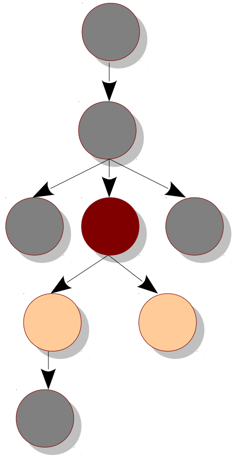
- An SDT is done by attaching rules or program fragments to productions.
- The order induced by the syntax analysis produces a translation of the input program.

Attributes

- Inherited
  - In terms of the attributes of the node, its parent and siblings.
  - e.g., int x, y, z; or nested scoping



- Synthesized
  - In terms of the attributes of the node and its children.
  - e.g., a + b * c or most of the constructs from your assignments

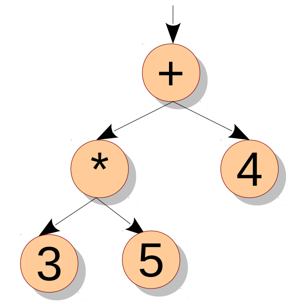


SDD for Calculator

Input string

3 * 5 + 4 $

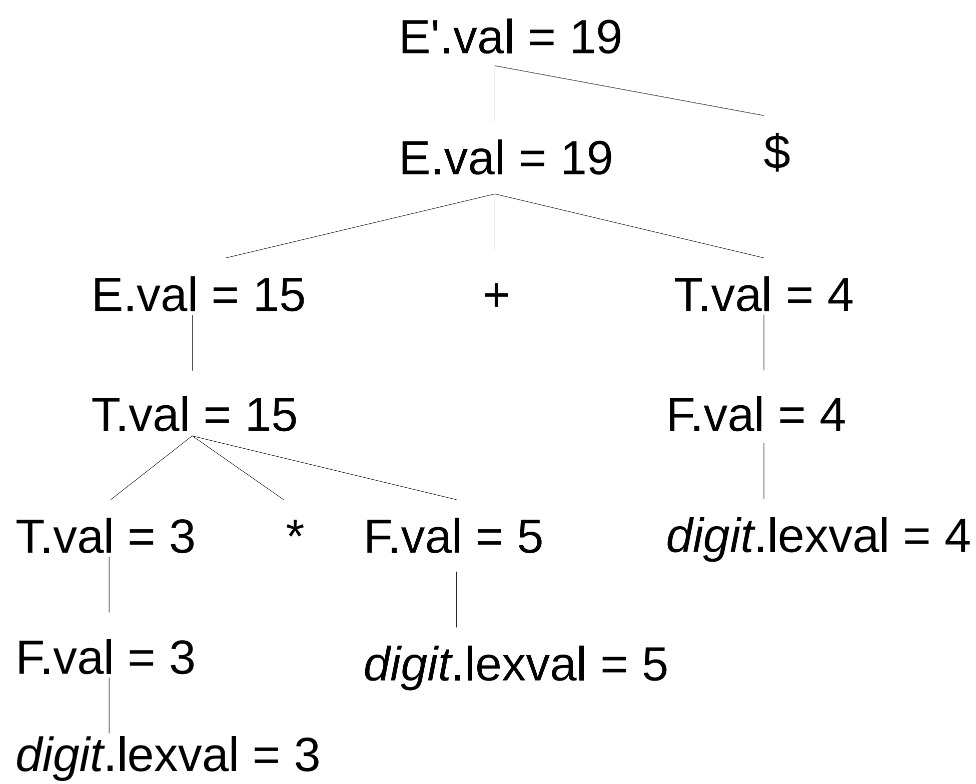
Parse Tree



SDD

Sr. No.	Production	Semantic Rules
1	E' → E $	E'.val = E.val
2	E → E_1 + T	E.val = E_1.val + T.val
3	E → T	...
4	T → T_1 * F	...
5	T → F	...
6	F → (E)	...
7	F → *digit*	F.val = *digit*.lexval

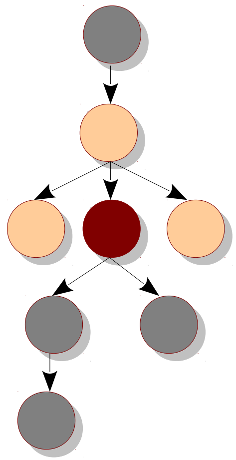
Annotated Parse Tree

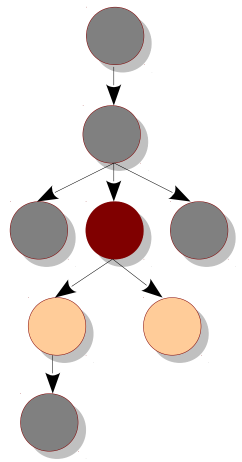


Order of Evaluation

- If there are only synthesized attributes in the SDD, there exists an evaluation order.
- Any bottom-up order would do; for instance, post-order.
- Helpful for LR parsing.
- How about when the attributes are both synthesized as well as inherited?
- How about when the attributes are only inherited?

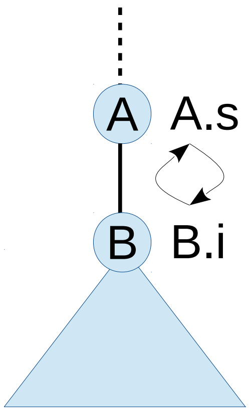
Inherited





Synthesized

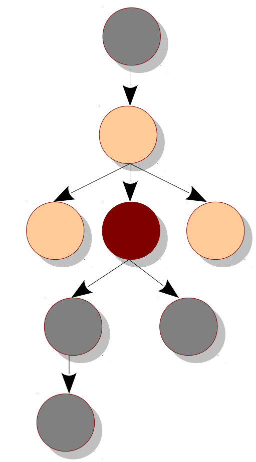
Order of Evaluation

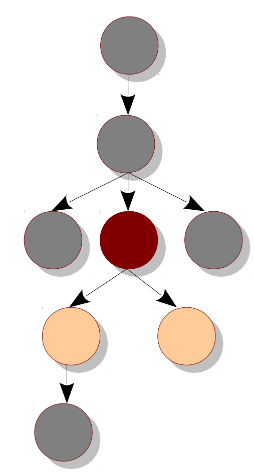


Production	Semantic Rule
A → B	A.s = B.i; B.i = A.s + 1;

- This SDD uses a combination of synthesized and inherited attributes.
- A.s (head) is defined in terms of B.i (body non-terminal). Hence, it is synthesized.
- B.i (body non-terminal) is defined in terms of A.s (head). Hence, it is inherited.
- There exists a *circular dependency* between their evaluations.
- In practice, subclasses of SDDs required for our purpose do have an order.

Inherited





Synthesized

Classwork

- Write semantic rules for the following grammar.
  - It computes terms like 3 * 5 and 3 * 5 * 7.
- Now write the annotated parse tree for 3 * 5 * 7.
- What is the associativity of *?

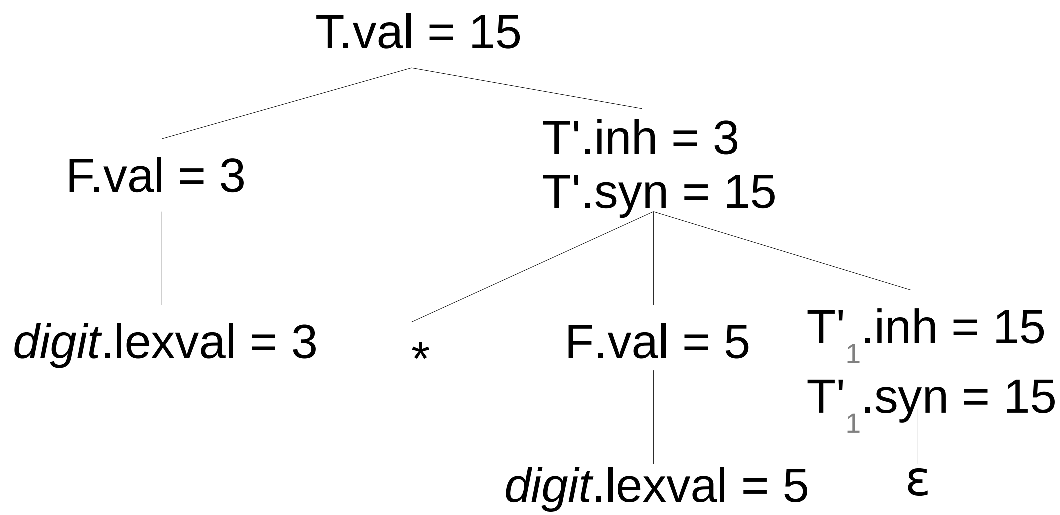
Sr. No.	Production	Semantic Rules
1	T → F T'	T.val = F.val * T'.val
2	T' → * F T'_1	T'.val = F.val * T'_1.val
3	T' → ε	T'.val = 1
4	F → *digit*	F.val = *digit*.lexval

Classwork

- Write semantic rules for the following grammar.
  - It computes terms like 3 * 5 and 3 * 5 * 7.
- Now write the annotated parse tree for 3 * 5 * 7.
- What is the associativity of *?
- Can you make it left-associative?

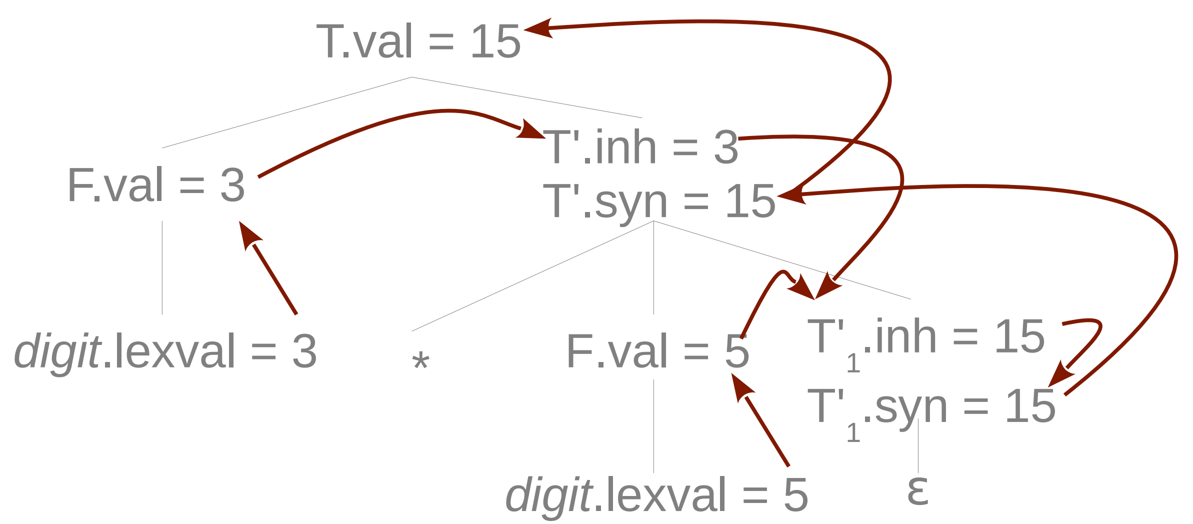
Sr. No.	Production	Semantic Rules
1	T → F T'	T'.inh = F.val T.val = T'.syn
2	T' → * F T'_1	T'_1.inh = T'.inh * F.val T'.syn = T'_1.syn
3	T' → ε	T'.syn = T'.inh
4	F → *digit*	F.val = *digit*.lexval

Classwork



Sr. No.	Production	Semantic Rules
1	T → F T'	T'.inh = F.val T.val = T'.syn
2	T' → * F T'_1	T'_1.inh = T'.inh * F.val T'.syn = T'_1.syn
3	T' → ε	T'.syn = T'.inh
4	F → *digit*	F.val = *digit*.lexval

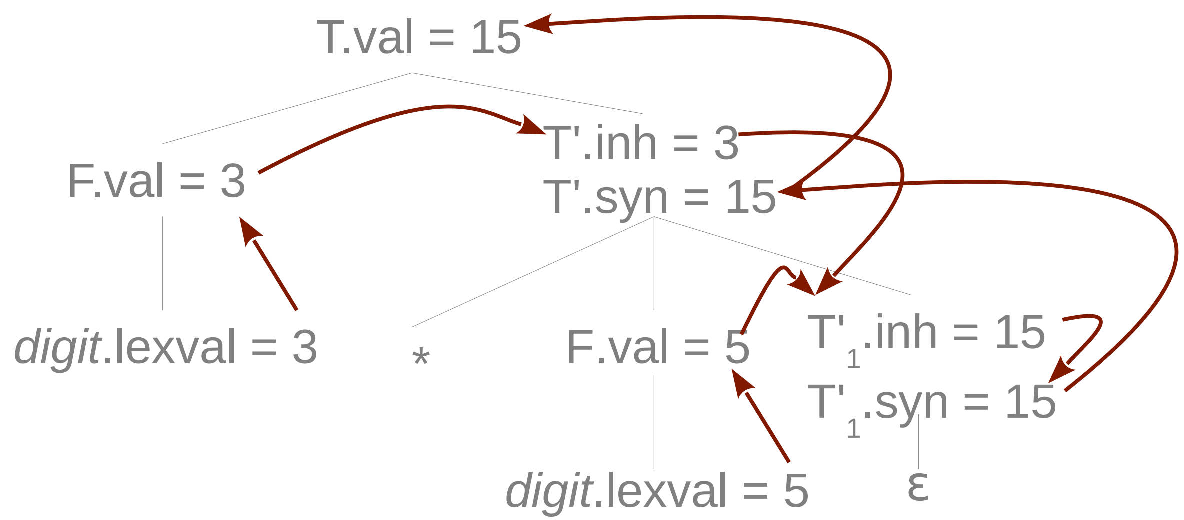
Classwork



What is the order in which rules are evaluated?

Sr. No.	Production	Semantic Rules
1	T → F T'	T'.inh = F.val T.val = T'.syn
2	T' → * F T'_1	T'_1.inh = T'.inh * F.val T'.syn = T'_1.syn
3	T' → ε	T'.syn = T'.inh
4	F → *digit*	F.val = *digit*.lexval

Dependency Graph



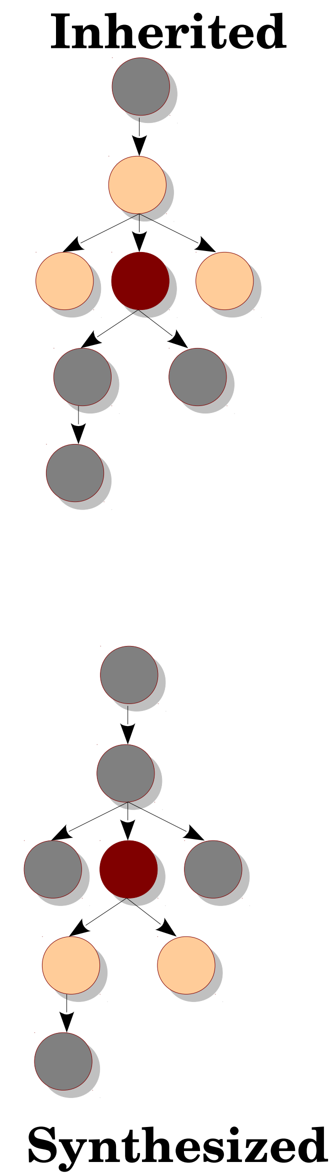
- A dependency graph depicts the flow of information amongst attributes.
- An edge *attr1* → *attr2* means that the value of *attr1* is needed to compute *attr2*.
- Thus, allowable evaluation orders are those sequences of rules N1, N2, …, Nk such that if Ni → Nj, then i < j.
  - What are such allowable orders?
  - Topological sort
  - What about cycles?

Order of Evaluation

- If there are only synthesized attributes in the SDD, there exists an evaluation order.

S-attributed

- Any bottom-up order would do; for instance, post-order.
- Helpful for LR parsing.
- How about when the attributes are both synthesized as well as inherited?
- How about when the attributes are only inherited?



SDD for Calculator

Input string

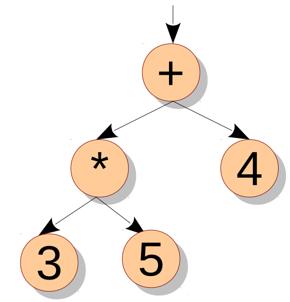
3 * 5 + 4 $

S-attributed

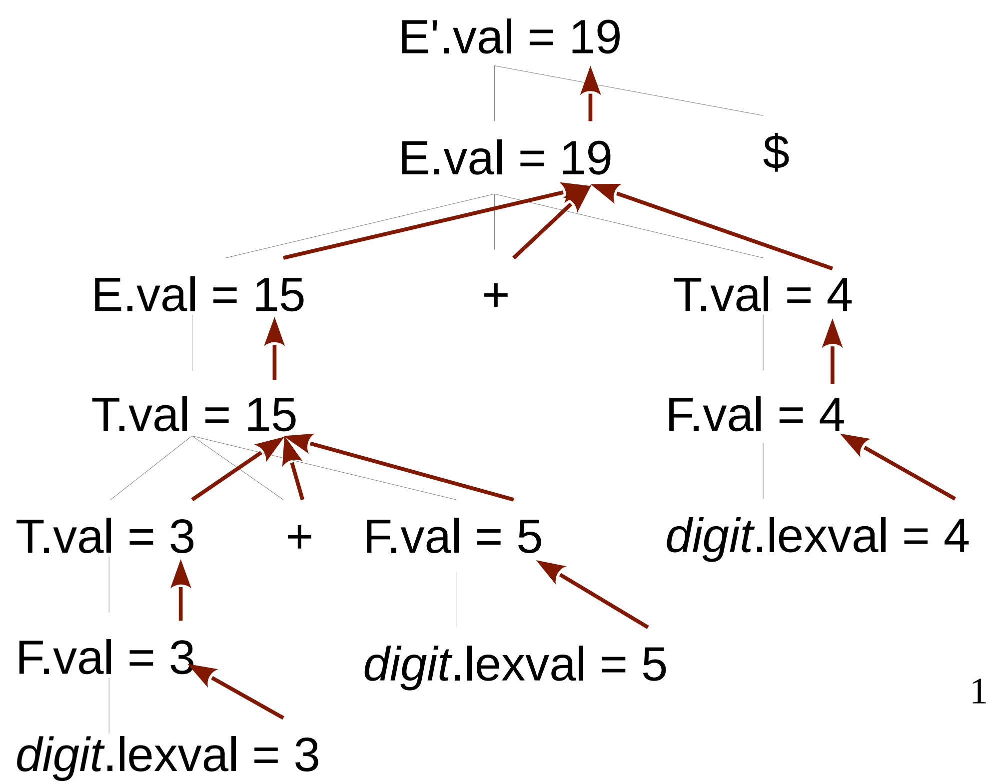
SDD

Sr. No.	Production	Semantic Rules
1	E' → E $	E'.val = E.val
2	E → E_1 + T	E.val = E_1.val + T.val
3	E → T	...
4	T → T_1 * F	...
5	T → F	...
6	F → (E)	...
7	F → *digit*	F.val = *digit*.lexval

Parse Tree



Annotated Parse Tree



S-attributed SDD

- Every attribute is synthesized.
- A topological evaluation order is well-defined.
- Any bottom-up order of the parse tree nodes.
- In practice, preorder is used.

```
preorder(N) {
    for (each child C of N, from the left) preorder(C)
    evaluate attributes of N
}
```

Can we allow more orderings?

Issues with S-attributed SDD

- It is too strict!
- There exist reasonable non-cyclic orders that it disallows.
  - If a non-terminal uses attributes of its parent only (no sibling attributes)
  - If a non-terminal uses attributes of its left-siblings only (and not of right siblings).
- The rules may use information "from above" and "from left".

L-attributed

L-attributed SDD

- Each attribute must be either
  - synthesized, or
  - inherited, but with restriction.

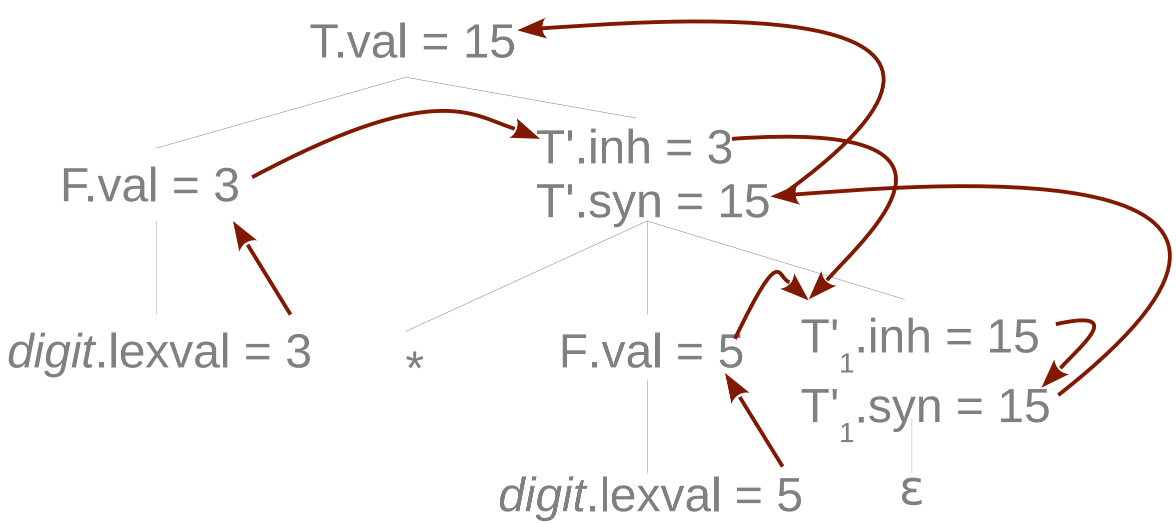
    For production $A \rightarrow X_1 X_2 \dots X_n$ with inherited attributes $X_i.a$ computed by an action, the rule may use only

    - inherited attributes of A.
    - either inherited or synthesized attributes of $X_1, X_2, \dots, X_{i-1}$.
    - inherited or synthesized attributes of X_i with no cyclic dependence.
- L is for left-to-right.

Have you seen any such SDD?

Example of L-attributed SDD

Sr. No.	Production	Semantic Rules
1	T → F T'	T'.inh = F.val T.val = T'.syn
2	T' → * F T'_1	T'_1.inh = T'.inh * F.val T'.syn = T'_1.syn
3	T' → ε	T'.syn = T'.inh
4	F → *digit*	F.val = *digit*.lexval



Example of non-L-attributed SDD

Production	Semantic rule
A → B C	A.s = B.b; B.i = C.c + A.s

- First rule uses synthesized attributes.
- Second rule has inherited attributes.
- However, B's attribute is dependent on C's attribute, which is on the right.
- Hence, it is not L-attributed SDD.

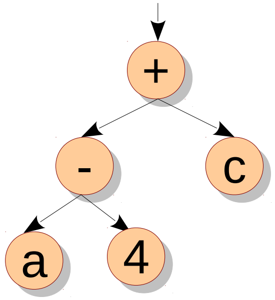
S → L . L | L
L → L B | B
B → 0 | 1

Classwork:

- What does this grammar generate?
- Design L-attributed SDD to compute S.val, the decimal value of an input string.
- For instance, 101.101 should output 5.625.
- Idea: Use an inherited attribute L.side that tells which side (left or right) of the decimal point a bit is on.

SDT Applications

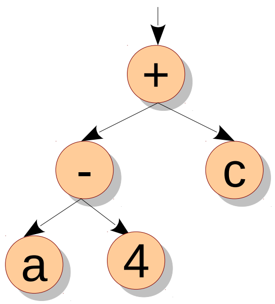
- Creating an explicit syntax tree.
  - e.g., a – 4 + c
    - p1 = new Leaf(id_a);
    - p2 = new Leaf(num_4);
    - p3 = new Op(p1, '-', p2);
    - p4 = new Leaf(id_c);
    - p5 = new Op(p3, '+', p4);



Production	Semantic Rules
E → E + T	$$.node = new Op($1.node, '+', $3.node)
E → E - T	$$.node = new Op($1.node, '-', $3.node)
E → T	$$.node = $1.node
T → (E)	$$.node = $2.node
T → *id*	$$.node = new Leaf($1)
T → *num*	$$.node = new Leaf($1)

SDT Applications

- Creating an explicit syntax tree.
  - e.g., a – 4 + c

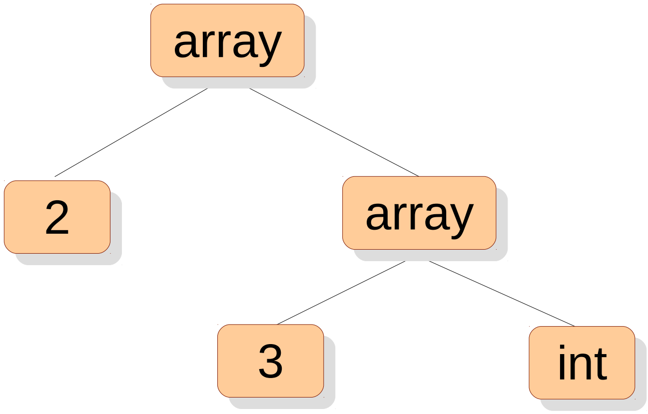


- **Classwork**:
  - Generate syntax tree using the following grammar.

Production	Semantic Rules
E → T E'	$$.node = $2.syn $2.inh = $1.node
E' → + T E'$_1$	$3.inh = new Op($$.inh, '+', $2.node) $$.syn = $3.syn
E' → - T E'$_1$	$3.inh = new Op($$.inh, '-', $2.node) $$.syn = $3.syn
E' → ε	$$.syn = $$.inh
T → (E)	$$.node = $2.node
T → *id*	$$.node = new Leaf($1)
T → *num*	$$.node = new Leaf($1)

SDT Applications

- Finding type expressions
  - int a[2][3] is array of 2 arrays of 3 integers.
  - in functional style: *array(2, array(3, int))*



Production	Semantic Rules
T → B id C	T.t = C.t C.i = B.t
B → *int*	B.t = *int*
B → *float*	B.t = *float*
C → [num] C_1	C.t = array(num, C_1.t) C_1.i = C.i
C → ε	C.t = C.i

Classwork: Write productions and semantic rules for creating type expressions from array declarations.

SDD for Calculator

Sr. No.	Production	Semantic Rules
1	E' → E $	E'.val = E.val
2	E → E_1 + T	E.val = E_1.val + T.val
3	E → T	...
4	T → T_1 * F	...
5	T → F	...
6	F → (E)	...
7	F → *digit*	F.val = *digit*.lexval

SDT for Calculator

Sr. No.	Production	Semantic Rules
1	E' → E $	**print(E.val)**
2	E → E_1 + T	E.val = E_1.val + T.val
3	E → T	...
4	T → T_1 * F	...
5	T → F	...
6	F → (E)	...
7	F → *digit*	F.val = *digit*.lexval

SDT for Calculator

Postfix SDT

$E' \rightarrow E\ \$$	**{ print(E.val); }**
$E \rightarrow E_1 + T$	{ E.val = E_1.val + T.val; }
$E \rightarrow T$	...
$T \rightarrow T_1 * F$	...
$T \rightarrow F$	...
$F \rightarrow (E)$	...
$F \rightarrow$ *digit*	{ F.val = *digit*.lexval; }

- SDTs with all the actions at the right ends of the production bodies are called *postfix SDTs*.
- Only synthesized attributes are useful here.
- Can be implemented during LR parsing by executing actions when reductions occur.
- The attribute values can be put on a stack and can be retrieved.

Parsing Stack

A → X Y Z

	X	Y	Z	State / grammar symbol
	X.x	Y.y	Z.z	Synthesized attribute

↑ stack top

Compare with $1, $2, … in Yacc.

Production	**Actions**
E' → E $	{ print(stack[top – 1].val); --top; }
E → E_1 + T	{ stack[top – 2].val += stack[top].val; top -= 2; }
E → T	{ stack[top].val = stack[top].val; }
T → T_1 * F	{ stack[top – 2].val *= stack[top].val; top -= 2; }
T → F	{ stack[top].val = stack[top].val; }
F → (E)	{ stack[top – 2].val = stack[top – 1].val; top -= 2; }
F → *digit*	{ stack[top].val = stack[top].val; }

Actions within Productions

- Actions may be placed at any position within production body. Considered as empty non-terminals called *markers*.
- For production B → X {action} Y, action is performed
  - as soon as X appears on top of the parsing stack in bottom-up parsing.
  - just before expanding Y in top-down parsing if Y is a non-terminal.
  - just before we check for Y on the input in top-down parsing if Y is a terminal.
- SDTs that can be implemented during parsing are
  - Postfix SDTs (S-attributed definitions)
  - SDTs implementing L-attributed definitions

Classwork: Write SDT for infix-to-prefix translation.

Infix-to-Prefix

- What is the issue with this SDT?
- The SDT has shift-reduce and reduce-reduce conflicts.
- Recall that each marker is an empty non-terminal. Thus, the parser doesn't know whether to reduce or reduce or shift on seeing a digit.
- Note that the grammar had no conflicts prior to adding actions.
- Such an SDT won’t work with top-down or bottom-up parsing.

E' → E $

E → **{ print '+'; }** E_1 + T

E → T

T → **{ print '*'; }** T_1 * F

T → F

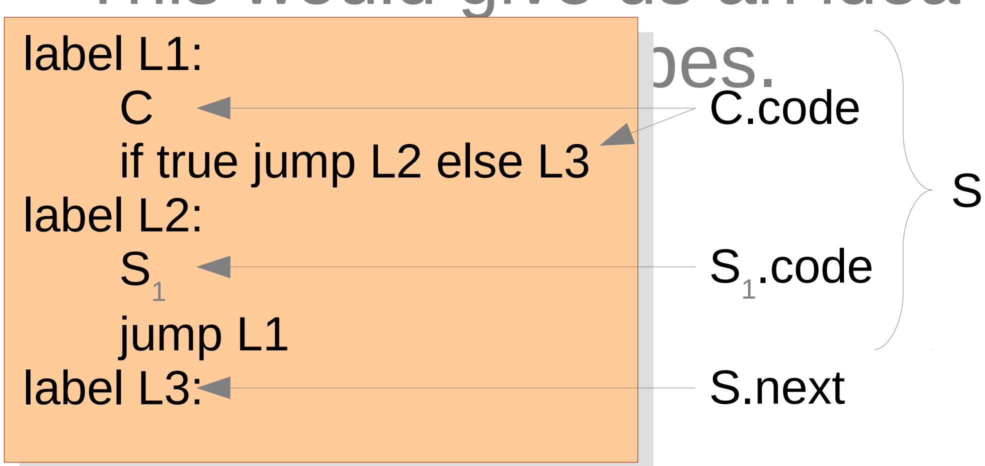
F → (E)

F → digit **{ print digit.lexval; }**

Classwork: Write SDT for infix-to-prefix translation.

Code Generation for *while*

- We want to generate code for while-construct
  - S → while (C) S_1
- We assume that code for S_1 and C are available.
- We also (for now) generate a single code string.
- **Classwork**: What all do we require to generate this code?
  - This would give us an idea of what attributes we … bes.



Code Generation for *while*

- Assume we have the following mechanism.
  - newLabel() returns a new label name.

    You may have used a similar one for temporaries.
  - Each statement has an attribute next, that points to the next statement to be executed.
  - Each conditional has two branches true and false.
  - Each non-terminal has an attribute code.

SDD for *while*

$S \rightarrow$ while (C) S_1

L1	= newLabel();
L2	= newLabel();
S_1.next	= L1;
C.false	= S.next;
C.true	= L2;
S.code	= “label” + L1 + C.code + ”label” + L2 + S_1.code;

SDT

$S \rightarrow$	while (	{ L1 = newLabel(); L2 = newLabel(); C. false = S.next; C.true = L2; }
	C)	{ S_1.next = L2; }
	S_1	{ S.code = “label” + L1 + C.code + “label” + L2 + S_1.code; }

What is the type of this SDD?

SDD for *while*

$S \rightarrow$ while (C) S_1

L1	= newLabel();
L2	= newLabel();
S_1.next	= L1;
C.false	= S.next;
C.true	= L2;
S.code	= "label" + L1 + C.code + "label" + L2 + S_1.code;

SDT

$S \rightarrow$ while ({ L1 = newLabel(); L2 = newLabel(); C. false = S.next; C.true = L2; print("label", L1); }

C) { S_1.next = L2; print("label", L2); }

S_1

On-the-fly code generation

What is the type of this SDD?

Homework

- Exercises 5.5.5 from ALSU book.