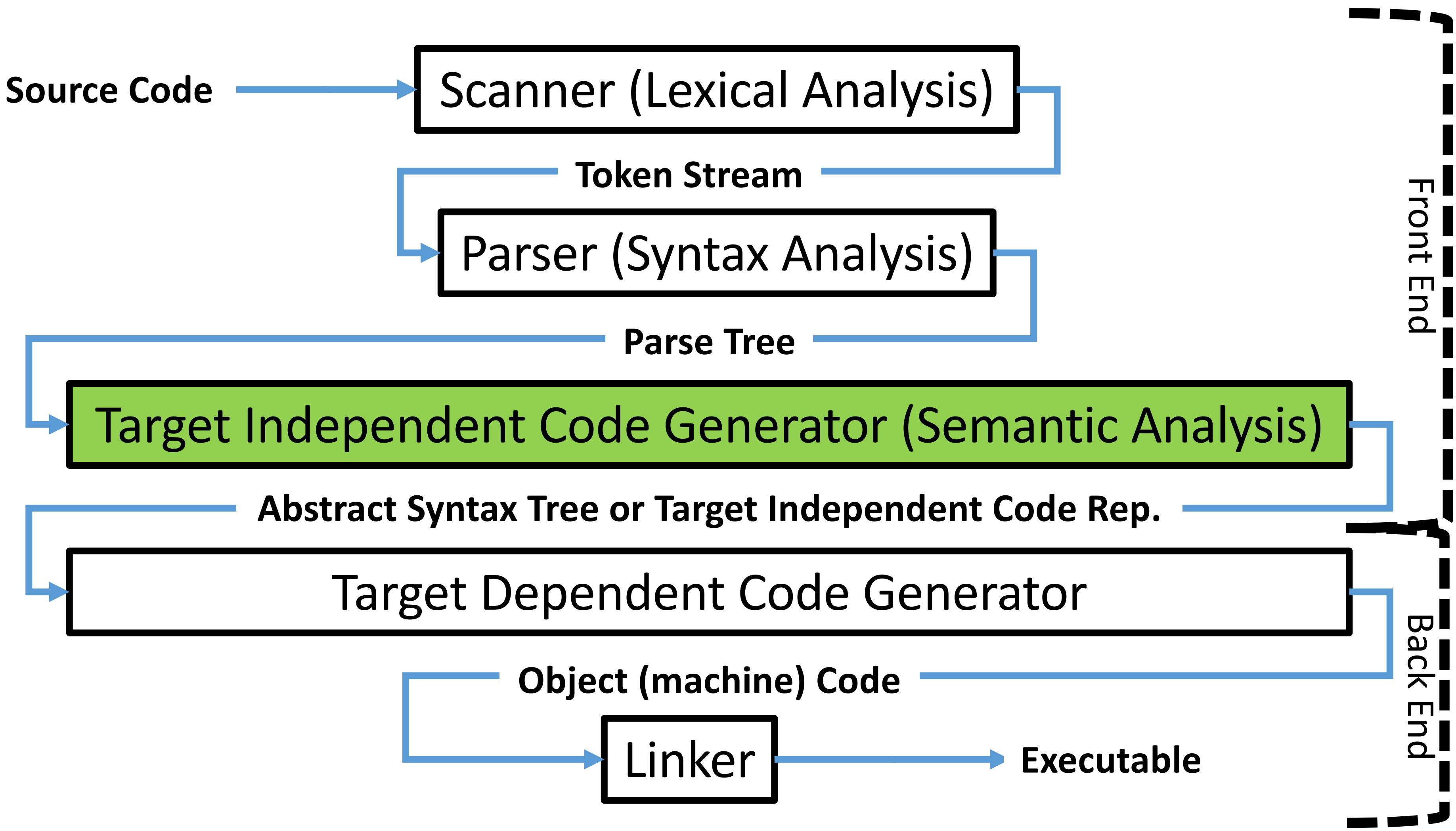
Semantic Analysis and Attribute Grammars

CSCI 3136: Principles of Programming Languages

Agenda

- Announcements
  - Assignment 5 is out and due June 28.
- Readings: Read Chapter 4
- Lecture Contents
  - S-Attributed and L-Attributed Grammars
  - Examples
  - Action Routines

Recall: Phases of Compilation



Attribute Grammars

- Definition: An *attribute grammar* is an augmented context free grammar
  - Symbols are augmented with 0 or more attributes
    - Attributes are variables that store state or data
  - Productions are augmented with semantic rules (operations)
- Semantic rules
  - Copy attribute values between symbols
  - Evaluate attribute values using semantic functions
  - Enforce constraints on attribute values
  - Generate errors or warnings

Computing on the Parse Tree

- **Key Idea: Attribute grammars specify a computation on the parse tree**
- Examples of computations:
  - Symbol table generation
  - Type checking
  - Expression evaluation
  - Extended syntax checking
  - Code generation
  - **Code execution (in an interpreter)!**

Example 0: Expression Evaluation

CFG with Labeled Symbols	**Semantic Rules**
$S \rightarrow + S_1 S_2$	◃ $S.val = S_1.val + S_2.val$
$S \rightarrow - S_1 S_2$	◃ $S.val = S_1.val - S_2.val$
$S \rightarrow * S_1 S_2$	◃ $S.val = S_1.val * S_2.val$
$S \rightarrow / S_1 S_2$	◃ $S.val = S_1.val / S_2.val$
$S \rightarrow neg\ S_1$	◃ $S.val = - S_1.val$
$S \rightarrow Integer_1$	◃ $S.val = int(Integer_1.val)$

Symbol	**Attributes**
S	val : int
Integer	val : String

- Idea: We can apply semantic rules directly to our parse tree.
  E.g. + - 1 2 * 3 4

Example 1: $L = \{a^n b^n c^n \mid n \geq 0\}$ Extended Syntax Analysis

- This is not a context free language, but can be specified by an attribute grammar

CFG w/ Labeled Symbols	Semantic Rules
$S \rightarrow A_1\ B_1\ C_1$	◂ **if** A_1.count != B_1.count **or** A_1.count != C_1.count, **error**
$A \rightarrow A_1\ a$	◂ A.count = A_1.count + 1
$A \rightarrow \varepsilon$	◂ A.count = 0
$B \rightarrow B_1\ b$	◂ B.count = B_1.count + 1
$B \rightarrow \varepsilon$	◂ B.count = 0
$C \rightarrow C_1\ c$	◂ C.count = C_1.count + 1
$C \rightarrow \varepsilon$	◂ C.count = 0

Symbol	Attributes
A	count : int
B	count : int
C	count : int

- Example: Consider parsing: aaaabbbbcccc

Example 2: Extended Syntax …
$L = \{\sigma \in \{a,b,c\}^* : |\sigma|_a = |\sigma|_b = |\sigma|_c\}$

CFG w/ Labeled Symbols	Semantic Rules
$S \rightarrow X_1$	◃ **if** X_1.aCount != X_1.bCount **or** X_1.aCount != X_1.cCount, **error**
$X \rightarrow a\ X_1$	◃ X.aCount = X_1.aCount + 1; X.bCount = X_1.bCount; X.cCount = X_1.cCount;
$X \rightarrow b\ X_1$	◃ X.bCount = X_1.bCount + 1; X.aCount = X_1.aCount; X.cCount = X_1.cCount;
$X \rightarrow c\ X_1$	◃ X.cCount = X_1.cCount + 1; X.bCount = X_1.bCount; X.aCount = X_1.aCount;
$X \rightarrow \varepsilon$	◃ X.aCount = 0; X.bCount = 0; X.cCount = 0;

Symbol	Attributes
X	aCount : int bCount : int cCount : int

Why do we need the **S → X** production?

Types of Attributes

- The previous examples are of *synthesized* (bottom up) attribute grammars.
- There are two types of Attributes
  - ***Synthesized* attributes** are computed using RHS values and stored in LHS
  - ***Inherited* attributes** are computed using LHS and RHS and used by symbols further to the right.

Example 3: $L = \{a^n b^n c^n \mid n \geq 0\}$

- Using inherited attributes instead of synthesized.

CFG w/ Labeled Symbols	Semantic Rules
$S \rightarrow A_1\ B_1\ C_1$	B_1.iCount = A_1.count; C_1.iCount = A.count
$A \rightarrow A_1\ a$	A.count = A_1.count + 1
$A \rightarrow \varepsilon$	A.count = 0
$B \rightarrow B_1\ b$	B_1.iCount = B.iCount - 1
$B \rightarrow \varepsilon$	**if** B.iCount != 0, **error**
$C \rightarrow C_1\ c$	C_1.iCount = C.iCount - 1
$C \rightarrow \varepsilon$	**if** C.iCount != 0, **error**

Symbol	Attributes
A	count : int
B	**iCount : int**
C	**iCount : int**

- Example: Consider parsing: aaabbbccc

inherited

synthetic

Example 4: Using Inherited Attributes

$L = \{\sigma \in \{a,b,c\}^* : |\sigma|_a = |\sigma|_b = |\sigma|_c\}$

CFG w/ Labeled Symbols	Semantic Rules
$S \rightarrow X_1$	◂ X_1.aCount = 0; X_1.bCount = 0; X_1.cCount = 0;
$X \rightarrow a\ X_1$	◂ X_1.aCount = X.aCount + 1; X_1.bCount = X.bCount; X_1.cCount = X.cCount;
$X \rightarrow b\ X_1$	◂ X_1.bCount = X.bCount + 1; X_1.aCount = X.aCount; X_1.cCount = X.cCount;
$X \rightarrow c\ X_1$	◂ X_1.cCount = X.cCount + 1; X_1.bCount = X.bCount; X_1.aCount = X.aCount;
$X \rightarrow \varepsilon$	◂ **if** X.aCount != X.bCount **or** X.aCount != X.cCount , **error**

Symbol	Attributes
X	aCount : int bCount : int cCount : int

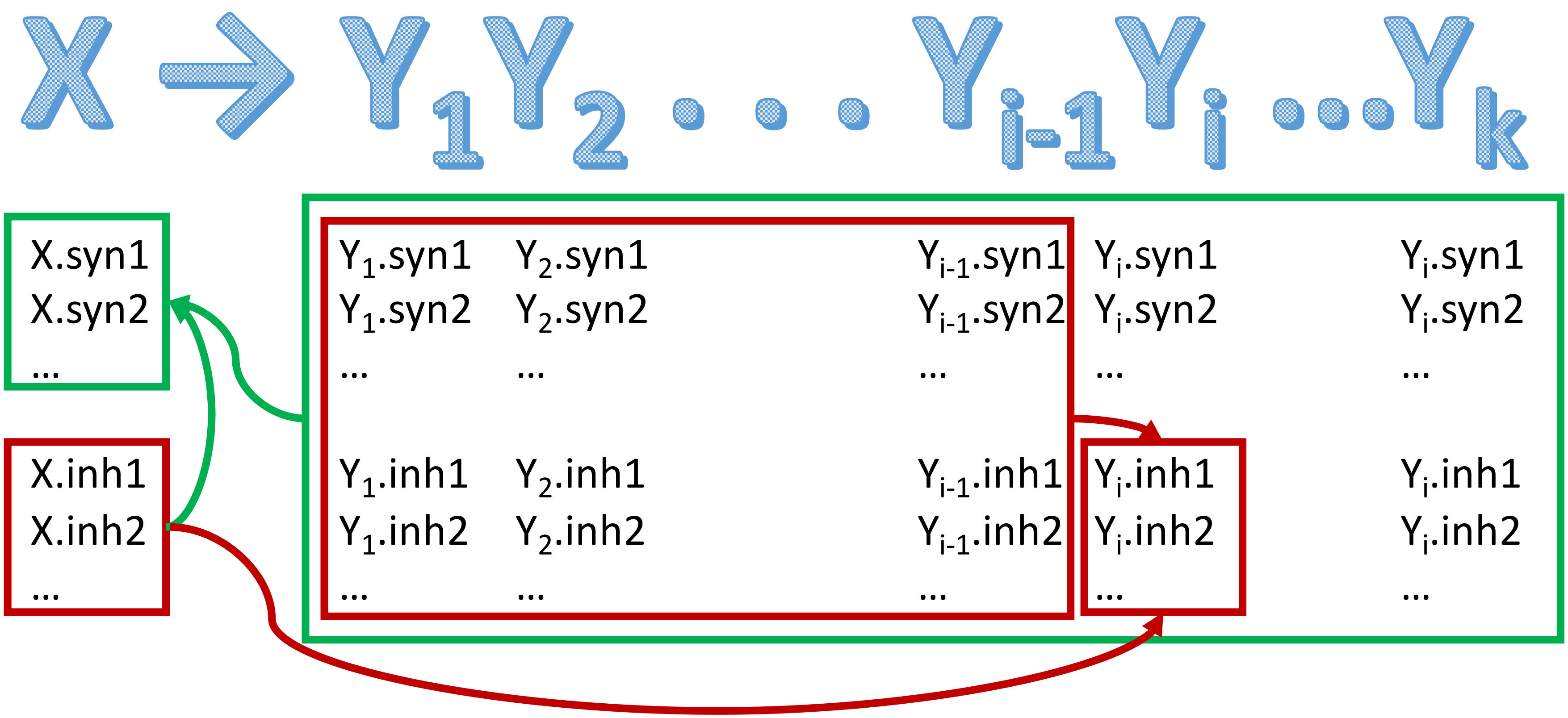
Recap

- Parse trees can be annotated or decorated with attributes and rules, which are executed as the tree is traversed.
- Synthesized attributes
    - Attributes of LHS of production are computed from attributes of RHS
    - Attributes flow bottom-up in the parse tree.
- Inherited attributes
    - Attributes in RHS are computed from attributes of LHS and symbols in RHS preceding them.
    - Attributes flow top-down in the parse tree.

S-Attributed and L-Attributed Grammars

- S-attributed grammar
  - All attributes are synthesized.
  - Attributes flow bottom-up.
- L-attributed grammar
  - Symbols have both inherited and synthetic attributes
  - For each production $X \rightarrow Y_1Y_2 \ldots Y_k$,
    - X.syn depends on
      - X.inh
      - Y_1.inh, Y_1.syn, Y_2.inh, Y_2.syn, . . . Y_k.inh, Y_k.syn
  - For all $1 \leq i \leq k$, Y_i.inh depends on
    - X.inh
    - Y_1.inh, Y_1.syn, Y_2.inh, Y_2.syn, . . . , Y_{i-1}.inh, Y_{i-1}.syn
- S-attributed grammars are a special case of L-attributed grammars.

Data Flow in L-Attributed Grammars



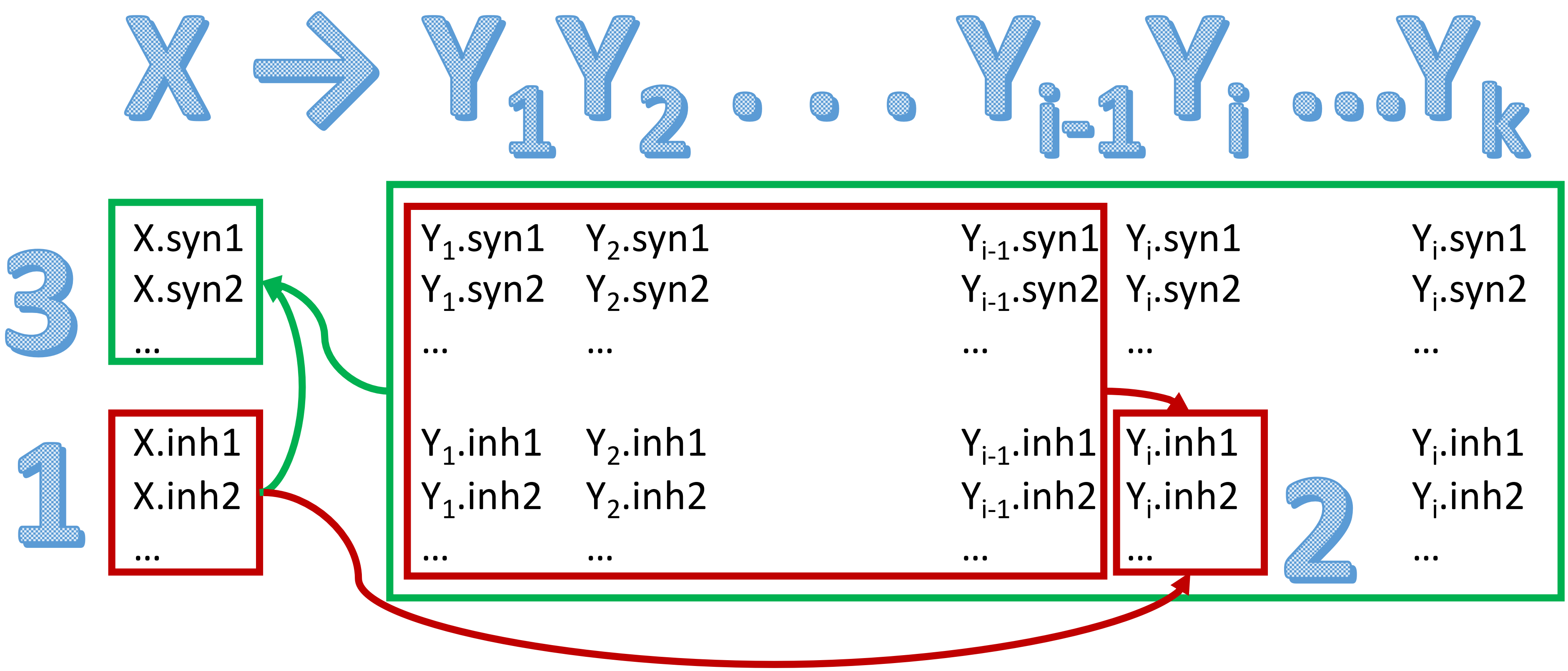
Computing L-Attributed Grammars

```
execute_rules(Node t, Node [] left_sibs):
  # Don’t use t.synthetic and t.parent.synthetic    1
  t.compute_inherited(t.parent, left_sibs)

  children = []                                     2
  for each child of t:
    execute_rules(child, children)
    children.add(child)

  # Don’t use t.synthetic and t.parent.synthetic    3
  t.compute_synthetic(children)
  return
```

Data Flow in L-Attributed Grammars



Motivation: Why are they useful?

- In many cases context free grammars that capture associativity rules are not LL(1)
- We can rewrite the grammars to be LL(1) but…
- Resulting grammars do no capture associativity rules
- So, use attribute (L-attributed) grammars to capture the associativity rules.

Example: Left Associative Grammar

- Grammar
  - E → E + T
  - E → E - T
  - E→T
  - T→ Int
- Parsing the expression

  5 – 2 + 3 illlustrates left associativity: (5 – 2) + 3
- This grammar is not LL(1)

Predictor Table	
Production	**Predictor Set**
E → E + T	{Int}
E → E - T	{Int}
E → T	{Int}
T→ Int	{Int}

Example: Refactored Grammar

- Grammar
  - E → T E'
  - E' → ε
  - E' → + T E'
  - E' → - T E'
  - T→ Int
- Parsing the expression

  5 – 2 + 3 illlustrates wrong associativity: 5 – (2 + 3)
- This grammar is LL(1)

Predictor Table	
Production	**Predictor Set**
E → T E'	{Int}
E' → ε	{ε}
E' → + T E'	(+}
E' → - T E'	(-}
T→ Int	{Int}

Use an L-Attributed Grammar to Fix Left Associativity

Sym	Attributes
E	val : int
E’	val : int **tmp : int**
T	val : int
Int	val : String

Idea: Carry forward the left most computed value to ensure left associativity.

- Try parsing: 5 - 2 + 3

Labeled CFG	Semantic Rules
$E \rightarrow T\ E'_1$	**E_1'.tmp = T_1.val**; E.val = E’.val
$E' \rightarrow \varepsilon$	E’.val = E’.tmp
$E' \rightarrow +\ T_1\ E'_1$	**E_1'.op = E’.tmp + T_1.val;** E’.val = E_1'.val
$E' \rightarrow -\ T_1\ E'_1$	**E_1'.op = E’.tmp - T_1.val**; E’.val = E_1'.val
$T \rightarrow Int_1$	T.val = Str2Int(Int_1.val)

Example: Error Checking

Labeled CFG	Semantic Rules
Assignment → $LValue_1$ '=' $Expr_1$	◂ **if not** assignable($Lvalue_1$.t, $Expr_1$.t), **error**
LValue → Id_1 $ArrIdx_1$	◂ **if not** declared(Id_1.name), **error** ◂ **if not** indexable(Id_1.name, $ArrIdx_1$.dim), **error**
ArrIdx → ε	◂ ArrIdx.dim = 0
ArrIdx → '[' $Expr_1$ ']' $ArrIdx_1$	◂ **if not** isType($Expr_1$.t, Integer), **error** ◂ ArrIdx.dim = $ArrIdx_1$.dim + 1

Sym	Attributes
Assignment	
LValue	t : Type
Id	name : String
ArrIdx	dim : int
Expr	t : Type

Example: Generate Java Code

Labeled CFG	**Semantic Rules**
$E \rightarrow E_1 + T_1$	◂ E.tmp = tmpSeqNum++ **output(** “int tmp%d = tmp%d + %s;”, E.tmp, E_1.tmp, T_1.var **)**
$E \rightarrow T_1$	◂ E.tmp = tmpSeqNum++ **output(** “int tmp%d = %s;”, E.tmp, T_1.var **)**
$T \rightarrow Id_1$	◂ T.var = id_1.name

Sym	**Attributes**
E	tmp : int
T	var : String
Id	name : String

Try generating Java code for the expression: a + b - c

Action Routines

- Action routines are instructions for ad-hoc translation interleaved with parsing
- Parser generators allow programmers to specify action routines as part of the grammar
- Action routines can appear anywhere in a rule (as long as the grammar is LL(1)).
- Example
  - $E_1 \rightarrow A\ T$ **{E_2.op = A.fun(E_1.op,T.val)}** E_2 **{E_1.val = E_2.val}**
- Action routines are supported, for example, in yacc and bison