CMPT 379
Compilers

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Syntax directed Translation

- Models for translation from parse trees into assembly/machine code
- Representation of translations
  - Attribute Grammars (semantic actions for CFGs)
  - Tree Matching Code Generators
  - Tree Parsing Code Generators

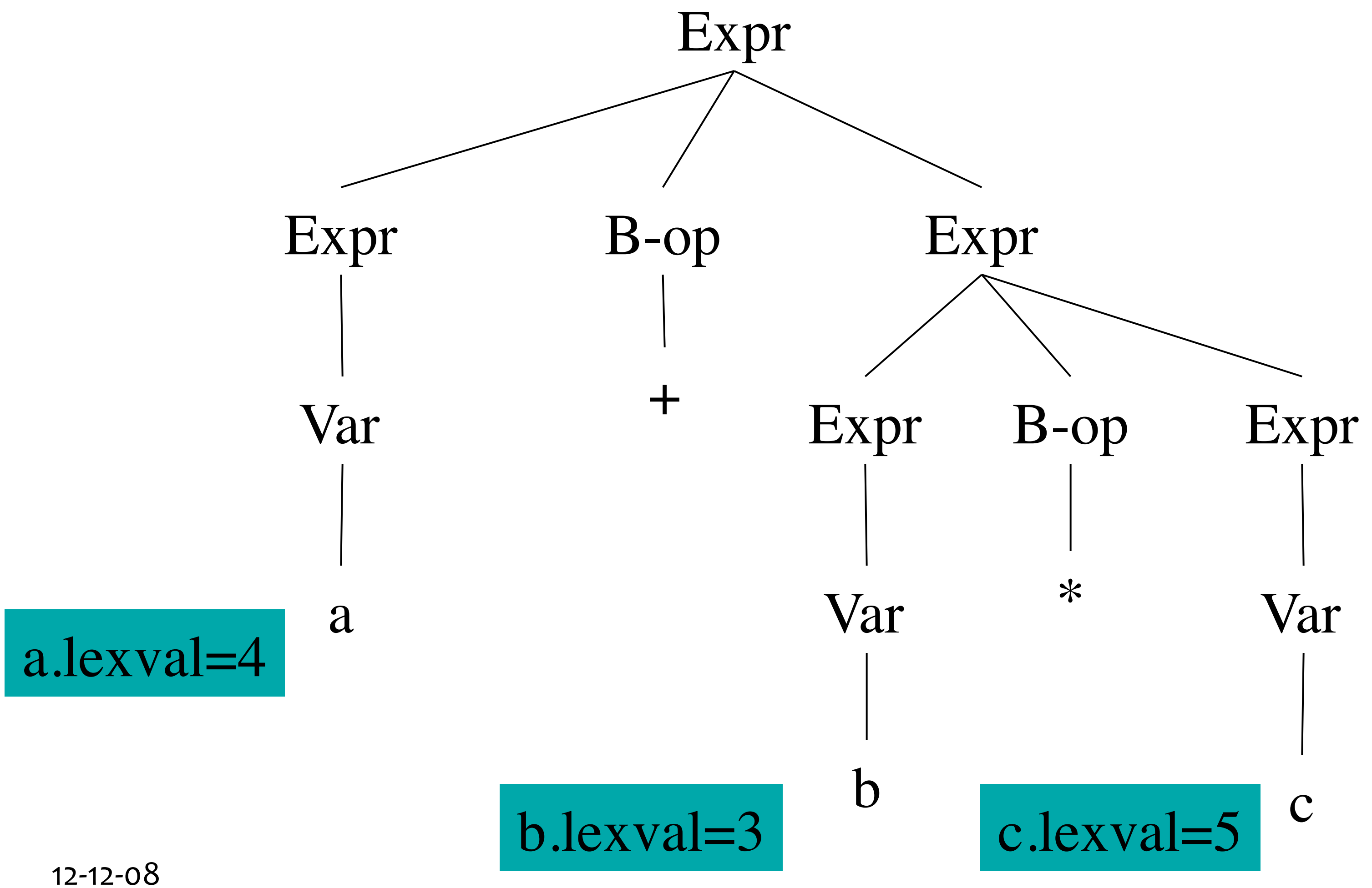
Attribute Grammars

- Syntax-directed translation uses a grammar to produce code (or any other "semantics")
- Consider this technique to be a generalization of a CFG definition
- Each grammar symbol is associated with an attribute
- An attribute can be anything: a string, a number, a tree, any kind of record or object

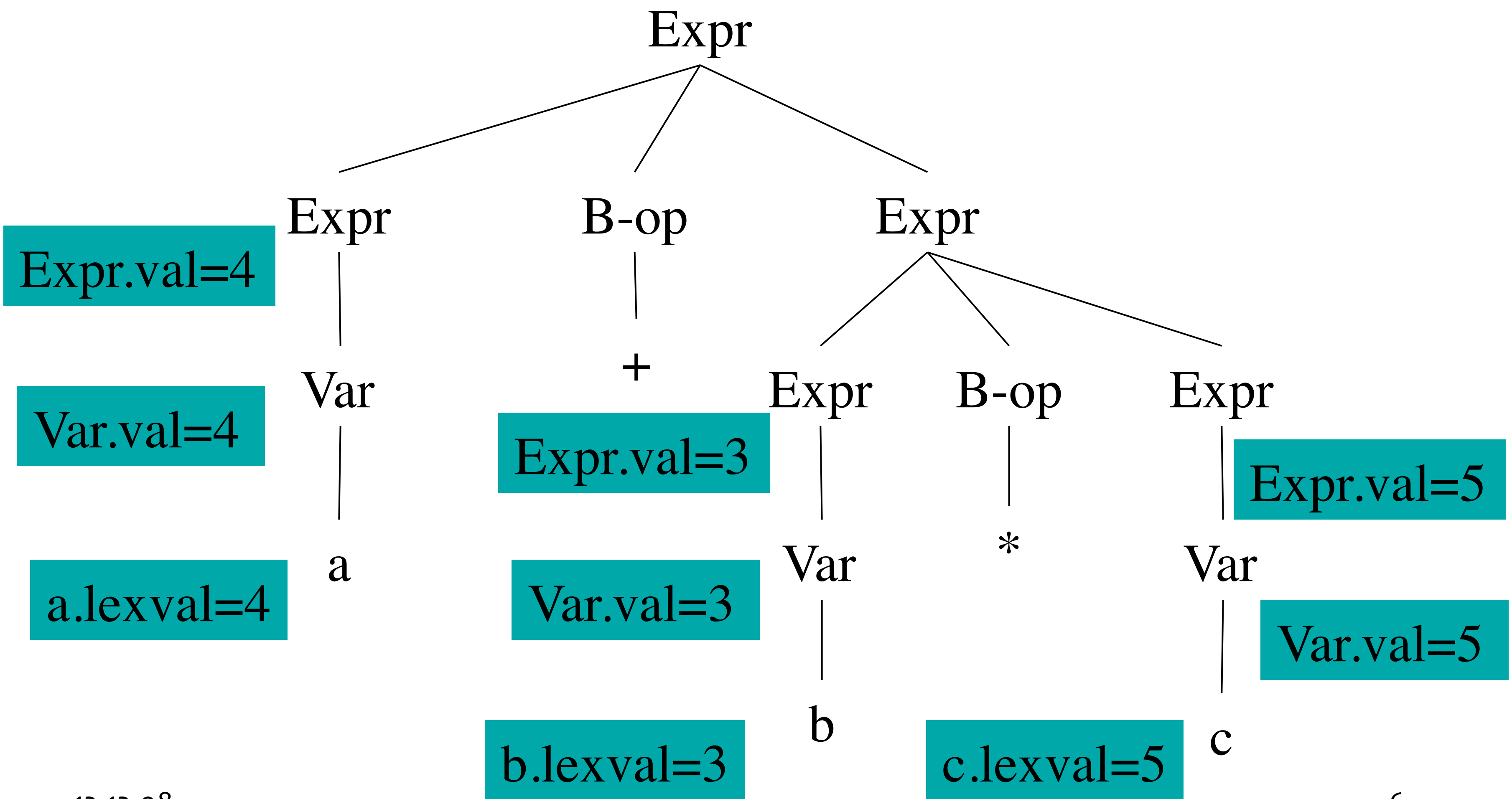
Attribute Grammars

- A CFG can be viewed as a (finite) representation of a function that relates strings to parse trees
- Similarly, an attribute grammar is a way of relating strings with "meanings"
- Since this relation is syntax-directed, we associate each CFG rule with a semantics (rules to build an abstract syntax tree)
- In other words, attribute grammars are a method to *decorate* or *annotate* the parse tree

Example

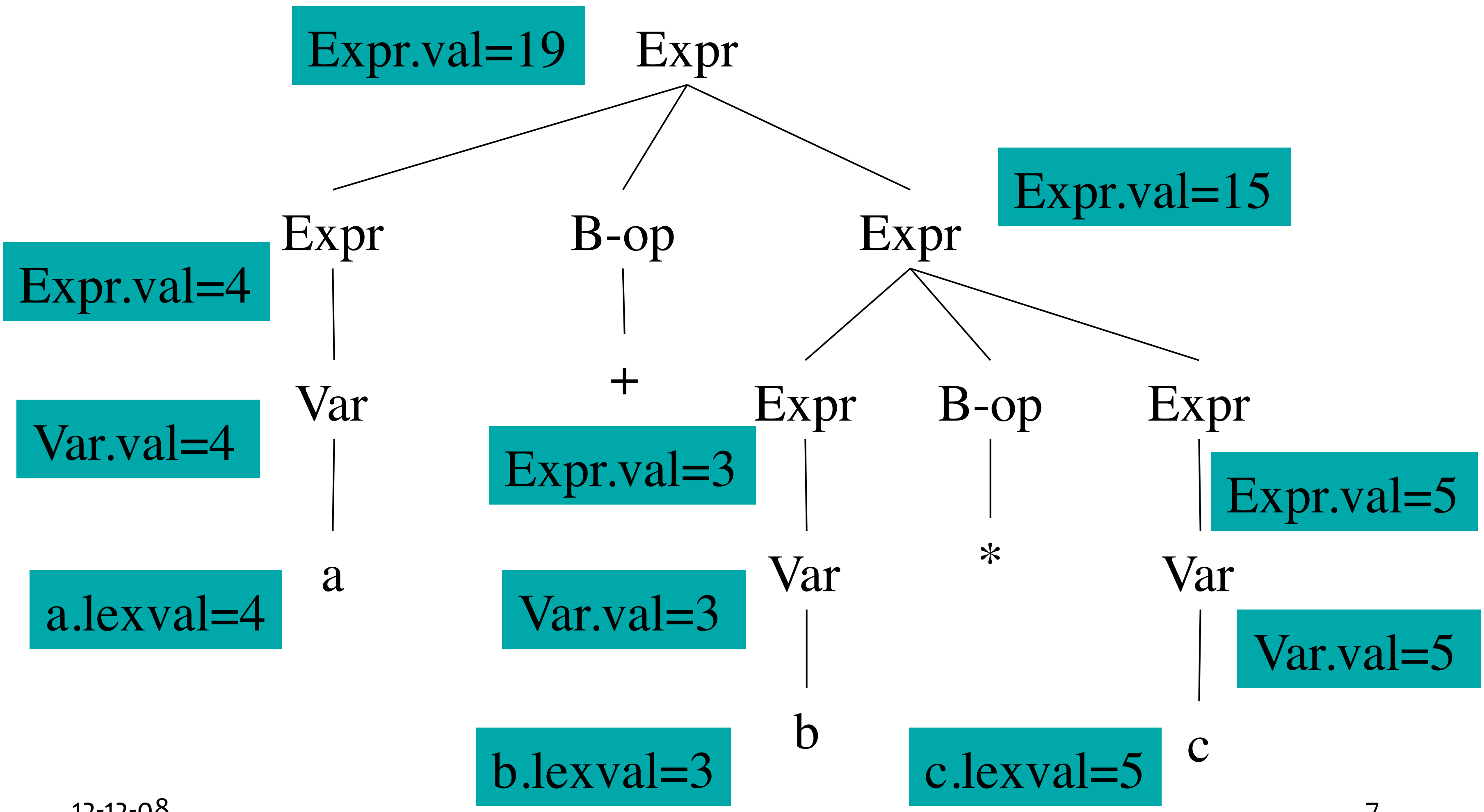

Expr
Expr
B-op
Expr
Var
+
Expr
B-op
Expr
a
Var
*
Var
b
c
a.lexval=4
b.lexval=3
c.lexval=5

Example



Expr
Expr
B-op
Expr
Expr.val=4
Var
+
Expr
B-op
Expr
Var.val=4
Expr.val=3
Expr.val=5
a
Var
*
Var
a.lexval=4
Var.val=3
Var.val=5
b
c
b.lexval=3
c.lexval=5

Example



Expr.val=19
Expr
Expr
B-op
Expr
Expr.val=15
Expr.val=4
Var
+
Expr
B-op
Expr
Var.val=4
Expr.val=3
Expr.val=5
a
Var
*
Var
a.lexval=4
Var.val=3
Var.val=5
b
c
b.lexval=3
c.lexval=5

Syntax directed definition

Var → IntConstant

  { \$0.val = \$1.lexval; }   In yacc: { \$\$ = \$1 }

Expr → Var

  { \$0.val = \$1.val; }

Expr → Expr B-op Expr

  { \$0.val = \$2.val (\$1.val, \$3.val); }

B-op → +

  { \$0.val = PLUS; }

B-op → *

  { \$0.val = TIMES; }

Flow of Attributes in *Expr*

- Consider the flow of the attributes in the *Expr* syntax-directed defn
- The lhs attribute is computed using the rhs attributes
- Purely bottom-up: compute attribute values of all children (rhs) in the parse tree
- And then use them to compute the attribute value of the parent (lhs)

Synthesized Attributes

- **Synthesized attributes** are attributes that are computed purely bottom-up
- A grammar with semantic actions (or syntax-directed definition) can choose to use *only* synthesized attributes
- Such a grammar plus semantic actions is called an **S-attributed definition**

Inherited Attributes

- Synthesized attributes may not be sufficient for all cases that might arise for semantic checking and code generation
- Consider the (sub)grammar:

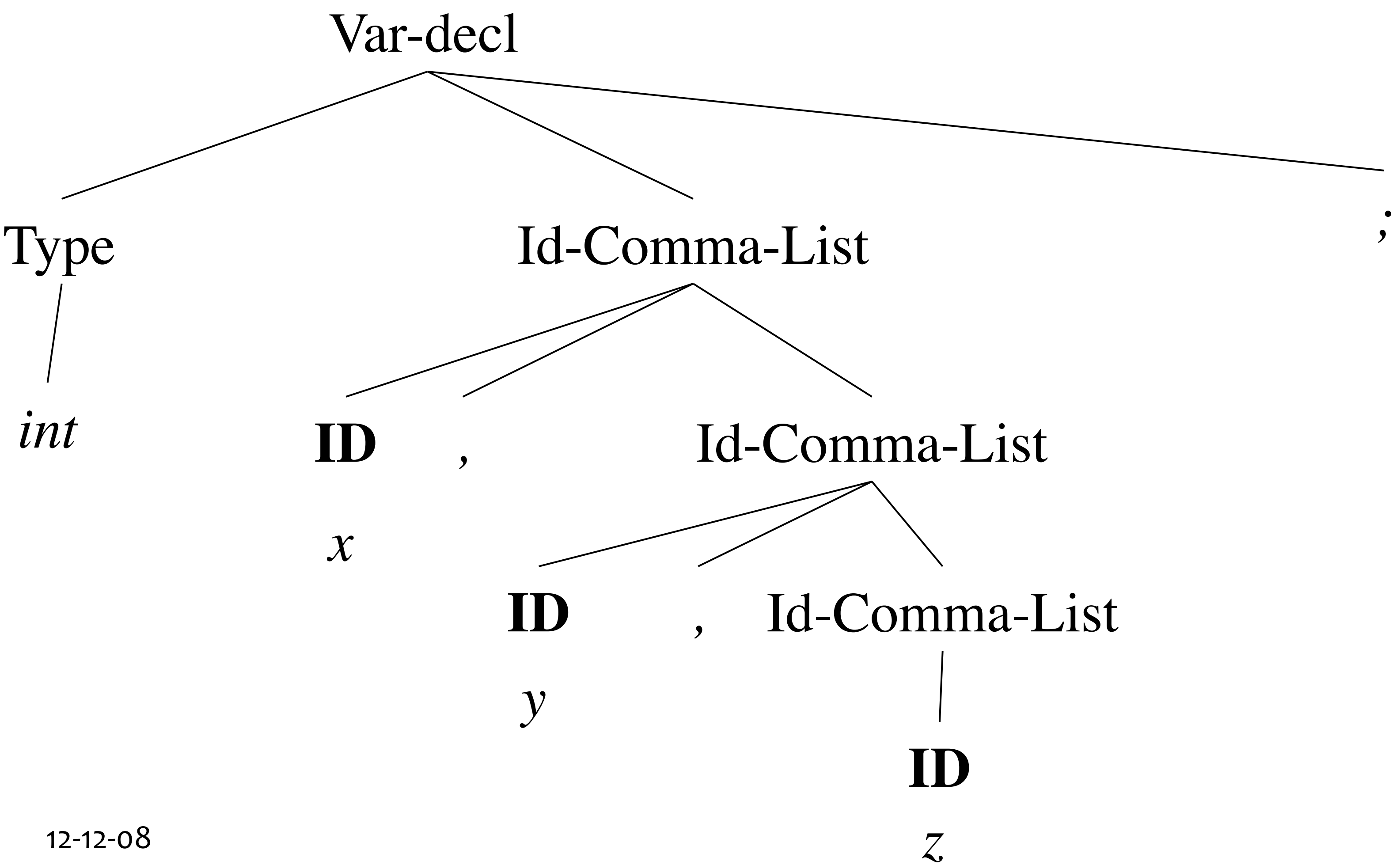
  Var-decl → Type Id-comma-list **;**

  Type → **int** | **bool**

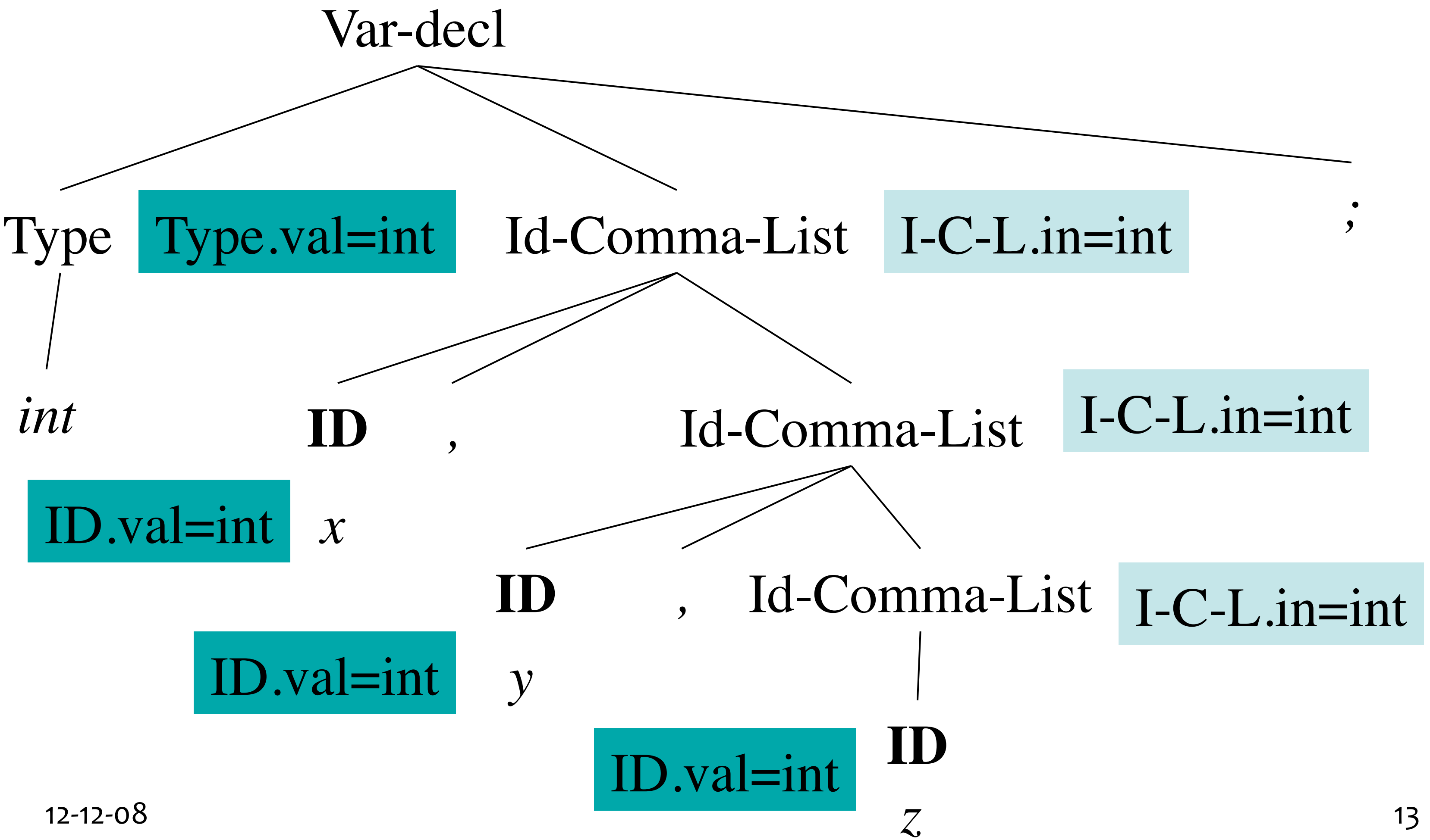
  Id-comma-list → **ID**

  Id-comma-list → **ID ,** Id-comma-list

Example: *int x, y, z ;*



Example: *int x, y, z ;*



Syntax-directed definition

Var-decl → Type Id-comma-list **;**

{ \$2.in = \$1.val; }

Type → **int** | **bool**

{ \$0.val = int; } & { \$0.val = bool; }

Id-comma-list → **ID**

{ \$1.val = \$0.in; }

Id-comma-list → **ID ,** Id-comma-list

{ \$1.val = \$0.in; \$3.in = \$0.in; }

Syntax-directed definition

Var-decl → Type Id-comma-list **;**

In yacc: Var-decl → Type { $<val>$ = $1 } Id-comma-list

Type → **int** | **bool**

{ $0.val = int; } & { $0.val = bool; }

Id-comma-list → **ID**

{ $1.val = $0.in; }

In yacc: { $1 = $<val>0 }

Id-comma-list → **ID ,** Id-comma-list

{ $1.val = $0.in; $3.in = $0.in; }

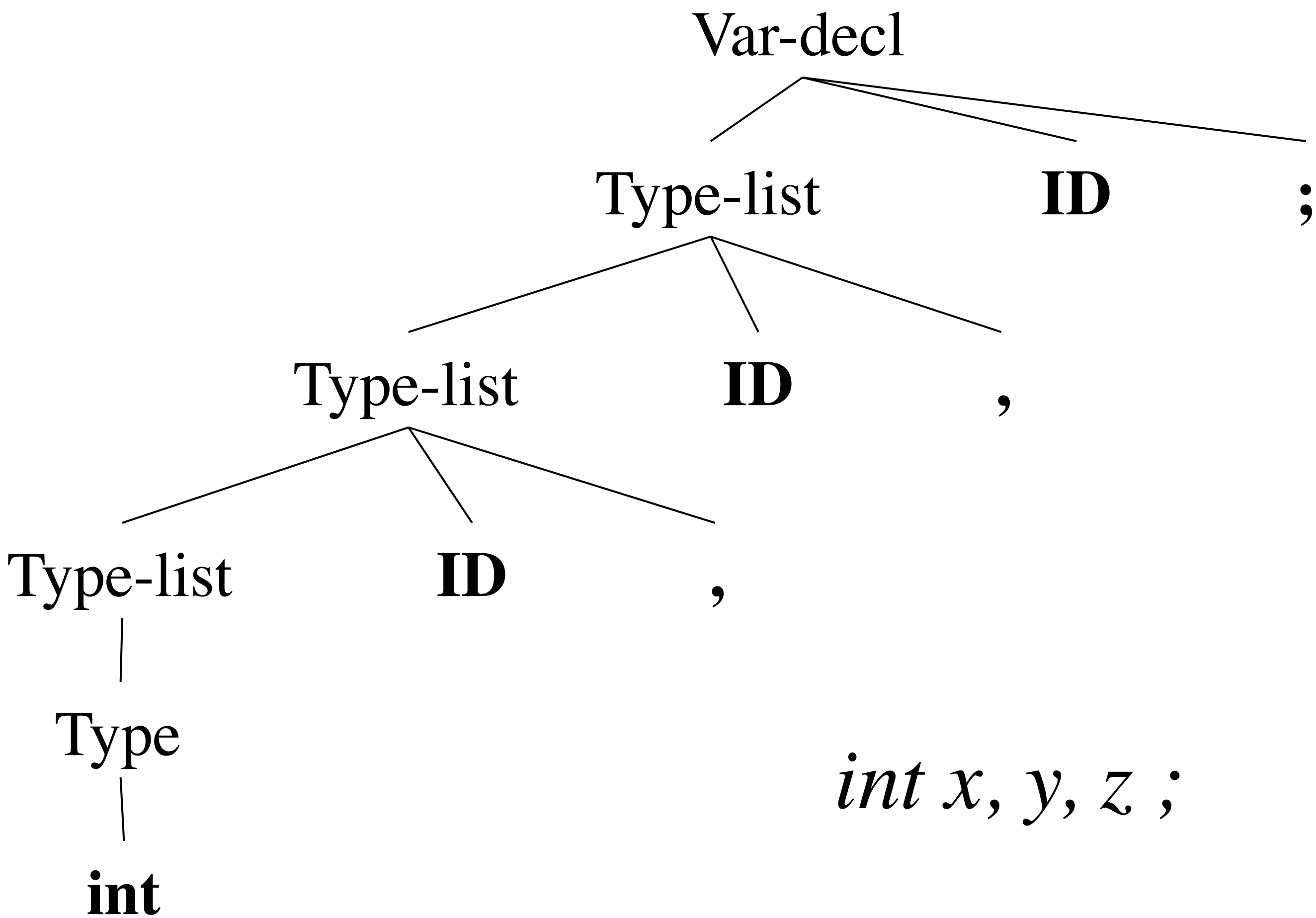
Flow of Attributes in *Var-decl*

- How do the attributes flow in the *Var-decl* grammar
- **ID** takes its attribute value from its parent node
- *Id-Comma-List* takes its attribute value from its left sibling *Type*
- Computing attributes purely bottom-up is not sufficient in this case
- Do we need synthesized attributes in this grammar?

Inherited Attributes

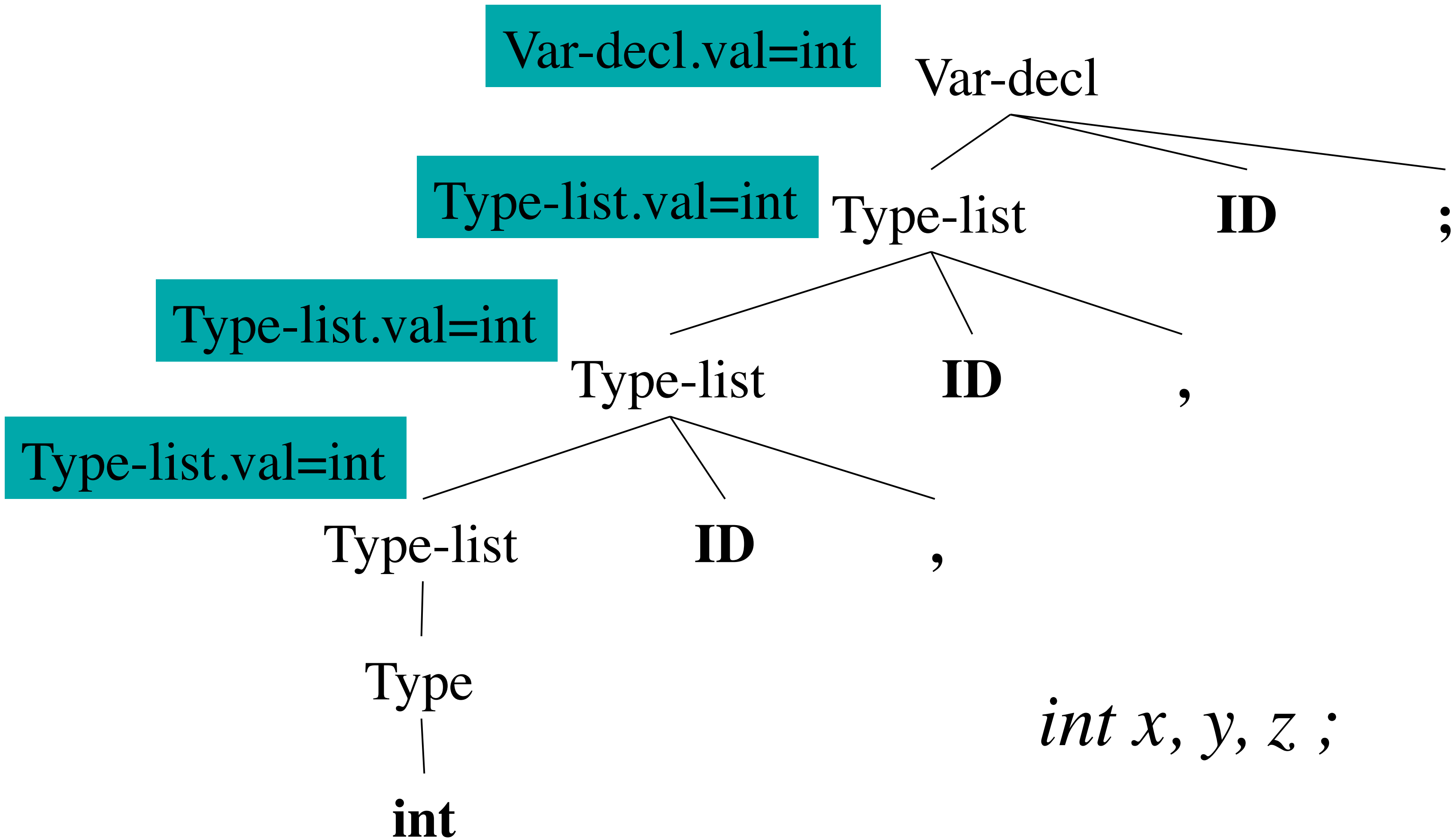
- **Inherited attributes** are attributes that are computed at a node based on attributes from siblings or the parent
- Typically we combine synthesized attributes and inherited attributes
- It is possible to convert the grammar into a form that *only* uses synthesized attributes

Removing Inherited Attributes



int x, y, z ;

Removing Inherited Attributes



Removing inherited attributes

Var-decl → Type-List **ID ;**

{ \$0.val = \$1.val; }

Type-list → Type-list **ID ,**

{ \$0.val = \$1.val; }

Type-list → Type

{ \$0.val = \$1.val; }

Type → **int** | **bool**

{ \$0.val = int; } & { \$0.val = bool; }

Direction of inherited attributes

- Consider the syntax directed defns:

  A → L M

  { \$1.in = \$0.in; \$2.in = \$1.val; \$0.val = \$2.val; }

  A → Q R

  { \$2.in = \$0.in; \$1.in = \$2.val; \$0.val = \$1.val; }
- Problematic definition: \$1.in = \$2.val
- Difference between incremental processing vs. using the completed parse tree

Incremental Processing

- Incremental processing: constructing output as we are parsing
- Bottom-up or top-down parsing
- Both can be viewed as left-to-right and depth-first construction of the parse tree
- Some inherited attributes cannot be used in conjunction with incremental processing

L-attributed Definitions

- A syntax-directed definition is **L-attributed** if for a CFG rule

  $A \rightarrow X_1..X_{j-1}X_j..X_n$ two conditions hold:
  - Each inherited attribute of X_j depends on $X_1..X_{j-1}$
  - Each inherited attribute of X_j depends on A
- These two conditions ensure left to right and depth first parse tree construction
- Every S-attributed definition is L-attributed

Syntax-directed defns

- Two important classes of SDTs:

1. LR parser, syntax directed definition is S-attributed
2. LL parser, syntax directed definition is L-attributed

Syntax-directed defns

- LR parser, S-attributed definition
  - Implementing S-attributed definitions in LR parsing is easy: execute action on reduce, all necessary attributes have to be on the stack
- LL parser, L-attributed definition
  - Implementing L-attributed definitions in LL parsing is similarly easy: we use an additional action record for storing synthesized and inherited attributes on the parse stack

Top-down translation

- Assume that we have a top-down predictive parser
- Typical strategy: take the CFG and eliminate left-recursion
- Suppose that we start with an attribute grammar
- Can we still eliminate left-recursion?

Top-down translation

$E \rightarrow E + T$

{ \$0.val = \$1.val + \$3.val; }

$E \rightarrow E - T$

{ \$0.val = \$1.val - \$3.val; }

$T \rightarrow$ IntConstant

{ \$0.val = \$1.lexval; }

$E \rightarrow T$

{ \$0.val = \$1.val; }

$T \rightarrow (E)$

{ \$0.val = \$2.val; }

Top-down translation

$E \rightarrow T\ R$

{ \$2.in = \$1.val; \$0.val = \$2.val; }

$R \rightarrow +\ T\ R$

{ \$3.in = \$0.in + \$2.val; \$0.val = \$3.val; }

$R \rightarrow -\ T\ R$

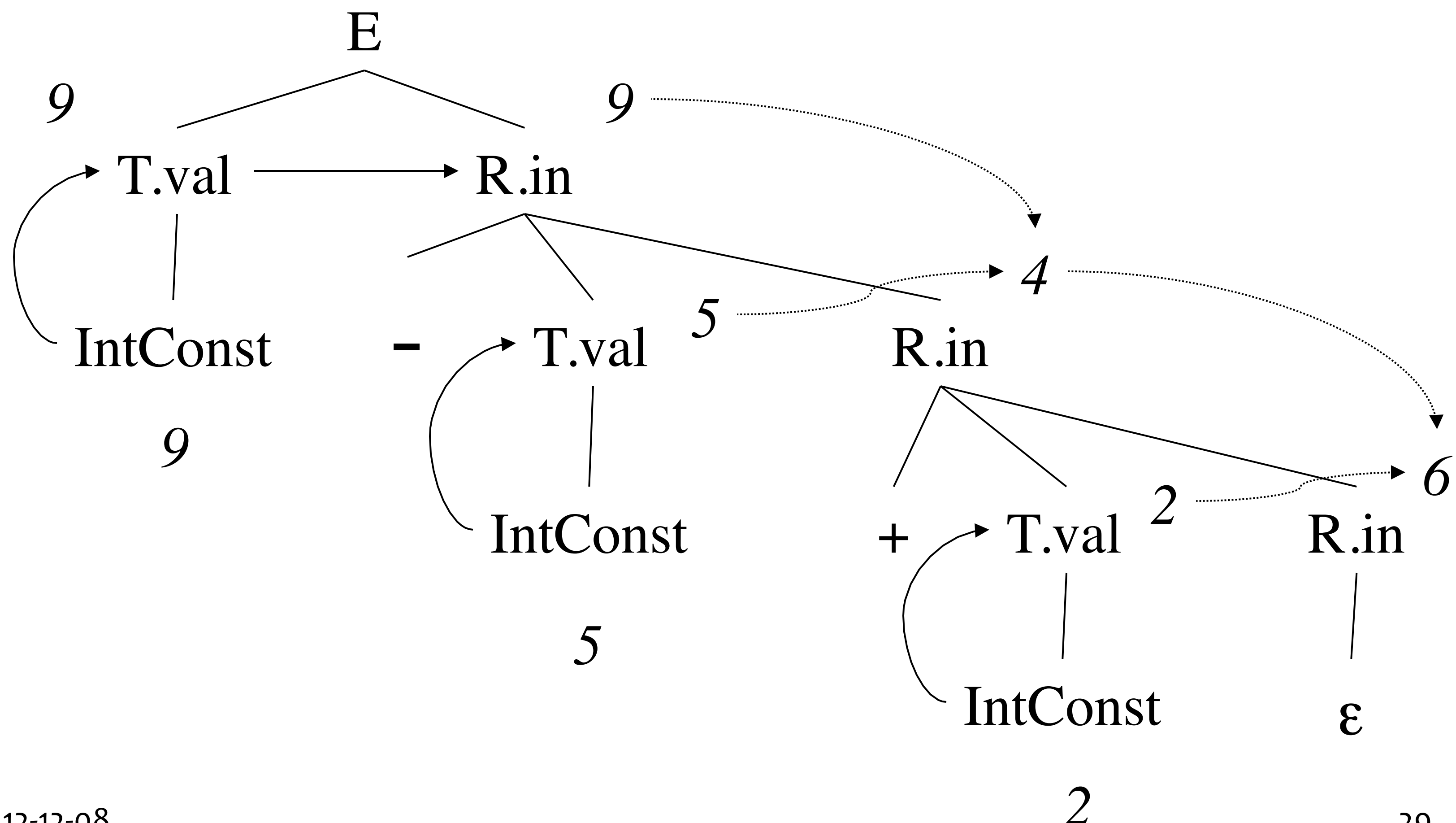
{ \$3.in = \$0.in - \$2.val; \$0.val = \$3.val; }

$R \rightarrow \varepsilon$ { \$0.val = \$0.in; }

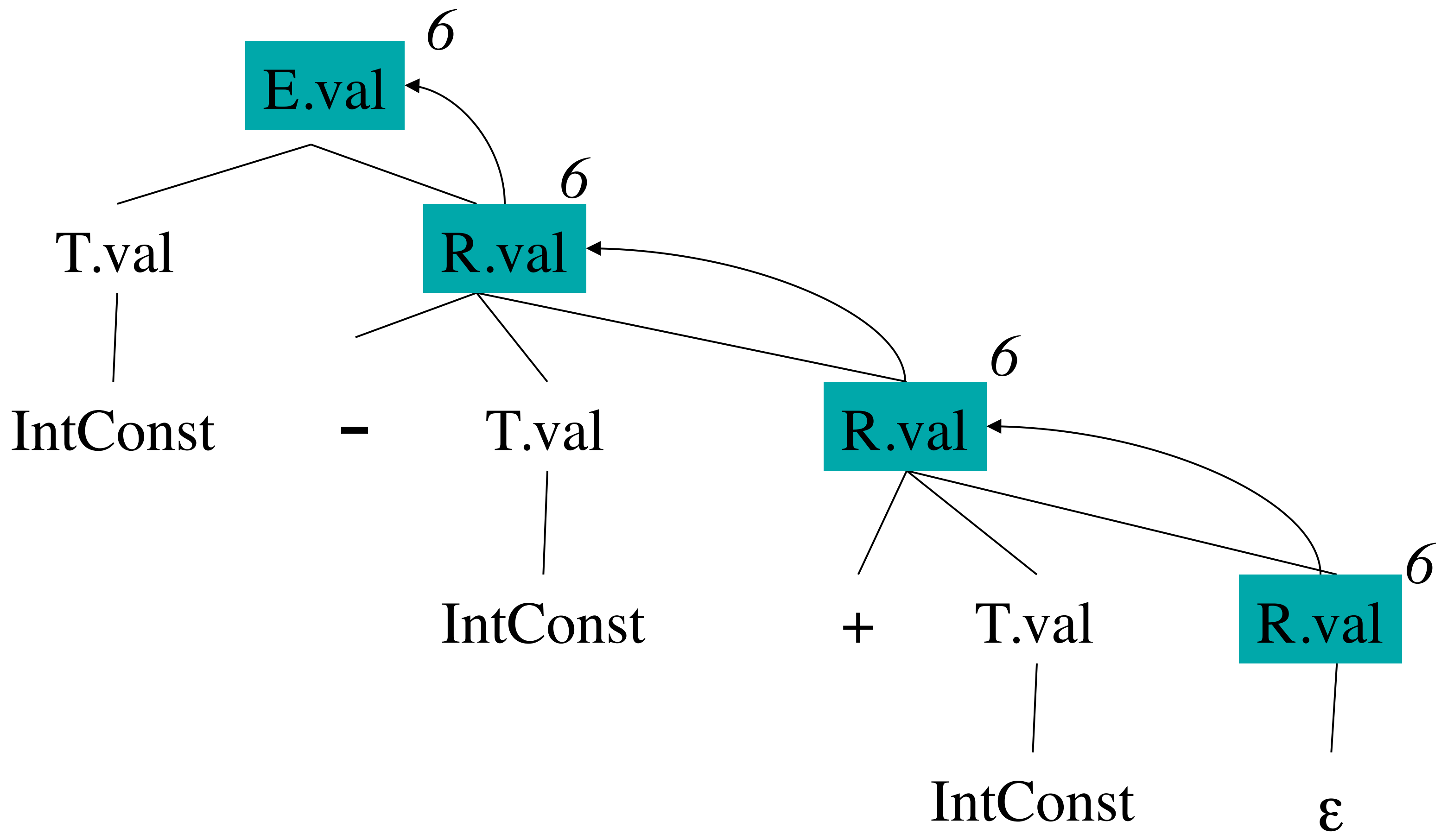
$T \rightarrow (\ E\ )$ { \$0.val = \$2.val; }

$T \rightarrow$ IntConstant { \$0.val = \$1.lexval; }

Example: 9 - 5 + 2


E
9
9
T.val
R.in
4
5
IntConst
-
T.val
R.in
9
6
2
IntConst
+
T.val
R.in
5
IntConst
ε
2

Example: 9 - 5 + 2



E.val
6
T.val
R.val
6
IntConst
-
T.val
R.val
6
IntConst
+
T.val
R.val
6
IntConst
ε

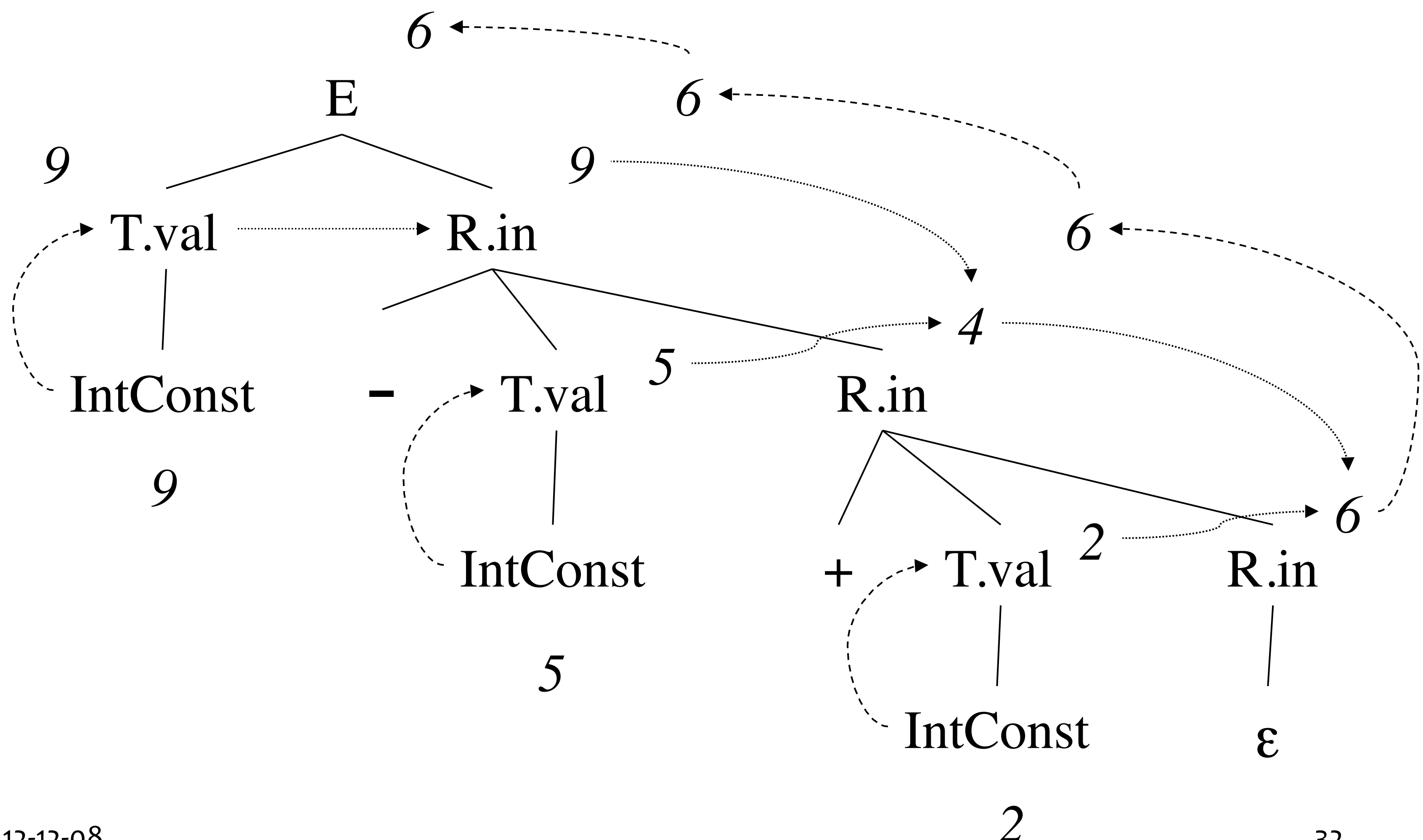
Dependencies and SDTs

- There can be circular definitions:

A → B { \$0.val = \$1.in; \$1.in = \$0.val + 1; }

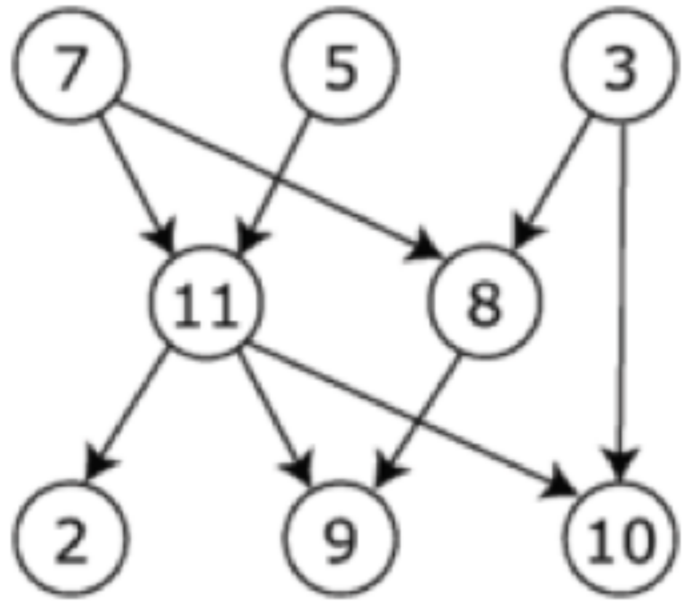
- It is impossible to evaluate either \$0.val or \$1.in first (each value depends on the other)
- We want to avoid circular dependencies
- Detecting such cases in all parse trees takes exponential time!
- S-attributed or L-attributed definitions cannot have cycles

Dependency Graphs



Dependency Graphs

- A dependency graph is drawn based on the syntax directed definition
- Each dependency shows the flow of information in the parse tree
- There are many ways to order these dependencies
- Each ordering is called a **topological sort** of the dependency edges
- A graph with a cycle has no possible topological sorting

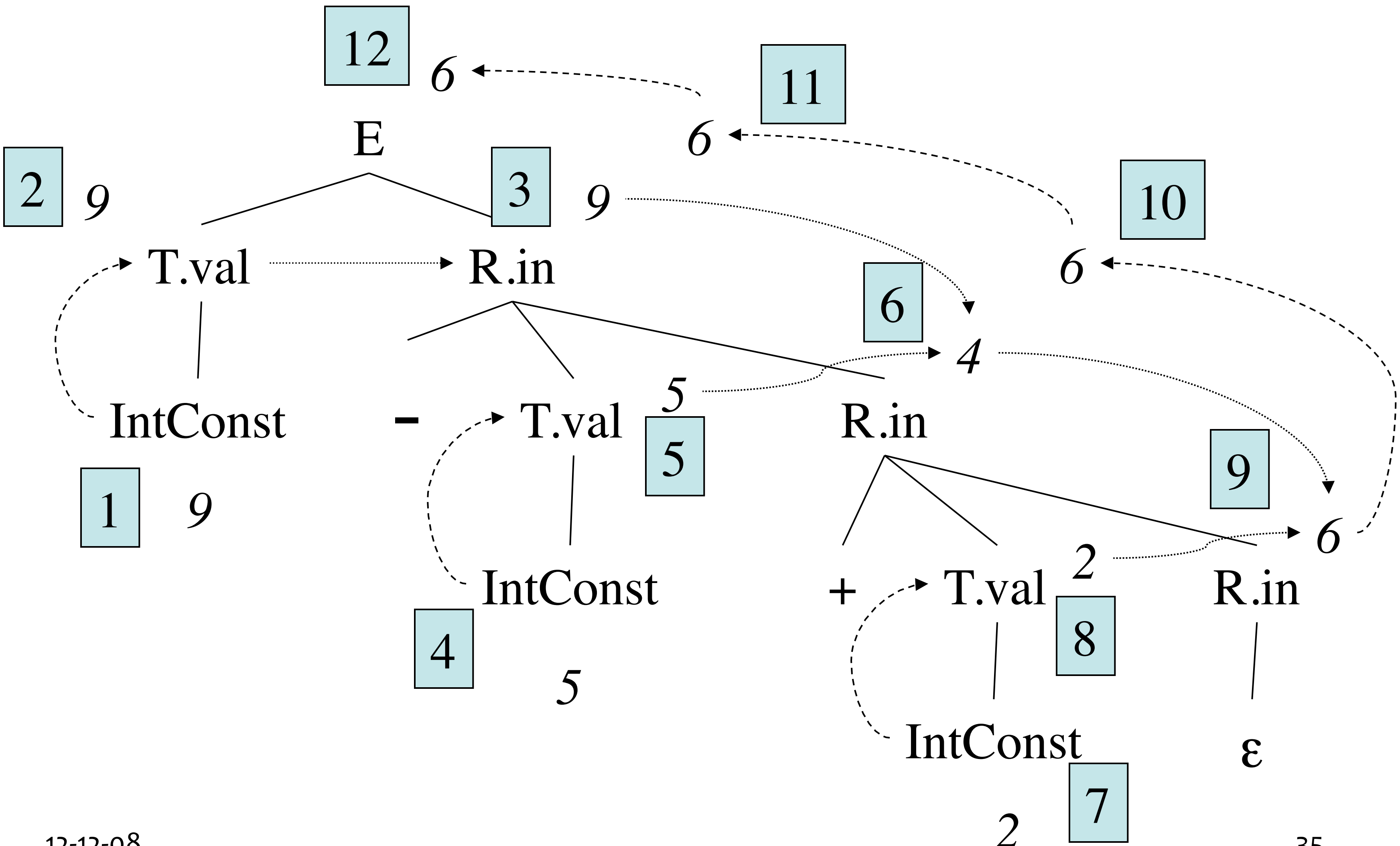


The graph shown to the left has many valid topological sorts, including:

- 7, 5, 3, 11, 8, 2, 9, 10 (visual left-to-right, top-to-bottom)
- 3, 5, 7, 8, 11, 2, 9, 10 (smallest-numbered available vertex first)
- 3, 7, 8, 5, 11, 10, 2, 9
- 5, 7, 3, 8, 11, 10, 9, 2 (least number of edges first)
- 7, 5, 11, 3, 10, 8, 9, 2 (largest-numbered available vertex first)
- 7, 5, 11, 2, 3, 8, 9, 10

Source: Wikipedia

Dependency Graphs



Dependency Graphs

- A topological sort is defined on a set of nodes $N_1, \ldots, N_k$ such that if there is an edge in the graph from N_i to N_j then $i < j$
- One possible topological sort for previous dependency graph is:
  - 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
- Another possible sorting is:
  - 4, 5, 7, 8, 1, 2, 3, 6, 9, 10, 11, 12

Syntax-directed definition with actions

- Some definitions can have side-effects:

E → T R { printf("%s", $2); }

- Can we predict when these side-effects will occur?
- In general, we cannot and so the translation will depend on the parser

Syntax-directed definition with actions

- A definition with side-effects:

E → T R { printf("%s", $2); }

- We can impose a condition: allow side-effects if the definition obeys a condition:
  - The same translation is produced for **any topological sort** of the dependency graph
- In the above example, this is true because the print statement is executed at the end

SDTs with Actions

- A syntax directed definition that maps infix expressions to postfix:

$E \rightarrow T\ R$

$R \rightarrow +\ T$ { print('+'); } R

$R \rightarrow -\ T$ { print('–'); } R

$R \rightarrow \varepsilon$

$T \rightarrow$ **id** { print(**id**.lookup); }

SDTs with Actions

- A buggy syntax directed definition that tries to map infix expressions to prefix:

$E \rightarrow T\ R$

$R \rightarrow$ { print('+'); } + T R

$R \rightarrow$ { print('–'); } – T R

$R \rightarrow \varepsilon$

$T \rightarrow$ **id** { print(**id**.lookup); }

Problematic for left to right processing. Translation on the parse tree is possible

Marker non-terminals

- Convert L-attributed into S-attributed definition
- Prerequisite: use embedded actions to compute inherited attributes, e.g.

  R → + T { \$3.in = \$0.in + \$2.val; } R {\$0.val = \$3.val}

- For each embedded action introduce a new marker non-terminal and replace action with the marker

  R → + T M R {\$0.val = \$-1.val}

  M → ε { \$0.val = \$–1.val +\$–3.in; }

note the use of –1, –2, etc. to access attributes

Marker Non-terminals

$E \rightarrow T\ R$

$R \rightarrow +\ T$ { print('+'); } R

$R \rightarrow -\ T$ { print('-'); } R

$R \rightarrow \varepsilon$

$T \rightarrow$ **id** { print(**id**.lookup); }

Actions that should be done after recognizing T but before predicting R

Marker Non-terminals

$E \rightarrow T\ R$

$R \rightarrow +\ T\ M\ R$

$R \rightarrow -\ T\ N\ R$

$R \rightarrow \varepsilon$

T → **id** { print(**id**.lookup); }

M → ε { print('+'); }

N → ε { print('-'); }

Equivalent SDT using *marker non-terminals*

Impossible Syntax-directed Definition

$E \rightarrow$ { print(‘+’); } E + T

$E \rightarrow T$

$T \rightarrow$ { print(‘*’); } T * R

$T \rightarrow F$

$T \rightarrow$ **id** { print $1.lexval; }

Tries to convert infix to prefix

Causes a reduce/reduce conflict when marker non-terminals are introduced.

Extra Slides

Syntax-directed defns

- LR parser, S-attributed definition
  - more details later …
- LL parser, L-attributed definition

Stack	Input	Output
$T')T'F	id)*id$	**T → F T' { $2.in = $1.val }**
$T')T'id	id)*id$	**F → id { $0.val = $1.val }**
$T')T'	)*id$	The action record stays on the stack when T' is replaced with rhs of rule

action record:
T'.in = F.val

LR parsing and inherited attributes

- As we just saw, inherited attributes are possible when doing top-down parsing
- How can we compute inherited attributes in a bottom-up shift-reduce parser
- Problem: doing it incrementally (while parsing)
- Note that LR parsing implies depth-first visit which matches L-attributed definitions

LR parsing and inherited attributes

- Attributes can be stored on the stack used by the shift-reduce parsing
- For synthesized attributes: when a reduce action is invoked, store the value on the stack based on value popped from stack
- For inherited attributes: transmit the attribute value when executing the **goto** function

Example: Synthesized Attributes

T → F { $0.val = $1.val; }

T → T * F

{ $0.val = $1.val * $3.val; }

F → **id**

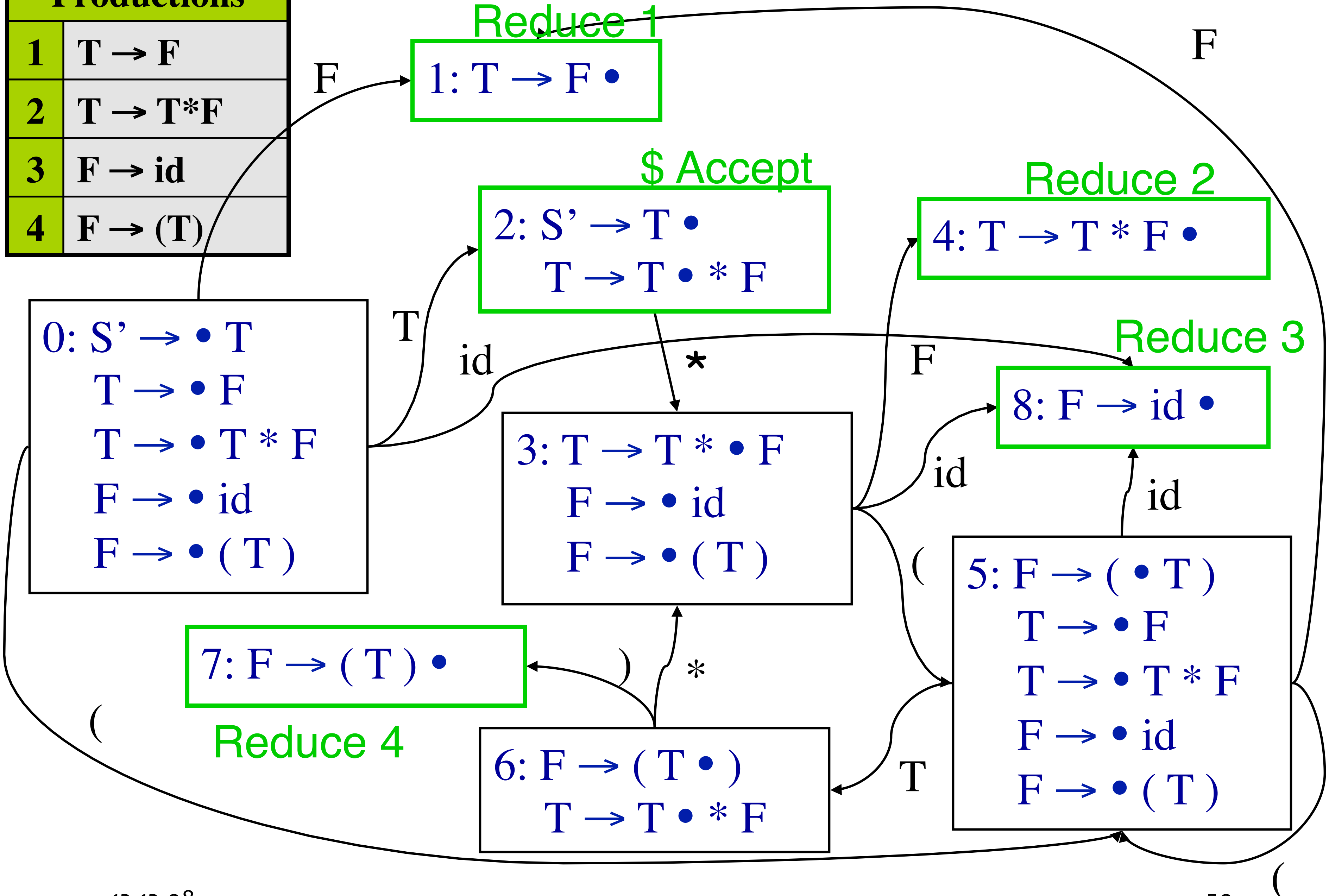
{ val := **id**.lookup();

if (val) { $0.val = $1.val; }

else { error; } }

F → (T) { $0.val = $2.val; }

Productions	
1	T → F
2	T → T*F
3	F → id
4	F → (T)



Trace “(id$_{val=3}$)*id$_{val=2}$”

Stack	Input	Action	Attributes
0	**(id) * id $**	**Shift 5**	
0 5	**id) * id $**	**Shift 8**	**a.Push id.val=3;**
0 5 8	**) * id $**	**Reduce 3 F→id,** **pop 8, goto [5,F]=1**	{ \$0.val = \$1.val } **a.Pop; a.Push 3;**
0 5 1	**) * id $**	**Reduce 1 T→ F,** **pop 1, goto [5,T]=6**	{ \$0.val = \$1.val } **a.Pop; a.Push 3;**
0 5 6	**) * id $**	**Shift 7**	
0 5 6 7	*** id $**	**Reduce 4 F→ (T),** **pop 7 6 5, goto [0,F]=1**	{ \$0.val = \$2.val } **3 pops; a.Push 3**

Trace “(id$_{val=3}$)*id$_{val=2}$”

Stack	Input	Action	Attributes
0 1	*** id $**	**Reduce 1 T→F,** **pop 1, goto [0,T]=2**	{ $0.val = $1.val } **a.Pop; a.Push 3**
0 2	*** id $**	**Shift 3**	**a.Push mul**
0 2 3	**id $**	**Shift 8**	**a.Push id.val=2**
0 2 3 8	**$**	**Reduce 3 F→id,** **pop 8, goto [3,F]=4**	**a.Pop a.Push 2**
0 2 3 4	**$**	**Reduce 2 T→T * F** **pop 4 3 2, goto [0,T]=2**	{ $0.val = $1.val * $3.val; } **3 pops;** **a.Push 3*2=6**
0 2	**$**	**Accept**	

Example: Inherited Attributes

$E \rightarrow T\ R$

{ \$2.in = \$1.val; \$0.val = \$2.val; }

$R \rightarrow +\ T\ R$

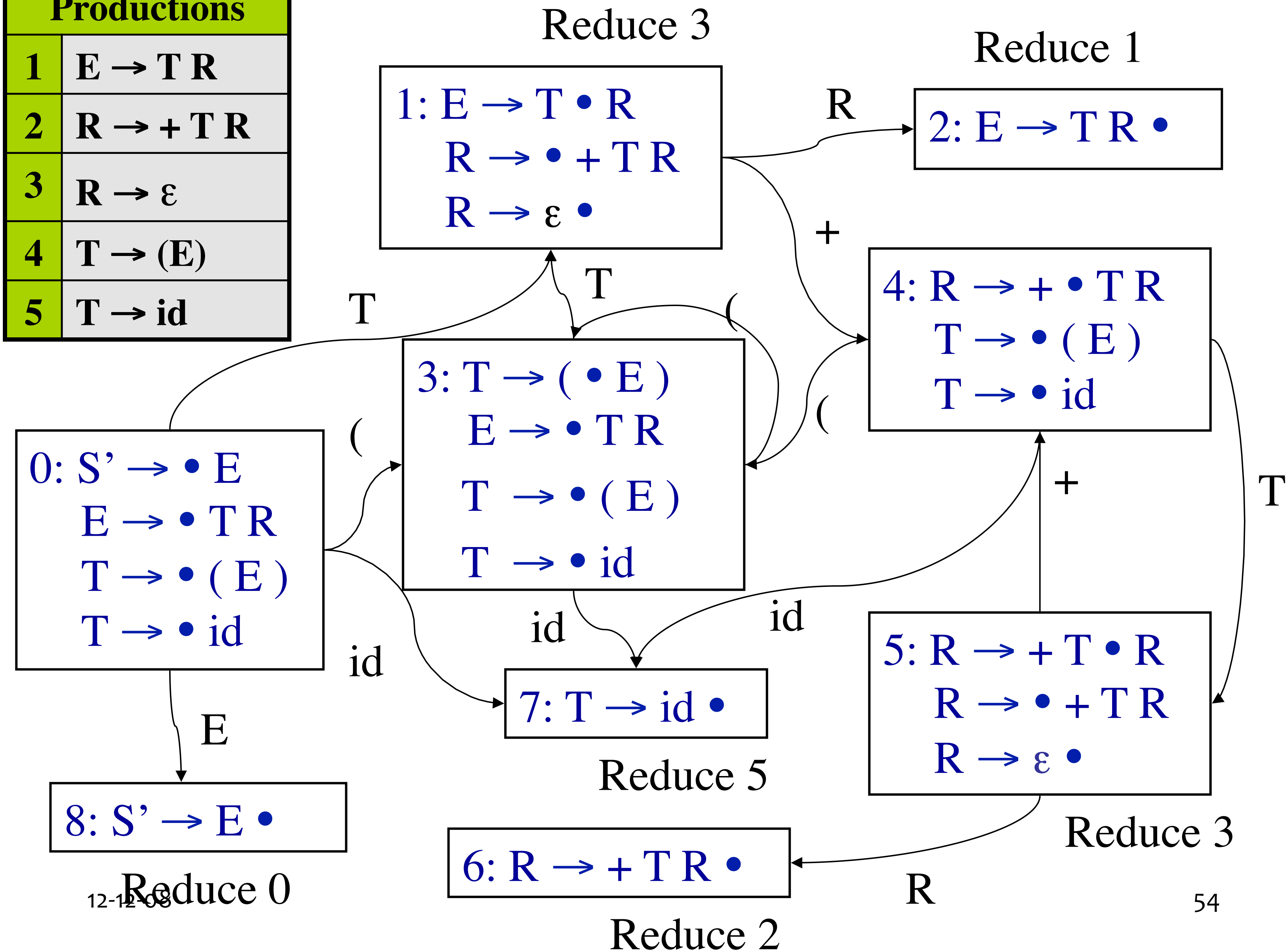
{ \$3.in = \$0.in + \$2.val; \$0.val = \$3.val; }

$R \rightarrow \varepsilon$ { \$0.val = \$0.in; }

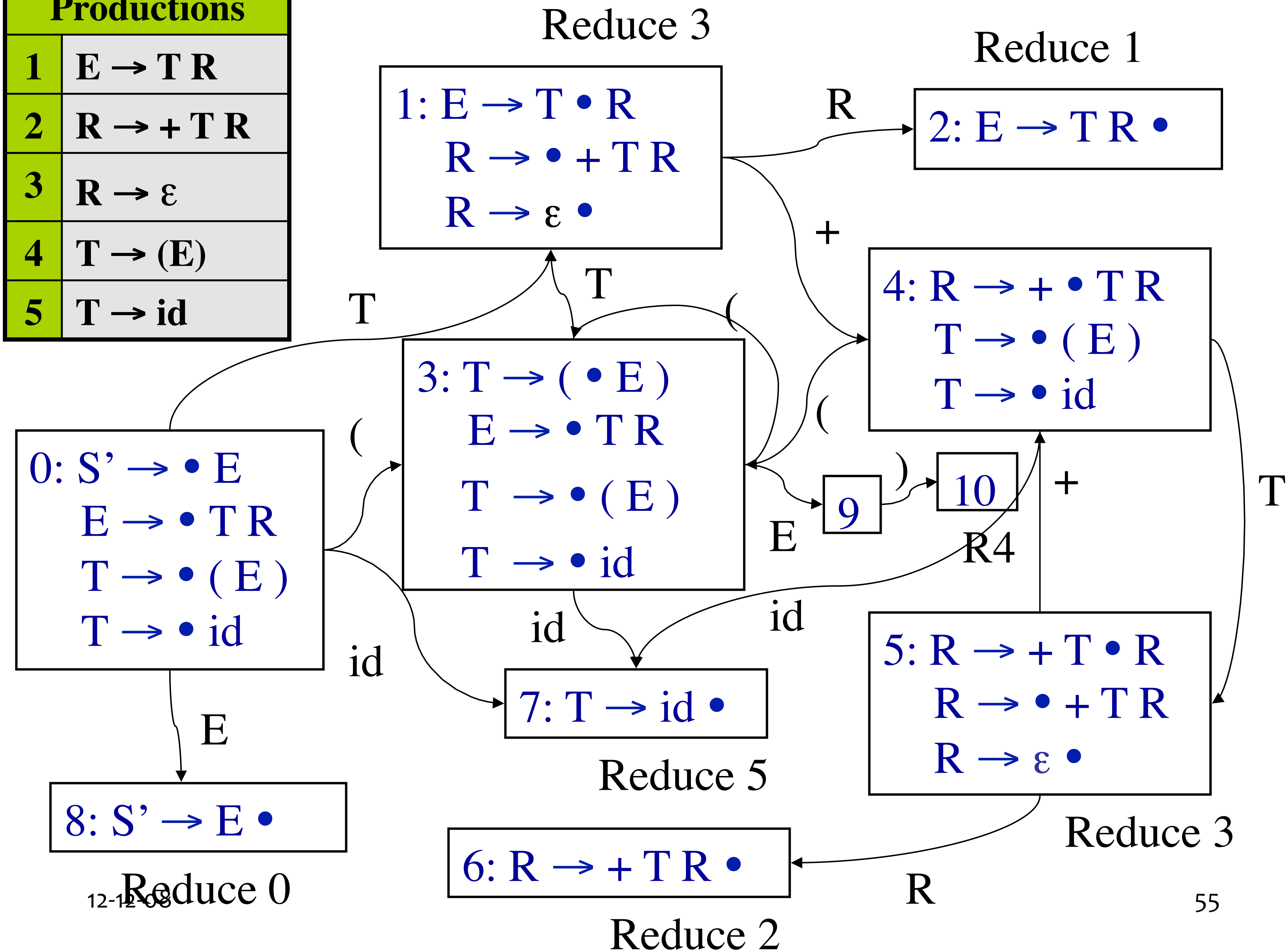
$T \rightarrow (\ E\ )$ { \$0.val = \$1.val; }

$T \rightarrow$ **id** { \$0.val = **id**.lookup; }

Productions	
1	E → T R
2	R → + T R
3	R → ε
4	T → (E)
5	T → id



Productions	
1	E → T R
2	R → + T R
3	R → ε
4	T → (E)
5	T → id



	Productions
1	**E → T R** { \$2.in = \$1.val; \$0.val = \$2.val; }
2	**R → + T R** { \$3.in = \$0.in + \$2.val; \$0.val = \$3.val; }
3	**R →** ε { \$0.val = \$0.in; }
4	**T → (E)** { \$0.val = \$1.val; }
5	**T → id** { \$0.val = **id**.lookup; }

			ttributes
0 7	**+ id \$**	**Reduce 5 T→id**	**{ \$0.val = id.lookup }**
		pop 7, goto [0,T]=1	**{ pop; attr.Push(3)**
			\$2.in = \$1.val
0 1	**+ id \$**	**Shift 4**	**\$2.in := (1).attr }**
0 1 4	**id \$**	**Shift 7**	
0 1 4 7	**\$**	**Reduce 5 T→id**	**{ \$0.val = id.lookup }**
		pop 7, goto [4,T]=5	**{ pop; attr.Push(2); }**
0 1 4 5	**\$**	**Reduce 3 R→ ε**	
		goto [5,R]=6	**{ \$3.in = \$0.in+\$1.val**
			(5).attr := (1).attr+2
			\$0.val = \$0.in
			\$0.val = (5).attr = 5 }

Trace “$id_{val=3}+id_{val=2}$”

Stack	Input	Action	Attributes
0	id + id $	Shift 7	
0 7	+ id $	Reduce 5 T→id	{ $0.val = id.lookup }
		pop 7, goto [0,T]=1	{ pop; attr.Push(3)
0 1	+ id $	Shift 4	$2.in = $1.val
0 1 4	id $	Shift 7	$2.in := (1).attr }
0 1 4 7	$	Reduce 5 T→id	{ $0.val = id.lookup }
		pop 7, goto [4,T]=5	{ pop; attr.Push(2); }
0 1 4 5	$	Reduce 3 R→ ε	
		goto [5,R]=6	{ $3.in = $0.in+$1.val
			(5).attr := (1).attr+2
			$0.val = $0.in
			$0.val = (5).attr = 5 }

Trace “$id_{val=3}$+$id_{val=2}$”

Stack	Input	Action	Attributes
0 1 4 5 6	**$**	**Reduce 2 R→ + T R** **Pop 4 5 6, goto [1,R]=2**	**{ $0.val = $3.val** **pop; attr.Push(5); }**
0 1 2	**$**	**Reduce 1 E→ T R** **Pop 1 2, goto [0,E]=8**	**{ $0.val = $3.val** **pop; attr.Push(5); }**
0 8	**$**	**Accept**	**{ $0.val = 5** **attr.top = 5; }**

A -> c { $0.val = $0.in }

LR parsing with inherited attributes

Bottom-Up/rightmost	
ccbca ⇐ Acbca	A→c
⇐ AcbB	B→ca
⇐ AB	B→cbB
⇐ S	S→AB

line 3

Parse stack at line 3:
[‘x’] A [‘x’] c b B

$1.in = ‘x’

$2.in = $1.val

Consider:

S→AB
{ $1.in = ‘x’;
$2.in = $1.val }

B→cbB
{ $0.val = $0.in + ‘y’; }

Parse stack at line 4:
[‘x’] A B

[‘xy’]

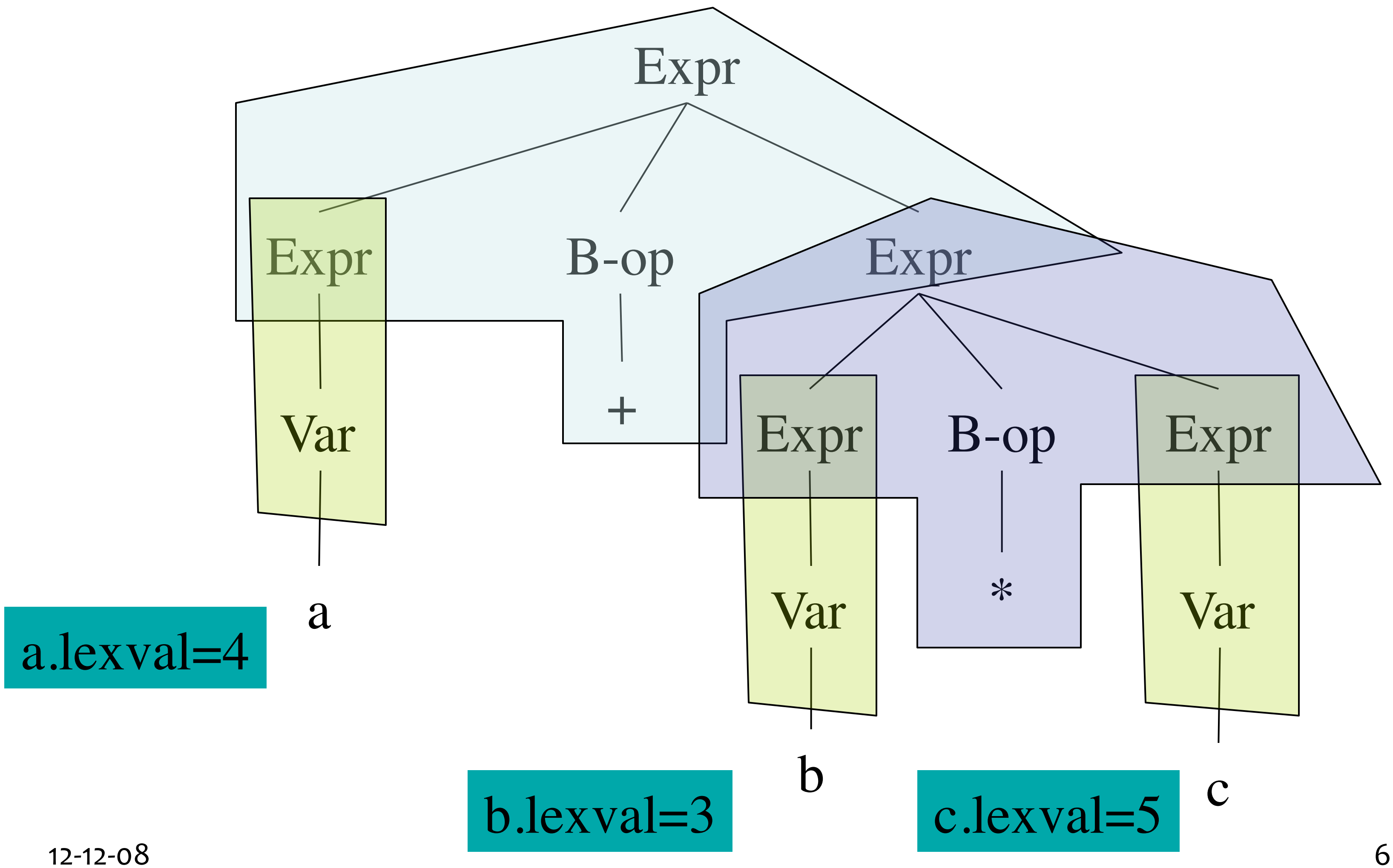
Tree Matching Code Generators

- Write tree patterns that match portions of the parse tree
- Each tree pattern can be associated with an action (just like attribute grammars)
- There can be multiple combinations of tree patterns that match the input parse tree

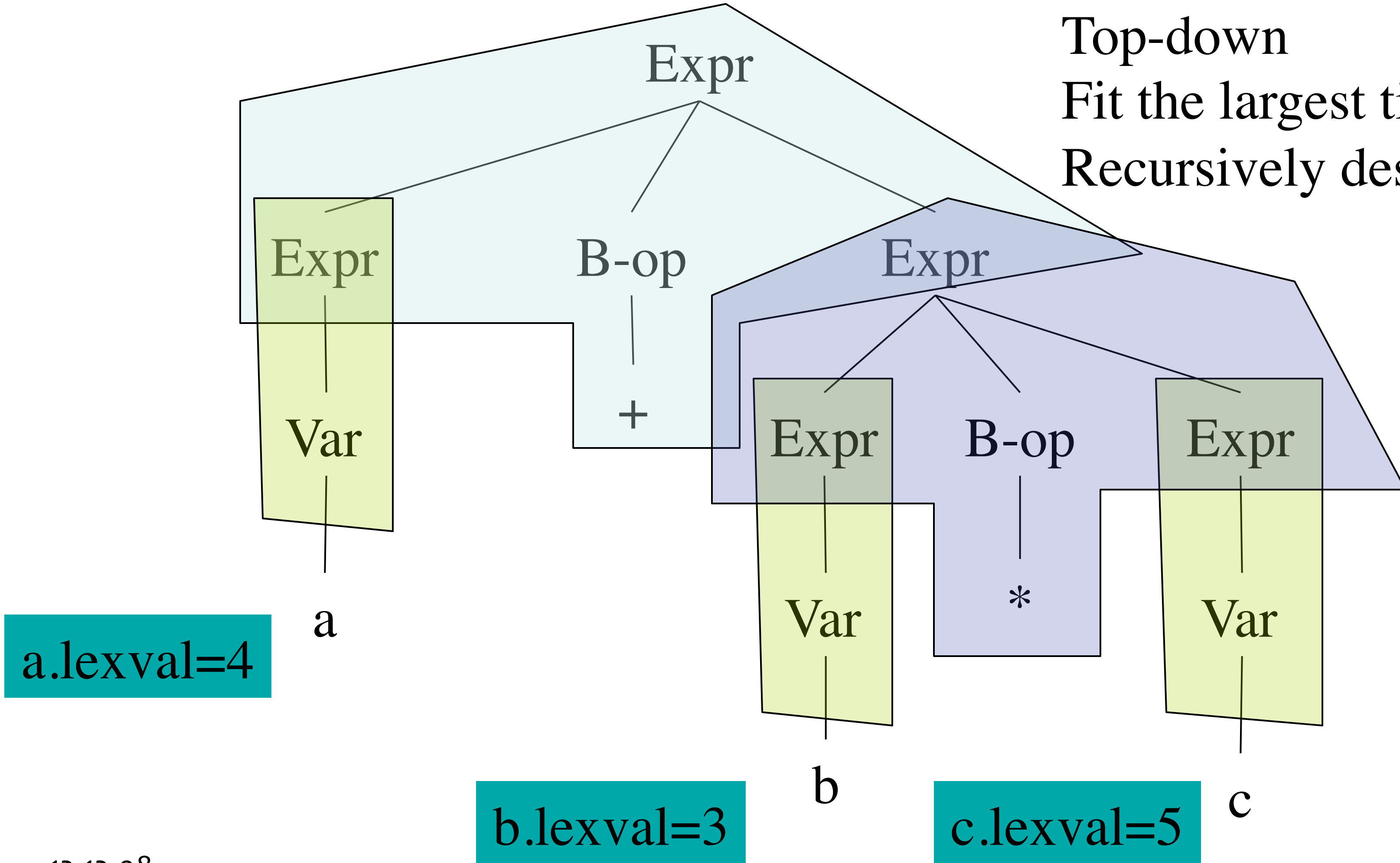
Tree Matching Code Generators

- To provide a unique output, we assign costs to the use of each tree pattern
- E.g. assigning uniform costs leads to smaller code or instruction costs can be used for optimizing code generation
- Three algorithms: Maximal Munch, Dynamic Programming, Tree Grammars
- Section 8.9 (Purple Dragon book)

Maximal Munch: Example 1

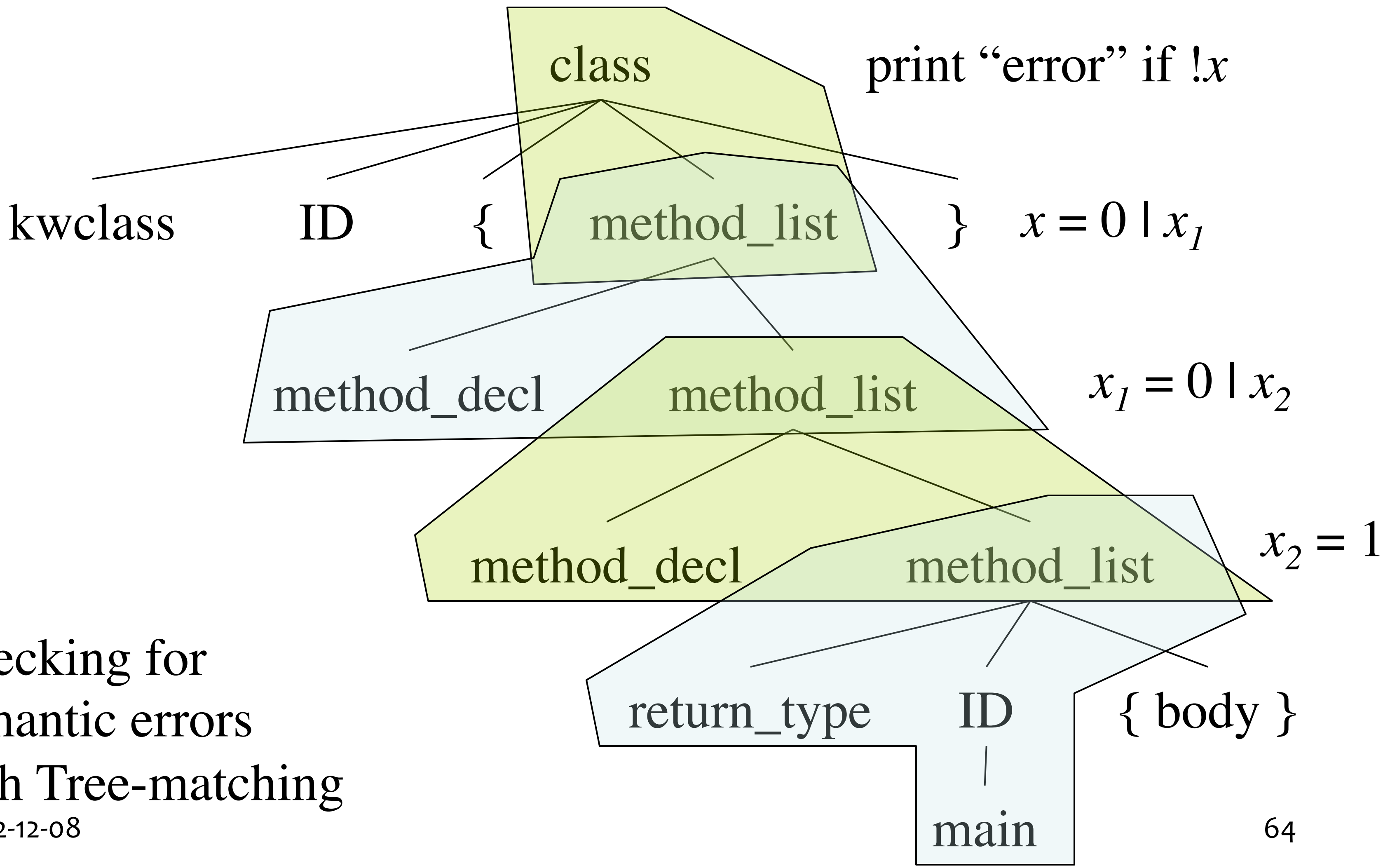


Maximal Munch: Example 1



Top-down
Fit the largest tile
Recursively descend

Maximal Munch: Example 2



Checking for semantic errors with Tree-matching

Tree Parsing Code Generators

- Take the prefix representation of the syntax tree
  - E.g. (+ (* c1 r1) (+ ma c2)) in prefix representation uses an inorder traversal to get + * c1 r1 + ma c2
- Write CFG rules that match substrings of the above representation and non-terminals are registers or memory locations
- Each matching rule produces some predefined output
- Section 8.9.3 (Purple Dragon book)

Code-generation Generators

- A CGG is like a compiler-compiler: write down a description and generate code for it
- Code generation by:
  - Adding semantic actions to the original CFG and each action is executed while parsing, e.g. yacc
  - Tree Rewriting: match a tree and commit an action, e.g. lcc
  - Tree Parsing: use a grammar that generates trees (not strings), e.g. twig, burs, iburg

Summary

- The parser produces concrete syntax trees
- Abstract syntax trees: define semantic checks or a syntax-directed translation to the desired output
- Attribute grammars: static definition of syntax-directed translation
  - Synthesized and Inherited attributes
  - S-attribute grammars
  - L-attributed grammars
- Complex inherited attributes can be defined if the full parse tree is available