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

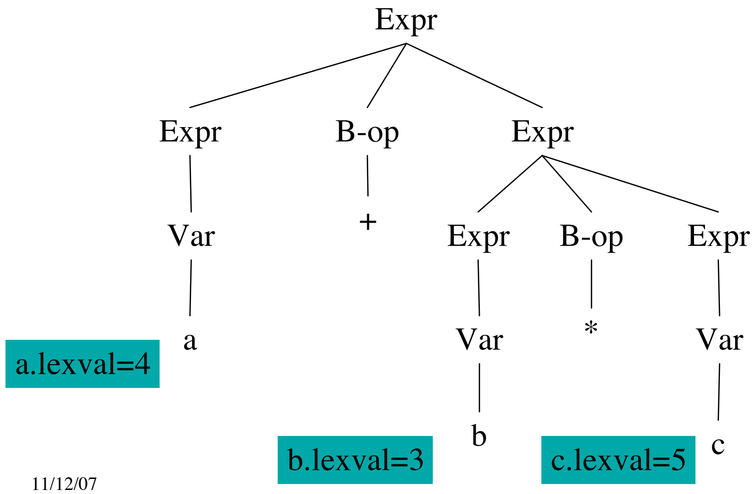
Attribute Grammars

- 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

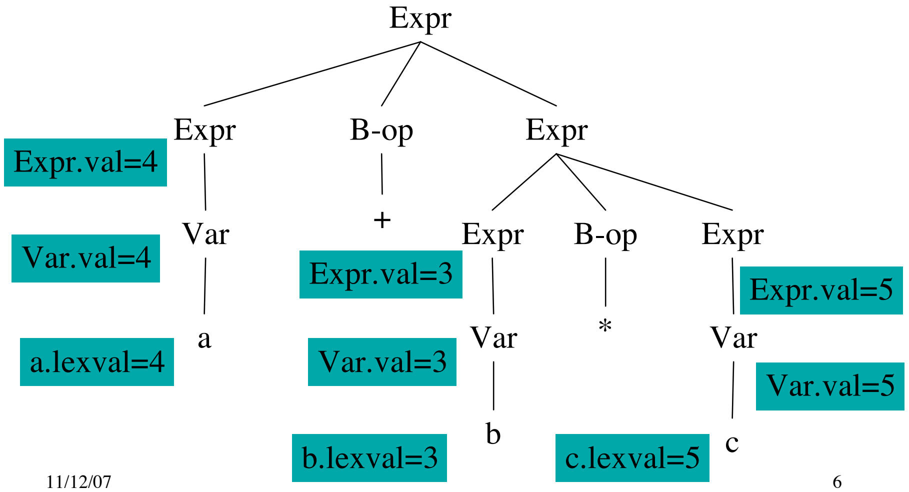
Attribute Grammars

- 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.lexval=4
a
Var
*
Var
b
c
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
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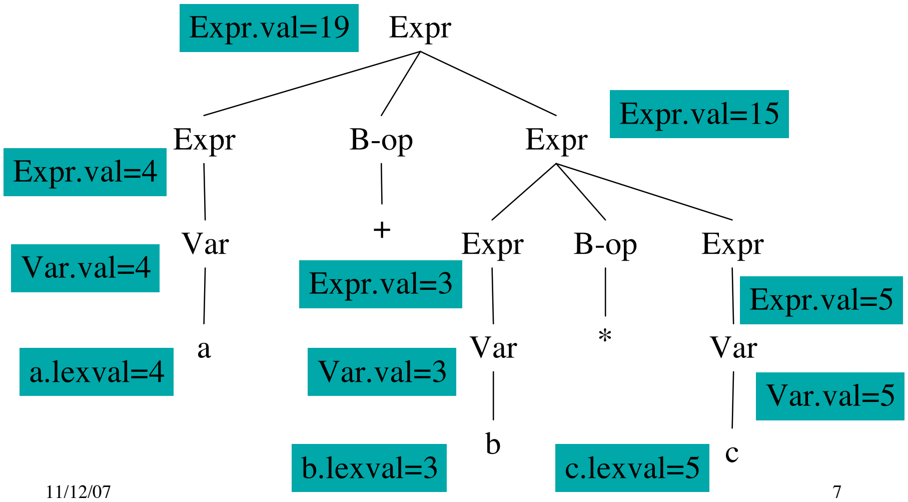
Example



Syntax directed definition

Var → IntConstant

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

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

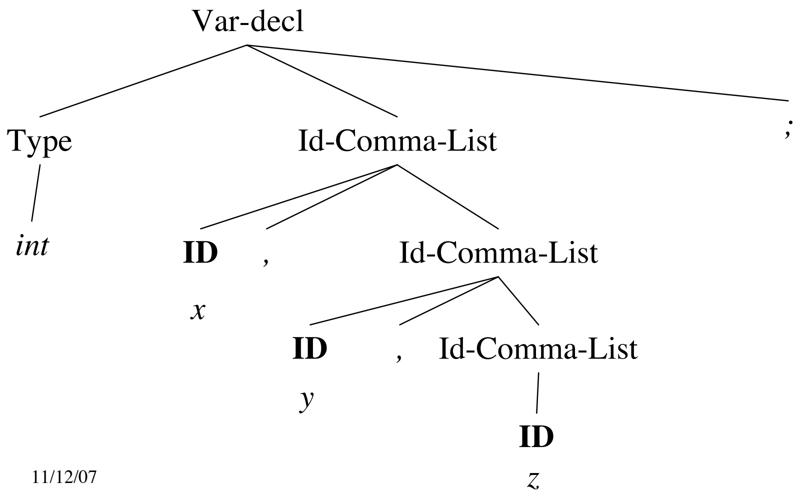
- **Synthesized attributes** are attributes that are computed purely bottom-up
- A grammar with semantic actions (or syntax-directed definition) can choose to use *only* synthesized attributes
- Such a grammar plus semantic actions is called an **S-attributed definition**

Inherited Attributes

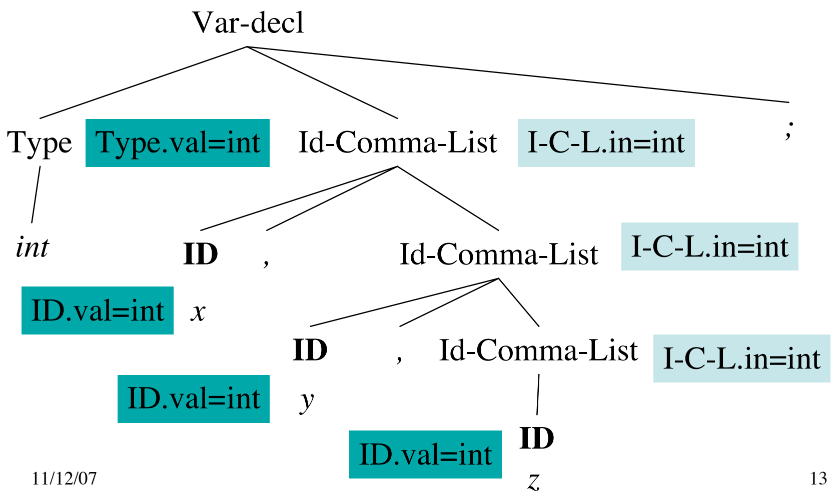
- Synthesized attributes may not be sufficient for all cases that might arise for semantic checking and code generation
- Consider the (sub)grammar:

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 ;*



Var-decl

Type

Type.val=int

Id-Comma-List

I-C-L.in=int

;

int

ID

,

Id-Comma-List

I-C-L.in=int

ID.val=int

x

ID

,

Id-Comma-List

I-C-L.in=int

ID.val=int

y

ID

ID.val=int

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; }

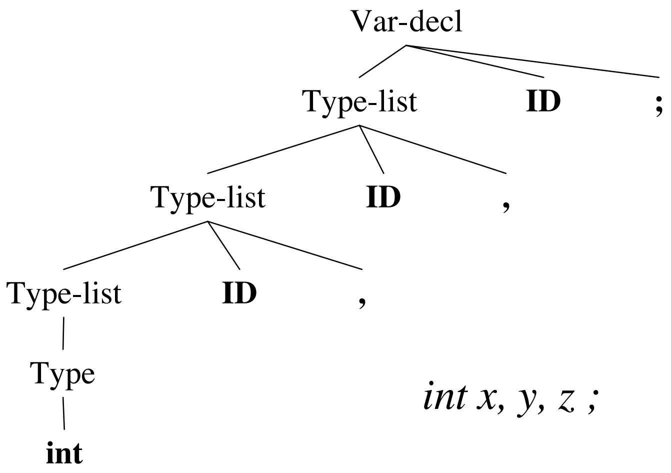
Flow of Attributes in *Var-decl*

- 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

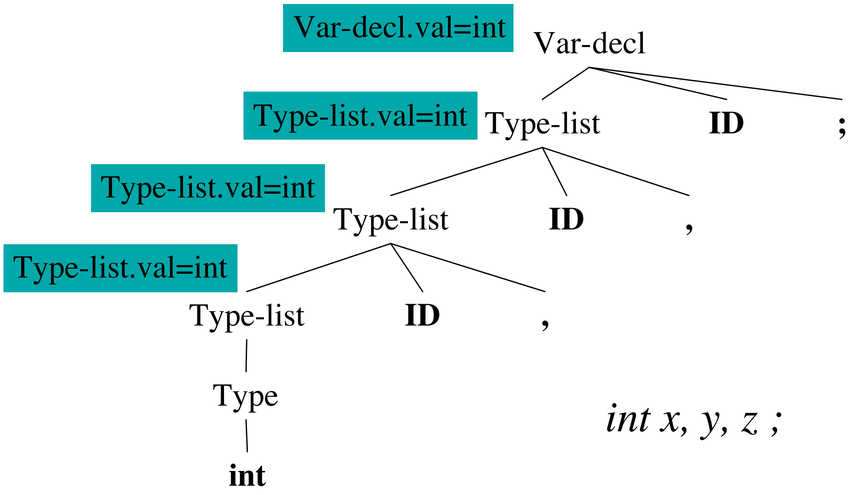
- **Inherited attributes** are attributes that are computed at a node based on attributes from siblings or the parent
- Typically we combine synthesized attributes and inherited attributes
- It is possible to convert the grammar into a form that *only* uses synthesized attributes

Removing Inherited Attributes



int x, y, z ;

Removing Inherited Attributes



int x, y, z ;

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

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

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 → E + T

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

E → E - T

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

T → IntConstant

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

E → T

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

T → (E)

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

Top-down translation

E → T R

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

R → + T R

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

R → - T R

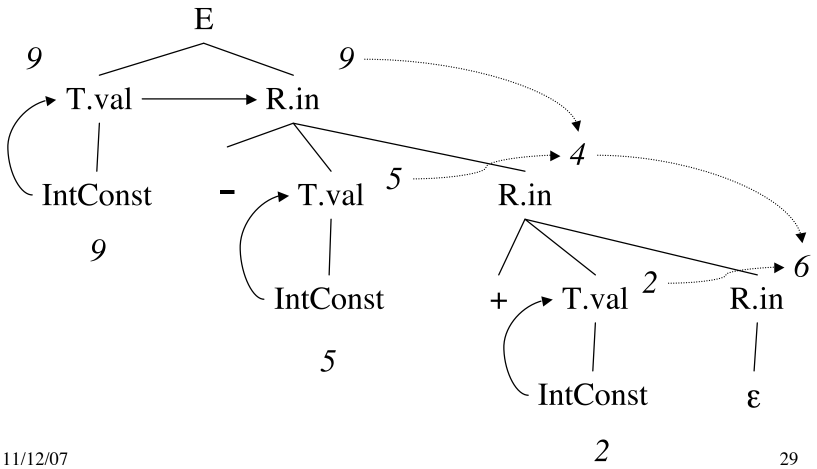
{ $3.in = $0.in - $2.val; $0.val = $3.val; }

R → ε { $0.val = $0.in; }

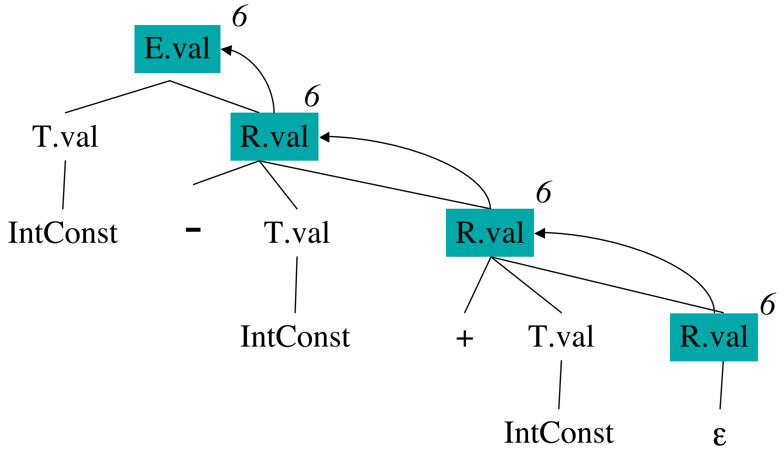
T → (E) { $0.val = $1.val; }

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

Example: *9 - 5 + 2*



Example: *9 - 5 + 2*



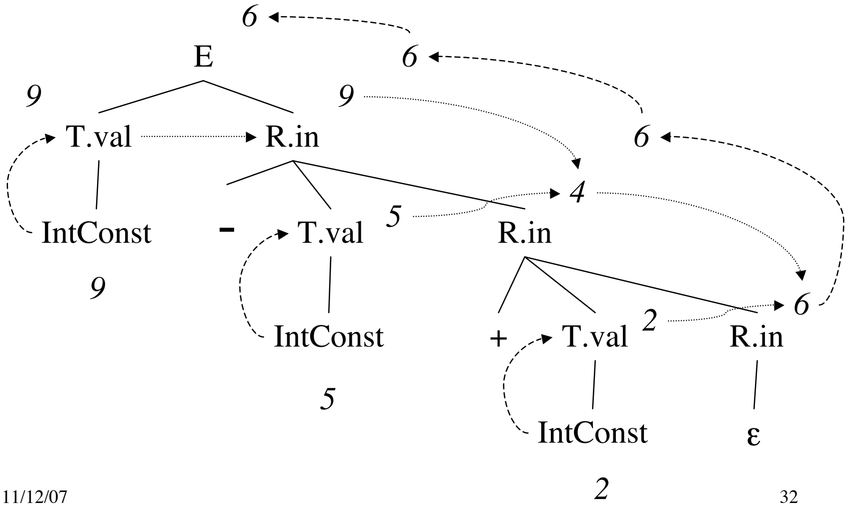
Dependencies and SDTs

- 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

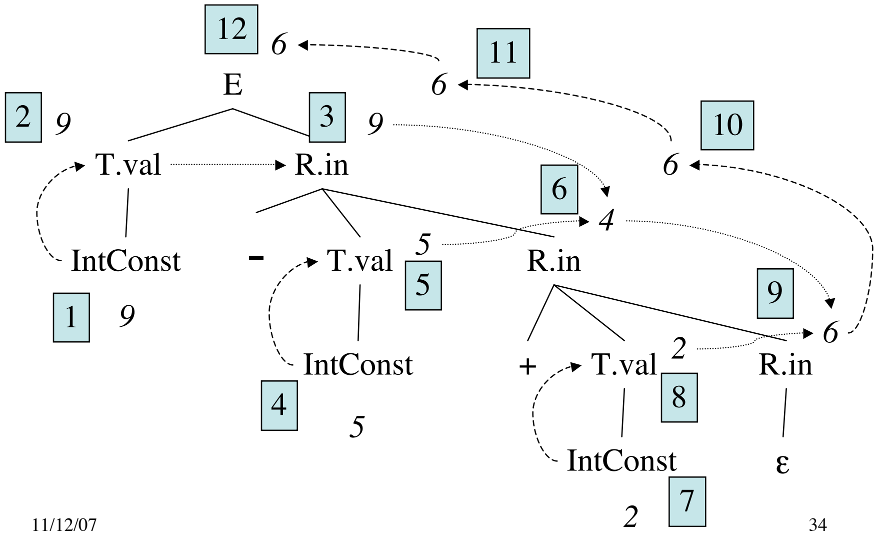
Dependency Graphs



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

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 → T R

R → + T { print(‘+’); } R

R → – T { print(‘–’); } R

R → ε

T → **id** { print(**id**.lookup); }

SDTs with Actions

- An impossible syntax directed definition that maps infix expressions to prefix:

E → T R

R → { print(‘+’); } + T R

R → { print(‘–’); } – T R

R → ε

T → **id** { print(**id**.lookup); }

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

LR parsing and inherited attributes

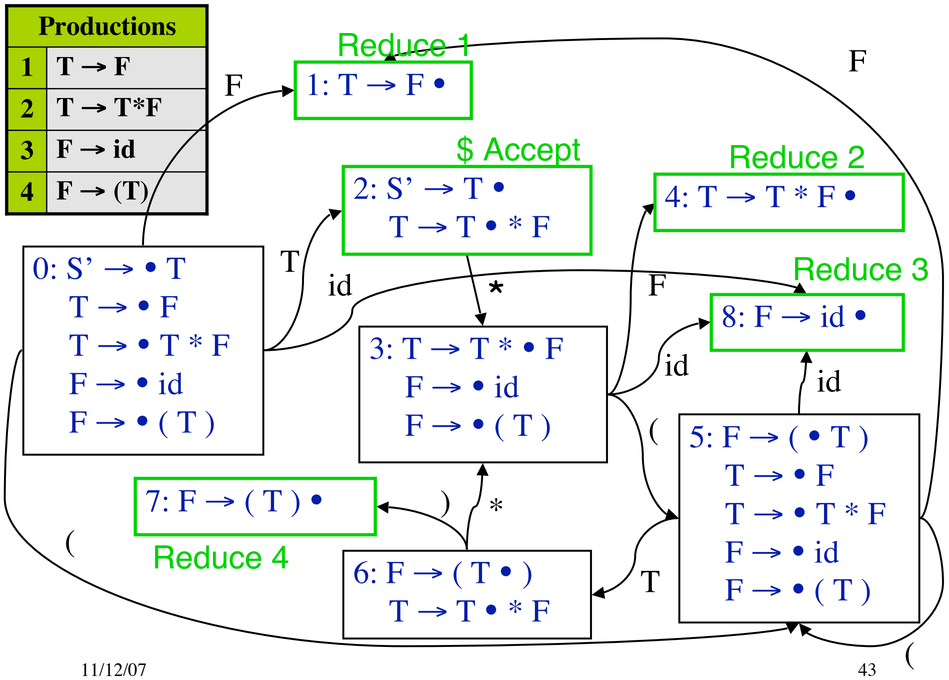
- As we just saw, inherited attributes are possible when doing top-down parsing
- How can we compute inherited attributes in a bottom-up shift-reduce parser
- Problem: doing it incrementally (while parsing)
- Note that LR parsing implies depth-first visit which matches L-attributed definitions

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 = $1.val; }
```



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 * $2.val; }
			3 pops;

0 2	**$**	**Accept**	**a.Push 3*2=6**

Example: Inherited Attributes

E → T R

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

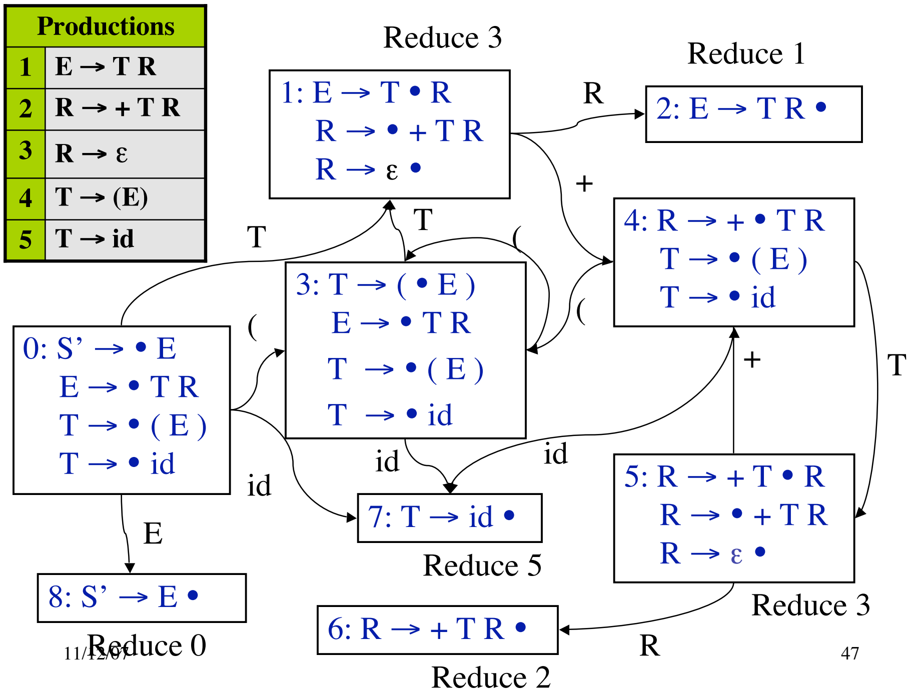
R → + T R

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

R → ε { $0.val = $0.in; }

T → (E) { $0.val = $1.val; }

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



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

0: S' → • E
E → • T R
T → • (E)
T → • id

1: E → T • R
R → • + T R
R → ε •

Reduce 3

2: E → T R •

Reduce 1

3: T → (• E)
E → • T R
T → • (E)
T → • id

4: R → + • T R
T → • (E)
T → • id

5: R → + T • R
R → • + T R
R → ε •

Reduce 3

6: R → + T R •

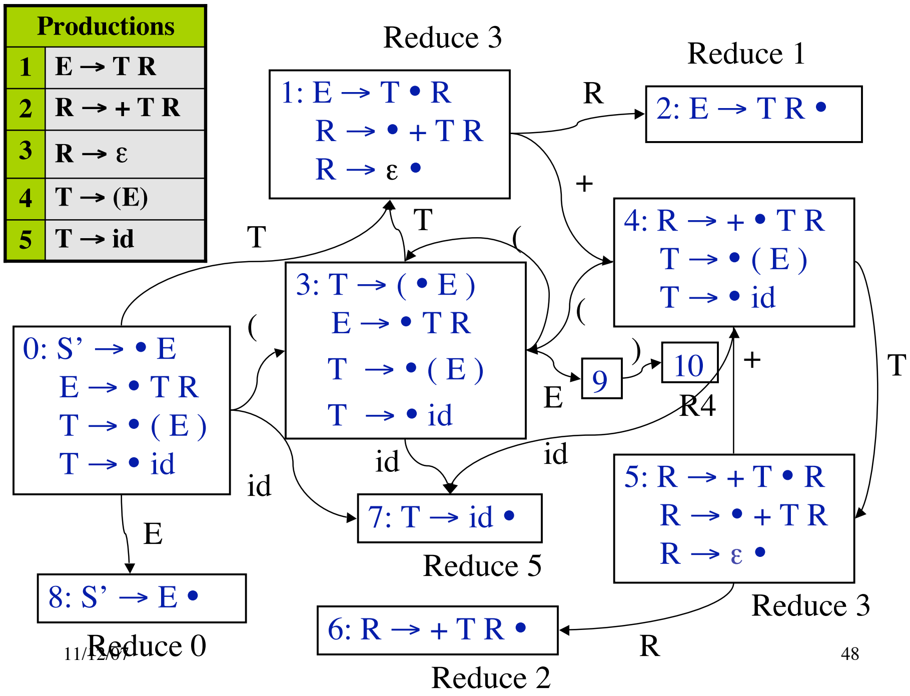
Reduce 2

7: T → id •

Reduce 5

8: S' → E •

Reduce 0



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

0: S' → • E
E → • T R
T → • (E)
T → • id

1: E → T • R
R → • + T R
R → ε •

Reduce 3

2: E → T R •

Reduce 1

3: T → (• E)
E → • T R
T → • (E)
T → • id

4: R → + • T R
T → • (E)
T → • id

5: R → + T • R
R → • + T R
R → ε •

Reduce 3

6: R → + T R •

Reduce 2

7: T → id •

Reduce 5

8: S' → E •

Reduce 0

9

10

R4

	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)
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	{ $3.in = $0.in+$1.val
		goto [5,R]=6	(5).attr := (1).attr+2
			$0.val = $0.in
			$0.val = (5).attr = 5 }

Trace “$\text{id}_{\text{val=3}}$+$\text{id}_{\text{val=2}}$”

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	{ $3.in = $0.in+$1.val
		goto [5,R]=6	(5).attr := (1).attr+2
			$0.val = $0.in
			$0.val = (5).attr = 5 }

Trace “$\text{id}_{\text{val=3}}$+$\text{id}_{\text{val=2}}$”

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; }**

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’]

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

  R → + T M R

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

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

Marker Non-terminals

E → T R

R → + T { print('+'); } R

R → - T { print('-'); } R

R → ε

T → **id** { print(**id**.lookup); }

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

Marker Non-terminals

E → T R
R → + T M R
R → - T N R
R → ε
T → **id** { print(**id**.lookup); }
M → ε { print(‘+’); }
N → ε { print(‘-’); }

Equivalent SDT using *marker non-terminals*

Impossible Syntax-directed Definition

E → { print(‘+’); } E + T
E → T
T → { print(‘*’); } T * R
T → F
T → **id** { print $1.lexval; }

Tries to convert infix to prefix

Impossible either top-down or bottom-up. Problematic only for left-to-right processing, ok for generation from parse tree.

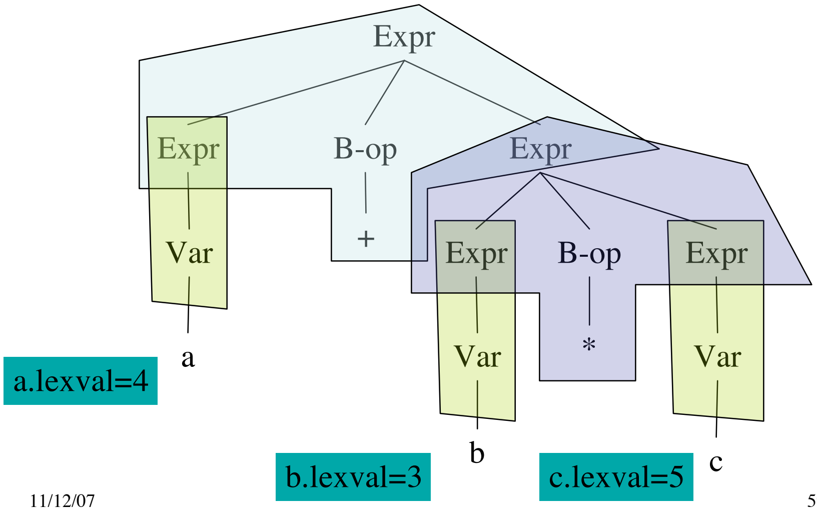
Tree Matching Code Generators

- 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

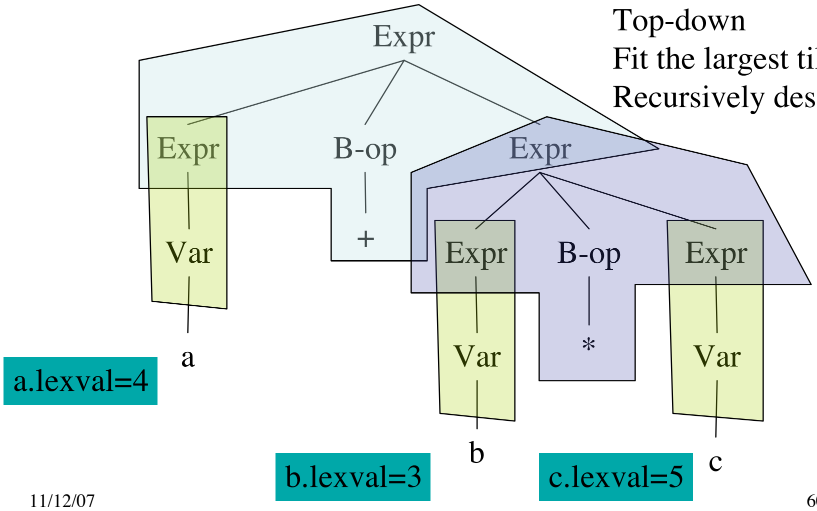
- To provide a unique output, we assign costs to the use of each tree pattern
- E.g. assigning uniform costs leads to smaller code or instruction costs can be used for optimizing code generation
- Three algorithms: Maximal Munch, Dynamic Programming, Tree Grammars
- Section 8.9 (Purple Dragon book)

Maximal Munch: Example 1

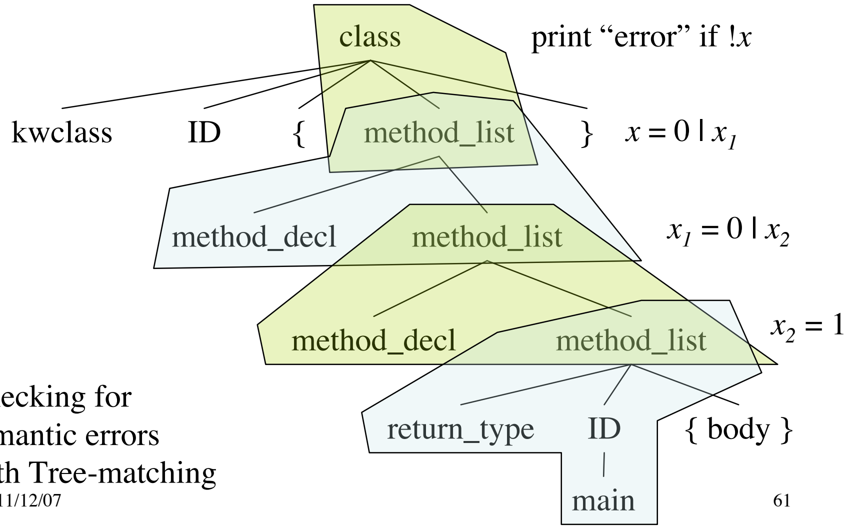


Maximal Munch: Example 1

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