Syntax-Directed Translation and Intermediate Code Generation

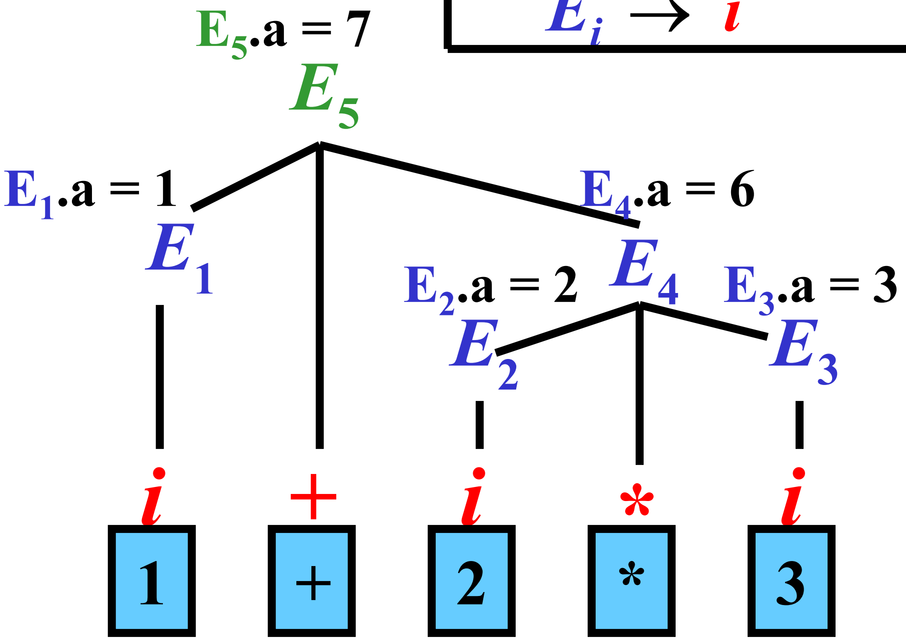
Chapter 6

Syntax-Directed Translation

Gist: *Semantic actions* are attached to gramatical rules. Most importantly, these actions make intermediate code generation and type checking.

Example:

Rule:	Semantic Action:
$E_i \to E_j + E_k$	$\{E_i.a := E_j.a + E_k.a\}$
$E_i \to E_j * E_k$	$\{E_i.a := E_j.a * E_k.a\}$
$E_i \to (E_j)$	$\{E_i.a := E_j.a\}$
$E_i \to i$	$\{E_i.a := i.val\}$



Rule:	Action:
$E_1 \to i$	$E_1.a := i.val$
$E_2 \to i$	$E_2.a := i.val$
$E_3 \to i$	$E_3.a := i.val$
$E_4 \to E_2 * E_3$	$E_4.a := E_2.a * E_3.a$
$E_5 \to E_1 + E_4$	$E_5.a := E_1.a + E_4.a$

Intermediate Code: Three–Address Code

- Instruction in **three–address code** (**3AC**) has the form:

(o, ☛a, ☛b, ☛r)

- **o** – operator (+, –, *, …)
- **a** – operand 1 (☛*a* = address of *a*)
- **b** – operand 2 (☛*b* = address of *b*)
- **r** – result (☛*r* = address of *r*)

Examples:

```
(:=   ,  a,   ,  c )  ... c := a
(+    ,  a, b,  c )  ... c := a + b
(not  ,  a,   ,  b )  ... b := not(a)
(goto,     ,   , L1)  ... goto L1
(goto,  a,   , L1)  ... if a = true then goto L1
(lab  , L1,   ,   )  ... label L1:
```

Syntax-Directed Generation of 3AC

Basic approaches:

1) Parser directs the creation of an ***abstract-syntax tree*** **(AST)** , which is then converted to **3AC**.

Syntax analyzer ⟷ **Semantic analyzer** → **AST** → **Intermediate code generator** → **3AC**

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2) Parser directs the creation of a ***postfix notation*** **(PN)** , which is then converted to **3AC**.

Syntax analyzer ⟷ **Semantic analyzer** → **Stack-code** → **Intermediate code generator** → **3AC**

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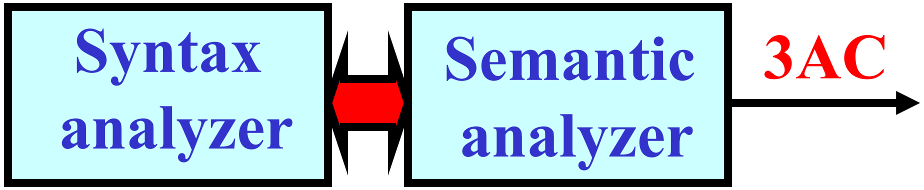
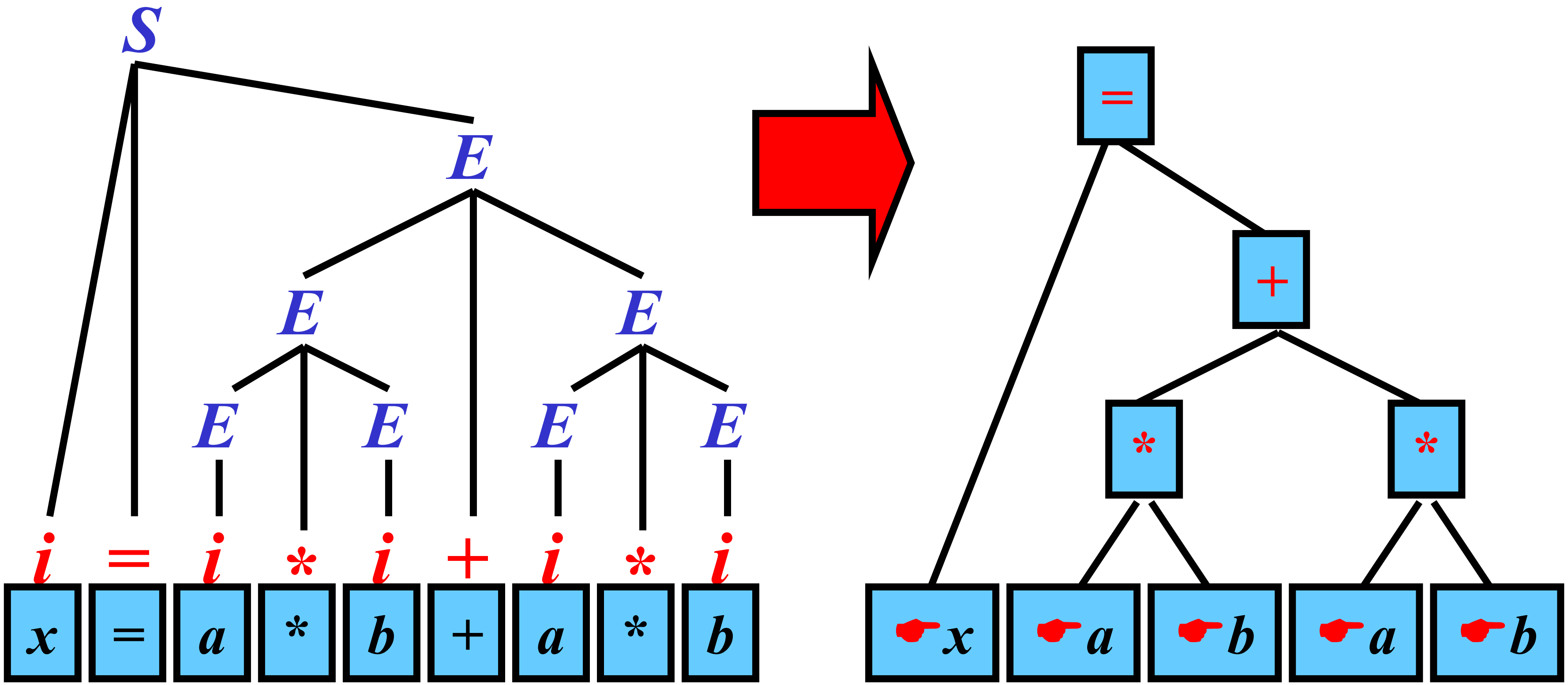
3) A parser directs the creation of **3AC.**



Syntax analyzer ⟷ **Semantic analyzer** → **3AC**

From a Parse Tree (PT) to an AST: Example

- **PT for**
  ***x = a*b + a*b*:**
- **AST for**
  ***x = a*b + a*b*:**



Generation of AST

Gist: A parser simulates the construction of PT and, simultaneously, calls some semantic actions to create AST.

Example:

Rule:	Semantic Action:
$S \rightarrow i := E_k$	{ $S.a$:= MakeTree('=', $i.a$, $E_k.a$) }
$E_i \rightarrow E_j + E_k$	{ $E_i.a$:= MakeTree('+', $E_j.a$, $E_k.a$) }
$E_i \rightarrow E_j * E_k$	{ $E_i.a$:= MakeTree('*', $E_j.a$, $E_k.a$) }
$E_i \rightarrow (E_j)$	{ $E_i.a$:= $E_j.a$ }
$E_i \rightarrow i$	{ $E_i.a$:= MakeLeaf($i.a$) }

Notes:

- **MakeTree(*o*, *a*, *b*)** creates a new node *o*, attaches sons *a* (left) and *b*, and returns a pointer to node *o*
- **MakeLeaf(*i.a*)** creates a new node *i.a* (*i.a* is a symbol-table address) and returns a pointer to this new node

AST Generation: Example 1/2

Pushdown	Input	Rule	Semantic action
$\$$	$i = (i + i) * i\$$		
$\$i$	$= (i + i) * i\$$		
$\$i =$	$(i + i) * i\$$		
$\$i = ($	$i + i) * i\$$		
$\$i = (i$	$+ \mathrm{i}) * i\$$	$E_1 \to i$	$E_1.a := \mathrm{MakeLeaf}(i.a)$
$\$i = (E_1$	$+ i) * i\$$		
$\$i = (E_1 +$	$i) * i\$$		
$\$i = (E_1 + i$	$) * i\$$	$E_2 \to i$	$E_2.a := \mathrm{MakeLeaf}(i.a)$
$\$i = (E_1 + E_2$	$) * i\$$	$E_3 \to E_1{+}E_2$	$E_3.a := \mathrm{MakeTree}(\text{‘+’}, E_1.a, E_2.a)$
$\$i = (E_3$	$) * i\$$		
$\$i = (E_3)$	$* i\$$	$E_4 \to (E_3)$	$E_4.a := E_3.a$
$\$i = E_4$	$* i\$$		
$\$i = E_4 *$	$i\$$		
$\$i = E_4 * i$	$\$$	$E_5 \to i$	$E_5.a := \mathrm{MakeLeaf}(i.a)$
$\$i = E_4 * E_5$	$\$$	$E_6 \to E_4{*}E_5$	$E_6.a := \mathrm{MakeTree}(\text{‘*’}, E_4.a, E_5.a)$
$\$i = E_6$	$\$$	$S \to i = E_6$	$S.a := \mathrm{MakeTree}(\text{‘=’}, i.a, E_6.a)$
$\$S$	$\$$		

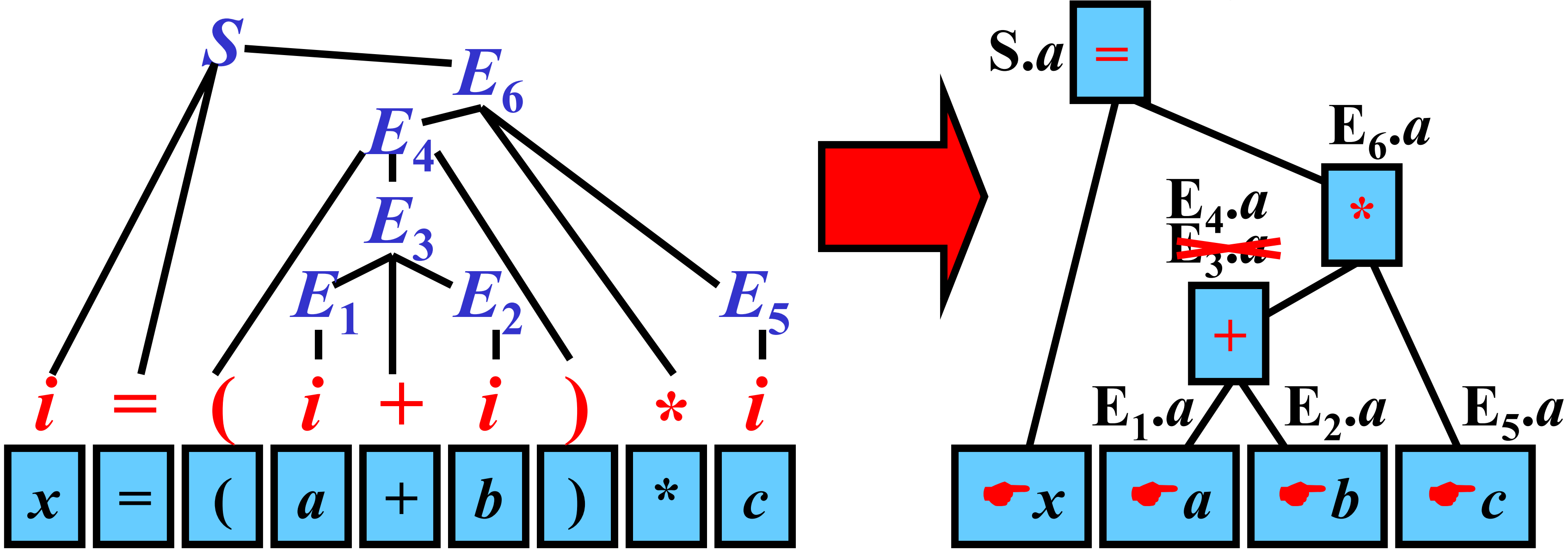
Bottom-Up parsing

Semantic actions

AST Generation: Example 2/2

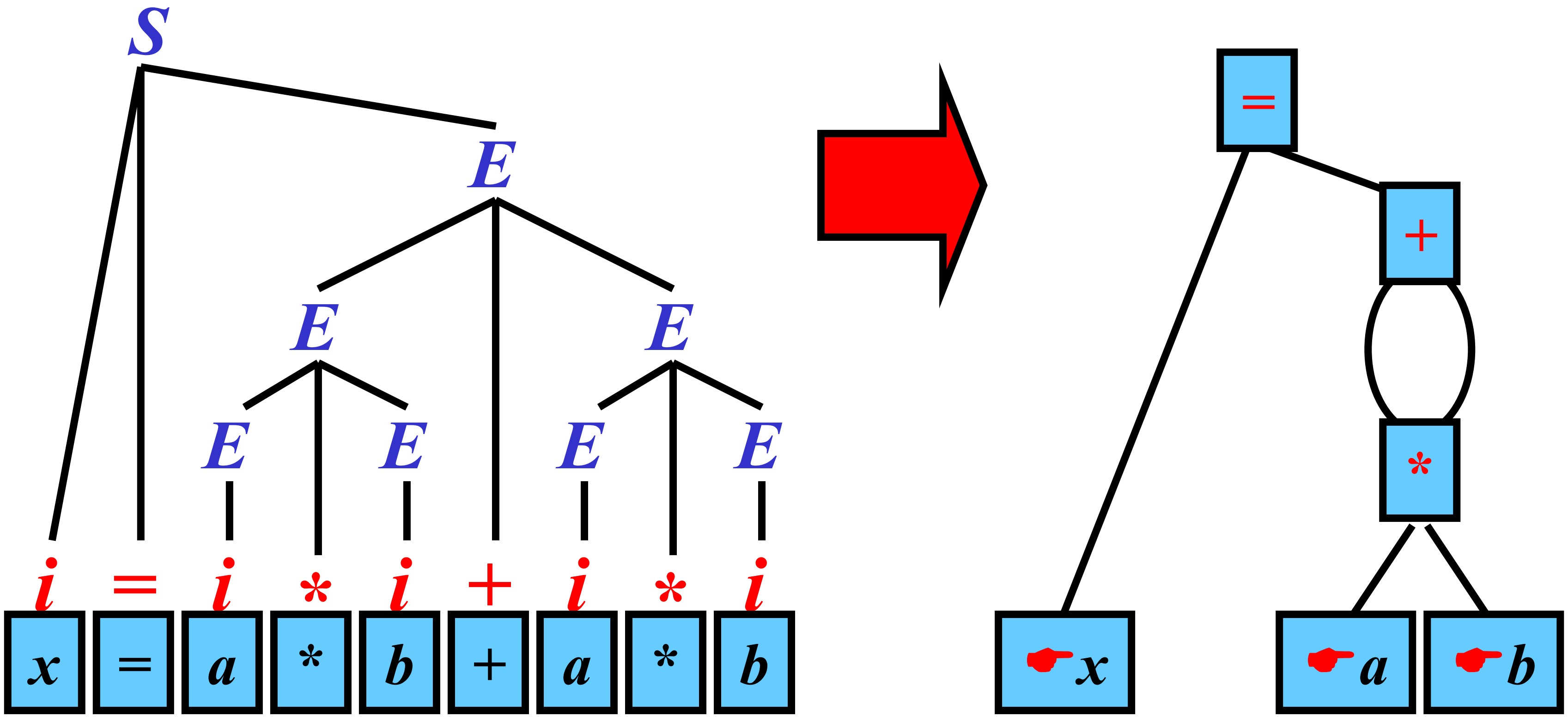
Rule:	Semantic Action:
$E_1 \rightarrow i$	$E_1.a$:= MakeLeaf($i.a$)
$E_2 \rightarrow i$	$E_2.a$:= MakeLeaf($i.a$)
$E_3 \rightarrow E_1+E_2$	$E_3.a$:= MakeTree('+', $E_1.a, E_2.a$)
$E_4 \rightarrow (E_3)$	$E_4.a$:= $E_3.a$
$E_5 \rightarrow i$	$E_5.a$:= MakeLeaf($i.a$)
$E_6 \rightarrow E_4 * E_5$	$E_6.a$:= MakeTree('*', $E_4.a, E_5.a$)
$S \rightarrow i = E_6$	$S.a$:= MakeTree('=', $i.a, E_6.a$)

Simulated Parse tree: **Abstract syntax tree:**



Direct Acyclic Graph(DAG): Example

- **Parse tree for** $x = a*b + a*b$:
- **DAG for** $x = a*b + a*b$:



Note: DAG has no redundant nodes.

Postfix Notation

Gist: Every operator occurs behind its operands.

Example:

Infix notation	Postfix notation
$a + b$	$a\ b\ +$
$a = b$	$a\ b\ =$
if C **then** S_1 **else** S_2	$C\ S_1\ S_2$ **if-then-else**

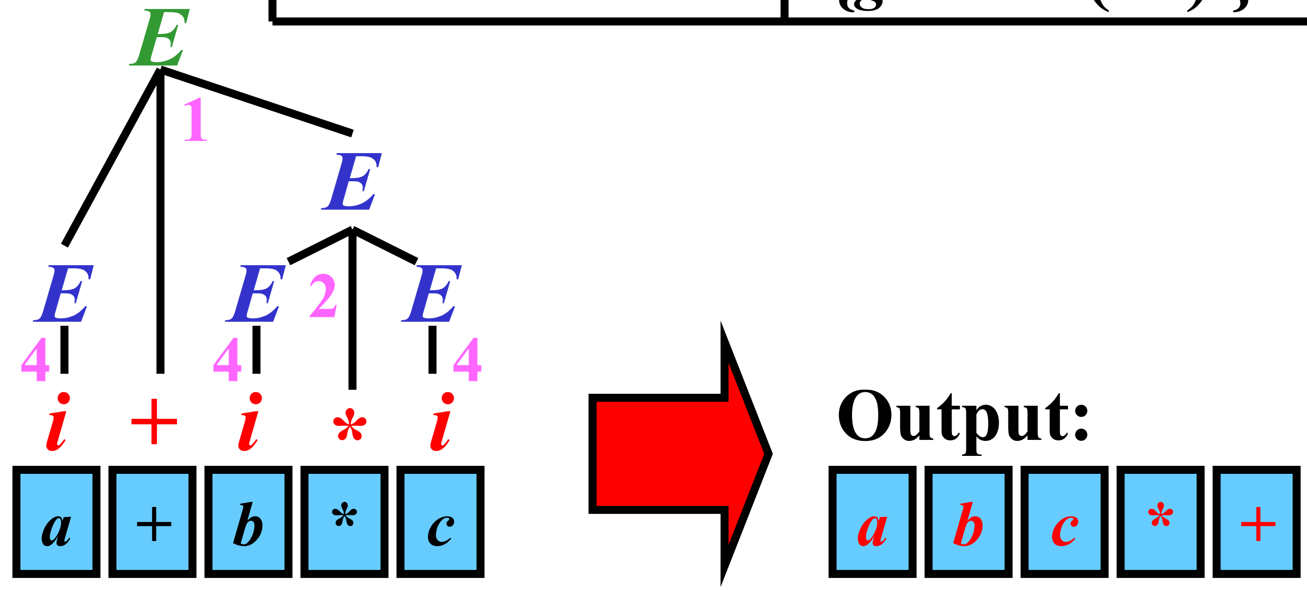
Note: Postfix notation is achievable by the postorder traversal of AST.

Infix to Postfix Directed by a BU Parser

Gist: Semantic actions produce the postfix version of the tokenized source program.

Example:

Rule:	Semantic Action:
1: $E \rightarrow E+E$	{*generate*('+')}
2: $E \rightarrow E*E$	{*generate*('*')}
3: $E \rightarrow (E)$	{ - }
4: $E \rightarrow i$	{*generate*(*i.a*) }



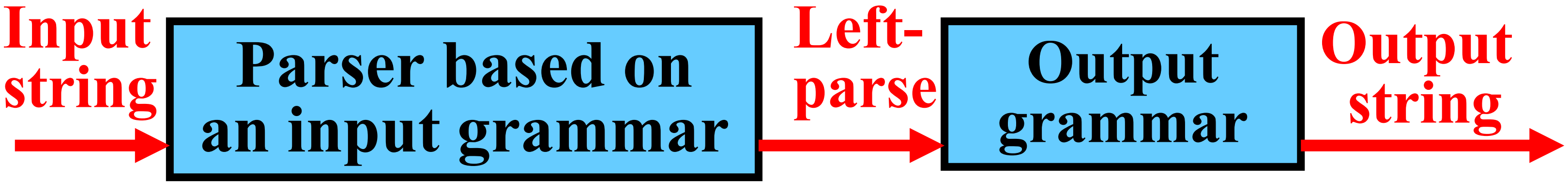
Input: *a* + *b* * *c*

Output: *a* *b* *c* * +

Translation Grammars

Gist: Translation grammars translate input strings to output strings

1) Translation by two grammars:



Input string

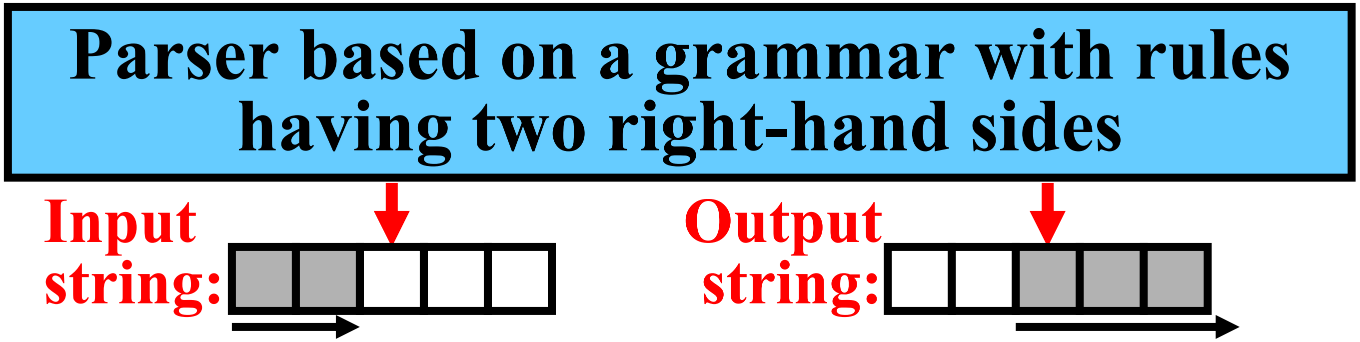
Parser based on an input grammar

Left-parse

Output grammar

Output string

2) Translation by a single grammar



Parser based on a grammar with rules having two right-hand sides

Input string:

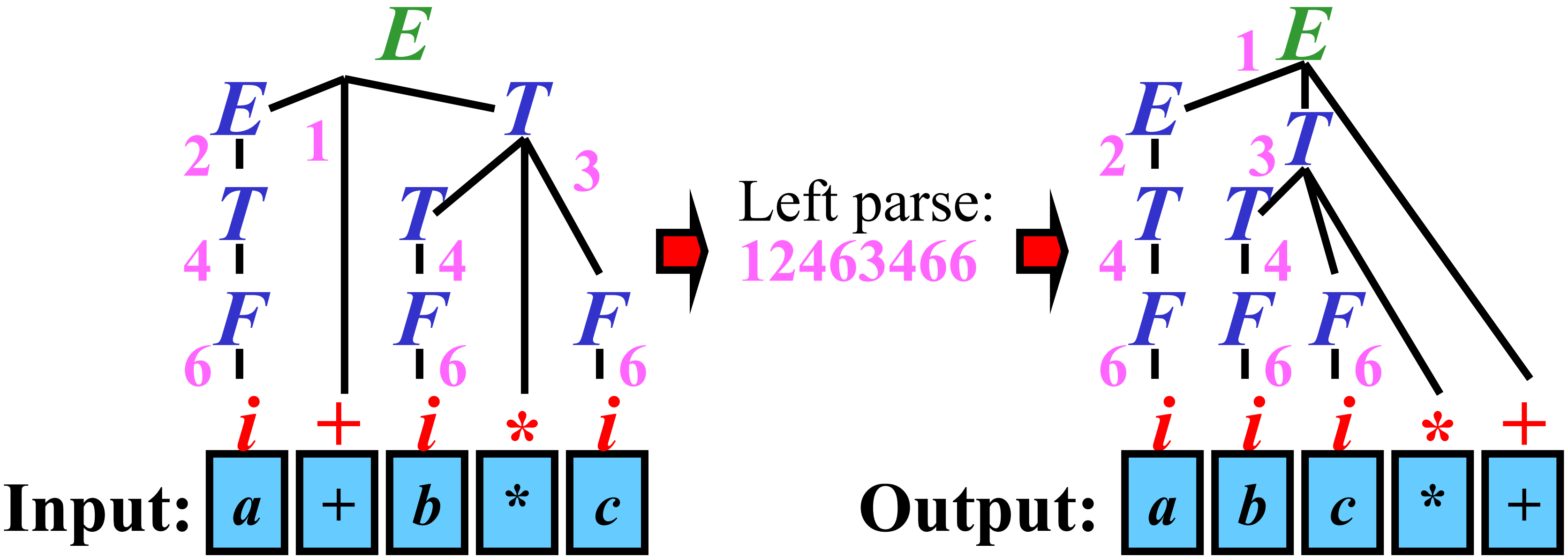
Output string:

Note: During the parse of an input string, a simultaneous generation f an output string occurs

Two-Grammar Translation

Infix to postfix translation:

Rules of G_1	Rules of G_2
1: $E \rightarrow E+T$	1: $E \rightarrow ET+$
2: $E \rightarrow T$	2: $E \rightarrow T$
3: $T \rightarrow T*F$	3: $T \rightarrow TF*$
4: $T \rightarrow F$	4: $T \rightarrow F$
5: $F \rightarrow (E)$	5: $F \rightarrow E$
6: $F \rightarrow i$	6: $F \rightarrow i$

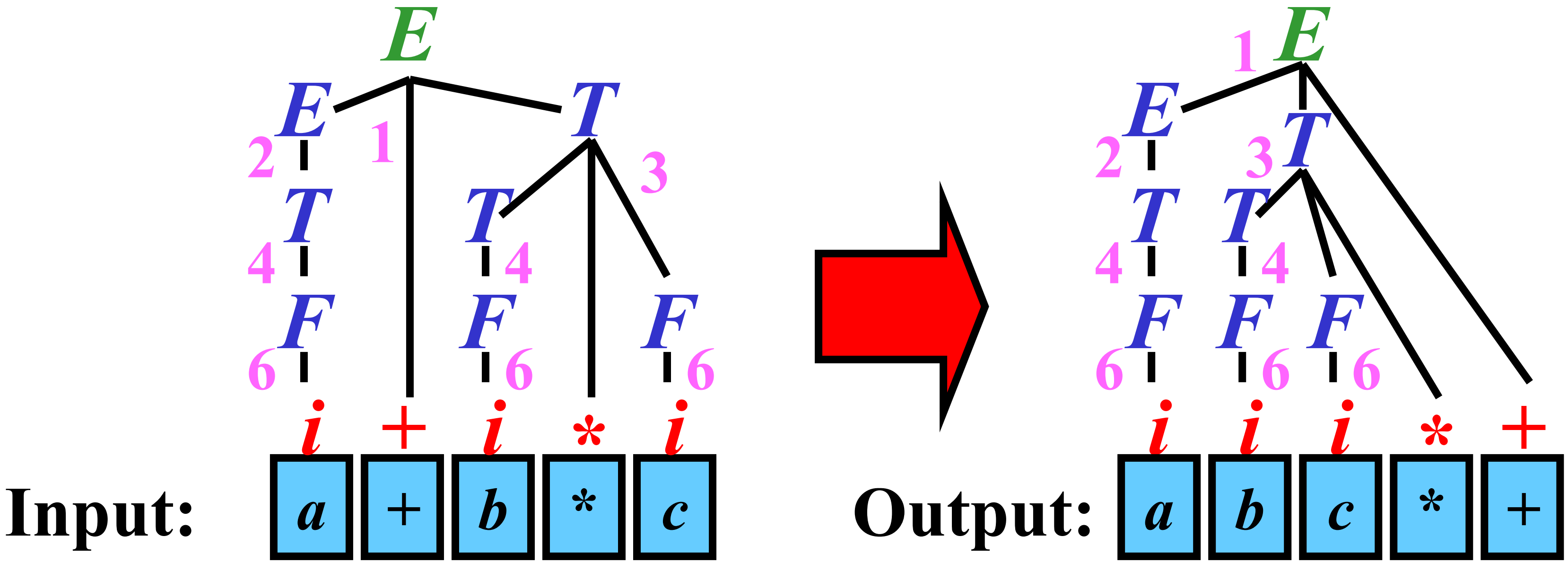


Left parse: 12463466

One-Grammar Translation

Infix to postfix translation:

Rule	Tran. Element
1: $E \to E+T$	$ET+$
2: $E \to T$	T
3: $T \to T*F$	$TF*$
4: $T \to F$	F
5: $F \to (E)$	E
6: $F \to i$	i

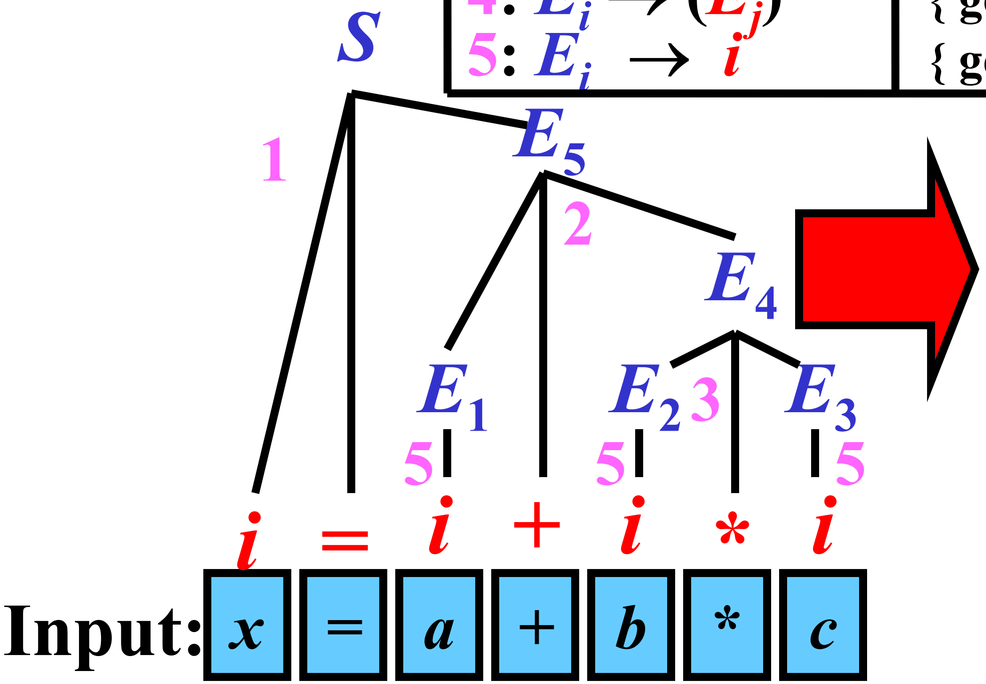


Direct Generation of 3AC

Gist: BU parser directs the generation of 3AC directly.

Example:

Rule:	Semantic Action:
1: $S \rightarrow i = E_k$	{ generate(‘=’, $E_k.loc$, , $i.loc$)}
2: $E_i \rightarrow E_j + E_k$	{ generate(‘+’, $E_j.loc$, $E_k.loc$, $E_i.loc$)}
3: $E_i \rightarrow E_j * E_k$	{ generate(‘*’, $E_j.loc$, $E_k.loc$, $E_i.loc$)}
4: $E_i \rightarrow (E_j)$	{ generate(‘=’, $E_j.loc$, , $E_i.loc$)}
5: $E_i \rightarrow i$	{ generate(‘=’, $i.loc$, , $E_i.loc$)}



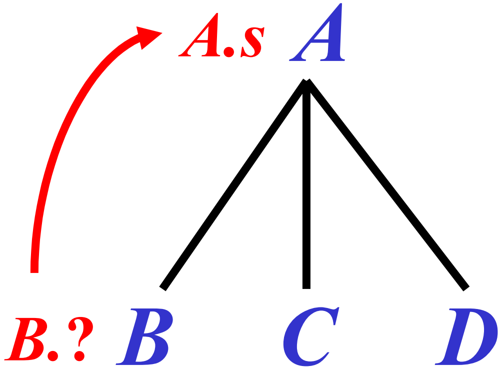
Output:

(‘=’, ☛a, , $E_1.loc$)
(‘=’, ☛b, , $E_2.loc$)
(‘=’, ☛c, , $E_3.loc$)
(‘*’, $E_2.loc$, $E_3.loc$, $E_4.loc$)
(‘+’, $E_1.loc$, $E_4.loc$, $E_5.loc$)
(‘=’, $E_5.loc$, , ☛x)

Top-Down Translation: Introduction

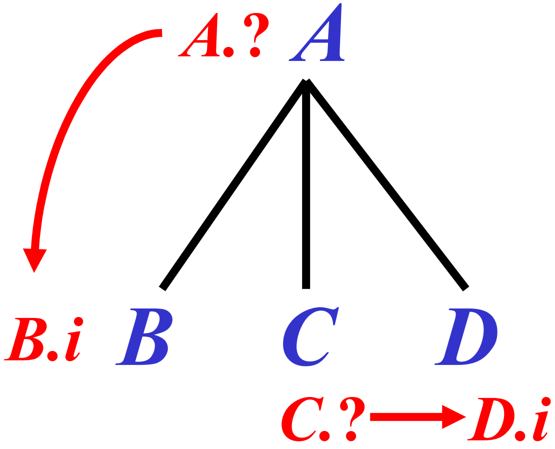
- **LL-grammar with attributes**
- **Two pushdown:**
  - **parser pushdown × semantic pushdown**
- **Two type of attributes:**
  - **synthesized:**

(from children to parent)



iherited:

(from parent to children or between siblings)

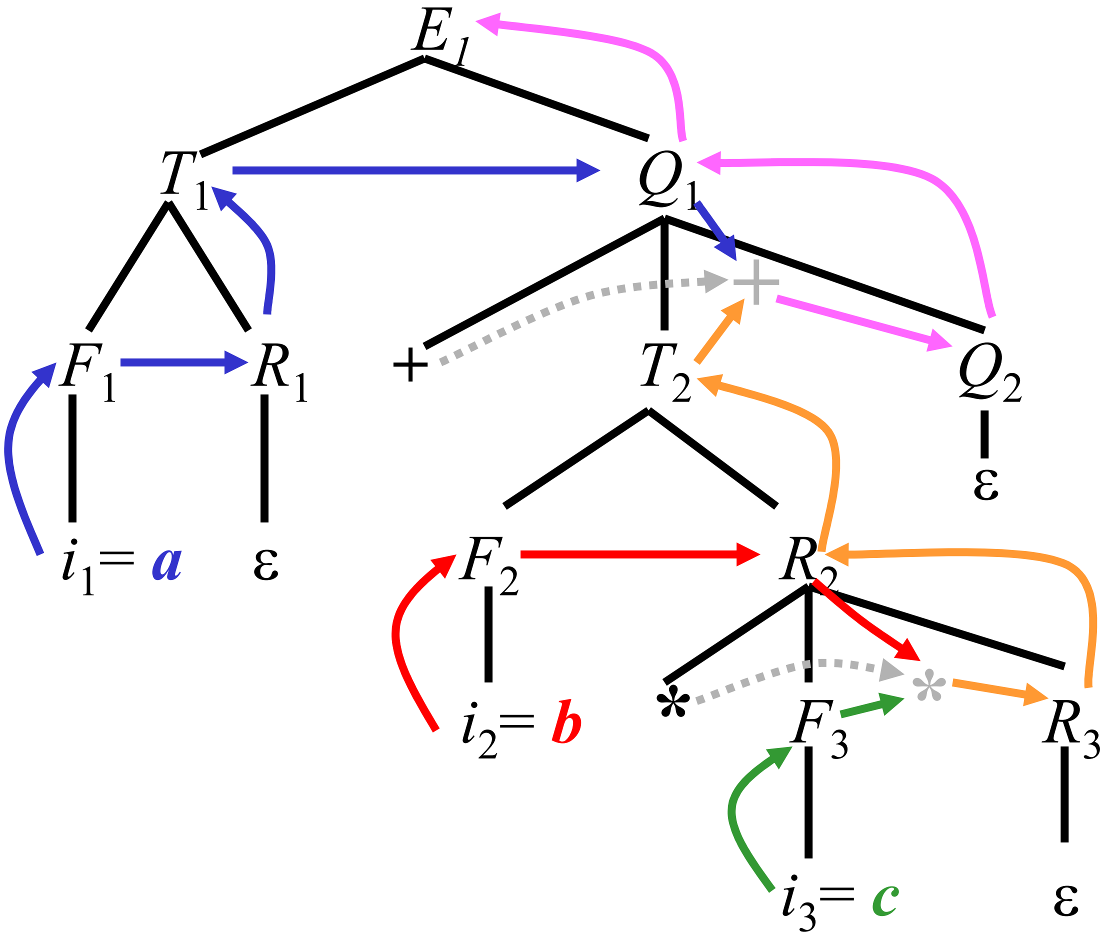


Top-Down Translation: Expressions

Grammar:

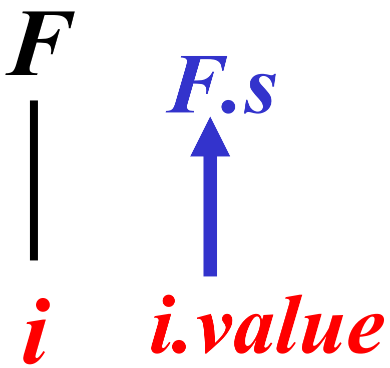
$E \rightarrow TQ$
$Q \rightarrow +TQ$
$Q \rightarrow \varepsilon$
$T \rightarrow FR$
$R \rightarrow *FR$
$R \rightarrow \varepsilon$
$F \rightarrow (E)$
$F \rightarrow i$

Parse tree for *a* + *b* * *c*:



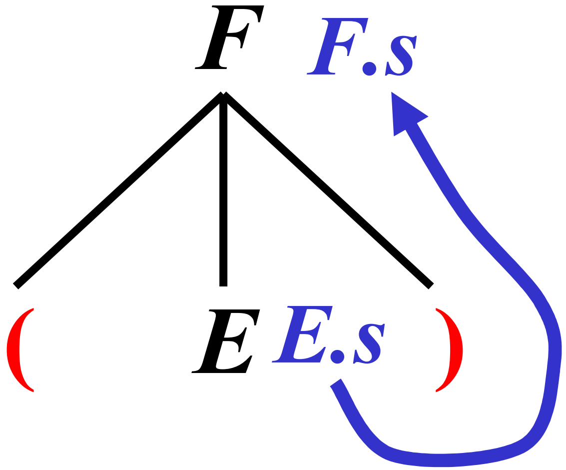
Expressions: Variable & Parentheses

Variable:



$F \rightarrow i\ \{F.s := i.value\}$

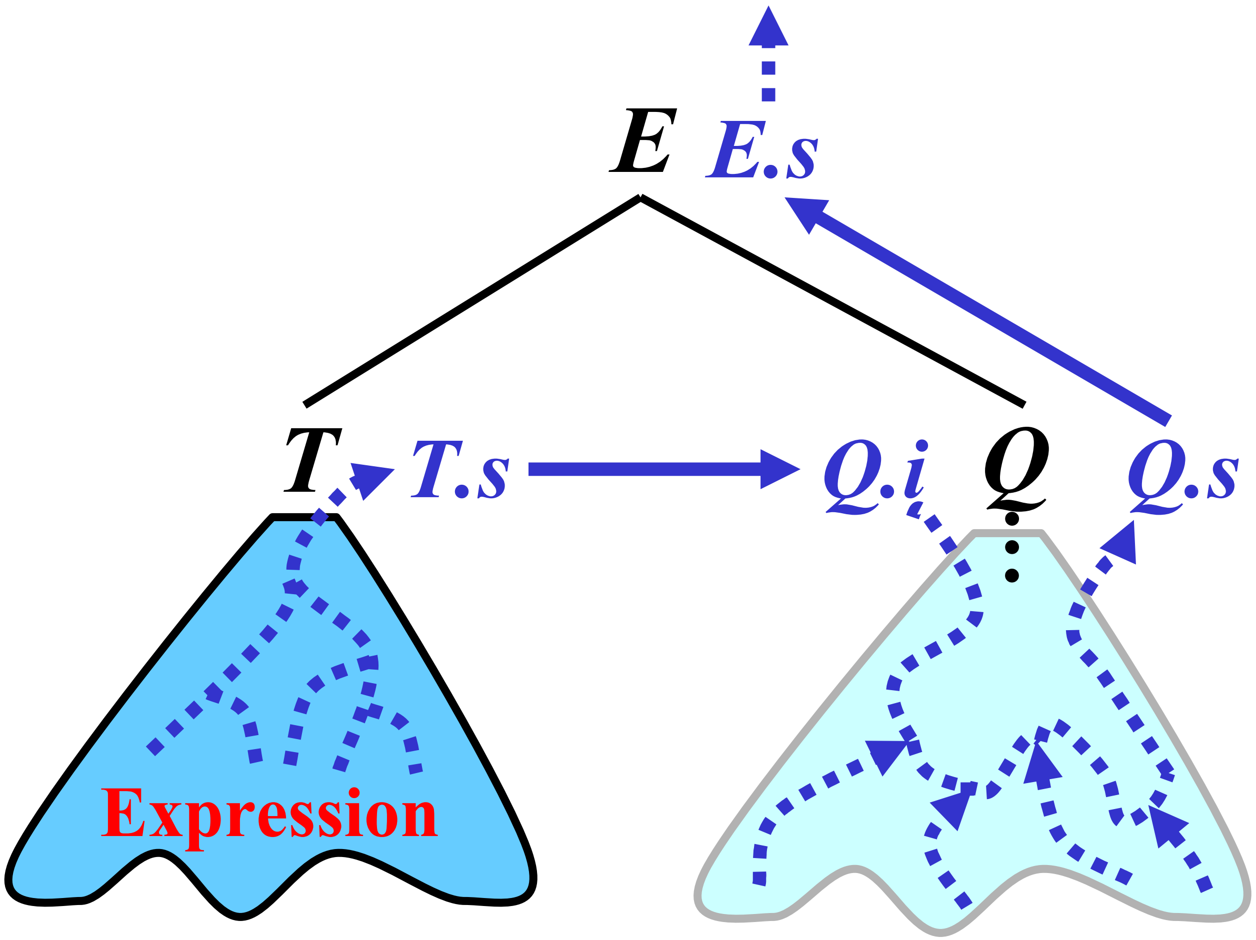
Parentheses:



$E \rightarrow (F\ \{F.s := E.s\}\ )$

Expressions: Addition 1/4

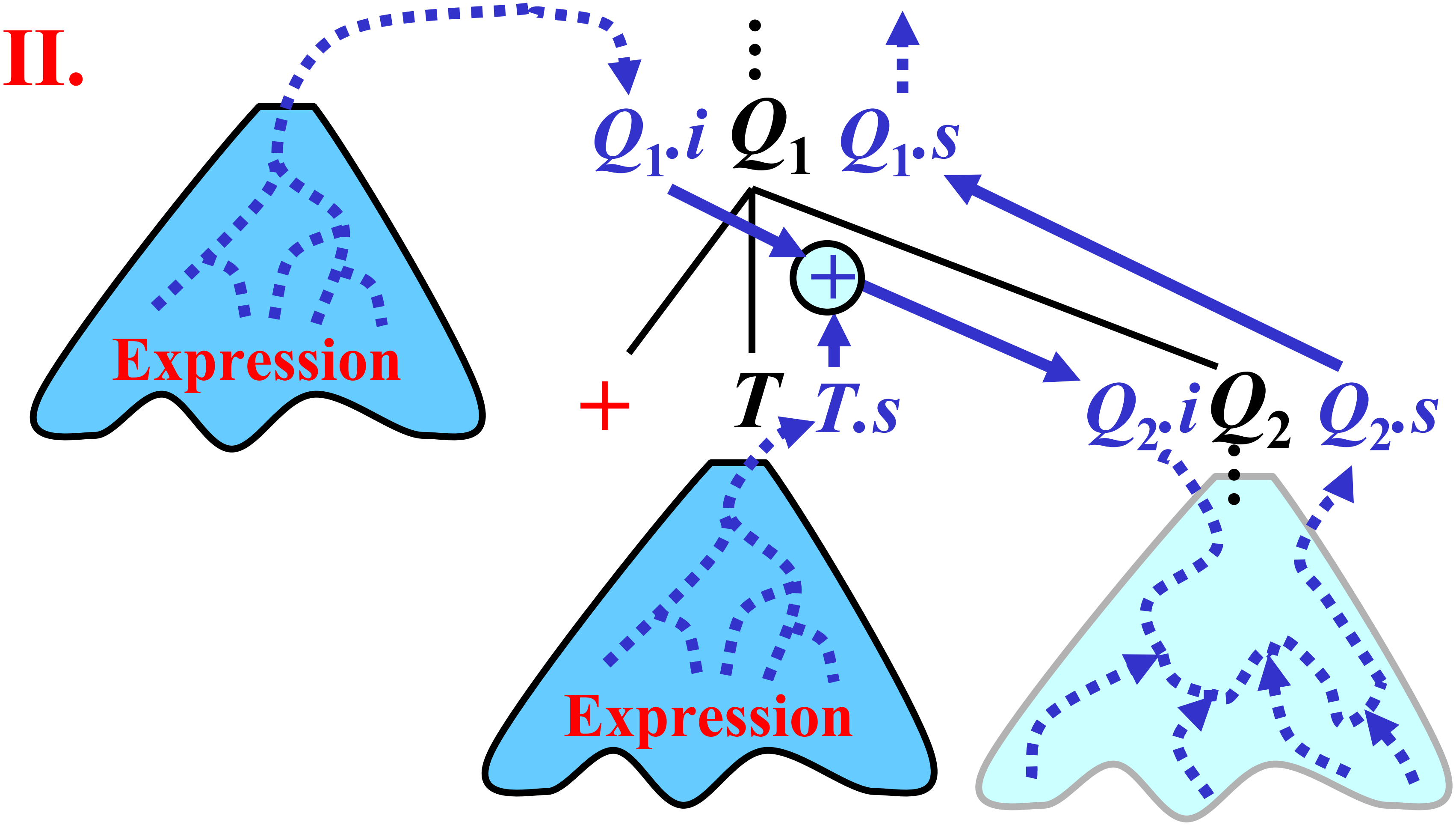
I.



$E \rightarrow T \; \{ \, Q.i := T.s \, \} \; Q \; \{ \, E.s := Q.s \, \}$

Expressions: Addition 2/4

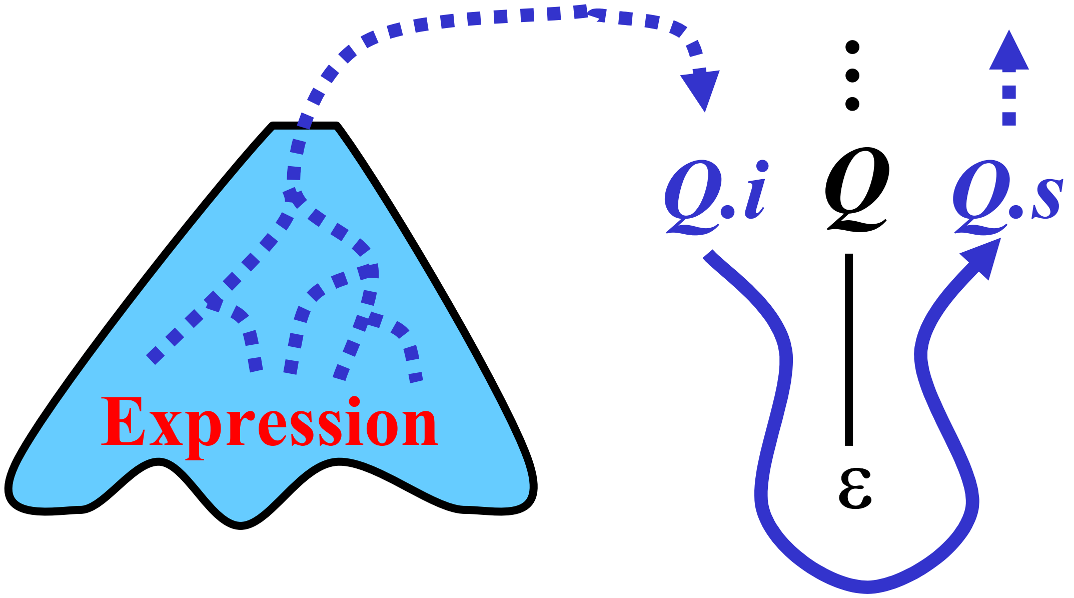
II.



$$Q_1 \rightarrow +T \, \{ \, Q_2.i := Q_1.i + T.s \, \} \; Q_2 \, \{ Q_1.s := Q_2.s \, \}$$

Expressions: Addition 3/4

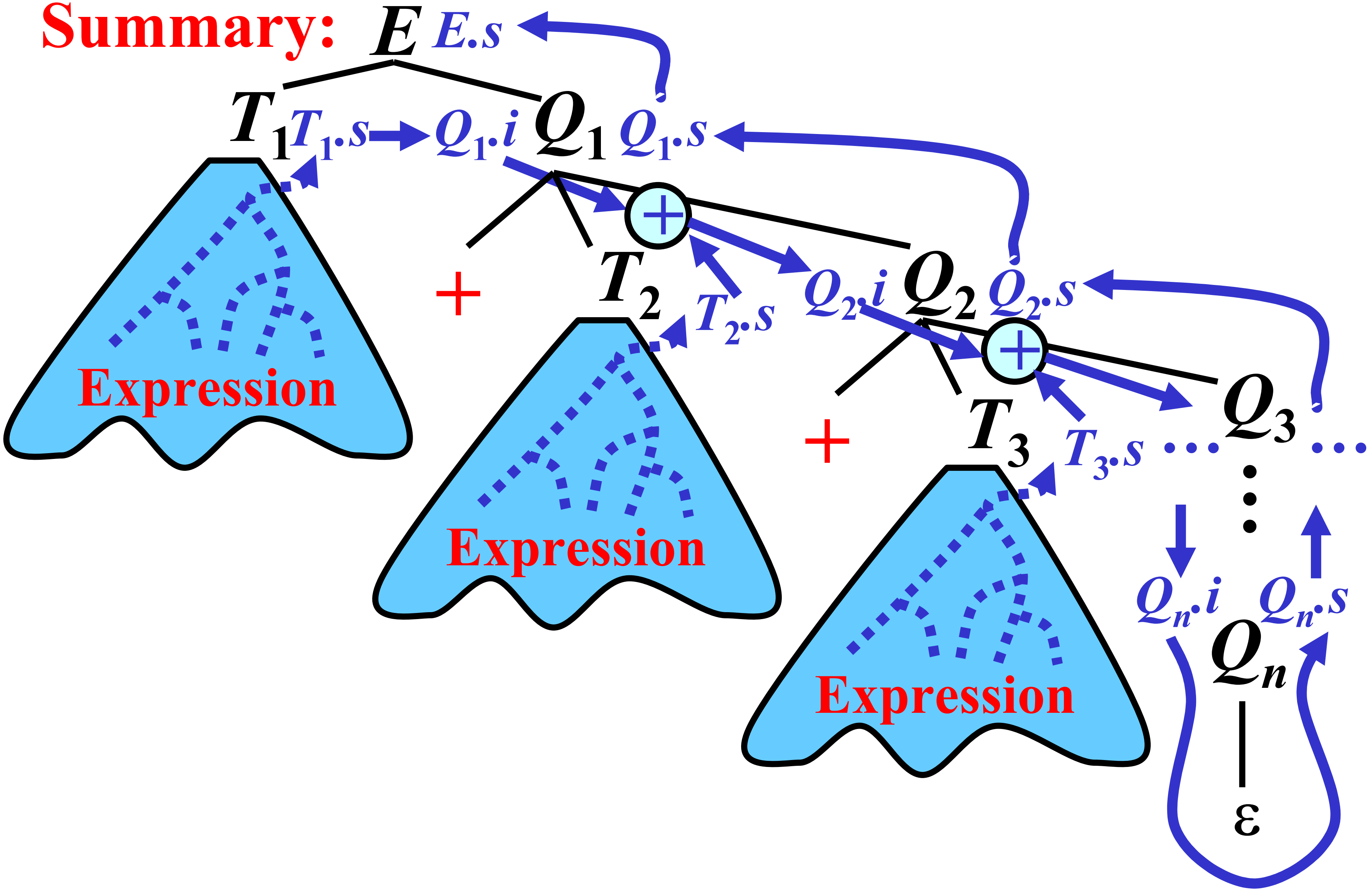
III.



$Q \rightarrow \varepsilon \quad \{Q.s := Q.i\}$

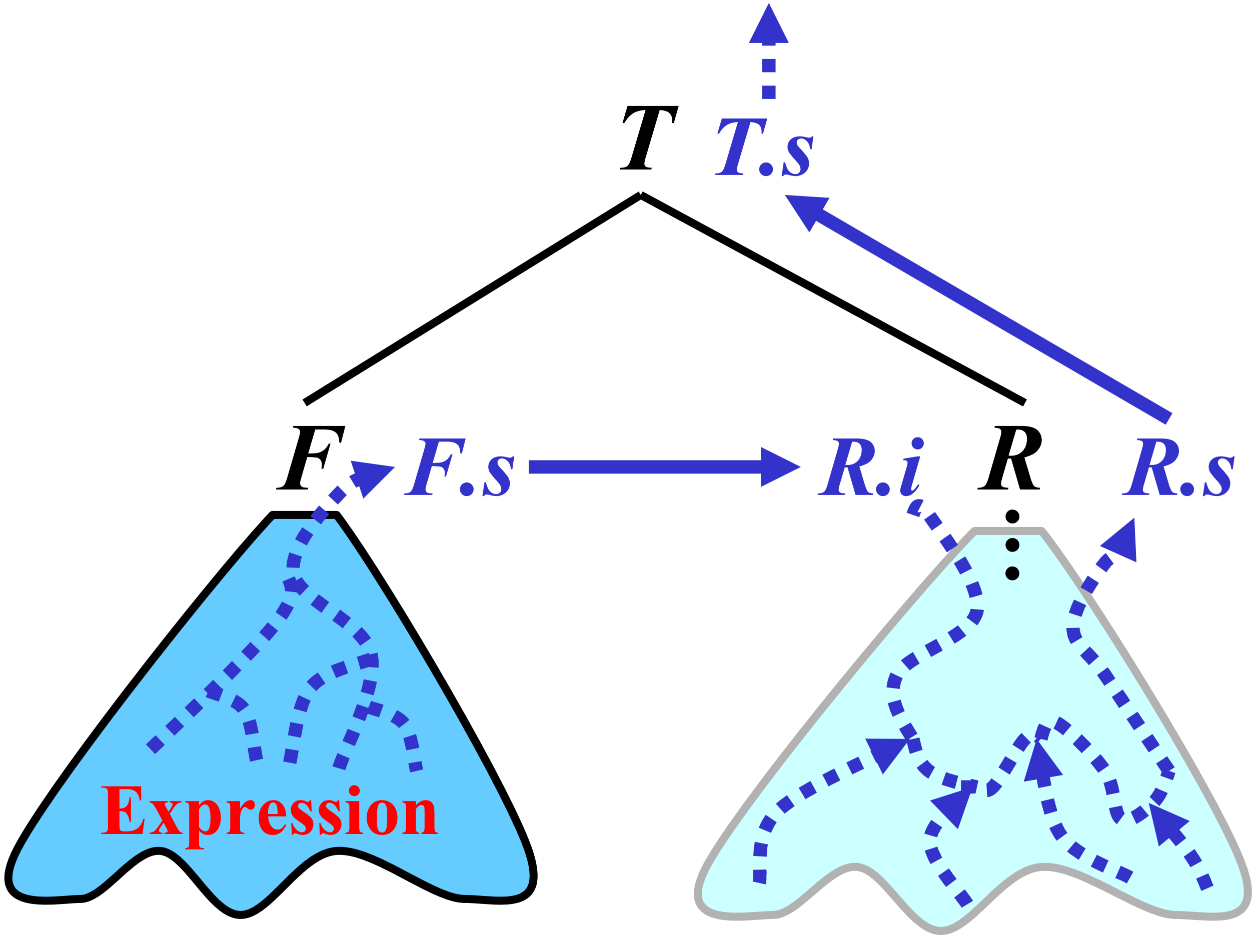
Expressions: Addition 4/4

Summary:



Expressions: Multiplication 1/4

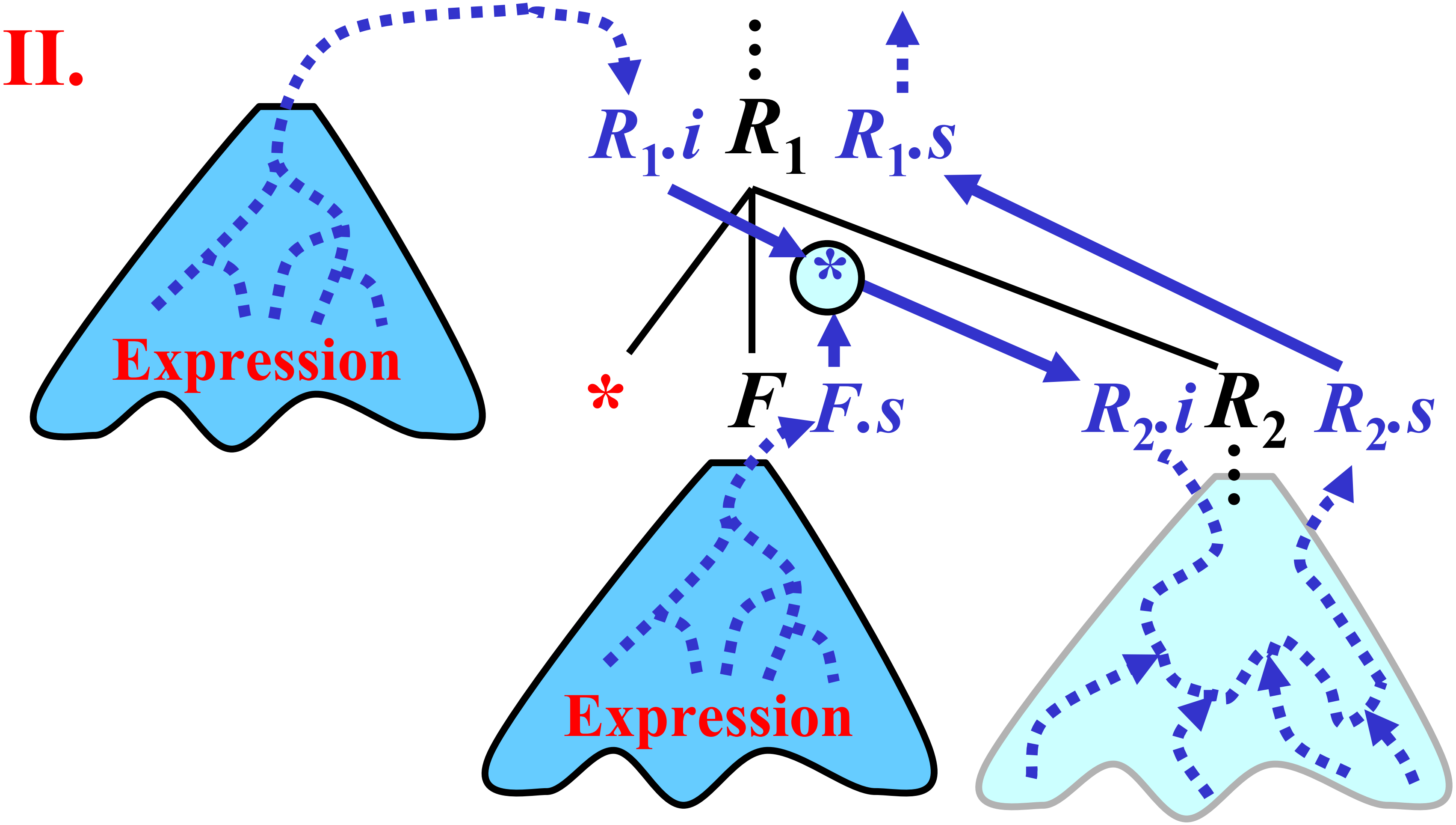
I.



$T \rightarrow F$ { $R.i := F.s$ } R { $T.s := R.s$ }

Expressions: Multiplication 2/4

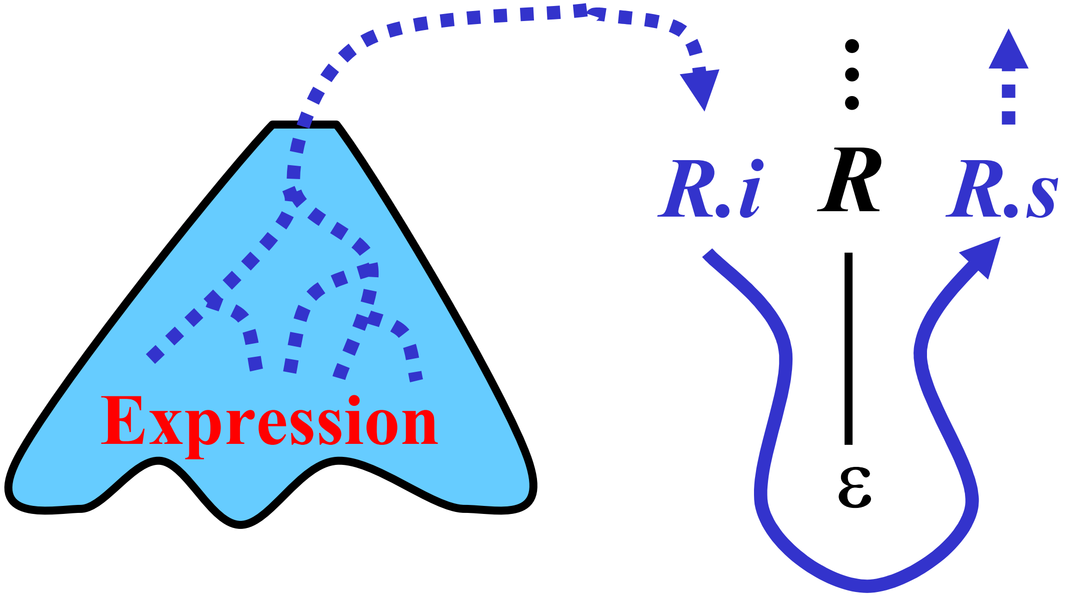
II.



$R_1 \rightarrow *F \ \{ R_2.i := R_1.i * F.s \} \ Q_2 \{ R_1.s := R_2.s \}$

Expressions: Multiplication 3/4

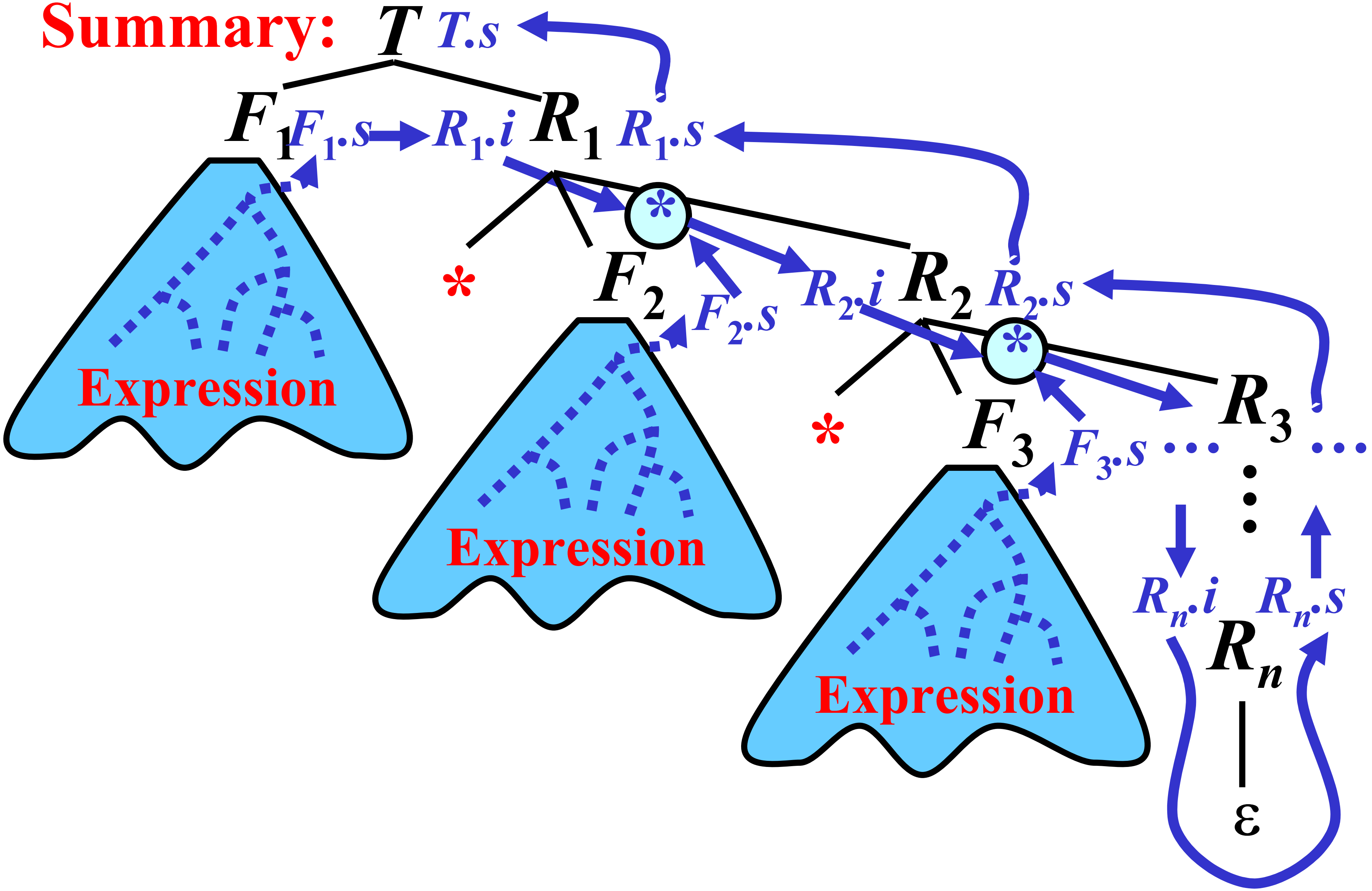
III.



$R \rightarrow \varepsilon \quad \{R.s := R.i\}$

Expressions: Multiplication 4/4

Summary:



Grammar for Expressions: Summary

1. $E \rightarrow T \; \{Q.i := T.s\} \; Q \; \{E.s := Q.s\}$
2. $Q_1 \rightarrow +T \; \{Q_2.i := Q_1.i + T.s\} \; Q_2 \; \{Q_1.s := Q_2.s\}$
3. $Q \rightarrow \varepsilon \; \{Q.s := Q.i\}$
4. $T \rightarrow F \; \{R.i := F.s\} \; R \; \{T.s := R.s\}$
5. $R_1 \rightarrow {*}F \; \{R_2.i := R_1.i * F.s\} \; R_2 \; \{R_1.s := R_2.s\}$
6. $R \rightarrow \varepsilon \; \{R.s := R.i\}$
7. $F \rightarrow (E \; \{F.s := E.s\} \;)$
8. $F \rightarrow i \; \{F.s := i.value\}$

Evaluation of Expressions: Example 1/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: $i_1 + i_2\ \$$

Rule: $E \rightarrow T_1\ \{Q_1.i := T_1.s\}\ Q_1\ \{E.s := Q_1.s\}$

Parser pushdown:

E

$\$$

Semantic pushdown:

Illustration:

E

10 + 20

Evaluation of Expressions: Example 2/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: $i_1 + i_2\ \$$

Rule: $T_1 \rightarrow F_1\ \{R_1.i := F_1.s\}\ R_1\ \{T_1.s := R_1.s\}$

Parser pushdown:

T_1

$\{Q_1.i := T_1.s\}$

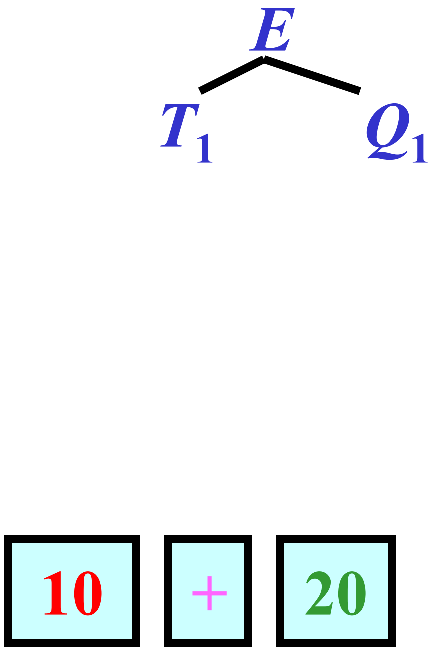
Q_1

$\{E.s := Q_1.s\}$

$\$$

Semantic pushdown:

Illustration:



Evaluation of Expressions: Example 3/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: $i_1 + i_2$ \$

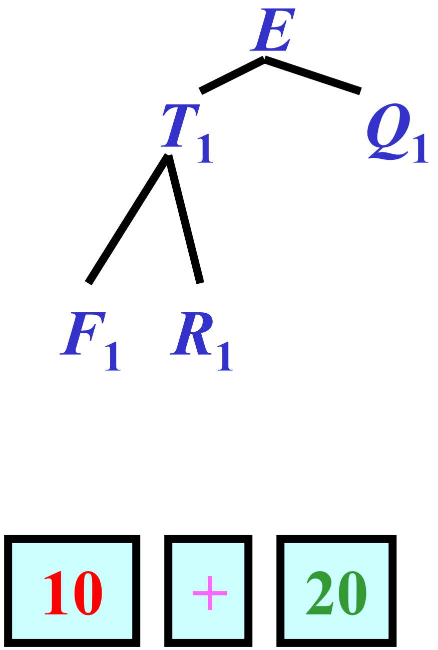
Rule: $F_1 \rightarrow i_1$ $\{F_1.s := i.value\}$

Parser pushdown:

F_1
$\{R_1.i := F_1.s\}$
R_1
$\{T_1.s := R_1.s\}$
$\{Q_1.i := T_1.s\}$
Q_1
$\{E.s := Q_1.s\}$
\$

Semantic pushdown:

Illustration:



Evaluation of Expressions: Example 4/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: $i_1 + i_2\ \$$

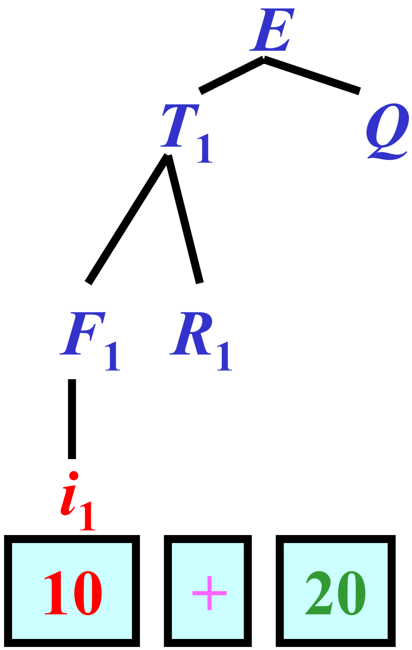
Rule:

Parser pushdown:

i_1
$\{F_1.s := i.value\}$
$\{R_1.i := F_1.s\}$
R_1
$\{T_1.s := R_1.s\}$
$\{Q_1.i := T_1.s\}$
Q_1
$\{E.s := Q_1.s\}$
$\$$

Semantic pushdown:

Illustration:



Evaluation of Expressions: Example 5/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: $+ \; i_2 \; \$$

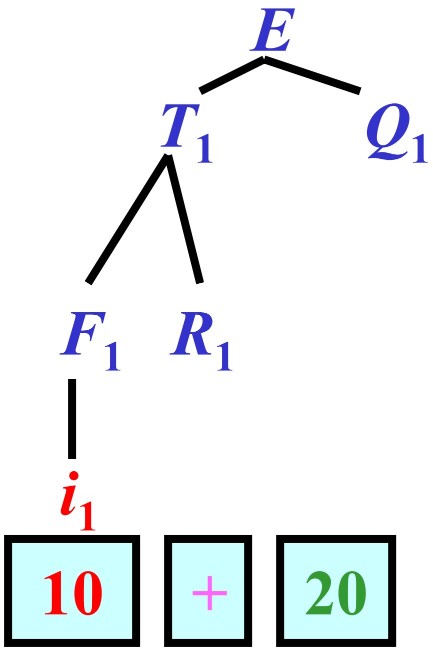
Rule:

Parser pushdown:

$\{F_1.s := i.value\}$
$\{R_1.i := F_1.s\}$
R_1
$\{T_1.s := R_1.s\}$
$\{Q_1.i := T_1.s\}$
Q_1
$\{E.s := Q_1.s\}$
$\$$

Semantic pushdown:

Illustration:



Evaluation of Expressions: Example 6/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: $+\ i_2\ \$$

Rule: $R_1 \rightarrow \varepsilon\ \{R_1.s := R_1.i\}$

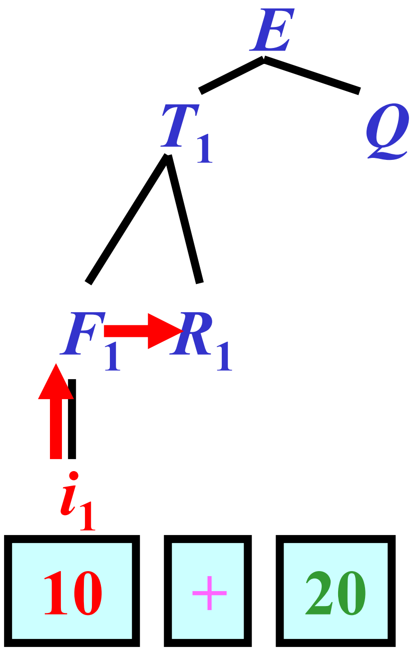
Parser pushdown:

R_1
$\{T_1.s := R_1.s\}$
$\{Q_1.i := T_1.s\}$
Q_1
$\{E.s := Q_1.s\}$
$\$$

Semantic pushdown:

$R_1.i = 10$

Illustration:



Evaluation of Expressions: Example 7/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: $+\ i_2\ \$$

Rule: $Q_1 \rightarrow +T_2\ \{Q_2.i := Q_1.i + T_2.s\}\ Q_2\ \{Q_1.s := Q_2.s\}$

Parser pushdown:

Q_1

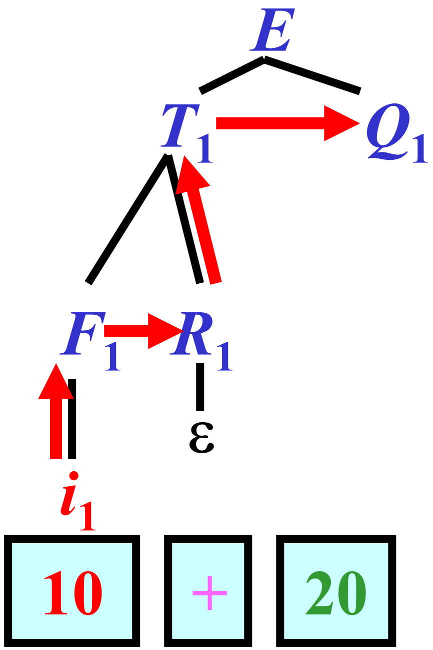
$\{E.s := Q_1.s\}$

$\$$

Semantic pushdown:

$Q_1.i = 10$

Illustration:



Evaluation of Expressions: Example 8/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: $+\ i_2\ \$$

Rule:

Parser pushdown:

$+$

T_2

$\{Q_2.i := Q_1.i + T_2.s\}$

Q_2

$\{Q_1.s := Q_2.s\}$

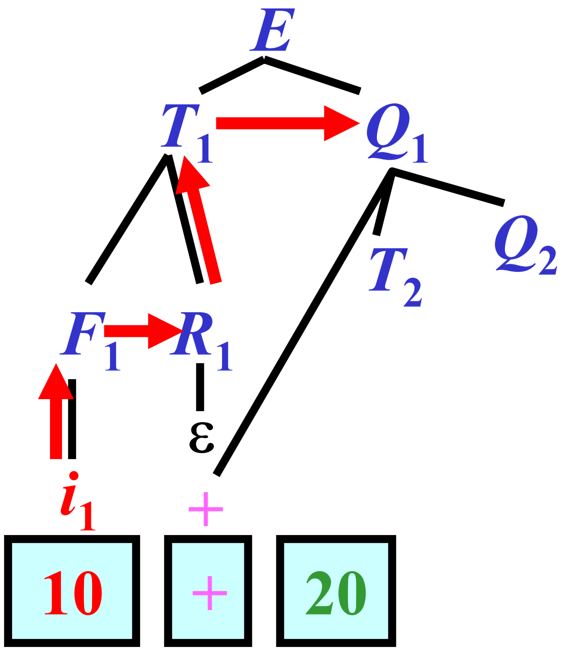
$\{E.s := Q_1.s\}$

$\$$

Semantic pushdown:

$Q_1.i = 10$

Illustration:



Evaluation of Expressions: Example 9/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: i_2 \$

Rule: $T_2 \rightarrow F_2 \; \{R_2.i := F_2.s\} \; R_2 \; \{T_2.s := R_2.s\}$

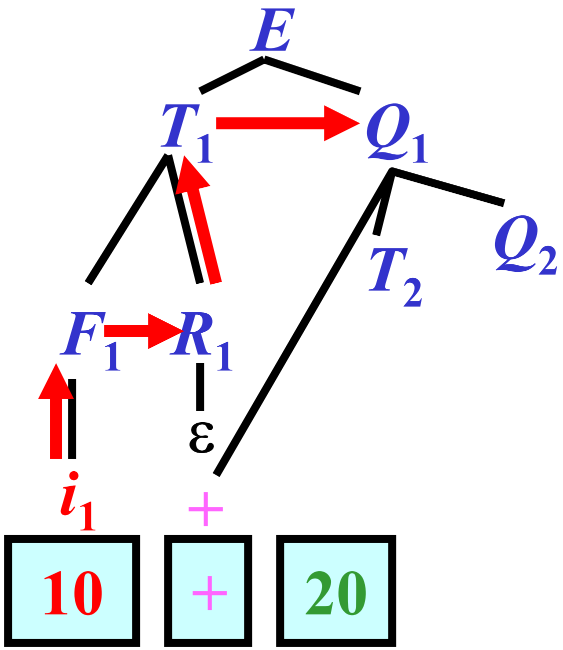
Parser pushdown:

T_2
$\{Q_2.i := Q_1.i + T_2.s\}$
Q_2
$\{Q_1.s := Q_2.s\}$
$\{E.s := Q_1.s\}$
\$

Semantic pushdown:

$Q_1.i = 10$

Illustration:



Evaluation of Expressions: Example 10/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: i_2 \$

Rule: $F_2 \rightarrow i_2$ $\{F_2.s := i.value\}$

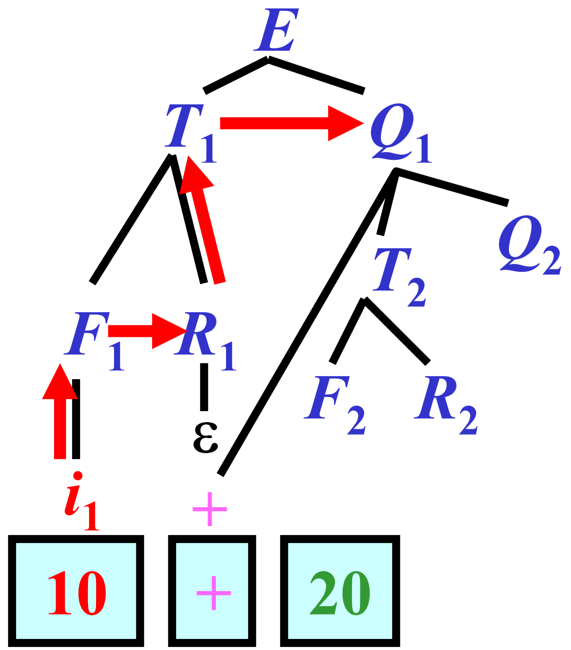
Parser pushdown:

F_2
$\{R_2.i := F_2.s\}$
R_2
$\{T_2.s := R_2.s\}$
$\{Q_2.i := Q_1.i + T_2.s\}$
Q_2
$\{Q_1.s := Q_2.s\}$
$\{E.s := Q_1.s\}$
\$

Semantic pushdown:

$Q_1.i = 10$

Illustration:



Evaluation of Expressions: Example 11/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: i_2 $

Rule:

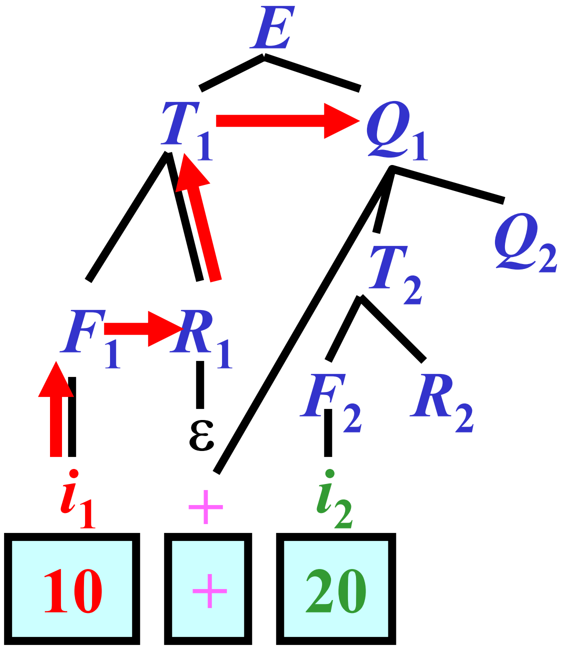
Parser pushdown:

i_2
$\{F_2.s := i.value\}$
$\{R_2.i := F_2.s\}$
R_2
$\{T_2.s := R_2.s\}$
$\{Q_2.i := Q_1.i + T_2.s\}$
Q_2
$\{Q_1.s := Q_2.s\}$
$\{E.s := Q_1.s\}$
$

Semantic pushdown:

$Q_1.i = 10$

Illustration:



Evaluation of Expressions: Example 12/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: $

Rule:

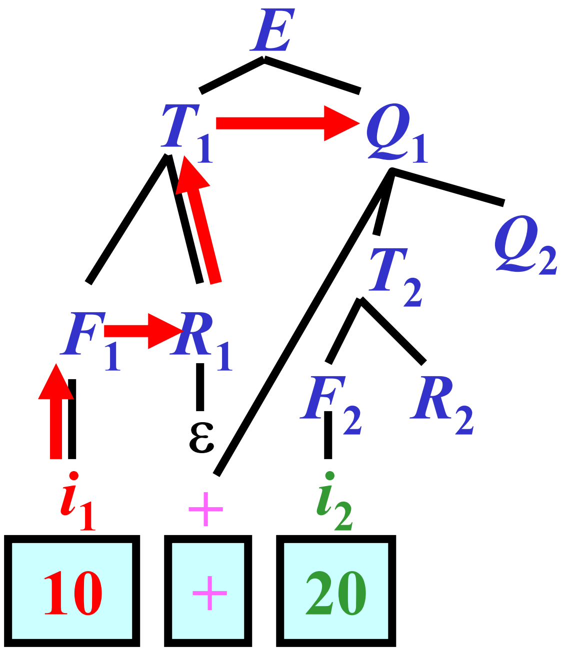
Parser pushdown:

$\{F_2.s := i.value\}$
$\{R_2.i := F_2.s\}$
R_2
$\{T_2.s := R_2.s\}$
$\{Q_2.i := Q_1.i + T_2.s\}$
Q_2
$\{Q_1.s := Q_2.s\}$
$\{E.s := Q_1.s\}$
$

Semantic pushdown:

$Q_1.i = 10$

Illustration:



Evaluation of Expressions: Example 13/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: $

Rule: $R_2 \rightarrow \varepsilon \; \{R_2.s := R_2.i\}$

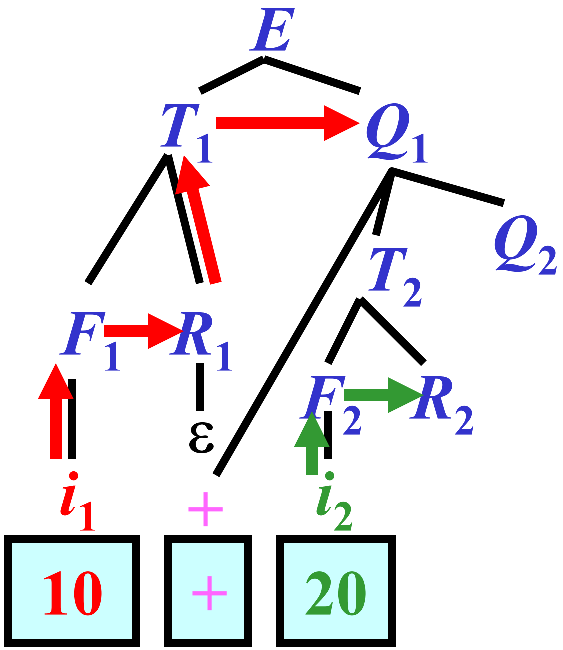
Parser pushdown:

R_2
$\{T_2.s := R_2.s\}$
$\{Q_2.i := Q_1.i + T_2.s\}$
Q_2
$\{Q_1.s := Q_2.s\}$
$\{E.s := Q_1.s\}$
$

Semantic pushdown:

$R_2.i = 20$
$Q_1.i = 10$

Illustration:



Evaluation of Expressions: Example 14/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: $\$$

Rule:

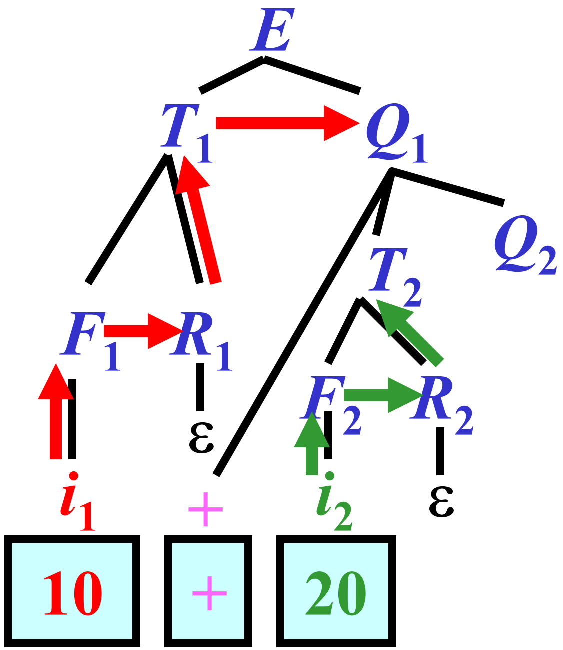
Parser pushdown:

$\{Q_2.i := Q_1.i + T_2.s\}$
Q_2
$\{Q_1.s := Q_2.s\}$
$\{E.s := Q_1.s\}$
$\$$

Semantic pushdown:

$T_2.s = 20$
$Q_1.i = 10$

Illustration:



Evaluation of Expressions: Example 15/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: $\$$

Rule: $Q_2 \rightarrow \varepsilon$ $\{Q_2.s := Q_2.i\}$

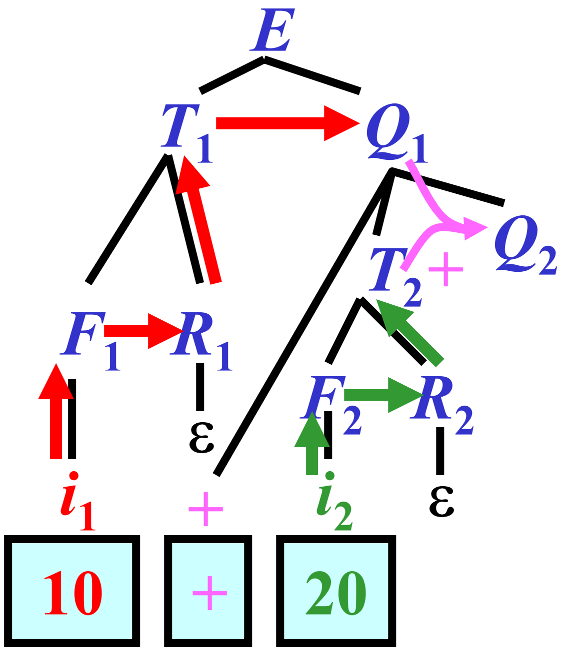
Parser pushdown:

Q_2
$\{Q_1.s := Q_2.s\}$
$\{E.s := Q_1.s\}$
$\$$

Semantic pushdown:

$Q_2.i = 30$

Illustration:



Evaluation of Expressions: Example 16/16

Example for $a + b$, where $a.value = 10$, $b.value = 20$

Input: $

Rule:

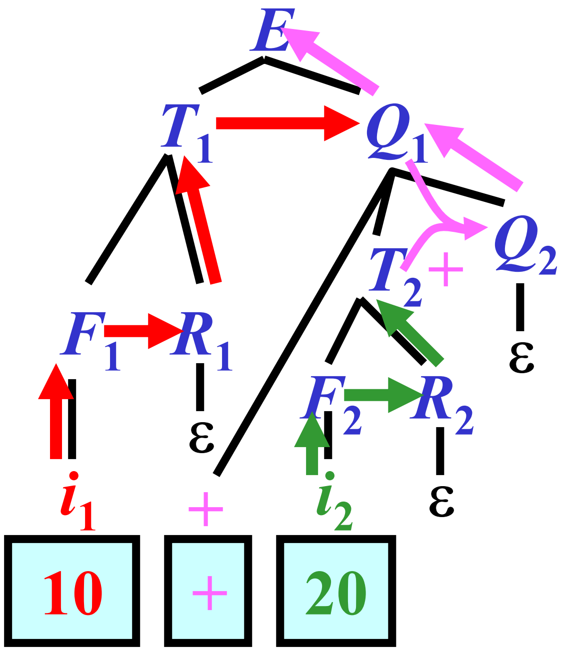
Parser pushdown:

$

Semantic pushdown:

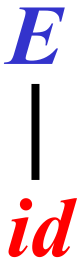
$E.s = 30$

Illustration:



Semantic Analysis: Type Checking

1) **Rule:**

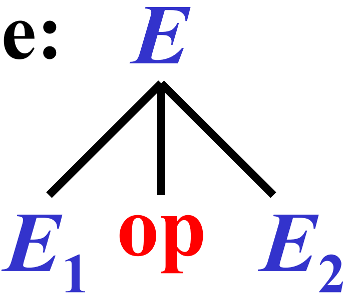


Action:

E.type := *id*.type

---

2) **Rule:**



Operation op is defined over types:

t_1 **op** $t_2 \rightarrow t_3$

Action:

if (E_1.type = t_1 **or**

E_1.type is convertable to t_1)

and

(E_2.type = t_2 **or**

E_2.type is convertable to t_2)

then

E.type := t_3

else

Semantic Error.

Type Checking: Example 1/3

- **Make a type-checking for a grammar:**
- $G_{expr1} = (N, T, P, E)$, where $N = \{E, F, T\}$, $T = \{i, +, *, (,)\}$,
  $P = \{ E \to E+T, E \to T, T \to T*F, T \to F, F \to (E), F \to i \}$

- **Operators *, + are defined as:**
  - **int * int → int**
  - **int + int → int**
  - **real * real → real**
  - **real + real → real**

Possible Conversion:

- **From int to real**

Rule: $F \to i$	$\{F.type := i.type;$ generate$(:=, i.loc, ,F.loc)\ \}$
Rule: $F_i \to (E_j)$	$\{F_i.type := E_j.type\}$
Rule: $T_i \to F_j$	$\{T_i.type := F_j.type\}$
Rule: $E_i \to T_j$	$\{E_i.type := T_j.type\}$

Type Checking: Example 2/3

```
Rule: $E_i \rightarrow E_j+T_k$ { if $E_j.type = T_k.type$ then begin
                                      $E_i.type := E_j.type$
                                      generate(+, $E_j.loc$, $T_k.loc$, $E_i.loc$)
                                  end
                                  else begin
                                      generate(new.loc, $h$, , )
                                      if $E_j.type = int$ then begin
                                          generate(int-to-real, $E_j.loc$ , , $h$)
                                          generate(+, $h$, $T_k.loc$, $E_i.loc$)
                                      end
                                      else begin
                                          generate(int-to-real, $T_k.loc$ , , $h$)
                                          generate(+, $E_j.loc$, $h$, $E_i.loc$)
                                      end
                                      $E_i.type := real$
                                   end
                                 }
```

Type Checking: Example 3/3

```
Rule: $T_i \rightarrow T_j * F_k$ {  if $T_j$.type = $F_k$.type then begin
                                         $T_i$.type := $T_j$.type
                                         generate(*, $T_j$.loc, $F_k$.loc, $T_i$.loc)
                                     end
                                     else begin
                                         generate(new.loc, h, ,  )
                                         if $T_j$.type = int then begin
                                             generate(int-to-real, $T_j$.loc , , h)
                                             generate(*, h, $F_k$.loc, $T_i$.loc)
                                         end
                                         else begin
                                             generate(int-to-real, $F_k$.loc , , h)
                                             generate(*, $T_j$.loc, h, $T_i$.loc)
                                         end
                                         $T_i$.type := real
                                      end
                                   }
```

Short Evaluation (Jumping Code)

Idea:

- *a* = ***true*** **implies** *a* **or (… ? …) =** ***true***
- *a* = ***false*** **implies** *a* **and (… ? …) =** ***false***

Note: (… ? …) is not evaluated.

---

1) (*a* and *b*) = *p*:

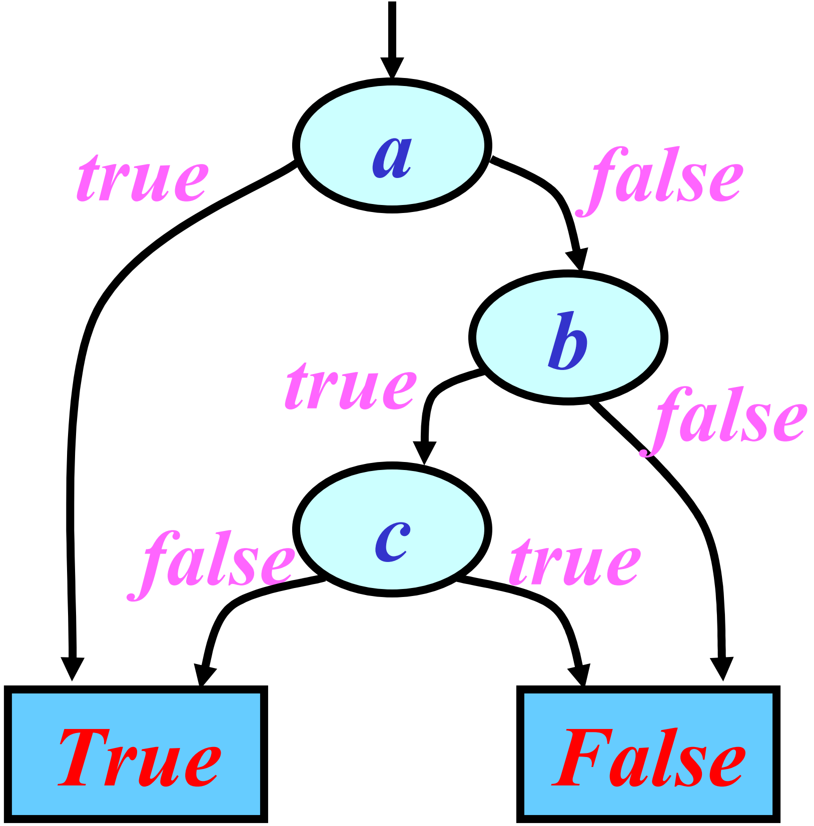
if a = ***false*** **then** p = ***false***
else $p = b$

2) (*a* or *b*) = *p*:

if a = ***true*** **then** p = ***true***
else $p = b$

Short Evaluation: Graphic Representation

Example: ***a* or (*b* and (not *c*)):**



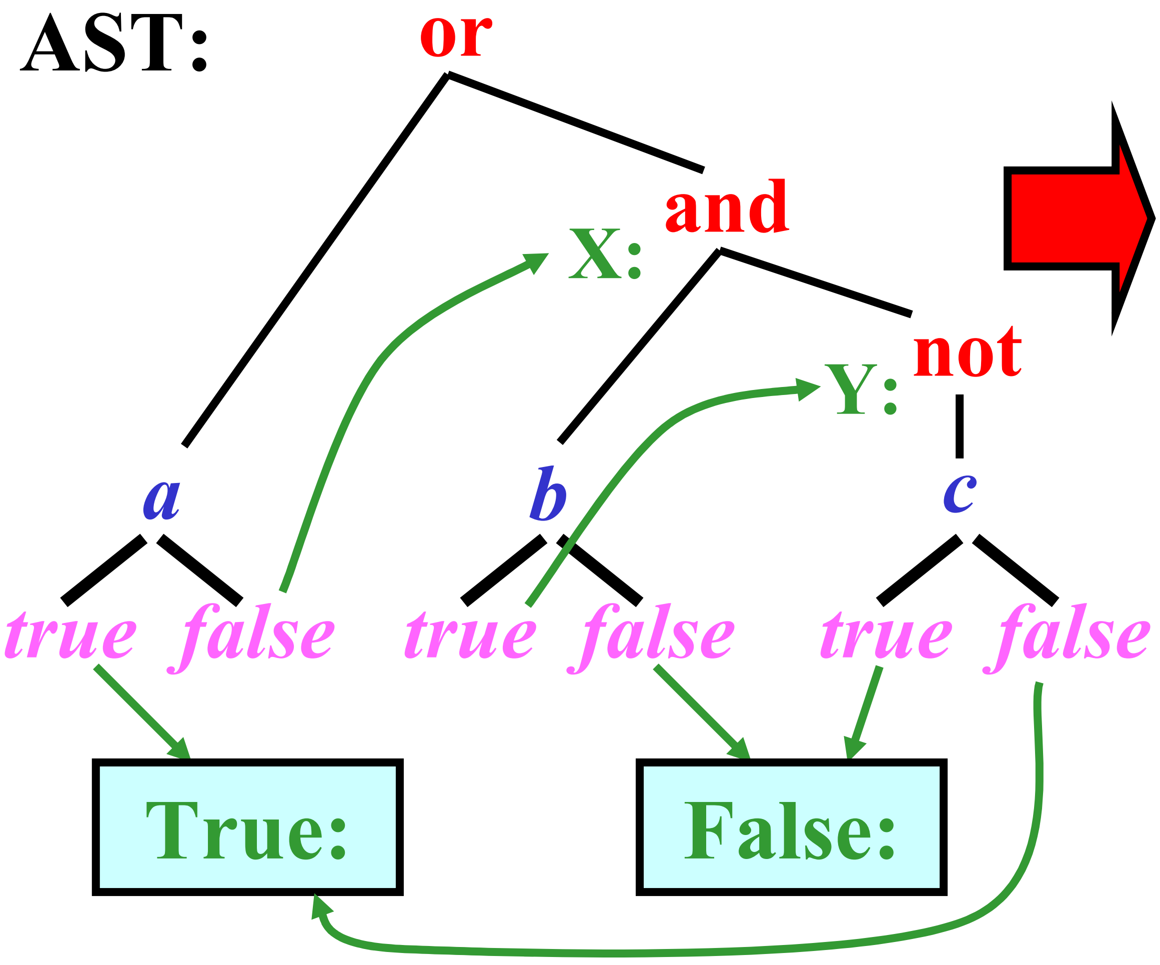
```
if a goto True
goto X
X:
if b goto Y
goto False
Y:
if c goto False
goto True
True: ...
False: ...
```

- Simulation of this graphic representation by 3AC jumps

Short Evaluation Using AST: Introduction

Example: *a* **or** (*b* **and** (**not** *c*)):

AST:



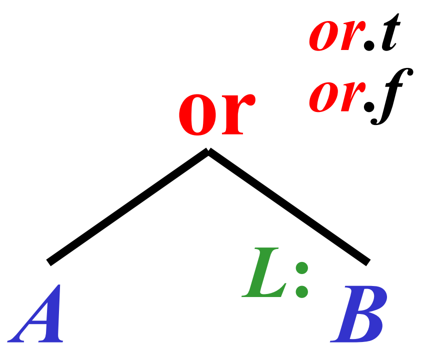
```
if a goto True
goto X
X:
if b goto Y
goto False
Y:
if c goto False
goto True
True: …
False: …
```

Short Evaluation Using AST: Implementation

- Every AST node, X, has assigned two attributes $X.t$, $X.f$

Elementary ASTs:

1)

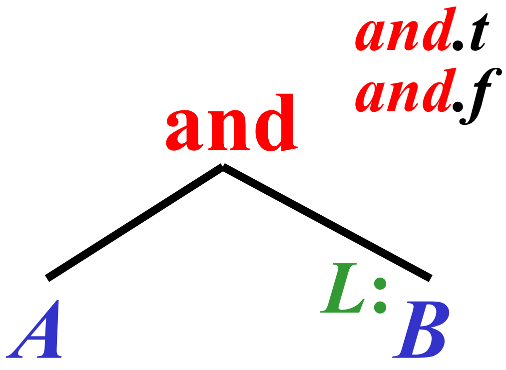


$A.t := \mathit{or}.t$ $\quad$ $B.t := \mathit{or}.t$

$A.f := L$ $\quad$ $B.f := \mathit{or}.f$

- **Note:** L = a new label

2)

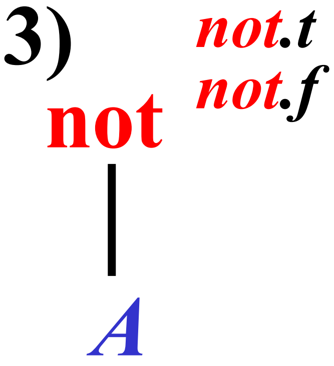


$A.t := L$ $\quad$ $B.t := \mathit{and}.t$

$A.f := \mathit{and}.f$ $\quad$ $B.f := \mathit{and}.f$

- **Note:** L = a new label

3)



$A.t := \mathit{not}.f$

$A.f := \mathit{not}.t$

- **Initialization:** Let R is the root of AST, then:

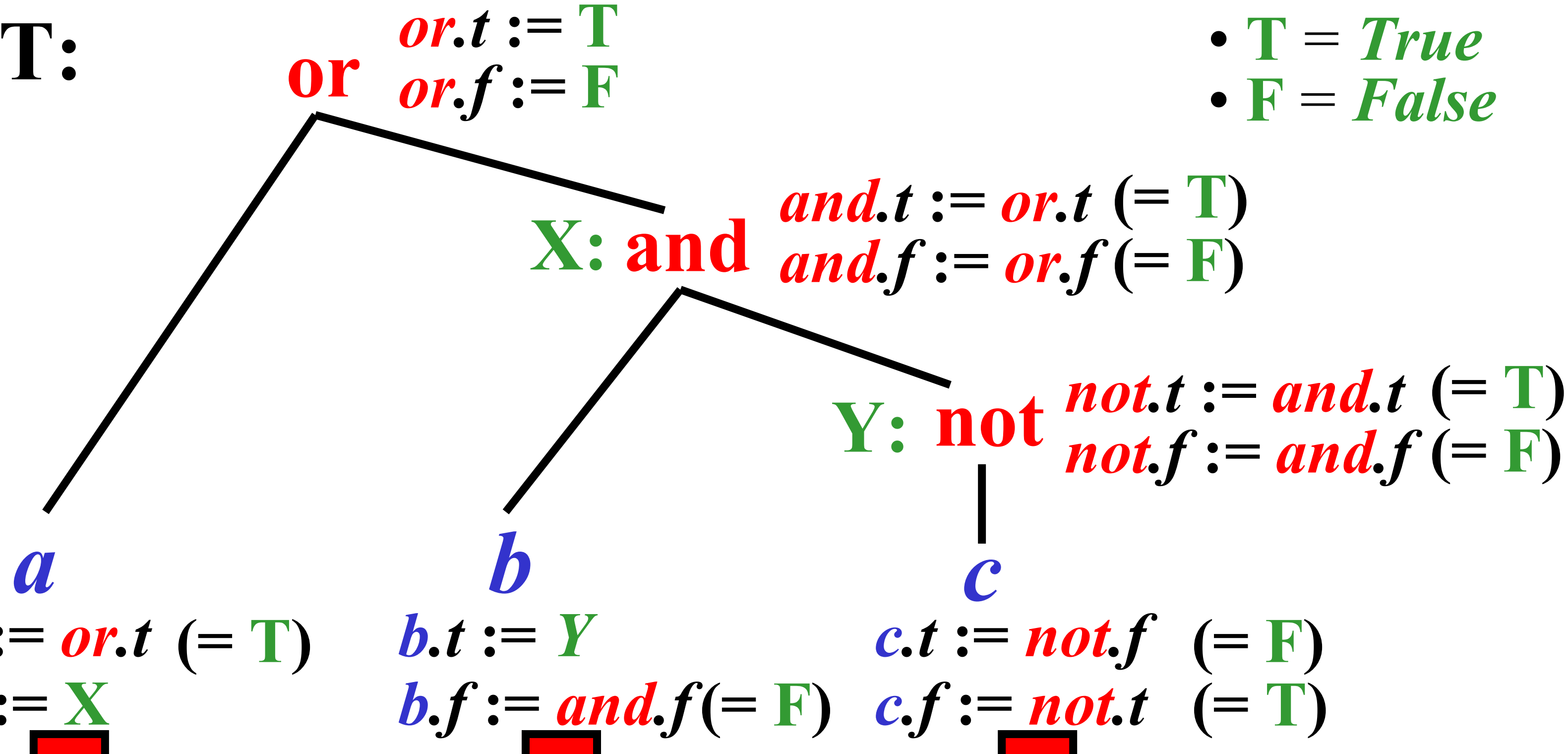
  $R.t :=$ **True**, $R.f :=$ **False** (**True** & **False** are labels)
- **Propagation:** Attributes are propagated from root to leaves in AST using rules **1)**, **2)** and **3)**.

Short Evaluation Using AST: Example

Example: a **or** (b **and** (**not** c)):

Note:
- T = *True*
- F = *False*

AST:



or
$or.t :=$ T
$or.f :=$ F

X: and
$and.t := or.t$ (= T)
$and.f := or.f$ (= F)

Y: not
$not.t := and.t$ (= T)
$not.f := and.f$ (= F)

a
$a.t := or.t$ (= T)
$a.f :=$ X

b
$b.t :=$ Y
$b.f := and.f$ (= F)

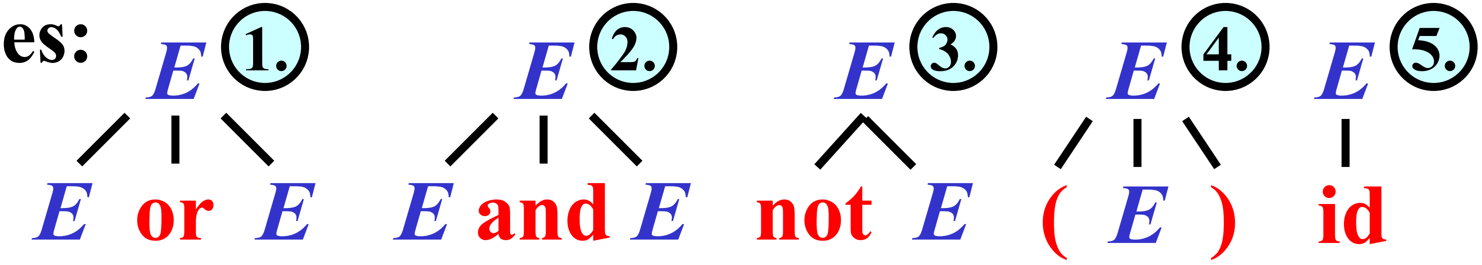
c
$c.t := not.f$ (= F)
$c.f := not.t$ (= T)

```
if a goto T
goto X

X:
if b goto Y
goto F

Y:
if c goto F
goto T

T: ...
F: ...
```

Short Evaluation: Direct Code Generation 1/5

- **Grammar for boolean expressions:**

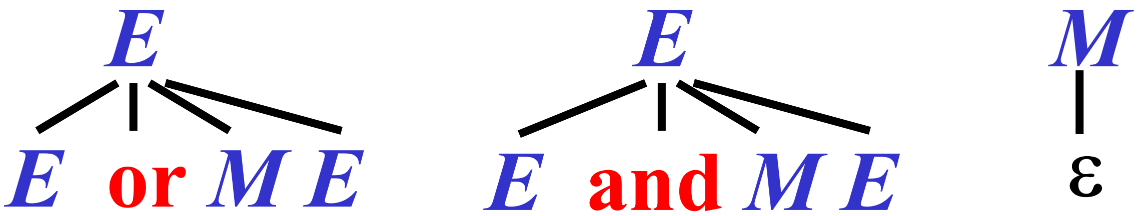
Rules:



Note: Ambiguity!

- **Modification of grammar:**

1) Replace rules ① & ② with:



2) Assign to each rule the following semantic action

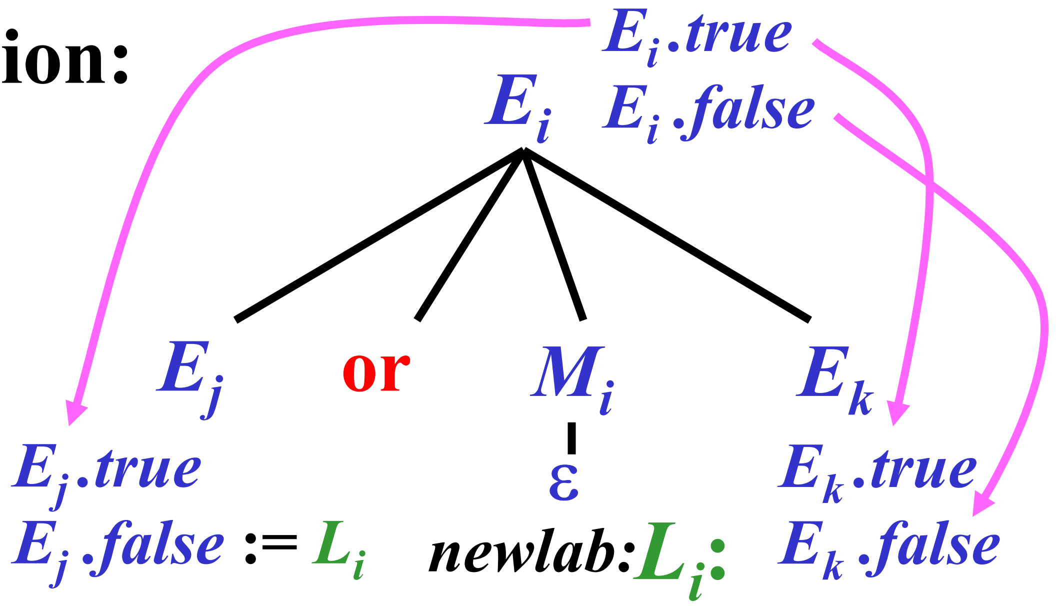
Short Evaluation: Direct Code Generation 2/5

$\boldsymbol{M_i} \rightarrow \varepsilon$ {generate "$\boldsymbol{M_i . lab:}$"} // Generation of a new label

---

$\boldsymbol{E_i} \rightarrow \boldsymbol{E_j}$ **or** $\boldsymbol{M_i}\ \boldsymbol{E_k}$ {$\boldsymbol{M_i}.lab := GenerateNewLab;$
$\boldsymbol{E_j}.true := \boldsymbol{E_i}.true;\ \boldsymbol{E_j}.false := \boldsymbol{M_i}.lab$
$\boldsymbol{E_k}.true := \boldsymbol{E_i}.true;\ \boldsymbol{E_k}.false := \boldsymbol{E_i}.false$ }

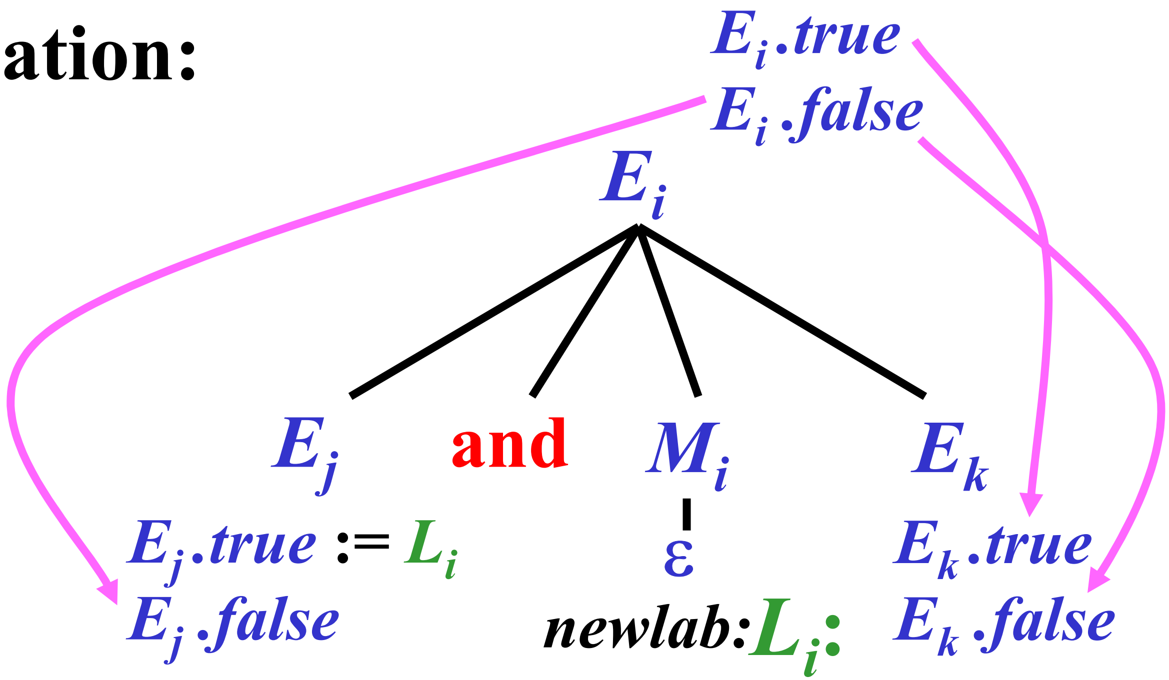
Illustration:



Short Evaluation: Direct Code Generation 3/5

$$\boldsymbol{E_i} \rightarrow \boldsymbol{E_j}\ \textbf{and}\ \boldsymbol{M_i}\ \boldsymbol{E_k}\ \{\boldsymbol{M_i}.lab := GenerateNewLab;$$
$$\boldsymbol{E_j}.true := \boldsymbol{M_i}.lab;\ \boldsymbol{E_j}.false := \boldsymbol{E_i}.false$$
$$\boldsymbol{E_k}.true := \boldsymbol{E_i}.true;\ \boldsymbol{E_k}.false := \boldsymbol{E_i}.false\ \}$$

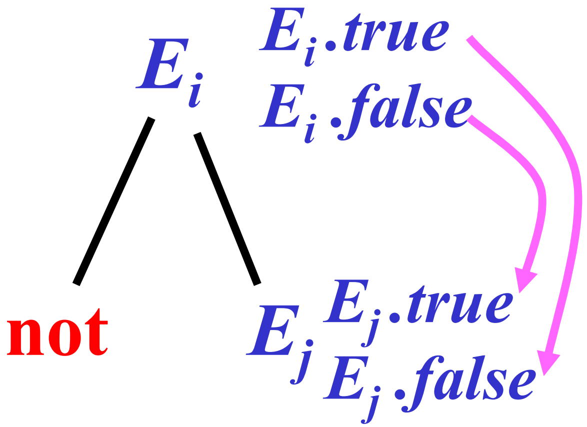
Illustration:



Short Evaluation: Direct Code Generation 4/5

$E_i \rightarrow$ **not** E_j { $E_j.true := E_i.false;$
$E_j.false := E_i.true$ }

Illustration:

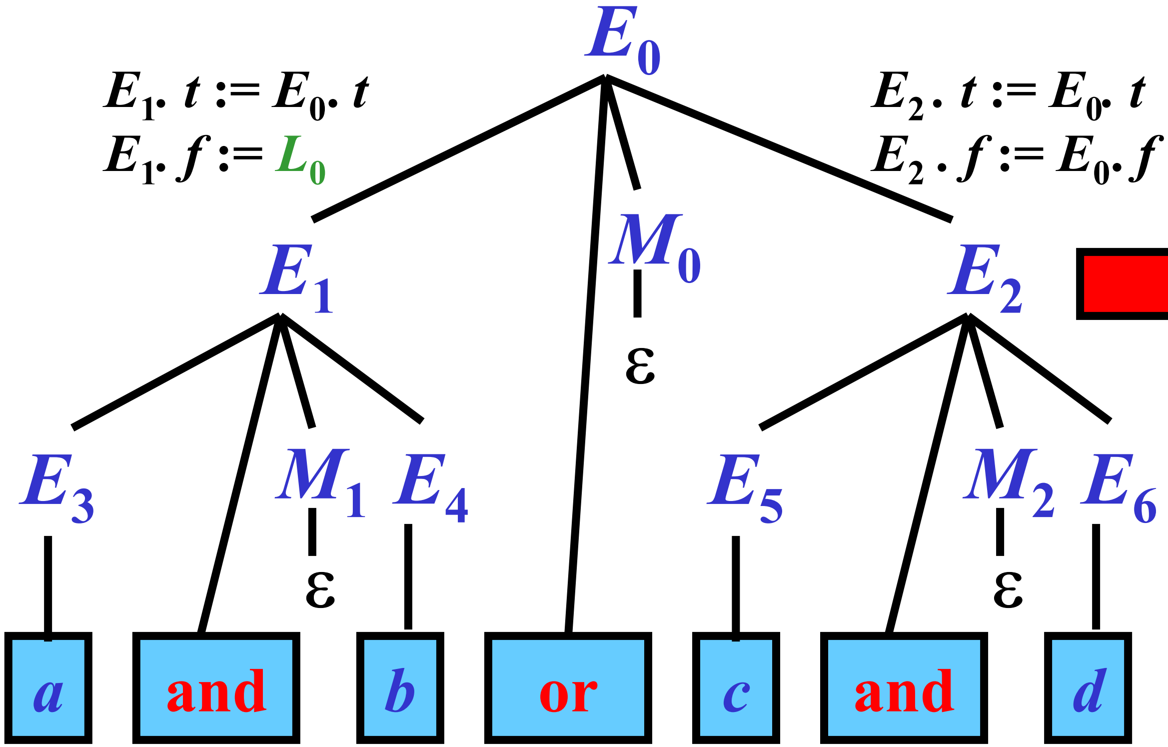


$E_i \rightarrow (E_j)$ {$E_j.true := E_i.true;$
$E_j.false := E_i.false$ }

$E_i \rightarrow id_j$ { generate "**if** $id_j.val$ **goto** $E_i.true$";
generate "**goto** $E_i.false$" }

Short Evaluation: Direct Code Generation 5/5

Example: ***a*** **and** ***b*** **or** ***c*** **and** ***d*:**



$E_0.t := L_{true}$
$E_0.f := L_{false}$

$E_1.t := E_0.t$
$E_1.f := L_0$

$E_2.t := E_0.t$
$E_2.f := E_0.f$

$E_3.t := L_1$
$E_3.f := E_1.f$

$E_4.t := E_1.t$
$E_4.f := E_1.f$

$E_5.t := L_2$
$E_5.f := E_2.f$

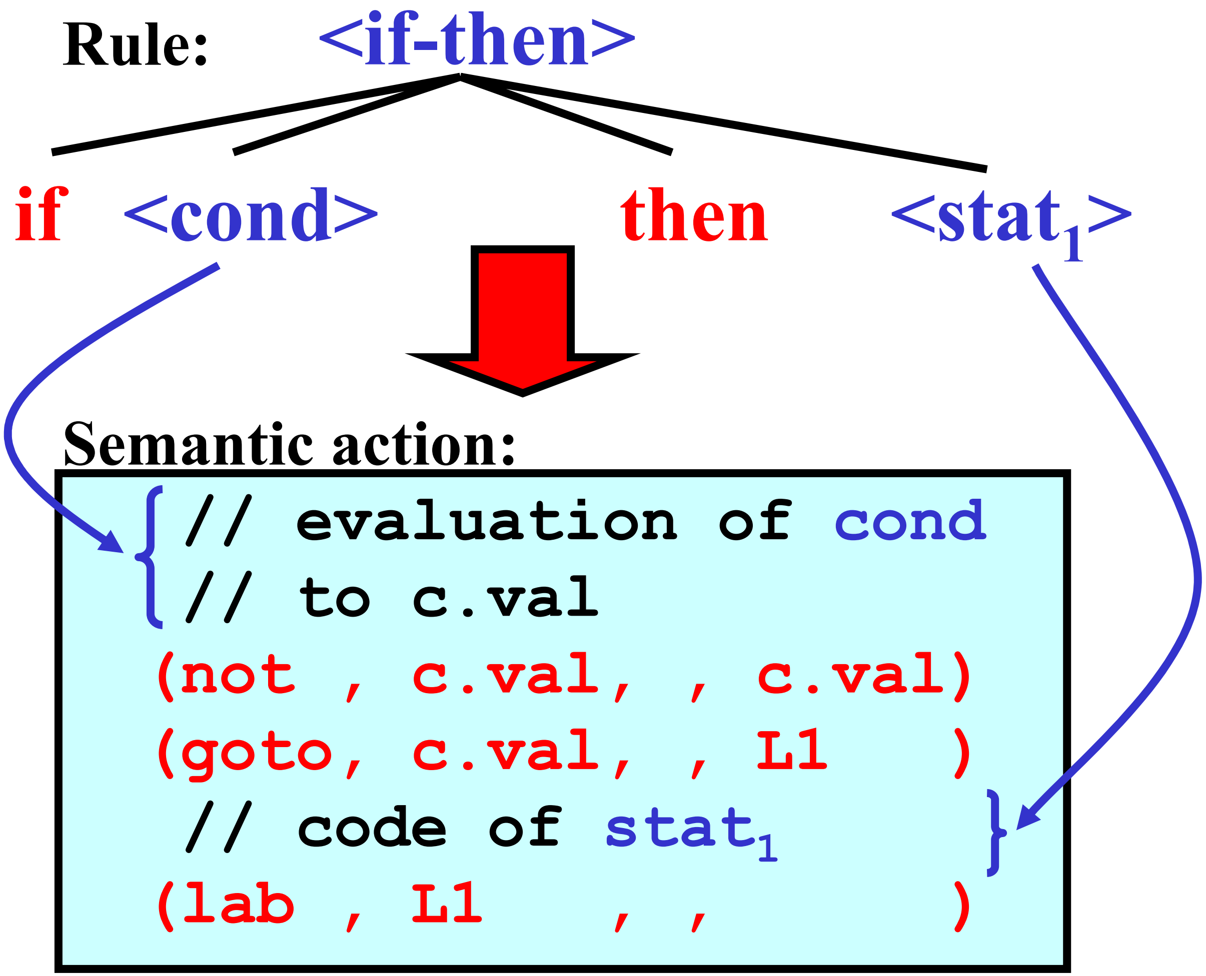
$E_6.t := E_2.t$
$E_6.f := E_2.f$

if ***a*** *goto* L_1
goto L_0
L_1:
if ***b*** *goto* L_{true}
goto L_0
L_0:
if ***c*** *goto* L_2
goto L_{false}
L_2:
if ***d*** *goto* L_{true}
goto L_{false}

L_{true}: …

L_{false}: …

Branching: If-Then



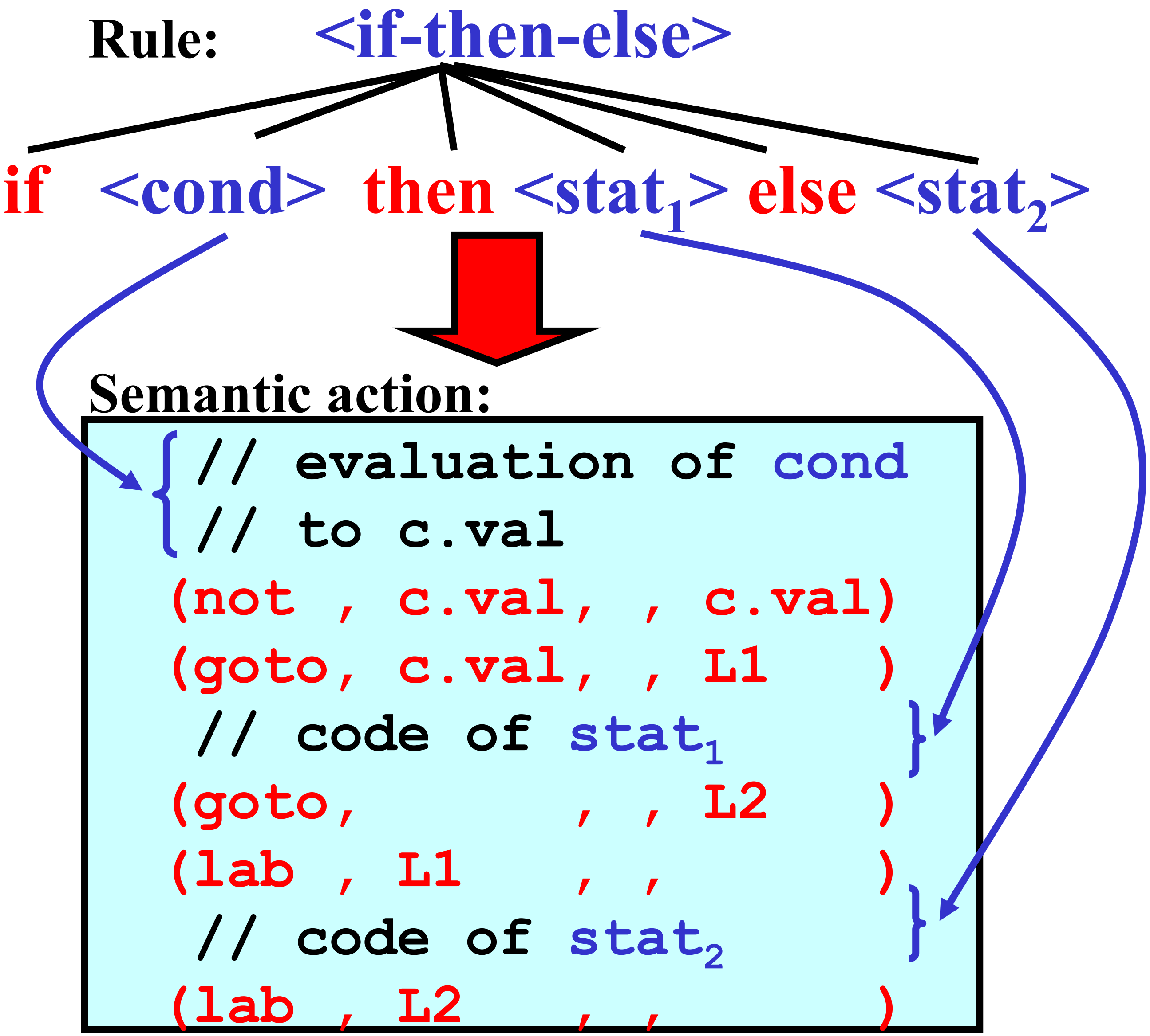
Rule: <if-then>

if <cond> then $<stat_1>$

Semantic action:

```
// evaluation of cond
// to c.val
(not , c.val, , c.val)
(goto, c.val, , L1   )
 // code of stat1
(lab , L1   , ,      )
```

Branching: If-Then-Else



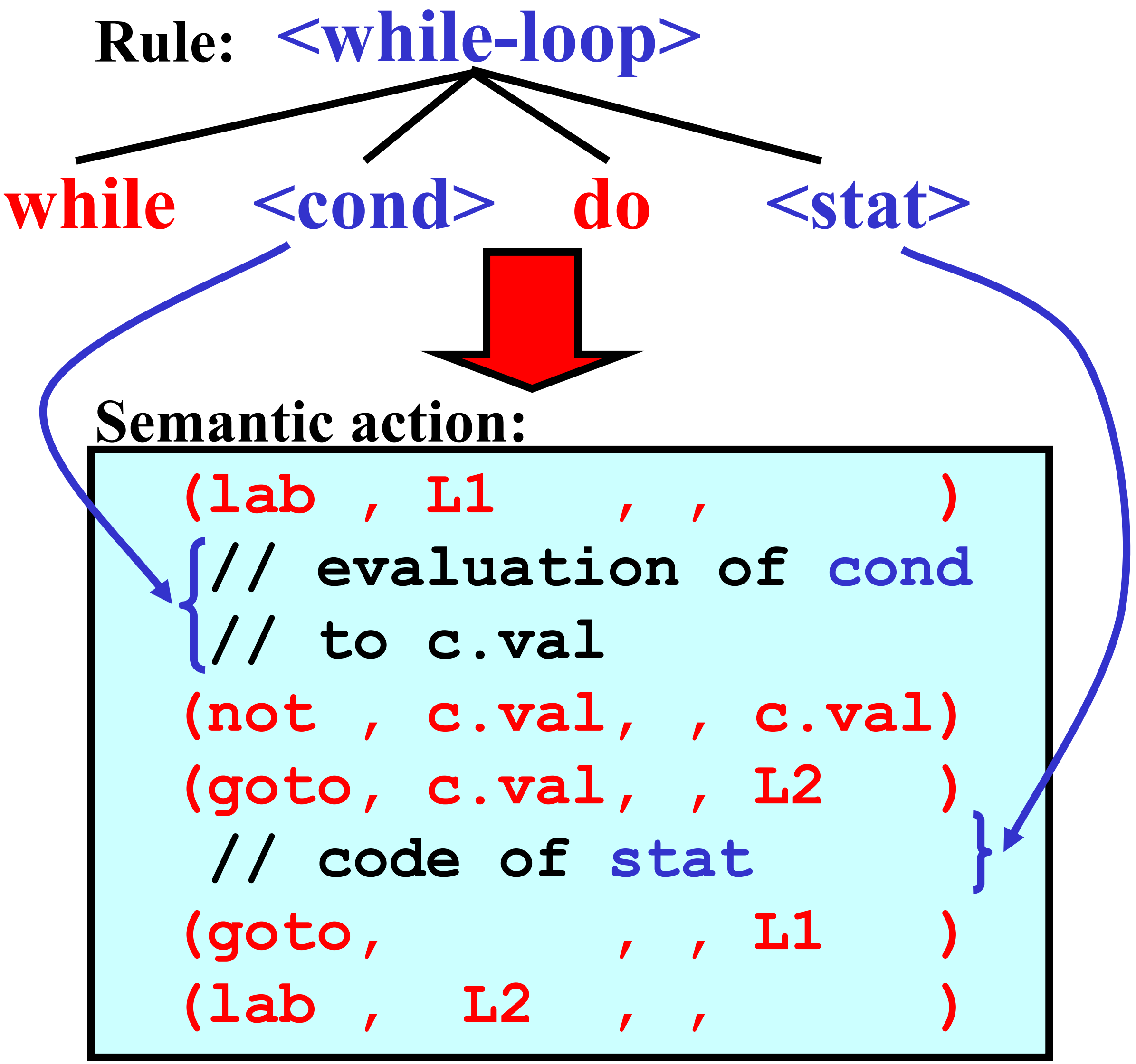
Rule: <if-then-else>

if <cond> then <stat$_1$> else <stat$_2$>

Semantic action:

```
// evaluation of cond
// to c.val
(not , c.val, , c.val)
(goto, c.val, , L1   )
 // code of stat1
(goto,      , , L2   )
(lab , L1   , ,      )
 // code of stat2
(lab , L2   , ,      )
```

While Loop



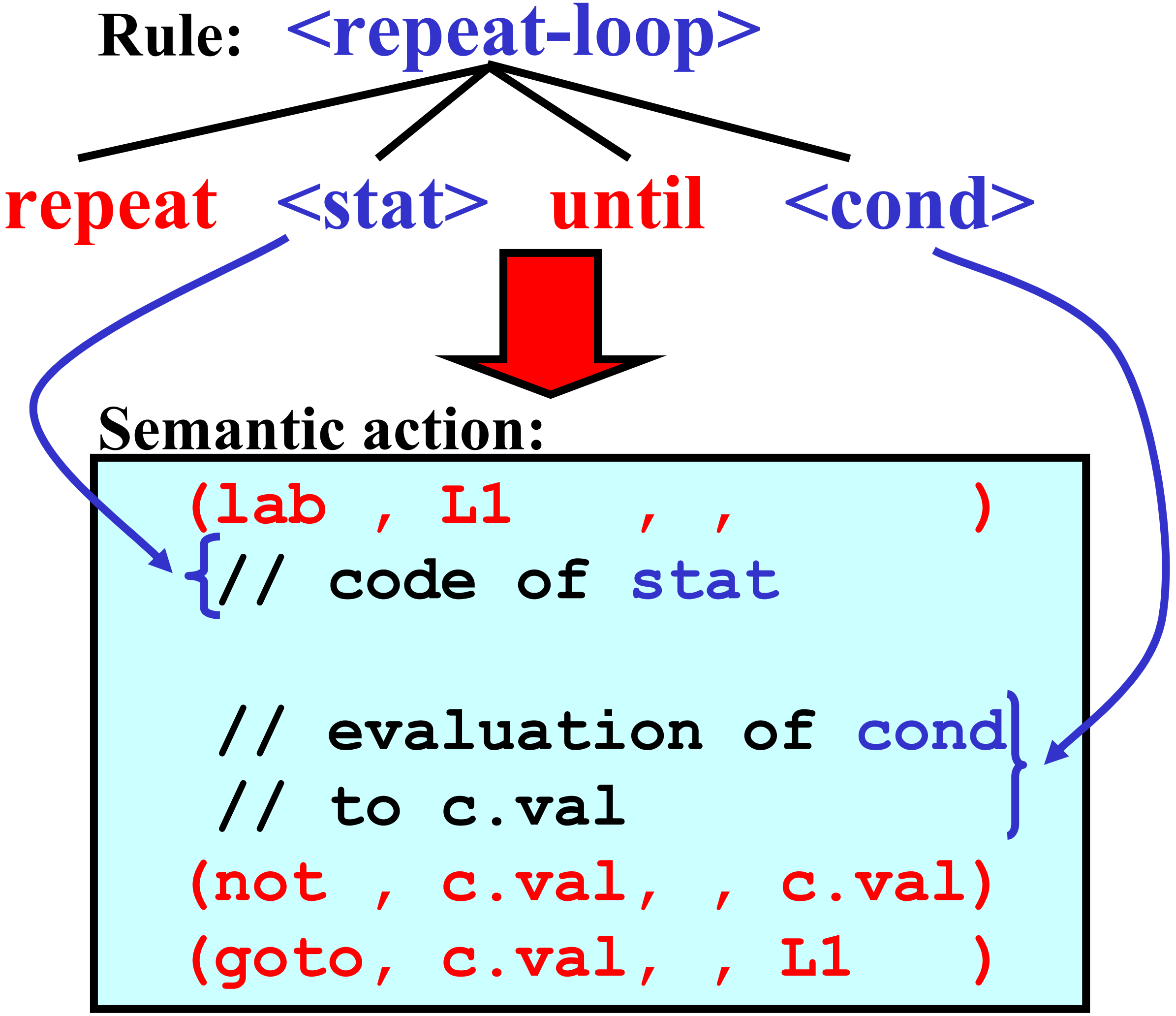
Rule: <while-loop>

while <cond> do <stat>

Semantic action:

```
(lab , L1    , ,       )
// evaluation of cond
// to c.val
(not , c.val, , c.val)
(goto, c.val, , L2    )
 // code of stat
(goto,        , , L1    )
(lab ,  L2    , ,       )
```

Repeat Loop



Rule: <repeat-loop>

repeat <stat> until <cond>

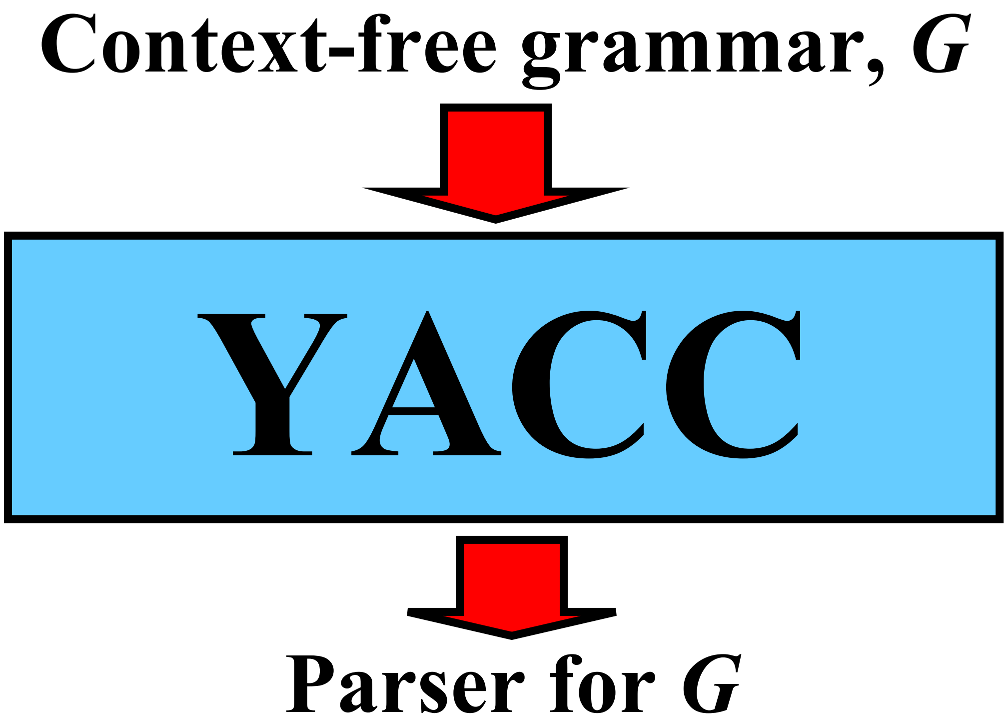
Semantic action:

```
(lab , L1    , ,      )
{// code of stat

 // evaluation of cond}
 // to c.val
(not , c.val, , c.val)
(goto, c.val, , L1    )
```

Yacc: Basic Idea

- Automatic construction of **parser** from **CFG**
- Yacc compiler × Yacc language
- *Yacc* from *Y*et *a*nother *c*ompiler *c*ompiler

Ilustrace:

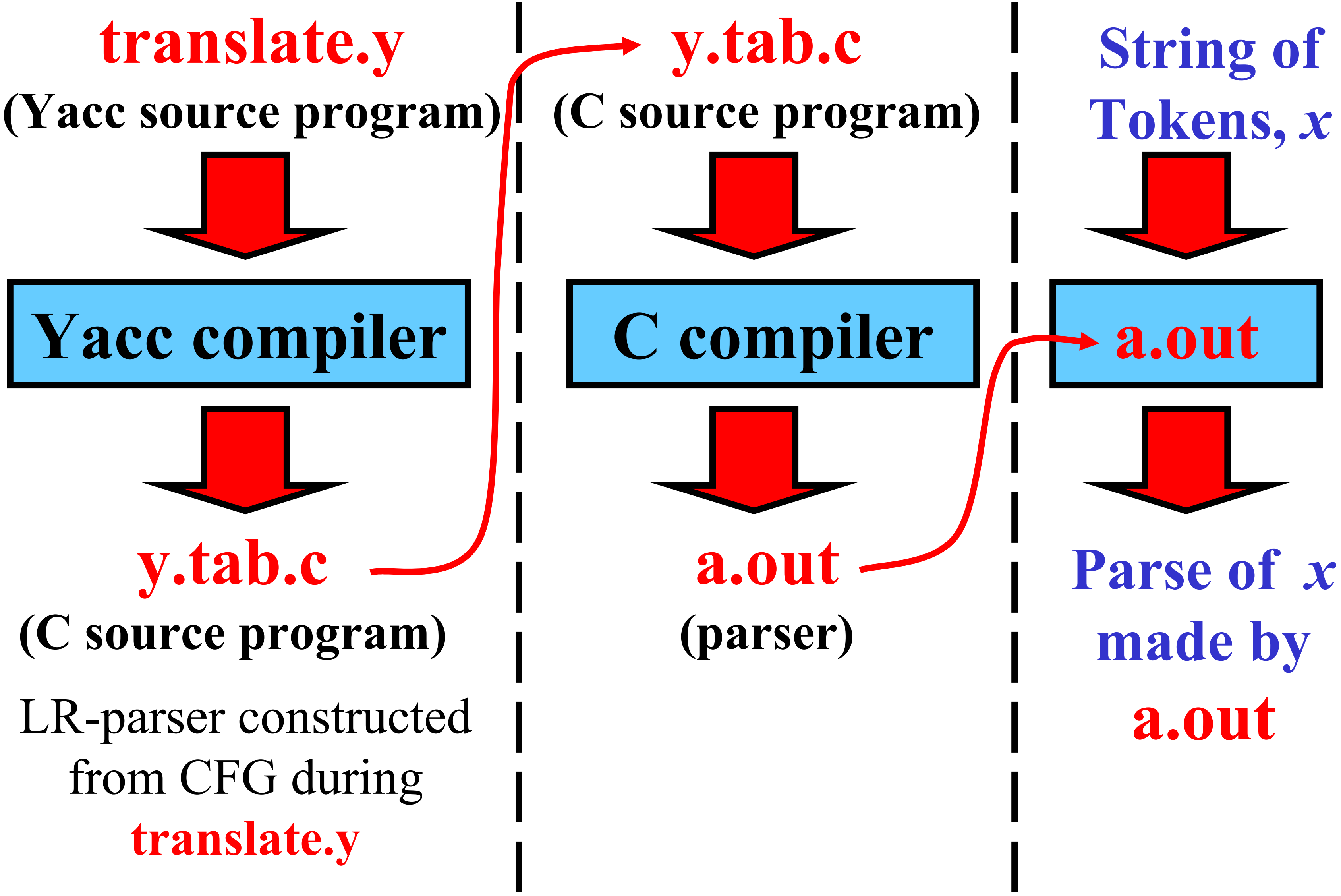


Context-free grammar, *G*

YACC

Parser for *G*

Yacc: Phases of Compilation



translate.y
(Yacc source program)

Yacc compiler

y.tab.c
(C source program)

LR-parser constructed from CFG during **translate.y**

y.tab.c
(C source program)

C compiler

a.out
(parser)

String of Tokens, *x*

a.out

Parse of *x* made by a.out

Structure of Yacc Source Program

/* **Section I:** **Declaration** */

$d_1, d_2, \ldots, d_i$

`%%` /* **End of Section I** */

/* **Section II:** **Translation rules** */

$r_1, r_2, \ldots, r_j$

`%%` /* **End of Section II** */

/* **Section III:** **Auxiliary procedures** */

$p_1, p_2, \ldots, p_k$

Description of Grammar in Yacc

- **Nonterminals:** names (= strings)
- **Example:** `prog`, `stat`, `expr`, …

- **Terminals:** Characters in quotes or declared tokens
- **Example:** `‘+’`, `‘*’`, `‘(’`, `‘)’`, `ID`, `INTEGER`

- **Rules:** Set of A-rules $\{ A \rightarrow x_1, A \rightarrow x_2, \ldots A \rightarrow x_n \}$

  is written as

```
A : x1
  | x2
  ...
  | xn
```

- **Example:**

```
expr : expr ‘+’ expr
     | ID
```

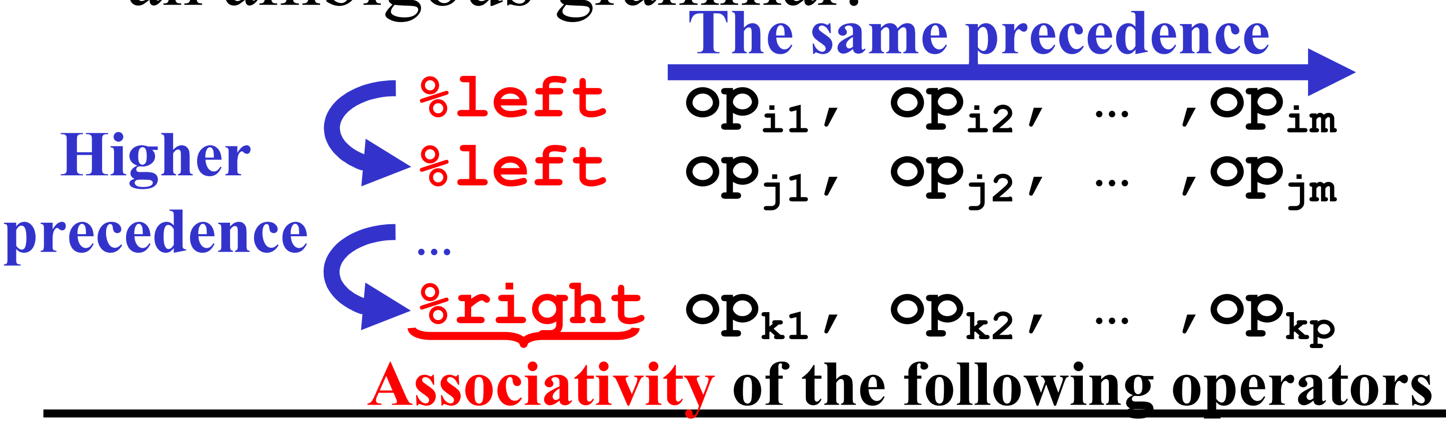
- **Start Nonterminal:** A left side of the first rule.

Section I: Declaration

1) Declaration of tokens

```
%token TYPE_OF_TOKEN
```

2) Specification of asociativity & precedence in an ambigous grammar.



The same precedence

Higher precedence

%left op_{i1}, op_{i2}, … , op_{im}

%left op_{j1}, op_{j2}, … , op_{jm}

…

%right op_{k1}, op_{k2}, … , op_{kp}

Associativity of the following operators

Example:

```
%token INTEGER
%token ID
%left '+'
%left '*'
```

Section II: Translation Rules

- Translation rules are in the form:

```
Rule      Semantic_Action
```

- `Semantic_Action` is a program routine that specifies what to do if `Rule` is used.

Special symbols for a rule, *r*:

`$$` = attribute of *r*’s left-hand side

`$i` = attribute of the *i*-th symbols on *r*’s right-hand side

---

Example:

```
expr : expr ‘+’ expr {$$ = $1 + $3}
     | expr ‘*’ expr {$$ = $1 * $3}
     | ‘(’ expr ‘)’   {$$ = $2}
     | INTEGER
     | ID
```

Section III: Auxiliary Procedures

- Auxiliary procedures used by translation rules

Note: If the Yacc-parser do not cooperate with a scanner (e.g. Lex), then there is **yylex()** implemented in this section.

Example:

```
int yylex() {
      /* Get the next token */
      &yylval = attribute;
      return TYPE_OF_TOKEN;
}
```

Complete Source Program in Yacc

```
%token INTEGER
%token ID
%left ‘+’
%left ‘*’

%%

expr : expr ‘+’ expr {$$ = $1 + $3}
     | expr ‘*’ expr {$$ = $1 * $3}
     | ‘(’ expr ‘)’  {$$ = $2}
     | INTEGER
     | ID

%%

int yylex () { … }
```