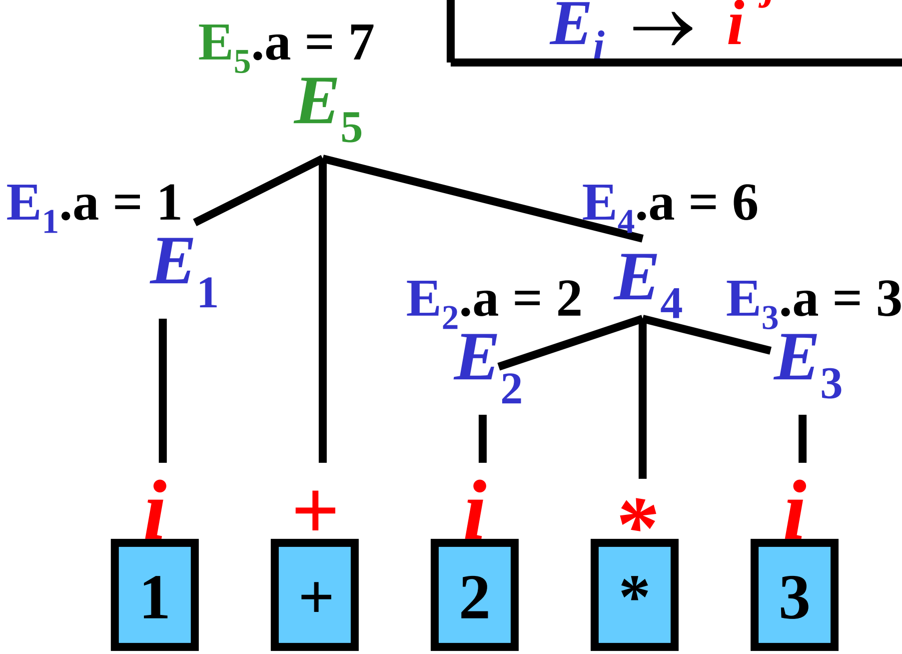
Part XI.
Syntax Directed Translation and Intermediate Code

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:
$E_i \rightarrow E_j + E_k$	`{ E_i.a := E_j.a + E_k.a}`
$E_i \rightarrow E_j * E_k$	`{ E_i.a := E_j.a * E_k.a}`
$E_i \rightarrow (E_j)$	`{ E_i.a := E_j.a }`
$E_i \rightarrow i$	`{ E_i.a := i.val }`



Rule:	Action:
$E_1 \rightarrow i$	`E1.a:= i.val`
$E_2 \rightarrow i$	`E2.a:= i.val`
$E_3 \rightarrow i$	`E3.a:= i.val`
$E_4 \rightarrow E_2 * E_3$	`E4.a:= E2.a*E3.a`
$E_5 \rightarrow E_1 + E_4$	`E5.a:= E1.a+E4.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:
```

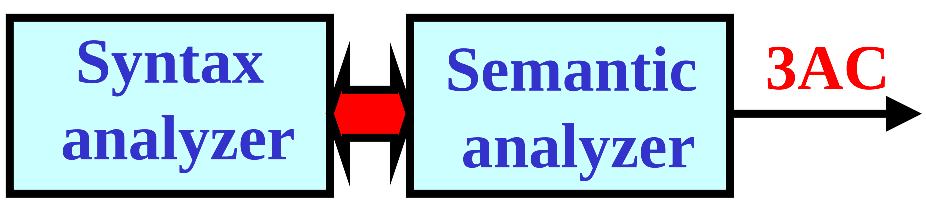
Syntax-Directed Generation of 3AC

Basic approaches:

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

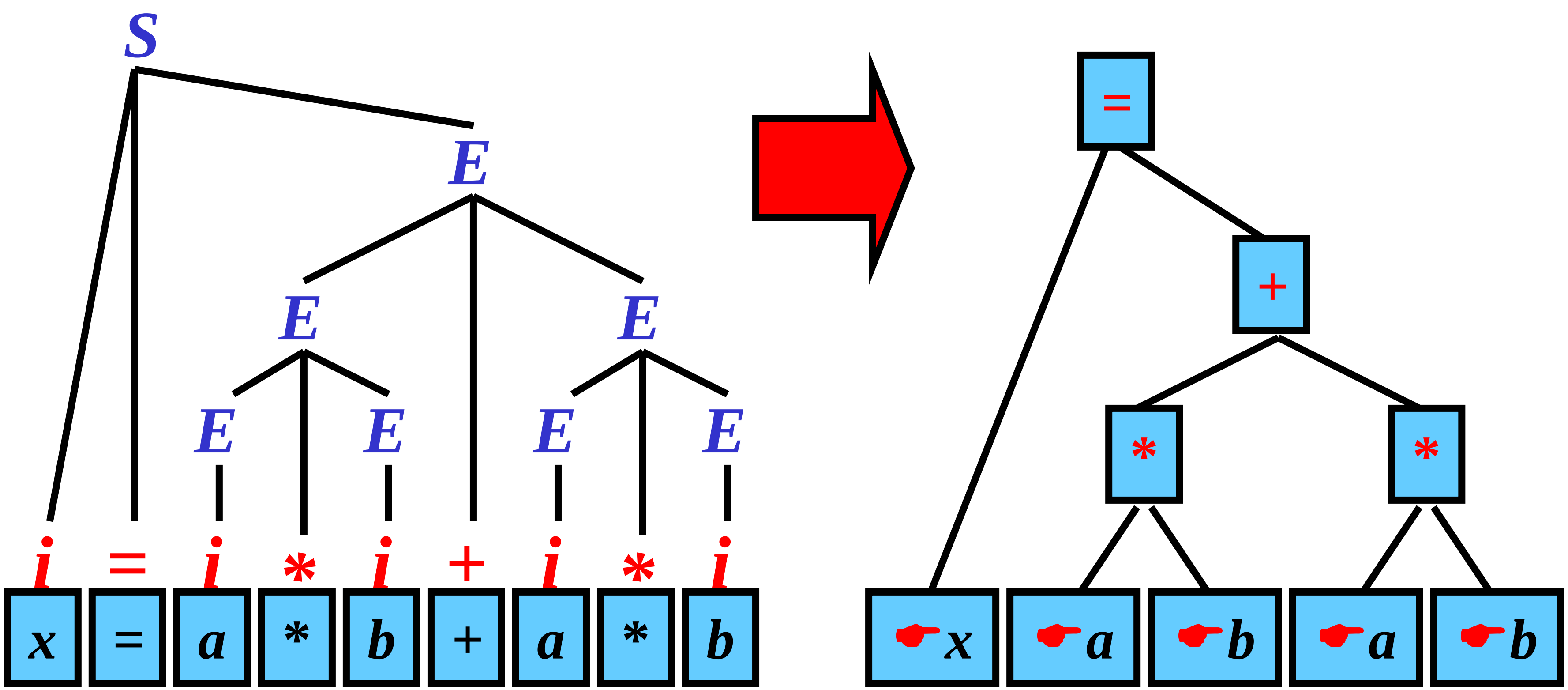
2) Parser directs the creation of a ***postfix notation*** **(PN)** , which is then converted to **3AC**.

3) A parser directs the creation of **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

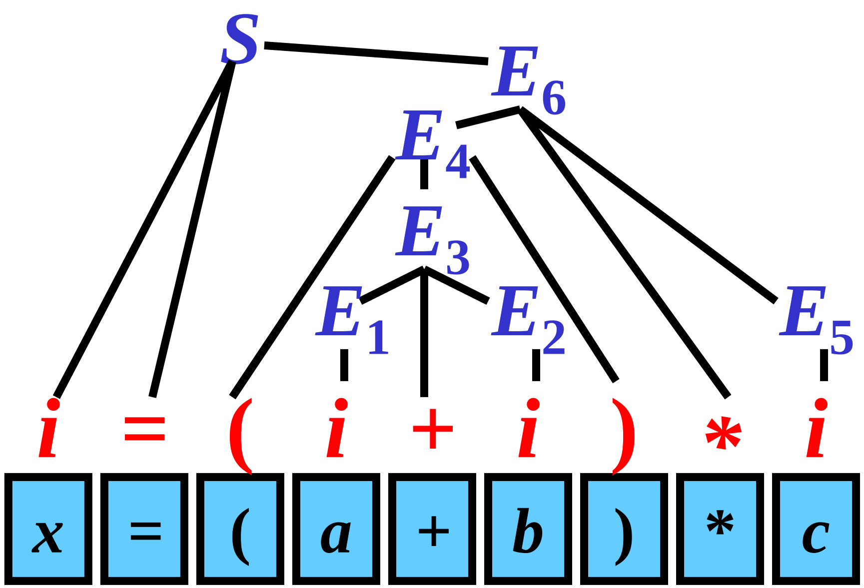
Pushdown	Input	Rule	Semantic action
$\$$	$i = (i + i) * i\$$		
$\$i$	$= (i + i) * i\$$		
$\$i =$	$(i + i) * i\$$		
$\$i = ($	$i + i) * i\$$		
$\$i = (i$	$+ i) * i\$$	$E_1 \rightarrow i$	$E_1.a$:= MakeLeaf($i.a$)
$\$i = (E_1$	$+ i) * i\$$		
$\$i = (E_1 +$	$i) * i\$$		
$\$i = (E_1 + i$	$) * i\$$	$E_2 \rightarrow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

Bottom-Up parsing (Pushdown, Input, Rule) **Semantic actions** (Semantic action)

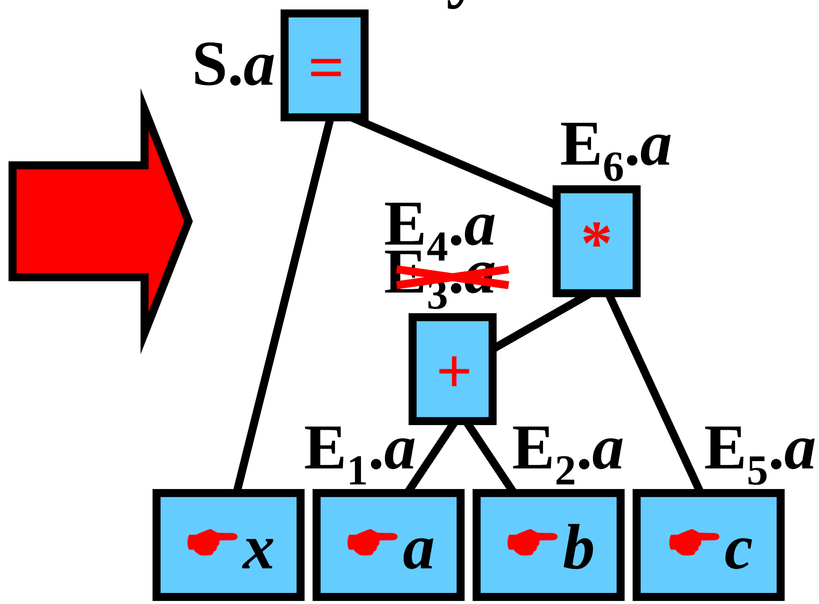
AST Generation: Example 2/2

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:

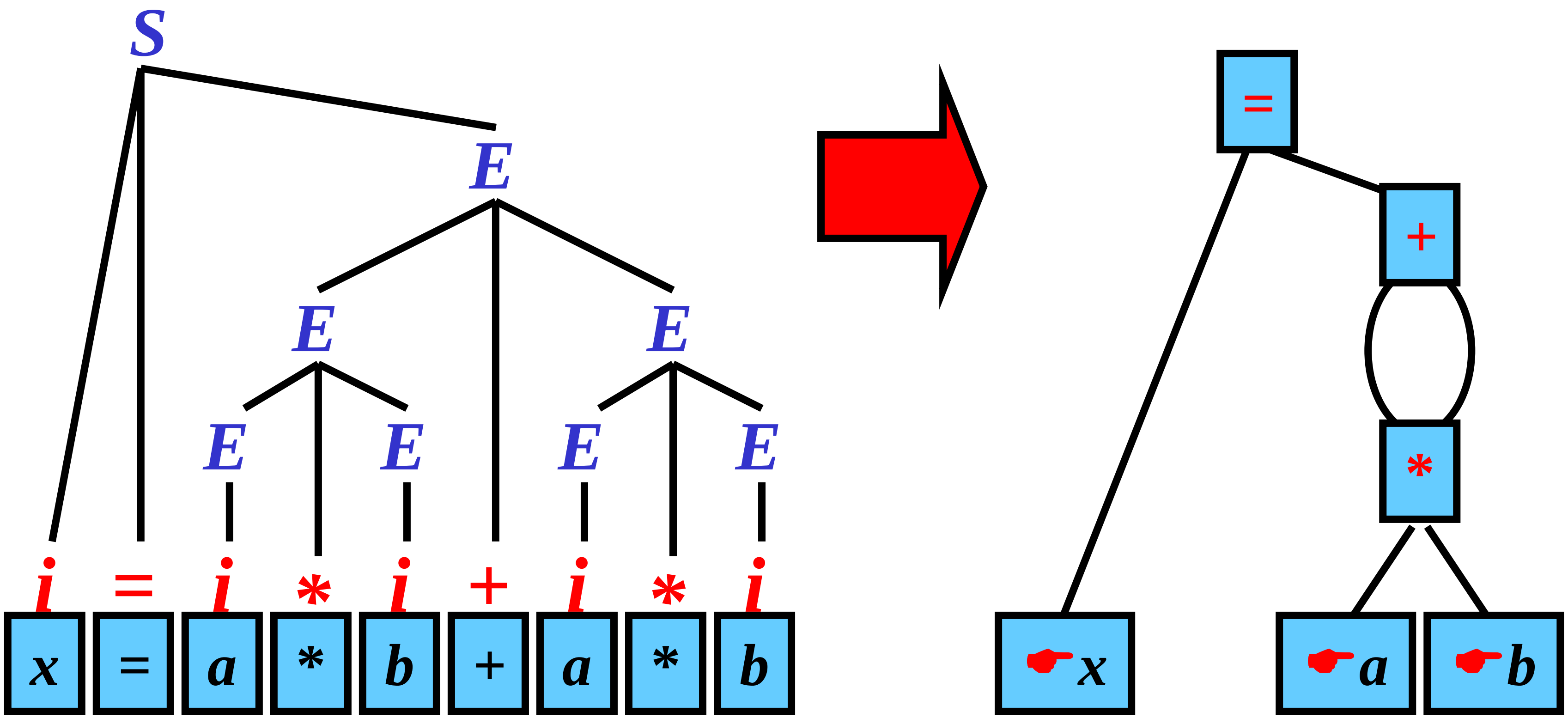


Abstract syntax tree:



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**

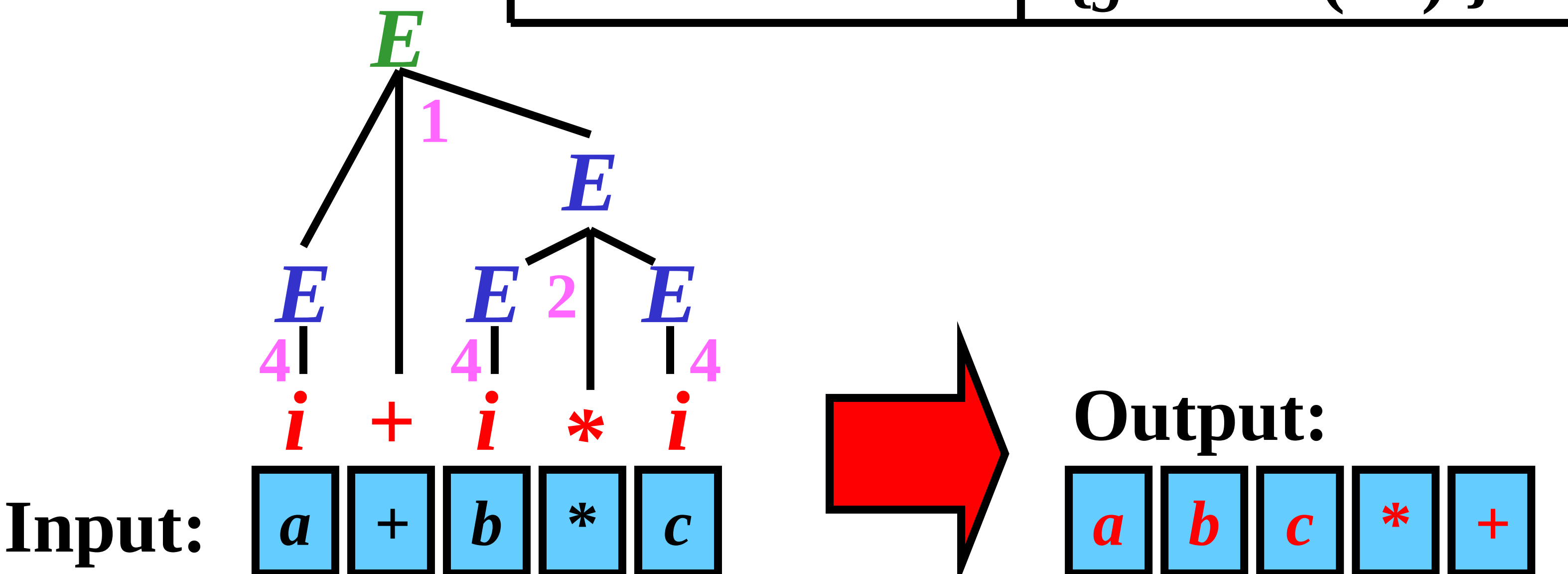
Note: Postfix notation is achievable by the postorder traversal of AST.

Infix to Postfix Directed by a BU Parser

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

Example:

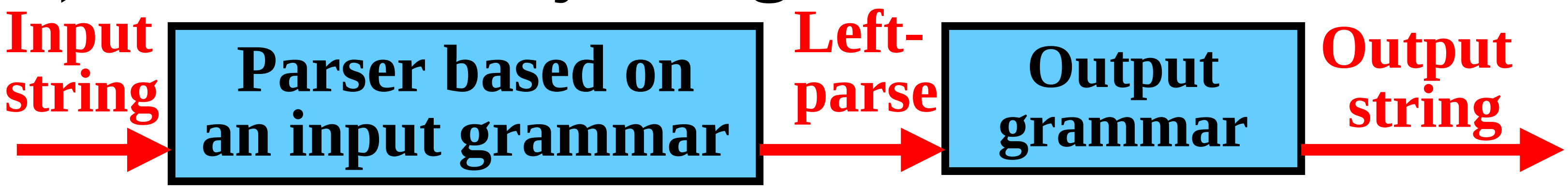
Rule:	Semantic Action:
1: $E \rightarrow E+E$	{*generate*('+')}
2: $E \rightarrow E*E$	{*generate*('*')}
3: $E \rightarrow (E)$	{ - }
4: $E \rightarrow i$	{*generate*(*i.a*) }



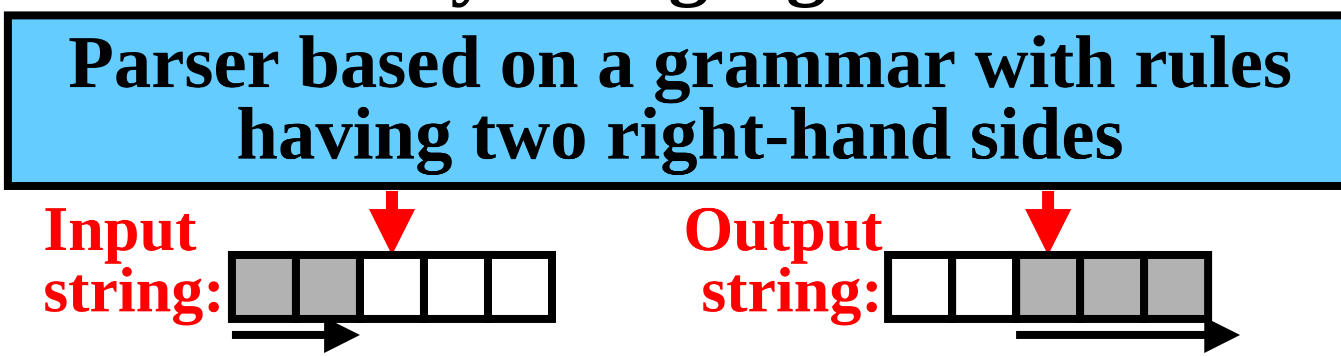
Translation Grammars

Gist: Translation grammars translate input strings to output strings

1) Translation by two grammars:



2) Translation by a single grammar

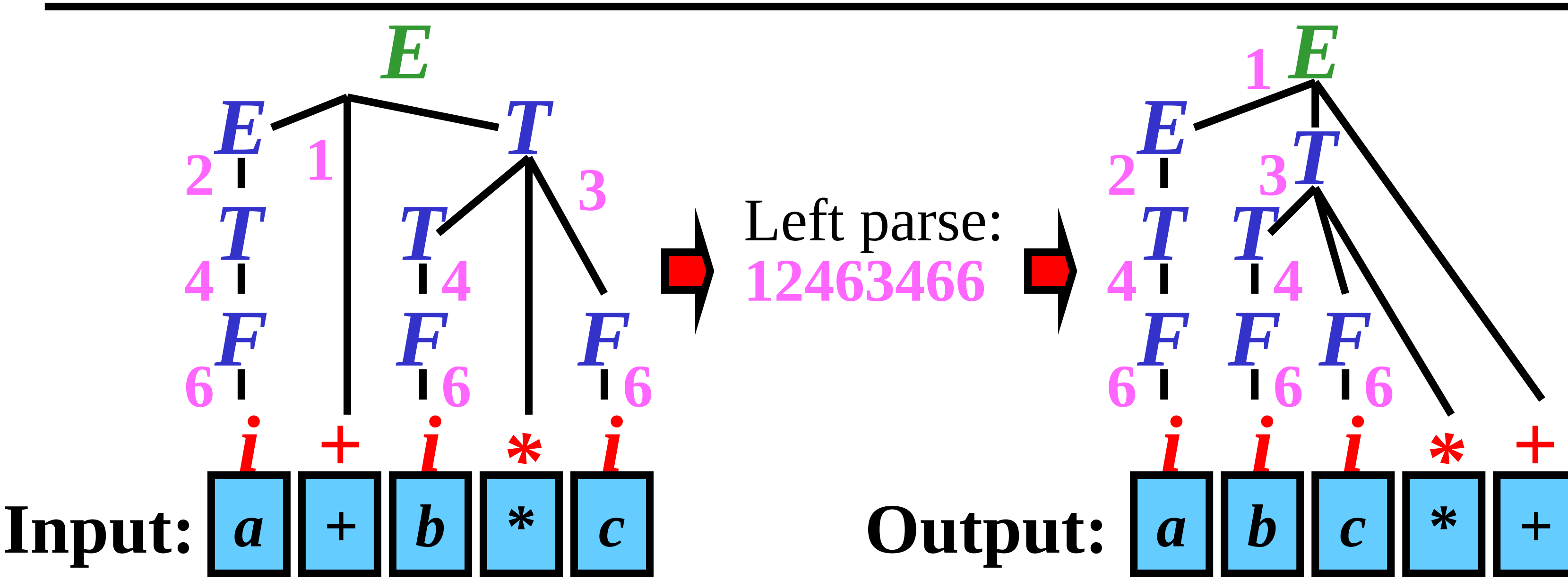


Note: During the parse of an input string, a simultaneous generation f an output string occurs

Two-Grammar Translation

Infix to postfix translation:

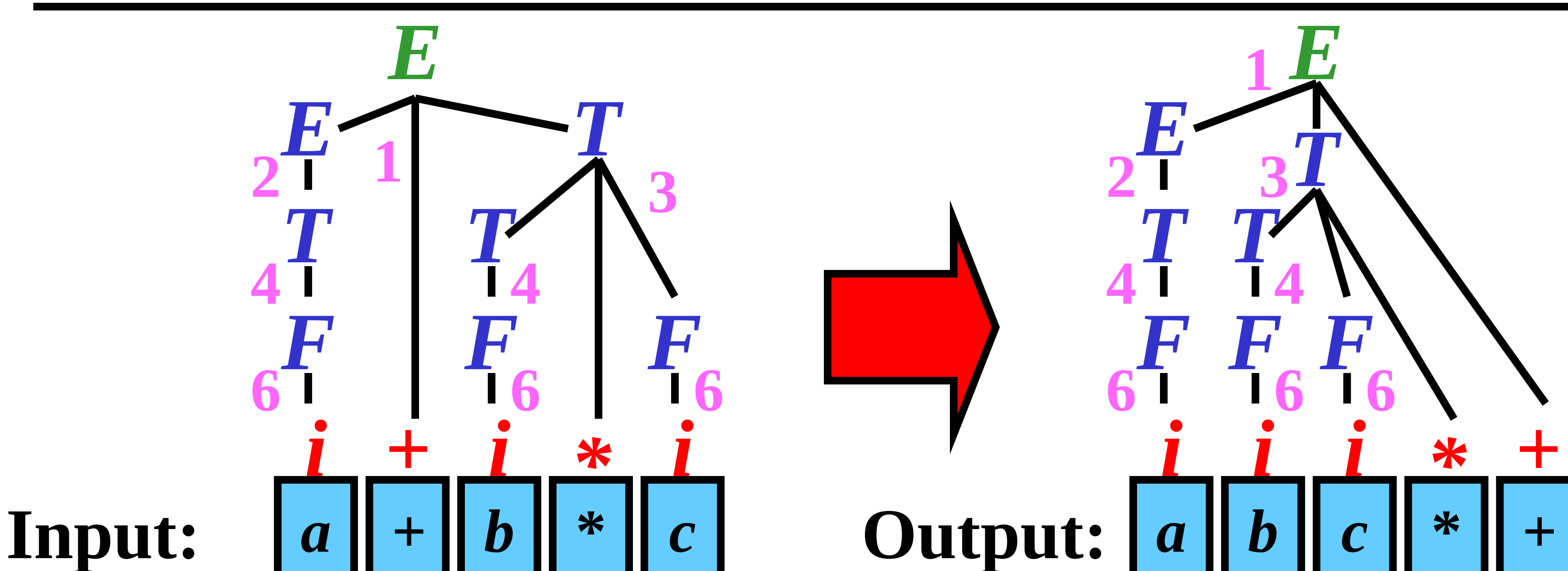
Rules of G_1	Rules of G_2
1: $E \rightarrow E+T$	1: $E \rightarrow ET+$
2: $E \rightarrow T$	2: $E \rightarrow T$
3: $T \rightarrow T*F$	3: $T \rightarrow TF*$
4: $T \rightarrow F$	4: $T \rightarrow F$
5: $F \rightarrow (E)$	5: $F \rightarrow E$
6: $F \rightarrow i$	6: $F \rightarrow i$



One-Grammar Translation

Infix to postfix translation:

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

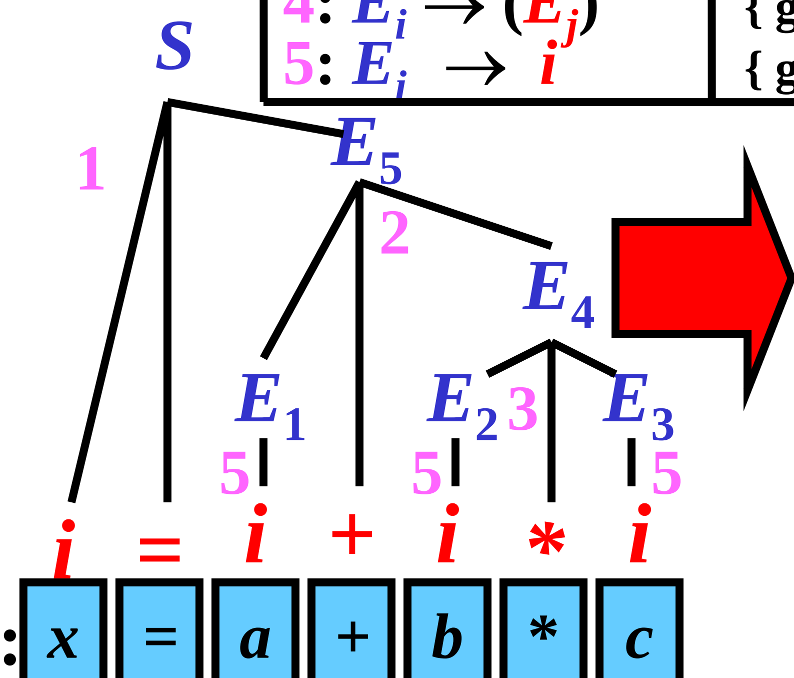


Direct Generation of 3AC

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)}



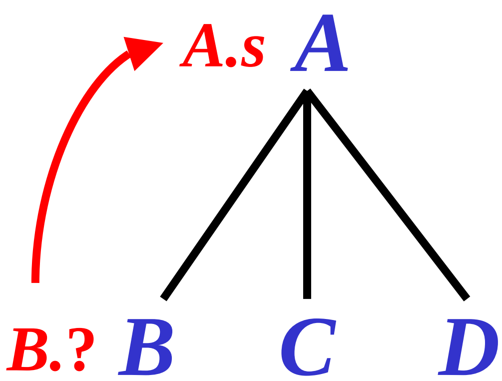
Input:

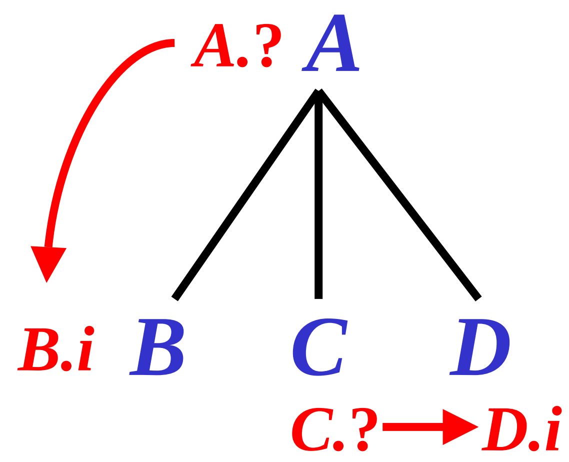
Output:

('=', ☛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)



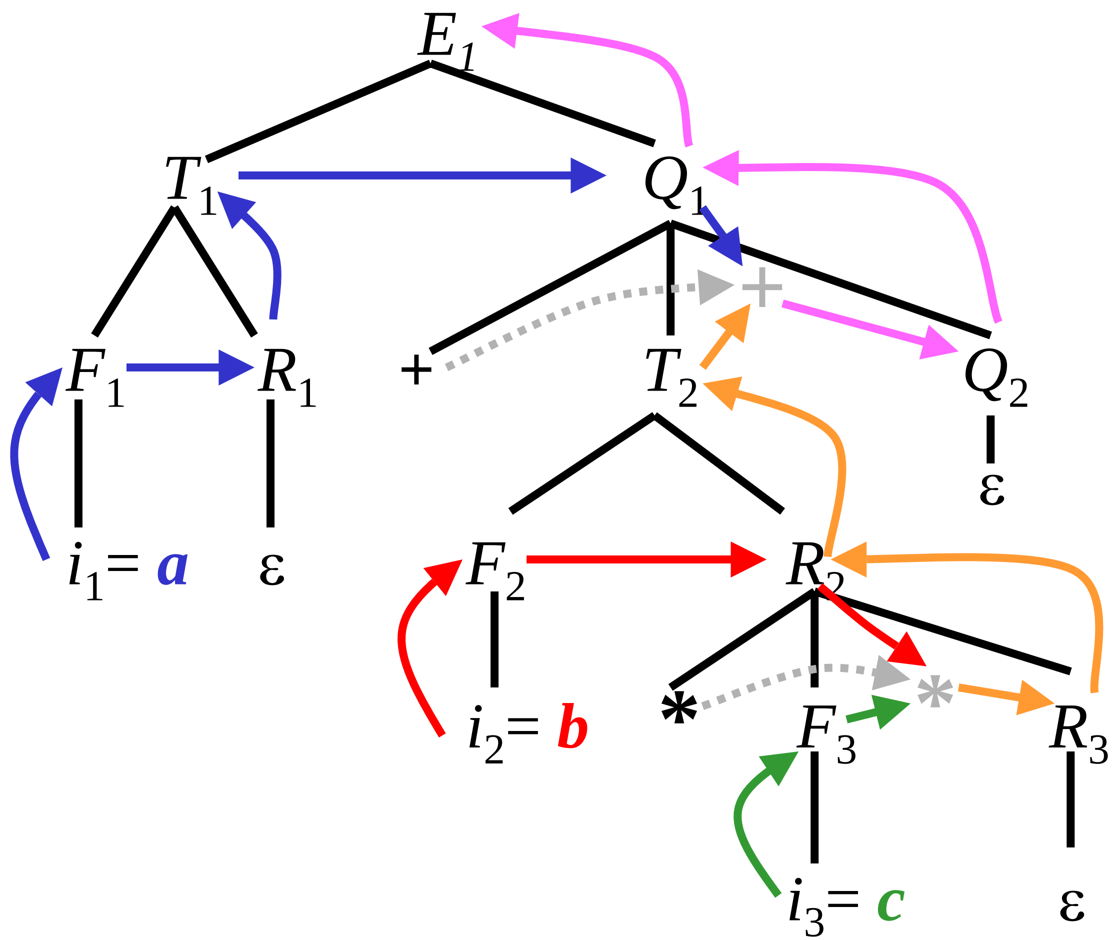


Top-Down Translation: Expressions

Grammar:

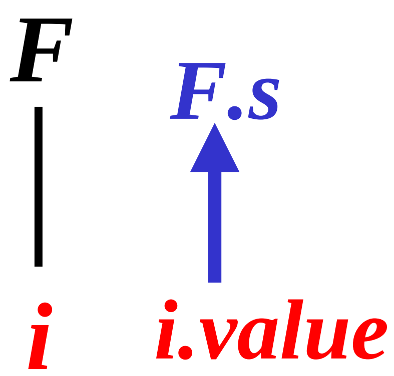
$E \to TQ$
$Q \to +TQ$
$Q \to \varepsilon$
$T \to FR$
$R \to *FR$
$R \to \varepsilon$
$F \to (E)$
$F \to i$

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



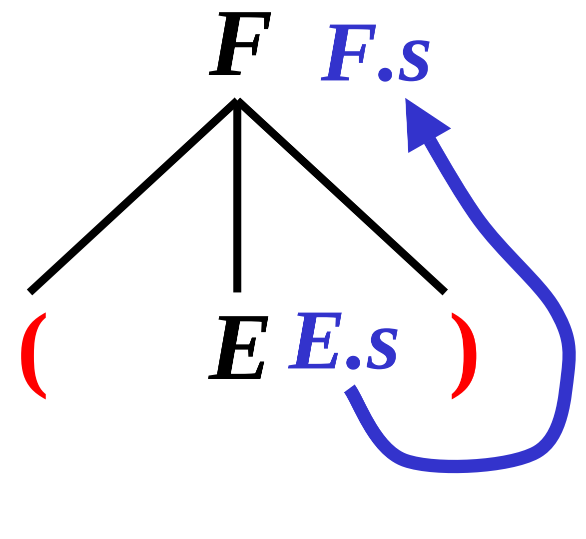
Expressions: Variable & Parentheses

Variable:



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

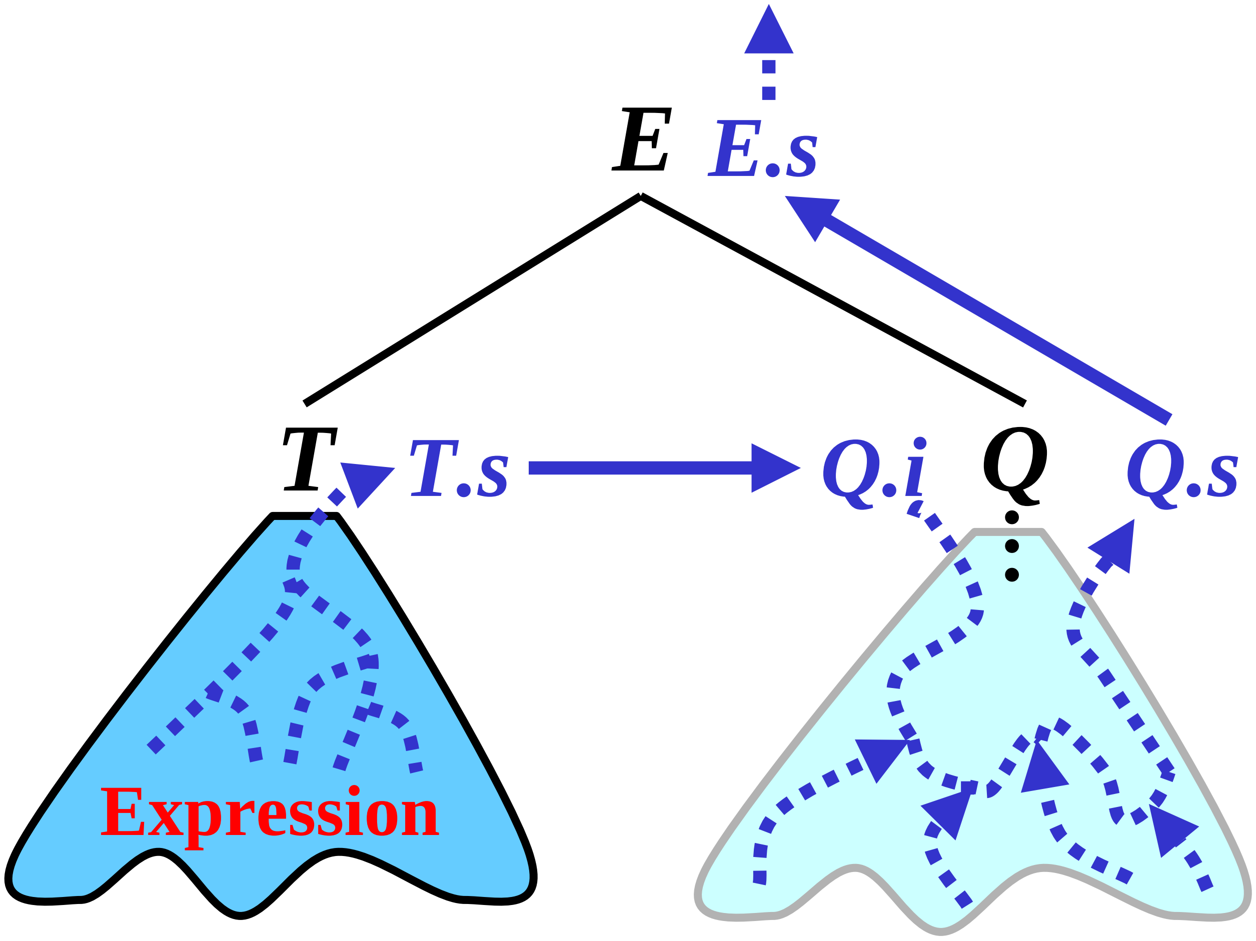
Parentheses:



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

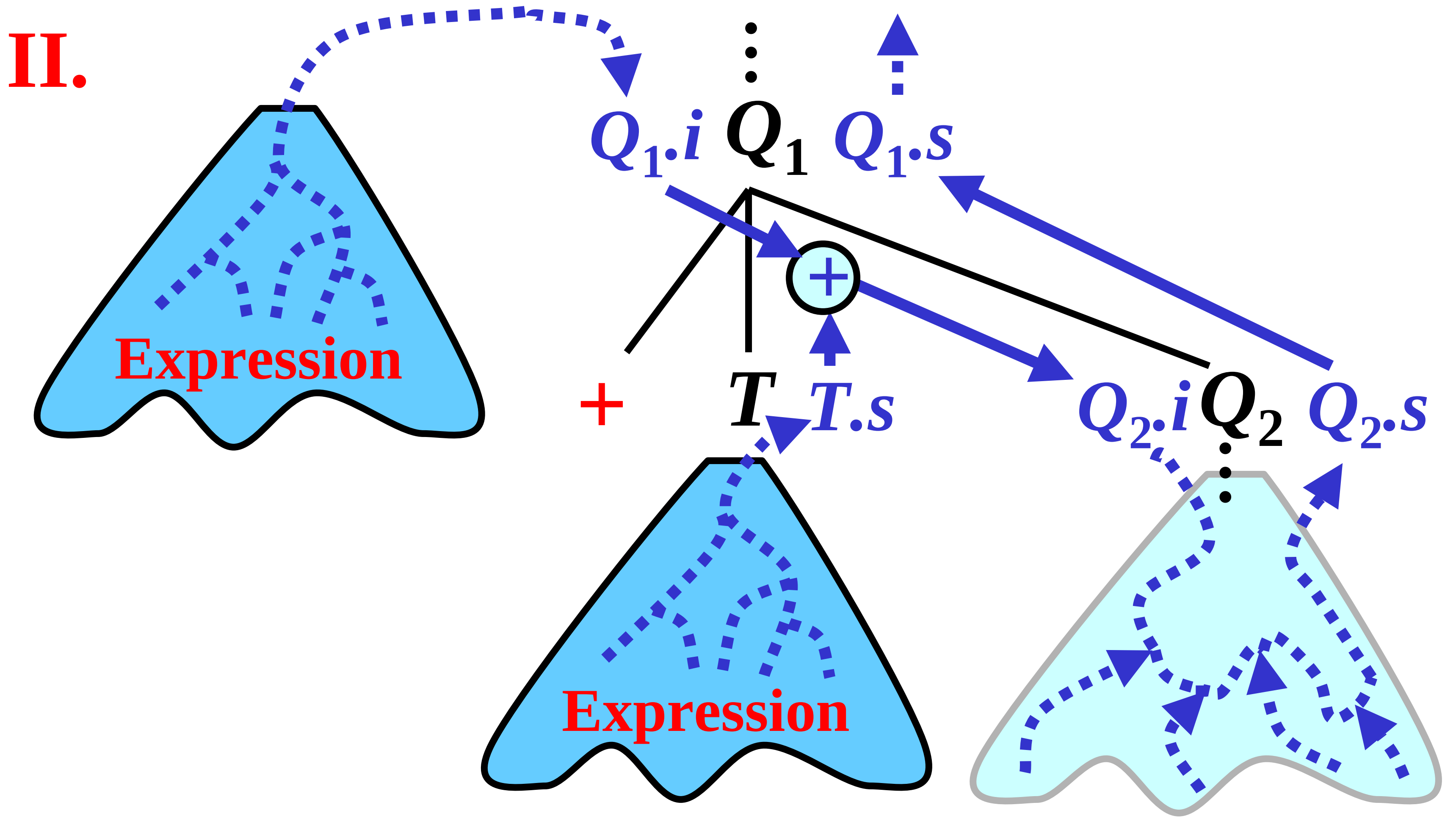
Expressions: Addition 1/4

I.



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

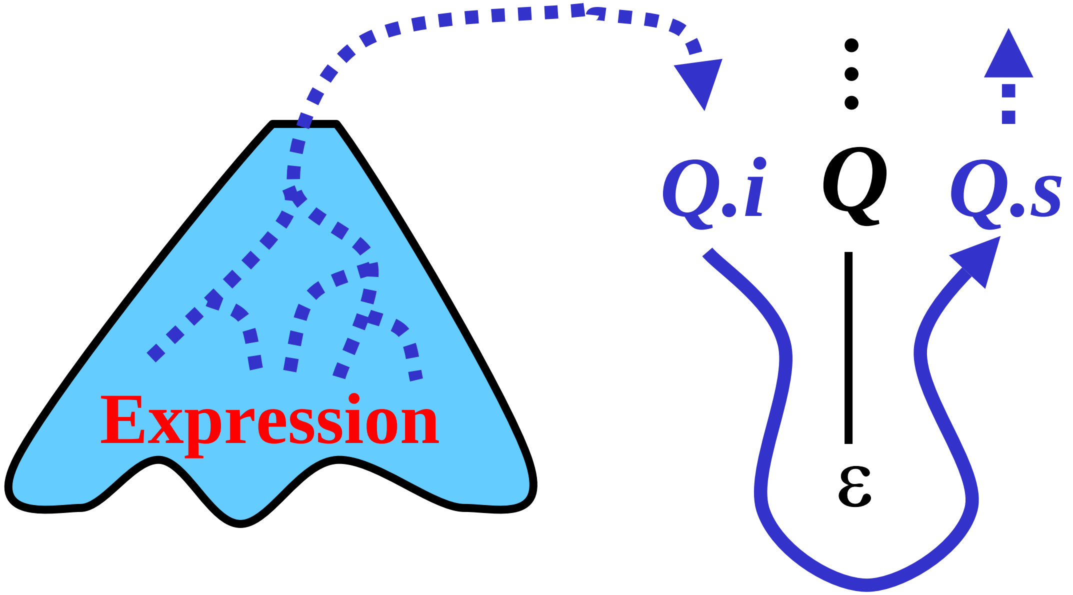
Expressions: Addition 2/4



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

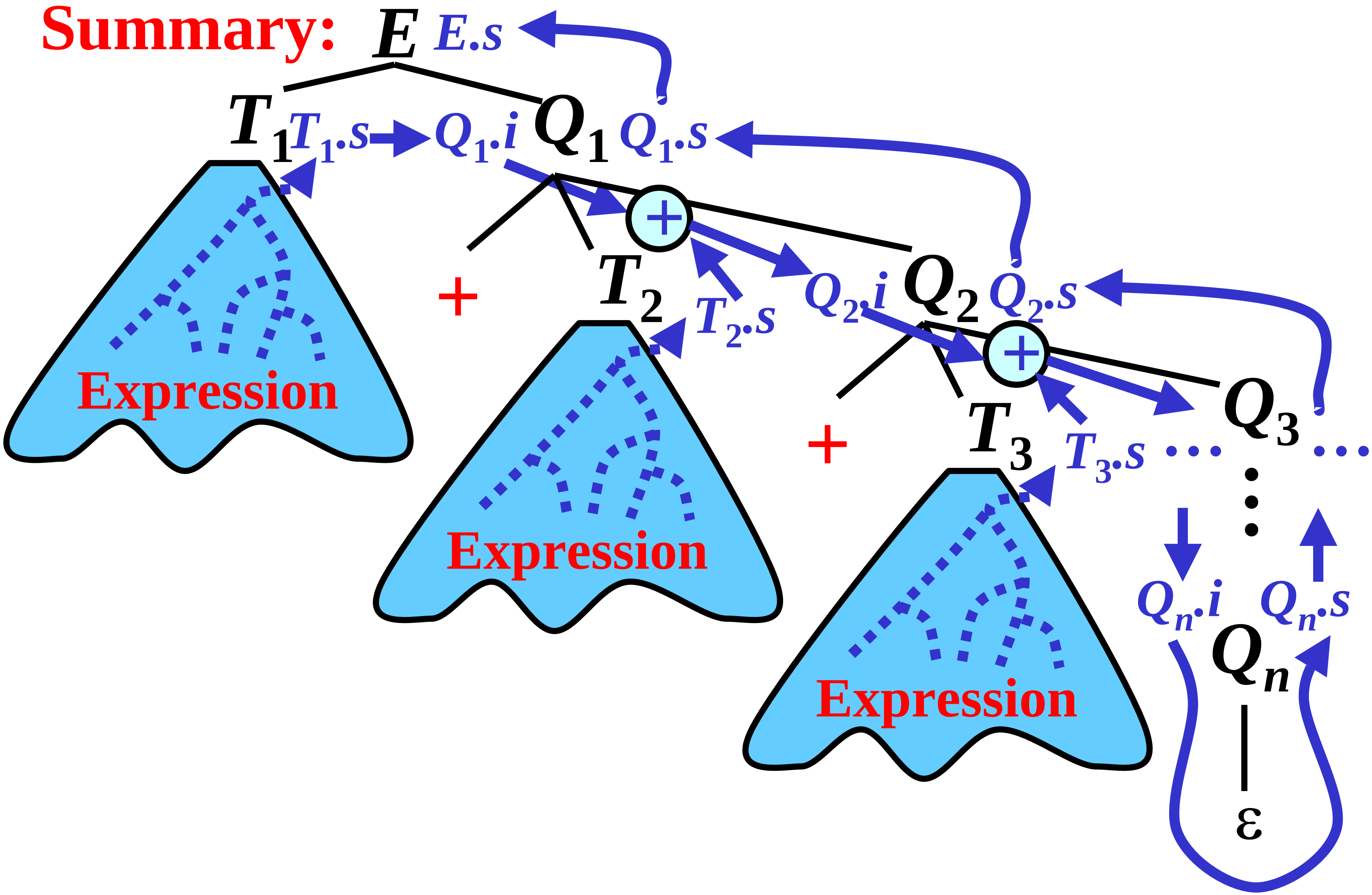
Expressions: Addition 3/4

III.



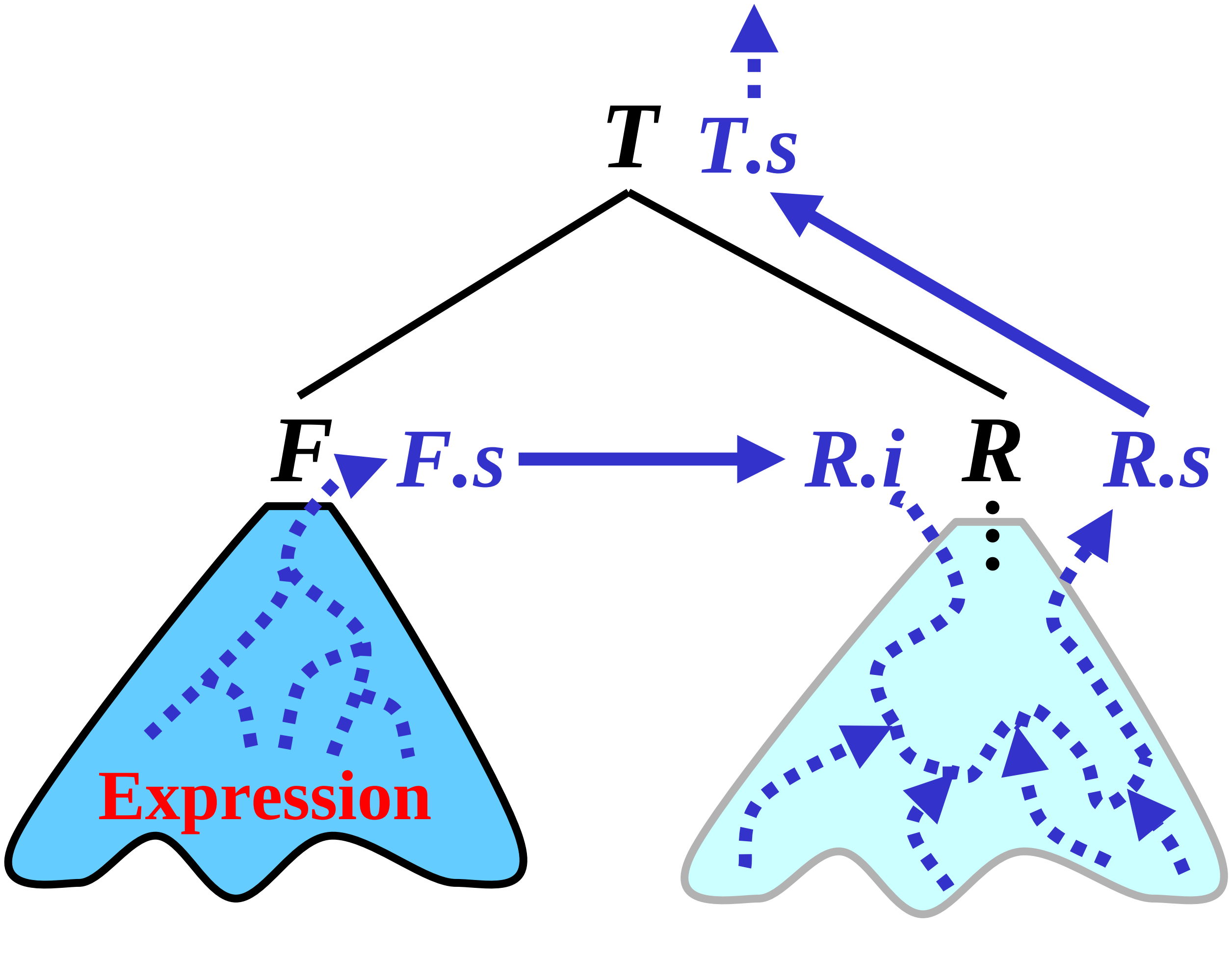
$Q \rightarrow \varepsilon$ $\{Q.s := Q.i\}$

Expressions: Addition 4/4



Expressions: Multiplication 1/4

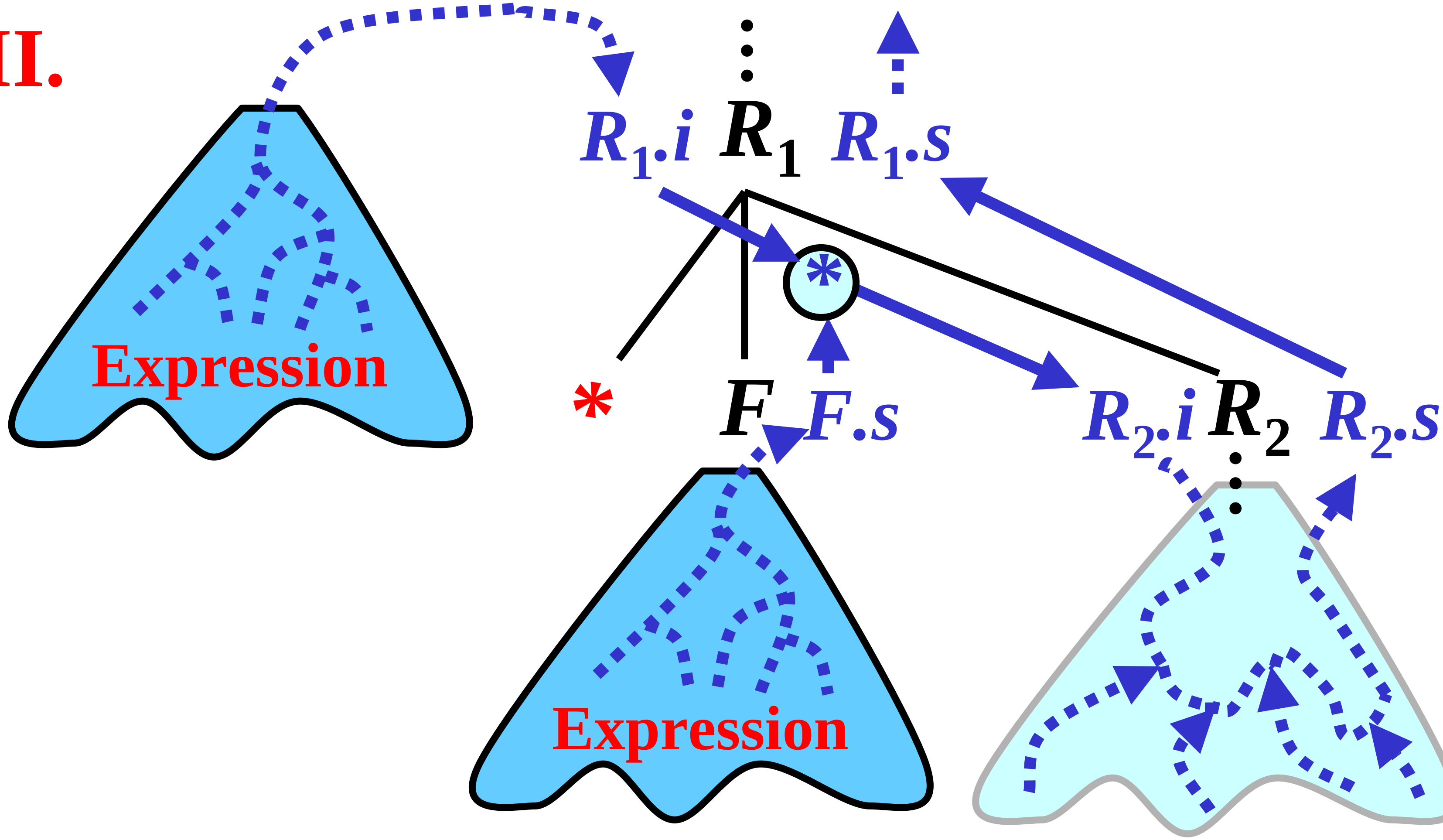
I.



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

Expressions: Multiplication 2/4

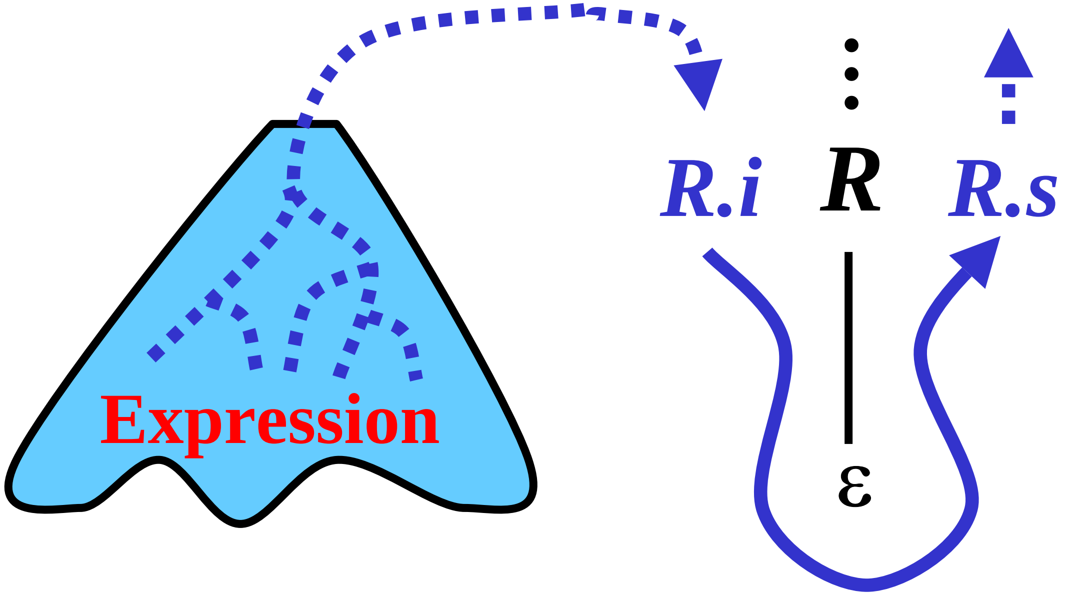
II.



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

Expressions: Multiplication 3/4

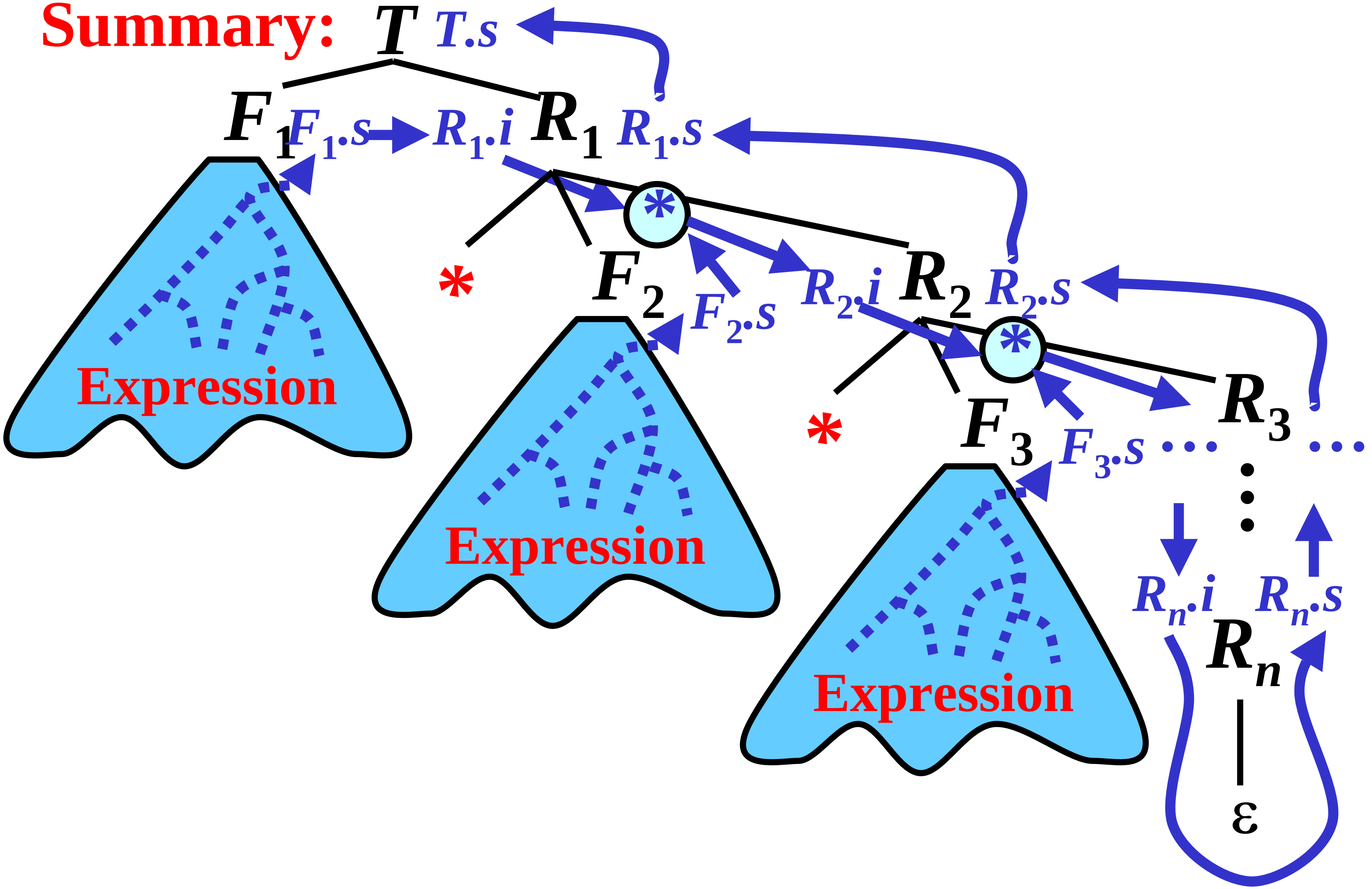
III.



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

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: $i_1 + i_2\ \$$

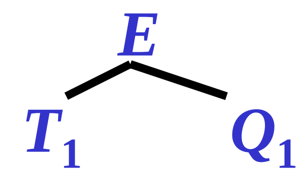
Rule: $T_1 \rightarrow F_1\ \{R_1.i := F_1.s\}\ R_1\ \{T_1.s := R_1.s\}$

Parser pushdown:

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

Semantic pushdown:

Illustration:



10 + 20

Evaluation of Expressions: Example 3/16

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

Input: $i_1 + i_2$ \$

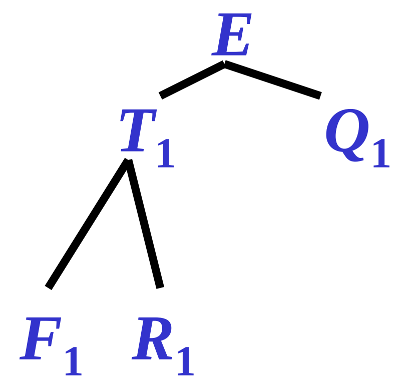
Rule: $F_1 \rightarrow i_1$ $\{F_1.s := i.value\}$

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:



| 10 | + | 20 |

Evaluation of Expressions: Example 4/16

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

Input: $i_1 + i_2\ \$$

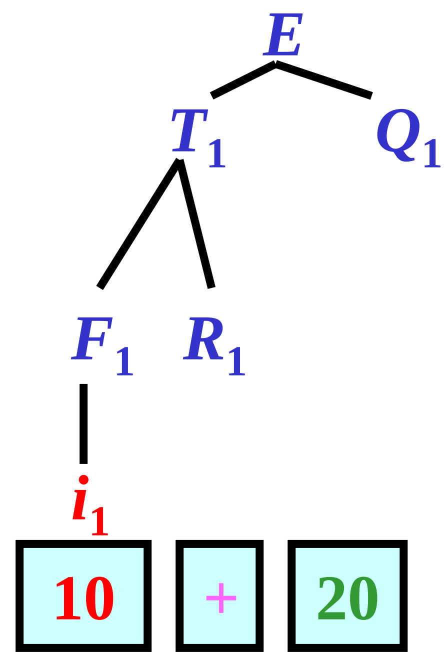
Rule:

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: $+\ i_2\ \$$

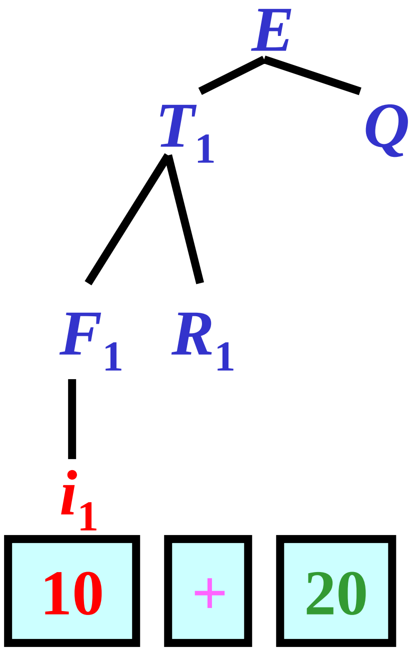
Rule:

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

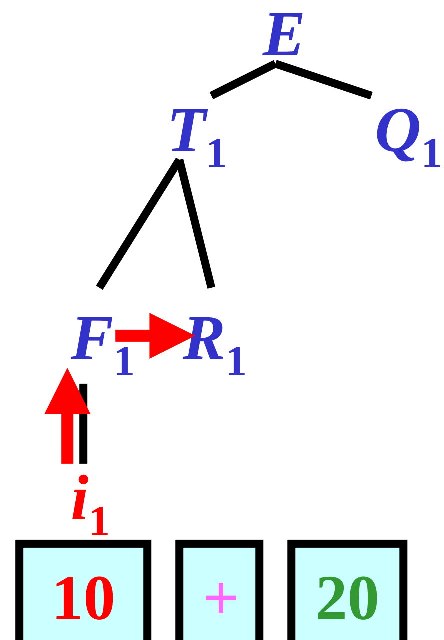
Parser pushdown:

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

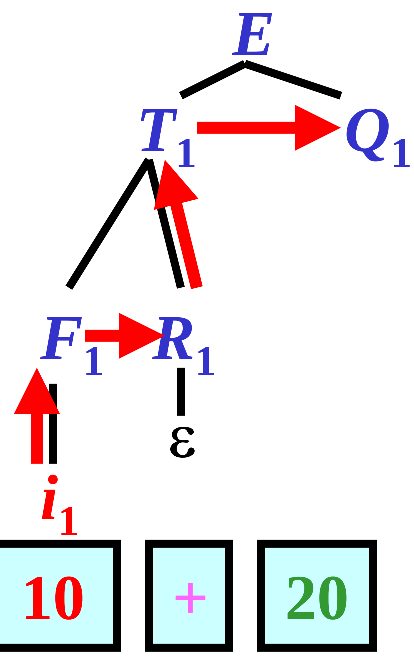
$\{E.s := Q_1.s\}$

$\$$

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:

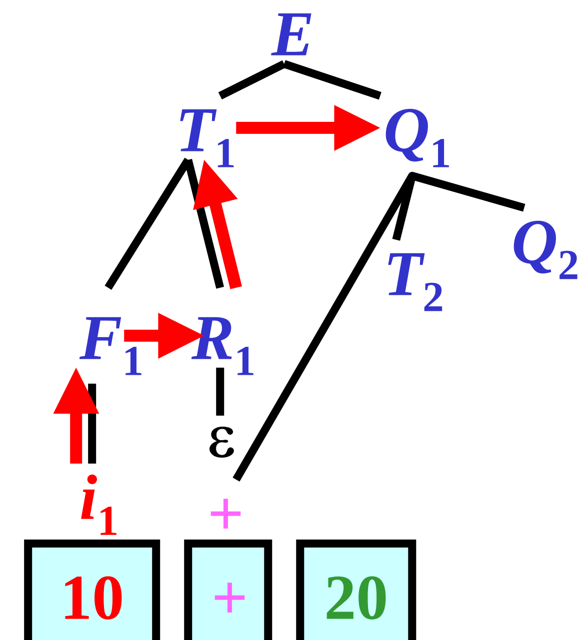
Parser pushdown:

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

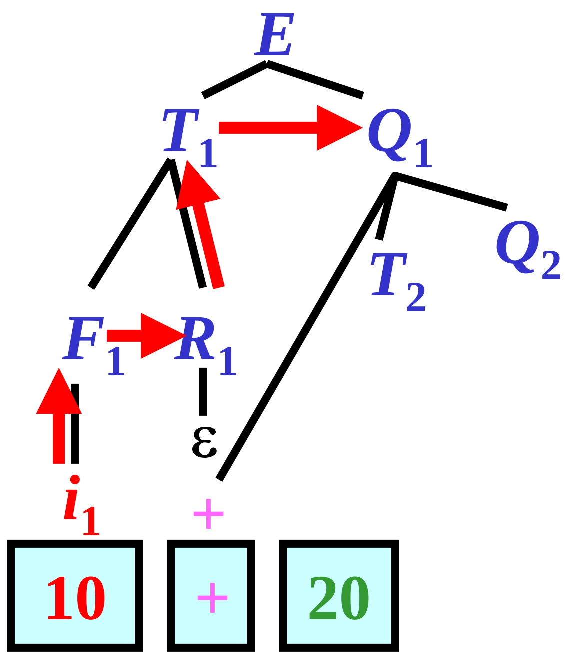
Parser pushdown:

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

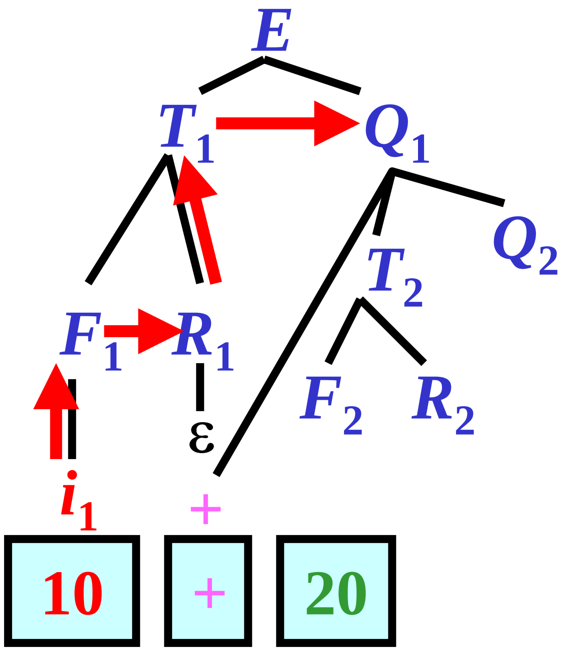
Parser pushdown:

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:

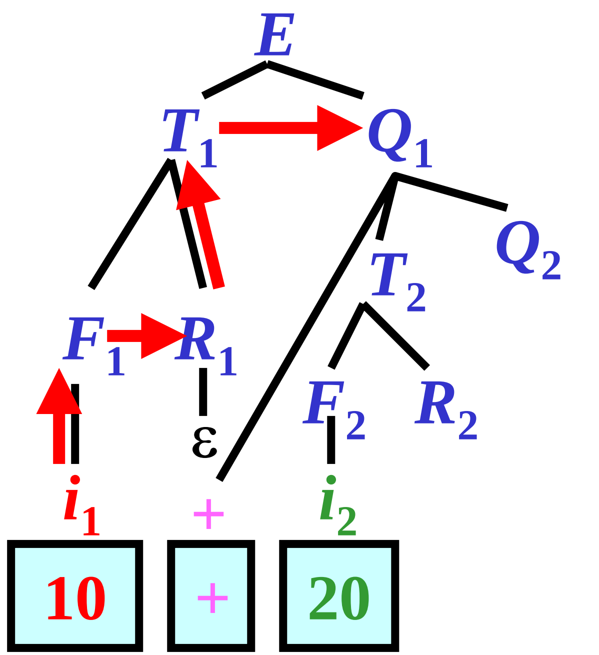
Parser pushdown:

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:

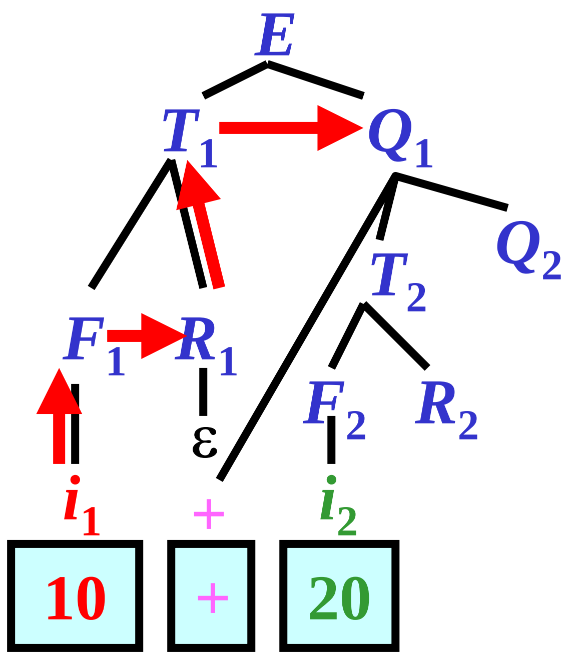
Parser pushdown:

$\{F_2.s := i.value\}$
$\{R_2.i := F_2.s\}$
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: $R_2 \rightarrow \varepsilon$ $\{R_2.s := R_2.i\}$

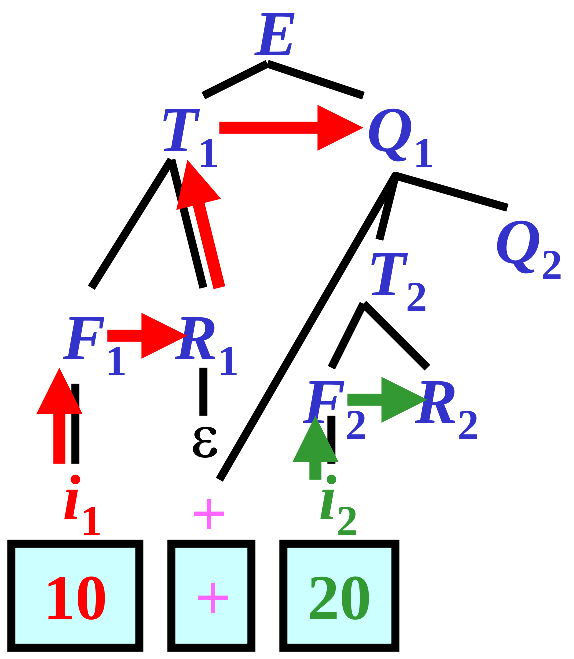
Parser pushdown:

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:

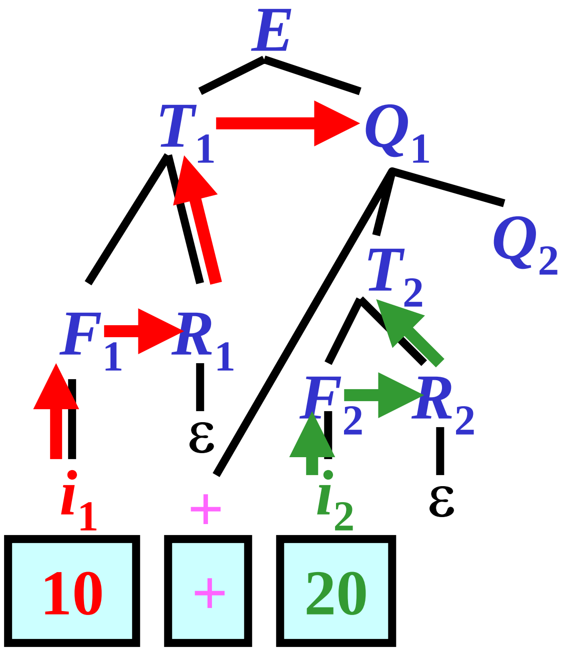
Parser pushdown:

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

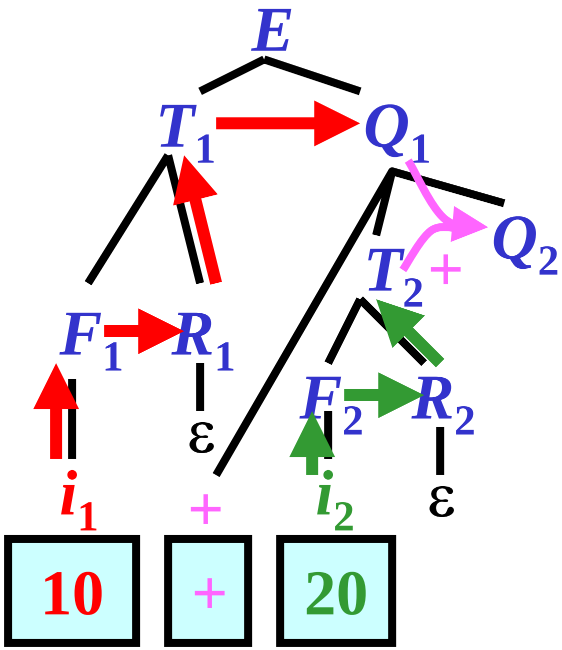
Parser pushdown:

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:

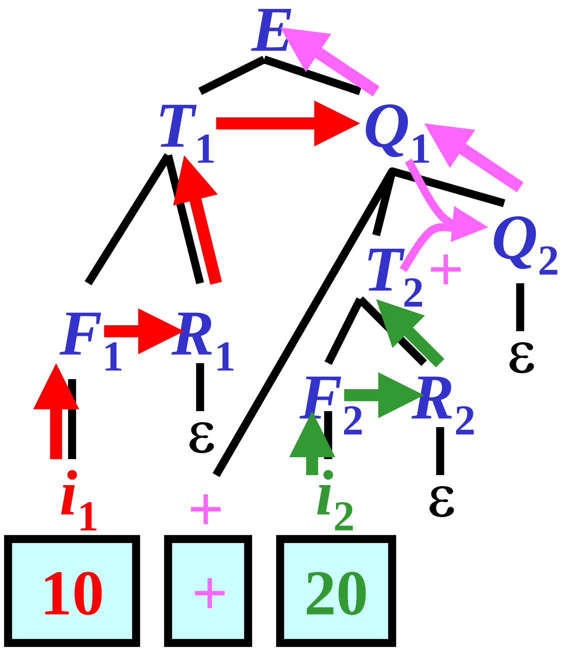
Parser pushdown:

$

Semantic pushdown:

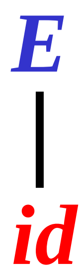
E.s = 30

Illustration:



Semantic Analysis: Type Checking

1) Rule:

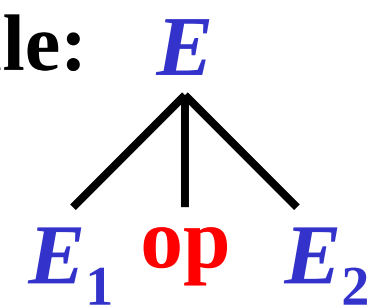


Action:

E.type := *id*.type

---

2) Rule:



Operation op is defined over types:

$$t_1 \text{ op } t_2 \rightarrow t_3$$

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*

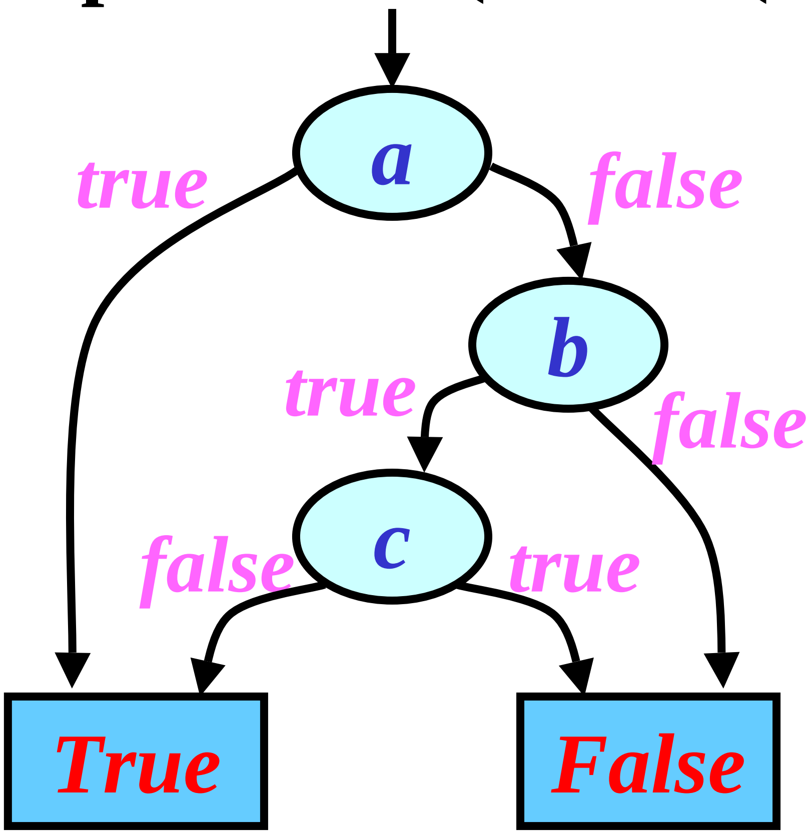
2) (*a* **or** *b*) = *p*:

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: …

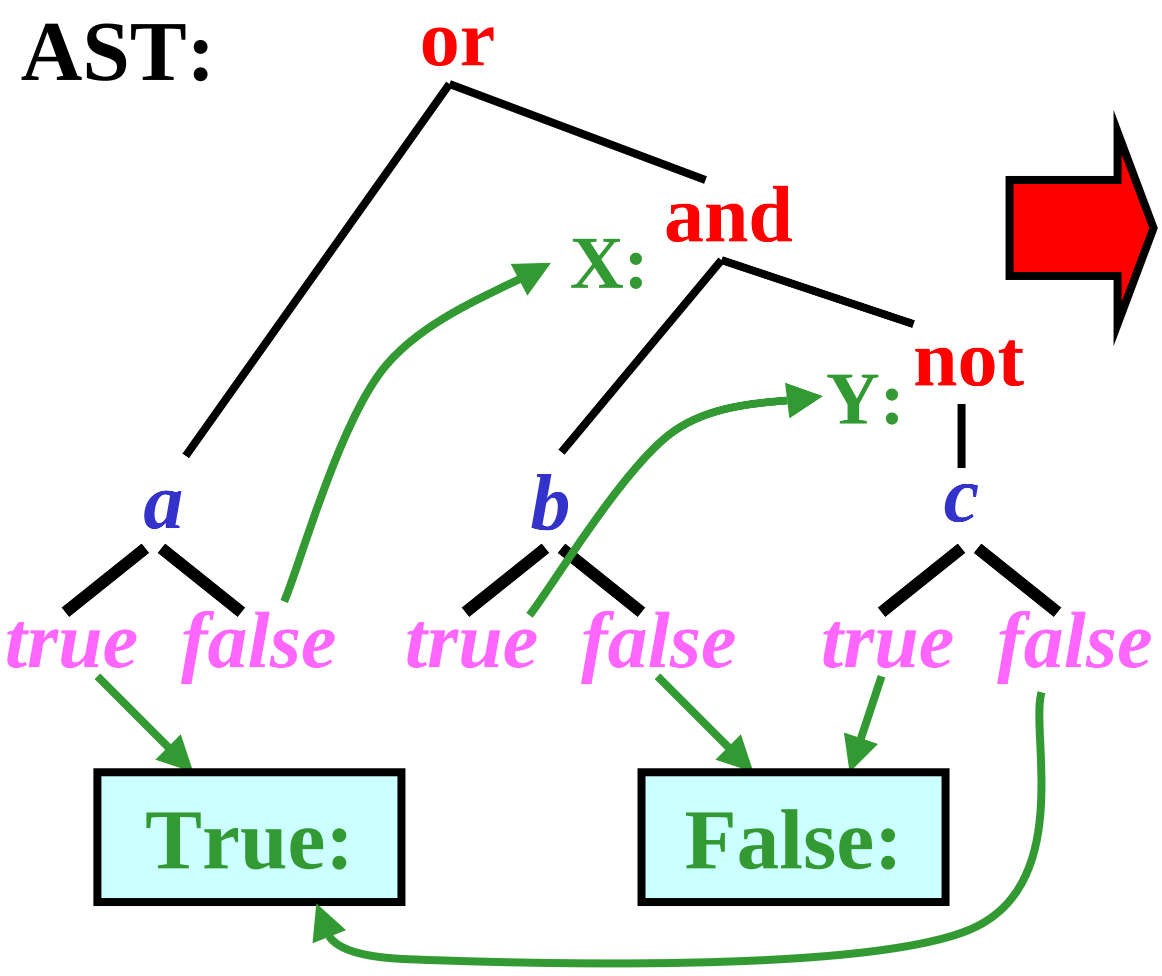
False: …

- 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: …

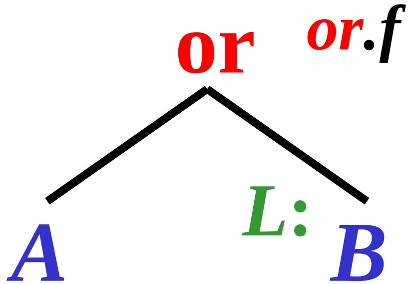
False: …

Short Evaluation Using AST: Implementation

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

Elementary ASTs:

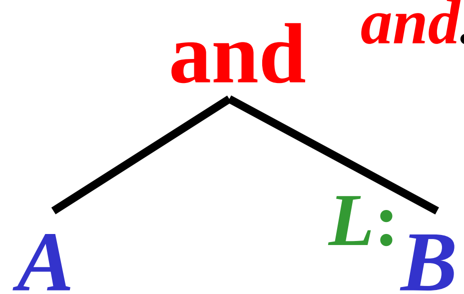
1) ***or*.*t***, ***or*.*f***



A*.*t := ***or*.*t*** ***B*.*t*** := ***or*.*t***
A*.*f := ***L*** ***B*.*f*** := ***or*.*f***

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

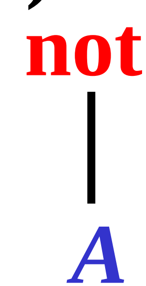
2) ***and*.*t***, ***and*.*f***



A*.*t := ***L*** ***B*.*t*** := ***and*.*t***
A*.*f := ***and*.*f*** ***B*.*f*** := ***and*.*f***

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

3) ***not*.*t***, ***not*.*f***



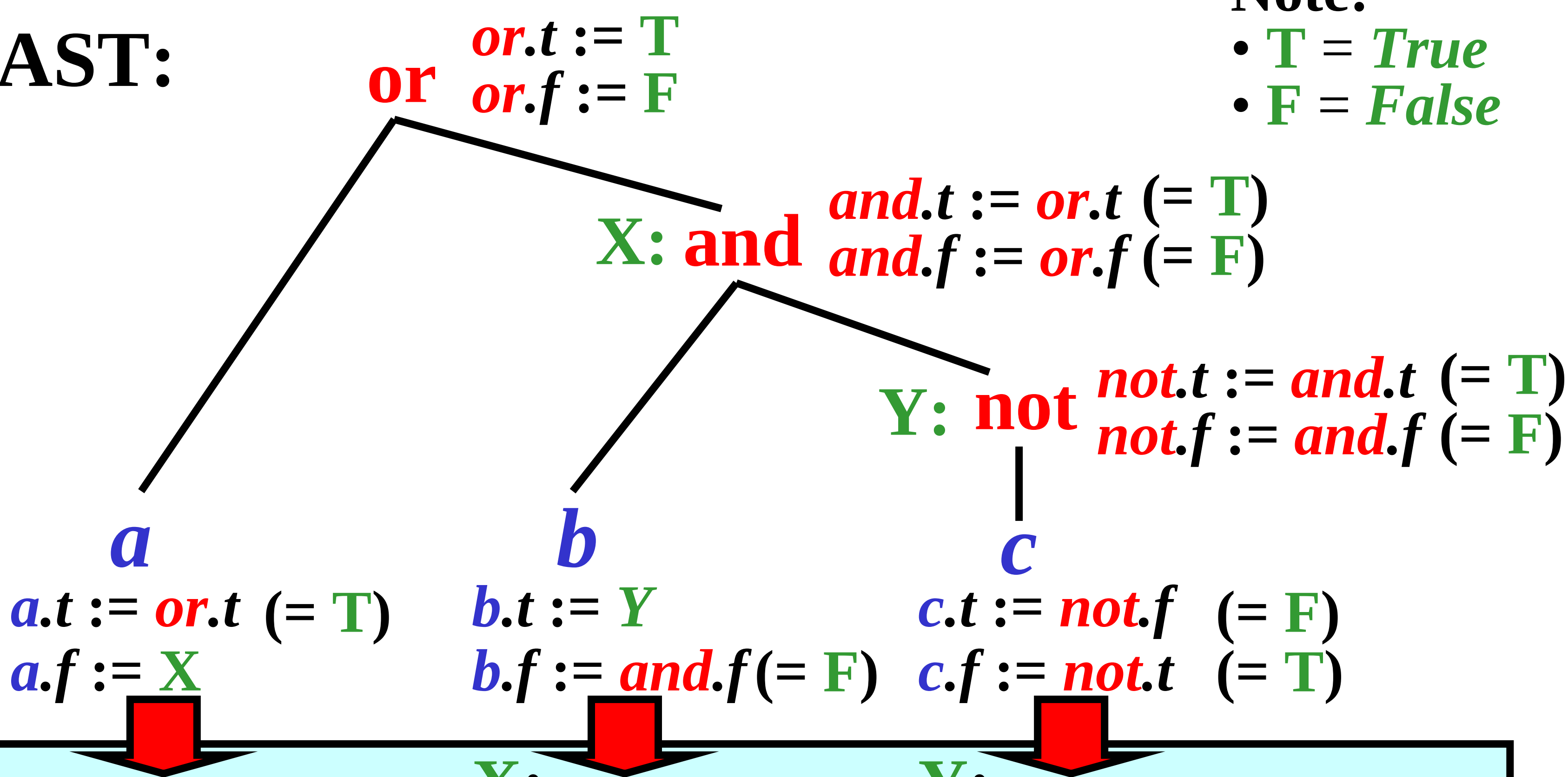
A*.*t := ***not*.*f***
A*.*f := ***not*.*t***

- **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*)):**

AST:



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:

1. $E \rightarrow E$ **or** E
2. $E \rightarrow E$ **and** E
3. $E \rightarrow$ **not** E
4. $E \rightarrow$ **(** E **)**
5. $E \rightarrow$ **id**

Note: Ambiguity!

- **Modification of grammar:**

1) Replace rules 1. & 2. with:

$E \rightarrow E$ **or** $M\ E$

$E \rightarrow E$ **and** $M\ E$

$M \rightarrow \varepsilon$

2) Assign to each rule the following semantic action

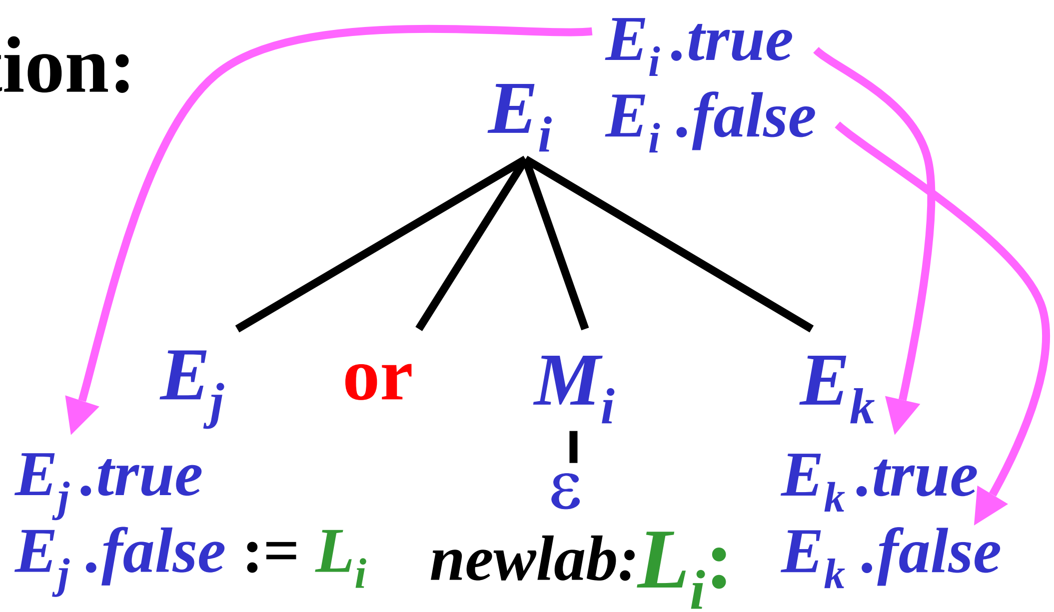
Short Evaluation: Direct Code Generation 2/5

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

---

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

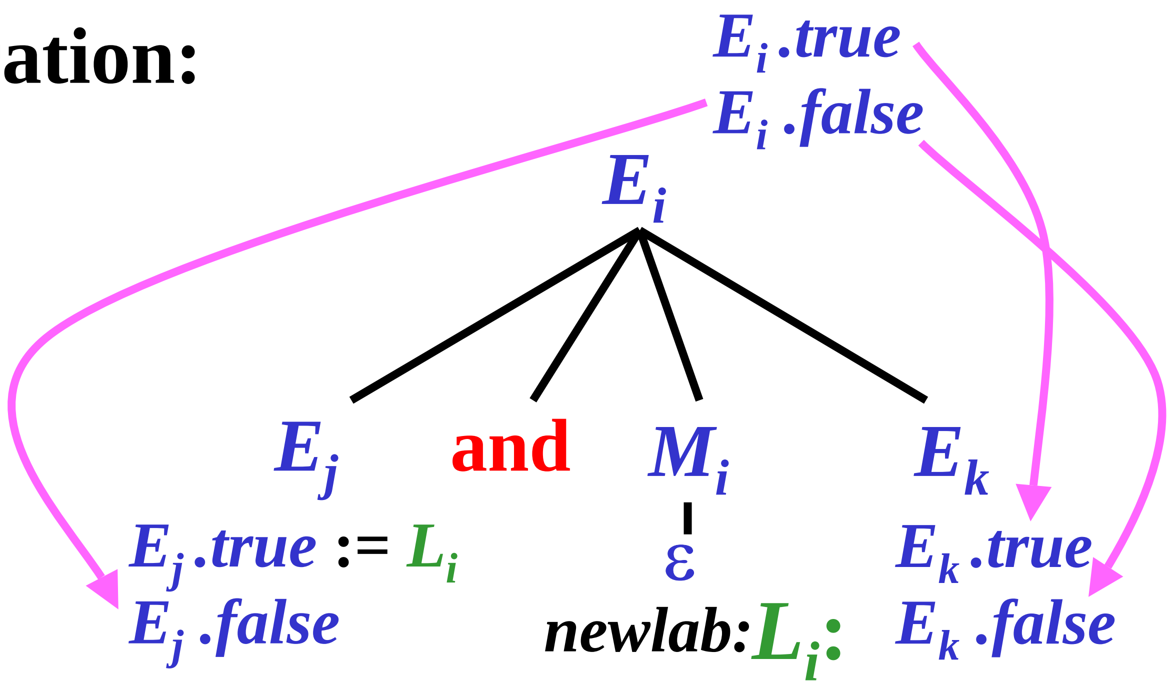
Illustration:



Short Evaluation: Direct Code Generation 3/5

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

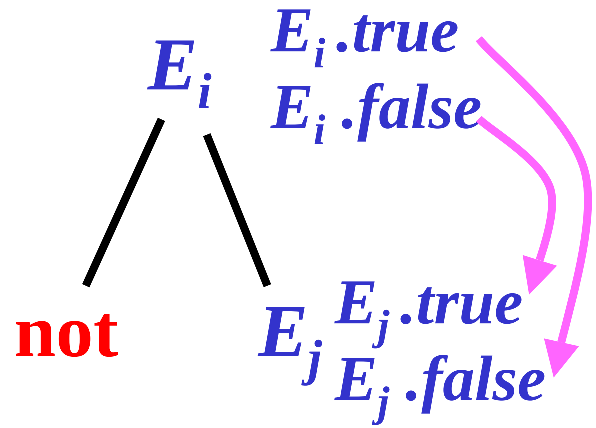
Illustration:



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:

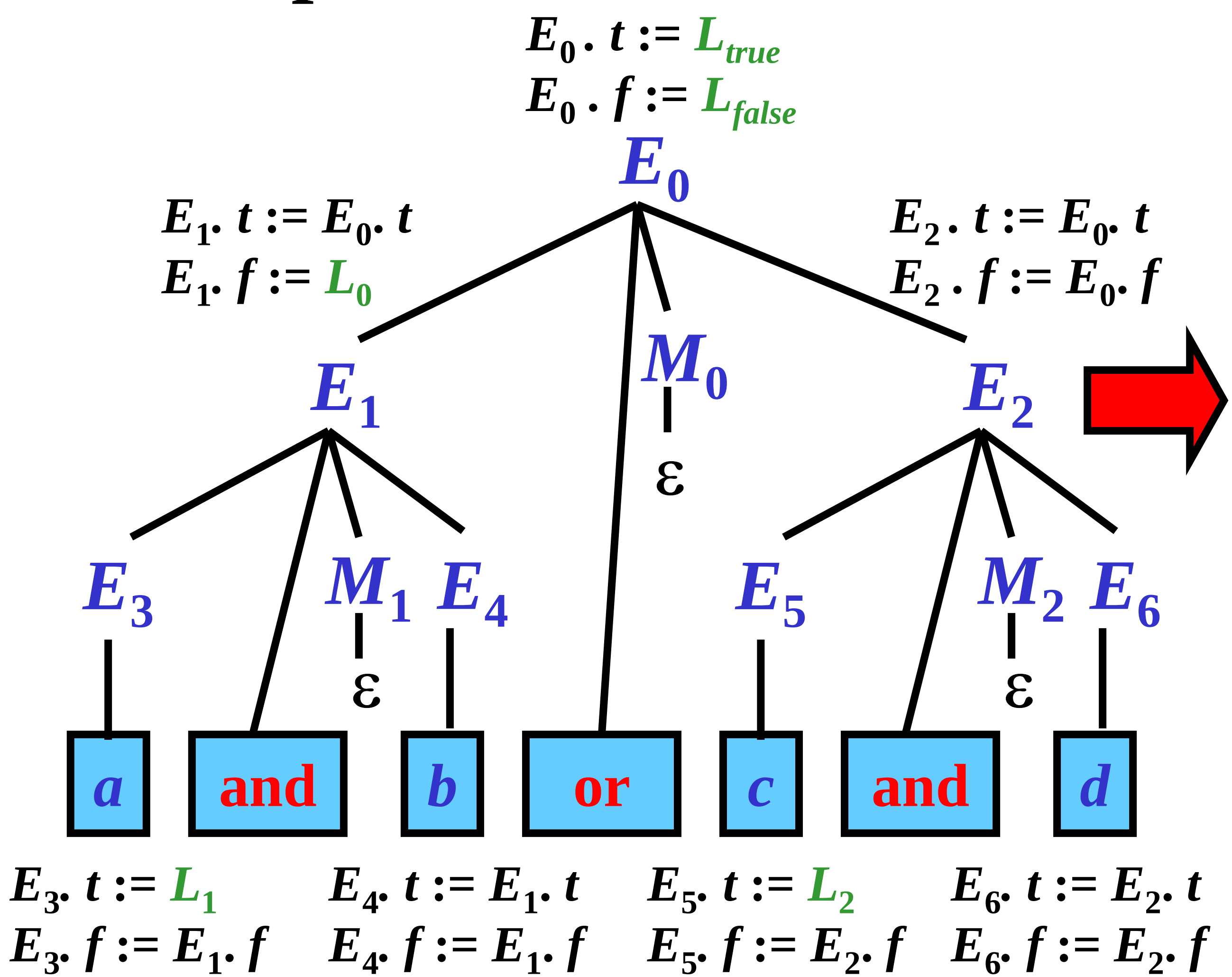


$E_i \rightarrow$ **(**E_j**)** {$E_j.true$:= $E_i.true$;
$E_j.false$:= $E_i.false$ }

$E_i \rightarrow id_j$ { 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*:**



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:

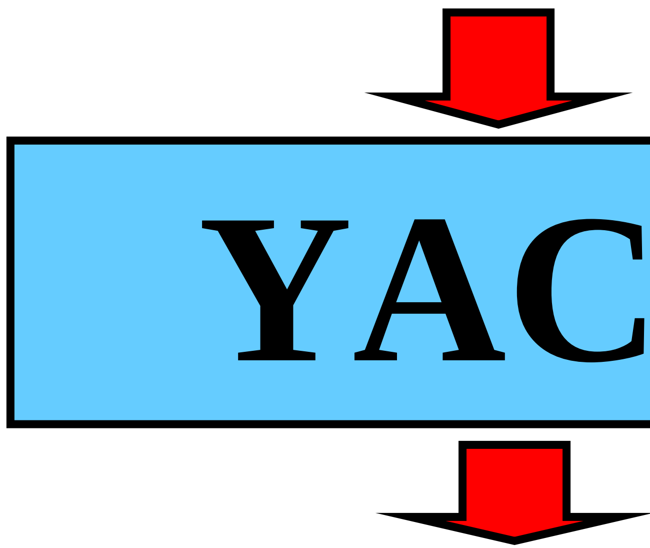
```
(lab , L1     , ,       )
{// code of stat

 // 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

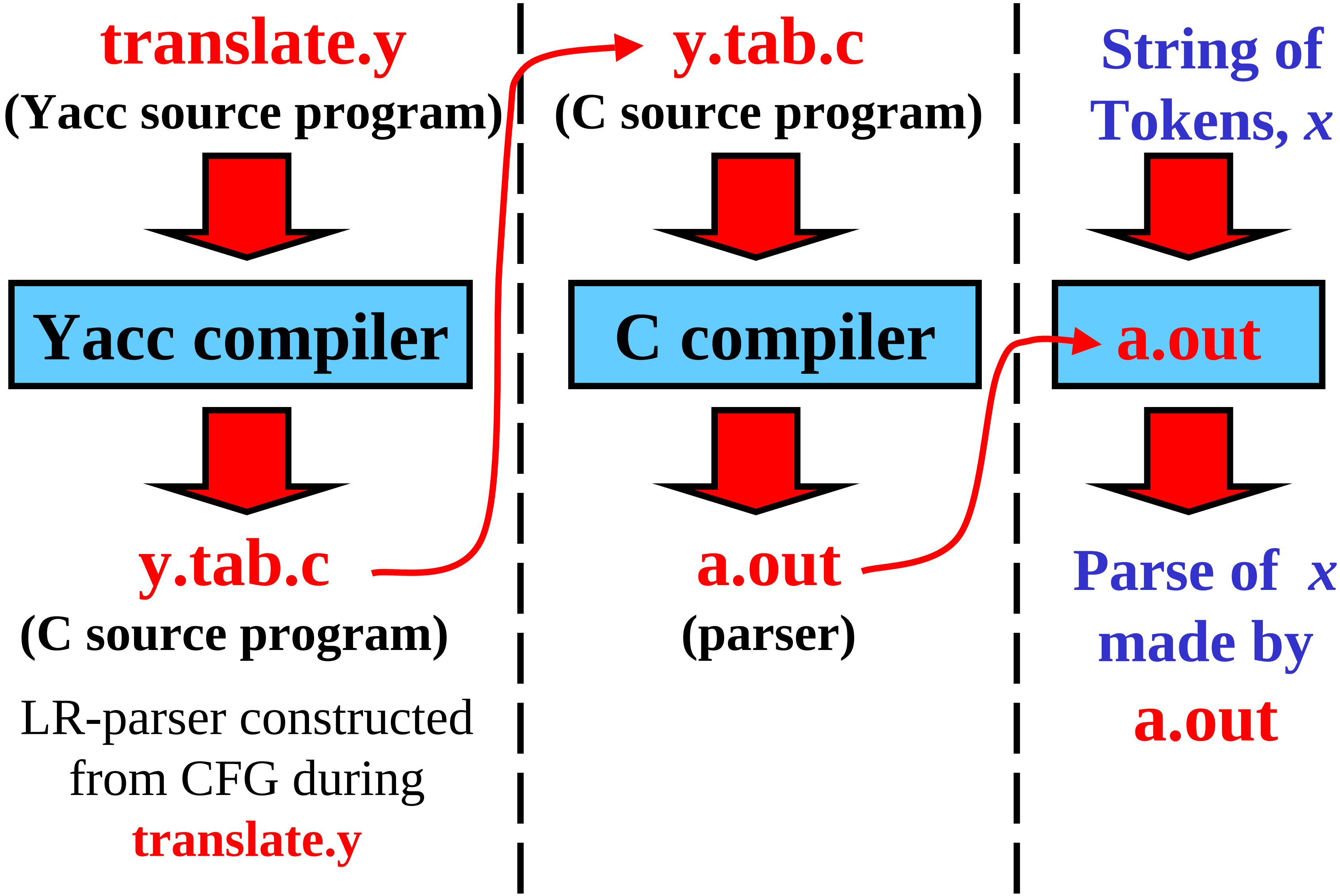
Ilustrace:

Context-free grammar, *G*



Parser for *G*

Yacc: Phases of Compilation



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 { $A \to x_1$, $A \to x_2$, … $A \to x_n$ }

  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  opi1, opi2, … ,opim
%left  opj1, opj2, … ,opjm
…
%right opk1, opk2, … ,opkp
```

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 () { … }
```