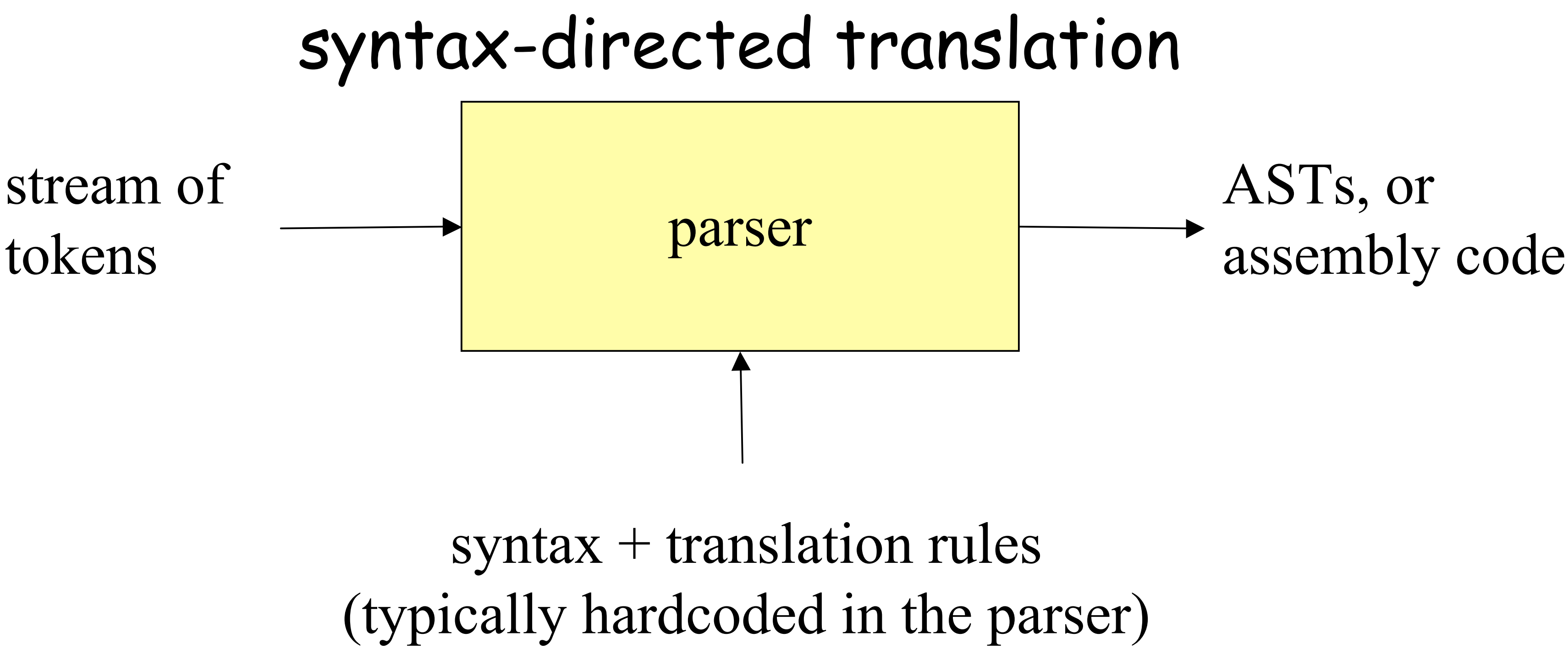
Syntax-Directed Translation

Lecture 14

(adapted from slides by R. Bodik)

Motivation: parser as a translator



Outline

- Syntax-directed translation: *specification*
  - translate parse tree to its value, or to an AST
  - type check the parse tree
- Syntax-directed translation: *implementation*
  - during LR parsing
  - during recursive-descent parsing

Mechanism of syntax-directed translation

- syntax-directed translation is done by extending the CFG
  - a *translation rule* is defined for each production

given

$X \rightarrow d\ A\ B\ c$

the translation of X is defined recursively using

- translation of nonterminals A, B
- values of attributes of terminals d, c
- constants

To translate an input string:

1. Build the parse tree.
2. Working bottom-up
   - Use the translation rules to compute the translation of each nonterminal in the tree

Result: the translation of the string is the translation of the parse tree's root nonterminal.

Why bottom up?

- a nonterminal's value may depend on the value of the symbols on the right-hand side,
- so translate a non-terminal node only after children translations are available.

Example 1: Arithmetic expression to value

Syntax-directed translation rules:

$E \rightarrow E + T$	E_1.trans = E_2.trans + T.trans
$E \rightarrow T$	E.trans = T.trans
$T \rightarrow T * F$	T_1.trans = T_2.trans * F.trans
$T \rightarrow F$	T.trans = F.trans
$F \rightarrow$ int	F.trans = int.value
$F \rightarrow (E)$	F.trans = E.trans

Example 1: Bison/Yacc Notation

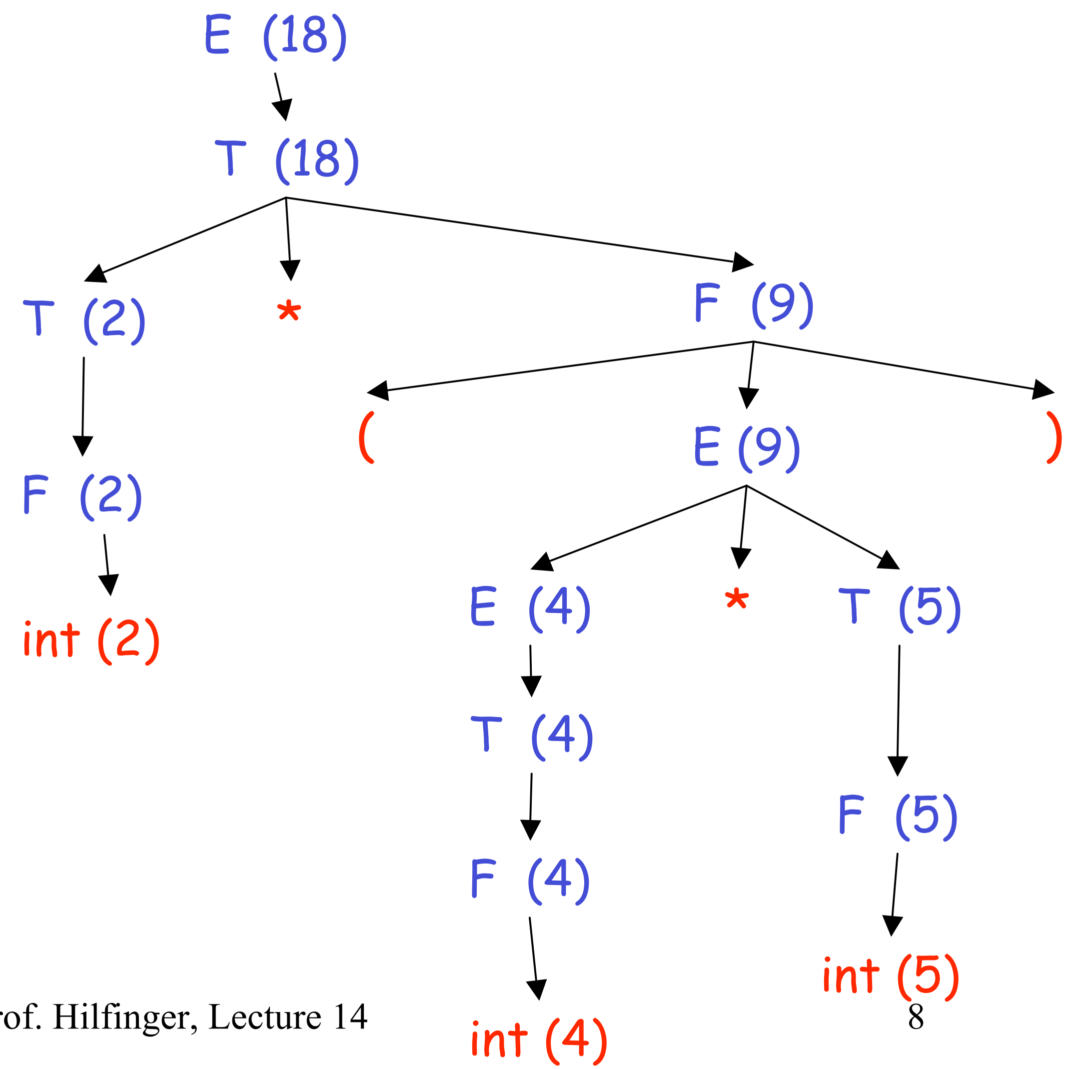
```
E : E + T        { $$ = $1 + $3;  }
T : T * F        { $$ = $1 * $3;  }
F : int          { $$ = $1; }
F : '(' E ')'    { $$ = $2; }
```

- ***KEY:*** `$$` : Semantic value of left-hand side

  `$n` : Semantic value of n^{th} symbol on right-hand side

Example 1 (cont): Annotated Parse Tree

Input: 2 * (4 + 5)

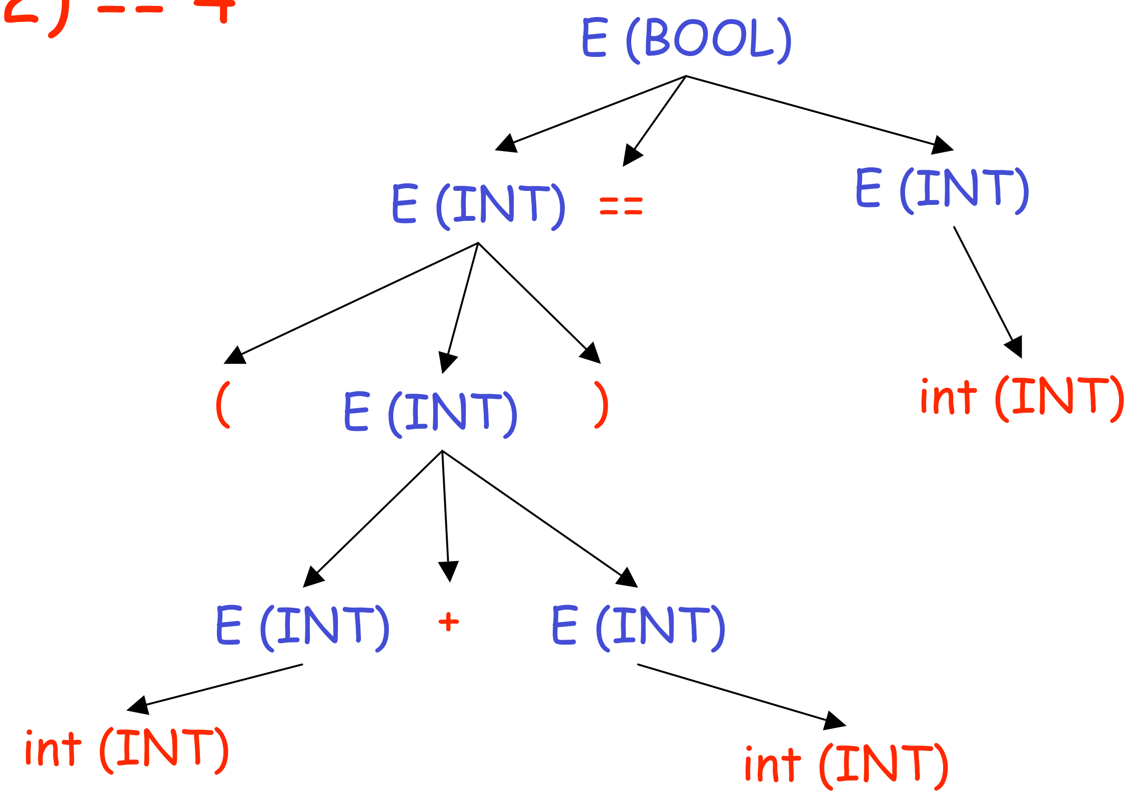


Example 2: Compute the type of an expression

```
E -> E + E       if $1 == INT and $3 == INT:
                         $$ = INT
                 else: $$ = ERROR
E -> E and E     if $1 == BOOL and $3 == BOOL:
                         $$ = BOOL
                 else: $$ = ERROR
E -> E == E      if $1 == $3 and $2 != ERROR:
                         $$ = BOOL
                 else: $$ = ERROR
E -> true        $$ = BOOL
E -> false       $$ = BOOL
E -> int         $$ = INT
E -> ( E )       $$ = $2
```

Example 2 (cont)

- Input: (2 + 2) == 4



Building Abstract Syntax Trees

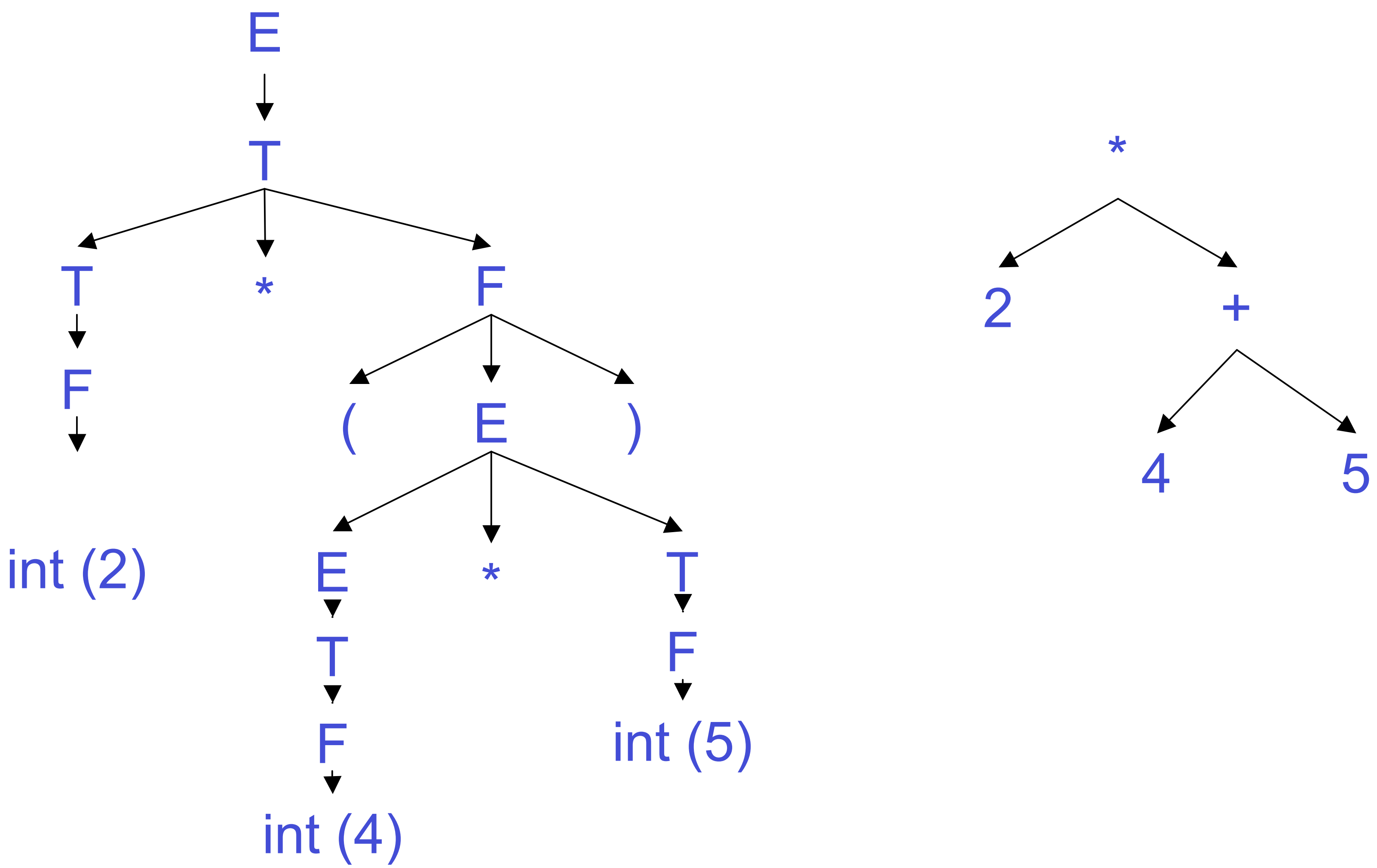
- Examples so far, streams of tokens translated into
  - integer values, or
  - types

- Translating into ASTs is not very different

AST vs. Parse Tree

- AST is condensed form of a parse tree
  - operators appear at *internal* nodes, not at leaves.
  - "Chains" of single productions are collapsed.
  - Lists are "flattened".
  - Syntactic details are omitted
    - e.g., parentheses, commas, semi-colons
- AST is a better structure for later compiler stages
  - omits details having to do with the source language,
  - only contains information about the *essential* structure of the program.

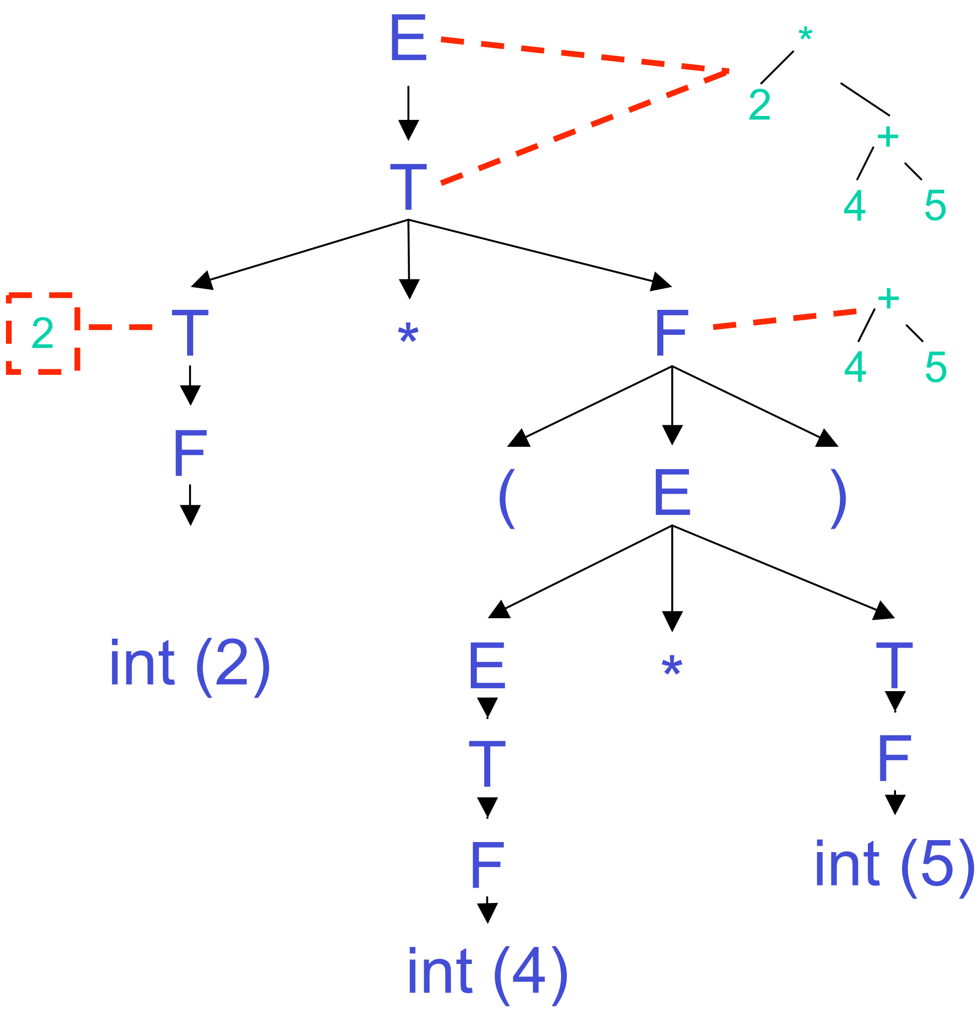
Example: 2 * (4 + 5) Parse tree *vs.* AST



AST-building translation rules

E → E + T	$$ = new PlusNode($1, $3)
E → T	$$ = $1
T → T * F	$$ = new TimesNode($1, $3)
T → F	$$ = $1
F → int	$$ = new IntLitNode($1)
F → (E)	$$ = $2

Example: 2 * (4 + 5): Steps in Creating AST



(Only some of the semantic values are shown)

Syntax-Directed Translation and LR Parsing

- add semantic stack,
  - parallel to the parsing stack:
    - each symbol (terminal or non-terminal) on the parsing stack stores its value on the semantic stack
  - holds terminals' attributes, and
  - holds nonterminals' translations
  - when the parse is finished, the semantic stack will hold just one value:
    - the translation of the root non-terminal (which is the translation of the whole input).

Semantic actions during parsing

- when shifting
  - push the value of the terminal on the semantic stack
- when reducing
  - pop k values from the semantic stack, where k is the number of symbols on production's RHS
  - push the production's value on the semantic stack

An LR example

Grammar + translation rules:

$E \rightarrow E + (E)$	`$$ = $1 + $4`
$E \rightarrow int$	`$$ = $1`

Input:

2 + (3) + (4)

Shift-Reduce Example with evaluations

parsing stack		semantic stack
I int + (int) + (int)$	shift	I

Shift-Reduce Example with evaluations

I int + (int) + (int)$	shift	I
int I + (int) + (int)$	red. E → int	2 I

Shift-Reduce Example with evaluations

I int + (int) + (int)$	shift	I
int I + (int) + (int)$	red. $E \rightarrow$ int	2 I
E I + (int) + (int)$	shift 3 times	2 I

Shift-Reduce Example with evaluations

I int + (int) + (int)$	shift	I
int I + (int) + (int)$	red. E → int	2 I
E I + (int) + (int)$	shift 3 times	2 I
E + (int I) + (int)$	red. E → int	2 '+' '(' 3 I

Shift-Reduce Example with evaluations

| int + (int) + (int)$ shift |

int | + (int) + (int)$ red. E → int   2 |

E | + (int) + (int)$ shift 3 times   2 |

E + (int |) + (int)$ red. E → int   2 '+' '(' 3 |

E + (E |) + (int)$ shift   2 '+' '(' 3 |

Shift-Reduce Example with evaluations

I int + (int) + (int)$	shift	I
int I + (int) + (int)$	red. E → int	2 I
E I + (int) + (int)$	shift 3 times	2 I
E + (int I) + (int)$	red. E → int	2 '+' '(' 3 I
E + (E I) + (int)$	shift	2 '+' '(' 3 I
E + (E) I + (int)$	red. E → E + (E)	2 '+' '(' 3 ')' I

Shift-Reduce Example with evaluations

I int + (int) + (int)$	shift	I
int I + (int) + (int)$	red. E → int	2 I
E I + (int) + (int)$	shift 3 times	2 I
E + (int I) + (int)$	red. E → int	2 '+' '(' 3 I
E + (E I) + (int)$	shift	2 '+' '(' 3 I
E + (E) I + (int)$	red. E → E + (E)	2 '+' '(' 3 ')' I
E I + (int)$	shift 3 times	5 I

Shift-Reduce Example with evaluations

I int + (int) + (int)$	shift	I
int I + (int) + (int)$	red. E → int	2 I
E I + (int) + (int)$	shift 3 times	2 I
E + (int I) + (int)$	red. E → int	2 '+' '(' 3 I
E + (E I) + (int)$	shift	2 '+' '(' 3 I
E + (E) I + (int)$	red. E → E + (E)	2 '+' '(' 3 ')' I
E I + (int)$	shift 3 times	5 I
E + (int I)$	red. E → int	5 '+' '(' 4 I

Shift-Reduce Example with evaluations

I int + (int) + (int)$	shift	I
int I + (int) + (int)$	red. E → int	2 I
E I + (int) + (int)$	shift 3 times	2 I
E + (int I) + (int)$	red. E → int	2 '+' '(' 3 I
E + (E I) + (int)$	shift	2 '+' '(' 3 I
E + (E) I + (int)$	red. E → E + (E)	2 '+' '(' 3 ')' I
E I + (int)$	shift 3 times	5 I
E + (int I)$	red. E → int	5 '+' '(' 4 I
E + (E I)$	shift	5 '+' '(' 4 I

Shift-Reduce Example with Evaluations

I int + (int) + (int)$	shift	I
int I + (int) + (int)$	red. E → int	2 I
E I + (int) + (int)$	shift 3 times	2 I
E + (int I) + (int)$	red. E → int	2 '+' '(' 3 I
E + (E I) + (int)$	shift	2 '+' '(' 3 I
E + (E) I + (int)$	red. E → E + (E)	2 '+' '(' 3 ')' I
E I + (int)$	shift 3 times	5 I
E + (int I)$	red. E → int	5 '+' '(' 4 I
E + (E I)$	shift	5 '+' '(' 4 I
E + (E) I $	red. E → E + (E)	5 '+' '(' 4 ')' I

Shift-Reduce Example with evaluations

∣ int + (int) + (int)$	shift	∣
int ∣ + (int) + (int)$	red. E → int	2 ∣
E ∣ + (int) + (int)$	shift 3 times	2 ∣
E + (int ∣) + (int)$	red. E → int	2 '+' '(' 3 ∣
E + (E ∣) + (int)$	shift	2 '+' '(' 3 ∣
E + (E) ∣ + (int)$	red. E → E + (E)	2 '+' '(' 3 ')' ∣
E ∣ + (int)$	shift 3 times	5 ∣
E + (int ∣)$	red. E → int	5 '+' '(' 4 ∣
E + (E ∣)$	shift	5 '+' '(' 4 ∣
E + (E) ∣ $	red. E → E + (E)	5 '+' '(' 4 ')' ∣
E ∣ $	accept	9 ∣

Taking Advantage of Derivation Order

- So far, rules have been *functional;* no side effects except to define (once) value of LHS.
- LR parsing produces reverse rightmost derivation.
- Can use the ordering to do control semantic actions with side effects.

Example of Actions with Side Effects

E → E + T	print "+",
E → T	pass
T → T * F	print "*",
T → F	pass
F → int	print $1,
F → (E)	pass

We know that reduction taken after all the reductions that form the nonterminals on right-hand side.
So what does this print for 3+4(7+1)?*

3 4 7 1 + * +

Recursive-Descent Translation

- Translating with recursive descent is also easy.
- The semantic values (what Bison calls $$, $1, etc.), become *return values of the parsing functions*
- We'll also assume that the lexer has a way to return lexical values (e.g., the scan function introduced in Lecture 9 might do so).

Example of Recursive-Descent Translation

- E → T | E+T   T → P | T*P   P → int | '(' E ')'

```
def E():
    T ()
    while next() == "+":
        scan("+"); T()

def T():
    P()
    while next() == "*":
        scan("*"); P()
```

```
def P():
    if next()==int:
        scan (int)
    elif next()=="(":
        scan("(")
        E()
        scan(")")
    else: ERROR()
```

(we've cheated and used loops; see end of lecture 9)

Example contd.: Add Semantic Values

- E → T | E+T   T → P | T*P   P → int | '(' E ')'

```
def E():
   v = T ()
    while next() == "+":
        scan("+"); v += T()
    return v
def T():
    v = P()
    while next() == "*":
        scan("*"); v *= P()
    return v
```

```
def P():
    if next()==int:
        v = scan (int)
    elif next()=="(":
        scan("(")
        v = E()
        scan(")")
    else: ERROR()
    return v
```

Table-Driven LL(1)

- We can automate all this, and add to the LL(1) parser method from Lecture 9.
- However, this gets a little involved, and I'm not sure it's worth it.
- (That is, let's leave it to the LL(1) parser generators for now!)