Announcement: Midterm Prep

Midterm is Tuesday, 3/10 here

List of topics

- Up to and including lecture on Tuesday's the 5th

Length 1hr 10min

No extra material allowed – just bring a pen

Sample midterm available online

- Recommended that you do this by Thursday
- We'll review it in class

Syntax Directed Translation for Top-Down Parsing

Last Time: Built LL(1) Predictive Parser

FIRST and FOLLOW sets define the parse table

If the grammar is LL(1), the table is unambiguous

- i.e., each cell has at most one entry

If the grammar is not LL(1) we can attempt a transformation sequence:

1. Remove left recursion
2. Left-factoring

Grammar transformations affect the structure of the parse tree. How does this affect syntax-directed translation (in particular, parse tree → AST)?

Today

Review Parse Table Construction

- 2 examples

Show how to do Syntax-Directed Translation using an LL(1) parser

FIRST(α) for $\alpha = Y_1\ Y_2 \ldots Y_k$

Add FIRST(Y_1) - {ε}

If ε is in FIRST($Y_{1\ to\ i-1}$): add FIRST(Y_i) – {ε}

If ε is in all RHS symbols, add ε

FOLLOW(A) for $X \longrightarrow \alpha\ A\ \beta$

If A is the start, add **eof**

Add FIRST(β) – {ε}

Add FOLLOW(*X*) if ε in FIRST(β) or β empty

Table[X][t]

```
for each production X ⟶ α
 for each terminal t in FIRST(α)
   put α in Table[X][t]
 if ε is in FIRST(α){
   for each terminal t in FOLLOW(X){
     put α in Table[X][t]
```

FIRST (S) = { **a, c, d** }

FIRST (B) = { **a, c** }

FIRST (D) = { **d**, ε }

FIRST (B **c**) = { **a, c** }

FIRST (D B) = { **d, a, c** }

FIRST (**a b**) = { **a** }

FIRST (**c** *S*) = { **c** }

FIRST (**d**) = { **d** }

FIRST (ε) = { ε }

FOLLOW (S) = { **eof, c** }

FOLLOW (B) = { **c, eof** }

FOLLOW (D) = { **a, c** }

CFG

S ⟶ B **c** | D B

B ⟶ **a b** | **c** S

D ⟶ **d** | ε

Not LL(1)

	a	**b**	**c**	**d**	**eof**
S	B **c** D B		B **c** D B	D B	
B	**a b**		**c** *S*		
D	ε		ε	**d**	

FIRST(α) for $\alpha = Y_1\ Y_2 \ldots Y_k$

Add FIRST(Y_1) - {ε}

If ε is in FIRST($Y_{1\ to\ i-1}$): add FIRST(Y_i) – {ε}

If ε is in all RHS symbols, add ε

FOLLOW(A) for $X \longrightarrow \alpha\ A\ \beta$

If A is the start, add **eof**

Add FIRST(β) – {ε}

Add FOLLOW(*X*) if ε in FIRST(β) or β empty

Table[X][t]

```
for each production X ⟶ α
 for each terminal t in FIRST(α)
   put α in Table[X][t]
 if ε is in FIRST(α){
   for each terminal t in FOLLOW(X){
     put α in Table[X][t]
```

CFG

$$S \rightarrow (\ S\ ) \mid \{\ S\ \} \mid \varepsilon$$

FIRST (*S*) = { **{** , **(** , **ε** }

FIRST (**(** *S* **)**) = { **(** }

FIRST (**{** *S* **}**) = { **{** }

FIRST (ε) = { ε }

FOLLOW (S) = { **eof,), }** }

	(	**)**	**{**	**}**	**eof**
S	(S)	ε	{ S }	ε	ε

FIRST(α) for $\alpha = Y_1\ Y_2 \ldots Y_k$

Add FIRST(Y_1) - {ε}

If ε is in FIRST($Y_{1\ to\ i-1}$): add FIRST(Y_i) – {ε}

If ε is in all RHS symbols, add ε

FOLLOW(A) for $X \longrightarrow \alpha\ A\ \beta$

If A is the start, add **eof**

Add FIRST(β) – {ε}

Add FOLLOW(*X*) if ε in FIRST(β) or β empty

Table[X][t]

```
for each production X ⟶ α
 for each terminal t in FIRST(α)
   put α in Table[X][t]
 if ε is in FIRST(α){
   for each terminal t in FOLLOW(X){
     put α in Table[X][t]
```

CFG

$$S \rightarrow + S \mid \varepsilon$$

FIRST (*S*) = { **+**, **ε** }

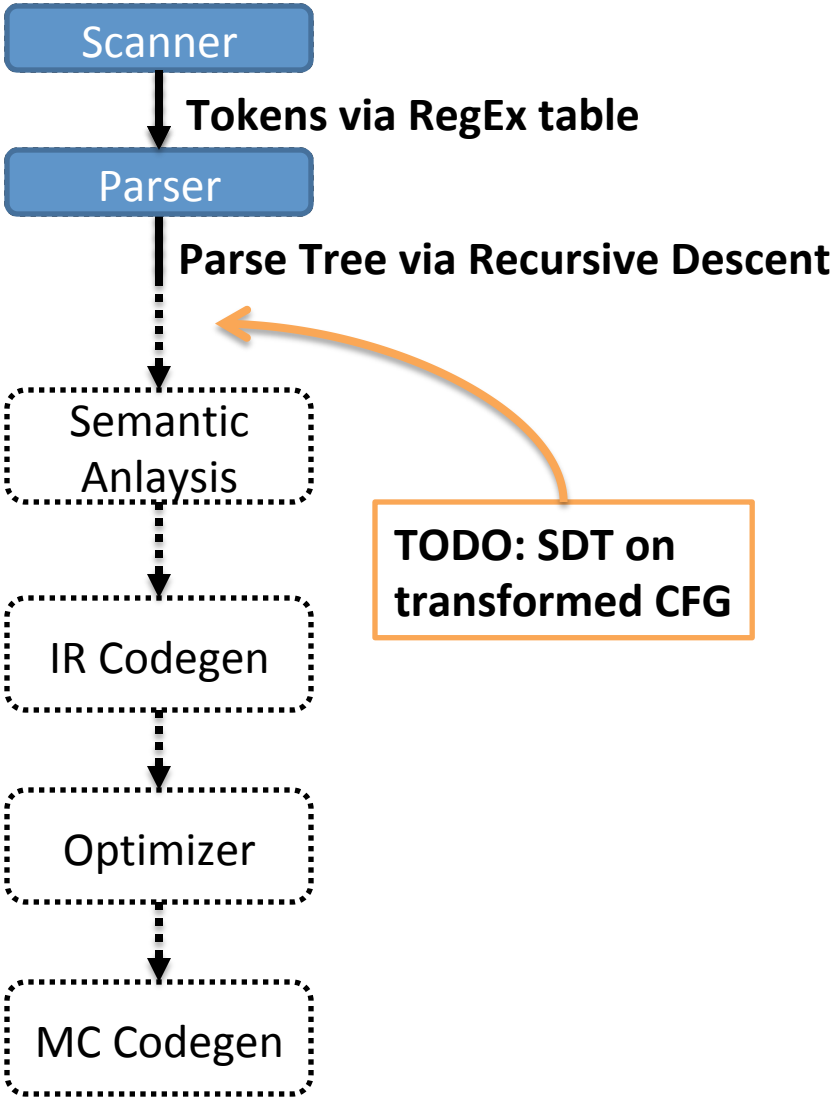
FIRST (**+** *S*) = { **+** }

FIRST (ε) = { ε }

FOLLOW (S) = { **eof** }

	+	**eof**
S	**+** S	ε

How's that Compiler Looking?



Implementing SDT for LL(1) Parser

So far, SDT shown as second (bottom-up) pass over parse tree

The LL(1) parser never needed to explicitly build the parse tree (implicitly tracked via stack)

Naïve approach: build the parse tree explicitly

Semantic Stack

Instead of building the parse tree, give parser second, *semantic* stack

- Holds nonterminals' tra
- SDT rules converted to
- Pop translations of RHS nonterminals off
- Push computed translation of LHS nonterm on

Translation goal:

- Count the number of occurrences of matched pairs of rounded parens: "**(** … **)**"
- Ignore occurrences of matched pairs of square brackets: "**[** … **]**"

CFG	**SDT Rules**	**SDT Actions**
Expr ⟶ ε	Expr.trans = 0	push 0
| **(** Expr **)**	Expr.trans = $Expr_2$.trans + 1	$Expr_2$.trans = pop; push $Expr_2$.trans + 1
| **[** Expr **]**	Expr.trans = $Expr_2$.trans	$Expr_2$.trans = pop; push $Expr_2$.trans

Action Numbers

Need to define *when* to fire the SDT Action

- Not immediately obvious since SDT is bottom-up

Solution

- Number actions and put them on the symbol stack!
- Add action number symbols at end of the productions

CFG		**SDT Actions**	
Expr ⟶	ε #1	#1	push 0
|	**(** Expr **)** #2	#2	$Expr_2$.trans = pop; push $Expr_2$.trans + 1
|	**[** Expr **]** #3	#3	$Expr_2$.trans = pop; push $Expr_2$.trans

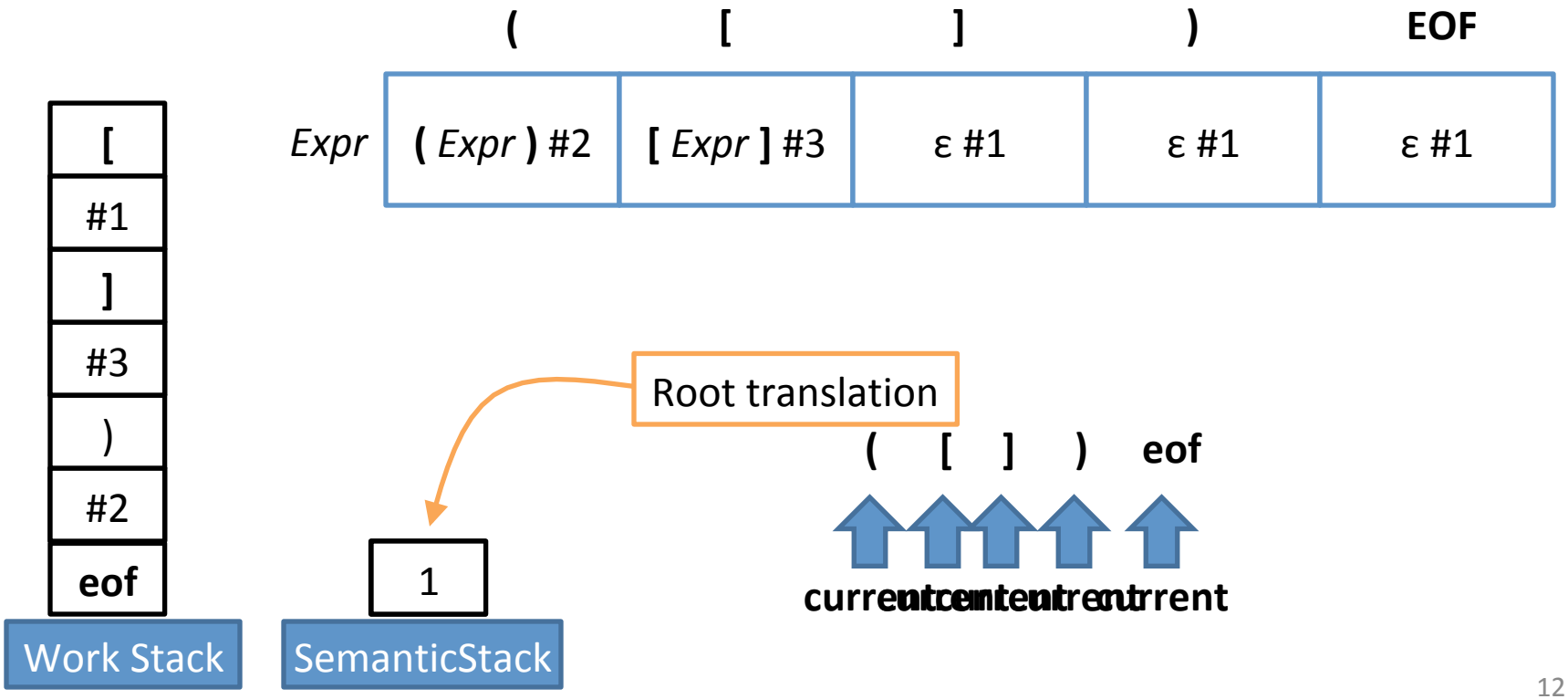
Action Numbers: Example 1

CFG

Expr ⟶ ε #1
| **(** *Expr* **)** #2
| **[** *Expr* **]** #3

SDT Actions: Counting Max Parens Depth

#1 push 0
#2 $Expr_2$.trans = pop; push($Expr_2$.trans + 1)
#3 $Expr_2$.trans = pop; push($Expr_2$.trans)



No-op SDT Actions

CFG

Expr ⟶ ε #1
| **(** *Expr* **)** #2
| **[** *Expr* **]** #3

SDT Actions: Counting Max Parens Depth

#1 push 0
#2 $Expr_2$.trans = pop; push($Expr_2$.trans + 1)
#3 $Expr_2$.trans = pop; push($Expr_2$.trans)

Useless rule

CFG

Expr ⟶ ε #1
| **(** *Expr* **)** #2
| **[** *Expr* **]**

SDT Actions: Counting Max Parens Depth

#1 push 0
#2 $Expr_2$.trans = pop; push($Expr_2$.trans + 1)

Placing Action Numbers

Action numbers go <u>after</u> their corresponding nonterminals, <u>before</u> their corresponding terminal

Translations popped right to left in action

<u>CFG</u>

Expr ⟶ *Expr + Term* #1
| *Term*

Term ⟶ *Term* * *Factor* #2
| *Factor*

Factor ⟶ #3 **intlit**

<u>SDT Actions</u>

#1 tTrans = pop ; eTrans = pop ; push(tTrans + eTrans)

#2 fTrans = pop; tTrans = pop ; push(fTrans * tTrans)

#3 push(**intlit**.value)

Placing Action Numbers: Example

Write SDT Actions and place action numbers to get the **product** of a *ValList* (i.e. multiply all elements)

CFG

List ⟶ *Val List'* #1

List' ⟶ *Val List'* #2

| ε #3

Val ⟶#4 **intlit**

SDT Actions

#1 LTrans = pop ; vTrans = pop ; push(LTrans * vTrans)

#2 LTrans = pop; vTrans = pop ; push(LTrans * vTrans)

#3 push(1)

#4 push(**intlit**.value)

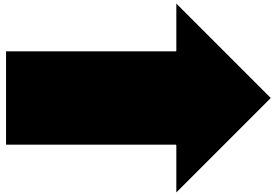
Action Numbers: Benefits

Plans SDT actions using the work stack

Robust to previously introduced grammar transformations

CFG

Expr ⟶ *Expr + Term* #1
| *Term*
Term ⟶ *Term* * *Factor* #2
| *Factor*
Factor ⟶ #3 **intlit**



Expr ⟶ *Term Expr'*
Expr' ⟶ **+** *Term* #1 *Expr'*
| ε
Term ⟶ Factor *Term'*
Term' ⟶ * *Factor* #2 *Term'*
| ε
Factor ⟶ #3 **intlit**

SDT Actions

#1 tTrans = pop ; eTrans = pop ; push(tTrans + eTrans)
#2 fTrans = pop; tTrans = pop ; push(fTrans * tTrans)
#3 push(**intlit**.value)

Example: SDT on Transformed Grammar

CFG

Expr ⟶ *Term Expr'*
Expr' ⟶ **+** *Term* #1 *Expr'*
| ε
Term ⟶ *Factor Term'*
Term' ⟶ * *Factor* #2 *Term'*
| ε
Factor ⟶ #3 **intlit**
| **(** *Expr* **)**

SDT Actions

#1 tTrans = pop ; eTrans = pop ; push(eTrans + tTrans)
#2 fTrans = pop; tTrans = pop ; push(tTrans * fTrans)
#3 push(**intlit**.value)

Example: SDT on Transformed Grammar

CFG

Expr ⟶ *Term Expr'*
Expr' ⟶ **+** *Term* #1 *Expr'*
| ε
Term ⟶ *Factor Term'*
Term' ⟶ * *Factor* #2 *Term'*
| ε
Factor ⟶ #3 **intlit**
| **(** *Expr* **)**

SDT

#1 tTr

rans + tTrans)

ans * fTrans)

First(Factor) = { intlit, (}
First(Term') = { *, }
First(Term) = { intlit, (}
First(Expr') = { +, }
First(Expr) = { intlit, (}

First(Term Expr') = { intlit, (}
First(+ Term #1 Expr') = { + }
First() = { }
First(Factor Term') = { intlit, (}
First(* Factor #2 Term) = { * }
First() = { }
First(#3 intlit) = { intlit }
First((Expr)) = { (}

Follow(Expr) = { eof,) }
Follow(Expr') = { eof,) }
Follow(Term) = { +, eof,) }
Follow(Term') = { +, eof,) }
Follow(Factor) = { *, +, eof,) }

Example: SDT on Transformed Grammar

CFG

Expr ⟶ *Term Expr'*
Expr' ⟶ **+** *Term* #1 *Expr'*
| ε
Term ⟶ *Factor Term'*
Term' ⟶ * *Factor* #2 *Term'*
| ε
Factor ⟶ #3 **intlit**
| **(** *Expr* **)**

SDT Actions

#1 tTrans = pop ; eTrans = pop ; push(eTrans + tTrans)
#2 fTrans = pop; tTrans = pop ; push(tTrans * fTrans)
#3 push(**intlit**.value)

	+	*	(	)	intlit	eof
Expr			*Term Expr'*		*Term Expr'*	
Expr'	+ *Term* #1 *Expr'*			ε		ε
Term			*Factor Term'*		*Factor Term'*	
Term'	ε	* *Factor* #2 *Term'*		ε		ε
Factor			**(** *Expr* **)**		#3 **intlit**	

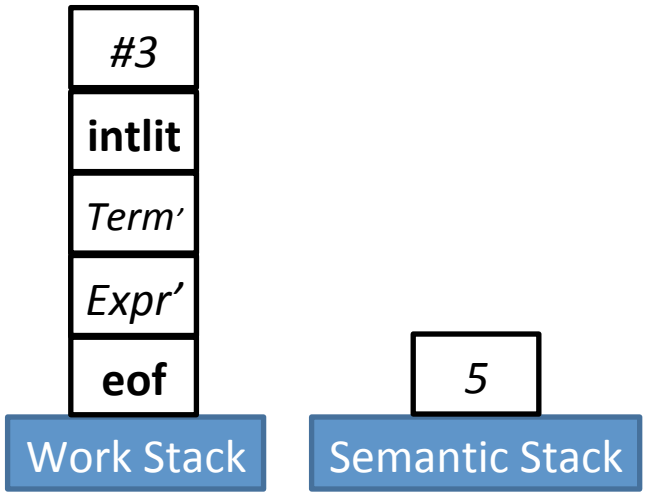
CFG

Expr ⟶ *Term Expr'*
Expr' ⟶ **+** *Term* #1 *Expr'*
| ε
Term ⟶ *Factor Term'*
Term' ⟶ * *Factor* #2 *Term'*
| ε
Factor ⟶ #3 **intlit**
| **(** *Expr* **)**

SDT Actions

#1 tTrans = pop ; eTrans = pop ; push(eTrans + tTrans)
#2 fTrans = pop; tTrans = pop ; push(tTrans * fTrans)
#3 push(**intlit**.value)

	+	*	(	)	intlit	eof
Expr			*Term Expr'*		*Term Expr'*	
Expr'	+ *Term* #1 *Expr'*			ε		ε
Term			*Factor Term'*		*Factor Term'*	
Term'	ε	* *Factor* #2 *Term'*		ε		ε
Factor			**(** *Expr* **)**		#3 **intlit**	



Input: 5 + 3 * 2 **eof**

current

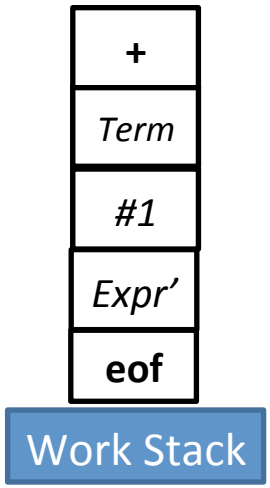
CFG

Expr ⟶ *Term Expr'*
Expr' ⟶ **+** *Term* #1 *Expr'*
| ε
Term ⟶ *Factor Term'*
Term' ⟶ * *Factor* #2 *Term'*
| ε
Factor ⟶ #3 **intlit**
| **(** *Expr* **)**

SDT Actions

#1 tTrans = pop ; eTrans = pop ; push(eTrans + tTrans)
#2 fTrans = pop; tTrans = pop ; push(tTrans * fTrans)
#3 push(**intlit**.value)

	+	*	(	)	intlit	eof
Expr			*Term Expr'*		*Term Expr'*	
Expr'	*+ Term #1 Expr'*			ε		ε
Term			*Factor Term'*		*Factor Term'*	
Term'	ε	* *Factor* #2 *Term'*		ε		ε
Factor			**(** *Expr* **)**		#3 **intlit**	



Input: 5 + 3 * 2 **eof**

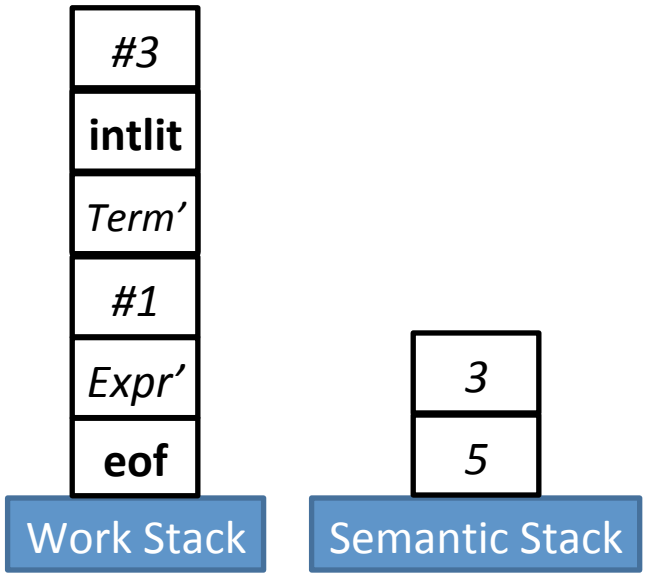
CFG

Expr ⟶ *Term Expr'*
Expr' ⟶ **+** *Term* #1 *Expr'*
| ε
Term ⟶ *Factor Term'*
Term' ⟶ * *Factor* #2 *Term'*
| ε
Factor ⟶ #3 **intlit**
| **(** *Expr* **)**

SDT Actions

#1 tTrans = pop ; eTrans = pop ; push(eTrans + tTrans)
#2 fTrans = pop; tTrans = pop ; push(tTrans * fTrans)
#3 push(**intlit**.value)

	+	*	(	)	intlit	eof
Expr			*Term Expr'*		*Term Expr'*	
Expr'	*+ Term* #1 *Expr'*			ε		ε
Term			*Factor Term'*		*Factor Term'*	
Term'	ε	* *Factor* #2 *Term'*		ε		ε
Factor			**(** *Expr* **)**		#3 **intlit**	



Input: 5 + 3 * 2 **eof**

current

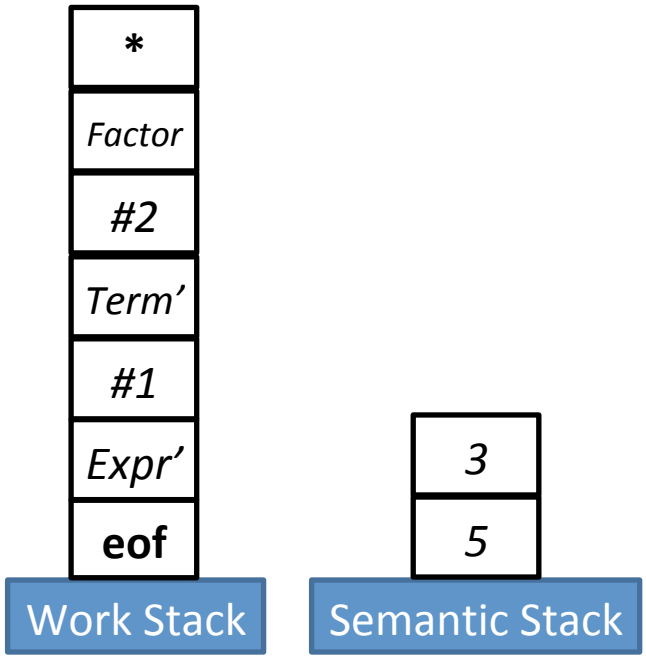
CFG

Expr ⟶ *Term Expr'*
Expr' ⟶ **+** *Term* #1 *Expr'*
| ε
Term ⟶ *Factor Term'*
Term' ⟶ * *Factor* #2 *Term'*
| ε
Factor ⟶ #3 **intlit**
| **(** *Expr* **)**

SDT Actions

#1 tTrans = pop ; eTrans = pop ; push(eTrans + tTrans)
#2 fTrans = pop; tTrans = pop ; push(tTrans * fTrans)
#3 push(**intlit**.value)

	+	*	(	)	intlit	eof
Expr			*Term Expr'*		*Term Expr'*	
Expr'	*+ Term #1 Expr'*			ε		ε
Term			*Factor Term'*		*Factor Term'*	
Term'	ε	** Factor #2 Term'*		ε		ε
Factor			**(** *Expr* **)**		#3 **intlit**	



Input: 5 + 3 * 2 **eof**

current current

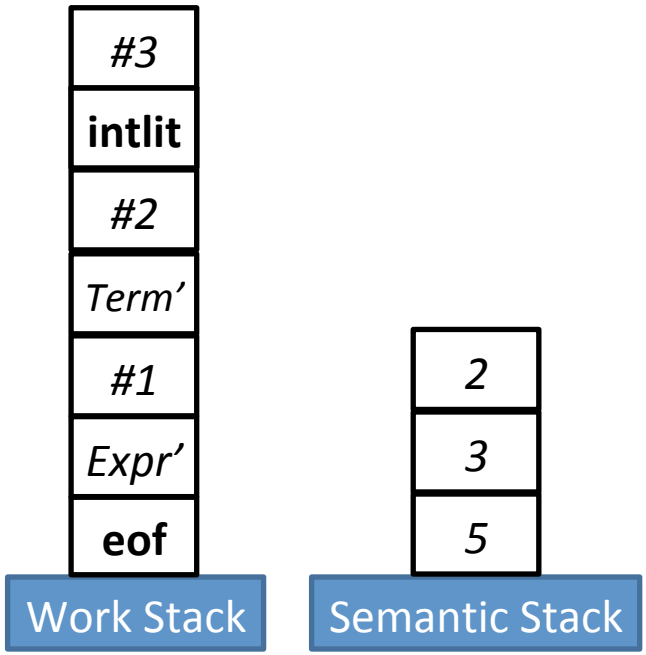
CFG

Expr ⟶ *Term Expr'*
Expr' ⟶ **+** *Term* #1 *Expr'*
| ε
Term ⟶ *Factor Term'*
Term' ⟶ * *Factor* #2 *Term'*
| ε
Factor ⟶ #3 **intlit**
| **(** *Expr* **)**

SDT Actions

#1 tTrans = pop ; eTrans = pop ; push(eTrans + tTrans)
#2 fTrans = pop; tTrans = pop ; push(tTrans * fTrans)
#3 push(**intlit**.value)

	+	*	(	)	intlit	eof
Expr			*Term Expr'*		*Term Expr'*	
Expr'	*+ Term #1 Expr'*			ε		ε
Term			*Factor Term'*		*Factor Term'*	
Term'	ε	* *Factor #2 Term'*		ε		ε
Factor			**(** *Expr* **)**		#3 **intlit**	



Input: 5 + 3 * 2 **eof**

current **current**

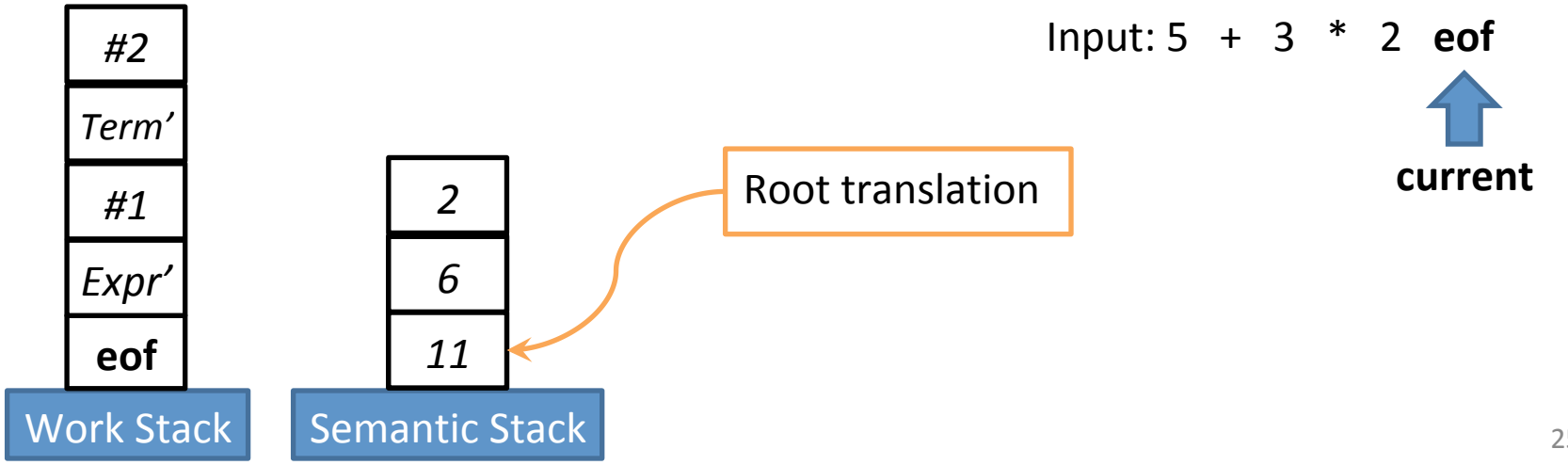
CFG

Expr ⟶ *Term Expr'*
Expr' ⟶ **+** *Term* #1 *Expr'*
| ε
Term ⟶ *Factor Term'*
Term' ⟶ * *Factor* #2 *Term'*
| ε
Factor ⟶ #3 **intlit**
| **(** *Expr* **)**

SDT Actions

#1 tTrans = pop ; eTrans = pop ; push(eTrans + tTrans)
#2 fTrans = pop; tTrans = pop ; push(tTrans * fTrans)
#3 push(**intlit**.value)

	+	*	(	)	intlit	eof
Expr			*Term Expr'*		*Term Expr'*	
Expr'	*+ Term #1 Expr'*			ε		ε
Term			*Factor Term'*		*Factor Term'*	
Term'	ε	* *Factor #2 Term'*		ε		ε
Factor			**(** *Expr* **)**		#3 **intlit**	



What about ASTs?

Push and pop AST nodes on the stack

Keep field references to nodes that we pop

CFG

Expr ⟶ *Expr + Term* #1
| *Term*
Term ⟶ #2 **intlit**

Transformed CFG

Expr ⟶ Term *Expr'*
Expr' ⟶ **+** *Term* #1 *Expr'*
| ε
Term ⟶ #2 **intlit**

"Evaluation" SDT Actions

#1 tTrans = pop ;
eTrans = pop ;
push(eTrans + tTrans)

#2 push(**intlit**.value)

"AST" SDT Actions

#1 tTrans = pop ;
eTrans = pop ;
push(new PlusNode(tTrans, eTrans))

#2 push(new IntLitNode(**intlit**.value))

AST Example

Transformed CFG

$E \longrightarrow T\ E'$

$E' \longrightarrow +\ T\ \#1\ E'$

$\quad\quad\ |\ \ \varepsilon$

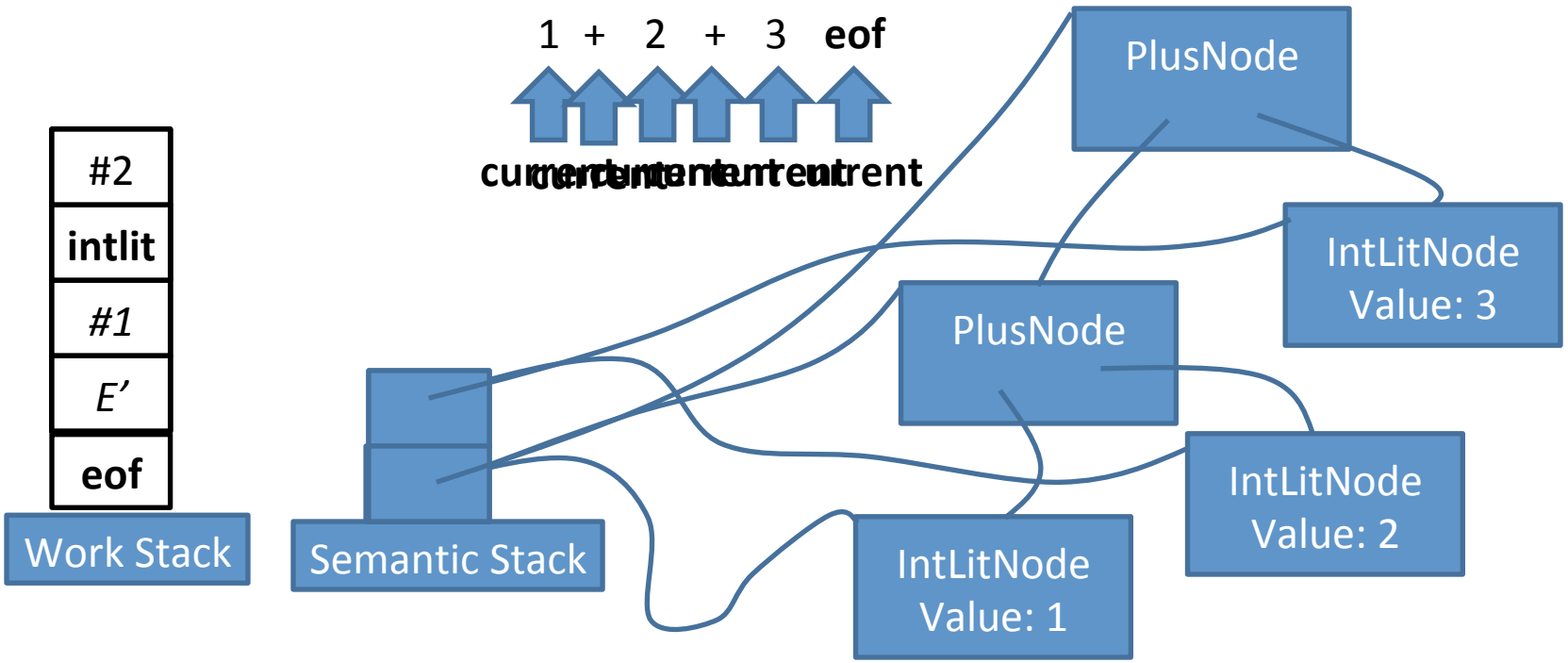
$T \longrightarrow \#2$ **intlit**

"AST" SDT Actions

#1 tTrans = pop ;
eTrans = pop ;
push(new PlusNode(tTrans, eTrans))

#2 push(new IntLitNode(**intlit**.value))

	intlit	+	**EOF**
E	*T E'*		
E'		+ *T* #1 *E'*	ε
T	**#2 intlit**		



We now have an AST

At this point, we have completed the frontend for (a) compiler

- Only recognize LL(1)

LL(1) is not a great class of languages

```
if (e1)
   stmt1
if (e2)
    stmt2
else
   stmt3
```

Grammar Snippet

IfStmt -> **if lparens** Exp **rparens** *Stmts*
| **if lparens** Exp **rparens** *Stmts* **else** *Stmts*