Principles of Programming Languages

Ting Zhang

Iowa State University
Computer Science Department

Lecture Note 5
September 8, 10, 2009
LR(0) Parsing

Outline

1. LR Parsing Procedure
2. LR(0) Parsing Table Generation
3. Grammar and Language Classes

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Bottom-up Parsing

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- A bottom-up parse starts with the terminals and reduces them to the start symbol by applying the production rules backwards.
- In general, bottom-up parsing methods are more powerful than top-down methods.

☞ LR(k) parsing is the class of the most commonly used bottom-up parsing algorithms.

LR Parsing

Repeatedly preform the following actions.

- Reduce: If we find a rule $S \rightarrow \alpha$, and if the contents of the stack are $\beta\alpha$ for some (possibly empty) β, then we reduce the stack to βS.

LR Parsing

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- ☞ Shift: If it is impossible to perform a reduction and there are tokens remaining in the input, then we transfer a token from the input onto the stack.

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Report success when reaching the end of input stream with the **accept** state.

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An LR parser uses two tables:

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- Action table: Action[s,a] tells the parser what to do when the state on top of the stack is s and terminal a is the next input token.
- ☞ Goto table: Goto[s,X] indicates the new state to place on top of the stack after a reduction of the nonterminal X while state s is on top of the stack.

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- Action[top,a] = acc: parsing ends with success
- ☞ Action[top,a] = -: syntax error

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LR(0) Parsing: An Example

LR(0) grammar:

1. $S \rightarrow S(S)$
2. $S \rightarrow \epsilon$

LR(0) Parsing: An Example

LR(0) grammar:

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Parsing table:

State	Action			Goto
	(	)	$	S
0	r2	r2	r2	1
1	s2		acc	
2	r2	r2	r2	3
3	s2	s4		
4	r1	r1	r1	

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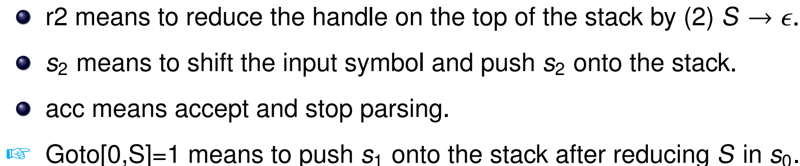

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- s_2 means to shift the input symbol and push s_2 onto the stack.
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- ☞ Goto[0,S]=1 means to push s_1 onto the stack after reducing S in s_0.

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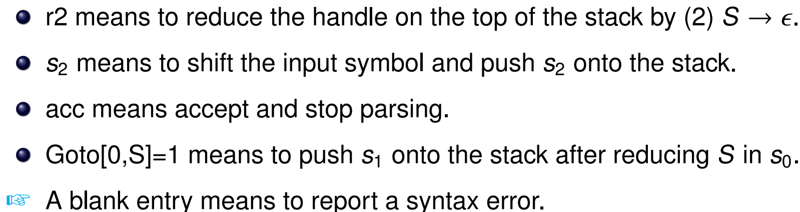

- r2 means to reduce the handle on the top of the stack by (2) $S \to \epsilon$.
- s_2 means to shift the input symbol and push s_2 onto the stack.
- acc means accept and stop parsing.
- Goto[0,S]=1 means to push s_1 onto the stack after reducing S in s_0.
- ☞ A blank entry means to report a syntax error.

LR(0) Parsing of $()()$

Stack	Input	Action
s_0	()()$	reduce by (2) $S \to \epsilon$ and push s_1 onto the stack
$s_0 s_1$	()()$	shift s_2 onto the stack
$s_0 s_1 s_2$	)()$	reduce by (2) $S \to \epsilon$ and push s_3
$s_0 s_1 s_2 s_3$	)()$	shift s_4 onto the stack
$s_0 s_1 s_2 s_3 s_4$	()$	reduce by (1) $S \to S(S)$ and push s_1
$s_0 s_1$	()$	shift s_2 onto the stack
$s_0 s_1 s_2$	)$	reduce by (2) $S \to \epsilon$ and push s_3
$s_0 s_1 s_2 s_3$	)$	shift s_4 onto the stack
$s_0 s_1 s_2 s_3 s_4$	$	reduce by (1) $S \to S(S)$ and push s_1
$s_0 s_1$	$	accept

LR(0) Parsing: A Bigger Example

LR(0) grammar:

1. $S \rightarrow E$
2. $E \rightarrow T$
3. $E \rightarrow E + T$
4. $T \rightarrow id$
5. $T \rightarrow (E)$

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Parsing Table

State	Action					Goto	
	id	+	(	)	$	E	T
s_0	s4		s3			1	2
s_1		s5			acc		
s_2	r2	r2	r2	r2	r2		
s_3	s4		s3			6	2
s_4	r4	r4	r4	r4	r4		
s_5	s4		s3				8
s_6		s5		s7			
s_7	r3	r3	r3	r3	r3		
s_8	r1	r1	r1	r1	r1		

LR(0) Parsing of $id + (id)$

Stack	Input	Action
s_0	id+(id)$	shift s_4 onto the stack, move ahead in input
$s_0 s_4$	+(id)$	reduce by (4) $T \rightarrow id$, pop the stack, goto s_2
$s_0 s_2$	+(id)$	reduce by (2) $E \rightarrow T$ and goto s_1
$s_0 s_1$	+(id)$	shift s_5 onto the stack
$s_0 s_1 s_5$	(id)$	shift s_3 onto the stack
$s_0 s_1 s_5 s_3$	id)$	shift s_4 onto the stack
$s_0 s_1 s_5 s_3 s_4$	)$	reduce by (4) $T \rightarrow id$, goto s_2
$s_0 s_1 s_5 s_3 s_2$	)$	reduce by (2) $E \rightarrow T$ and goto s_6
$s_0 s_1 s_5 s_3 s_6$	)$	shift s_7 onto the stack
$s_0 s_1 s_5 s_3 s_6 s_7$	$	reduce by (3) $T \rightarrow (E)$ and goto s_8
$s_0 s_1 s_5 s_8$	$	reduce by (1) $E \rightarrow E + T$ and goto s_1
$s_0 s_1$	$	accept

The Essentials of LR Parsing

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- It builds a parse tree from the bottom up.
- ☞ The states keep track of which productions we might reduce.

The Problems of LR(0) Parsing

- Shift-Reduce Conflict: for example

$$
\begin{array}{lll}
1. & S & \rightarrow E \\
2. & E & \rightarrow E + T \\
3. & & \rightarrow T \\
4. & T & \rightarrow T * F \\
5. & & \rightarrow F \\
6. & F & \rightarrow id \\
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\end{array}
$$

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☞ Reduce-Reduce Conflict: for example

$$
\begin{array}{lll}
1. & S & \rightarrow X \\
2. & X & \rightarrow Y \\
3. & & \rightarrow id \\
4. & Y & \rightarrow id
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$$

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- $A \rightarrow \cdot\alpha$ indicates that we are about to match $A \rightarrow \alpha$.
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- $A \rightarrow \cdot\alpha$ indicates that we are about to match $A \rightarrow \alpha$.
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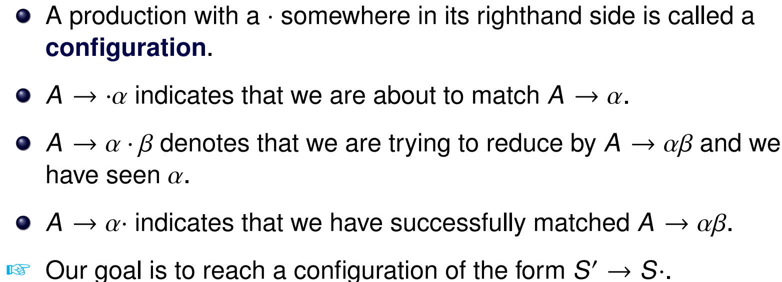
- ☞ $A \rightarrow \alpha\cdot$ indicates that we have successfully matched $A \rightarrow \alpha\beta$.

Configuration



State, Successor, and State Set

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State, Successor, and State Set

- We may not know which production will eventually be fully matched.
- A **state** is a configuration set consisting of all possible configurations that are matchable at a time.
- When we match a symbol, we need move to the **successor** state.

☞ Repeatedly compute successor state, we eventually have a DFA.

Computing Configurations: Start

- When we predict a production, we place $\cdot$ at the beginning of a production: $A \rightarrow \cdot\alpha$.

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- When we predict a production, we place $\cdot$ at the beginning of a production: $A \to \cdot\alpha$.
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- When we predict a production, we place $\cdot$ at the beginning of a production: $A \to \cdot\alpha$.
- When we predict $A \to \cdot\epsilon$, the match is immediate and so we just use $A \to \epsilon\cdot$.
- ☞ At the start, we have to use the start symbol S. We do not yet know which one, so we predict them all. For example,

1. $S \to \cdot S(S)$
2. $S \to \cdot\epsilon$

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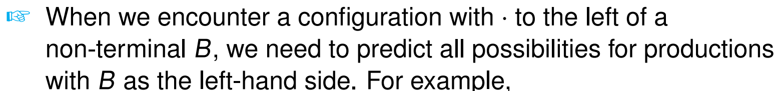

☞ When we encounter a configuration with $\cdot$ to the left of a non-terminal B, we need to predict all possibilities for productions with B as the left-hand side. For example,

  1. $B \rightarrow \cdot\beta_1$
  2. $B \rightarrow \cdot\beta_2$
  3. ......

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- The newly added configurations may predict other non-terminals, forcing additional productions to be included.
- ☞ We continue this process until no additional configurations can be added. The final configuration set is called **closure** of the original configuration set.

Computing Closures

```
1: ConfigSet Closure(ConfigSet C) {
2: repeat
3:     if A → α · Bβ is in C then
4:         add all configurations of the form B → ·γ to C
5:     end if
6: until no more configurations can be added
7: return C
8: }
```

Example: Computing Closures

Grammar:

$$
\begin{array}{lll}
1. & S & \rightarrow A\ b \\
2. & A & \rightarrow C\ D \\
3. & C & \rightarrow D \\
4. & C & \rightarrow c \\
5. & D & \rightarrow d
\end{array}
$$

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Example: Computing Closures

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5. & D & \rightarrow & d
\end{array}
$$

Compute Closure($S \rightarrow \cdot Ab$):

☞ First we include $A \rightarrow \cdot CD$.

Example: Computing Closures

Grammar:

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\begin{array}{lll}
1. & S & \to A\ b \\
2. & A & \to C\ D \\
3. & C & \to D \\
4. & C & \to c \\
5. & D & \to d
\end{array}
$$

Compute Closure($S \to \cdot Ab$):

- First we include $A \to \cdot CD$.
- ☞ Then we include $C \to \cdot D$ and $C \to \cdot c$.

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Example: Computing Closures

Grammar:

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Compute Closure($S \rightarrow \cdot Ab$):

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Example: Computing Closures

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Closure($S \rightarrow \cdot Ab$) is:

$$\begin{array}{lll} 1. & S & \rightarrow \cdot\ A\ b \\ 2. & A & \rightarrow \cdot\ C\ D \\ 3. & C & \rightarrow \cdot\ D \\ 4. & C & \rightarrow \cdot c \\ 5. & D & \rightarrow \cdot d \end{array}$$

Successor State

☞ When we match a symbol, we shift · past the symbol just matched symbol.

```
1: ConfigSet Successor(ConfigSet C, Symbol X) {
2: B = ∅
3: for each configuration c in C do
4:     if c is of the form A → α · Xβ then
5:         add A → αX · β to B
6:     end if
7: end for
8: return Closure(B)
9: }
```

Successor State

- When we match a symbol, we shift $\cdot$ past the symbol just matched symbol.
- ☞ Configurations that do not have a dot to the left of the matched symbol are deleted.

```
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```

Example: Computing Successors

The successor of

$$
\begin{array}{lll}
1. & S & \rightarrow \cdot\, A\ b \\
2. & A & \rightarrow \cdot\, C\ D \\
3. & C & \rightarrow \cdot\, D \\
4. & C & \rightarrow \cdot c \\
5. & D & \rightarrow \cdot d
\end{array}
$$

with respect to C is

$$
\begin{array}{lll}
6. & A & \rightarrow C\ \cdot\ D \\
7. & D & \rightarrow \cdot\, d
\end{array}
$$

State Set

```
1:  StateSet BuildStates(ConfigSet C_0) {
2:  F = ∅
3:  for each configuration C in F do
4:      for each symbol X do
5:          if Successor(C, X) is not empty then
6:              add Successor(C, X) to F
7:          end if
8:      end for
9:  end for
10: return F
11: }
```

Example: State Set

$$I_0: \quad E \rightarrow \cdot E + T$$
$$E \rightarrow \cdot T$$
$$T \rightarrow \cdot (E)$$
$$T \rightarrow \cdot id$$

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Example: State Set

$$
\begin{aligned}
I_0 : \quad & E \rightarrow \cdot E + T \\
& E \rightarrow \cdot T \\
& T \rightarrow \cdot (E) \\
& T \rightarrow \cdot id
\end{aligned}
$$

4 successors:

E	T	id	(
$I_1 : E \rightarrow E \cdot + T$	$I_2 : E \rightarrow T \cdot$	$I_4 : T \rightarrow id \cdot$	$I_3 : T \rightarrow (\cdot E)$ $E \rightarrow \cdot E + T$ $E \rightarrow \cdot T$ $T \rightarrow \cdot (E)$ $T \rightarrow \cdot id$

Example: State Set

$I_1 : E \rightarrow E \cdot + T$

Example: State Set

$I_1 : E \rightarrow E \cdot + T$

1 successor:

$+$
$I_5 : E \rightarrow E + \cdot T$ $T \rightarrow \cdot (E)$ $T \rightarrow \cdot id$

Example: State Set

$$\begin{aligned} I_5 : E &\rightarrow E\ +\ \cdot T \\ T &\rightarrow \cdot\ (\ E\ ) \\ T &\rightarrow \cdot\ id \end{aligned}$$

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Example: State Set

$$
\begin{aligned}
I_5 : E &\rightarrow E + \cdot T \\
T &\rightarrow \cdot (E) \\
T &\rightarrow \cdot id
\end{aligned}
$$

3 successors:

T	id	(
$I_8 : E \rightarrow E + T \cdot$	$I_4 : T \rightarrow id \cdot$	$I_3 : T \rightarrow (\cdot E)$ $E \rightarrow \cdot E + T$ $E \rightarrow \cdot T$ $T \rightarrow \cdot (E)$ $T \rightarrow \cdot id$

Example: State Set

$$
\begin{aligned}
I_3 : T &\rightarrow (\cdot E) \\
E &\rightarrow \cdot E + T \\
E &\rightarrow \cdot T \\
T &\rightarrow \cdot (E) \\
T &\rightarrow \cdot id
\end{aligned}
$$

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Example: State Set

$$
\begin{aligned}
I_3 : T &\rightarrow (\ \cdot E\ ) \\
E &\rightarrow \cdot E + T \\
E &\rightarrow \cdot T \\
T &\rightarrow \cdot (\ E\ ) \\
T &\rightarrow \cdot\, id
\end{aligned}
$$

4 successors:

T	id	E	(
$I_2 : E \rightarrow T\ \cdot$	$I_4 : T \rightarrow id\ \cdot$	$I_6 : T \rightarrow (\ E \cdot\ )$ $E \rightarrow E\ \cdot + T$	$I_3 : T \rightarrow (\ \cdot E\ )$ $E \rightarrow \cdot E + T$ $E \rightarrow \cdot T$ $T \rightarrow \cdot (\ E\ )$ $T \rightarrow \cdot\, id$

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Example: State Set

$$I_6 : T \rightarrow (\ E \cdot\ )$$
$$E \rightarrow E\ \cdot + T$$

Example: State Set

$$I_6 : T \rightarrow (\; E \cdot)$$
$$E \rightarrow E \; \cdot + T$$

2 successors:

$+$	$)$
$I_5 : E \rightarrow E \; + \; \cdot T$ $T \rightarrow \cdot (\; E \;)$ $T \rightarrow \cdot \, id$	$I_7 : T \rightarrow (\; E \;) \cdot$

Example: State Set

$I_2 : E \rightarrow T \cdot$
$I_4 : T \rightarrow id \cdot$
$I_7 : T \rightarrow (E) \cdot$
$I_8 : E \rightarrow E + T \cdot$

Example: State Set

$I_2 : E \rightarrow T \cdot$
$I_4 : T \rightarrow id \cdot$
$I_7 : T \rightarrow (E) \cdot$
$I_8 : E \rightarrow E + T \cdot$

None has a successor!

Parsing Table

```
1:  ParsingTable BuildTable(StateSet 𝓕 = {C_0, ..., C_n}) {
2:  for each configuration set C_i in 𝓕 do
3:      if S' → S· is in C_i then
4:          set Action[i, $] to accept
5:      else if A → α· in C_i then
6:          set Action[i, a] to A → α for all terminal a
7:      else if A → α · aβ is in C_i and Successor(C_i, a) = C_j then
8:          set Action[i, a] to shift j
9:      end if
10:     for each nonterminal A do
11:         if Successor(C_i, A) = C_j then
12:             set Goto[i, A] = j
13:         end if
14:     end for
15: end for
16: }
```

Outline

1 LR Parsing Procedure

2 LR(0) Parsing Table Generation

3 Grammar and Language Classes

Beyond LR(0)

- SLR: peeks at upcoming input and use FOLLOW sets to resolve conflicts.

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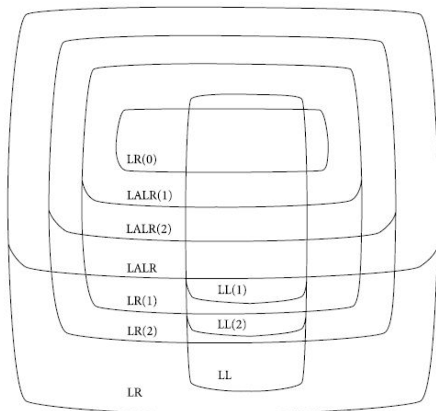
- LALR: improves on SLR by using **state specific** FOLLOW sets instead.
- ☞ LR: duplicates states in order to resolve conflicts.

Grammar Containment Relation



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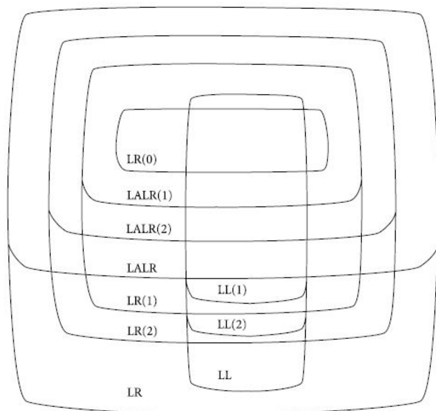

(a) SLL(k) is just inside LL(k), for $k \geq 2$, but has the same relationship to everything else.

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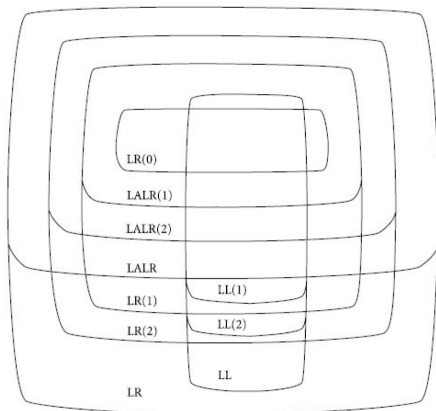

(a) SLL(k) is just inside LL(k), for $k \geq 2$, but has the same relationship to everything else.

(b) SLR(k) is just inside LALR(k), for $k \geq 1$, but has the same relationship to everything else.

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Language Containment Relation