CS 314 Principles of Programming Languages

Lecture 9: LL(1) Parsing Review

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October 3, 2018

Class Information

- Homework 4 will be posted after lecture 10.
- Project 1 will be posted after homework 4 is due.

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Review: FIRST and FOLLOW Sets

FIRST(α):

For some $\alpha \in (T \cup NT \cup EOF \cup \varepsilon)^*$, define **FIRST** (α) as the set of tokens that appear as the first symbol in some string that derives from α.

That is, $\mathbf{x} \in \text{FIRST}(\alpha)$ iff $\alpha \Rightarrow^* \mathbf{x}\gamma$ for some γ

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T: terminals   NT: non-terminals

First Set Example

Start ::= S **eof**
S ::= **a** S **b** | ε

$\mathit{FIRST}(\varepsilon) = \{\varepsilon\}$

S can be rewritten as the following:

ab
aaabbb
aabb
ε
…

$\mathit{FIRST}(S) = \{a, \varepsilon\}$

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aSb can be rewritten as the following:

ab
aabb
…

$\mathit{FIRST}(aSb) = \{a\}$

Computing *FIRST* Sets

For a production $A \rightarrow B_1 B_2 \ldots B_k$:

- FIRST(A) includes FIRST(B_1) - ε
- FIRST(A) includes FIRST(B_2) - ε if B_1 can be rewritten as ε
- FIRST(A) includes FIRST(B_3) - ε if both B_1 *and* B_2 can derive ε
- …
- FIRST(A) includes FIRST(B_m) - ε if $B_1 B_2 \ldots B_{m-1}$ can derive ε

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FIRST(A) includes FIRST(B_1) … FIRST(B_m) excluding ε iff
$\varepsilon \in$ FIRST(B_1), FIRST(B_2), FIRST(B_3), …, FIRST(B_{m-1})

FIRST(A) includes ε iff
$\varepsilon \in$ FIRST(B_1), FIRST(B_2), FIRST(B_3), …, FIRST(B_k)

First Set Construction

Build FIRST(X) for all grammar symbols X:

- For each X as a terminal, then FIRST(X) is {X}
- If X ::= ε, then ε ∈ FIRST(X)
- For each X as a non-terminal, initialize FIRST(X) to ∅
- ***Iterate until*** no more terminals or ε can be added to any FIRST(X):

```
    For each rule in the grammar of the form  $X ::= Y_1Y_2\ldots Y_k$
        add a to FIRST(X) if $a \in FIRST(Y_1)$
        add a to FIRST(X) if $a \in FIRST(Y_i)$ and $\varepsilon \in FIRST(Y_j)$
                                            for all $1 \le j \le i-1$ and $i \ge 2$
        add ε to FIRST(X) if $\varepsilon \in FIRST(Y_i)$ for all $1 \le i \le k$
    EndFor
End iterate
```

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An Example

parentheses grammar

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= <u>LP</u> List <u>RP</u>

Iter. 1 means iteration 1

Where <u>LP</u> is **(** and <u>RP</u> is **)**

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Initialization

- For each X as a terminal, then FIRST(X) is {X}
- If X ::= ε, then ε ∈ FIRST(X)
- For each X as a non-terminal, initialize FIRST(X) to ∅
- ***Iterate until*** no more terminals or ε can be added to any FIRST(X):

```
  For each rule in the grammar of the form  $X ::= Y_1Y_2\ldots Y_k$
      add a to FIRST(X) if $a \in FIRST(Y_1)$
      add a to FIRST(X) if $a \in FIRST(Y_i)$ and $\varepsilon \in FIRST(Y_j)$
                    for all $1 \leq j \leq i-1$ and $i \geq 2$
      add ε to FIRST(X) if $\varepsilon \in FIRST(Y_i)$ for all $1 \leq i \leq k$
  EndFor
End iterate
```

Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅		
List	∅		
Pair	∅		
LP	<u>LP</u>	<u>LP</u>	<u>LP</u>
RP	<u>RP</u>	<u>RP</u>	<u>RP</u>
EOF	EOF	EOF	EOF

An Example

parentheses grammar

1	Goal ::= List
2	List ::= Pair List
3	| ε
4	Pair ::= LP List RP

Iter. 1 means iteration 1

Where LP is (and RP is)

Iteration 1 (of the outer loop below):

- For each X as a terminal, then FIRST(X) is {X}
- If X ::= ε, then ε ∈ FIRST(X)
- For each X as a non-terminal, initialize FIRST(X) to ∅
- ***Iterate until*** no more terminals or ε can be added to any FIRST(X):

```
  For each rule in the grammar of the form  X ::= $Y_1Y_2\ldots Y_k$
      add a to FIRST(X) if a ∈ FIRST($Y_1$)
      add a to FIRST(X) if a ∈ FIRST($Y_i$) and ε ∈ FIRST($Y_j$)
                  for all $1 \le j \le i-1$ and $i \ge 2$
      add ε to FIRST(X) if ε ∈ FIRST($Y_i$) for all $1 \le i \le k$
   EndFor
End iterate
```

Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅		
List	∅		
Pair	∅		
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

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An Example

parentheses grammar

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Iter. 1 means iteration 1

Where LP is (and RP is)

FIRST sets in progress

Iteration 1:

The order of the rules do not affect the final FIRST set results:

If we visit the rules in order 4, 3, 2, 1 ⇒

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Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅		
List	∅		
Pair	∅		
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

An Example

parentheses grammar

```
1   Goal ::= List
2   List  ::= Pair List
3           |   ε
4   Pair ::= LP List RP
```

Iter. 1 means iteration 1

Where LP is (and RP is)

FIRST sets in progress

Iteration 1:

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Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅		
List	∅		
Pair	∅	?	
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Applying Rule 4

Pair ::= LP List RP

add first(LP list RP) to first(Pair)

An Example

parentheses grammar

```
1  Goal ::= List
2  List  ::= Pair List
3           |   ε
4  Pair ::= LP List RP
```

Iter. 1 means iteration 1

Where LP is (and RP is)

FIRST sets in progress

Iteration 1:

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Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅		
List	∅		
Pair	∅	LP	
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Applying Rule 4

Pair ::= LP List RP

add first(LP list RP) to first(Pair)

An Example

parentheses grammar

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Iter. 1 means iteration 1

Where LP is (and RP is)

FIRST sets in progress

Iteration 1:

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Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅		
List	∅		
Pair	∅	LP	
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Applying Rule 4

Pair ::= LP List RP

add first(LP list RP) to first(Pair)

An Example

parentheses grammar

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Iter. 1 means iteration 1

Where LP is (and RP is)

FIRST sets in progress

Iteration 1:

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Symbol	***Initial***	Iter. 1	Iter. 2
Goal	∅		
List	∅	?	
Pair	∅	LP	
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Applying Rule 2 and Rule 3

List ::= Pair List
| ε

add first(Pair List) to first(List)

add first(ε) to first(List)

An Example

parentheses grammar

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Iter. 1 means iteration 1

Where LP is (and RP is)

FIRST sets in progress

Iteration 1:

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Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅		
List	∅	LP, ε	
Pair	∅	LP	
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Applying Rule 2 and Rule 3

List ::= Pair List
| ε

add first(Pair List) to first(List)

add first(ε) to first(List)

An Example

parentheses grammar

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Iter. 1 means iteration 1

Where LP is (and RP is)

FIRST sets in progress

Iteration 1:

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Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅		
List	∅	LP, ε	
Pair	∅	LP	
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Applying Rule 2 and Rule 3

List ::= Pair List
| ε

add first(Pair List) to first(List)

add first(ε) to first(List)

An Example

parentheses grammar

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Iter. 1 means iteration 1

Where LP is (and RP is)

FIRST sets in progress

Iteration 1:

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Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅	?	
List	∅	LP, ε	
Pair	∅	LP	
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Applying Rule 1
Goal ::= List

add first(List) to first(Goal)

An Example

parentheses grammar

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Iter. 1 means iteration 1

Where LP is (and RP is)

FIRST sets in progress

Iteration 1:

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Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅	LP, ε	
List	∅	LP, ε	
Pair	∅	LP	
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Applying Rule 1
Goal ::= List

add first(List) to first(Goal)

An Example

parentheses grammar

```
1  Goal ::= List
2  List  ::= Pair List
3          |   ε
4  Pair ::= LP List RP
```

Iter. 1 means iteration 1

Where LP is (and RP is)

FIRST sets in progress

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Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅	LP, ε	
List	∅	LP, ε	
Pair	∅	LP	
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

We just finished the first iteration!
Recall that one iteration reviews all the rules!

An Example

parentheses grammar

```
1  Goal ::= List
2  List  ::= Pair List
3         |   ε
4  Pair ::= LP List RP
```

Iter. 1 means iteration 1

Where LP is (and RP is)

FIRST sets in progress

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Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅	LP, ε	
List	∅	LP, ε	
Pair	∅	LP	
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Before the second iteration starts…

An Example

parentheses grammar

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Iter. 1 means iteration 1

Where LP is (and RP is)

FIRST sets in progress

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Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅	LP, ε	LP, ε
List	∅	LP, ε	LP, ε
Pair	∅	LP	LP
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Before the second iteration starts…

An Example

parentheses grammar

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Where LP is (and RP is)

Iteration 2:

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FIRST sets in progress

Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅	LP, ε	LP, ε
List	∅	LP, ε	LP, ε
Pair	∅	LP	LP
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Applying Rule 4

Pair ::= LP List RP

add first(LP list RP) to first(Pair)

LP is already in first(Pair)

An Example

parentheses grammar

```
1  Goal ::= List
2  List  ::= Pair List
3          |   ε
4  Pair ::= LP List RP
```

Where LP is (and RP is)

FIRST sets in progress

Iteration 2:

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Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅	LP, ε	LP, ε
List	∅	LP, ε	LP, ε
Pair	∅	LP	LP
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Applying Rule 2 and Rule 3

List ::= Pair List
| ε

add first(Pair List) to first(List)

add first(ε) to first(List)

LP and ε are already in FIRST(List)

An Example

parentheses grammar

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Where LP is (and RP is)

FIRST sets in progress

Iteration 2:

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Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅	LP, ε	LP, ε
List	∅	LP, ε	LP, ε
Pair	∅	LP	LP
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Applying Rule 1
Goal ::= List

add first(List) to first(Goal)

LP and ε are already in FIRST(Goal)

An Example

parentheses grammar

```
1  Goal ::= List
2  List  ::= Pair List
3          |   ε
4  Pair ::= LP List RP
```

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FIRST Sets

Symbol	*Initial*	Iter. 1	Iter. 2
Goal	∅	LP, ε	LP, ε
List	∅	LP, ε	LP, ε
Pair	∅	LP	LP
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

Comparing the FIRST sets at the end of iteration 1 and the end of iteration 2, nothing new is added.

Reached fixed point! We have constructed complete FIRST sets!

FOLLOW Sets

FOLLOW(A):

For A ∈ **NT** , define **FOLLOW**(A) as the set of ***tokens*** that can occur immediately after A in a valid sentential form.

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FOLLOW set is defined over the set of non-terminal symbols, **NT**.

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Back to Our Example

Start ::= S **eof**
S ::= **a** S **b** |
ε

One possible derivation process from the start symbol:

Start ⇒ S **eof** ⇒ **a** S **b eof** ⇒ **a b eof**

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FOLLOW(S) = { eof , b }

FIRST and FOLLOW Sets

FOLLOW(A):

For A ∈ **NT** , define **FOLLOW**(A) as the set of tokens that can occur immediately after A in a valid sentential form.

FOLLOW set is defined over the set of non-terminal symbols (**NT**)

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Follow Set Construction

Given a rule *p* in the grammar:

$$A \rightarrow B_1B_2\ldots\boxed{B_i}\underline{B_{i+1}\ldots B_k}$$

If B_i is a non-terminal, FOLLOW(B_i) includes

- FIRST($B_{i+1}\ldots B_k$) - {ε} U FOLLOW(A), if $\varepsilon \in$ FIRST($B_{i+1}\ldots B_k$)
- FIRST($B_{i+1}\ldots B_k$) otherwise

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Relationship between FOLLOW sets and FIRST sets of different symbols

Follow Set Construction

To Build FOLLOW(X) for non-terminal X:

- Place EOF in FOLLOW(<start>)
- For each X as a non-terminal, initialize FOLLOW(X) to ∅

```
Iterate until no more terminals can be added to any FOLLOW(X):
        For each rule p in the grammar
              If p is of the form $A ::= \alpha B \beta$, then
                  if $\varepsilon \in FIRST(\beta)$
                        Place {FIRST(β) - ε, FOLLOW(A)} in FOLLOW(B)
                  else
                        Place {FIRST(β)} in FOLLOW(B)
              If p is of the form $A ::= \alpha B$, then
                        Place FOLLOW(A) in FOLLOW(B)
End iterate
```

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An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

```
1   Goal ::= List
2   List  ::= Pair List
3           |   ε
4   Pair ::= LP List RP
```

Symbol	***Initial***	1^{st}
Goal	**EOF**	
List	∅	
Pair	∅	

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Initialization

```
•  Place EOF in FOLLOW(<start>)
•  For each X as a non-terminal, initialize FOLLOW(X) to ∅
Iterate until no more terminals can be added to any FOLLOW(X):
    For each rule p in the grammar
        If p is of the form A ::= αBβ, then
            if ε ∈ FIRST(β)
                Place {FIRST(β) - ε, FOLLOW(A)} in FOLLOW(B)
            else
                Place {FIRST(β)} in FOLLOW(B)
        If p is of the form A ::= αB, then
                Place FOLLOW(A) in FOLLOW(B)
End iterate
```

Symbol	***FIRST*** Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Symbol	*Initial*	1^{st}
Goal	**EOF**	**EOF**
List	∅	
Pair	∅	

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Iteration 1 (of the outer loop below):

```
• Place EOF in FOLLOW(<start>)
• For each X as a non-terminal, initialize FOLLOW(X) to ∅
  Iterate until no more terminals can be added to any FOLLOW(X):
     For each rule p in the grammar
        If p is of the form A ::= αBβ, then
           if ε ∈ FIRST(β)
                Place {FIRST(β) - ε, FOLLOW(A)} in FOLLOW(B)
           else
                Place {FIRST(β)} in FOLLOW(B)
        If p is of the form A ::= αB, then
                Place FOLLOW(A) in FOLLOW(B)
  End iterate
```

Symbol	*FIRST* Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

An Example for FOLLOW Set Construction

parentheses grammar

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

FOLLOW sets in progress

Symbol	*Initial*	1st
Goal	**EOF**	**EOF**
List	∅	
Pair	∅	

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Iteration 1:

The order of the rules do not affect the final FOLLOW set results:

If we visit the rules
in order 1, 2, 3, 4

Symbol	***FIRST*** Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Symbol	*Initial*	1st
Goal	**EOF**	**EOF**
List	∅	?
Pair	∅	

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Iteration 1:

Symbol	***FIRST*** Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

Rule 1 Goal ::= List

- Add FOLLOW(Goal) to FOLLOW(List)

An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Symbol	*Initial*	1st
Goal	**EOF**	**EOF**
List	∅	**EOF**
Pair	∅	

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Iteration 1:

Symbol	***FIRST*** Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

Rule 1 Goal ::= List

- Add FOLLOW(Goal) to FOLLOW(List)

An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Symbol	*Initial*	1st
Goal	**EOF**	**EOF**
List	∅	**EOF**
Pair	∅	

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Iteration 1:

Symbol	*FIRST* Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

Rule 2 List ::= Pair List

An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Symbol	***Initial***	1st
Goal	**EOF**	**EOF**
List	∅	**EOF**
Pair	∅	**?**

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Iteration 1:

Symbol	***FIRST*** Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

Rule 2 List ::= Pair List

- Add FIRST(List) to FOLLOW(Pair)
- Add FOLLOW(List) to FOLLOW(Pair)

An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Symbol	*Initial*	1^{st}
Goal	**EOF**	**EOF**
List	∅	**EOF**
Pair	∅	**EOF**, LP

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Iteration 1:

Symbol	*FIRST* Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

Rule 2 List ::= Pair List

- Add FIRST(List) to FOLLOW(Pair)
- Add FOLLOW(List) to FOLLOW(Pair)

An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Symbol	*Initial*	1st
Goal	**EOF**	**EOF**
List	∅	**EOF**
Pair	∅	**EOF**, LP

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Iteration 1:

Symbol	***FIRST*** Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

Rule 4 Pair ::= LP List RP

An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

1	Goal ::= List
2	List ::= Pair List
3	| ε
4	Pair ::= LP List RP

Symbol	*Initial*	1st
Goal	**EOF**	**EOF**
List	∅	**EOF**, ?
Pair	∅	**EOF**, LP

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Iteration 1:

Symbol	***FIRST*** Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

Rule 4 Pair ::= LP List RP

- Add FIRST(RP) to FOLLOW(List)

An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Symbol	*Initial*	1^{st}
Goal	**EOF**	**EOF**
List	∅	**EOF**, RP
Pair	∅	**EOF**, LP

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Iteration 1:

Symbol	***FIRST*** Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

Rule 4 Pair ::= LP List RP

- Add FIRST(RP) to FOLLOW(List)

An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

1	Goal ::= List
2	List ::= Pair List
3	| ε
4	Pair ::= LP List RP

Symbol	*Initial*	1^{st}
Goal	**EOF**	**EOF**
List	∅	**EOF**, RP
Pair	∅	**EOF**, LP

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Symbol	*FIRST* Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

End of First Iteration and Before the Second Iteration starts

An Example for FOLLOW Set Construction

parentheses grammar

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

FOLLOW sets in progress

Symbol	***Initial***	1^{st}	2^{nd}
Goal	**EOF**	**EOF**	**EOF**
List	∅	**EOF**, RP	**EOF**, RP
Pair	∅	**EOF**, LP	**EOF**, LP

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Symbol	***FIRST*** Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

End of First Iteration and Before the Second Iteration starts

An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Symbol	Initial	1st	2nd
Goal	EOF	EOF	EOF
List	∅	EOF, RP	EOF, RP
Pair	∅	EOF, LP	EOF, LP

Iteration 2:

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Symbol	FIRST Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

Rule 1 Goal ::= List

- Add FOLLOW(Goal) to FOLLOW(List)

EOF already in FOLLOW(list)

An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Symbol	***Initial***	1st	2nd
Goal	**EOF**	**EOF**	**EOF**
List	∅	**EOF**, RP	**EOF**, RP
Pair	∅	**EOF**, LP	**EOF**, LP, RP

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Iteration 2:

Symbol	***FIRST*** Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

Rule 2 List ::= Pair List

- Add FIRST(List)-ε to FOLLOW(Pair)
- Add FOLLOW(List) to FOLLOW(Pair)

Added RP

An Example for FOLLOW Set Construction

parentheses grammar

FOLLOW sets in progress

```
1  Goal ::= List
2  List ::= Pair List
3         |  ε
4  Pair ::= LP List RP
```

Symbol	*Initial*	1st	2nd
Goal	**EOF**	**EOF**	**EOF**
List	∅	**EOF**, RP	**EOF**, RP
Pair	∅	**EOF**, LP	**EOF**, RP, LP

Iteration 2:

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Symbol	***FIRST*** Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

Rule 4 Pair ::= LP List RP

- Add FIRST(RP) to FOLLOW(List)

RP already in FOLLOW(list)

An Example for FOLLOW Set Construction

parentheses grammar

```
1  Goal ::= List
2  List  ::= Pair List
3          |  ε
4  Pair ::= LP List RP
```

FOLLOW sets in progress

Symbol	***Initial***	1st	2nd
Goal	**EOF**	**EOF**	**EOF**
List	∅	**EOF**, RP	**EOF**, RP
Pair	∅	**EOF**, LP	**EOF**, RP, LP

Iteration 2:

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Iteration 3 produces the same result
⇒ reached a fixed point

We omit the results of Iteration 3.

Symbol	***FIRST*** Set
Goal	LP, ε
List	LP, ε
Pair	LP
LP	LP
RP	RP
EOF	EOF

Building Top-down Parsers

Building the PREDICT set

- Need a ***PREDICT set*** for every rule

Define *PREDICT*(A ::= δ) for rule A ::= δ

- *FIRST* (δ) - { ε } U Follow (A), if ε ∈ *FIRST*(δ)
- *FIRST* (δ) otherwise

Symbol	*FIRST*	*FOLLOW*
Goal	LP, ε	**EOF**
List	LP, ε	**EOF**, RP
Pair	LP	**EOF**, RP, LP
LP	LP	-
RP	RP	-
EOF	EOF	-

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1 Goal ::= List

2 List ::= Pair List

3 List ::= ε

4 Pair ::= LP List RP

Rule	*PREDICT*
1	**EOF, LP**
2	**LP**
3	**EOF**, RP
4	LP

Building Top-down Parsers

Building the PREDICT set

- Need a ***PREDICT set*** for every rule

Define *PREDICT*(A ::= δ) for rule A ::= δ

- *FIRST* (δ) - { ε } U Follow (A), if ε ∈ *FIRST*(δ)
- *FIRST* (δ) otherwise

Symbol	***FIRST***	***FOLLOW***
Goal	LP, ε	**EOF**
List	LP, ε	**EOF**, RP
Pair	LP	**EOF**, RP, LP
LP	LP	-
RP	RP	-
EOF	EOF	-

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1	Goal ::= List
2	List ::= Pair List
3	List ::= ε
4	Pair ::= LP List RP

Rule	***PREDICT***	
1	**EOF, LP**	
2	**LP**	← FIRST(Pair List)
3	**EOF**, RP	← FOLLOW(List)
4	LP	

Building Top-down Parsers

Parentheses grammar

1 Goal ::= List

2 List ::= Pair List

3 List ::= ε

4 Pair ::= <u>LP</u> List <u>RP</u>

PREDICT Sets

Rule	*PREDICT*
1	**EOF, LP**
2	**LP**
3	**EOF**, RP
4	LP

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Is this grammar LL(1)?

Building Top-down Parsers

Parentheses grammar

1 Goal ::= List

2 List ::= Pair List

3 List ::= ε

4 Pair ::= LP List RP

PREDICT Sets

Rule	*PREDICT*
1	**EOF, LP**
2	**LP**
3	**EOF**, RP
4	LP

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Is this grammar LL(1)?

Since only Rule 2 and Rule 3 correspond to the same non-terminal, and PREDICT(Rule 2) and PREDICT(Rule 3) are disjoint, the grammar is LL(1).

Building Top-down Parsers

Building the complete parse table

- Need a row for every **NT** and a column for every **T**
- Need an interpreter for the table (skeleton parser)

1	Goal ::= List
2	List ::= Pair List
3	List ::= ε
4	Pair ::= LP List RP

Rule	***PREDICT***
1	EOF, LP
2	LP
3	EOF, RP
4	LP

	LP	***RP***	***EOF***
Goal			
List			
Pair			

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Building the complete parse table

- Need a row for every **NT** and a column for every **T**
- Need an interpreter for the table (skeleton parser)

1 Goal ::= List

2 List ::= Pair List

3 List ::= ε

4 Pair ::= LP List RP

Rule	*PREDICT*
1	EOF, LP
2	LP
3	EOF, RP
4	LP

	LP	*RP*	*EOF*
Goal	1		1
List			
Pair			

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Building Top-down Parsers

Building the complete parse table

- Need a row for every **NT** and a column for every **T**
- Need an interpreter for the table (skeleton parser)

1	Goal ::= List
2	List ::= Pair List
3	List ::= ε
4	Pair ::= LP List RP

Rule	*PREDICT*
1	EOF, RP
2	LP
3	EOF, RP
4	LP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	**2**	**3**	**3**
Pair			

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Building Top-down Parsers

Building the complete parse table

- Need a row for every **NT** and a column for every **T**
- Need an interpreter for the table (skeleton parser)

1 Goal ::= List
2 List ::= Pair List
3 | ε
4 Pair ::= LP List RP

Rule	*PREDICT*
1	**EOF, RP**
2	LP
3	EOF, RP
4	LP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		

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Review: Table Driven LL(1) Parsing

Input: *a string w and a parsing table M for G*

```
push eof
push Start Symbol
token ← next_token()
X ← top-of-stack
repeat
    if X is a terminal then
        if X == token then
            pop X
            token ← next_token()
        else error()
    else /* X is a non-terminal */
        if M[X, token] == X → $Y_1 Y_2 \dots Y_k$ then
            pop X
            push $Y_k, Y_{k-1}, \dots, Y_1$
        else error()
    X ← top-of-stack
until X = EOF
if token != EOF then error()
```

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	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		

M is the parse table

LL(1) Parsing Example

1 Goal ::= List

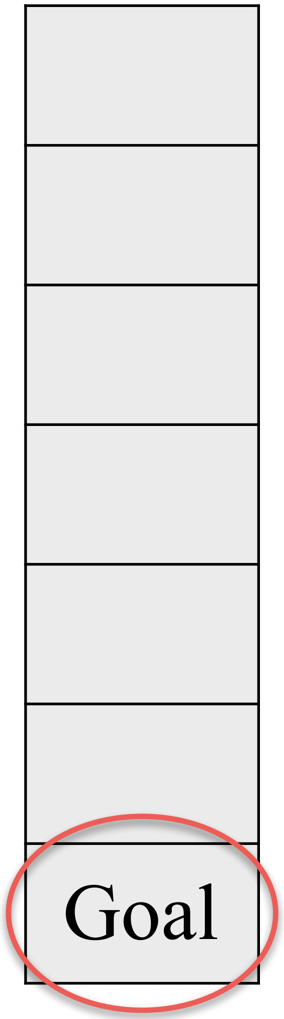
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		

Goal



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Remaining Input:
LP RP LP LP RP RP

Sentential Form:
Goal

Applied Production:

LL(1) Parsing Example

1 Goal ::= List

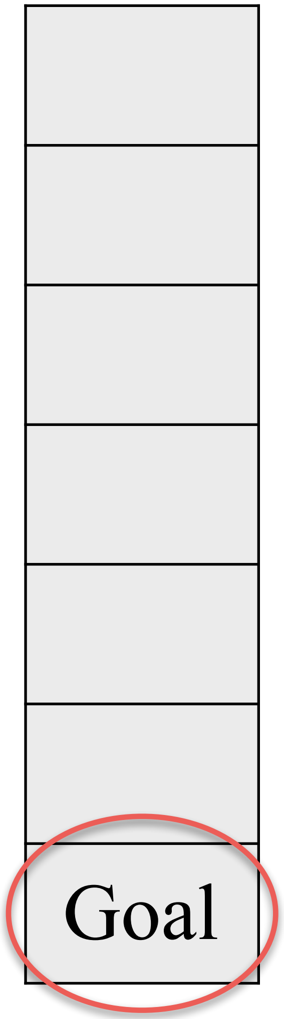
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

Goal

	LP	*RP*	*EOF*
Goal	1		1
List	2	3	3
Pair	4		



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Remaining Input:
LP RP LP LP RP RP

Sentential Form:
Goal

Applied Production:

LL(1) Parsing Example

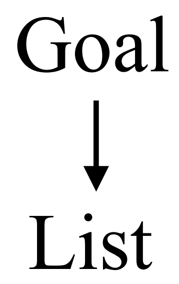
1 Goal ::= List

2 List ::= Pair List

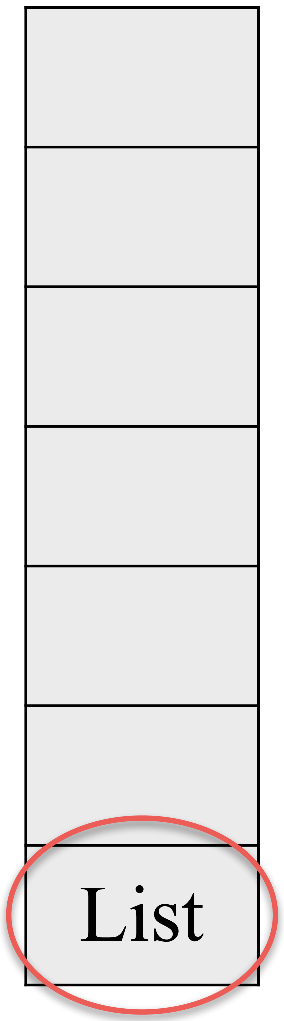
3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		


Goal

List


List

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Remaining Input:
LP RP LP LP RP RP

Sentential Form:
List

Applied Production:
1. Goal ::= List

LL(1) Parsing Example

1 Goal ::= List

2 List ::= Pair List

3 | ε

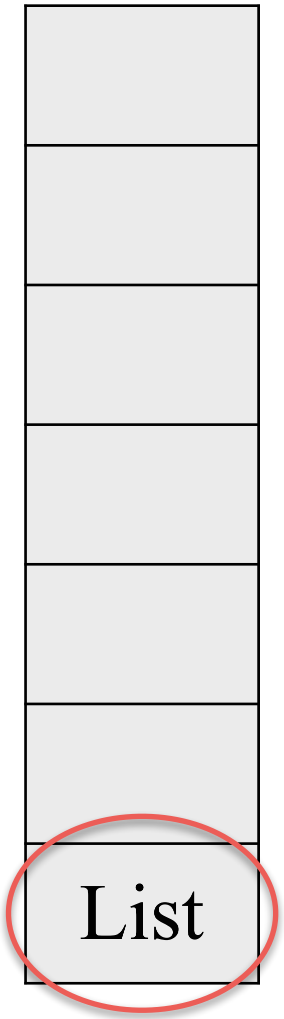
4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		

Goal

↓

List



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Remaining Input:
LP RP LP LP RP RP

Sentential Form:
List

Applied Production:
1. Goal ::= List

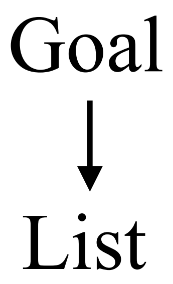
LL(1) Parsing Example

1 Goal ::= List

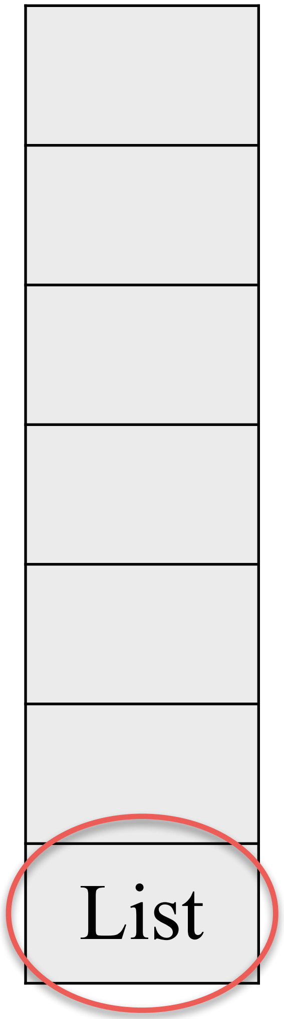
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP



	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		



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Remaining Input:
LP RP LP LP RP RP

Sentential Form:
List

Applied Production:
1. Goal ::= List

LL(1) Parsing Example

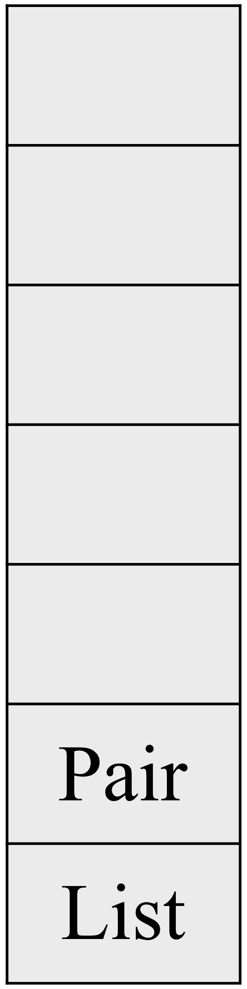
1 Goal ::= List

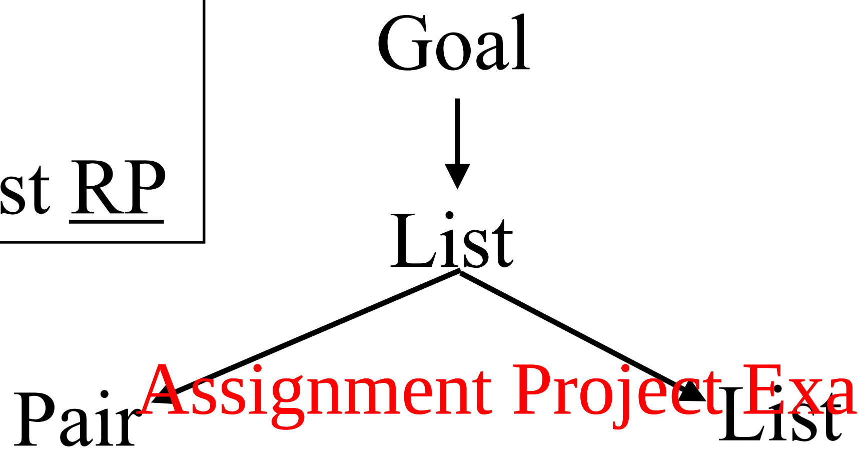
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		





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Remaining Input:
LP RP LP LP RP RP

Sentential Form:
Pair List

Applied Production:
2. List ::= Pair List

LL(1) Parsing Example

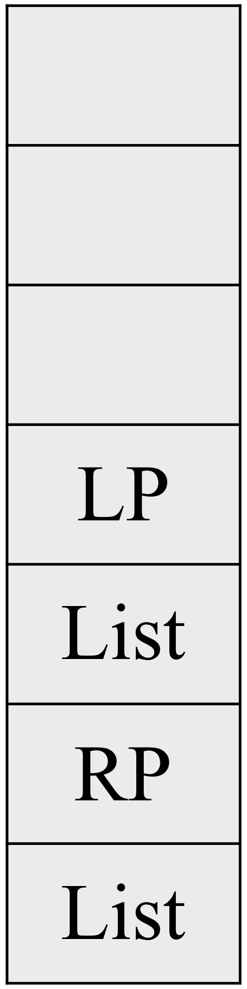
1 Goal ::= List

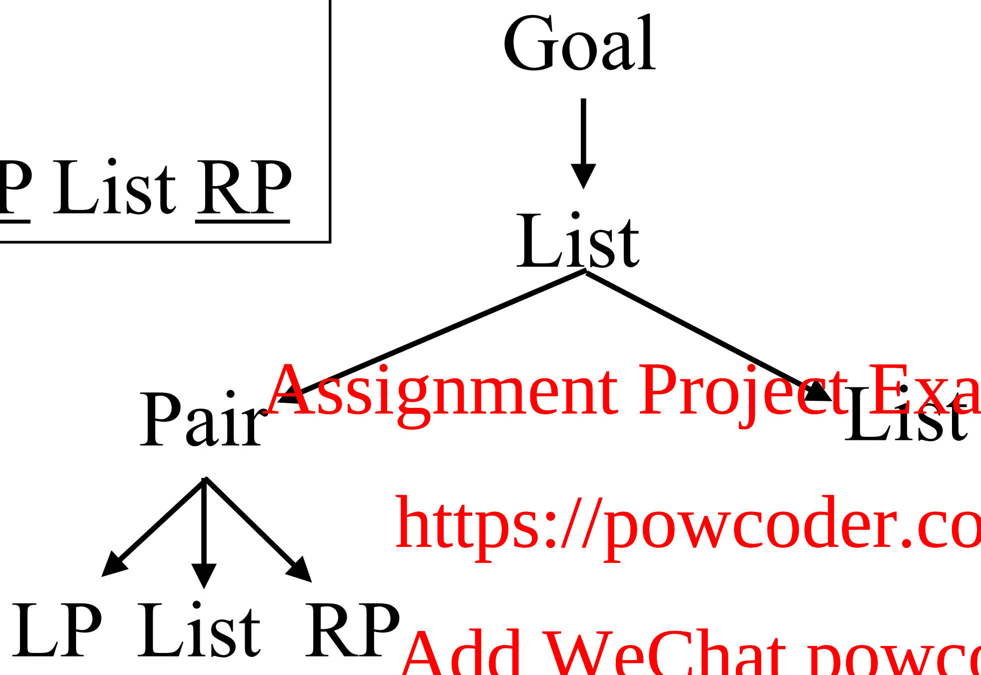
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		





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Remaining Input:
LP RP LP LP RP RP

Sentential Form:
LP List RP List

Applied Production:
4. Pair ::= LP List RP

LL(1) Parsing Example

1 Goal ::= List

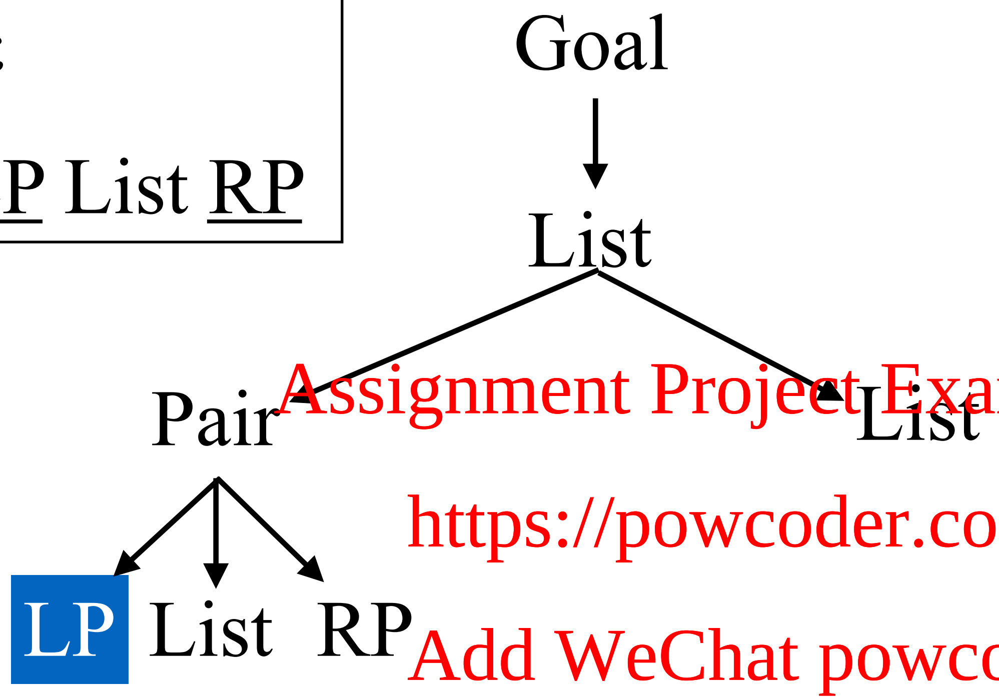
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		

LP
List
RP
List



Match!

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Remaining Input:
LP RP LP LP RP RP

Sentential Form:
LP List RP List

Applied Production:

LL(1) Parsing Example

1 Goal ::= List

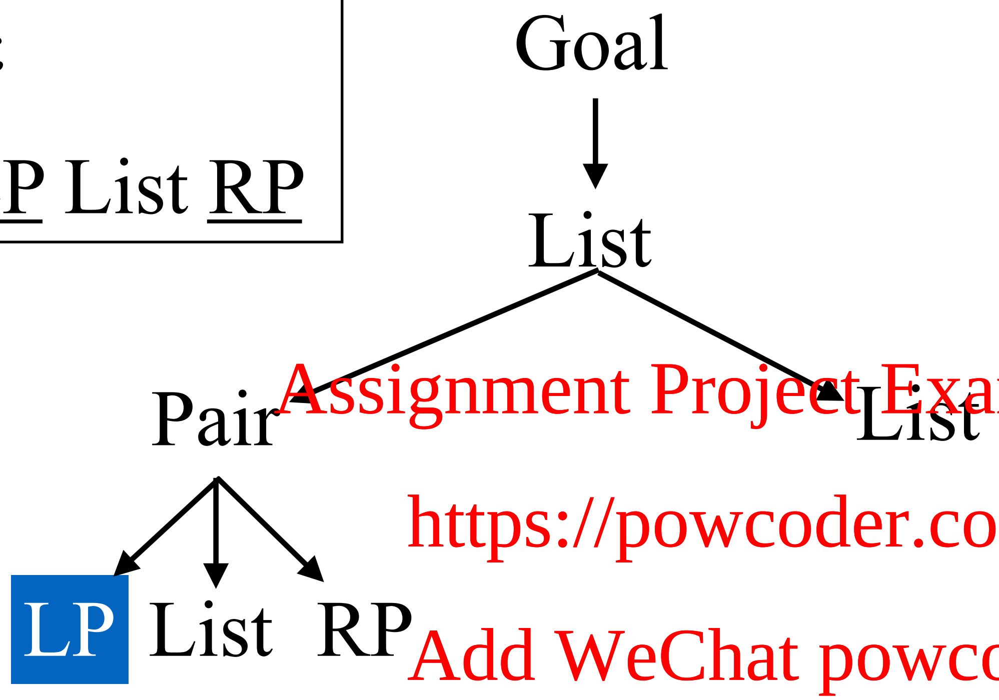
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	RP	EOF
Goal	**1**		**1**
List	2	3	3
Pair	4		

List
RP
List



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Remaining Input:
RP LP LP RP RP

Sentential Form:
LP List RP List

Applied Production:

LL(1) Parsing Example

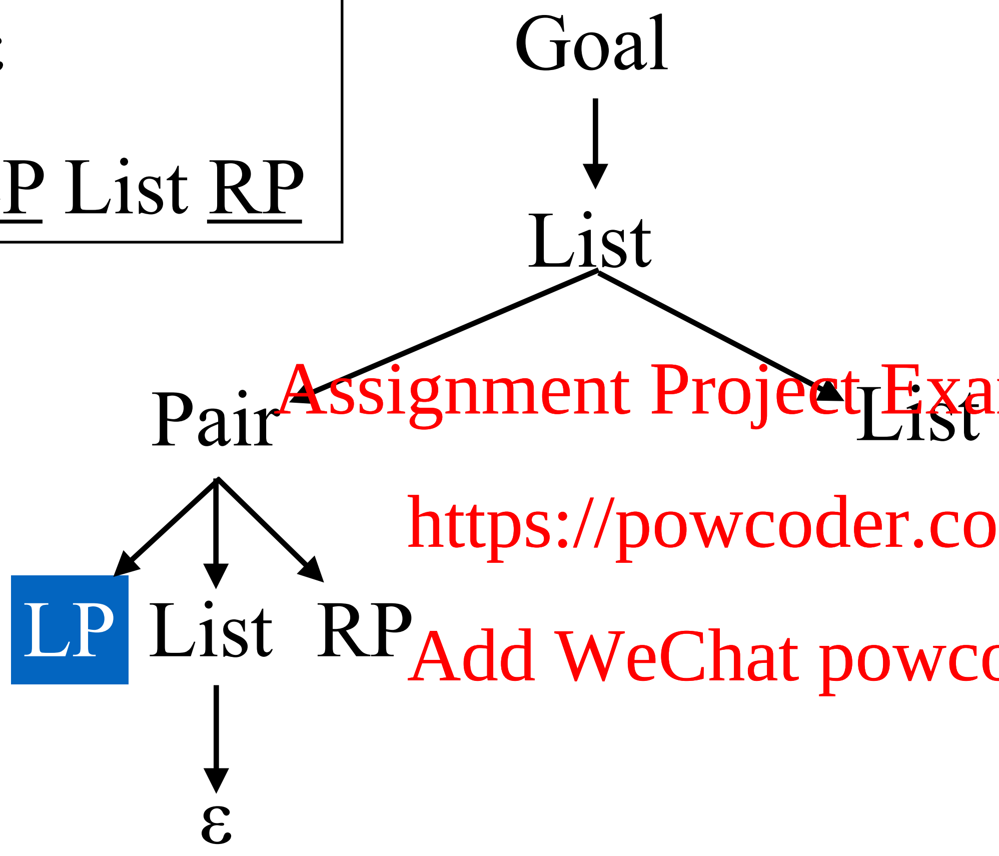
1 Goal ::= List

2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	RP	EOF
Goal	**1**		**1**
List	2	3	3
Pair	4		



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RP

List

Remaining Input:
RP LP LP RP RP

Sentential Form:
LP RP List

Applied Production:
3. List ::= ε

LL(1) Parsing Example

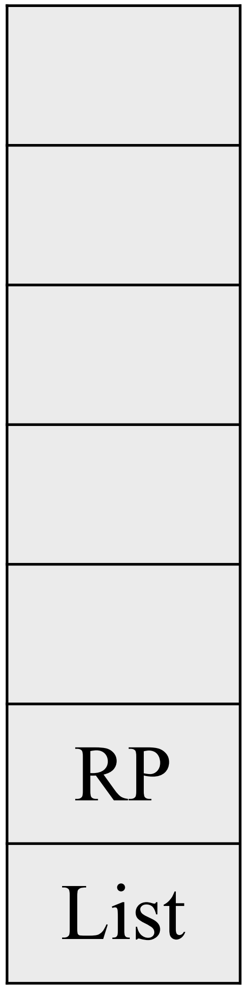
1 Goal ::= List

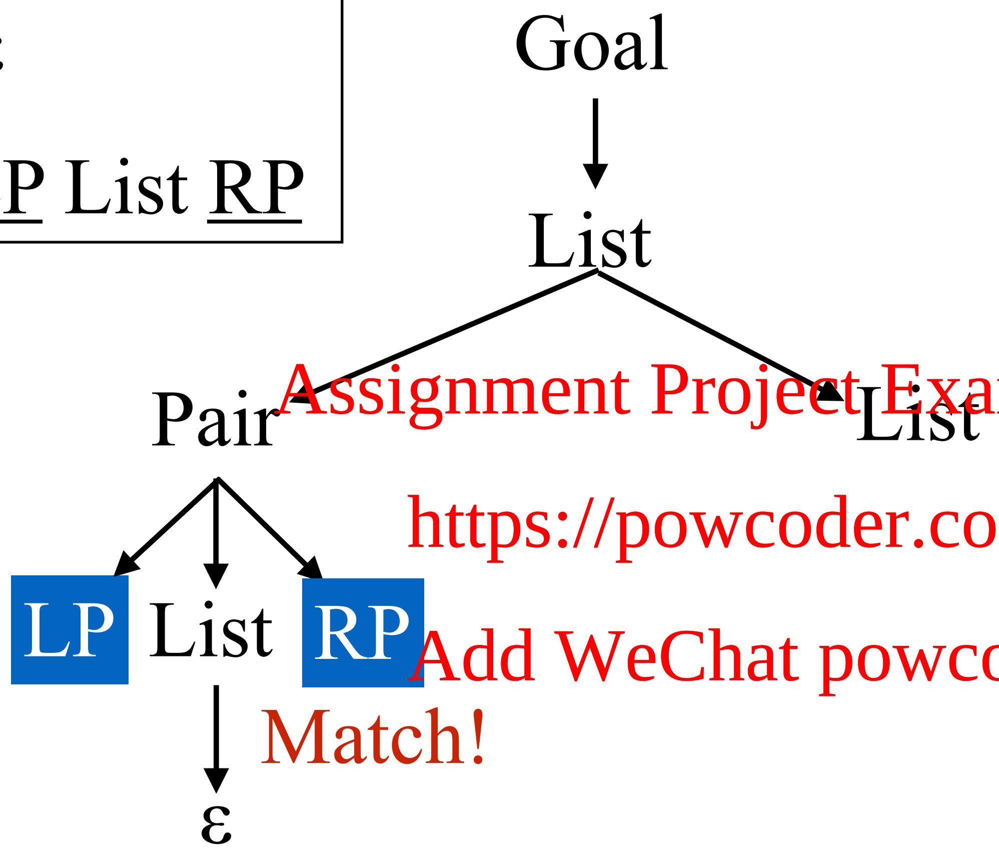
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		





Match!

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Remaining Input:
RP LP LP RP RP

Sentential Form:
LP RP List

Applied Production:

LL(1) Parsing Example

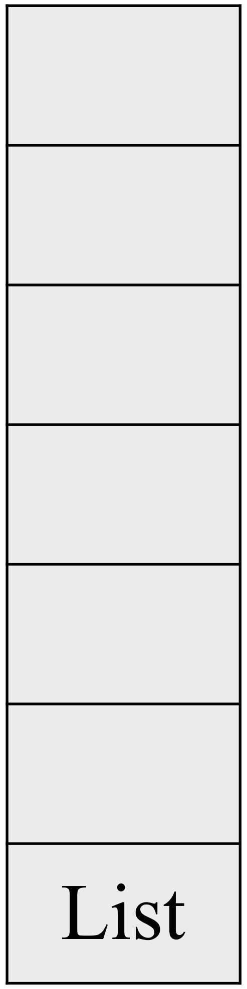
1 Goal ::= List

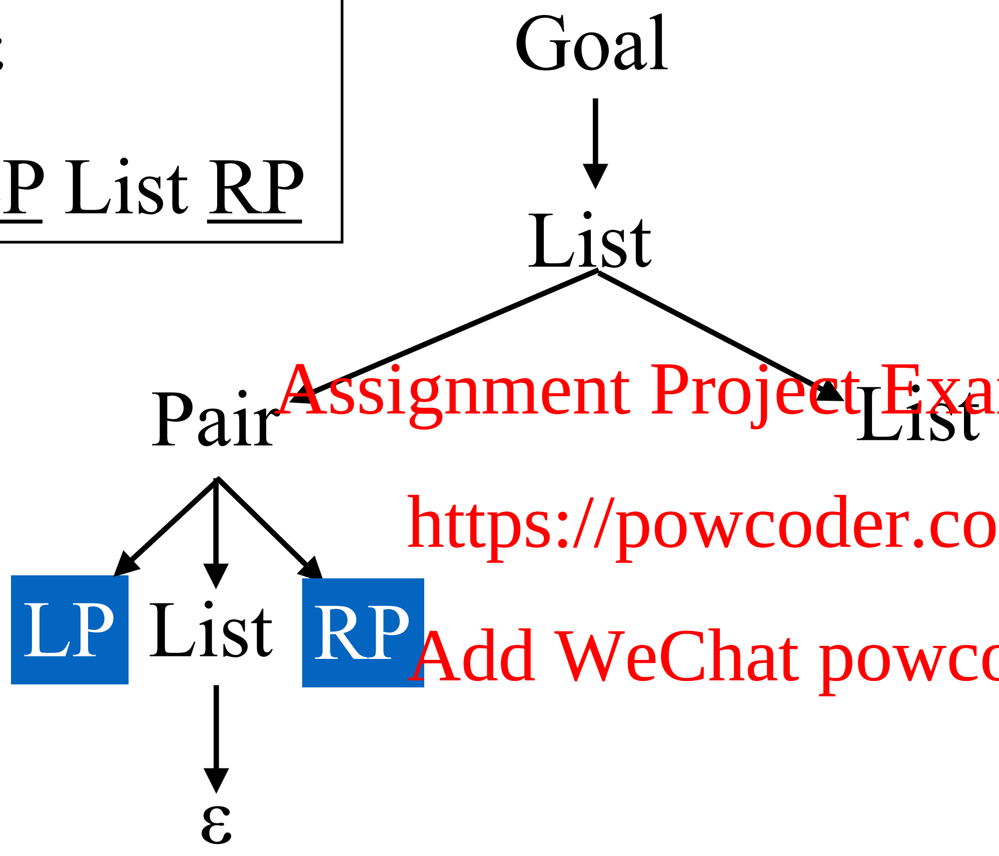
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		





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Remaining Input:
LP LP RP RP

Sentential Form:
LP RP List

Applied Production:

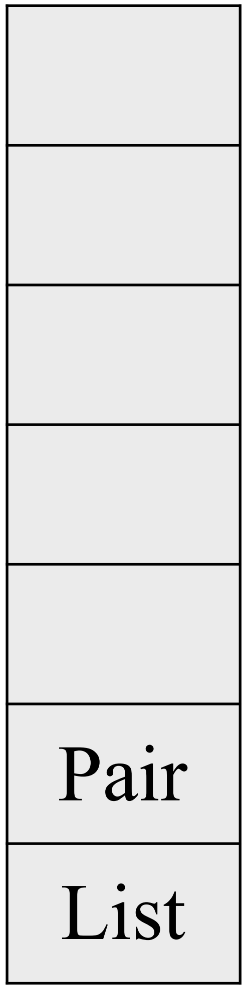
LL(1) Parsing Example

1 Goal ::= List

2 List ::= Pair List

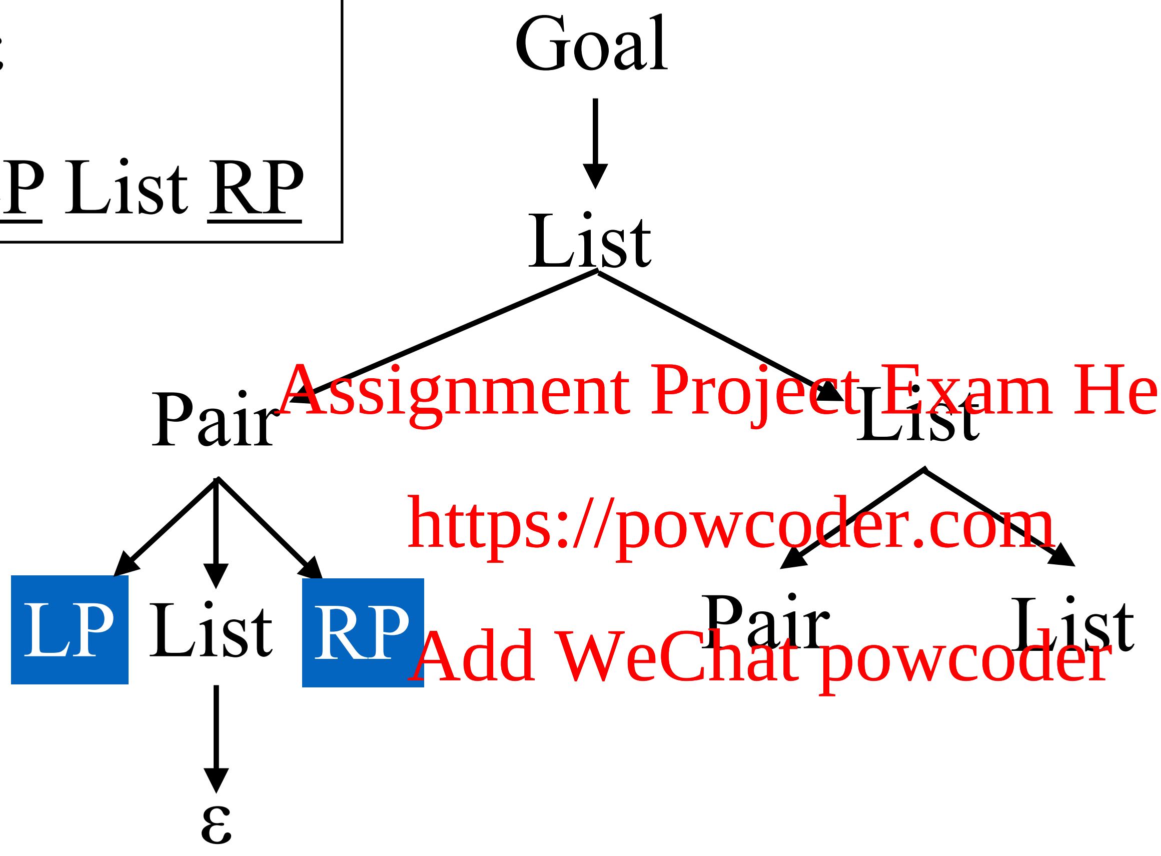
3 | ε

4 Pair ::= LP List RP



Pair

List



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	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		

Remaining Input:
LP LP RP RP

Sentential Form:
LP RP Pair List

Applied Production:
2. List ::= Pair List

LL(1) Parsing Example

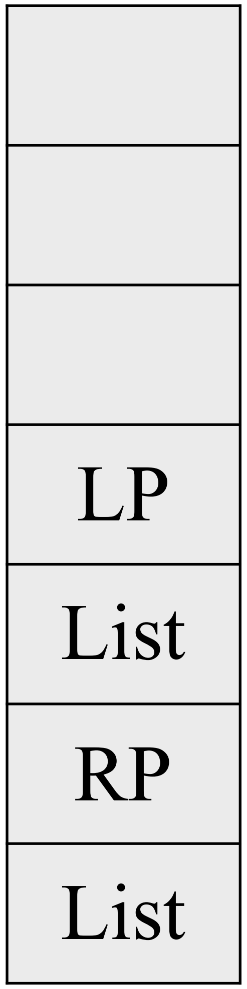
1 Goal ::= List

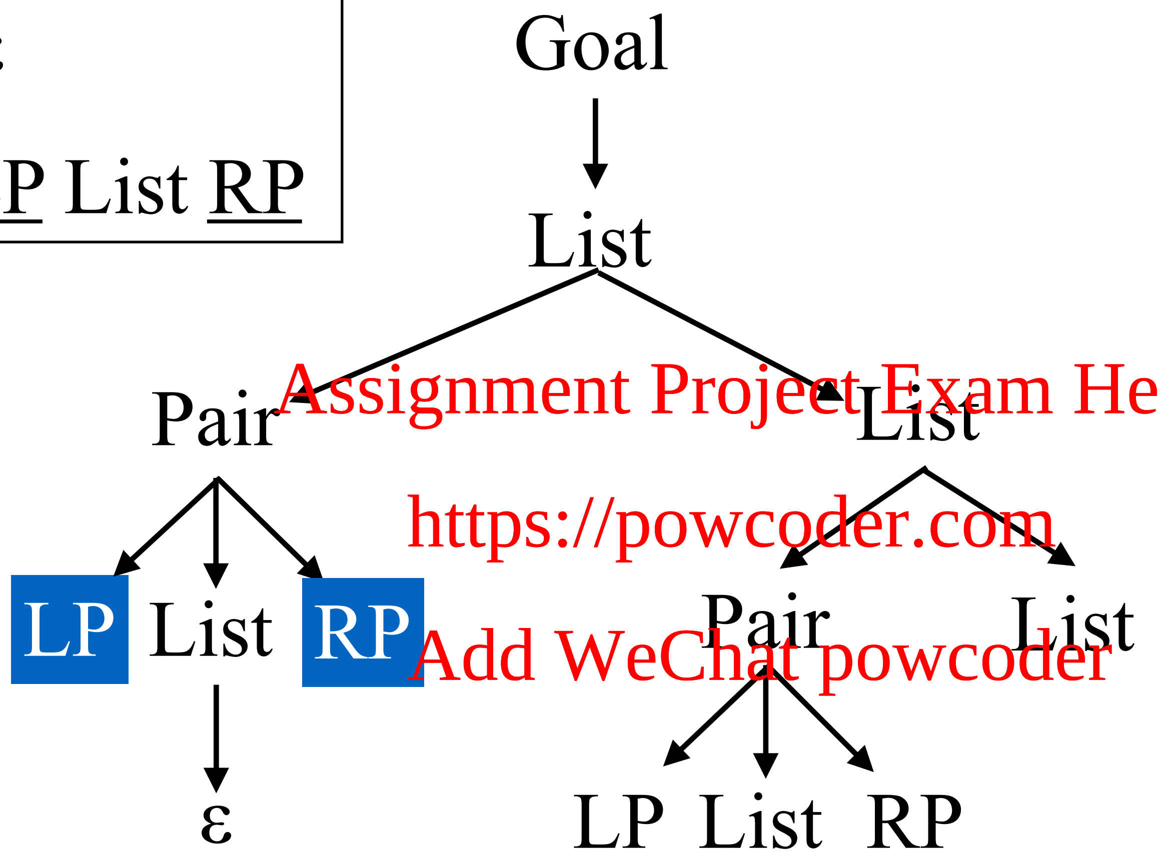
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		





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Remaining Input:
LP LP RP RP

Sentential Form:
LP RP LP List RP List

Applied Production:
4. Pair ::= LP List RP

LL(1) Parsing Example

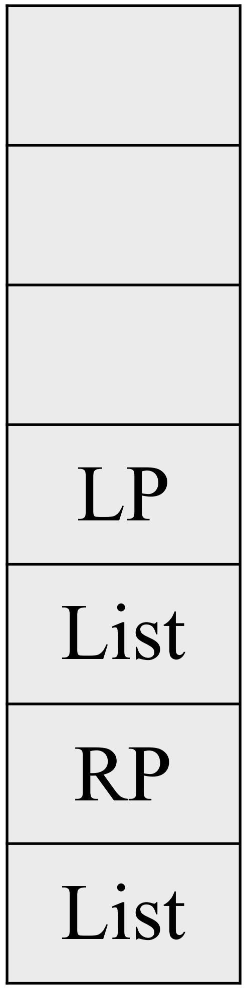
1 Goal ::= List

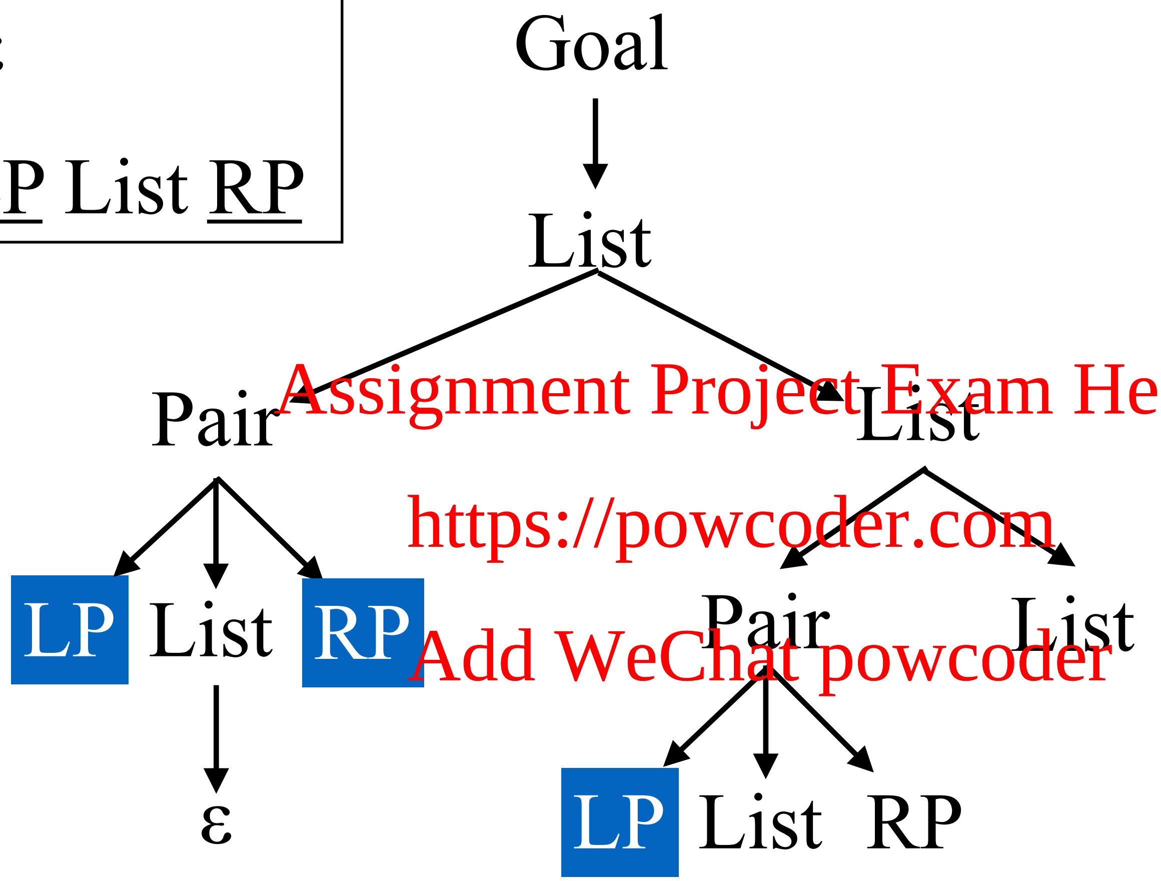
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		





Match!

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Remaining Input:
LP LP RP RP

Sentential Form:
LP RP LP List RP List

Applied Production:

LL(1) Parsing Example

1 Goal ::= List

2 List ::= Pair List

3 | ε

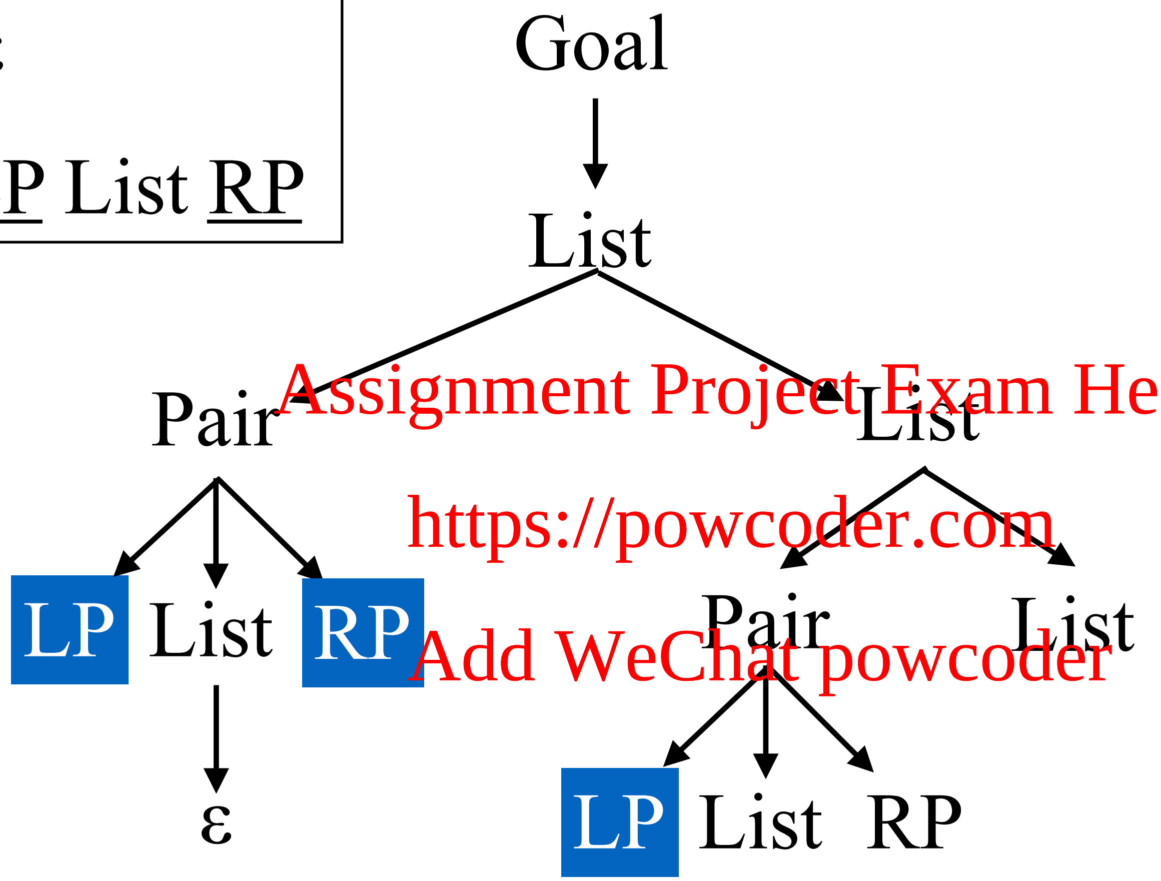
4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		

List

RP

List



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Remaining Input:
LP RP RP

Sentential Form:
LP RP LP List RP List

Applied Production:

LL(1) Parsing Example

1 Goal ::= List

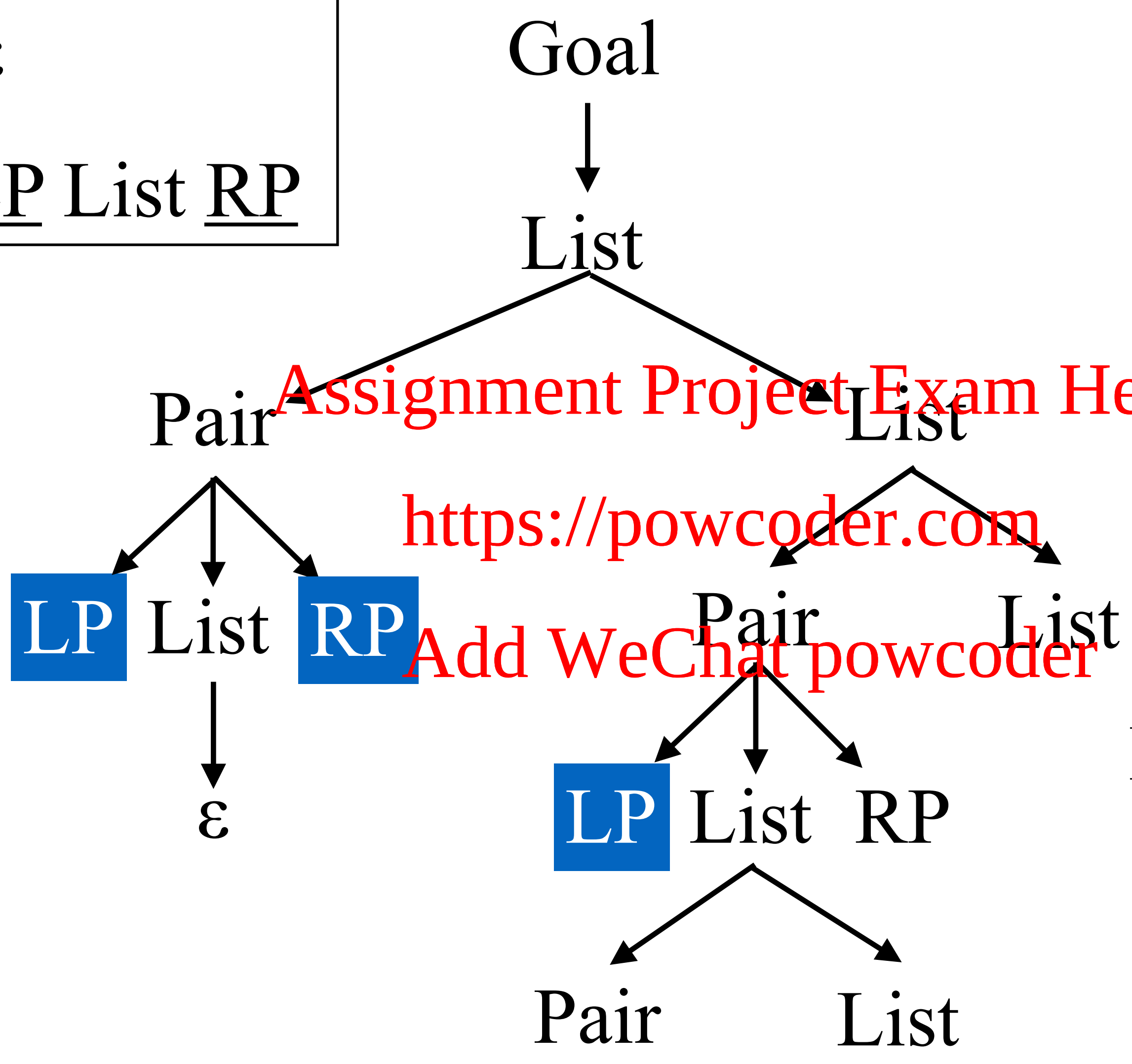
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		

Pair
List
RP
List



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Remaining Input:
LP RP RP

Sentential Form:
LP RP LP Pair List RP List

Applied Production:
2. List ::= Pair List

LL(1) Parsing Example

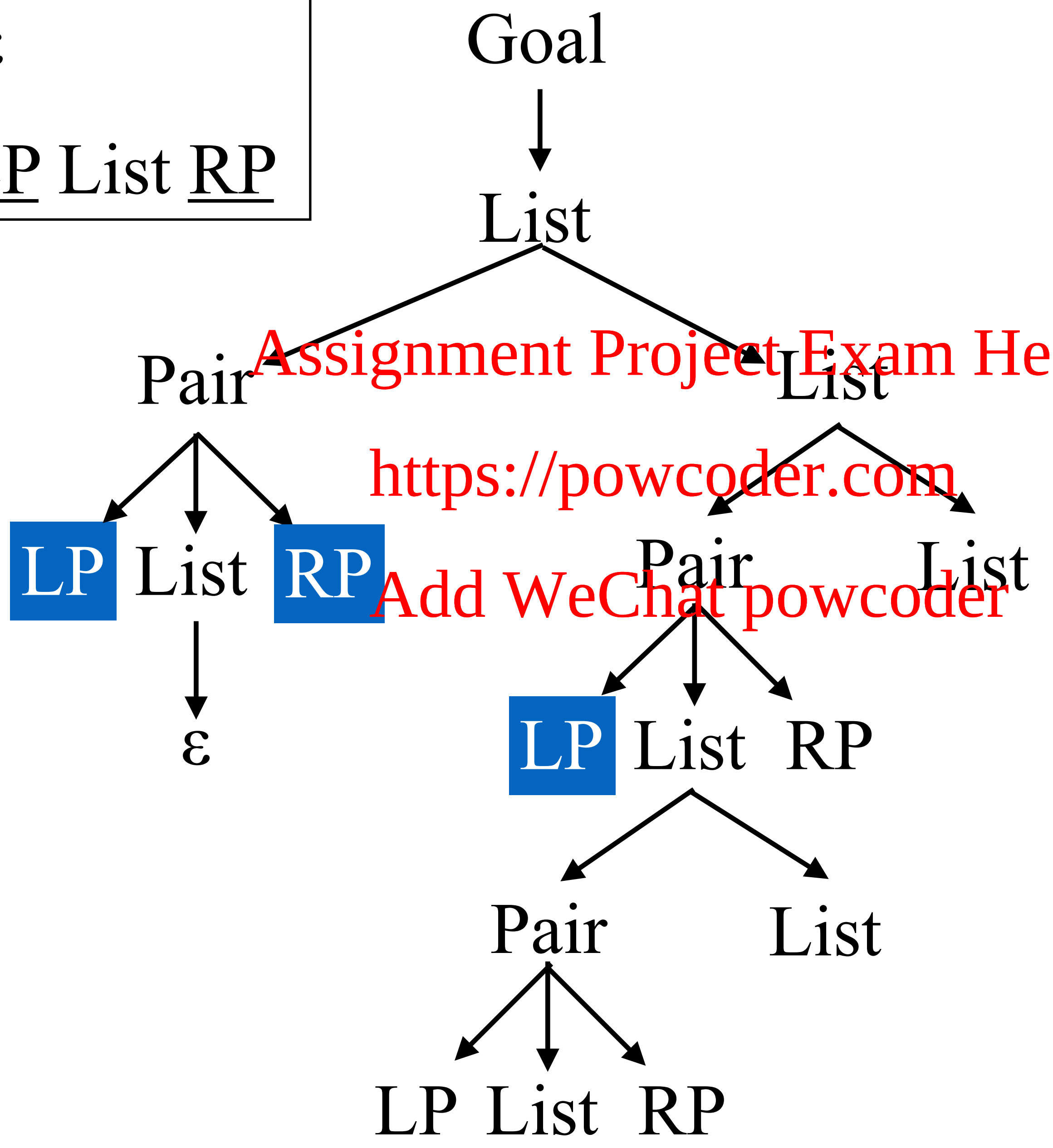
1 Goal ::= List

2 List ::= Pair List

3 | ε

4 Pair ::= <u>LP</u> List <u>RP</u>

LP
List
RP
List
RP
List



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	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		

Remaining Input:
LP RP RP

Sentential Form:
LP RP LP
LP List RP List RP List

Applied Production:
4. Pair ::= LP List RP

LL(1) Parsing Example

1 Goal ::= List

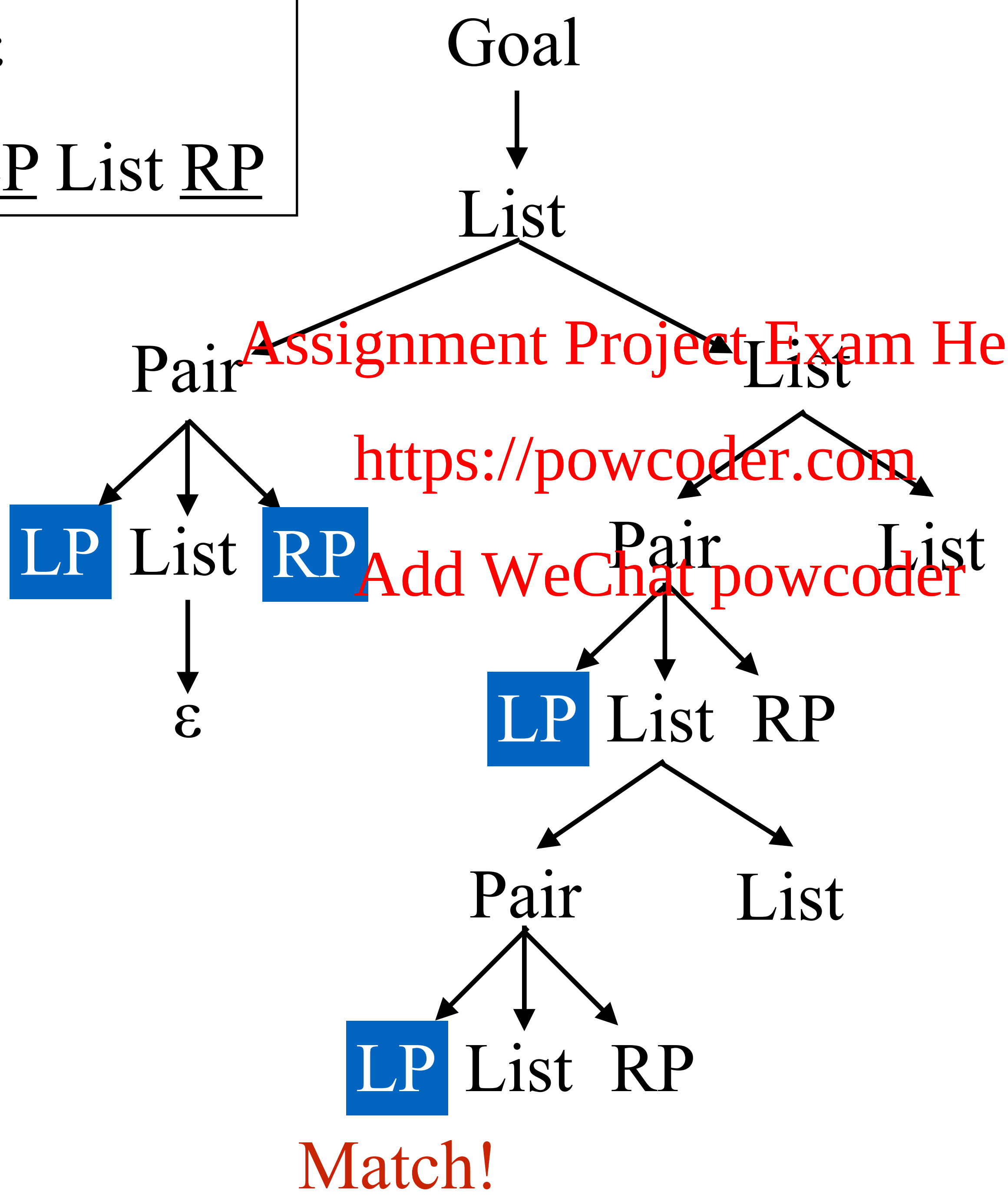
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		

LP
List
RP
List
RP
List



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Remaining Input:
LP RP RP

Sentential Form:
LP RP LP
LP List RP List RP List

Applied Production:

LL(1) Parsing Example

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2 List ::= Pair List

3 | ε

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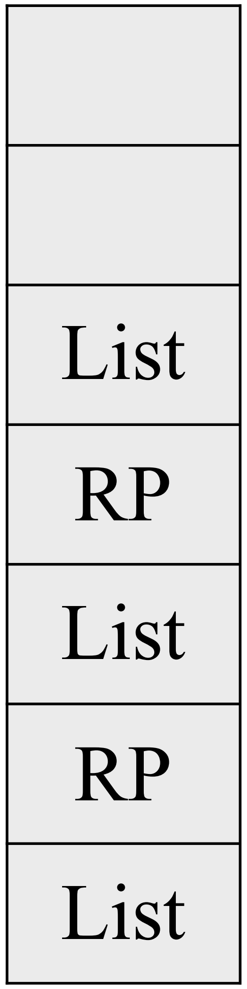

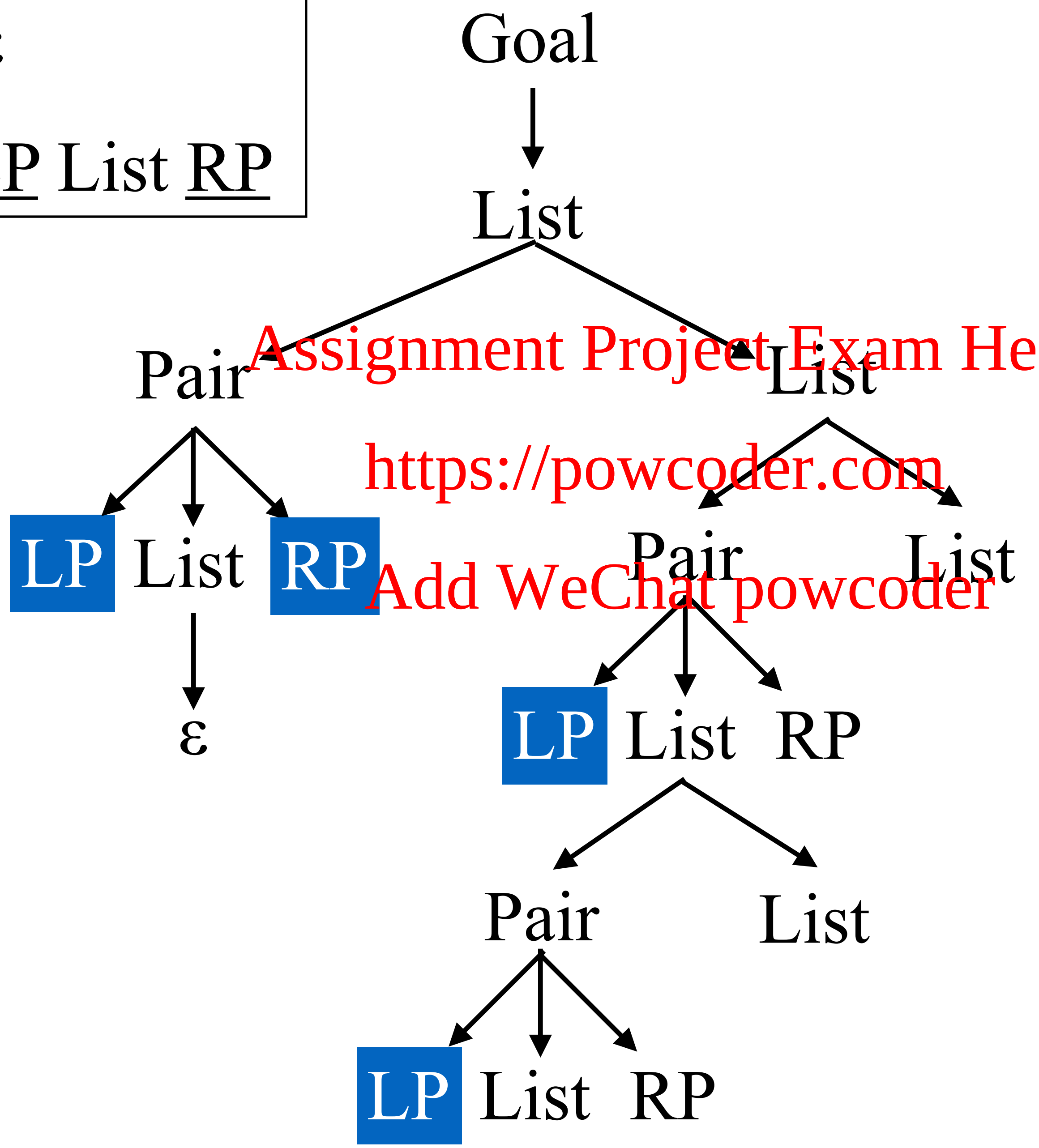

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Remaining Input:
RP RP

Sentential Form:
LP RP LP
LP List RP List RP List

Applied Production:

LL(1) Parsing Example

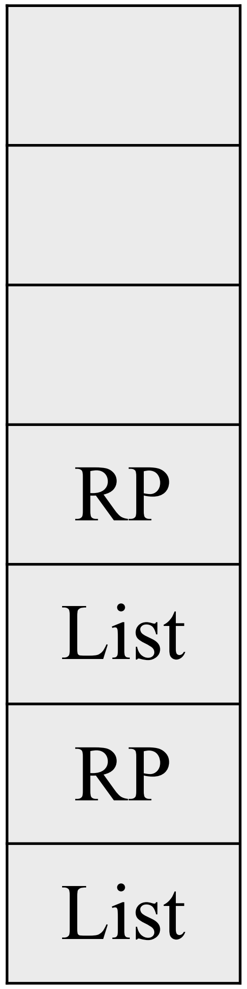
1 Goal ::= List

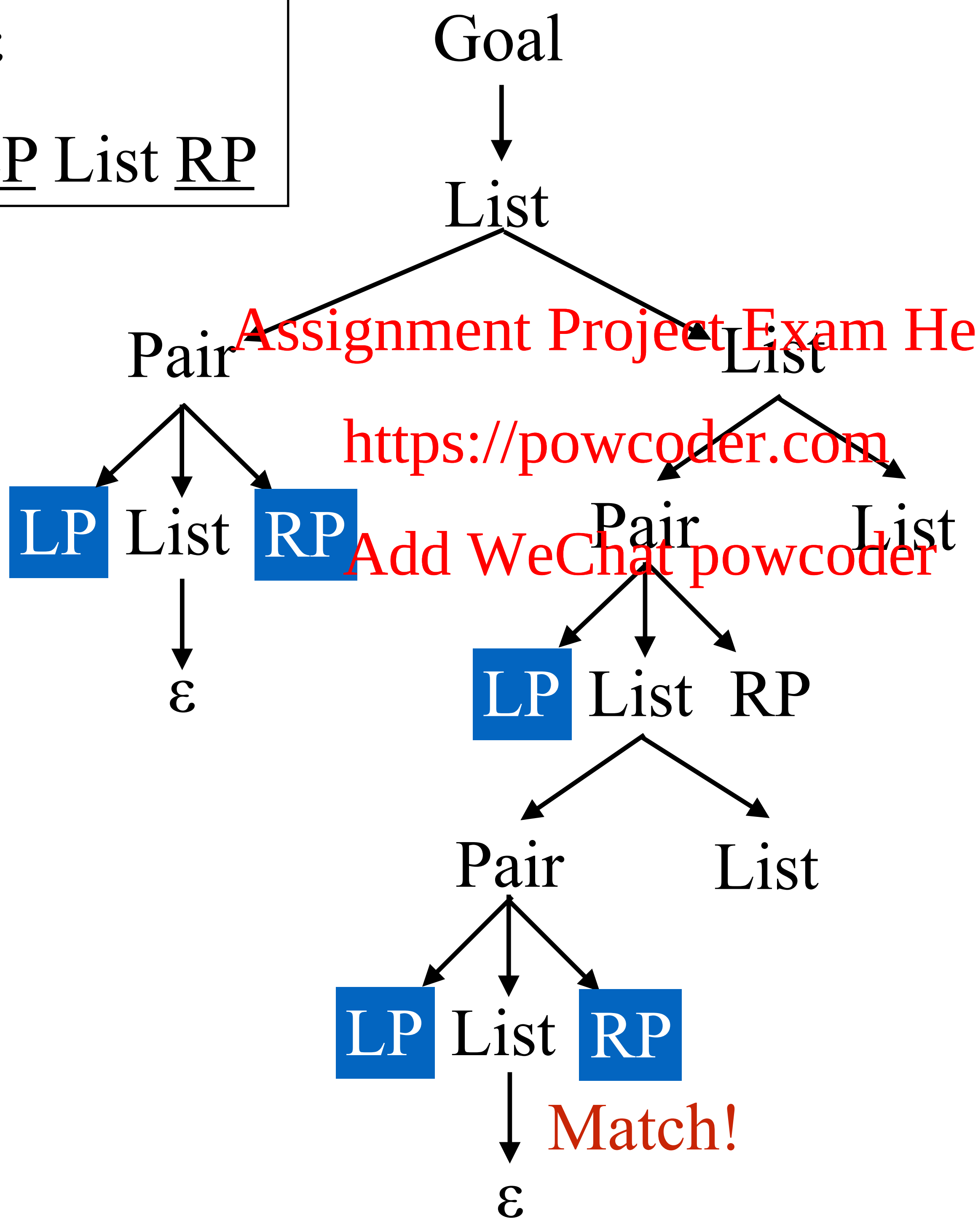
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		





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Remaining Input:
RP RP

Sentential Form:
LP RP LP
LP RP List RP List

Applied Production:

LL(1) Parsing Example

1 Goal ::= List

2 List ::= Pair List

3 | ε

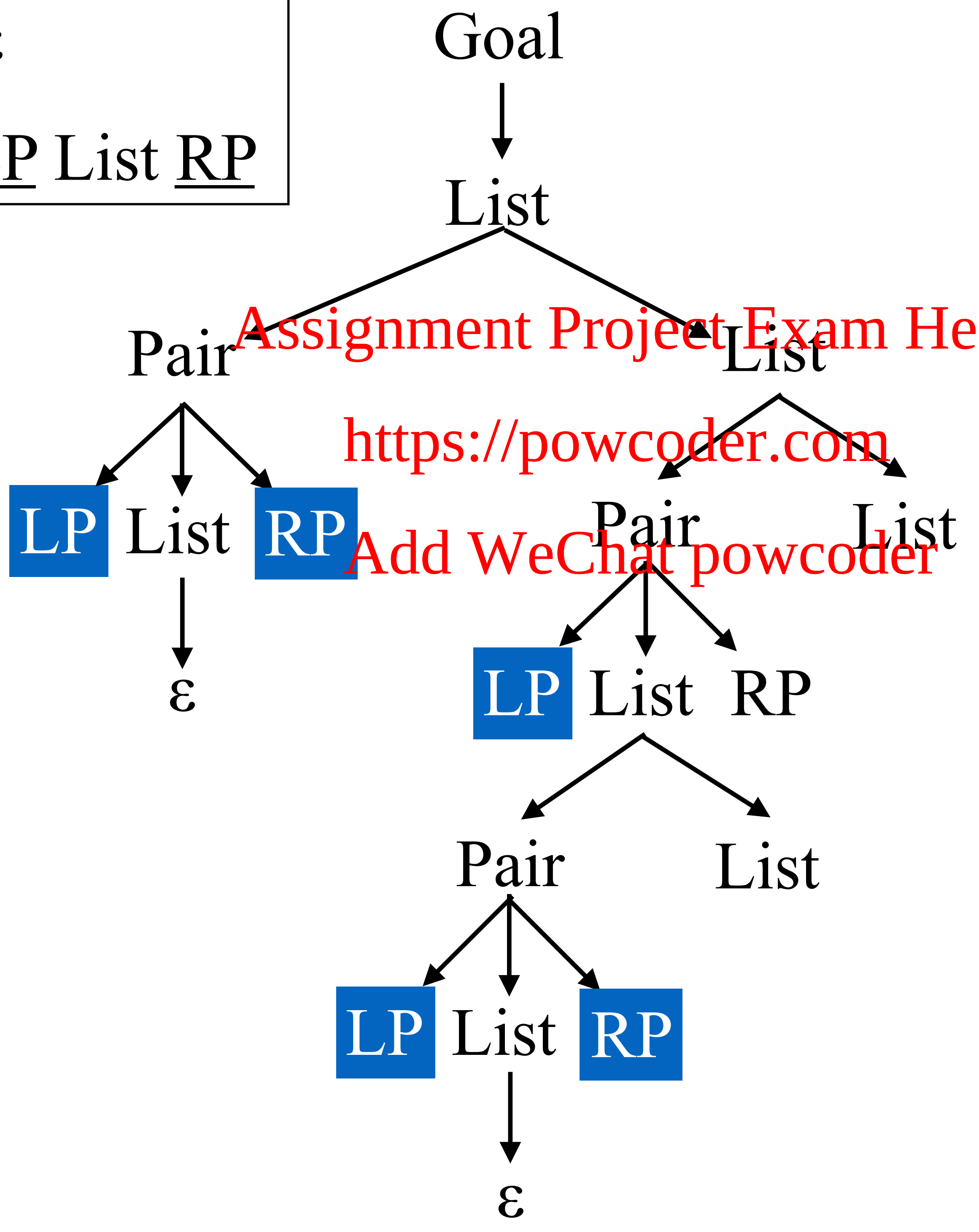
4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		

List

RP

List



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Remaining Input:
RP

Sentential Form:
LP RP LP
LP RP List RP List

Applied Production:

LL(1) Parsing Example

1 Goal ::= List

2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

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Goal	**1**		**1**
List	2	3	3
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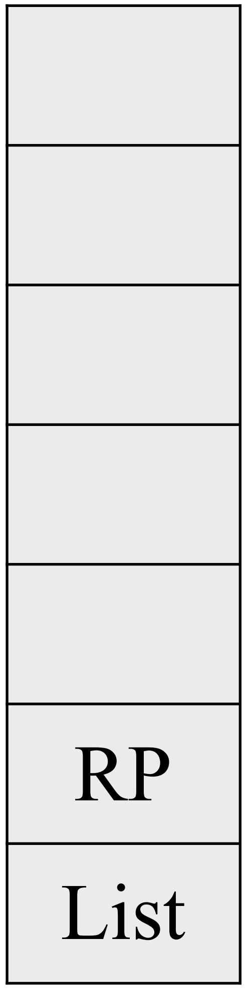
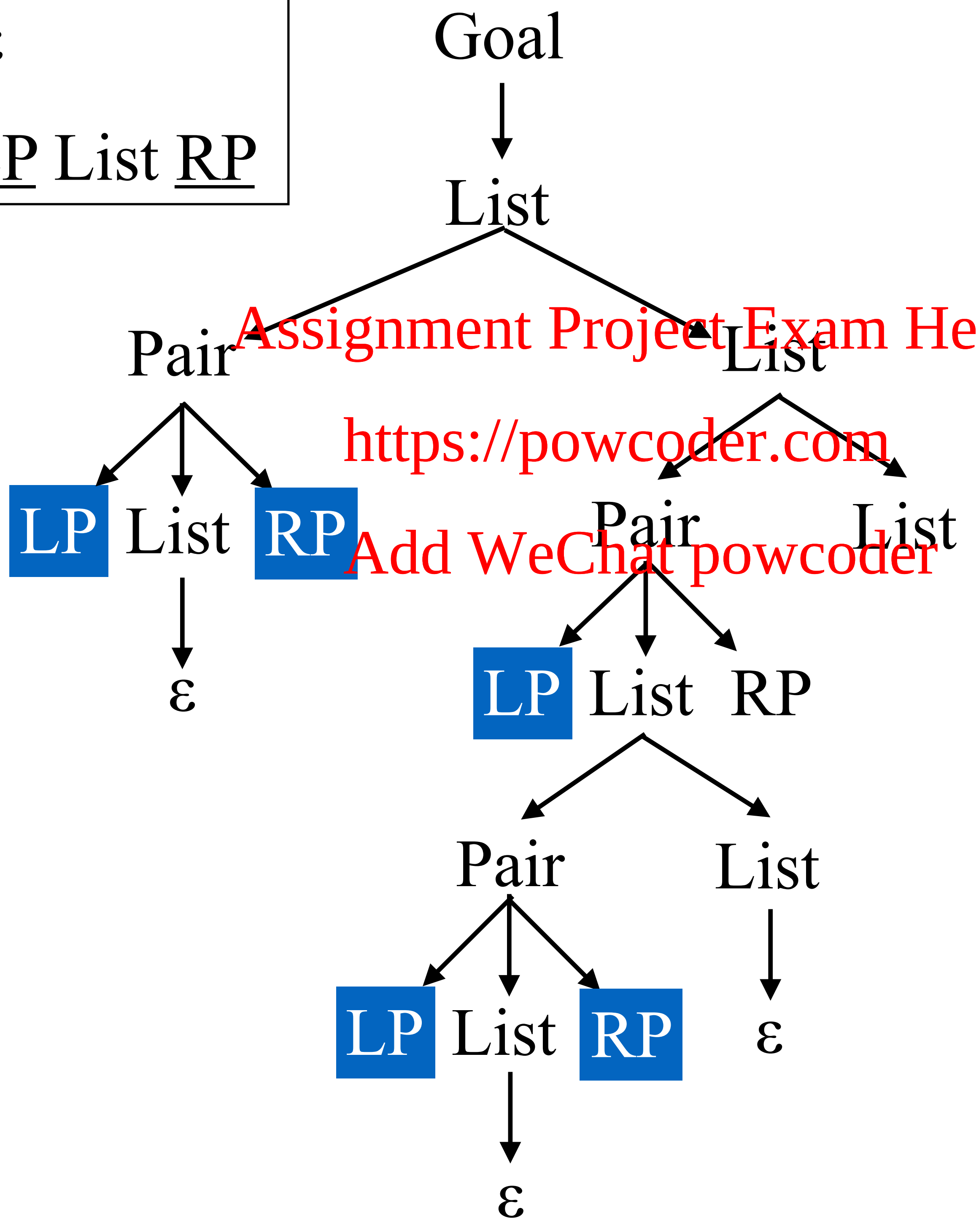


RP

List



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Remaining Input:
RP

Sentential Form:
LP RP LP
LP RP RP List

Applied Production:
3. List ::= ε

LL(1) Parsing Example

1 Goal ::= List

2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
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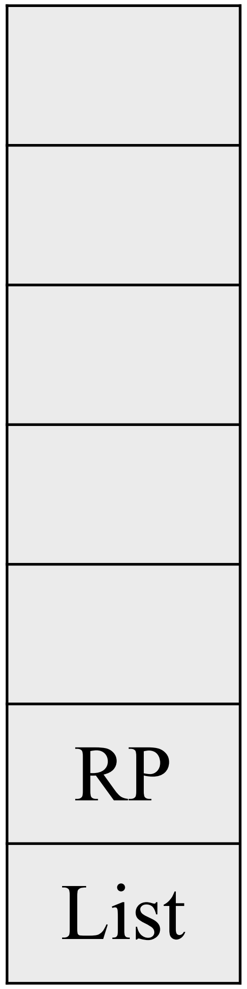

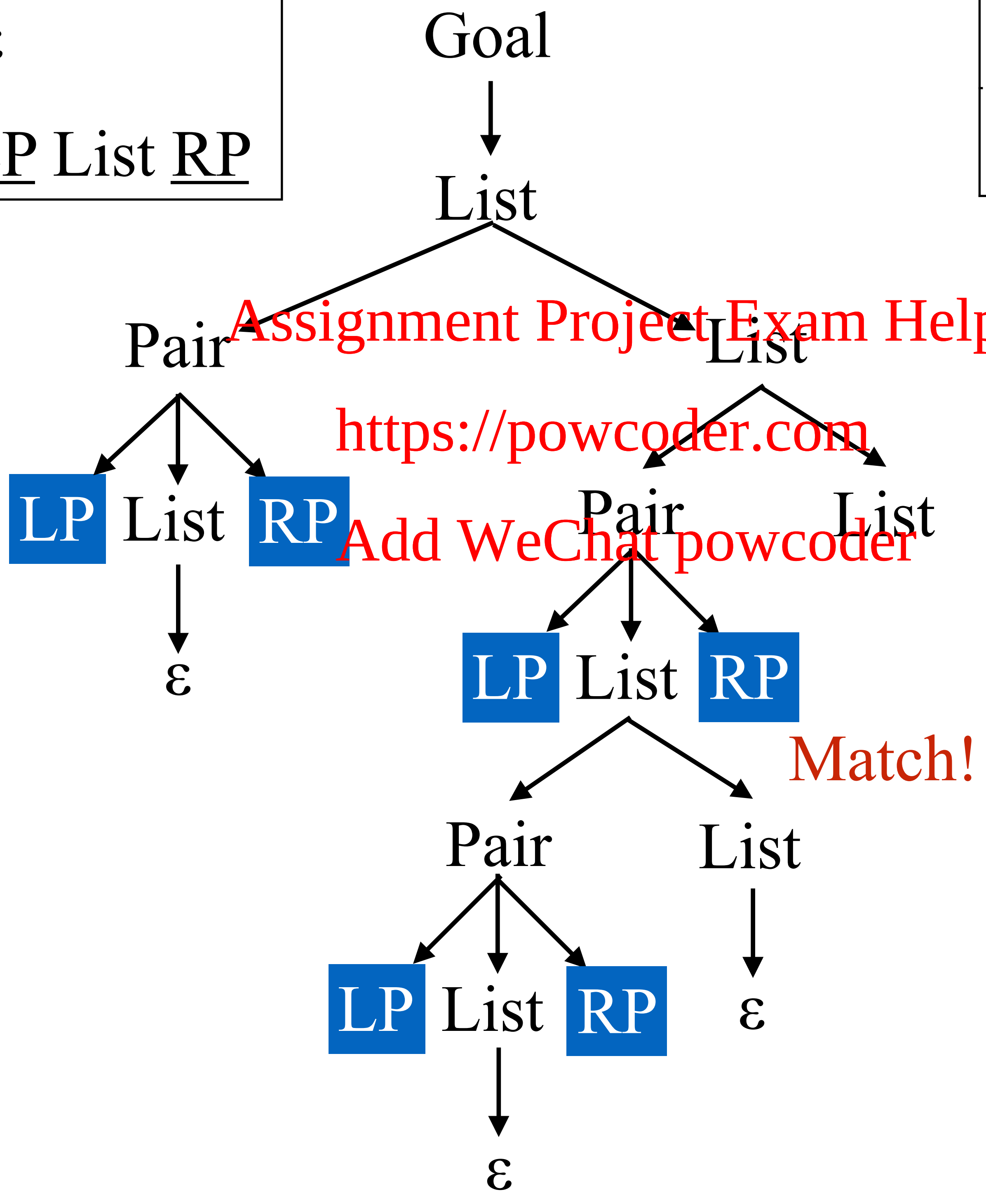

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Remaining Input:
RP

Sentential Form:
LP RP LP
LP RP RP List

Applied Production:

LL(1) Parsing Example

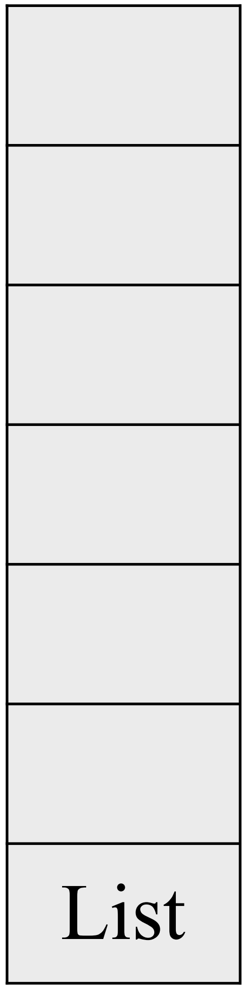
1 Goal ::= List

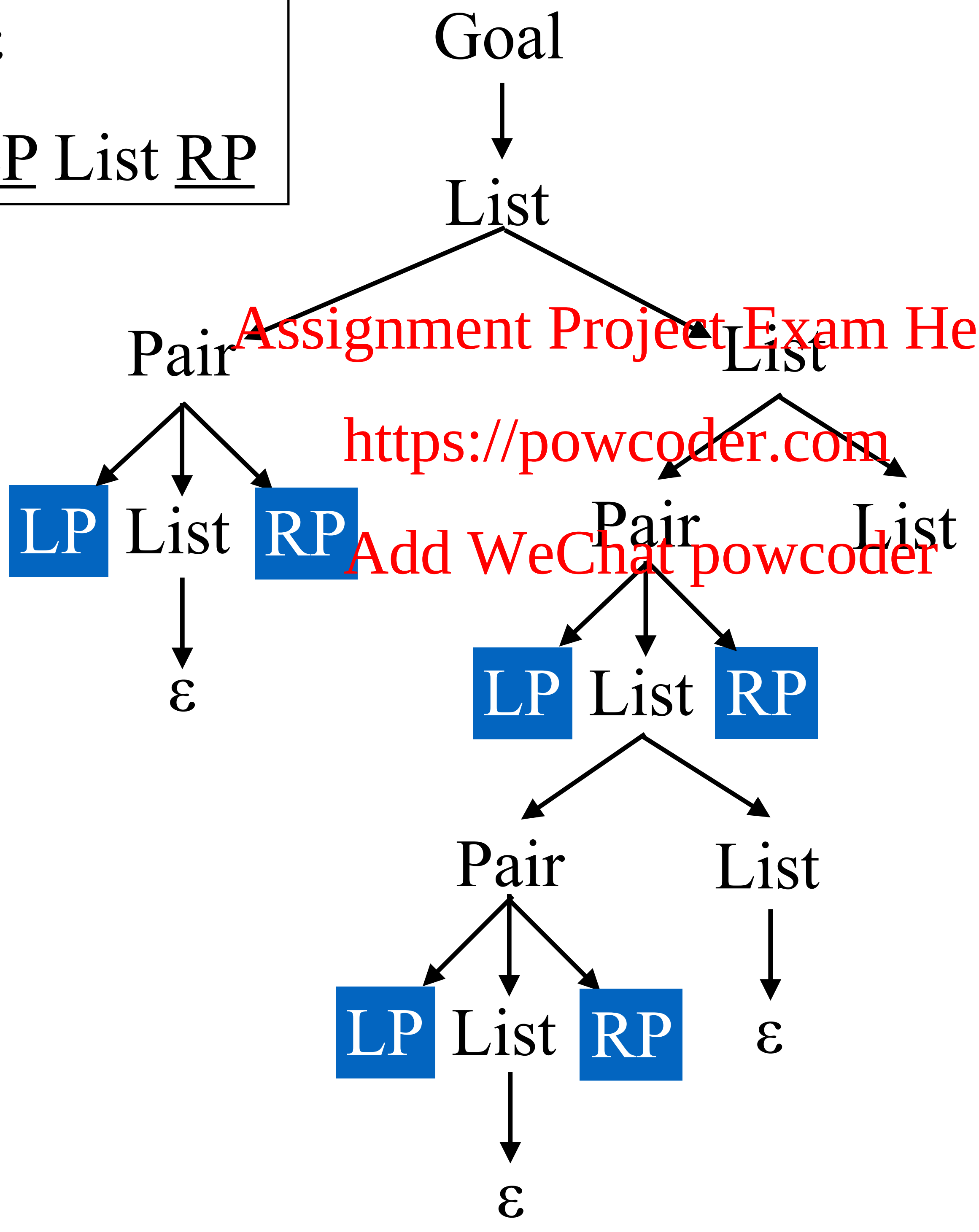
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		





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Remaining Input:

Sentential Form:
LP RP LP
LP RP RP List

Applied Production:

LL(1) Parsing Example

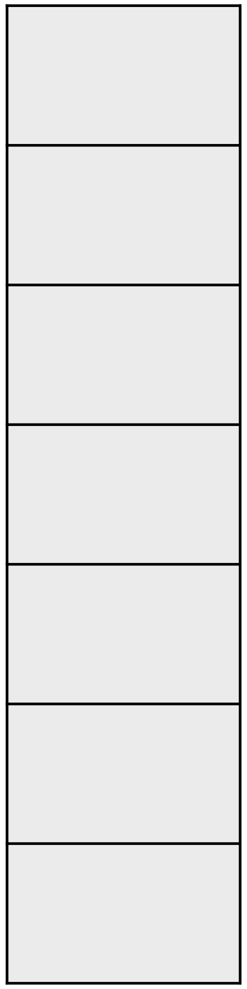
1 Goal ::= List

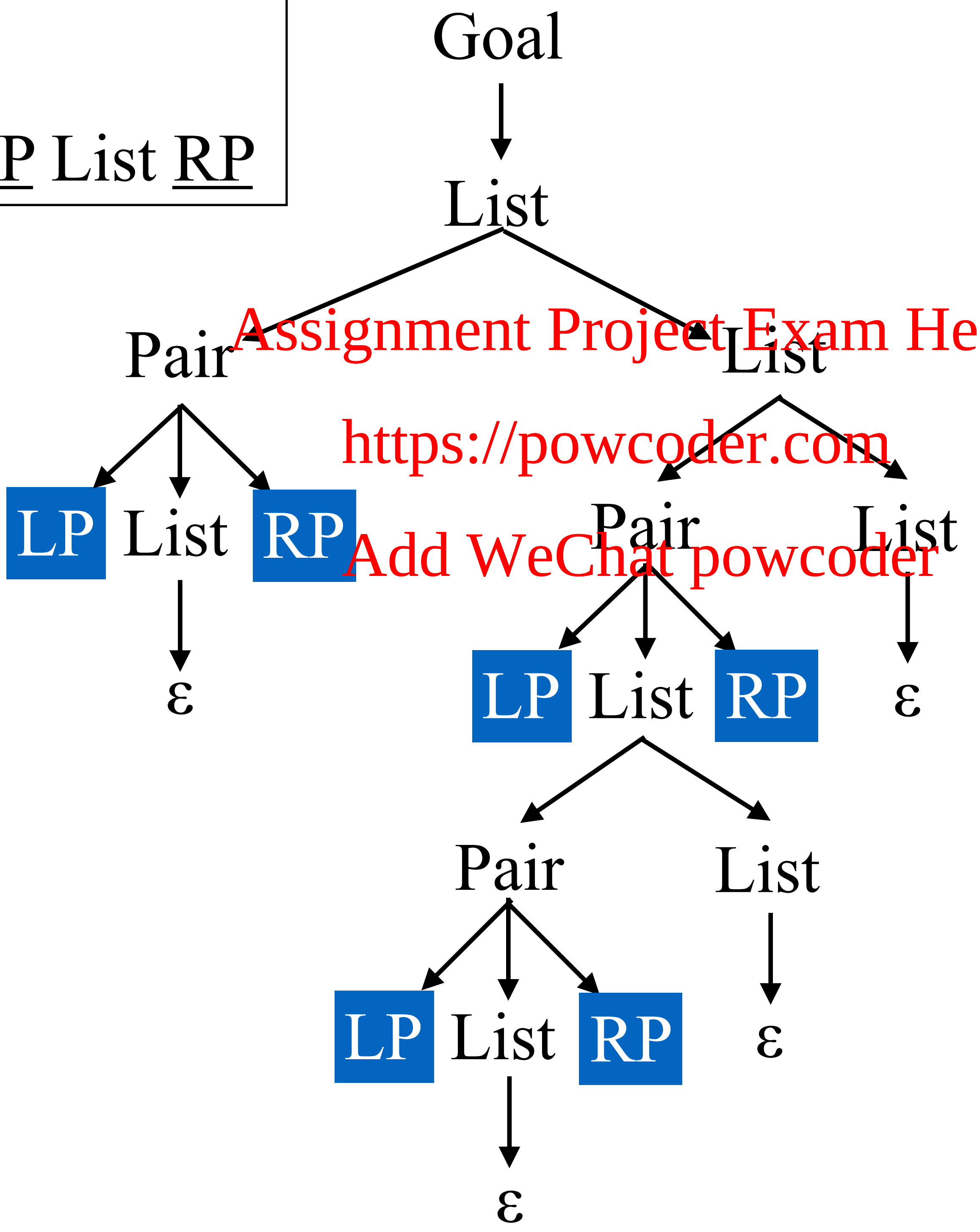
2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		





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Remaining Input:

Sentential Form:
LP RP LP LP RP RP

Applied Production:
3. List ::= ε

Recursive Descent Parsing

Recursive descent parser for LL(1)

- Each **non-terminal** has an associated parsing procedure that can recognize any sequence of tokens generated by that **non-terminal**
- There is a main routine to initialize all globals (e.g:the *token variable* in previous code example) and call the start symbol. On return, check whether token==EOF, and whether errors occurred.
- Within a parsing procedure, both **non-terminals** and **terminals** can be matched:
  - ➡ Non-terminal A: call procedure for A
  - ➡ Token t: compare t with current input token; if matched, **consume input**, otherwise, ERROR
- Parsing procedure may contain code that performs some useful "computations" (*syntax directed translation)*

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Recursive Descent Parsing (pseudo code)

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		

1 Goal ::= List

2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

```
main:  {
        token := next_token( );
        if ( List( ) and token == EOF) print “accept” else print “error”;
}
```

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Recursive Descent Parsing (pseudo code)

	LP	*RP*	*EOF*
Goal	**1**		**1**
List	2	3	3
Pair	4		

1 Goal ::= List

2 List ::= Pair List

3 | ε

4 Pair ::= LP List RP

```
bool List( ):  {
  switch token {
      case LP:
                    call Pair( );
                    call List( );
                    break;
      case RP:
      case EOF:  return true;
                    break;
      default: return false;
  }
  return true;
}
```

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```
bool Pair( ):  {
  switch token {
    case LP:  token := next_token( );
              call List( );
              if ( token == RP ) {
                  token := next_token( );
                  return true;
              }
              else
                  return false;
              break;
    default: return false;
  }
}
```

Syntax Directed Translation

Examples:

- Interpreter
- Code generator
- Type checker
- Performance estimator

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Use hand-written recursive descent LL(1) parser

Example: the Original Parser

1: < expr > ::= + < expr > < expr > |
2:                       < digit >
3: < digit > ::= 0 | 1 | 2 | 3 | … | 9

	+	0…9	other
< expr >	rule 1	rule 2	error
< digit >	error	rule 3	error

```
bool expr( ) {

      switch token {
            case +:      token := next_token( );
                         expr( );
                         expr( ); break;
            case 0..9:   digit( ); break;
            …
        }
      }
bool digit( ) {  // return value of constant
      switch token {
            case 1: token := next_token( ); break;
            case 2: token := next_token( ); break;
          …
      }
      }
```

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Example: the Original Parser

1: < expr > ::= + < expr > < expr > |
2:                        < digit >
3: < digit > ::= 0 | 1 | 2 | 3 | … | 9

	+	0…9	other
< expr >	rule 1	rule 2	error
< digit >	error	rule 3	error

call <expr>

What happens when you parse expression
“ + **2** + **1** **2**”

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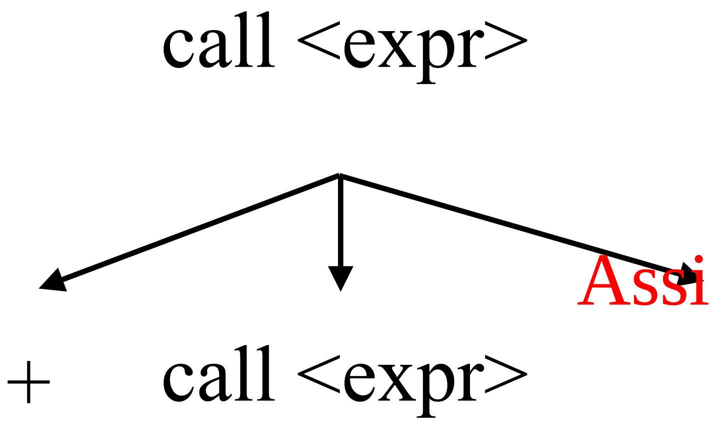
```
bool expr( ):  // return value of the expression

        switch token {
                case +:      token := next_token( );
                              expr( );
                              expr( ); break;
                case 0..9:   digit( ); break;
                …
        }

bool digit( ):  // return value of constant
        switch token {
                case 1: token := next_token( ); break;
                case 2: token := next_token( ); break;
              …
        }
```

Example: the Original Parser

1: < expr > ::= + < expr > < expr > |
2: < digit >
3: < digit > ::= 0 | 1 | 2 | 3 | … | 9

	+	0…9	other
< expr >	rule 1	rule 2	error
< digit >	error	rule 3	error



What happens when you parse expression
“ + **2** + **1 2**”

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```
bool expr( ):  // return value of the expression

        switch token {
                case +:        token := next_token( );
                                expr( );
                                expr( ); break;
                case 0..9:   digit( ); break;
                …
        }

bool digit( ):  // return value of constant
        switch token {
                case 1: token := next_token( ); break;
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              …
        }
```

Example: the Original Parser

1: < expr > ::= + < expr > < expr > |
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3: < digit > ::= 0 | 1 | 2 | 3 | … | 9

	+	0…9	other
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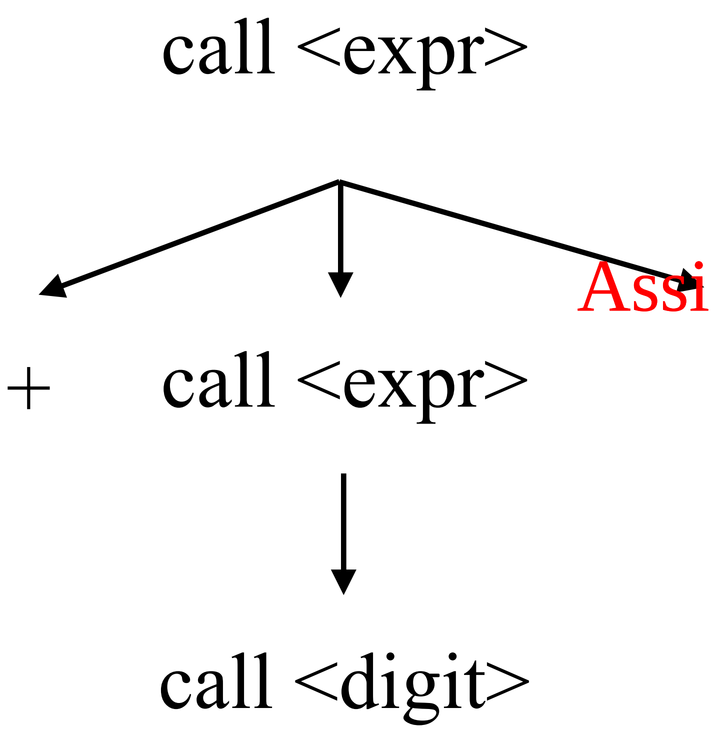
< digit >	error	rule 3	error



call <expr>

+ call <expr>

call <digit>

What happens when you parse expression
“ + **2** + **1 2**”

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Example: the Original Parser

1: < expr > ::= + < expr > < expr > |
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	+	0…9	other
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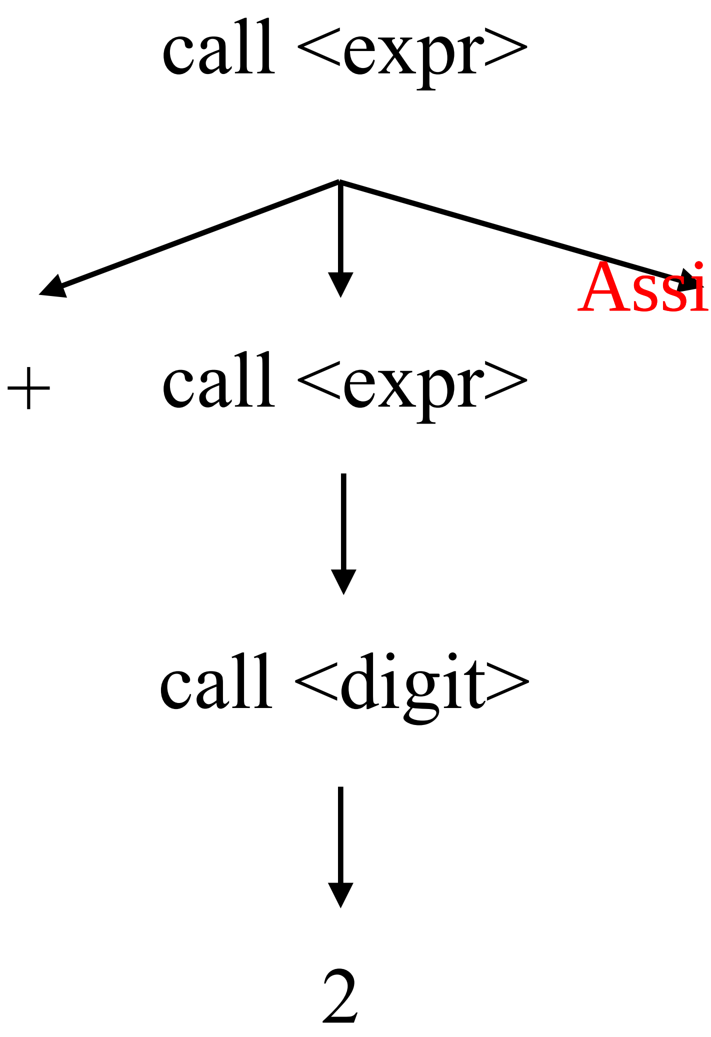

call <expr>

+

call <expr>

call <digit>

2

What happens when you parse expression
“ + **2** + **1 2**”

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Example: the Original Parser

1: < expr > ::= + < expr > < expr > |
2: < digit >
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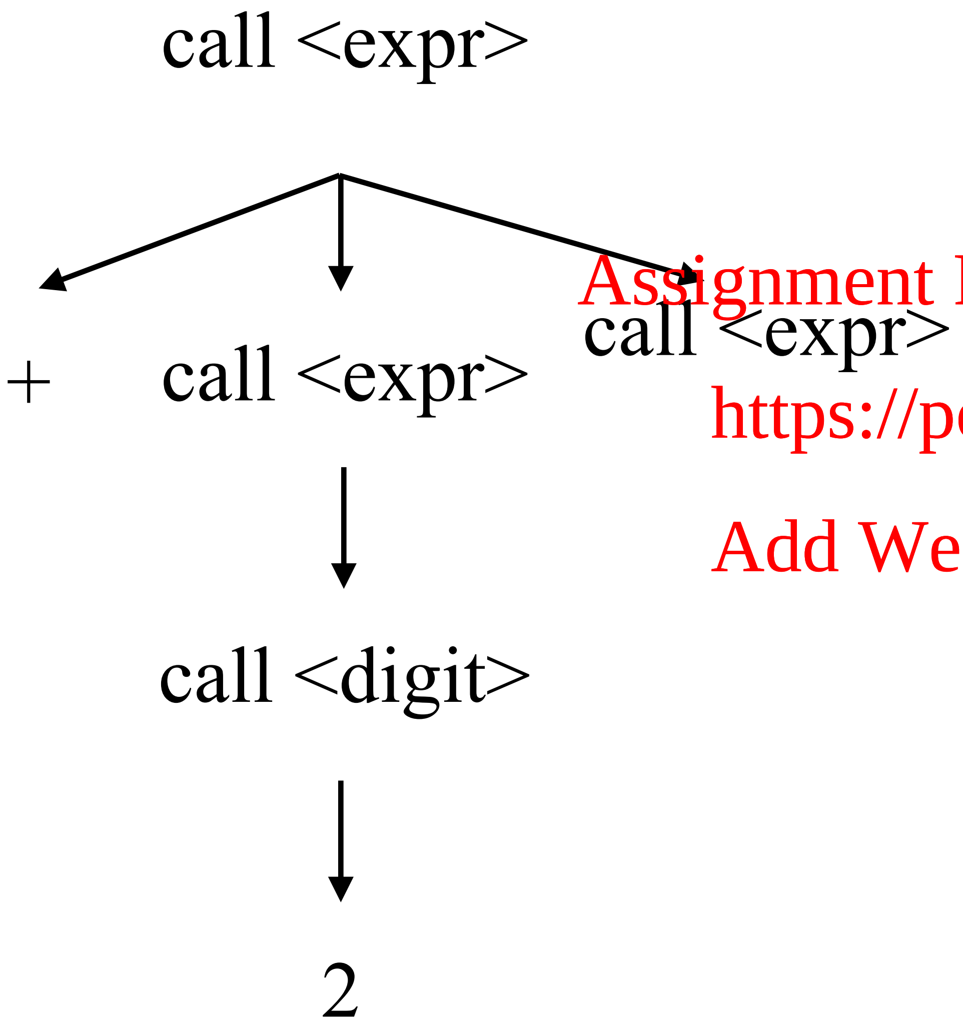
	+	0…9	other
< expr >	rule 1	rule 2	error
< digit >	error	rule 3	error



call <expr>

+

call <expr>

call <expr>

call <digit>

2

What happens when you parse expression
“ + **2** + **1 2**”

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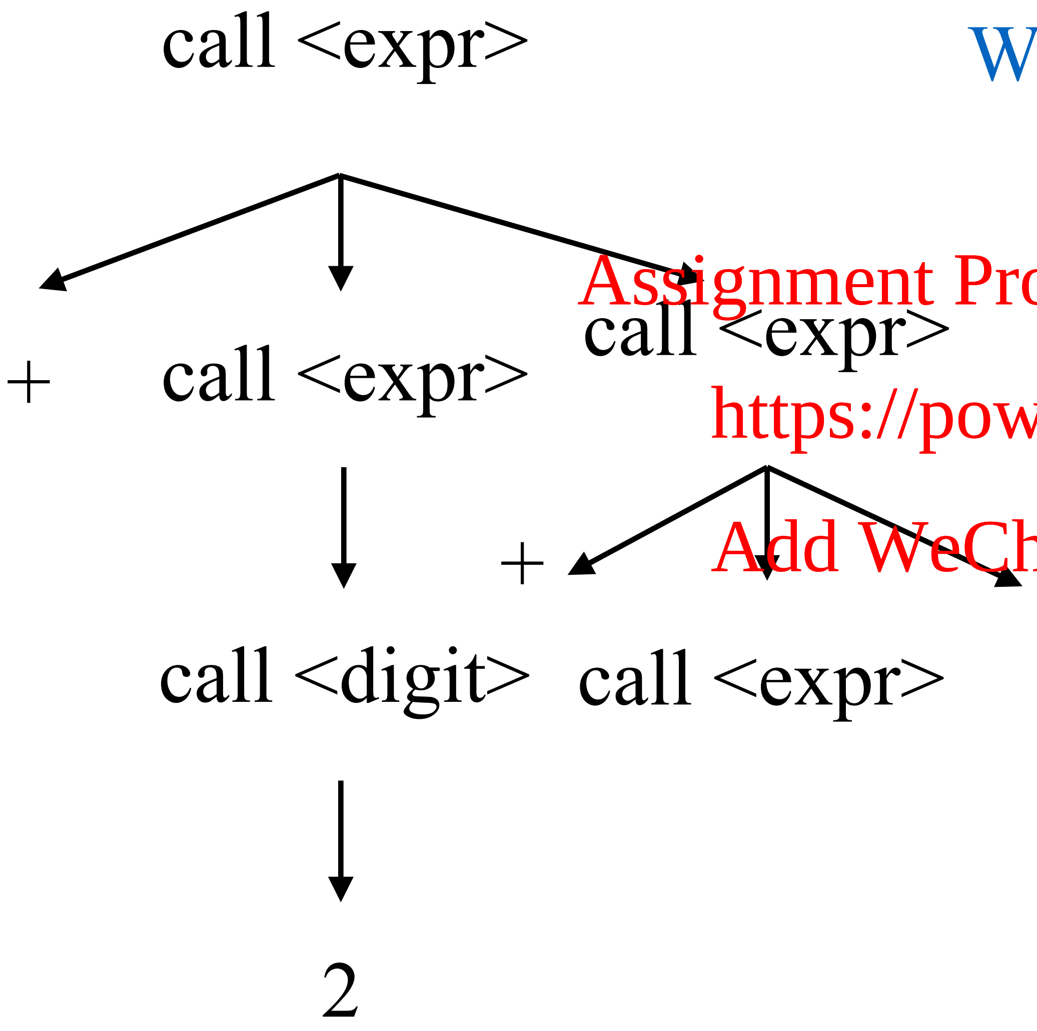

call <expr>

+ call <expr> call <expr>

call <digit> + call <expr>

2

What happens when you parse expression “ + **2** + **1** **2**”

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Example: the Original Parser

1: < expr > ::= + < expr > < expr > |
2: < digit >
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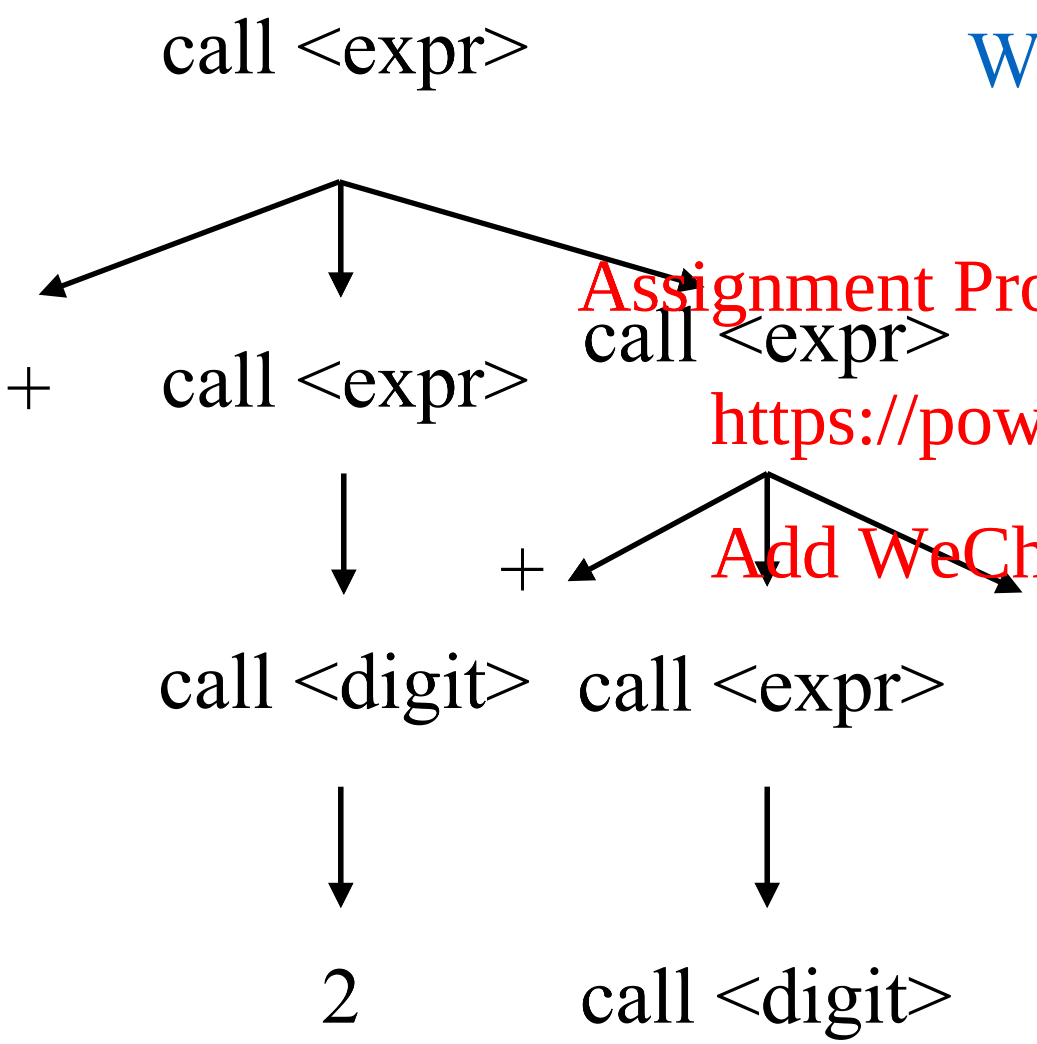

What happens when you parse expression
“ + **2** + **1 2**”

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Example: the Original Parser

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2: < digit >
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What happens when you parse expression
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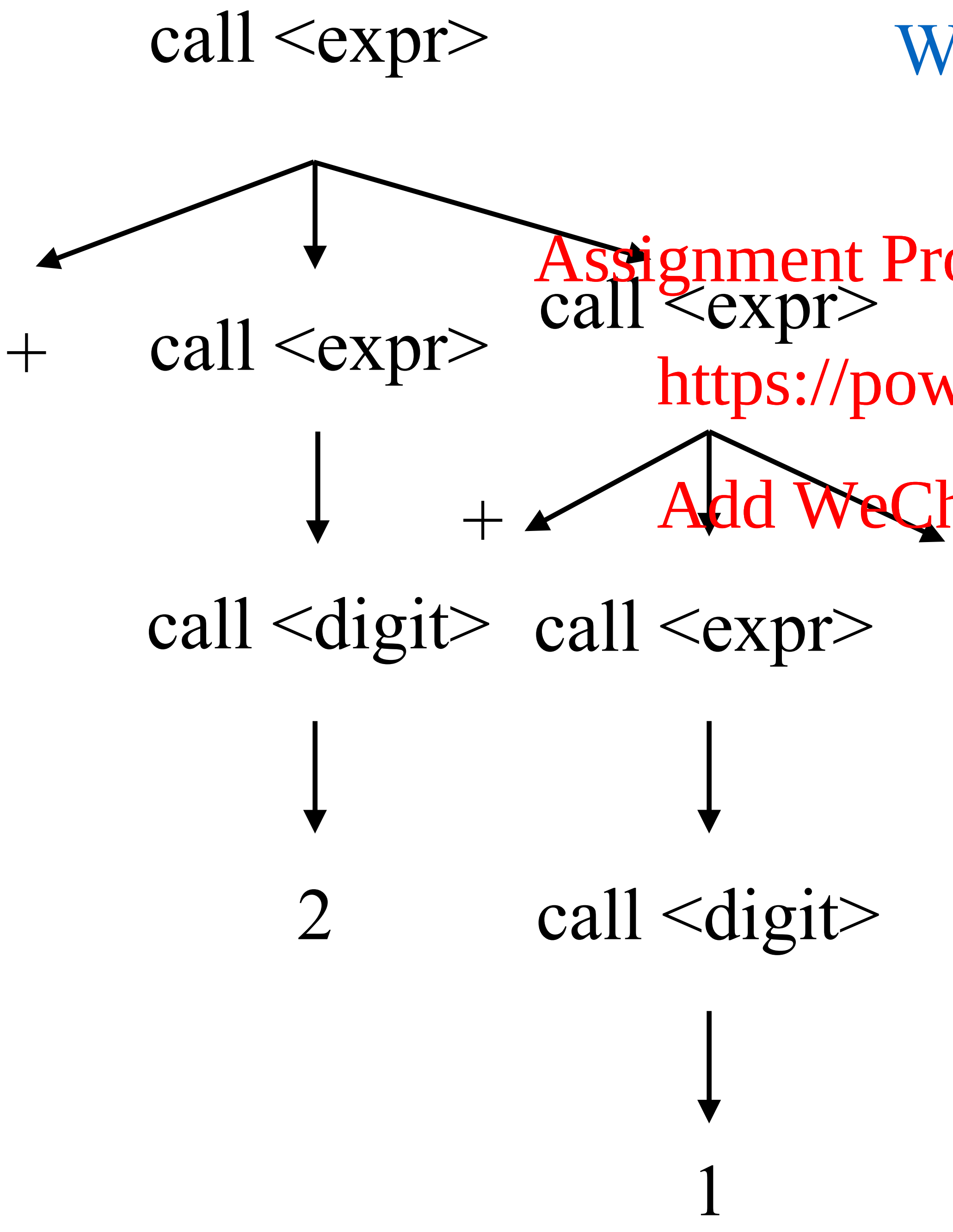

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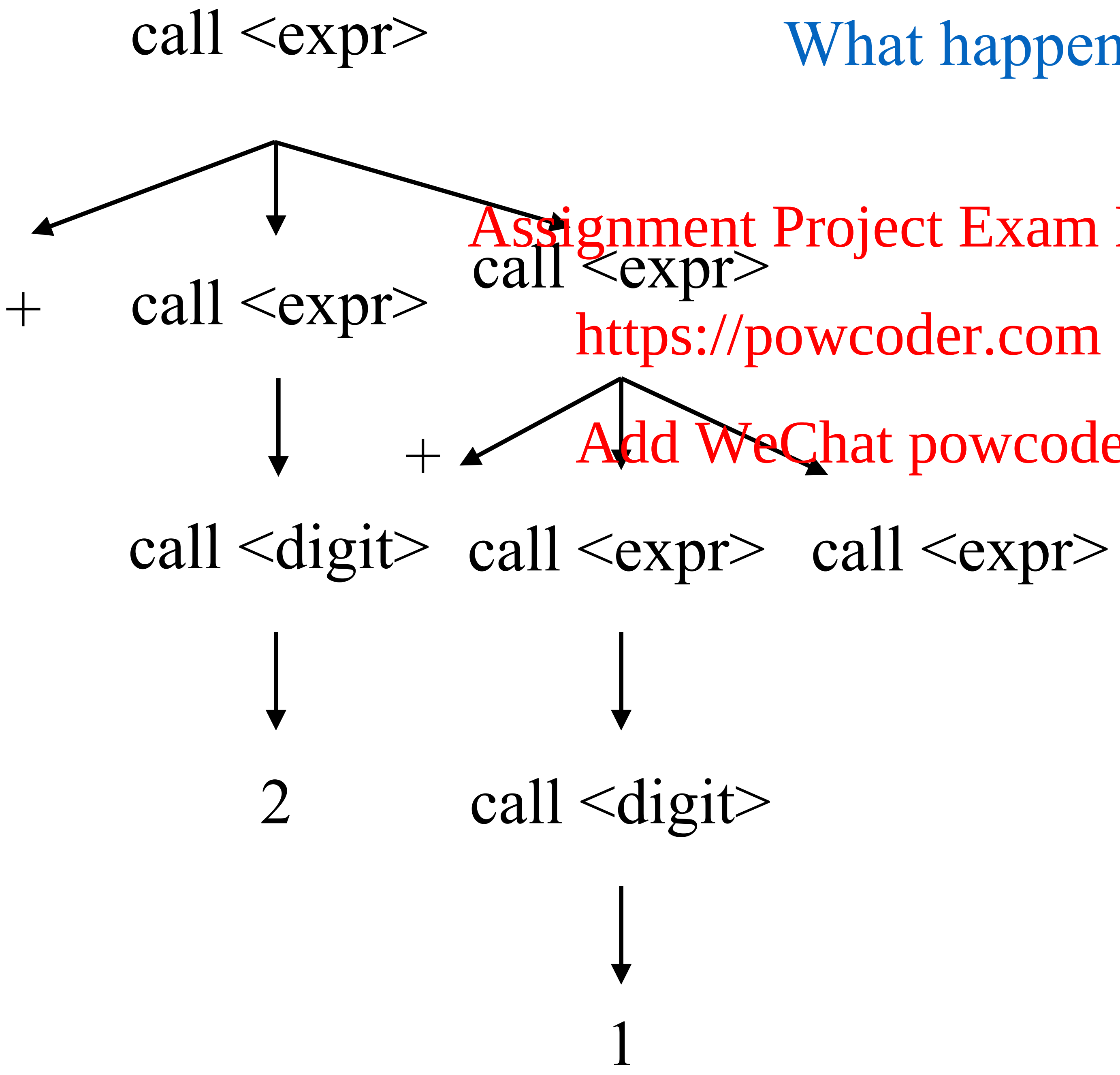
What happens when you parse expression
“ + **2** + **1 2**”


call <expr>
+
call <expr>
call <expr>
call <digit>
+
call <expr>
call <expr>
2
call <digit>
1

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Example: the Original Parser

1: < expr > ::= + < expr > < expr > |
2: < digit >
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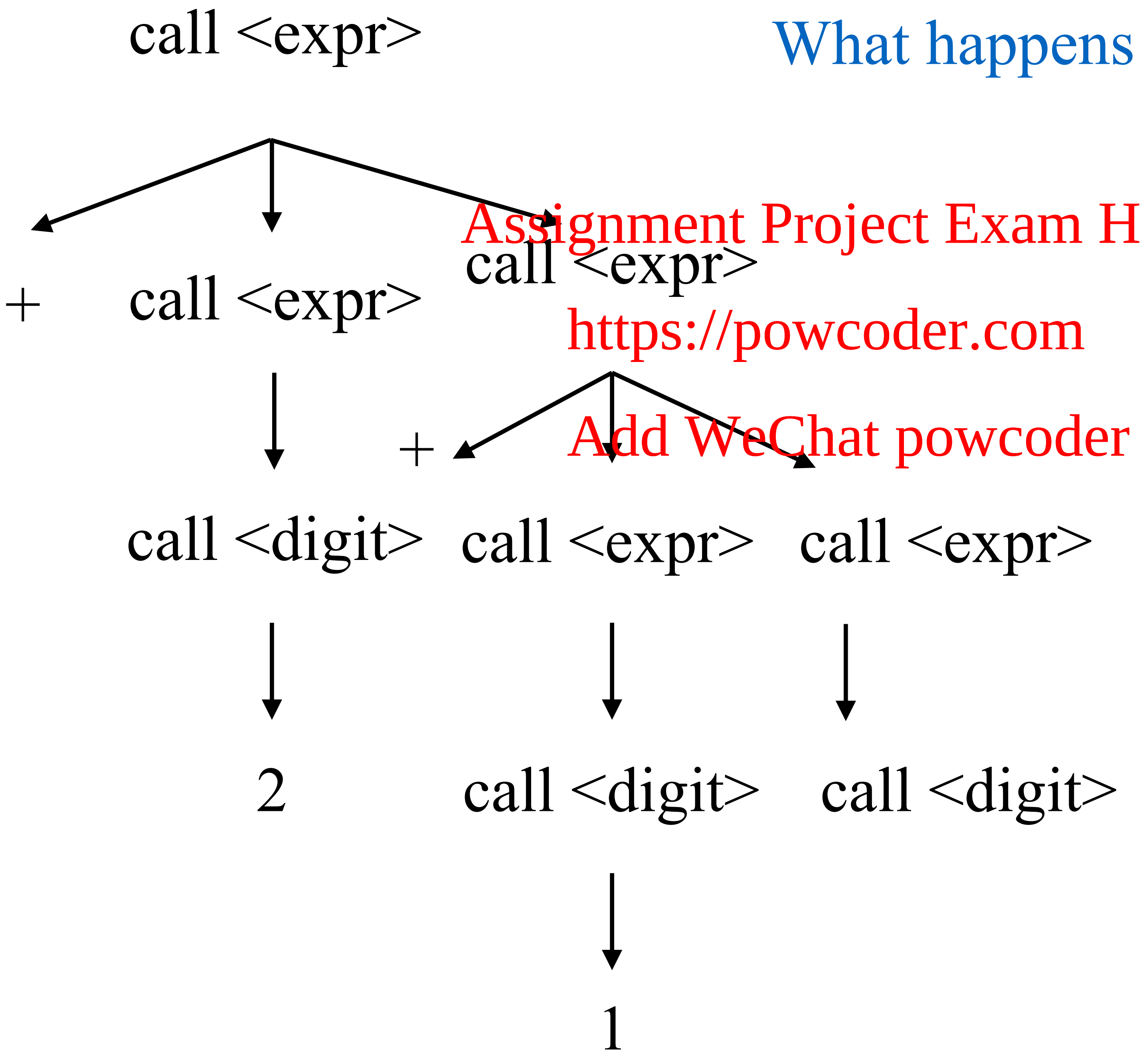
	+	0…9	other
< expr >	rule 1	rule 2	error
< digit >	error	rule 3	error

What happens when you parse expression "+ **2** + **1** **2**"



call <expr>

+ call <expr> call <expr>

call <digit> + call <expr> call <expr>

2 call <digit> call <digit>

1

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Example: the Original Parser

1: < expr > ::= + < expr > < expr > |
2:                              < digit >
3: < digit > ::= 0 | 1 | 2 | 3 | … | 9

	+	0…9	other
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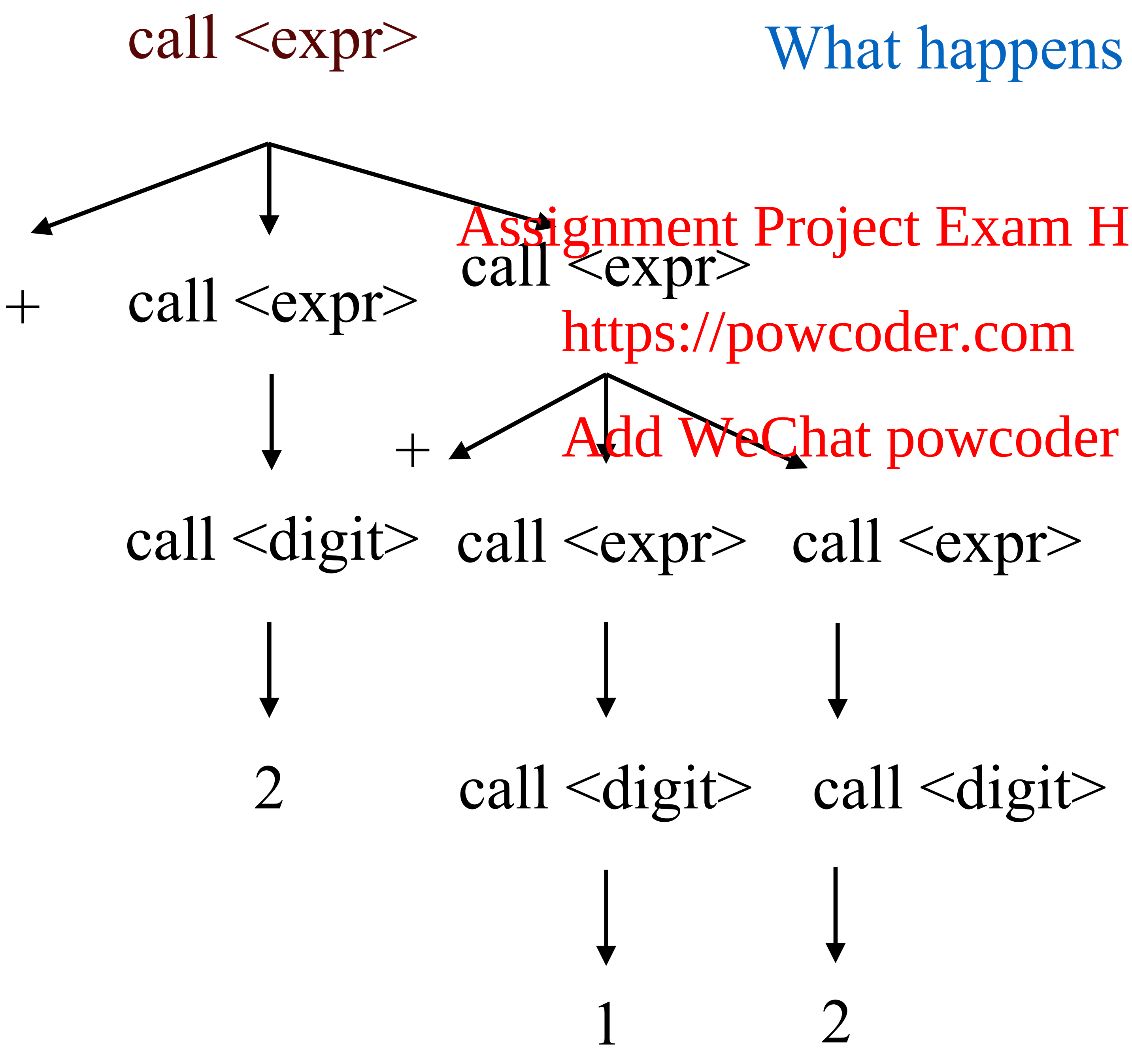
What happens when you parse expression
“ + **2** + **1 2**”



call <expr>

+ call <expr> call <expr>

call <digit> + call <expr> call <expr>

2 call <digit> call <digit>

1 2

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Example: the Original Parser

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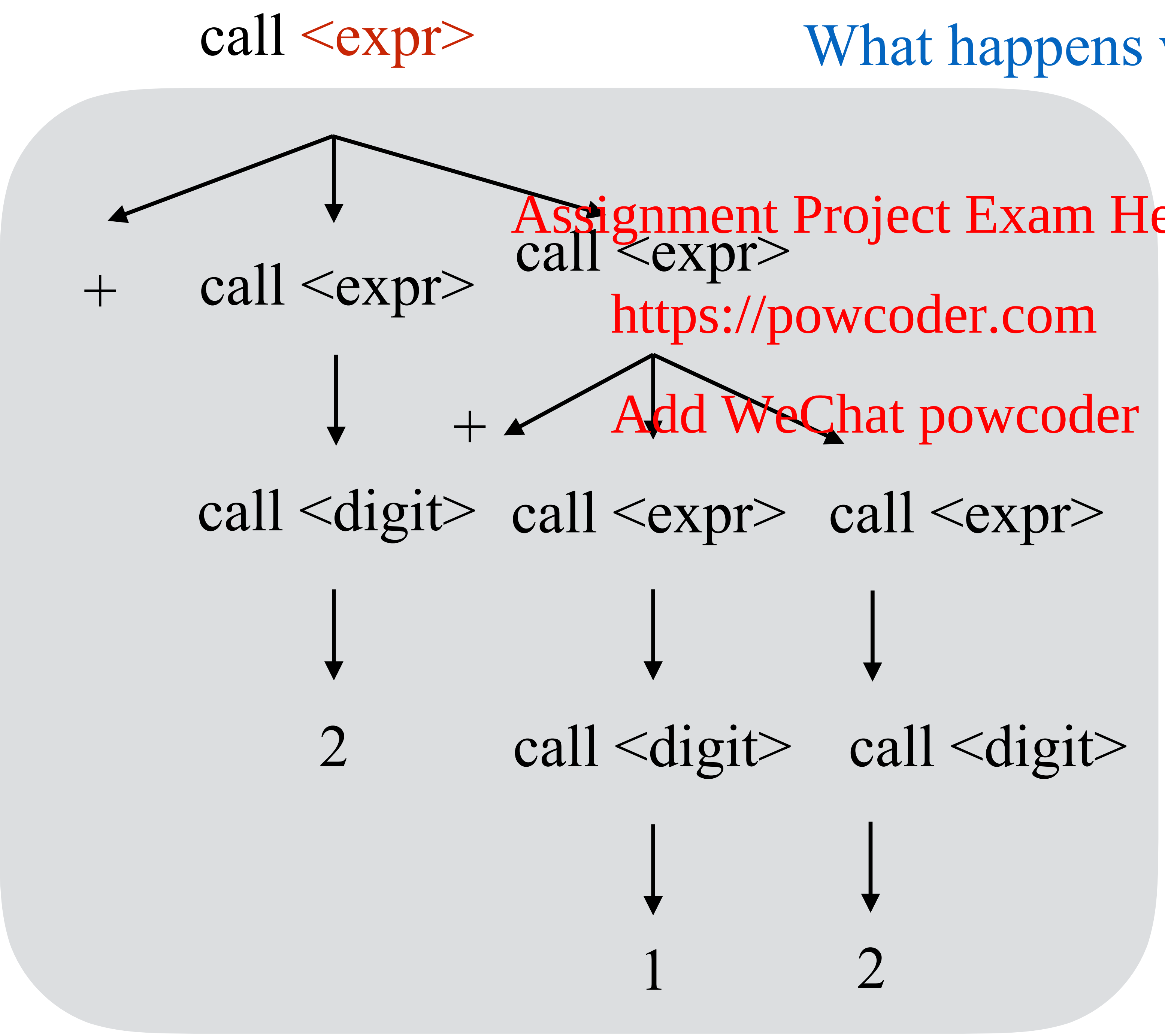

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Example: the Original Parser

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	+	0…9	other
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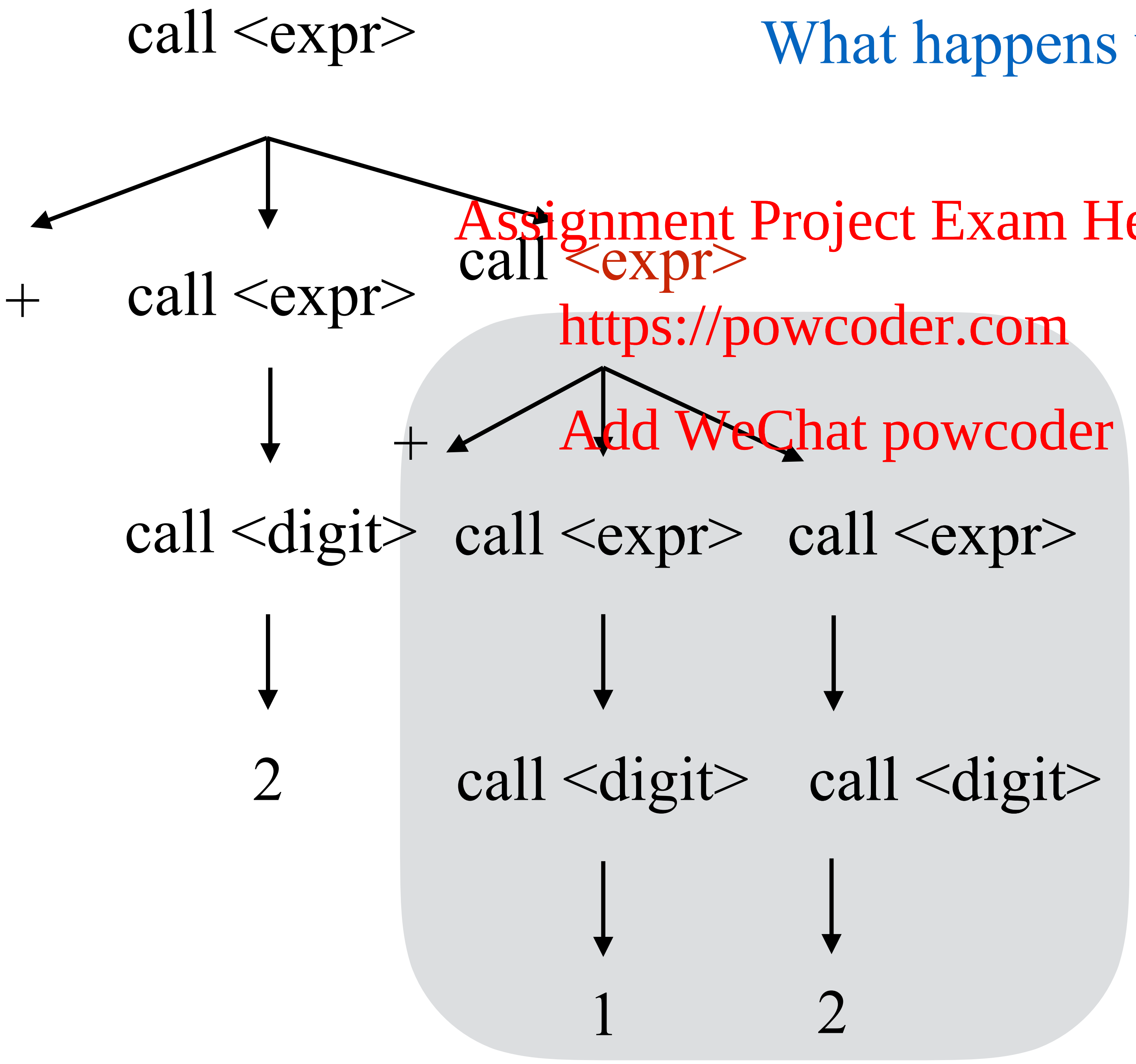
< digit >	error	rule 3	error



What happens when you parse expression
“ + **2** + **1** **2**”

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Next Lecture

Things to do:

- Start programming in C.
- Read Scott, Chapter 3.1 - 3.3; ALSU 7.1
- Read Scott, Chapter 8.1 - 8.2; ALSU 7.1 - 7.3

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