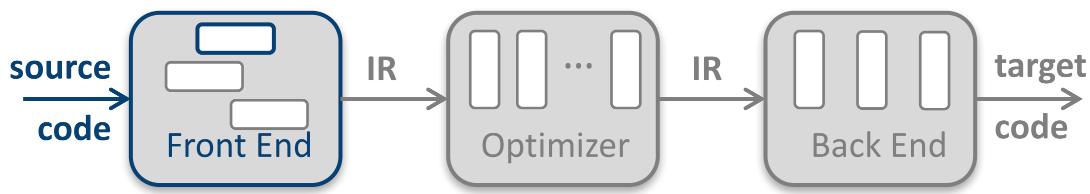
COMP 412
FALL 2017

Syntax Analysis, IV

Comp 412



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Chapter 3 in EaC2e

Review

Last Class

- Introduced **FIRST, FOLLOW,** and **FIRST$^+$** sets
- Introduced the **LL(1)** condition

  A grammar G can be parsed predictively with one symbol of lookahead if for all pairs of productions $A \rightarrow \beta$ and $A \rightarrow \gamma$ that have the same lhs A:

  $$\textbf{FIRST}^+(A \rightarrow \beta) \cap \textbf{FIRST}^+(A \rightarrow \gamma) = \varnothing$$

- Observed that predictively parsable, or **LL(1)** grammars
- Showed how to construct a recursive-descent parser for an **LL(1)** grammar

We did not cover

- An algorithm to construct **FIRST** sets
- An algorithm to construct **FOLLOW** sets

FIRST and **FOLLOW** Sets

FIRST(α)

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

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

FIRST is defined over strings of grammar symbols: $(T \cup NT \cup \textbf{EOF} \cup \varepsilon)^*$

FOLLOW(A)

For some $A \in NT$, define **FOLLOW**(A) as the set of symbols that can occur immediately after A in a valid sentential form

FOLLOW(S) = {**EOF**}, where S is the start symbol

FOLLOW is defined over the set of nonterminal symbols, **NT**

To build **FOLLOW** sets, we need **FIRST** sets …

EOF $\cong$ end of file

FIRST and **FOLLOW** Sets

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To build **FOLLOW** sets, we need **FIRST** sets …

EOF ≅ end of file

Conceptual Sketch: Computing **FIRST** Sets

for each x $\in$ $(T \cup$ **EOF** $\cup\ \varepsilon)$
    FIRST$(x) \leftarrow \{x\}$

for each A $\in$ *NT, FIRST(A)* $\leftarrow \emptyset$

while (FIRST sets are still changing) do
  for each p $\in$ *P, of the form* $A \rightarrow \beta$ *do*
    rhs $\leftarrow$ *FIRST*$(B_1) - \{\varepsilon\}$
    Some details go here to handle ε *productions*
    FIRST(A) $\leftarrow$ *FIRST(A)* $\cup$ *rhs*
    end // for loop
  end // while loop

To begin, we will ignore ε productions

- Initially, set **FIRST** for each nonterminal, terminal **EOF**, and ε
- Then, loop through the productions and set **FIRST** for the *lhs* nonterminal to **FIRST** of the leading symbol on the *rhs*
- Need to iterate because *rhs* can start with a nonterminal

Filling in the Details: Computing **FIRST** Sets

```
for each x ∈ (T ∪ EOF ∪ ε)
      FIRST(x) ← {x}

for each A ∈ NT, FIRST(A) ← Ø

while (FIRST sets are still changing) do
   for each p ∈ P, of the form A→ B1B2…Bk do
      rhs ← FIRST(B1) − {ε}
      for i ← 1 to k−1 by 1 while ε ∈ FIRST(Bi) do
         rhs ← rhs ∪ ( FIRST(Bi+1) − { ε } )
         end      // for loop
      if i = k and ε ∈ FIRST(Bk)
         then rhs ← rhs ∪ {ε}
      FIRST(A) ← FIRST(A) ∪ rhs
      end  // for loop
   end     // while loop
```

ε complicates matters

If **FIRST**(B_1) contains ε, then we need to add **FIRST**(B_2) to *rhs*, and …

If the entire *rhs* can go to **ε**, then we add **ε** to **FIRST**(*lhs*)

See also, Fig. 3.7, EaC2e, p. 104

Computing **FIRST** Sets

for each x $\in$ ($T \cup$ **EOF** $\cup\ \varepsilon$)
    FIRST(x) $\leftarrow$ {x}

for each A $\in$ *NT, FIRST(A)* $\leftarrow \emptyset$

while (FIRST sets are still changing) do
  for each p $\in$ *P, of the form* $A \rightarrow B_1 B_2 \ldots B_k$ *do*
    rhs $\leftarrow$ *FIRST*(B_1) $-$ {ε}
    for i $\leftarrow$ *1 to k–1 by 1 while* $\varepsilon \in$ *FIRST*(B_i) *do*
      rhs $\leftarrow$ *rhs* $\cup$ (*FIRST*(B_{i+1}) $-$ {ε})
      end // for loop
    if i = k and $\varepsilon \in$ *FIRST*(B_k)
      then rhs $\leftarrow$ *rhs* $\cup$ {ε}
    FIRST(A) $\leftarrow$ ***FIRST(A)*** $\cup$ ***rhs***
    end // for loop
  end // while loop

Outer loop is **monotone increasing** for **FIRST** sets

$\Rightarrow$ | T $\cup$ NT $\cup$ **EOF** $\cup\ \varepsilon$ | is bounded, so it terminates

Inner loop is bounded by the length of the productions in the grammar

See also, Fig. 3.7, EaC2e, p. 104

Example

Consider the *SheepNoise* grammar & its FIRST sets

0	*Goal*	$\rightarrow$	*SheepNoise*
1	*SheepNoise*	$\rightarrow$	*SheepNoise* <u>baa</u>
2		|	<u>baa</u>

Left-recursive SheepNoise Grammar

Clearly and intuitively, **FIRST**(x) = { <u>baa</u> }, $\forall\ x \in (T \cup NT)$

Symbol	FIRST Set
Goal	{ <u>baa</u> }
SheepNoise	{ <u>baa</u> }
<u>baa</u>	{ <u>baa</u> }

Computing **FIRST** Sets

for each $x \in (T \cup$ **EOF** $\cup\ \varepsilon)$
    $FIRST(x) \leftarrow \{x\}$
for each $A \in NT$, $FIRST(A) \leftarrow \emptyset$

while (FIRST sets are still changing) do
  for each $p \in P$*, of the form* $A \rightarrow \beta$ *do*
    $rhs \leftarrow FIRST(B_1) - \{\varepsilon\}$
    if β *is* $B_1B_2 \ldots B_k$ *then begin;*
      for $i \leftarrow 1$ *to* $k{-}1$ *by 1 while* $\varepsilon \in FIRST(B_i)$ *do*
        $rhs \leftarrow rhs \cup (FIRST(B_{i+1}) - \{\varepsilon\})$
      end   // for loop
    end   // if-then
    if $i = k$ *and* $\varepsilon \in FIRST(B_k)$
      then $rhs \leftarrow rhs \cup \{\varepsilon\}$
      $FIRST(A) \leftarrow FIRST(A) \cup rhs$
    end // for loop
  end   // while loop

See also, Fig. 3.7, EaC2e, p. 104

Initialization assigns each **FIRST** set a value

Symbol	FIRST Set
Goal	$\emptyset$
SheepNoise	$\emptyset$
<u>baa</u>	{ <u>baa</u> }

Computing **FIRST** Sets

for each $x \in (T \cup$ **EOF** $\cup\ \varepsilon)$
    $FIRST(x) \leftarrow \{x\}$

for each $A \in NT$, $FIRST(A) \leftarrow \emptyset$

while (FIRST sets are still changing) do
  for each $p \in P$, *of the form* $A \rightarrow \beta$ *do*
    $\boxed{rhs \leftarrow FIRST(B_1) - \{\varepsilon\}}$
    if β *is* $B_1B_2 \ldots B_k$ *then begin;*
      for $i \leftarrow 1$ *to* $k{-}1$ *by 1 while* $\varepsilon \in FIRST(B_i)$ *do*
        $rhs \leftarrow rhs \cup (FIRST(B_{i+1}) - \{\varepsilon\})$
      end   // for loop
    end   // if-then
    if $i = k$ *and* $\varepsilon \in FIRST(B_k)$
      then $rhs \leftarrow rhs \cup \{\varepsilon\}$
    $\boxed{FIRST(A) \leftarrow FIRST(A) \cup rhs}$
    end // for loop
  end   // while loop

See also, Fig. 3.7, EaC2e, p. 104

Production 2

(1) sets *rhs* to **FIRST**{ <u>baa</u> } &

(2) copies *rhs* into **FIRST**(*SheepNoise*)

Symbol	FIRST Set
Goal	Ø
SheepNoise	{ <u>baa</u> }
<u>baa</u>	{ <u>baa</u> }

Computing **FIRST** Sets

for each x $\in$ *(T* $\cup$ **EOF** $\cup$ ε)
    FIRST(x) $\leftarrow$ *{x}*

for each A $\in$ *NT, FIRST(A)* $\leftarrow$ Ø

while (FIRST sets are still changing) do
  for each p $\in$ *P, of the form A*$\rightarrow\beta$ *do*
    $\boxed{rhs \leftarrow FIRST(B_1) - \{\varepsilon\}}$
    if β *is* $B_1B_2 \ldots B_k$ *then begin;*
      for i $\leftarrow$ *1 to k–1 by 1 while* $\varepsilon \in FIRST(B_i)$ *do*
        $rhs \leftarrow rhs \cup (FIRST(B_{i+1}) - \{\varepsilon\})$
      end   *// for loop*
    end   *// if-then*
    if $i = k$ *and* $\varepsilon \in FIRST(B_k)$
      then $rhs \leftarrow rhs \cup \{\varepsilon\}$
      $\boxed{FIRST(A) \leftarrow FIRST(A) \cup rhs}$
    end *// for loop*
  end   *// while loop*

See also, Fig. 3.7, EaC2e, p. 104

Production 0

(1) sets *rhs* to **FIRST**(*Sheepnoise*) &

(2) copies *rhs* into **FIRST**(*Goal)*

… and one more iteration to recognize that the **FIRST** *sets have stopped changing*

Symbol	FIRST Set
Goal	{ baa }
SheepNoise	{ baa }
baa	{ baa }

An Example

Consider the simple parentheses grammar

0	*Goal*	$\rightarrow$	*List*
1	*List*	$\rightarrow$	*Pair List*
2		|	ε
3	*Pair*	$\rightarrow$	<u>LP</u> *List* <u>RP</u>

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

	FIRST
Symbol	**Initial**
Goal	Ø
List	Ø
Pair	Ø
LP	<u>LP</u>
RP	<u>RP</u>
EOF	EOF

An Example

Consider the simple parentheses grammar

0	*Goal*	$\rightarrow$	*List*
1	*List*	$\rightarrow$	*Pair List*
2		|	ε
3	*Pair*	$\rightarrow$	LP *List* RP

where LP *is* (*and* RP *is*)

- Iteration 1 adds LP to **FIRST**(Pair) and LP, ε to **FIRST**(*List*) & **FIRST**(*Goal*)
  → *If we take them in order 3, 2, 1, 0*
- Algorithm reaches fixed point[†]

Symbol	FIRST Sets: Initial	FIRST Sets: 1st	FIRST Sets: 2nd
Goal	Ø	LP, ε	LP, ε
List	Ø	LP, ε	LP, ε
Pair	Ø	LP	LP
LP	LP	LP	LP
RP	RP	RP	RP
EOF	EOF	EOF	EOF

[†] In the adversarial order (0, 1, 2, 3), propagating {LP, ε} through *Pair, List,* and *Goal* would require one iteration for each set.

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, $\underline{x} \in$ **FIRST**(α) *iff* $\alpha \Rightarrow^* \underline{x}\,\gamma$, for some γ

FIRST is defined over strings of grammar symbols: $(T \cup NT \cup$ **EOF** $\cup\ \varepsilon)^*$

FOLLOW(A)

For some $A \in NT$, define **FOLLOW**(A) as the set of symbols that can occur immediately after A in a valid sentential form

FOLLOW(S) = {**EOF**}, where S is the start symbol

FOLLOW is defined over the set of nonterminal symbols, **NT**

To build **FOLLOW** sets, we need **FIRST** sets …

EOF $\cong$ end of file

Computing **FOLLOW** Sets

for each $A \in NT$
    $FOLLOW(A) \leftarrow \emptyset$

$FOLLOW(S) \leftarrow$ { **EOF** }

while ($FOLLOW$ *sets are still changing*)

  for each $p \in P$, *of the form* $A \rightarrow B_1 B_2 \ldots B_k$

    $TRAILER \leftarrow FOLLOW(A)$

    for $i \leftarrow k$ *down to* 1
      if $B_i \in NT$ *then*   *// domain check*
        $FOLLOW(B_i) \leftarrow FOLLOW(B_i) \cup TRAILER$
        if $\varepsilon \in FIRST(B_i)$ *// add right context*
          then $TRAILER \leftarrow TRAILER \cup (FIRST(B_i) - \{\varepsilon\})$
          else $TRAILER \leftarrow FIRST(B_i)$ *// no* ε *=> truncate the right context*
      else $TRAILER \leftarrow \{B_i\}$ *//* $B_i \in T$ *=> only 1 symbol*

Don't add ε

Figure 3.8, page 106, EaC2e

Computing **FOLLOW** Sets

This algorithm has a completely different feel than computing FIRST sets

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

- It works its way backward through the production: $B_k, B_{k-1}, \ldots B_1$
- It builds the **FOLLOW** sets for the *rhs* symbols, $B_1, B_2, \ldots B_k$, not A
- In the absence of ε, **FOLLOW**(B_i) is just **FIRST**(B_{i+1})
  - *As always, ε makes the algorithm more complex*

To handle ε, the algorithm keeps track of the *first word* in the trailing right context as it works its way back through the *rhs*: $B_k, B_{k-1}, \ldots B_1$

- It uses **FOLLOW**(A) to initialize the *Trailer* for B_k
  - That use is the only mention of **FOLLOW**(A) in the algorithm
- *Trailer* approximates the **FIRST$^+$** set for the trailing left context

An Example

Consider, again, the simple parentheses grammar

0	*Goal*	$\rightarrow$	*List*
1	*List*	$\rightarrow$	*Pair List*
2		|	ε
3	*Pair*	$\rightarrow$	*LP List RP*

	FOLLOW Sets	
Symbol	Initial	1st
Goal	**EOF**	**EOF**
List	Ø	**EOF**, RP
Pair	Ø	**EOF**, LP

Initial Values:

- *Goal, List,* and *Pair* are set to Ø
- Goal is then set to { **EOF** }

An Example

Consider, again, the simple parentheses grammar

0	*Goal*	$\rightarrow$	*List*
1	*List*	$\rightarrow$	*Pair List*
2		|	ε
3	*Pair*	$\rightarrow$	*LP List RP*

Symbol	FOLLOW Sets: Initial	FOLLOW Sets: 1st
Goal	**EOF**	**EOF**
List	Ø	**EOF**, RP
Pair	Ø	**EOF**, LP

Symbol	FIRST
Goal	<u>LP</u>, ε
List	<u>LP</u>, ε
Pair	<u>LP</u>
LP	<u>LP</u>
RP	<u>RP</u>
EOF	**EOF**

Iteration 1:

- Production 0 adds **EOF** to FOLLOW(*List*)
- Production 1 adds LP to FOLLOW(*Pair*)
  - → from **FIRST**(*List*)
- Production 2 does nothing
- Production 3 adds RP to FOLLOW(*List*)
  - → from **FIRST**(*RP*)

An Example

Consider, again, the simple parentheses grammar

0	*Goal*	$\rightarrow$	*List*
1	*List*	$\rightarrow$	*Pair List*
2		|	ε
3	*Pair*	$\rightarrow$	*LP List RP*

Symbol	FOLLOW Sets Initial	1st	2nd
Goal	EOF	EOF	EOF
List	Ø	EOF, RP	EOF, RP
Pair	Ø	EOF, LP	EOF, LP, RP

Iteration 2:

- Production 0 adds nothing new
- Production 1 adds RP to FOLLOW(*Pair*)
  → from FOLLOW(*List*), $\varepsilon \in$ FIRST(*List*)
- Production 2 does nothing
- Production 3 adds nothing new

Iteration 3 produces the same result $\Rightarrow$ reached a fixed point

Classic Expression Grammar

0	*Goal*	$\rightarrow$	*Expr*
1	*Expr*	$\rightarrow$	*Term Expr'*
2	*Expr'*	$\rightarrow$	+ *Term Expr'*
3		|	- *Term Expr'*
4		|	ε
5	*Term*	$\rightarrow$	*Factor Term'*
6	*Term'*	$\rightarrow$	* *Factor Term'*
7		|	/ *Factor Term'*
8		|	ε
9	*Factor*	$\rightarrow$	(*Expr*)
10		|	number
11		|	identifier

FIRST$^+$(A$\rightarrow\beta$) is identical to FIRST(β) except for productions 4 and 8

FIRST$^+$(Expr'$\rightarrow$ ε) is {ε,), eof}

FIRST$^+$(Term'$\rightarrow$ ε) is {ε,+,-,), eof}

Symbol	FIRST	FOLLOW
num	num	Ø
id	id	Ø
+	+	Ø
-	-	Ø
*	*	Ø
/	/	Ø
(	(	Ø
)	)	Ø
eof	eof	Ø
ε	ε	Ø
Goal	(,id,num	eof
Expr	(,id,num	), eof
Expr'	+, -, ε	), eof
Term	(,id,num	+, -,), eof
Term'	*, /, ε	+, -,), eof
Factor	(,id,num	+, -,* ,/,), eof

*

Classic Expression Grammar

0	*Goal*	$\rightarrow$	*Expr*
1	*Expr*	$\rightarrow$	*Term Expr'*
2	*Expr'*	$\rightarrow$	+ *Term Expr'*
3		|	- *Term Expr'*
4		|	ε
5	*Term*	$\rightarrow$	*Factor Term'*
6	*Term'*	$\rightarrow$	* *Factor Term'*
7		|	/ *Factor Term'*
8		|	ε
9	*Factor*	$\rightarrow$	<u>(</u> *Expr* <u>)</u>
10		|	<u>number</u>
11		|	<u>identifier</u>

Prod'n	**FIRST$^+$**
0	<u>(</u>,<u>id</u>,<u>num</u>
1	<u>(</u>,<u>id</u>,<u>num</u>
2	+
3	-
4	**ε**,<u>)</u>, eof
5	<u>(</u>,<u>id</u>,<u>num</u>
6	*
7	/
8	**ε**,+,-, <u>)</u>, eof
9	<u>(</u>
10	<u>number</u>
11	<u>identifier</u>

Recursive Descent Parsing (Procedural)

A couple of routines from the expression parser

```
Goal( )
    token ← next_token( );
    if (Expr( ) = true & token = EOF)
        then next compilation step;
        else
            report syntax error;
            return false;

Expr( )
  if (Term( ) = false)
    then return false;
    else return Eprime( );
```

```
Factor( )
  if (token = number) then
     token ← next_token( );
     return true;
  else if (token = identifier) then
     token ← next_token( );
     return true;
  else if (token = lparen)
     token ← next_token( );
     if (Expr( ) = true & token = rparen) then
        token ← next_token( );
        return true;
  // fall out of if statement
  report syntax error;
     return false;
```

looking for number, identifier, or (, found token instead, or failed to find *Expr* or) after (

EPrime, Term, & TPrime follow the same basic lines (Figure 3.10, EaC2e)

Implementing a Recursive Descent Parser

A nest of if-then else statements may be slow

- A good case statement would be an improvement[†] ***Python?***
  - See EaC2e, § 7.8.3
  - Encode with computation rather than repeated branches
- Order the cases by expected frequency, to drop average cost

What about encoding the decisions in a table?

- Replace if then else or case statement with an address computation
- Branches are slow and disruptive
- Interpret the table with a skeleton parser, as we did in scanning

[†] a good case statement can be hard to find

Building Table-Driven Top-down Parsers

Strategy

- Encode knowledge in a table
- Use a standard “skeleton” parser to interpret the table

Example

- The non-terminal *Factor* has 3 expansions
  - (*Expr*) or Identifier or Number
- Table might look like:

0	*Goal*	→	*Expr*
1	*Expr*	→	*Term Expr’*
2	*Expr’*	→	+ *Term Expr’*
3		|	- *Term Expr’*
4		|	ε
5	*Term*	→	*Factor Term’*
6	*Term’*	→	* *Factor Term’*
7		|	/ *Factor Term’*
8		|	ε
9	*Factor*	→	(*Expr*)
10		|	number
11		|	identifier

Terminal Symbols

Non-terminal Symbols

	EOF	+	-	*	/	(	)	id.	num.
Factor	—	—	—	—	—	9	—	11	10

Cannot expand *Factor* into an operator ⇒ *error*

Expand *Factor* by rule 10 with input “number”

Building Top-down Parsers

Building the complete table

- Need a row for every *NT* & a column for every *T*

LL(1) Table for the Expression Grammar

	EOF	+	-	*	/	(	)	id.	num.
Goal	—	—	—	—	—	0	—	0	0
Expr	—	—	—	—	—	1	—	1	1
Expr'	4	2	3	—	—	—	4	—	—
Term	—	—	—	—	—	5	—	5	5
Term'	8	8	8	6	7	—	8	—	—
Factor	—	—	—	—	—	9	—	11	10

Row we built earlier

Figure 3.11(b), page 112, EaC2e

Building Top-down Parsers

Building the complete table

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

LL(1) Skeleton Parser

```
word ← NextWord()                // Initial conditions, including
push EOF onto Stack              // a stack to track local goals
push the start symbol, S, onto Stack
TOS ← top of Stack

loop forever
  if TOS = EOF and word = EOF then
     break & report success    // exit on success

  else if TOS is a terminal then
     if TOS matches word then
        pop Stack                // recognized TOS
        word ← NextWord()
     else report error looking for TOS  // error exit

  else                           // TOS is a non-terminal
     if TABLE[TOS,word] is A→B1B2…Bk then
        pop Stack                // get rid of A
        push Bk, Bk-1, …, B1     // in that order
     else break & report error expanding TOS

  TOS ← top of Stack
```

Building Top-down Parsers

Building the complete table

- Need a row for every *NT* & a column for every *T*
- Need a table-driven interpreter for the table
- Need an algorithm to build the table

Filling in TABLE[X,y], X $\in$ *NT*, y $\in$ *T*

1. entry is the rule $X \rightarrow \beta$, if y $\in$ FIRST$^+$($X \rightarrow \beta$)
2. entry is *error* if rule 1 does not define

If any entry has more than one rule, G is not **LL**(1)

Incrementally tests the **LL(1)** criterion on each ***NT***.

An efficient way to determine if a grammar is **LL(1)**

This algorithm is the LL(1) table construction algorithm

In Lab 2, you would have built a recursive descent parser for a modified form of **BNF** and build **LL(1)** tables for the grammars that are **LL(1)**. (A good weekend project)

Recap of Top-down Parsing

- Top-down parsers build syntax tree from root to leaves
- Left-recursion causes non-termination in top-down parsers
  - Transformation to eliminate left recursion
  - Transformation to eliminate common prefixes in right recursion
- **FIRST**, **FIRST**$^+$, & **FOLLOW** sets + **LL(1)** condition
  - **LL(1)** uses left-to-right scan of the input, leftmost derivation of the sentence, and 1 word lookahead
  - **LL(1)** condition means grammar works for predictive parsing
- Given an **LL(1)** grammar, we can
  - Build a recursive descent parser
  - Build a table-driven **LL(1)** parser
- **LL(1)** parser doesn't build the parse tree
  - Keeps lower fringe of partially complete tree on the stack

STOP