Parsing IIIa

(Top-down parsing: recursive descent & *LL(1)*)

COMP 412
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Roadmap (Where are we?)

We set out to study parsing

- Specifying syntax
  - Context-free grammars ✓
  - Ambiguity ✓

- Top-down parsers
  - Algorithm & its problem with left recursion ✓
  - Left-recursion removal ✓

- Predictive top-down parsing ✓
  - The LL(1) condition ✓
  - Simple recursive descent parsers ✓
  - First and Follow sets today
  - Table-driven LL(1) parsers today

Recursive Descent (Summary)

1. Build FIRST (and FOLLOW) sets
2. Massage grammar to have *LL(1)* condition
   a. Remove left recursion
   b. Left factor it
3. Define a procedure for each non-terminal
   a. Implement a case for each right-hand side
   b. Call procedures as needed for non-terminals
4. Add extra code, as needed
   a. Perform context-sensitive checking
   b. Build an IR to record the code

Can we automate this process?

FIRST and FOLLOW Sets

FIRST(α)

For some $\alpha \in (T \cup NT)^*$, 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

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

To build FIRST sets, we need FOLLOW sets …

Computing FIRST Sets

for each $x \in T$, *FIRST(x)* $\leftarrow$ { x }
for each $A \in NT$, *FIRST(A)* $\leftarrow \varnothing$

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

clumsy test on exit condition of loop

For *SheepNoise:*

FIRST(*Goal*) = { baa }
FIRST(*SN*) = { baa }
FIRST(baa) = { baa }

Computing FIRST Sets

```
for each x ∈ T, FIRST(x) ← { x }
for each A ∈ NT, FIRST(A) ← Ø

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

- Outer loop is monotone increasing for FIRST sets
  - → $|\ T \cup NT \cup \varepsilon\ |$ is bounded, so it terminates
- Inner loop is bounded by length of productions in grammar

Computing FOLLOW Sets

```
FOLLOW(S) ← {EOF }
for each A ∈ NT, FOLLOW(A) ← Ø

while (FOLLOW sets are still changing)
    for each p ∈ P, of the form A→B1B2 … Bk
        TRAILER ← FOLLOW(A)
        for i ← k down to 1
            if Bi ∈ NT then                         // domain check
                FOLLOW(Bi) ← FOLLOW(Bi) ∪ TRAILER
                if ε ∈ FIRST(Bi ) then             // add right context
                    TRAILER ← TRAILER ∪ ( FIRST(Bi) – { ε } )
                else TRAILER ← FIRST(Bi)           // no ε => no right context
            else TRAILER ← {Bi }                   // Bi ∈ T => only 1 symbol
```

For *SheepNoise:*

FOLLOW(*Goal*) = { EOF }

FOLLOW(*SN*) = { baa, EOF }

Building Top-down Parsers

Given an *LL(1)* grammar, and its FIRST & FOLLOW sets …

- Emit a routine for each non-terminal
  - Nest of if-then-else statements to check alternate rhs's
  - Each returns true on success and throws an error on false
  - Simple, working *(, perhaps ugly,)* code
- This automatically constructs a recursive-descent parser

I don't know of a system that does this …

Improving matters

- Nest of if-then-else statements may be slow
  - Good case statement implementation would be better
- What about a table to encode the options?
  - Interpret the table with a skeleton, as we did in scanning

Building Top-down Parsers

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

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:

Terminal Symbols

Non-terminal Symbols	+	-	*	/	Id.	Num.	(	)	EOF
Factor	—	—	—	—	10	11	12	—	—

Error on `+'

Reduce by rule 10 on `id'

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

LL(1) Skeleton Parser

```
token ← next_token()                 // 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 token = EOF then
     break & report success  ◄──────── exit on success
  else if TOS is a terminal then
     if TOS matches token then
        pop Stack                    // recognized TOS
        token ← next_token()
     else report error looking for TOS
  else                               // TOS is a non-terminal
     if TABLE[TOS,token] 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  ◄──── exit on failure
  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)*

This is the *LL(1)* table construction algorithm

LL(1) Expression Parser

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

FIRST(*Goal*) = FIRST(*Expr*) =
FIRST(*Term*) = FIRST(*Factor*) =
{ id, number, (}

FIRST(*Expr′*) = { +, -, ε }

FIRST(*Term′*) = { *, /, ε }

FOLLOW(*Goal*) = { EOF }

FOLLOW(*Expr*) = {), EOF }

FOLLOW(*Expr′*) = {), EOF }

FOLLOW(*Term*) = { +, -,), EOF }

FOLLOW(*Term′*) = { +, -,), EOF }

FOLLOW(*Factor*) =
{ +, -, *, /,), EOF }

LL(1) Expression Parsing Table

	+	-	*	/	Id	Num	(	)	EOF
Goal	—	—	—	—	1	1	1	—	—
Expr	—	—	—	—	2	2	2	—	—
Expr'	3	4	—	—	—	—	—	5	5
Term	—	—	—	—	6	6	6	—	—
Term'	9	9	7	8	—	—	—	9	9
Factor	—	—	—	—	10	11	12	—	—

Recursive Descent in OO Languages

- Shortcomings of Recursive Descent
  - Too procedural
  - No convenient way to build parse tree
- Solution
  - Associate a class with each non-terminal symbol
    - Allocated object contains pointer to the parse tree

```
Class NonTerminal {
public:
        NonTerminal(Scanner & scnr) { s = &scnr; tree = NULL; }
        virtual ~NonTerminal() { }
        virtual bool isPresent() = 0;
        TreeNode * abSynTree() { return tree; }
protected:
        Scanner * s;
        TreeNode * tree;
}
```

Non-terminal Classes

```
Class Expr : public NonTerminal {
public:
        Expr(Scanner & scnr) : NonTerminal(scnr) { }
        virtual bool isPresent();
}

Class EPrime : public NonTerminal {
public:
        EPrime(Scanner & scnr, TreeNode * p) :
                NonTerminal(scnr) { exprSofar = p; }
        virtual bool isPresent();
protected:
        TreeNode * exprSofar;
}

…  // definitions for Term and TPrime

Class Factor : public NonTerminal {
public:
        Factor(Scanner & scnr) : NonTerminal(scnr) { };
        virtual bool isPresent();
}
```

Implementation of isPresent

```
bool Expr::isPresent() {  // Expr -> Term Expr'

        Term * operand1 = new Term(*s);   // instantiate Term & check for its presence
        if (!operand1->isPresent()) return FALSE;

        Eprime * operand2 = new EPrime(*s, NULL);  // instantiate Eprime & check

        if (!operand2->isPresent()) return TRUE;
        else return FALSE;

}
```

Implementation of isPresent

```
bool EPrime::isPresent() {   // Expr' -> + Term Expr' | - Term Expr' | ε

    token_type op = s->nextToken();
    if (op == PLUS || op == MINUS) {      // check for presence of + or =
        s->advance();

        Term * operand2 = new Term(*s);   // instantiate Term & check it
        if (!operand2->isPresent()) throw SyntaxError(*s);

        Eprime * operand3 = new EPrime(*s, NULL);  // instantiate & check EPrime

        if (operand3->isPresent()) return TRUE;
        else return FALSE

    }
    else return TRUE; // corresponds to EPRIME → ε

}
```

Abstract Syntax Tree Construction

```
bool Expr::isPresent() { // with code to build a parse tree

        Term * operand1 = new Term(*s);
        if (!operand1->isPresent()) return FALSE;
        tree = operand1->abSynTree();

        EPrime * operand2 = new EPrime(*s, tree);
        if (operand2->isPresent()) {
                tree  = operand2->absSynTree();
                return TRUE;
        }
        else return FALSE

        // upon return, tree is either the tree for the Term
        //              or the tree for Term followed by EPrime
}
```

Abstract Syntax Tree Construction

```
bool EPrime::isPresent() { // with code to build a parse tree
    token_type op = s->nextToken();
    if (op == PLUS || op == MINUS) {
        s->advance();

        Term * operand2 = new Term(*s);
        if (!operand2->isPresent()) throw SyntaxError(*s);

        TreeNode * t2 = operand2->absSynTree();
        tree = new TreeNode(op, exprSofar, t2);

        Eprime * operand3 = new Eprime(*s, tree);
        if (operand3->isPresent()) {
            tree = operand3->absSynTree();
            return TRUE;
        }
        else return FALSE;
    }
    else return TRUE; // corresponds to EPRIME → ε
}
```

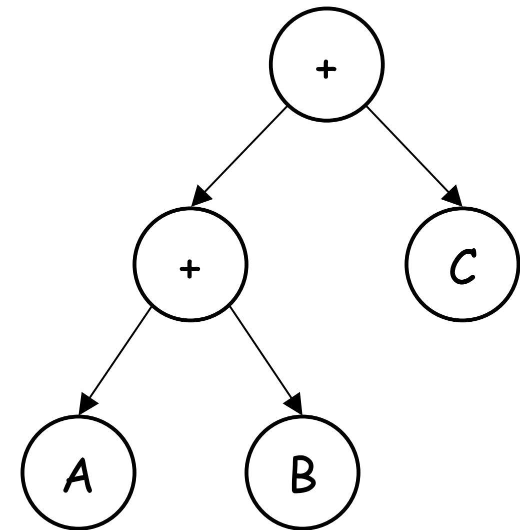
Factor

```
bool Factor::isPresent() { // with code to build a parse tree
    token_type op = s->nextToken();

    if (op == IDENTIFIER | op == NUMBER) {
        tree = new TreeNode(op, s->tokenValue());
        s->advance();
        return TRUE;
    }
    else if (op == LPAREN) {
        s->advance();
        Expr * operand = new Expr(*s);
        if (!operand->isPresent()) throw SyntaxError(*s);
        if (s->nextToken() != RPAREN) throw SyntaxError(*s);
        s->advance();
        tree = operand->absSynTree();
        return TRUE;
    }
    else return FALSE;
}
```

OO Recursive Descent Example: A+B+C

- Instantiate Expr
  - Instantiate Term, Factor
    - Factor returns True, tree = A
    - Term returns True, tree = A
  - Instantiate Eprime (exprsofar = A)
    - Match +, Instantiate Term
    - Term returns True, tree = B
    - Eprime tree = A + B
  - Instantiate Eprime (exprsofar = {A + B})
    - Match +, Instatiate Term
    - Term returns tree = C
    - Eprime tree = {A+B}+C
  - Instantiate Eprime (exprsofar ={{A + B} + C})
    - Return true with no new tree



Extra Slides Start Here

Computing FIRST Set for a String

if β *is* ε *then*

    FIRST(β) ← { ε }

else

    let β *be* $B_1B_2 \ldots B_k$

    FIRST(β) ← *FIRST*(B_1) – { ε }

    for i ← *1 to k–1 by 1 while* $\varepsilon \in$ *FIR*[illegible]

        FIRST(β) ← *FIRST*(β) ∪ (*F*[illegible] ε })

    if i = k and $\varepsilon \in$ *FIRST*(*B*[illegible]

        then FIRST(β) ← [illegible] ε }

Since EaC, and the slides, use the augmented FIRST set, FIRST+, I elided this slide and moved it to the back of the set…

FIRST is defined on symbols, not strings

- LL(1) construction needs to apply it to an entire RHS
- Either extend FIRST to strings or introduce FIRST+ set