CMPT 379
Compilers

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Parsing - Roadmap

- Parser:
  - decision procedure: builds a parse tree
- Top-down vs. bottom-up
- LL(1) – Deterministic Parsing
  - recursive-descent
  - table-driven
- LR(k) – Deterministic Parsing
  - LR(0), SLR(1), LR(1), LALR(1)
- Parsing arbitrary CFGs – Polynomial time parsing

Top-Down vs. Bottom Up

Grammar: $S \rightarrow A\ B$
$A \rightarrow c \mid \varepsilon$
$B \rightarrow cbB \mid ca$

Input String: ccbca

Top-Down/leftmost		Bottom-Up/rightmost	
$S \Rightarrow AB$	$S \rightarrow AB$	$ccbca \Leftarrow Acbca$	$A \rightarrow c$
$\Rightarrow cB$	$A \rightarrow c$	$\Leftarrow AcbB$	$B \rightarrow ca$
$\Rightarrow ccbB$	$B \rightarrow cbB$	$\Leftarrow AB$	$B \rightarrow cbB$
$\Rightarrow ccbca$	$B \rightarrow ca$	$\Leftarrow S$	$S \rightarrow AB$

Top-Down: Backtracking

$S \rightarrow A\ B$

$A \rightarrow c \mid \varepsilon$

$B \rightarrow cbB \mid ca$

True/False

$S \Rightarrow^* cbca$?

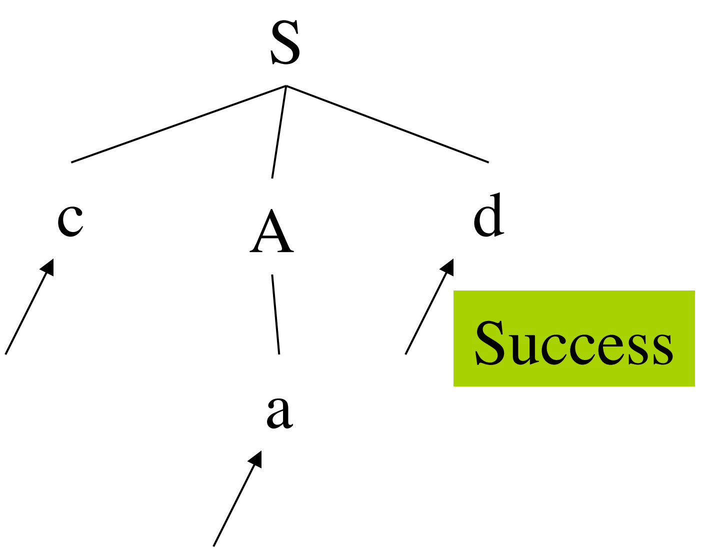
S	cbca	try S→AB
AB	cbca	try A→c
cB	cbca	match c
B	bca	dead-end, try A→ε
εB	cbca	try B→cbB
cbB	cbca	match c
bB	bca	match b
B	ca	try B→cbB
cbB	ca	match c
bB	a	dead-end, try B→ca
ca	ca	match c
a	a	match a, Done!

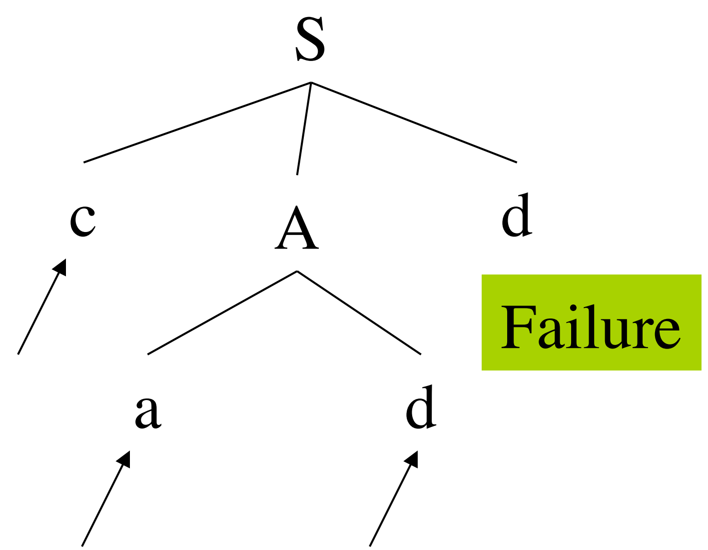
Backtracking

$S \rightarrow cAd \mid c$
$A \rightarrow a \mid ad$

Input: cad

$S \rightarrow cAd \mid c$
$A \rightarrow ad \mid a$



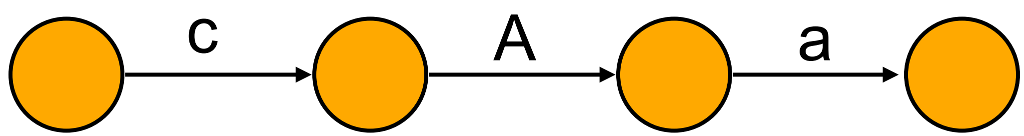


For some grammars, rule ordering is crucial for backtracking parsers, e.g $S \rightarrow aSa$, $S \rightarrow aa$

Transition Diagram

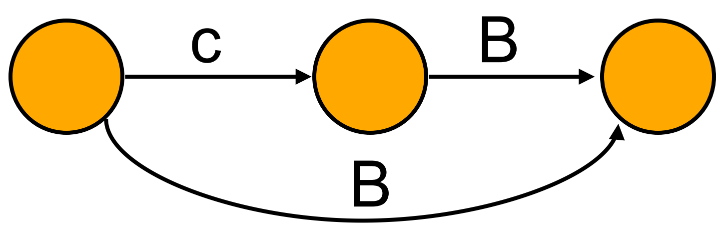
$S \rightarrow cAa$

S:



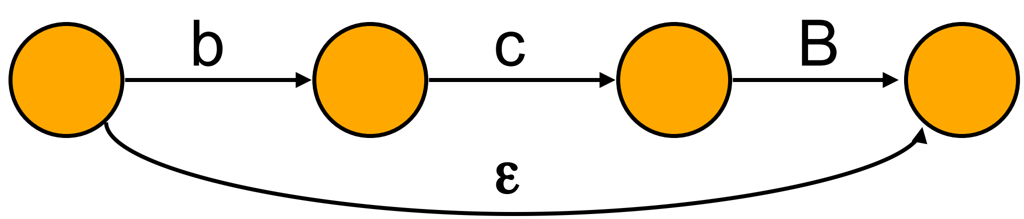
$A \rightarrow cB \mid B$

A:



$B \rightarrow bcB \mid \varepsilon$

B:



Predictive Top-Down Parser

- Knows which production to choose based on single lookahead symbol
- Need LL(1) grammars
  - First L: reads input Left to right
  - Second L: produce Leftmost derivation
  - 1 : one symbol of lookahead
- Can't have left-recursion
- Must be left-factored (no left-factors)
- Not all grammars can be made LL(1)

Leftmost derivation for
id + id * id

$E \rightarrow E + E$
$E \rightarrow E * E$
$E \rightarrow (E)$
$E \rightarrow - E$
$E \rightarrow \mathbf{id}$

$E \Rightarrow E + E$
$\Rightarrow \mathbf{id} + E$
$\Rightarrow \mathbf{id} + E * E$
$\Rightarrow \mathbf{id} + \mathbf{id} * E$
$\Rightarrow \mathbf{id} + \mathbf{id} * \mathbf{id}$

$E \Rightarrow^{*}_{lm} \mathrm{id} + E \backslash * \ E$

Predictive Parsing Table

Productions	
1	T → F T'
2	T' → ε
3	T' → * F T'
4	F → id
5	F → (T)

	*	(	)	id	$
T		T → F T'		T → F T'	
T'	T' → * F T'		T' → ε		T' → ε
F		F → (T)		F → id	

Trace “(id)*id”

	*	(	)	id	$
T		**T → FT’**		**T → FT’**	
T’	**T’ → *FT’**		**T’ → ε**		**T’ → ε**
F		**F → (T)**		**F → id**	

Stack	Input	Output
$T	(id)*id$	
$T’F	(id)*id$	**T → F T’**
$T’)T(	(id)*id$	**F → (T)**
$T’)T	id)*id$	
$T’)T’F	id)*id$	**T → F T’**
$T’)T’id	id)*id$	**F → id**
$T’)T’	)*id$	
$T’)	)*id$	**T’ → ε**

Trace “(id)*id”

	*	(	)	id	$
T		**T → FT’**		**T → FT’**	
T’	**T’ → *FT’**		**T’ → ε**		**T’ → ε**
F		**F → (T)**		**F → id**	

Stack	Input	Output
$T’	*id$	
$T’F*	*id$	**T’ → * F T’**
$T’F	id$	
$T’id	id$	**F → id**
$T’	$	
$	$	**T’ → ε**

Table-Driven Parsing

stack.push($); stack.push(S);
a = input.read();
forever do begin
  X = stack.peek();
  if X = a **and** a = $ **then** return SUCCESS;
  elsif X = a **and** a != $ **then**
    pop X; a = input.read();
  elsif X != a **and** X ∈ **N and** M[X,a] **then**
    pop X; push right-hand side of M[X,a];
  else ERROR!
end

Predictive Parsing table

- Given a grammar produce the predictive parsing table
- We need to to know for all rules $A \rightarrow \alpha \mid \beta$ the lookahead symbol
- Based on the lookahead symbol the table can be used to pick which rule to push onto the stack
- This can be done using two sets: FIRST and FOLLOW

FIRST and FOLLOW

$$a \in \mathrm{FIRST}(\alpha) \text{ if } \alpha \Rightarrow^* a\beta$$

$$\text{if } \alpha \Rightarrow^* \epsilon \text{ then } \epsilon \in \mathrm{FIRST}(\alpha)$$

$$a \in \mathrm{FOLLOW}(A) \text{ if } S \Rightarrow^* \alpha A a\beta$$

$$a \in \mathrm{FOLLOW}(A) \text{ if } S \Rightarrow^* \alpha A \gamma a\beta$$

$$\text{and } \gamma \Rightarrow^* \epsilon$$

Conditions for LL(1)

- Necessary conditions:
  - no ambiguity
  - no left recursion
  - Left factored grammar
- A grammar G is LL(1) if - whenever $A \rightarrow \alpha \mid \beta$
  1. $\text{First}(\alpha) \cap \text{First}(\beta) = \varnothing$
  2. $\alpha \Rightarrow^* \varepsilon$ implies $!(\beta \Rightarrow^* \varepsilon)$
  3. $\alpha \Rightarrow^* \varepsilon$ implies $\text{First}(\beta) \cap \text{Follow}(A) = \varnothing$

ComputeFirst(α: string of symbols)

```
// assume α = X₁ X₂ X₃ … Xₙ
if X₁ ∈ T then First[α] := {X₁}
else begin
  i:=1; First[α] := ComputeFirst(X₁)\{ε};
  while Xᵢ ⇒* ε do begin
    if i < n then
      First[α] := First[α] ∪ ComputeFirst(Xᵢ₊₁)\{ε};
    else
      First[α] := First[α] ∪ {ε};
    i := i + 1;
  end
end
```

ComputeFirst(α: string of symbols)

```
// assume α = X₁ X₂ X₃ …  Xₙ
if X₁ ∈ T then First[α] := {X₁}
else begin
  i:=1; First[α] := ComputeFirst(X₁)\{ε};
  while Xᵢ ⇒* ε do begin
    if i < n then
      First[α] := First[α] ∪ ComputeFirst(Xᵢ₊₁)\{ε};
    else
     First[α] := First[α] ∪ {ε};
    i := i + 1;
  end
end
```

Recursion in computing FIRST causes problems when faced with recursive grammar rules

ComputeFirst; modified

foreach $X \in$ **T do** First[X] := {X};

foreach $p \in$ **P** : $X \rightarrow$ **ε do** First[X] := {ε};

repeat foreach $X \in$ **N**, $p : X \rightarrow Y_1\ Y_2\ Y_3 \ldots\ Y_n$ **do**

  begin i:=1;

   while $Y_i \Rightarrow^*$ **ε** and i <= n **do begin**

    First[X] := First[X] ∪ First[Y_i]\\{ε};

    i := i+1;

   end

  if i = n+1 **then** First[X] := First[X] ∪ {ε};

until no change in First[X] for any X;

ComputeFirst; modified

foreach $X \in$ **T** **do** First[X] := X;

foreach p $\in$ **P** : $X \rightarrow \varepsilon$ **do** First[X] := $\{\varepsilon\}$;

repeat **foreach** $X \in$ **N**, p : $X \rightarrow Y_1\ Y_2\ Y_3 \ldots\ Y_n$ **do**

begin i:=1;

while $Y_i \Rightarrow^*$

First[X] := F

i := i+1;

end

Non-recursive FIRST computation works with left-recursive grammars. Computes a fixed point for FIRST[X] for all non-terminals X in the grammar. But this algorithm is very inefficient.

if i = n+1 **then** First[X] := First[X] $\cup$ $\{\varepsilon\}$;

until no change in First[X] for any X;

ComputeFollow

```
Follow(S) := {$};
repeat
  foreach p ∈ P do
      case p = A → αBβ begin
        Follow[B] := Follow[B] ∪ ComputeFirst(β)\{ε};
        if ε ∈ First(β) then
          Follow[B] := Follow[B] ∪ Follow[A];
      end
     case p = A → αB
        Follow[B] := Follow[B] ∪ Follow[A];
until no change in any Follow[N]
```

Example First/Follow

$S \rightarrow AB$

$A \rightarrow c \mid \varepsilon$

$B \rightarrow cbB \mid ca$

Not an LL(1) grammar

$\text{First}(A) = \{c, \varepsilon\}$

$\text{First}(B) = \{c\}$

$\text{First}(cbB) =$

$\text{First}(ca) = \{c\}$

$\text{First}(S) = \{c\}$

$\text{Follow}(A) = \{c\}$

$\text{Follow}(A) \cap$

$\text{First}(c) = \{c\}$

$\text{Follow}(B) = \{\$\}$

$\text{Follow}(S) = \{\$\}$

ComputeFirst on Left-recursive Grammars

- ComputeFirst as defined earlier loops on left-recursive grammars
- Here is an alternative algorithm for ComputeFirst
  1. Compute non left-recursive cases of FIRST
  2. Create a graph of recursive cases where FIRST of a non-terminal depends on another non-terminal
  3. Compute Strongly Connected Components (SCC)
  4. Compute FIRST starting from root of SCC to avoid cycles

ComputeFirst on Left-recursive Grammars

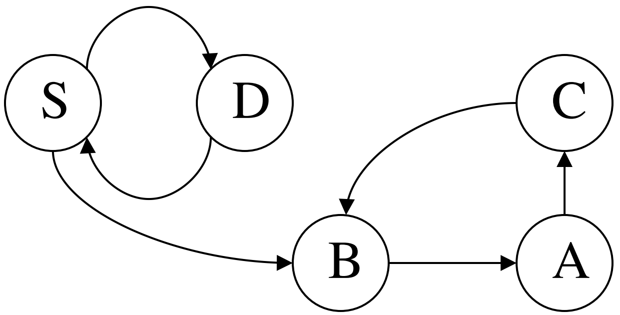
- Each Strongly Connected Component can have recursion
- But the connections between SCC means that (by defn) what we have now is a directed acyclic graph – hence without left recursion
- Unlike top-down LL parsing, bottom-up LR parsing allows left-recursive grammars, so this algorithm is useful for LR parsing

ComputeFirst on Left-recursive Grammars

- S → BD | D
- D → d | Sd

- A → CB | a
- C → Bb | ε
- B → Ab | b

Compute Strongly Connected Components



$FIRST_0[A] := \{a, b\}$

$FIRST_0[C] := \{\}$

$FIRST_0[B] := \{b\}$

$FIRST_0[S] := \{b, d\}$

$FIRST_0[D] := \{d\}$

2 SCCs: e.g. consider B-A-C

$FIRST[B] := FIRST_0[B] + FIRST[A]$

$FIRST[A] := FIRST_0[A] + FIRST[C]$

$FIRST[C] := FIRST_0[C] + FIRST_0[B]$

$FIRST[C] := FIRST[C] + \{\varepsilon\}$

How to compute: Does X $\Rightarrow^*$ ε ?

- The question \`Does X $\Rightarrow^*$ ε ?' can be written as the predicate: nullable(X)

```
Nullable = {} (set containing nullable non-terminals)
Changed = True
While (changed):
   changed = False
   if X is not in Nullable:
       if
         1. X → ε is in the grammar, or
         2. X → Y1 … Yn is in the grammar and Yi is in Nullable for all i
       then
         add X to Nullable; changed = True
```

Converting to LL(1)

S → AB

A → c | ε

B → cbB | ca

Note that grammar is regular: c? (cb)* ca

c (c b c b … c b) c a
(c b c b … c b) c a

→

c c (b c b … c b c) a
c (b c b … c b c) a

same as:

c c? (bc)* a

S → cAa

A → cB | B

B → bcB | ε

Verifying LL(1) using F/F sets

$S \rightarrow cAa$

$A \rightarrow cB \mid B$

$B \rightarrow bcB \mid \varepsilon$

$\text{First}(A) = \{b, c, \varepsilon\}$ $\text{Follow}(A) = \{a\}$

$\text{First}(B) = \{b, \varepsilon\}$ $\text{Follow}(B) = \{a\}$

$\text{First}(S) = \{c\}$ $\text{Follow}(S) = \{\$\}$

Building the Parse Table

- Compute First and Follow sets
- For each production $A \rightarrow \alpha$
  - foreach $a \in$ First(α) add $A \rightarrow \alpha$ to M[A,a]
  - If $\varepsilon \in$ First(α) add $A \rightarrow \alpha$ to M[A,b] for each b in Follow(A)
  - If $\varepsilon \in$ First(α) add $A \rightarrow \alpha$ to M[A,$] if $ $\in$ Follow(α)
  - All undefined entries are errors

Predictive Parsing Table

Productions	
1	T → F T'
2	T' → ε
3	T' → * F T'
4	F → id
5	F → (T)

FIRST(T) = {id, (}
FIRST(T') = {*, ε}
FIRST(F) = {id, (}

FOLLOW(T) = {$,)}
FOLLOW(T') = {$,)}
FOLLOW(F) = {*,$,)}

	*	(	)	id	$
T		T → F T'		T → F T'	
T'	T' → * F T'		T' → ε		T' → ε
F		F → (T)		F → id	

Revisit conditions for LL(1)

- A grammar G is LL(1) iff - whenever
  $A \rightarrow \alpha \mid \beta$
  1. $First(\alpha) \cap First(\beta) = \emptyset$
  2. $\alpha \Rightarrow^* \varepsilon$ implies **!**$(\beta \Rightarrow^* \varepsilon)$
  3. $\alpha \Rightarrow^* \varepsilon$ implies $First(\beta) \cap Follow(A) = \emptyset$
- No more than one entry per table field

Error Handling

- Reporting & Recovery
  – Report as soon as possible
  – Suitable error messages
  – Resume after error
  – Avoid cascading errors
- Phrase-level vs. Panic-mode recovery

Panic-Mode Recovery

- Skip tokens until *synchronizing set* is seen
  - Follow(A)
    - garbage or missing things after
  - Higher-level start symbols
  - First(A)
    - garbage before
  - Epsilon
    - if nullable
  - Pop/Insert terminal
    - “auto-insert”
- Add “synch” actions to table

Summary so far

- LL(1) grammars, necessary conditions
    - No left recursion
    - Left-factored
- Not all languages can be generated by LL(1) grammar
- LL(1) – Parsing: $O(n)$ time complexity
    - recursive-descent and table-driven predictive parsing
- LL(1) grammars can be parsed by simple predictive recursive-descent parser
    - Alternative: table-driven top-down parser