CMPT 379
Compilers

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Parsing CFGs

- Consider the problem of parsing with arbitrary CFGs
- For any input string, the parser has to produce a parse tree
- The simpler problem: print **yes** if the input string is generated by the grammar, print **no** otherwise
- This problem is called *recognition*

CKY Recognition Algorithm

- The Cocke-Kasami-Younger algorithm
- As we shall see it runs in time that is polynomial in the size of the input
- It takes space polynomial in the size of the input
- **Remarkable fact:** it can find all possible parse trees (exponentially many) in polynomial time

Chomsky Normal Form

- Before we can see how CKY works, we need to convert the input CFG into Chomsky Normal Form
- CNF means that the input CFG G is converted to a new CFG G' in which all rules are of the form:

  $A \rightarrow B\ C$

  $A \rightarrow a$

Epsilon Removal

- First step, remove epsilon rules

  $A \rightarrow B\ C$

  $C \rightarrow \varepsilon \mid C\ D \mid a$

  $D \rightarrow b \quad B \rightarrow b$

- After ε-removal:

  $A \rightarrow B \mid B\ C\ D \mid B\ a$

  $C \rightarrow D \mid C\ D\ D \mid a\ D \mid a$

  $D \rightarrow b \quad B \rightarrow b$

Removal of Chain Rules

- Second step, remove chain rules

  $A \rightarrow B\ C \mid C\ D\ C$

  $C \rightarrow D \mid a$

  $D \rightarrow d \qquad B \rightarrow b$

- After removal of chain rules:

  $A \rightarrow B\ a \mid B\ D \mid a\ D\ a \mid a\ D\ D \mid D\ D\ a \mid D\ D\ D$

  $D \rightarrow d \qquad B \rightarrow b$

Eliminate terminals from RHS

- Third step, remove terminals from the rhs of rules

  $A \rightarrow B\ a\ C\ d$

- After removal of terminals from the rhs:

  $A \rightarrow B\ N_1\ C\ N_2$

  $N_1 \rightarrow a$

  $N_2 \rightarrow d$

Binarize RHS with Nonterminals

- Fourth step, convert the rhs of each rule to have two non-terminals

  $A \rightarrow B\ N_1\ C\ N_2$

  $N_1 \rightarrow a$

  $N_2 \rightarrow d$

- After converting to binary form:

$A \rightarrow B\ N_3$	$N_1 \rightarrow a$
$N_3 \rightarrow N_1\ N_4$	$N_2 \rightarrow d$
$N_4 \rightarrow C\ N_2$	

CKY algorithm

- We will consider the working of the algorithm on an example CFG and input string
- Example CFG:

  $S \rightarrow A\ X \mid Y\ B$

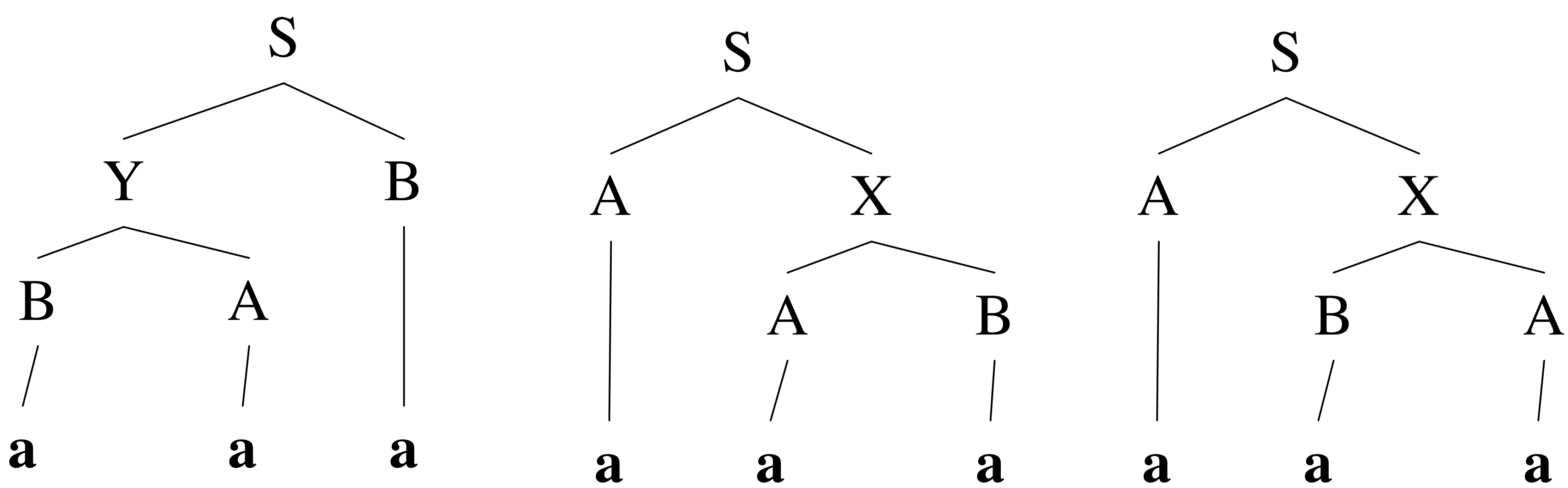
  $X \rightarrow A\ B \mid B\ A \qquad Y \rightarrow B\ A$

  $A \rightarrow a \qquad B \rightarrow a$
- Example input string: *aaa*

CKY Algorithm

	0	1	2	3
0		A, B $A \rightarrow a$ $B \rightarrow a$	X, Y $X \rightarrow A\ B \mid B\ A$ $Y \rightarrow B\ A$	S $S \rightarrow A_{(0,1)}\ X_{(1,3)}$ $S \rightarrow Y_{(0,2)}\ B_{(2,3)}$
1			A, B $A \rightarrow a$ $B \rightarrow a$	X, Y $X \rightarrow A\ B \mid B\ A$ $Y \rightarrow B\ A$
2				A, B $A \rightarrow a$ $B \rightarrow a$
		a	a	a

Parse trees



CKY Algorithm

Input string **input** of size *n*

Create a 2D table **chart** of size n^2

for i=0 **to** n-1

    chart[i][i+1] = A **if** there is a rule A → a and **input**[i]=a

for j=2 **to** N

    for i=j-2 **downto** 0

        for k=i+1 **to** j-1

            chart[i][j] = A **if** there is a rule A → B C **and**
            chart[i][k] = B **and chart**[k][j] = C

return *yes* **if chart**[0][n] has the start symbol

else return *no*

CKY algorithm summary

- Parsing arbitrary CFGs
- For the CKY algorithm, the time complexity is $O(|G|^2 n^3)$
- The space requirement is $O(n^2)$
- The CKY algorithm handles arbitrary ambiguous CFGs
- All ambiguous choices are stored in the chart
- For compilers we consider parsing algorithms for CFGs that do not handle ambiguous grammars

Parsing - Roadmap

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

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

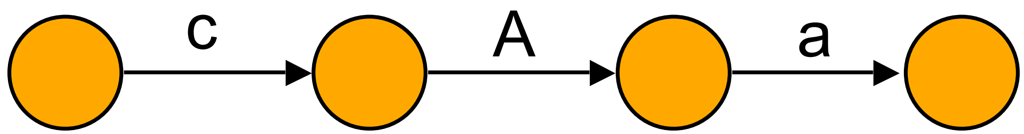
$S \Rightarrow^* cbca$?

S	cbca	try $S \rightarrow AB$
AB	cbca	try $A \rightarrow c$
cB	cbca	match c
B	bca	dead-end, try $A \rightarrow \varepsilon$
εB	cbca	try $B \rightarrow cbB$
cbB	cbca	match c
bB	bca	match b
B	ca	try $B \rightarrow cbB$
cbB	ca	match c
bB	a	dead-end, try $B \rightarrow ca$
ca	ca	match c
a	a	match a, Done!

Transition Diagram

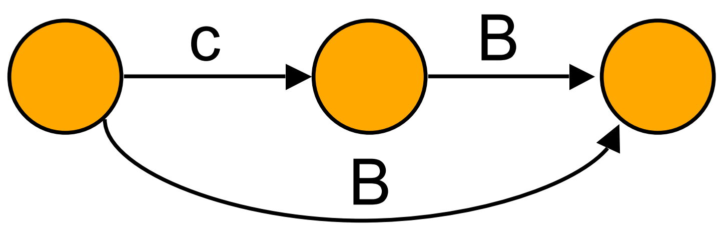
$S \rightarrow cAa$

S:



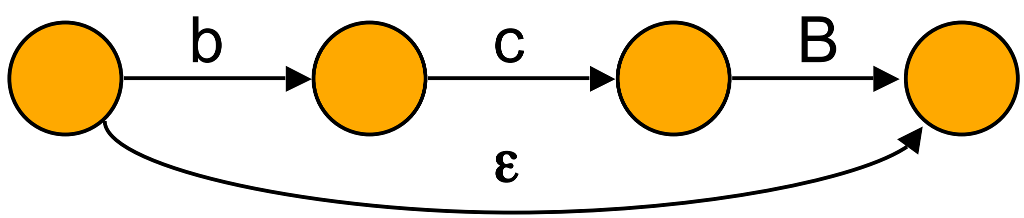
$A \rightarrow cB \mid B$

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

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

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

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”

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"

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

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

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

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

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

and $\gamma \Rightarrow^* \epsilon$

Conditions for LL(1)

- Necessary conditions:
  - no ambiguity
  - no left recursion
  - Left factored grammar
- A grammar G is LL(1) iff - whenever
  $A \rightarrow \alpha \mid \beta$

1. $\text{First}(\alpha) \cap \text{First}(\beta) = \varnothing$
2. $\alpha \Rightarrow^* \varepsilon$ implies $\mathbf{!}(\beta \Rightarrow^* \varepsilon)$
3. $\alpha \Rightarrow^* \varepsilon$ implies $\text{First}(\beta) \cap \text{Follow}(A) = \varnothing$

proc First(α: string of symbols)

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

proc First(X); 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 $Y_i \Rightarrow^* \boldsymbol{\varepsilon}$ and i **<=** n **do begin**

    First(X) := First(X) $\cup$ First(Y_i)\{**ε**};

    i := i+1;

   end

  if i **=** n+1 **then** First(X) := First(X) $\cup$ {**ε**};

  else First(X) := First(X) $\cup$ First(Y_i);

until no change in any First(X);

proc Follow(N: non-terminal)

```
Follow(S) := {$};
repeat
  foreach p ∈ P do
      case p = A → αBβ begin
        Follow(B) := Follow(B) ∪ First(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

First(A) = {c, ε}

First(B) = {c}

First(cbB) =

First(ca) = {c}

First(S) = {c}

Follow(A) = {c}

Follow(A) ∩

First(c) = {c}

Follow(B) = {\$}

Follow(S) = {\$}

Converting to LL(1)

$S \rightarrow AB$

$A \rightarrow c \mid \varepsilon$

$B \rightarrow cbB \mid ca$

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

c (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	c (b c b … c b c) a

same as:

c c? (bc)* a

$S \rightarrow cAa$

$A \rightarrow cB \mid B$

$B \rightarrow bcB \mid \varepsilon$

Verifying LL(1) using F/F sets

$S \to cAa$

$A \to cB \mid B$

$B \to bcB \mid \varepsilon$

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

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

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

Building the Parse Table

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

Revisit conditions for LL(1)

- A grammar G is LL(1) iff - whenever $A \rightarrow \alpha \mid \beta$
  1. $\text{First}(\alpha) \cap \text{First}(\beta) = \varnothing$
  2. $\alpha \Rightarrow^* \varepsilon$ implies $\boldsymbol{!}(\beta \Rightarrow^* \varepsilon)$
  3. $\alpha \Rightarrow^* \varepsilon$ implies $\text{First}(\beta) \cap \text{Follow}(A) = \varnothing$
- 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) grammars can be parsed by simple predictive recursive-descent parser
  - Alternative: table-driven top-down parser

Bottom-up parsing overview

- Start from terminal symbols, search for a path to the start symbol
- Apply shift and reduce actions: postpone decisions
- LR parsing:
  - L: left to right parsing
  - R: rightmost derivation (in reverse or bottom-up)
- LR(0) → SLR(1) → LR(1) → LALR(1)
  - 0 or 1 or *k* lookahead symbols

Actions in Shift-Reduce Parsing

- Shift
  - add terminal to parse stack, advance input
- Reduce
  - If αw on stack, and $A \rightarrow w$, and there is a $\beta \in T^*$ such that $S \Rightarrow^* \alpha A \beta \Rightarrow \alpha w \beta$ then we can *prune the handle* w; we reduce αw to αA on the stack
  - αw is a *viable prefix*
- Error
- Accept

Questions

- When to shift/reduce?
  - What are valid handles?
  - Ambiguity: Shift/reduce conflict
- If reducing, using which production?
  - Ambiguity: Reduce/reduce conflict

Rightmost derivation for **id + id * id**

$E \rightarrow E + E$	$E \Rightarrow E * E$	
$E \rightarrow E * E$	$\Rightarrow E * \textbf{id}$	
$E \rightarrow (E)$	$\Rightarrow E + E * \textbf{id}$	
$E \rightarrow - E$	$\Rightarrow E + \textbf{id} * \textbf{id}$	reduce with $E \rightarrow \textbf{id}$
$E \rightarrow \textbf{id}$	$\Rightarrow \textbf{id} + \textbf{id} * \textbf{id}$	shift

LR Parsing

- Table-based parser
  - Creates rightmost derivation (in reverse)
  - For “less massaged” grammars than LL(1)
- Data structures:
  - Stack of states/symbols {s}
  - Action table: **action**[s, a]; a $\in$ **T**
  - Goto table: **goto**[s, X]; X $\in$ **N**

Productions	
1	T → F
2	T → T*F
3	F → id
4	F → (T)

Action/Goto Table

	*	(	)	id	$	T	F
0		S5		S8		2	1
1	R1	R1	R1	R1	R1		
2	S3				Acc!		
3		S5		S8			4
4	R2	R2	R2	R2	R2		
5		S5		S8		6	1
6	S3		S7				
7	R4	R4	R4	R4	R4		
8	R3	R3	R3	R3	R3		

Trace “(id)*id”

Stack	Input	Action
0	**(id) * id $**	**Shift S5**
0 5	**id) * id $**	**Shift S8**
0 5 8	**) * id $**	**Reduce 3 F→id,**
		pop 8, goto [5,F]=1
0 5 1	**) * id $**	**Reduce 1 T→ F,**
		pop 1, goto [5,T]=6
0 5 6	**) * id $**	**Shift S7**
0 5 6 7	*** id $**	**Reduce 4 F→ (T),**
		pop 7 6 5, goto [0,F]=1
0 1	*** id $**	**Reduce 1 T → F**
		pop 1, goto [0,T]=2

Productions	
1	**T → F**
2	**T → T*F**
3	**F → id**
4	**F → (T)**

	*	(	)	id	$	T	F
0		S5		S8		2	1
1	R1	R1	R1	R1	R1		
2	S3				A		
3		S5		S8			4
4	R2	R2	R2	R2	R2		
5		S5		S8		6	1
6	S3		S7				
7	R4	R4	R4	R4	R4		
8	R3	R3	R3	R3	R3		

“(id)*id”

t	Input	A
0	**(id) * id $**	**Sh**
0 5	**id) * id $**	**Sh**
0 5 8	**) * id $**	**Re po**
0 5 1	**) * id $**	**Reduce 1 T→ F, pop 1, goto [5,T]=6**
0 5 6	**) * id $**	**Shift S7**
0 5 6 7	*** id $**	**Reduce 4 F→ (T), pop 7 6 5, goto [0,F]=1**
0 1	*** id $**	**Reduce 1 T → F pop 1, goto [0,T]=2**

Trace “(id)*id”

Stack	Input	Action
0 1	*** id $**	**Reduce 1 T→F,**
		pop 1, goto [0,T]=2
0 2	*** id $**	**Shift S3**
0 2 3	**id $**	**Shift S8**
0 2 3 8	**$**	**Reduce 3 F→id,**
		pop 8, goto [3,F]=4
0 2 3 4	**$**	**Reduce 2 T→T * F**
		pop 4 3 2, goto [0,T]=2
0 2	**$**	**Accept**

Productions	
1	**T → F**
2	**T → T*F**
3	**F → id**
4	**F → (T)**

“(id)*id”

	*	(	)	id	$	T	F
0		S5		S8		2	1
1	R1	R1	R1	R1	R1		
2	S3				A		
3		S5		S8			4
4	R2	R2	R2	R2	R2		
5		S5		S8		6	1
6	S3		S7				
7	R4	R4	R4	R4	R4		
8	R3	R3	R3	R3	R3		

Stack	Input	Actio
0 1	*** id $**	**Reduc**
		pop 1,
0 2	*** id $**	**Shift S**
0 2 3	**id $**	**Shift S8**
0 2 3 8	**$**	**Reduce 3 F→id,**
		pop 8, goto [3,F]=4
0 2 3 4	**$**	**Reduce 2 T→T * F**
		pop 4 3 2, goto [0,T]=2
0 2	**$**	**Accept**

Tracing LR: **action**[s, a]

- case **shift** u:
  - push state u
  - read new a
- case **reduce** r:
  - lookup production r: $X \rightarrow Y_1..Y_k$;
  - pop k states, find state u
  - push **goto**[u, X]
- case **accept**: done
- no entry in action table: **error**

Configuration set

- Each set is a parser state
- Consider

$$\mathbf{T \rightarrow T * \bullet F}$$

$$\mathbf{F \rightarrow \bullet (T)}$$

$$\mathbf{F \rightarrow \bullet id}$$

- Like NFA-to-DFA conversion

Closure

Closure property:

- If $\mathbf{T} \rightarrow \mathbf{X_1} \ldots \mathbf{X_i} \bullet \mathbf{X_{i+1}} \ldots \mathbf{X_n}$ is in set, and $\mathbf{X_{i+1}}$ is a nonterminal, then $\mathbf{X_{i+1}} \rightarrow \bullet\, \mathbf{Y_1} \ldots \mathbf{Y_m}$ is in the set as well for all productions $\mathbf{X_{i+1}} \rightarrow \mathbf{Y_1} \ldots \mathbf{Y_m}$
- Compute as fixed point

Starting Configuration

- Augment Grammar with S’
- Add production S’ → S
- Initial configuration set is

  closure(S’ → • S)

Example: closure(S' $\rightarrow \bullet$ T)

S' $\rightarrow \bullet$ T

T $\rightarrow \bullet$ T * F

T $\rightarrow \bullet$ F

F $\rightarrow \bullet$ id

F $\rightarrow \bullet$ (T)

S' $\rightarrow$ T
T $\rightarrow$ F | T * F
F $\rightarrow$ id | (T)

Successor(C, X)

Informally: "move by symbol X"

1. move dot to the right in all items where dot is before X
2. remove all other items

   (viable prefixes only!)
3. compute closure

Successor Example

$C = \{S' \rightarrow \bullet\, T,$

$T \rightarrow \bullet\, F,$

$T \rightarrow \bullet\, T * F,$

$F \rightarrow \bullet\, id,$

$F \rightarrow \bullet\, (T) \}$

$S' \rightarrow T$

$T \rightarrow F \mid T * F$

$F \rightarrow id \mid (T)$

Compute **Successor**(C, "(")

$\{ F \rightarrow (\bullet\, T), T \rightarrow \bullet\, F, T \rightarrow \bullet\, T * F,$

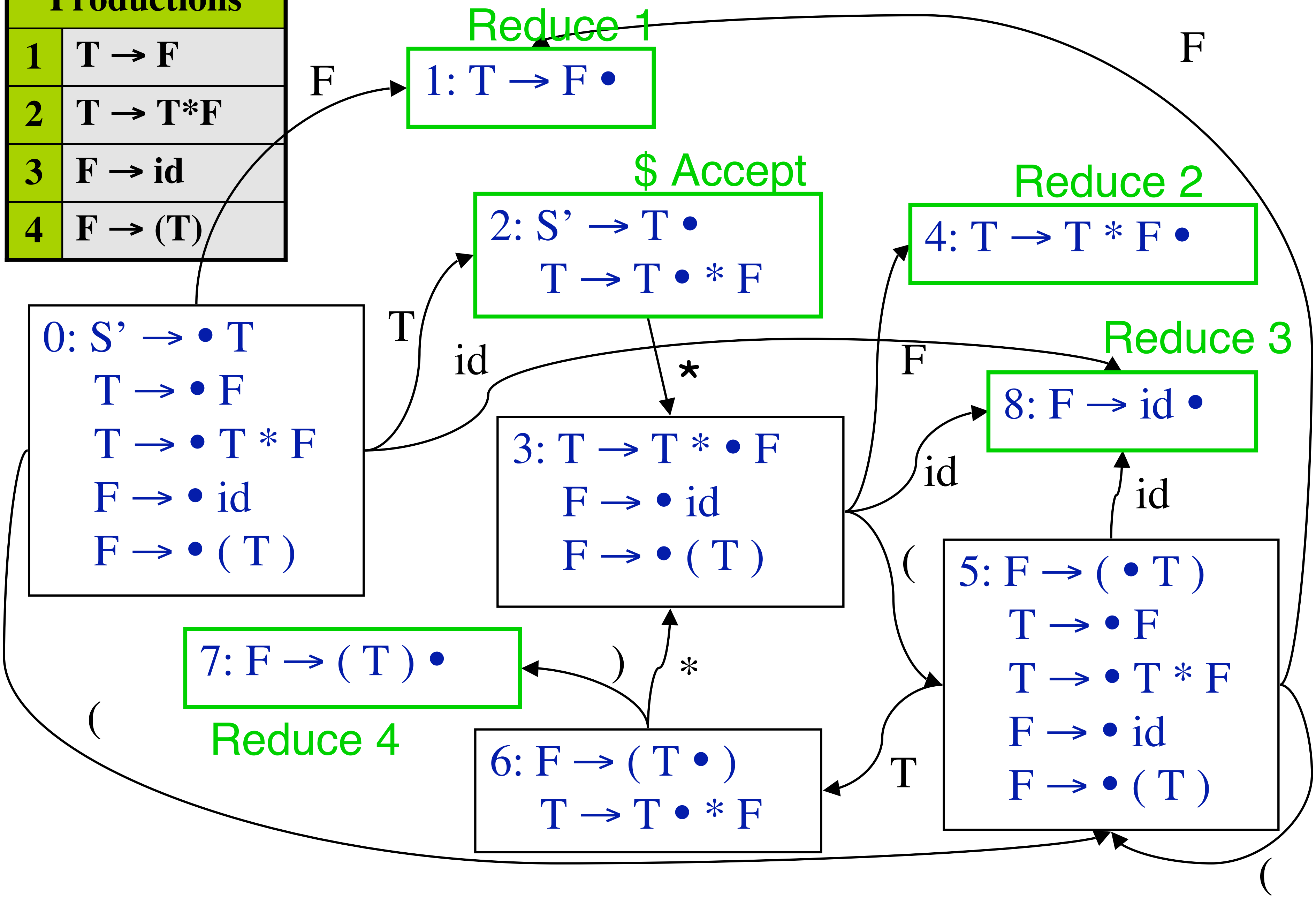
$F \rightarrow \bullet\, id, F \rightarrow \bullet\, (T) \}$

Sets-of-Items Construction

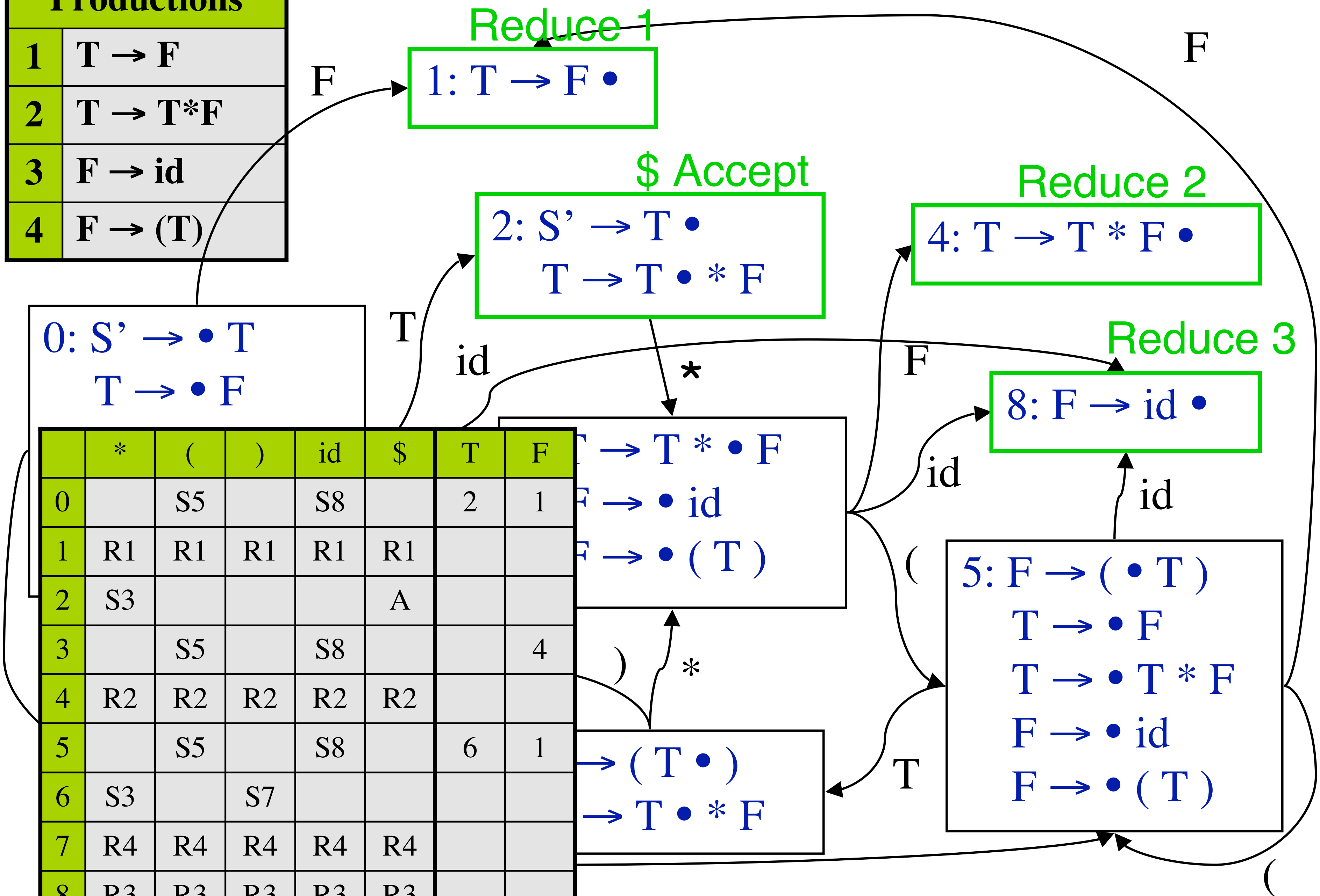
Family of configuration sets

function items(G')
    C = { closure({S' $\rightarrow \bullet$ S}) };
    do foreach I $\in$ C **do**
        foreach X $\in$ (**N** $\cup$ **T**) **do**
            C = C $\cup$ { **Successor**(I, X) };
    while C changes;

Productions	
1	T → F
2	T → T*F
3	F → id
4	F → (T)



Productions	
1	T → F
2	T → T*F
3	F → id
4	F → (T)



	*	(	)	id	$	T	F
0		S5		S8		2	1
1	R1	R1	R1	R1	R1		
2	S3				A		
3		S5		S8			4
4	R2	R2	R2	R2	R2		
5		S5		S8		6	1
6	S3		S7				
7	R4	R4	R4	R4	R4		
8	R3	R3	R3	R3	R3		

LR(0) Construction

1. Construct $F = \{I_0, I_1, \ldots I_n\}$
2. a) if $\{A \rightarrow \alpha\bullet\} \in I_i$ and $A \mathrel{!}= S$

   then action[i, _] := reduce $A \rightarrow \alpha$

   b) if $\{S' \rightarrow S\bullet\} \in I_i$

   then action[i,$] := accept

   c) if $\{A \rightarrow \alpha\bullet a\beta\} \in I_i$ and $\text{Successor}(I_i,a) = I_j$

   then action[i,a] := shift j
3. if $\text{Successor}(I_i,A) = I_j$ then goto[i,A] := j

LR(0) Construction (cont'd)

4. All entries not defined are errors
5. Make sure I_0 is the initial state

- Note: LR(0) always reduces if $\{A \rightarrow \alpha\bullet\} \in I_i$, no lookahead
- Shift and reduce items can't be in the same configuration set
  - Accepting state doesn't count as reduce item
- At most one reduce item per set

LR(0) conflicts:

$S' \rightarrow F$
$F \rightarrow id \mid (T)$
$F \rightarrow id = T ;$
$T \rightarrow T * F$
$T \rightarrow id$

5: $F \rightarrow id \bullet$
$F \rightarrow id \bullet = T$

Shift/reduce conflict

2: $F \rightarrow id \bullet$
$T \rightarrow id \bullet$

Reduce/Reduce conflict

Need more lookahead: SLR(1)

SLR(1) : Simple LR(1) Parsing

0: $S' \rightarrow \bullet\ T$
$T \rightarrow \bullet\ F$
$T \rightarrow \bullet\ T * F$
$T \rightarrow \bullet\ C\ (T)$
$F \rightarrow \bullet\ id$
$F \rightarrow \bullet\ id\ {++}$
$F \rightarrow \bullet\ (\ T\ )$
$C \rightarrow \bullet\ id$

id

$S' \rightarrow T$
$T \rightarrow F \mid T * F \mid C\ (\ T\ )$
$F \rightarrow id \mid id\ {++} \mid (\ T\ )$
$C \rightarrow id$

1: $F \rightarrow id\ \bullet$
$F \rightarrow id\ \bullet\ \mathbf{++}$
$C \rightarrow id\ \bullet$

Follow(F) = { *,), $ }

Follow(C) = { (}

action[1,*]= action[1,)] = action[1,$] = Reduce $F \rightarrow id$

action[1,(] = Reduce $C \rightarrow id$

action[1,++] = Shift

SLR(1) Construction

1. Construct $F = \{I_0, I_1, \ldots I_n\}$
2. a) if $\{A \rightarrow \alpha\bullet\} \in I_i$ and A != S'

   then action[i, b] := reduce $A \rightarrow \alpha$

   for all $b \in$ Follow(A)

   b) if $\{S' \rightarrow S\bullet\} \in I_i$

   then action[i, $] := accept

   c) if $\{A \rightarrow \alpha\bullet a\beta\} \in I_i$ and Successor(I_i, a) = I_j

   then action[i, a] := shift j
3. if Successor(I_i, A) = I_j then goto[i, A] := j

SLR(1) Construction (cont'd)

4. All entries not defined are errors
5. Make sure I_0 is the initial state

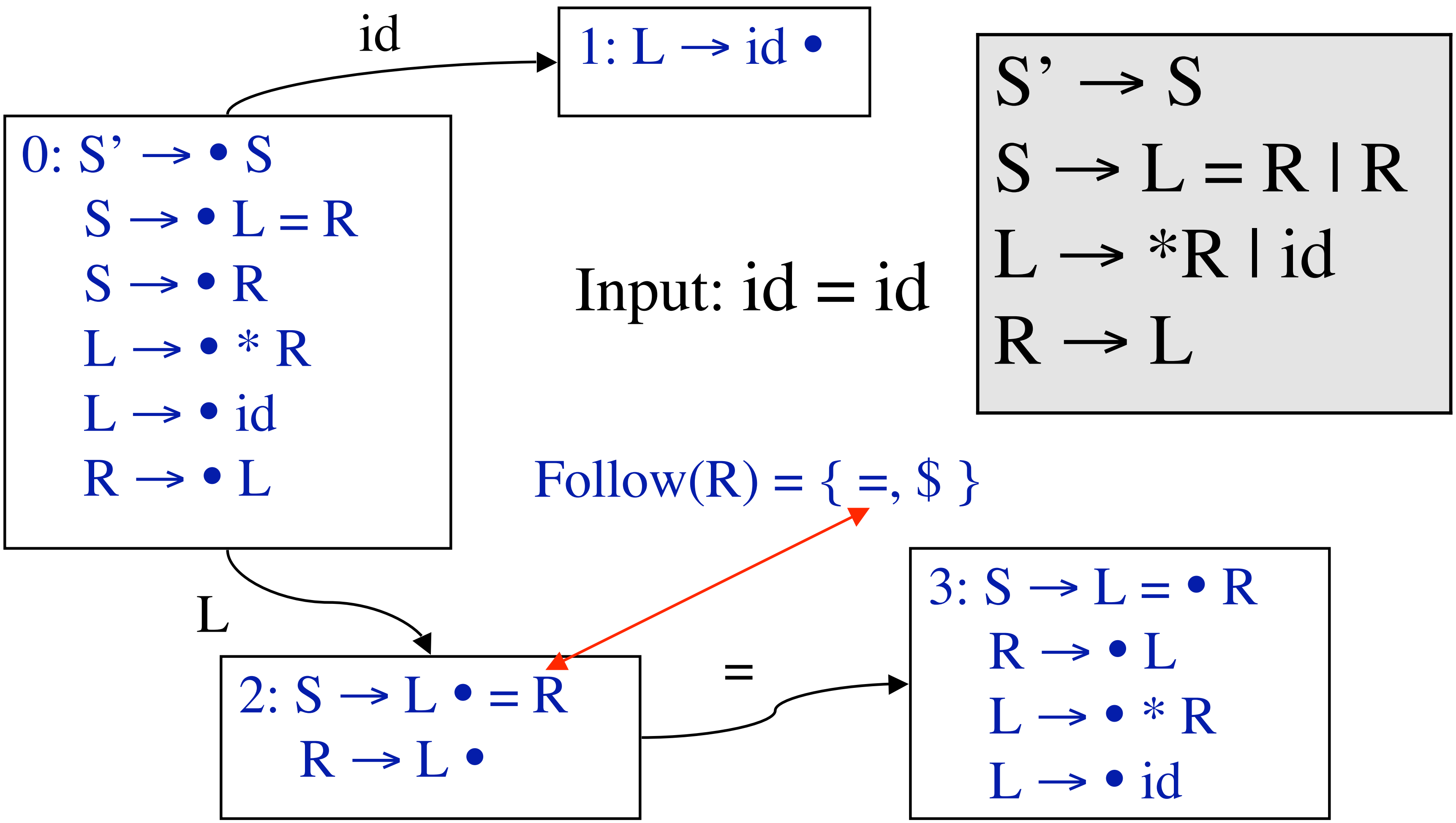
- Note: SLR(1) only reduces $\{A \rightarrow \alpha\bullet\}$ if lookahead in Follow(A)
- Shift and reduce items or more than one reduce item can be in the same configuration set as long as lookaheads are disjoint

SLR(1) Conditions

- A grammar is SLR(1) if for each configuration set:
  - For any item $\{A \rightarrow \alpha \bullet x\beta : x \in T\}$ there is no $\{B \rightarrow \gamma \bullet : x \in \text{Follow}(B)\}$
  - For any two items $\{A \rightarrow \alpha \bullet\}$ and $\{B \rightarrow \beta \bullet\}$ $\text{Follow}(A) \cap \text{Follow}(B) = \emptyset$

LR(0) Grammars $\subset$ SLR(1) Grammars

SLR limitation: lack of context



Solution: Canonical LR(1)

- Extend definition of configuration
  - Remember lookahead
- New closure method
- Extend definition of Successor

LR(1) Configurations

- $[A \rightarrow \alpha \bullet \beta, a]$ for $a \in T$ is valid for a viable prefix $\delta\alpha$ if there is a rightmost derivation
  $$S \Rightarrow^* \delta A \eta \Rightarrow^* \delta\alpha\beta\eta \text{ and}$$
  $$(\eta = a\gamma) \text{ or } (\eta = \varepsilon \text{ and } a = \$)$$
- Notation: $[A \rightarrow \alpha \bullet \beta, a/b/c]$
  - if $[A \rightarrow \alpha \bullet \beta, a]$, $[A \rightarrow \alpha \bullet \beta, b]$, $[A \rightarrow \alpha \bullet \beta, c]$ are valid configurations

LR(1) Closure

Closure property:

- If $[A \rightarrow \alpha \bullet B\beta, a]$ is in set, then $[B \rightarrow \bullet \gamma, b]$ is in set if $b \in \text{First}(\beta a)$
- Compute as fixed point
- Only include contextually valid lookaheads to guide reducing to B

Starting Configuration

- Augment Grammar with S' just like for LR(0), SLR(1)
- Initial configuration set is

$$\text{closure}([S' \rightarrow \bullet\, S, \$])$$

Example: closure([S' → • S, $])

- [S' → • S, $]
- [S → • L = R, $]
- [S → • R, $]
- [L → • * R, =]
- [L → • id, =]
- [R → • L, $]
- [L → • *R, $]
- [L → • id, $]

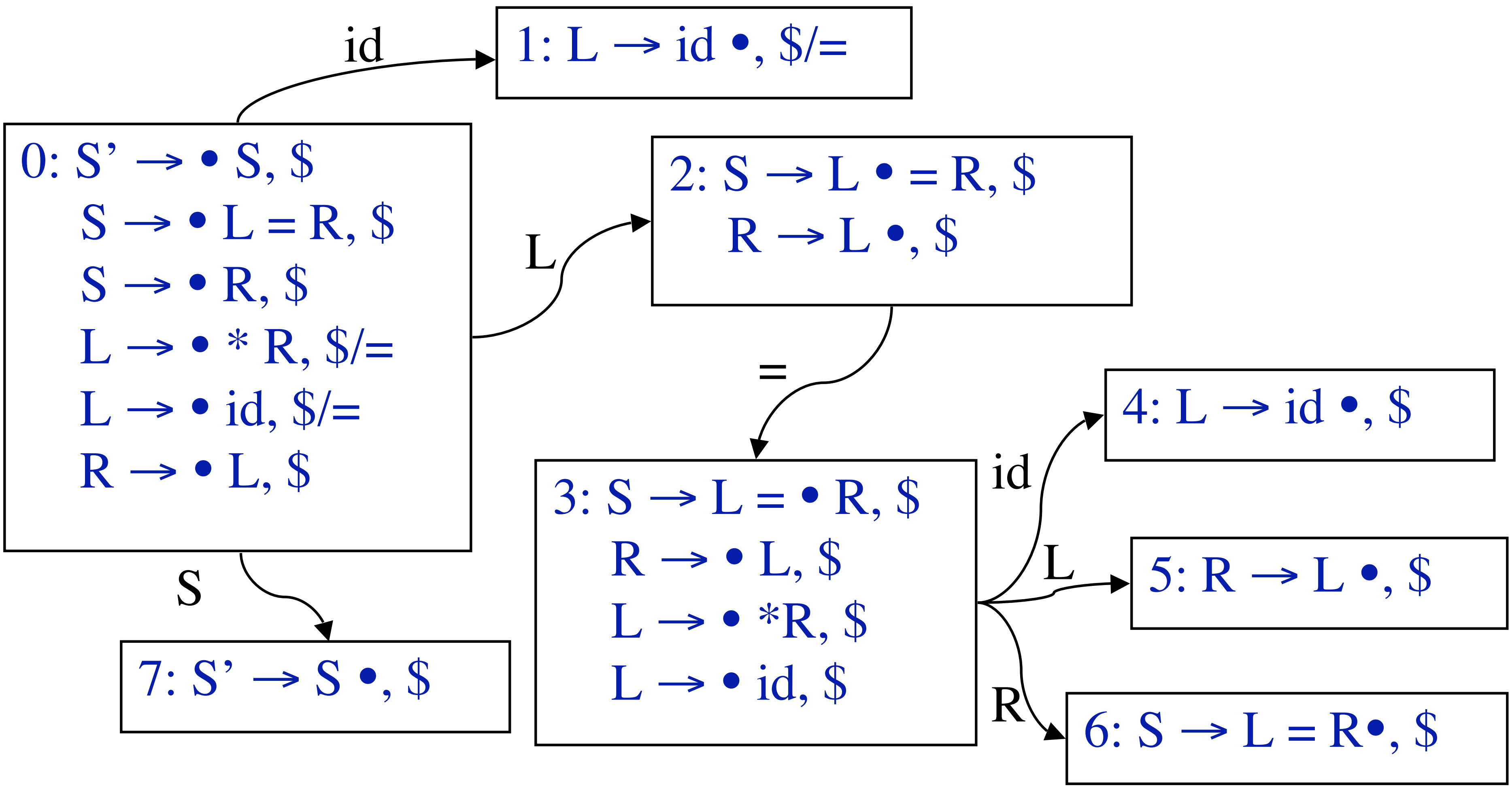
S' → S
S → L = R | R
L → *R | id
R → L

LR(1) Successor(C, X)

- Let $C = [A \rightarrow \alpha \bullet B\beta, a]$
- Successor(C, B)

  $= closure([A \rightarrow \alpha B \bullet \beta, a])$

LR(1) Example: id = id



LR(1) Construction

1. Construct $F = \{I_0, I_1, \ldots I_n\}$
2. a) if $[A \rightarrow \alpha\bullet, a] \in I_i$ and $A \mathrel{!=} S'$

   then action[i, a] := reduce $A \rightarrow \alpha$

   b) if $[S' \rightarrow S\bullet, \$] \in I_i$

   then action[i, \$] := accept

   c) if $[A \rightarrow \alpha\bullet a\beta, b] \in I_i$ and Successor(I_i, a)=I_j
   then action[i, a] := shift j
3. if Successor(I_i, A) = I_j then goto[i, A] := j

LR(1) Construction (cont'd)

4. All entries not defined are errors
5. Make sure I_0 is the initial state

- Note: LR(1) only reduces using $A \rightarrow \alpha$ for $[A \rightarrow \alpha\bullet, a]$ if a follows
- LR(1) states remember context by virtue of lookahead
- Possibly many states!
  - LALR(1) combines some states

LR(1) Conditions

- A grammar is LR(1) if for each configuration set holds:
  - For any item $[A \rightarrow \alpha \bullet x \beta, a]$ with $x \in T$ there is no $[B \rightarrow \gamma \bullet, x]$
  - For any two complete items $[A \rightarrow \gamma \bullet, a]$ and $[B \rightarrow \beta \bullet, b]$ it follows a and a != b.
- Grammars:
  - $LR(0) \subset SLR(1) \subset LR(1) \subset LR(k)$
- Languages expressible by grammars:
  - $LR(0) \subset SLR(1) \subset LR(1) = LR(k)$

S/R & ambiguous grammars

- Lx(k) Grammar vs. Language
  - Grammar is Lx(k) if it can be parsed by Lx(k) method – according to criteria that is specific to the method.
  - A Lx(k) grammar may or may not exist for a language.
- Even if a given grammar is not LR(k), shift/reduce parser can *sometimes* handle them by accounting for ambiguities
  - Example: ‘dangling’ else
    - Preferring shift to reduce means matching inner ‘if’

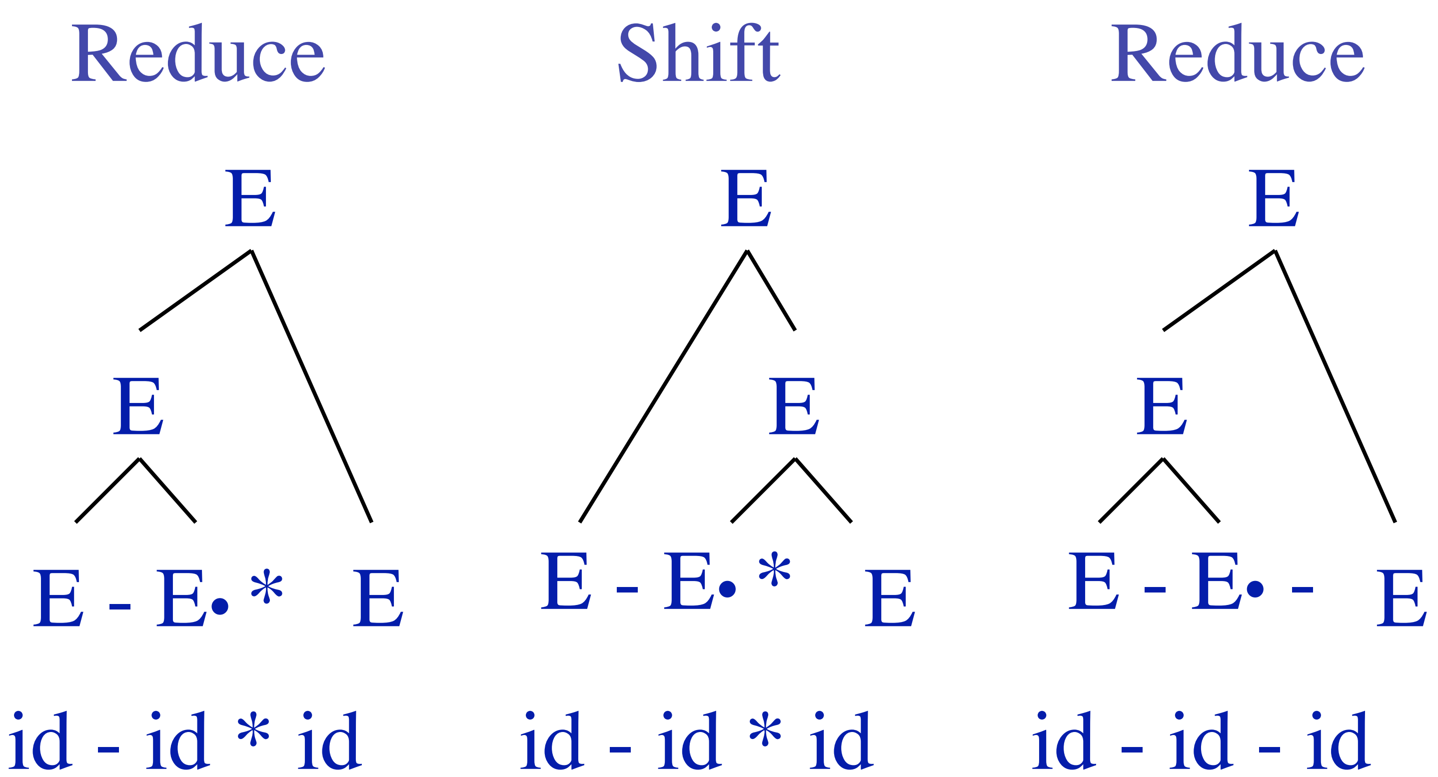
Dangling ‘else’

1. $S \rightarrow$ if E then S
2. $S \rightarrow$ if E then S else S

- Viable prefix “if E then if E then S”
  - Then read else
- Shift “else” (means go for 2)
- Reduce (reduce using production #1)
- NB: dangling else as written above is ambiguous
  - NB: Ambiguity can be resolved, but there’s still no LR(k) grammar

Precedence & Associativity

- Consider $E \rightarrow E - E \mid E * E \mid id$



Handling S/R & R/R Conflicts

1. Have a conflict?
   - No? – Done, grammar is compliant.
2. Already using most powerful parser available?
   - No? – Upgrade and goto 1
3. Can the grammar be rearranged so that the conflict disappears?
   - While preserving the language!

Conflicts revisited (cont'd)

3. Can the grammar be rearranged so that the conflict disappears?
   1. No?
      1. Is the conflict S/R and does shift-to-reduce preference yield desired result?
         1. Yes: Done. (Example: dangling else)
      2. Else: Bad luck
   2. Yes: Is it worth it?
      1. Yes, resolve conflict.
      2. No: live with default or specified conflict resolution (precedence, associativity)

Using precedence

- Precedence can be associated with tokens and productions
- If no precedence is associated:
  - Resolve S/R conflicts in favor of shift
  - Result R/R conflicts by picking productions that is listed first
- Tokens can have precedence & associativity

Using precedence (cont'd)

- Choice is between shifting token a and reducing by Rule $X \rightarrow \alpha$:
- Shift, unless:
  - Precedence (X) > Precedence(a)
  - Or Precedence(X) == Precedence(a) And Associativity(X) == left.

Canonical LR(1) Recap

- LR(1) uses left context, current handle and lookahead to decide when to reduce or shift
- Most powerful parser so far
- LALR(1) is practical simplification with fewer states

Merging States in LALR(1)

- $S' \rightarrow S$
  $S \rightarrow XX$
  $X \rightarrow aX$
  $X \rightarrow b$
- Same **Core Set**
- Different lookaheads

3: $X \rightarrow a \bullet X$, a/b
$X \rightarrow \bullet a X$, a/b
$X \rightarrow \bullet b$, a/b

6: $X \rightarrow a \bullet X$, \$
$X \rightarrow \bullet a X$, \$
$X \rightarrow \bullet b$, \$

36: $X \rightarrow a \bullet X$, a/b/\$
$X \rightarrow \bullet a X$, a/b/\$
$X \rightarrow \bullet b$, a/b/\$

R/R conflicts when merging

- B → d
  B → f X g
  X → …

- If R/R conflicts are introduced, grammar is not LALR(1)!

2: B → d •, c
B → f X g •, e

4: B → d •, g
B → f X g •, c

24: B → d •, c/g
B → f X g •, c/e

LALR(1)

- LALR(1) Condition:
  - Merging in this way does not introduce reduce/reduce conflicts
  - Shift/reduce can't be introduced
- Merging brute force or step-by-step
- More compact than canonical LR, like SLR(1)
- More powerful than SLR(1)
  - Not always merge to full Follow Set

GLR – Generalized LR Parsing

- Works for any CFG (just like CKY algorithm)
- Invented by Masaru Tomita [1986]
- If you have shift/reduce conflict, just clone your stack and shift in one clone, reduce in the other clone
  - proceed in lockstep
  - parser that get into error states die
  - merge parsers that lead to identical reductions (graph structured stack)

Parsing - Summary

- Parsing arbitrary CFGs: $O(n^3)$ time complexity
- Top-down vs. bottom-up
- Lookahead: FIRST and FOLLOW sets
- LL(1) – Parsing: $O(n)$ time complexity
  - recursive-descent and table-driven predictive parsing
- LR(k) – Parsing : $O(n)$ time complexity
  - LR(0), SLR(1), LR(1), LALR(1)
- Resolving shift/reduce conflicts
  - using precedence, associativity