Compilation Principle
编 译 原 理

第10讲：语法分析(7)

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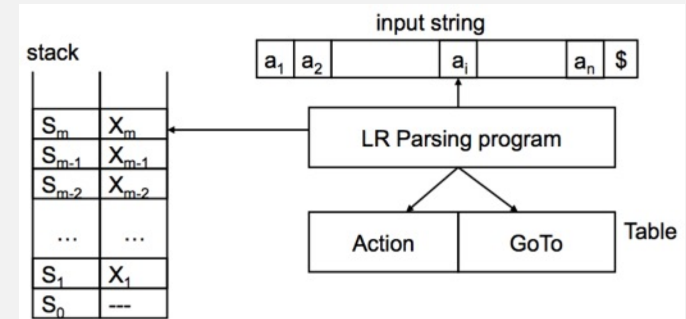
Review Questions

- What does LR(k) mean?

  L: scan the input from **l**eft to right

  R: construct a **r**ightmost derivation in reverse

  k: use **k** input symbols of lookahead



- What are the parts of a LR parser?

  Input buffer, stack, parse table, driver

- What are held in the stack of a LR parser?

  A sequence of states, and each has an associated grammar symbol

- The LR parsing table is split into two, what are they?

  Action table for terminals, Goto table for non-terminals

- What are the possible actions in Action table?

  Shift, reduce, accept, error

Example: Parse Table

Grammar:

(1) S → BB

(2) B → aB

(3) B → b

String: bab

State	ACTION			GOTO	
	a	b	$	S	B
0	s3	s4		1	2
1			acc		
2	s3	s4			5
3	s3	s4			6
4	r3	r3	r3		
5	r1	r1	r1		
6	r2	r2	r2		

state → 0

b a b symbol → $ b a b $

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Parser Actions[解析动作]

	Stack	Input
Initial	s_0 $	$a_1a_2...a_n$$
General	$s_0s_1 ... s_m$ $$X_1...X_m$	$a_ia_{i+1}...a_n$$

- If ACTION[s_m, a_i] = sx, then do **shift**[移进]
  - Pushes a_i on stack
    - a_i is removed from input
  - Enters state x
    - i.e., pushes state x on stack
    - 自带下一状态

Stack	Input
$s_0s_1 ... s_m x$ $$X_1...X_m a_i$	$a_{i+1}...a_n$$

Parser Actions (cont.)

Initial

s_0

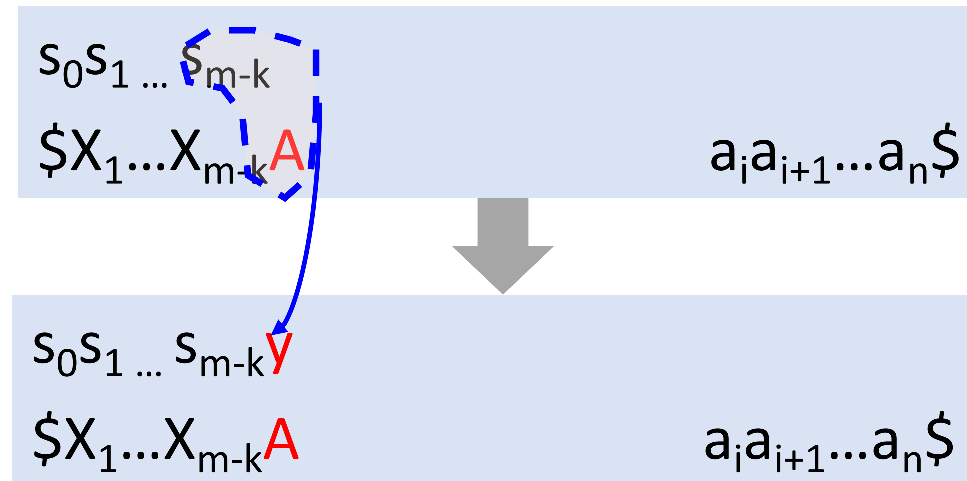
$\$$ $\quad a_1a_2 \ldots a_n\$$

General

$s_0s_1 \ldots s_m$

$\$X_1 \ldots X_m$ $\quad a_ia_{i+1} \ldots a_n\$$

- If ACTION[s_m, a_i] = r**x**, (i.e., the xth production: $A \rightarrow X_{m-(k-1)} \ldots X_m$), then do **reduce**[规约]
  - Pops *k* symbols from stack
  - Pushes *A* on stack
  - No change on input
  - GOTO[S_{m-k}, A] = y, then
    - 需寻找下一状态



Parser Actions (cont.)

Initial	s_0 $\$$	$a_1a_2...a_n\$$
General	$s_0s_1 ... s_m$ $\$X_1...X_m$	$a_ia_{i+1}...a_n\$$

- If ACTION[s_m, a_i] = acc, then parsing is **complete**[接收]

- If ACTION[s_m, a_i] = <empty>, then report **error** and stop[报错]

LR Parsing Program[解析程序]

- **Input**: input string ω and parse table with ACTION/GOTO
- **Output**: shift-reduce steps of ω's bottom-up parsing, or error
- **Initial**: s_0 on the stack, ω$ in the input buffer

```
let a be the first symbol of ω$
while (1) { /* repeat forever */
      let s be the state on top of the stack;
      if (ACTION[s,a] = shift t) {
            push a onto the stack;
            push t onto the stack;
            advance to next symbol in ω;
      } else if (ACTION[s,a] = reduce A -> β) {
            pop |β| symbols off the stack;
            let state t now be on top of the stack;
            push GOTO[t,A] onto the stack;
            output the production A-> β;
      } else if (ACTION[s,a] = accept) break; /* parsing is done */
      else call error-recovery routine;
}
```

Construct Parse Table[构建解析表]

- Construct parsing table: identify the possible states and arrange the transitions among them[状态及转换]
- **LR(0)** parsing
  - Simplest LR parsing, only considers stack to decide shift/reduce
  - Weakest, not used much in practice because of its limitations
- **SLR(1)** parsing / SLR
  - Simple LR, lookahead from first/follow rules derived from LR(0)
  - Keeps table as small as LR(0)
- **LR(1)** parsing / canonical LR / LR
  - LR parser that considers next token (lookahead of 1)
  - Compared to LR(0), more complex alg and much bigger table
- **LALR(1)** parsing / lookahead LR / LALR
  - Lookahead LR(1): fancier lookahead analysis using the same LR(0) automaton as SLR(1)

State	ACTION			GOTO	
	a	b	$	S	B
0	s3	s4		1	2
1			acc		
2	s3	s4			5
3	s3	s4			6
4	r3	r3	r3		
5	r1	r1	r1		
6	r2	r2	r2		

State in LR Parsing[状态]

- How does a shift-reduce parser know when to shift and when to reduce?[何时移进？何时规约？]
  - For the example, how does parser know that *int* on the top of the stack is not a handle, so the action is shift but not to reduce (T ← int)?
- An LR parser makes shift-reduce decisions by maintaining **states** to keep track of where we are in a parse[状态追踪]
  - States represent sets of "**items**"

Grammar

E → T+E|T

T → int*T | int | (E)

String

int * int + int

Step	Operation
#int * int + int	Shift
int# * int + int	Shift
int * #int + int	Shift
int * **int** # + int	Reduce T → int
int * T # + int	Reduce T → int*T

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Item[项目]

- An **item** is a production with a "·" somewhere on the RHS
  - Dot indicates extent of RHS already seen in the parsing process
    - Everything to the left of the dot has been shifted onto the parsing stack
  - The only item for X → ε is X → ·
  - Items are often called "**LR(0) items**" (a.k.a., **configuration**)
- The items for A → XYZ are
  - A → ·XYZ
    - Indicates that we hope to see a string derivable from XYZ next on the input
  - A → X·YZ
    - Indicates that we have just seen on the input a string derivable from X and that we hope next to see a string derivable from YZ
  - A → XY·Z
  - A → XYZ·
    - Indicates that we have seen the body XYZ and that it may be time to reduce XYZ to A

Item (cont.)

- Example:
  - Suppose we are currently in this position

    A → X·YZ
  - We have just recognized X and expect the upcoming input to contain a sequence derivable from YZ (say, Y → u|w)[已经识别了X，期待YZ推导的串]
    - Y is further derivable from either u or w

      A → X·YZ

      Y → ·u

      Y → ·w
  - The above three items can be placed into a set, called as **configuration set**[配置集] of the LR parser
- Parsing tables have one **state** corresponding to each set
  - The states can be modeled as a finite automaton where we move from one state to another via transitions marked with a symbol of the CFG

Augmented Grammar[增广文法]

- We want to start with an item with a dot before the start symbol *S* and move to an item with a dot after *S*
  - Represents shifting and reducing an entire sentence of the grammar[完成了整个句子的移进规约]
  - Thus, we need *S* to appear on the right side of a production
  - Only one ‘acc’ in the table
- Modify the grammar by adding the production[修改文法]
  S’ → ·S

Grammar:

(1) E → E + T
(2) E → T
(3) T → T * F
… …

Augmented grammar:

(0) E’ → E
(1) E → E + T
(2) E → T
(3) T → T * F
… …

Example

(0) S' → S	(1) S → BB	(2) B → aB	(3) B → b
	S → ·BB	B → ·aB	
S' → ·S	S → B·B	B → a·B	B → ·b
S' → S·	S → BB·	B → aB·	B → b·

Initial item

Reduce item

Accept item

- **Closure**: the action of adding equivalent items to a set
  - Example: S' → ·S S → ·BB B → ·aB B → ·b
- Intuitively, A → α·Bβ means that we might next see a substring derivable from Bβ (_*sub*) as input. The _*sub* will have a prefix derivable from B by applying one of the B-productions[期待意义等价]
  - Thus, we add items for all the B-productions, i.e., if B → γ is a production, we add B → ·γ in the closure

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Example

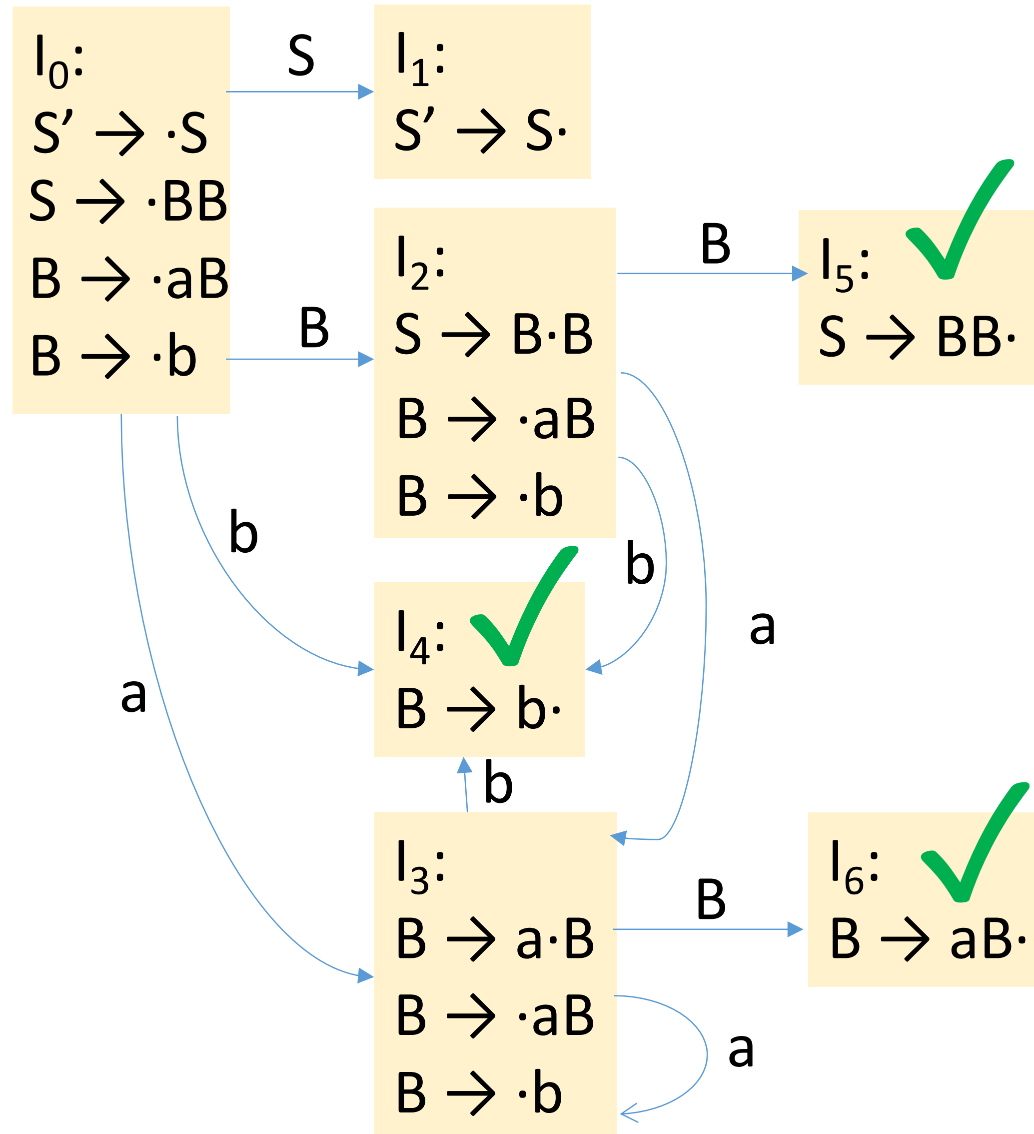
Grammar:

(0) S' → S

(1) S → BB

(2) B → aB

(3) B → b



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Example (cont.)

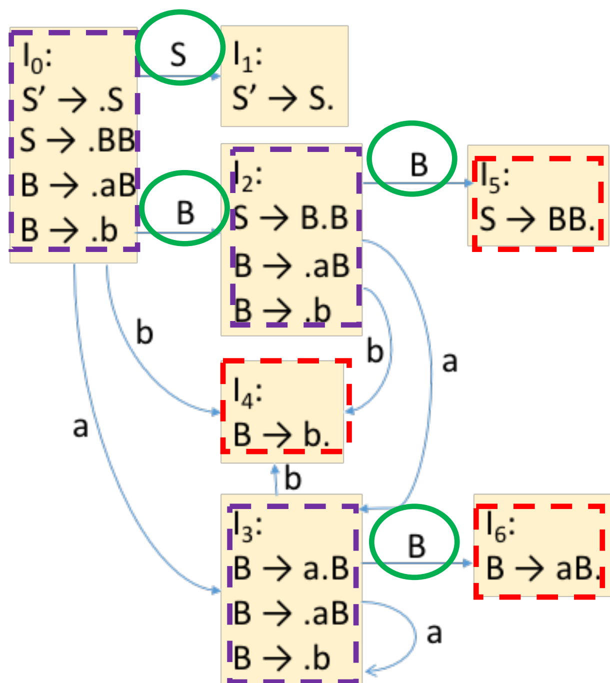
Grammar:

(0) S' → S

(1) S → BB

(2) B → aB

(3) B → b



State	ACTION			GOTO	
	a	b	$	S	B
0	s3	s4		1	2
1			acc		
2	s3	s4			5
3	s3	s4			6
4	r3	r3	r3		
5	r1	r1	r1		
6	r2	r2	r2		

"state *j*" refers to the state corresponding to the set of items I_j

CLOSURE()[闭包]

- **Closure of item sets**: if *I* is a set of items for a grammar *G*, then *closure(I)* is the set of items constructed from *I* by the two rules:
  - Initially, add every item in *I* to *CLOSURE(I)*
  - If A → α·Bβ is in *CLOSURE(I)* and B → γ is a production, then add item B → ·γ to *CLOSURE(I)*, if it is not already there
    - Apply this rule until no more new items can be added to *CLOSURE(I)*

Grammar:

(0) S' → S

(1) S → BB

(2) B → aB

(3) B → b

S' → ·S

S' → ·S

S → ·BB

B → ·aB

B → ·b

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GOTO()[跳转]

- GOTO(*I*, *X*): returns state (i.e., set of items) that can be reached by advancing X
  - Where *I* is a set of items and *X* is a grammar symbol
  - The closure of the set of all items [A → αX·β] such that [A → α·Xβ] is in *I*
  - Used to define the transitions in the LR(0) automaton
    - The states of the automaton correspond to sets of items, and GOTO(I, X) specifies the transition from the state for *I* under input *X*

Grammar:

(0) S' → S

(1) S → BB

(2) B → aB

(3) B → b

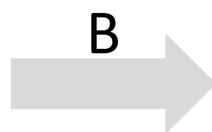
I_0:

S' → ·S

S → ·BB

B → ·aB

B → ·b



I_2:

S → B·B

B → ·aB

B → ·b

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Construct LR(0) States

- [增广文法]Create augmented grammar G’ for G
  - Given G: $S \rightarrow \alpha \mid \beta$, create G’: $S' \rightarrow S \quad S \rightarrow \alpha \mid \beta$
  - Creates a single rule $S' \rightarrow S$ that when reduced, signals acceptance
- [初始状态]Create 1st state by performing a closure on initial item $S' \rightarrow \cdot S$
  - Closure(I): creates state from an initial set of items I
  - $\text{Closure}(\{S' \rightarrow \cdot S\}) = \{S' \rightarrow \cdot S, S \rightarrow \cdot\alpha, S \rightarrow \cdot\beta\}$
- [添加状态]Create additional states by performing a goto on each symbol
  - Goto(I, X): creates state that can be reached from I by advancing X
  - If α was single symbol, the following new state would be created:

    $\text{Goto}(\{S' \rightarrow \cdot S, S \rightarrow \cdot\alpha, S \rightarrow \cdot\beta\}, \alpha) =$

    $\text{Closure}(\{S \rightarrow \alpha\cdot\}) = \{S \rightarrow \alpha\cdot\}$
- [重复操作]Repeatedly perform gotos until there are no more states to add

Construct DFA

- Compute canonical LR(0) collection[规范LR(0)项集族, C], i.e., set of all states in DFA
  - One collection of sets of LR(0) items provides the basis for constructing a DFA that is used to make parsing decisions
  - Such an automaton is called an **LR(0) automaton**
    - Each state of the LR(0) automaton represents a set of items in the C
- All new states are added through GOTO(I, X)
  - State transitions are done on symbol X

```
void items(G') {                        // G': the augmented grammar
   C = { CLOSURE({[S' → ·S]}) }; // C: the canonical collection of sets of LR(0) items
   repeat
      for ( each state I in C )
            for ( each grammar symbol X )
               if ( GOTO(I, X) is not empty and not in C)
                  add GOTO(I, X) to C;
    until no new states are added to C
}
```

LR(0) Automaton[自动机]

- The LR(0) automaton: each time we perform a shift we are following a transition to a new state
  - States: the sets of items in C
    - Start state: CLOSURE({[S' → ·S]})
    - State *j* refers to the state corresponding to the set of items I_j
  - Transitions are given by the GOTO function
- How can the automaton help with shift-reduce decisions?
  - Suppose that the string γ of grammar symbols takes the LR(0) automaton from the start state *0* to some state *j*
  - Then, shift on next input symbol *a* if state *j* has a transition on *a*
  - Otherwise, we choose to reduce
    - The items in state *j* tell us which production to use (e.g., $E \to \alpha$)
    - $E \to \alpha$: pop states for α, bringing state *x* to the top and look for a transition on *E* to state *y* (i.e., state *x* has a transition on *E* to state *y*), which is then pushed to stack

The Example

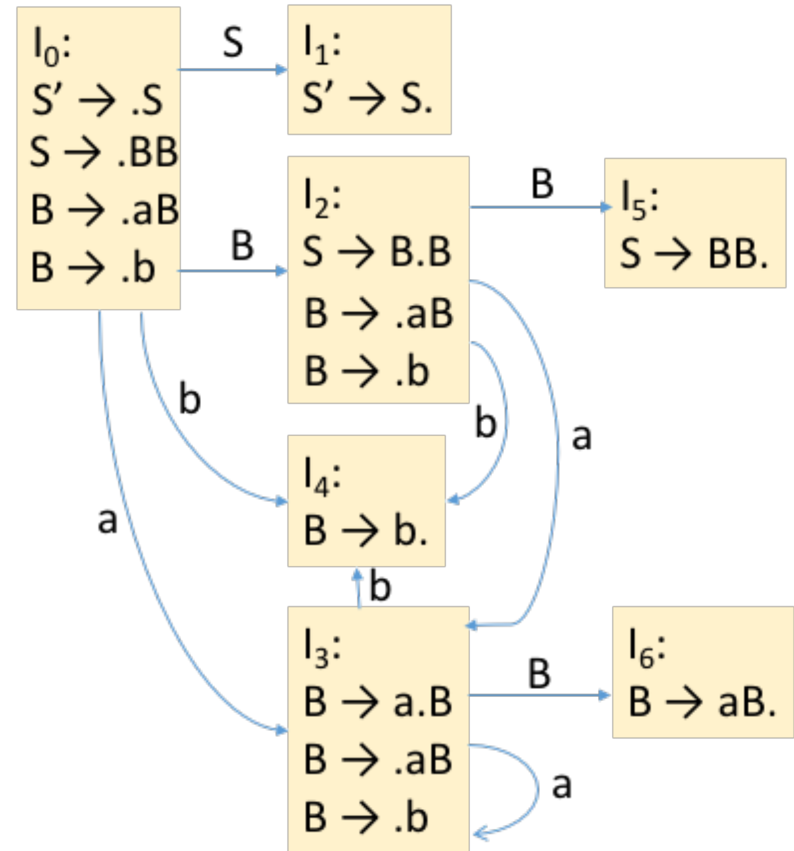
Grammar:

(0) S’ → S

(1) S → BB

(2) B → aB

(3) B → b



- S_0 = Closure({S’ → .S})
  = {S’ →.S, S →.BB, B → .aB, B → .b}
- Goto(S_0, B) = closure({S → B.B})
  S_2 = {S →B.B, B → .aB, B → .b}
- Goto(S_0, a) = closure({B → a.B})
  S_3 = {B →a.B, B → .aB, B → .b}
- Goto(S_0, b) = closure({B → b.})
  S_4 = {B → b.}

… … …

Build Parse Table from DFA

- ACTION [*state, terminal symbol*]
- GOTO [*state, non-terminal symbol*]
- ACTION[动作]
  - If [A→α·aβ] is in S_i and goto(S_i, a) = S_j, where "a" is a terminal then ACTION[S_i, a] = shift j (s*j*)
  - If [A→α·] is in S_i and A→α is rule numbered j then ACTION[S_i, a] = reduce j (r*j*)
  - If [S' →S·] is in S_i then ACTION[S_i, $] = accept
  - If no conflicts among 'shift' and 'reduce' (the first two 'if's) then this parser is able to parse the given grammar
- GOTO[跳转]
  - if goto(S_i, A) = S_j then GOTO[S_i, A] = *j*
- All entries not filled are rejects

State	ACTION			GOTO	
	a	b	$	S	B
0	s3	s4		1	2
1			acc		
2	s3	s4			5
3	s3	s4			6
4	r3	r3	r3		
5	r1	r1	r1		
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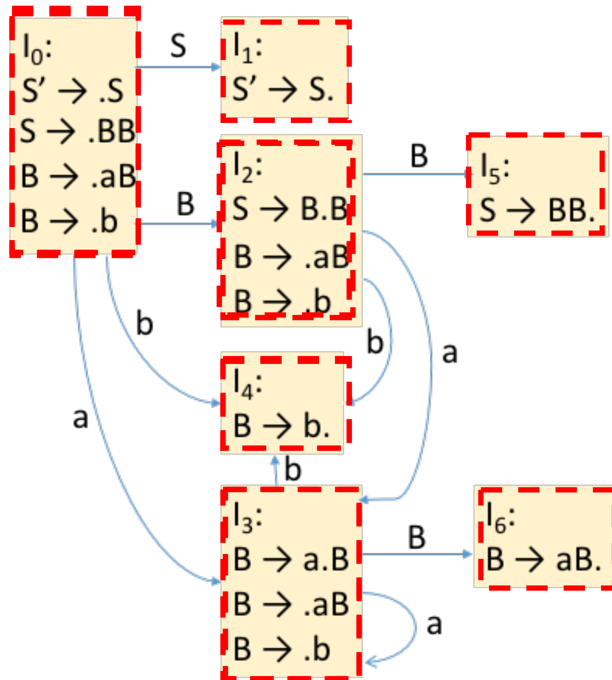

State	ACTION			GOTO	
	a	b	$	S	B
0	s3	s4		1	2
1			acc		
2	s3	s4			5
3	s3	s4			6
4	r3	r3	r3		
5	r1	r1	r1		
6	r2	r2	r2		

String: bab

#bab$ => b#ab$ => B#ab$ => Ba#b$
=> Bab#$ => BaB#$ => BB#$ => S#$