LL Parsing

Traditional Parsing Algorithms

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Recap: Lexical Analysis
lessons learned

What are the formalisms to describe regular languages?

- regular grammars
- regular expressions
- finite state automata

Why are these formalisms equivalent?

- constructive proofs

How can we generate compiler tools from that?

- implement DFAs
- generate transition tables

Overview

today's lecture

Overview
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efficient parsing algorithms

- predictive/recursive descent parsing
- LL parsing

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grammar classes

- LL(k) grammars
- LR(k) grammars

Overview
today's lecture

efficient parsing algorithms

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grammar classes

- LL(k) grammars
- LR(k) grammars

more top-down parsing algorithms

- Parser Combinators
- Parsing Expression Grammars
- ALL(*)

I

Predictive (Recursive Descent) Parsing

Recap: A Theory of Language

formal languages

Recap: A Theory of Language

formal languages

vocabulary Σ

finite, nonempty set of elements (words, letters)

alphabet

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finite, nonempty set of elements (words, letters)

alphabet

string over Σ

finite sequence of elements chosen from Σ

word, sentence, utterance

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finite, nonempty set of elements (words, letters)

alphabet

string over Σ

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word, sentence, utterance

formal language λ

set of strings over a vocabulary Σ

$\lambda \subseteq \Sigma^*$

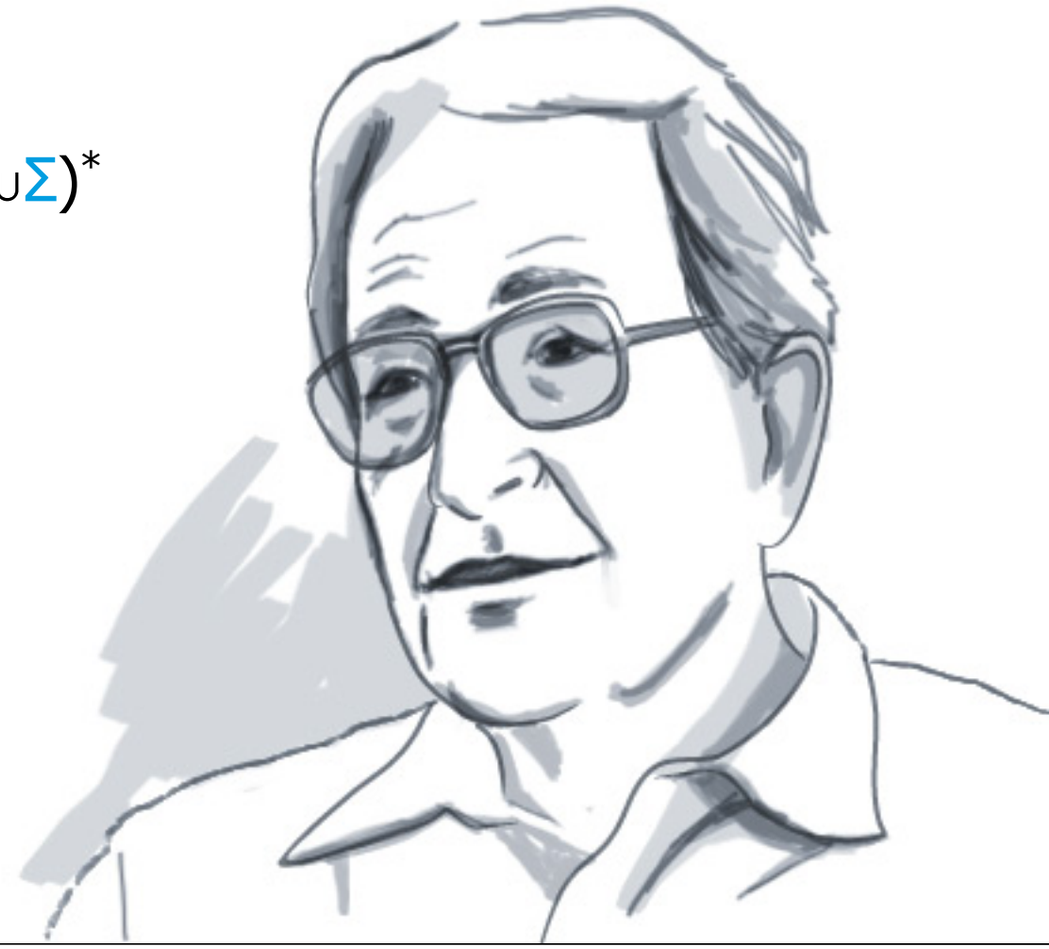
Recap: A Theory of Language

formal grammars

Recap: A Theory of Language
formal grammars

formal grammar $G = (N, \Sigma, P, S)$

- nonterminal symbols N
- terminal symbols Σ
- production rules $P \subseteq (N \cup \Sigma)^* \; N \; (N \cup \Sigma)^* \times (N \cup \Sigma)^*$
- start symbol $S \in N$



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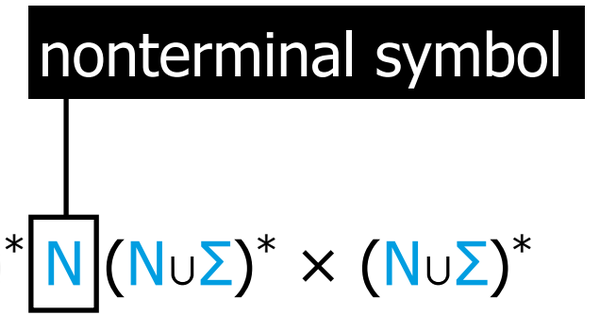

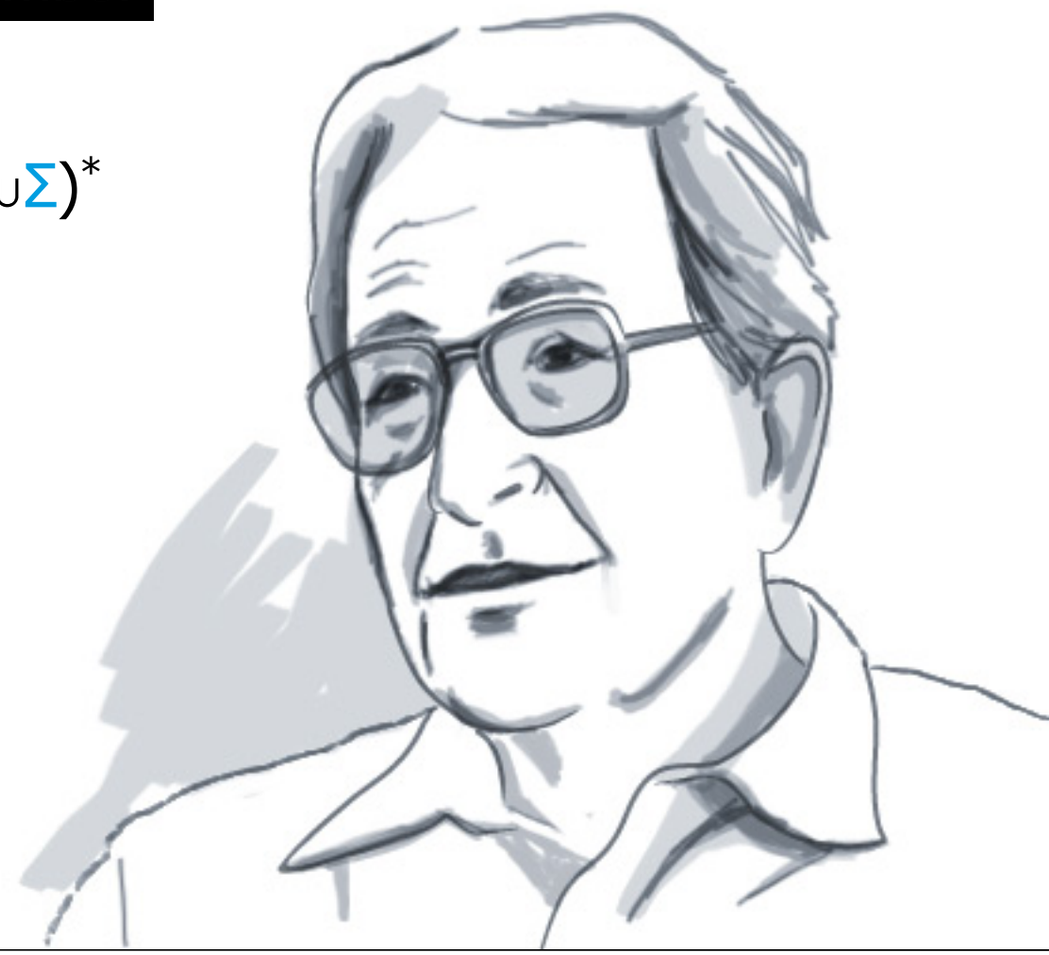

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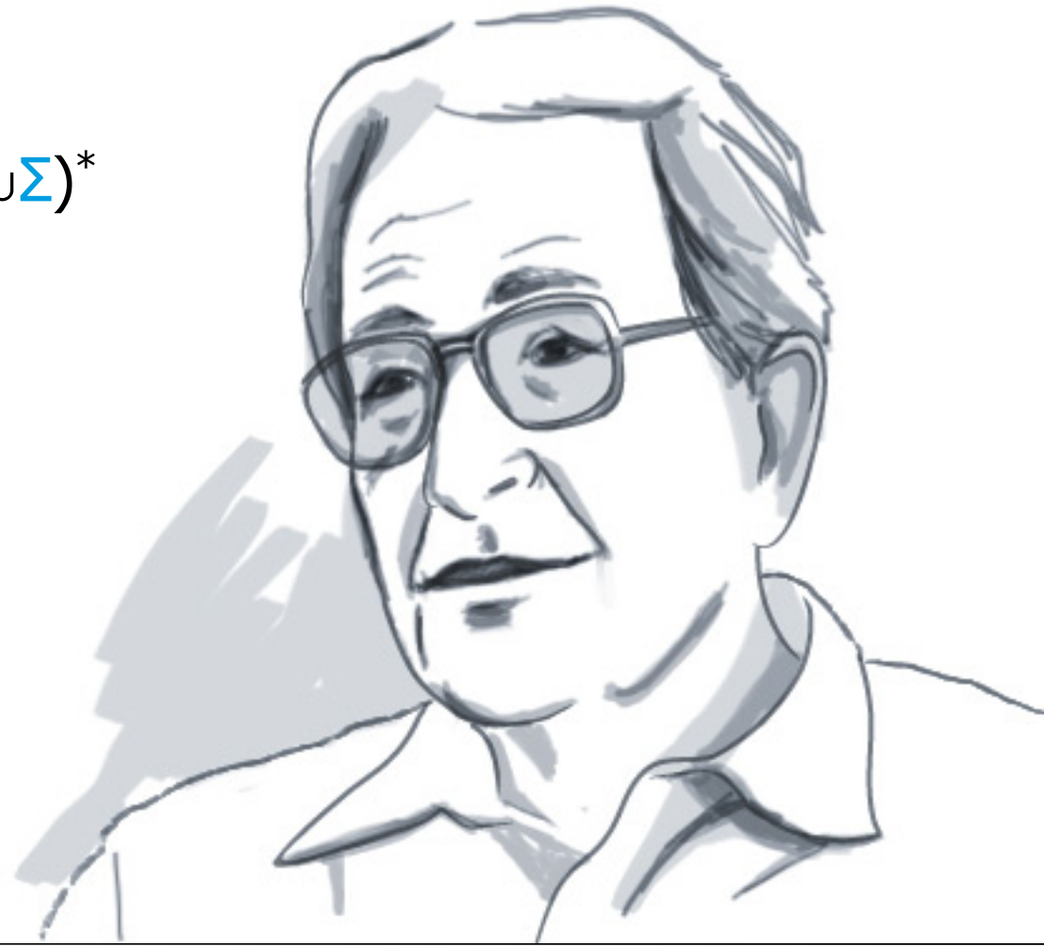
context



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- start symbol $S \in N$

replacement

Recap: A Theory of Language
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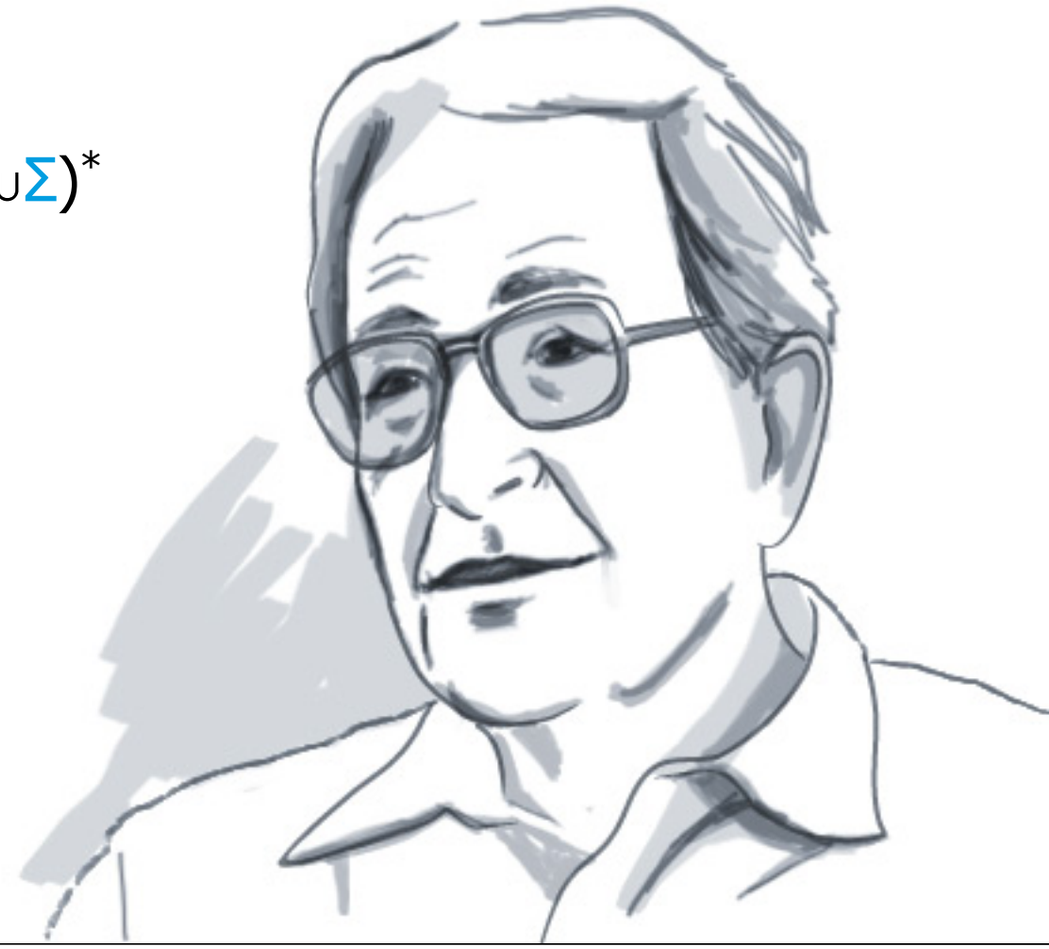
- start symbol $S \in N$

grammar classes

- type-0, unrestricted
- type-1, context-sensitive: (a A c, a b c)
- type-2, context-free: $P \subseteq N \times (N \cup \Sigma)^*$
- type-3, regular: (A, x) or (A, xB)



Recap: A Theory of Language

formal languages

Recap: A Theory of Language

formal languages

formal grammar G = (N, Σ, P, S)

Recap: A Theory of Language
formal languages

formal grammar $G = (N, \Sigma, P, S)$

derivation relation $\Rightarrow_G \subseteq (N \cup \Sigma)^* \times (N \cup \Sigma)^*$

$w \Rightarrow_G w' \Leftrightarrow$

$\exists (p, q) \in P: \exists u, v \in (N \cup \Sigma)^*:$

$w = u\ p\ v \wedge w' = u\ q\ v$

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formal language $L(G) \subseteq \Sigma^*$

$L(G) = \{w \in \Sigma^* \mid S \Rightarrow_G^* w\}$

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formal language $L(G) \subseteq \Sigma^*$

$L(G) = \{w \in \Sigma^* \mid S \Rightarrow_G^* w\}$

classes of formal languages

Predictive parsing
recursive descent

Exp → “while” Exp “do” Exp

```
public void parseExp() {
    consume(WHILE);
    parseExp();
    consume(DO);
    parseExp();
}
```

Predictive parsing

look ahead

Exp → “while” Exp “do” Exp

Exp → “if” Exp “then” Exp “else” Exp

```
public void parseExp() {

   switch current() {
      case WHILE: consume(WHILE); parseExp(); ...; break;
      case IF   : consume(IF); parseExp(); ...; break;
      default   : error();
   }
}
```

Predictive parsing

parse table

rows

- nonterminal symbols N

- symbol to parse

columns

- terminal symbols Σ^k

- look ahead k

entries

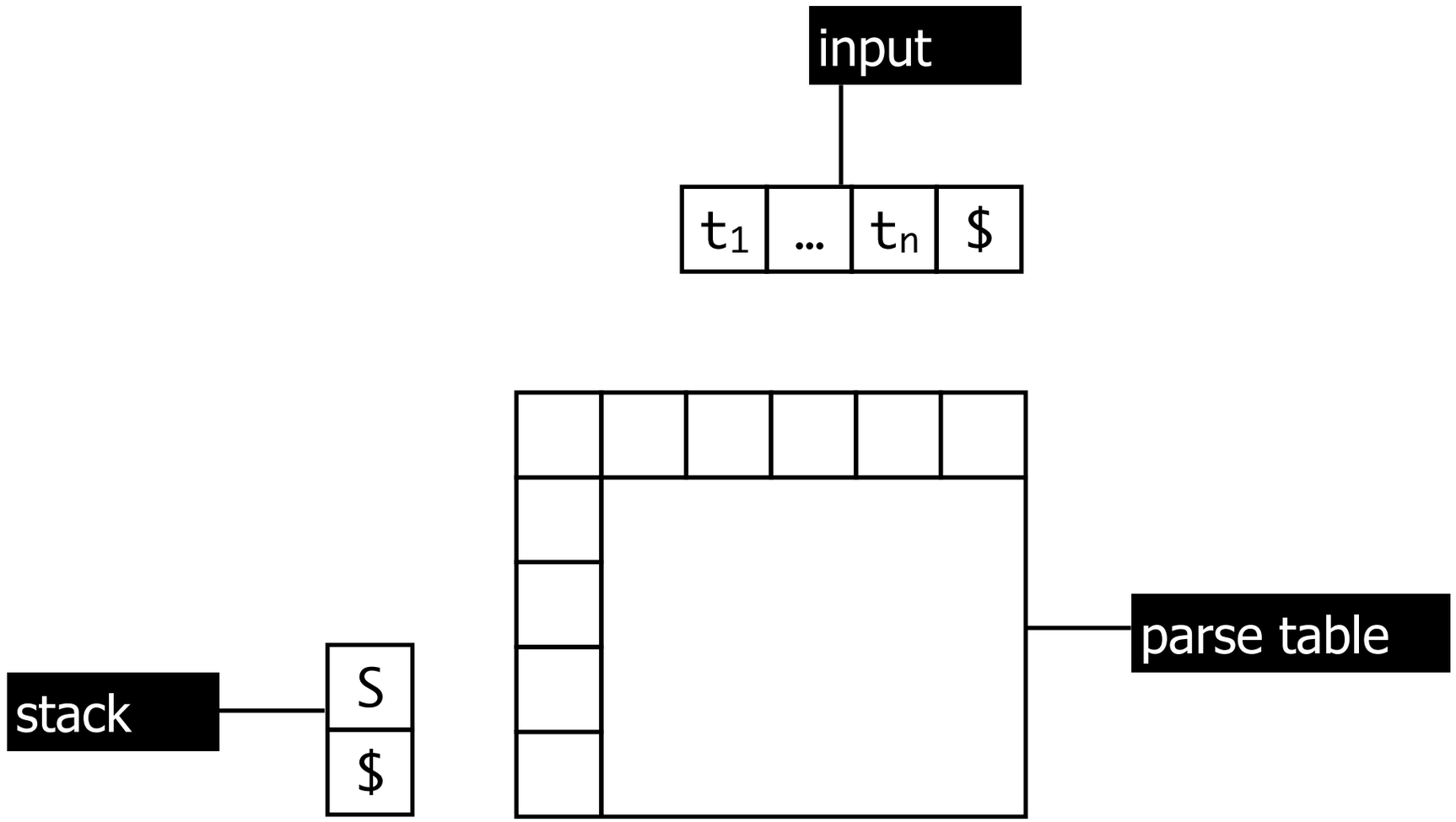
- production rules P

- possible conflicts

	T_1	T_2	T_3	...
N_1	$N_1 \rightarrow$...		$N_1 \rightarrow$...	
N_2		$N_2 \rightarrow$...		
N_3		$N_3 \rightarrow$...	$N_3 \rightarrow$...	
N_4	$N_4 \rightarrow$...			
N_5		$N_5 \rightarrow$...		
N_6	$N_6 \rightarrow$...	$N_6 \rightarrow$...		
N_7			$N_7 \rightarrow$...	
N_8	$N_8 \rightarrow$...	$N_8 \rightarrow$...	$N_8 \rightarrow$...	
...				

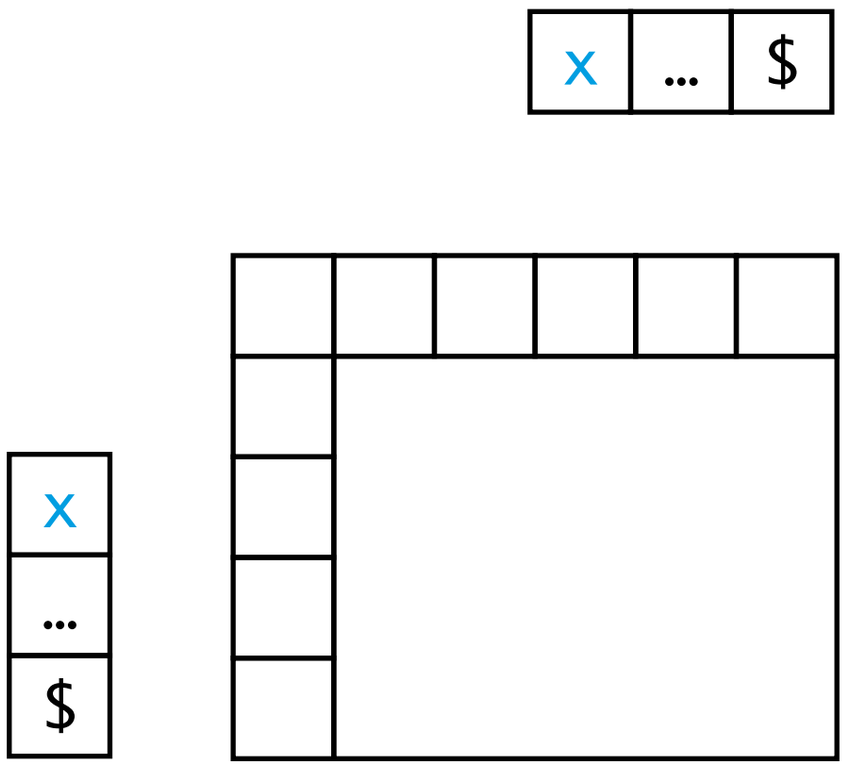
Predictive parsing

automaton



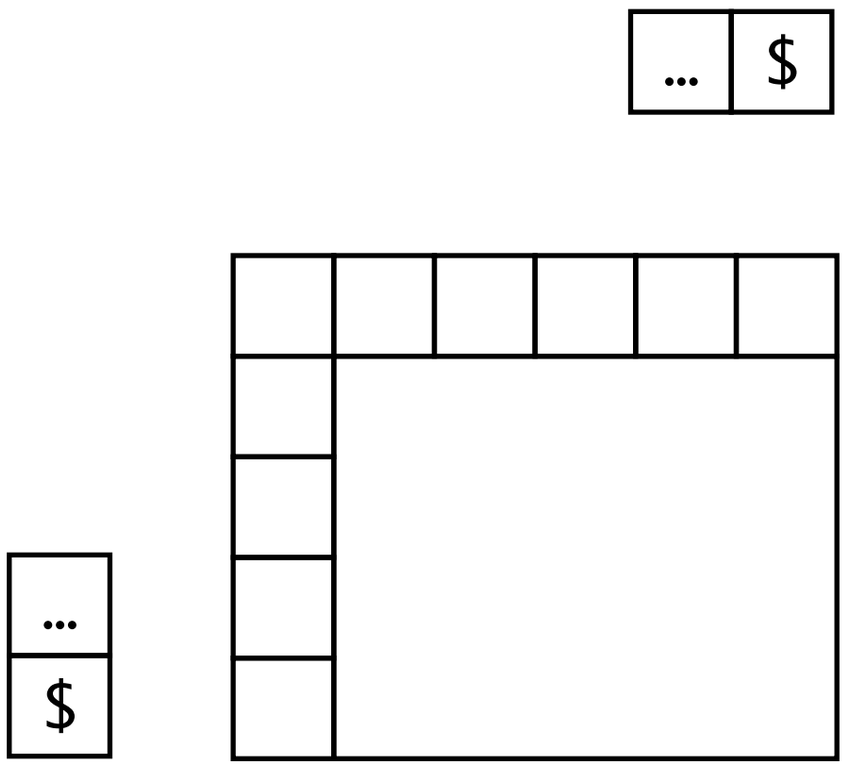
Predictive parsing

automaton



Predictive parsing

automaton



Predictive parsing

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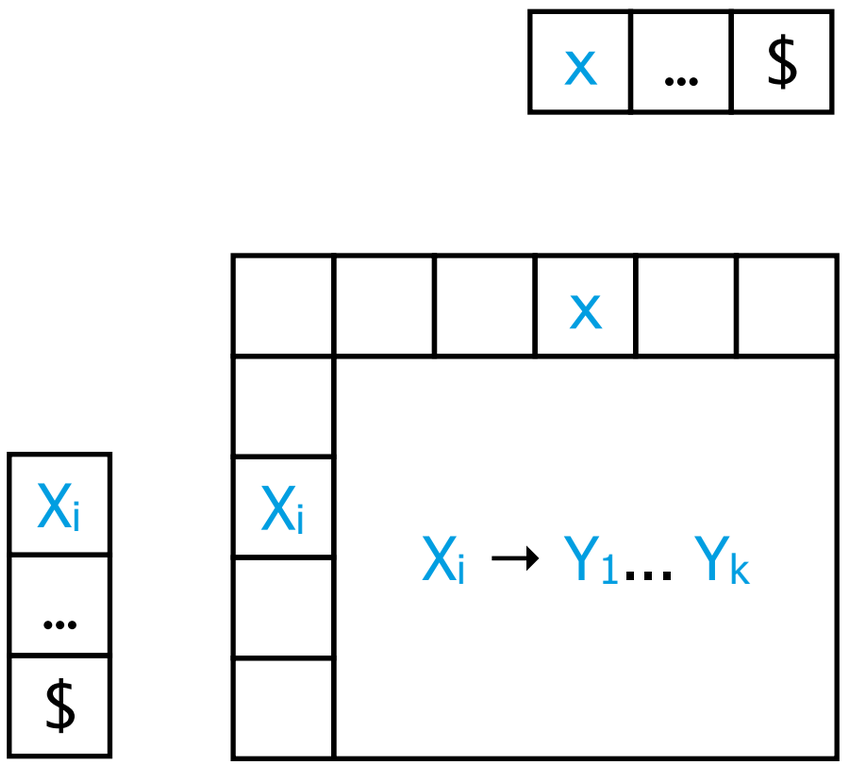
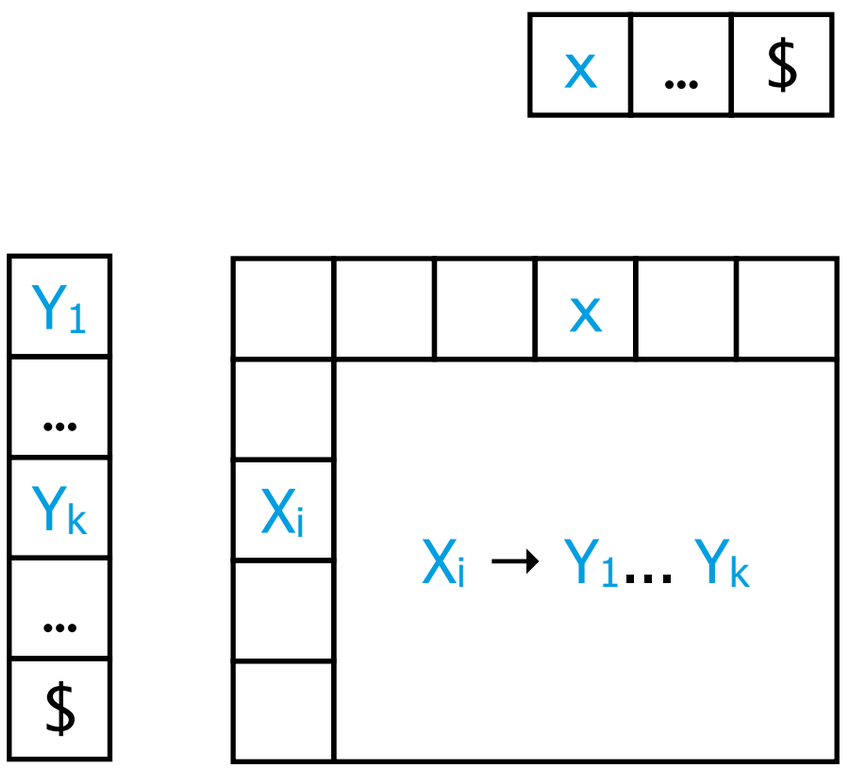


Predictive parsing

automaton



II

LL Parse Tables

Predictive parsing
filling the table

entry $(X, w) \in P$ at row X and column T

$T \in \text{FIRST}(w)$

$\text{nullable}(w) \wedge T \in \text{FOLLOW}(X)$

Predictive parsing
filling the table

entry $(X, w) \in P$ at row X and column T

$T \in$ FIRST(w) — letters that w can start with

nullable$(w) \wedge T \in$ FOLLOW(X)

Predictive parsing
filling the table

entry $(X, w) \in P$ at row X and column T

$T \in \text{FIRST}(w)$

$\text{nullable}(w) \wedge T \in \text{FOLLOW}(X)$

$w \Rightarrow_G^* \varepsilon$

Predictive parsing
filling the table

entry $(X, w) \in P$ at row X and column T

$T \in \text{FIRST}(w)$

$\text{nullable}(w) \wedge T \in \text{FOLLOW}(X)$ — letters that can follow X

Predictive parsing
nullable

nullable(X)

$(X, \varepsilon) \in P \Rightarrow \text{nullable}(X)$

$(X_0, X_1 \ldots X_k) \in P \wedge \text{nullable}(X_1) \wedge \ldots \wedge \text{nullable}(X_k) \Rightarrow \text{nullable}(X_0)$

nullable(w)

nullable(ε)

$\text{nullable}(X_1 \ldots X_k) = \text{nullable}(X_1) \wedge \ldots \wedge \text{nullable}(X_k)$

Predictive parsing

first sets

FIRST(X)

$X \in \Sigma$: FIRST(X) = {X}

$(X_0, X_1 \ldots X_i \ldots X_k) \in P \wedge \text{nullable}(X_1 \ldots X_i) \Rightarrow \text{FIRST}(X_0) \supseteq \text{FIRST}(X_{i+1})$

FIRST(w)

FIRST(ε) = {}

¬nullable(X) ⇒ FIRST(Xw) = FIRST(X)

nullable(X) ⇒ FIRST(Xw) = FIRST(X) ∪ FIRST(w)

Predictive parsing

follow sets

FOLLOW(X)

$(X_0, X_1 \ldots X_i \ldots X_k) \in P \wedge \text{nullable}(X_{i+1} \ldots X_k) \Rightarrow \text{FOLLOW}(X_i) \supseteq \text{FOLLOW}(X_0)$

$(X_0, X_1 \ldots X_i \ldots X_k) \in P \Rightarrow \text{FOLLOW}(X_i) \supseteq \text{FIRST}(X_{i+1} \ldots X_k)$

Example

p0: Start → Exp EOF
p1: Exp → Term Exp’
p2: Exp’ → “+” Term Exp’
p3: Exp’ →
p4: Term → Fact Term’
p5: Term’ → “*” Fact Term’
p6: Term’ →
p7: Fact → Num
p8: Fact → “(” Exp “)”

	nullable	FIRST	FOLLOW
Start			
Exp			
Exp’			
Term			
Term’			
Fact			

Example
nullable

$(X, \varepsilon) \in P \Rightarrow \text{nullable}(X)$

$(X_0, X_1 \ldots X_k) \in P \wedge$

$\text{nullable}(X_1) \wedge \ldots \wedge \text{nullable}(X_k) \Rightarrow \text{nullable}(X_0)$

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p8: Fact → “(” Exp “)”

	nullable	FIRST	FOLLOW
Start	no		
Exp	no		
Exp’	yes		
Term	no		
Term’	yes		
Fact	no		

Example

FIRST sets

$(X_0, X_1 \ldots X_i \ldots X_k) \in P \wedge$

$\text{nullable}(X_1 \ldots X_i) \Rightarrow \text{FIRST}(X_0) \supseteq \text{FIRST}(X_{i+1})$

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p8: Fact → “(” Exp “)”

	nullable	FIRST	FOLLOW
Start	no		
Exp	no		
Exp’	yes		
Term	no		
Term’	yes		
Fact	no		

Example

FIRST sets

$(X_0, X_1 \ldots X_i \ldots X_k) \in P \wedge$

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p6: Term’ →
p7: Fact → Num
p8: Fact → “(” Exp “)”

	nullable	FIRST	FOLLOW
Start	no	Num (	
Exp	no	Num (	
Exp’	yes	+	
Term	no	Num (	
Term’	yes	*	
Fact	no	Num (	

Example
FOLLOW sets

$(X_0, X_1 \ldots X_i \ldots X_k) \in P \wedge$

$\text{nullable}(X_{i+1} \ldots X_k) \Rightarrow \text{FOLLOW}(X_i) \supseteq \text{FOLLOW}(X_0)$

$(X_0, X_1 \ldots X_i \ldots X_k) \in P \Rightarrow \text{FOLLOW}(X_i) \supseteq \text{FIRST}(X_{i+1} \ldots X_k)$

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	nullable	FIRST	FOLLOW
Start	no	Num (	
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Term	no	Num (	
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Example
FOLLOW sets

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p7: Fact → Num
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	nullable	FIRST	FOLLOW
Start	no	Num (	
Exp	no	Num (	) EOF
Exp’	yes	+	) EOF
Term	no	Num (	+) EOF
Term’	yes	*	+) EOF
Fact	no	Num (	* +) EOF

Example

LL parse table

entry (X, w)∈P at row X and column T

T∈ FIRST(w)

nullable(w) ∧ T∈ FOLLOW(X)

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	+	*	Num	(	)	EOF
Start						
Exp						
Exp’						
Term						
Term’						
Fact						

Example

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	+	*	Num	(	)	EOF
Start			p0	p0		
Exp			p1	p1		
Exp’	p2				p3	p3
Term			p4	p4		
Term’	p6	p5			p6	p6
Fact			p7	p8		

Example

parsing (4+3)*6 EOF

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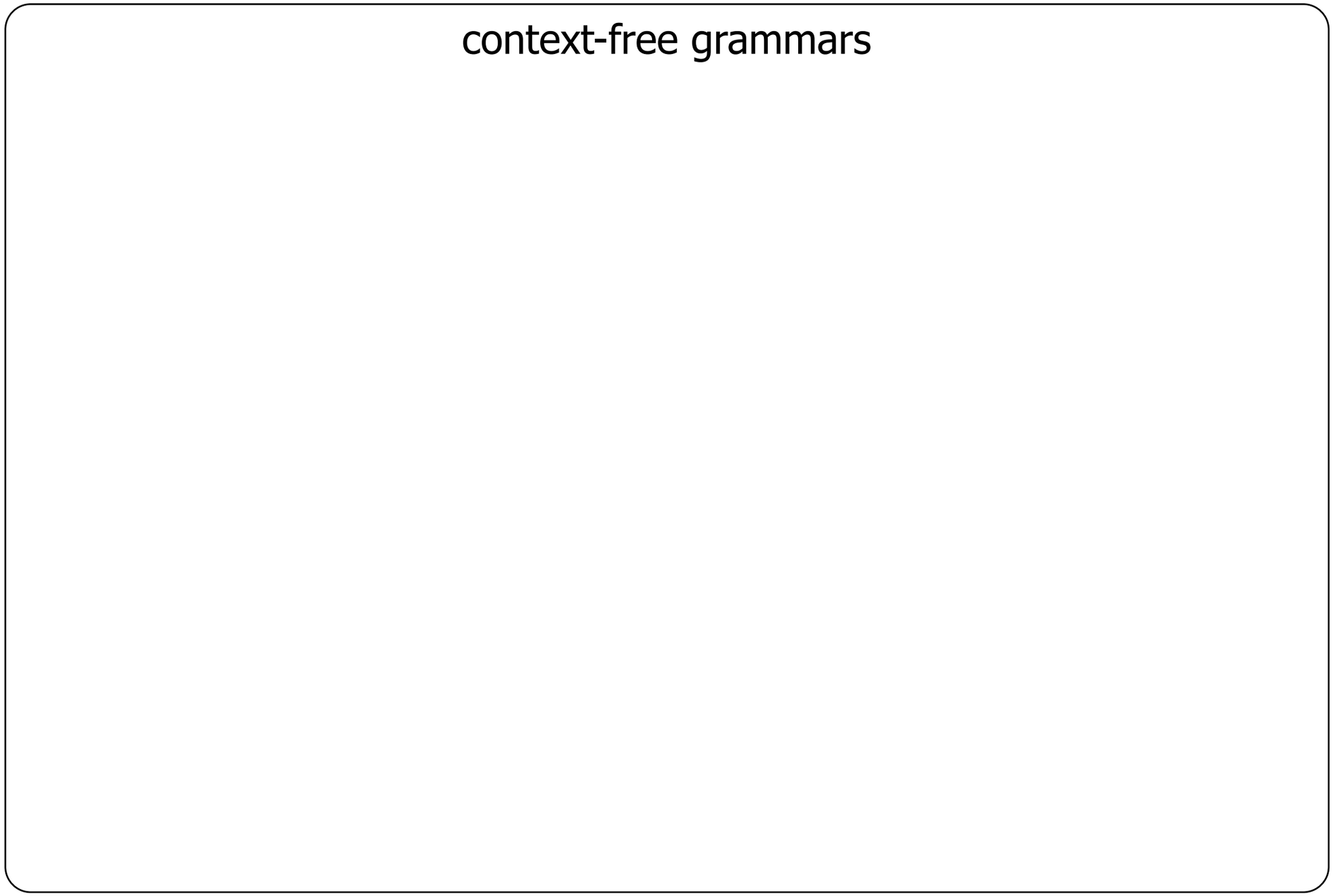
	+	*	Num	(	)	EOF
Start			p0	p0		
Exp			p1	p1		
Exp’	p2				p3	p3
Term			p4	p4		
Term’	p6	p5			p6	p6
Fact			p7	p8		

Grammar classes



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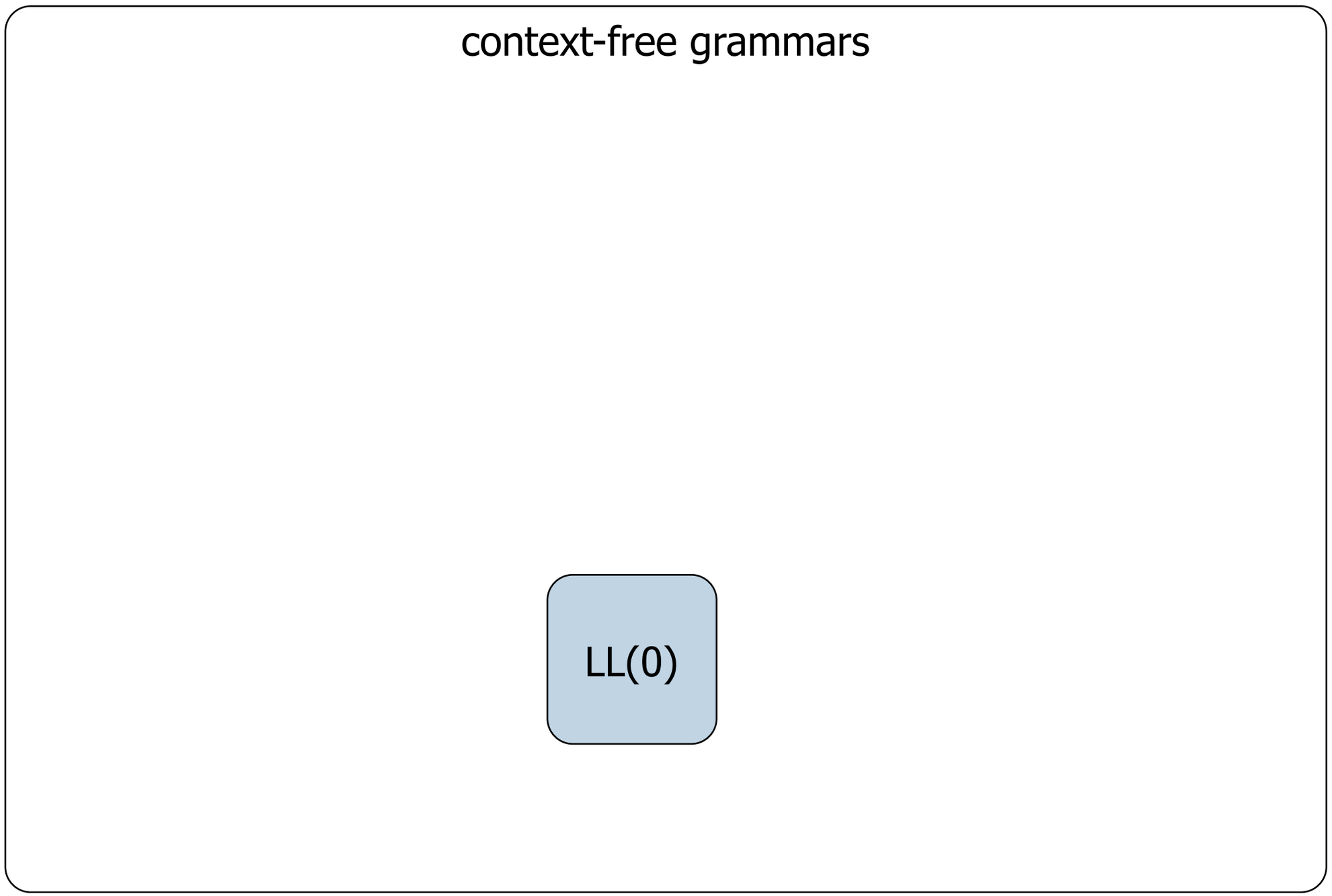
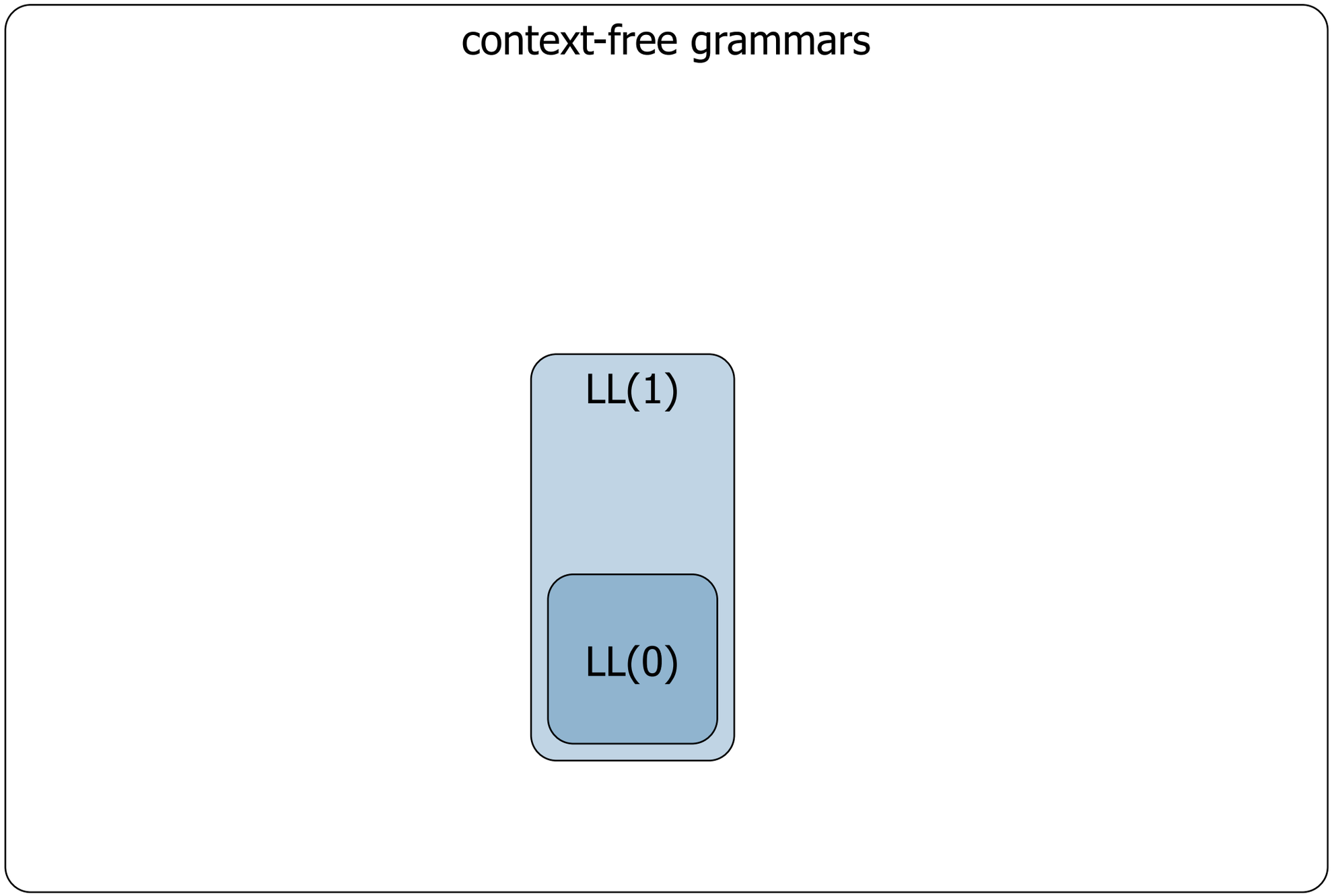


Grammar classes



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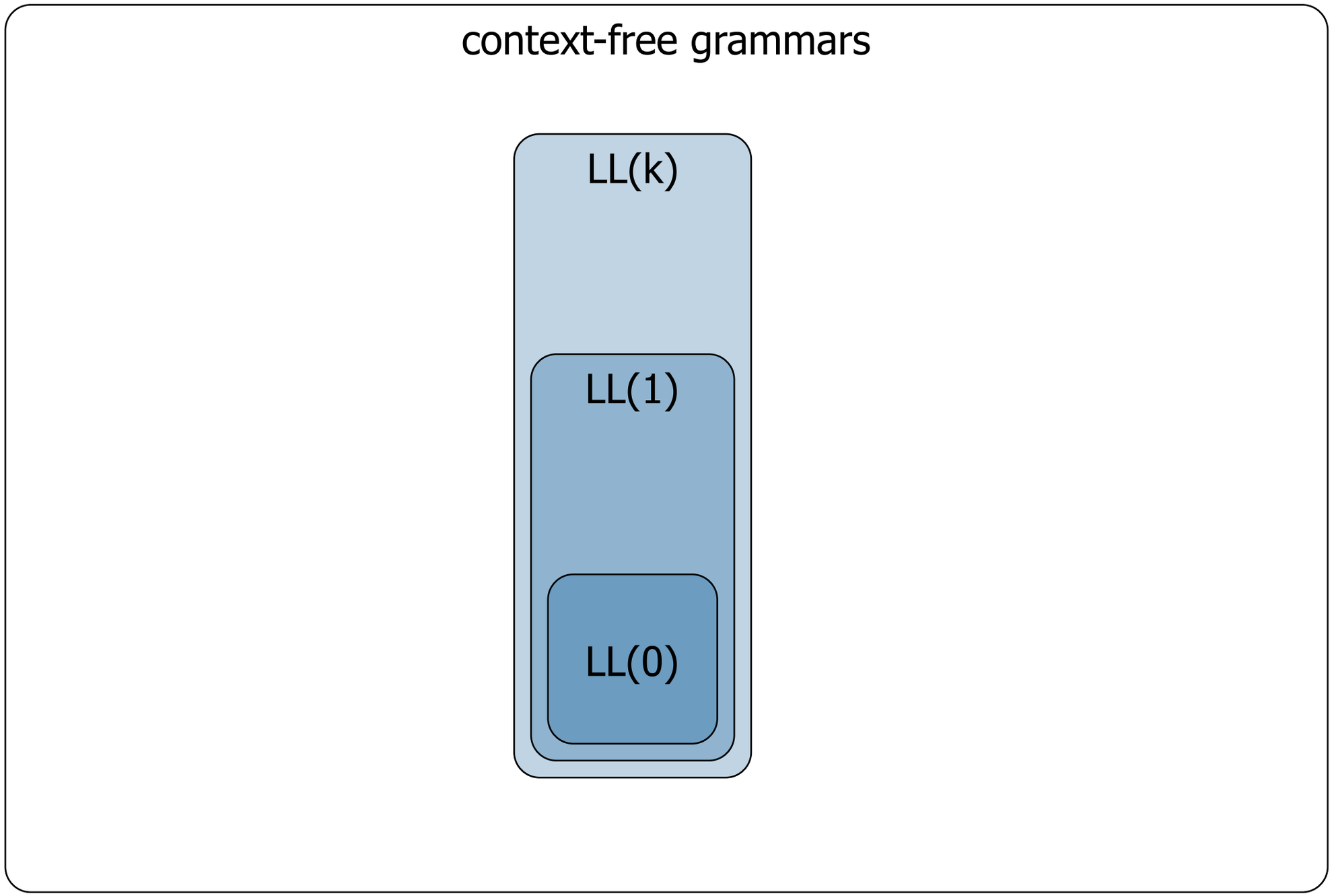


Predictive parsing
encoding precedence

Exp → Num
Exp → "(" Exp ")"
Exp → Exp "*" Exp
Exp → Exp "+" Exp

Fact → Num
Fact → "(" Exp ")"
Term → Term "*" Fact
Term → Fact
Exp → Exp "+" Term
Exp → Term

Predictive parsing
eliminating left recursion

Term → Term "*" Fact
Term → Fact
Exp → Exp "+" Term
Exp → Term

Term′ → "*" Fact Term′
Term′ →
Term → Fact Term′
Exp′ → "+" Term Exp′
Exp′ →
Exp → Term Exp′

Predictive parsing
left factoring

Exp → “if” Exp “then” Exp “else” Exp
Exp → “if” Exp “then” Exp

Exp → “if” Exp “then” Exp Else
Else → “else” Exp
Else →

III

Parser Combinators

Parser Combinators

- Parsers are modeled as functions, and larger parsers are built from smaller ones using higher-order functions.

- Can be implemented in any lazy functional language with higher-order style type system (e.g. Haskell, Scala).

- Parser combinators enable a recursive descent parsing strategy that facilitates modular piecewise construction and testing.

Parser Combinators

```
type Parser = String -> Tree
```

Parser Combinators

What about intermediate parsers?

type Parser = String -> Tree

Parser Combinators

Return the remainder of the input!

~~type Parser = String -> Tree~~

type Parser = String -> (Tree, String)

Parser Combinators

What about parsers that fail?

~~type Parser = String -> Tree~~

type Parser = String -> (Tree, String)

Parser Combinators

Returns either a singleton or
an empty list!

~~type Parser = String -> Tree~~

~~type Parser = String -> (Tree, String)~~

type Parser = String -> [(Tree, String)]

Parser Combinators

~~type Parser = String -> Tree~~

~~type Parser = String -> (Tree, String)~~

~~type Parser = String -> [(Tree, String)]~~

type Parser a = String -> [(a, String)]

A parser p returns either a singleton list [(a, String)] indicating success, or an empty list [] indicating failure. Returning a list of results, also allow to express ambiguities.

Primitive Parsers

success

```
success :: a -> Parser a
success v = \inp -> [(v, inp)]
```

or

```
success :: a String -> [(a, String)]
success v inp -> [(v, inp)]
```

fail

```
fail :: Parser a
fail = \inp -> []
```

match

```
match :: Parser Char
match = \inp -> case inp of
                  []     -> []
                  (x:xs) -> [(x,xs)]
```

Parser Combinators

alternation

```
alt :: Parser a -> Parser a -> Parser a
p 'alt' q = \inp -> (p inp ++ q inp)
```

sequencing

```
seq :: Parser a -> Parser b -> Parser (a, b)
p ‘seq‘ q = \inp -> [((v,w), inp’’) | (v, inp’) <- p inp
                                    , (w, inp’’) <- q inp’]
```

Parser Combinators

- Parser combinators can use semantic actions to manipulate intermediate results, being able to produce values rather than trees.

- More powerful combinators can be build to allow parsing context-sensitive languages (by passing the context together with parsing results).

- Parser Combinators in Scala:
  A. Moors, F. Piessens, Martin Odersky. Parser combinators in Scala. Technical Report Department of Computer Science, K.U. Leuven, February 2008.

IV

Parsing Expression Grammars

Parsing Expression Grammars (PEGs)

Rules are of the form:

$$A \leftarrow \mathbf{e}$$

where A is a non-terminal and **e** is a parsing expression.

PEG operators

Operator	Type	Precedence	Description
' '	primary	5	Literal string
" "	primary	5	Literal string
[ ]	primary	5	Character class
.	primary	5	Any character
(e)	primary	5	Grouping
$e?$	unary suffix	4	Optional
$e*$	unary suffix	4	Zero-or-more
$e+$	unary suffix	4	One-or-more
$\&e$	unary prefix	3	And-predicate
$!e$	unary prefix	3	Not-predicate
$e_1\ e_2$	binary	2	Sequence
e_1 / e_2	binary	1	Prioritized Choice

Syntactic Predicates

&**e** and !**e** : preserves the knowledge whether e fails or not.

Comment ← '//' (!EndOfLine .)* EndOfLine

Parsing Expression Grammars

- Prioritized choice '/'.

S ← **a b** / **a**

S ← **a** / **a b**

Parsing Expression Grammars

- Prioritized choice '/'.

S ← **a b** / **a** ≠ S ← **a** / **a b**

- Backtracks when parsing an alternative fails.
- Uses memoization of intermediate results to parse in linear time, called packrat parsing.
- Does not allow left-recursion.

V

ANTLR / ALL(*)

LL(*)

- Parses LL-regular grammars: for any given non-terminal, parsers can use the entire remaining of the input to differentiate the alternative productions.

- Statically builds a DFA from the grammar productions to recognize lookahead.

- When in conflict, chooses the first alternative and backtracks when DFA lookahead recognition fails.

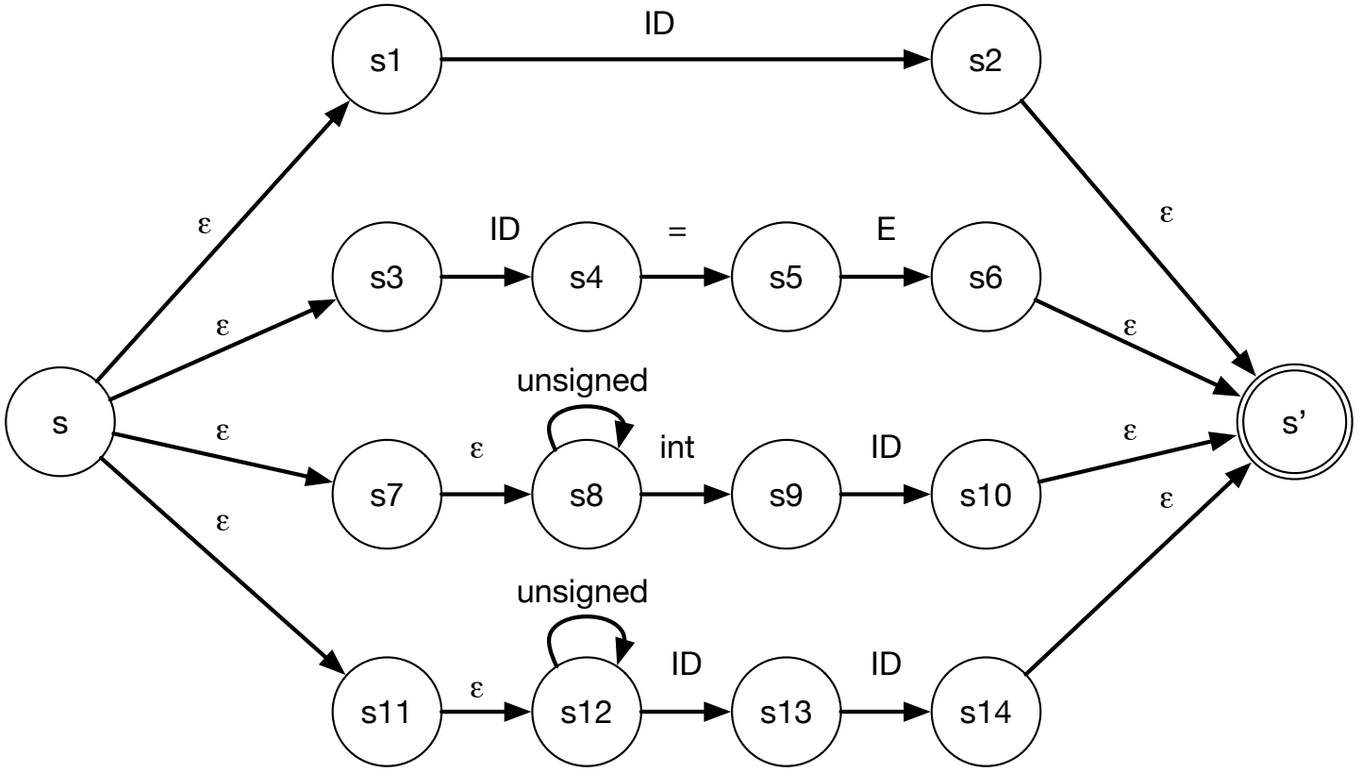
LL(*) Grammar Analysis

S : ID
  | ID **=** E
  | **unsigned*** **int** ID
  | **unsigned*** ID ID

LL(*) Grammar Analysis

terminals: ID, **=**, **int**, **unsigned**

S : ID (1)
| ID **=** E (2)
| **unsigned*** **int** ID (3)
| **unsigned*** ID ID (4)

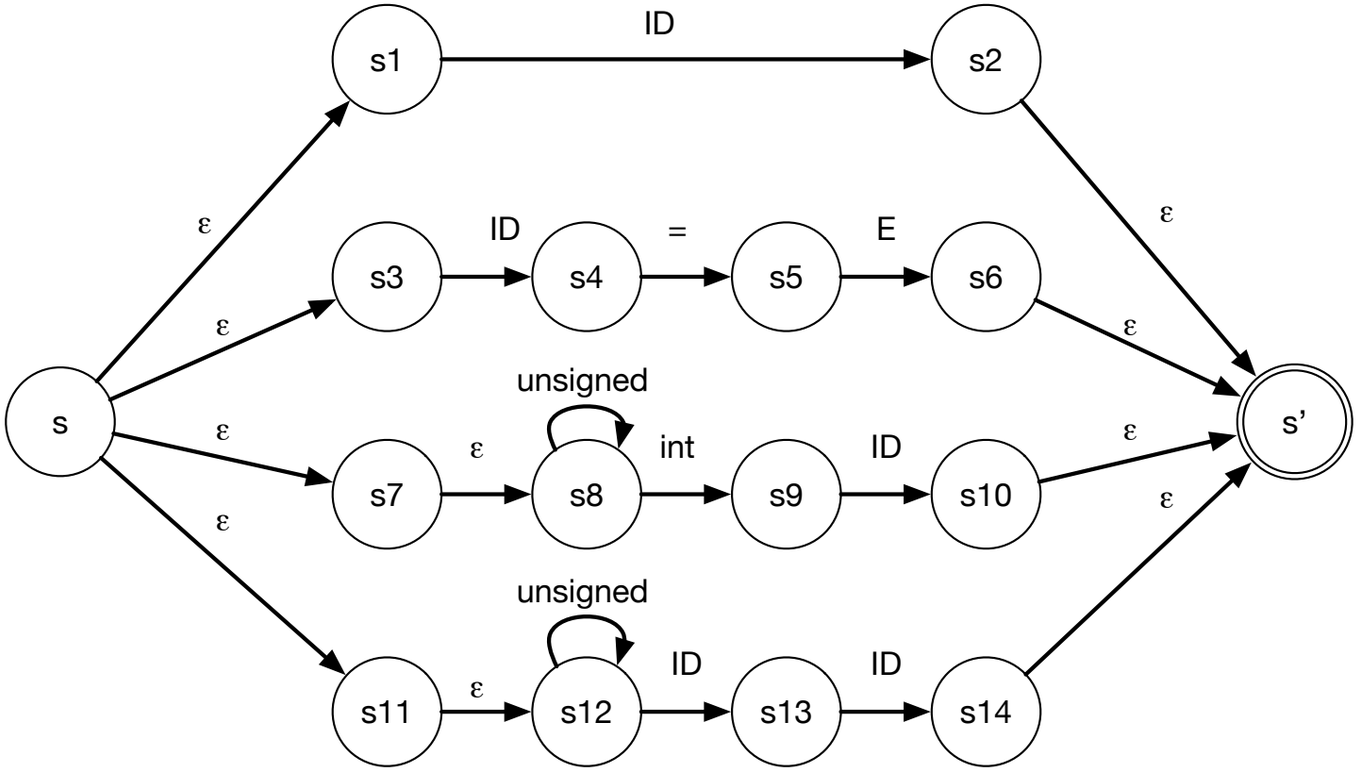


augmented recursive transition network (ATN)

LL(*) Grammar Analysis

terminals: ID, **=**, **int**, **unsigned**

S : ID (1)
| ID **=** E (2)
| **unsigned*** **int** ID (3)
| **unsigned*** ID ID (4)



converts ATN to DFA

(i) Initial state = closure(s);

(ii) Create a final state for each production;

(iii) While DFA state contains ATN states from multiple paths, create transitions with terminals (or EOF if DFA contains s');

(iv) If DFA state contain ATN states from a single path, add transition to corresponding final DFA state;

LL(*) Grammar Analysis

terminals: ID, **=**, **int**, **unsigned**

S : ID (1)
| ID **=** E (2)
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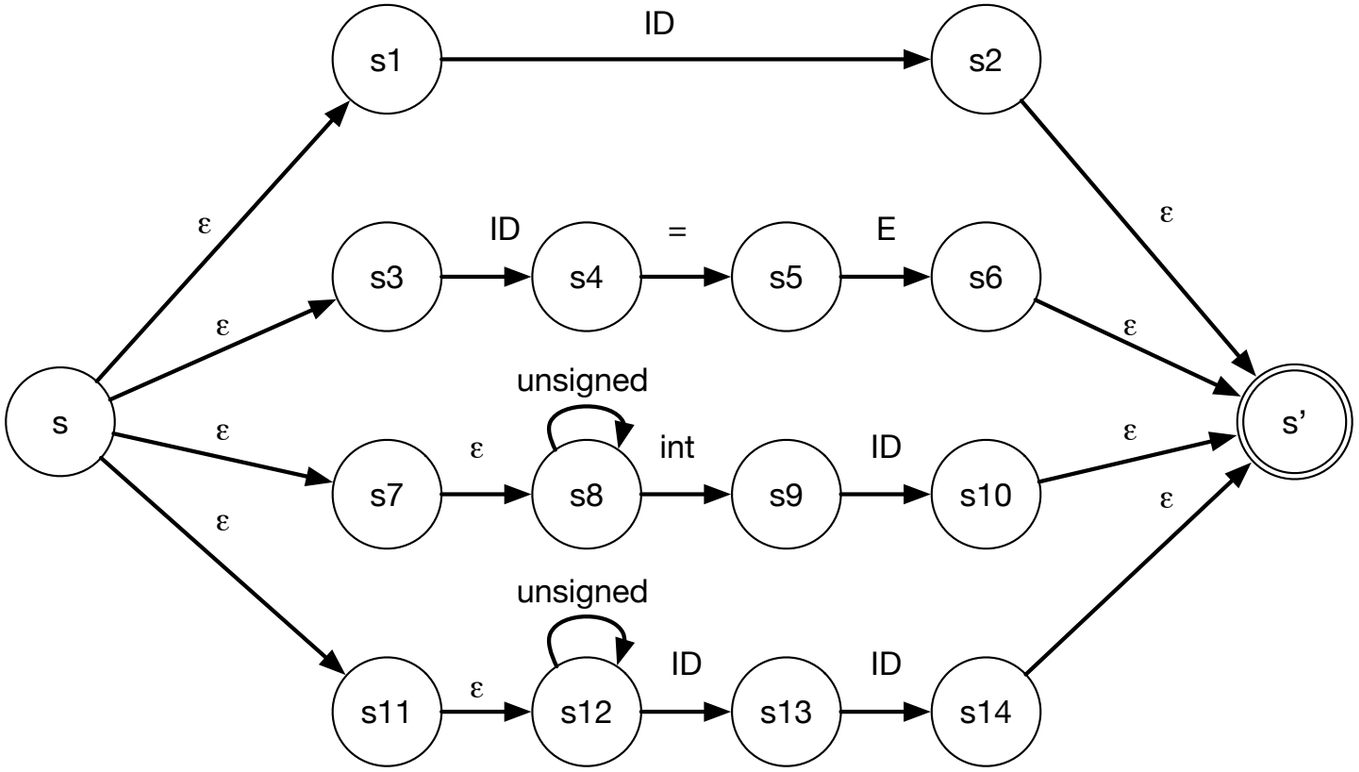
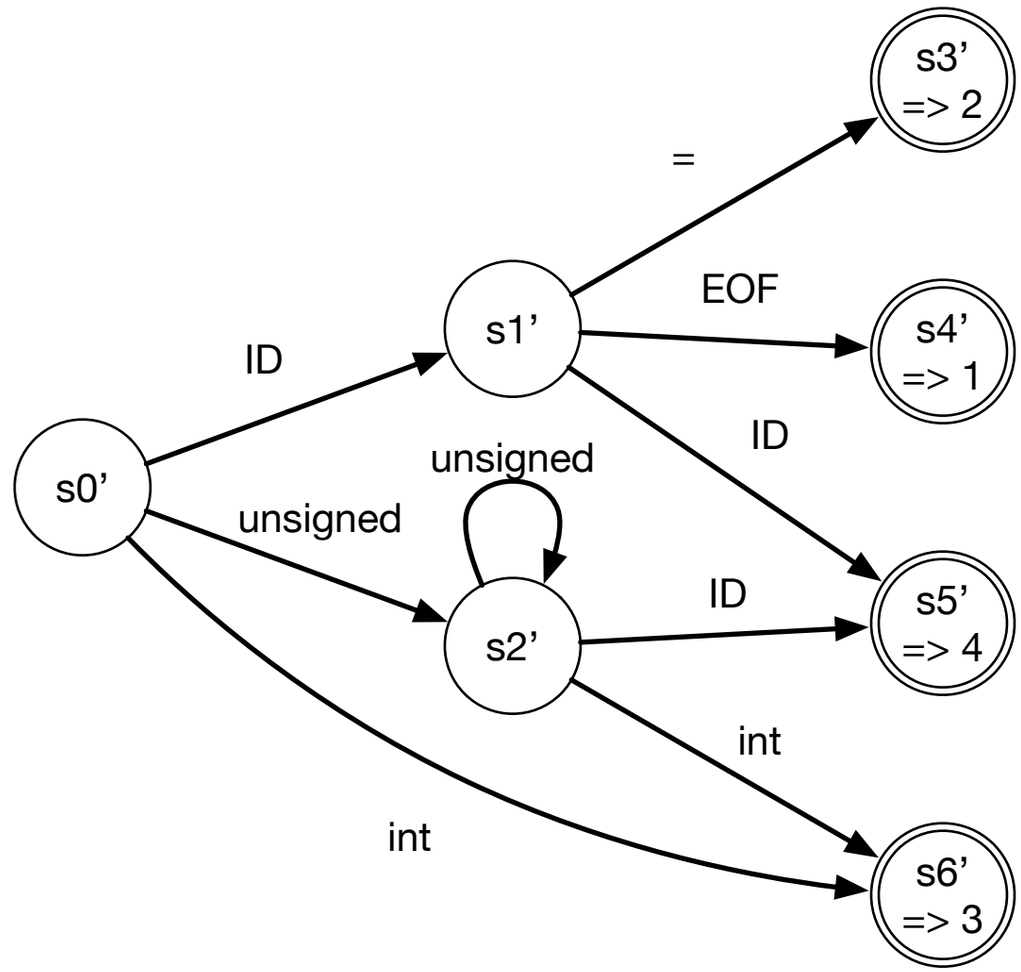
| **unsigned*** ID ID (4)





Adaptive LL(*)

```
S : E = E;
  | E;

E : E * E
  | E + E
  | E ( E )
  | ID
```

```
void S() {
  switch (adaptivePredict("S", callStack)){
    case 1 :
      E(); match('='); E();
      match(';'); break;
    case 2:
      E(); match(';'); break;
  }
}
```

Adaptive LL(*)

Dynamically builds the lookahead DFA.

```
S : E = E ;
  | E ;

E : E * E
  | E + E
  | E ( E )
  | ID
```

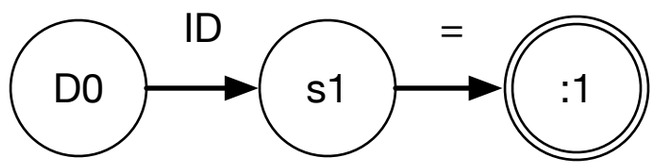
terminals: **=**, **;**, ***, **+**, **(**, **)**, ID

Adaptive LL(*)

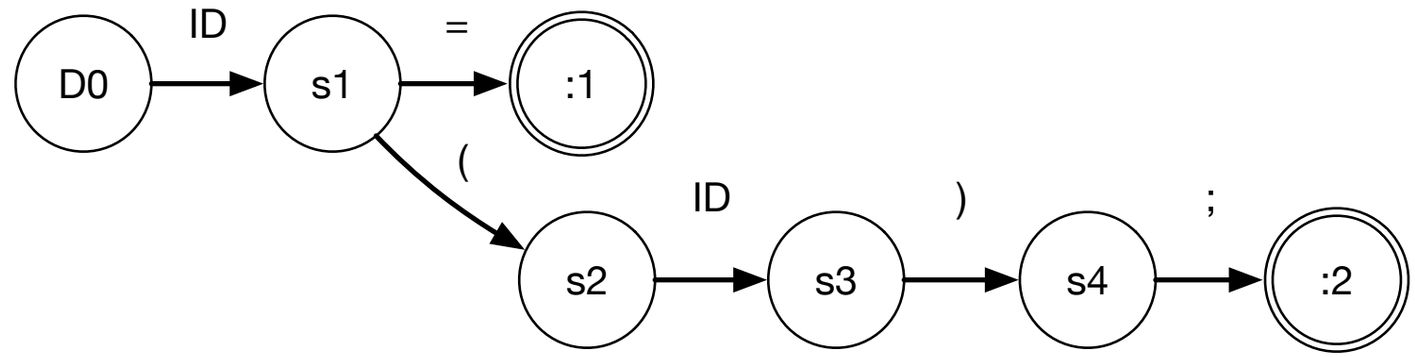
Dynamically builds the lookahead DFA.

After parsing:

x = y;



f(x);



Adaptive LL(*)

parse: **yba**

S : **x** B
  | **y** C

B : A **a**

C : A **b a**

A : **b**
  | ε

Adaptive LL(*)

S : **x** B
  | **y** C

B : A **a**

C : A **b a**

A : **b**
  | ε

input: **yba**

stack: S

Adaptive LL(*)

S : **x** B
  | **y** C

B : A **a**

C : A **b a**

A : **b**
  | ε

input: **yba**

stack: **y**C

Adaptive LL(*)

S : **x** B
  | **y** C

B : A **a**

C : A **b a**

A : **b**
  | ε

input: **ba**

stack: C

Adaptive LL(*)

S : **x** B
  | **y** C

B : A **a**

C : A **b a**

A : **b**
  | ε

input: **ba**

stack: A **ba**

Adaptive LL(*)

S : **x** B
  | **y** C

B : A **a**

C : A **b a**

A : **b** A_1
  | ε A_2

input: **ba**

stack: A **ba**

b in First(A)
b in Follow(A)

A_1 or A_2?

Adaptive LL(*)

- Tries to parse using **strong LL** (without looking at the call stack), when there are multiple alternatives, splits the parser to try all possibilities.

- Parsing continues with a graph, handling multiple stacks in paralell to explore all alternatives.

- Eventually, if the grammar is unambiguous, only one stack "survives". If multiple stacks survive, an ambiguty has been found and the parser picks the production with lower value.

ANTLR 4

- Accepts as input any context-free grammar that does not contain indirect or hidden left-recursion.
- Generates ALL(*) parses in Java or C#.
- Grammars contain lexical and syntactic rules and generate a lexer and a parser.
- ANTLR4 grammars can be scannerless and composable by using individual characters as input symbols.

VI

Summary

Summary

lessons learned

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How can we parse context-free languages effectively?

- predictive parsing algorithms

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Which grammar classes are supported by these algorithms?

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- generate parse tables

Summary
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Which grammar classes are supported by these algorithms?

- LL(k) grammars, LL(k) languages

How can we generate compiler tools from that?

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- generate parse tables

What are other techniques for implementing top-down parsers?

- Parser Combinators
- PEGs
- ALL(*)

Literature

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formal languages

Noam Chomsky: Three models for the description of language. 1956

J. E. Hopcroft, R. Motwani, J. D. Ullman: Introduction to Automata Theory, Languages, and Computation. 2006

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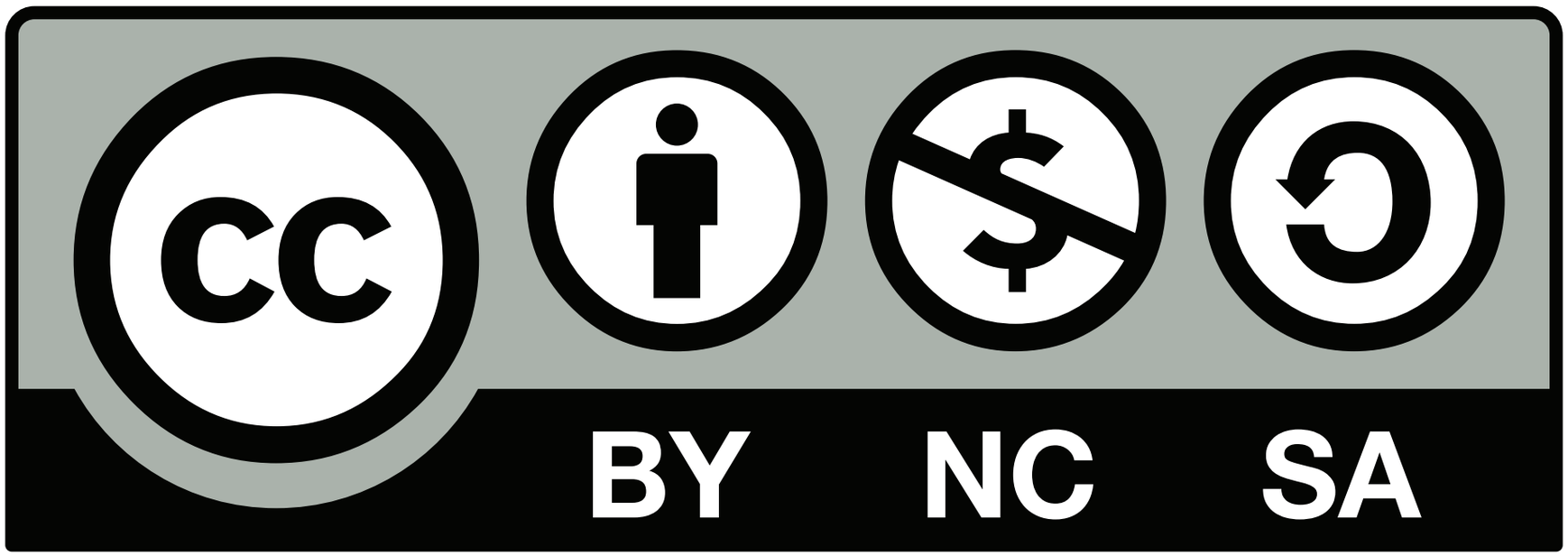
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