Parsing VI
The Last Parsing Lecture

Quiz : The Left Recursive SheepNoise Grammar

1. Goal → SheepNoise
2. SheepNoise → SheepNoise baa
3. | baa

Example From SheepNoise

Initial step builds the item [*Goal*→•*SheepNoise*,EOF] and takes its *closure( )*

Closure([*Goal*→•*SheepNoise*,EOF] *)*

Item	*From*
[*Goal*→•*SheepNoise*,EOF]	Original item
[*SheepNoise*→•*SheepNoise* baa,EOF]	1, δa is EOF
[*SheepNoise*→ • baa,EOF]	1, δa is EOF
[*SheepNoise*→•*SheepNoise* baa,baa]	2, δa is baa EOF
[*SheepNoise*→ • baa,baa]	2, δa is baa EOF

So, S_0 is

{ [*Goal*→ • *SheepNoise*,EOF], [*SheepNoise*→ • *SheepNoise* baa,EOF], [*SheepNoise*→ • baa,EOF], [*SheepNoise*→ • *SheepNoise* baa,baa], [*SheepNoise*→ • baa,baa] }

Example from SheepNoise

S_0 is { [*Goal*→ • *SheepNoise*,EOF], [*SheepNoise*→ • *SheepNoise* baa,EOF],
[*SheepNoise*→ • baa,EOF], [*SheepNoise*→ • *SheepNoise* baa,baa],
[*SheepNoise*→ • baa,baa] }

Goto(S_0 , baa)

- Loop produces

Item	*From*
[*SheepNoise*→baa•, EOF]	Item 3 in s_0
[*SheepNoise*→baa•, baa]	Item 5 in s_0

- Closure adds nothing since • is at end of *rhs* in each item

In the construction, this produces s_2

{ [*SheepNoise*→baa •, {EOF,baa}]}

New, but *obvious*, notation for two distinct items

[*SheepNoise*→baa •, EOF] &
[*SheepNoise*→baa •, baa]

Example from SheepNoise

Starts with S_0

S_0 : { [*Goal*→ • *SheepNoise*, EOF], [*SheepNoise*→ • *SheepNoise* baa, EOF],
[*SheepNoise*→ • baa, EOF], [*SheepNoise*→ • *SheepNoise* baa, baa],
[*SheepNoise*→ • baa, baa] }

Example from SheepNoise

Starts with S_0

S_0 : { [*Goal*→ • *SheepNoise*, EOF], [*SheepNoise*→ • *SheepNoise* baa, EOF],
[*SheepNoise*→• baa, EOF], [*SheepNoise*→ • *SheepNoise* baa, baa],
[*SheepNoise*→ • baa, baa] }

Iteration 1 computes

S_1 = *Goto*(S_0 , *SheepNoise*) =

{ [*Goal*→ *SheepNoise* •, EOF], [*SheepNoise*→ *SheepNoise* • baa, EOF],
[*SheepNoise*→ *SheepNoise* • baa, baa] }

S_2 = *Goto*(S_0 , baa) = { [*SheepNoise*→ baa •, EOF],
[*SheepNoise*→ baa •, baa] }

Example from SheepNoise

Starts with S_0

S_0 : { [*Goal*→ • *SheepNoise*, EOF], [*SheepNoise*→ • *SheepNoise* baa, EOF],
[*SheepNoise*→• baa, EOF], [*SheepNoise*→ • *SheepNoise* baa, baa],
[*SheepNoise*→ • baa, baa] }

Iteration 1 computes

S_1 = *Goto*(S_0 , ***SheepNoise***) =

{ [*Goal*→ *SheepNoise* •, EOF], [*SheepNoise*→ *SheepNoise* • baa, EOF],
[*SheepNoise*→ *SheepNoise* • baa, baa] }

S_2 = *Goto*(S_0 , baa) = { [*SheepNoise*→ baa •, EOF],
[*SheepNoise*→ baa •, baa] }

Iteration 2 computes

S_3 = *Goto*(S_1 , baa) = { [*SheepNoise*→ *SheepNoise* baa •, EOF],
[*SheepNoise*→ *SheepNoise* baa •, baa] }

Example from SheepNoise

Starts with S_0

S_0 : { [*Goal*→ • *SheepNoise*, EOF], [*SheepNoise*→ • *SheepNoise* baa, EOF],
[*SheepNoise*→ • baa, EOF], [*SheepNoise*→ • *SheepNoise* baa, baa],
[*SheepNoise*→ • baa, baa] }

Iteration 1 computes

S_1 = *Goto*(S_0 , *SheepNoise*) =

{ [*Goal*→ *SheepNoise* •, EOF], [*SheepNoise*→ *SheepNoise* • baa, EOF],
[*SheepNoise*→ *SheepNoise* • baa, baa] }

S_2 = *Goto*(S_0 , baa) = { [*SheepNoise*→ baa •, EOF],
[*SheepNoise*→ baa •, baa] }

Iteration 2 computes

S_3 = *Goto*(S_1 , baa) = { [*SheepNoise*→ *SheepNoise* baa •, EOF],
[*SheepNoise*→ *SheepNoise* baa •, baa] }

Nothing more to compute, since • is at the end of every item in S_3.

Example from SheepNoise

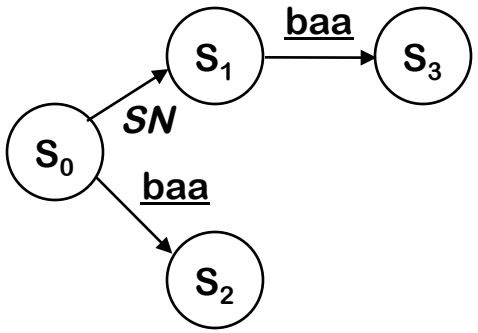
S_0 : { [*Goal*→ • *SheepNoise*, EOF], [*SheepNoise*→ • *SheepNoise* baa, EOF],
[*SheepNoise*→ • baa, EOF], [*SheepNoise*→ • *SheepNoise* baa, baa],
[*SheepNoise*→ • baa, baa] }

S_1 = *Goto*(S_0 , *SheepNoise*) =
{ [*Goal*→ *SheepNoise* •, EOF], [*SheepNoise*→ *SheepNoise* • baa, EOF],
[*SheepNoise*→ *SheepNoise* • baa, baa] }

S_2 = *Goto*(S_0 , baa) = { [*SheepNoise*→ baa •, EOF],
[*SheepNoise*→ baa •, baa] }

S_3 = *Goto*(S_1 , baa) = { [*SheepNoise*→ *SheepNoise* baa •, EOF],
[*SheepNoise*→ *SheepNoise* baa •, baa] }

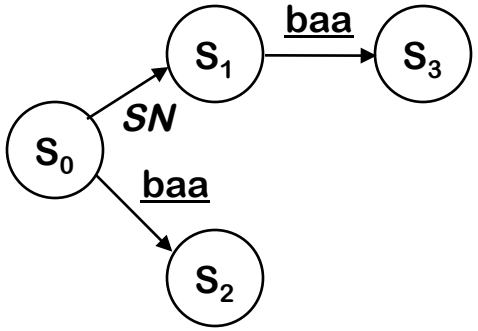
Control DFA for SN



Filling in the ACTION and GOTO Tables

∀ set $s_x \in S$
  ∀ item $i \in s_x$
    if i is $[A \rightarrow \beta \cdot \underline{a}d, \underline{b}]$ and $goto(s_x, \underline{a}) = s_k$, $\underline{a} \in T$
      then ACTION$[x, \underline{a}] \leftarrow$ "*shift k*"
    else if i is $[S' \rightarrow S \cdot, EOF]$
      then ACTION$[x, \underline{a}] \leftarrow$ "*accept*"
    else if i is $[A \rightarrow \beta \cdot, \underline{a}]$
      then ACTION$[x, \underline{a}] \leftarrow$ "*reduce* $A \rightarrow \beta$"
  ∀ $n \in NT$
    if $goto(s_x, n) = s_k$
      then GOTO$[x, n] \leftarrow k$

Control DFA for SN



S_0 : { [*Goal*→ • *SheepNoise*, EOF], [*SheepNoise*→ • *SheepNoise* baa, EOF],
[*SheepNoise*→ • baa, EOF], [*SheepNoise*→ • *SheepNoise* baa, baa],
[*SheepNoise*→ • baa, baa] }

S_1 = *Goto*(S_0 , ***SheepNoise***) =
{ [*Goal*→ *SheepNoise* •, EOF], [*SheepNoise*→ *SheepNoise* • baa, EOF],
[*SheepNoise*→ *SheepNoise* • baa, baa] }

S_2 = *Goto*(S_0 , baa) = { [*SheepNoise*→ baa •, EOF], [*SheepNoise*→ baa •, baa] }

Filling in the ACTION and GOTO Tables

∀ *set* $s_x \in S$
  ∀ *item* $i \in s_x$
    if *i is* $[A \rightarrow \beta \cdot \underline{a}d, \underline{b}]$ *and* $goto(s_x, \underline{a}) = s_k$, $\underline{a} \in T$
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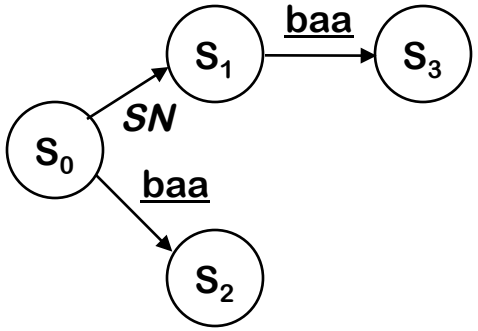
Control DFA for SN



S_1 = *Goto*(S_0 , ***SheepNoise***) =
  { [***Goal*** → ***SheepNoise*** ·, **EOF**], [***SheepNoise*** → ***SheepNoise*** · **baa**, **EOF**],
  [***SheepNoise*** → ***SheepNoise*** · **baa**, **baa**] }

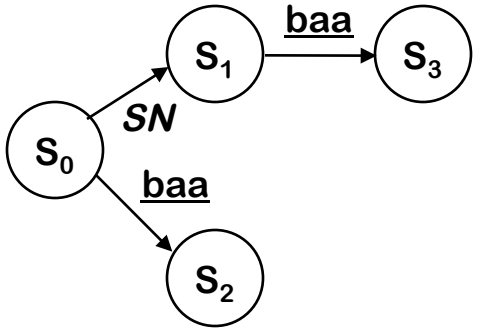
S_2 = *Goto*(S_0 , **baa**) = { [***SheepNoise*** → **baa** ·, **EOF**],
[***SheepNoise*** → **baa** ·, **baa**] }

S_3 = *Goto*(S_1 , **baa**) = { [***SheepNoise*** → ***SheepNoise*** **baa** ·, **EOF**],
  [***SheepNoise*** → ***SheepNoise*** **baa** ·, **baa**] }

Filling in the ACTION and GOTO Tables

∀ *set* $s_x \in S$
  ∀ *item* $i \in s_x$
    if *i is* $[A \rightarrow \beta \cdot \underline{a}d, \underline{b}]$ *and* $goto(s_x, \underline{a}) = s_k$, $\underline{a} \in T$
      then ACTION$[x, \underline{a}] \leftarrow$ "*shift k*"
    else if *i is* $[S' \rightarrow S \cdot, EOF]$
      then ACTION$[x, \underline{a}] \leftarrow$ "*accept*"
    else if *i is* $[A \rightarrow \beta \cdot, \underline{a}]$
      then ACTION$[x, \underline{a}] \leftarrow$ "*reduce* $A \rightarrow \beta$"
  ∀ $n \in NT$
    if $goto(s_x, n) = s_k$
      then GOTO$[x, n] \leftarrow k$

Control DFA for SN



ACTION		
State	EOF	baa
0	—	shift 2
1	accept	shift 3
2	reduce 3	reduce 3
3	reduce 2	reduce 2

GOTO	
State	*SheepNoise*
0	1
1	-
2	-
3	-

Shrinking the Tables

Three options:

- Combine terminals such as number & identifier, + & -, * & /
  - → Directly removes a column, may remove a row
  - → For expression grammar, 198 (vs. 384) table entries
- Combine rows or columns (*table compression*)
  - → Implement identical rows once & remap states
  - → Requires extra indirection on each lookup
  - → Use separate mapping for ACTION & for GOTO
- Use another construction algorithm
  - → Both LALR(1) and SLR(1) produce smaller tables
  - → Implementations are readily available

What can go wrong with LR table construction?

What if set *s* contains [*A*→β•a γ,b] and [*B*→β•,a] ?

- First item generates "shift", second generates "reduce"
- Both define ACTION[s,a] — cannot do both actions
- This is a fundamental ambiguity, called a *shift/reduce error*
- Modify the grammar to eliminate it *(if-then-else)*
- Shifting will often resolve it correctly

EaC includes a worke example

What if set *s* contains [*A*→γ•, a] and [*B*→γ•, a] ?

- Each generates "reduce", but with a different production
- Both define ACTION[s,a] — cannot do both reductions
- This fundamental ambiguity is called a *reduce/reduce error*
- Modify the grammar to eliminate it

In either case, the grammar is not LR(1)

Summary of top-down and LR(1) parsing

	Advantages	*Disadvantages*
Top-down recursive descent	Fast Good locality Simplicity Good error detection	Hand-coded High maintenance Right associativity
LR(1)	Fast (Direct encoding) Deterministic langs. Automatable Left associativity	Large working sets Poor error messages Large table sizes

CYK Parser

- Simple context-free-language parser
  - running time is $O(n^3)$, space is $O(n^2)$

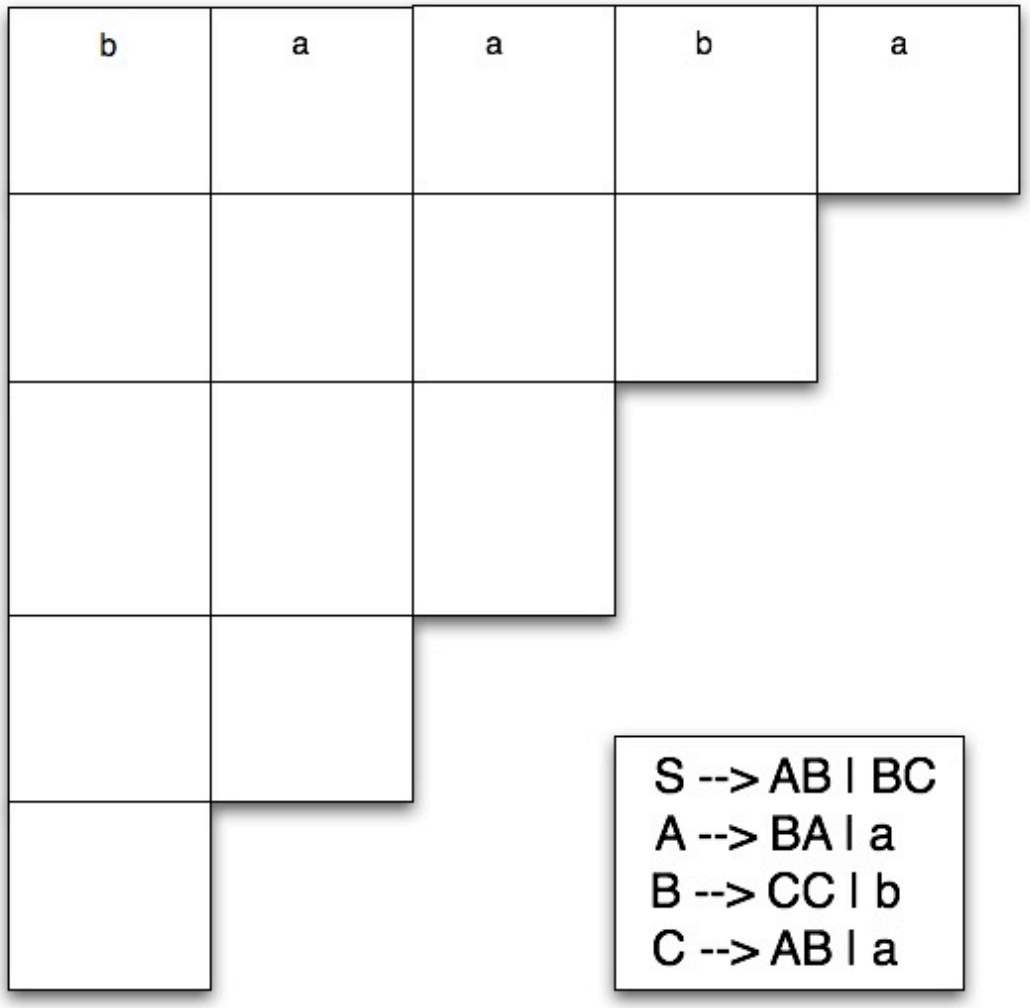
- Shunned for many years

  "Even tabular methods [CYK, Earley] should be avoided if the language at hand has a grammar for which more efficient algorithms [LL, LALR] are available." The Theory of Parsing …., Aho, Ullman, 1972

- But in practice, running time is more like $O(n^{\approx 1.2})$
  - Plus computers are now 1,000,000-times faster than in 1972

Source: Ras Bodik, Slides: Browsing Web 3.0 on 3.0 Watts

CYK Parser (Sequential Version)



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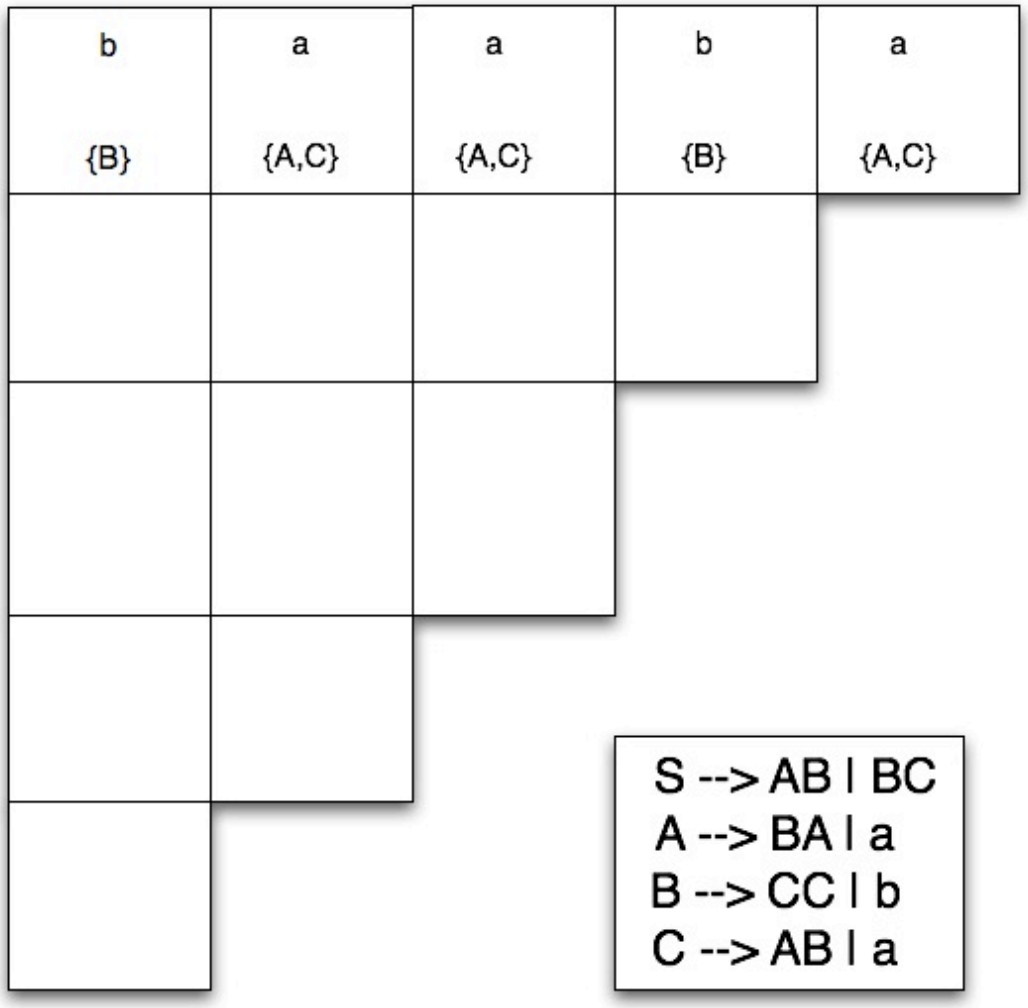

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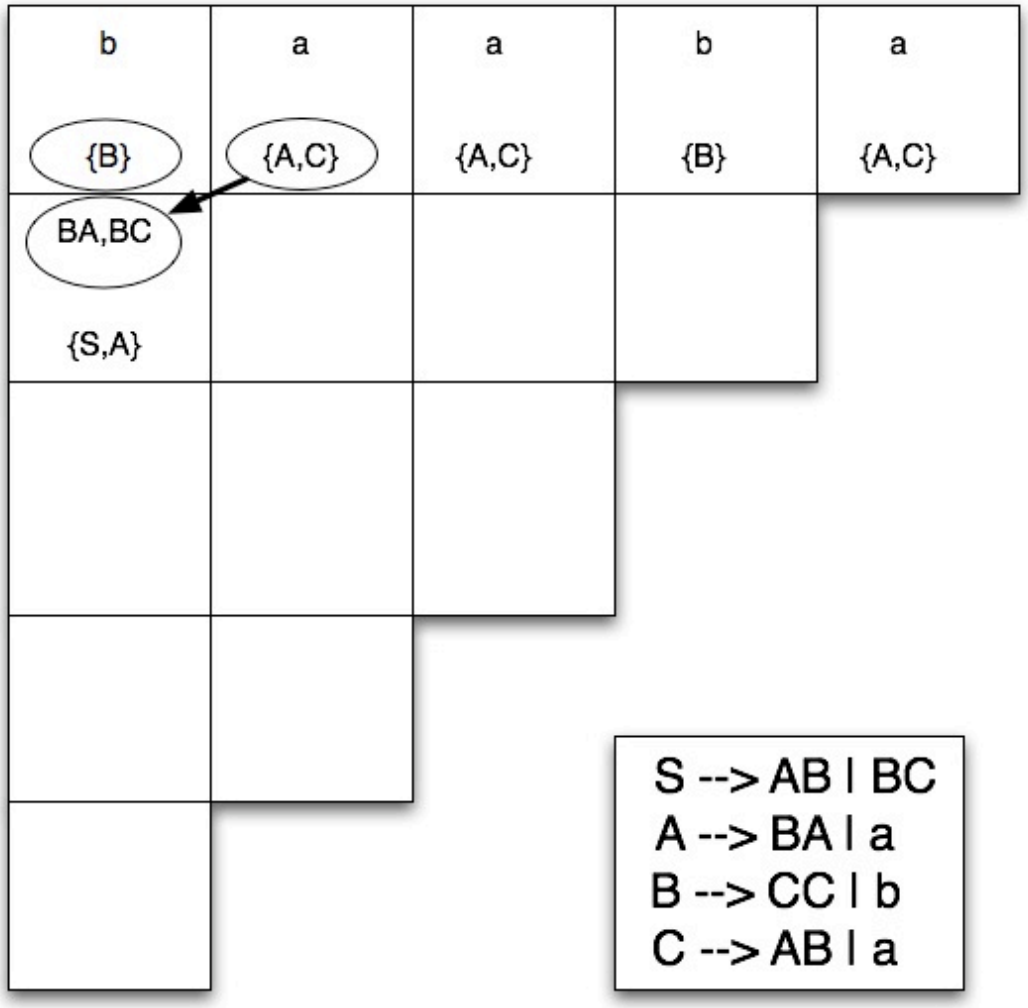
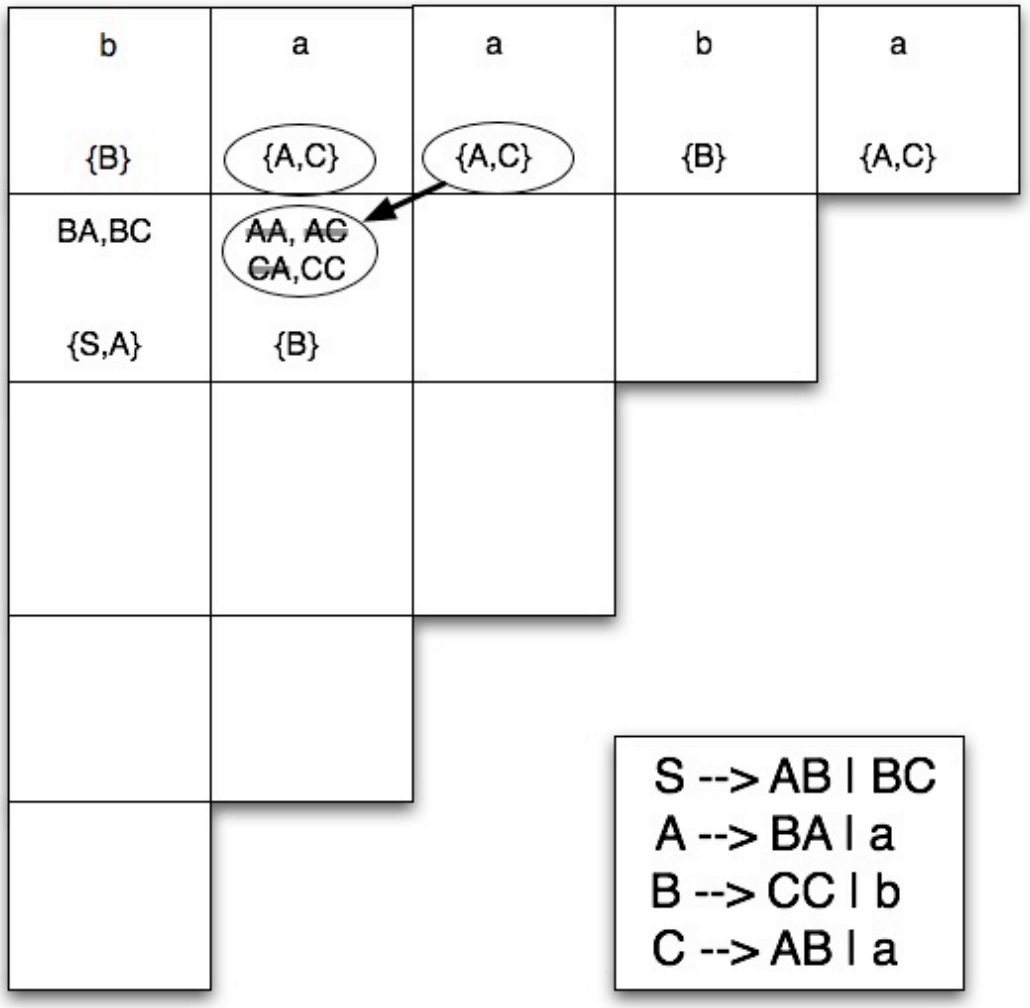
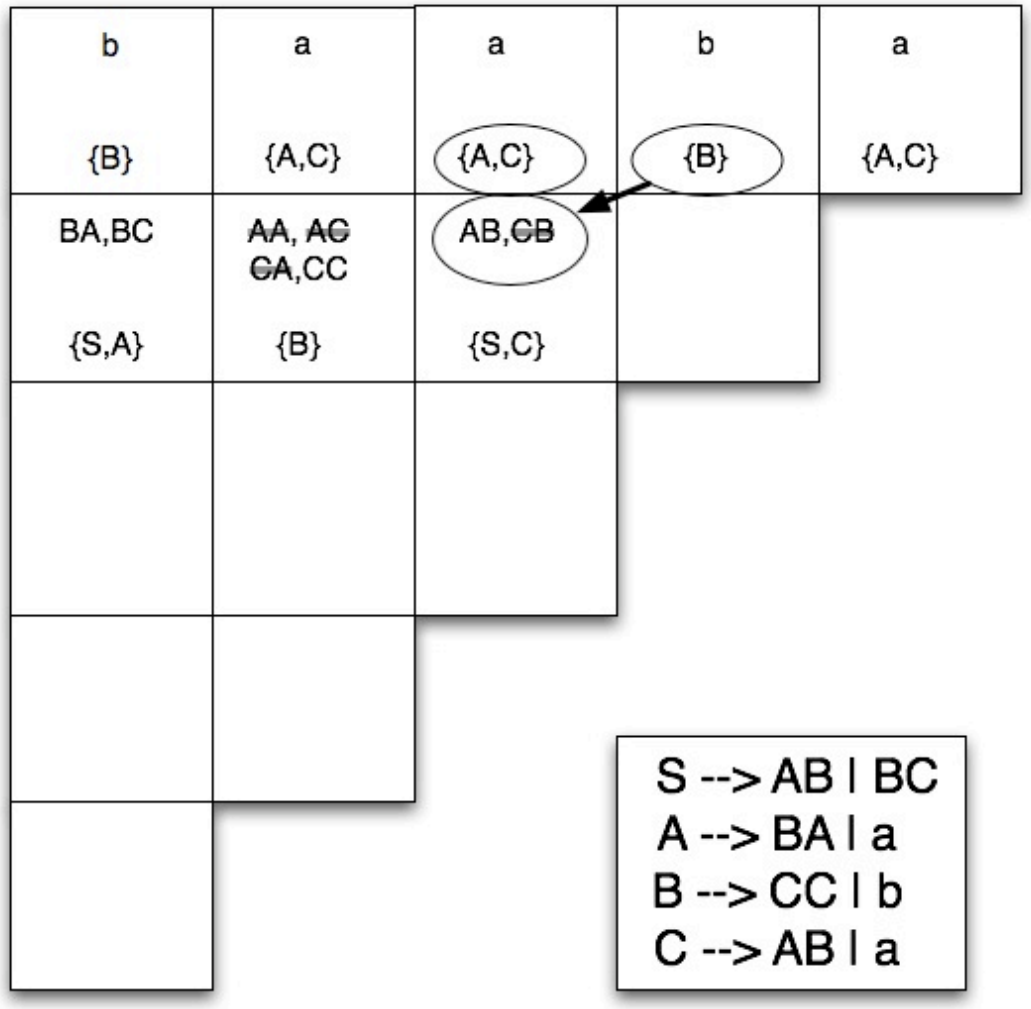


S --> AB | BC
A --> BA | a
B --> CC | b
C --> AB | a

CYK Parser (Sequential Version)



CYK Parser (Sequential Version)



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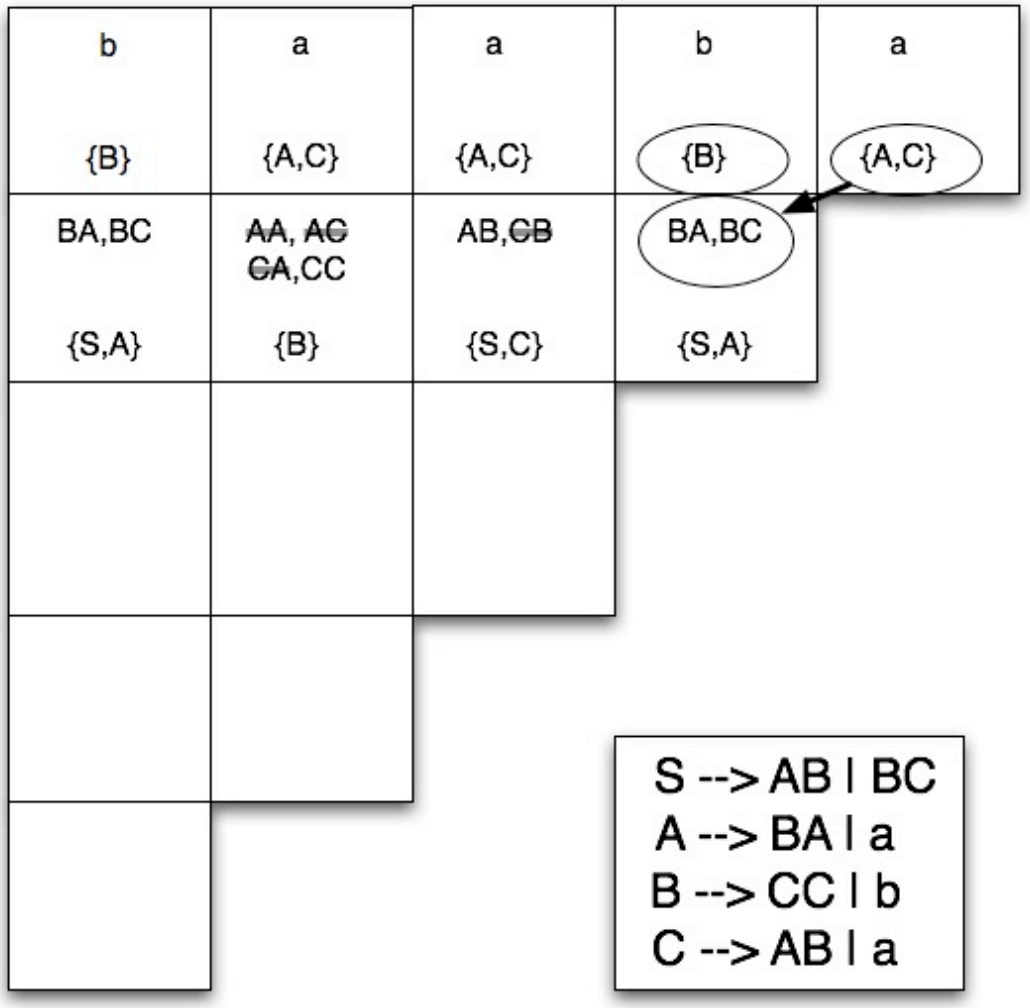

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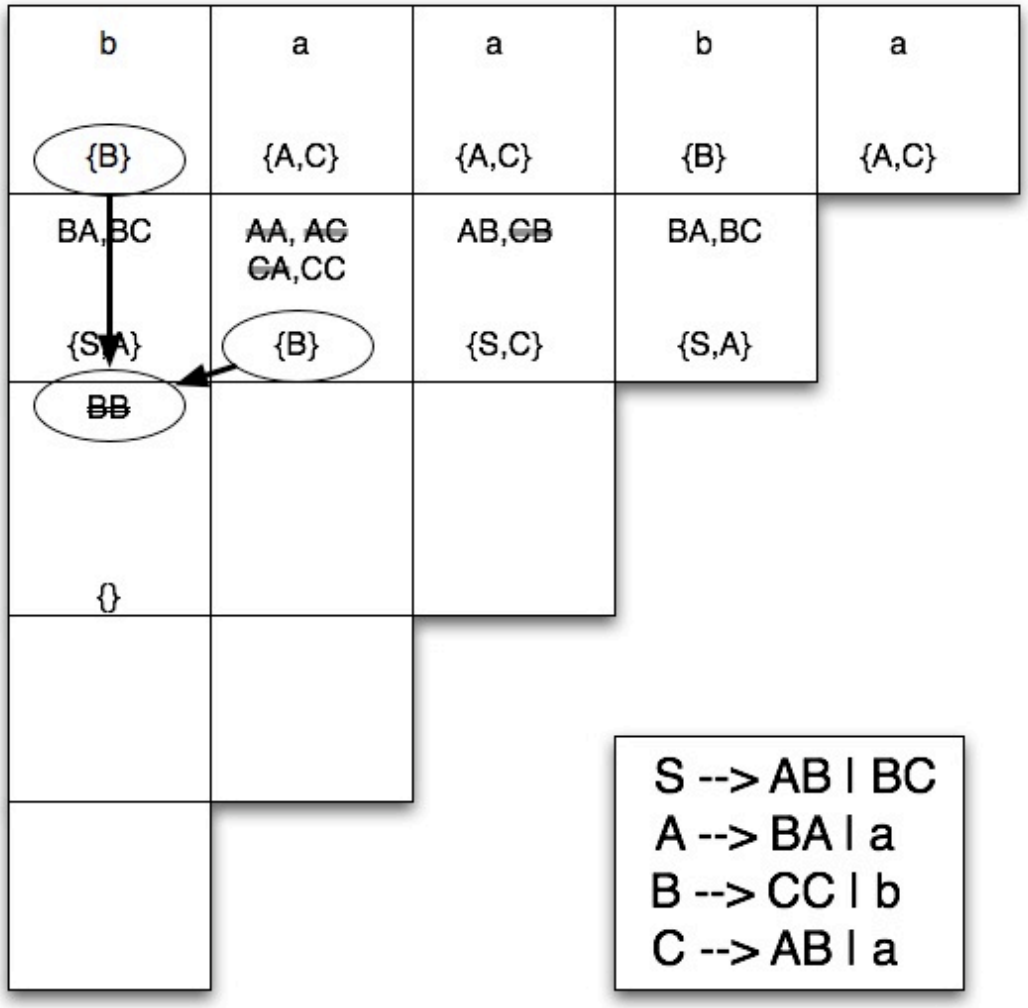

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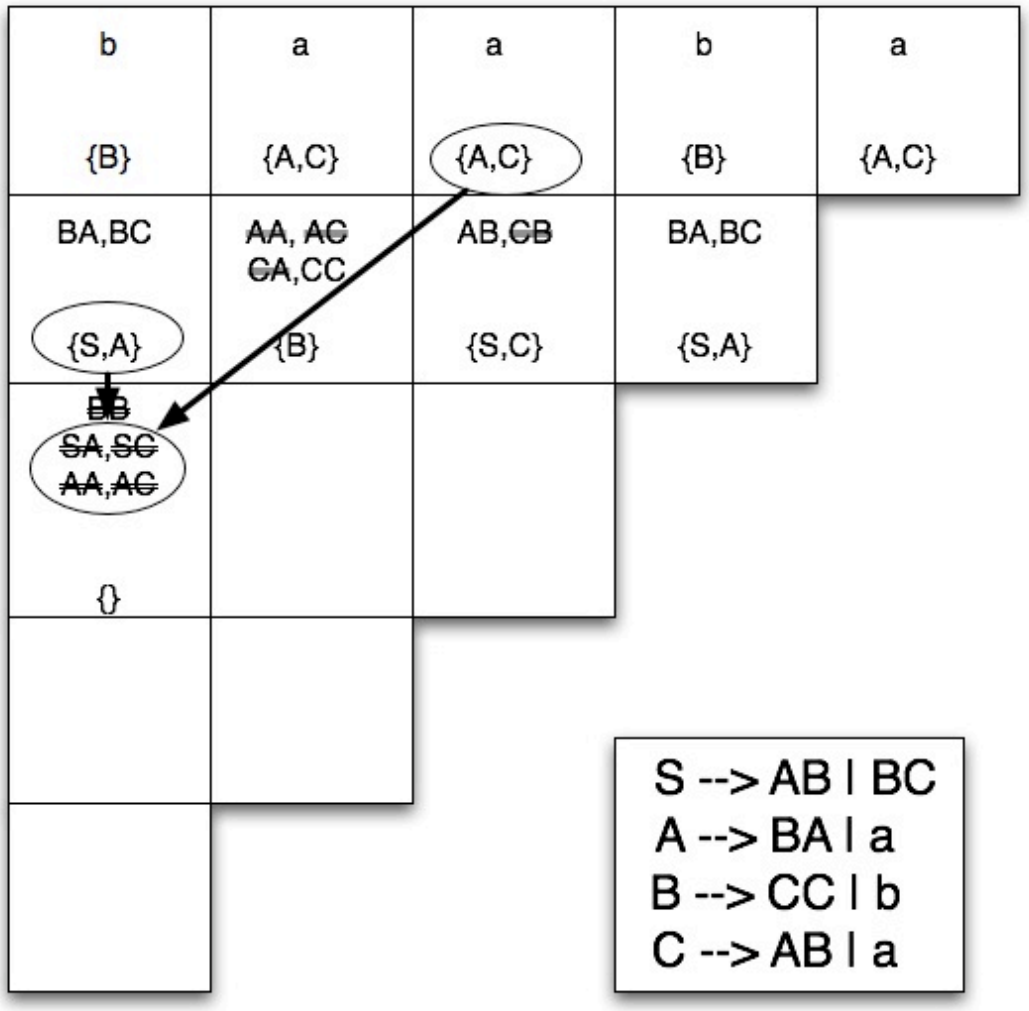

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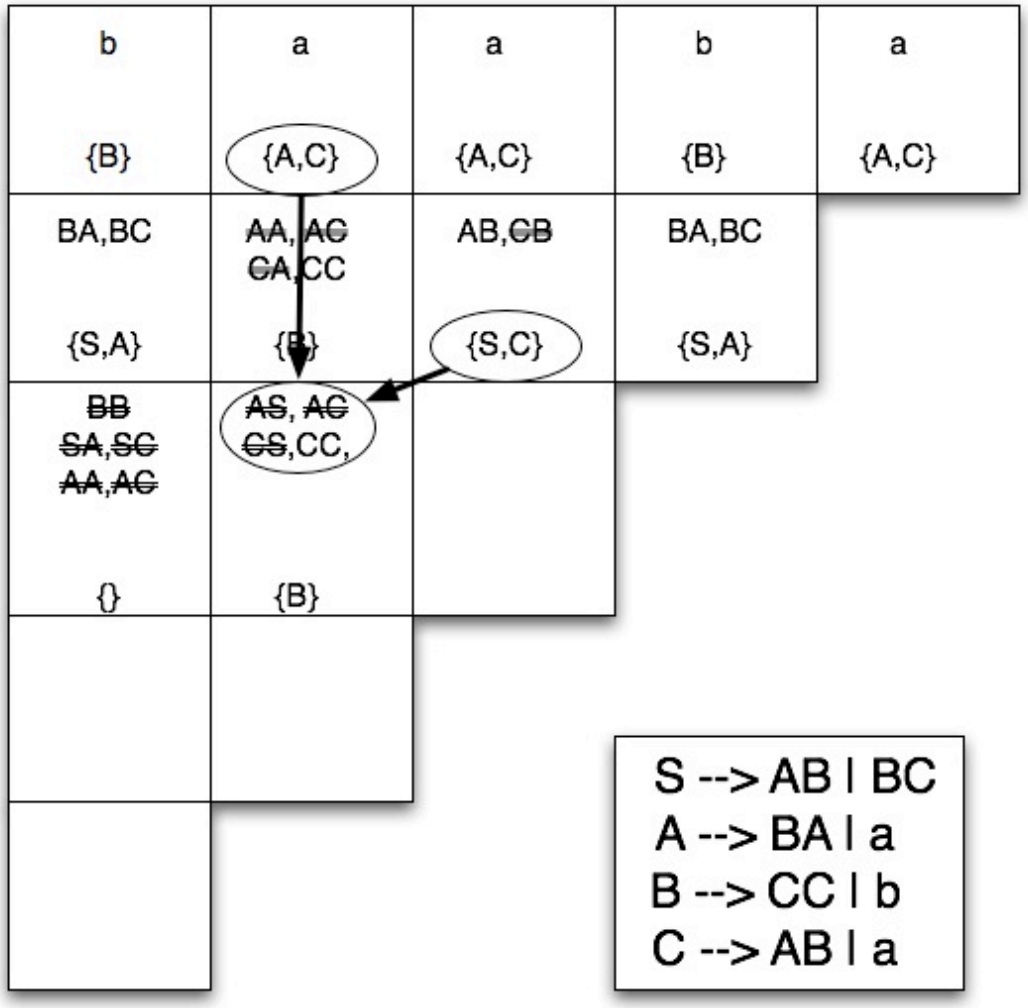

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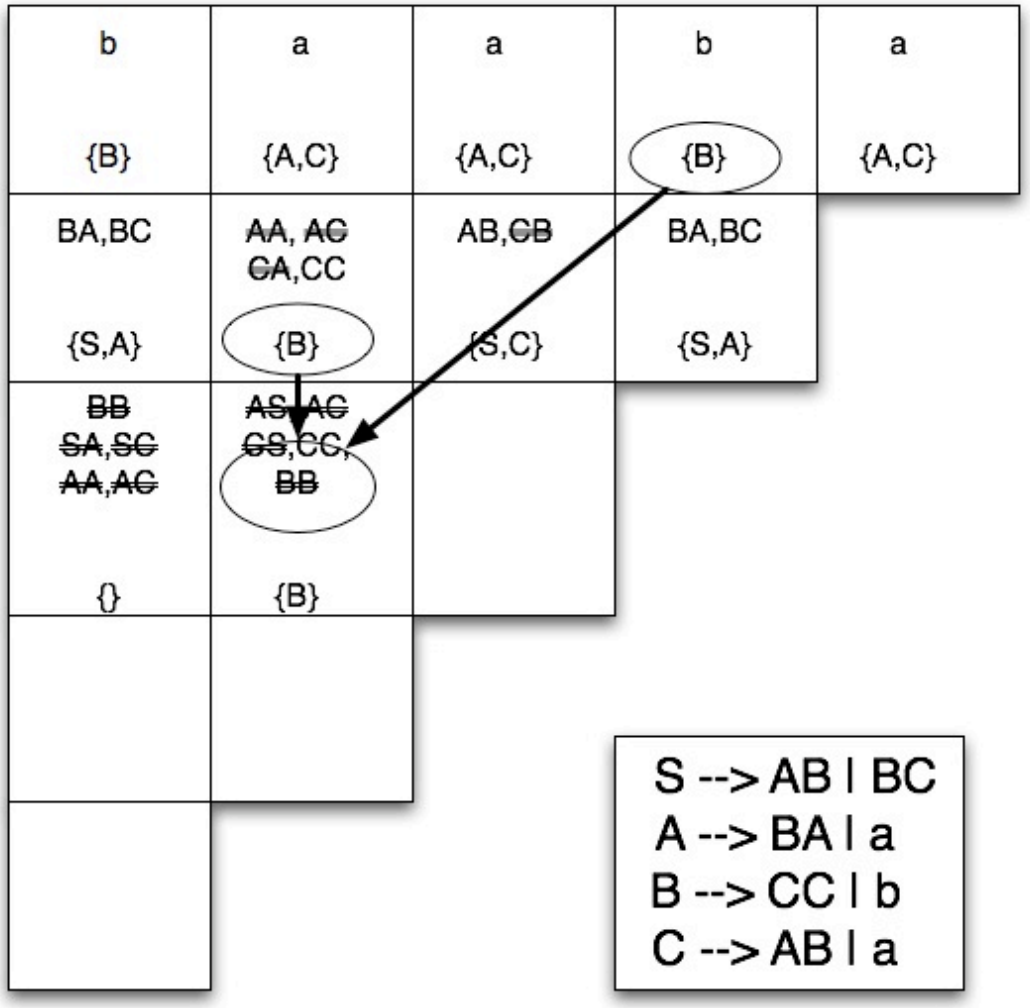
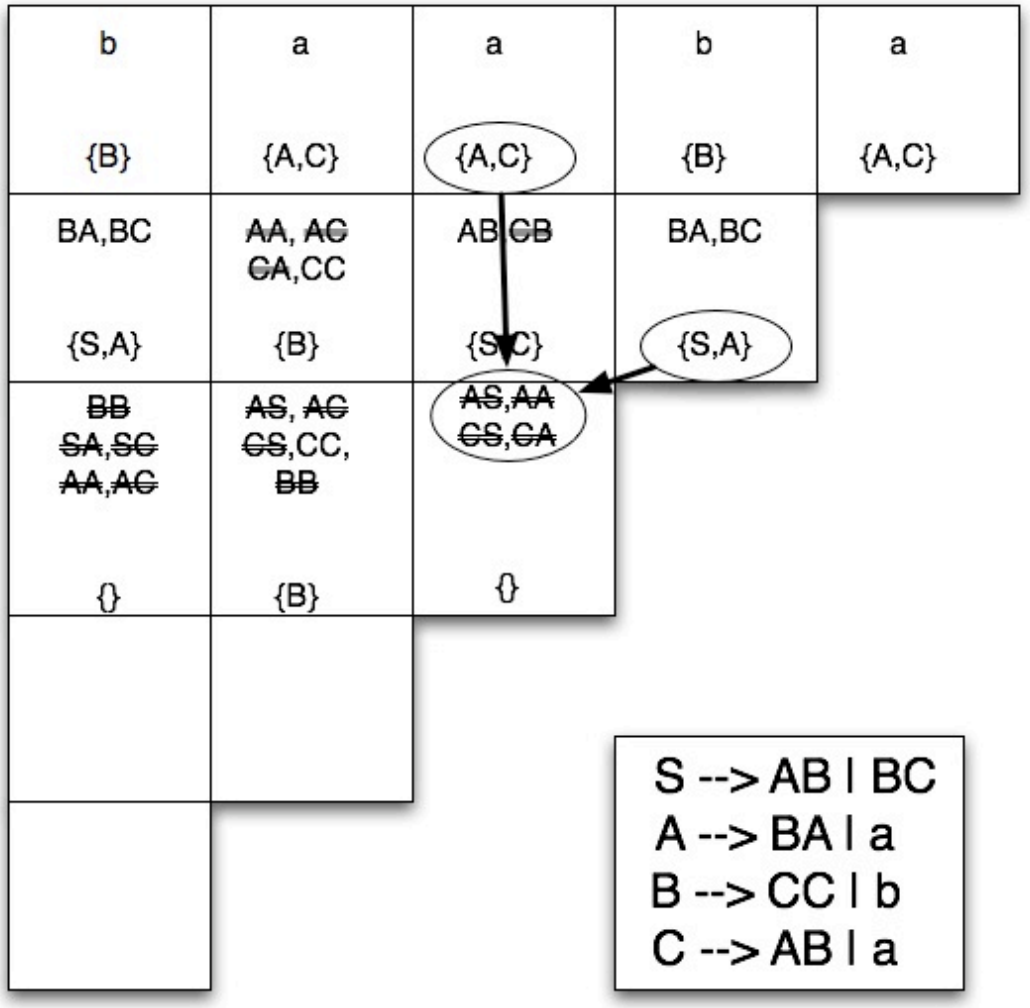


S --> AB | BC
A --> BA | a
B --> CC | b
C --> AB | a

CYK Parser (Sequential Version)



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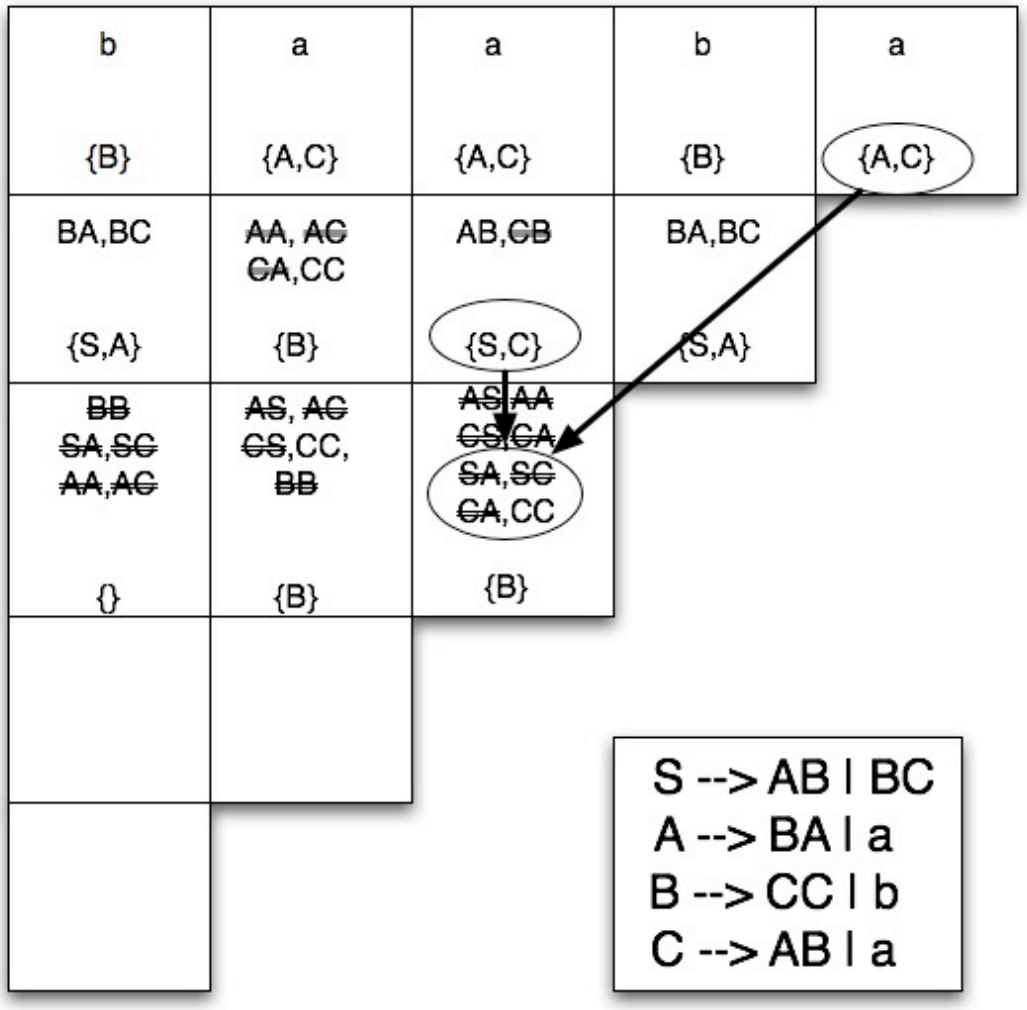

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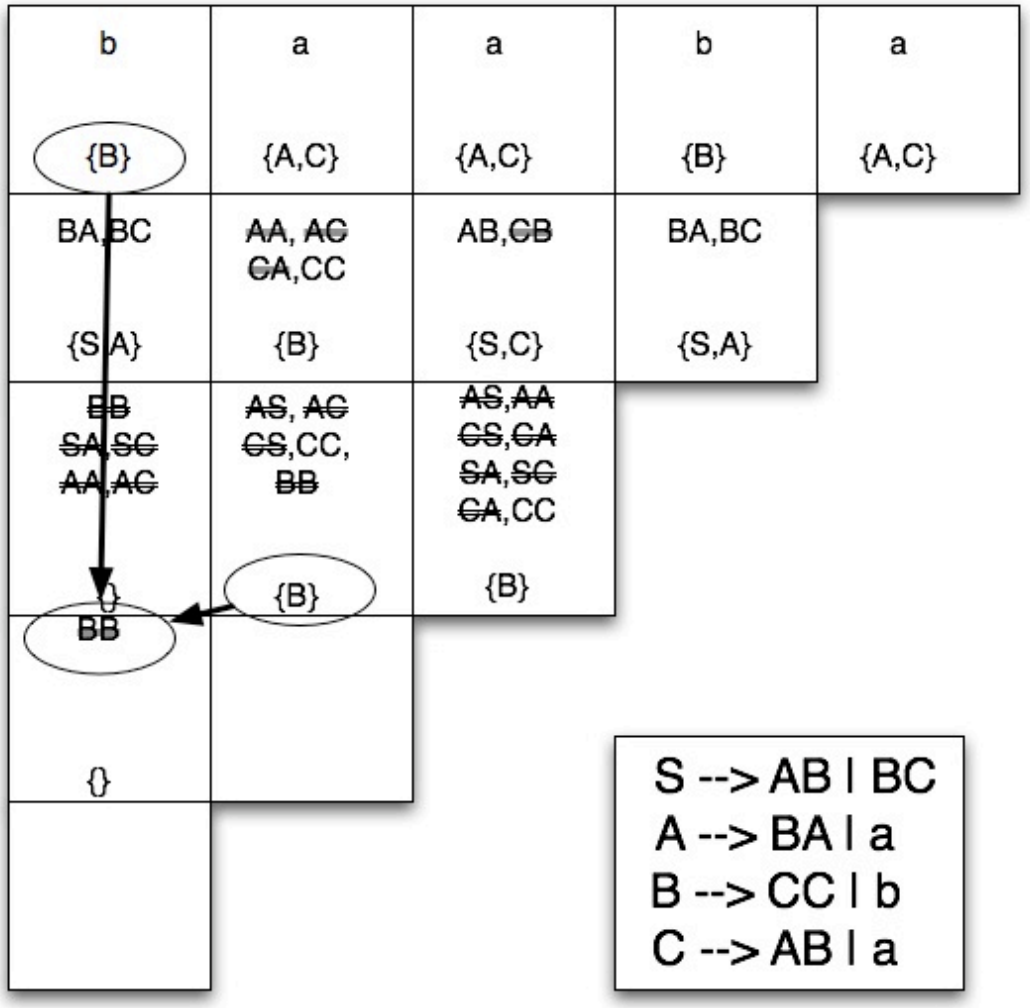

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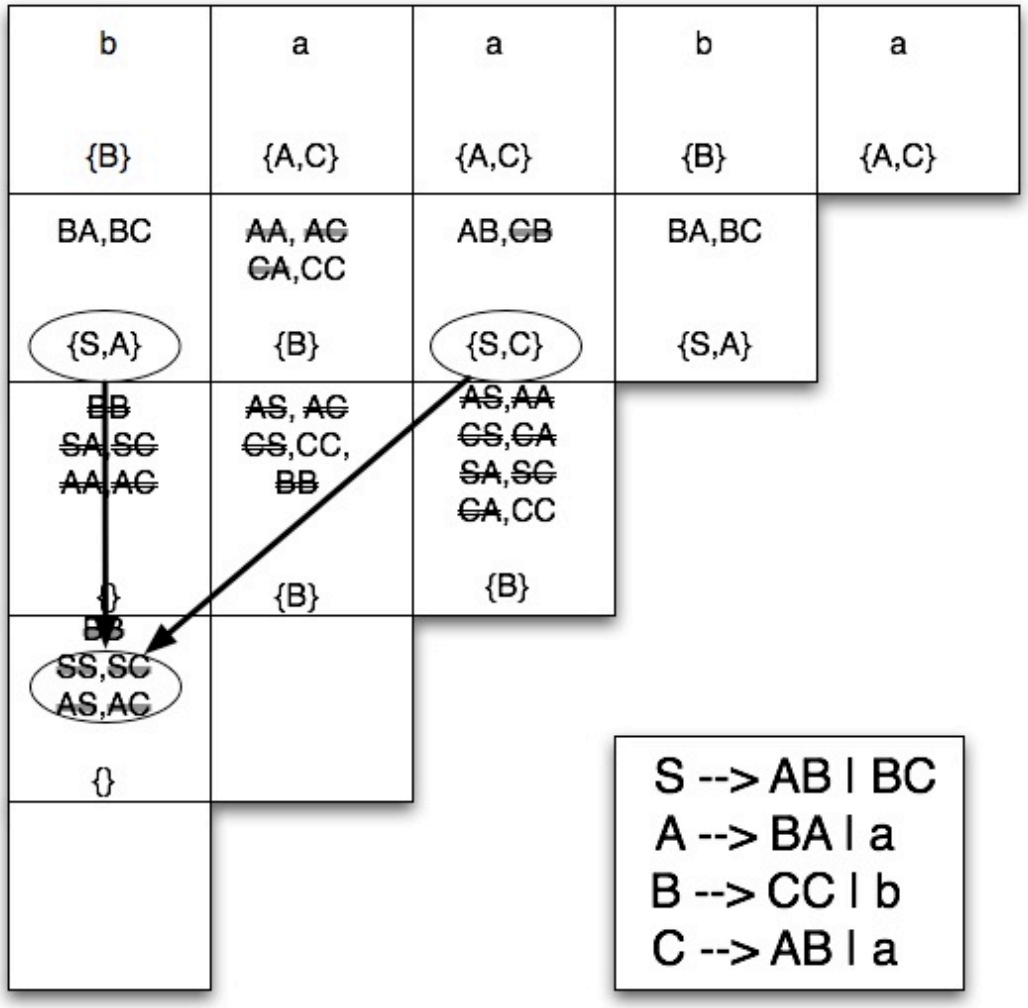

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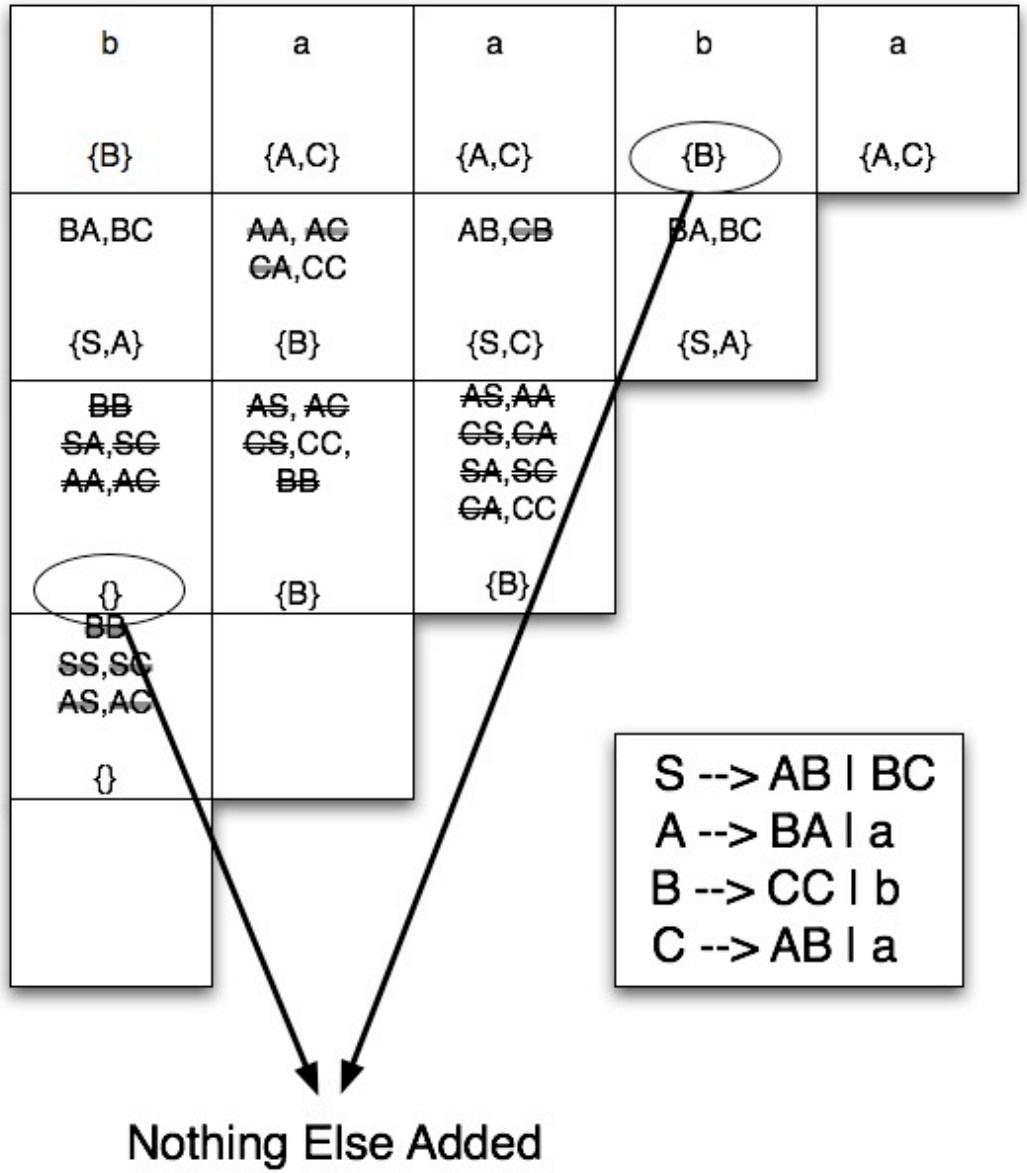

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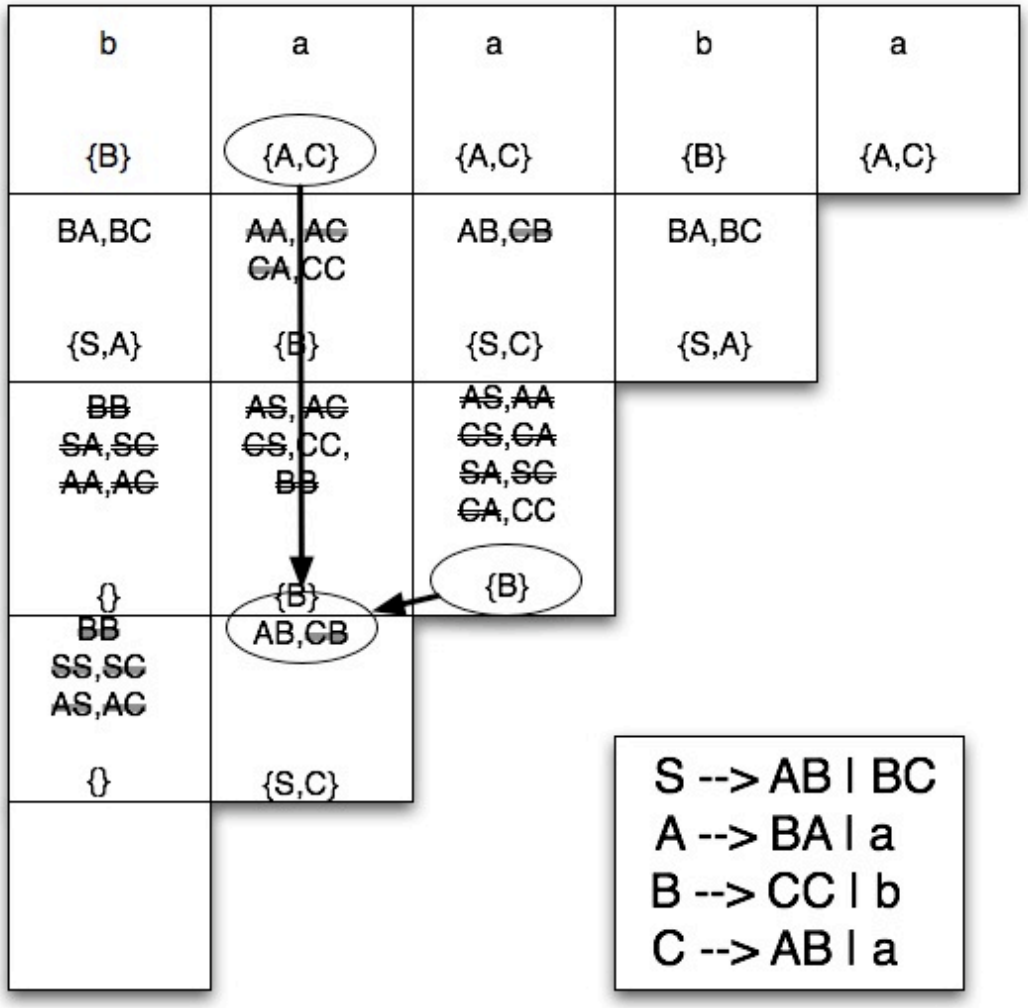

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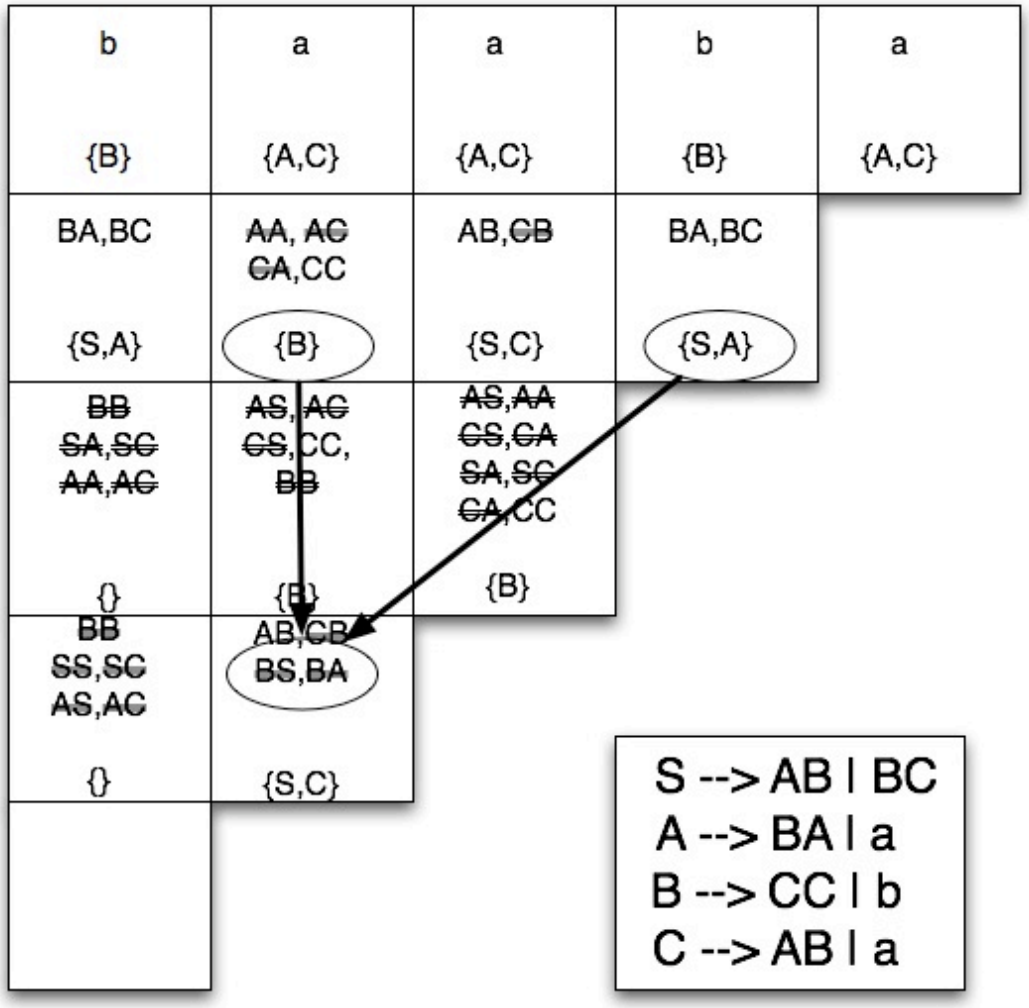

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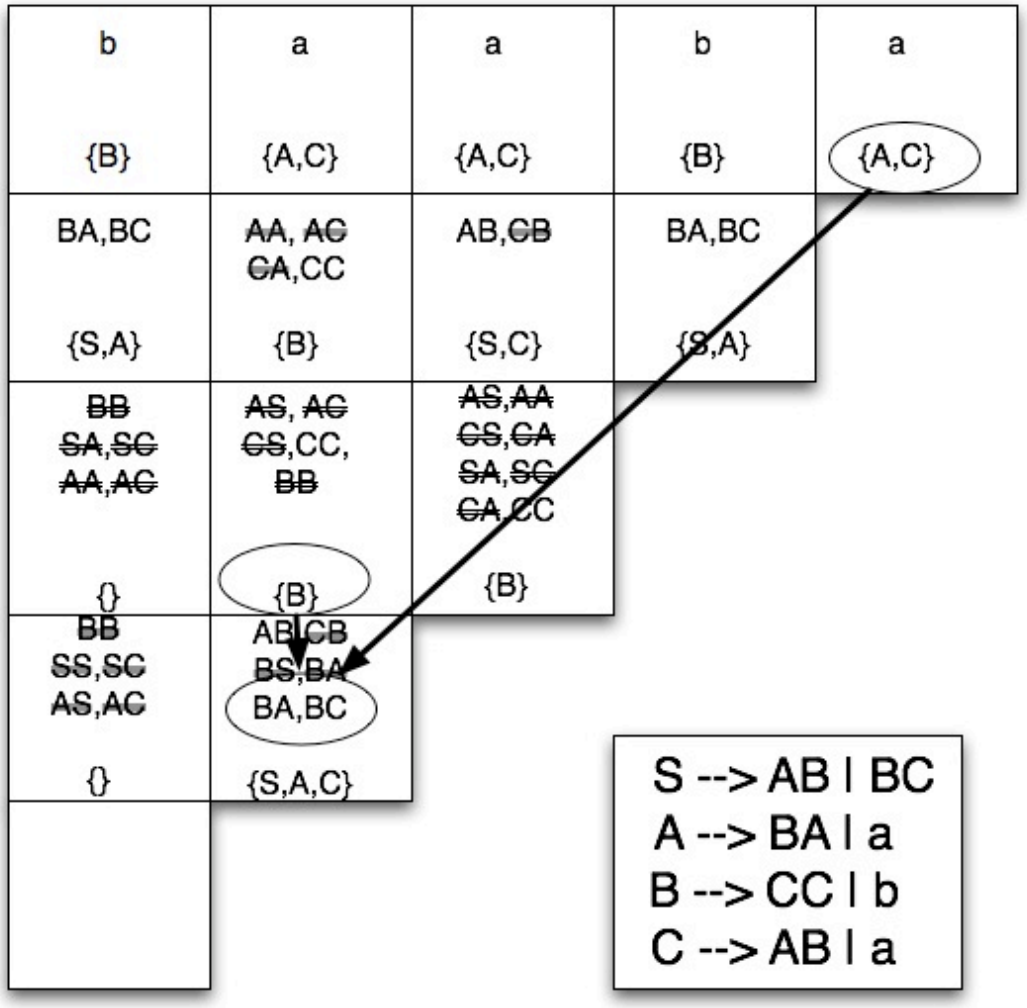

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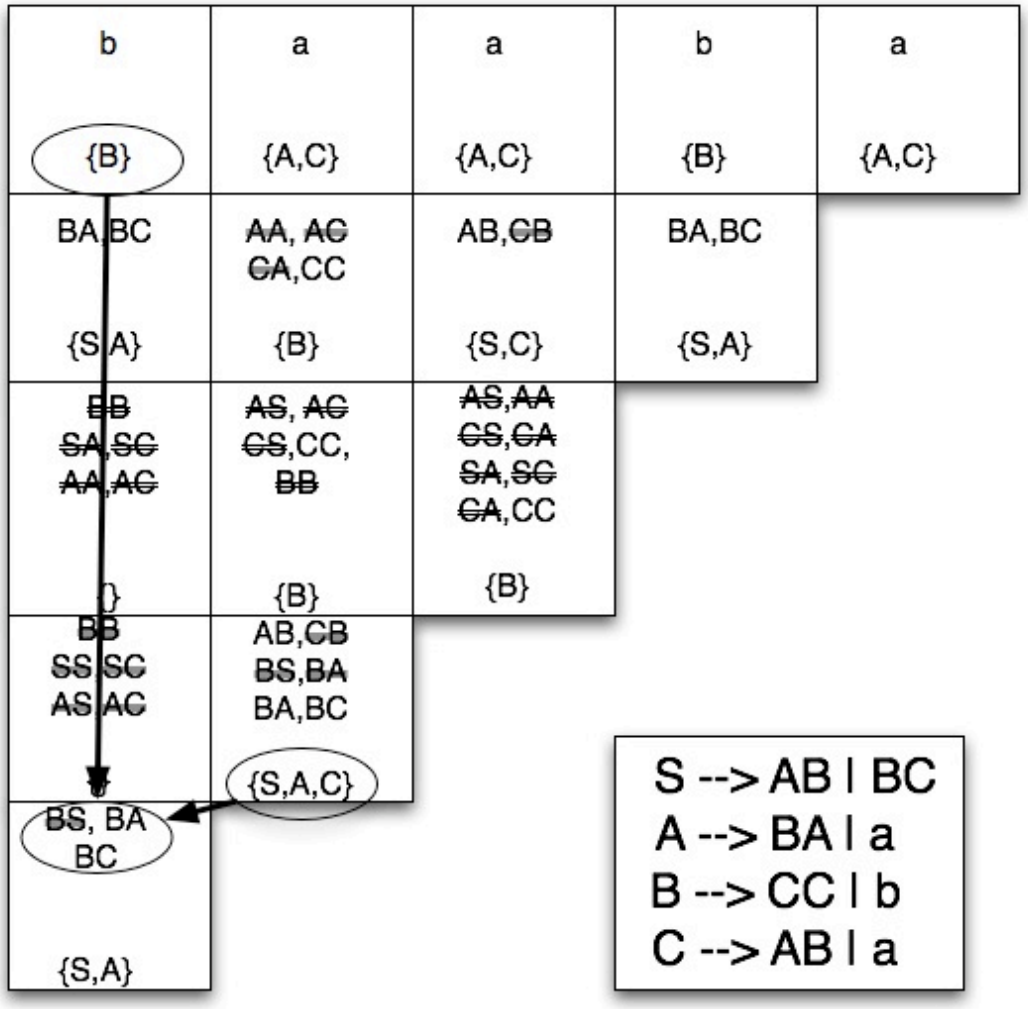

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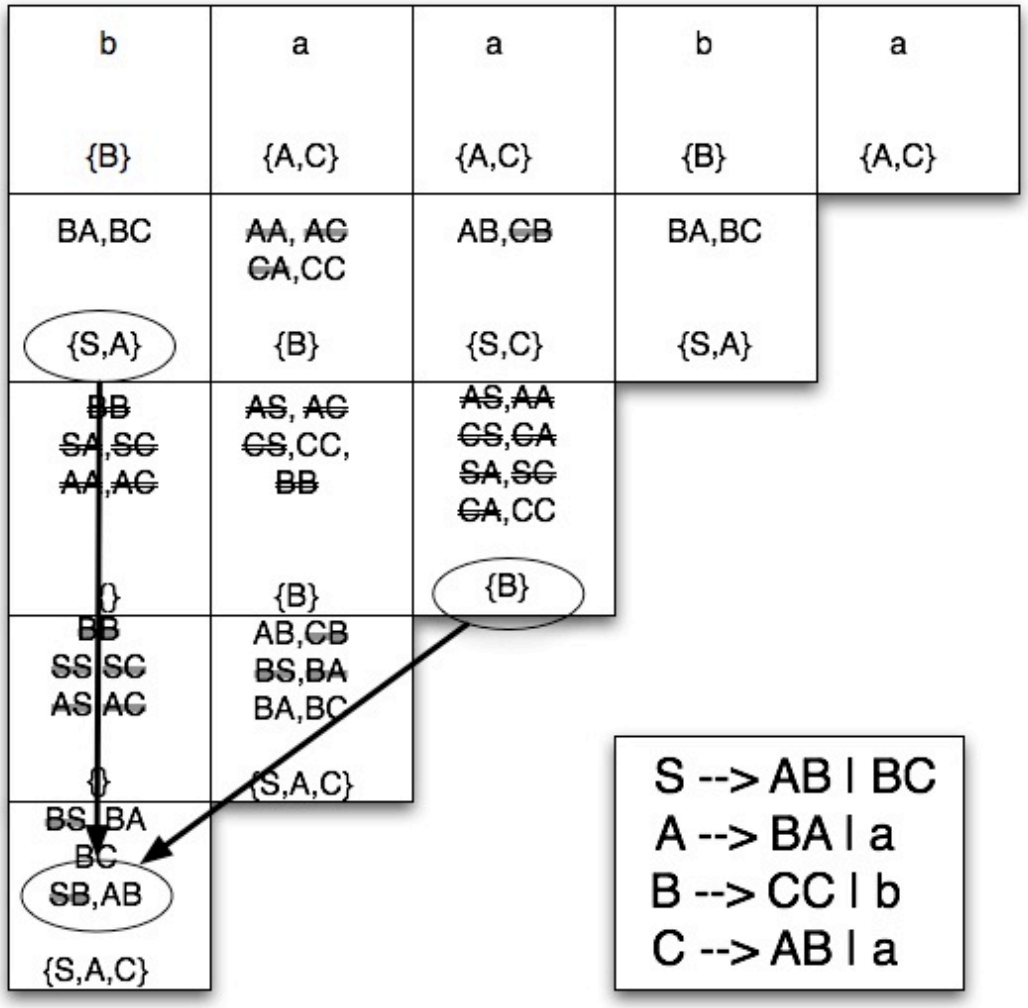
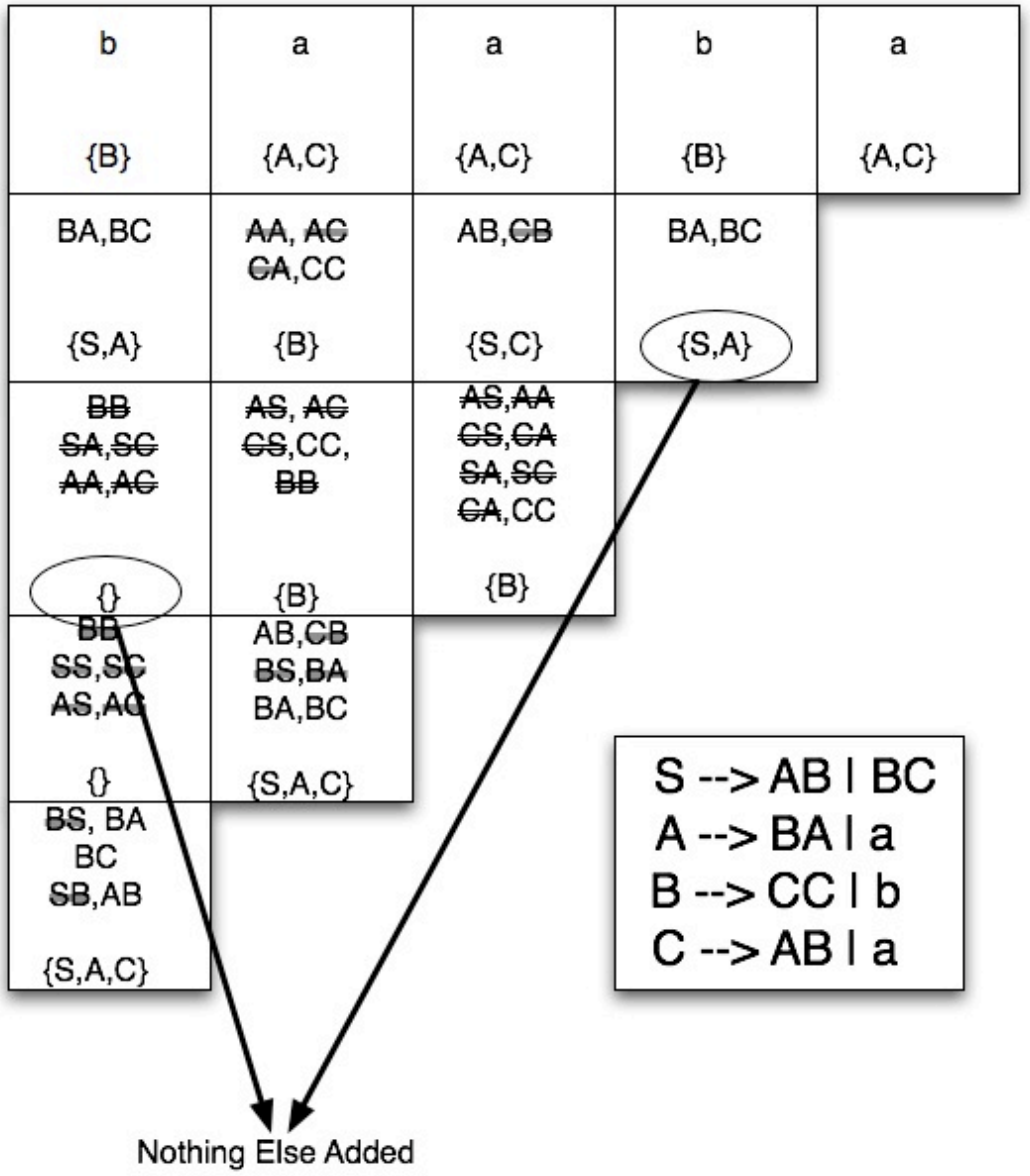
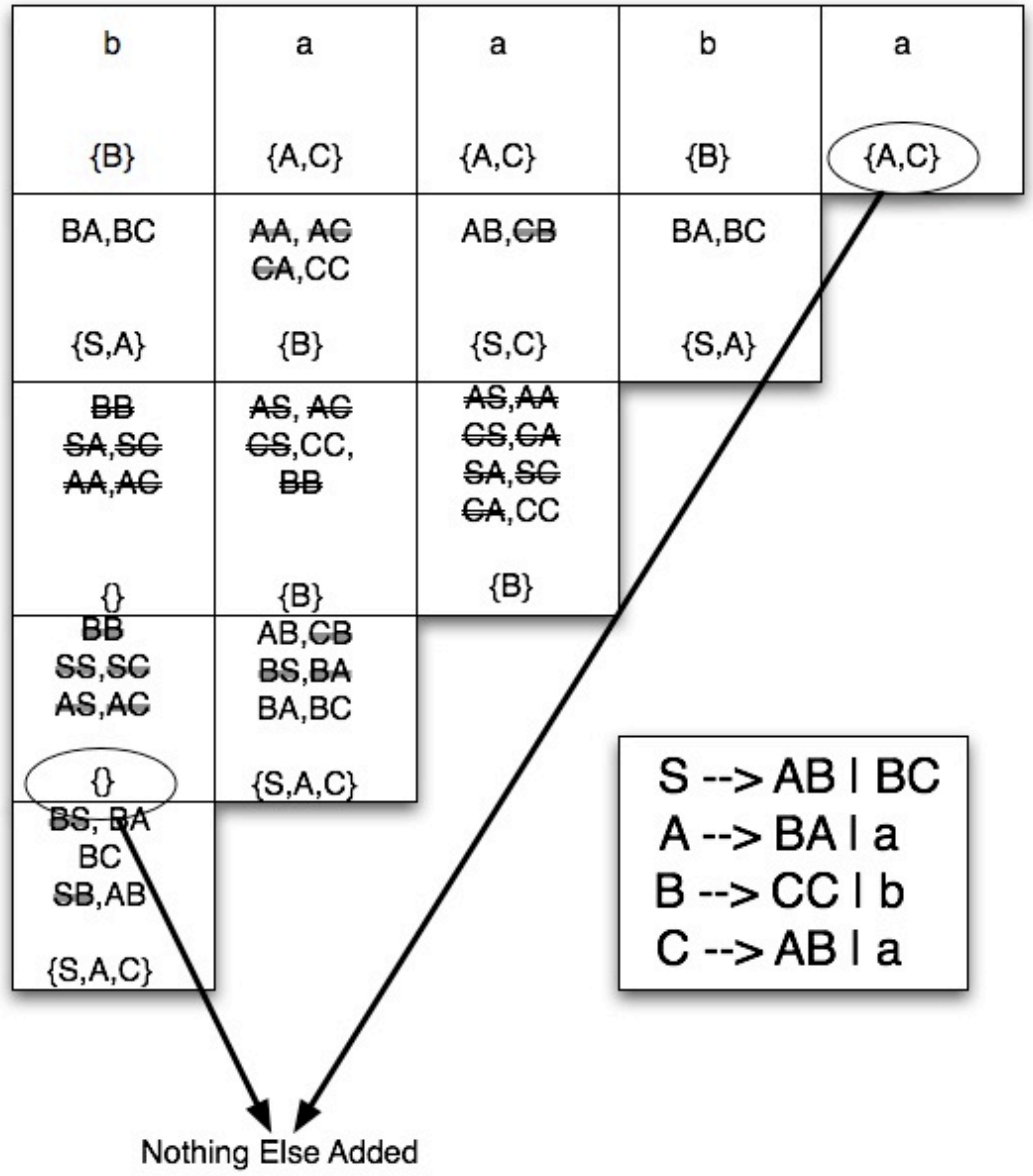


CYK Parser (Sequential Version)



CYK Parser (Sequential Version)



CYK Parser (Sequential Version)

b {B}	a {A,C}	a {A,C}	b {B}	a {A,C}
BA,BC {S,A}	~~AA~~, ~~AC~~ ~~CA~~,CC {B}	AB,~~CB~~ {S,C}	BA,BC {S,A}	
~~BB~~ ~~SA~~,~~SC~~ ~~AA~~,~~AC~~ {}	~~AS~~, ~~AC~~ ~~CS~~,CC, ~~BB~~ {B}	~~AS~~,~~AA~~ ~~CS~~,~~CA~~ ~~SA~~,~~SC~~ ~~CA~~,CC {B}		
~~BB~~ ~~SS~~,~~SC~~ ~~AS~~,~~AC~~ {}	AB,~~CB~~ ~~BS~~,~~BA~~ BA,BC {S,A,C}			
~~BS~~, BA BC ~~SB~~,AB {S,A,C}				

S --> AB | BC
A --> BA | a
B --> CC | b
C --> AB | a

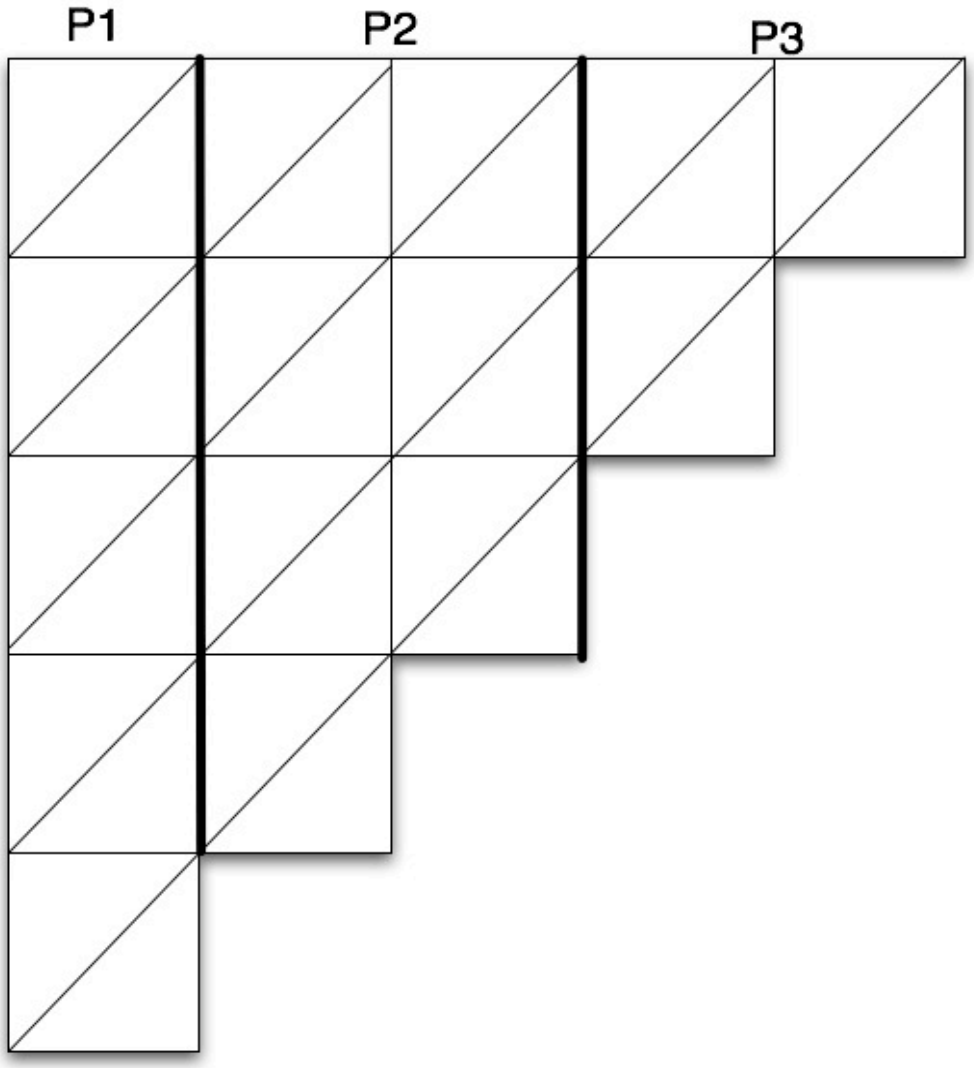
The CYK Parser Algorithm (Sequential Version)

```
(* for the first row *)
    1) for i := 1 to n do
    2)     V_i1 := { A | A --> a is a production
                       rule and the ith symbol of s
                       is a}

(* for subsequent rows *)
    3) for j := 2 to n do
    4)     for i := 1 to (n - j + 1) do
    5)         V_ij := {}
    6)         for k := 1 to (j - 1) do
    7)             V_ij := V_ij  U  { A | A --> BC
                                      is a production
                                          rule,
                                      B is in V_ik,
                                      C is in
                                        V_i+k,j-k  }
```

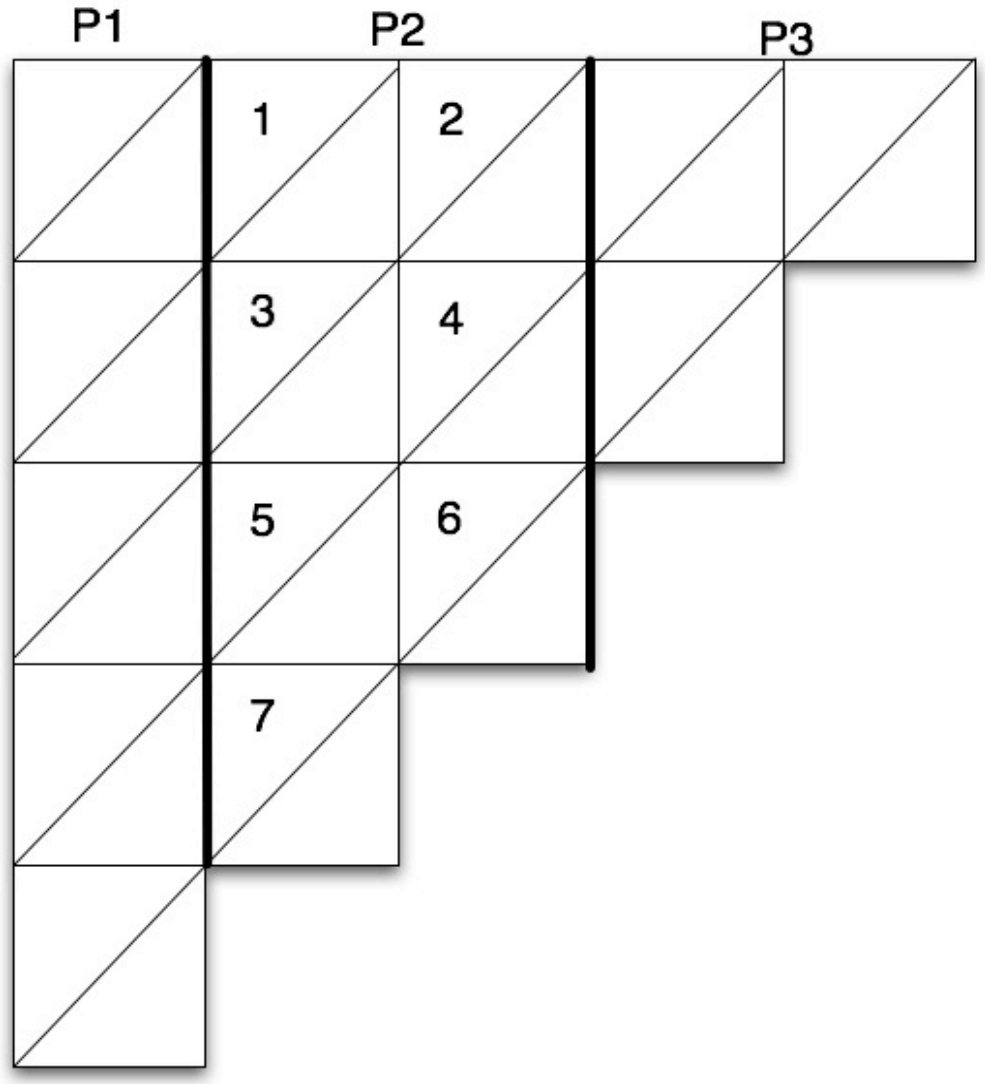
Figure3: Pseudo-code for the sequential CYK algorithm. Adapted from Hopcroft, Ullman, 1979, pp139-140.

CYK Parser (Parallel Version)



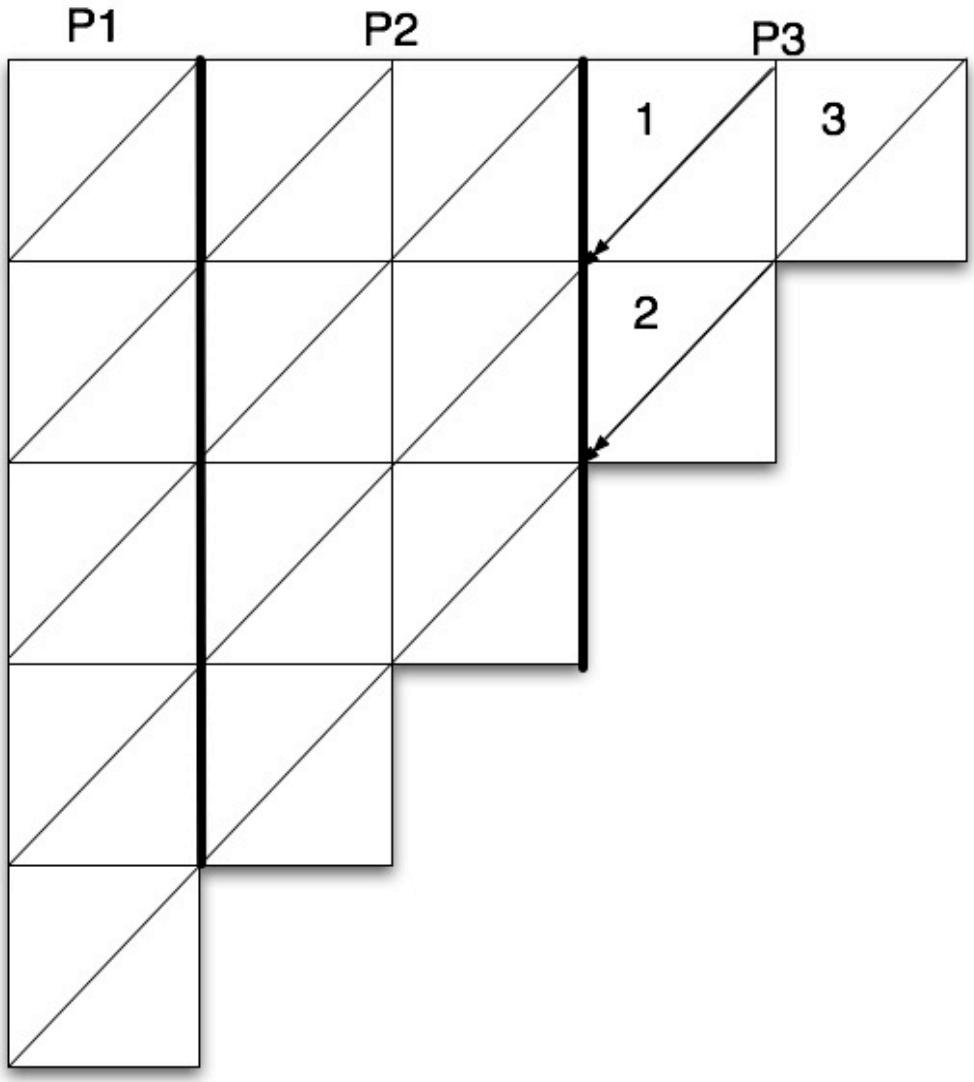
Matrix for a string of length 5 using 3 processors

CYK Parser (Parallel Version)



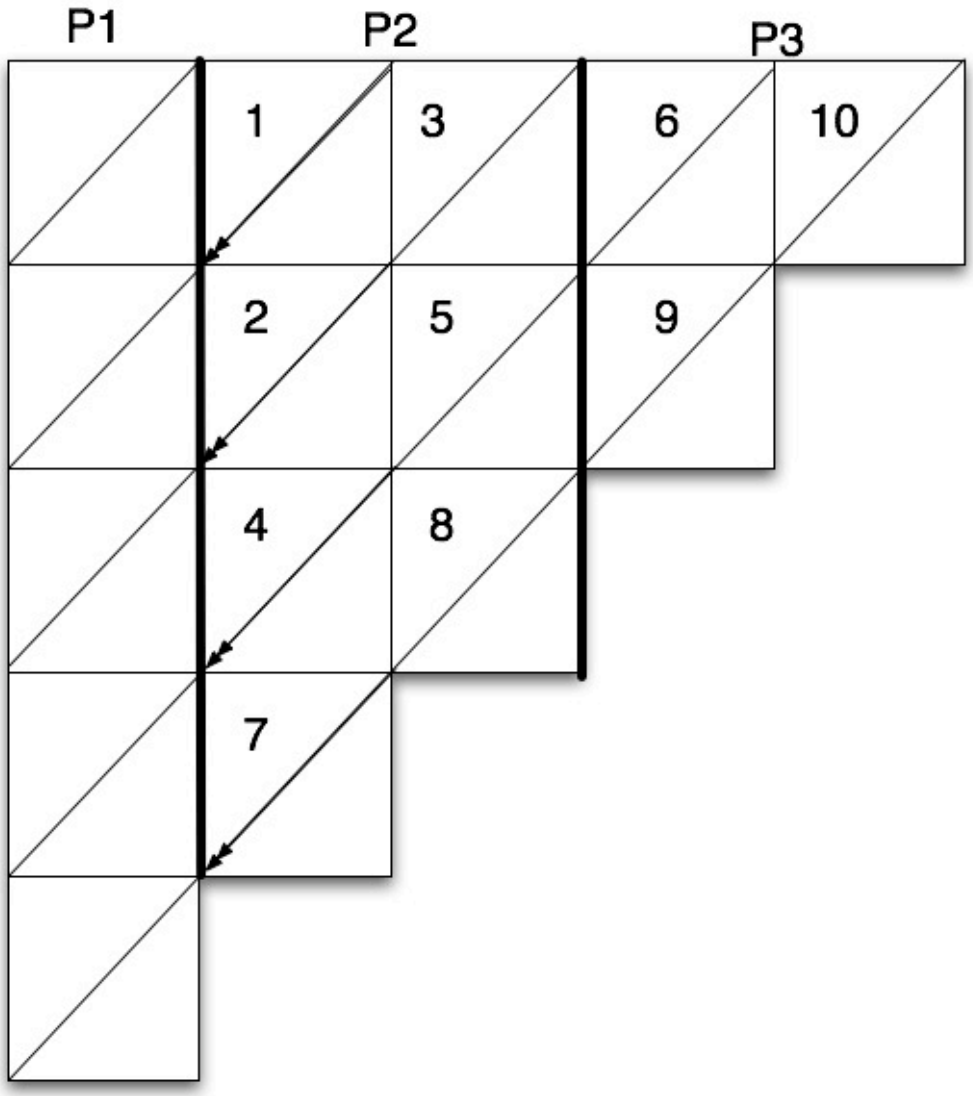
Order of calculation for processor P2. P2 calculates a diagonal at a time.

CYK Parser (Parallel Version)



Order of information received by P2. P2 receives a diagonal at a time.

CYK Parser (Parallel Version)



Order of information P2 sends to P1. P2 sends a diagonal at a time.

The CYK Parser Algorithm (Parallel Version)

if not last processor send all along to P_{i+1}

let $l = \sum_{q=1}^{p}$ length of substring for P_q

for j := 1 to l do
    if necessary get diagonal from p_{i+1}
    let m = length of the diagonal within P_i
    for k := 1 to m do
        calculate $V_{j-k+1,k}$
    if i <> 1
        then send back new diagonal to P_{i-1}
        else send back $V_{1,n}$ to Host

Extra Slides Start Here

Example (*grammar & sets*)

Simplified, right recursive expression grammar

Goal → *Expr*
Expr → *Term* - *Expr*
Expr → *Term*
Term → *Factor* * *Term*
Term → *Factor*
Factor → *ident*

Symbol	FIRST
Goal	{ ident }
Expr	{ ident }
Term	{ ident }
Factor	{ ident }
-	{ - }
*	{ * }
ident	{ ident }

Example (*building the collection*)

Initialization Step

$s_0 \leftarrow$ *closure(* { [*Goal* → • *Expr* , EOF] } *)*

{ [*Goal* → • *Expr* , EOF], [*Expr* → • *Term* – *Expr* , EOF],
[*Expr* → • *Term* , EOF], [*Term* → • *Factor* * Term , EOF],
[*Term* → • *Factor* * *Term* , –], [*Term* → • *Factor* , EOF],
[*Term* → • *Factor* , –], [*Factor* → • ident , EOF],
[*Factor* → • ident , –], [*Factor* → • ident , *] }

S $\leftarrow \{s_0\}$

Example (*building the collection*)

Iteration 1

$s_1 \leftarrow goto(s_0 , Expr)$

$s_2 \leftarrow goto(s_0 , Term)$

$s_3 \leftarrow goto(s_0 , Factor)$

$s_4 \leftarrow goto(s_0 , \underline{ident})$

Iteration 2

$s_5 \leftarrow goto(s_2 , -)$

$s_6 \leftarrow goto(s_3 , *)$

Iteration 3

$s_7 \leftarrow goto(s_5 , Expr)$

$s_8 \leftarrow goto(s_6 , Term)$

Example (*Summary*)

S_0 : { [*Goal* → • *Expr* , EOF], [*Expr* → • *Term* – *Expr* , EOF],
[*Expr* → • *Term* , EOF], [*Term* → • *Factor* * *Term* , EOF],
[*Term* → • *Factor* * *Term* , –], [*Term* → • *Factor* , EOF],
[*Term* → • *Factor* , –], [*Factor* → • ident , EOF],
[*Factor* → • ident , –], [*Factor*→ • ident, *] }

S_1 : { [*Goal* → *Expr* •, EOF] }

S_2 : { [*Expr* → *Term* • – *Expr* , EOF], [*Expr* → *Term* •, EOF] }

S_3 : { [*Term* → *Factor* • * *Term* , EOF],[*Term* → *Factor* • * *Term* , –],
[*Term* → *Factor* •, EOF], [*Term* → *Factor* •, –] }

S_4 : { [*Factor* → ident •, EOF],[*Factor* → ident •, –], [*Factor* → ident •, *] }

S_5 : { [*Expr* → *Term* – • *Expr* , EOF], [*Expr* → • *Term* – *Expr* , EOF],
[*Expr* → • *Term* , EOF], [*Term* → • *Factor* * *Term* , –],
[*Term* → • *Factor* , –], [*Term* → • *Factor* * *Term* , EOF],
[*Term* → • *Factor* , EOF], [*Factor* → • ident , *],
[*Factor* → • ident , –], [*Factor* → • ident , EOF] }

Example (*Summary*)

S_6 : { [*Term* → *Factor* * • *Term* , EOF], [*Term* → *Factor* * • *Term* , –],
[*Term* → • *Factor* * *Term* , EOF], [*Term* → • *Factor* * *Term* , –],
[*Term* → • *Factor* , EOF], [*Term* → • *Factor* , –],
[*Factor* → • ident , EOF], [*Factor* → • ident , –], [*Factor* → • ident , *] }

S_7: { [*Expr* → *Term* – *Expr* •, EOF] }

S_8 : { [*Term* → *Factor* * *Term* •, EOF], [*Term* → *Factor* * *Term* •, –] }

Example (*Summary*)

The Goto Relationship *(from the construction)*

State	Expr	Term	Factor	-	*	Ident
0	1	2	3			4
1						
2				5		
3					6	
4						
5	7	2	3			4
6		8	3			4
7						
8						

Filling in the ACTION and GOTO Tables

The algorithm

x is the number of the state for s_x

∀ *set* $s_x \in S$
  ∀ *item* $i \in s_x$
    if *i is* $[A \rightarrow \beta \cdot \underline{a} d, \underline{b}]$ *and* $goto(s_x, \underline{a}) = s_k$, $\underline{a} \in T$
      then ACTION$[x, \underline{a}] \leftarrow$ "*shift k*"
    else if *i is* $[S' \rightarrow S \cdot, EOF]$
      then ACTION$[x, EOF] \leftarrow$ "*accept*"
    else if *i is* $[A \rightarrow \beta \cdot, \underline{a}]$
      then ACTION$[x, \underline{a}] \leftarrow$ "*reduce* $A \rightarrow \beta$"
  ∀ $n \in NT$
    if $goto(s_x, n) = s_k$
      then GOTO$[x, n] \leftarrow k$

Many items generate no table entry

e.g., $[A \rightarrow \beta \cdot B \alpha, \underline{a}]$ does not, but *closure* ensures that all the rhs' for *B* are in s_x

Example (*Filling in the tables*)

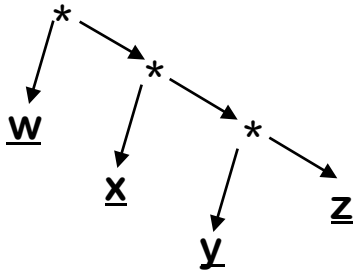
The algorithm produces the following table

	ACTION				GOTO		
	Ident	-	*	EOF	*Expr*	*Term*	*Factor*
0	s 4				1	2	3
1				acc			
2		s 5		r 3			
3		r 5	s 6	r 5			
4		r 6	r 6	r 6			
5	s 4				7	2	3
6	s 4					8	3
7				r 2			
8		r 4		r 4			

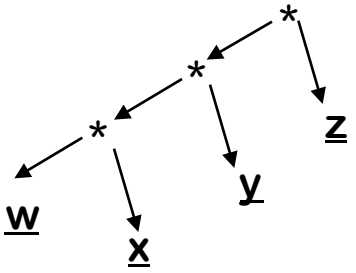
Plugs into the skeleton LR(1) parser

Left Recursion versus Right Recursion

- Right recursion
- Required for termination in top-down parsers
- Uses (on average) more stack space
- Produces right-associative operators
- Left recursion
- Works fine in bottom-up parsers
- Limits required stack space
- Produces left-associative operators
- Rule of thumb
- Left recursion for bottom-up parsers
- Right recursion for top-down parsers



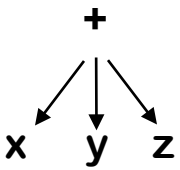
w * (x * (y * z))



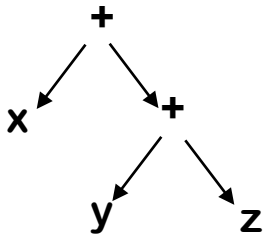
((w * x) * y) * z

Associativity

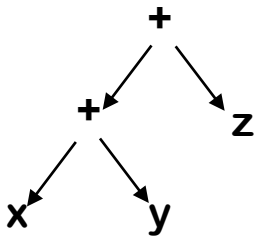
- What difference does it make?
- Can change answers in floating-point arithmetic
- Exposes a different set of common subexpressions
- Consider x+y+z



Ideal operator



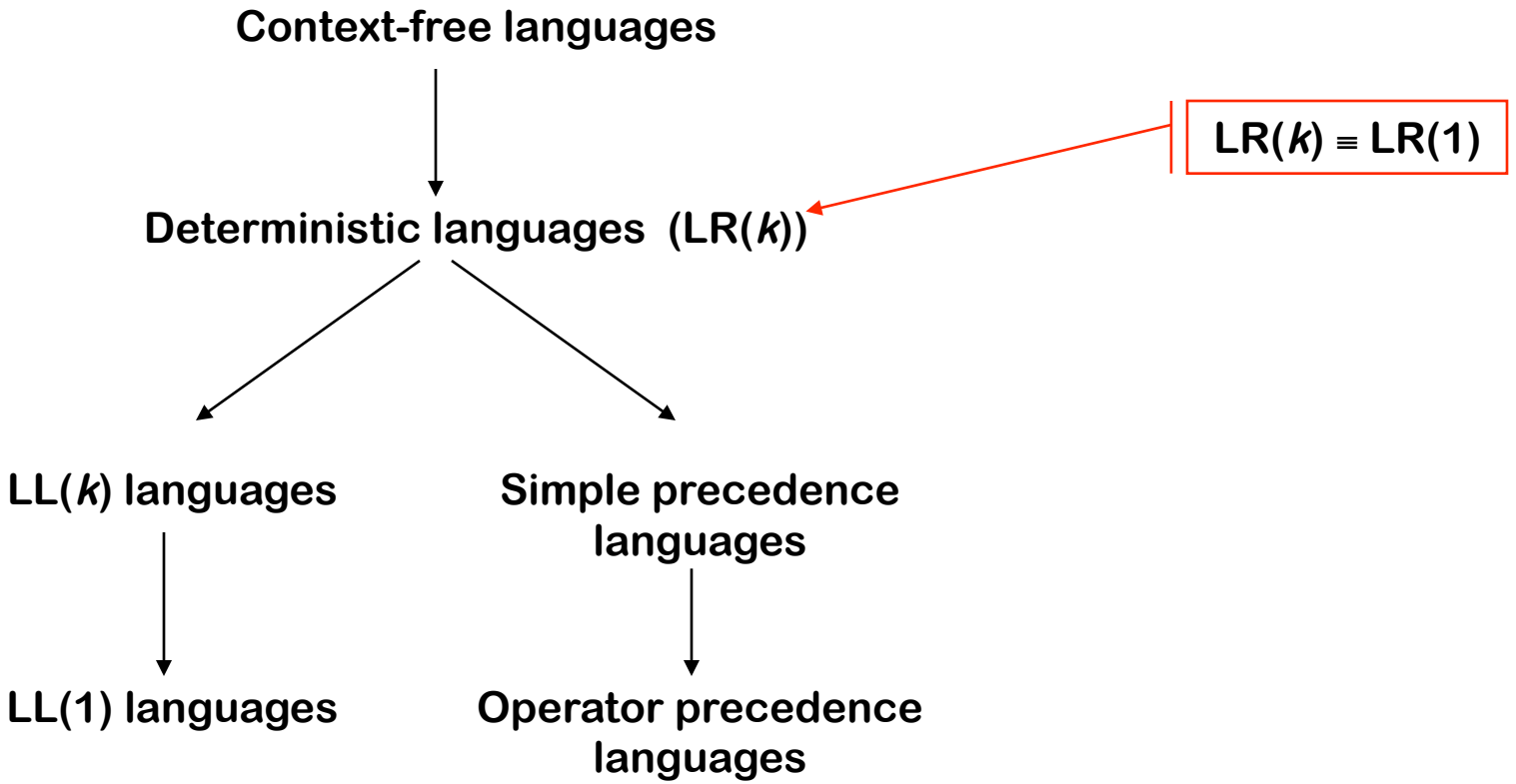
Left association



Right association

- What if y+z occurs elsewhere? Or x+y? or x+z?
- What if x = 2 & z = 17 ? Neither left nor right exposes 19.
- Best choice is function of surrounding context

Hierarchy of Context-Free Languages



The inclusion hierarchy for context-free languages

Beyond Syntax

There is a level of correctness that is deeper than grammar

```
fie(a,b,c,d)
   int a, b, c, d;
{ … }
fee() {
   int f[3],g[0],
     h, i, j, k;
  char *p;
   fie(h,i,"ab",j, k);
   k = f * i + j;
   h = g[17];
   printf("<%s,%s>.\n",
     p,q);
   p = 10;
}
```

What is wrong with this program?

(let me count the ways …)

To generate code, we need to understand its meaning !

There is a level of correctness that is deeper than grammar

```
fie(a,b,c,d)
   int a, b, c, d;
{ … }
fee() {
   int f[3],g[0],
     h, i, j, k;
  char *p;
   fie(h,i,"ab",j, k);
   k = f * i + j;
   h = g[17];
   printf("<%s,%s>.\n",
     p,q);
   p = 10;
}
```

What is wrong with this program?

(let me count the ways …)

- declared g[0], used g[17]
- wrong number of args to fie()
- "ab" is not an int
- wrong dimension on use of f
- undeclared variable q
- 10 is not a character string

All of these are "deeper than syntax"

Beyond Syntax

To generate code, the compiler needs to answer many questions

- Is "x" a scalar, an array, or a function? Is "x" declared?
- Are there names that are not declared? Declared but not used?
- Which declaration of "x" does each use reference?
- Is the expression "x * y + z" type-consistent?
- In "*a*[i,j,k]", does *a* have three dimensions?
- Where can "z" be stored? *(register, local, global, heap, static)*
- In "f ← 15", how should 15 be represented?
- How many arguments does "fie()" take? What about "printf ()" ?
- Does "*p" reference the result of a "malloc()" ?
- Do "p" & "q" refer to the same memory location?
- Is "x" defined before it is used?

These cannot be expressed in a CFG

Beyond Syntax

These questions are part of context-sensitive analysis

- Answers depend on values, not parts of speech
- Questions & answers involve non-local information
- Answers may involve computation

How can we answer these questions?

- Use formal methods
  - → Context-sensitive grammars?
  - → Attribute grammars? *(attributed grammars?)*
- Use *ad-hoc* techniques
  - → Symbol tables
  - → *Ad-hoc* code *(action routines)*

In scanning & parsing, formalism won; different story here.

Beyond Syntax

Telling the story

- The attribute grammar formalism is important
  - → Succinctly makes many points clear
  - → Sets the stage for actual, *ad-hoc* practice
- The problems with attribute grammars motivate practice
  - → Non-local computation
  - → Need for centralized information
- Some folks in the community still argue for attribute grammars
  - → Knowledge is power
  - → Information is immunization

We will cover attribute grammars, then move on to *ad-hoc* ideas