A little more CFG parsing

Computational Linguistics (LING 455)

Rutgers University   Nov 23, 2021

Summary

CFGs

CFGs have rewrite rules of the shape $A \longrightarrow \varphi$, where φ is a string of terminals and non-terminals.

- The restriction is on the LHS. This is what makes it context-free.

We can contemplate restrictions on the RHS as well:

- Rules like $A \longrightarrow x$, $A \longrightarrow xB$ only: finite-state/regular
- Rules like $A \longrightarrow x$, $A \longrightarrow BC$ only: Chomsky Normal Form

CNF is a convenience, not a restriction in expressive power.

The parsing task

A **grammar** is a way of finitely and succinctly specifying a (typically infinite) number of objects with a certain shape.

Parsing is the task of structuring a linear representation in a way sanctioned by some grammar.

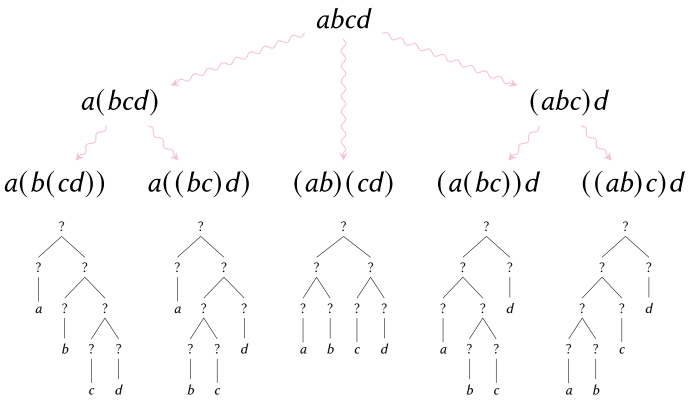
Naive CFG parsing

```
parse g [x] = [ n | n :- y <- g, y==x ]
parse g xs  = [ n | (ls,rs) <- breaks xs,
                    nl <- parse g ls,
                    nr <- parse g rs,
                    n :> (l,r) <- g, l==nl, r==nr ]
```

For non-singleton strings:

- Break the input string into two (every possible way)
- Recurse, parsing the left half and the right half (given `g`)
- Try to combine the resulting yields `nl` and `nr` (given `g`)
- Return the resulting categories

Naive parsing is inefficient: each substring under a given length is parsed multiple (depending on the string length, maybe many) times.


abcd
a(bcd)
(abc)d
a(b(cd))
a((bc)d)
(ab)(cd)
(a(bc))d
((ab)c)d

CYK

Each substring is identified by a **span**, a pair of numbers (i, j):

| `"Mary"` | `"saw"` | `"the"` | `"elk"` |

0 1 2 3 4

Spans can arranged in a table. Then parsing amounts to filling the table in. The key to efficiency: each span occurs exactly **once!**

`"Mary"`	0,1	0,2	0,3	0,4
`"saw"`		1,2	1,3	1,4
`"the"`			2,3	2,4
`"elk"`				3,4

CYK

Each substring is identified by a **span**, a pair of numbers (i, j):

$$\underset{0}{|}\ \texttt{"Mary"}\ \underset{1}{|}\ \texttt{"saw"}\ \underset{2}{|}\ \texttt{"the"}\ \underset{3}{|}\ \texttt{"elk"}\ \underset{4}{|}$$

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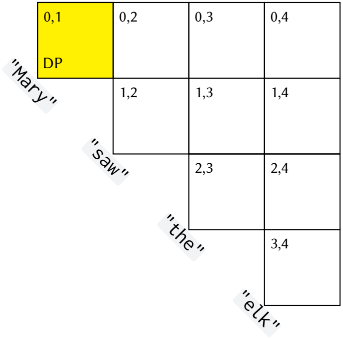

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`| "Mary" | "saw" | "the" | "elk" |`
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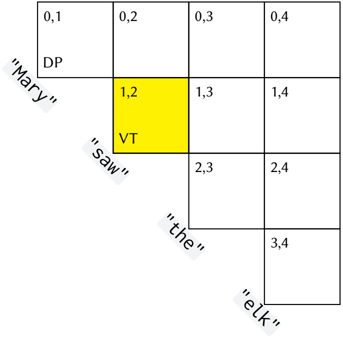

CYK

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```
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0        1       2       3       4
```

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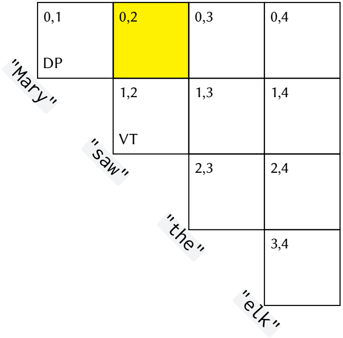

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```
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```

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"Mary"	0,1 DP	0,2	0,3	0,4
"saw"		1,2 VT	1,3	1,4
"the"			2,3 D	2,4
"elk"				3,4

CYK

Each substring is identified by a **span**, a pair of numbers (i, j):

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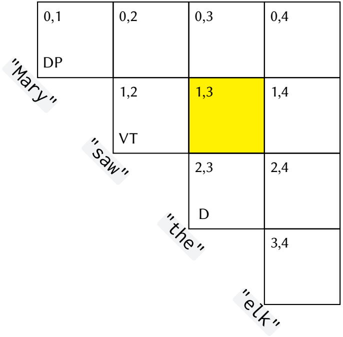

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	`"saw"`	2,3 D	2,4
		`"the"`	3,4
			`"elk"`

CYK

Each substring is identified by a **span**, a pair of numbers (i, j):

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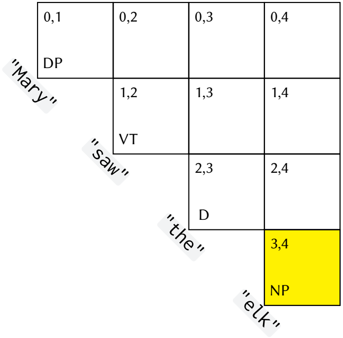

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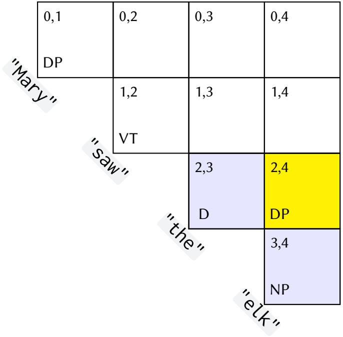

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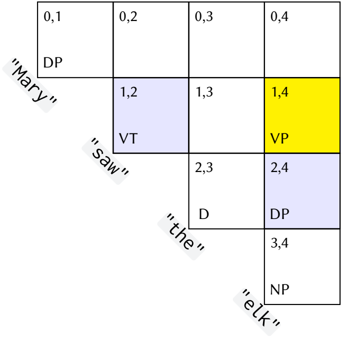

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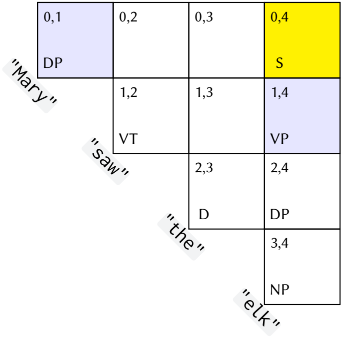

CYK

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| `"Mary"` | `"saw"` | `"the"` | `"elk"` |

0 1 2 3 4

Spans can arranged in a table. Then parsing amounts to filling the table in. The key to efficiency: each span occurs exactly **once!**

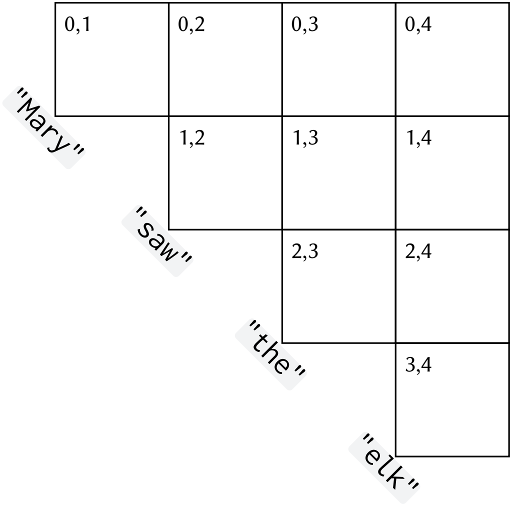
0,1 DP	0,2	0,3	0,4 S
`"Mary"`	1,2 VT	1,3	1,4 VP
	`"saw"`	2,3 D	2,4 DP
		`"the"`	3,4 NP
			`"elk"`

Enriched parsing

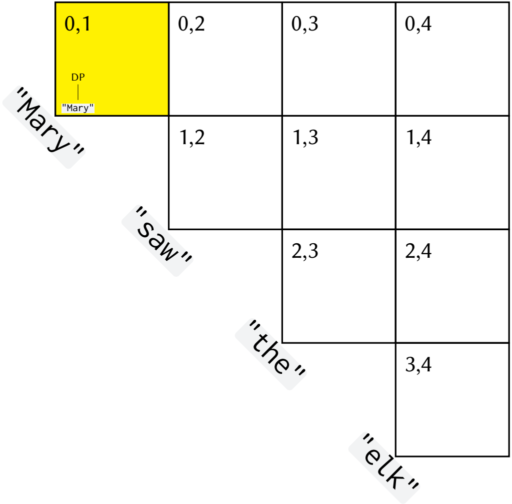
These parsing algorithms treat parse yields as (lists of) categories. We might be interested in other kinds of yields:

- Trees (e.g., `LBT`'s) that encode the structure of the parsed object
- Weights that report (e.g.) how probable a derivation is
- Costs associated with a derivation

Parsing to trees



Parsing to trees



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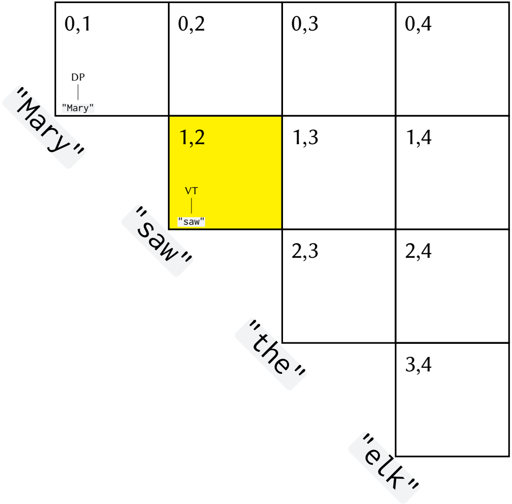

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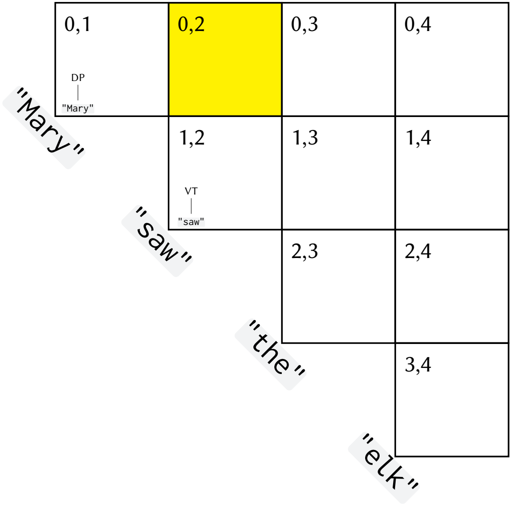
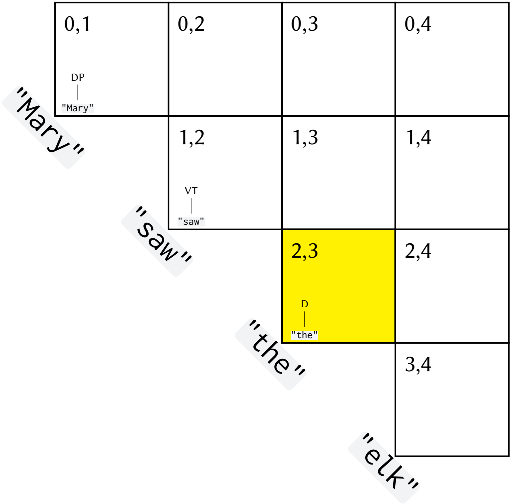
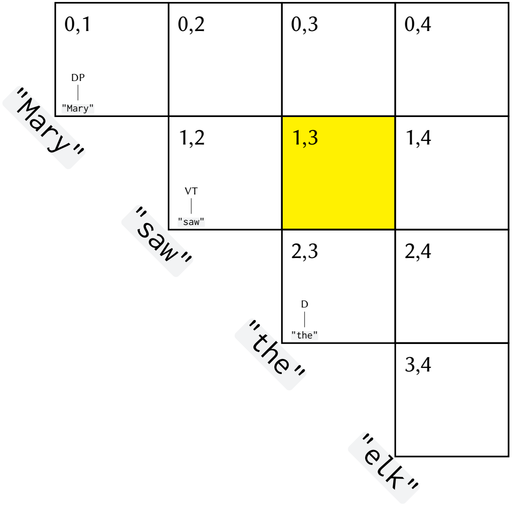


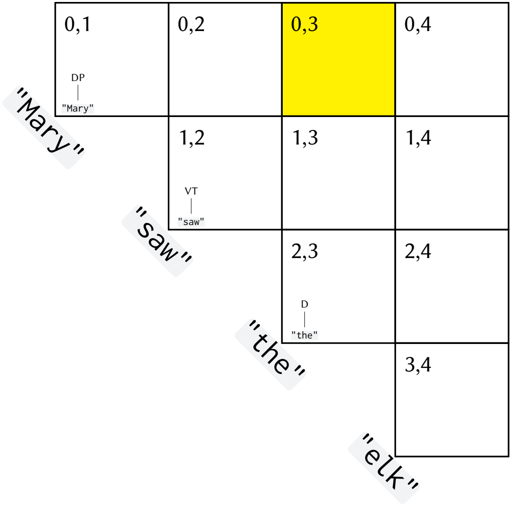
Parsing to trees



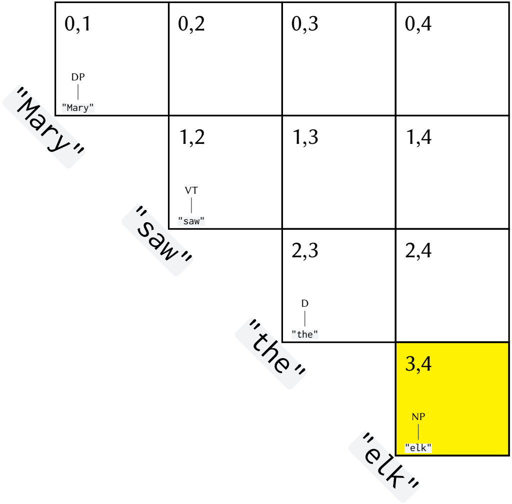
Parsing to trees



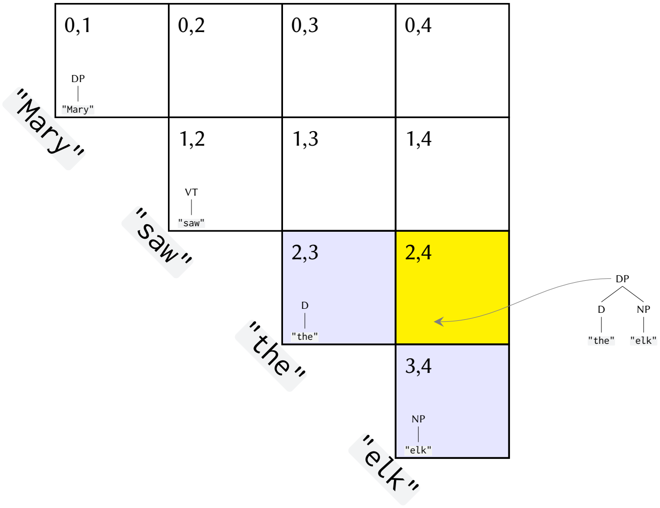
Parsing to trees



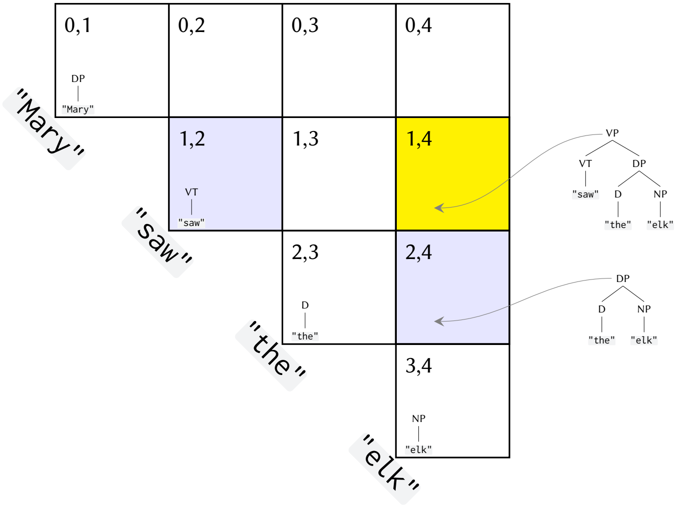
Parsing to trees



Parsing to trees



Parsing to trees



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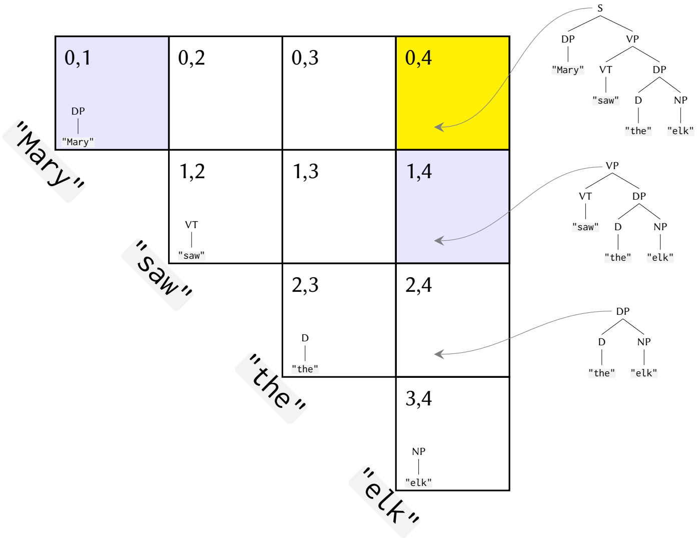
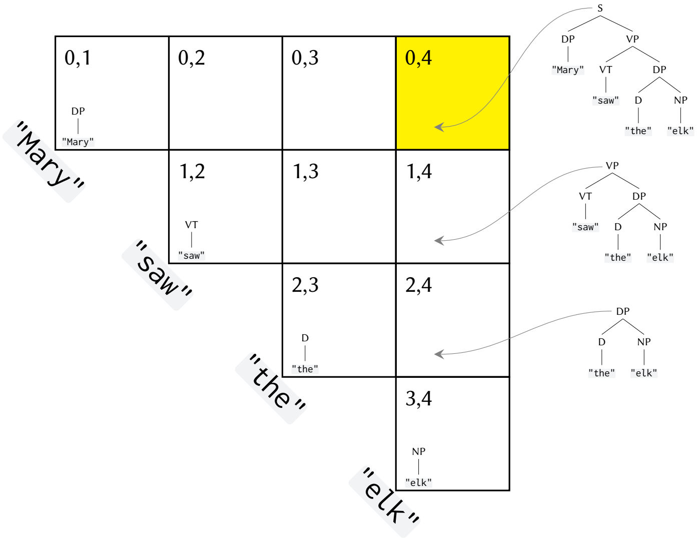


Parsing to trees



Enriched parsing

The strategy for parsing to `LBT`'s is quite reminiscent of how we generalized FSA parsing to FST parsing:

```
step delta x (q,m) = [ (s, m<>n) | (r,y,n,s) <- delta,
                                   q==r, y==x ]
```

```
parseToLBT g [x] = [ Leaf n x | n :- y <- g, y==x ]
parseToLBT g xs  =
  [ Branch n tl tr | (ls, rs) <- breaks xs,
      tl <- parseToLBT g ls,
      tr <- parseToLBT g rs,
      n :> (l, r) <- g, label tl == l, label tr == r ]
```

The old result of a parse (previously, a state; now, a category) is **enriched** with some extra info (previously, a string; now, a tree).

Weighted or probabilistic CFGs

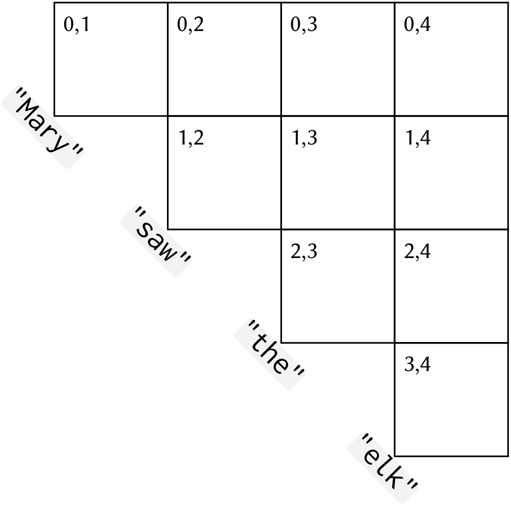
A straightforward extension of CFGs pairs rules with **weights**, **probabilities**, or **costs**.

```
type WCFG cat term weight = [(Rule cat term, weight)]
type PCFG cat term = WCFG cat term Double
```

Computing the weight of a whole analysis means **accumulating** the weights, via a monoid! (Exercise: change CYK.)

```
parseW g [x] = [ (n, w) | (n :- y, w) <- g, y==x ]
parseW g xs  =
  [ (n, w<>wl<>wr) | (ls, rs) <- breaks xs,
                     (nl, wl) <- parseW g ls,
                     (nr, wr) <- parseW g rs,
                     (n :> (l,r), w) <- g, l==nl, r==nr ]
```

Parsing with weights (assume all $A \longrightarrow BC$ rules weighted 1)



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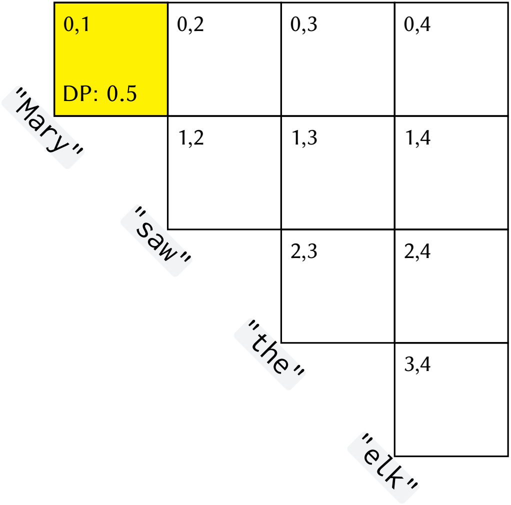

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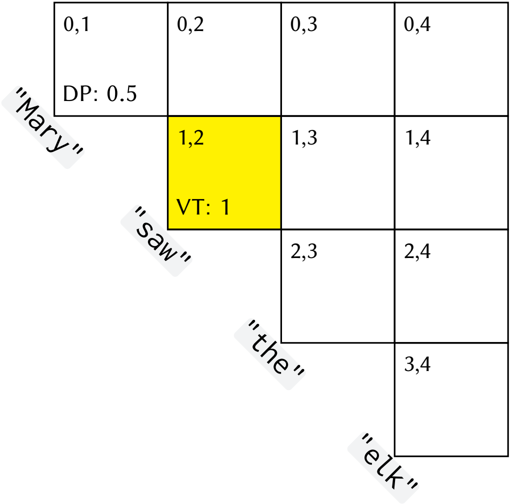
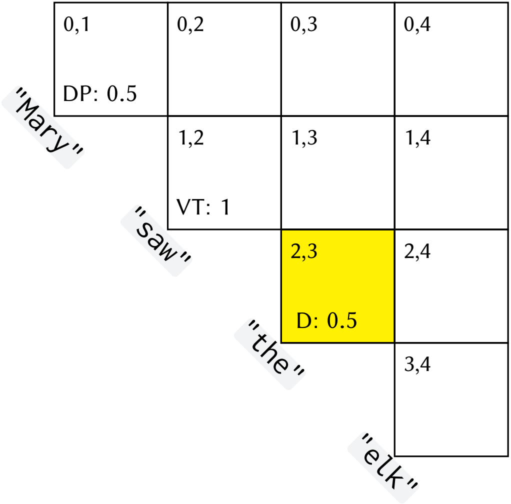


Parsing with weights (assume all $A \to BC$ rules weighted 1)

0,1 DP: 0.5	0,2	0,3	0,4
"Mary"	1,2 VT: 1	1,3	1,4
	"saw"	2,3	2,4
		"the"	3,4
			"elk"

Parsing with weights (assume all $A \longrightarrow BC$ rules weighted 1)



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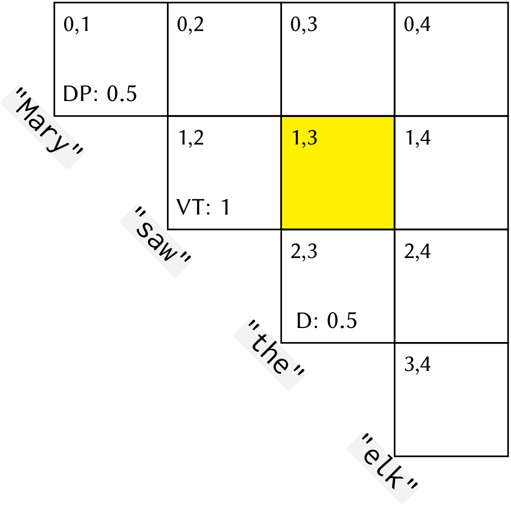

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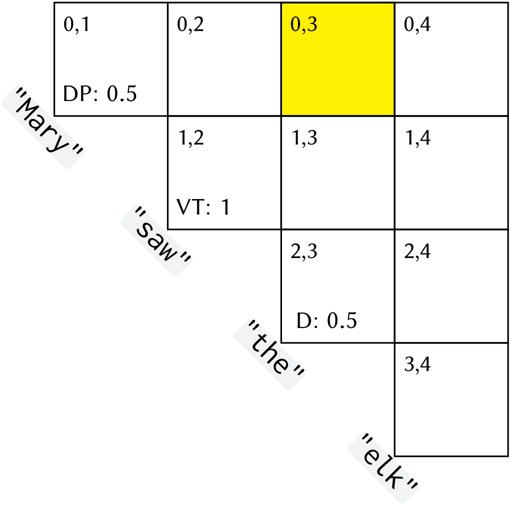
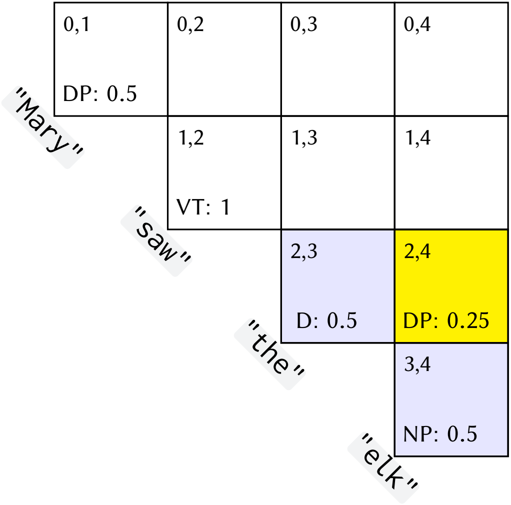


Parsing with weights (assume all $A \longrightarrow BC$ rules weighted 1)

0,1 DP: 0.5	0,2	0,3	0,4
"Mary"	1,2 VT: 1	1,3	1,4
	"saw"	2,3 D: 0.5	2,4
		"the"	3,4 NP: 0.5
			"elk"

Parsing with weights (assume all $A \longrightarrow BC$ rules weighted 1)



Parsing with weights (assume all $A \rightarrow BC$ rules weighted 1)

"Mary"	0,1 DP: 0.5	0,2	0,3	0,4
"saw"		1,2 VT: 1	1,3	1,4 VP: 0.25
"the"			2,3 D: 0.5	2,4 DP: 0.25
"elk"				3,4 NP: 0.5

Parsing with weights (assume all $A \longrightarrow BC$ rules weighted 1)

"Mary"	0,1 DP: 0.5	0,2	0,3	0,4 S: 0.125
"saw"		1,2 VT: 1	1,3	1,4 VP: 0.25
"the"			2,3 D: 0.5	2,4 DP: 0.25
"elk"				3,4 NP: 0.5

Parsing with weights (assume all $A \to BC$ rules weighted 1)

"Mary"	0,1 DP: 0.5	0,2	0,3	0,4 S: 0.125
"saw"		1,2 VT: 1	1,3	1,4 VP: 0.25
"the"			2,3 D: 0.5	2,4 DP: 0.25
"elk"				3,4 NP: 0.5

Transition-based parsing

Parsing as state transitions

Another way to conceptualize parsing is via transitions:

- Specify what a **starting stage** is
- Specify what a **goal stage** is
- Specify a **transition relation on stages**

Example: finite-state parsing

- A starting stage is a pair (A, xs), where $A \in I$ and xs is the input
- A goal stage is a pair (A, ε), where $A \in F$
- $(A, x_i x_{i+1} \dots x_n) \Rightarrow (B, x_{i+1} \dots x_n)$ iff $(A, x_i, B) \in \Delta$

Shift-reduce parsing

CFG parsing can work in a similar way. Given a set of rules G:

- A starting stage is (ε, xs), where xs is the input
- A goal stage is (A, ε), where A is a nonterminal
- Transitions either read a terminal or reduce 2 nonterminals:
    1. SHIFT: $(\Phi, x_i x_{i+1} \ldots x_n) \Rightarrow (A\Phi, x_{i+1} \ldots x_n)$, where $A \rightarrow x_i \in G$
    2. REDUCE: $(RL\Phi, xs) \Rightarrow (A\Phi, xs)$, where $A \rightarrow LR \in G$

An example

	Type	Rule	Configuration
0			(ε, Mary saw the elk)

An example

	Type	Rule	Configuration
0			(ε, Mary saw the elk)
1	SHIFT	DP $\rightarrow$ Mary	(DP, saw the elk)

An example

	Type	Rule	Configuration
0			(ε, Mary saw the elk)
1	SHIFT	DP $\rightarrow$ Mary	(DP, saw the elk)
2	SHIFT	VT $\rightarrow$ saw	(VT DP, the elk)

An example

	Type	Rule	Configuration
0			(ε, Mary saw the elk)
1	SHIFT	DP $\longrightarrow$ Mary	(DP, saw the elk)
2	SHIFT	VT $\longrightarrow$ saw	(VT DP, the elk)
3	SHIFT	D $\longrightarrow$ the	(D VT DP, elk)

An example

	Type	Rule	Configuration
0			(ε, Mary saw the elk)
1	SHIFT	DP $\longrightarrow$ Mary	(DP, saw the elk)
2	SHIFT	VT $\longrightarrow$ saw	(VT DP, the elk)
3	SHIFT	D $\longrightarrow$ the	(D VT DP, elk)
4	SHIFT	NP $\longrightarrow$ elk	(NP D VT DP, ε)

An example

	Type	Rule	Configuration
0			(ε, Mary saw the elk)
1	SHIFT	DP $\longrightarrow$ Mary	(DP, saw the elk)
2	SHIFT	VT $\longrightarrow$ saw	(VT DP, the elk)
3	SHIFT	D $\longrightarrow$ the	(D VT DP, elk)
4	SHIFT	NP $\longrightarrow$ elk	(NP D VT DP, ε)
5	REDUCE	DP $\longrightarrow$ D NP	(DP VT DP, ε)

An example

	Type	Rule	Configuration
0			(ε, Mary saw the elk)
1	SHIFT	DP $\longrightarrow$ Mary	(DP, saw the elk)
2	SHIFT	VT $\longrightarrow$ saw	(VT DP, the elk)
3	SHIFT	D $\longrightarrow$ the	(D VT DP, elk)
4	SHIFT	NP $\longrightarrow$ elk	(NP D VT DP, ε)
5	REDUCE	DP $\longrightarrow$ D NP	(DP VT DP, ε)
6	REDUCE	VP $\longrightarrow$ VT DP	(VP DP, ε)

An example

	Type	Rule	Configuration
0			(ε, Mary saw the elk)
1	SHIFT	DP $\longrightarrow$ Mary	(DP, saw the elk)
2	SHIFT	VT $\longrightarrow$ saw	(VT DP, the elk)
3	SHIFT	D $\longrightarrow$ the	(D VT DP, elk)
4	SHIFT	NP $\longrightarrow$ elk	(NP D VT DP, ε)
5	REDUCE	DP $\longrightarrow$ D NP	(DP VT DP, ε)
6	REDUCE	VP $\longrightarrow$ VT DP	(VP DP, ε)
7	REDUCE	S $\longrightarrow$ DP VP	(S, ε)

Another example

	Type	Rule	Configuration
0			(ε, the elk saw Mary)

Another example

	Type	Rule	Configuration
0			(ε, the elk saw Mary)
1	SHIFT	D $\rightarrow$ the	(D, elk saw Mary)

Another example

	Type	Rule	Configuration
0			(ε, the elk saw Mary)
1	SHIFT	D $\longrightarrow$ the	(D, elk saw Mary)
2	SHIFT	NP $\longrightarrow$ elk	(NP D, saw Mary)

Another example

	Type	Rule	Configuration
0			(ε, the elk saw Mary)
1	SHIFT	D $\longrightarrow$ the	(D, elk saw Mary)
2	SHIFT	NP $\longrightarrow$ elk	(NP D, saw Mary)
3	REDUCE	DP $\longrightarrow$ D NP	(DP, saw Mary)

Another example

	Type	Rule	Configuration
0			(ε, the elk saw Mary)
1	SHIFT	D $\longrightarrow$ the	(D, elk saw Mary)
2	SHIFT	NP $\longrightarrow$ elk	(NP D, saw Mary)
3	REDUCE	DP $\longrightarrow$ D NP	(DP, saw Mary)
4	SHIFT	VT $\longrightarrow$ saw	(VT DP, Mary)

Another example

	Type	Rule	Configuration
0			(ε, the elk saw Mary)
1	SHIFT	D $\longrightarrow$ the	(D, elk saw Mary)
2	SHIFT	NP $\longrightarrow$ elk	(NP D, saw Mary)
3	REDUCE	DP $\longrightarrow$ D NP	(DP, saw Mary)
4	SHIFT	VT $\longrightarrow$ saw	(VT DP, Mary)
5	SHIFT	DP $\longrightarrow$ Mary	(DP VT DP, ε)

Another example

	Type	Rule	Configuration
0			(ε, the elk saw Mary)
1	SHIFT	D $\longrightarrow$ the	(D, elk saw Mary)
2	SHIFT	NP $\longrightarrow$ elk	(NP D, saw Mary)
3	REDUCE	DP $\longrightarrow$ D NP	(DP, saw Mary)
4	SHIFT	VT $\longrightarrow$ saw	(VT DP, Mary)
5	SHIFT	DP $\longrightarrow$ Mary	(DP VT DP, ε)
6	REDUCE	VP $\longrightarrow$ VT DP	(VP DP, ε)

Another example

	Type	Rule	Configuration
0			(ε, the elk saw Mary)
1	SHIFT	D $\longrightarrow$ the	(D, elk saw Mary)
2	SHIFT	NP $\longrightarrow$ elk	(NP D, saw Mary)
3	REDUCE	DP $\longrightarrow$ D NP	(DP, saw Mary)
4	SHIFT	VT $\longrightarrow$ saw	(VT DP, Mary)
5	SHIFT	DP $\longrightarrow$ Mary	(DP VT DP, ε)
6	REDUCE	VP $\longrightarrow$ VT DP	(VP DP, ε)
7	REDUCE	S $\longrightarrow$ DP VP	(S, ε)

Ambiguity in shift-reduce parsing

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)

Ambiguity in shift-reduce parsing

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)
…	…	…	…
5	SHIFT	DP $\longrightarrow$ Mary	(DP P NP D VT, ε)

Ambiguity in shift-reduce parsing

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)
…	…	…	…
5	SHIFT	DP $\rightarrow$ Mary	(DP P NP D VT, ε)
6	REDUCE	PP $\rightarrow$ P DP	(PP NP D VT, ε)

Ambiguity in shift-reduce parsing

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)
…	…	…	…
5	SHIFT	DP $\longrightarrow$ Mary	(DP P NP D VT, ε)
6	REDUCE	PP $\longrightarrow$ P DP	(PP NP D VT, ε)
7	REDUCE	NP $\longrightarrow$ NP PP	(NP D VT, ε)
…	…	…	…

Ambiguity in shift-reduce parsing

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)
…	…	…	…
5	SHIFT	DP $\rightarrow$ Mary	(DP P NP D VT, ε)
6	REDUCE	PP $\rightarrow$ P DP	(PP NP D VT, ε)
7	REDUCE	NP $\rightarrow$ NP PP	(NP D VT, ε)
…	…	…	…

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)

Ambiguity in shift-reduce parsing

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)
…	…	…	…
5	SHIFT	DP $\rightarrow$ Mary	(DP P NP D VT, ε)
6	REDUCE	PP $\rightarrow$ P DP	(PP NP D VT, ε)
7	REDUCE	NP $\rightarrow$ NP PP	(NP D VT, ε)
…	…	…	…

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)
…	…	…	…

Ambiguity in shift-reduce parsing

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)
…	…	…	…
5	SHIFT	DP $\to$ Mary	(DP P NP D VT, ε)
6	REDUCE	PP $\to$ P DP	(PP NP D VT, ε)
7	REDUCE	NP $\to$ NP PP	(NP D VT, ε)
…	…	…	…

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)
…	…	…	…
3	SHIFT	NP $\to$ elk	(NP D VT, with Mary)

Ambiguity in shift-reduce parsing

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)
...	...	...	...
5	SHIFT	DP $\rightarrow$ Mary	(DP P NP D VT, ε)
6	REDUCE	PP $\rightarrow$ P DP	(PP NP D VT, ε)
7	REDUCE	NP $\rightarrow$ NP PP	(NP D VT, ε)
...	...	...	...

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)
...	...	...	...
3	SHIFT	NP $\rightarrow$ elk	(NP D VT, with Mary)
4	REDUCE	DP $\rightarrow$ D NP	(DP VT, with Mary)

Ambiguity in shift-reduce parsing

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)
…	…	…	…
5	SHIFT	DP $\rightarrow$ Mary	(DP P NP D VT, ε)
6	REDUCE	PP $\rightarrow$ P DP	(PP NP D VT, ε)
7	REDUCE	NP $\rightarrow$ NP PP	(NP D VT, ε)
…	…	…	…

	Type	Rule	Configuration
0			(ε, saw the elk with Mary)
…	…	…	…
3	SHIFT	NP $\rightarrow$ elk	(NP D VT, with Mary)
4	REDUCE	DP $\rightarrow$ D NP	(DP VT, with Mary)
5	REDUCE	VP $\rightarrow$ VT DP	(VP, with Mary)
…	…	…	…

Stage's, shift, and reduce

```
type Stage cat term = ([cat], [term])

shift
  :: Eq term =>
     CFG cat term -> Stage cat term -> [Stage cat term]
shift g (cs, t:ts) = [(n:cs, ts) | n:-x <- g, x==t]

reduce
  :: Eq cat =>
     CFG cat term -> Stage cat term -> [Stage cat term]
reduce g (r:l:cs, ts) = [(n:cs, ts) | n:>(l',r') <- g,
                                       l'==l, r'==r]
```

Nondeterminism in parsing

At any stage, the next course is not necessarily fully determined.

- This is how ambiguity can arise. After stage 3 in our derivation of *saw the elk with Mary*, do we SHIFT or REDUCE next?

This means that a single `Stage` in general begets a `[Stage]`. We need to try everything we can, to ensure we explore every path.

Trying everything

```haskell
step
  :: (Eq cat, Eq term) =>
     CFG cat term -> Stage cat term -> [Stage cat term]
step g st@(r:l:cs, t:ts) = shift g st ++ reduce g st
step g st@(cs    , t:ts) = shift g st
step g st@(r:l:cs, ts)   = reduce g st
step g st                = [st]
```

Keep taking steps till nothing changes

`helper` takes steps until we reach a **fixed point**:

```
parseSR :: (Eq cat, Eq term) =>
             CFG cat term -> [term] -> [Stage cat term]
parseSR g ws = helper g [([], ws)] where
  once stages = stages >>= step g     -- taking 1 step
  helper g stages
    | once stages == stages = stages -- fixed point
    | otherwise             = helper g (once stages)
```

```
*W12> s = words "Mary saw the elk with the binoculars"
*W12> parseSR eng s
[([S],[]),([S],[])]
```

`parseSR` is really just a recognizer. Could you enrich it to parse to `LBT`'s, or associate parse paths with weights, costs, etc?

Top-down parsing

Shift-reduce parsing works bottom-up: we find out what categories our terminals are, and start building structure.

- Bottom-up is also how CYK and naive parsing algos worked

Top-down parsers **predict** how a derivation will go:

- A starting stage is (A, xs), where $A \in N$ and xs is the input
- A goal stage is $(\varepsilon, \varepsilon)$
- Transitions either expand a non-terminal or match a terminal:
  1. PREDICT: $(A\Phi, x_i \dots x_n) \Rightarrow (BC\Phi, x_i \dots x_n)$, where $A \rightarrow BC \in G$
  2. MATCH: $(A\Phi, x_i x_{i+1} \dots x_n) \Rightarrow (\Phi, x_{i+1} \dots x_n)$, where $A \rightarrow x_i \in G$

An example

	Type	Rule	Configuration
0			(S, Mary saw the elk)

An example

	Type	Rule	Configuration
0			(S, Mary saw the elk)
1	PREDICT	S $\longrightarrow$ DP VP	(DP VP, Mary saw the elk)

An example

	Type	Rule	Configuration
0			(S, Mary saw the elk)
1	PREDICT	S $\longrightarrow$ DP VP	(DP VP, Mary saw the elk)
2	MATCH	DP $\longrightarrow$ Mary	(VP, saw the elk)

An example

	Type	Rule	Configuration
0			(S, Mary saw the elk)
1	PREDICT	S ⟶ DP VP	(DP VP, Mary saw the elk)
2	MATCH	DP ⟶ Mary	(VP, saw the elk)
3	PREDICT	VP ⟶ VT DP	(VT DP, saw the elk)

An example

	Type	Rule	Configuration
0			(S, Mary saw the elk)
1	PREDICT	S $\longrightarrow$ DP VP	(DP VP, Mary saw the elk)
2	MATCH	DP $\longrightarrow$ Mary	(VP, saw the elk)
3	PREDICT	VP $\longrightarrow$ VT DP	(VT DP, saw the elk)
4	MATCH	VT $\longrightarrow$ saw	(DP, the elk)

An example

	Type	Rule	Configuration
0			(S, Mary saw the elk)
1	PREDICT	S $\longrightarrow$ DP VP	(DP VP, Mary saw the elk)
2	MATCH	DP $\longrightarrow$ Mary	(VP, saw the elk)
3	PREDICT	VP $\longrightarrow$ VT DP	(VT DP, saw the elk)
4	MATCH	VT $\longrightarrow$ saw	(DP, the elk)
5	PREDICT	DP $\longrightarrow$ D NP	(D NP, the elk)

An example

	Type	Rule	Configuration
0			(S, Mary saw the elk)
1	PREDICT	S ⟶ DP VP	(DP VP, Mary saw the elk)
2	MATCH	DP ⟶ Mary	(VP, saw the elk)
3	PREDICT	VP ⟶ VT DP	(VT DP, saw the elk)
4	MATCH	VT ⟶ saw	(DP, the elk)
5	PREDICT	DP ⟶ D NP	(D NP, the elk)
6	MATCH	D ⟶ the	(NP, elk)

An example

	Type	Rule	Configuration
0			(S, Mary saw the elk)
1	PREDICT	S $\longrightarrow$ DP VP	(DP VP, Mary saw the elk)
2	MATCH	DP $\longrightarrow$ Mary	(VP, saw the elk)
3	PREDICT	VP $\longrightarrow$ VT DP	(VT DP, saw the elk)
4	MATCH	VT $\longrightarrow$ saw	(DP, the elk)
5	PREDICT	DP $\longrightarrow$ D NP	(D NP, the elk)
6	MATCH	D $\longrightarrow$ the	(NP, elk)
7	MATCH	NP $\longrightarrow$ elk	(ε, ε)

There's something naturally incremental in top-down parsing. We build, or hypothesize, structure, immediately. In bottom-up parsing, REDUCE steps often depend on further-right SHIFT/REDUCE steps.

Another example

	Type	Rule	Configuration
0			(S, the elk saw Mary)

Another example

	Type	Rule	Configuration
0			(S, the elk saw Mary)
1	PREDICT	S $\rightarrow$ DP VP	(DP VP, the elk saw Mary)

Another example

	Type	Rule	Configuration
0			(S, the elk saw Mary)
1	PREDICT	S $\longrightarrow$ DP VP	(DP VP, the elk saw Mary)
2	PREDICT	DP $\longrightarrow$ D NP	(D NP VP, the elk saw Mary)

Another example

	Type	Rule	Configuration
0			(S, the elk saw Mary)
1	PREDICT	S $\longrightarrow$ DP VP	(DP VP, the elk saw Mary)
2	PREDICT	DP $\longrightarrow$ D NP	(D NP VP, the elk saw Mary)
3	MATCH	D $\longrightarrow$ the	(NP VP, elk saw Mary)

Another example

	Type	Rule	Configuration
0			(S, the elk saw Mary)
1	PREDICT	S ⟶ DP VP	(DP VP, the elk saw Mary)
2	PREDICT	DP ⟶ D NP	(D NP VP, the elk saw Mary)
3	MATCH	D ⟶ the	(NP VP, elk saw Mary)
4	MATCH	NP ⟶ elk	(VP, saw Mary)

Another example

	Type	Rule	Configuration
0			(S, the elk saw Mary)
1	PREDICT	S $\longrightarrow$ DP VP	(DP VP, the elk saw Mary)
2	PREDICT	DP $\longrightarrow$ D NP	(D NP VP, the elk saw Mary)
3	MATCH	D $\longrightarrow$ the	(NP VP, elk saw Mary)
4	MATCH	NP $\longrightarrow$ elk	(VP, saw Mary)
5	PREDICT	VP $\longrightarrow$ VT DP	(VT DP, saw Mary)

Another example

	Type	Rule	Configuration
0			(S, the elk saw Mary)
1	PREDICT	S $\longrightarrow$ DP VP	(DP VP, the elk saw Mary)
2	PREDICT	DP $\longrightarrow$ D NP	(D NP VP, the elk saw Mary)
3	MATCH	D $\longrightarrow$ the	(NP VP, elk saw Mary)
4	MATCH	NP $\longrightarrow$ elk	(VP, saw Mary)
5	PREDICT	VP $\longrightarrow$ VT DP	(VT DP, saw Mary)
6	MATCH	VT $\longrightarrow$ saw	(DP, Mary)

Another example

	Type	Rule	Configuration
0			(S, the elk saw Mary)
1	PREDICT	S → DP VP	(DP VP, the elk saw Mary)
2	PREDICT	DP → D NP	(D NP VP, the elk saw Mary)
3	MATCH	D → the	(NP VP, elk saw Mary)
4	MATCH	NP → elk	(VP, saw Mary)
5	PREDICT	VP → VT DP	(VT DP, saw Mary)
6	MATCH	VT → saw	(DP, Mary)
7	MATCH	DP → Mary	(ε, ε)

Non-termination

	Type	Rule	Configuration
…	…	…	…
6	MATCH	D → the	(NP, elk)

Non-termination

	Type	Rule	Configuration
…	…	…	…
6	MATCH	D $\longrightarrow$ the	(NP, elk)
7	PREDICT	NP $\longrightarrow$ NP PP	(NP PP, elk)

Non-termination

	Type	Rule	Configuration
...	...	...	...
6	MATCH	D $\longrightarrow$ the	(NP, elk)
7	PREDICT	NP $\longrightarrow$ NP PP	(NP PP, elk)
8	PREDICT	NP $\longrightarrow$ NP PP	(NP PP PP, elk)

Non-termination

	Type	Rule	Configuration
...	...	...	...
6	MATCH	D $\longrightarrow$ the	(NP, elk)
7	PREDICT	NP $\longrightarrow$ NP PP	(NP PP, elk)
8	PREDICT	NP $\longrightarrow$ NP PP	(NP PP PP, elk)
9	PREDICT	NP $\longrightarrow$ NP PP	(NP PP PP PP, elk)

If we keep PREDICT-ing, the parsing algorithm never terminates.
Which rules are problematic?

Non-termination

	Type	Rule	Configuration
...	...	...	...
6	MATCH	D $\longrightarrow$ the	(NP, elk)
7	PREDICT	NP $\longrightarrow$ NP PP	(NP PP, elk)
8	PREDICT	NP $\longrightarrow$ NP PP	(NP PP PP, elk)
9	PREDICT	NP $\longrightarrow$ NP PP	(NP PP PP PP, elk)

If we keep PREDICT-ing, the parsing algorithm never terminates.
Which rules are problematic? **Left-recursive** rules, $A \longrightarrow AB$.

Non-termination is **bad**. How might we deal with it here?

Non-termination

	Type	Rule	Configuration
...	...	...	...
6	MATCH	D $\longrightarrow$ the	(NP, elk)
7	PREDICT	NP $\longrightarrow$ NP PP	(NP PP, elk)
8	PREDICT	NP $\longrightarrow$ NP PP	(NP PP PP, elk)
9	PREDICT	NP $\longrightarrow$ NP PP	(NP PP PP PP, elk)

If we keep PREDICT-ing, the parsing algorithm never terminates.
Which rules are problematic? **Left-recursive** rules, $A \longrightarrow AB$.

Non-termination is **bad**. How might we deal with it here?

- Look-ahead: curtail the expansions based on length of the input

Earley parsers

Another example of a parser that works top-down, but which does not suffer from non-termination in left-recursive grammars is an **Earley** parser.

We won't discuss Earley parsers in depth in this course, but the way that they avoid non-termination is easy enough to understand:

- Earley parsers have an **agenda** consisting of rules to try next
- A rule like NP $\rightarrow$ NP PP can be added to the agenda
- But adding this rule twice is no different from adding it once: it's already on the agenda!
- Once an agenda is stable (everything **new** that can be added has been), the parser gets to work trying its items

Transition-based parsing

In effect, transition-based parsing constructs something known as a **pushdown automaton** (PDA), in which a pushdown stack of nonterminals functions as an auxiliary memory source.

A pushdown stack is a special kind of memory in which we can only **pop** the top element off the stack, **push** a new element onto the stack, or do composite actions built out of those primitives.

CFG parsing is akin to finite-state parsing, with (pushdown) memory!