Advanced PCFG Parsing

Computational Linguistics

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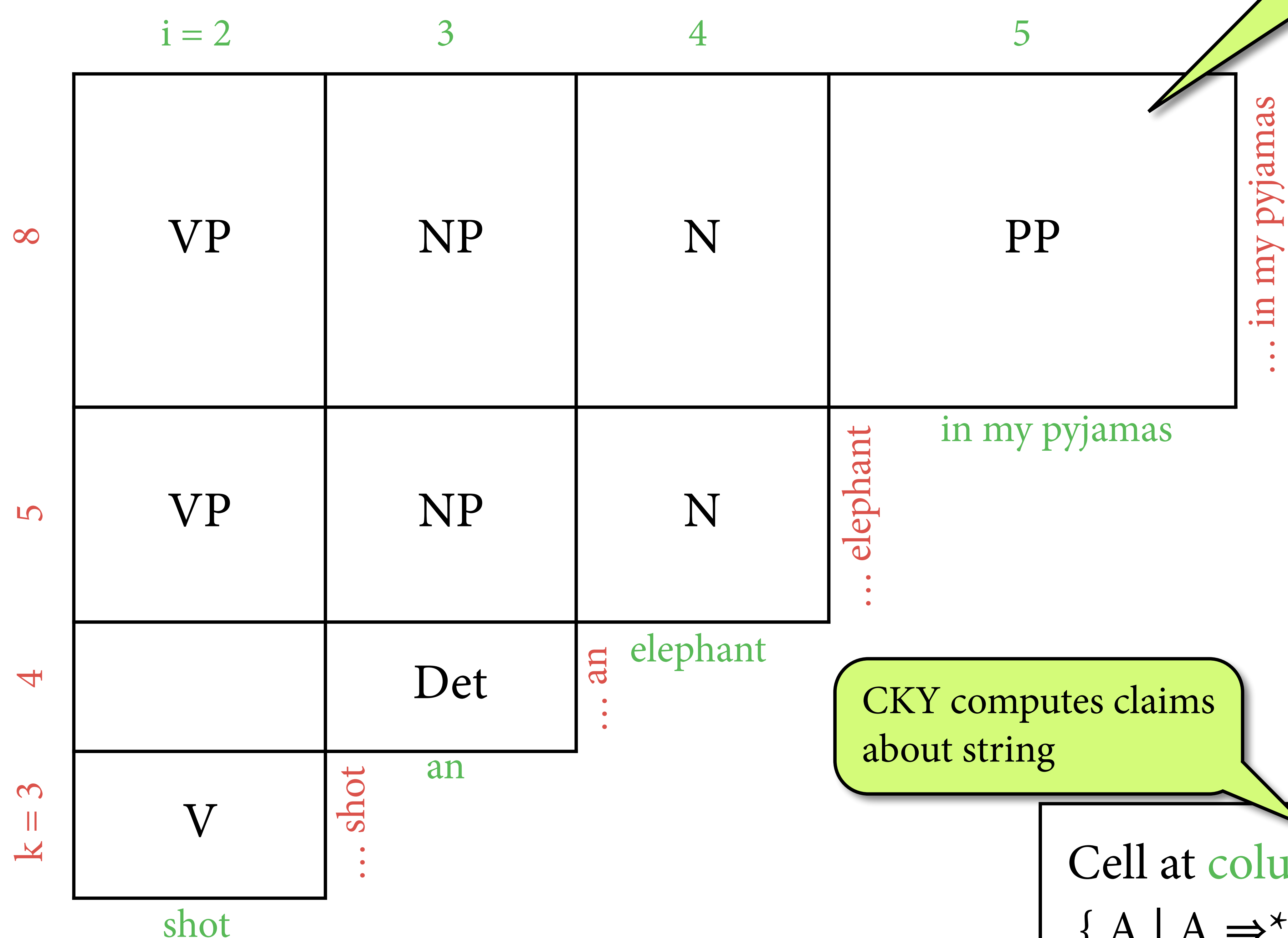
8 December 2017

Today

- Parsing schemata and agenda-based parsing.
- Semiring parsing.
- Pruning techniques for chart parsing.

The CKY Algorithm

Chart



CKY computes claims about string

Cell at column i, row k:

$\{ A \mid A \Rightarrow^* w_i \ldots w_{k-1} \}$

CKY as parsing schema

- Makes *claims* about the string: Entering A into Ch(i,k) means algorithm thinks $A \Rightarrow^* w_i \ldots w_{k-1}$.

- Write this claim as *item* (A, i, k). This is like a logic formula that is true iff $A \Rightarrow^* w_i \ldots w_{k-1}$.

- Write *parsing schema* that shows how new items can be derived from old items.
  - very general view; applies to algorithms beyond CKY
  - supports generalized implementations

CKY as parsing schema

- Parsing schema for CKY has a single rule:

$$\frac{A \rightarrow B\ C \qquad (B, i, j) \qquad (C, j, k)}{(A, i, k)}$$

- One benefit: can literally read off parsing complexity.
  - rules have at most three independent variables for string positions (i, j, k)
  - therefore complexity is $O(n^3)$

Implementing schemas

- Can generally implement parser for given schema in the following way:
  - maintain an *agenda*: queue of items that we have discovered, but not yet attempted to combine with other items
  - maintain a *chart* of all seen items for the sentence

```
initialize chart and agenda with all start items

while agenda not empty:
  item = dequeue(agenda)
  for each combination c of item with other item in the chart:
    if c not in chart:
      add c to chart
      enqueue c in agenda

if chart contains a goal item, claim w ∈ L(G)
```

rules of parsing schema used here

Implementing schemas

- Can generally implement parser for given schema in the following way:
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      enqueue c in agenda

if chart contains a goal item, claim w ∈ L(G)
```

rules of parsing schema used here

essential to do this efficiently

Example

agenda:

(PP, 5, 8) (V, 2, 3) (Det, 3, 4) (N, 4, 5)

chart:

	2…	3…	4…	5…
…8				PP
…5			N	
…4		Det		
…3	V			

Example

agenda:

(PP, 5, 8) (V, 2, 3) (Det, 3, 4) (N, 4, 5) (N, 4, 8)

chart:

	2…	3…	4…	5…
…8			N	PP
…5			N	
…4		Det		
…3	V			

Example

agenda:

(V, 2, 3) (Det, 3, 4) (N, 4, 5) (N, 4, 8)

chart:

	2…	3…	4…	5…
…8			N	PP
…5			N	
…4		Det		
…3	V			

Example

agenda:

(Det, 3, 4) (N, 4, 5) (N, 4, 8)

chart:

	2…	3…	4…	5…
…8			N	PP
…5			N	
…4		Det		
…3	V			

Example

agenda:

(Det, 3, 4) (N, 4, 5) (N, 4, 8) (NP, 3, 5)

chart:

	2…	3…	4…	5…
…8			N	PP
…5		NP	N	
…4		Det		
…3	V			

Example

agenda:

(Det, 3, 4) (N, 4, 5) (N, 4, 8) (NP, 3, 5)

(NP, 3, 8)

chart:

	2…	3…	4…	5…
…8		NP	N	PP
…5		NP	N	
…4		Det		
…3	V			

Example

agenda:

(N, 4, 5) (N, 4, 8) (NP, 3, 5)

(NP, 3, 8)

chart:

	2…	3…	4…	5…
…8		NP	N	PP
…5		NP	N	
…4		Det		
…3	V			

Example

agenda:

(N, 4, 8) (NP, 3, 5)

(NP, 3, 8)

chart:

	2…	3…	4…	5…
…8		NP	N	PP
…5		NP	N	
…4		Det		
…3	V			

Example

agenda:

(NP, 3, 5)

(NP, 3, 8)

chart:

	2…	3…	4…	5…
…8		NP	N	PP
…5		NP	N	
…4		Det		
…3	V			

Example

agenda:

(NP, 3, 5)

(NP, 3, 8) (VP, 2, 5)

chart:

	2…	3…	4…	5…
…8		NP	N	PP
…5	VP	NP	N	
…4		Det		
…3	V			

Example

agenda:

(NP, 3, 8)   (VP, 2, 5)

chart:

	2…	3…	4…	5…
…8		NP	N	PP
…5	VP	NP	N	
…4		Det		
…3	V			

Example

agenda:

(NP, 3, 8) (VP, 2, 5) (VP, 2, 8)

chart:

	2…	3…	4…	5…
…8	VP	NP	N	PP
…5	VP	NP	N	
…4		Det		
…3	V			

Example

agenda:

(VP, 2, 5)   (VP, 2, 8)

chart:

	2…	3…	4…	5…
…8	VP	NP	N	PP
…5	VP	NP	N	
…4		Det		
…3	V			

Example

agenda:

(VP, 2, 8)

chart:

	2…	3…	4…	5…
…8	VP	NP	N	PP
…5	VP	NP	N	
…4		Det		
…3	V			

Example

agenda:

chart:

	2…	3…	4…	5…
…8	VP	NP	N	PP
…5	VP	NP	N	
…4		Det		
…3	V			

Semiring parsing

- We have seen a number of algorithms on CKY charts that all look basically the same.
  - decide word problem
  - compute best parse
  - compute inside probabilities
  - compute number of parse trees

- What exactly do they have in common?
  Can we use it to build better algorithms?

CKY for recognition

```
for each i from 1 to n:
  for each production rule A → wᵢ:
    Ch(A, i, i+1) = true

for each width b from 2 to n:
  for each start position i from 1 to n-b+1:
    for each left width k from 1 to b-1:
      for each production rule A → B C:
        Ch(A, i, i+b)
          = Ch(A, i, i+b) ∨
            (Ch(B, i, i+k) ∧ Ch(C, i+k, i+b) ∧ true)

return Ch(S, 1, n+1)
```

Viterbi-CKY

```
for each i from 1 to n:
  for each production rule A → wᵢ:
    Ch(A, i, i+1) = P(A → wᵢ)

for each width b from 2 to n:
  for each start position i from 1 to n-b+1:
    for each left width k from 1 to b-1:
      for each production rule A → B C:
        Ch(A, i, i+b)
          = max(Ch(A, i, i+b),
                Ch(B, i, i+k) * Ch(C, i+k, i+b) * P(A → B C))

return Ch(S, 1, n+1)
```

Inside

```
for each i from 1 to n:
  for each production rule A → wᵢ:
    Ch(A, i, i+1) = P(A → wᵢ)

for each width b from 2 to n:
  for each start position i from 1 to n-b+1:
    for each left width k from 1 to b-1:
      for each production rule A → B C:
        Ch(A, i, i+b)
          = Ch(A, i, i+b) +
            (Ch(B, i, i+k) * Ch(C, i+k, i+b) * P(A → B C))

return Ch(S, 1, n+1)
```

Counting

```
for each i from 1 to n:
  for each production rule A → wi:
    Ch(A, i, i+1) = 1

for each width b from 2 to n:
  for each start position i from 1 to n-b+1:
    for each left width k from 1 to b-1:
      for each production rule A → B C:
        Ch(A, i, i+b)
          = Ch(A, i, i+b) +
            (Ch(B, i, i+k) * Ch(C, i+k, i+b) * 1)

return Ch(S, 1, n+1)
```

Semirings

- A *semiring* is a 5-tuple consisting of
  - a nonempty set V of values
  - an *addition* $\oplus : V \times V \to V$, associative and commutative
  - a *multiplication* $\otimes : V \times V \to V$, must be associative and distribute over $\oplus$
  - an *abstract zero* $0 \in V$ such that $0 \oplus v = v \oplus 0 = v$ and $0 \otimes v = v \otimes 0 = 0$, for all v
  - an *abstract one* $1 \in V$ such that $1 \otimes v = v \otimes 1 = v$, for all v

A semiring where $\oplus$ has inverse elements is called a *ring*
— really important in math, but not so much in this course.

Some important semirings

	values	addition	multiplication	zero	one
counting	$\mathbf{N_0}$	$+$	$*$	0	1
boolean	{true, false}	$\vee$	$\wedge$	false	true
Viterbi	$[0, 1]$	max	$*$	0	1
inside	$[0, \infty]$	$+$	$*$	0	1

Generic CKY with semirings

assume evaluation function R: rules → V

```
for each i from 1 to n:
  for each production rule A → wᵢ:
    Ch(A, i, i+1) = R(A → wᵢ)

for each width b from 2 to n:
  for each start position i from 1 to n-b+1:
    for each left width k from 1 to b-1:
      for each production rule A → B C:
        Ch(A, i, i+b)
          = Ch(A, i, i+b) ⊕
            (Ch(B, i, i+k) ⊗ Ch(C, i+k, i+b) ⊗ R(A → B C))

return Ch(S, 1, n+1)
```

This generalizes all the variants we saw above.

Semirings and agenda parsing

```
for each start item I:
  enqueue I in agenda
  chart(I) = R(I)

while agenda not empty:
  item = dequeue(agenda)
  for each combination c of item with other item in the chart:
    if Chart(c) = 0:
      enqueue c in agenda
    chart(c) = chart(c) ⊕ R(c)

return chart(goal item)
```

$R(c) = R(\text{rule}) \otimes \text{chart}(\text{premise}_1) \otimes \ldots \otimes \text{chart}(\text{premise}_n)$

Some further details

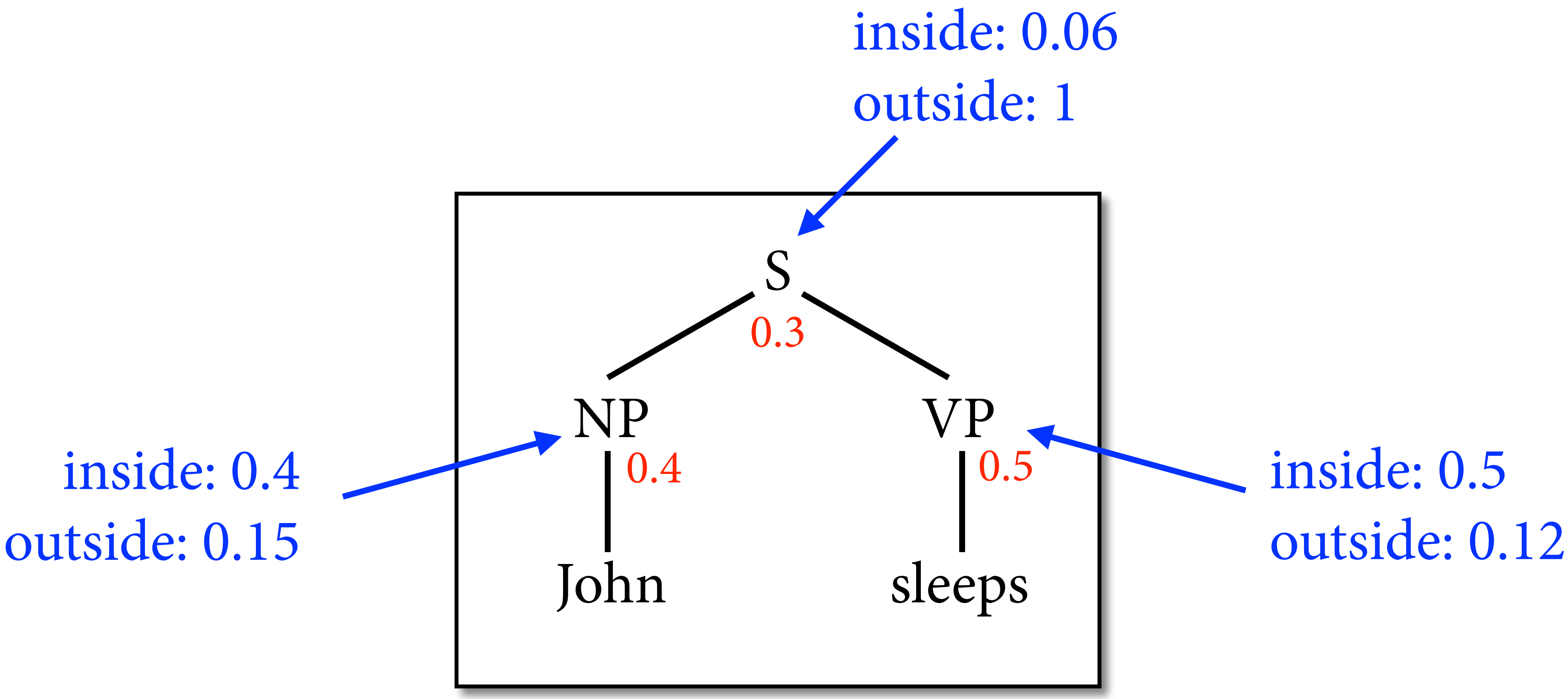
- Can define top-down variant to compute outside.

- Works best for charts without cycles.
    - cycles appear when grammar has unary rules A → B
    - but can be made to work for charts *with* cycles under certain circumstances, see Goodman paper

Pruning techniques

- If grammar is big and sentence is not short, computing the full chart is expensive.
  - runtime of CKY is $O(|G| * n^3)$
  - for treebank grammars, almost every substring can be derived from some nonterminal
- Most chart entries not used to build best parse tree.
- *Pruning:* avoid computing the full chart
  - *beam search:* limit number of entries per chart cell
  - *best-first search:* manipulate order in which items are taken from the agenda

Inside and outside probs



- For each individual parse tree, the product of inside and outside probabilities is same at every node.
- If we could calculate (inside * outside) for each chart item, then we could focus search on just the items that are needed for best parse.

Figures of Merit

- Challenge in bottom-up parsing:
  - We can easily compute (Viterbi) inside of each item. (Viterbi inside = max P(t); inside = Σ P(t).)
  - We cannot easily compute (Viterbi) outside, because we haven't combined item with other words yet.

- Idea: estimate (inside * outside) with a *figure of merit* (FOM) of the parse item.
  - FOM = Viterbi inside prob: underestimates quality of long substrings
  - FOM = (Viterbi inside)$^{1 / |\text{substring}|}$: works okay in practice, but still ignores outside probs

Beam search

- In CKY parsing, easiest way of using FOMs is *beam search:*
  - fix a number k of nonterminals that can be stored in each chart cell
  - only retain the k nonterminals with the best FOM
  - variant: only retain the nonterminals whose FOM is at least $\theta * f$, where f is FOM of best nonterminal in same cell

- Beam search very standard technique in parsing and machine translation (including decoding of neural network outputs).

Best-first parsing

- Idea: Agenda contains parse items (A, i, k); order them in descending order of their FOMs.

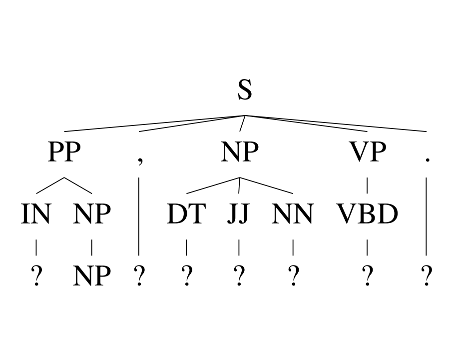
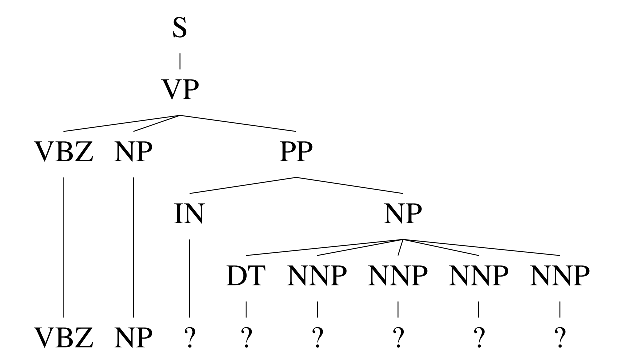
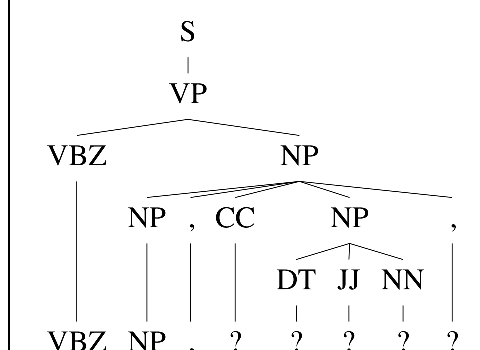
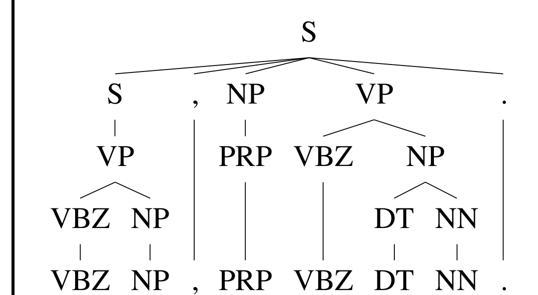
- If FOM were perfect, then first discovered goal item represents the best parse, and many unexplored items still on agenda $\Rightarrow$ faster parser.

- If FOM is not perfect, parser can make *search errors:* first discovered goal item is not optimal.
  - can still be much faster than exhaustive parsing
  - accuracy depends on quality of FOM

A* parsing

- A* search: general method for heuristic search in AI
  - FOM h = (distance f from start) + (estimated distance g to goal)
  - g must *underestimate* distance, i.e. never be larger than true distance
  - guarantees that first path to goal we find is optimal
- Apply this to parsing (Klein & Manning 03):
  - f = - log inside
  - g = estimate of - log outside

Outside estimates

Estimate	SX	SXL	SXLR	TRUE
Summary	(1,6,NP)	(1,6,NP,VBZ)	(1,6,NP,VBZ,”,”)	(entire context)
Best Tree				
Score	-11.3	-13.9	-15.1	-18.1
	(a)	(b)	(c)	(d)

- Represent each parse item with a *summary,* which abstracts over the concrete sentence we are parsing.
- Compute outside estimates for each possible summary from grammar, before we start parsing actual sentences.

A* parsing: Results

Estimate	Savings	w/ Filter	Storage	Precomp
NULL	11.2	58.3	0K	none
S	40.5	77.8	2.5K	1 min
SX	80.3	95.3	5M	1 min
SXL	83.5	96.1	250M	30 min
S_1XLR	93.5	96.5	500M	480 min
SXR	93.8	96.9	250M	30 min
SXMLR	94.3	97.1	500M	60 min
B	94.6	97.3	1G	540 min

Coarse-to-fine parsing

- Idea: make coarser-grained grammar by combining "similar" nonterminals into one (Charniak et al. 06).
  - combine S, VP, S-bar, etc. into "S_"
  - combine S_ and N_ into "HP" (head phrase); etc.

- Compute complete parse chart with coarse-grained grammar; calculate exact inside and outside.

- Prune out entries with low inside * outside.
Refine the others, then repeat until we have chart of original grammar.

CTF parsing: Results

Level	Constits Produced $*10^6$	Constits Pruned $*10^6$	% Pruned
0	8.82	7.55	86.5
1	9.18	6.51	70.8
2	11.2	9.48	84.4
3	11,8	0	0.0
total	40.4	–	–
3-only	392.0	0	0

Figure 5: Total constituents pruned at all levels for WSJ section 23, sentences of length ≤ 100

Level	Time for Level	Running Total
0	1598	1598
1	2570	4168
2	4303	8471
3	1527	9998
3-only	114654	–

Figure 6: Running times in seconds on WSJ section 23, with and without pruning

… at no loss in f-score with their grammar.

Summary

- PCFG parsing one of the most successful fields of NLP research.

- Current parsers are fast and quite accurate.
  - in practice, most people use Berkeley or Stanford parser for good speed-accuracy-convenience tradeoff

- Techniques from PCFG parsing carry over to many other problems in computational linguistics.