K-best Parsing: Algorithms and Applications

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July 30, 2007

k-best Parsing

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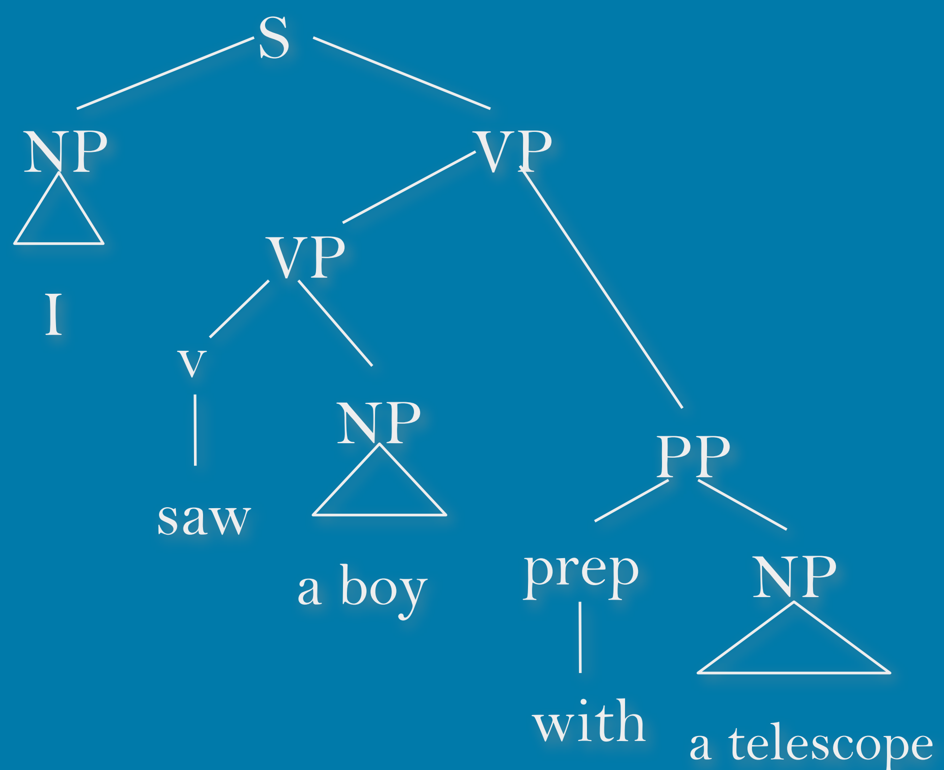
I saw a boy with a telescope.

k-best Parsing



1-best

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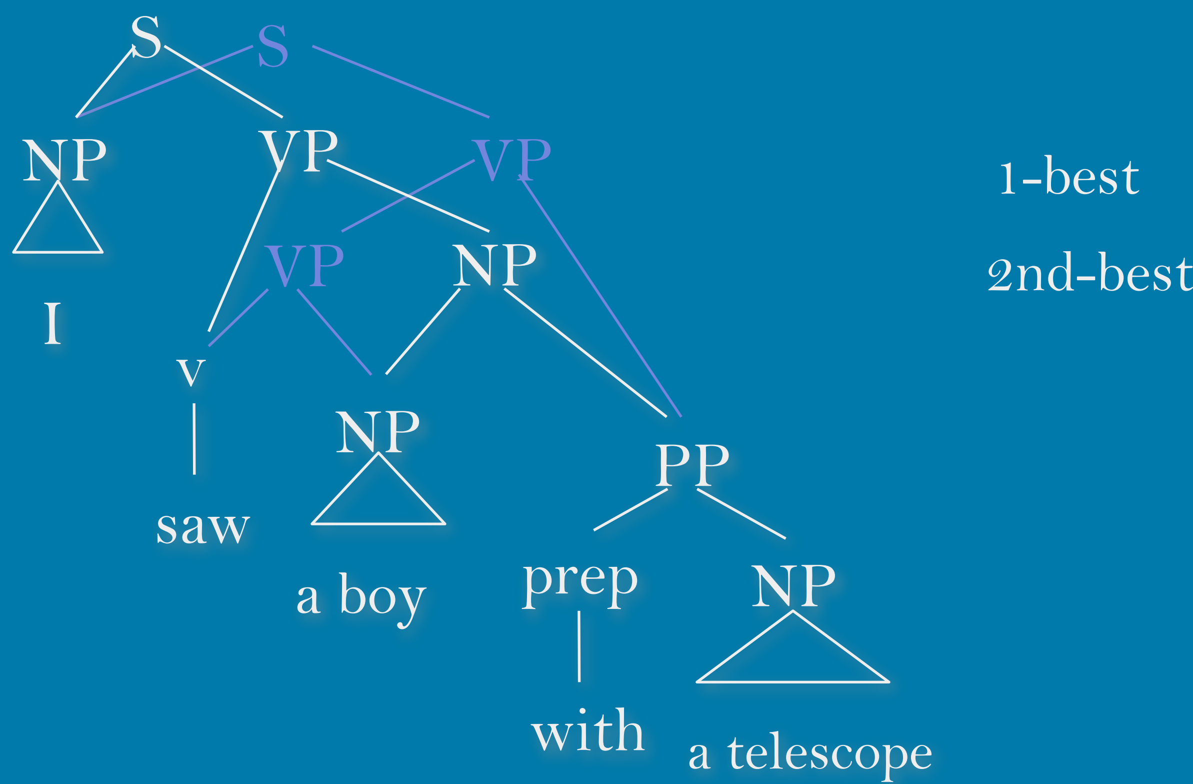
k-best Parsing



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Not a trivial task…

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Aravind Joshi

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I saw her duck.

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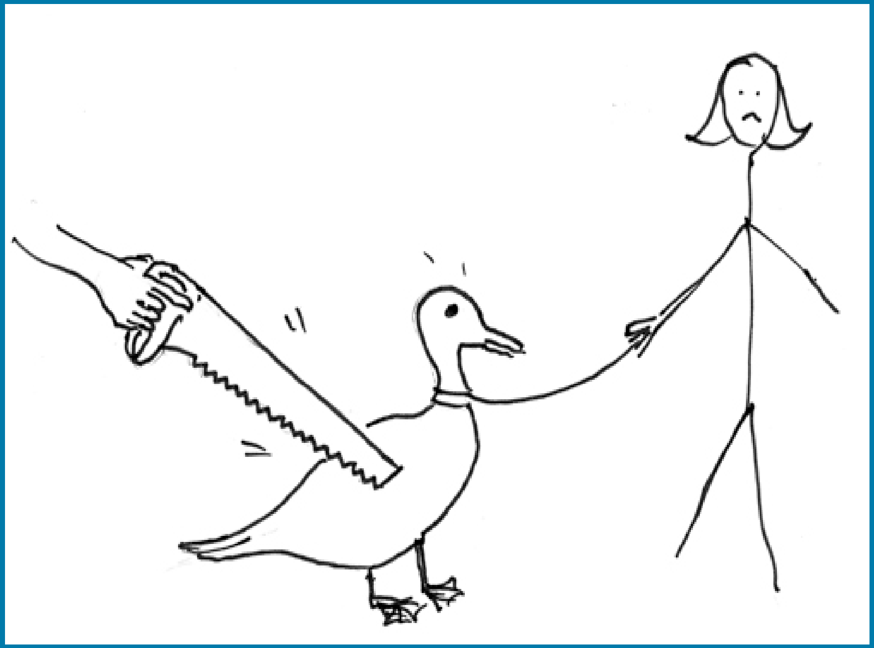

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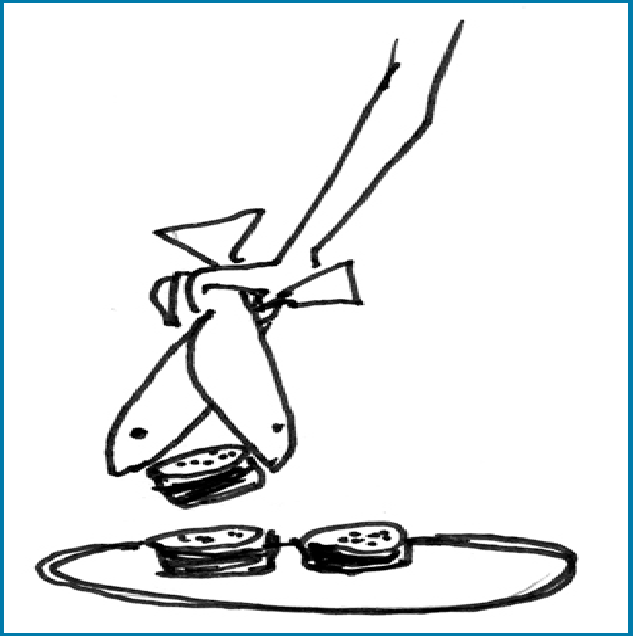

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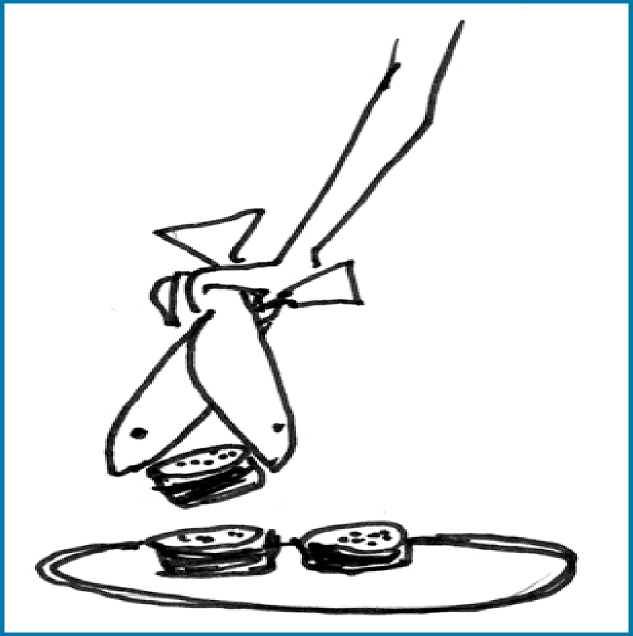
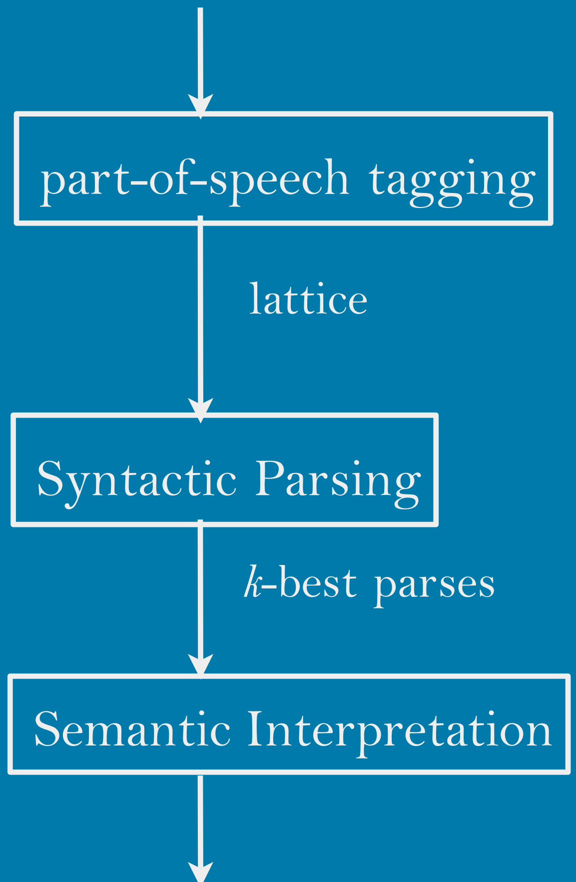
… you'd improve your *k*-best parser



Why *k*-best?

- postpone disambiguation in a pipeline
  - 1-best is not always optimal in the future
  - propagate k-best lists instead of 1-best
  - e.g.: semantic role labeler uses *k*-best parses
- approximate the set of all possible interpretations
  - reranking (Collins, 2000)
  - minimum error training (Och, 2003)
  - online training (McDonald et al., 2005)



In this talk...

- Formulations
  - parsing as deduction; the CKY algorithm
  - directed monotonic hypergraphs
- Algorithms
  - Algorithm 0 thru Algorithm 3
- Experiments
- Applications in Machine Translation

Parsing as Deduction

- Parsing with **context-free grammars** (CFGs)
  - Dynamic Programming (CKY algorithm)

$$\frac{(B, i, j) \quad (C, j+1, k)}{(A, i, k)} \; A \rightarrow B\ C \qquad \frac{(\mathrm{NP}, 1, 3) \quad (\mathrm{VP}, 4, 6)}{(\mathrm{S}, 1, 6)} \; \mathrm{S} \rightarrow \mathrm{NP\ VP}$$

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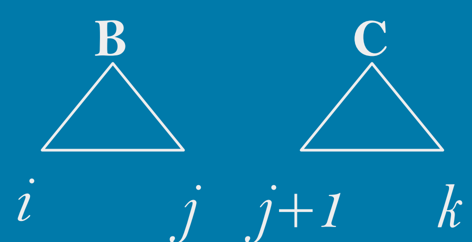

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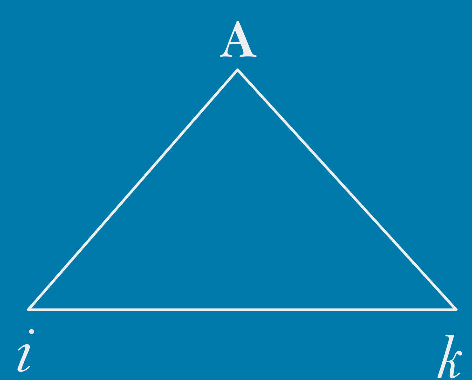

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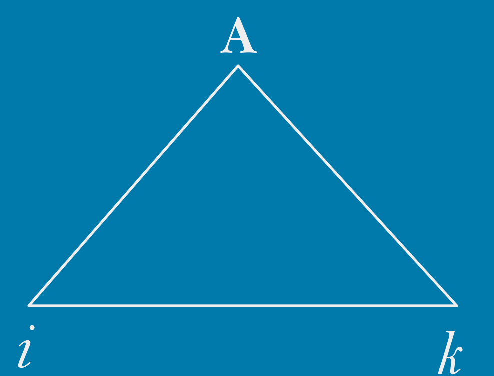


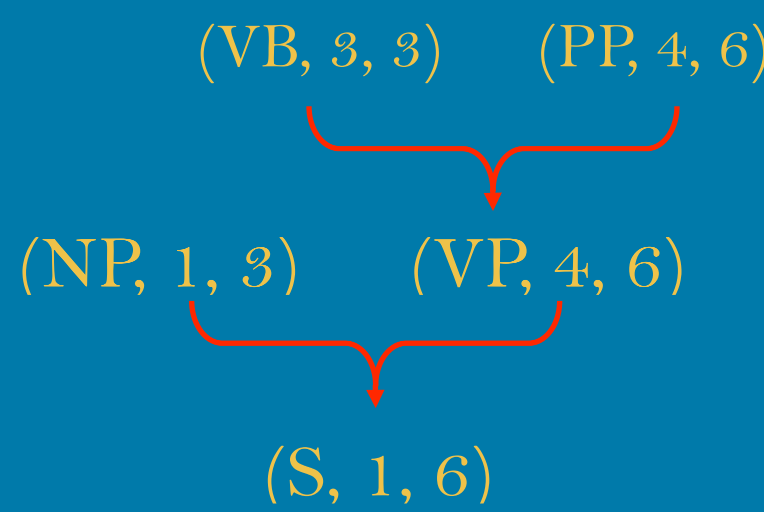
computational complexity: $O(n^3\ |P|)$

P is the set of productions (rules)

Deduction => Hypergraph

- hypergraph is a generalization of graph
  - each hyperedge connects several vertices to one vertex

$$\frac{(NP, 1, 3) \qquad \dfrac{(VB, 3, 3) \quad (PP, 4, 6)}{(VP, 4, 6)}}{(S, 1, 6)}$$



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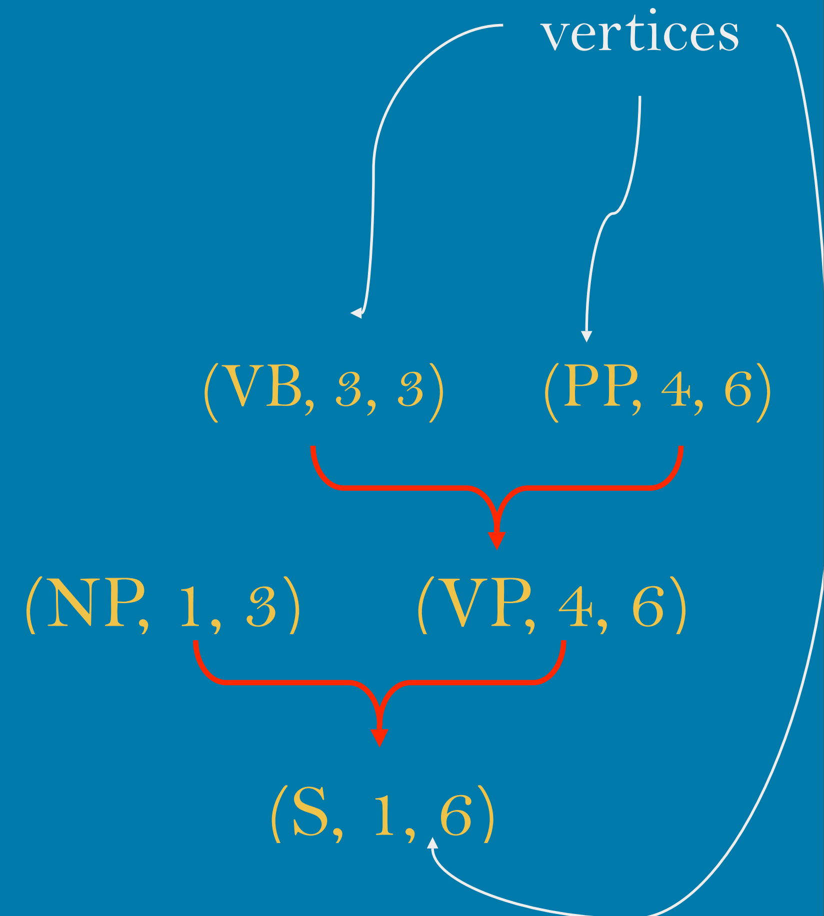

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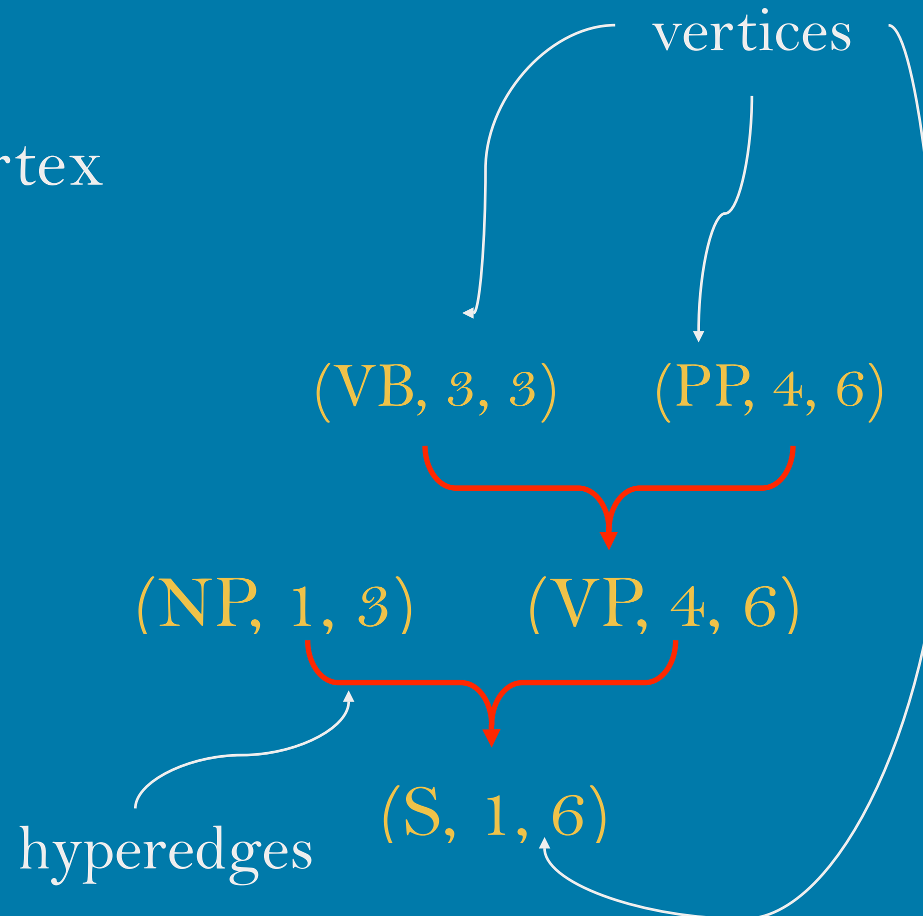
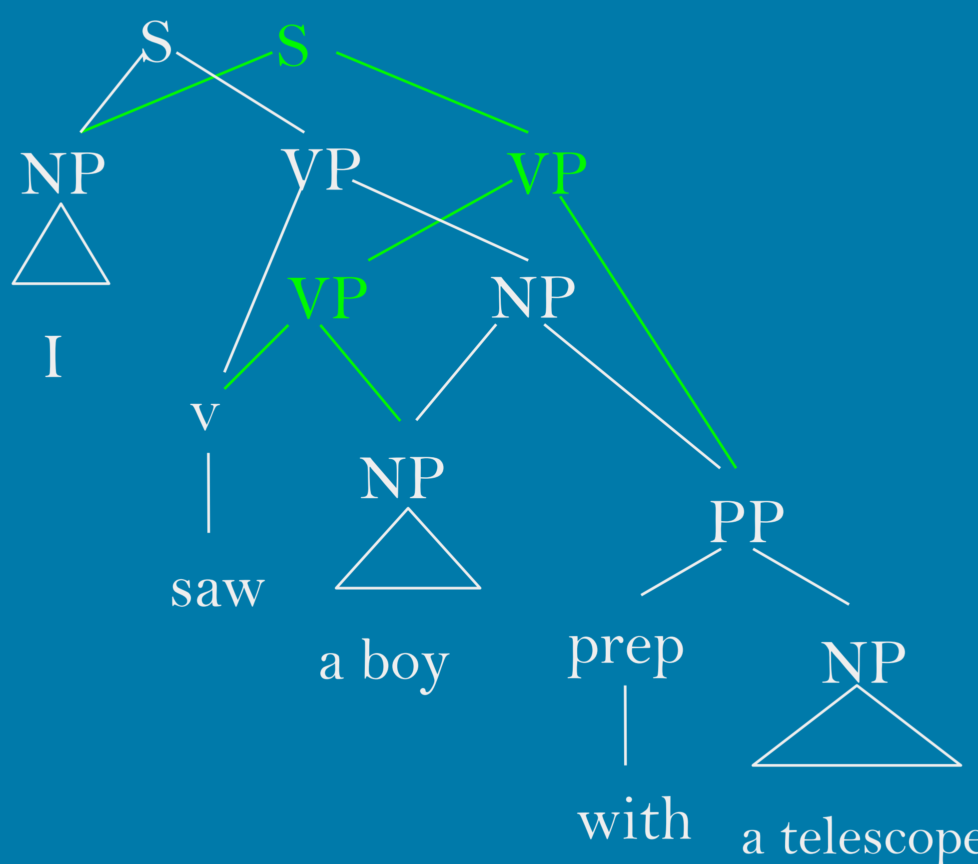


Packed Forest as Hypergraph

I saw a boy with a telescope



packed forest

a compact representation of all parse trees

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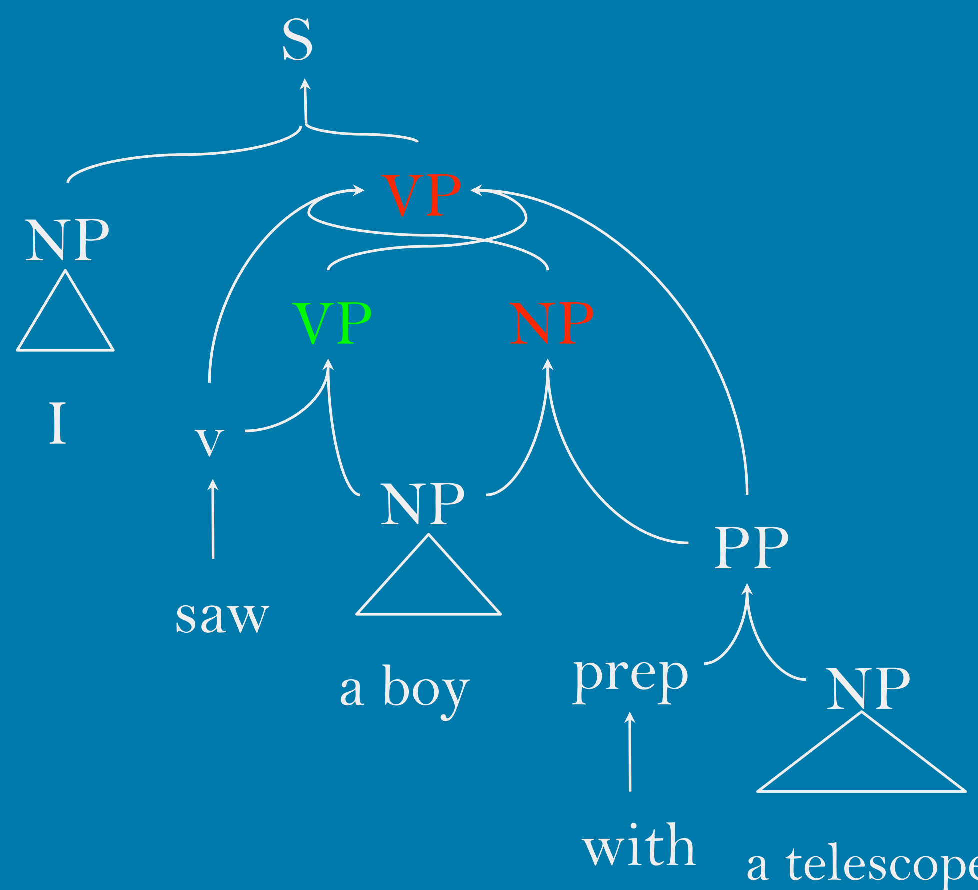

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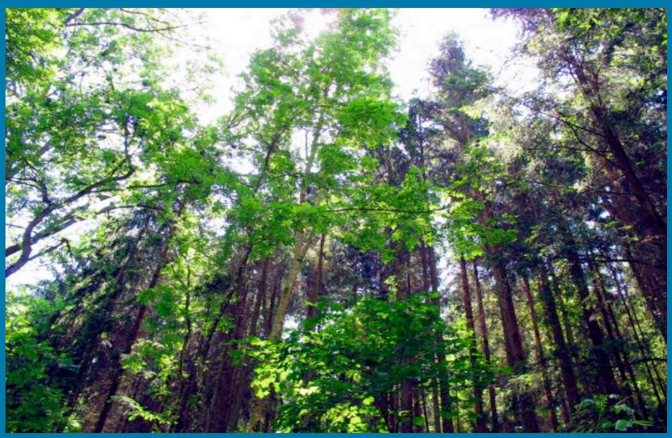

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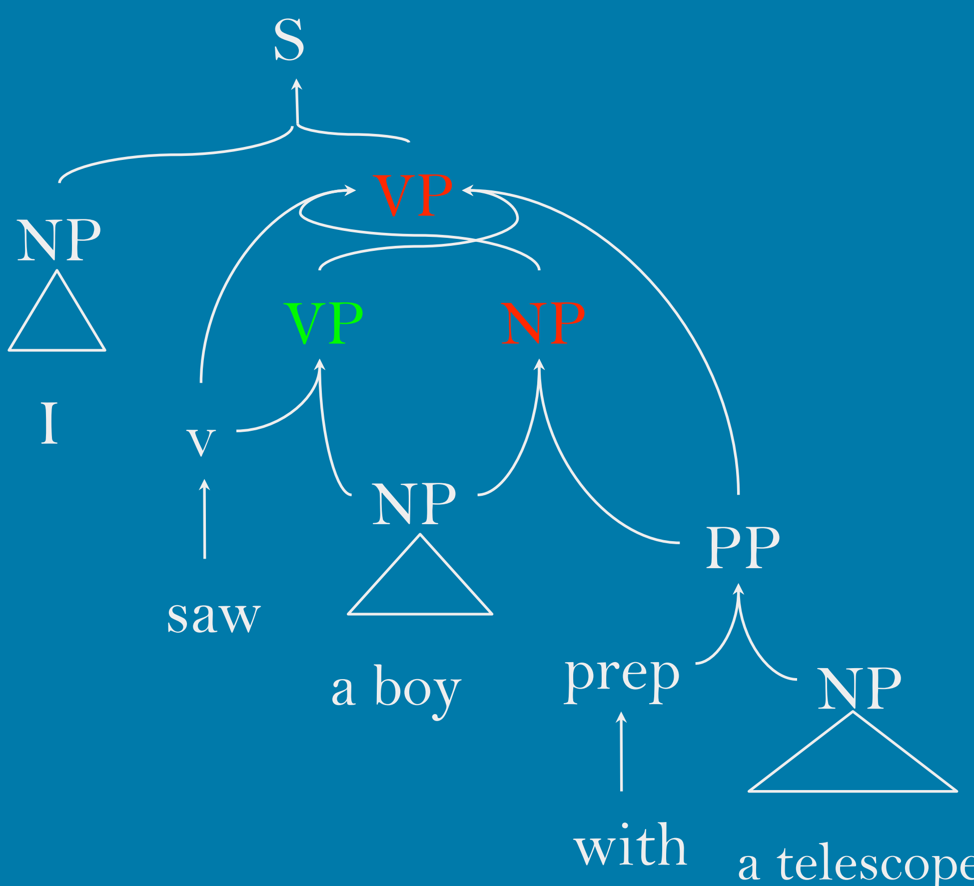


Weighted Deduction/Hypergraph

$$\frac{(B, i, j): \mathrm{p} \qquad (C, j+1, k): \mathrm{q}}{(A, i, k): f\ (\mathrm{p}, \mathrm{q})} \quad A \longrightarrow B\ C$$

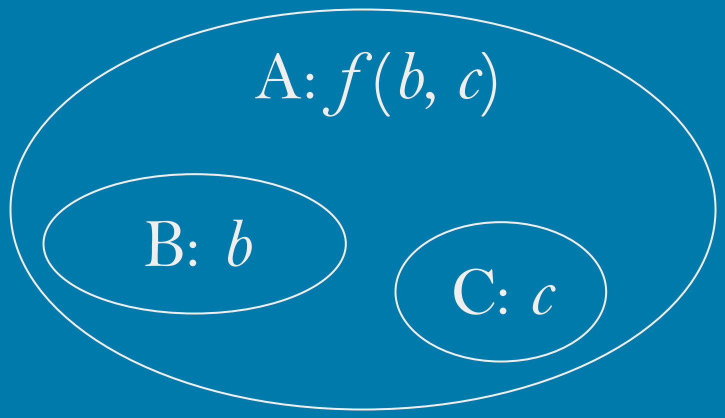
- f is the weight function

  e.g.: in Probabilistic Context-Free Grammars:

  $$f\ (\mathrm{p}, \mathrm{q}) = \mathrm{p} \cdot \mathrm{q} \cdot \Pr(\mathrm{A} \rightarrow \mathrm{B}\ \mathrm{C})$$

Monotonic Weight Functions

- all weight functions must be *monotonic* on each of their arguments
- optimal sub-problem property in dynamic programming



CKY example:

$A = (S, 1, 5)$

$B = (NP, 1, 2)$, $C = (VP, 3, 5)$

$f\,(b, c) = b \bullet c \bullet \Pr(S \rightarrow NP\ VP)$

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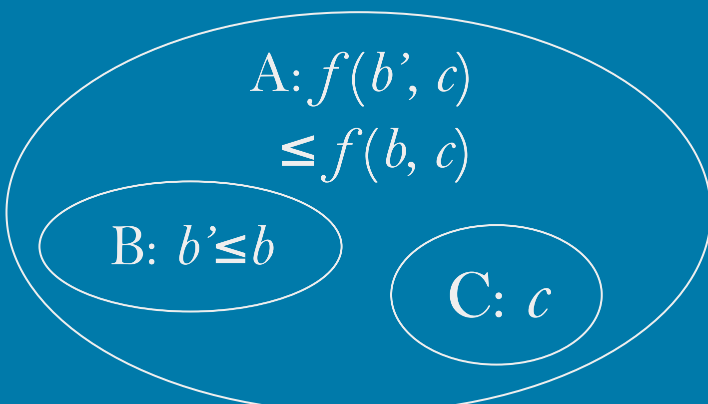

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$A = (S, 1, 5)$

$B = (NP, 1, 2),\ C = (VP, 3, 5)$

$f(b, c) = b \cdot c \cdot \Pr(S \rightarrow NP\ VP)$

k-best Problem in Hypergraphs

- 1-best problem
  - find the best derivation of the target vertex t
- *k*-best problem
  - find the top *k* derivations of the target vertex t

in CKY, $t = (S, 1, n)$

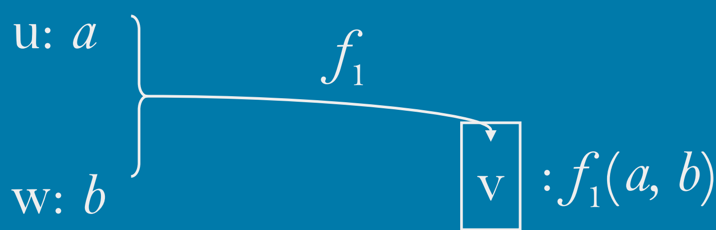
- assumption
  - acyclic: so that we can use topological order

Outline

- Formulations
- **Algorithms**
  - Generic 1-best Viterbi Algorithm
  - **Algorithm 0:** naïve
  - **Algorithm 1:** hyperedge-level
  - **Algorithm 2:** vertex (item)-level
  - **Algorithm 3:** lazy algorithm
- Experiments
- Applications to Machine Translation

Generic 1-best Viterbi Algorithm

- traverse the hypergraph in topological order ("bottom-up")
  - for each vertex
    - for each incoming hyperedge
      - compute the result of the f function along the hyperedge
      - update the 1-best value for the current vertex if possible



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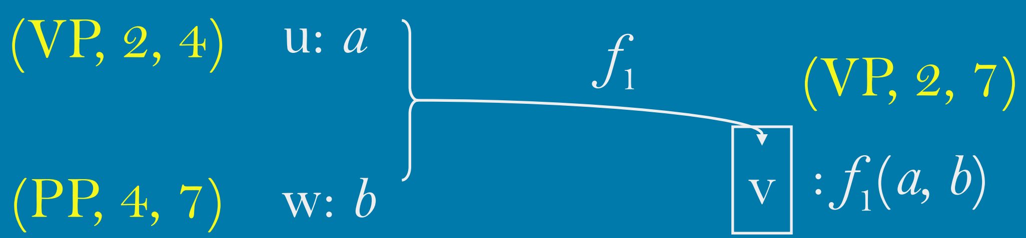

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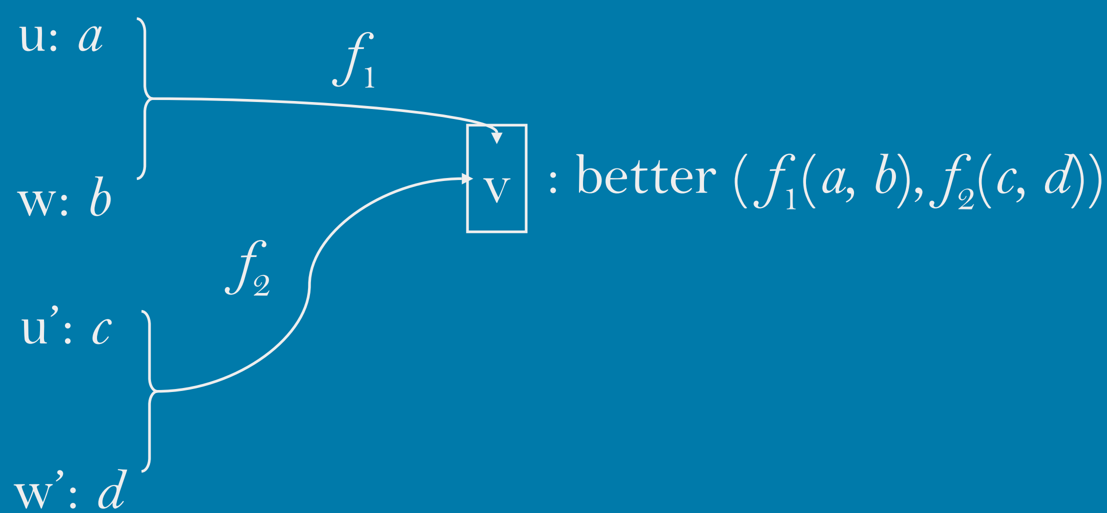

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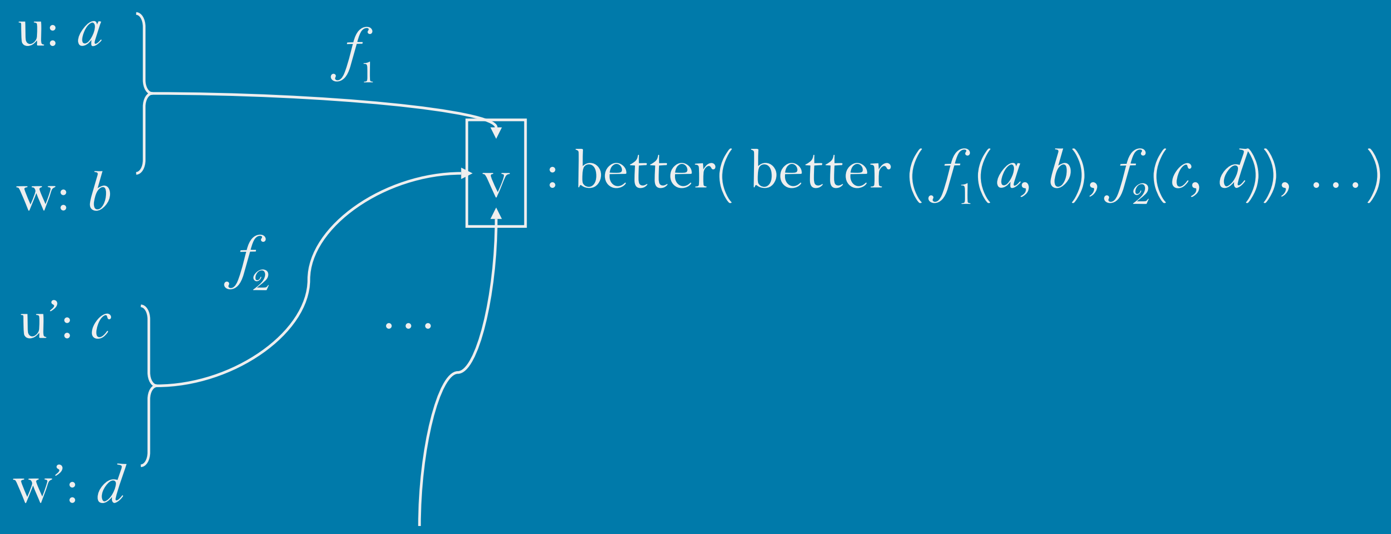

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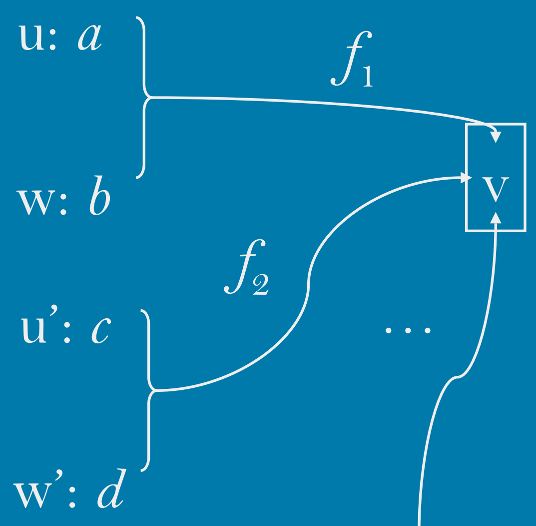

: better(better ($f_1(a, b), f_2(c, d)$), ...)

overall time complexity: $O(|E|)$

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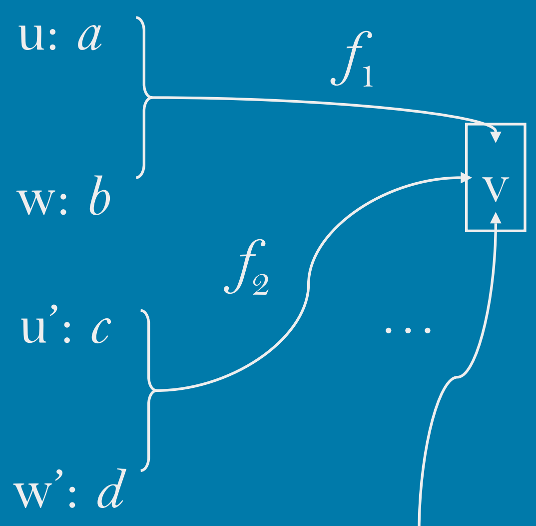

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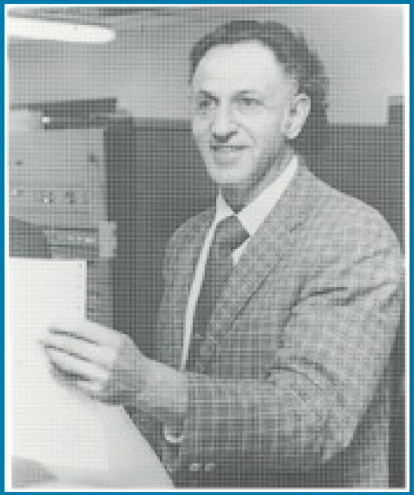
in CKY: $|E| = O(n^3|P|)$

Dynamic Programming: 1950's



Richard Bellman

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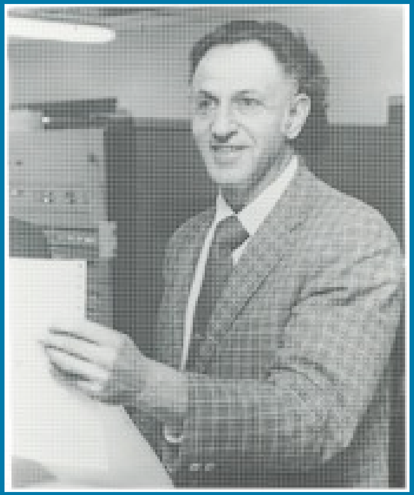

Richard Bellman

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We knew everything so far
in your talk 40 years ago

k-best Viterbi algorithm 0: naïve

- straightforward k-best extension:
  - a vector of length k instead of a single value
  - vector components maintain *sorted*
  - now what's $f(\mathbf{a}, \mathbf{b})$?
    - k^2 values -- Cartesian Product $f(a_i, b_j)$
    - just need top k out of the k^2 values

$$\boxed{\mathbf{mult}_k(f, \mathbf{a}, \mathbf{b}) = \mathbf{top}_k\{f(a_i, b_j)\}}$$

u: **a**

w: **b**

f_1

$\boxed{\mathrm{v}}$: $\mathbf{mult}_k(f_1, \mathbf{a}, \mathbf{b})$

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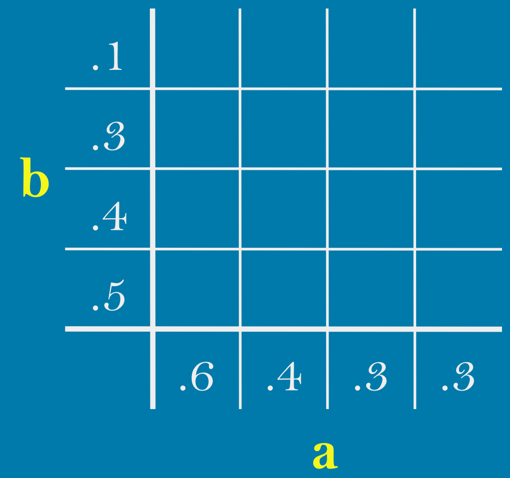

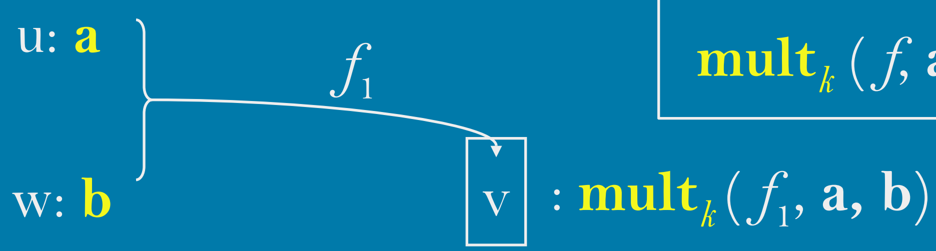

$$\mathbf{mult}_k(f, \mathbf{a}, \mathbf{b}) = \mathbf{top}_k\{f(a_i, b_j)\}$$

Algorithm 0: naïve

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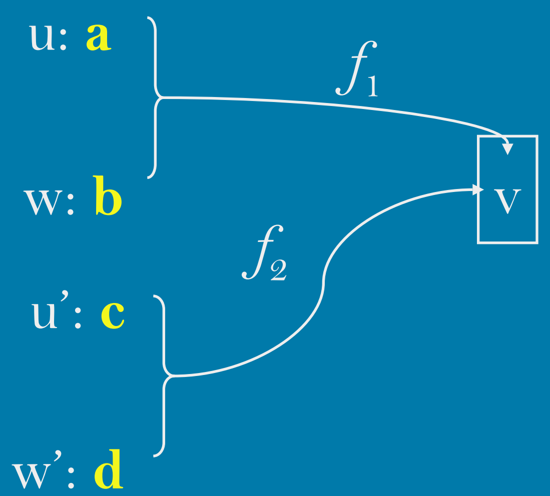
  - and how to update?
    - from two *k*-lengthed vectors ($2k$ elements)
    - select the top *k* elements: $O(k)$



: $\mathbf{merge}_k(\mathbf{mult}_k(f_1, \mathbf{a}, \mathbf{b}), \mathbf{mult}_k(f_2, \mathbf{c}, \mathbf{d}))$

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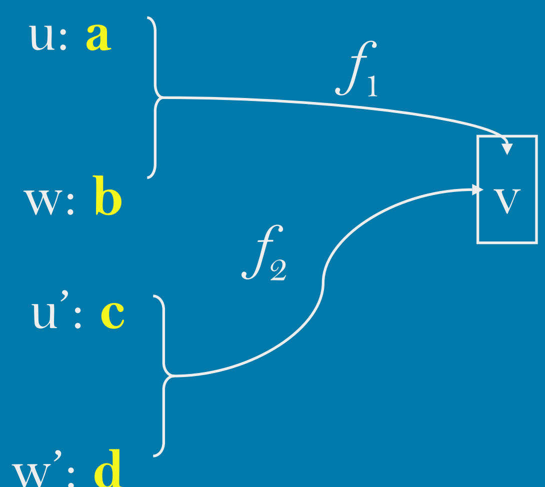

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overall time complexity: $O(k^2|E|)$

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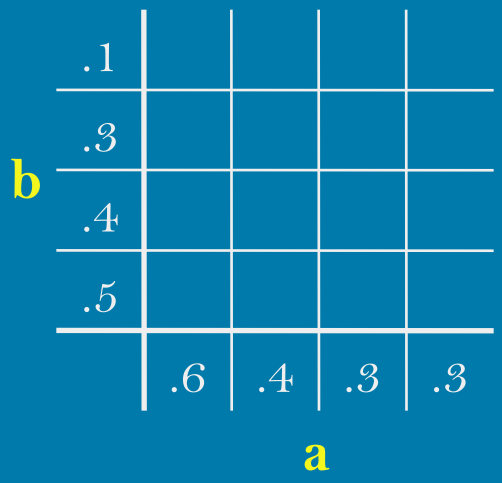
$$\mathbf{mult}_k(f, \mathbf{a}, \mathbf{b}) = \mathbf{top}_k\{ f\ (a_i, b_j) \}$$



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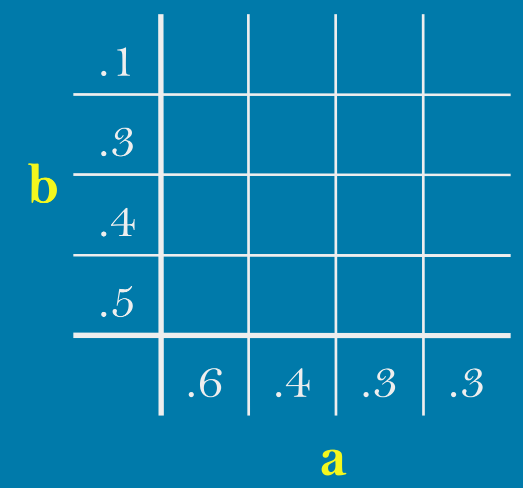

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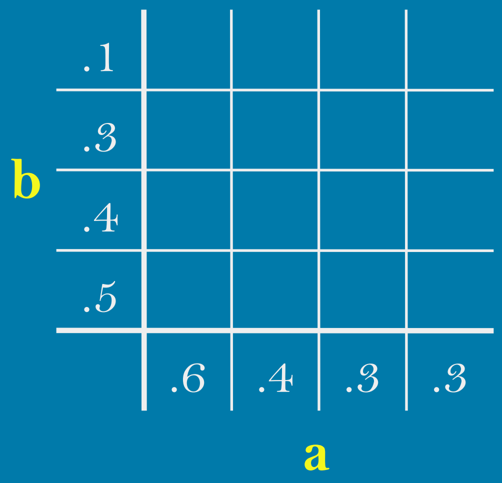

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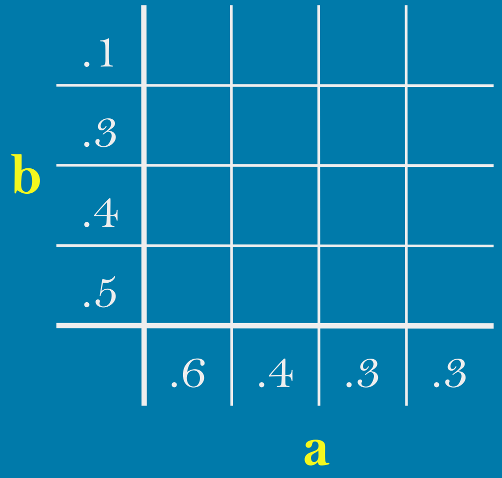

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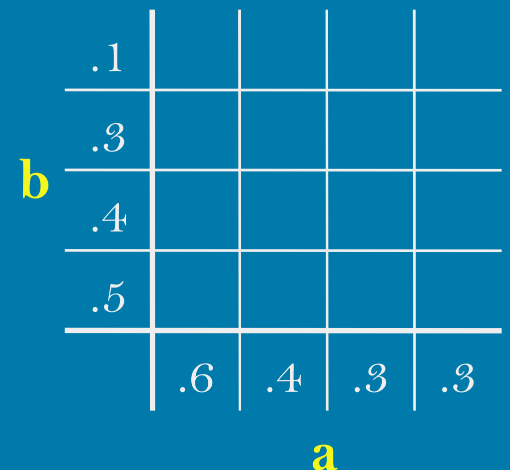

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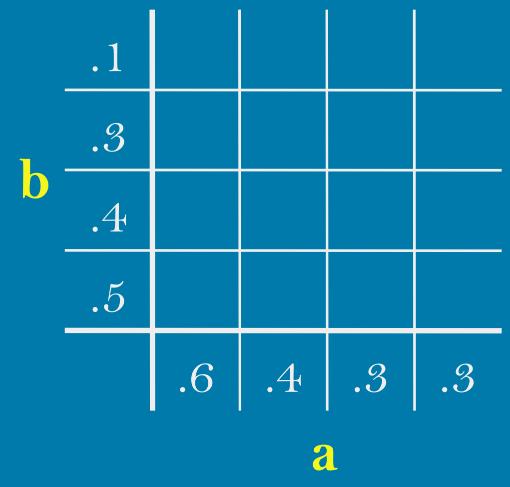
  - either $f(a_2, b_1)$ or $f(a_1, b_2)$



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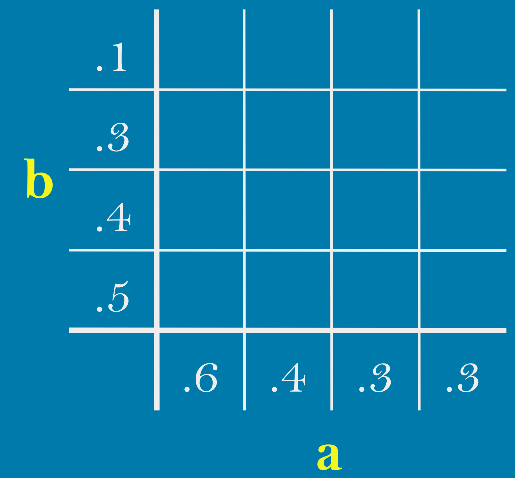
- $f(a_1, b_1)$ must be the 1-best
- the 2nd-best must be…
  - either $f(a_2, b_1)$ or $f(a_1, b_2)$
- what about the 3rd-best?



Algorithm 1 (Demo)

$$f(\mathrm{a}, \mathrm{b}) = \mathrm{ab}$$

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b_j				
$.1$				
$.3$				
$.4$				
$.5$				
	$.6$	$.4$	$.3$	$.3$

a_i

Algorithm 1 (Demo)

$f(\mathrm{a}, \mathrm{b}) = \mathrm{ab}$

b_j				
.1				
.3				
.4				
.5	.30			
	.6	.4	.3	.3
	a_i			

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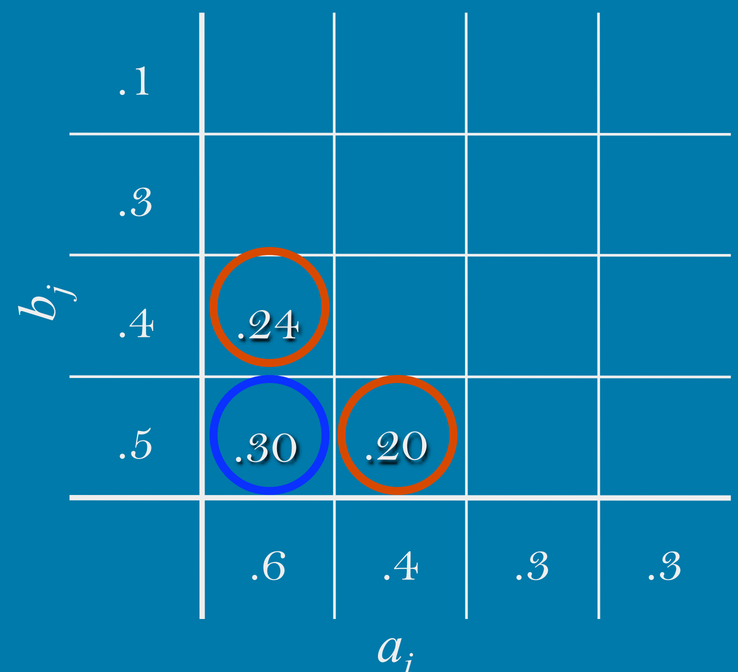

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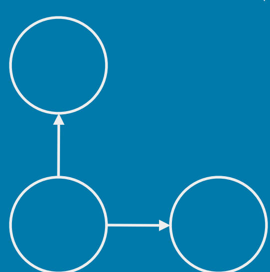
b_j				
.1				
.3				
.4	.24			
.5	.30	.20		
	.6	.4	.3	.3
	a_i			



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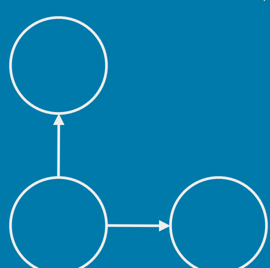

b_j				
.1				
.3				
.4	.24			
.5	.30	.20		
	.6	.4	.3	.3

a_i

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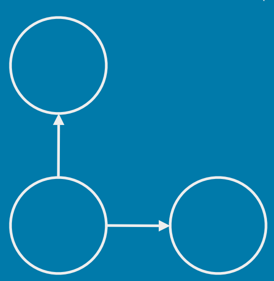
$f(\mathrm{a}, \mathrm{b}) = \mathrm{ab}$



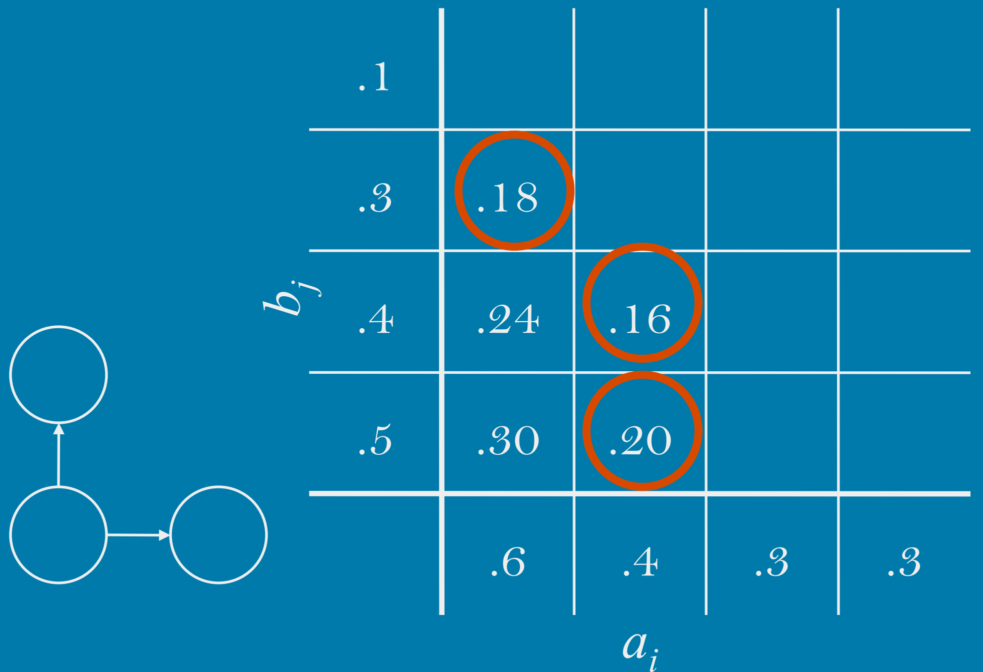
b_j

.1				
.3	.18			
.4	.24	.16		
.5	.30	.20		
	.6	.4	.3	.3

a_i

Algorithm 1 (Demo)

use a priority queue (heap) to
store the candidates (*frontier*)



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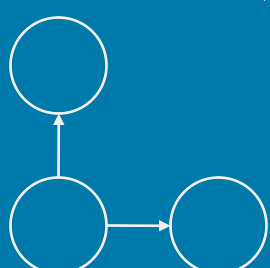

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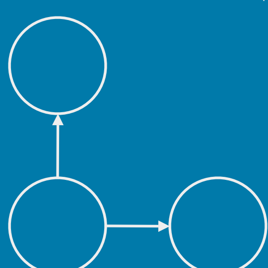

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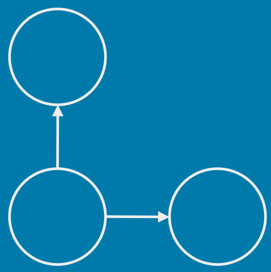


in each iteration:

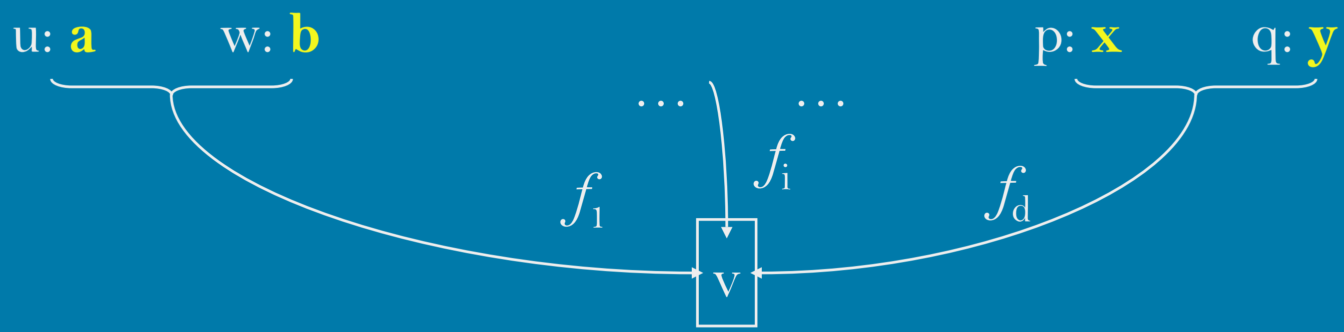
1. extract-max from the heap
2. push the two "shoulders" into the heap

k iterations.

$O(k \log k \; |E|)$ overall time

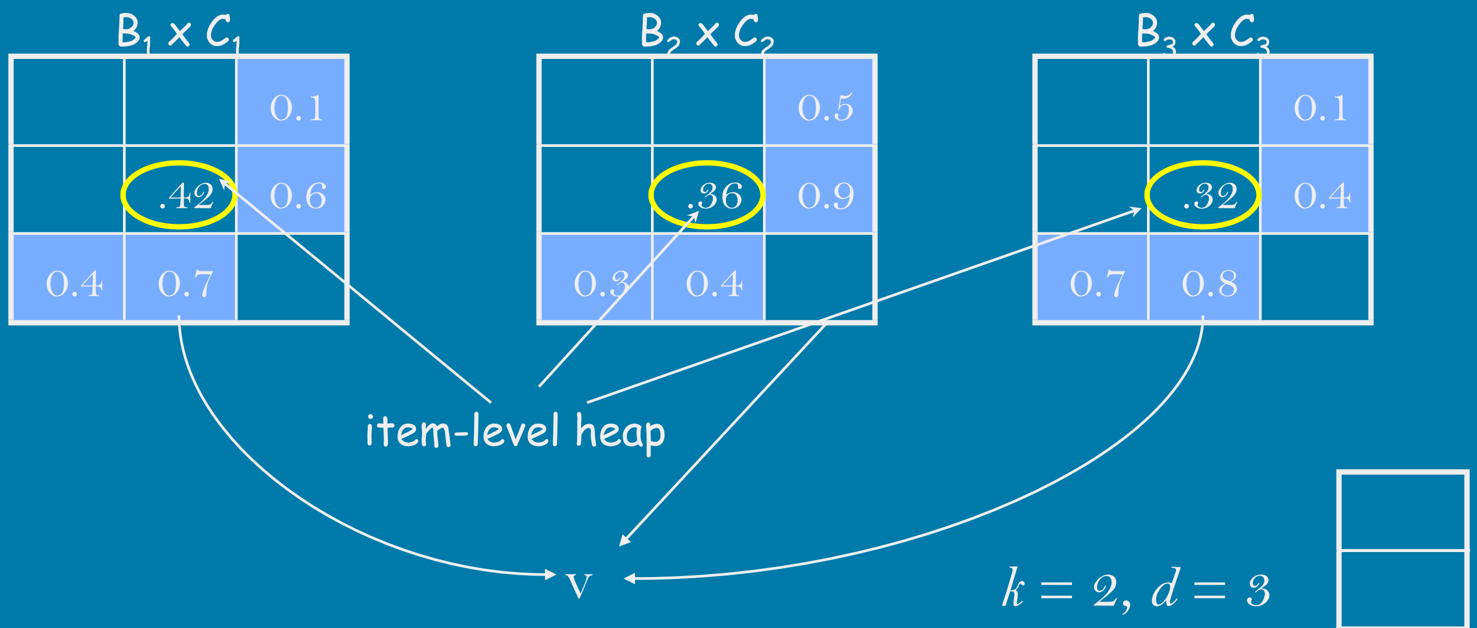
Algorithm 2: speedup **merge**$_k$

- Algorithm 1 works on each hyperedge sequentially
- can we process them simultaneously?



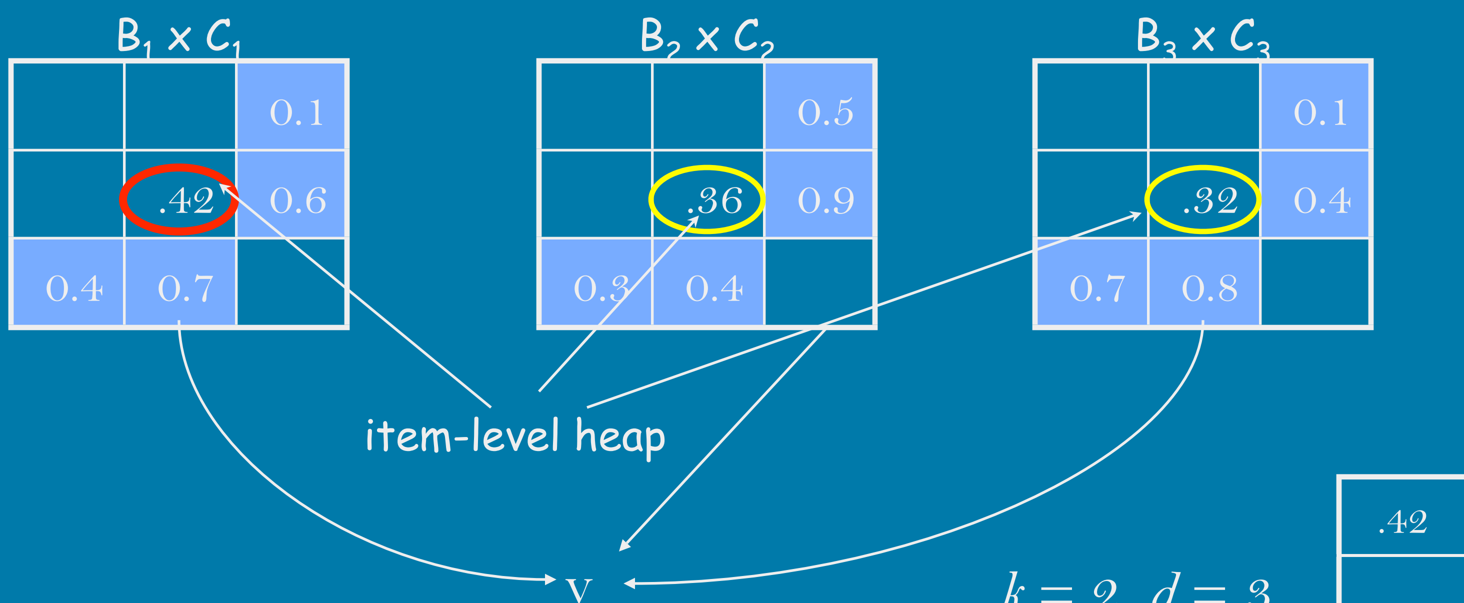
Algorithm 2 (Demo)

starts with an initial heap of the 1-best derivations from each hyperedge



Algorithm 2 (Demo)

pop the best (.42) and …

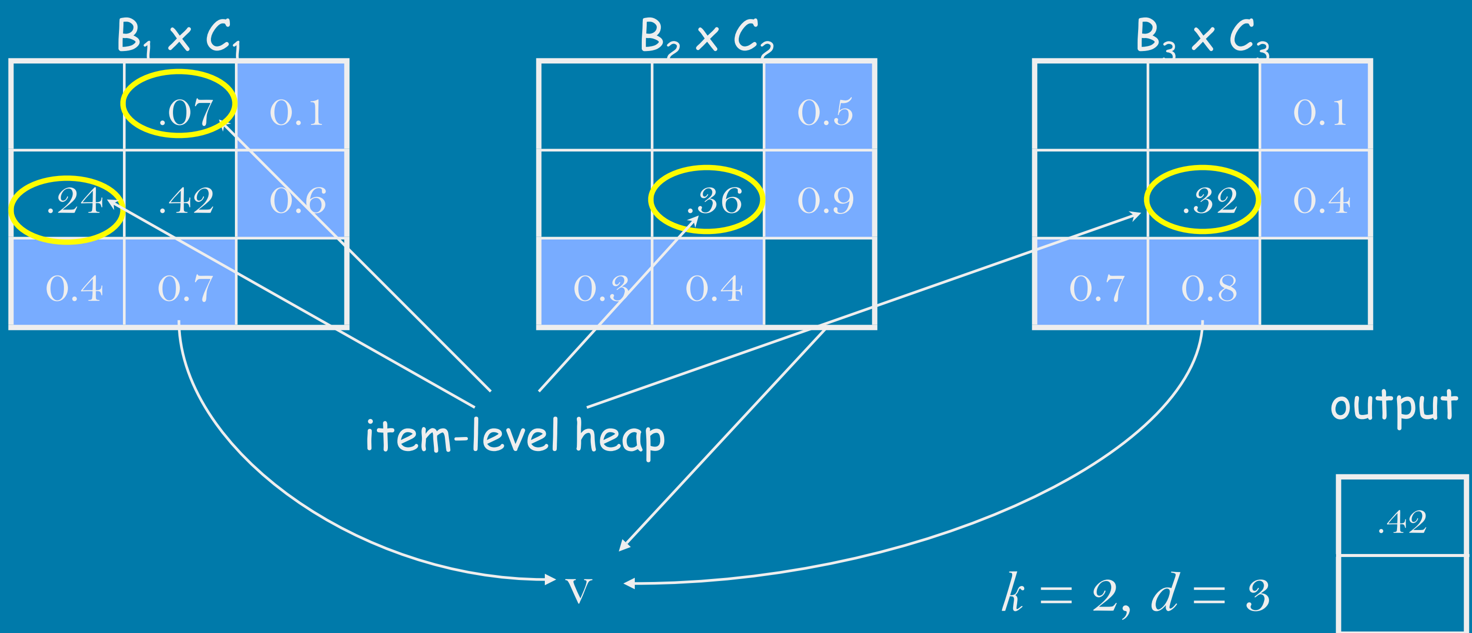


$k = 2,\ d = 3$

Algorithm 2 (Demo)

pop the best (.42) and …

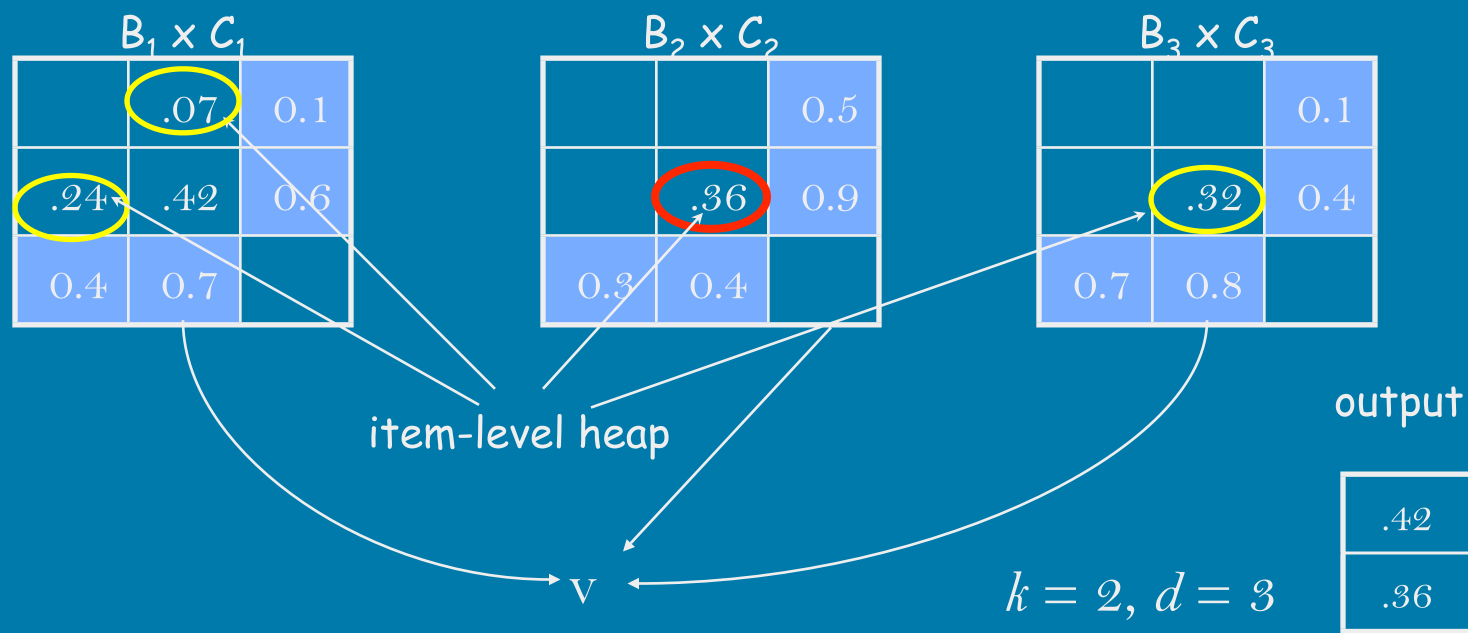
push the two successors (.07 and .24)



$k = 2,\ d = 3$

Algorithm 2 (Demo)

pop the 2^{nd}-best (.36)



$k = 2,\ d = 3$

Algorithm 3: Offline (lazy)

- from Algorithm 0 to Algorithm 2:
  - delaying the calculations until needed -- lazier
  - larger locality
- even lazier… (one step further)
  - we are interested in the *k*-best derivations of the **final item only!**

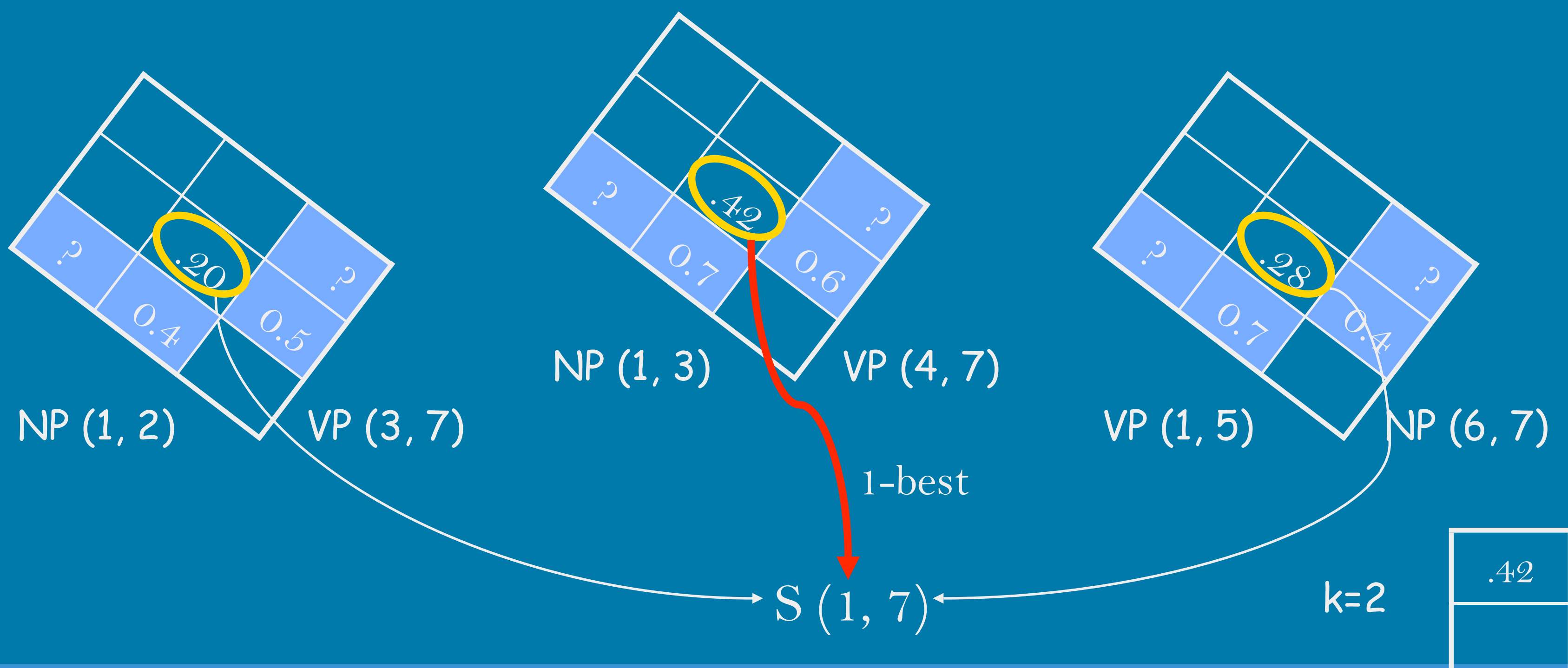
Algorithm 3: Offline (lazy)

- forward phase
  - do a normal 1-best search till the final item
  - *but* construct the hypergraph (*forest*) along the way
- recursive backward phase
  - ask the final item: what's your 2nd-best?
  - final item will propagate this question till the leaves
  - then ask the final item: what's your 3rd-best?

Algorithm 3 demo

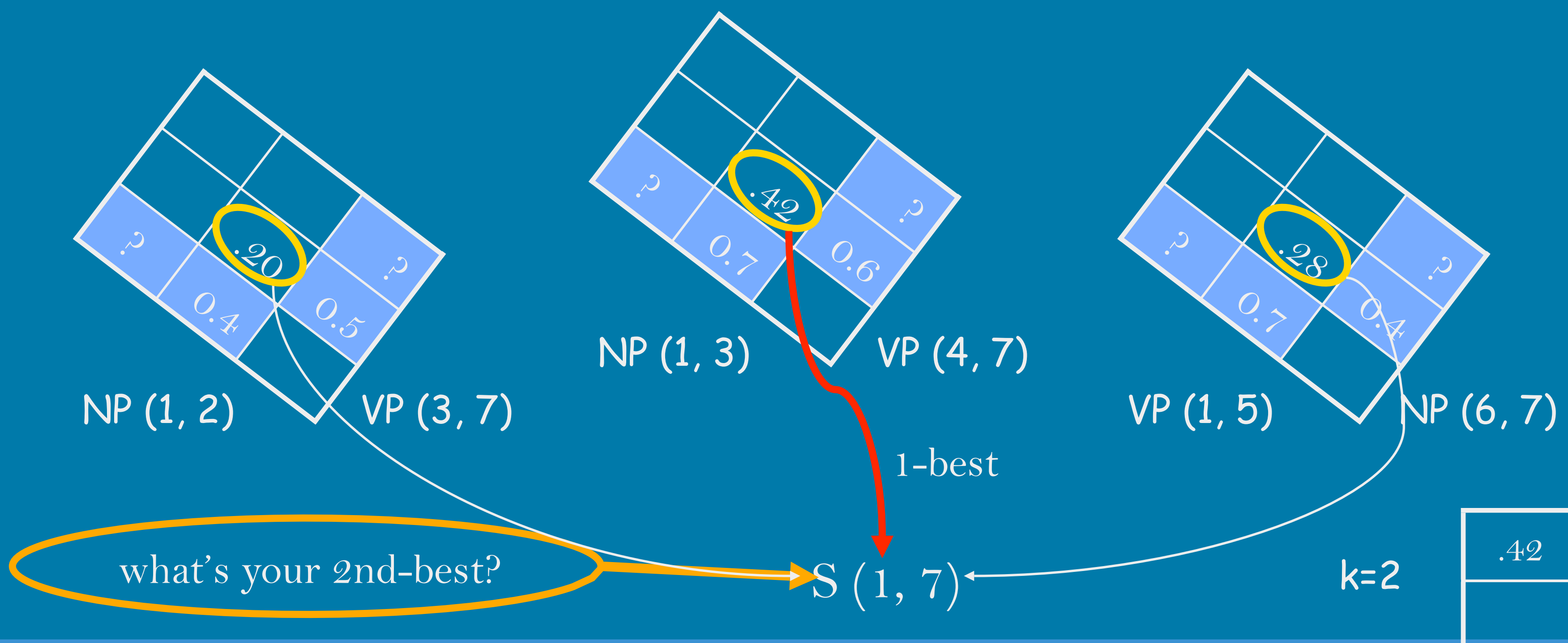
after the "forward" step (1-best parsing):

forest = 1-best derivations from each hyperedge

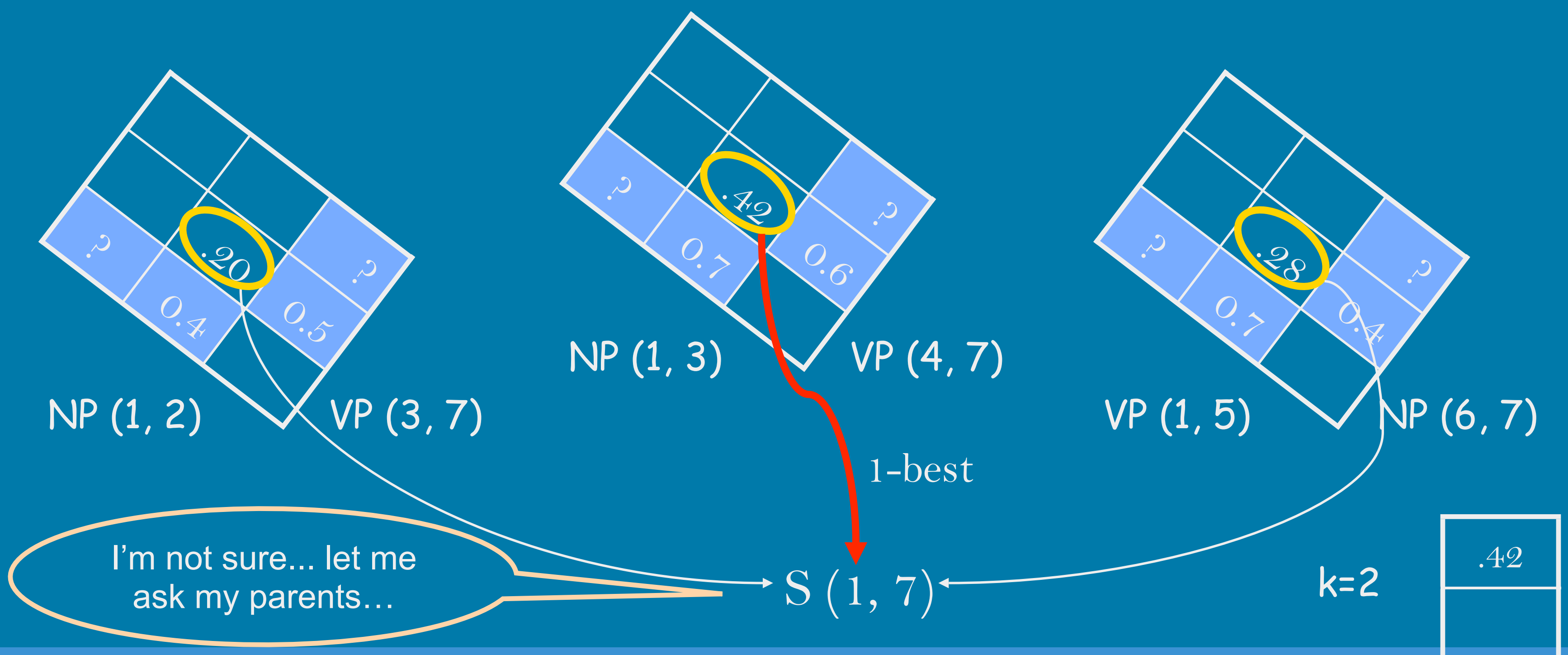


Algorithm 3 demo

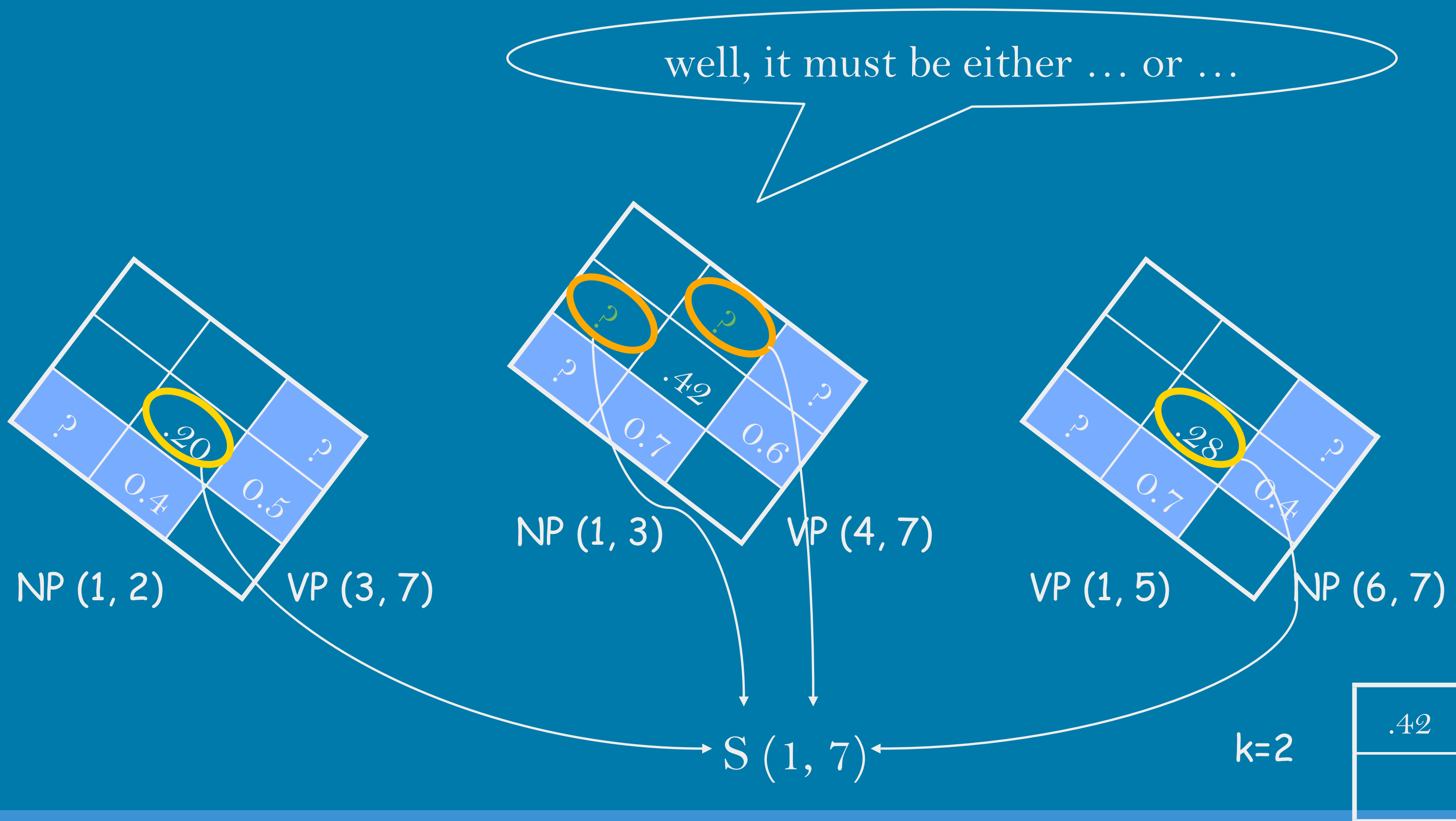
now the backward step



Algorithm 3 demo

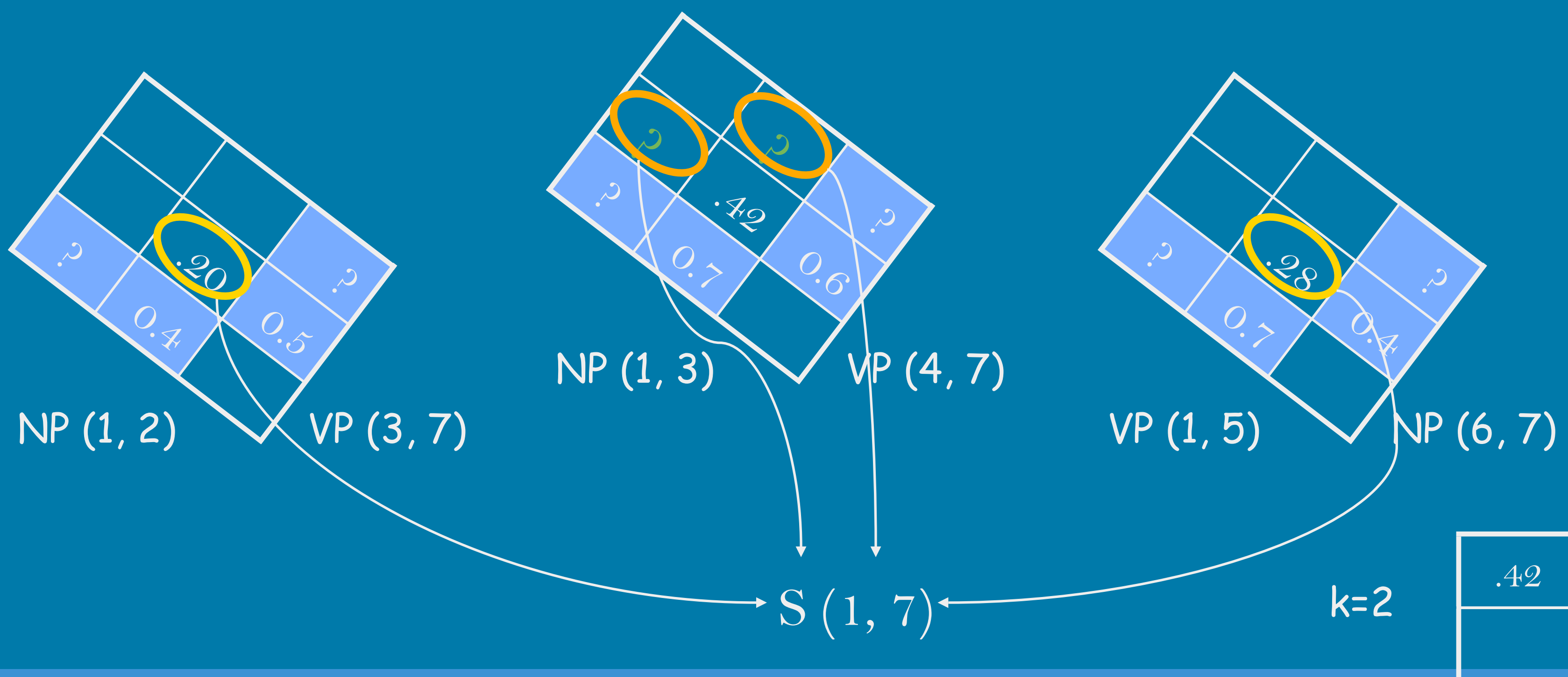


Algorithm 3 demo



Algorithm 3 demo

but wait a minute… did you already know the ?'s ?



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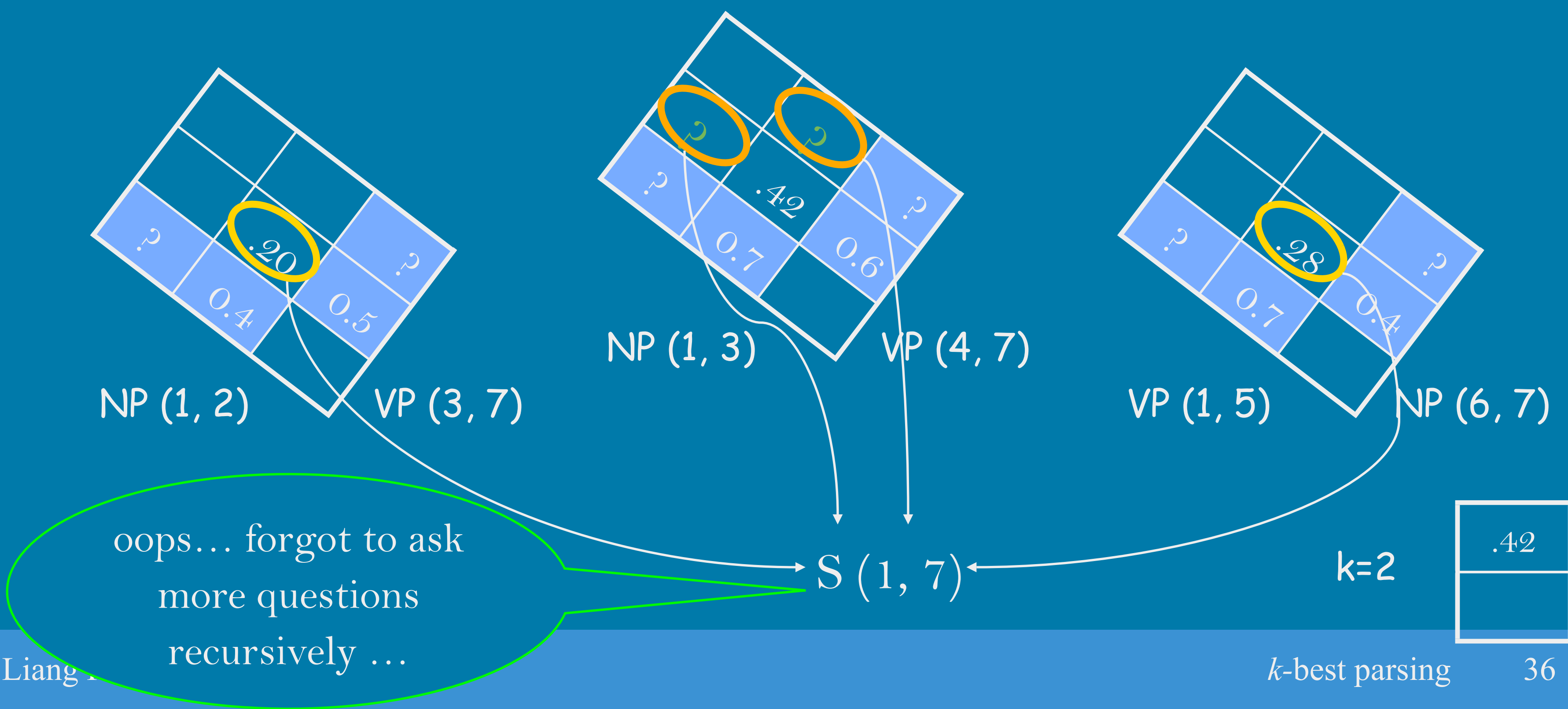
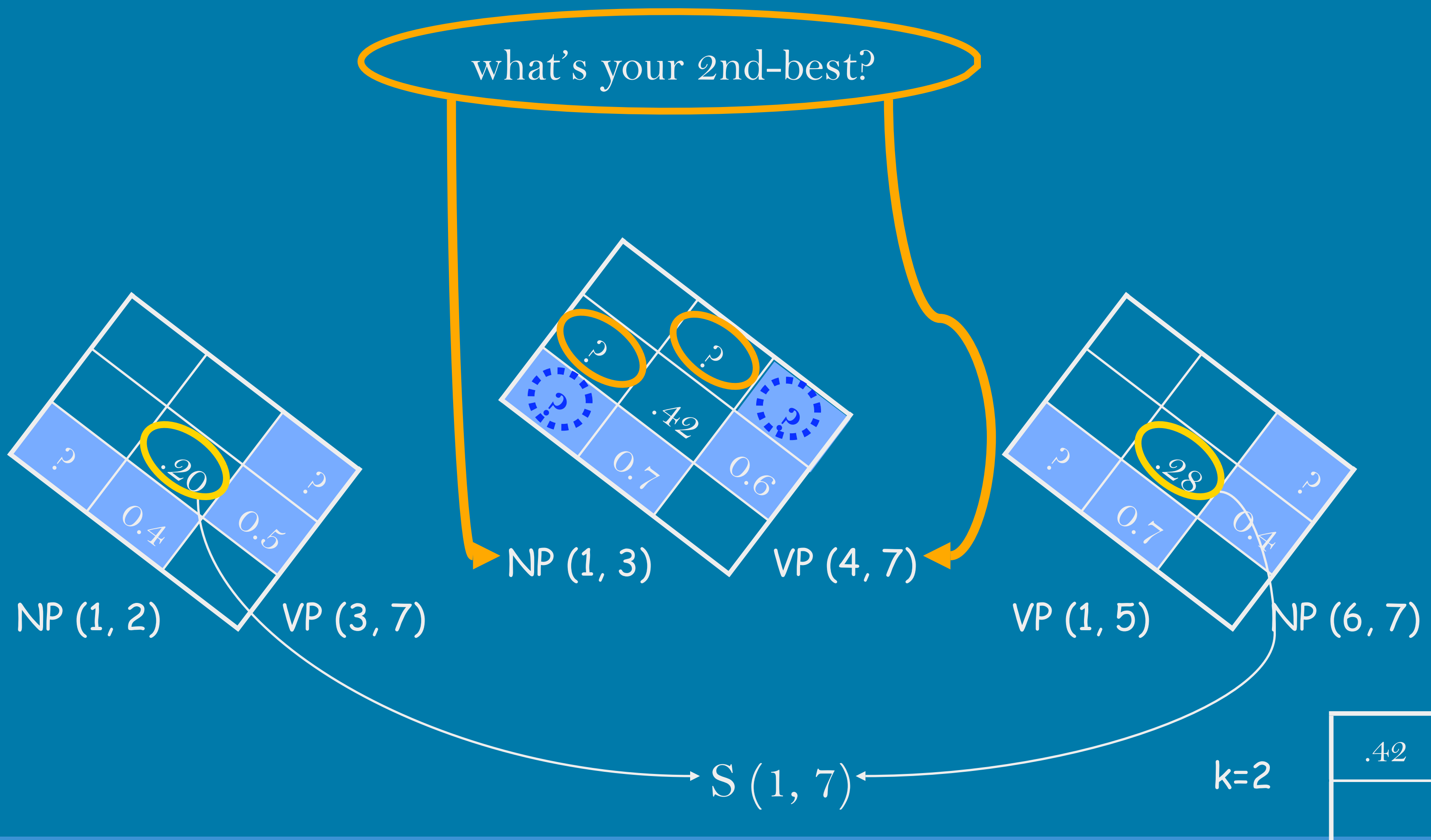
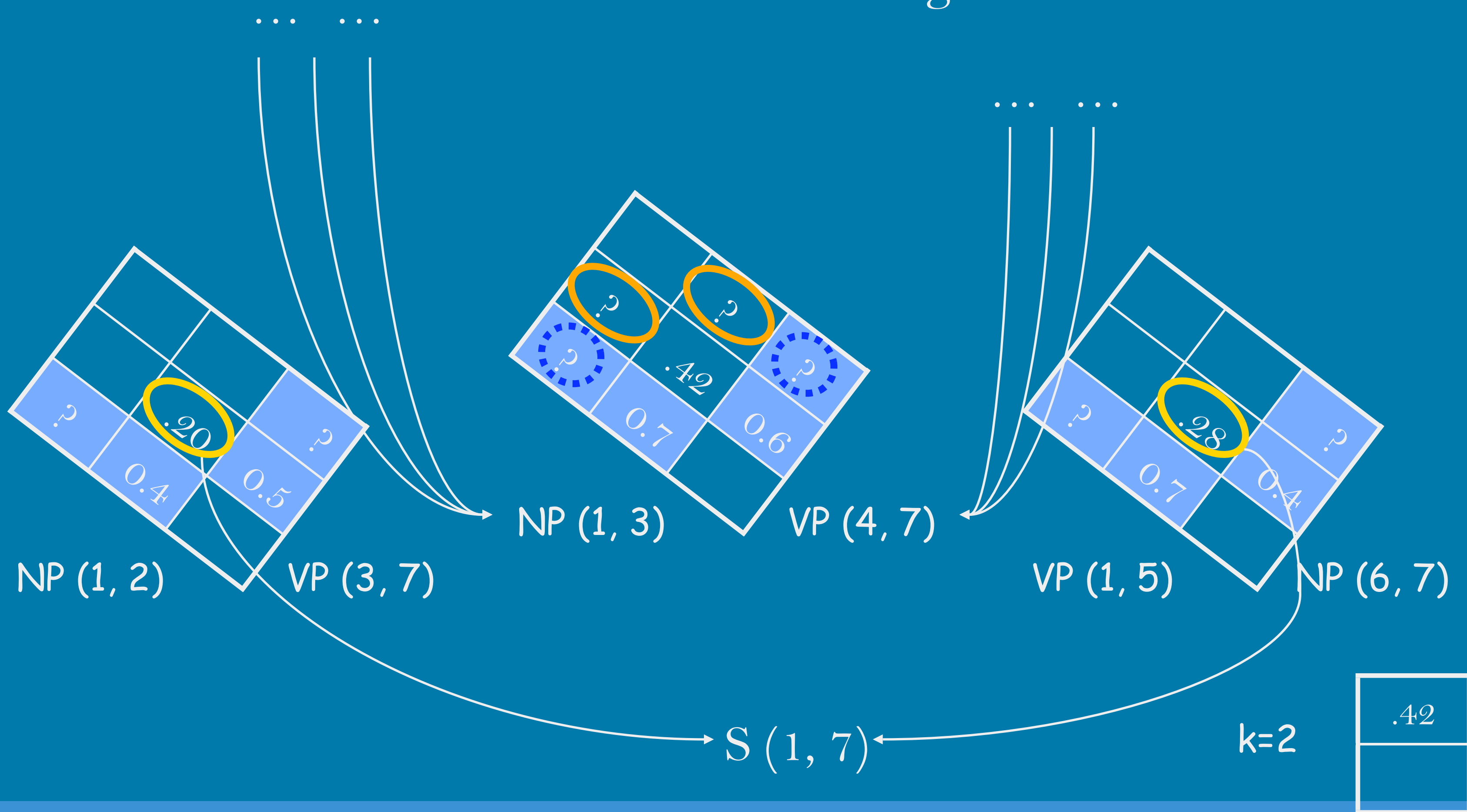


Algorithm 3 demo



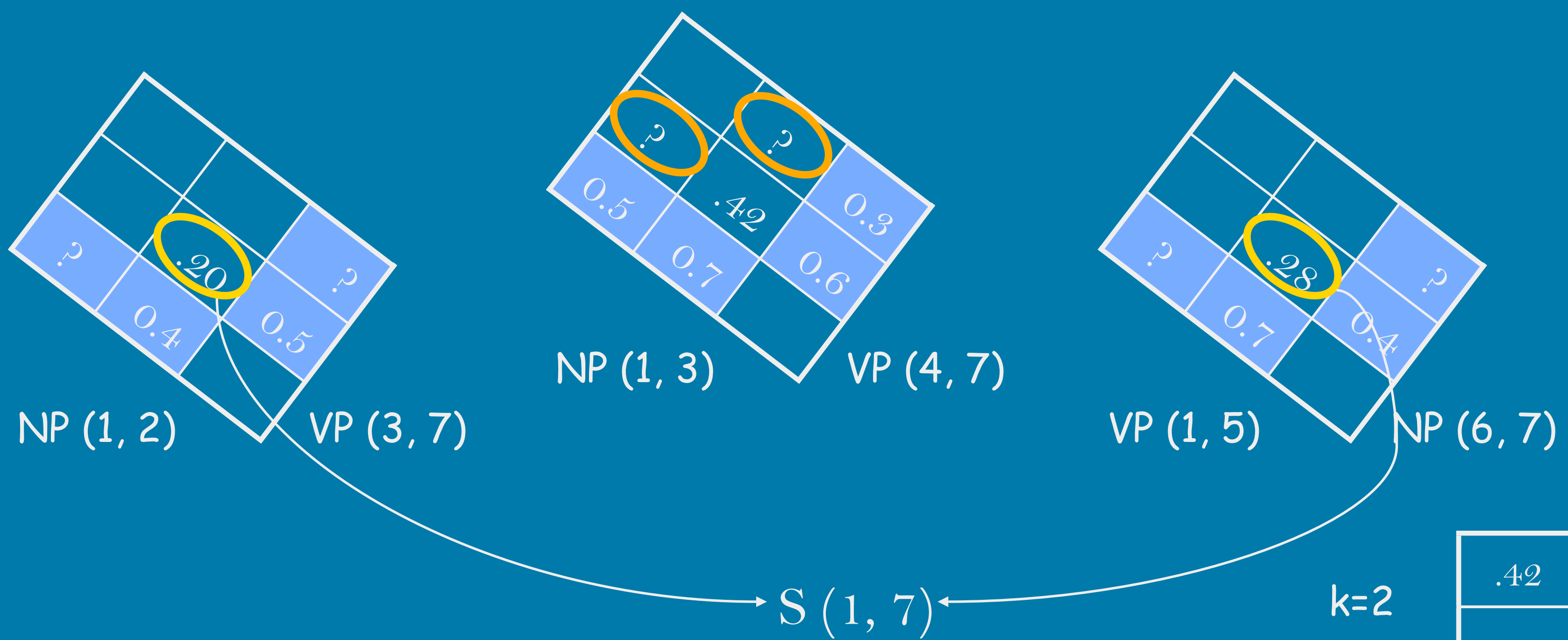
Algorithm 3 demo

recursion goes on to the leaf nodes



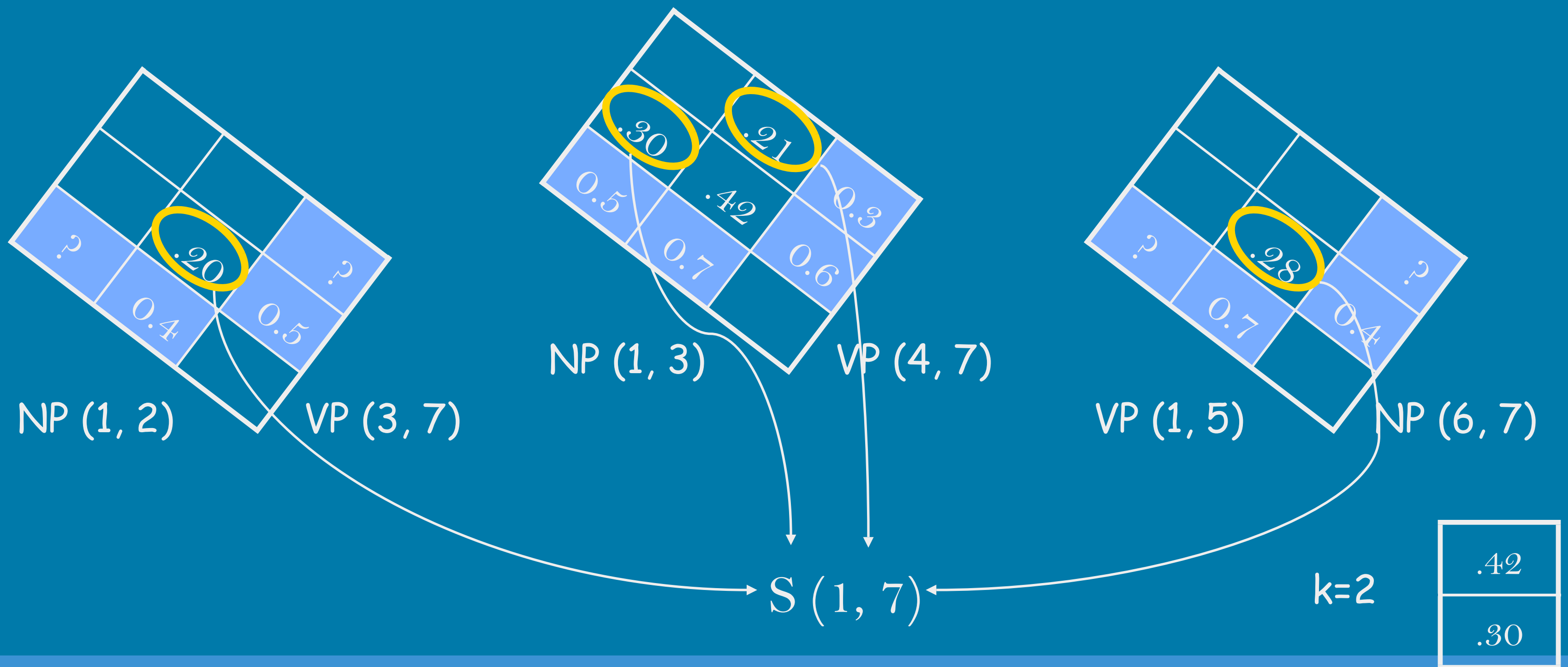
Algorithm 3 demo

and reports back the numbers…



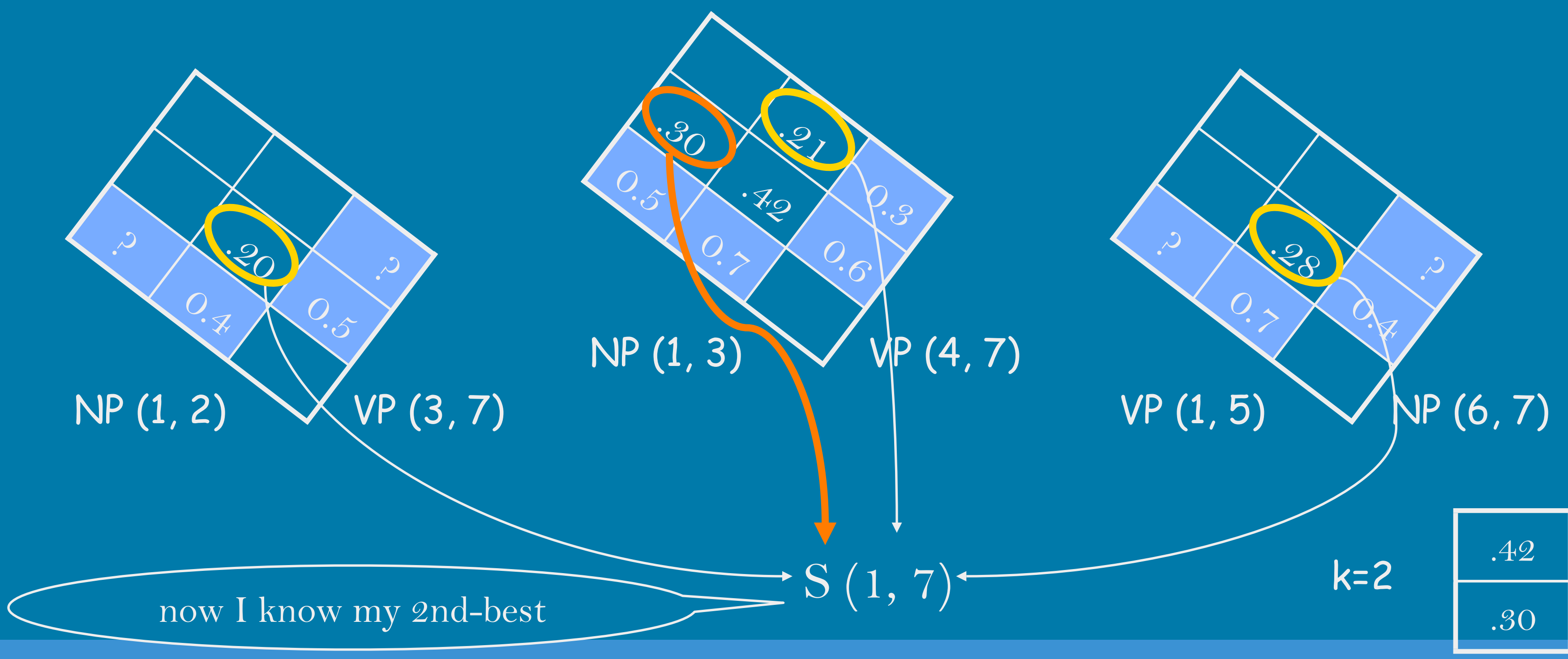
Algorithm 3 demo

push .30 and .21 to the candidate heap (priority queue)



Algorithm 3 demo

pop the root of the heap (.30)



Interesting Properties

- 1-best is best everywhere (all decisions optimal)
- 2nd-best is optimal everywhere except one decision
  - and that decision must be 2nd-best
  - and it's the best of all 2nd-best decisions
- so what about the 3rd-best?
- *k*th-best is…

$$\sum_{\delta \in \Delta} (rank(\delta) - 1) \leq k - 1$$

local picture:

b_j				
.1	.06	.04	.03	.03
.3	.18	.12	.09	.09
.4	.24	.16	.12	.12
.5	.30	.20	.15	.15
	.6	.4	.3	.3

a_i

$$(i-1) + (j-1) = 3 - 1$$

Summary of Algorithms

Algorithms	Time Complexity	Locality
1-best	$O(\lvert E \rvert)$	hyperedge
alg. 0: naïve	$O(k^a \lvert E \rvert)$	hyperedge (mult_k)
alg. 1	$O(k \log k \, \lvert E \rvert)$	hyperedge (mult_k)
alg. 2	$O(\lvert E \rvert + \lvert V \rvert k \log k)$	item (merge_k)
alg. 3: lazy	$O(\lvert E \rvert + \lvert D \rvert k \log k)$	global

for CKY: $a=2$, $\lvert E \rvert = O(n^3 \lvert P \rvert)$, $\lvert V \rvert = O(n^2 \lvert N \rvert)$, $\lvert D \rvert = O(n)$

a is the arity of the grammar

Outline

- Formulations
- Algorithms: Alg.0 thru Alg. 3
- **Experiments**
  - **Collins/Bikel Parser**
  - **both efficiency and accuracy**
- Applications in Machine Translation

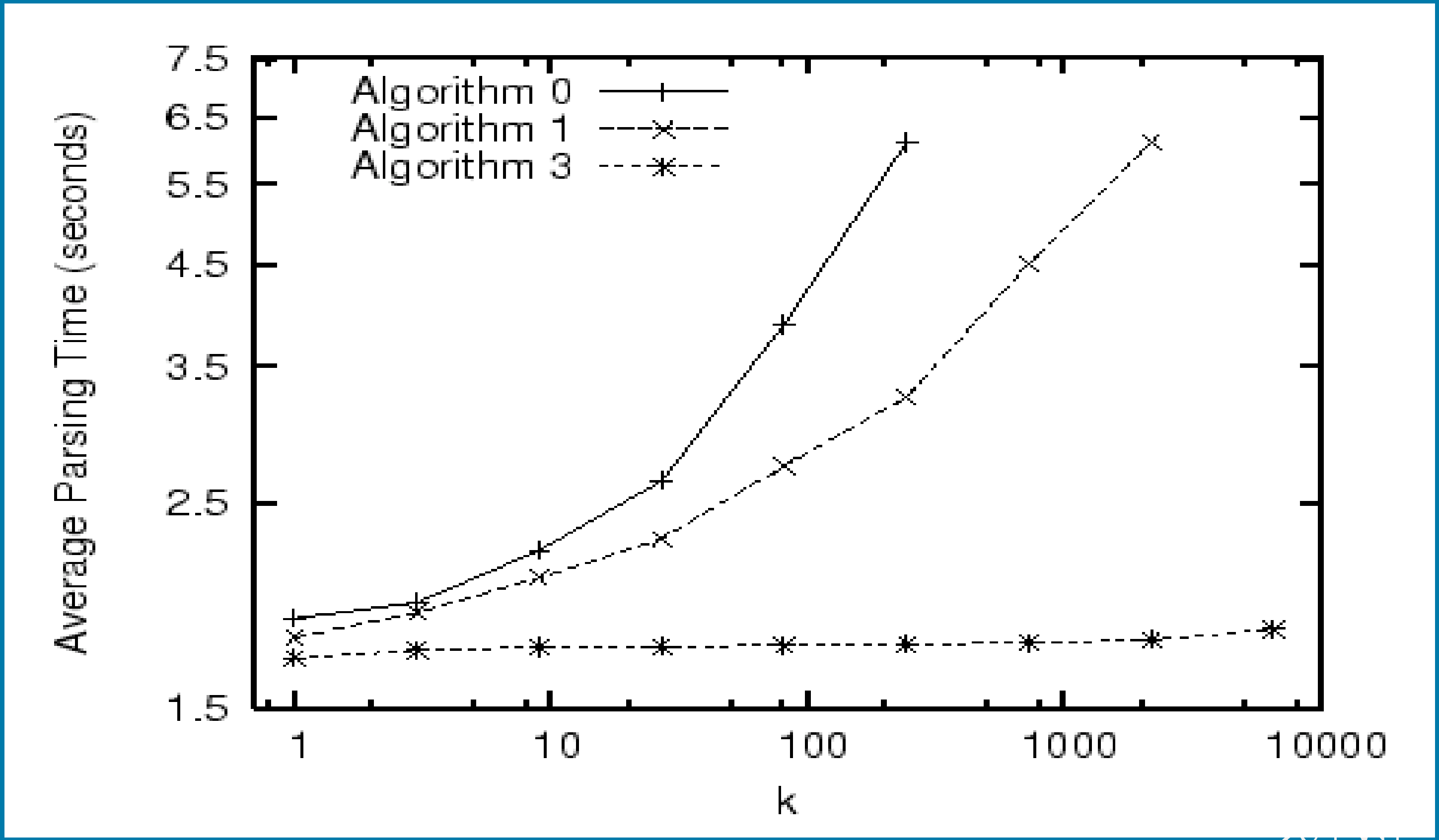
Background: Statistical Parsing

- Probabilistic Grammar
  - induced from a treebank (Penn Treebank)
- State-of-the-art Parsers
  - Collins (1999), Bikel (2004), Charniak (2000), etc.
- Evaluation of Accuracy
  - PARSEVAL: tree-similarity (English treebank: ~90%)
- Previous work on k-best Parsing:
  - Collins (2000): turn off dynamic programming
  - Charniak/Johnson (2005): coarse-to-fine, still too slow

Efficiency

Implemented Algorithms 0, 1, 3 on top of Collins/Bikel Parser

Average (wall-clock) time on Penn Treebank (per sentence):



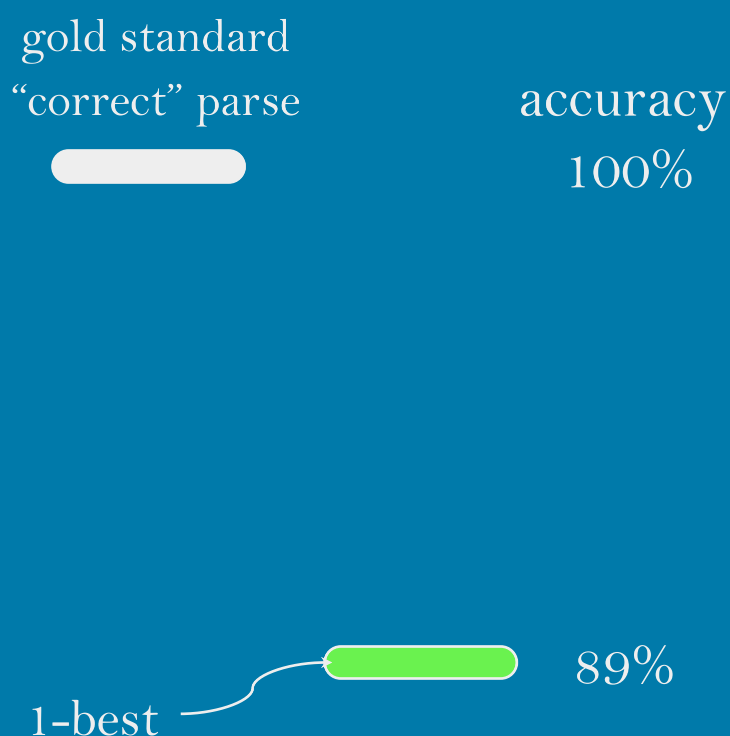
$O(|E|+|D|k\log k)$

Oracle Reranking

given *k* parses of a sentence

- oracle reranking: pick the best parse according to the gold-standard

- real reranking: pick the best parse according to the score function



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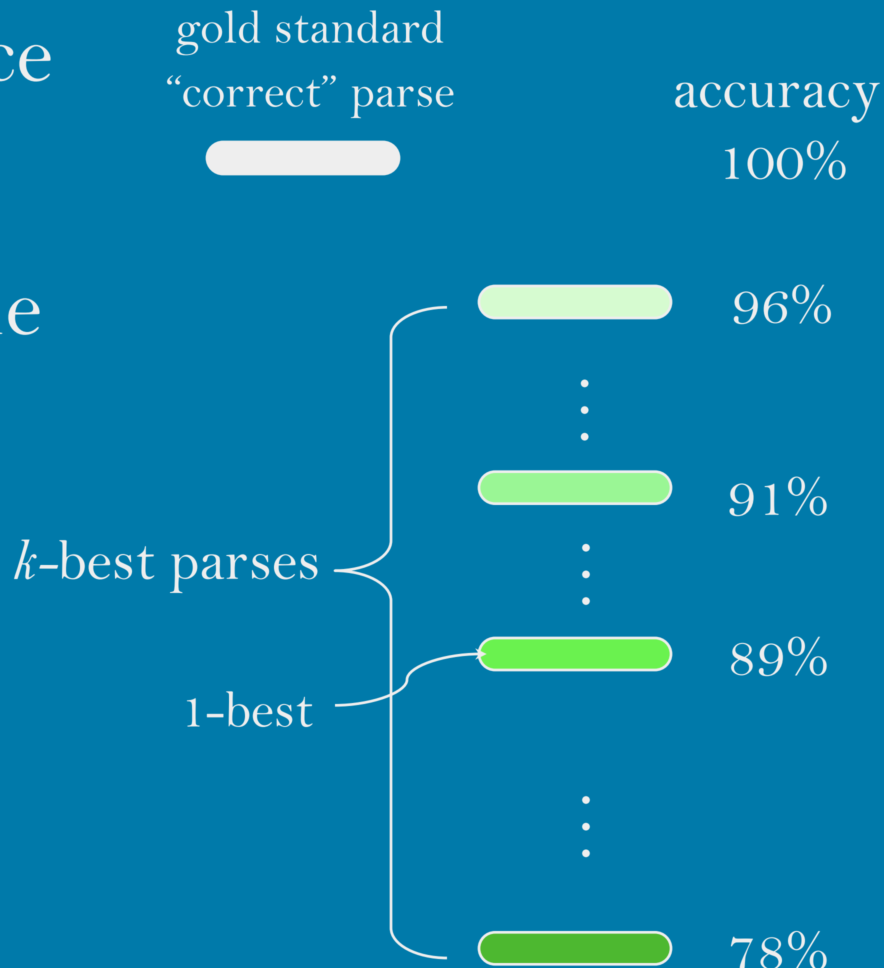

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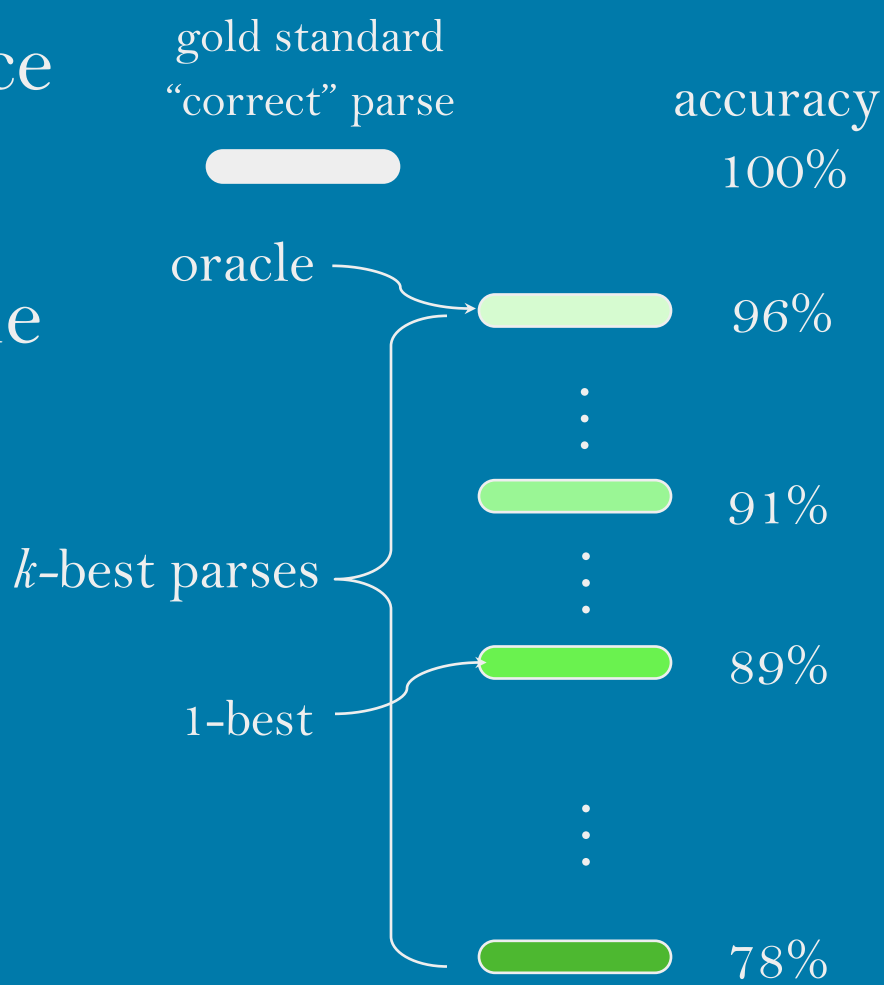
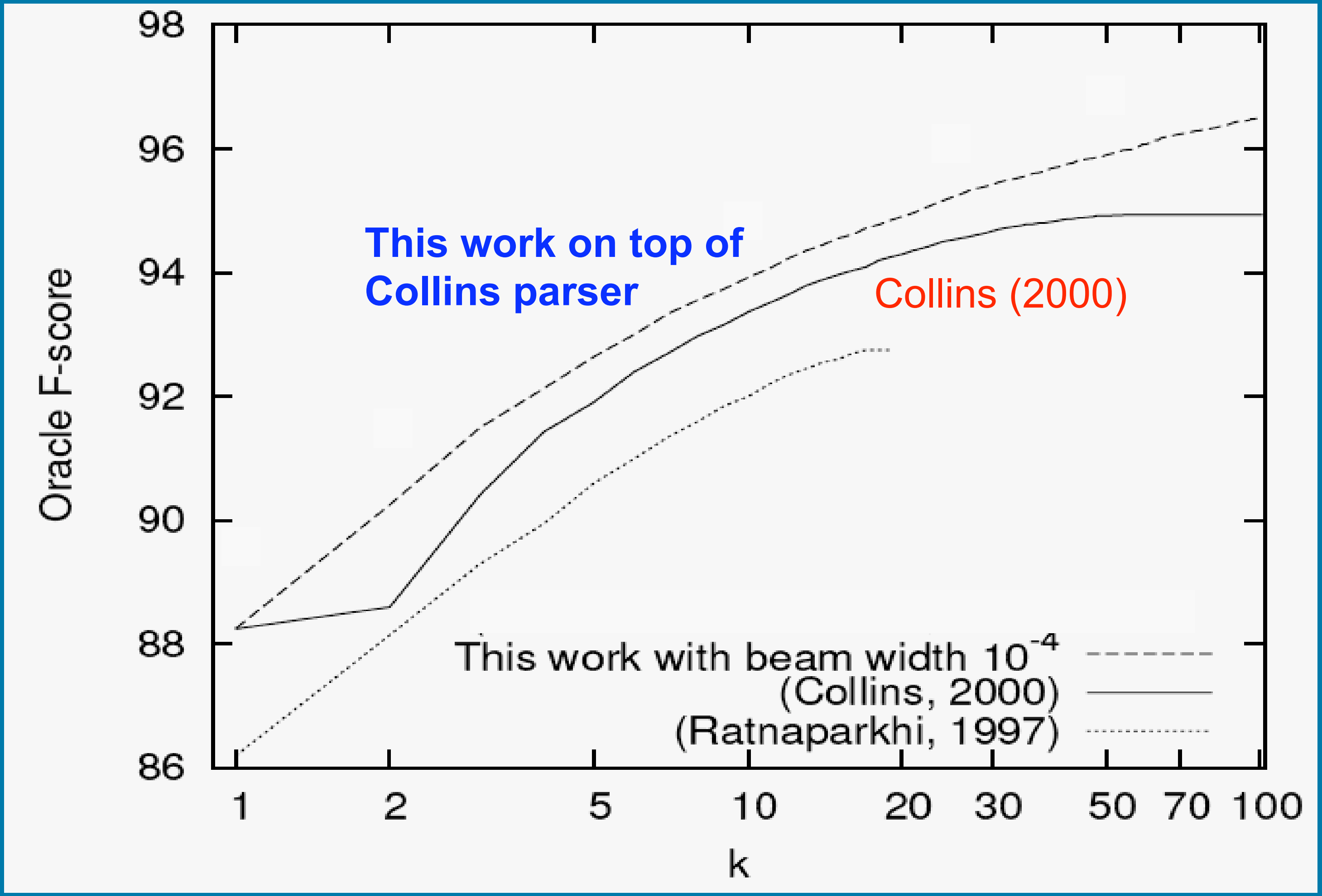


Quality of the *k*-best lists



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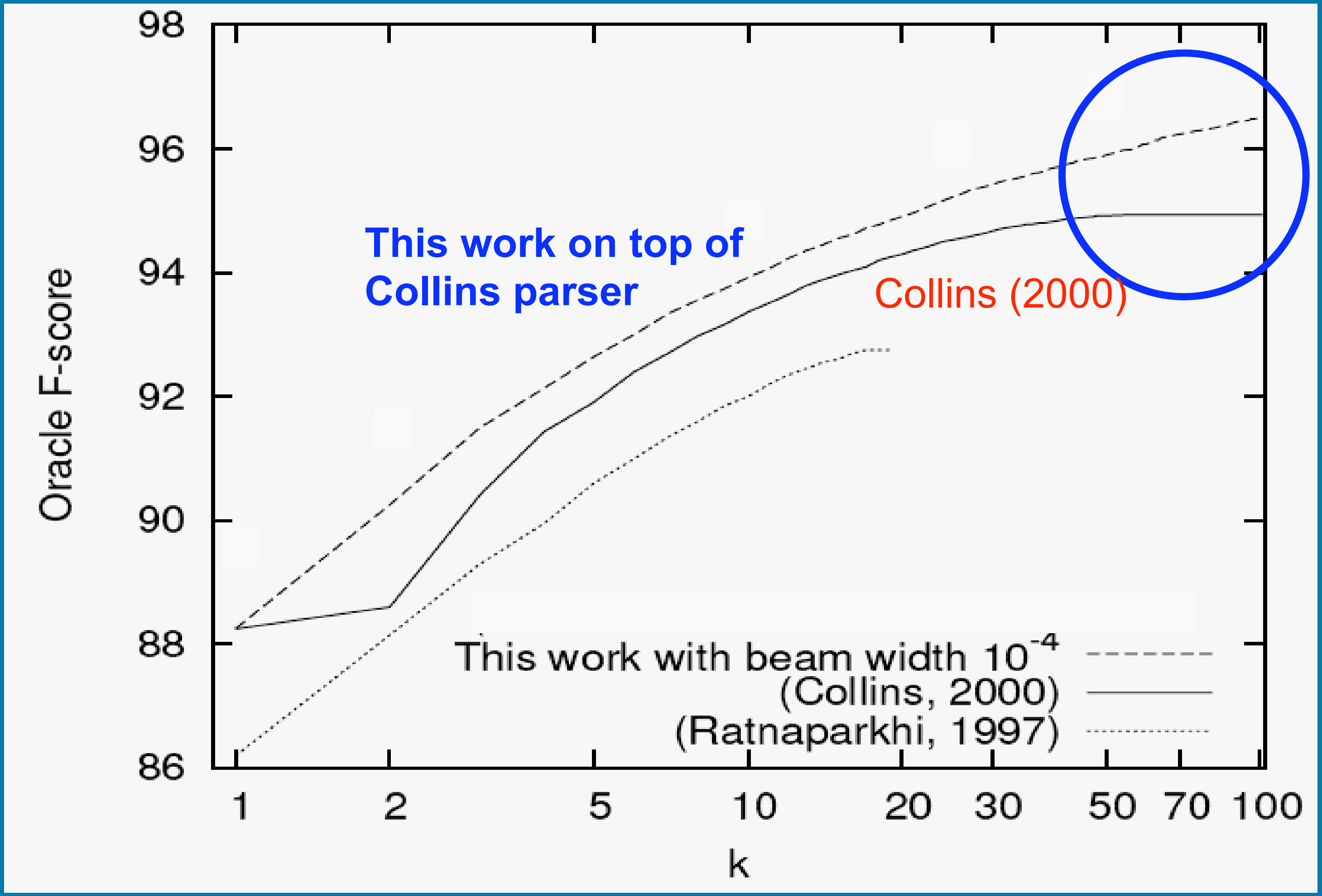
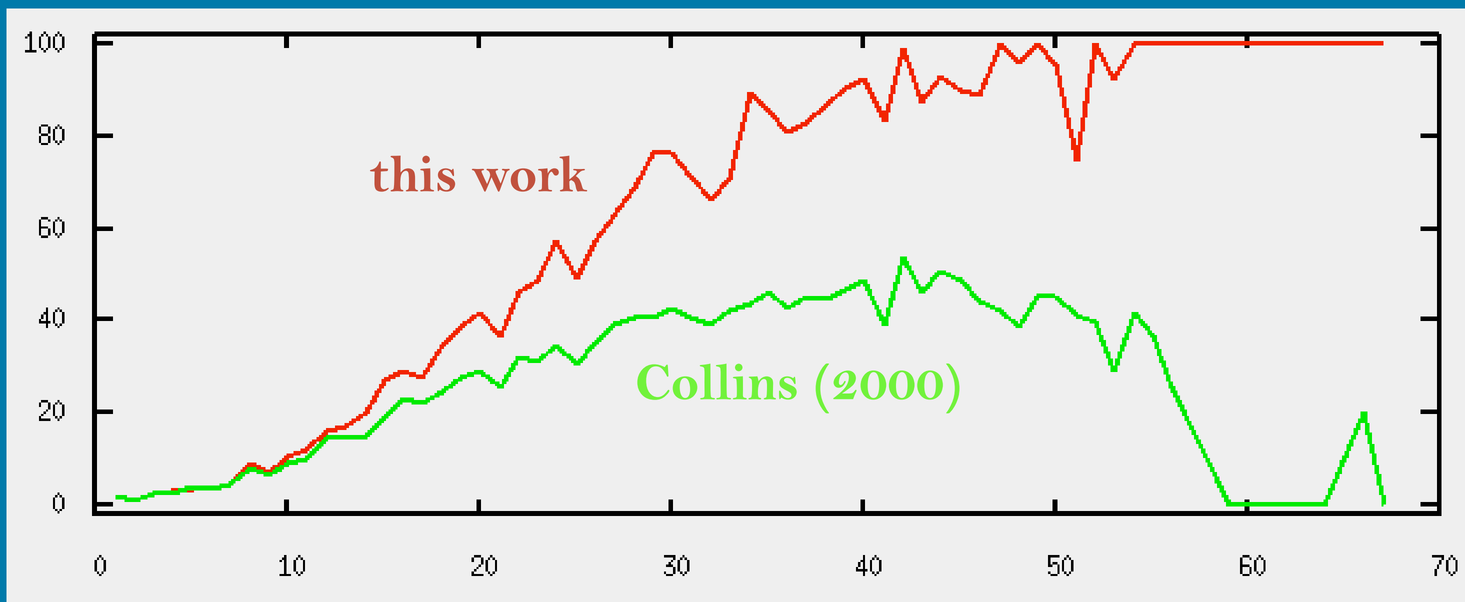


Why are our *k*-best lists better?

average number of parses for sentences of certain length

average number of parses



sentence length

Collins (2000): turn down dynamic programming

theoretically exponential time complexity;

aggressive beam pruning to make it tractable in practice

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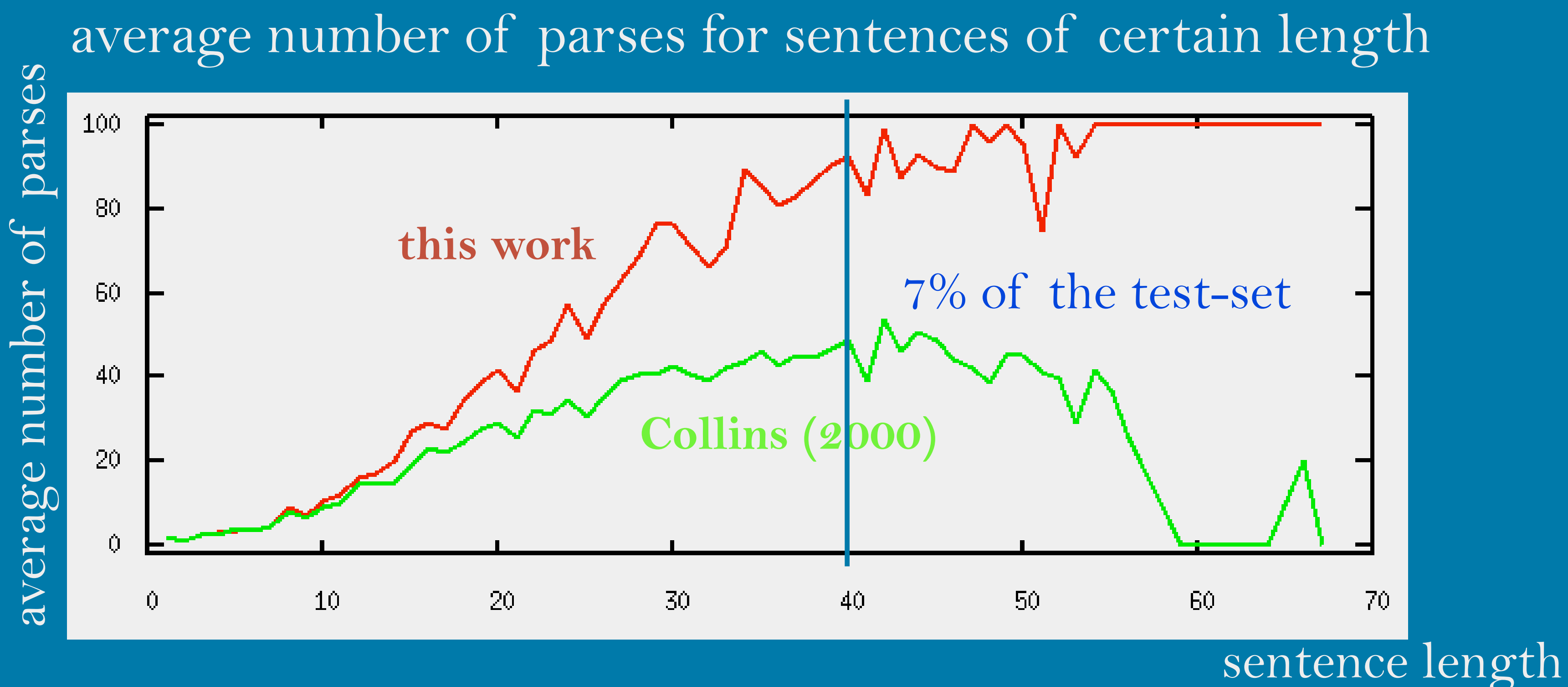

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Implemented in ...

– state-of-the-art statistical parsers
  - Charniak parser (2005); Berkeley parser (2006)
  - McDonald et al. dependency parser (2005)
  - Microsoft Research (Redmond) dependency parser (2006)

– generic dynamic programming languages/packages
  - Dyna (Eisner et al., 2005) and Tiburon (May and Knight, 2006)

– state-of-the-art syntax-based translation systems
  - Hiero (Chiang, 2005)
  - ISI syntax-based system (2005)
  - CMU syntax-based system (2006)
  - BBN syntax-based system (2007)

Applications in Machine Translation

Syntax-based Translation

- synchronous context-free grammars (SCFGs)
  - generating pairs of strings/trees simultaneously
  - co-indexed nonterminal further rewritten as a unit

$$
\begin{array}{rcll}
\mathbf{S} & \rightarrow & \mathbf{NP}^{(1)}\ \mathbf{VP}^{(2)}, & \mathbf{NP}^{(1)}\ \mathbf{VP}^{(2)} \\
\mathbf{VP} & \rightarrow & \mathbf{PP}^{(1)}\ \mathbf{VP}^{(2)}, & \mathbf{VP}^{(2)}\ \mathbf{PP}^{(1)} \\
\mathbf{NP} & \rightarrow & \textit{Baoweier}, & \text{Powell} \\
 & \ldots & &
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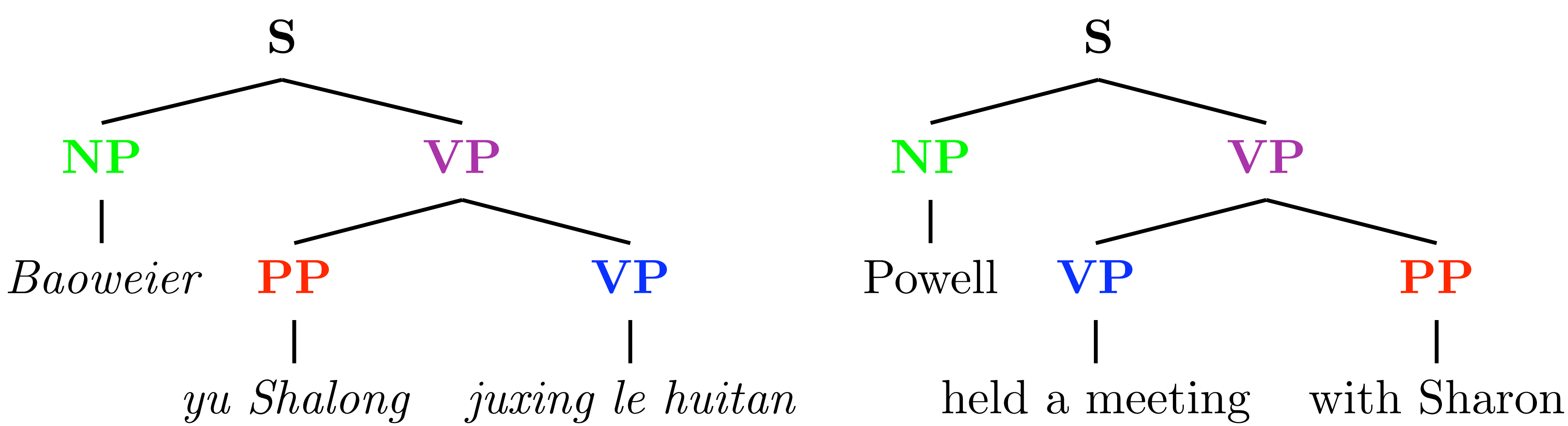

Translation as Parsing

- translation ("decoding") => monolingual parsing
- parse the source input with the source projection
  - build the corresponding target sub-strings in parallel

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Baoweier yu Shalong juxing le huitan

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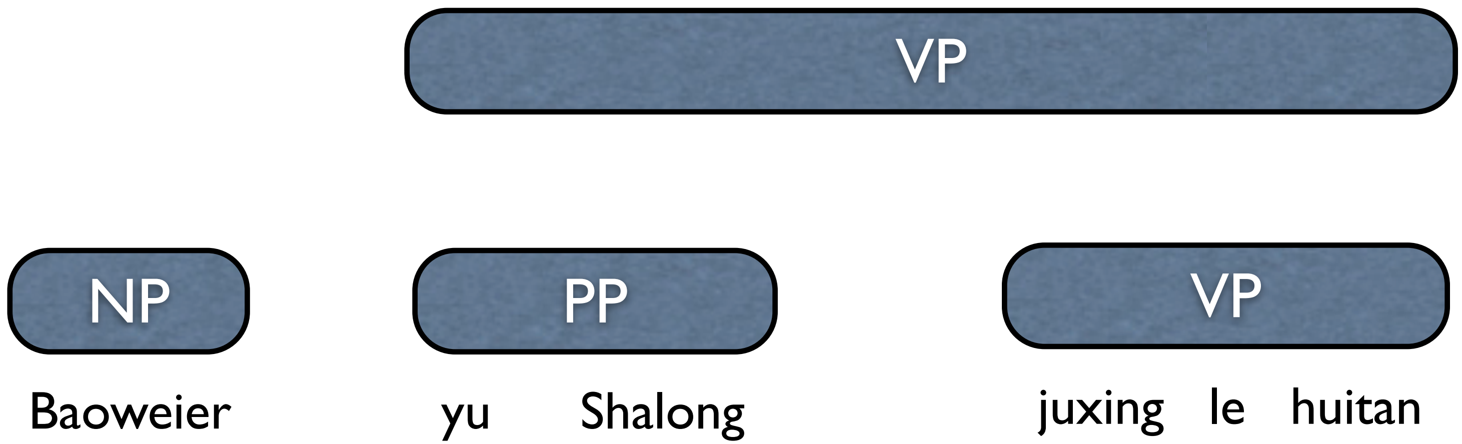

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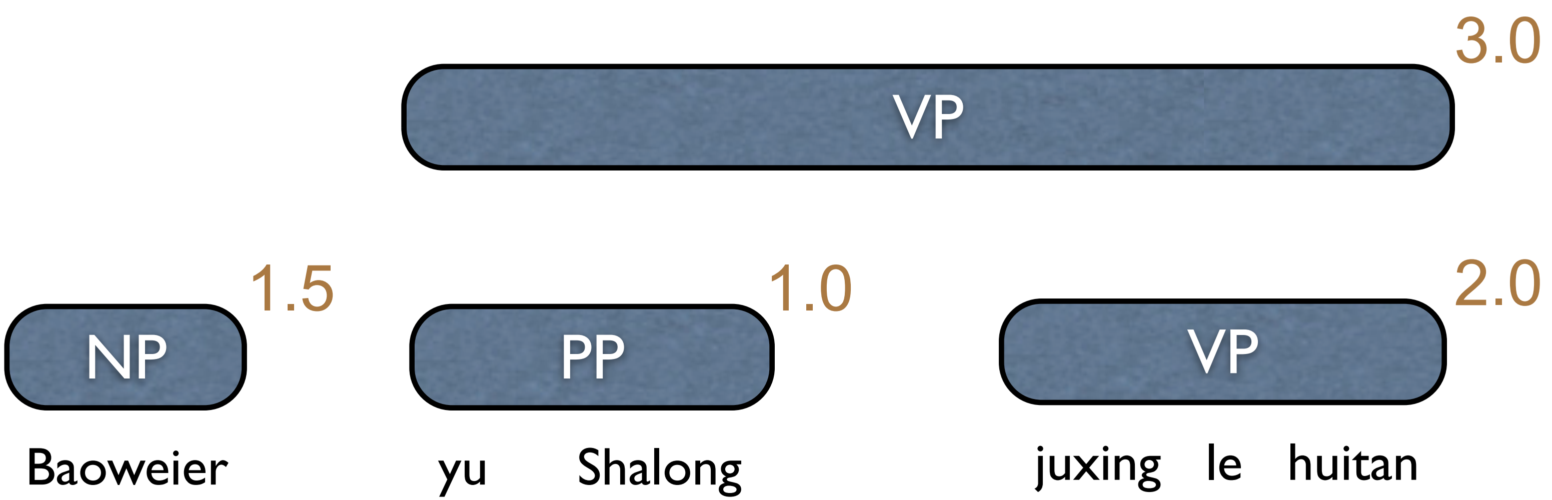

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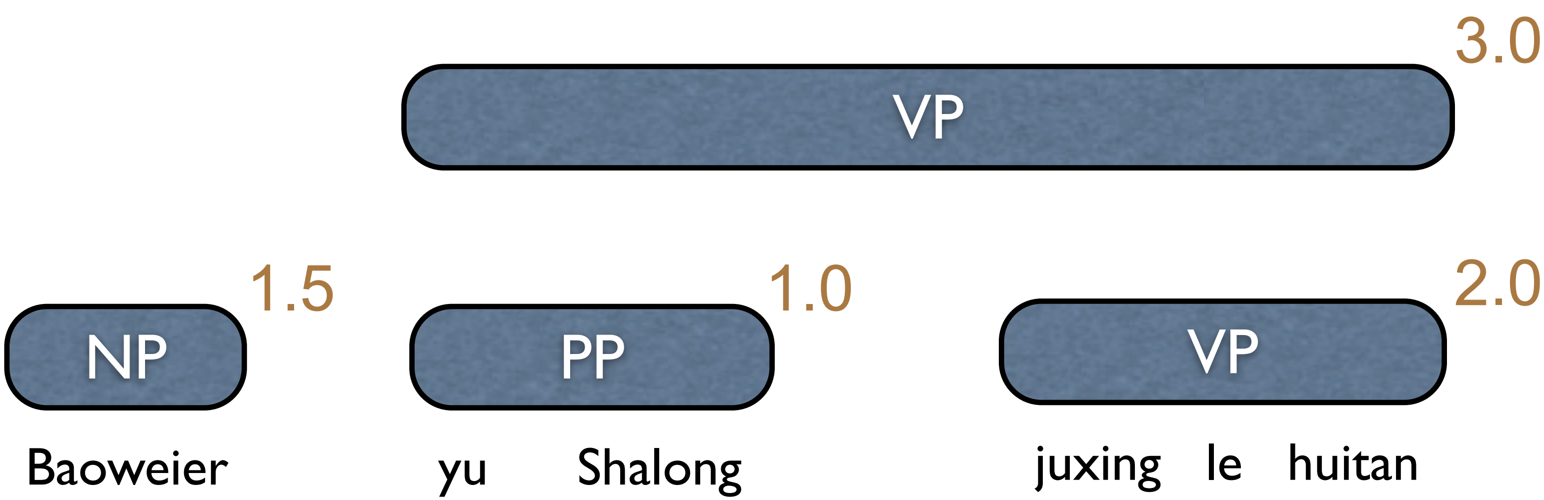

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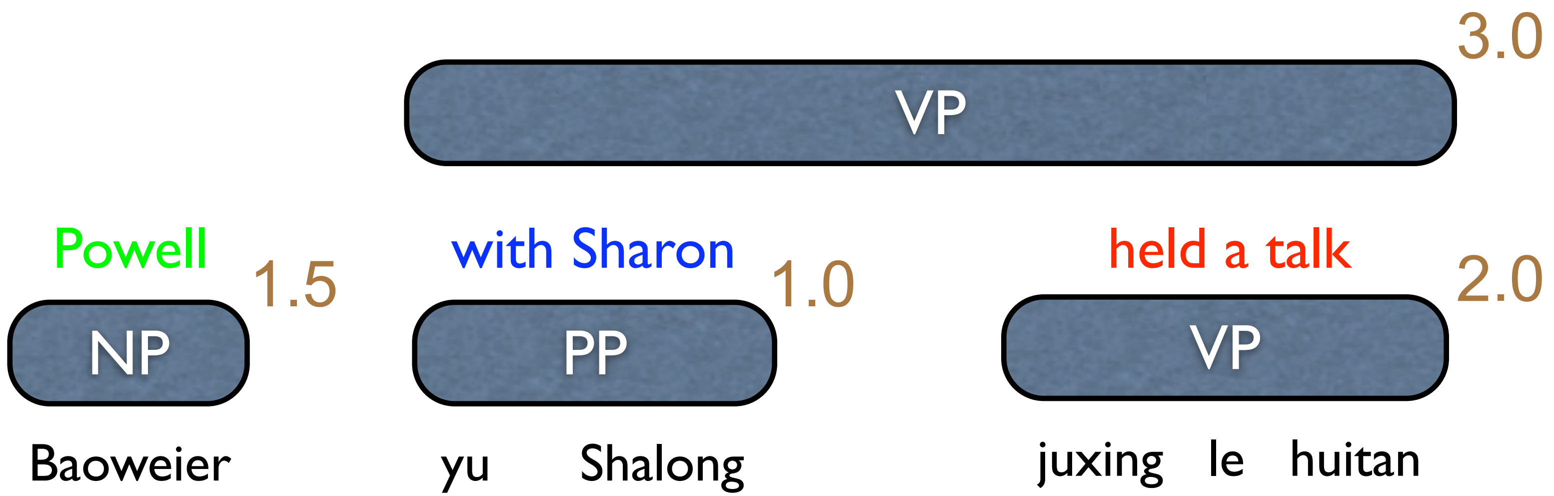

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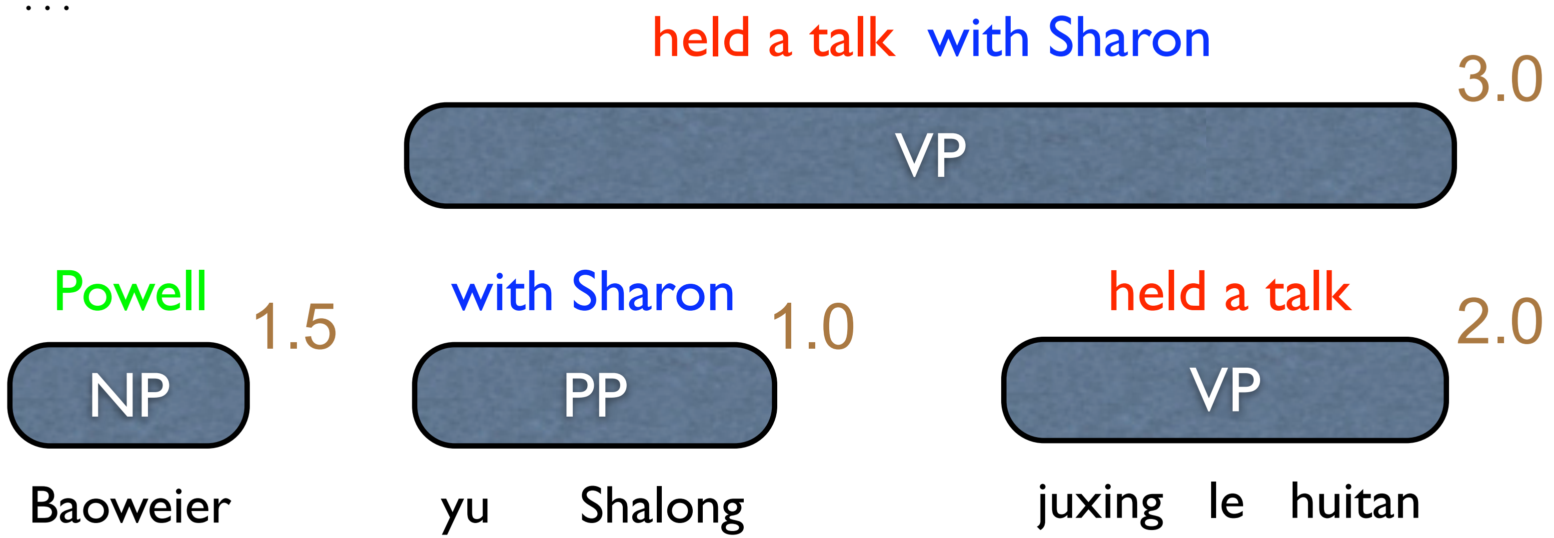
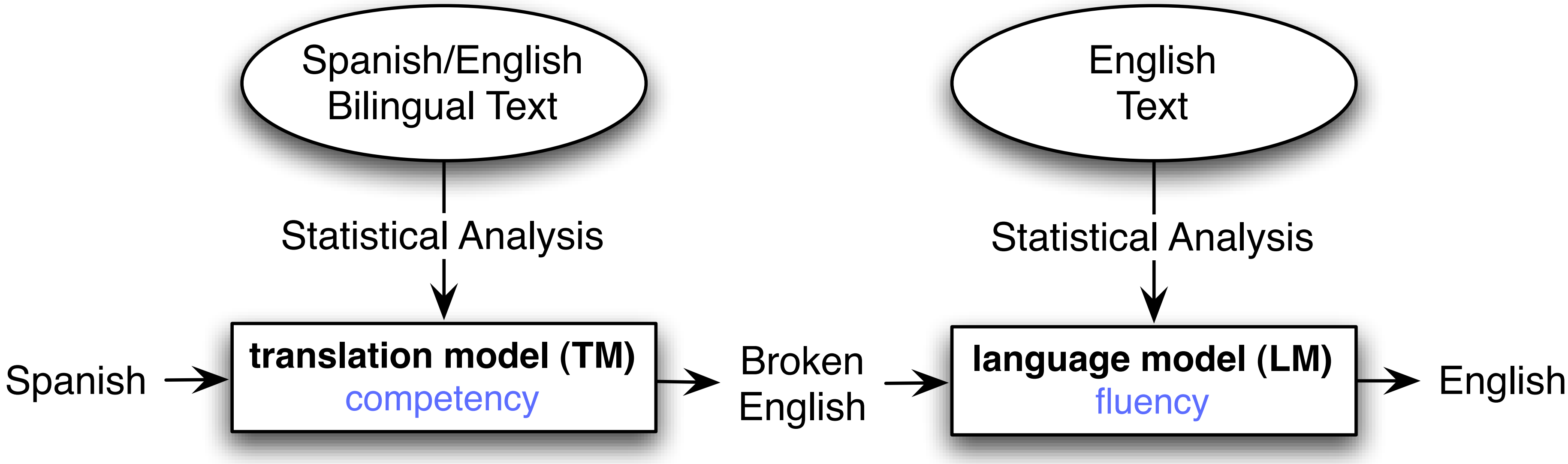


Language Model: Rescoring



Que hambre tengo yo → What hunger have I / Hungry I am so / Have I that hunger / I am so hungry / How hunger have I / ... → I am so hungry

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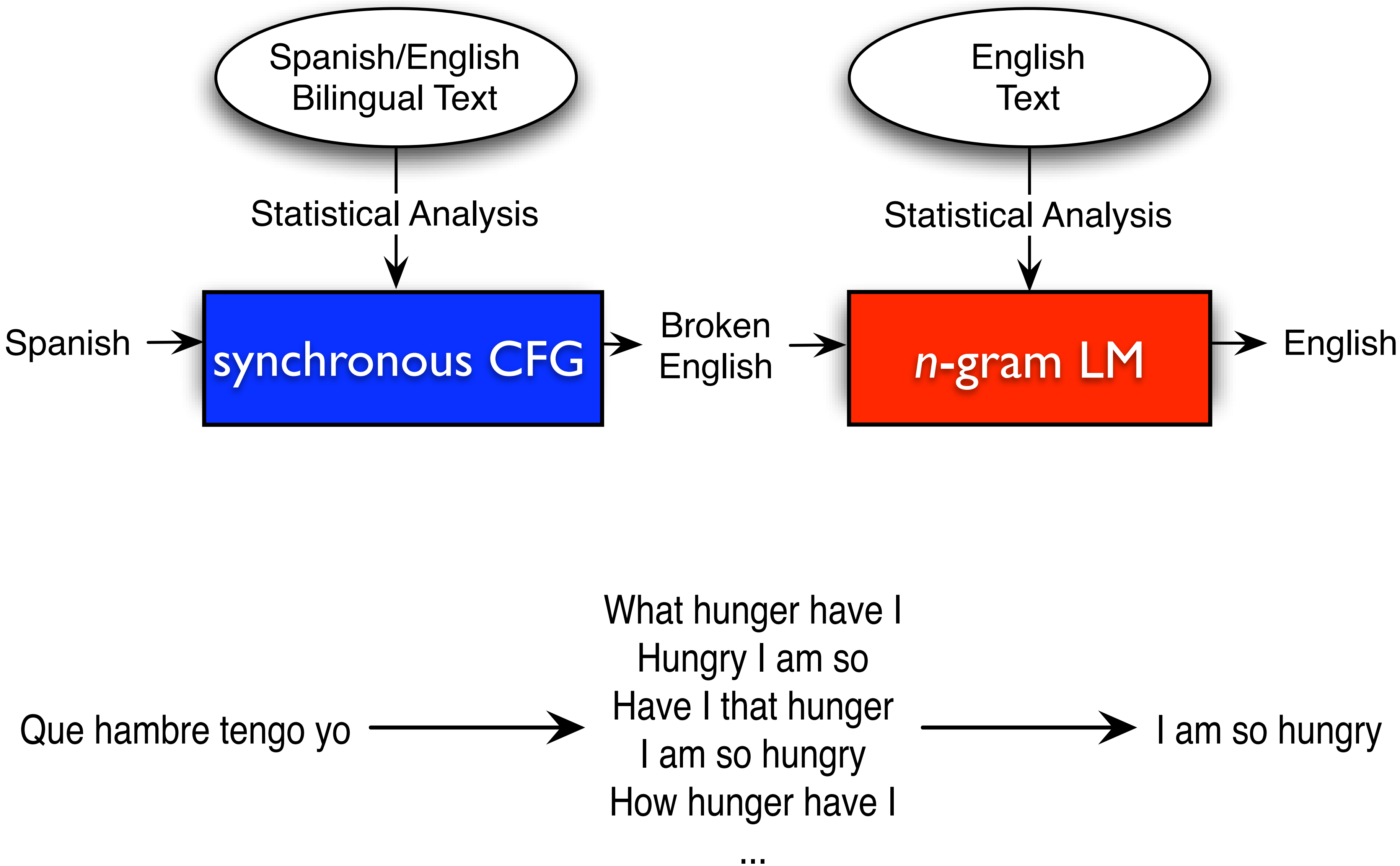

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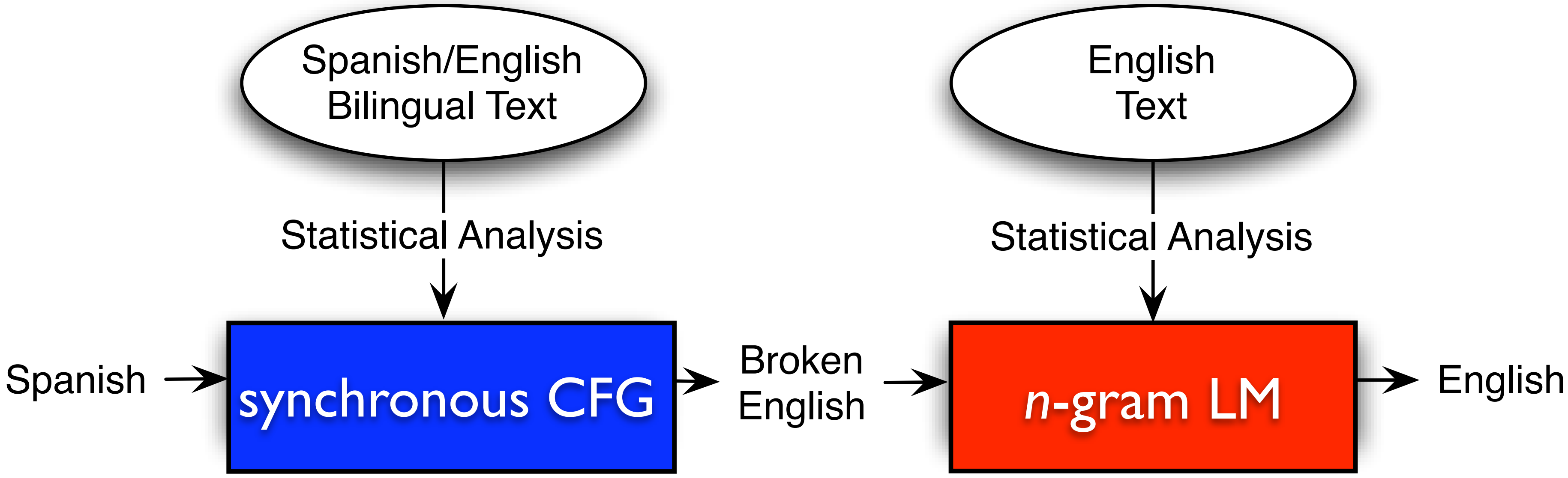
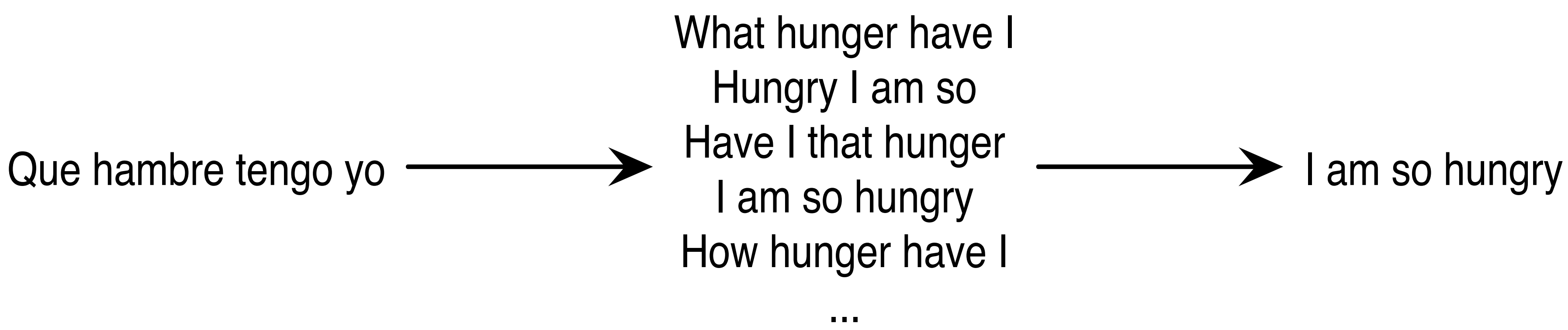


k-best rescoring



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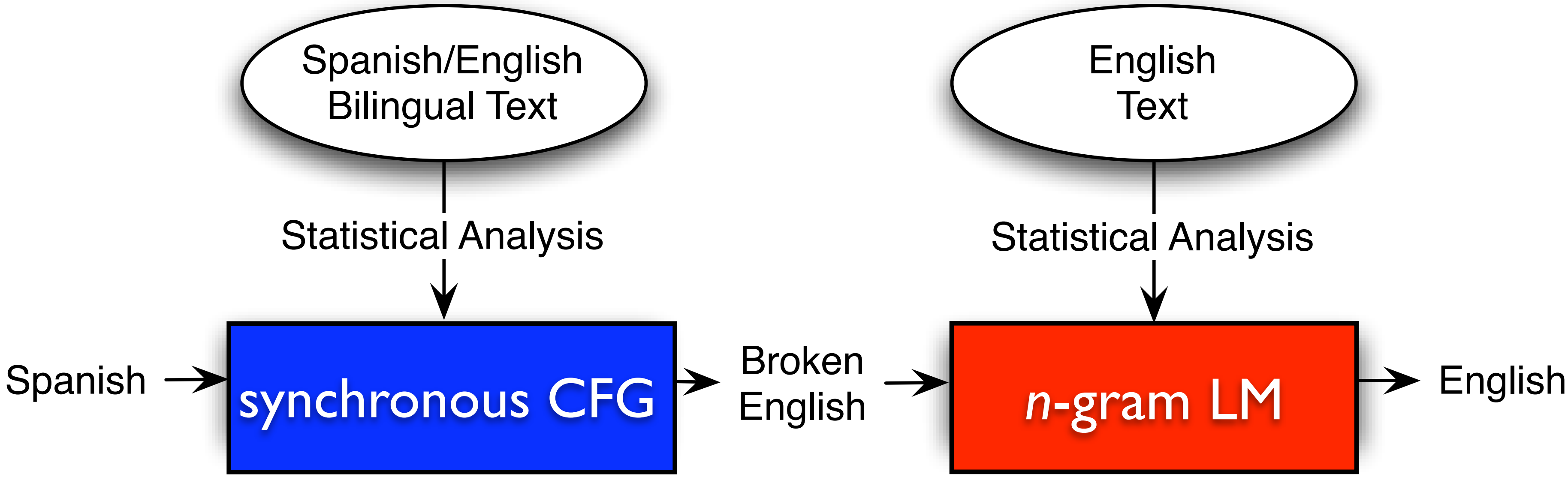

k-best rescoring

	TM			
	3.7	What hunger have I		
	3.8	Hungry I am so		
Que hambre tengo yo →	4.1	Have I that hunger	→	I am so hungry
	4.5	I am so hungry		
	7.2	How hunger have I		
		...		

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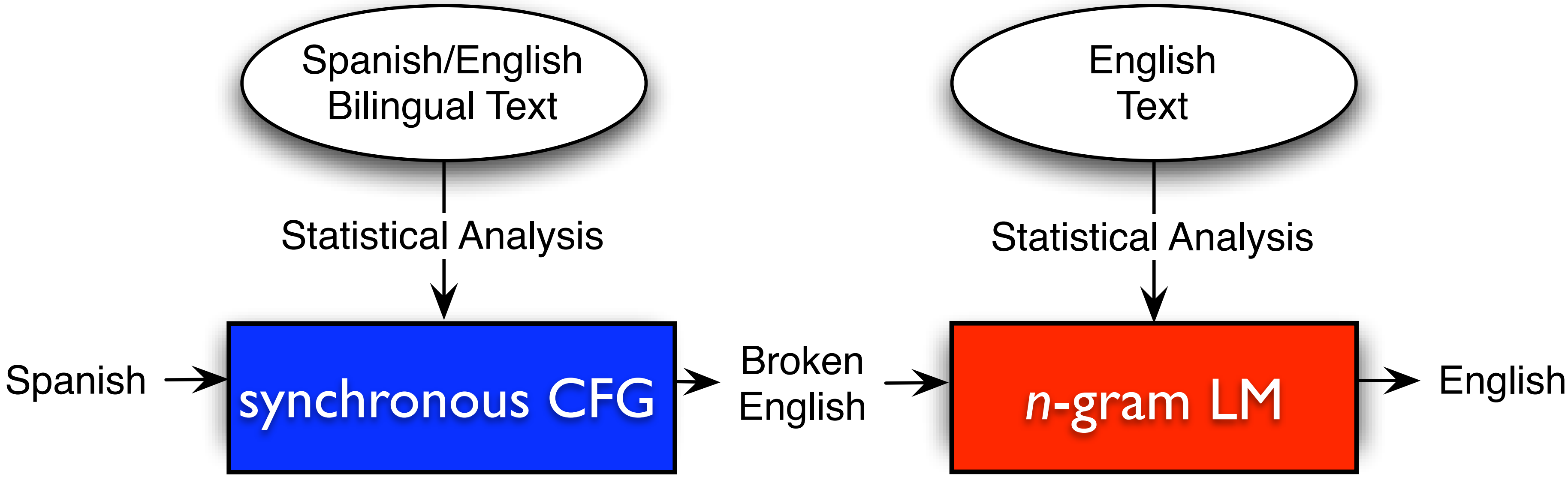


k-best rescoring

Que hambre tengo yo →

TM		LM
3.7	What hunger have I	5.4
3.8	Hungry I am so	7.0
4.1	Have I that hunger	9.8
4.5	I am so hungry	0.2
7.2	How hunger have I	8.7
	...	

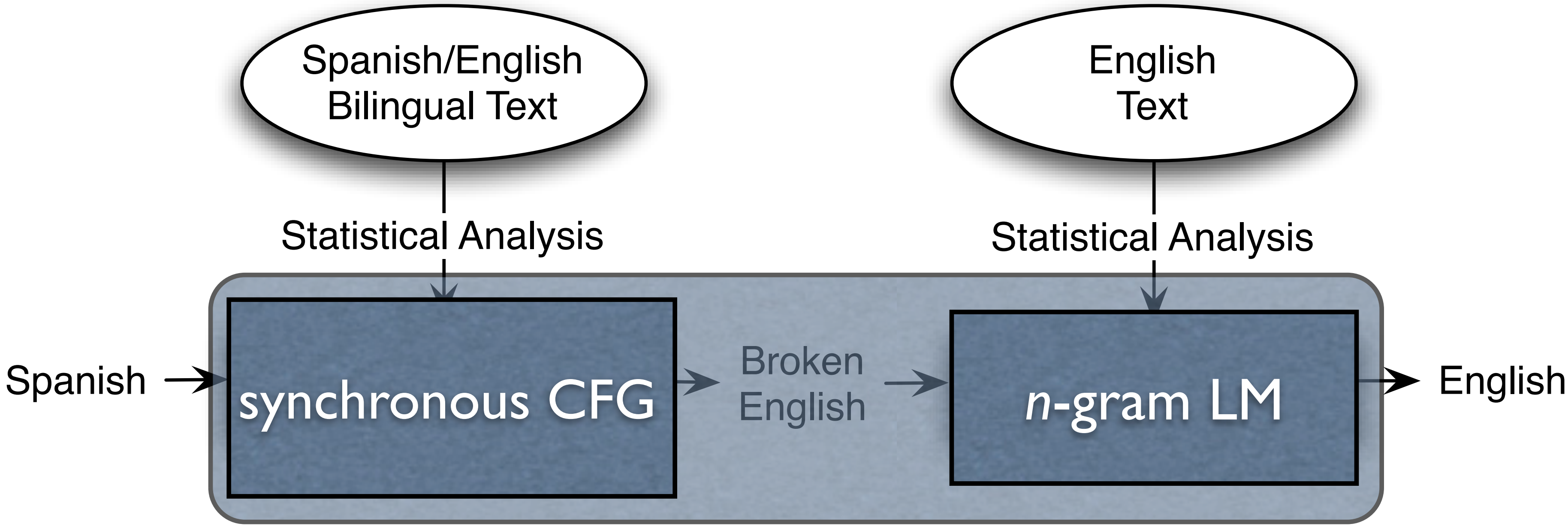
→ I am so hungry

k-best rescoring results

- The ISI syntax-based translation system
  - currently the best performing system on Chinese to English task in NIST evaluations
  - based on synchronous grammars

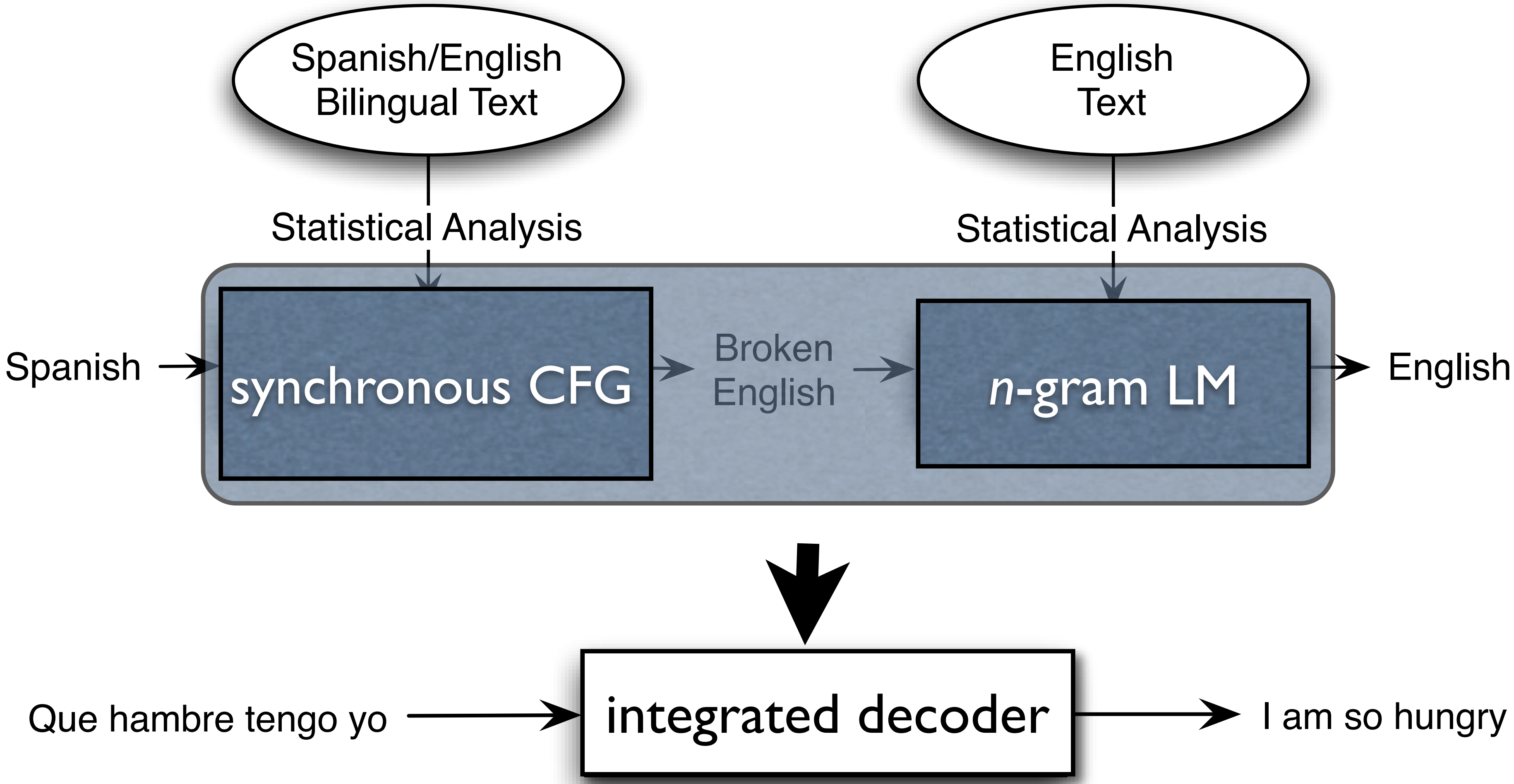
	BLEU score
translation model (TM) only:	24.45
rescoring with trigram LM on 25000-best list:	34.58

Language Model: Integration



(Knight and Koehn, 2003)

Language Model: Integration



computationally challenging! ☹

(Knight and Koehn, 2003)

Integrated Decoding Results

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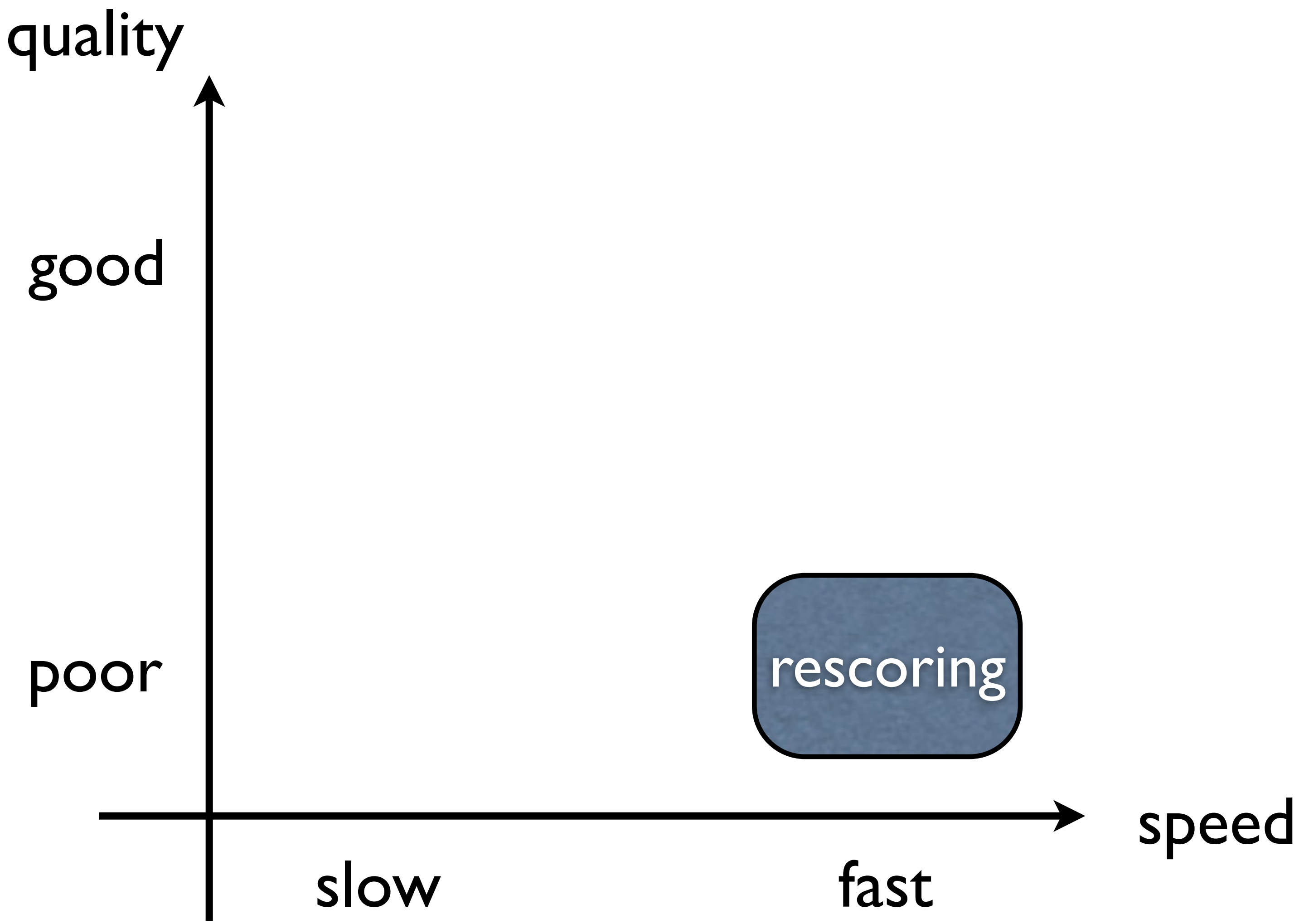
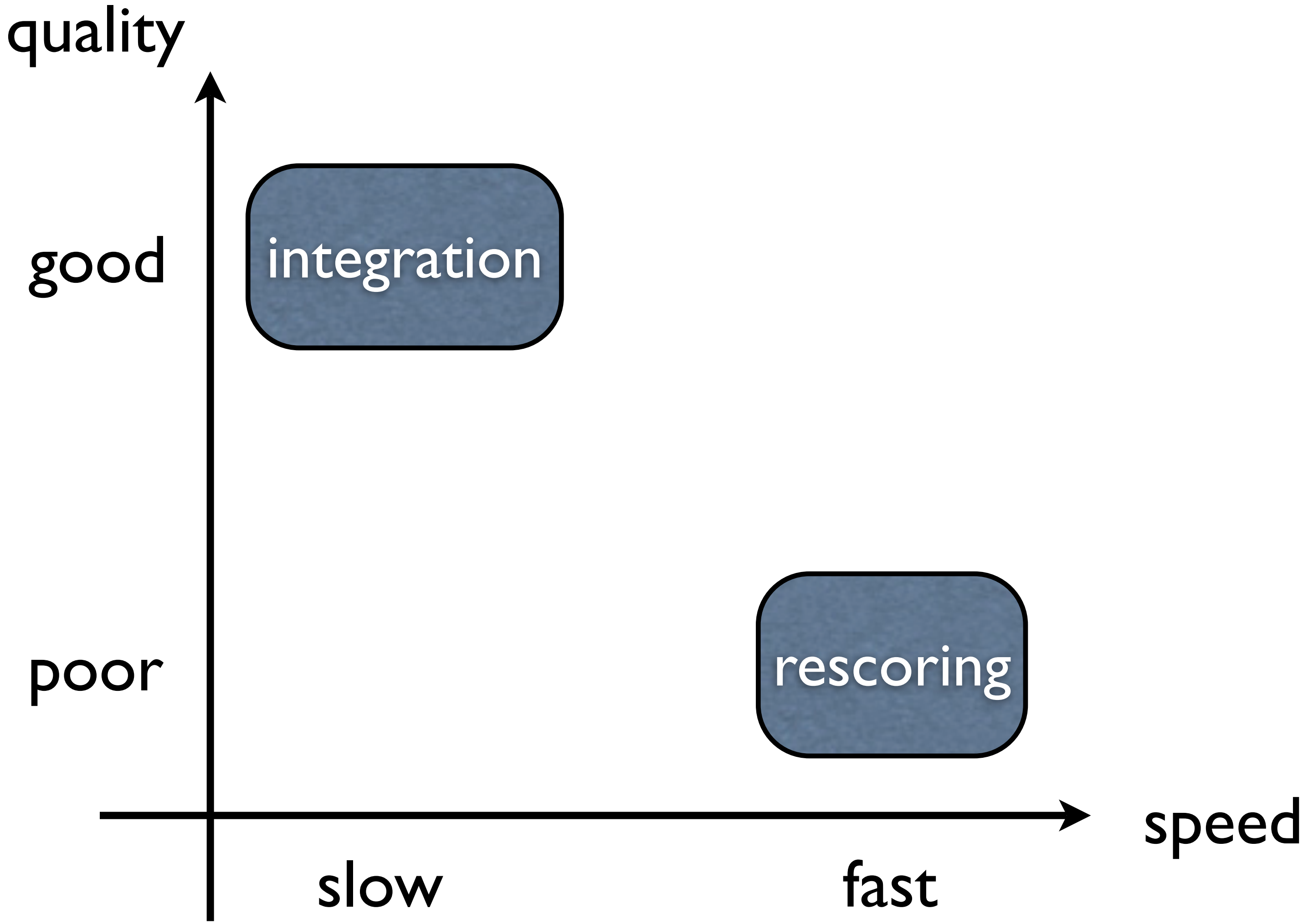
trigram integrated decoding:	38.44

but very slow!

Rescoring vs. Integration



Rescoring vs. Integration



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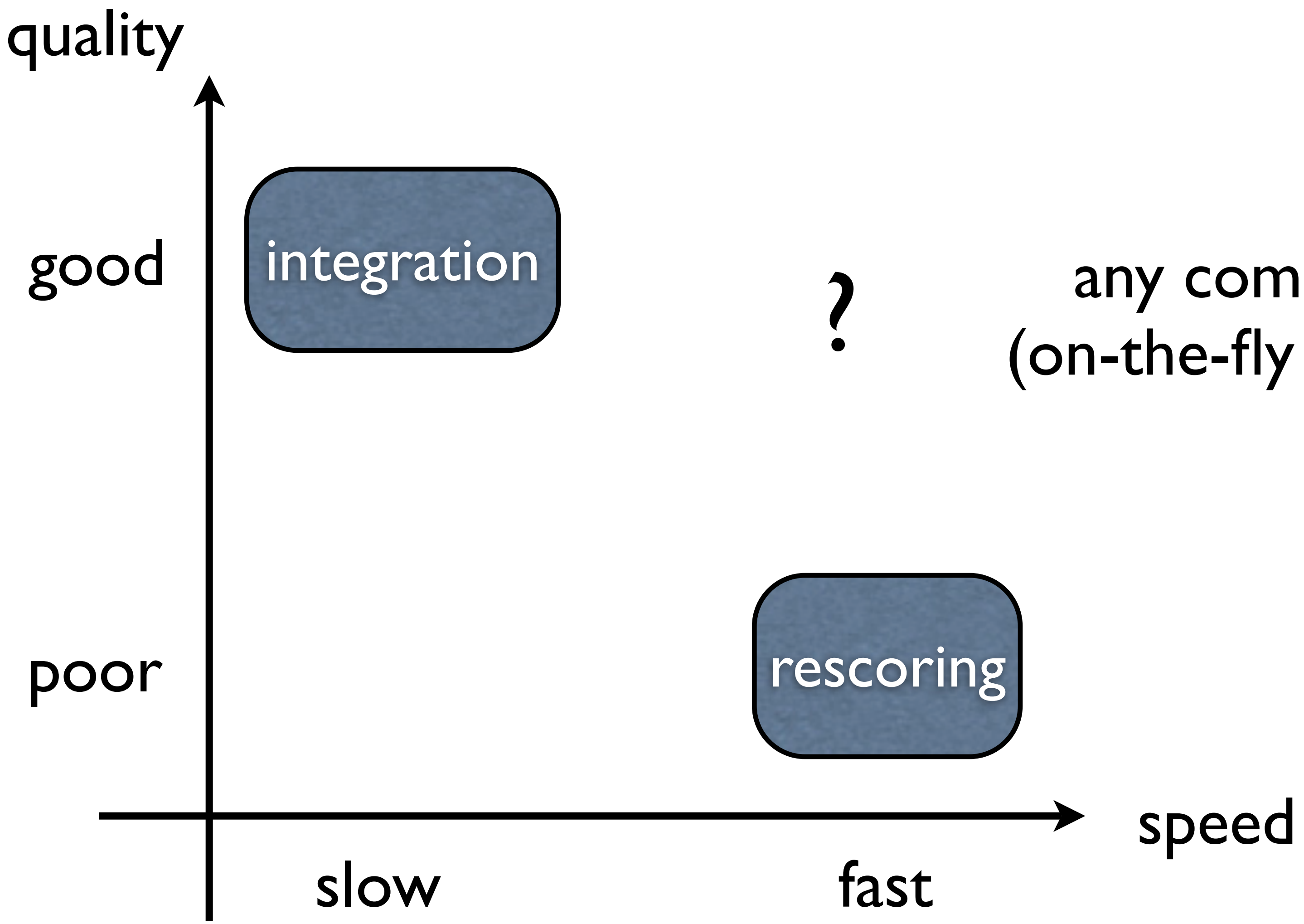
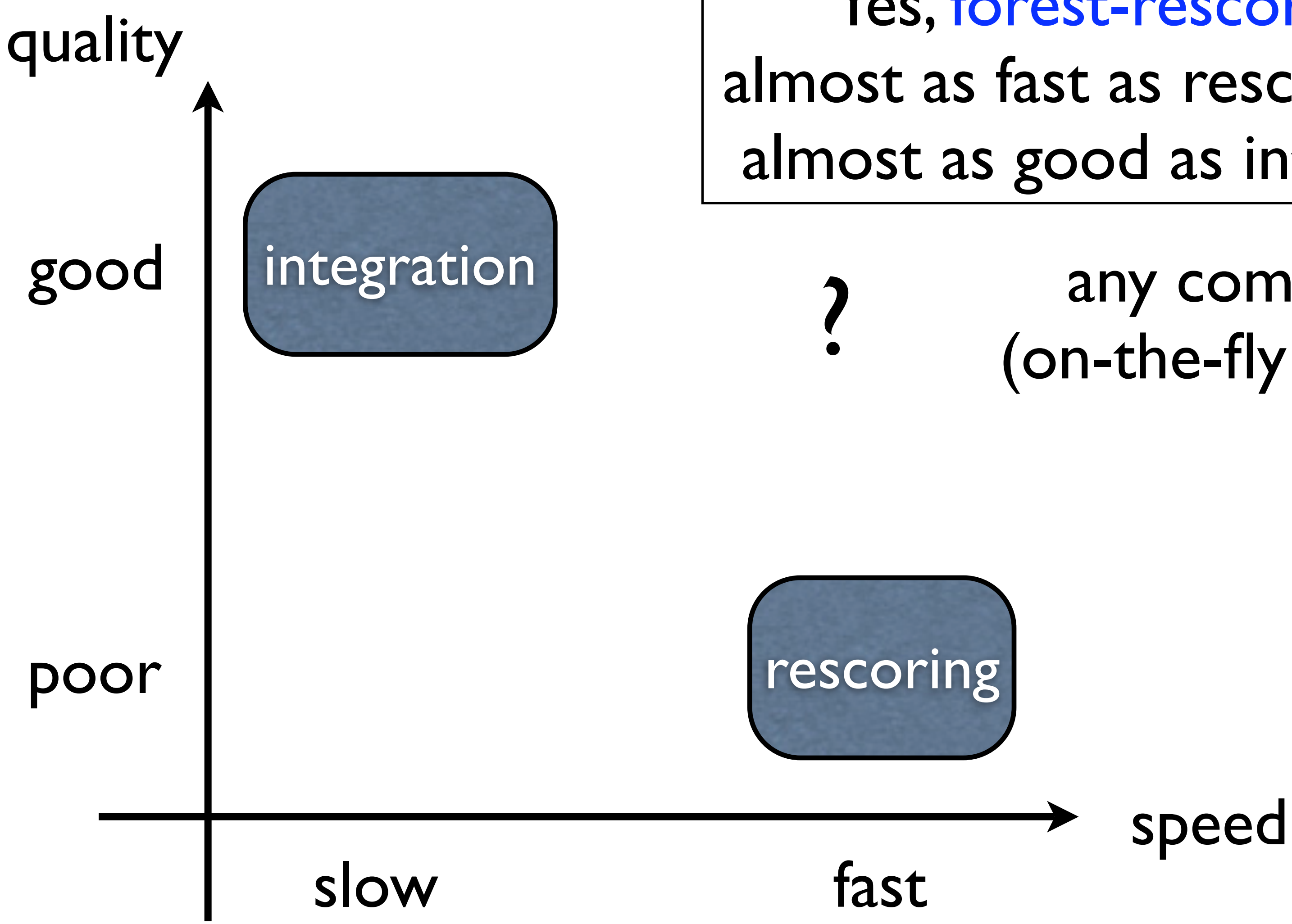


any compromise?
(on-the-fly rescoring?)

Rescoring vs. Integration

Yes, forest-rescoring --
almost as fast as rescoring, and
almost as good as integration



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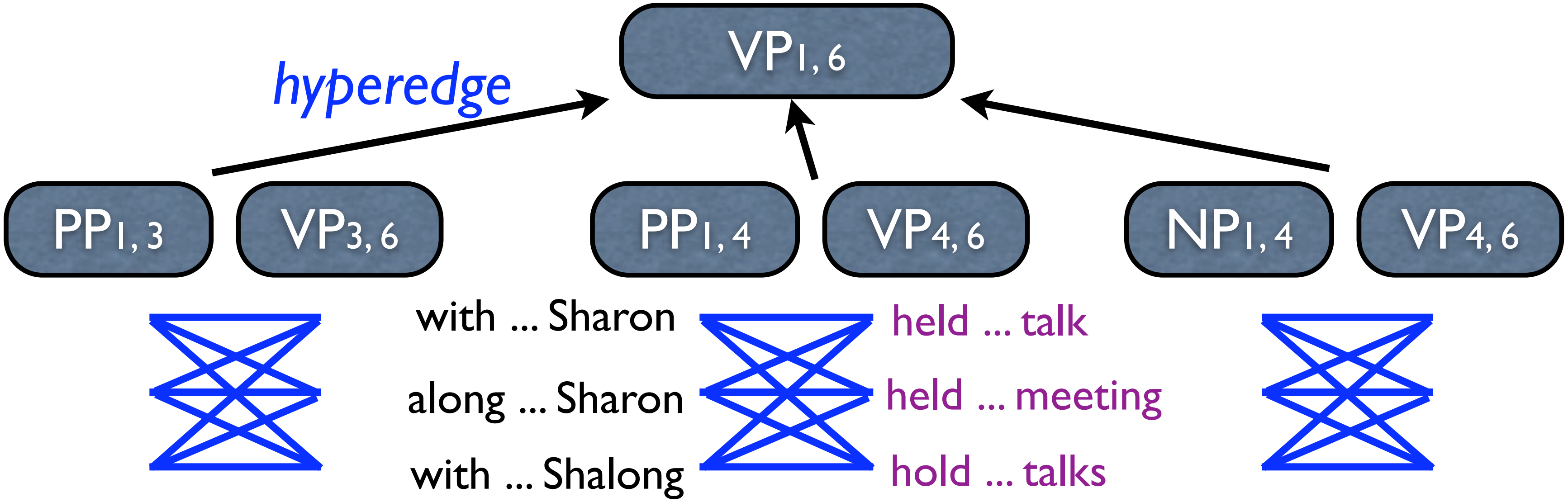
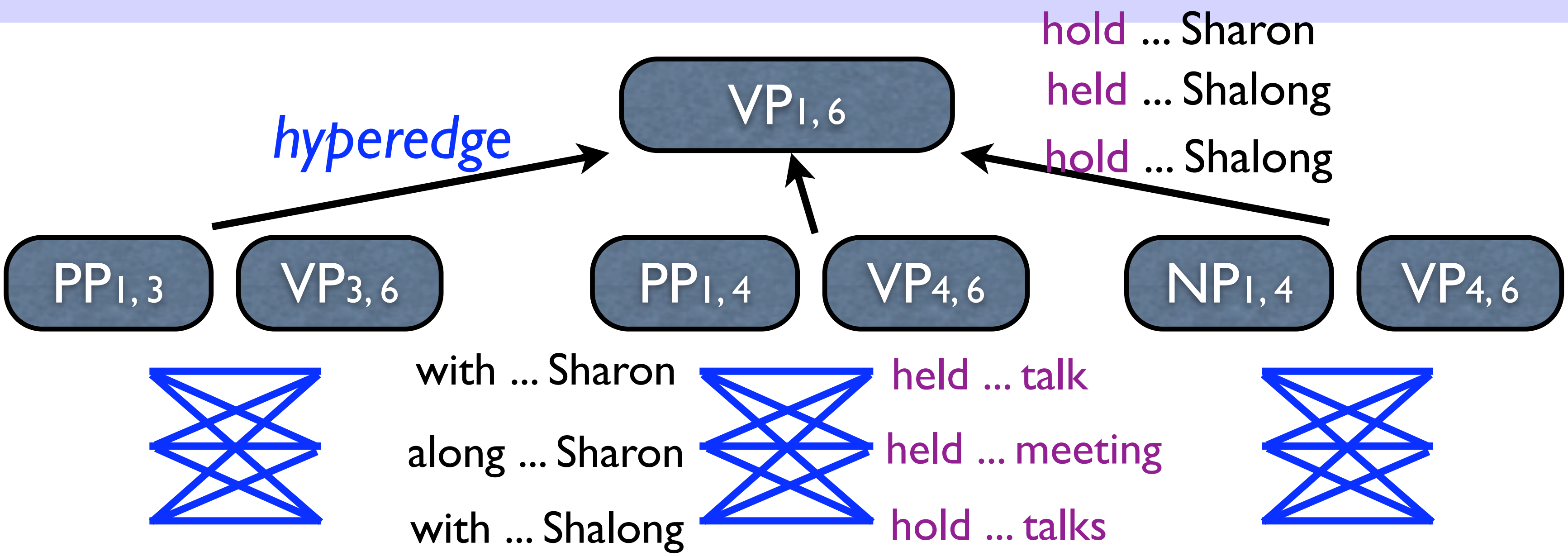
Why Integration is Slow?



- split each node into +LM items (w/ boundary words)
- beam search: only keep top-*k* +LM items at each node
- but there are many ways to derive each node
- can we avoid enumerating all combinations?

Why Integration is Slow?

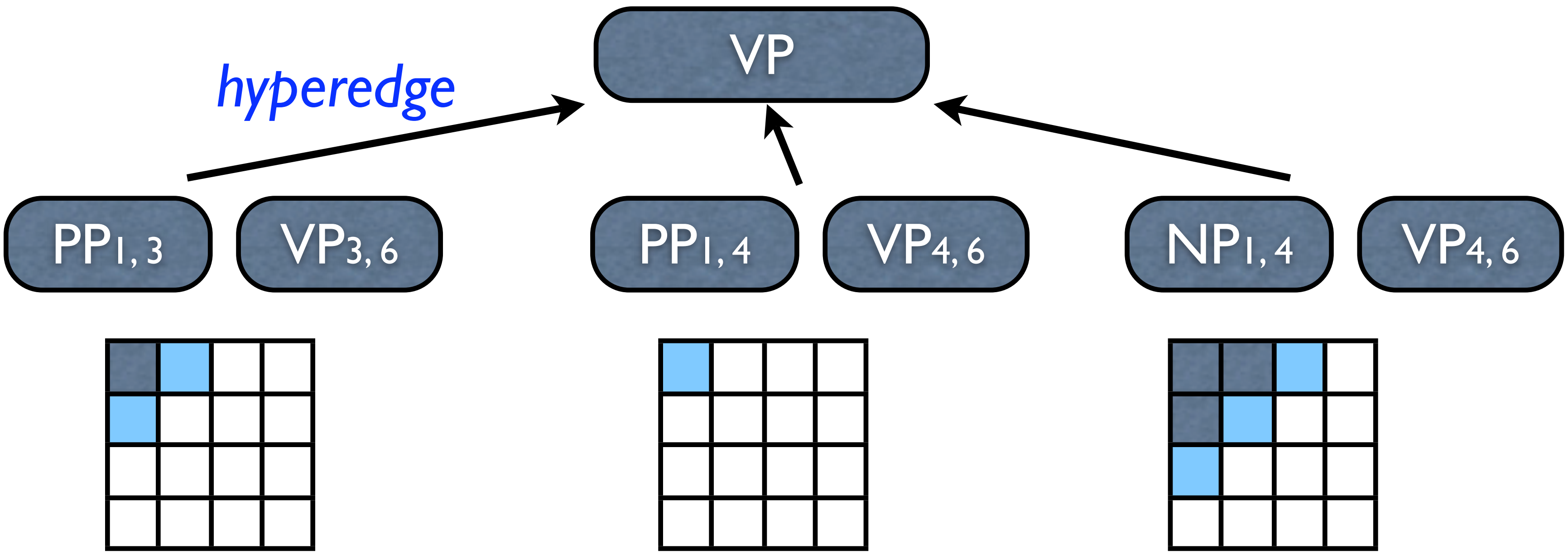


- split each node into +LM items (w/ boundary words)
- beam search: only keep top-*k* +LM items at each node
- but there are many ways to derive each node
- can we avoid enumerating all combinations?

Forest Rescoring

k-best parsing
Algorithm 2

with LM cost, we can only do *k*-best approximately.



process all hyperedges simultaneously!
significant savings of computation

Forest Rescoring Results

- on the Hiero system (Chiang, 2005)
  - ~10 fold speed-up at the same level of BLEU
- on my syntax-directed system (Huang et al., 2006)
  - ~10 fold speed-up at the same level of search-error
- on a typical phrase-based system (Pharaoh)
  - ~30 fold speed-up at the same level of search-error
  - ~100 fold speed-up at the same level of BLEU
- also used in
  - ISI, CMU, and BBN syntax-based systems

see my ACL '07 paper for details

Conclusions

- monotonic hypergraph formulation
  - the *k*-best derivations problem
- *k*-best Algorithms
  - Algorithm 0 (naïve) to Algorithm 3 (lazy)
- experimental results
  - efficiency
  - accuracy (effectively searching over larger space)
- applications in machine translation
  - *k*-best rescoring and forest rescoring

Thank you!
谢谢!

Questions?
Comments?

Thank you!
谢谢!

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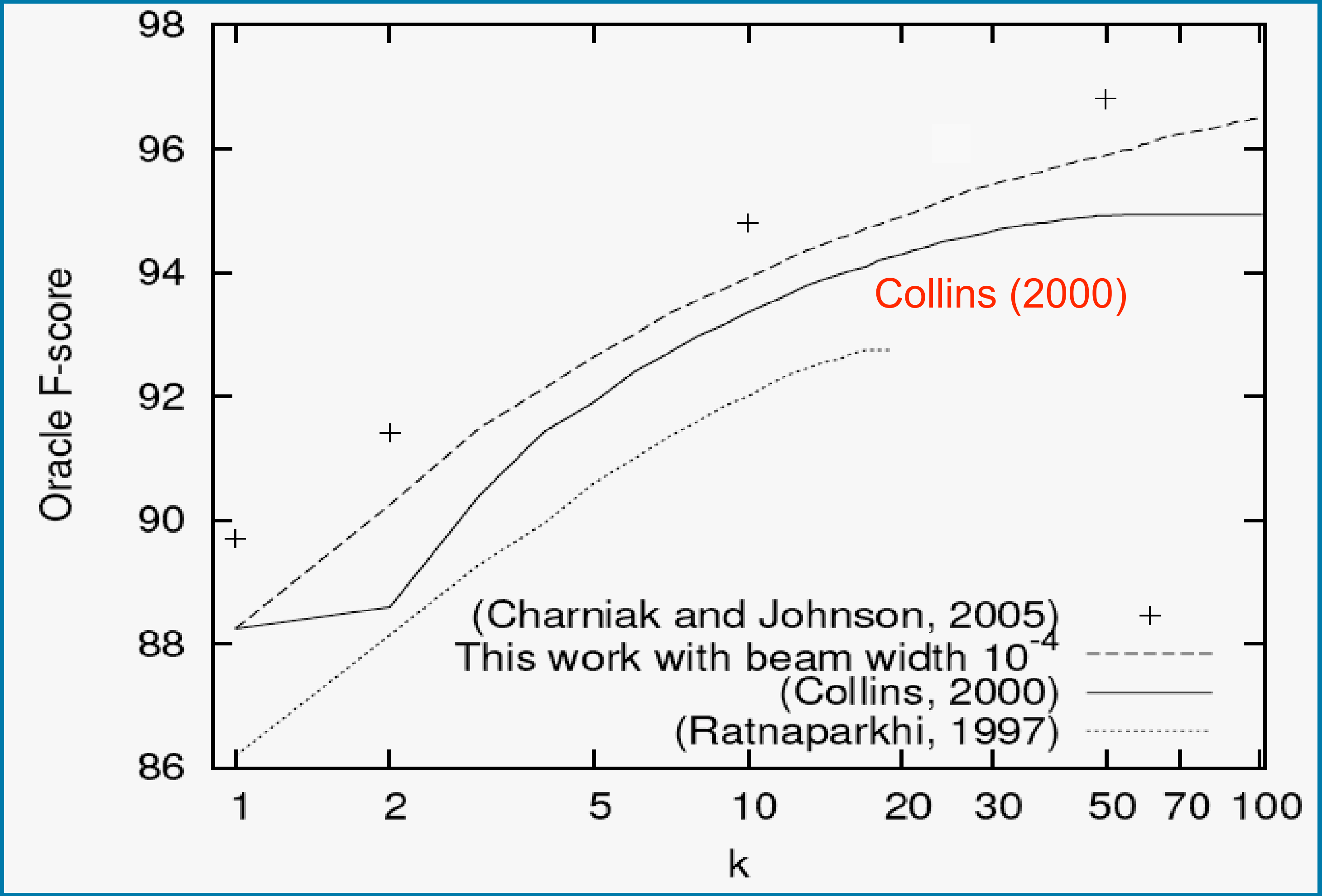
Thank you!
谢谢!

Questions?
Comments?

- Liang Huang and David Chiang (2005).
  Better k-best Parsing.
  In Proceedings of IWPT, Vancouver, B.C.
- Liang Huang and David Chiang (2007).
  Forest Rescoring: Faster Decoding with Integrated Language Models.
  In Proceedings of ACL, Prague, Czech Rep.

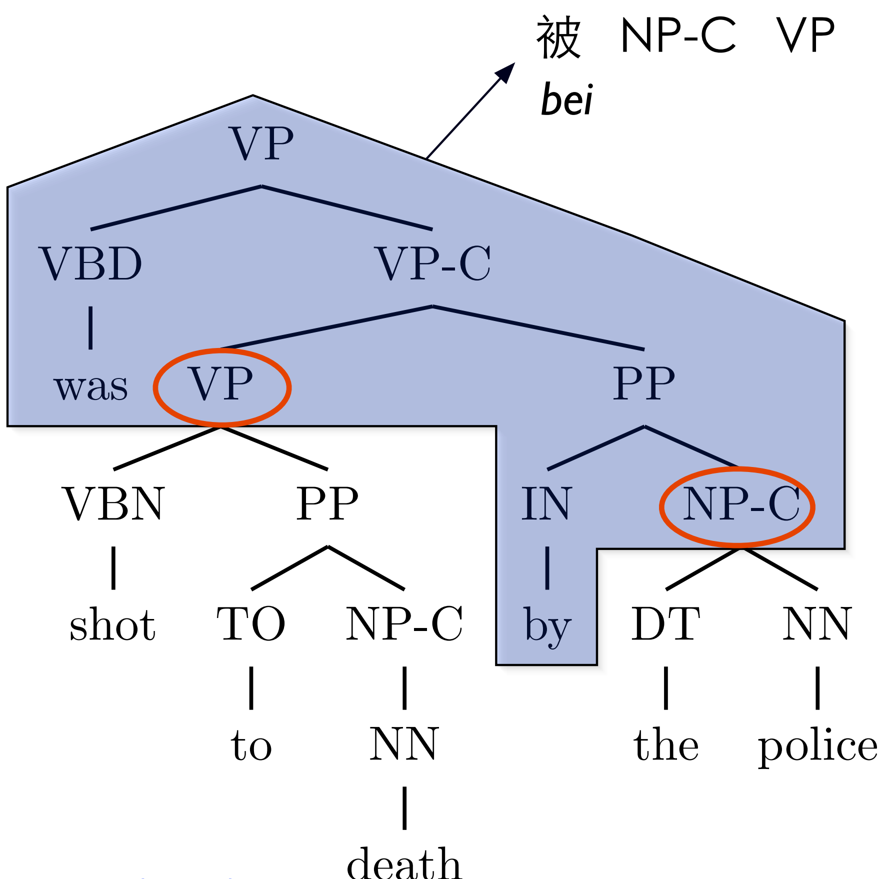
Quality of the *k*-best lists



Syntax-based Experiments

Tree-to-String System

- syntax-directed, English to Chinese (Huang, Knight, Joshi, 2006)
- the reverse direction is found in (Liu et al., 2006)



synchronous tree-substitution grammars (STSG)

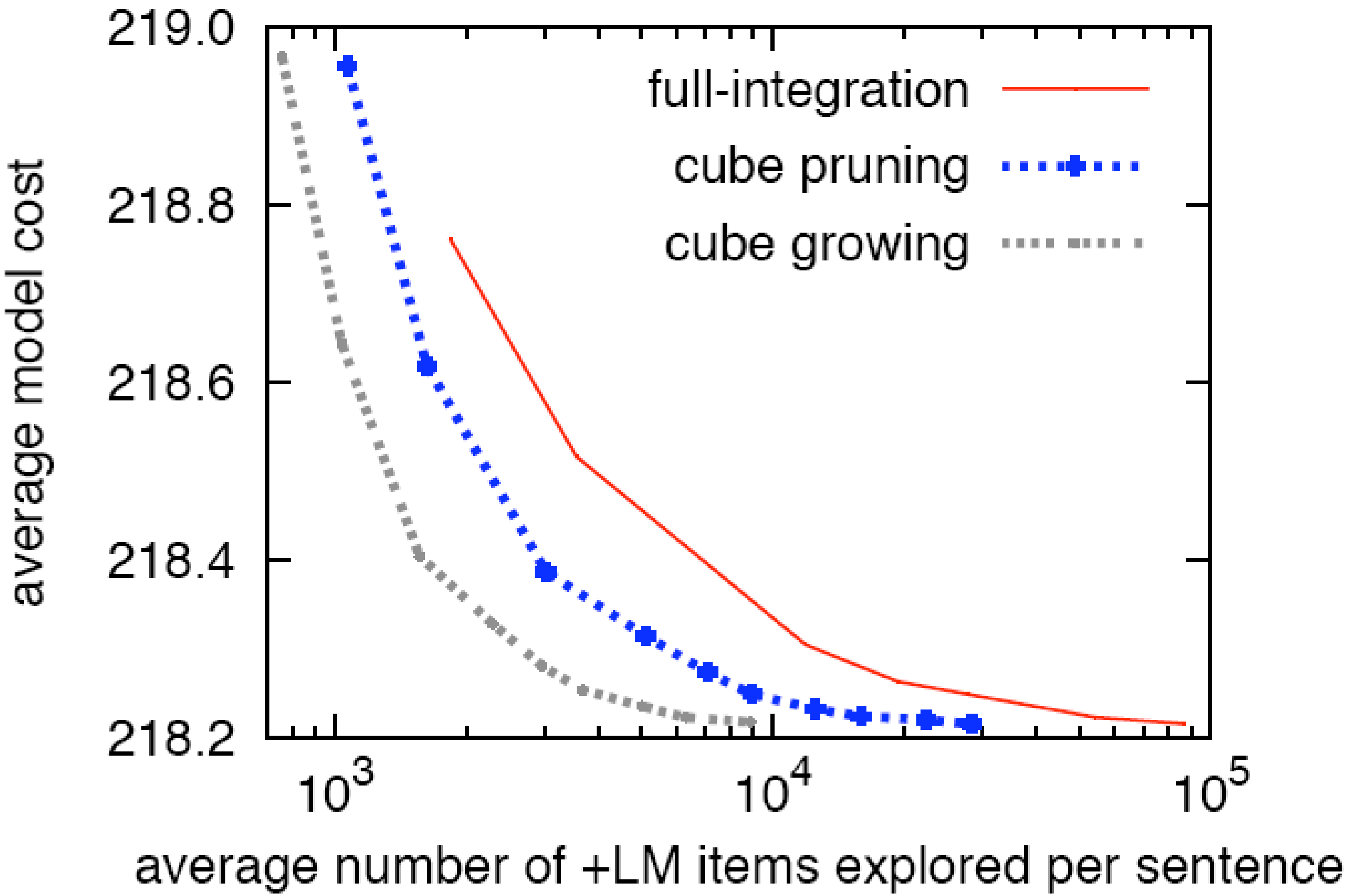
(Galley et al., 2004; Eisner, 2003)

related to

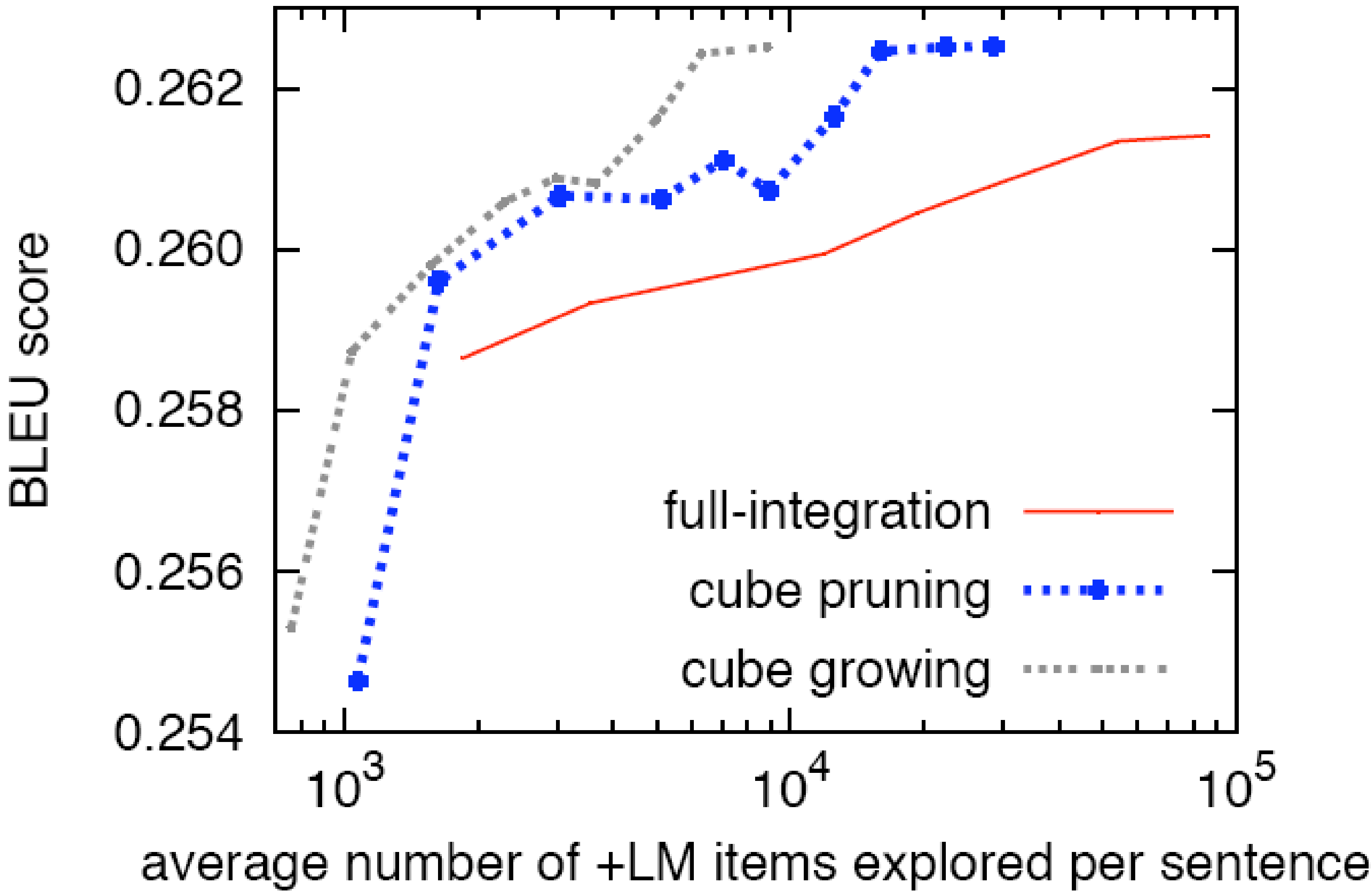
STAG (Shieber/Schabes, 90)

tested on 140 sentences
slightly better BLEU scores than Pharaoh

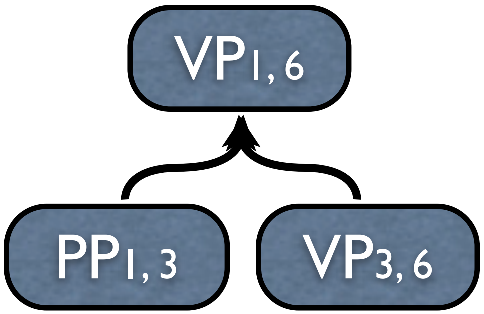
Speed vs. Search Quality



Speed vs. Translation Accuracy



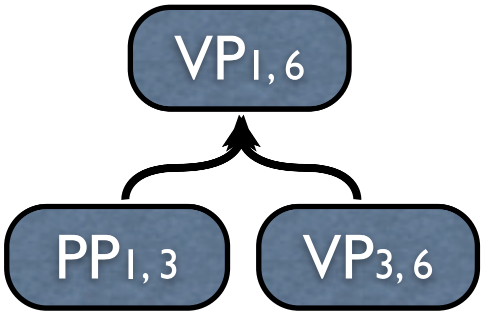
Cube Pruning



monotonic grid?

	$(\mathrm{PP}^{\text{with} \star \text{Sharon}}_{1,3})$	$(\mathrm{PP}^{\text{along} \star \text{Sharon}}_{1,3})$	$(\mathrm{PP}^{\text{with} \star \text{Shalong}}_{1,3})$
	1.0	3.0	8.0
$(\mathrm{VP}^{\text{held} \star \text{meeting}}_{3,6})$ 1.0	2.0	4.0	9.0
$(\mathrm{VP}^{\text{held} \star \text{talk}}_{3,6})$ 1.1	2.1	4.1	9.1
$(\mathrm{VP}^{\text{hold} \star \text{conference}}_{3,6})$ 3.5	4.5	6.5	11.5

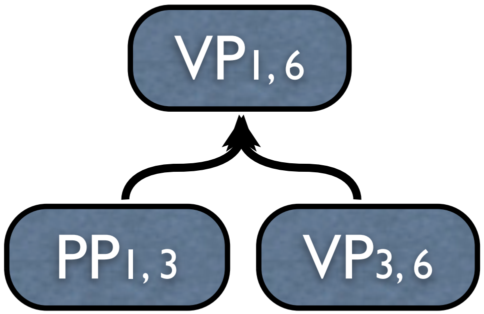
Cube Pruning



non-monotonic grid due to LM combo costs

		$(PP_{1,3}^{\text{with} \star \text{Sharon}})$	$(PP_{1,3}^{\text{along} \star \text{Sharon}})$	$(PP_{1,3}^{\text{with} \star \text{Shalong}})$
		1.0	3.0	8.0
$(VP_{3,6}^{\text{held} \star \text{meeting}})$	1.0	2.0 + 0.5	4.0 + 5.0	9.0 + 0.5
$(VP_{3,6}^{\text{held} \star \text{talk}})$	1.1	2.1 + 0.3	4.1 + 5.4	9.1 + 0.3
$(VP_{3,6}^{\text{hold} \star \text{conference}})$	3.5	4.5 + 0.6	6.5 + 10.5	11.5 + 0.6

Cube Pruning



bigram (meeting, with)

non-monotonic grid
due to LM combo costs

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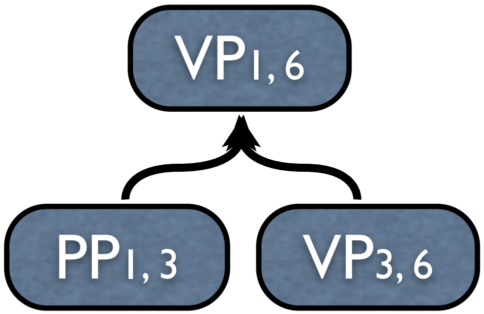

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$(\mathrm{VP}^{\text{held} \star \text{talk}}_{3,6})$	1.1	2.4	9.5	9.4
$(\mathrm{VP}^{\text{hold} \star \text{conference}}_{3,6})$	3.5	5.1	17.0	12.1

Cube Pruning

k-best parsing
Algorithm 1

- a priority queue of candidates
- extract the best candidate

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- push the two successors

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Cube Pruning

items are popped out-of-order

solution: keep a buffer of pop-ups

2.5 2.4 5.1

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finally re-sort the buffer and return inorder:

2.4 2.5 5.1

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