Decoding

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Decoding

- We have a mathematical model for translation

$$p(\mathbf{e}|\mathbf{f})$$

- Task of decoding: find the translation $\mathbf{e}_{\text{best}}$ with highest probability

$$\mathbf{e}_{\text{best}} = \text{argmax}_{\mathbf{e}}\ p(\mathbf{e}|\mathbf{f})$$

- Two types of error
  - the most probable translation is bad → fix the model
  - search does not find the most probably translation → fix the search

- Decoding is evaluated by search error, not quality of translations (although these are often correlated)

translation process

Translation Process

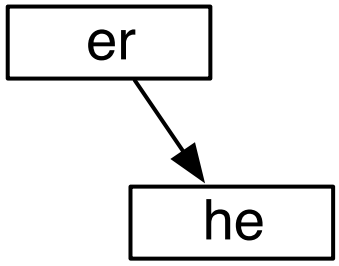
- Task: translate this sentence from German into English

er geht ja nicht nach hause

Translation Process

- Task: translate this sentence from German into English

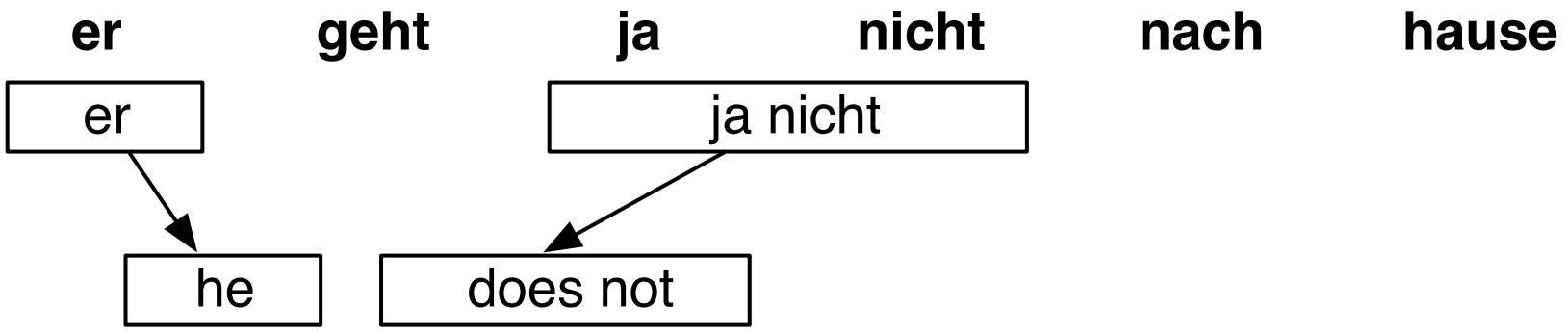
er geht ja nicht nach hause



- Pick phrase in input, translate

Translation Process

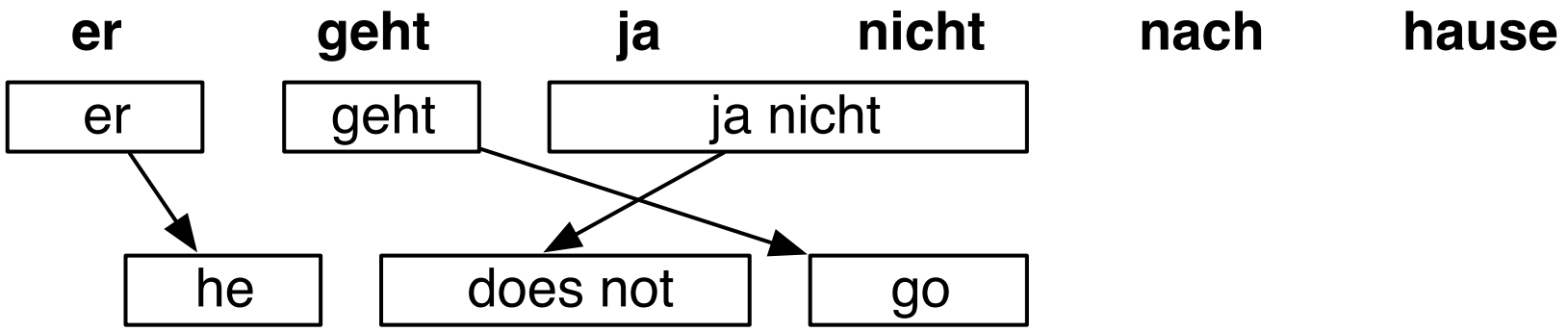
- Task: translate this sentence from German into English



- Pick phrase in input, translate
  - it is allowed to pick words out of sequence reordering
  - phrases may have multiple words: many-to-many translation

Translation Process

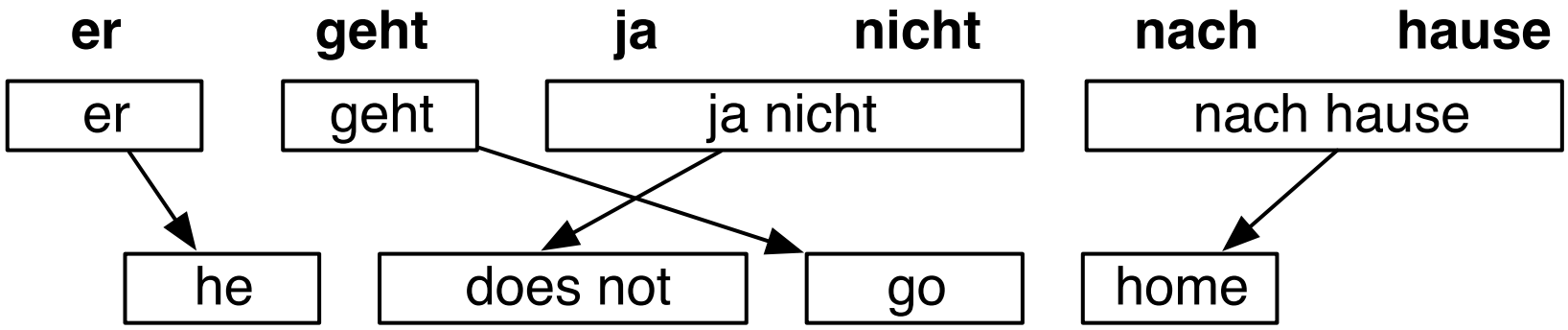
- Task: translate this sentence from German into English



- Pick phrase in input, translate

Translation Process

- Task: translate this sentence from German into English



- Pick phrase in input, translate

Computing Translation Probability

- Probabilistic model for phrase-based translation:

$$\mathbf{e}_{\text{best}} = \text{argmax}_{\mathbf{e}} \prod_{i=1}^{I} \phi(\bar{f}_i|\bar{e}_i)\ d(start_i - end_{i-1} - 1)\ p_{\text{LM}}(\mathbf{e})$$

- Score is computed incrementally for each partial hypothesis

- Components

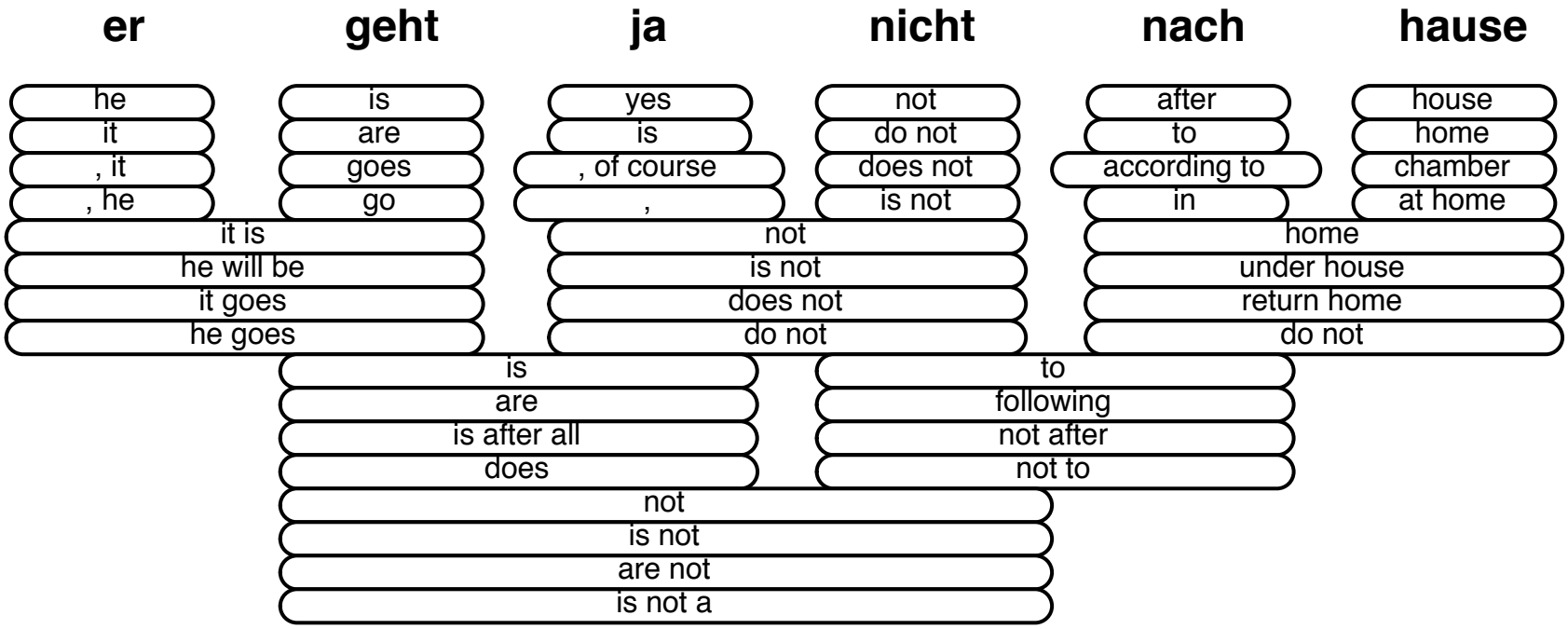
Phrase translation Picking phrase $\bar{f}_i$ to be translated as a phrase $\bar{e}_i$
→ look up score $\phi(\bar{f}_i|\bar{e}_i)$ from phrase translation table

Reordering Previous phrase ended in end_{i-1}, current phrase starts at $start_i$
→ compute $d(start_i - end_{i-1} - 1)$

Language model For n-gram model, need to keep track of last $n-1$ words
→ compute score $p_{\text{LM}}(w_i|w_{i-(n-1)}, ..., w_{i-1})$ for added words w_i

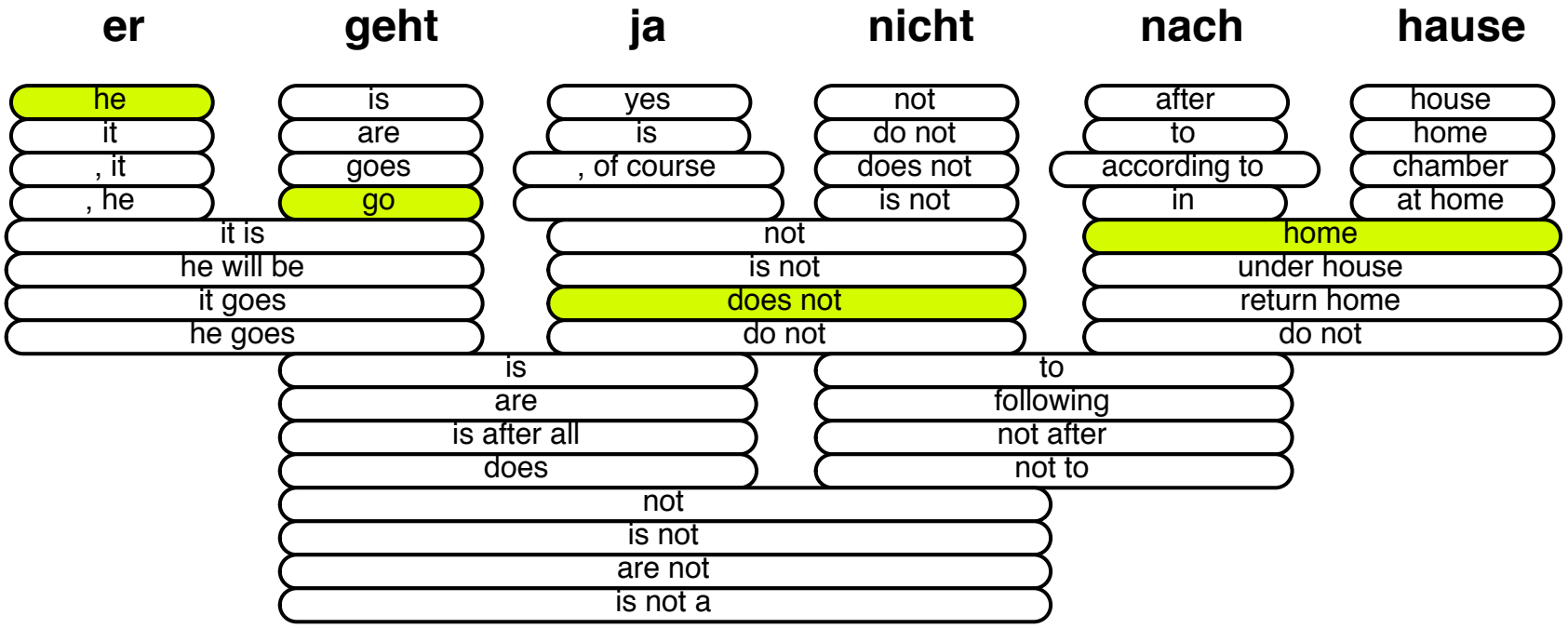
decoding process

Translation Options



- Many translation options to choose from
  - in Europarl phrase table: 2727 matching phrase pairs for this sentence
  - by pruning to the top 20 per phrase, 202 translation options remain

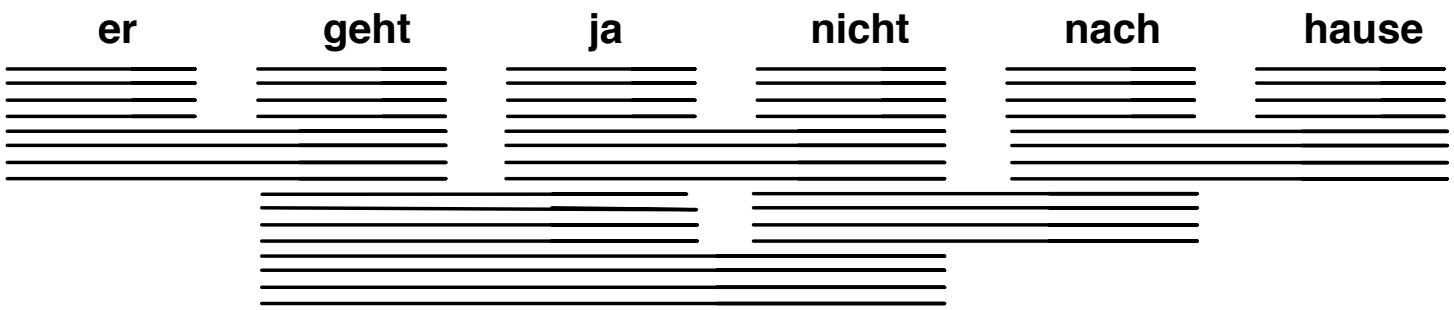
Translation Options



- The machine translation decoder does not know the right answer
  - picking the right translation options
  - arranging them in the right order

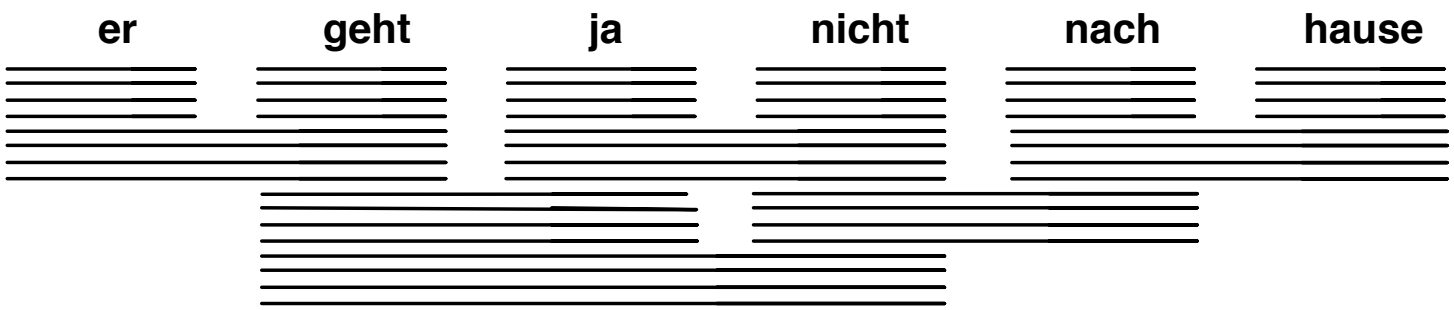
→ Search problem solved by heuristic beam search

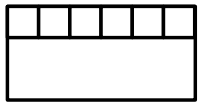
Decoding: Precompute Translation Options



consult phrase translation table for all input phrases

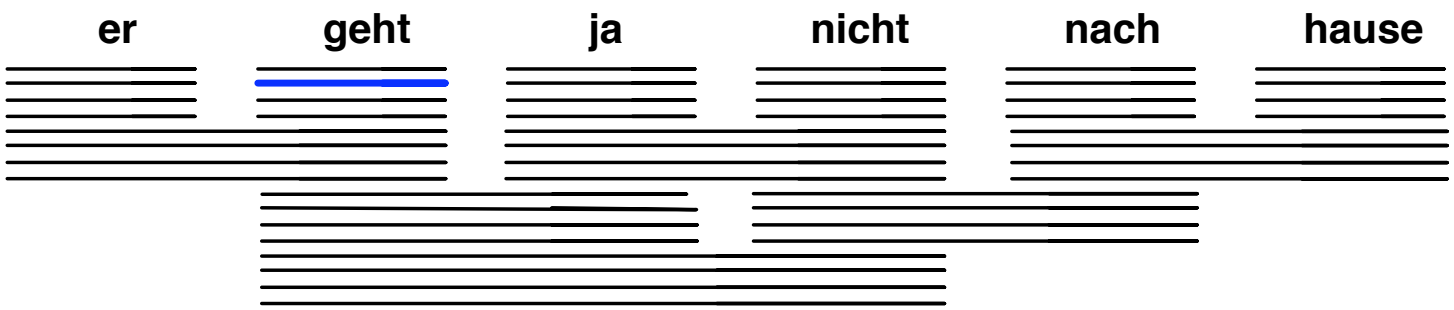
Decoding: Start with Initial Hypothesis

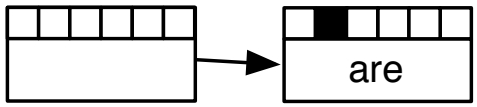




initial hypothesis: no input words covered, no output produced

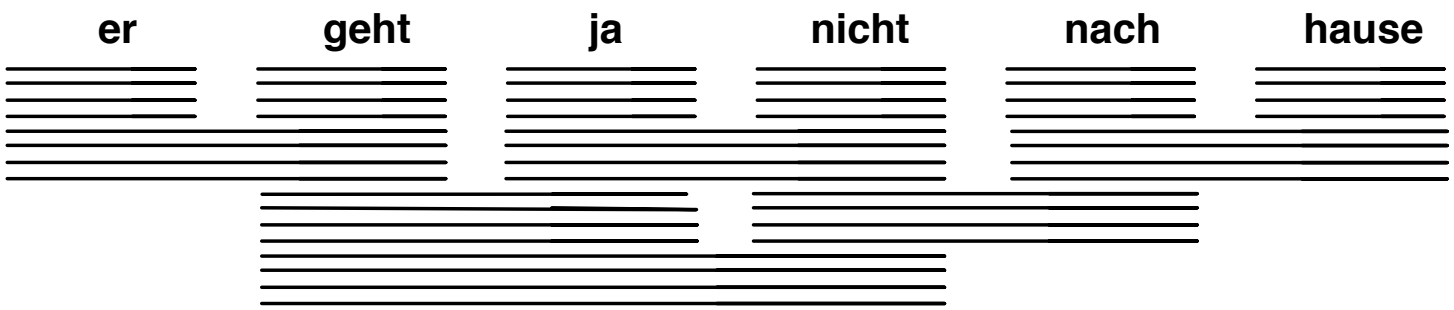
Decoding: Hypothesis Expansion

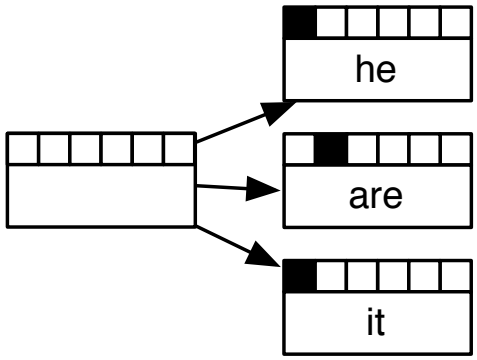




pick any translation option, create new hypothesis

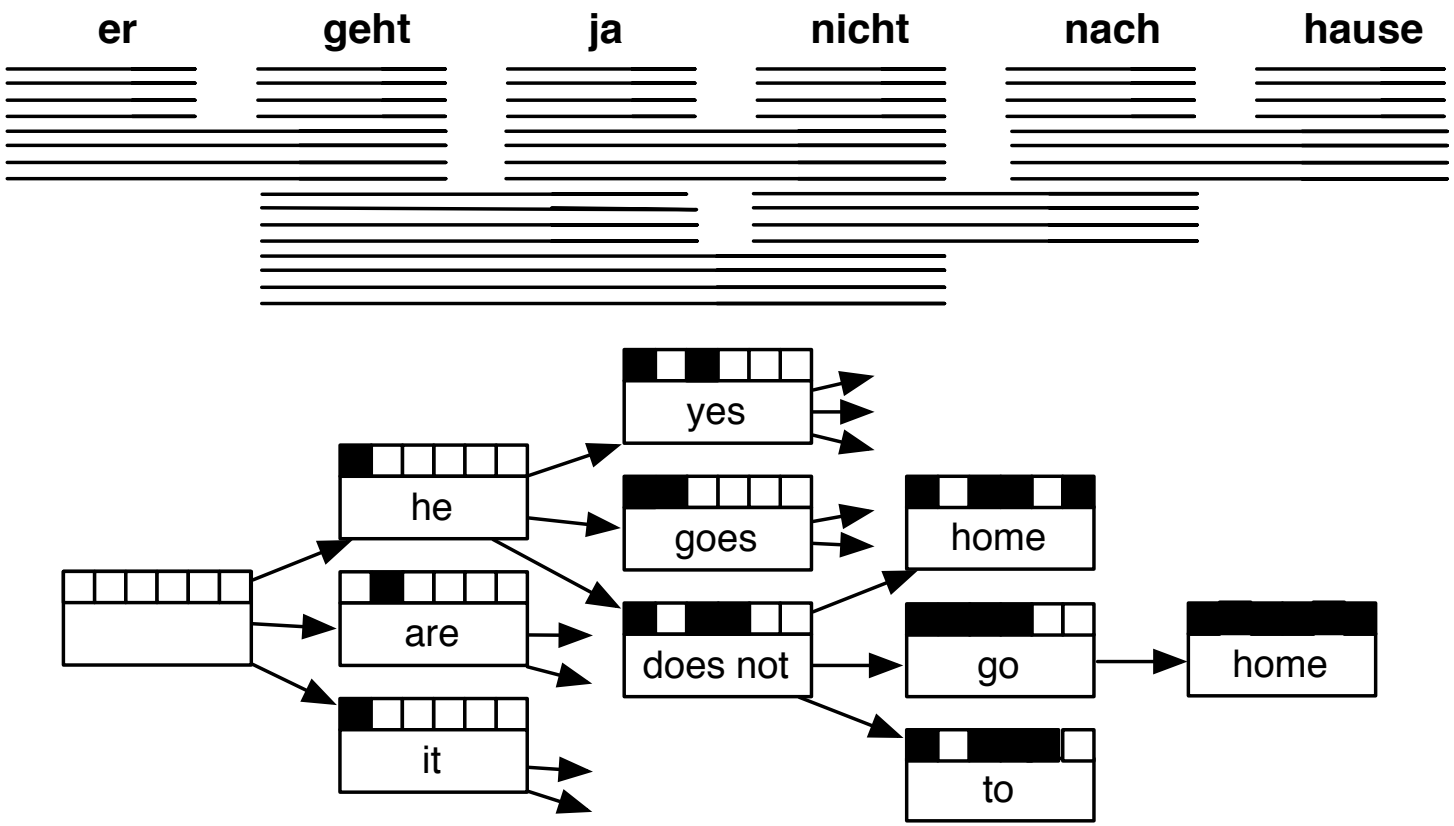
Decoding: Hypothesis Expansion





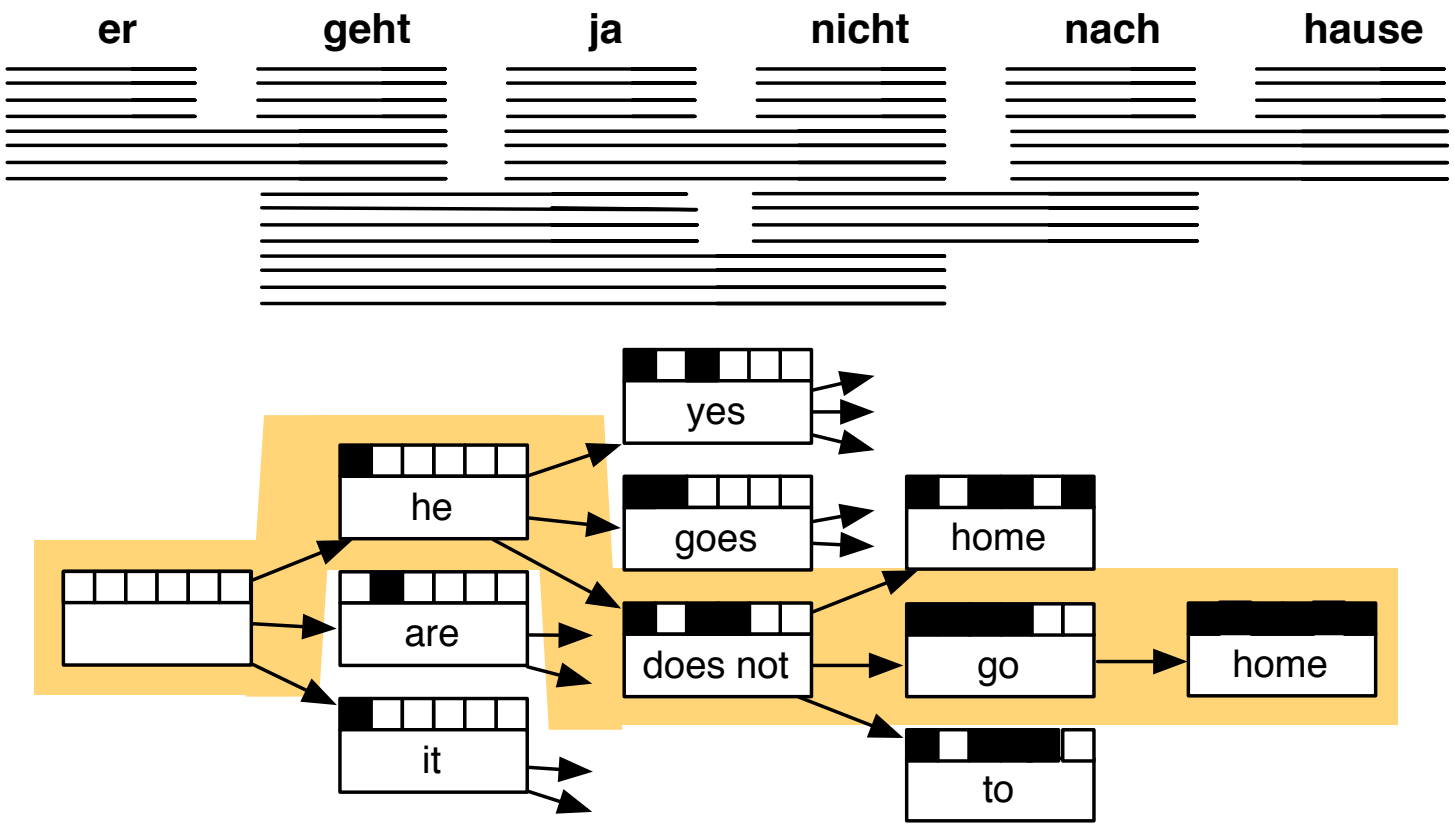
create hypotheses for all other translation options

Decoding: Hypothesis Expansion



also create hypotheses from created partial hypothesis

Decoding: Find Best Path



backtrack from highest scoring complete hypothesis

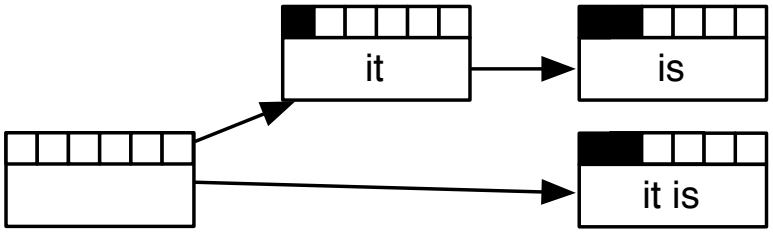
dynamic programming

Computational Complexity

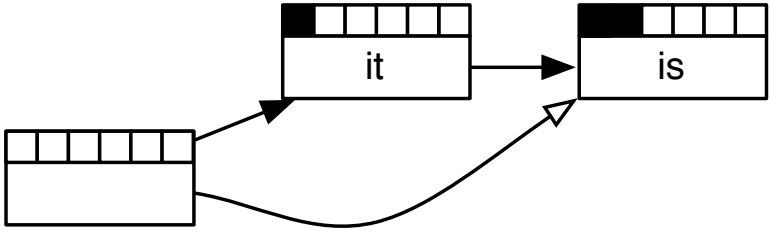
- The suggested process creates exponential number of hypothesis
- Machine translation decoding is NP-complete
- Reduction of search space:
  - recombination (risk-free)
  - pruning (risky)

Recombination

- Two hypothesis paths lead to two matching hypotheses
  - same foreign words translated
  - same English words in the output

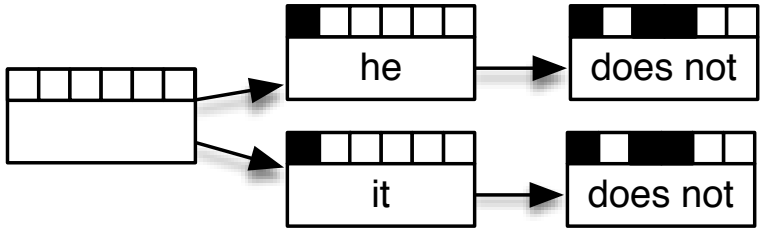


- Worse hypothesis is dropped

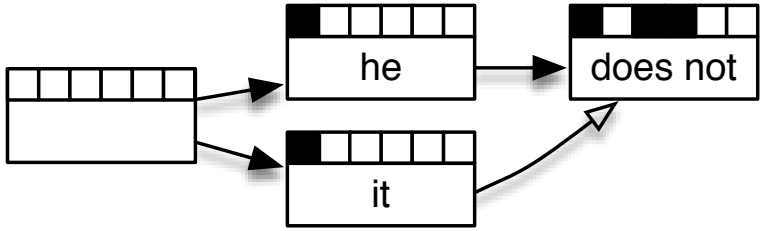


Recombination

- Two hypothesis paths lead to hypotheses indistinguishable in subsequent search
  - same foreign words translated
  - same last two English words in output (assuming trigram language model)
  - same last foreign word translated



- Worse hypothesis is dropped



Restrictions on Recombination

- **Translation model:** Phrase translation independent from each other

  → no restriction to hypothesis recombination

- **Language model:** Last $n-1$ words used as history in n-gram language model

  → recombined hypotheses must match in their last $n-1$ words

- **Reordering model:** Distance-based reordering model based on distance to end position of previous input phrase

  → recombined hypotheses must have that same end position

- Other feature function may introduce additional restrictions

pruning

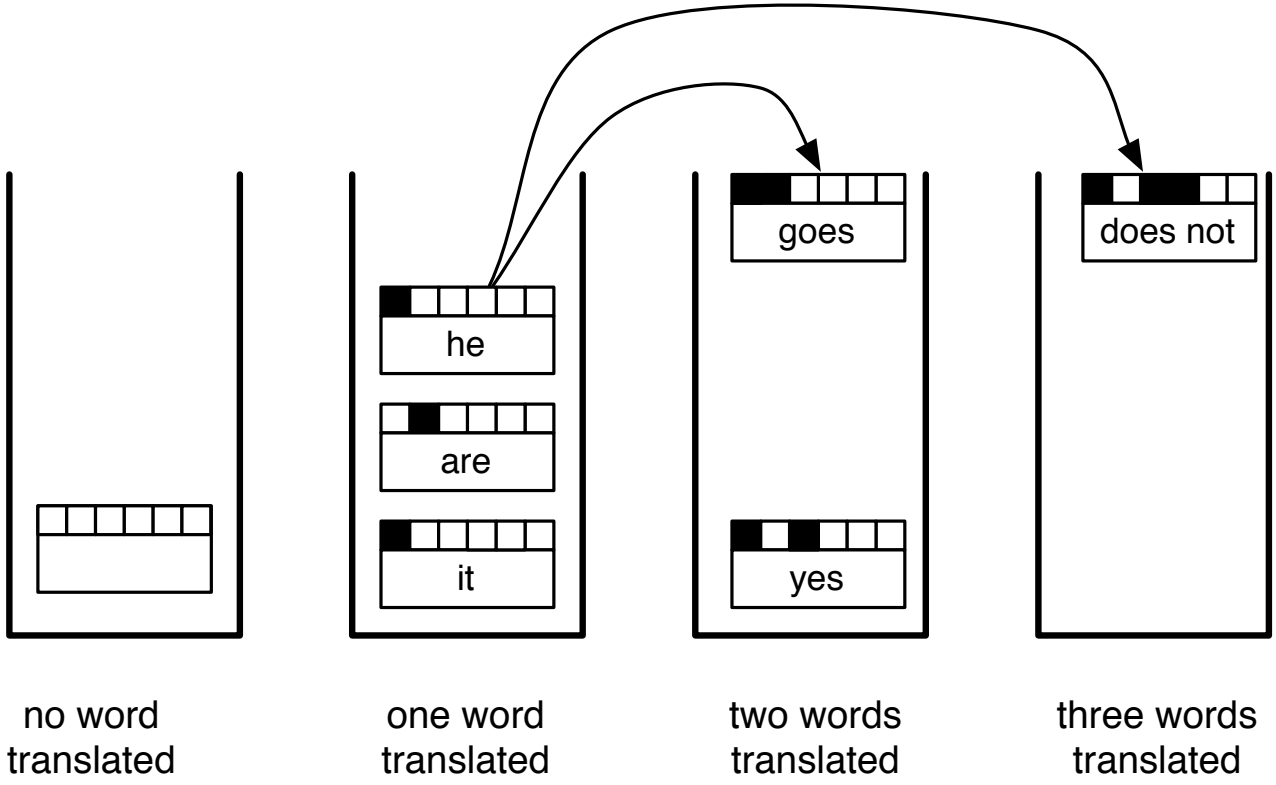
Pruning

- Recombination reduces search space, but not enough

  (we still have a NP complete problem on our hands)

- Pruning: remove bad hypotheses early
  - put comparable hypothesis into stacks
    (hypotheses that have translated same number of input words)
  - limit number of hypotheses in each stack

Stacks



- Hypothesis expansion in a stack decoder
  - translation option is applied to hypothesis
  - new hypothesis is dropped into a stack further down

Stack Decoding Algorithm


```
1:  place empty hypothesis into stack 0
2:  for all stacks 0...n − 1 do
3:      for all hypotheses in stack do
4:          for all translation options do
5:              if applicable then
6:                  create new hypothesis
7:                  place in stack
8:                  recombine with existing hypothesis if possible
9:                  prune stack if too big
10:             end if
11:         end for
12:     end for
13: end for
```

Pruning

- Pruning strategies
  - histogram pruning: keep at most k hypotheses in each stack
  - stack pruning: keep hypothesis with score $\alpha \times$ best score ($\alpha < 1$)

- Computational time complexity of decoding with histogram pruning

$$O(\text{max stack size} \times \text{translation options} \times \text{sentence length})$$

- Number of translation options is linear with sentence length, hence:

$$O(\text{max stack size} \times \text{sentence length}^2)$$

- Quadratic complexity

Reordering Limits

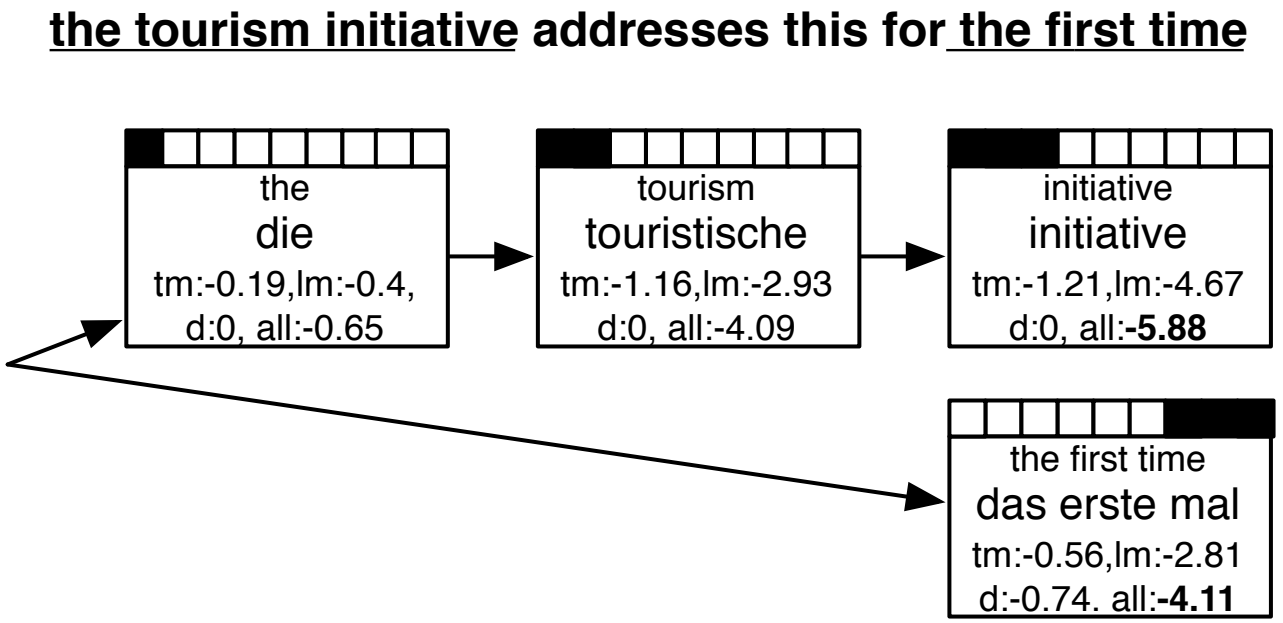
- Limiting reordering to maximum reordering distance
- Typical reordering distance 5–8 words
  - depending on language pair
  - larger reordering limit hurts translation quality
- Reduces complexity to linear

$$O(\text{max stack size} \times \text{sentence length})$$

- Speed / quality trade-off by setting maximum stack size

future cost estimation

Translating the Easy Part First?

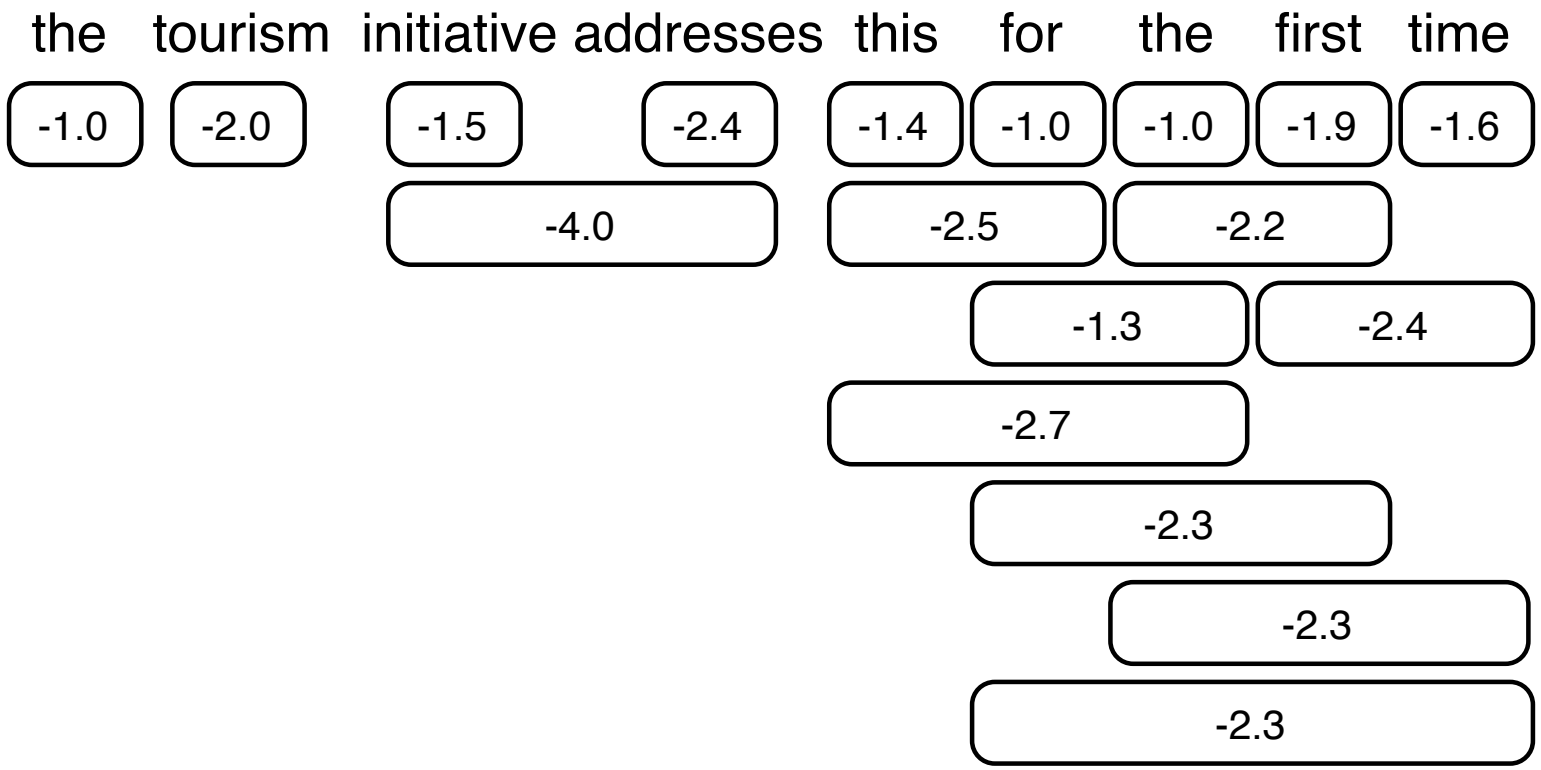


both hypotheses translate 3 words
worse hypothesis has better score

Estimating Future Cost

- Future cost estimate: how expensive is translation of rest of sentence?
- Optimistic: choose cheapest translation options
- Cost for each translation option
  - **translation model**: cost known
  - **language model:** output words known, but not context
    $\rightarrow$ estimate without context
  - **reordering model:** unknown, ignored for future cost estimation

Cost Estimates from Translation Options



cost of cheapest translation options for each input span (log-probabilities)

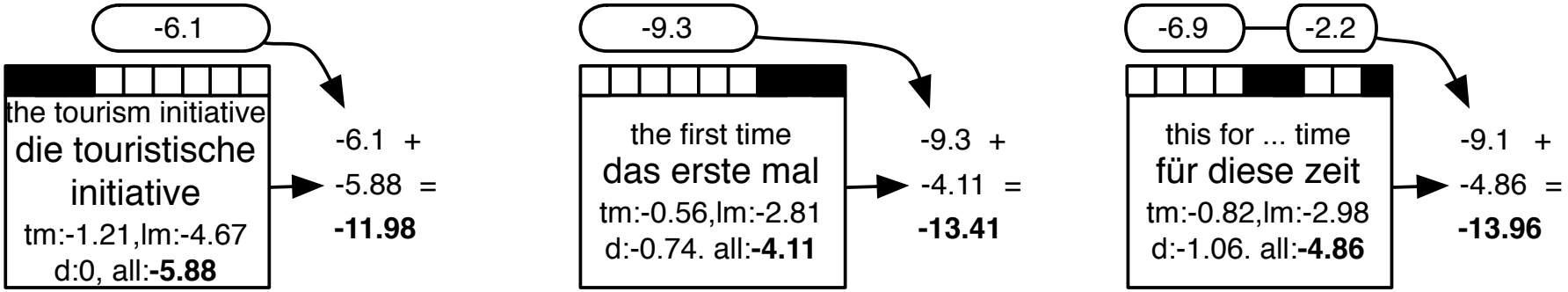
Cost Estimates for all Spans

- Compute cost estimate for all contiguous spans by combining cheapest options

first word	future cost estimate for n words (from first)								
	1	2	3	4	5	6	7	8	9
the	-1.0	-3.0	-4.5	-6.9	-8.3	-9.3	-9.6	-10.6	-10.6
tourism	-2.0	-3.5	-5.9	-7.3	-8.3	-8.6	-9.6	-9.6	
initiative	-1.5	-3.9	-5.3	-6.3	-6.6	-7.6	-7.6		
addresses	-2.4	-3.8	-4.8	-5.1	-6.1	-6.1			
this	-1.4	-2.4	-2.7	-3.7	-3.7				
for	-1.0	-1.3	-2.3	-2.3					
the	-1.0	-2.2	-2.3						
first	-1.9	-2.4							
time	-1.6								

- Function words cheaper (the: -1.0) than content words (tourism -2.0)
- Common phrases cheaper (for the first time: -2.3)
  than unusual ones (tourism initiative addresses: -5.9)

Combining Score and Future Cost



- Hypothesis score and future cost estimate are combined for pruning
  - left hypothesis starts with hard part: the tourism initiative
    score: -5.88, future cost: -6.1 → total cost -11.98
  - middle hypothesis starts with easiest part: the first time
    score: -4.11, future cost: -9.3 → total cost -13.41
  - right hypothesis picks easy parts: this for ... time
    score: -4.86, future cost: -9.1 → total cost -13.96

cube pruning

Stack Decoding Algorithm

- Exhaustive matching of hypotheses to applicable translations options
  $\rightarrow$ too much computation

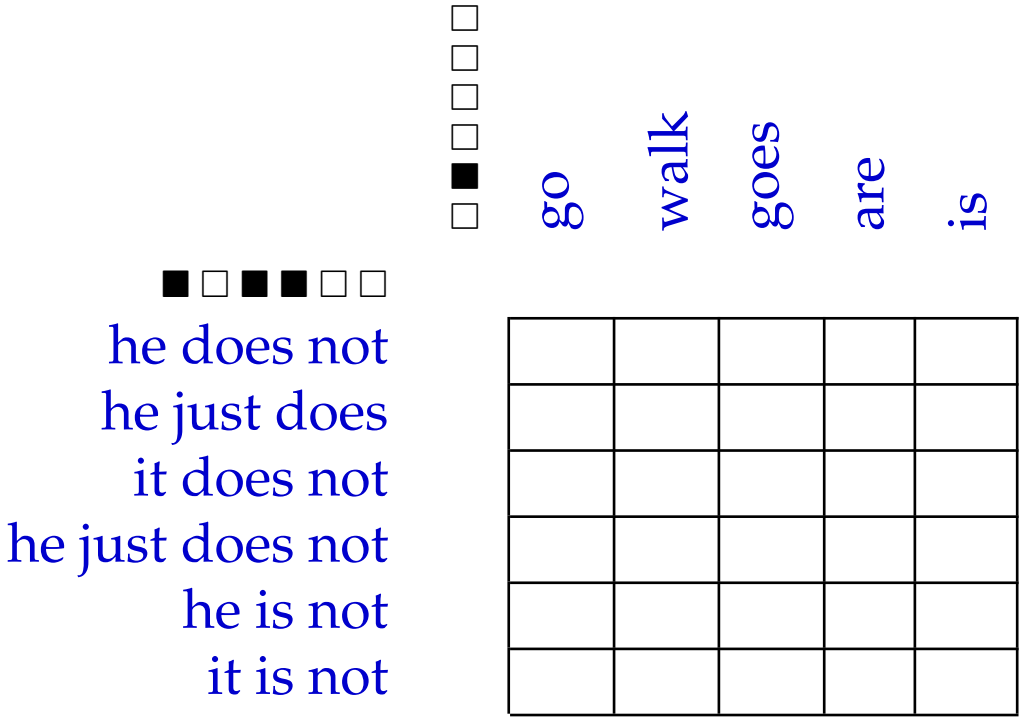
```
1:  place empty hypothesis into stack 0
2:  for all stacks 0...n − 1 do
3:    for all hypotheses in stack do
4:      for all translation options do
5:        if applicable then
6:          create new hypothesis
7:          place in stack
8:          recombine with existing hypothesis if possible
9:          prune stack if too big
10:       end if
11:     end for
12:   end for
13: end for
```

Group Hypotheses and Options

- Group hypotheses by coverage vector
  - ■ ■ ■ □ □ □
  - ■ ■ □ ■ □ □
  - ■ □ ■ ■ □ □
  - ...
- Group translation options by span
  - □ □ □ ■ □ □
  - □ □ □ □ ■ □
  - □ □ □ ■ ■ □
  - ...

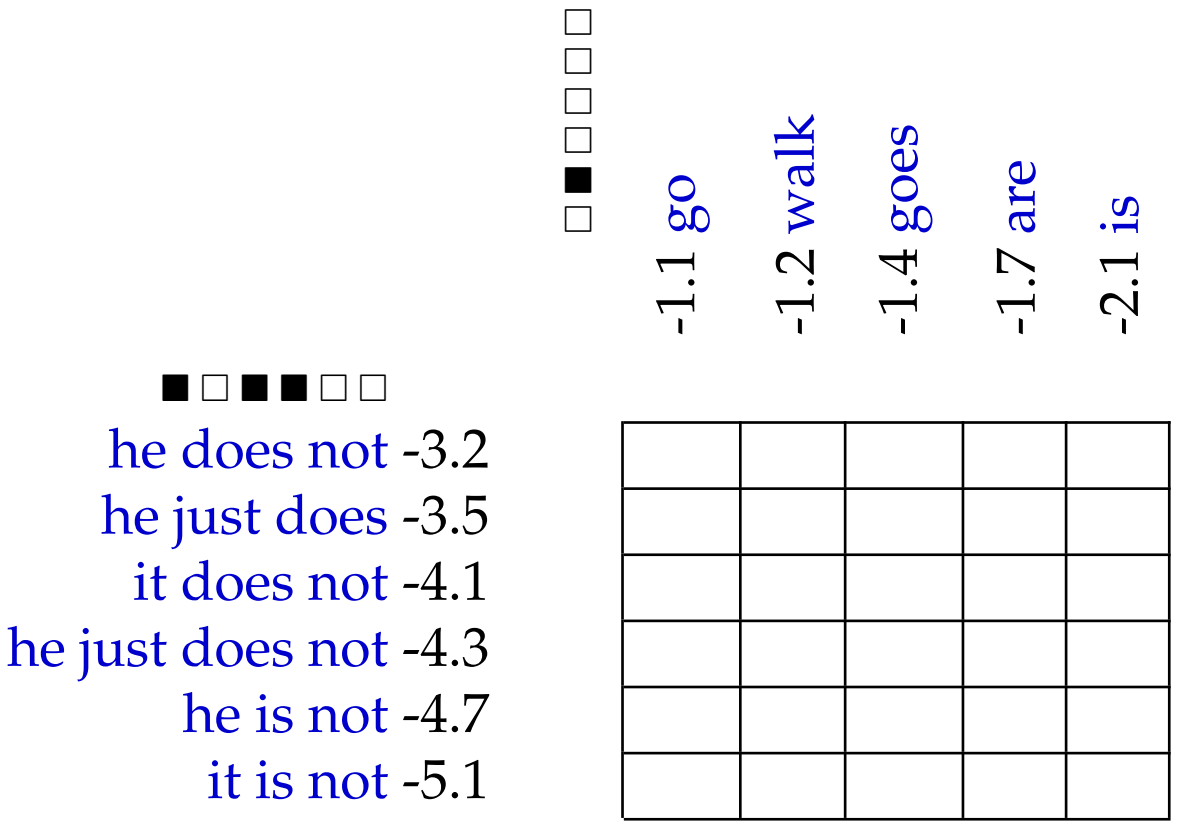
⇒ Loop over groups, check for applicability once for each pair of groups (not much gained so far)

All Hypotheses, All Options



- Example: group with 6 hypotheses, group with 5 translation options
- Should we really create all 6×5 of them?

Rank by Score



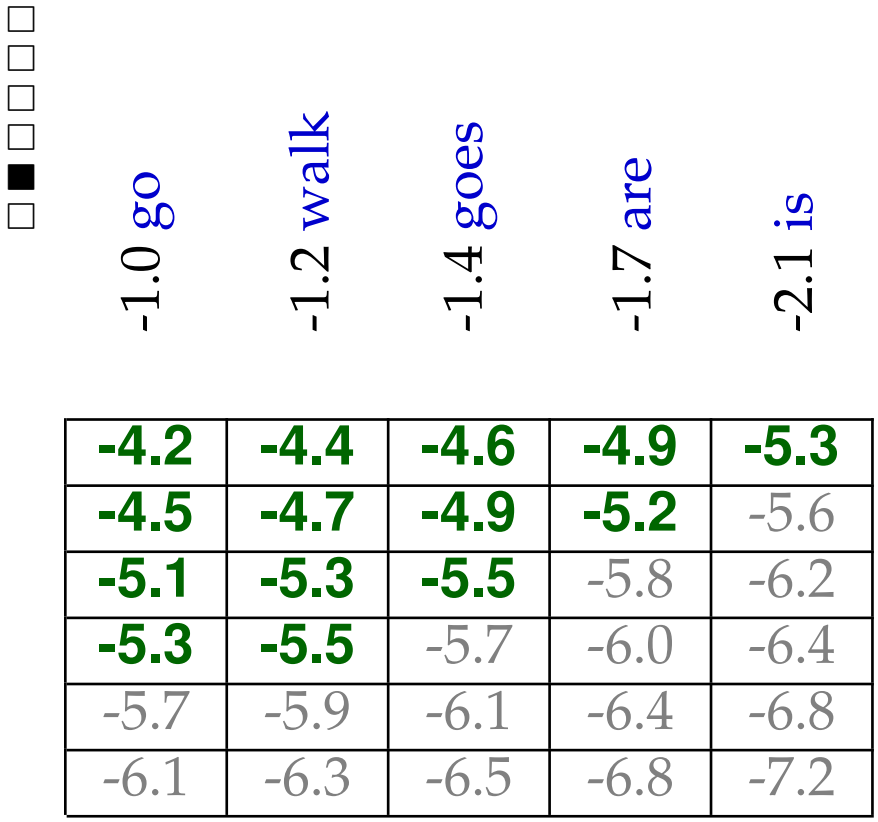
- Rank hypotheses by score so far
- Rank translation options by score estimate

Expected Score of New Hypothesis

	-1.0 go	-1.2 walk	-1.4 goes	-1.7 are	-2.1 is
					
he does not -3.2	-4.2	-4.4	-4.6	-4.9	-5.3
he just does -3.5	-4.5	-4.7	-4.9	-5.2	-5.6
it does not -4.1	-5.1	-5.3	-5.5	-5.8	-6.2
he just does not -4.3	-5.3	-5.5	-5.7	-6.0	-6.4
he is not -4.7	-5.7	-5.9	-6.1	-6.4	-6.8
it is not -5.1	-6.1	-6.3	-6.5	-6.8	-7.2

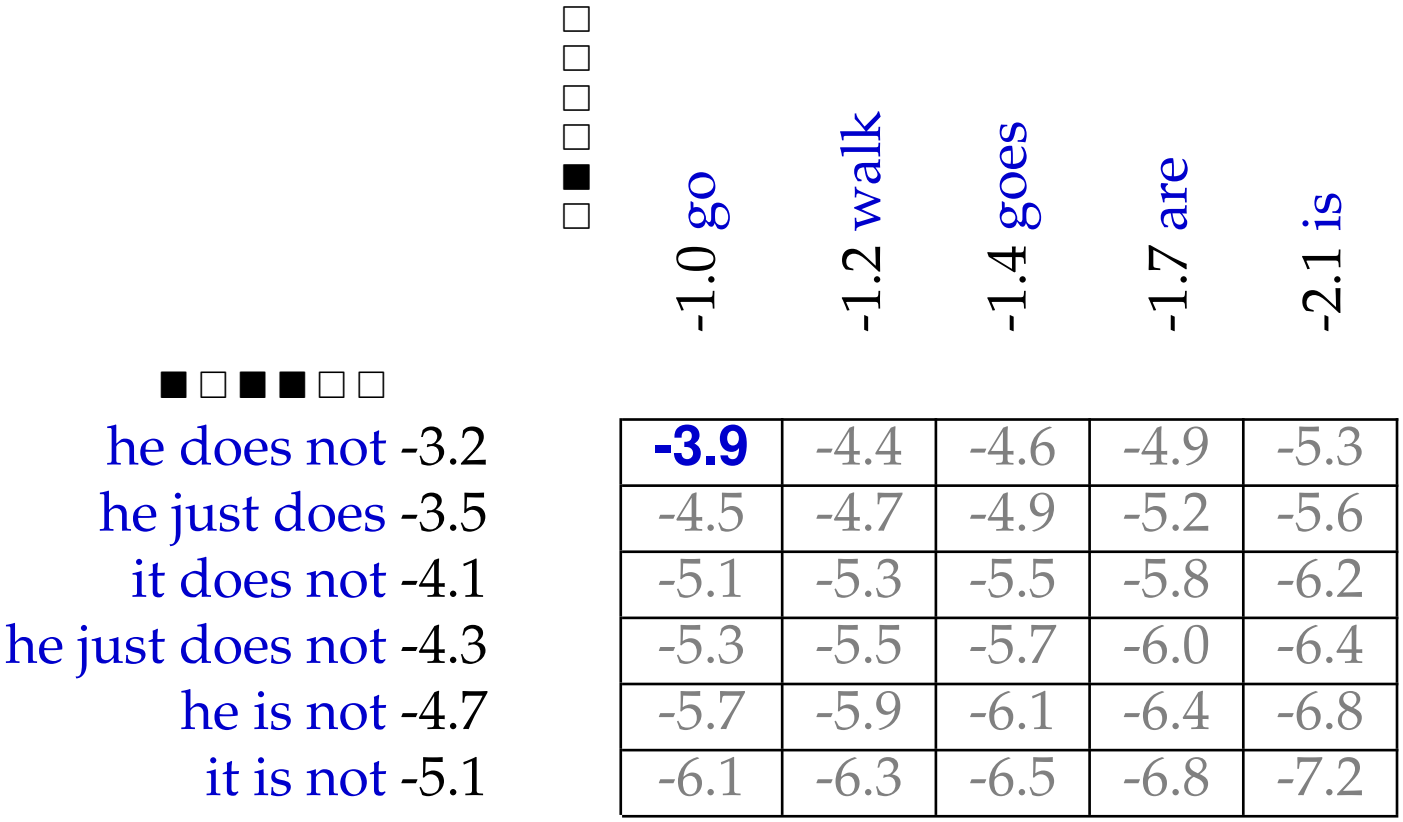
- Expected score: hypothesis score + translation option score
- Real score will be different, since language model score depends on context

Only Compute Half



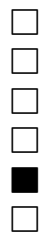
- If we want to save computational cost, we could decide to only compute some
- One way to do this: based on expected score

Cube Pruning



- Start with best hypothesis, best translation option
- Create new hypothesis (actual score becomes available)

Cube Pruning (2)



	-1.0 go	-1.2 walk	-1.4 goes	-1.7 are	-2.1 is
■□■■□□					
he does not -3.2	**-3.9**	**-4.1**	-4.6	-4.9	-5.3
he just does -3.5	**-4.3**	-4.7	-4.9	-5.2	-5.6
it does not -4.1	-5.1	-5.3	-5.5	-5.8	-6.2
he just does not -4.3	-5.3	-5.5	-5.7	-6.0	-6.4
he is not -4.7	-5.7	-5.9	-6.1	-6.4	-6.8
it is not -5.1	-6.1	-6.3	-6.5	-6.8	-7.2

- Commit it to the stack
- Create its neighbors

Cube Pruning (3)

	-1.0 go	-1.2 walk	-1.4 goes	-1.7 are	-2.1 is
■□■■□□					
he does not -3.2	**-3.9**	**-4.1**	**-4.7**	-4.9	-5.3
he just does -3.5	**-4.3**	**-4.4**	-4.9	-5.2	-5.6
it does not -4.1	-5.1	-5.3	-5.5	-5.8	-6.2
he just does not -4.3	-5.3	-5.5	-5.7	-6.0	-6.4
he is not -4.7	-5.7	-5.9	-6.1	-6.4	-6.8
it is not -5.1	-6.1	-6.3	-6.5	-6.8	-7.2

- Commit best neighbor to the stack
- Create its neighbors in turn

Cube Pruning (4)

	-1.0 go	-1.2 walk	-1.4 goes	-1.7 are	-2.1 is
■□■■□□					
he does not -3.2	**-3.9**	**-4.1**	**-4.7**	-4.9	-5.3
he just does -3.5	**-4.3**	**-4.4**	-4.9	-5.2	-5.6
it does not -4.1	**-4.0**	-5.3	-5.5	-5.8	-6.2
he just does not -4.3	-5.3	-5.5	-5.7	-6.0	-6.4
he is not -4.7	-5.7	-5.9	-6.1	-6.4	-6.8
it is not -5.1	-6.1	-6.3	-6.5	-6.8	-7.2

- Keep doing this for a specific number of hypothesis
- Different hypothesis / translation options groups compete as well

heafield pruning

Heafield Pruning

- Main idea
  - a lot of hypotheses share suffixes
  - a lot of translation options share prefixes
  - combining
    * the last word of a hypothesis
    * the first word of a translation options

    may already indicate if we should pursue further

- Method
  - organize hypotheses by suffix tree
  - organize translation options by prefix tree
  - process priority queue based on pairs of nodes in these trees

Example

Hypotheses with 2 words translated

- -2.1 a big country
- -2.2 large countries
- -2.7 the big countries
- -2.8 a large country
- -2.9 the big country
- -3.1 a big nation

Translation options for a source span

- -1.1 does not waver
- -1.5 do not waver
- -1.7 wavers not
- -1.9 does not hesitate
- -2.1 does rarely waver

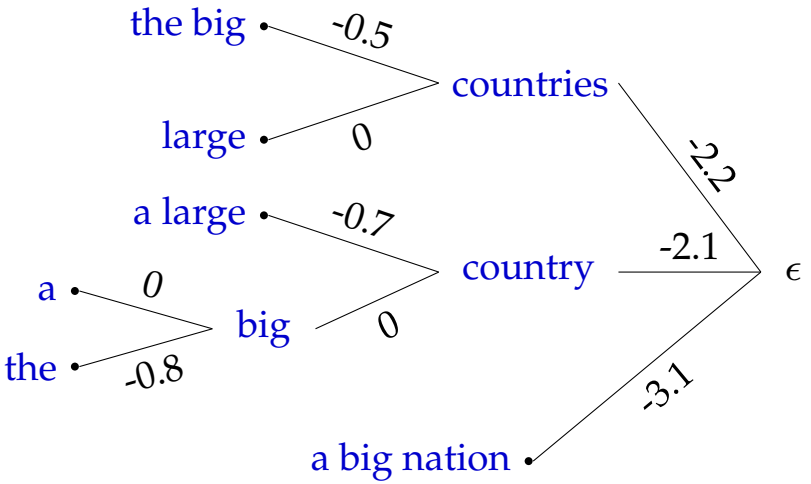
Encode in Suffix and Prefix Trees

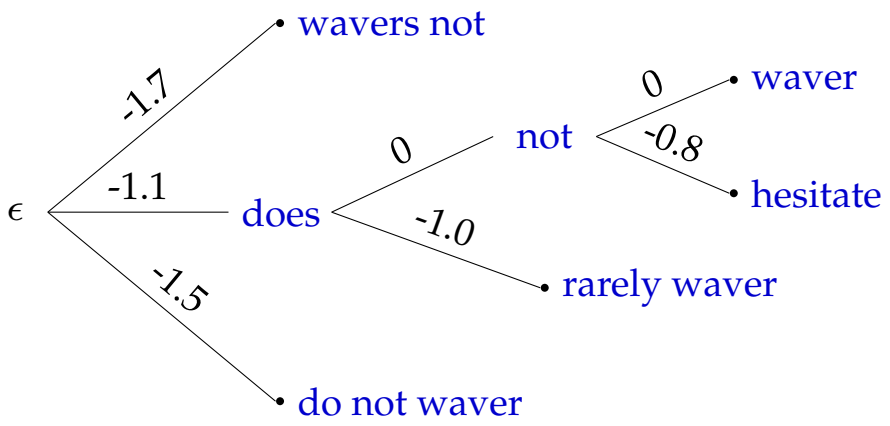
Hypotheses with 2 words translated

- -2.1 a big country
- -2.2 large countries
- -2.7 the big countries
- -2.8 a large country
- -2.9 the big country
- -3.1 a big nation

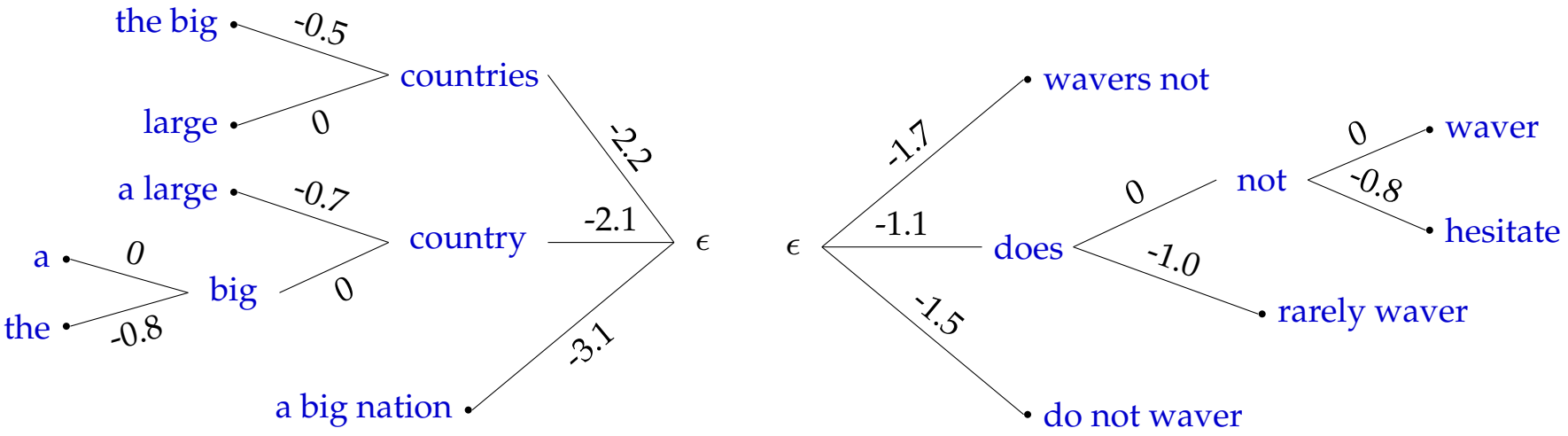
Translation options for a source span

- -1.1 does not waver
- -1.5 do not waver
- -1.7 wavers not
- -1.9 does not hesitate
- -2.1 does rarely waver



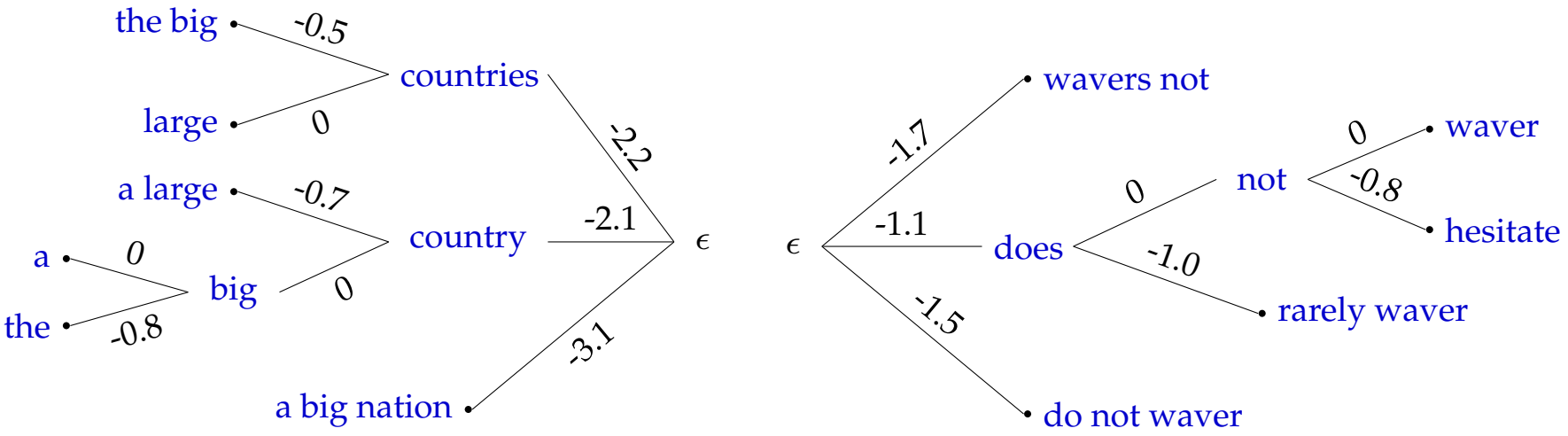


Set up Priority Queue



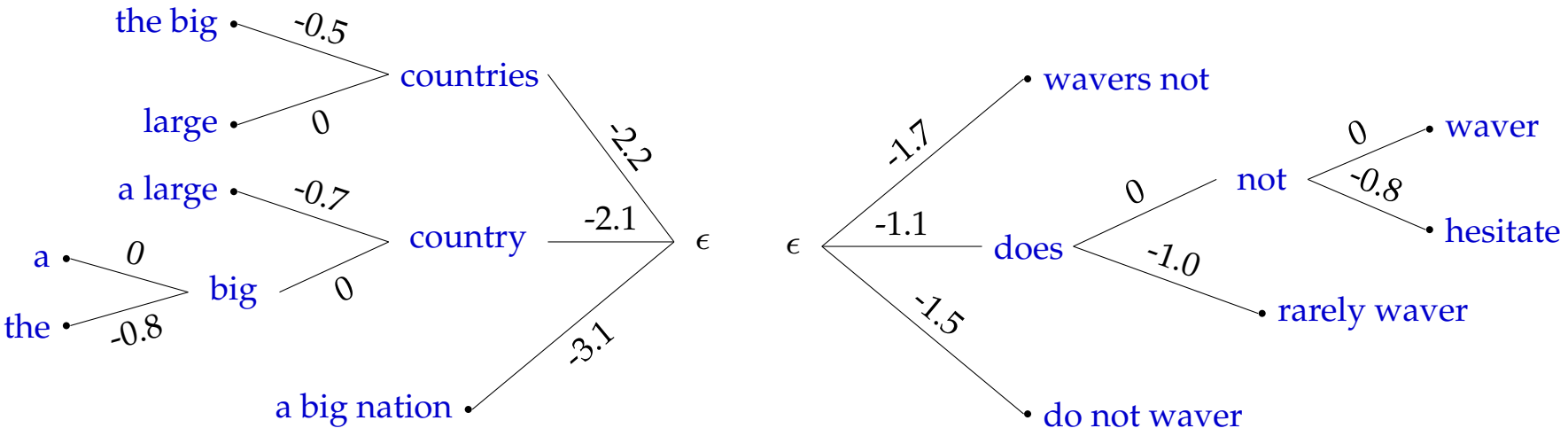
- Priority queue
  - (ϵ,ϵ), score: -3.2 (-2.1 + -1.1)

Pop off First Item



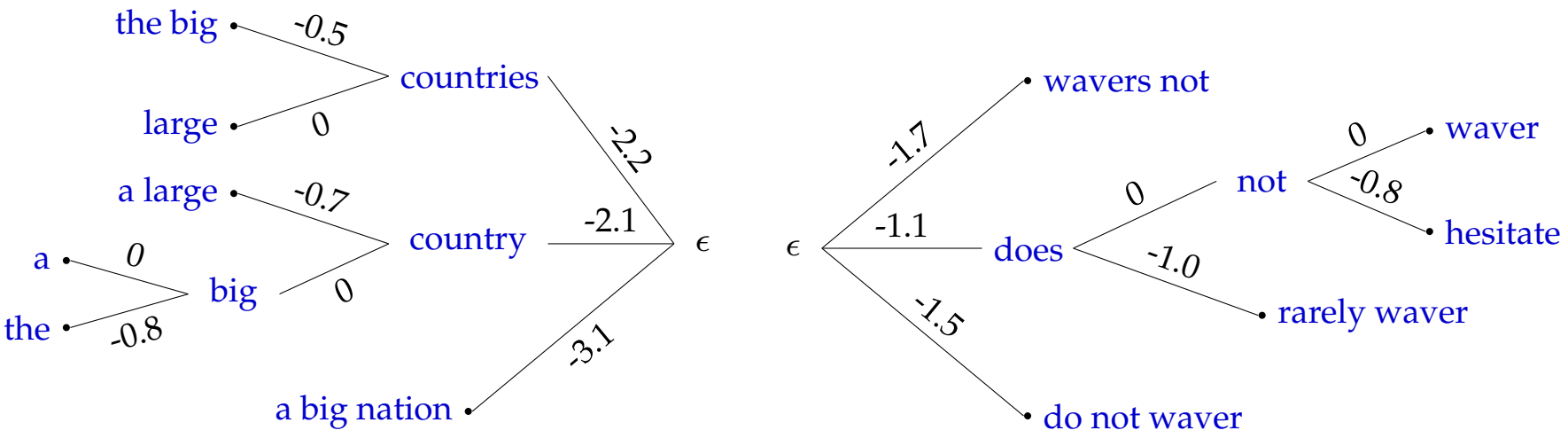
- Priority queue
  - (ϵ,ϵ), score: -3.2 (-2.1 + -1.1)
- Pop off: (ϵ,ϵ)
- Expand left (hypothesis): best is country
- Add new items
  - (country,ϵ), score: -3.2 (-2.1 + -1.1)
  - (ϵ[1+],ϵ), score: -3.3 (-2.2 + -1.1)

Pop off Second Item



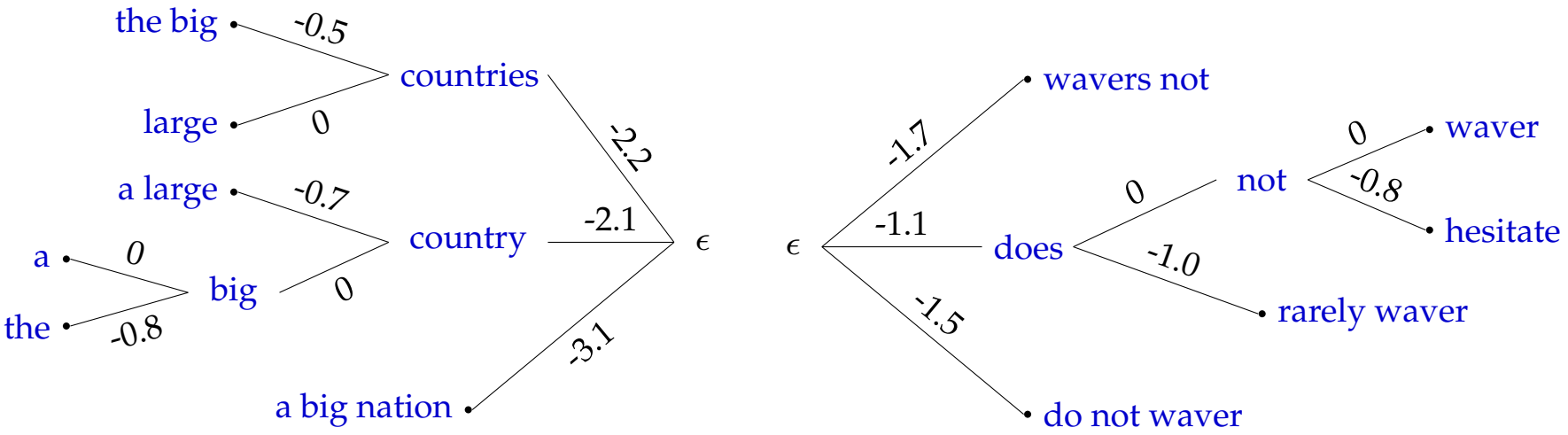
- Priority queue
  - (country,ϵ), score: -3.2 (-2.1 + -1.1)
  - (ϵ[1+],ϵ), score: -3.3 (-2.2 + -1.1)
- Pop off: (country,ϵ)
- Expand left (translation option): best is does
- Update language model probability estimate $\log \frac{p(\text{does}|\text{country})}{p(\text{does})} = +0.2$
- Add new items
  - (country,does), score: -3.0 (-2.1 + -1.1 + +0.2)
  - (country,ϵ[1+]), score: -3.6 (-2.1 + -1.5)

Pop off Next Item



- Priority queue
  - (country,does), score: -3.0 (-2.1 + -1.1 + +0.2)
  - (ϵ[1+],ϵ), score: -3.3 (-2.2 + -1.1)
  - (country,ϵ[1+]), score: -3.6 (-2.1 + -1.5)
- Pop off: (country,does)
- Expand left (hypothesis): best is big
- Update language model probability estimate $\log \frac{p(\text{does}|\text{big country})}{p(\text{does}|\text{country})} = +0.1$
- Add new items
  - (big country,does), score: -2.9 (-2.1 + -1.1 + +0.2 + +0.1)
  - (country[1+],does), score: -3.7 (-2.1 + -1.1 + +0.2 + -0.7)

Continue...



- Priority queue
  - (big country,does), score: -2.9 (-2.1 + -1.1 + +0.2 + +0.1)
  - (ϵ[1+],ϵ), score: -3.3 (-2.2 + -1.1)
  - (country,ϵ[1+]), score: -3.6 (-2.1 + -1.5)
  - (country[1+],does), score: -3.7 (-2.1 + -1.1 + +0.2 + -0.7)
- And so on...
  - once a full combination is completed (a big country,does not waver), add it to the stack
  - badly matching updates will push items down the priority queue
    e.g., $\log \frac{p(\text{does}|\text{countries})}{p(\text{does})} = -2.1$

Performance

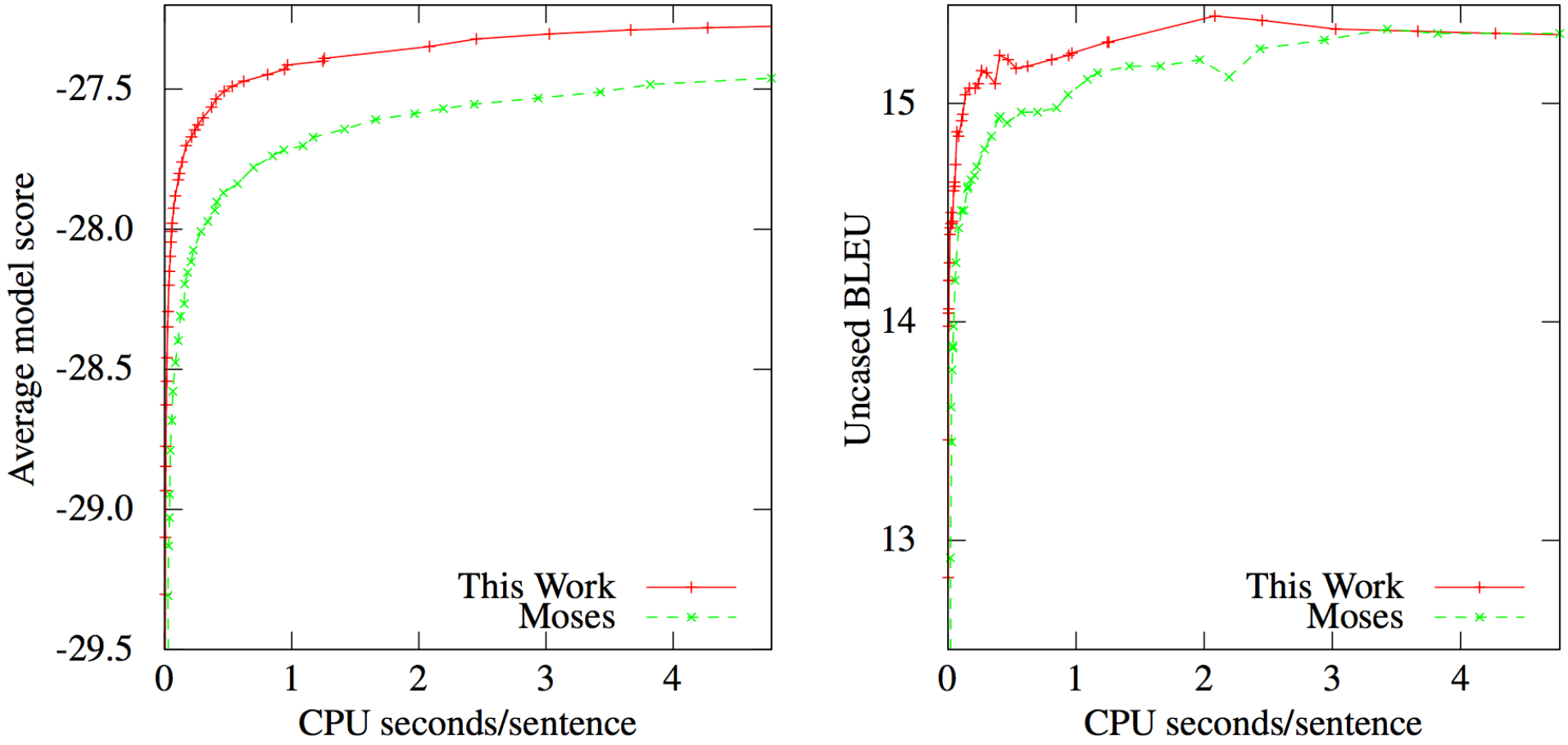


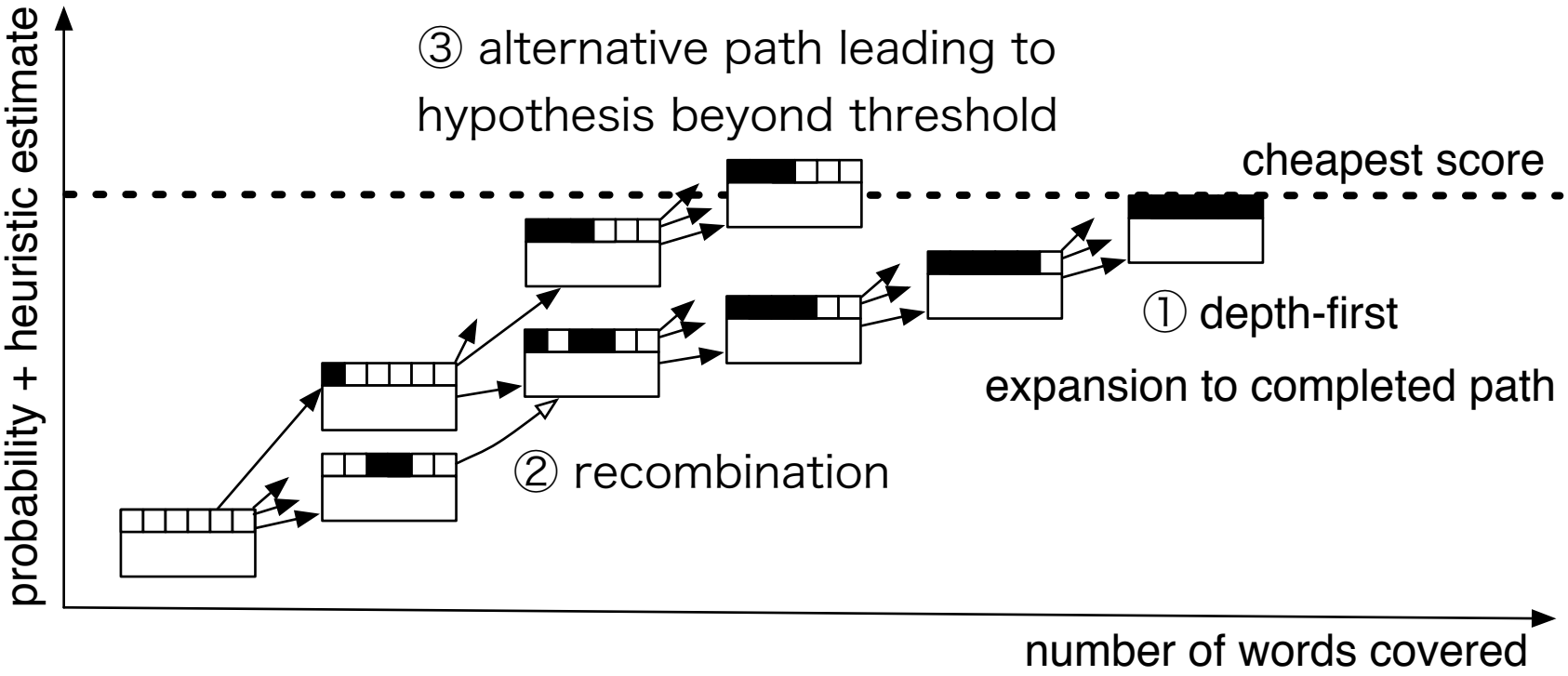
Figure 4: Performance of our decoder and Moses for various stack sizes k.

other decoding algorithms

Other Decoding Algorithms

- A* search
- Greedy hill-climbing
- Using finite state transducers (standard toolkits)

A* Search



- Uses *admissible* future cost heuristic: never overestimates cost
- Translation agenda: create hypothesis with lowest score + heuristic cost
- Done, when complete hypothesis created

Greedy Hill-Climbing

- Create one complete hypothesis with depth-first search (or other means)
- Search for better hypotheses by applying change operators
  - change the translation of a word or phrase
  - combine the translation of two words into a phrase
  - split up the translation of a phrase into two smaller phrase translations
  - move parts of the output into a different position
  - swap parts of the output with the output at a different part of the sentence
- Terminates if no operator application produces a better translation

Summary

- Translation process: produce output left to right
- Translation options
- Decoding by hypothesis expansion
- Reducing search space
  - recombination
  - pruning (requires future cost estimate)
- Other decoding algorithms