Statistical Machine Translation
Lecture 2
Theory and Praxis of Decoding

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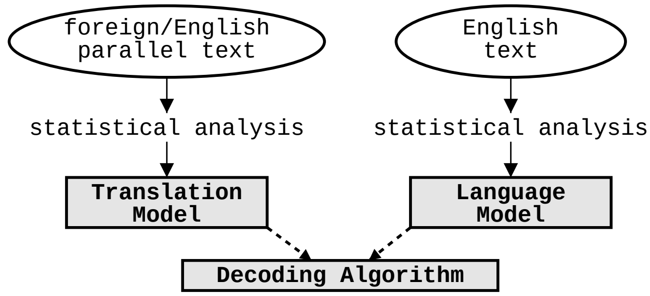
Statistical Machine Translation

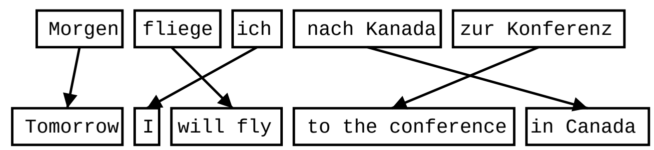
- Components: Translation model, language model, decoder



Phrase-Based Systems

- A number of research groups developed phrase-based systems (RWTH Aachen, Univ. of Southern California/ISI, CMU, IBM, Johns Hopkins Univ., Cambridge Univ., Univ. of Catalunya, ITC-irst, Univ. Edinburgh, Univ. of Maryland...)
- Systems differ in
  - training methods
  - model for phrase translation table
  - reordering models
  - additional feature functions
- Currently best method for SMT (MT?)
  - top systems in DARPA/NIST evaluation are phrase-based
  - best commercial system for Arabic-English is phrase-based

Phrase-Based Translation



- Foreign input is segmented in phrases
  - any sequence of words, not necessarily linguistically motivated
- Each phrase is translated into English
- Phrases are reordered

Phrase Translation Table

- Phrase Translations for “den Vorschlag”:

English	$\phi(e\|f)$	English	$\phi(e\|f)$
the proposal	0.6227	the suggestions	0.0114
’s proposal	0.1068	the proposed	0.0114
a proposal	0.0341	the motion	0.0091
the idea	0.0250	the idea of	0.0091
this proposal	0.0227	the proposal ,	0.0068
proposal	0.0205	its proposal	0.0068
of the proposal	0.0159	it	0.0068
the proposals	0.0159	...	...

Decoding Process

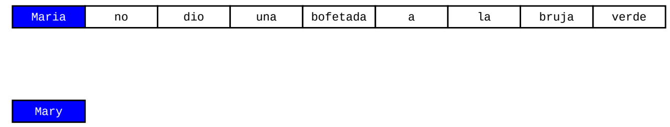
Maria	no	dio	una	bofetada	a	la	bruja	verde

- Build translation left to right
  - select foreign words to be translated

Decoding Process

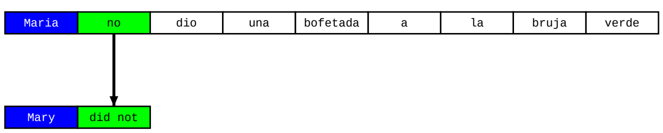
- Build translation left to right
  - select foreign words to be translated
  - find English phrase translation
  - add English phrase to end of partial translation

Decoding Process



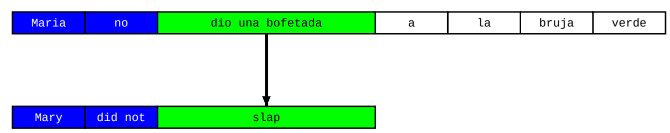
- Build translation left to right
  - select foreign words to be translated
  - find English phrase translation
  - add English phrase to end of partial translation
  - mark foreign words as translated

Decoding Process



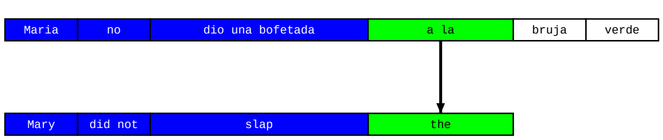
- One to many translation

Decoding Process



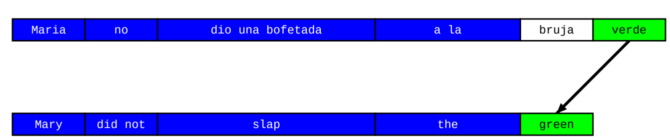
- Many to one translation

Decoding Process



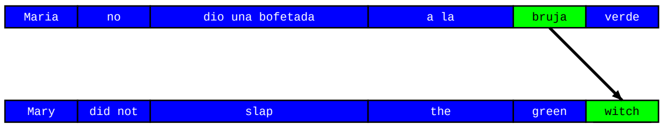
- Many to one translation

Decoding Process



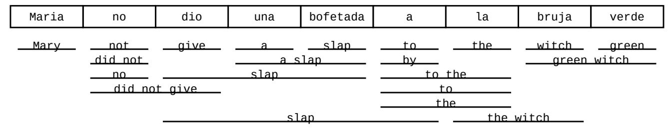
- Reordering

Decoding Process



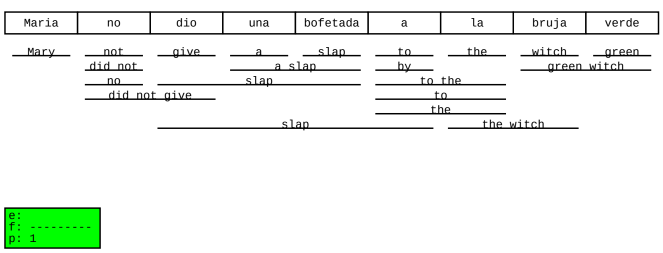
- Translation finished

Translation Options



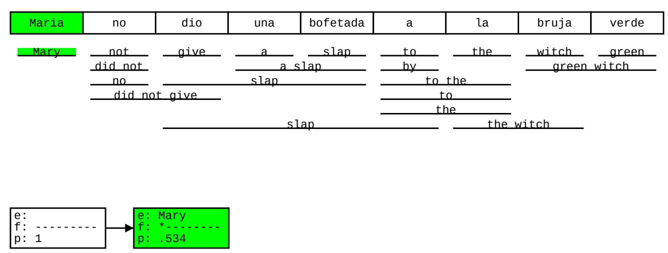
- Look up possible phrase translations
  - many different ways to segment words into phrases
  - many different ways to translate each phrase

Hypothesis Expansion



- Start with empty hypothesis
  - e: no English words
  - f: no foreign words covered
  - p: probability 1

Hypothesis Expansion

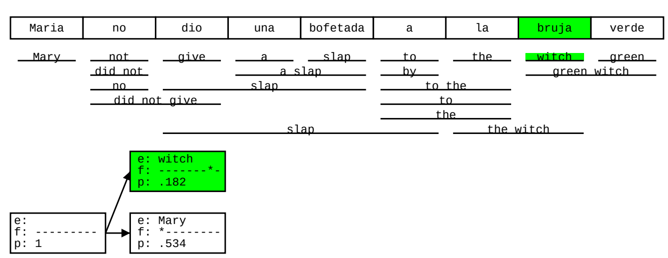


- Pick translation option
- Create hypothesis
  - e: add English phrase `Mary`
  - f: first foreign word covered
  - p: probability 0.534

A Quick Word on Probabilities

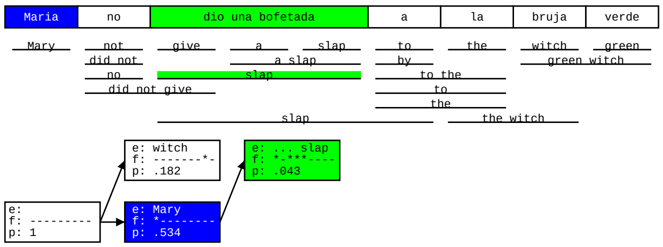
- Not going into detail here, but...
- Translation Model
  - phrase translation probability p(Mary|Maria)
  - reordering costs
  - phrase/word count costs
  - ...
- Language Model
  - uses trigrams:
  - p(Mary did not) = p(Mary| <s>) * p(did|Mary,<s>) * p(not|Mary did)

Hypothesis Expansion



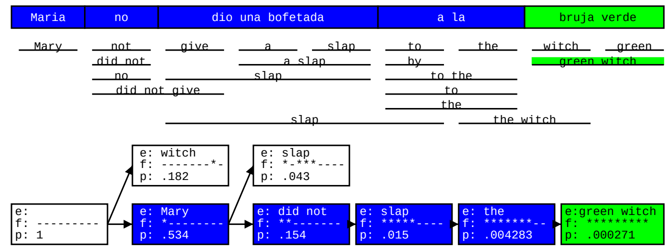
- Add another hypothesis

Hypothesis Expansion



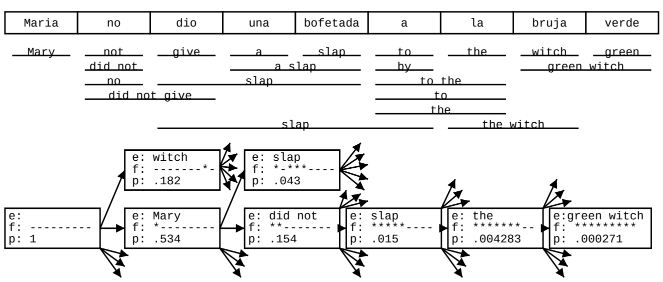
- Further hypothesis expansion

Hypothesis Expansion



- ... until all foreign words covered
  - find best hypothesis that covers all foreign words
  - backtrack to read off translation

Hypothesis Expansion



- Adding more hypothesis

⇒ Explosion of search space

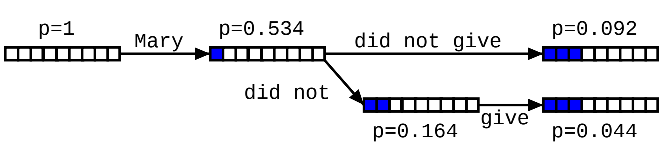
Explosion of Search Space

- Number of hypotheses is exponential with respect to sentence length

⇒ Decoding is NP-complete [Knight, 1999]

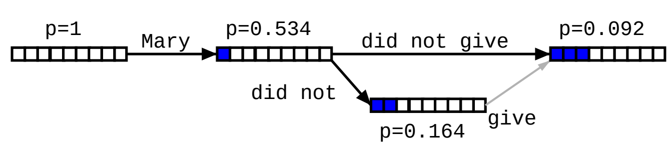
⇒ Need to reduce search space
  - risk free: hypothesis recombination
  - risky: histogram/threshold pruning

Hypothesis Recombination



- Different paths to the same partial translation

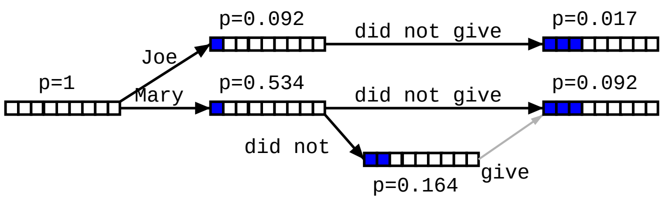
Hypothesis Recombination



- Different paths to the same partial translation

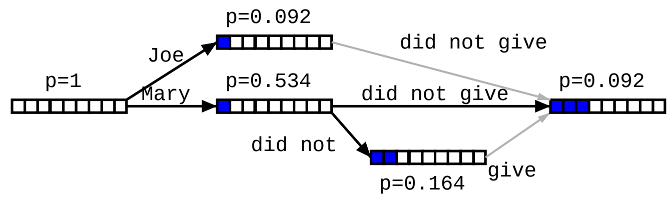
⇒ Combine paths
  - drop weaker hypothesis
  - keep pointer from worse path

Hypothesis Recombination



- Recombined hypotheses do not have to match completely
- No matter what is added, weaker path can be dropped, if:
  - last two English words match (matters for language model)
  - foreign word coverage vectors match (effects future path)

Hypothesis Recombination



- Recombined hypotheses do not have to match completely
- No matter what is added, weaker path can be dropped, if:
  - last two English words match (matters for language model)
  - foreign word coverage vectors match (effects future path)

⇒ Combine paths

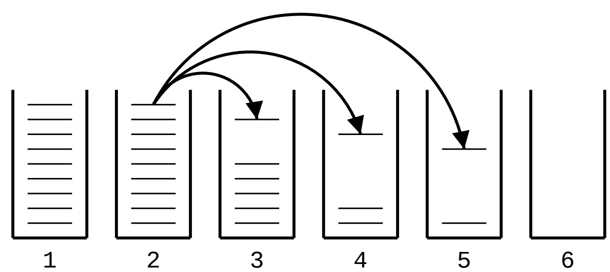
Pruning

- Hypothesis recombination is not sufficient

⇒ Heuristically discard weak hypotheses

- Organize Hypothesis in stacks, e.g. by
  - same foreign words covered
  - same number of foreign words covered (Pharaoh does this)
  - same number of English words produced
- Compare hypotheses in stacks, discard bad ones
  - histogram pruning: keep top n hypotheses in each stack (e.g., n=100)
  - threshold pruning: keep hypotheses that are at most α times the cost of best hypothesis in stack (e.g., α = 0.001)

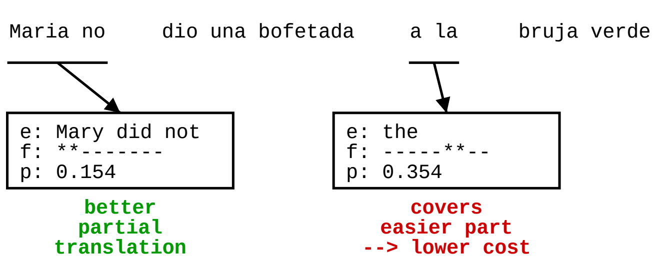
Hypothesis Stacks



- Organization of hypothesis into stacks
  - here: based on number of foreign words translated
  - during translation all hypotheses from one stack are expanded
  - expanded Hypotheses are placed into stacks

Comparing Hypotheses

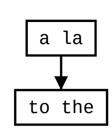
- Comparing hypotheses with same number of foreign words covered



- Hypothesis that covers *easy* part of sentence is preferred

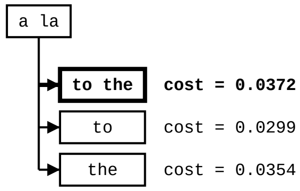
⇒ Need to consider future cost of uncovered parts

Future Cost Estimation



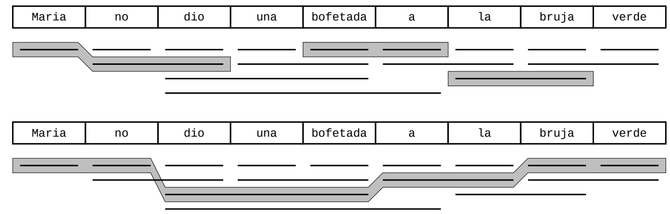
- Estimate cost to translate remaining part of input
- Step 1: estimate future cost for each translation option
  - look up translation model cost
  - estimate language model cost (no prior context)
  - ignore reordering model cost
  - → LM * TM = p(to) * p(the|to) * p(to the|a la)

Future Cost Estimation: Step 2



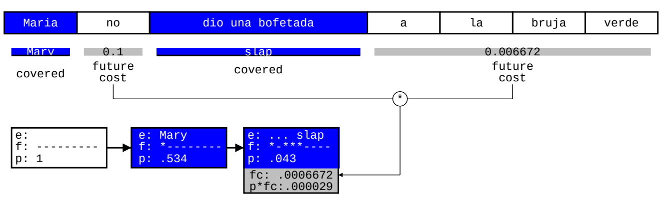
- Step 2: find cheapest cost among translation options

Future Cost Estimation: Step 3



- Step 3: find cheapest future cost path for each span
  - can be done efficiently by dynamic programming
  - future cost for every span can be precomputed

Future Cost Estimation: Application



- Use future cost estimates when pruning hypotheses
- For each uncovered contiguous span:
  - look up future costs for each maximal contiguous uncovered span
  - factor them to actually accumulated cost for translation option for pruning

Pharaoh

- A beam search decoder for phrase-based models
  - works with various phrase-based models
  - beam search algorithm
  - time complexity roughly linear with input length
  - good quality takes about 1 second per sentence
- Very good performance in DARPA/NIST Evaluation
- Freely available for researchers

  `http://www.isi.edu/licensed-sw/pharaoh/`

Running the decoder

- An example run of the decoder:

```
% echo 'das ist ein kleines haus' | pharaoh -f pharaoh.ini > out
Pharaoh v1.2.9, written by Philipp Koehn
a beam search decoder for phrase-based statistical machine
translation models
(c) 2002-2003 University of Southern California
(c) 2004 Massachusetts Institute of Technology
(c) 2005 University of Edinburgh, Scotland
loading language model from europarl.srilm
loading phrase translation table from phrase-table, stored 21, pruned
0, kept 21
loaded data structures in 2 seconds
reading input sentences
translating 1 sentences.translated 1 sentences in 0 seconds

% cat out
this is a small house
```


Phrase Translation Table

- Core model component is the phrase translation table:

```
der ||| the ||| 0.3
das ||| the ||| 0.4
das ||| it ||| 0.1
das ||| this ||| 0.1
die ||| the ||| 0.3
ist ||| is ||| 1.0
ist ||| 's ||| 1.0
das ist ||| it is ||| 0.2
das ist ||| this is ||| 0.8
es ist ||| it is ||| 0.8
es ist ||| this is ||| 0.2
ein ||| a ||| 1.0
ein ||| an ||| 1.0
klein ||| small ||| 0.8
klein ||| little ||| 0.8
kleines ||| small ||| 0.2
kleines ||| little ||| 0.2
haus ||| house ||| 1.0
alt ||| old ||| 0.8
altes ||| old ||| 0.2
gibt ||| gives ||| 1.0
es gibt ||| there is ||| 1.0
```

Trace

- Running the decoder with switch "-t"

```
% echo 'das ist ein kleines haus' | pharaoh -f pharaoh.ini -t
[...]
this is |0.014086|0|1| a |0.188447|2|2| small |0.000706353|3|3|
house |1.46468e-07|4|4|
```

- Trace for each applied phrase translation:
  - output phrase (there is)
  - cost incurred by this phrase (0.014086)
  - coverage of foreign words (0-1)

Reordering Example

- Sometimes phrases have to be reordered:

```
% echo 'ein kleines haus ist das' | pharaoh -f pharaoh.ini -t -d 0.5
[...]
this |0.000632805|4|4| is |0.13853|3|3| a |0.0255035|0|0|
small |0.000706353|1|1| house |1.46468e-07|2|2|
```

- First output phrase (this) is translation of the 4th word

Hypothesis Accounting

- The switch "-v" allows for detailed run time information:

```
% echo 'das ist ein kleins haus' | pharaoh -f pharaoh.ini -v 2
[...]
HYP: 114 added, 284 discarded below threshold, 0 pruned, 58 merged.
BEST: this is a small house -28.9234
```

- Statistics over how many hypothesis were generated
  - 114 hypotheses were added to hypothesis stacks
  - 284 hypotheses were discarded because they were too bad
  - 0 hypotheses were pruned, because a stack got too big
  - 58 hypotheses were merged due to recombination
- Probability of the best translation: exp(-28.9234)

Translation Options

- Even more run time information is revealed with "-v 3":

```
[das;2]
          the<1>, pC=-0.916291, c=-5.78855
          it<2>, pC=-2.30259, c=-8.0761
          this<3>, pC=-2.30259, c=-8.00205
[ist;4]
          is<4>, pC=0, c=-4.92223
          's<5>, pC=0, c=-6.11591
[ein;7]
          a<8>, pC=0, c=-5.5151
          an<9>, pC=0, c=-6.41298
[kleines;9]
          small<10>, pC=-1.60944, c=-9.72116
          little<11>, pC=-1.60944, c=-10.0953
[haus;10]
          house<12>, pC=0, c=-9.26607
[das ist;5]
          it is<6>, pC=-1.60944, c=-10.207
          this is<7>, pC=-0.223144, c=-10.2906
```

- Translation model cost (pC) and future cost estimates (c)

Future Cost Estimation

- Pre-computation of the future cost estimates:

```
future costs from 0 to 0 is -5.78855
future costs from 0 to 1 is -10.207
future costs from 0 to 2 is -15.7221
future costs from 0 to 3 is -25.4433
future costs from 0 to 4 is -34.7094
future costs from 1 to 1 is -4.92223
future costs from 1 to 2 is -10.4373
future costs from 1 to 3 is -20.1585
future costs from 1 to 4 is -29.4246
future costs from 2 to 2 is -5.5151
future costs from 2 to 3 is -15.2363
future costs from 2 to 4 is -24.5023
future costs from 3 to 3 is -9.72116
future costs from 3 to 4 is -18.9872
future costs from 4 to 4 is -9.26607
```


Hypothesis Expansion

- Start of beam search: First hypothesis (das $\rightarrow$ the)

```
creating hypothesis 1 from 0 ( ...  </s> <s> )
          base score 0
          covering 0-0:  das
          translated as:  the => translation cost -0.916291
          distance 0 => distortion cost 0
          language model cost for 'the' -2.03434
          word penalty -0
          score -2.95064 + futureCost -29.4246 = -32.3752
new best estimate for this stack
merged hypothesis on stack 1, now size 1
```

Hypothesis Expansion

- Another hypothesis (das ist $\rightarrow$ this is)

```
creating hypothesis 12 from 0 ( ...  </s> <s> )
          base score 0
          covering 0-1:  das ist
          translated as:  this is => translation cost -0.223144
          distance 0 => distortion cost 0
          language model cost for 'this' -3.06276
          language model cost for 'is' -0.976669
          word penalty -0
          score -4.26258 + futureCost -24.5023 = -28.7649
new best estimate for this stack
merged hypothesis on stack 2, now size 2
```


Hypothesis Expansion

- Hypothesis recombination

```
creating hypothesis 27 from 3 ( ...  <s> this )
          base score -5.36535
          covering 1-1:  ist
          translated as:  is => translation cost 0
          distance 0 => distortion cost 0
          language model cost for 'is' -0.976669
          word penalty -0
          score -6.34202 + futureCost -24.5023 = -30.8443
worse than existing path to 12, discarding
```


Hypothesis Expansion

- Bad hypothesis that falls out of the beam

```
creating hypothesis 52 from 6 ( ...  <s> a )
          base score -6.65992
          covering 0-0:  das
          translated as:  this => translation cost -2.30259
          distance -3 => distortion cost -3
          language model cost for 'this' -8.69176
          word penalty -0
          score -20.6543 + futureCost -23.9095 = -44.5637
estimate below threshold, discarding
```


Generating Best Translation

- Generating best translation
  - find best final hypothesis (442)
  - trace back path to initial hypothesis

```
best hypothesis 442
[ 442 => 343 ]
[ 343 => 106 ]
[ 106 => 12 ]
[ 12 => 0 ]
```


Translation Table Pruning

- Limiting translation table size speeds up search
- Histogram pruning: keeping only top n entries
- Threshold pruning: keep only entries that score α times worse than best

Beam Size

- Trade-off between speed and quality via beam size

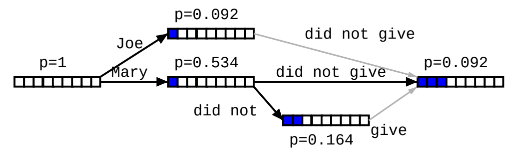
```
% echo 'das ist ein kleines haus' | pharaoh -f pharaoh.ini -s 10 -v 2
[...]
collected 12 translation options
HYP: 78 added, 122 discarded below threshold, 33 pruned, 20 merged.
BEST: this is a small house -28.9234
```

Beam size	Threshold	Hyp. added	Hyp. discarded	Hyp. pruned	Hyp. merged
1000	unlimited	634	0	0	1306
100	unlimited	557	32	199	572
100	0.00001	144	284	0	58
10	0.00001	78	122	33	20
1	0.00001	9	19	4	0

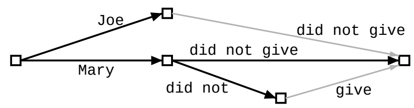
Limits on Reordering

- Reordering may be limited
  - Monotone Translation: No reordering at all
  - Only phrase movements of at most n words
- Reordering limits speed up search
- Current reordering models are weak, so limits improve translation quality

Word Lattice Generation



- Search graph can be easily converted into a word lattice
  - can be further mined for n-best lists
  - → enables reranking approaches
  - → enables discriminative training



Sample N-Best List

- N-best list from Pharaoh:

```
Translation ||| Reordering LM TM WordPenalty ||| Score
this is a small house ||| 0 -27.0908 -1.83258 -5 ||| -28.9234
this is a little house ||| 0 -28.1791 -1.83258 -5 ||| -30.0117
it is a small house ||| 0 -27.108 -3.21888 -5 ||| -30.3268
it is a little house ||| 0 -28.1963 -3.21888 -5 ||| -31.4152
this is an small house ||| 0 -31.7294 -1.83258 -5 ||| -33.562
it is an small house ||| 0 -32.3094 -3.21888 -5 ||| -35.5283
this is an little house ||| 0 -33.7639 -1.83258 -5 ||| -35.5965
this is a house small ||| -3 -31.4851 -1.83258 -5 ||| -36.3176
this is a house little ||| -3 -31.5689 -1.83258 -5 ||| -36.4015
it is an little house ||| 0 -34.3439 -3.21888 -5 ||| -37.5628
it is a house small ||| -3 -31.5022 -3.21888 -5 ||| -37.7211
this is an house small ||| -3 -32.8999 -1.83258 -5 ||| -37.7325
it is a house little ||| -3 -31.586 -3.21888 -5 ||| -37.8049
this is an house little ||| -3 -32.9837 -1.83258 -5 ||| -37.8163
the house is a little ||| -7 -28.5107 -2.52573 -5 ||| -38.0364
the is a small house ||| 0 -35.6899 -2.52573 -5 ||| -38.2156
is it a little house ||| -4 -30.3603 -3.91202 -5 ||| -38.2723
the house is a small ||| -7 -28.7683 -2.52573 -5 ||| -38.294
it 's a small house ||| 0 -34.8557 -3.91202 -5 ||| -38.7677
this house is a little ||| -7 -28.0443 -3.91202 -5 ||| -38.9563
it 's a little house ||| 0 -35.1446 -3.91202 -5 ||| -39.0566
this house is a small ||| -7 -28.3018 -3.91202 -5 ||| -39.2139
```


XML Interface

```
Er erzielte <NUMBER english='17.55'>17,55</NUMBER> Punkte .
```

- Add additional translation options
  - number translation
  - noun phrase translation [Koehn, 2003]
  - name translation
- Additional options
  - provide multiple translations
  - provide probability distribution along with translations
  - allow bypassing of provided translations

Thank You!

- Questions?