Natural Language Processing
Machine Translation

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Borrows slides Kevin Knight, Dan Klein, and Bill MacCartney

IBM Models 1,2,3,4,5

- Models for P(**f**|**e**) and P(**a**|**f**,**e**) via P(**f**,**a**|**e**)
- There is a set of English words and the extra English word NULL
- Each English word generates and places 0 or more French words
- Any remaining French words are deemed to have been produced by NULL

Applying IBM Generative Models

P(*f*, *a* | *e*) can be used as a *translation model* or an *alignment model*

As translation model $$P(f|e) = \sum_a P(f,a|e)$$

As alignment model $$P(a|e,f) = \frac{P(f,a|e)}{P(f|e)} = \frac{P(f,a|e)}{\sum_{a'} P(f,a'|e)}$$

IBM StatMT Translation Models

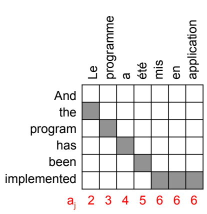
- IBM1 – lexical probabilities only
- IBM2 – lexicon plus absolute position
- HMM – lexicon plus relative position
- IBM3 – plus fertilities
- IBM4 – inverted relative position alignment
- IBM5 – non-deficient version of model 4

- All the models we discuss today handle 0:1, 1:0, 1:1, 1:n alignments *only*

[Brown et al. 93, Vogel et al. 96]

MT Word Alignment Models: IBM Model 1 parameters

$$P(f,a|e) = P(J|I)\prod_j P(a_j)P(f_j|e_{a_j})$$
$$= \epsilon \prod_j P(a_j)P(f_j|e_{a_j})$$
$$= \epsilon \prod_j \frac{1}{I+1} P(f_j|e_{a_j})$$
$$= \frac{\epsilon}{(I+1)^J} \prod_j P(f_j|e_{a_j})$$



Model 1: Word alignment learning with Expectation-Maximization (EM)

- Start with P(f^p|e^q) uniform, including P(f^p|NULL)
- For each sentence pair (*e*, *f*)
  - For each French position *j*

E
    - Calculate posterior over English positions P(a_j | *e*, *f*)

$$P(a_j = i \mid f, e) = \frac{P(f_j \mid e_i)}{\sum_{i'} P(f_j \mid e_{i'})}$$

    - Increment count of word f_j with word e_{a_j}
      - C(f_j|e_i) += P(a_j = *i* | *f*,*e*)

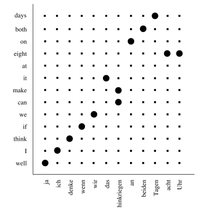
M
- Renormalize counts to give probs $P(f^p \mid e^q) = \frac{C(f^p \mid e^q)}{\sum_{f^x} C(f^x \mid e^q)}$
- Iterate until convergence

Do some reading!

- ~~Brown et al. 1993 "The Mathematics of Statistical Machine Translation"~~
- K. Knight, tutorial
- M. Collins, notes
- D. Jurafsky, ch. 25
- A. Lopez, survey article

IBM Models 1,2,3,4,5

- In Model 2, the placement of a word in the French depends on where it was in the English



- Unlike Model 1, Model 2 captures the intuition that translations should usually "lie along the diagonal".
- The main focus of PA #1.

IBM Models 1,2,3,4,5

- In Model 3, we model how many French words an English word can produce, using a concept called *fertility*

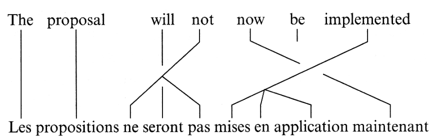
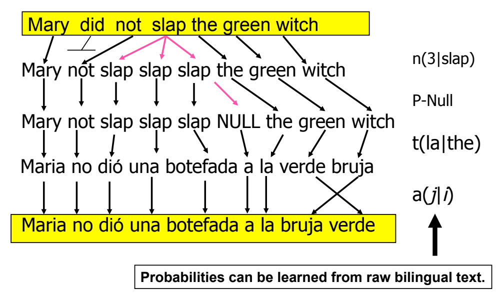


Figure 32.3
Alignment example.

Model 3 generative story



IBM Model 3 (from Knight 99)

- For each word e_i in English sentence, choose a fertility Φ_i. The choice of Φ_i depends only on e_i, not other words or Φ's.
- For each word e_i, generate Φ_i Spanish words. Choice of Spanish word depends only on English word e_i, not English context or any Spanish words.
- Permute all the Spanish words. Each Spanish word gets assigned absolute target position slot (1,2,3, etc). Choice of Spanish word position dependent only on absolute position of English word generating it.

Model 3: P(f|e) parameters

- What are the parameters for this model?
- Words: P(casa|house) = t(casa|house)
- Spurious words: P(a|null)
- Fertilities: n(1|house): prob that "house" will produce 1 Spanish word whenever it appears.
- Distortions: a(5|2): prob that word in position 2 of English sentence generates word in position 5 of French translation
  - Actually, distortions are a(5|2,4,6) where 4 is length of English sentence, 6 is Spanish length

Spurious words

- We could have n(3|NULL) (probability of being exactly 3 spurious words in a Spanish translation)
- But instead, of n(0|NULL), n(1|NULL) … n(25|NULL), have a single parameter p_1
- After assign fertilities to non-NULL English words we want to generate (say) z Spanish words.
- As we generate each of z words, we optionally toss in spurious Spanish word with probability p_1
- Probability of not adding spurious word: $p_0 = 1 – p_1$

Distortion probabilities for spurious words

- Can't just have a(5|0,4,6), I.e., chance that NULL word will end up in position 5.
- Why? These are spurious words! Could occur anywhere!! Too hard to predict
- Instead,
  - Use normal-word distortion parameters to choose positions for normally-generated Spanish words
  - Put NULL-generated words into empty slots left over
  - If three NULL-generated words, and three empty slots, then there are 3!, or six, ways for slotting them all in
  - We'll assign a probability of 1/6 for each way

Detailed Model 3 story

- For each word e_i in English sentence, choose fertility Φ_i with prob $n(\Phi_i| e_i)$
- Choose number Φ_0 of spurious Spanish words to be generated from e_0=NULL using p_1 and sum of fertilities from step 1
- Let m be sum of fertilities for all words including NULL
- For each i = 0,1,2,…I , k=1,2,… Φ_i :
  - choose Spanish word τ_{ik} with probability $t(\tau_{ik}|e_i)$
- For each i=1,2,…I , k=1,2,… Φ_i :
  - choose target Spanish position π_{ik} with prob $a(\pi_{ik}|I,L,m)$
- For each k=1,2,…, Φ_0 choose position π_{0k} from Φ_0 – k+1 remaining vacant positions in 1,2,…m for total prob of $1/ \Phi_0!$
- Output Spanish sentence with words τ_{ik} in positions π_{ik} (0<=I<=1,1<=k<= Φ_I)

Model 3 parameters

- n, t, p, a
- Again, if we had complete data of English strings and step-by-step rewritings into Spanish, we could:
  - Compute n(0|did) by locating every instance of "did", and seeing how many words it translates to
  - t(maison|house) how many of all French words generated by "house" were "maison"
  - a(5|2,4,6) out of all times some second word was translated, how many times did it become the fifth word (in sentences of length 4 and 6 respectively)?

Since we don't have word-aligned data…

- We bootstrap alignments from incomplete data
- From a sentence-aligned bilingual corpus
  1) Assume some startup values for n, d, t, p.
  2) Use values for n, a, t, p in model 3 to work out chances of different possible alignments. Use these alignments to update values of n, a, t, p.
  3) Go to 2
- This is a more complicated case of the EM algorithm

Difficulty: Alignments are no longer independent of each other. Have to use approximate inference

Examples: translation & fertility

the

f	$t(f \mid e)$	ϕ	$n(\phi \mid e)$
le	0.497	1	0.746
la	0.207	0	0.254
les	0.155		
l'	0.086		
ce	0.018		
cette	0.011		

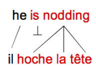
not

f	$t(f \mid e)$	ϕ	$n(\phi \mid e)$
ne	0.497	2	0.735
pas	0.442	0	0.154
non	0.029	1	0.107
rien	0.011		

farmers

f	$t(f \mid e)$	ϕ	$n(\phi \mid e)$
agriculteurs	0.442	2	0.731
les	0.418	1	0.228
cultivateurs	0.046	0	0.039
producteurs	0.021		

Example: idioms



nodding

f	$t(f \mid e)$	ϕ	$n(\phi \mid e)$
signe	0.164	4	0.342
la	0.123	3	0.293
tête	0.097	2	0.167
oui	0.086	1	0.163
fait	0.073	0	0.023
que	0.073		
hoche	0.054		
hocher	0.048		
faire	0.030		
me	0.024		
approuve	0.019		
qui	0.019		
un	0.012		
faites	0.011		

Example: morphology

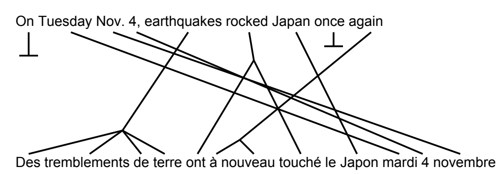
should

f	$t(f \mid e)$	ϕ	$n(\phi \mid e)$
devrait	0.330	1	0.649
devraient	0.123	0	0.336
devrions	0.109	2	0.014
faudrait	0.073		
faut	0.058		
doit	0.058		
aurait	0.041		
doivent	0.024		
devons	0.017		
devrais	0.013		

IBM Models 1,2,3,4,5

- In model 4 the placement of later French words produced by an English word depends on what happened to earlier French words generated by that same English word

Alignments: linguistics



IBM Models 1,2,3,4,5

- In model 5 they patch model 4. They make it do non-deficient alignment. That is, you can't put probability mass on impossible things.

Why all the models?

- We don't start with aligned text, so we have to get initial alignments from somewhere.
- The alignment space has many local maxima
- Model 1 is words only, a simple model that is relatively easy and fast to train.
- The output of M1 can be a good place to start M2
  - "Starting small". Also, it's convex.
- The sequence of models allows a better model to be found, faster
  - The intuition is like deterministic annealing

Evaluating Alignments: Alignment Error Rate (Och & Ney 2000)

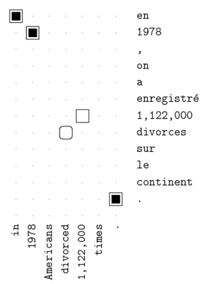
☐ = Sure

◯ = Possible

■ = Alignments (predicted)

$$AER(A,S,P) = \left(1 - \frac{|A \cap S| + |A \cap P|}{|A| + |S|}\right)$$

$$= \left(1 - \frac{3+3}{3+4}\right) = \frac{1}{7}$$



Most work has used AER and we do, but it is problematic, and it's better to use an alignment F measure (Fraser and Marcu 2007)

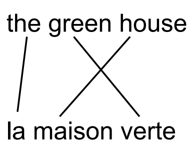
Comparative results (AER)

[Och & Ney 2003]

		Size of training corpus			
Model	Training scheme	0.5K	8K	128K	1.47M
Dice		50.9	43.4	39.6	38.9
Dice+C		46.3	37.6	35.0	34.0
Model 1	1^5	40.6	33.6	28.6	25.9
Model 2	$1^5 2^5$	46.7	29.3	22.0	19.5
HMM	$1^5 H^5$	26.3	23.3	15.0	10.8
Model 3	$1^5 2^5 3^3$	43.6	27.5	20.5	18.0
	$1^5 H^5 3^3$	27.5	22.5	16.6	13.2
Model 4	$1^5 2^5 3^3 4^3$	41.7	25.1	17.3	14.1
	$1^5 H^5 3^3 4^3$	26.1	20.2	13.1	9.4
	$1^5 H^5 4^3$	26.3	21.8	13.3	9.3
Model 5	$1^5 H^5 4^3 5^3$	26.5	21.5	13.7	9.6
	$1^5 H^5 3^3 4^3 5^3$	26.5	20.4	13.4	9.4
Model 6	$1^5 H^5 4^3 6^3$	26.0	21.6	12.8	8.8
	$1^5 H^5 3^3 4^3 6^3$	25.9	20.3	12.5	8.7

Common software: GIZA++/Berkeley Aligner

Alignments: linguistics



- There isn't enough linguistics to explain this in the translation model … have to depend on the language model … that may be unrealistic … and may be harming our translation model

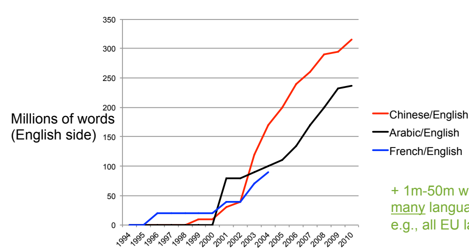
Getting Parallel Sentence Data

- Really hard way: pay $$$
  - Suppose 100 million words of parallel data were sufficient
  - At 5 cents/word, that's $5 million
- Pretty hard way: Find it, and then earn it!
  - Crawl web identifying likely parallel text (or use CommonCrawl)
  - De-formatting
  - Remove strange characters
  - Character code conversion
  - Document alignment
  - **Sentence alignment**
  - **Tokenization (also called Segmentation)**

Getting Parallel Sentence Data

- Easy way: Use existing data
  - Linguistic Data Consortium (LDC)
    - http://www.ldc.upenn.edu/
  - EuroParl:
    - http://www.statmt.org/europarl/
    - Around 50 million words per language for "old" EU countries

Ready-to-Use Online Bilingual Data



+ 1m-50m words for many language pairs, e.g., all EU languages)

(Data stripped of formatting, in sentence-pair format, available from the Linguistic Data Consortium at UPenn).

Tokenization (or Segmentation)

- English
  - Input (some character stream):
    `"There," said Bob.`
  - Output (7 “tokens” or “words”):
    `" There , " said Bob .`
- Chinese
  - Input (char stream): 美国关岛国际机场及其办公室均接获一名自称沙地阿拉伯富商拉登等发出的电子邮件。
  - Output: 美国 关岛国 际机 场 及其 办公 室 均接获 一名 自称 沙地 阿拉 伯富 商拉登 等发 出 的 电子邮件。

Sentence Alignment

The old man is happy. He has fished many times. His wife talks to him. The fish are jumping. The sharks await.

El viejo está feliz porque ha pescado muchos veces. Su mujer habla con él. Los tiburones esperan.

Sentence Alignment

1. The old man is happy.
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Done by similar Dynamic Programming or EM: see FSNLP ch. 13 for details

Search for Best Translation

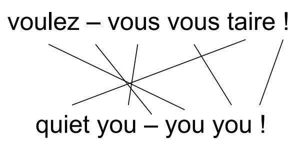
voulez – vous vous taire !

Search for Best Translation

voulez – vous vous taire !

you – you you quiet !

Search for Best Translation



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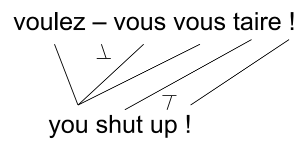

Searching for a translation

Of all conceivable English word strings, we want the one maximizing P(e) x P(f | e)

Exact search

- Even if we have the right words for a translation, there are **n!** permutations.
- We want the translation that gets the highest score under our model
- Finding the argmax with a n-gram language model is NP-complete [Germann et al. 2001].
- Equivalent to Traveling Salesman Problem

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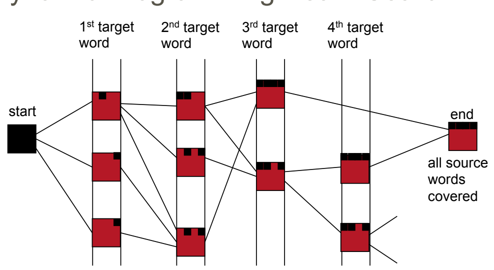
Searching for a translation

- Several search strategies are available
  - Usually a beam search where we keep multiple stacks for candidates covering the same number of source words
  - Or, we could try "greedy decoding", where we start by giving each word its most likely translation and then attempt a "repair" strategy of improving the translation by applying search operators (Germann et al. 2001)
- Each potential English output is called a *hypothesis*.

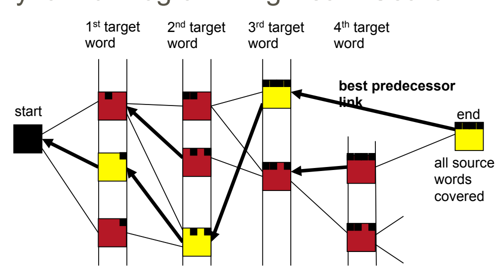
Dynamic Programming Beam Search



Each partial translation hypothesis contains:
- Last English word chosen + source words covered by it
- Next-to-last English word chosen
- Entire coverage vector (so far) of source sentence
- Language model and translation model scores (so far)

[Jelinek, 1969; Brown et al, 1996 US Patent; (Och, Ueffing, and Ney, 2001]

Dynamic Programming Beam Search



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MT Evaluation

Illustrative translation results

- *la politique de la haine .* *(Foreign Original)*
- politics of hate . (Reference Translation)
- the policy of the hatred . (IBM4+N-grams+Stack)

- *nous avons signé le protocole .* *(Foreign Original)*
- we did sign the memorandum of agreement . (Reference Translation)
- we have signed the protocol . (IBM4+N-grams+Stack)

- *où était le plan solide ?* *(Foreign Original)*
- but where was the solid plan ? (Reference Translation)
- where was the economic base ? (IBM4+N-grams+Stack)

对外经济贸易合作部今天提供的数据表明，今年至十一月中国实际利用外资四百六十九点五九亿美元，其中包括外商直接投资四百点零七亿美元。

the Ministry of Foreign Trade and Economic Cooperation, including foreign direct investment 40.007 billion US dollars today provide data include that year to November china actually using foreign 46.959 billion US dollars and

MT Evaluation

- Manual (the best!?):
  - SSER (subjective sentence error rate)
  - Correct/Incorrect
  - **Adequacy and Fluency** (5 or 7 point scales)
  - Error categorization
  - **Comparative ranking of translations**
- Testing in an application that uses MT as one sub-component
  - E.g., question answering from foreign language documents
    - May not test many aspects of the translation (e.g., cross-lingual IR)
- Automatic metric:
  - WER (word error rate) – why problematic?
  - **BLEU (Bilingual Evaluation Understudy)**

BLEU Evaluation Metric

(Papineni et al, ACL-2002)

Reference (human) translation:
The U.S. island of Guam is maintaining a high state of alert after the Guam airport and its offices both received an e-mail from someone calling himself the Saudi Arabian Osama bin Laden and threatening a biological/ chemical attack against public places such as the airport .

Machine translation:
The American [?] international airport and its the office all receives one calls self the sand Arab rich business [?] and so on electronic mail , which sends out ; The threat will be able after public place and so on the airport to start the biochemistry attack , [?] highly alerts after the maintenance.

- N-gram precision (score is between 0 & 1)
  - What percentage of machine n-grams can be found in the reference translation?
    - An n-gram is an sequence of n words
  - Not allowed to match same portion of reference translation twice at a certain n-gram level (two MT words *airport* are only correct if two reference words *airport;* can't cheat by typing out "the the the the the")
  - Do count unigrams also in a bigram for unigram precision, etc.
- Brevity Penalty
  - Can't just type out single word "the" (precision 1.0!)
- It was thought quite hard to "game" the system (i.e., to find a way to change machine output so that BLEU goes up, but quality doesn't)

BLEU Evaluation Metric

(Papineni et al, ACL-2002)

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- BLEU is a weighted geometric mean, with a brevity penalty factor added.
  - Note that it's precision-oriented
- BLEU4 formula
  (counts n-grams up to length 4)

exp (1.0 * log p1 +
0.5 * log p2 +
0.25 * log p3 +
0.125 * log p4 –
max(words-in-reference / words-in-machine – 1, 0)

p1 = 1-gram precision
P2 = 2-gram precision
P3 = 3-gram precision
P4 = 4-gram precision

Note: only works at corpus level (zeroes kill it); there's a smoothed variant for sentence-level

BLEU in Action

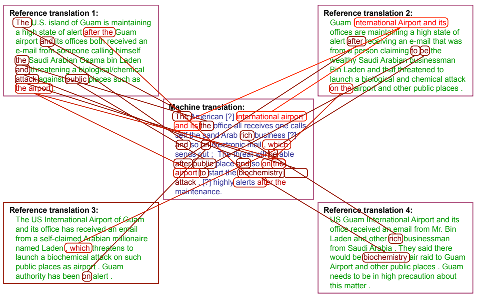
枪手被警方击毙。 **(Foreign Original)**

the gunman was shot to death by the police . **(Reference Translation)**

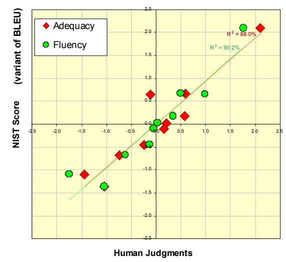
the gunman was police kill .	**#1**
wounded police jaya of	**#2**
the gunman was shot dead by the police .	**#3**
the gunman arrested by police kill .	**#4**
the gunmen were killed .	**#5**
the gunman was shot to death by the police .	**#6**
gunmen were killed by police ?SUB>0 ?SUB>0	**#7**
al by the police .	**#8**
the ringer is killed by the police .	**#9**
police killed the gunman .	**#10**

green = 4-gram match (good!)
red = word not matched (bad!)

Multiple Reference Translations



Initial results showed that BLEU predicts human judgments well



slide from G. Doddington (NIST)

Automatic evaluation of MT

- People started optimizing their systems to maximize BLEU score
  - BLEU scores improved rapidly
  - The correlation between BLEU and human judgments of quality went way, way down
  - StatMT BLEU scores now approach those of human translations but their true quality remains far below human translations
- Coming up with automatic MT evaluations has become its own research field
  - There are many proposals: TER, METEOR, MaxSim, SEPIA, our own RTE-MT
  - TERpA is a representative good one that handles some word choice variation.
- MT research **requires** *some* automatic metric to allow a rapid development and evaluation cycle.