

Statistical Machine Translation

Part IV – Log-Linear Models

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Where we have been

- Solving a problem where we are predicting a structured output:
 - Problem definition
 - Evaluation, i.e., how will we evaluate progress?
 - Model
 - Training = parameter estimation
- Still to come:
 - Search (= decoding, for SMT)

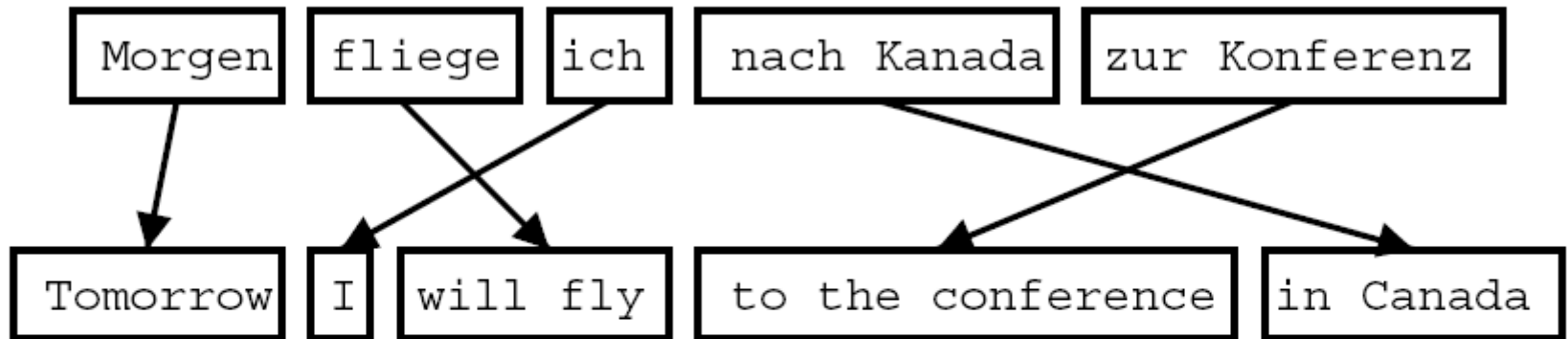
Where we are going today

- The generative models we have seen so far are good, but we can do better
 - Switch to **discriminative models** (this will be defined later)
 - We will see that this frees us from the structure of the generative model!
 - We can concentrate on new knowledge sources
 - Also, no more annoying open parameters
 - Discriminative models are used practically everywhere in NLP these days (including in deep learning approaches)

Outline

- Recap: original phrase-based model
- Optimizing parameters
- Deriving the log-linear model
- Tuning the log-linear model
- Adding new features

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-based translation model

- Major components of phrase-based model

- **phrase translation model** $\phi(\mathbf{f}|\mathbf{e})$
- **reordering model** d
- **language model** $p_{\text{LM}}(\mathbf{e})$

- Bayes rule

$$\begin{aligned}\operatorname{argmax}_{\mathbf{e}} p(\mathbf{e}|\mathbf{f}) &= \operatorname{argmax}_{\mathbf{e}} p(\mathbf{f}|\mathbf{e})p(\mathbf{e}) \\ &= \operatorname{argmax}_{\mathbf{e}} \phi(\mathbf{f}|\mathbf{e})p_{\text{LM}}(\mathbf{e})\omega^{\text{length}(\mathbf{e})}\end{aligned}$$

- Sentence \mathbf{f} is decomposed into I phrases $\bar{f}_1^I = \bar{f}_1, \dots, \bar{f}_I$

- Decomposition of $\phi(\mathbf{f}|\mathbf{e})$

$$\phi(\bar{f}_1^I|\bar{e}_1^I) = \prod_{i=1}^I \phi(\bar{f}_i|\bar{e}_i)d(a_i - b_{i-1})$$

Outline

- *Recap*
- Optimizing parameters
- Deriving the log-linear model
- Tuning the log-linear model
- Adding new features

Introduction

- We have seen that using Bayes' Rule we can decompose the problem of maximizing $P(e|f)$

$$\operatorname{argmax}_e P(e|f) = \operatorname{argmax}_e P(f|e) P(e)$$

Basic phrase-based model

- We make the Viterbi assumption for alignment (not summing over alignments, just taking the best one)
- We know how to implement $P(f,a|e)$ using a phrase-based translation model composed of a phrase-generation model and a reordering model
- We know how to implement $P(e)$ using a trigram model and a length bonus

$$P_{\text{TM}}(f, a | e) P_{\text{D}}(a) P_{\text{LM}}(e) C^{\text{length}(e)}$$

Example

Source: |Morgen| |fliege| |ich| |nach Kanada|

Hyp 1: |Tomorrow| |I| |will fly| |to Canada|

Hyp 2: |Tomorrow| |fly| |I| |to Canada|

- What do we expect the probabilities (or probability-like scores) to look like qualitatively?

	Phrase Trans	Reordering	Trigram LM	Length bonus
Hyp 1	Good	$Z^4 < 1$	Good	C^6
Hyp 2	Good	$Z^0 = 1$	Bad	$C^5 < C^6$

What determines which hyp is better?

- Which hyp gets picked?
 - Length bonus and trigram "like" hyp 1
 - Reordering "likes" hyp 2
- If we **optimize** Z and C for best performance, we will pick hyp 1

	Phrase Trans	Reordering	Trigram LM	Length bonus
Hyp 1	Good	$Z^4 < 1$	Good	C^6
Hyp 2	Good	$Z^0 = 1$	Bad	$C^5 < C^6$

How to optimize Z and C?

- Take a new corpus “dev” (1000 sentences, with gold standard references so we can score BLEU)
- Try out different parameters. [Take last C and Z printed]. How many runs?

```
Best = 0;
For (Z = 0; Z <= 1.0; Z += 0.1)
  For (C = 1.0; C <= 3.0; C += 0.1)
    Hyp = run_decoder(C, Z, dev)
    If (BLEU(Hyp) > Best)
      Best = BLEU(Hyp)
    Print C and Z
```

Adding weights

- But what if we know that the language model is really good; or really bad?
- We can take the probability output by this model to an exponent

$$P_{LM}(e)^{\lambda_{LM}}$$

- If we set the exponent to a very large positive number then we trust $P_{LM}(e)$ very much
 - If we set the exponent to zero, we do not trust it at all (probability is always 1, no matter what e is)

- Add a weight for each component

(Note, omitting length bonus here, it will be back soon; we'll set C to 1 for now so it is gone)

$$P_{TM}(f, a | e)^{\lambda_{TM}} P_D(a)^{\lambda_D} P_{LM}(e)^{\lambda_{LM}}$$

- To get a conditional probability, we will divide by all possible strings e and all possible alignments a

$$P(e, a | f) = \frac{P_{\text{TM}}(f, a | e)^{\lambda_{\text{TM}}} P_{\text{D}}(a)^{\lambda_{\text{D}}} P_{\text{LM}}(e)^{\lambda_{\text{LM}}}}{\sum_{e', a'} P_{\text{TM}}(f, a' | e')^{\lambda_{\text{TM}}} P_{\text{D}}(a')^{\lambda_{\text{D}}} P_{\text{LM}}(e')^{\lambda_{\text{LM}}}}$$

- To solve the decoding problem we maximize over e and a . But the term in the denominator is constant!

$$\begin{aligned} \operatorname{argmax}_{e,a} P(e, a | f) &= \operatorname{argmax}_{e,a} \frac{P_{\text{TM}}(f, a | e)^{\lambda_{\text{TM}}} P_{\text{D}}(a)^{\lambda_{\text{D}}} P_{\text{LM}}(e)^{\lambda_{\text{LM}}}}{\sum_{e',a'} P_{\text{TM}}(f, a' | e')^{\lambda_{\text{TM}}} P_{\text{D}}(a')^{\lambda_{\text{D}}} P_{\text{LM}}(e')^{\lambda_{\text{LM}}}} \\ &= \operatorname{argmax}_{e,a} P_{\text{TM}}(f, a | e)^{\lambda_{\text{TM}}} P_{\text{D}}(a)^{\lambda_{\text{D}}} P_{\text{LM}}(e)^{\lambda_{\text{LM}}} \end{aligned}$$

- Now let's add C back in and take the log (see formulation in a couple of slides)
- We now have two problems
 - Optimize Z and C and the three lambdas
 - Exponentiation is slow
 - Let's solve this one first...

Log probabilities

- Convenient to work in log space
- Use log base 10 because it is easy for humans
- $\log(1)=0$ because $10^0 = 1$
- $\log(1/10)=-1$ because $10^{-1} = 1/10$
- $\log(1/100)=-2$ because $10^{-2} = 1/100$
- $\text{Log}(a*b) = \log(a)+\log(b)$
- $\text{Log}(a^b) = b \log(a)$

So let's maximize the log

$$\operatorname{argmax}_{e,a} P(e, a | f)$$

$$= \operatorname{argmax}_{e,a} P_{\text{TM}}(f, a | e)^{\lambda_{\text{TM}}} P_{\text{D}}(a)^{\lambda_{\text{D}}} P_{\text{LM}}(e)^{\lambda_{\text{LM}}} C^{\text{length}(e)}$$

So let's maximize the log

$$\operatorname{argmax}_{e,a} P(e, a | f)$$

$$= \operatorname{argmax}_{e,a} P_{\text{TM}}(f, a | e)^{\lambda_{\text{TM}}} P_{\text{D}}(a)^{\lambda_{\text{D}}} P_{\text{LM}}(e)^{\lambda_{\text{LM}}} C^{\text{length}(e)}$$

$$= \operatorname{argmax}_{e,a} \log(P_{\text{TM}}(f, a | e)^{\lambda_{\text{TM}}} P_{\text{D}}(a)^{\lambda_{\text{D}}} P_{\text{LM}}(e)^{\lambda_{\text{LM}}} C^{\text{length}(e)})$$

So let's maximize the log

$$\operatorname{argmax}_{e,a} P(e, a | f)$$

$$= \operatorname{argmax}_{e,a} P_{\text{TM}}(f, a | e)^{\lambda_{\text{TM}}} P_{\text{D}}(a)^{\lambda_{\text{D}}} P_{\text{LM}}(e)^{\lambda_{\text{LM}}} C^{\text{length}(e)}$$

$$= \operatorname{argmax}_{e,a} \log(P_{\text{TM}}(f, a | e)^{\lambda_{\text{TM}}} P_{\text{D}}(a)^{\lambda_{\text{D}}} P_{\text{LM}}(e)^{\lambda_{\text{LM}}} C^{\text{length}(e)})$$

$$= \operatorname{argmax}_{e,a} \log(P_{\text{TM}}(f, a | e)^{\lambda_{\text{TM}}}) + \log(P_{\text{D}}(a)^{\lambda_{\text{D}}}) \\ + \log(P_{\text{LM}}(e)^{\lambda_{\text{LM}}}) + \log(C^{\text{length}(e)})$$

So let's maximize the log

$$\begin{aligned} & \operatorname{argmax}_{e,a} P(e, a | f) \\ &= \operatorname{argmax}_{e,a} P_{TM}(f, a | e)^{\lambda_{TM}} P_D(a)^{\lambda_D} P_{LM}(e)^{\lambda_{LM}} C^{\operatorname{length}(e)} \\ &= \operatorname{argmax}_{e,a} \log(P_{TM}(f, a | e)^{\lambda_{TM}} P_D(a)^{\lambda_D} P_{LM}(e)^{\lambda_{LM}} C^{\operatorname{length}(e)}) \\ &= \operatorname{argmax}_{e,a} \log(P_{TM}(f, a | e)^{\lambda_{TM}}) + \log(P_D(a)^{\lambda_D}) \\ &\quad + \log(P_{LM}(e)^{\lambda_{LM}}) + \log(C^{\operatorname{length}(e)}) \\ &= \operatorname{argmax}_{e,a} \lambda_{TM} \log(P_{TM}(f, a | e)) + \lambda_D \log(P_D(a)) \\ &\quad + \lambda_{LM} \log(P_{LM}(e)) + \log(C^{\operatorname{length}(e)}) \end{aligned}$$

Let's change the length bonus

$$= \operatorname{argmax}_{e,a} \lambda_{TM} \log(P_{TM}(f, a | e)) + \lambda_D \log(P_D(a)) \\ + \lambda_{LM} \log(P_{LM}(e)) + \lambda_{LB} \log(10^{\operatorname{length}(e)})$$

$$= \operatorname{argmax}_{e,a} \lambda_{TM} \log(P_{TM}(f, a | e)) + \lambda_D \log(P_D(a)) \\ + \lambda_{LM} \log(P_{LM}(e)) + \lambda_{LB} \operatorname{length}(e)$$

We set $C=10$ and add a new lambda, then simplify

Length penalty

$$= \operatorname{argmax}_{e,a} \lambda_{TM} \log(P_{TM}(f, a | e)) + \lambda_D \log(P_D(a)) \\ + \lambda_{LM} \log(P_{LM}(e)) + \lambda_{LP} (-\text{length}(e))$$

We like the values we work with to be zero or less
(like log probabilities)

We change from a length bonus to a length
penalty (LP)

But we know we want to encourage longer strings
so we expect that this lambda will be negative!

Reordering

$$= \operatorname{argmax}_{e,a} \lambda_{TM} \log(P_{TM}(f, a | e)) + \lambda_D (-D(a)) \\ + \lambda_{LM} \log(P_{LM}(e)) + \lambda_{LP} (-\text{length}(e))$$

Do the same thing for reordering. As we do more jumps, “probability” should go down.

So use $-D(a)$

$D(a)$ is the sum of the jump distances (4 for hyp 1 in our previous example)

Log-linear model

- So we now have a **log-linear model** with four components, and four lambda weights
 - The components are called **feature functions**
 - Given \mathbf{f} , \mathbf{e} and/or \mathbf{a} they generate a log probability value
 - Or a value looking like a log probability (Reordering, Length Penalty)
 - Other names: features, sub-models
- This is a discriminative model, not a generative model

The birth of SMT: generative models

- The definition of translation probability follows a **mathematical derivation**

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

- Occasionally, some **independence assumptions** are thrown in for instance IBM Model 1: word translations are independent of each other

$$p(\mathbf{e}|\mathbf{f}, a) = \frac{1}{Z} \prod_i p(e_i|f_{a(i)})$$

- Generative story leads to **straight-forward estimation**
 - maximum likelihood estimation of component probability distribution
 - **EM algorithm** for discovering hidden variables (alignment)

Discriminative vs. generative models

- Generative models
 - translation process is broken down to *steps*
 - each step is modeled by a *probability distribution*
 - each probability distribution is estimated from the data by *maximum likelihood*
- Discriminative models
 - model consist of a number of *features* (e.g. the language model score)
 - each feature has a *weight*, measuring its value for judging a translation as correct
 - feature weights are *optimized on development data*, so that the system output matches correct translations as close as possible

Search for the log-linear model

- We've derived the log-linear model!
- Next time we will talk about how to find the English string (and alignment) of maximum probability
 - For the old phrase-based model, the decoder needs to multiply unweighted probabilities as it did before
 - We only change it to **sum** (lambdas times log probabilities), to maximize this:

$$= \operatorname{argmax}_{e,a} \lambda_{TM} \log(P_{TM}(f | e)) + \lambda_D (-D(a)) \\ + \lambda_{LM} \log(P_{LM}(e)) + \lambda_{LP} (-\text{length}(e))$$

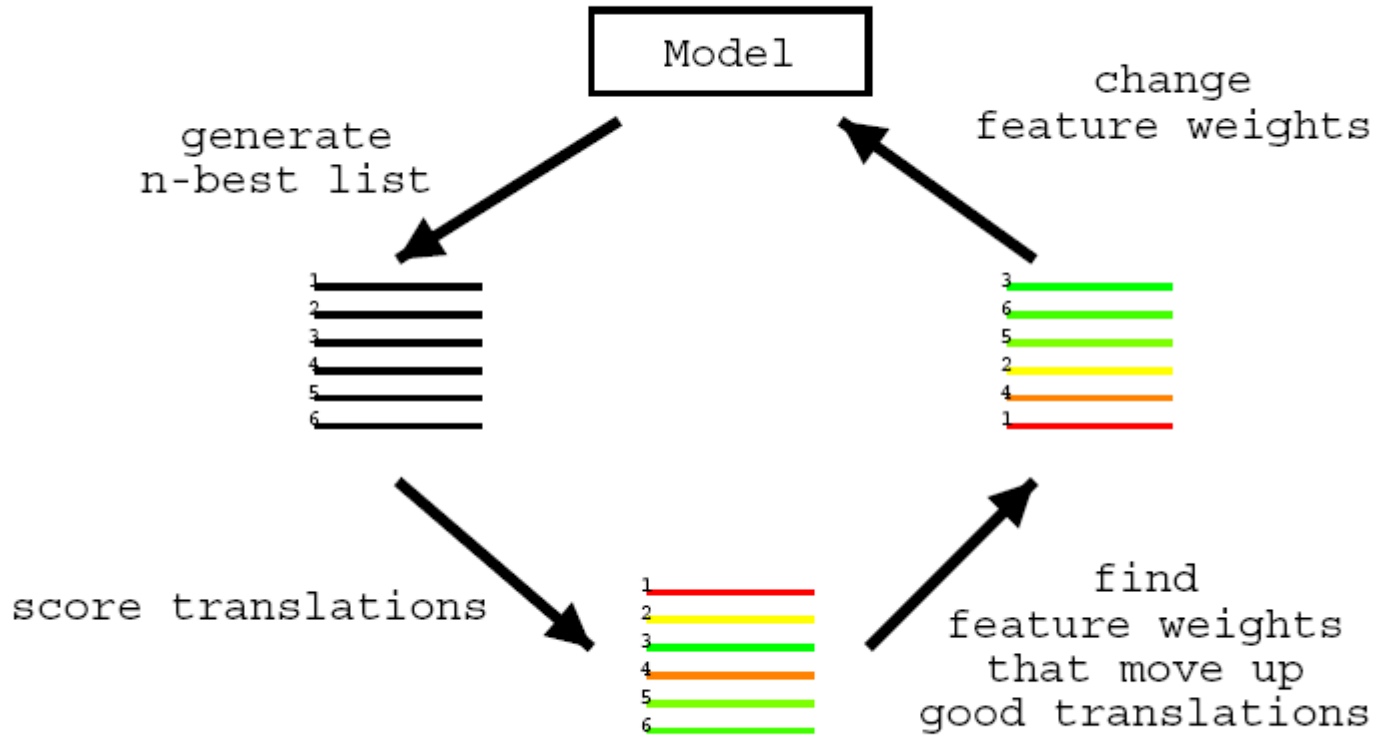
Discriminative training problem: optimizing lambda

- We are looking for the best lambda vector
 - A lambda vector consists of lambda scalars (4 for our model right now)
- How do we get an optimal lambda vector?
- We can use nested for-loops as we did before for C and Z
 - We need to try out a lot of values for the lambda scalars though, the differences could be very subtle
 - Many, many decoder runs; these take 10 minutes or longer each!
- At least we can reduce number of decoder runs
 - Use [n-best lists](#)

Discriminative training

- Training set (*development set*)
 - different from original training set
 - small (maybe 1000 sentences)
 - must be different from test set
- Current model *translates* this development set
 - *n-best list* of translations (n=100, 10000)
 - translations in n-best list can be *scored*
- Feature weights are *adjusted*
- N-Best list generation and feature weight adjustment repeated for a number of iterations

Learn feature weights



Learning Task

Source: |Morgen| |fliege| |ich| |nach Kanada|

Hyp 1: |Tomorrow| |I| |will fly| |to Canada|

Hyp 2: |Tomorrow| |fly| |I| |to Canada|

Assume that Hyp 1 has a better BLEU score

	Phrase Trans	Reordering	Trigram LM	Length
Hyp 1	-1	-4	-3	-6
Hyp 2	-1	0	-5	-5

Learning Task

Suppose we start with an initial lambda vector: 1 1 1 -1

Then: hyp 1 has a log score of -2 (1/100 probability)

hyp 2 has a log score of -1 (1/10 probability)

This is poor! Hyp 2 will be selected

	Phrase Trans	Reordering	Trigram LM	Length
Hyp 1	-1	-4	-3	-6
Hyp 2	-1	0	-5	-5

Learning Task

We would like to find a vector like: 1 0.5 2 -1

hyp 1 has a log score of -3

hyp 2 has a log score of -6

Hyp 1 is correctly selected!

	Phrase Trans	Reordering	Trigram LM	Length
Hyp 1	-1	-4	-3	-6
Hyp 2	-1	0	-5	-5

Learning Task

N-best lists contain several sentences and hypotheses for each sentence

The lambda vector 1 0.5 2 -1 picks Hyp 1 in the first sentence, and Hyp 2 in the second sentence.

Suppose sentence 2 Hyp 1 is better. Then choose a lambda like: 3 0.5 2 -1

It is easy to see that this does not change the ranking of the hypotheses in sentence 1.

Sentence	Hypothesis	Phrase Trans	Reordering	Trigram LM	Length bonus
1	Hyp 1	-1	-4	-3	-6
1	Hyp 2	-1	0	-5	-5
2	Hyp 1	-2	0	-3	-3
2	Hyp 2	-3	0	-2	-3

N-best lists result in big savings

- Run the for-loops on a small collection of hypotheses, do decoder runs only when you have good settings

Initialize: start with empty hypothesis collection

LOOP:

- Run the decoder with current lambda vector and add n-best list hypotheses to our collection
- Score collection of hypotheses with BLEU
- Use nested-for-loop to change individual lambda scalars in vector to get better BLEU on collection
- End program if lambda vector did not change

- OK, so we know how to set the lambda vector for our four feature functions
 - This means depending on the task we might, for instance, penalize reordering more or less
 - This is determined automatically by the performance on the dev corpus
- But what about new features?

New Feature Functions

- We can add new feature functions!
 - Simply add a new term and an associated lambda
 - Can be function of **e**, **f** and/or **a**
 - Can be either log probability (e.g., Trigram), or just look like one (e.g., Length Penalty)
- These can be very complex features to very simple features
 - Length penalty is simple
 - Phrase translation is complex
 - With right lambda settings they will trade-off against each other well!

New Feature Functions

- Features can overlap with one another!
 - In a generative model we do a sequence of steps, no overlapping allowed
 - In Model 1, you can't pick a generated word using two probability distributions
 - Note: Interpolation is not an answer here, would add the optimization of the interpolation weight into EM
 - Better to rework generative story if you must (this is difficult)
 - With a log-linear model we can score the probability of a phrase block using many different feature functions, because the model is not generative

Knowledge sources

- Many different **knowledge sources** useful
 - language model
 - reordering (distortion) model
 - phrase translation model
 - word translation model
 - word count
 - phrase count
 - drop word feature
 - phrase pair frequency
 - additional language models
 - additional features

Revisiting discriminative training: methods to adjust feature weights

- We will wind up with a lot of lambda scalars to optimize
- But there are algorithms to deal with this that are more efficient than nested for-loops
- In all cases, we have the same log-linear model
 - The only difference is in how to optimize the lambdas
 - We saw one way to do this already
 - Using nested for-loops on n-best lists
 - We will keep using n-best lists (but not nested for-loops)

Minimum Error Rate Training

- Maximize quality of top-ranked translation
 - Similarity according to metric (BLEU)
 - Implemented in Moses toolkit

Och's minimum error rate training (MERT)

- **Line search** for best feature weights

```
given: sentences with n-best list of
translations
iterate n times
    randomize starting feature weights
        iterate until convergences
            for each feature
                find best feature weight
                update if different from current
return best feature weights found in any
iteration
```

MERT is like “un-nesting” the for-loops

```
StartLambda = 1 1 1 -1
```

```
LOOP:
```

```
BestBLEU[1..4] = 0
```

```
For (i = 1 to 4)
```

```
  TryLambda = StartLambda
```

```
  For (L = 1.0; L <= 3.0; L += 0.1)
```

```
    TryLambda[i] = L
```

```
    Hyp = best_hyps_from_nbest_list(TryLambda)
```

```
    If (BLEU(Hyp) > BestBLEU[i])
```

```
      BestBLEU[i] = BLEU(Hyp)
```

```
      BestLambda[i] = L
```

Then simply check BestBLEU[1..4] for the best score.

Suppose it is BestBLEU[2].

Set StartLambda[2] = BestLambda[2] and go to top of loop (until you get no improvement).

However MERT is better than that

- We will not check discrete values (1.0, 1.1, ..., 3.0)
- We will instead do an exact line minimization in one pass through the n-best list
- Key observation is that varying just one weight means:
 - The score of each hypothesis (as we vary the weight) can be viewed as a line
 - For each sentence, we can look at the intercept points of these lines to see where the hypothesis with the best model score changes

Find Best Feature Weight

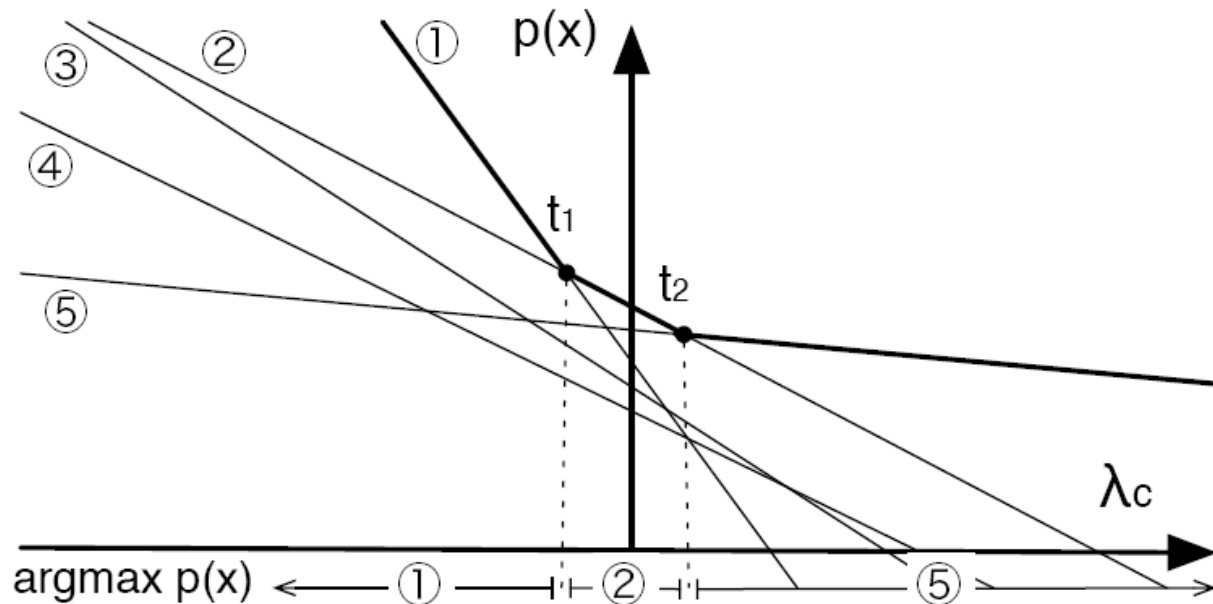
- Core task:
 - find optimal value for one parameter weight λ
 - ... while leaving all other weights constant

- Score of translation i for a sentence \mathbf{f} :

$$p(\mathbf{e}_i|\mathbf{f}) = \lambda a_i + b_i$$

- Recall that:
 - we deal with 100s of translations \mathbf{e}_i per sentence \mathbf{f}
 - we deal with 100s or 1000s of sentences \mathbf{f}
 - we are trying to find the value λ so that over all sentences, the error score is optimized

Translations for one Sentence



- each translation is a line $p(\mathbf{e}_i|\mathbf{f}) = \lambda a_i + b_i$
- the model-best translation for a given λ (x-axis), is highest line at that point
- there are one a few *threshold points* t_j where the model-best line changes

Finding the Optimal Value for λ

- Real-valued λ can have infinite number of values
- But only on threshold points, one of the model-best translation changes

⇒ Algorithm:

- find the threshold points
- for each interval between threshold points
 - * find best translations
 - * compute error-score
- pick interval with best error-score

Minimum Error Rate Training

[Och, ACL 2003]

- Maximize quality of **top-ranked translation**
 - Similarity according to metric (BLEU)
- This approach only works with up to around 20 feature functions
 - But very fast and easy to implement
- Implementation comes with Moses

Maximum Entropy

[Och and Ney, ACL 2002]

- Match **expectation** of feature values of model and reference translation
- Log-linear models are also sometimes called Maximum Entropy models (when trained this way)
- Great for binary classification, very many lightweight features
 - Also is a convex optimization – no problems with local maxima in the optimization
- Doesn't work well for SMT

Ordinal Regression

[Chiang et al., NAACL 2009;
many others previously]

- Separate k worst from the k best translations
 - E.g., separate hypotheses with lowest BLEU from hypotheses with highest BLEU
 - Approximately maximizes the **margin**
 - Support Vector machines do this non-approximately (but are too slow)
 - Often done in an online fashion, one sentence at a time (i.e., original Chiang approach)
- Recently become very popular
- Moses comes with Batch MIRA (not online), we use this
- Related approach (also in Moses) is Pairwise Ranking Optimization
- Both approaches scale to thousands of feature functions

Conclusion

- We have defined log-linear models
- And shown how to automatically tune them
- Log-linear models allow us to use any feature function that our decoder can score
 - Must be able to score a partial hypothesis extended from left to right (decoding/search lecture)
- Log-linear models are now used almost everywhere (also in non-structured prediction)

- Thanks for your attention!

BLEU error surface

- Varying one parameter: a rugged line with many local optima

