

# POS TAGGING

---

HMM, CRF, and search

and a bit of NER

Discourse

CommunicationEvent(e)  
Agent(e, Alice)  
Recipient(e, Bob)  
SpeakerContext(s)  
TemporalBefore(e, s)

Semantics

Word embeddings

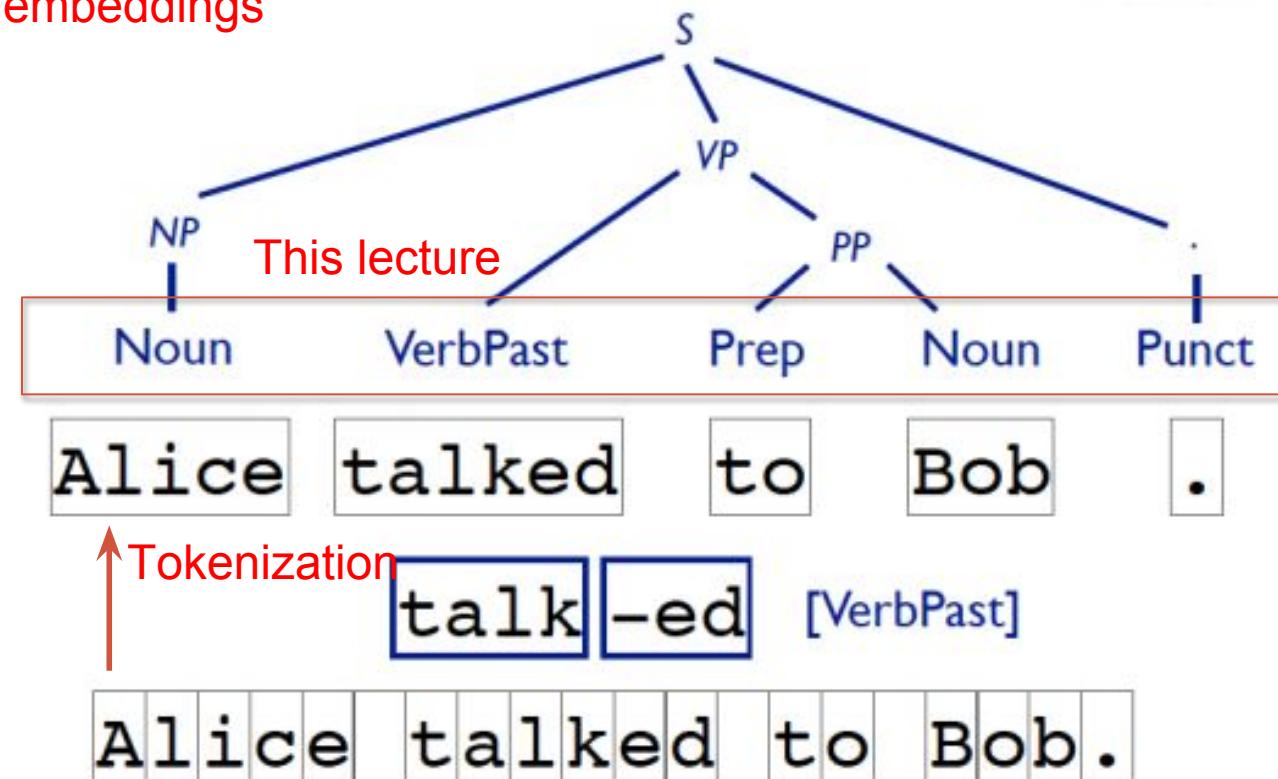
Syntax: Constituents

Syntax: Part of Speech

Words

Morphology

Characters



# Part-Of-Speech tagging

- Categorize words into similar **grammatical properties** (syntax)
  - Examples: Nouns, Verbs, Adjectives
- Actual applications often use more granular PoS labels
- PoS tags are often
  - Language specific
  - Application/corpus specific

Number	Tag	Description
1.	CC	Coordinating conjunction
2.	CD	Cardinal number
3.	DT	Determiner
4.	EX	Existential <i>there</i>
5.	FW	Foreign word
6.	IN	Preposition or subordinating conjunction
7.	JJ	Adjective
8.	JJR	Adjective, comparative
9.	JJS	Adjective, superlative
10.	LS	List item marker
11.	MD	Modal
12.	NN	Noun, singular or mass
13.	NNS	Noun, plural
14.	NNP	Proper noun, singular
15.	NNPS	Proper noun, plural
16.	PDT	Predeterminer
17.	POS	Possessive ending
18.	PRP	Personal pronoun
19.	PRP\$	Possessive pronoun
20.	RB	Adverb
21.	RBR	Adverb, comparative
22.	RBS	Adverb, superlative
23.	RP	Particle
24.	SYM	Symbol
25.	TO	<i>to</i>

# Part-Of-Speech tagging

- Input
  - They refuse to permit us to obtain the refuse permit.
- Output
  - They/*PRP* refuse/*VBP* to/*To* permit/*VB* us/*PRP* to/*TO* obtain/*VB* the/*DT* refuse/*NN* permit/*NN*

# PoS usage

- Word disambiguation
  - Different word vectors for different PoS of the same words
- Text-to-speech
  - Different pronunciations based on PoS tag
- Helps other NLP tasks
- PoS provides additional information that helps other tasks
  - **Tokenization**
  - **Name-Entity Recognition**
    - Identify group of words that refer to the same entity
    - เสก โลโซ ร้อง เพลง คุกเกี้ย เสี่ยงทาย
    - [เสกโลโซ]/person ร้อง เพลง [คุกเกี้ยเสี่ยงทาย]/title
- **Parsing**

# Overview

- What is PoS?
- Traditional methods
  - Frequency-based
  - Local methods
  - Sequence methods
    - HMM
    - CRF
      - Viterbi and beamsearch
- Neural network methods

# Frequency-based methods

- Tag using most frequent tag for each word in the vocabulary
- If OOV, tag using
  - Most frequent tag
- Decent accuracy on seen data, but overfits on the training data
  - They refuse to permit us to obtain the refuse permit.
  - They/*PRP* refuse/*VBP* to/*To* permit/*VB* us/*PRP* to/*TO* obtain/*VB* the/*DT* refuse/*VBP* permit/*VB*

# Local methods

- Decides the PoS tags using word and context feature
- PoS as a multiclass classification task
  - Logistic regression, naïve bayes, etc.
- Each PoS assignments are independent of each other
- Use local features
  - Word features
  - Context features

<b>word feature</b>	<b>example</b>
<i>Prefixes</i>	unfathomable: un- → adjective
<i>Suffixes</i>	surprisingly: -ly → adverb
<i>Capitalization</i>	Meridian: CAP → proper noun

Method	Seen word accuracy	Unseen word accuracy
Most Frequent Tag	90%	50%
Log-linear Model with word features	93.7%	82.6%
Log-linear Model with context features	96.6%	86.8%

# Sequence methods

- They refuse to permit us to obtain the refuse permit.
- They/*PRP* refuse/*VBP* to/*To* permit/*VB* us/*PRP* to/*TO* obtain/*VB* the/*DT* refuse/*NN* permit/*NN*
- Determining the PoS tag depends on the decision of the words around it
  - A sequence problem

# Problem setup

- Sequence of words

- $W := \{w_1, w_2, w_3, \dots, w_n\}$

$P(a,b)$  joint distribution

$P(a|b)$  conditional distribution

$P(a)$  marginal distribution

$$P(a) = \sum_b P(a,b)$$

- Sequence of tags

- $T := \{t_1, t_2, t_3, \dots, t_n\}$

- Given  $W$  predict  $T$

- $\operatorname{argmax}_T P(T|W)$

Discriminative Model

- Or

- $\operatorname{argmax}_T \frac{P(T,W)}{P(W)}$

$$= \operatorname{argmax}_T P(T,W) \quad \text{Generative Model}$$

$P(W)$  is constant does not affect the argmax

# Modeling $P(T,W)$

- $P(T,W) = P(w_1, w_2, w_3, \dots, w_n, t_1, t_2, t_3, \dots, t_n)$ 
  - Is there a problem with this?

# Modeling distributions

Wind in the morning

$$X \in \{\text{Calm}, \text{Windy}\}$$

PM2.5 level in the afternoon

$$Y \in \{\text{Low}, \text{Med}, \text{High}\}$$

$\operatorname{argmax} P(Y | X)$

Day	X	Y
1	C	H
2	C	M
3	W	M
4	W	H
5	C	L
6	W	L
7	C	H
8	W	L

# Modeling distributions

Wind in the morning

$$X \in \{\text{Calm}, \text{Windy}\}$$

PM2.5 level in the afternoon

$$Y \in \{\text{Low}, \text{Med}, \text{High}\}$$

$\operatorname{argmax} P(Y | X)$

Day	X	Y
1	W	M
2	C	M
3	W	M
4	W	H
5	C	L
6	W	L
7	C	H
8	W	L

P(X, Y)	L	M	H
C			
W			

Joint distribution

P(Y   X)	L	M	H
C			
W			

Conditional  
distribution

# Modeling distributions

Wind in the morning

$$X \in \{\text{Calm}, \text{Windy}\}$$

PM2.5 level in the afternoon

$$Y \in \{\text{Low}, \text{Med}, \text{High}\}$$

$\operatorname{argmax} P(Y | X)$

Joint distribution

Day	X	Y
1	W	M
2	C	M
3	W	M
4	W	H
5	C	L
6	W	L
7	C	H
8	W	L

P(X, Y)	L	M	H
C			
W			

Total data
8

count(X, Y)	L	M	H
C	1	1	1
W	2	2	1

$$P(X, Y) = \frac{\text{Count}(X, Y)}{\text{Total count}}$$

is the Maximum Likelihood Estimate (MLE) of  $P(X, Y)$

# Modeling distributions

Wind in the morning

$$X \in \{\text{Calm}, \text{Windy}\}$$

PM2.5 level in the afternoon

$$Y \in \{\text{Low}, \text{Med}, \text{High}\}$$

$\operatorname{argmax} P(Y | X)$

Day	X	Y
1	W	M
2	C	M
3	W	M
4	W	H
5	C	L
6	W	L
7	C	H
8	W	L

P(Y   X)	L	M	H
C			
W			

Conditional distribution

Total data
8

count(X,Y)	L	M	H	Total
C	1	1	1	3
W	2	2	1	5

$P(Y | X) = \frac{\text{Count}(X, Y)}{\text{Total count}(X)}$  is the Maximum Likelihood Estimate (MLE) of  $P(Y|X)$

# Curse of dimensionality

Wind in the morning

$$X \in \{\text{Calm, Windy}\}$$

PM2.5 level in the afternoon

$$Y \in \{\text{Low, Med, High}\}$$

PM2.5 level in the evening

$$Z \in \{\text{Low, Med, High}\}$$

$\operatorname{argmax} P(Y, Z | X)$

Day	X	Z	Y
1	W	L	M
2	C	M	M
3	W	H	M
4	W	M	H
5	C	H	L
6	W	M	L
7	C	L	H
8	W	H	L

P(Y,Z  X = C)	ZL	ZM	ZH
YL			
YM			
YH			

P(Y,Z  X = W)	ZL	ZM	ZH
YL			
YM			
YH			

# Simplifying assumptions

Wind in the morning

$$X \in \{\text{Calm}, \text{Windy}\}$$

PM2.5 level in the afternoon

$$Y \in \{\text{Low}, \text{Med}, \text{High}\}$$

PM2.5 level in the evening

$$Z \in \{\text{Low}, \text{Med}, \text{High}\}$$

$$\operatorname{argmax} P(Y, Z | X) = P(Z | X) P(Y | X)$$

Day	X	Z	Y
1	W	L	M
2	C	M	M
3	W	H	M
4	W	M	H
5	C	H	L
6	W	M	L
7	C	L	H
8	W	H	L

P(Y   X)	L	M	H
C			
W			

P(Z   X)	L	M	H
C			
W			

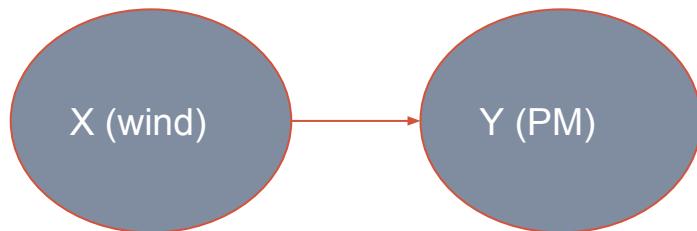
# Modeling $P(T,W)$

- $P(T,W) = P(w_1, w_2, w_3, \dots, w_n, t_1, t_2, t_3, \dots, t_n)$ 
  - Is there a problem with this? **Curse of dimensionality**
- Language modeling
  - $P(w_t)$  requires  $N$  table values
  - $P(w_t|w_{t-1})$  requires  $N^2$  table values
  - $P(w_t|w_{t-1}, w_{t-2})$  requires  $N^3$  table values
  - Many values have 0 counts (needs many tricks)
- We can use **Markov Assumptions**
  - Or more generally, we use **independence assumptions (conditional independence)** to simplify the distribution to model

# Dependence as graphical models

In probabilistic graphical models, we can draw the relationship between random variables using graph notations

- A node is a variable.
- An arrow refers to the **causal** relationship between the variables

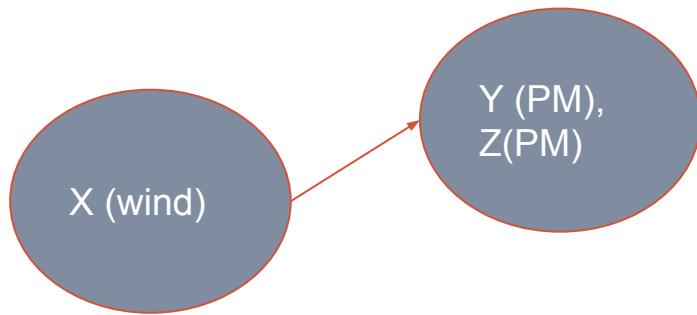


$$P(X, Y) = P(X) P(Y | X)$$

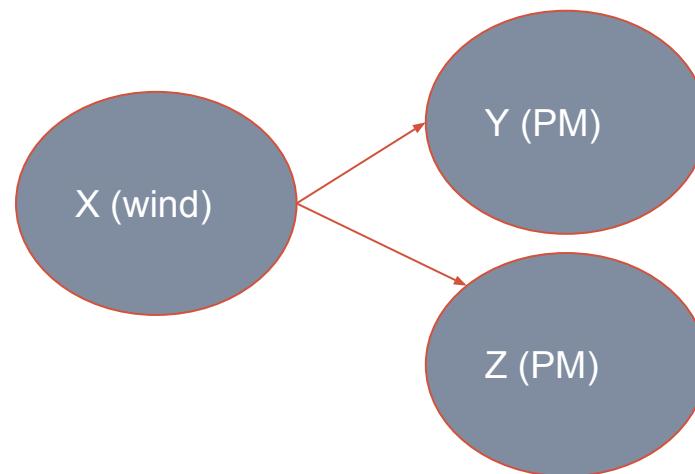
# Dependence as graphical models

In probabilistic graphical models, we can draw the relationship between random variables using graph notations

- A node is a variable.
- An arrow refers to the **causal** relationship between the variables



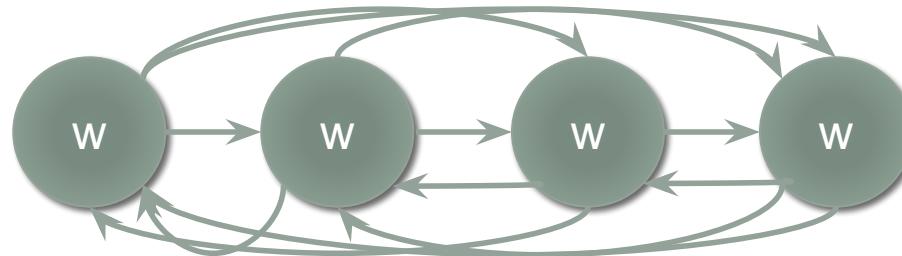
$$P(X, Y, Z) = P(X) P(Y, Z | X)$$



$$P(X, Y, Z) = P(X) P(Y | X) P(Z | X)$$

# Dependence as graphical models

$$P(W) =$$

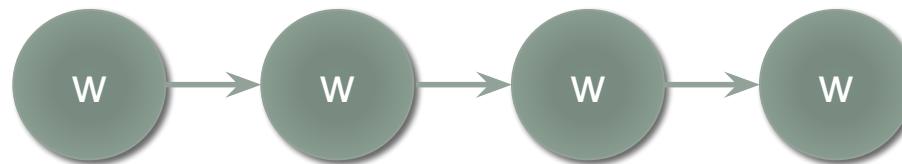


$$P(w_1, w_2, w_3, w_4)$$

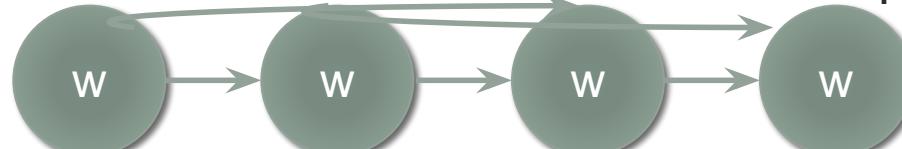
Full dependency



Unigrams  
 $P(w_1)P(w_2)P(w_3) P(w_4)$



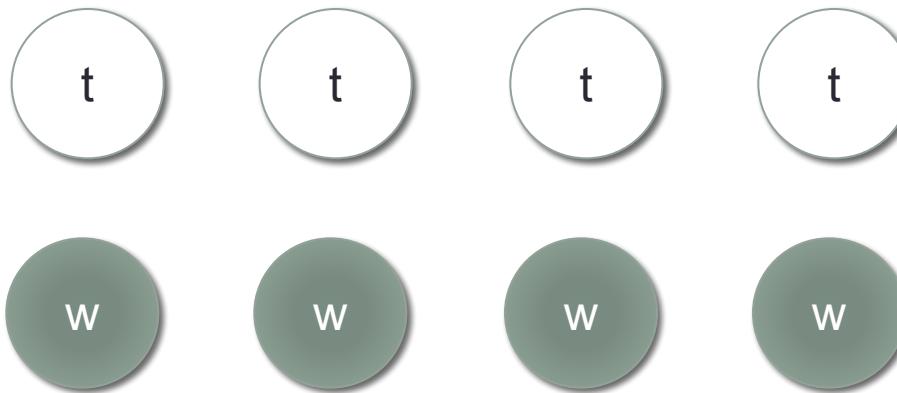
Bigrams  
 $P(w_1)P(w_2|w_1)P(w_3|w_2) P(w_4|w_3)$



Trigrams  
 $P(w_1)P(w_2|w_1)P(w_3|w_2w_1)P(w_4|w_3w_2)$

Graphical models summarize how to write the full probability of some joint probability distribution

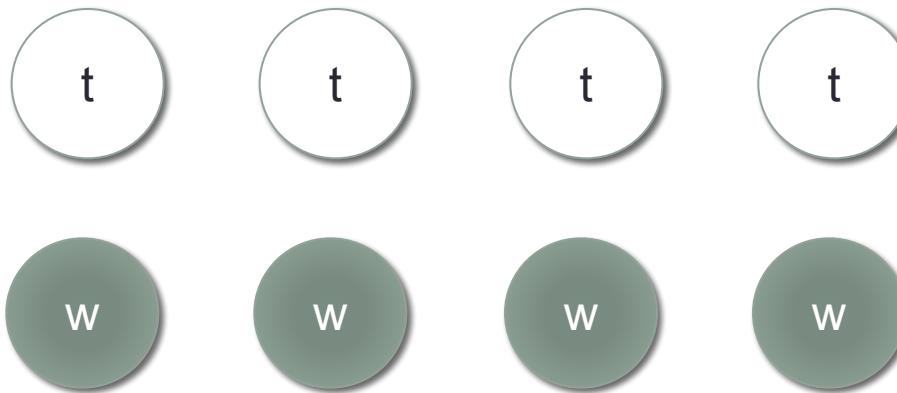
# Latent variables



We usually use dark colors the nodes for the variables that we observe from data (known values)

We usually use **light color** the nodes for the variables that do not know from data (unknown values, latent values)

# Latent variables

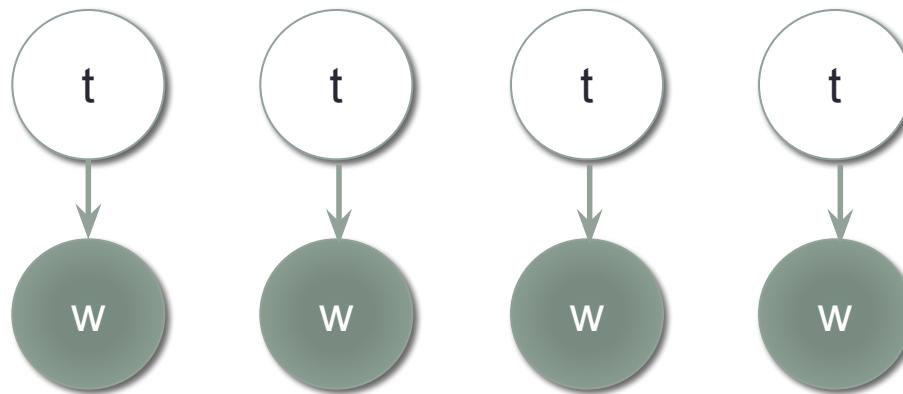


We usually use dark colors the nodes for the variables that we observe from data (known values)

We usually use **light color** the nodes for the variables that do not know from data (unknown values, latent values)

$P(T,W) = P(w_1, w_2, w_3, \dots, w_n, t_1, t_2, t_3, \dots, t_n)$  means?

# Local tagging



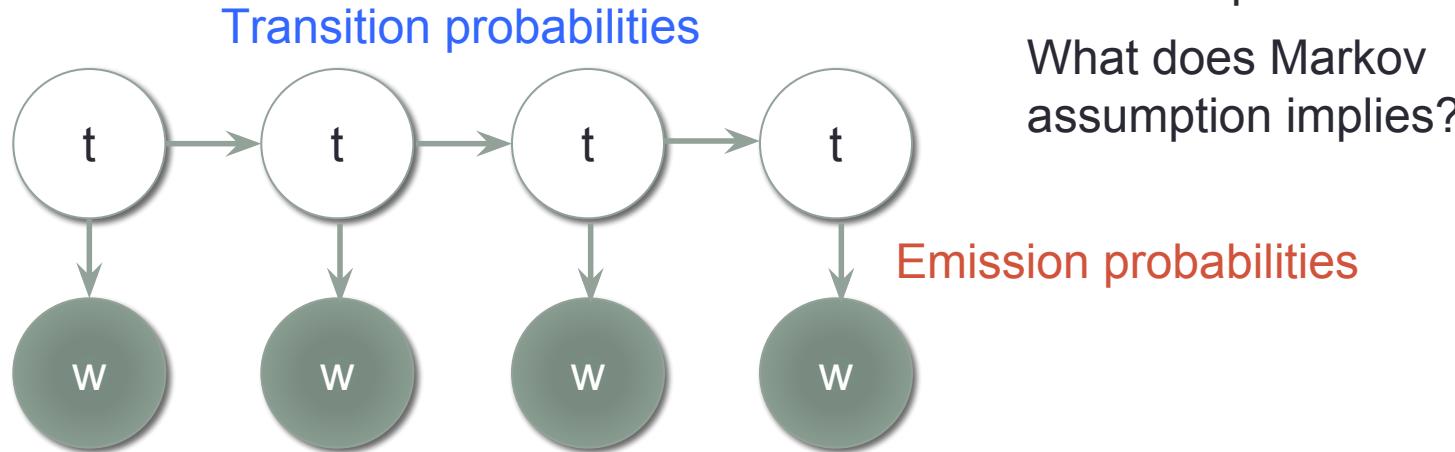
$$P(T, W) = P(w_1, w_2, w_3, \dots, w_n, t_1, t_2, t_3, \dots, t_n)$$

$$= P(w_1, t_1)P(w_2, t_2)P(w_3, t_3) P(w_4, t_4)$$

We want to introduce sequence dependence when doing PoS

Solution: Hidden Markov Model (HMM)

# Hidden Markov Model



**Markov assumption**

Current value only depends  
immediate pass

What does Markov  
assumption implies?

T are called the hidden states. Usually comes from a finite set of possibilities  
Ex:  $t \in \{\text{in, Adv, Adj, Verb}\}$

$$P(T,W) = P(t_1)P(t_2|t_1)P(t_3|t_2)P(t_4|t_3)P(w_1|t_1)P(w_2|t_2)P(w_3|t_3)P(w_4|t_4)$$

---

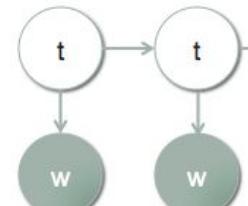
Initial state prob    Transition probabilities    Emission probabilities

# Hidden Markov Model

N = Noun  
NN = Not Noun  
 $i, j$  – state (tag) index  
 $k$  – emission (word) index

- Defining HMM requires
- 1. Starting state probability  $p_0 = [0.7 \ 0.3]$
- 2. Transition probability,  $A_{ij}$
- 3. Emission probably,  $B_{ik}$
- If emits discrete values
  - Discrete HMM
- If emits continuous values
  - Continuous HMM

$A_{ij}$	To N	To NN
From N	0.6	0.4
From NN	0.5	0.5



$B_{ik}$	I	eat	Chinese
State N	0.8	0.01	0.19
State NN	0.1	0.45	0.45

Question: What's the probability of  $P([I \ eat \ chinese] , [N \ NN \ N])$  ?

$$\begin{aligned} &= p_0(N) * A_{12} * A_{21} * B_{11} * B_{22} * B_{13} \\ &= 0.7 * 0.4 * 0.5 * 0.8 * 0.45 * 0.19 \end{aligned}$$

# Hidden Markov Model

- How to estimate A and B?

- Counts!

$$P(A_{11}) = \frac{\text{Count(from N to N)}}{\text{Count(N)}}$$

A <sub>ij</sub>	To N	To NN
From N	0.6	0.4
From NN	0.5	0.5

- Counts with **interpolation** to avoid 0 counts

$$\cdot P(A_{11}) = \rho \frac{\text{Count(from N to N)}}{\text{Count(N)}} + (1-\rho) \frac{\text{Count (N)}}{\text{Count (words)}}$$

bigram

unigram

$\rho$  is interpolation weight

# Hidden Markov Model

- How to estimate A and B?

- Counts!

$$P(B_{11}) = \frac{\text{Count("I", N)}}{\text{Count(N)}}$$

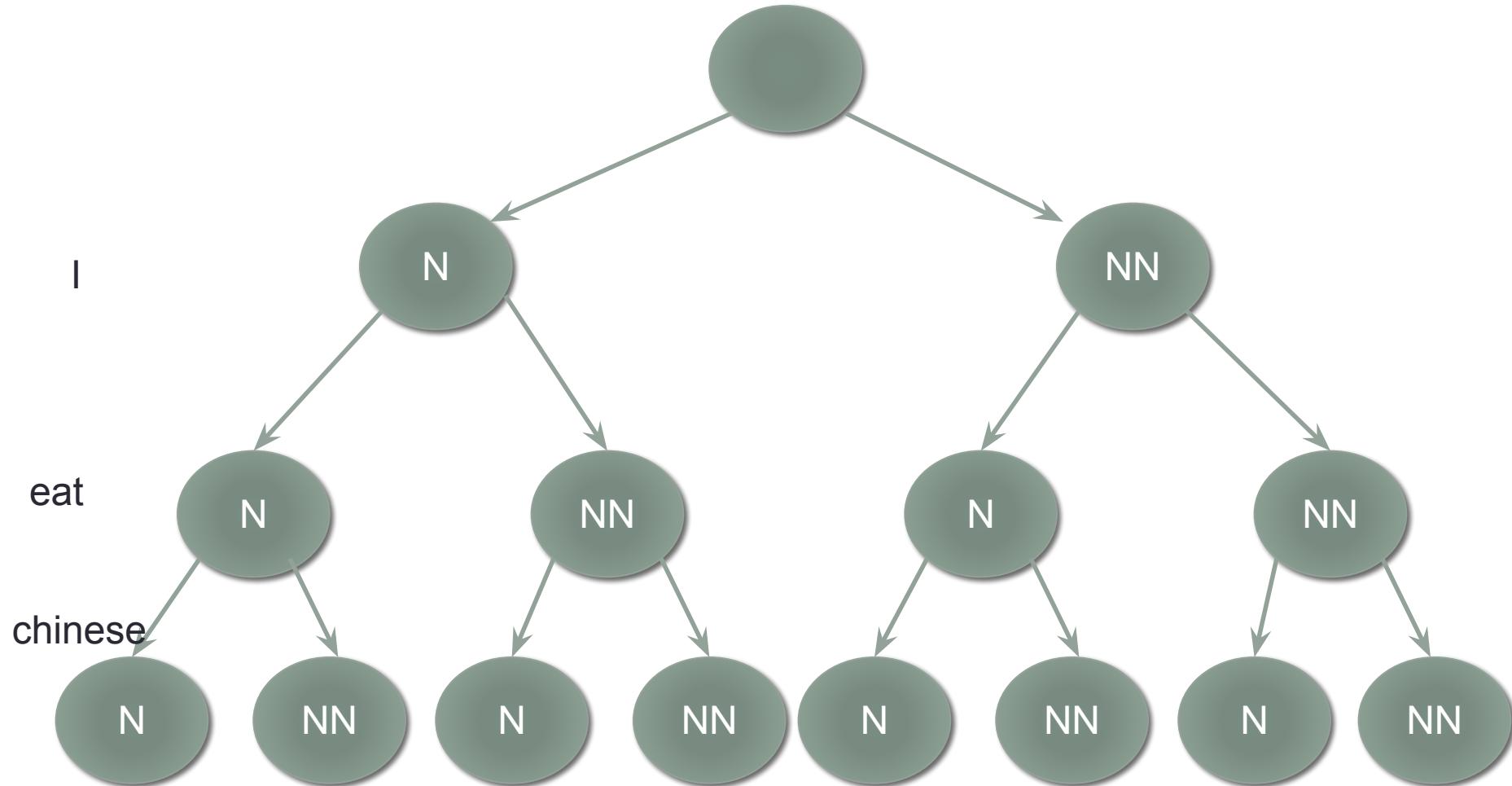
A <sub>ij</sub>	To N	To NN
From N	0.6	0.4
From NN	0.5	0.5

B <sub>ik</sub>	I	eat	Chinese
State N	0.8	0.01	0.19
State NN	0.1	0.45	0.45

# Decoding

- Recall we want to find the sequence of tags that maximizes the joint probability
  - $\text{argmax}_T P(T, W)$
- How to do this?
  - Brute force
    - Find all possible sequence of T, calculate  $P(T, W)$  and compare
    - Length N words, B possible tags
    - Big O = ?
  - Depth first search?
  - Breadth first search?

# Breadth first/depth first search

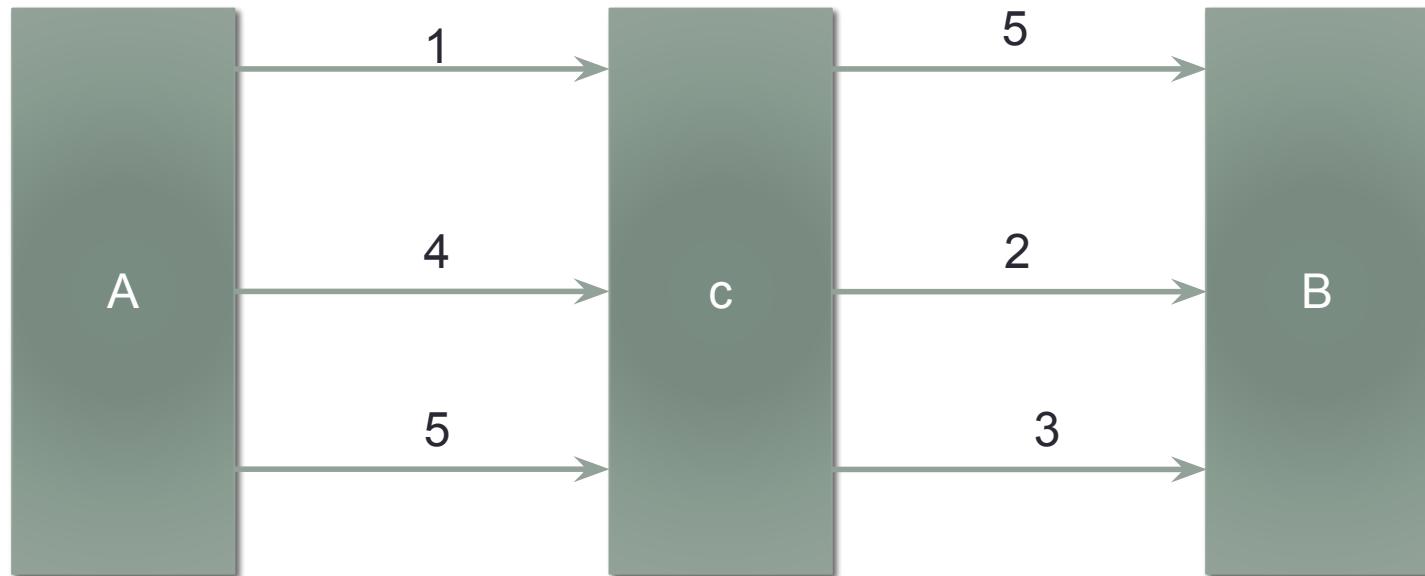


# The Viterbi Algorithm (Dynamic programming)

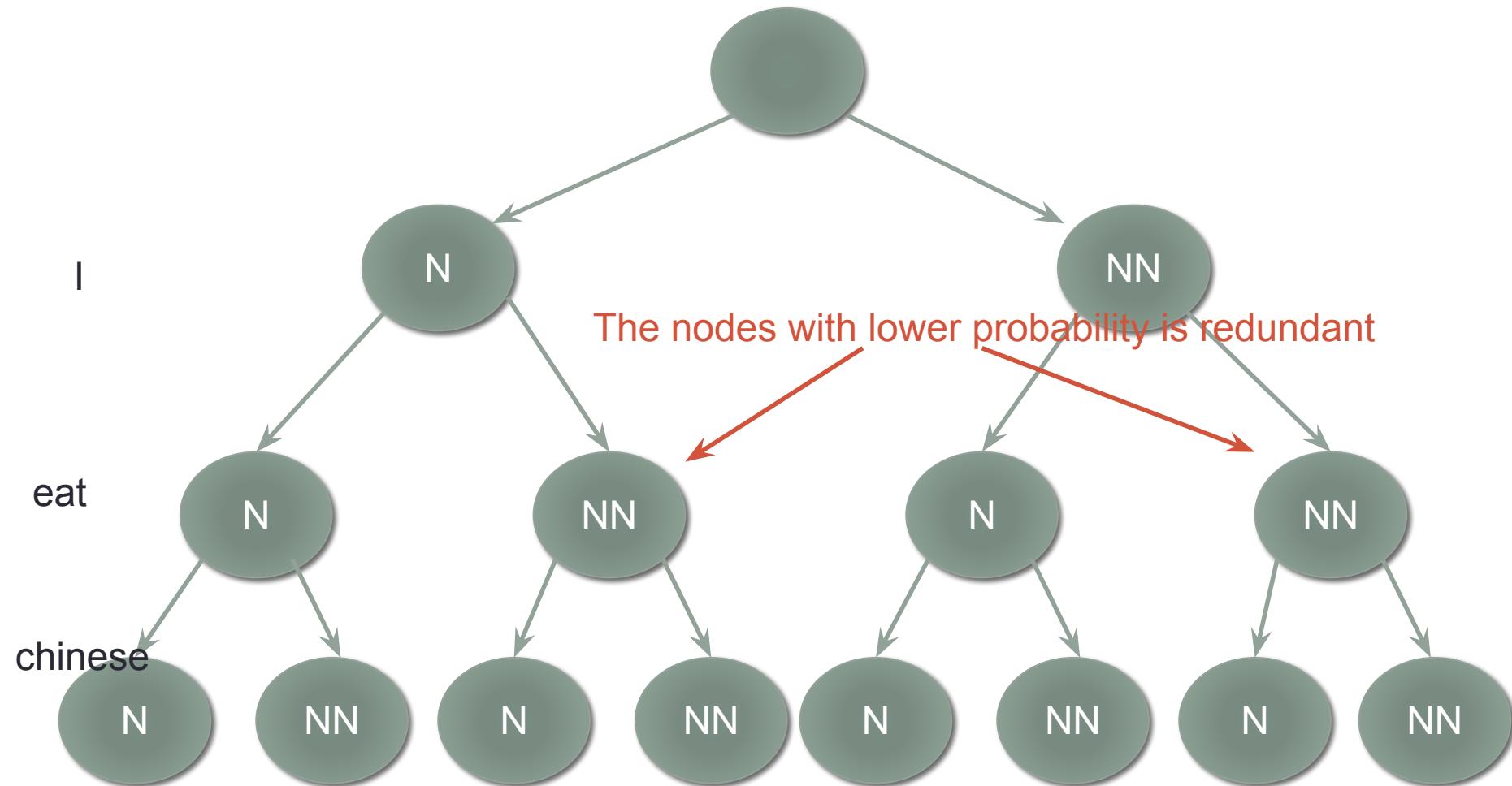
- Some computation are redundant
  - We can save computation from previous steps

# Dynamic programming

- Saving computation for future use. How?
- Example: Find best route from A to B



# Redundancy



# The Viterbi Algorithm (Dynamic programming)

- Some computation are redundant
  - We can save computation from previous steps
- Creates two matrices
  - $\pi[i, t]$  saves the best probability at word position  $i$  for hidden state  $t$
  - $B[i, t]$  saves the previous hidden state that maximize this current state probability

# Viterbi

**Base Step:**

$$\pi[0, < S >] = \log 1 = 0$$

$$\pi[0, t] = \log 0 = -\infty, \text{ if } t \neq < S >$$

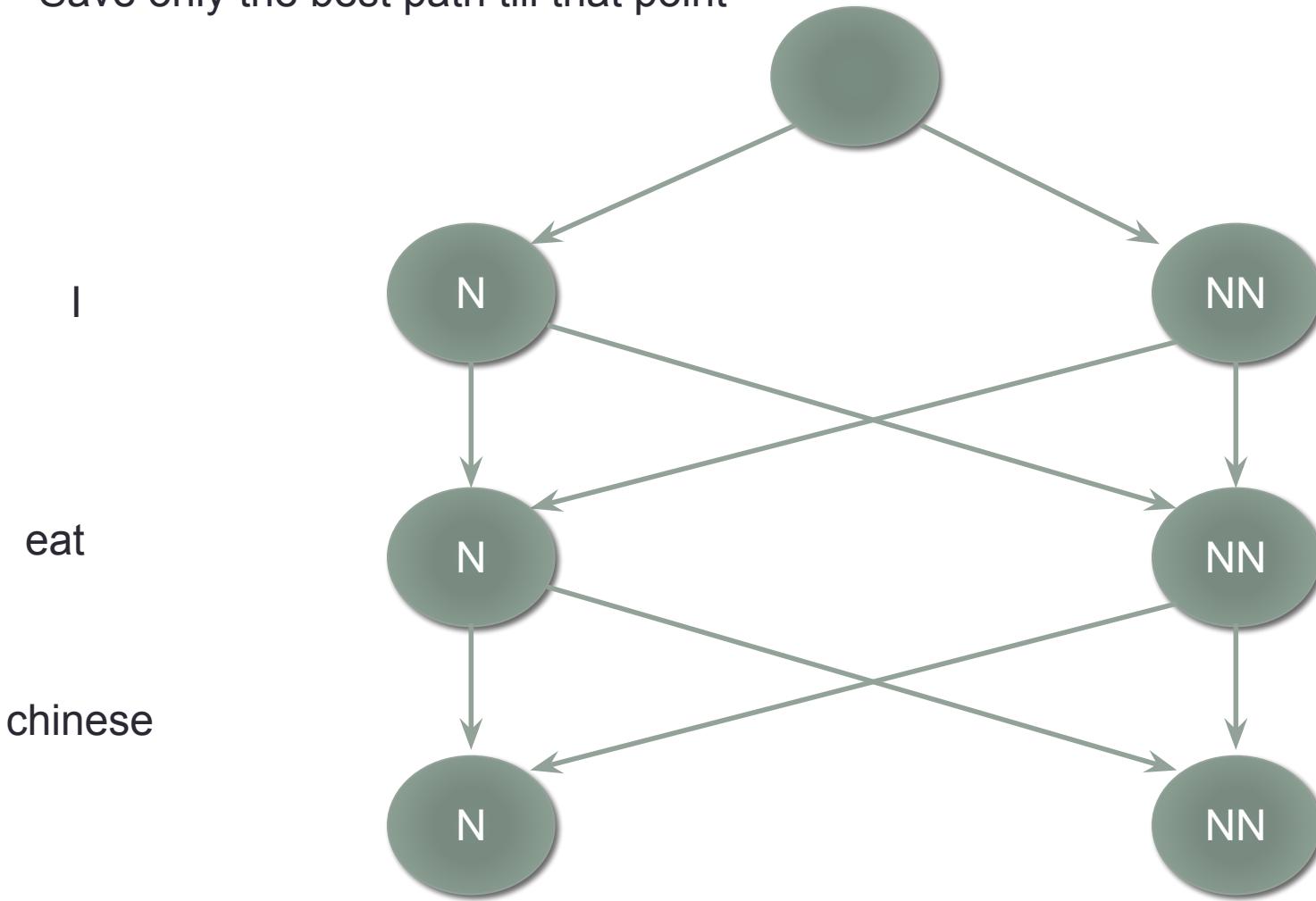
where  $< S >$  is the start symbol.

**Recursive Step:**

$$\pi[i, t] = \max_{t'} \{ \pi[i-1, t'] + \log P(t|t') + \log P(w_i|t) \}$$

# Viterbi

Save only the best path till that point



# Decoding (Reconstructing T)

- We can find the best T by
- Find that best probability at the end
- Backtrack according to  $B[i,t]$

$$t_N = \arg \max_t \pi[N, t]$$

- This gives a big O of
  - We need to compute and create a table of size  $O(BN)$
  - For each value we need to perform B computations
  - $O(B^2 N)$ , Space complexity of  $O(2BN)$
- What happens if B is big?

# Decoding example

$A_{ij}$	To N	To NN
From N	0.6	0.4
From NN	0.5	0.5

$B_{ik}$	I	eat	Chinese
State N	0.8	0.01	0.19
State NN	0.1	0.45	0.45

We ignore the log to do easy compute

$\pi[i, t]$	I	eat	Chinese
State N	0.8		
State NN	0.1		

$B[i, t]$	I	eat	Chinese
State N	-		
State NN	-		

**Recursive Step:**

$$\pi[i, t] = \max_{t'} \{ \pi[i - 1, t'] + \log P(t|t') + \log P(w_i|t) \}$$

# Decoding example

$A_{ij}$	To N	To NN
From N	0.6	0.4
From NN	0.5	0.5

$B_{ik}$	I	eat	Chinese
State N	0.8	0.01	0.19
State NN	0.1	0.45	0.45

$\pi[i, t]$	I	eat	Chinese
State N	0.8	0.005	
State NN	0.1		

$B[i, t]$	I	eat	Chinese
State N	-	N	
State NN	-		

$$0.8 * 0.6 * 0.01 \text{ vs } 0.1 * 0.5 * 0.01 \\ 0.0048 \text{ vs } 0.0005$$

**Recursive Step:**

$$\pi[i, t] = \max_{t'} \{ \pi[i - 1, t'] + \log P(t|t') + \log P(w_i|t) \}$$

# Decoding example

$A_{ij}$	To N	To NN
From N	0.6	0.4
From NN	0.5	0.5

$B_{ik}$	I	eat	Chinese
State N	0.8	0.01	0.19
State NN	0.1	0.45	0.45

$\pi[i, t]$	I	eat	Chinese
State N	0.8	0.005	0.014
State NN	0.1	0.144	0.032

$B[i, t]$	I	eat	Chinese
State N	-	N	NN
State NN	-	N	NN

**Recursive Step:**

$$\pi[i, t] = \max_{t'} \{ \pi[i - 1, t'] + \log P(t|t') + \log P(w_i|t) \}$$

# Decoding example (backtrack)

$A_{ij}$	To N	To NN
From N	0.6	0.4
From NN	0.5	0.5

$B_{ik}$	I	eat	Chinese
State N	0.8	0.01	0.19
State NN	0.1	0.45	0.45

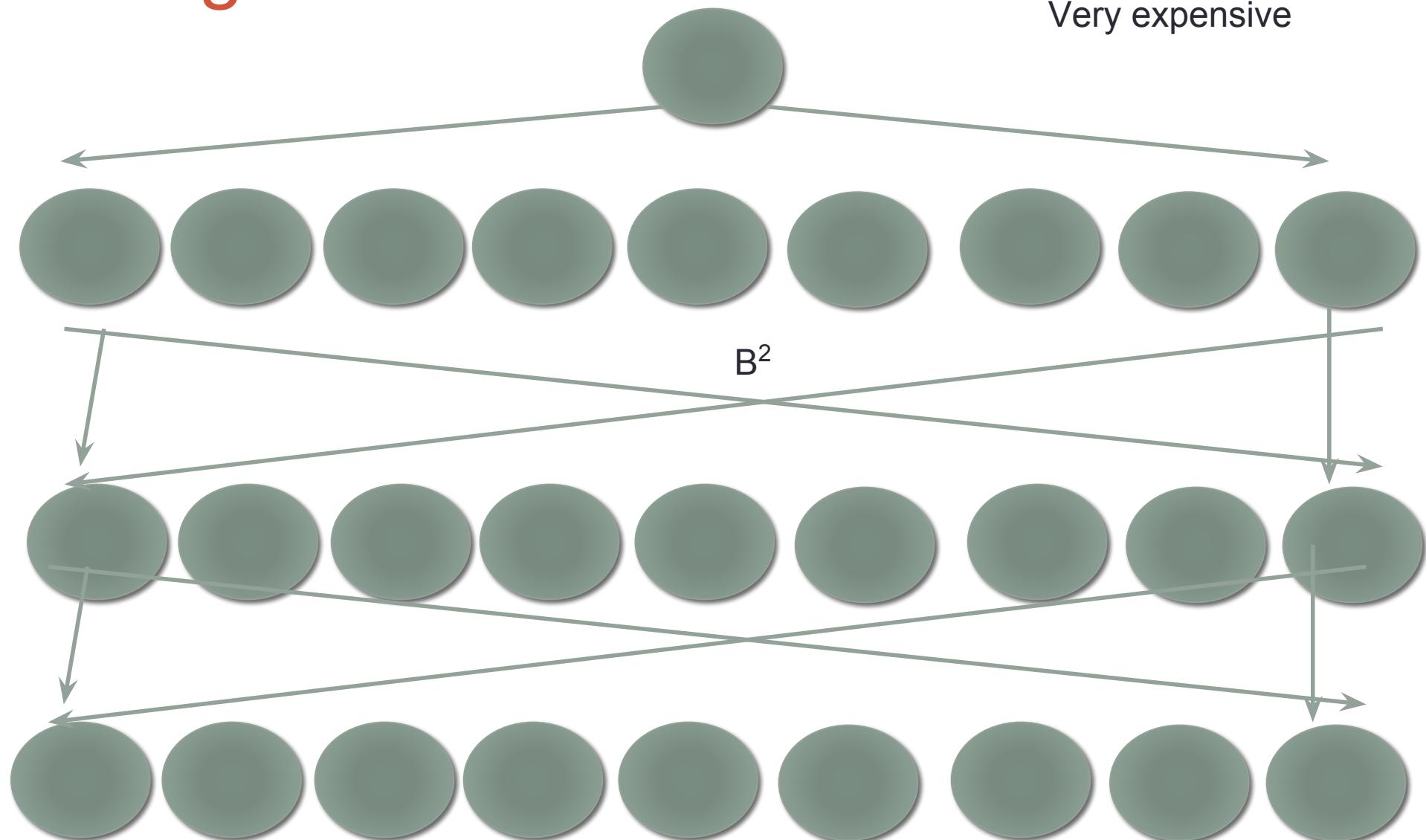
$\pi[i, t]$	I	eat	Chinese
State N	0.8	0.005	0.014
State NN	0.1	0.144	0.032

$B[i, t]$	I	eat	Chinese
State N	-	N	NN
State NN	-	N	NN

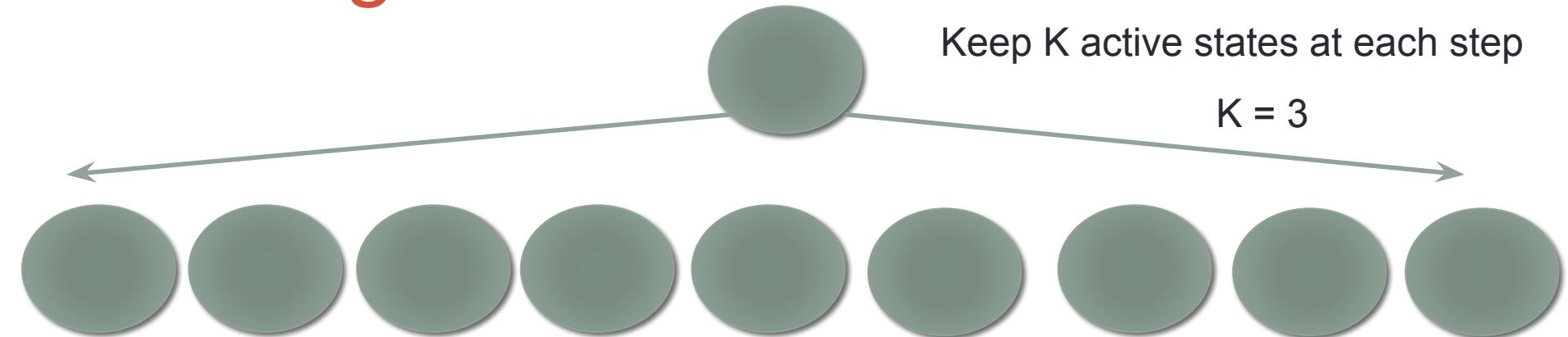
N, NN, NN

# Large hidden states

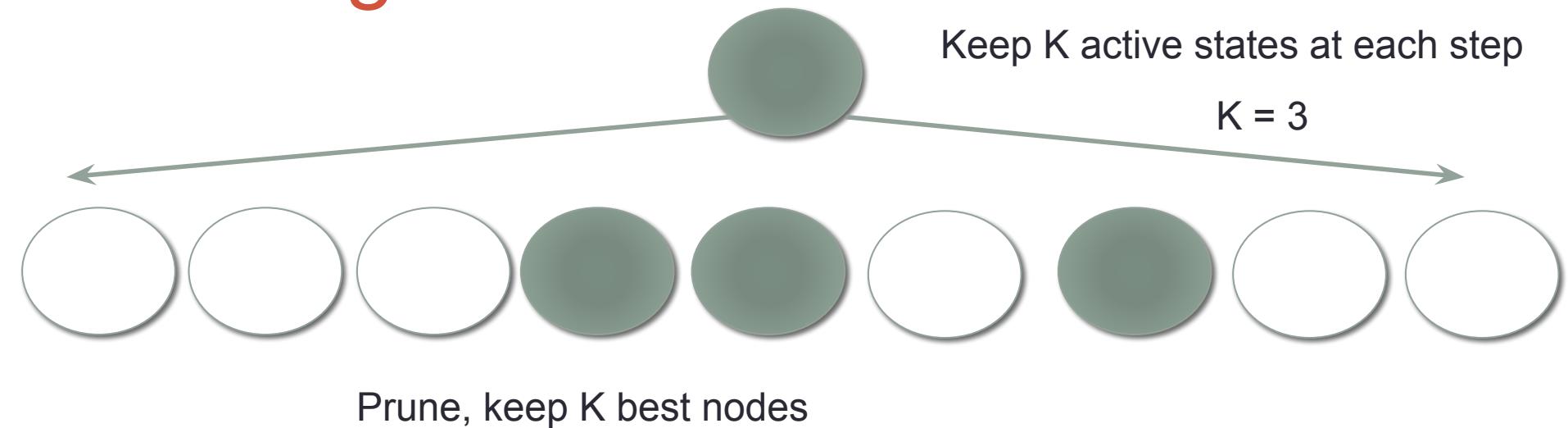
Very expensive



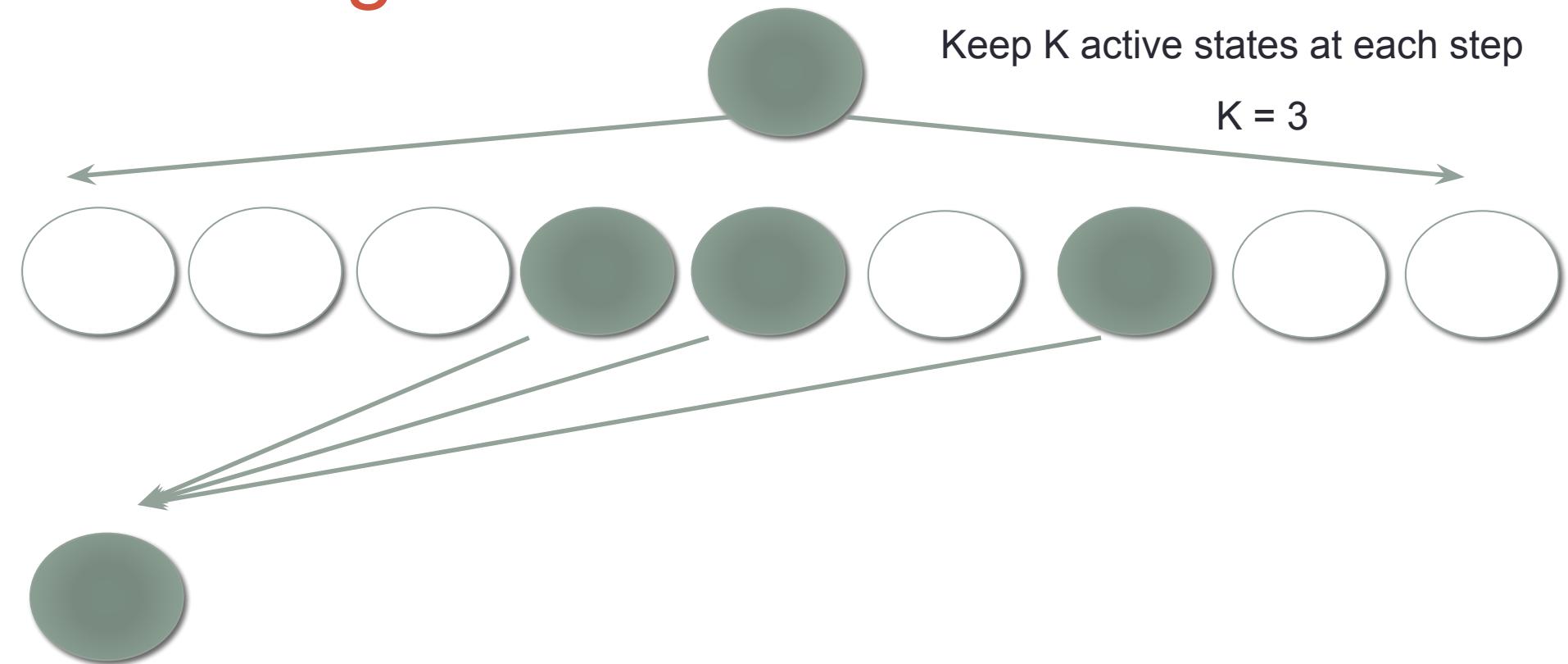
# Pruning with Beamsearch



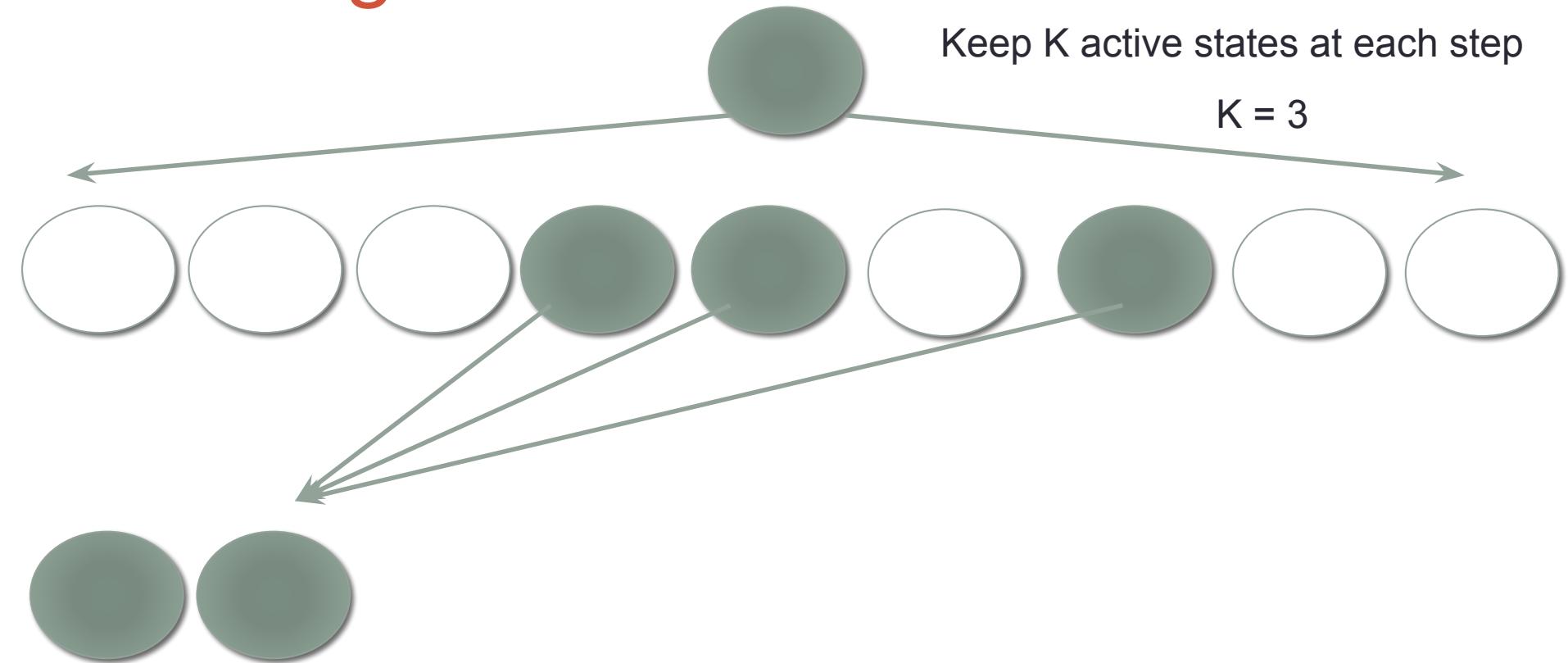
# Pruning with Beamsearch



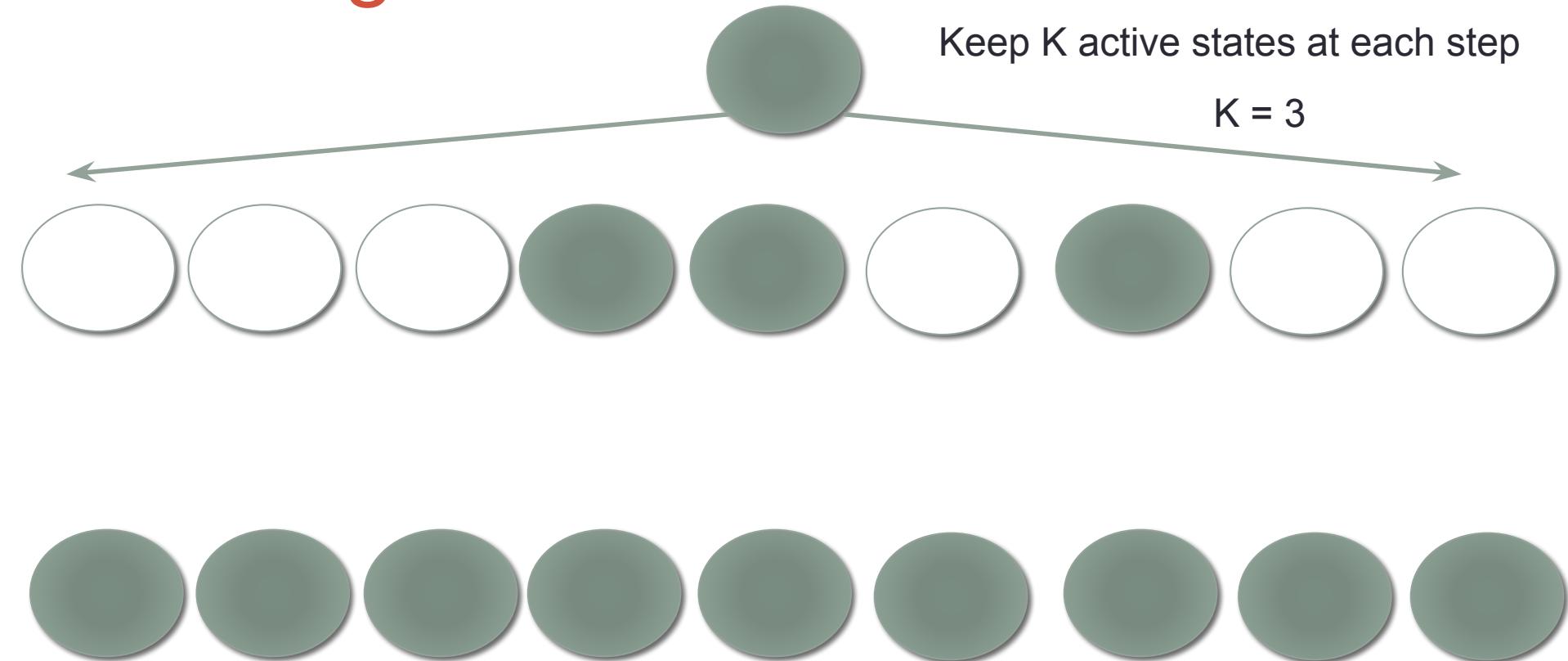
# Pruning with Beamsearch



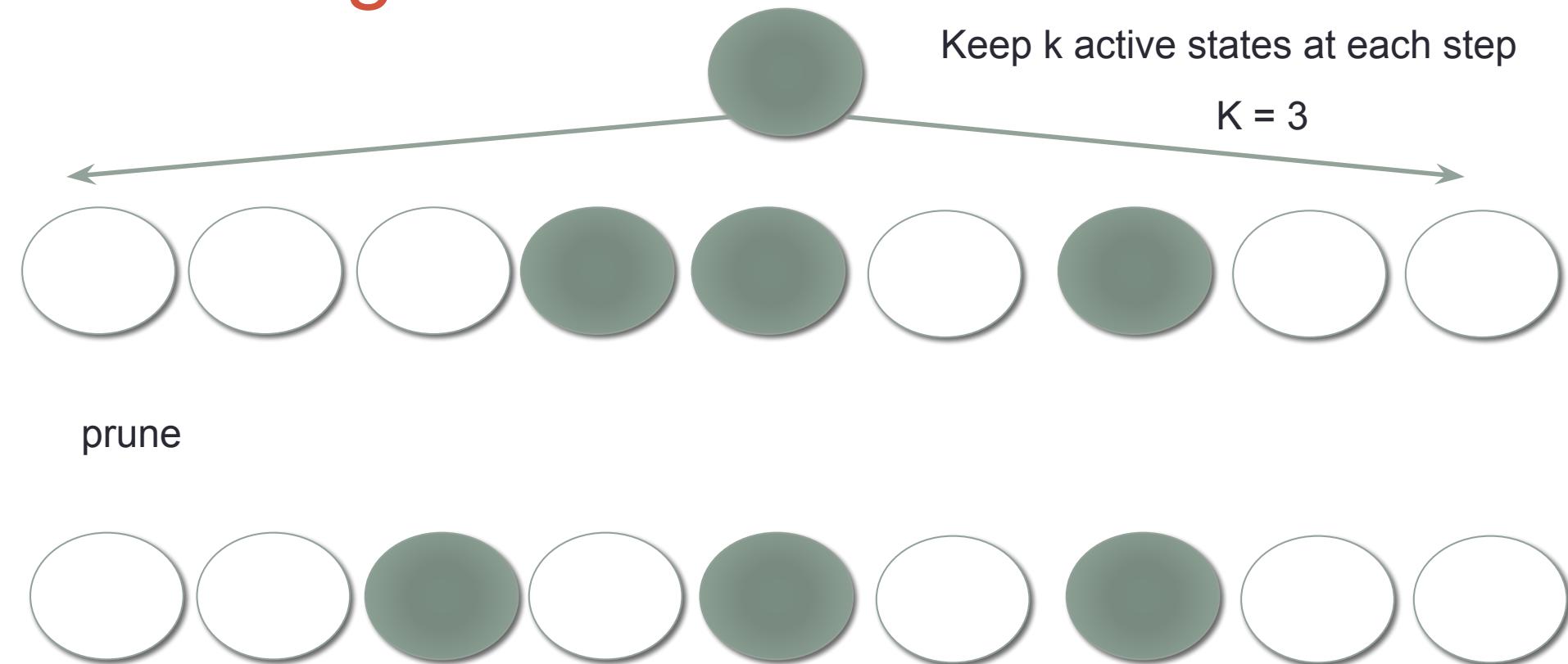
# Pruning with Beamsearch



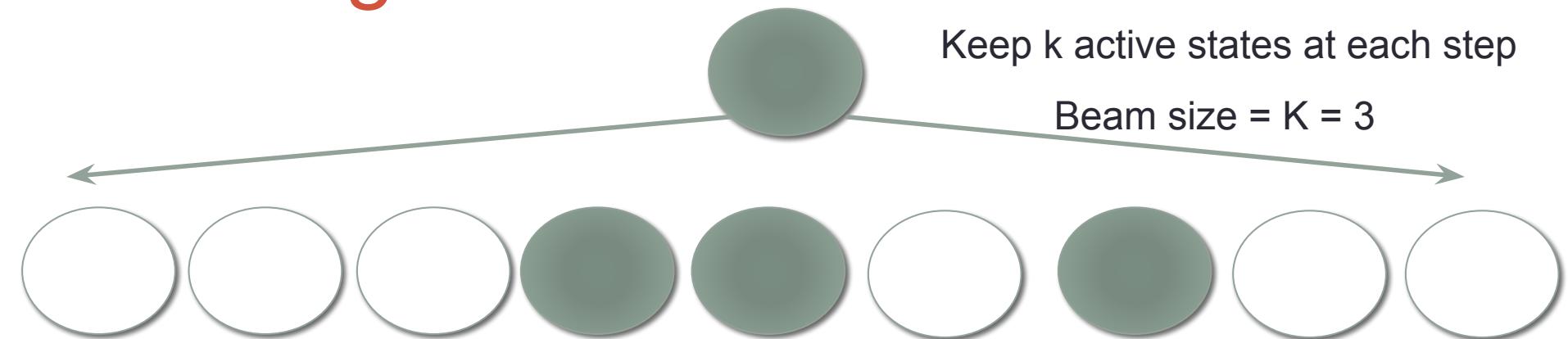
# Pruning with Beamsearch



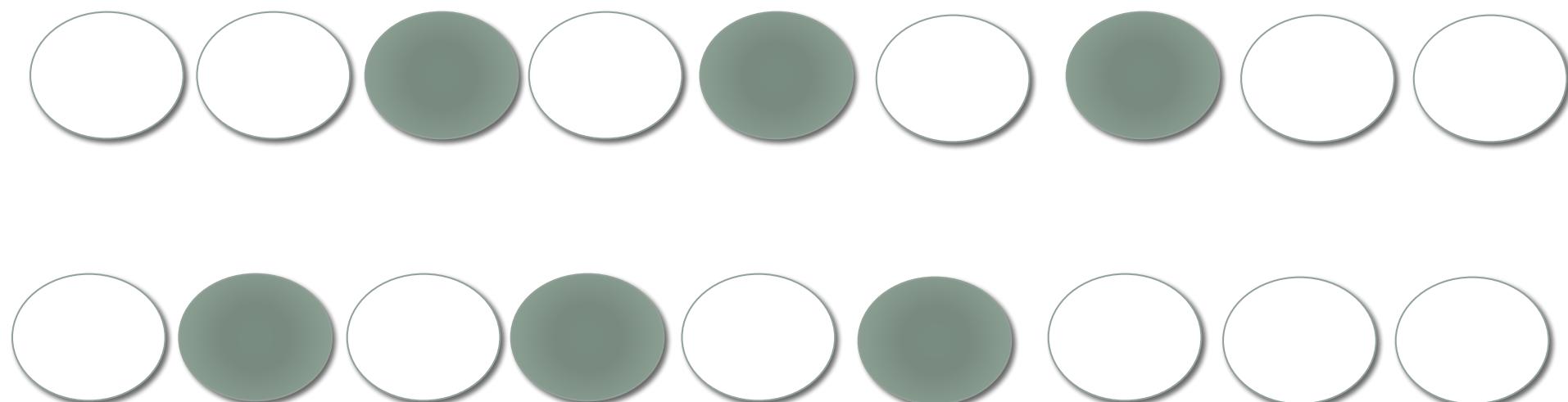
# Pruning with Beamsearch



# Pruning with Beamsearch

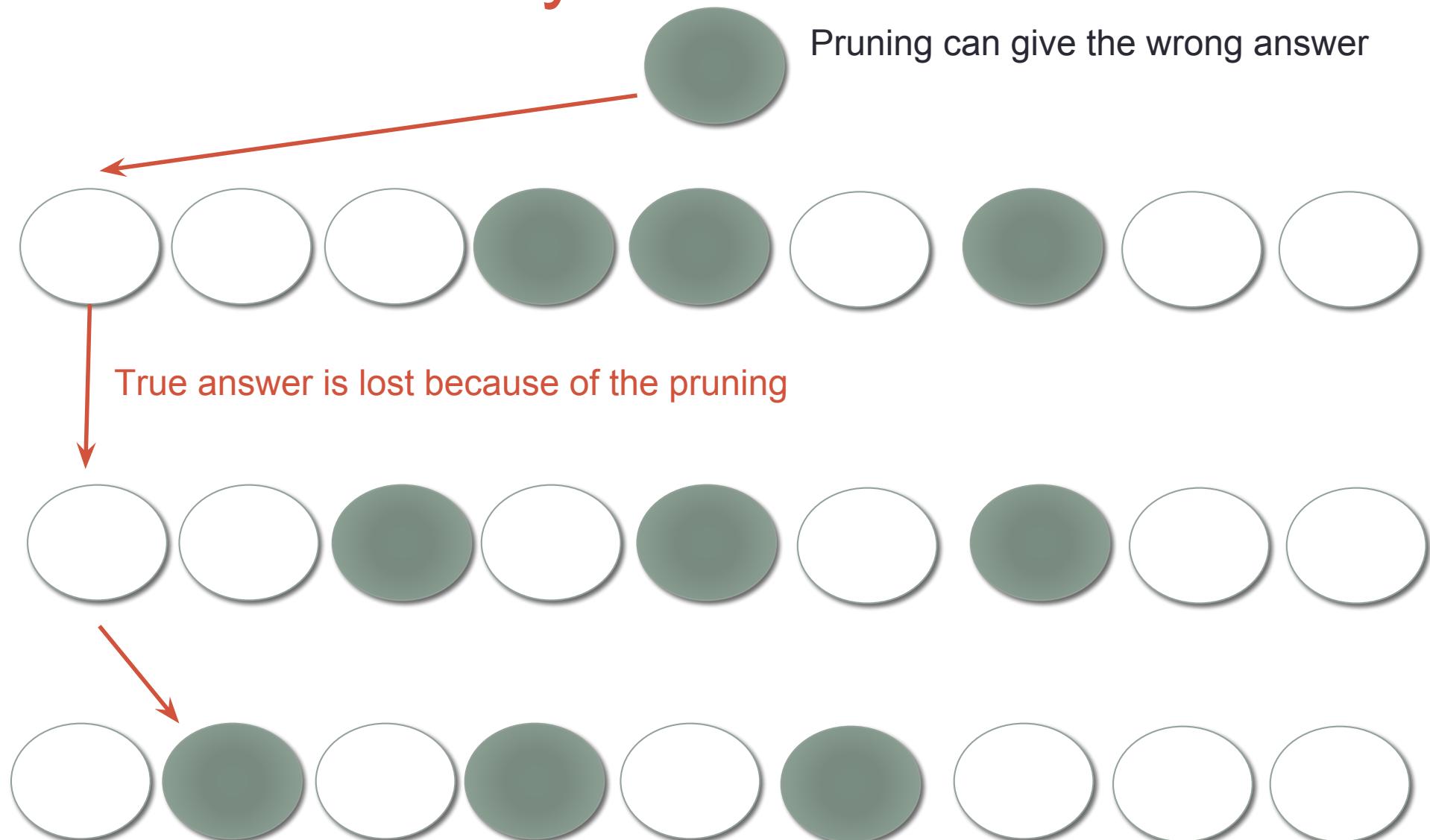


$O(kB)$  per word index



# Inadmissibility

Pruning can give the wrong answer

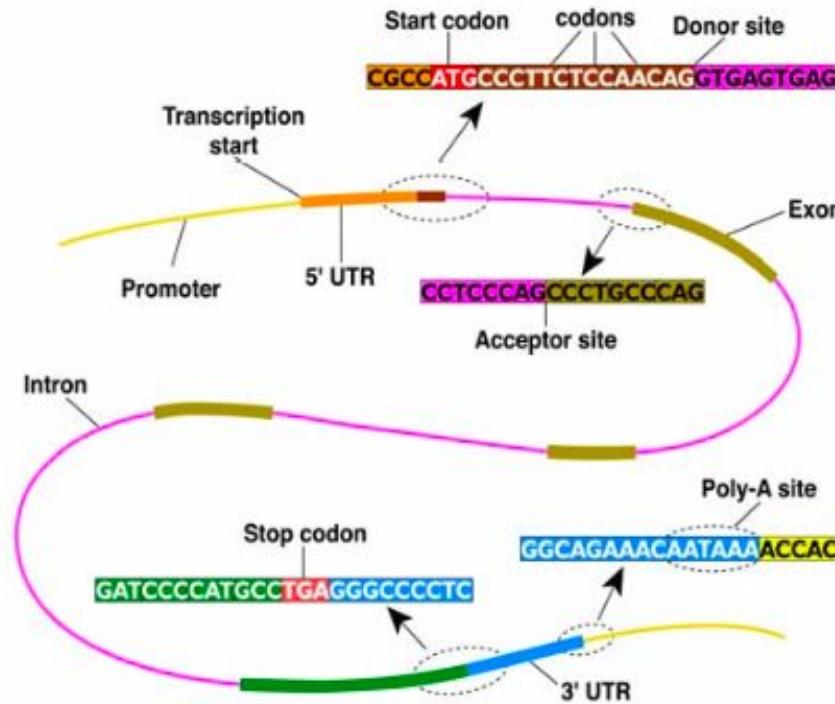


# Beam search

- Beam search is inadmissible (can be wrong)
- Size of beam affect the quality of the answer
  - Practically still useful even for small size ( $K < 10$  in machine translation)
- We will use beam search again for text generation.

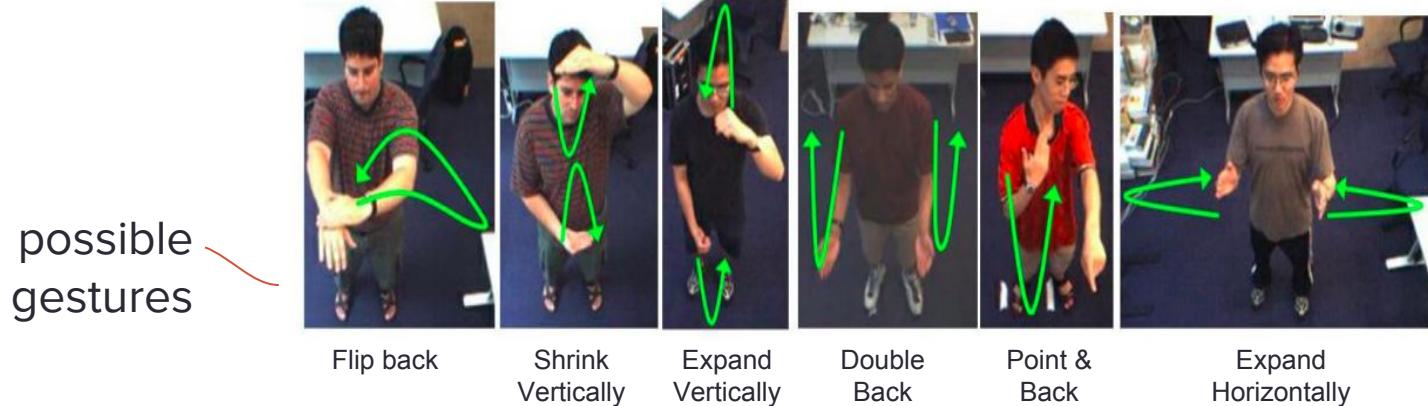
# Other applications for sequence modeling

- Finance
- Speech recognition
- Genetics and molecular biology



# Sequence Labeling in non-NLP task

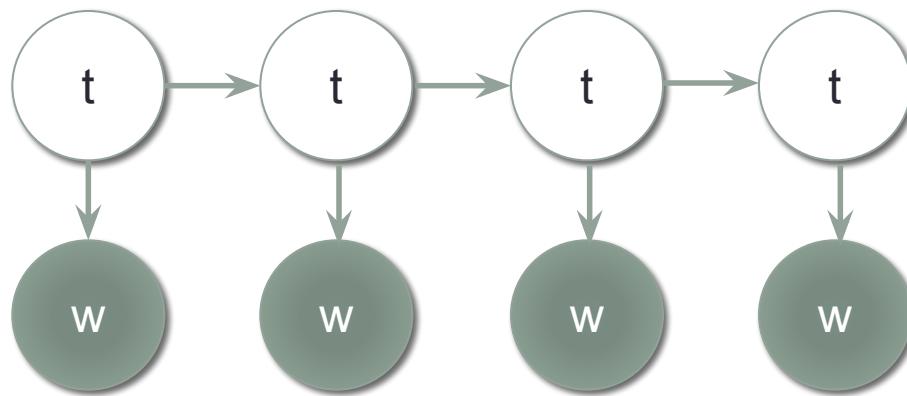
## Gesture recognition



sequence of photos



# HMM assumptions and disadvantages

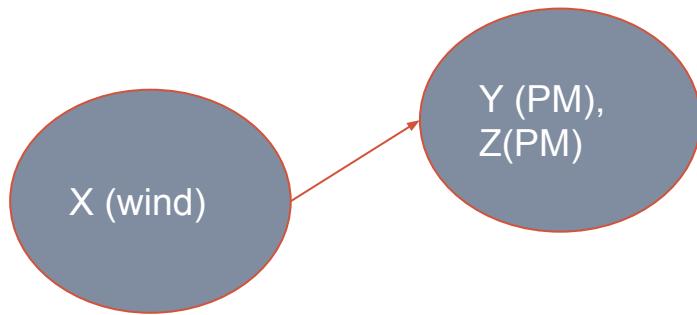


- No dependency across words
- HMM is a generative model  $P(T, W)$ 
  - But we care about  $P(T | W)$
  - Mismatch between final objective and model learning objective

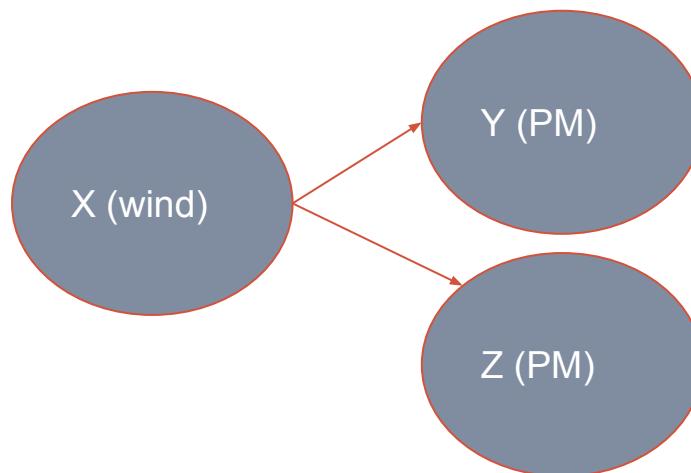
# Dependence as graphical models

In probabilistic graphical models, we can draw the relationship between random variables using graph notations

- A node is a variable.
- An arrow refers to the **causal** relationship between the variables



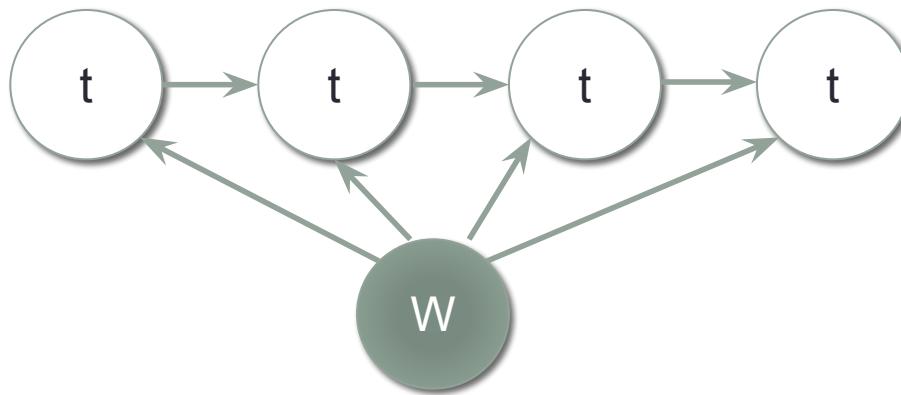
$$P(X, Y, Z) = P(X) P(Y, Z | X)$$



$$P(X, Y, Z) = P(X) P(Y | X) P(Z | X)$$

# Solution: Conditional Random Fields (CRF)

Random variable  
Random/stochastic process  
Random field



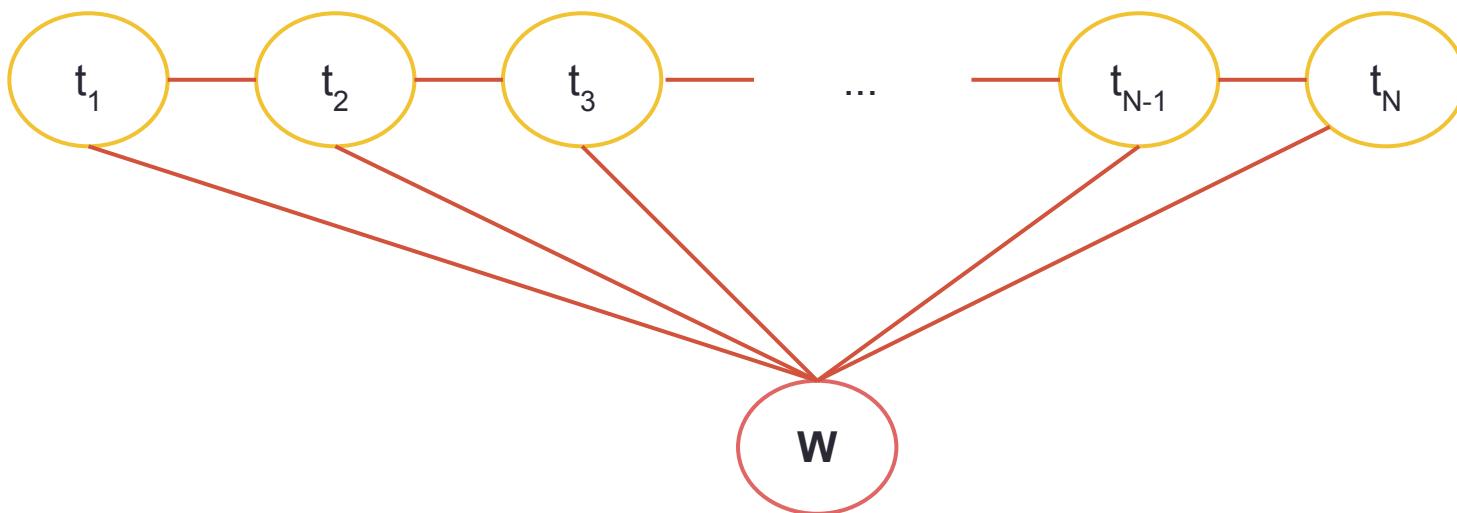
$$P(T|W) = \pi P(t_n | t_{n-1}, W) = P(t_1 | W) P(t_2 | t_1, W) P(t_3 | t_2, W) P(t_4 | t_3, W)$$

- Every point in the chain now depends on the entire sentence
- CRF is a discriminative model

# Linear chain CRF

Linear-chain CRF models with these independent assumption:

- (1) each label  $t_n$  only depends on previous label  $t_{n-1}$
- (2) each label  $t_n$  globally depends on  $x$

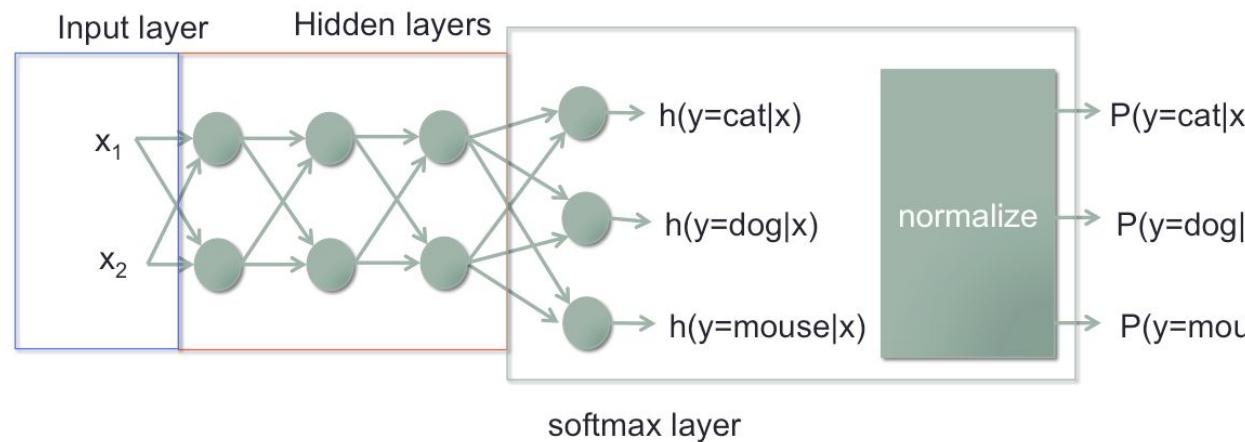


**Problem:** This is a big function (depends on  $n + 2$  things). Hard to estimate using our previous method (counting)

# Workaround

- Probability distribution is a function (with special constraints)
- Find a **function** that will represent “probabilities”
- We can turn functions into probabilities easily.
  - Softmax function normalization
  - We just need to have **a function that give higher values to more likely inputs**

$$P(y = j|x) = \frac{e^{h(y=j|x)}}{\sum_y e^{h(y|x)}}$$



# Goal

- Find a function that will represent “probabilities”
- Turn functions into probabilities
  - Softmax function normalization
  - We just need to have function that give higher to more likely inputs
- Building functions that represent the whole sequence is hard
  - We'll build by combining pieces
  - But each piece should have the form  $f(t_n, t_{n-1}, \mathbf{W}, n) \rightarrow \mathbb{R}$ 
    - This is from our independence assumption.
  - We call these functions, **feature functions**

# Feature function

At each time step, a feature function  $f(t_n, t_{n-1}, \mathbf{W}, n) \rightarrow \mathbb{R}$  is used to capture some characteristics of current label and the observation.

A feature function in linear-CRF:

$$f(t_n, t_{n-1}, \mathbf{W}, n) \rightarrow \mathbb{R}$$

current label      previous label      input sequence      current index      returns a real value

The diagram illustrates the inputs to the feature function  $f$ . It shows four inputs: the current label ( $t_n$ ), the previous label ( $t_{n-1}$ ), the weight matrix ( $\mathbf{W}$ ), and the current index ( $n$ ). The output of the function is a real value, represented by the symbol  $\mathbb{R}$ .

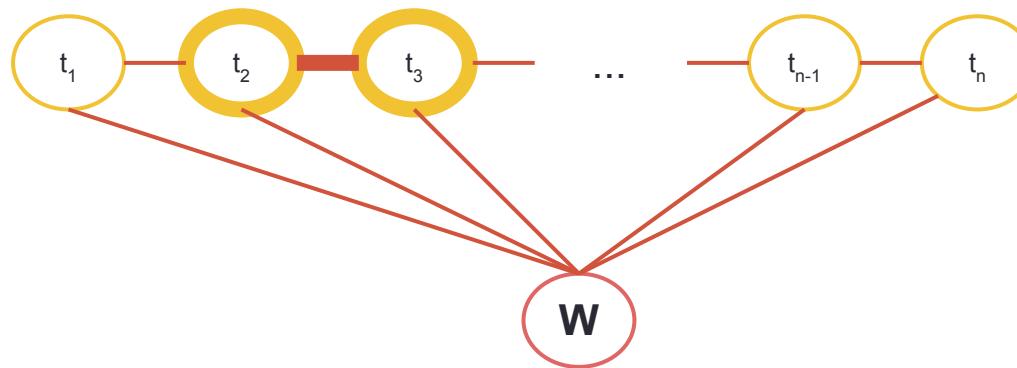
# Example features

In general, we often define a feature function as a binary function, taking current label and its dependent variable into account. For example:

- transition function

$$f_1(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{NOUN} \text{ and } t_{n-1} = \text{ADJ}. \\ 0, & \text{otherwise.} \end{cases}$$

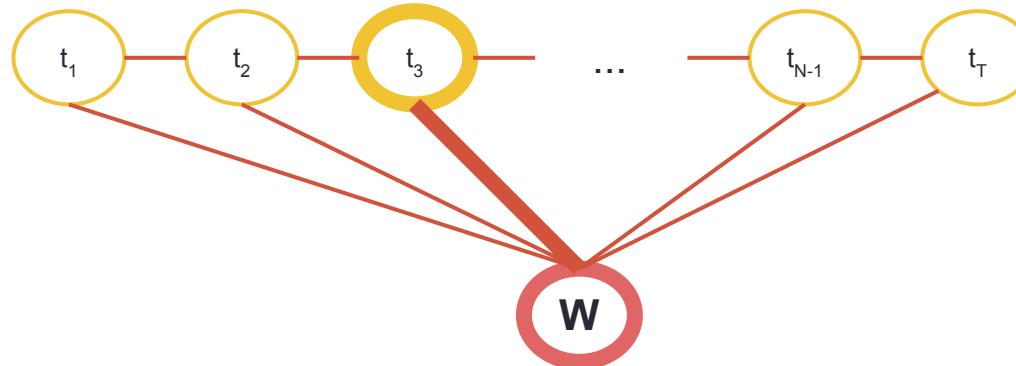
$n = 3$



# Feature function: More example

- state function

$$f_2(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{NOUN} \text{ and } w_n = \text{fox}. \\ 0, & \text{otherwise.} \end{cases}$$



- The whole input sequences can be used in a feature function.

$$f_3(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{NOUN} \text{ and } w_{n-1} = \text{an}. \\ 0, & \text{otherwise.} \end{cases}$$

# Feature function: More example

Other features other than word form can be used too.

$$f_4(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{PROPER NOUN and } w_n \text{ is capitalized.} \\ 0, & \text{otherwise.} \end{cases}$$

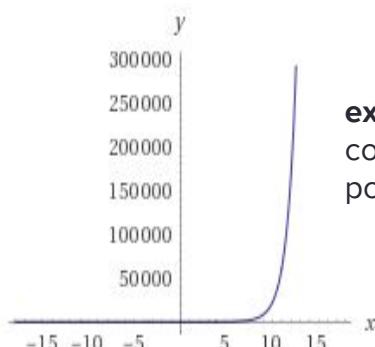
$$f_5(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{NOUN and } w_{n-1} \text{ ends with "est".} \\ 0, & \text{otherwise.} \end{cases}$$

# Potential

At each time step, a potential  $\Psi_n(t_n, t_{n-1}, \mathbf{W}) \rightarrow \mathbb{R}^+$  is a function that takes all feature functions into account, by summing their products with the associated weight

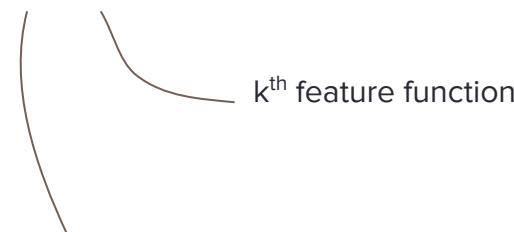
factors at time n

$$\Psi_n(t_n, t_{n-1}, \mathbf{W}) = \exp\left[\sum_k^K \theta_k f_k(t_n, t_{n-1}, \mathbf{W}, n)\right]$$



**exponential function:** used to convert the summation to the positive range

number of all feature functions



**weight** associated with each feature function, estimated within training process

# Potential: Example

n	n=1	n=2	n=3	n=4	...
t*	NOUN	VERB	NOUN	VERB	...
w	The	fastest	fox	jumps	...

From feature functions and trained weights on the right, we can compute potentials for the predicted label sequence  $\mathbf{t}^*$  at time step n=3 as following:

$$f_1(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{NOUN} \text{ and } t_{n-1} = \text{ADJ.} \\ 0, & \text{otherwise.} \end{cases}$$

$$f_2(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{NOUN} \text{ and } w_n = \text{fox.} \\ 0, & \text{otherwise.} \end{cases}$$

$$f_3(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{NOUN} \text{ and } w_{n-1} = \text{an.} \\ 0, & \text{otherwise.} \end{cases}$$

$$f_4(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{PROPER NOUN} \text{ and } w_n \text{ is cap.} \\ 0, & \text{otherwise.} \end{cases}$$

$$f_5(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{NOUN} \text{ and } w_{n-1} \text{ ends with "es".} \\ 0, & \text{otherwise.} \end{cases}$$

$$\theta_1 = 2.54, \theta_2 = 0.13, \theta_3 = 1.12, \theta_4 = 2.01, \theta_5 = 0.97$$

$$\begin{aligned} \Psi_3(t_3, t_2, \mathbf{W}) &= \exp[\sum_1^5 \theta_k f_k(t_3, t_2, \mathbf{W})] \\ &= \exp\{(0 \times 2.54) + (1 \times 0.13) + (0 \times 1.12) + (0 \times 2.01) + (1 \times 0.97)\} \\ &= 3.00 \end{aligned}$$

# Probability of the whole sequence

Joint probability distribution of input and output sequence can be represented as:

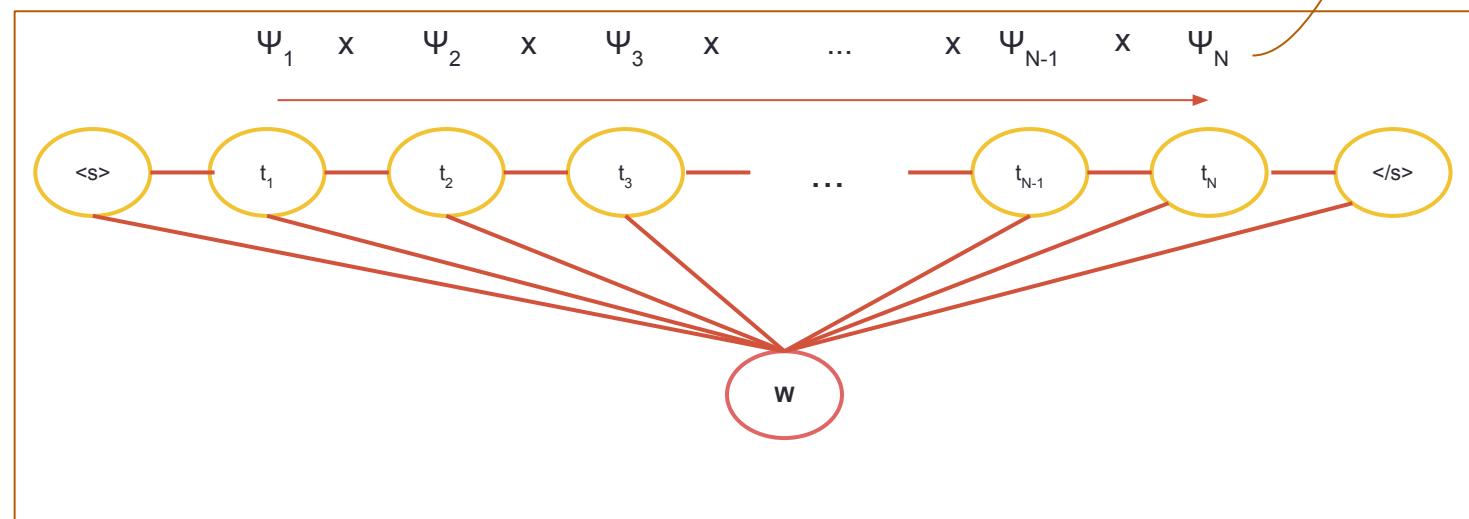
$$P(\mathbf{T}, \mathbf{W}) = \frac{1}{Z} \prod_{n=1}^N \Psi_n(t_n, t_{n-1}, \mathbf{W})$$

Sum of scores for all possible labels with all possible input sequences

$$Z = \sum_{T,W} \prod_{n=1}^N \Psi_n(t_n, t_{n-1}, \mathbf{W})$$

With  $p(\mathbf{T}, \mathbf{W})$  we can compare and pick the best  $\mathbf{T}$

Score of a sequence label  $\mathbf{T}$  for a given sequence input  $\mathbf{W}$

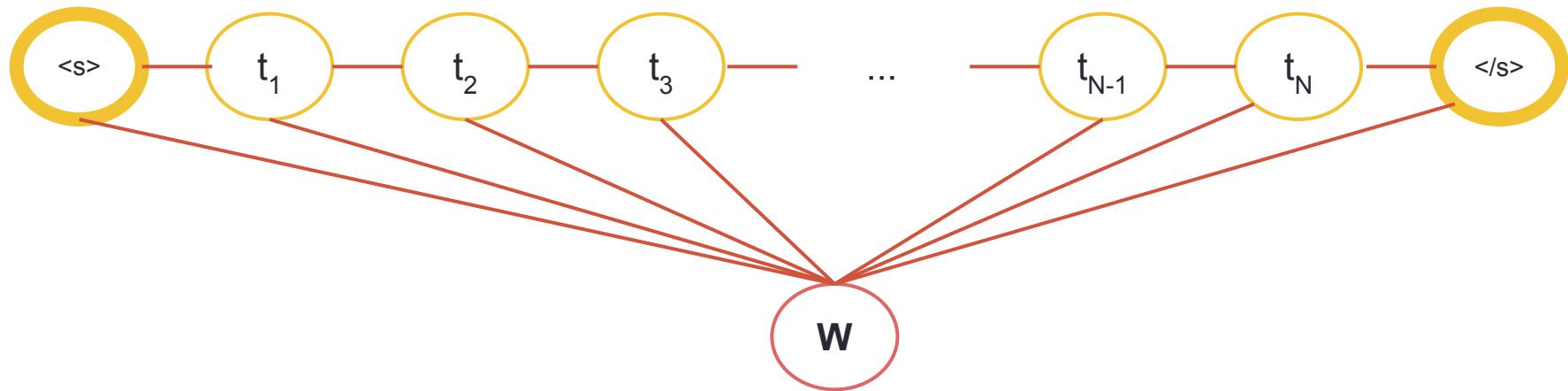


# Special states and characters

To simplify modeling, we add two new special states and characters:

**< s >** indicates the beginning of the sequence

**</s>** indicates the end of the sequence



# Product of sum over feature functions

From the definition of factors, the joint distribution can be represented by a number of feature functions

$$P(\mathbf{T}, \mathbf{W}) = \frac{1}{Z} \prod_{n=1}^N \Psi_n(t_n, t_{n-1}, \mathbf{W})$$

$$P(T, W) = \frac{1}{Z} \prod_{n=1}^N \exp\left[\sum_k^K \theta_k f_k(t_n, t_{n-1}, \mathbf{W}, n)\right]$$

$$Z = \sum_{T,W} \prod_{n=1}^N \Psi_n(t_n, t_{n-1}, \mathbf{W})$$

Computing  $Z$  is intractable:

Imagine a sentence of 20 words with vocabulary size of 100,000

we have to consider all  $(100000)^{20}$  possible input sequences!

# Linear-chain CRF

Modeling conditional probability distribution  $P(T|W)$  is enough for classification tasks.

So, in linear-chain CRF, we model the conditional distribution by using these two equations:

$$P(T|W) = \frac{P(T, W)}{P(W)} = \frac{P(T, W)}{\sum_{T'} P(T', W)}$$

$$P(T, W) = \frac{1}{Z} \prod_{n=1}^N \exp \left[ \sum_k^K \theta_k f_k(t_n, t_{n-1}, \mathbf{W}, n) \right]$$

# Linear-chain CRF

A linear-chain CRF is a conditional distribution

$$P(T|W) = \frac{1}{Z(W)} \prod_{n=1}^N \exp\left[\sum_k \theta_k f_k(t_n, t_{n-1}, \mathbf{W}, n)\right]$$

, where  $Z(\mathbf{x})$  is an instance-specific normalization function

$$Z(W) = \sum_T \prod_{n=1}^N \exp\left[\sum_k \theta_k f_k(t_n, t_{n-1}, \mathbf{W}, n)\right]$$

$$Z = \sum_{T,W} \prod_{n=1}^N \Psi_n(t_n, t_{n-1}, \mathbf{W})$$

# Linear-chain CRF

$$P(T|W) = \frac{1}{Z(W)} \prod_{n=1}^N \exp \left[ \sum_k^K \theta_k f_k(t_n, t_{n-1}, \mathbf{W}, n) \right]$$

**normalization  
function**

the sum of products  
of all possible  
output sequences

not the same as **Z** in  
the joint distribution

multiply  
over  
all time  
steps

**sum** of weighted  
feature functions at one  
time step, then taken to  
the **exponential**  
function

# Linear-chain CRF big picture

- Wants  $P(T|W)$
- Assumes independence, where we only consider  $P(t_{t-1}, t_t, W)$
- How to model  $P(t_{t-1}, t_t, W)$ ?
  - Still too hard, let's make it into a function where high value means high probability – potential functions  $\Psi_n(t_n, t_{n-1}, W) \rightarrow \mathbb{R}^+$
  - Still too hard, let's build it from pieces – feature functions  $f(t_n, t_{n-1}, W, n)$
- We can get  $P(T, W)$  by multiplying all  $\Psi_n(t_n, t_{n-1}, W) \rightarrow \mathbb{R}^+$ 
  - This is not a probability, need a normalization
- We can also get  $P(T|W)$  from multiplying all  $\Psi_n(t_n, t_{n-1}, W)$ 
  - Still need a normalization, but easier.
- This is our model, but!
  - How to use? How to estimate potential functions? What features functions?

# How to use?

- If we are given the model, and  $\mathbf{W}$

$$P(T|W) = \frac{1}{Z(W)} \prod_{n=1}^N \exp\left[\sum_k^K \theta_k f_k(t_n, t_{n-1}, \mathbf{W}, n)\right]$$

- Find  $\mathbf{T}$ 
  - Not so straight forward, many possible  $\mathbf{T}$ 
    - Noun, adjective, verb
    - Noun, noun, verb
    - Verb, noun, noun
    - Too many possibilities to compare
- Solution ??????

# Viterbi algorithm

Viterbi algorithm is an algorithm for decoding based on dynamic programming.

From the equation, we can see the  $Z(W)$  is the same for all possible label sequences, so we can consider only the part in the rectangle

$$P(T|W) = \frac{1}{Z(W)} \left[ \prod_{n=1}^N \exp \left[ \sum_k \theta_k f_k(t_n, t_{n-1}, \mathbf{W}, n) \right] \right]$$

Goes over time step just like HMM viterbi

Find the label sequence  $\mathbf{T}$  that maximize this value

# Viterbi: Structure

$$P(T|W) = \frac{1}{Z(W)} \left| \prod_{n=1}^N \exp \left[ \sum_k \theta_k f_k(t_n, t_{n-1}, \mathbf{W}, n) \right] \right|$$

Create two 2D arrays: VTB and Var

	0	1	...	N	N+1
ADJ					
ADP					
...					
<S>					
</S>					

**VTB(<s>, T)** stores the highest value a label sequence that  $y_T$  is  $<s>$  can take

	0	1	...	N	N+1
ADJ					
ADP					
...					
<S>					
</S>					

**Var(<s>, T)** stores the label  $y_{T-1}$  in the sequence that yields the value in  $\text{VTB}(<s>, T)$

# Viterbi: Initialization

$$P(T|W) = \frac{1}{Z(W)} \prod_{n=1}^N \exp \left[ \sum_k \theta_k f_k(t_n, t_{n-1}, \mathbf{W}, n) \right]$$

VTB

	0	1	...	N	N+1
ADJ	0	0.12			
ADP	0	0.03			
...	...	...			
</S>	0	10e-9			
<S>	1	10e-3			

For all other labels,  
apply the same way  
as ADJ

$$\text{VTB(ADJ,1)} = \Psi_1(\text{ADJ}, \langle s \rangle, \mathbf{x}) \text{VTB}(\langle s \rangle, 0)$$

Factors at time t=1, for  
current label=ADJ,  
previous label=<s>

1

Var

	0	1	...	N	N+1
ADJ	-	<S>			
ADP	-	<S>			
...	...	...			
</S>	-	<S>			
<S>	-	<S>			

The first label of the output  
sequence must be <s>

# Viterbi: Iteration

$$P(T|W) = \frac{1}{Z(W)} \prod_{n=1}^N \exp\left[\sum_k \theta_k f_k(t_n, t_{n-1}, \mathbf{W}, n)\right]$$

VTB

	0	1	...	N	N+1
ADJ	0	0.12	...	2.32	0.22
ADP	0	0.03	...	0.02	0.10
...	...	...	...	...	...
</S>	0	10e-9	...	0.03	3.09
<S>	1	10e-3	...	1.12	0.02

Iterate from n=2 to n=N+1

Var

	0	1	...	N	N+1
ADJ	-	<S>	...	NOUN	PREPO
ADP	-	<S>	...	NOUN	ADJ
...	...	...	...	...	...
</S>	-	<S>	...	VERB	ADJ
<S>	-	<S>	...	X	X

$$VTB(ADJ, n) = \max_{i \in Tags} \Psi_n(ADJ, i, W) VTB(i, n - 1)$$

Find the max among values from all previous label i

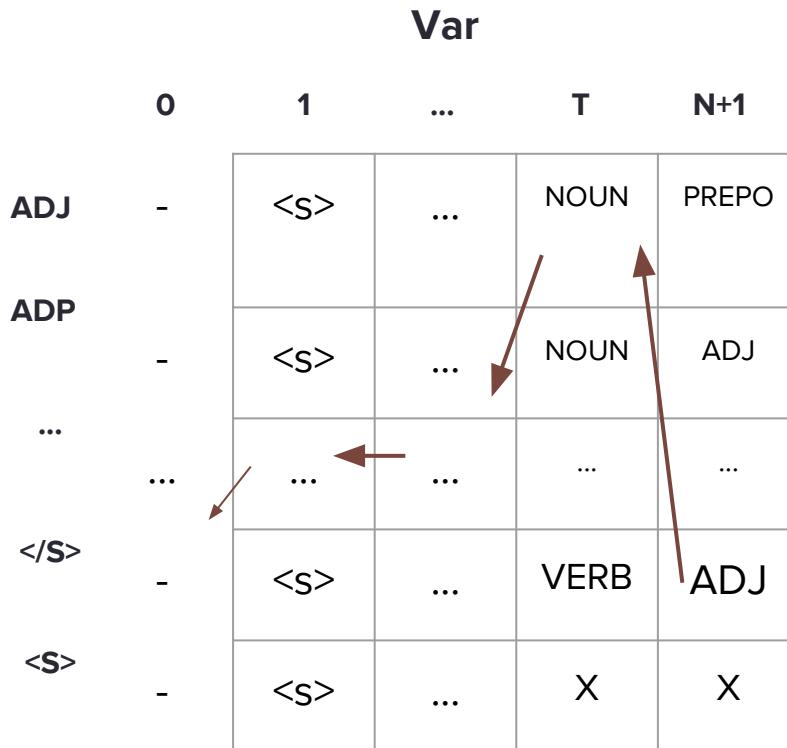
Factors at time n

Maximum value that label i can take at time n-1

Var(t, n) Stores the value i that maximize the value of VTB(t,n)

# Viterbi: Finalize

Backtrack from  $\text{Var}(</s>, N+1)$  to get the label sequences that maximize  $P(T|W)$



For example:  
output sequence =  
<S>, NOUN, ..., NOUN, ADJ, </s>

# Linear-chain CRF big picture

- Wants  $P(T|W)$
- Assumes independence, where we only consider  $P(t_{t-1}, t_t, W)$
- How to model  $P(t_{t-1}, t_t, W)$ ?
  - Still too hard, let's make it into a function where high value means high probability – potential functions  $\Psi_n(t_n, t_{n-1}, W) \rightarrow \mathbb{R}^+$
  - Still too hard, let's build it from pieces – feature functions  $f(t_n, t_{n-1}, W, n)$
- We can get  $P(T, W)$  by multiplying all  $\Psi_n(t_n, t_{n-1}, W) \rightarrow \mathbb{R}^+$ 
  - This is not a probability, need a normalization
- We can also get  $P(T|W)$  from multiplying all  $\Psi_n(t_n, t_{n-1}, W)$  and use chain rule.
  - Still need a normalization, but easier.
- This is our model, but!
  - How to use? Viterbi
  - How to estimate potential functions? What features functions?

# Parameters?

Parameters to be learned are weights associated to each feature functions. So, the number of parameters equals the number of feature functions.

$$P(T|W) = \frac{1}{Z(W)} \prod_{n=1}^N \exp\left[\sum_k^K \theta_k f_k(t_n, t_{n-1}, \mathbf{W}, n)\right]$$


parameters

# Training loss

For linear-chain CRF, parameters are trained by **maximum likelihood**.

$$l(\theta) = \sum_{i=1}^N \log P(T^{(i)} | W^{(i)}) \quad (\text{Negative loss})$$

To clarify, parameters  $\theta$  are trained to maximize the log probability of all pairs of label  $T^{(i)}$  and input  $W^{(i)}$  in the training set. (i) represents the  $i^{\text{th}}$  training sentence.

# Learning algorithm

To learn parameters from the loss function  $\ell(\theta)$ , several learning algorithm can be used. Some popular learning algorithms for linear-chain CRFs are

- Limited-memory BFGS
- Stochastic Gradient Descent

# Feature functions?

- Anything you can think of, the more the better.
  - The model will learn what is important.

$$f_1(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{NOUN} \text{ and } t_{n-1} = \text{ADJ}. \\ 0, & \text{otherwise.} \end{cases}$$

$$f_2(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{NOUN} \text{ and } w_n = \text{fox}. \\ 0, & \text{otherwise.} \end{cases}$$

$$f_3(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{NOUN} \text{ and } w_{n-1} = \text{an}. \\ 0, & \text{otherwise.} \end{cases}$$

$$f_4(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{PROPER NOUN} \text{ and } w_n \text{ is capitalized}. \\ 0, & \text{otherwise.} \end{cases}$$

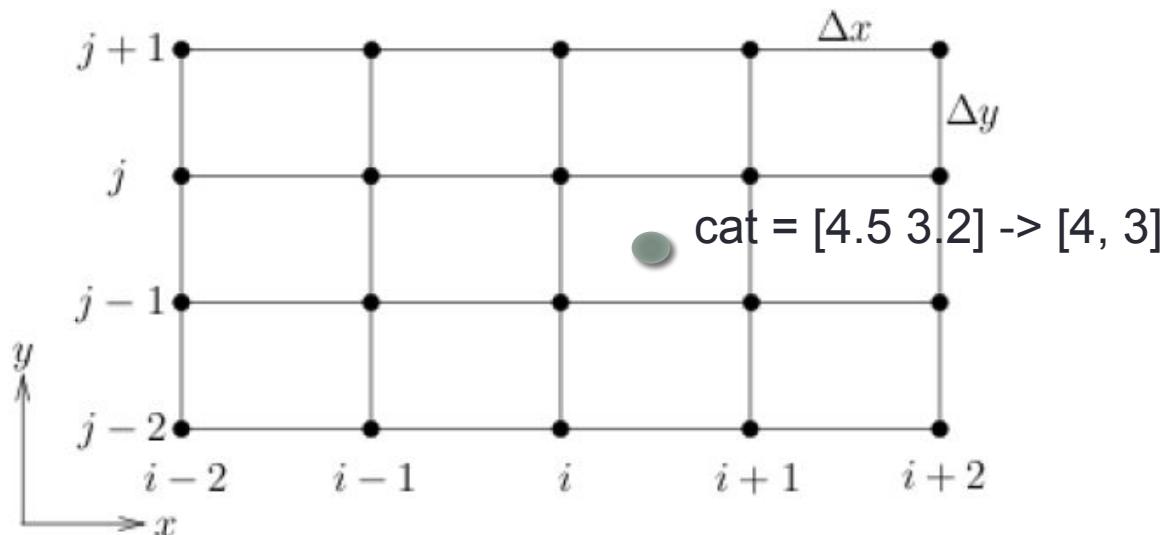
$$f_5(t_n, t_{n-1}, \mathbf{W}, n) = \begin{cases} 1, & \text{if } t_n = \text{NOUN} \text{ and } w_{n-1} \text{ ends with "est"}. \\ 0, & \text{otherwise.} \end{cases}$$

# CRFsuite

- An implementation of CRFs for labeling sequential data in C++  
SWIG API is provided to be an interface for various languages  
<http://www.chokkan.org/software/crfsuite/>
- python-crfsuite: Python binding for crfsuite  
<https://github.com/scrapinghub/python-crfsuite>
- An example use of python-crfsuite can be found at  
<https://github.com/scrapinghub/python-crfsuite/blob/master/examples/CoNLL%202002.ipynb>

# CRF with neural networks

- Many ways to use neural networks with CRFs
  - Caveats: most CRF takes discrete features.
- Neural networks features (embeddings) are continuous.
- Solution1: discretize the embeddings



# CRF with neural networks

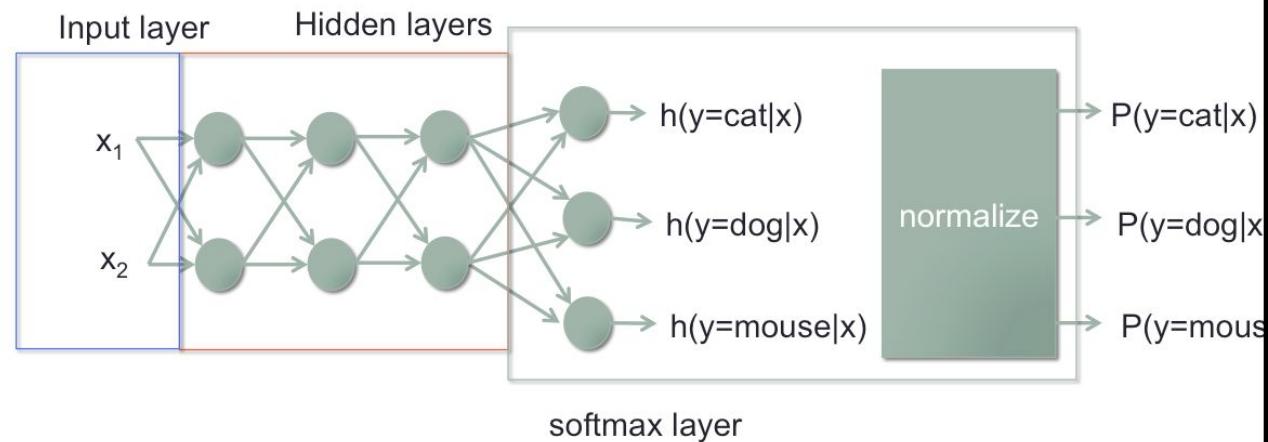
- Many ways to use neural networks with CRFs
  - Caveats: most CRF takes discrete features.
- Neural networks features (embeddings) are continuous.
- Solution2: Use continuous version of CRF

# CRF with neural networks

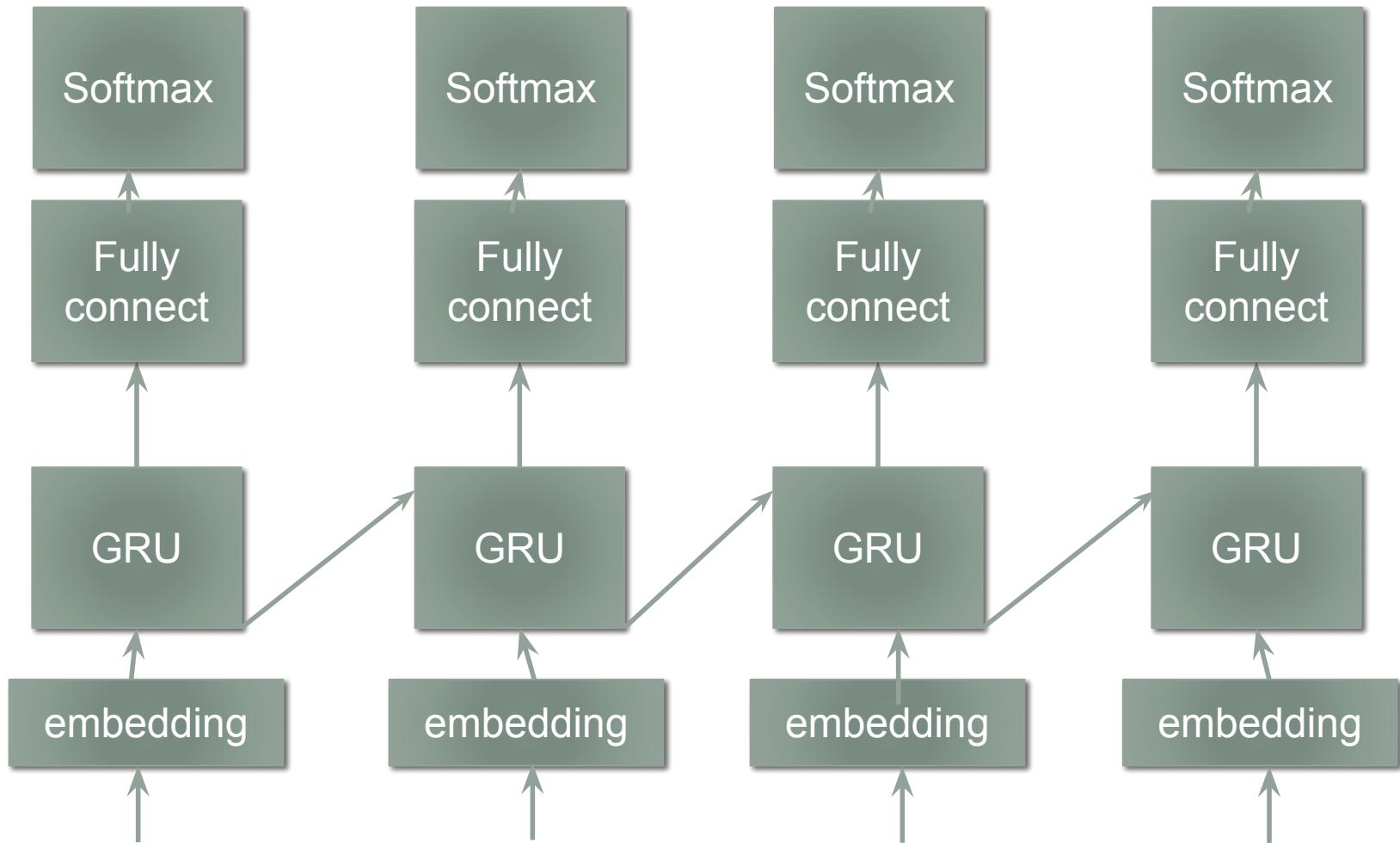
- Solution3: change the softmax layer and loss function
- CRFlayer:  $P(y|x)$  not just  $P(y_t|x_t)$

Typical softmax only considers current word label  
not the sequence

$$P(y = j|x) = \frac{e^{h(y=j|x)}}{\sum_y e^{h(y|x)}}$$

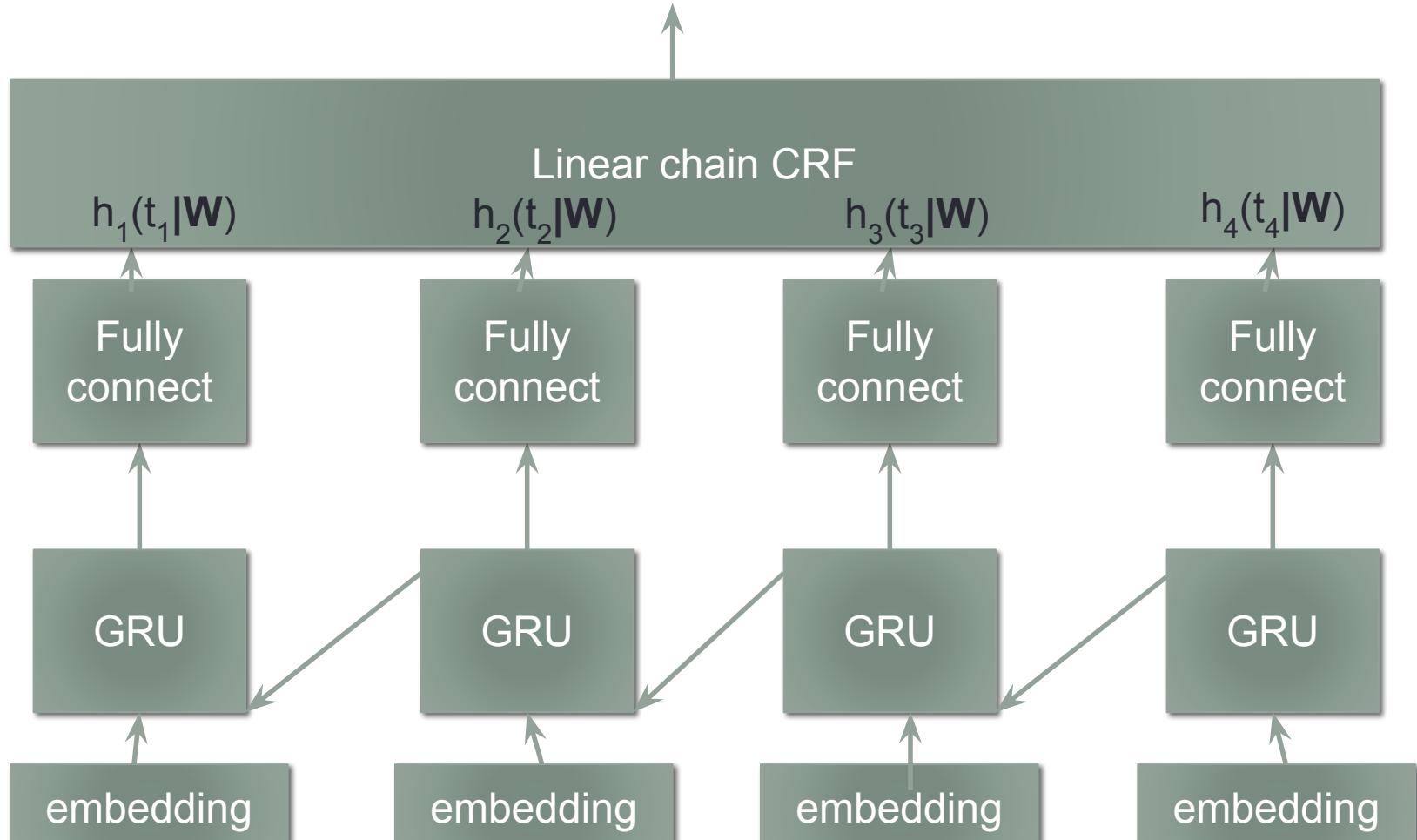


# Neural network for POS



# Neural network for POS with CRF output

$$P(T|W) = \frac{1}{Z(W)} \prod_{n=1}^N \exp h_n(t_n|W)$$



# Neural network for POS with CRF output

- Need to use Viterbi for finding the best sequence
  - Or instead of using the full sequence when decoding, consider each time step instead (marginal inference – faster decoding)
    - This is pretty much a regular softmax during decoding
- Loss function: still cross-entropy
  - Loss =  $-\log(P(T^*|W))$  where  $T^*$  is the true output

$$P(T|W) = \frac{1}{Z(W)} \prod_{n=1}^N \exp h_n(t_n|x)$$

Example code: Tensorflow

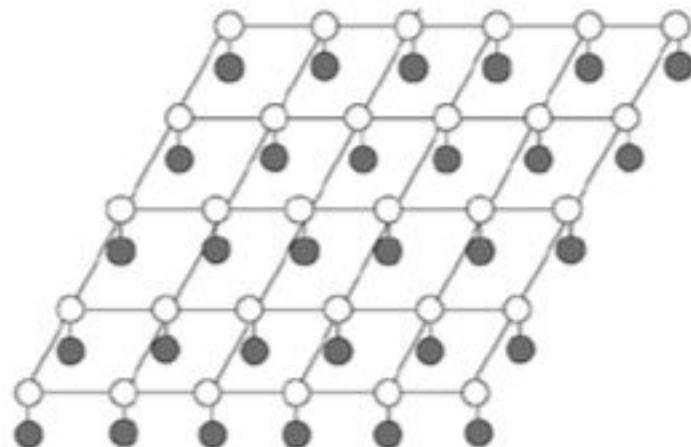
<https://guillaumegenthial.github.io/sequence-tagging-with-tensorflow.html>

Example code: Keras

[https://github.com/keras-team/keras-contrib/blob/master/keras\\_contrib/layers/crf.py](https://github.com/keras-team/keras-contrib/blob/master/keras_contrib/layers/crf.py)

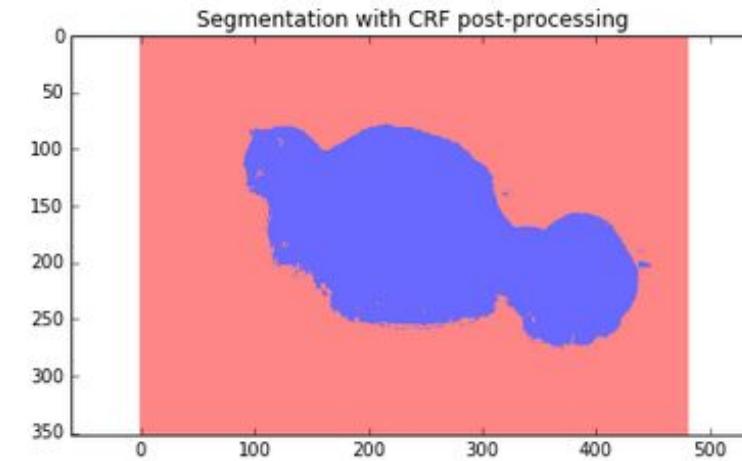
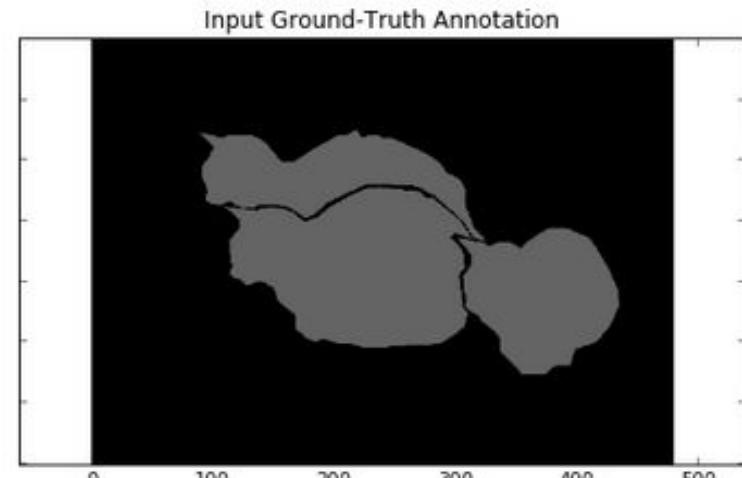
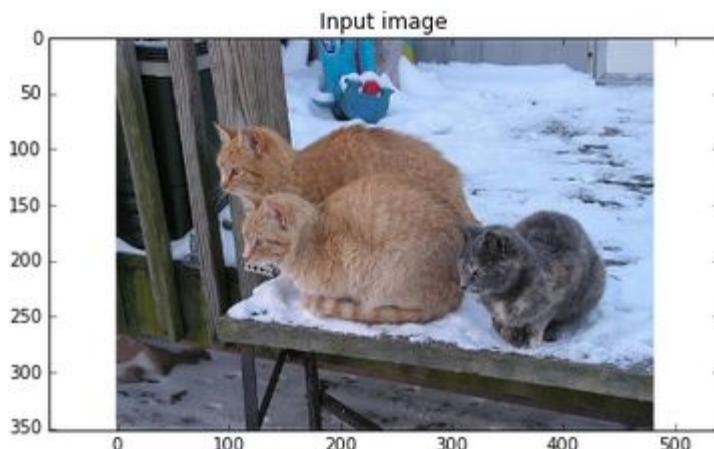
# Conditional Random Fields

- So far we talked about 1-d chain CRF
- We can also have CRF for any graph structure
  - Thus, the name random fields



# Conditional Random Fields in image

- Image segmentation



# NER

- **Name-Entity Recognition**

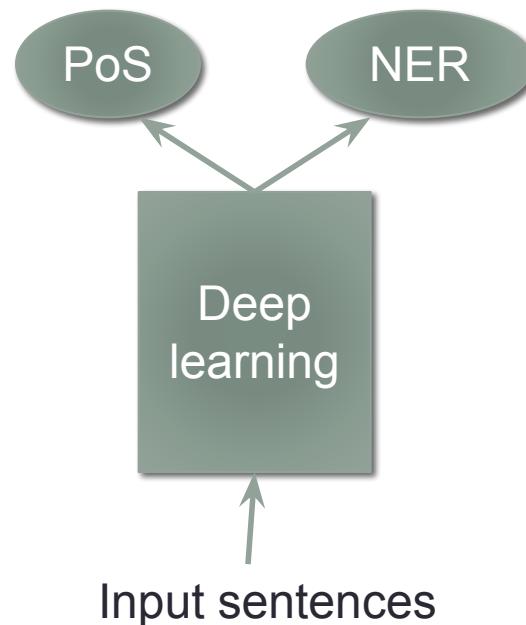
- Identify group of words that refer to the same entity
- เสก โลโซ ร้อง เพลง คุกเกี้ย เสี่ยงตาย
- [เสกโลโซ]/person ร้อง เพลง [คุกเกี้ยเสี่ยงตาย]/title

Biomedical publication mining

L-2 gene expression and NF-kappa B activation through CD28 requires reactive oxygen production by 5-lipoxygenase.

# NER

- Consider as PoS just different output labels
  - Sometimes use PoS as additional inputs
  - Or train PoS and NER jointly!



# NER in applications

- Classifying/tagging content
  - Information retrieval
  - Trends analysis

When Michael Jordan was at the peak of his powers as an NBA superstar, his Chicago Bulls teams were mowing down the competition, winning six National Basketball Association titles and setting a record for wins in a season that was broken by the Golden State Warriors two seasons ago.

Extract

## KEYWORDS

Place: Chicago

Name: Michael Jordan

Group: National Basketball Association

# Performance

Model	Acc.
Giménez and Màrquez (2004)	97.16
Toutanova et al. (2003)	97.27
Manning (2011)	97.28
Collobert et al. (2011) <sup>‡</sup>	97.29
Santos and Zadrozny (2014) <sup>‡</sup>	97.32
Shen et al. (2007)	97.33
Sun (2014)	97.36
Søgaard (2011)	97.50
<b>This paper</b>	<b>97.55</b>

Table 4: POS tagging accuracy of our model on test data from WSJ proportion of PTB, together with top-performance systems. The neural network based models are marked with ‡.

Model	F1
Chieu and Ng (2002)	88.31
Florian et al. (2003)	88.76
Ando and Zhang (2005)	89.31
Collobert et al. (2011) <sup>†</sup>	89.59
Huang et al. (2015) <sup>†</sup>	90.10
Chiu and Nichols (2015) <sup>‡</sup>	90.77
Ratinov and Roth (2009)	90.80
Lin and Wu (2009)	90.90
Passos et al. (2014)	90.90
Lample et al. (2016) <sup>‡</sup>	90.94
Luo et al. (2015)	91.20
<b>This paper</b>	<b>91.21</b>

Table 5: NER F1 score of our model on test data set from CoNLL-2003. For the purpose of comparison, we also list F1 scores of previous top-performance systems. <sup>†</sup> marks the neural models.

# Conclusion

- What is PoS?
- Traditional methods
  - Frequency-based
  - Local methods
  - Sequence methods
    - HMM
    - CRF
      - Viterbi and beamsearch
- Neural network methods
  - CRF loss

# Orchid PoS corpus

- Building A Thai Part-Of-Speech Tagged Corpus (ORCHID) (1999)

<http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.34.3496>

- 47 tags

No.	POS	Description	Example
1	NPRP	Proper noun	วินโคเวส 95, โคโรน่า, โค้ก, พระอาทิตย์
2	NCNM	Cardinal number	หนึ่ง, สี่, สาม, 1, 2, 3
3	NONM	Ordinal number	ที่หนึ่ง, ที่สอง, ที่สาม, ที่1, ที่2, ที่3
4	NLBL	Label noun	1, 2, 3, 4, ก, ข, a, b
5	NCMN	Common noun	หนังสือ, อาหาร, อาคาร, คน
6	NTTL	Title noun	คร., พลเอก
7	PPRS	Personal pronoun	คุณ, เขายัง, ฉัน
8	PDMN	Demonstrative pronoun	นี่, นั้น, ที่นั้น, ที่นี่
9	PNTR	Interrogative pronoun	ใคร, จะไร, อาย่างไร
10	PREL	Relative pronoun	ที่, ซึ่ง, อัน, ผู้
11	VACT	Active verb	ทำงาน, ร้องเพลง, กิน
12	VSTA	Stative verb	เห็น, รู้, คือ
13	VATT	Attributive verb	อ้วน, ดี, สวย
14	XVBM	Pre-verb auxiliary, before negator “ไม่”	เกิด, เก็บ, กำลัง
15	XVAM	Pre-verb auxiliary, after negator “ไม่”	ค่อย, น่า, ได้
16	XVMM	Pre-verb, before or after negator “ไม่”	ควร, เคย, ต้อง
17	XVBB	Pre-verb auxiliary, in imperative mood	กรุณา, จง, เชิญ, อย่า, ห้าม
18	XVAE	Post-verb auxiliary	ไป, มา, ชี้น

19	DDAN	Definite determiner, after noun without classifier in between	นี่, นั้น, โน่น, ที่งหนด
20	DDAC	Definite determiner, allowing classifier in between	นี่, นั้น, โน่น, นู้น
21	DDBQ	Definite determiner, between noun and classifier or preceding quantitative expression	ทั้ง, อีก, เพียง
22	DDAQ	Definite determiner, following quantitative expression	พอดี, ถ้วน
23	DIAC	Indefinite determiner, following noun; allowing classifier in between	ไหน, อื่น, ต่างๆ
24	DIBQ	Indefinite determiner, between noun and classifier or preceding quantitative expression	บาง, ประมาณ, เกือบ
25	DIAQ	Indefinite determiner, following quantitative expression	กว่า, เထะ
26	DCNM	Determiner, cardinal number expression	หนึ่งคน, เสือ 2 ตัว
27	DONM	Determiner, ordinal number expression	ที่หนึ่ง, ที่สอง, ที่สุดท้าย
28	ADVN	Adverb with normal form	เก่ง, เร็ว, ช้า, สม่ำเสมอ
29	ADVI	Adverb with iterative form	เร็วๆ, เสมอๆ, ช้าๆ
30	ADVP	Adverb with prefixed form	โดยเรื่อง
31	ADVS	Sentential adverb	โดยปกติ, ธรรมชาติ
32	CNIT	Unit classifier	ตัว, คน, เล่น
33	CLTV	Collective classifier	คู่, กู่กัน, ผูง, เชิง, ทาง, ด้าน, แบบ, รุ่น
34	CMTR	Measurement classifier	กิโลกรัม, แก้ว, ช้อนไมง
35	CFQC	Frequency classifier	ครั้ง, เพิ่ง
36	CVBL	Verbal classifier	ม้วน, มัด

37	JCRG	Coordinating conjunction	และ, หรือ, แต่
38	JCMP	Comparative conjunction	กว่า, เหนือกว่า, เพื่อกัน
39	JSBR	Subordinating conjunction	เพราะว่า, เมื่อจาก, ที่, แม้ว่า, ถ้า
40	RPRE	Preposition	จาก, ละ, ของ, ได้, บน
41	INT	Interjection	ไอ้, อี้, เออ, เอ๊, อ່ວ
42	FIXN	Nominal prefix	การทำงาน, ความสนุกสนาน
43	FIXV	Adverbial prefix	อย่างเร็ว
44	EAFF	Ending for affirmative sentence	จี๊, จ๊ะ, กะ, กรับ, นะ, น่า, เกอะ
45	EITT	Ending for interrogative sentence	หรือ, เหรอ, ไหน, นั้น
46	NEG	Negator	ไม่, มิได้, ไม่ได้, มิ
47	PUNC	Punctuation	(,), “, „, ;