Language Models

Computational Linguistics: Jordan Boyd-Graber
University of Maryland
INTRODUCTION

Slides adapted from Philip Koehn

Roadmap

After this class, you'll be able to:

- Understand probability distributions through the metaphor of the Chinese Restaurant Process
- Be able to calculate Kneser-Ney smoothing
- Understand the role of contexts in language models

Intuition

- Some words are “sticky”
- “San Francisco” is very common (high ungram)
- But Francisco only appears after one word

Intuition

- Some words are “sticky”
- “San Francisco” is very common (high ungram)
- But Francisco only appears after one word
- Our goal: to tell a statistical story of bay area restaurants to account for this phenomenon
- How to model this phenomena

Interpolation

- Higher and lower order n-gram models have different strengths and weaknesses
  - high-order n-grams are sensitive to more context, but have sparse counts
  - low-order n-grams consider only very limited context, but have robust counts
- Combine them

$$\begin{aligned} p_I(w_3 \mid w_1, w_2) = & \quad \lambda_1\, p_1(w_3) \\ & + \lambda_2\, p_2(w_3 | w_2) \\ & + \lambda_3\, p_3(w_3 | w_1, w_2) \end{aligned}$$

Back-Off

- Trust the highest order language model that contains n-gram

$$p_n^{BO}(w_i|w_{i-n+1},...,w_{i-1}) = \\ = \begin{cases} \alpha_n(w_i|w_{i-n+1},...,w_{i-1}) \\ \qquad\qquad \text{if count}_n(w_{i-n+1},...,w_i) > 0 \\ d_n(w_{i-n+1},...,w_{i-1})\, p_{n-1}^{BO}(w_i|w_{i-n+2},...,w_{i-1}) \\ \qquad\qquad \text{else} \end{cases}$$

- Requires
  - adjusted prediction model $\alpha_n(w_i|w_{i-n+1},...,w_{i-1})$
  - discounting function $d_n(w_1,...,w_{n-1})$

Let's remember what a language model is

- It is a distribution over the next word in a sentence
- Given the previous $n-1$ words

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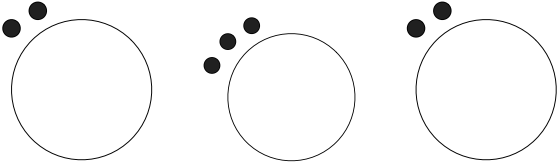
- It is a distribution over the next word in a sentence
- Given the previous $n-1$ words
- The challenge: backoff and sparsity

The Chinese Restaurant as a Distribution

To generate a word, you first sit down at a table. You sit down at a table proportional to the number of people sitting at the table.



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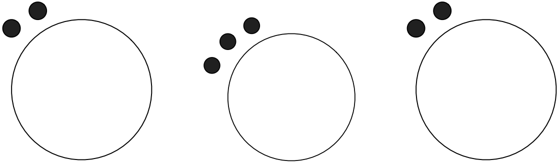

$\frac{2}{7}$ $\frac{3}{7}$ $\frac{2}{7}$

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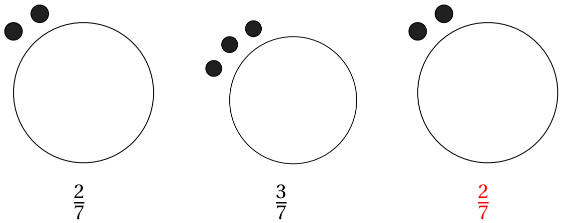

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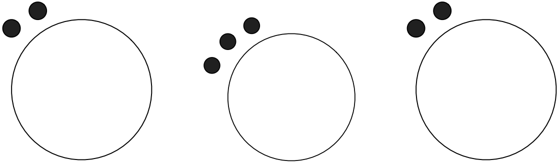

$\frac{2}{7}$ dog $\frac{3}{7}$ cat $\frac{2}{7}$ purple

The Chinese Restaurant as a Distribution

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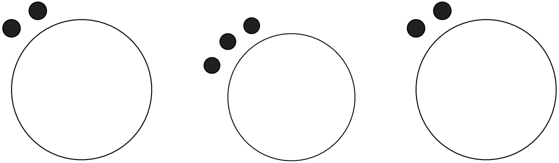
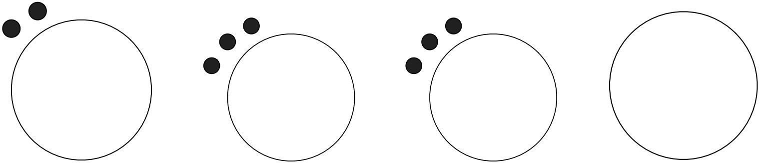


$\frac{2}{7}$ dog $\frac{3}{7}$ cat $\frac{2}{7}$ purple

But this is just Maximum Likelihood

Why are we talking about Chinese Restaurants?

Always one more table . . .



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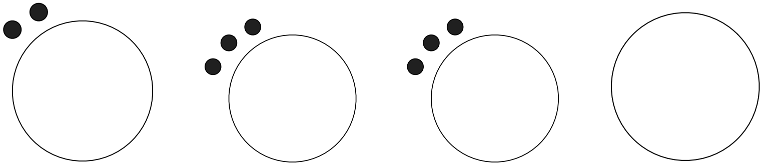
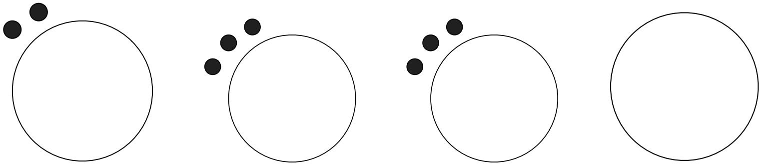


$\frac{2}{7+\alpha}$ $\frac{3}{7+\alpha}$ $\frac{2}{7+\alpha}$ $\frac{\alpha}{7+\alpha}$

Always one more table . . .



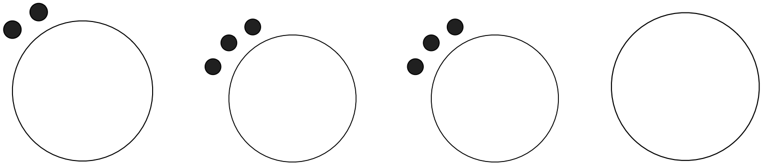
$\frac{2}{7+\alpha}$ dog

$\frac{3}{7+\alpha}$ cat

$\frac{2}{7+\alpha}$ purple

$\frac{\alpha}{7+\alpha}$???

Always one more table . . .



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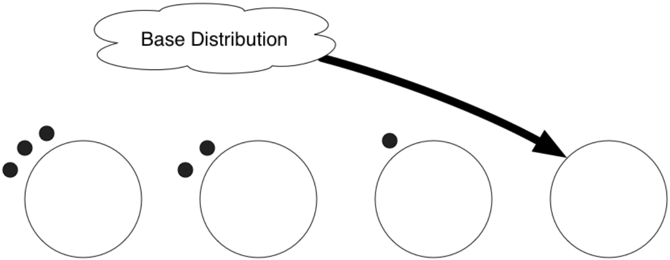
$\frac{3}{7+\alpha}$ cat

$\frac{2}{7+\alpha}$ purple

$\frac{\alpha}{7+\alpha}$???

What to do with a new table?



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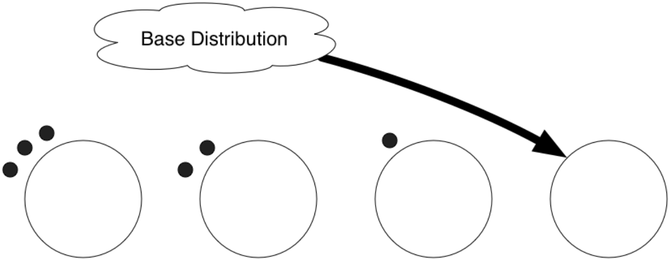
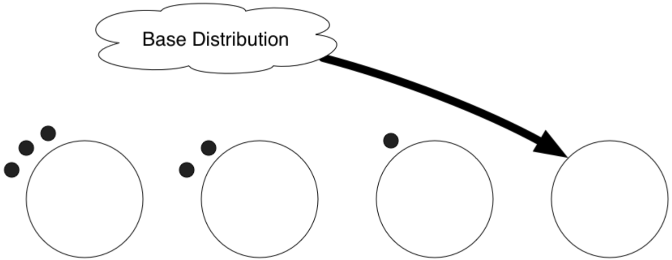


What can be a base distribution?

- Uniform (Dirichlet smoothing)

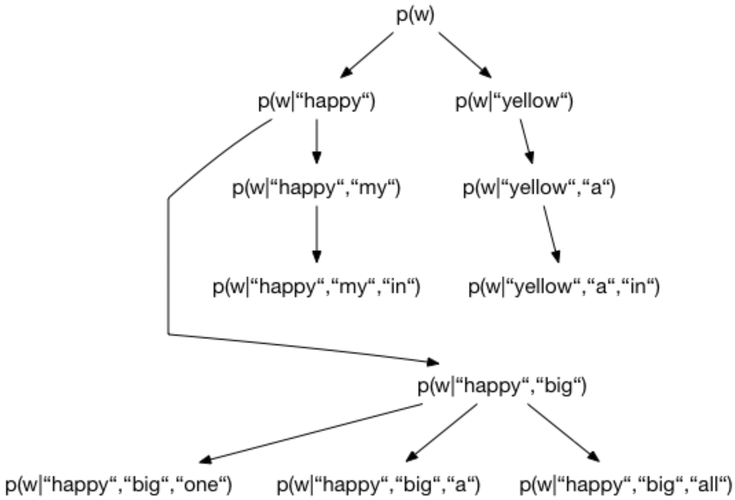
What to do with a new table?



What can be a base distribution?

- Uniform (Dirichlet smoothing)
- Specific contexts ⟶ less-specific contexts (backoff)

A hierarchy of Chinese Restaurants



Seating Assignments

Dataset:

<s> a a a b a c </s>

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

<s> Restaurant

a Restaurant

b Restaurant

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

<s> Restaurant

$\boxed{*}$ 1

a Restaurant

b Restaurant

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

$\boxed{*}^{1}$

<s> Restaurant

$\boxed{*}^{1}$

a Restaurant

b Restaurant

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a [1]

<s> Restaurant

a [1]

a Restaurant

c Restaurant

b Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a 1

<s> Restaurant

a 1

a Restaurant

* 1

b Restaurant

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a 1

<s> Restaurant

a 1

a Restaurant

* 1

b Restaurant

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a 2

<s> Restaurant

a 1

a Restaurant

a 1

b Restaurant

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a [2]

<s> Restaurant

a [1]

a Restaurant

a [1]

b Restaurant

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a [2]

<s> Restaurant

a [1]

a Restaurant

a [2]

b Restaurant

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

$\boxed{a}^{2}$

<s> Restaurant

$\boxed{a}^{1}$

a Restaurant

$\boxed{a}^{2}$ $\boxed{*}^{1}$

b Restaurant

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a[2] *[1]

<s> Restaurant

a[1]

a Restaurant

a[2] *[1]

b Restaurant

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a 2 b 1

<s> Restaurant

a 1

a Restaurant

a 2 * 1

b Restaurant

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a [2] b [1]

<s> Restaurant

a [1]

a Restaurant

a [2] b [1]

b Restaurant

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a 2 b 1

<s> Restaurant

a 1

a Restaurant

a 2 b 1

b Restaurant

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a 2 b 1

<s> Restaurant

a 1

a Restaurant

a 2 b 1

b Restaurant

* 1

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a[2] b[1]

<s> Restaurant

a[1]

a Restaurant

a[2] b[1]

b Restaurant

*[1]

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a [3] b [1]

<s> Restaurant

a [1]

a Restaurant

a [2] b [1]

b Restaurant

a [1]

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a[3] b[1]

<s> Restaurant

a[1]

b Restaurant

a[1]

a Restaurant

a[2] b[1]

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

$\boxed{\texttt{a}}^{3}$ $\boxed{\texttt{b}}^{1}$

<s> Restaurant

$\boxed{\texttt{a}}^{1}$

b Restaurant

$\boxed{\texttt{a}}^{1}$

a Restaurant

$\boxed{\texttt{a}}^{2}$ $\boxed{\texttt{b}}^{1}$ $\boxed{*}^{1}$

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

$\boxed{a}^{3}$ $\boxed{b}^{1}$ $\boxed{*}^{1}$

<s> Restaurant

$\boxed{a}^{1}$

a Restaurant

$\boxed{a}^{2}$ $\boxed{b}^{1}$ $\boxed{*}^{1}$

b Restaurant

$\boxed{a}^{1}$

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a 3 | b 1 | c 1

<s> Restaurant

a 1

b Restaurant

a 1

a Restaurant

a 2 | b 1 | c 1

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

$\boxed{a}^{3}$ $\boxed{b}^{1}$ $\boxed{c}^{1}$

<s> Restaurant

$\boxed{a}^{1}$

b Restaurant

$\boxed{a}^{1}$

a Restaurant

$\boxed{a}^{2}$ $\boxed{b}^{1}$ $\boxed{c}^{1}$

c Restaurant

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a	3	b	1	c	1

<s> Restaurant

a	1

a Restaurant

a	2	b	1	c	1

b Restaurant

a	1

c Restaurant

*	1

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a	b	c	*
3	1	1	1

<s> Restaurant

a
1

a Restaurant

a	b	c
2	1	1

b Restaurant

a
1

c Restaurant

*
1

Seating Assignments

Dataset:

<s> a a a b a c </s>

Unigram Restaurant

a [3] b [1] c [1] </s> [1]

<s> Restaurant

a [1]

a Restaurant

a [2] b [1] c [1]

b Restaurant

a [1]

c Restaurant

</s> [1]

Real examples

- San Francisco

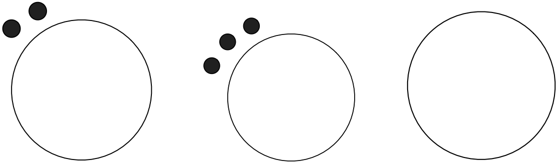
Real examples

- San Francisco
- Star Spangled Banner

Real examples

- San Francisco
- Star Spangled Banner
- Bottom Line: Counts go to the context that explains it best

The rich get richer



$\frac{2}{5+\theta}$ $\frac{3}{5+\theta}$ $\frac{\theta}{5+\theta}$

Computing the Probability of an Observation

$$p(w = x|\vec{s}, \theta, u) = \underbrace{\frac{c_{u,x}}{\theta + c_{u,\cdot}}}_{\text{existing table}} + \underbrace{\frac{\theta}{\theta + c_{u,\cdot}} p(w = x|\vec{s}, \theta, \pi(u))}_{\text{new table}} \quad (1)$$

- Word type x
- Seating assignments $\vec{s}$
- Concentration θ
- Context u
- Number seated at table serving x in restaurant u, $c_{u,x}$
- Number seated at all tables in restaurant u, $c_{u,\cdot}$
- The backoff context $\pi(u)$

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Computing the Probability of an Observation

$$p(w=x|\vec{s},\theta,u)= \underbrace{\frac{c_{u,x}}{\theta+c_{u,\cdot}}}_{\text{existing table}} + \underbrace{\frac{\theta}{\theta+c_{u,\cdot}}p(w=x|\vec{s},\theta,\pi(u))}_{\text{new table}} \tag{1}$$

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Example: $p(w = \mathbf{b} | \vec{s}, \theta = 1.0, u = \mathbf{a})$

Unigram Restaurant

a [3] b [1] c [1] </s> [1]

<s> Restaurant

a [1]

a Restaurant

a [2] b [1] c [1]

b Restaurant

a [1]

c Restaurant

</s> [1]

$$p(w = \mathrm{b} | \ldots) = \frac{c_{\mathrm{a},\mathrm{b}}}{\theta + c_{u,\cdot}} + \frac{\theta}{\theta + c_{u,\cdot}} p(w = x | \vec{s}, \theta, \pi(u)) \quad (2)$$

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<s> Restaurant

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</s> [1]

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Unigram Restaurant

$\boxed{\texttt{a}}^{3}$ $\boxed{\texttt{b}}^{1}$ $\boxed{\texttt{c}}^{1}$ $\boxed{\texttt{</s>}}^{1}$

<s> Restaurant

$\boxed{\texttt{a}}^{1}$

a Restaurant

$\boxed{\texttt{a}}^{2}$ $\boxed{\texttt{b}}^{1}$ $\boxed{\texttt{c}}^{1}$

b Restaurant

$\boxed{\texttt{a}}^{1}$

c Restaurant

$\boxed{\texttt{</s>}}^{1}$

$$p(w = \texttt{b} | \ldots) = \frac{1}{\theta + c_{u,\cdot}} + \frac{\theta}{\theta + c_{u,\cdot}} p(w = x | \vec{s}, \theta, \pi(u)) \tag{2}$$

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Unigram Restaurant

a[3] b[1] c[1] </s>[1]

<s> Restaurant

a[1]

a Restaurant

a[2] b[1] c[1]

b Restaurant

a[1]

c Restaurant

</s>[1]

$$p(w = \mathrm{b} | \ldots) = \frac{1}{1.0 + c_{u,\cdot}} + \frac{1.0}{1.0 + c_{u,\cdot}} p(w = x | \vec{s}, \theta, \pi(u)) \quad (2)$$

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<s> Restaurant

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a Restaurant

a [2] b [1] c [1]

b Restaurant

a [1]

c Restaurant

</s> [1]

$$p(w = \mathrm{b} | \ldots) = \frac{1}{1.0 + 4} + \frac{1.0}{1.0 + 4} p(w = x | \vec{s}, \theta, \pi(u)) \quad (2)$$

Example: $p(w = \mathbf{b} | \vec{s}, \theta = 1.0, u = \mathbf{a})$

Unigram Restaurant

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<s> Restaurant

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b Restaurant

a [1]

c Restaurant

</s> [1]

$$p(w = \mathrm{b} | \ldots) = \frac{1}{1.0 + 4} + \frac{1.0}{1.0 + 4} p(w = x | \vec{s}, \theta, \pi(u)) \tag{2}$$

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b Restaurant

a [1]

c Restaurant

</s> [1]

$$p(w = \text{b} | \ldots) = \frac{1}{1.0 + 4} + \frac{1.0}{1.0 + 4} p(w = x | \vec{s}, \theta, \pi(\emptyset)) \quad (2)$$

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Example: $p(w = \mathbf{b} | \vec{s}, \theta = 1.0, u = \mathbf{a})$

Unigram Restaurant

a	b	c	</s>
3	1	1	1

<s> Restaurant

a
1

a Restaurant

a	b	c
2	1	1

b Restaurant

a
1

c Restaurant

</s>
1

$$p(w = \mathrm{b} | \ldots) = \frac{1}{5} + \frac{1}{5}\left(\frac{c_{\emptyset,\mathrm{b}}}{c_{\emptyset,\cdot} + \theta} + \frac{\theta}{c_{\emptyset,\cdot} + \theta} \frac{1}{V} \right) \tag{2}$$

Example: $p(w = \mathbf{b} | \vec{s}, \theta = 1.0, u = \mathbf{a})$

Unigram Restaurant

$\boxed{\texttt{a}}^{3}$ $\boxed{\texttt{b}}^{1}$ $\boxed{\texttt{c}}^{1}$ $\boxed{\texttt{</s>}}^{1}$

<s> Restaurant

$\boxed{\texttt{a}}^{1}$

a Restaurant

$\boxed{\texttt{a}}^{2}$ $\boxed{\texttt{b}}^{1}$ $\boxed{\texttt{c}}^{1}$

b Restaurant

$\boxed{\texttt{a}}^{1}$

c Restaurant

$\boxed{\texttt{</s>}}^{1}$

$$p(w = \texttt{b} | \ldots) = \frac{1}{5} + \frac{1}{5} \left(\frac{c_{\emptyset,\texttt{b}}}{c_{\emptyset,\cdot} + \theta} + \frac{\theta}{c_{\emptyset,\cdot} + \theta} \frac{1}{5} \right) \tag{2}$$

Example: $p(w = \mathbf{b} | \vec{s}, \theta = 1.0, u = \mathbf{a})$

Unigram Restaurant

a[3] b[1] c[1] </s>[1]

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c Restaurant

</s>[1]

$$p(w = \mathrm{b} | \ldots) = \frac{1}{5} + \frac{1}{5} \left(\frac{c_{\emptyset,\mathrm{b}}}{c_{\emptyset,\cdot} + 1.0} + \frac{1.0}{c_{\emptyset,\cdot} + 1.0} \frac{1}{5} \right) \quad (2)$$

Example: $p(w = \mathbf{b} | \vec{s}, \theta = 1.0, u = \mathbf{a})$

Unigram Restaurant

a[3] b[1] c[1] </s>[1]

<s> Restaurant

a[1]

a Restaurant

a[2] b[1] c[1]

b Restaurant

a[1]

c Restaurant

</s>[1]

$$p(w = \mathrm{b} | \dots) = \frac{1}{5} + \frac{1}{5}\left(\frac{1}{c_{\emptyset,\cdot} + 1.0} + \frac{1.0}{c_{\emptyset,\cdot} + 1.0}\frac{1}{5}\right) \quad (2)$$

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Unigram Restaurant

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$\texttt{<s>}$ Restaurant

$\texttt{a}^{1}$

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$\texttt{b}$ Restaurant

$\texttt{a}^{1}$

$\texttt{c}$ Restaurant

$\texttt{</s>}^{1}$

$$p(w = \mathrm{b} | \ldots) = \frac{1}{5} + \frac{1}{5}\left(\frac{1}{7} + \frac{1}{7}\frac{1}{5}\right) = 0.24 \tag{2}$$

Discounting

- Empirically, it helps favor the backoff if you have more tables
- Otherwise, it gets too close to maximum likelihood
- Idea is called <u>discounting</u>
- Steal a little bit of probability mass δ from every table and give it to the new table (backoff)

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Interpolated Kneser-Ney!

More advanced models

- Interpolated Kneser-Ney assumes **one table with a dish (word)** per restaurant
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- Neural language models ...