LM Smoothing
(The EM Algorithm)

Introduction to Natural Language Processing

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The Zero Problem

- "Raw" n-gram language model estimate:
  – necessarily, some zeros
    - !many: trigram model $\rightarrow 2.16 \times 10^{14}$ parameters, data ~10^{9} words

  – which are true 0?
    - optimal situation: even the least grequent trigram would be seen several times, in order to distinguish it's probability vs. other trigrams
    - optimal situation cannot happen, unfortunately (open question: how many data would we need?)

  – $\rightarrow$ we don't know

  – we must eliminate zeros
- Two kinds of zeros: p(w|h) = 0, or even p(h) = 0!

Why do we need Nonzero Probs?

- To avoid infinite Cross Entropy:
  – happens when an event is found in test data which has not been seen in training data

  H(p) = ∞: prevents comparing data with $\geq$ 0 "errors"

- To make the system more robust
  – low count estimates:
    - they typically happen for "detailed" but relatively rare appearances

  – high count estimates: reliable but less "detailed"

Eliminating the Zero Probabilites: Smoothing

- Get new p'(w) (same Ω): almost p(w) but no zeros
- Discount w for (some) p(w) > 0: new p'(w) < p(w)

$$\Sigma_{w \in discounted}\ (p(w) - p'(w)) = D$$

- Distribute d to all w; p(w) = 0: new p'(w) > p(w)
  – possibly also to other w with low p(w)
- For some w (possibly): p'(w) = p(w)
- Make sure $\Sigma_{w \in \Omega}$p'(w) = 1
- There are many ways of *smoothing*

Smoothing by Adding 1

- Simplest but not really usable:
  – Predicting words w from a vocabulary V, training data T:
  p'(w|h) = (c(h,w) + 1) / (c(h + |V|)
  - for non-conditional distributions: p'(w) = (c(w) + 1) / (|T| + |V|)

  – Problem if |V| > c(h) (as is often the case; even » c(h)!)
- Example:

Training data: <s> what is it what is small? |T| = 8

V = {what, is, it, small, ?,<s> ,flying, birds, are, a, bird, .}, |V| = 12

p(it) = .125, p(what) = .25, p(.)=0

p(what is it?) = $.25^2 \times .125^2 \cong .001$

p(it is flying?) = $.125 \times .25 \times 0^2 = 0$

p'(it) = .1, p'(what) = .15, p'(.) = .05

p'(what is it?) = $.15^{\times} .1^2 \cong .0002$

p'(what is flying?) = $.1 \times .15 \times .05^2 \cong .00004$

Adding *less than 1*

- Equally simple:
  – Predicting word w from a vocabulary V, training data T:
  p'(w|h) = (c(h,w) + λ / (c(h) + λ|V|), λ < 1
  - for non-conditional distributions: p'(w) = (c(w) + λ / (|T| +λ|V|)
- Example:

Training data: <s> what is it what is small? |T| = 8

V = {what, is, it, small, ?,<s> ,flying, birds, are, a, bird, .}, |V| = 12

p(it) = .125, p(what) = .25, p(.)=0

p(what is it?) = $.25^2 \times .125^2 \cong .001$

p(it is flying?) = $.125 \times .25 \times 0^2 = 0$

Use λ = .1

p'(it) $\cong$ .12, p'(what) $\cong$ .23,

p'(.) $\cong$ .01

p'(what is it?) = $.23^2 \times .12^2 \cong .0007$

p'(it is flying) = $.12 \times .23 \times .01^2 \cong .000003$

Good-Turing

- Suitable for estimation from large data

  – similar idea: discount/boost the relative frequency estimate:

  $$p_r(\mathrm{w}) = (\mathrm{c(w)} + 1) \times \mathrm{N(c(w)} + 1) / (|\mathrm{T}| \times \mathrm{N}(0))$$

  where N(c) is the count of words with count c (count-of-counts)

  specifically, for c(w) = 0 (unseen words), $\mathrm{p}_r(\mathrm{w}) = \mathrm{N}(1) / (|\mathrm{T}| \times \mathrm{N}(0))$

  – good for small counts (< 5–10, where N(c) is high)

  – variants (see MS)

  – normalization! (so that we have $\Sigma_w \mathrm{p'(w)} = 1$)

Good-Turing: An Example

- Example: remember: p_r(w) = (c(w) + 1) × N(c(w) + 1) / (|T| × N(c(w)))

  Training data: <s> what is it what is small? |T| = 8
  V = {what, is, it, small, ?,<s> ,flying, birds, are, a, bird, .}, |V| = 12
  p(it) = .125, p(what) = .25, p(.)=0 p(what is it?) = $.25^2 \times .125^2 \cong .001$
  p(it is flying?) = $.125 \times .25 \times 0^2 = 0$

  - Raw estimation (N(0) = 6, N(1) = 4, N(2) = 2, N(i) = 0, for i > 2):
    p_r(it) = (1+1)×N(1+1)/(8×xN(1)) = 2×2/(8×4) = .125
    p_r(what) = (2+1)×N(2+1)/(8×+N(2)) = 3×0/(8×2) = 0: keep orig. p(what)
    p_r(.) = (0+1)×N(0+1)/(8×+N(0)) = 1×4/(8×6) ≅ .083
  - Normalize (divide by 1.5 = $\Sigma_{w \in |V|} p_r(w)$) and compute:
    p'(it) ≅ .08, p'(what) ≅ .17, p'(.) ≅ .06
    p'(what is it?) = $.17^2 \times .08^2 \cong .0002$
    p'(it is flying.) = $.08^2 \times .17 \times .06^2 \cong .00004$

Smoothing by Combination: Linear Interpolation

- Combine what?
  - distribution of various level of detail vs. reliability
- n-gram models:
  - use (n-1)gram, (n-2)gram, ..., uniform
    $\longrightarrow$ reliability
    $\longleftarrow$ detail
- Simplest possible combination:
  – sum of probabilities, normalize:
  - p(0|0) = .8, p(1|0) = .2, p(0|1) = 1, p(1|1) = 0, p(0) = .4, p(1) = .6:
  - p'(0|0) = .6, p'(1|0) = .4, p'(1|0) = .7, p'(1|1) = .3

Typical n-gram LM Smoothing

- Weight in less detailed distributions using $\lambda = (\lambda_0, \lambda_1, \lambda_2, \lambda_3)$:
  $$p'_\lambda(w_i|w_{i-2}, w_{i-1}) = \lambda_3 p_3(w_i|w_{i-2}, w_{i-1}) + \lambda_2 p_2(w_i|w_{i-1}) + \lambda_1 p_1(w_i) + \lambda_0/|V|$$
- Normalize:
  $\lambda_i > 0, \Sigma i = 0..n\lambda_i = 1$ is sufficient ($\lambda_0 = 1 - \Sigma i = 1..n\lambda_i$)(n = 3)
- Estimation using MLE:
  – fix the p_3, p_2, p_1 and |V| parameters as estimated from the training data
  – then find such $\{\lambda_i\}$ which minimizes the cross entropy (maximazes probablity of data): $-(1/|D|)\Sigma_{i=1..|D|} log_2(p'_\lambda(w_i|h_i))$

Held-out Data

- What data to use?
  – try training data T: but we will always get λ_3 = 1
  - why? let p_{iT} be an i-gram distribution estimated using r.f. from T)
  - minimizing H_T(p'$_\lambda$) over a vector λ, p'$_\lambda$ = $\lambda_3 p_{3T} + \lambda_2 p_{2T} + \lambda_1 p_{1T} + \lambda_0/|V|$
    – remember H_T(p'$_\lambda$) = H(p_{3T}) + D(p_{3T}||p'$_\lambda$); p_{3T}fixed $\rightarrow$ H(p_{3T}) fixed, best)
    – which p'$_\lambda$ minimizes H_T(p'$_\lambda$)? Obviously, a p'$_\lambda$ for which D(p_{3T}||p'$_\lambda$) = 0
    – ...and that's p_{3T} (because D(p||p) = 0, as we know)
    – ...and certainly p'$_\lambda$ = p_{3T}if$\lambda_3 = 1$ (maybe in some other cases, too).
    – (p'$_\lambda$ = 1 $\times$ p_{3T} + 0 $\times$ p_{2T} + 1 $\times$ p_{1T} + 0/|V|)

  – thus: do <u>not use the training data for estimation of λ!</u>
  - must hold out part of the training data (***heldout*** data, <u>H</u>)
  - ...call remaining data the (true/raw) ***training*** data, <u>T</u>
  - the ***test*** data <u>S</u> (e.g., for comparison purposes): still different data!

The Formulas

- Repeat: minimizing $(-1/|H|)\Sigma_{i=1..|H|} log_2(\text{p'}_\lambda(w_i|h_i))$ over λ

$$\boxed{\text{p'}_\lambda(w_i|h_i) = \text{p'}_\lambda(w_i|w_{i-2}, w_{i-1}) = \lambda_3 p_3(w_i|w_{i-2}, w_{i-1}) + \lambda_2 p_2(w_i|w_{i-1}) + \lambda_1 p_1(w_i) + \lambda_0/|V| \quad \textbf{!}}$$

- "Expected counts of lambdas": j = 0..3

$$\boxed{\text{c}(\lambda_j) = \Sigma i = 1..|H|(\lambda_j p_j(w_i|h_i) \;/\; \text{p'}_\lambda(w_i|h_i)) \quad \textbf{!}}$$

- "Next λ": j = 0..3

$$\boxed{\lambda_{j,next} = c(\lambda_j)/\Sigma_{k=0..3}(c(\lambda_k)) \quad \textbf{!}}$$

The (Smoothing) EM Algorithm

1. Start with some λ, such that λ > 0 for all j $\in$ 0..3
2. Compute "Expected Counts" for eachλ_j.
3. Compute new set of λ_j, using "Next λ" formula.
4. Start over at step 2, unless a termination condition is met.

- Termination condition: convergence of λ.
  – Simply set an ε, and finish if $|\lambda_j - \lambda_{j,next}| < \varepsilon$ for each j (step 3).
- Guaranteed to converge: follows from Jensen's inequality, plus a technical proof.

Remark on Linear Interpolation Smoothing

- "Bucketed Smoothing":
  – use several vectors of λ instead of one, based on (the frequency of) history: λ(h)
  - e.g. for h = (micrograms,per) we will have

    λ(h) = (.999, .0009, .00009, .00001)
    (because "cubic" is the only word to follow...)

  – actually: not a separate set for each history, but rather a set for "similar" histories ("bucket"):

  λ(b(h)), where b: $V^2 \to N$ (in the case of trigrams)
  b classifies histories according to their reliability (~frequency)

Bucketed Smoothing: The Algorithm

- First, determine the bucketing function <u>b</u> (use heldout!):
  – decide in advance you want e.g. 1000 buckets
  – compute the total frequency of histories in 1 bucket (f_{max}(b))
  – gradually fill your buckets from the most frequent bigrams so that the sum of frequencies does not exceed f_{max}(b) (you might end up with slightly more than 1000 buckets)
- Divide your heldout data according to buckets
- Apply the previous algorithm to each bucket and its data

Simple Example

- Raw distribution (unigram only; smooth with uniform):
  p(a) = .25, p(b) = .5, p(α) = 1/64 for $\alpha \in \{c..r\}$, = 0 for the rest: s, t, u, v, w, x, y, z
- Heldout data: baby; use one set of λ (λ_1: unigram, λ_2: uniform)
- Start with λ = 5:

$$p'_\lambda(b) = .5 \times .5 + .5/26 = .27$$
$$p'_\lambda(a) = .5 \times .25 + .5/26 = .14$$
$$p'_\lambda(y) = .5 \times 0 + .5/26 = .02$$

$c(\lambda_1) = .5\times.5/.27 + .5\times.25/.14 + .5\times.5/.27 + .5\times0/.02 = 2.27$
$c(\lambda_0) = .5\times.04/.27 + .5\times.04/.14 + .5\times.04/.27 + .5\times.04/.02 = 1.28$
Normalize $\lambda_{1,next} = .68$, $\lambda_{0,next} = .32$
Repeat from step 2 (recomputep'$_\lambda$ first for efficient computation, then c(λ_i), ...).
Finish when new lambdas almost equal to the old ones (say, < 0.01 difference).

Some More Technical Hints

- Set V = {all words from training data}.
  - You may also consider $V = T \cup H$, but it does not make the coding in any way simpler (in fact, harder).
  - But: you must *never* use the test data for your vocabulary
- Prepend two "words" in front of all data:
  - avoids beginning-of-data problems
  - call these index -1 and 0: then the formulas hold exactly
- When $c_n(w,h) = 0$:
  - Assing 0 probability to $p_n(w|h)$ where $c_{n-1}(h) > 0$, but a uniform probablity (1/|V|) to those $p_n(w|h)$ where $c_{n-1}(h) = 0$ (this must be done both when working on the heldout data during EM, as well as when computing cross-entropy on the test data!)