Mixture of Categoricals
Expectation Maximization

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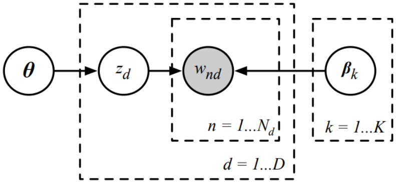
A mixture of categoricals model



$$z_d \sim Cat(\vec{\theta})$$
$$w_{nd}|z_d \sim Cat(\vec{\beta}_{z_d})$$

We want to allow for a mixture of K categoricals parametrised by $\vec{\beta}_1, \ldots, \vec{\beta}_K$.
Each of those categorical distributions corresponds to a document category.

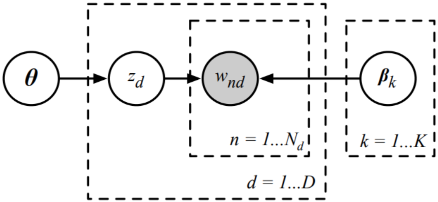
- $z_d \in 1, \ldots, K$ assigns document d to one of the K categories.
- $\theta_k = p(z_d = k)$ is the probability any document d is assigned to category k.
- so $\vec{\theta} = [\theta_1, \ldots, \theta_K]$ is the parameter of a categorical distribution over K categories.

We have introduced a new set of hidden variables z_d.

- How do we fit those variables? What do we do with them?
- Are these variables interesting? Or are we only interested in $\vec{\theta}$ and $\vec{\beta}$?

A mixture of categoricals model: the likelihood

$$
\begin{aligned}
p(w|\vec{\theta}, \vec{\beta}) &= \prod_{d=1}^{D} p(w_d|\vec{\theta}, \vec{\beta}) \\
&= \prod_{d=1}^{D} \sum_{k=1}^{K} p(w_d, z_d = k|\vec{\theta}, \vec{\beta}) \\
&= \prod_{d=1}^{D} \sum_{k=1}^{K} p(z_d = k|\vec{\theta}) p(w_d|z_d = k, \vec{\beta}_k) \\
&= \prod_{d=1}^{D} \sum_{k=1}^{K} p(z_d = k|\vec{\theta}) \prod_{n=1}^{N_d} p(w_{nd}|z_d = k, \vec{\beta}_k)
\end{aligned}
$$



$$z_d \sim Cat(\vec{\theta})$$

$$w_{nd}|z_d \sim Cat(\vec{\beta}_{z_d})$$

w: all the words in all the documents,
w_d: all the words in a document d,
w_{nd}: the n-th word in document d.

Expectation Maximization and Mixture of Categoricals

We want to maximize the likelihood of the data:

$$p(w|\vec{\theta}, \vec{\beta}) = \prod_{d=1}^{D} \sum_{k=1}^{K} p(z_d = k|\vec{\theta}) \prod_{n=1}^{N_d} p(w_{nd}|z_d = k, \vec{\beta}_k)$$

However, the latent variables (document categories) are unknown.

Expectation-Maximization algorithm:

1. Initialize $\vec{\theta}$ and $\vec{\beta}$ randomly.
2. *E-step*: For each d and k, compute responsibilities r_{kd} as probabilities $q(z_d = k|\vec{\theta}, \vec{\beta})$
3. *M-step*: Maximize the likelihood of the model with weighted by the responsibilities r_{kd} from step 2 and update the parameters $\vec{\beta}$ and $\vec{\theta}$.
4. Repeat steps 2 and 3 until convergence.

Expectation Maximization and Mixture of Categoricals

E-step: For each document, compute posterior distribution over categories:

$$r_{kd} = q(z_d = k) \propto p(z_d = k|\vec{\theta}) \prod_{n=1}^{N_d} p(w_{nd}|z_d = k, \vec{\beta}_k) = \theta_k \prod_{m=1}^{M} \beta_{km}^{c_{md}}$$

M-step: Maximize the log-likelihood weighted by the responsibilities r_{kd}:

$$\sum_{d=1}^{D} \sum_{k=1}^{K} r_{kd} \log p(w, z_d) = \sum_{k,d} r_{kd} \log[p(z_d = k|\vec{\theta}) \prod_{n=1}^{N_d} p(w_{nd}|z_d = k, \vec{\beta}_k)]$$

$$= \sum_{k,d} r_{kd} (\log \theta_k + \log \prod_{m=1}^{M} \beta_{km}^{c_{md}})$$

$$= \sum_{k,d} r_{kd} (\log \theta_k + \sum_{m=1}^{M} c_{md} \log \beta_{km})$$

M-step (continued): We need Lagrange multipliers to constrain the maximization of the function ensure proper distributions.

$$L_1 = \sum_{k=1}^{K} \sum_{d=1}^{D} r_{kd} (\log \theta_k + \sum_{m=1}^{M} c_{md} \log \beta_{km}) + \lambda (1 - \sum_{k'=1}^{K} \theta_{k'})$$

$$\frac{\partial L_1}{\partial \theta_k} = \sum_{d=1}^{D} r_{kd} \frac{1}{\theta_k} - \lambda = 0 \quad \Rightarrow \quad \theta_k = \frac{\sum_{d=1}^{D} r_{kd}}{\lambda} = \frac{\sum_{d=1}^{D} r_{kd}}{\sum_{k'=1}^{K} \sum_{d=1}^{D} r_{k'd}} = \frac{\sum_{d=1}^{D} r_{kd}}{D}$$

$$L_2 = \sum_{k=1}^{K} \sum_{d=1}^{D} r_{kd} (\log \theta_k + \sum_{m=1}^{M} c_{md} \log \beta_{km}) + \sum_{k'=1}^{K} \lambda_{k'} (1 - \sum_{m'=1}^{M} \beta_{k'm'})$$

$$\frac{\partial L_2}{\partial \beta_{km}} = \sum_{d=1}^{D} r_{kd} \frac{c_{md}}{\beta_{km}} - \lambda_k = 0 \quad \Rightarrow \quad \beta_{km} = \frac{\sum_{d=1}^{D} r_{kd} c_{md}}{\lambda_k} = \frac{\sum_{d=1}^{D} r_{kd} c_{md}}{\sum_{m'=1}^{M} \sum_{d=1}^{D} r_{kd} c_{m'd}}$$

Expectation Maximization and Mixture of Categoricals

EM Algorithm:

1. Initialize $\vec{\theta}$ and $\vec{\beta}$ randomly.
2. *E-step*: For each d and k, compute responsibilities r_{kd} using current parameters $\vec{\theta}$ and $\vec{\beta}$.

$$r_{kd} = \frac{\theta_k \prod_{m=1}^{M} \beta_{km}^{c_{md}}}{\sum_{k'=1}^{K} \theta_k' \prod_{m=1}^{M} \beta_{k'm}^{c_{md}}}$$

3. *M-step*: Maximize the likelihood of the model with weighted by the responsibilities r_{kd} from step 2 and update the parameters $\vec{\theta}$ and $\vec{\beta}$.

$$\beta_{km} = \frac{\sum_{d=1}^{D} r_{kd} c_{md}}{\sum_{m'=1}^{M} \sum_{d=1}^{D} r_{kd} c_{m'd}}, \qquad \theta_k = \frac{\sum_{d=1}^{D} r_{kd}}{D}$$

4. Repeat steps 2 and 3 until convergence.

Exercises

1. Let's have $K = 2$, $M = \{a, b, c\}$ and observe the following set of documents

$$D_1 = \{a, b, b\}, \quad D_2 = \{a, c, c\}, \quad D_3 = \{a, b\}, \quad D_4 = \{c\}.$$

   Could you estimate the resulting $\vec{\theta}$ and $\vec{\beta}$?

2. What would happen if we initialize the parameters $\vec{\theta}$ and $\vec{\beta}$ uniformly?