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Estimate $\theta$ from partly observed data — recap

- What if FAHN observed, but not S?
- Can’t calculate MLE
  \[
  \theta \leftarrow \arg \max_{\theta} \log \prod_{k} P(f_k, a_k, s_k, h_k, n_k|\theta)
  \]
- Let $X$ be all observed variable values (over all examples)
- Let $Z$ be all unobserved variable values
- Can’t calculate MLE
  \[
  \theta \leftarrow \arg \max_{\theta} \log P(X, Z|\theta)
  \]
- Estimate:
  \[
  \theta \leftarrow \arg \max_{\theta} \mathbb{E}_{Z|X,\theta} \log P(X, Z|\theta)
  \]
MLE estimate of $\theta_{s|i,j}$ from fully observed data - recap

- Maximum likelihood estimate
  $$\theta \leftarrow \text{arg max}_{\theta} \log P(\text{data}|\theta)$$

- Our case
  $$P(\text{data}|\theta) = \prod_{k=1}^{K} \left( P(f_k, a_k, s_k, h_k, n_k) \right)$$
  $$P(\text{data}|\theta) = \prod_{k=1}^{K} P(f_k) P(a_k) P(s_k|f_k a_k) P(h_k|s_k) P(n_k|s_k)$$
  $$\log P(\text{data}|\theta) = \sum_{k=1}^{K} \log P(f_k) + \log P(a_k) + \log P(s_k|f_k a_k) + \log P(h_k|s_k) + \log P(n_k|s_k)$$
  $$\frac{\partial \log P(\text{data}|\theta)}{\partial \theta_{s|i,j}} = \sum_{k=1}^{K} \frac{\partial \log P(s_k|f_k a_k)}{\partial \theta_{s|i,j}}$$
  $$\theta_{s|i,j} = \frac{\sum_{k=1}^{K} \delta(f_k = i, a_k = j, s_k = 1)}{\sum_{k=1}^{K} \delta(f_k = i, a_k = j)}$$
Estimate $\theta$ from partly observed data

- What if FAHN observed, but not S?
- Can’t calculate MLE

$$\theta \leftarrow \arg \max_\theta \log \prod_k P(f_k, a_k, s_k, h_k, n_k | \theta)$$

- Let $X$ be all observed variable values (over all examples)
- Let $Z$ be all unobserved variable values
- Can’t calculate MLE

$$\theta \leftarrow \arg \max_\theta \log P(X, Z | \theta)$$

- What to do?
Estimate $\theta$ from partly observed data

- What if FAHN observed, but not S?
- Can’t calculate MLE

\[
\theta \leftarrow \arg \max_{\theta} \log \prod_{k} P(f_k, a_k, s_k, h_k, n_k | \theta)
\]

- Let $X$ be all observed variable values (over all examples)
- Let $Z$ be all unobserved variable values
- Can’t calculate MLE

\[
\theta \leftarrow \arg \max_{\theta} \log P(X, Z | \theta)
\]

- EM seeks* to estimate:

\[
\boxed{\theta \leftarrow \arg \max_{\theta} E_{Z|X,\theta}[\log P(X, Z | \theta)]}
\]

* EM guaranteed to find local optima
Estimate $\theta$ from partly observed data

- EM seeks to estimate:

$$\theta \leftarrow \arg \max \theta E_{Z \mid X, \theta}[\log P(X, Z \mid \theta)]$$

- here, observed $X=\{F, A, H, N\}$, unobserved $Z=\{S\}$

$$\log P(X, Z \mid \theta) = \sum_{k=1}^{K} \log P(f_k) + \log P(a_k) + \log P(s_k \mid f_k, a_k) + \log P(h_k \mid s_k) + \log P(n_k \mid s_k)$$

$$E_{P(Z \mid X, \theta)}[\log P(X, Z \mid \theta)] = \sum_{k=1}^{K} \sum_{i=0}^{D} P(S_k = i \mid f_k, a_k, h_k, n_k) \left[ \log P(f_k) + \log P(a_k) + \log P(s_k \mid f_k, a_k) + \log P(h_k \mid s_k) + \log P(n_k \mid s_k) \right]$$
Estimate $\theta$ from partly observed data

- EM seeks to estimate:

$$\theta \leftarrow \arg \max_{\theta} E_{Z|X,\theta} [\log P(X, Z|\theta)]$$

- here, observed $X=\{F,A,H,N\}$, unobserved $Z=\{S\}$

$$\log P(X, Z|\theta) = \sum_{k=1}^{K} \log P(f_k) + \log P(a_k) + \log P(s_k|f_k,a_k) + \log P(h_k|s_k) + \log P(n_k|s_k)$$

$$E_{P(Z|X,\theta)} \log P(X, Z|\theta) = \sum_{k=1}^{K} \sum_{i=0}^{1} P(s_k = i|f_k, a_k, h_k, n_k) [\log P(f_k) + \log P(a_k) + \log P(s_k|f_k,a_k) + \log P(h_k|s_k) + \log P(n_k|s_k)]$$
EM algorithm — informally

- EM is a general procedure for learning from partly observed data
- Given observed variables $X$, unobserved $Z$ ($X=\{F,A,H,N\}$, $Z=\{S\}$)

Begin with arbitrary choice for parameters $\theta$

Iterate until convergence:

- **E Step**: estimate the values of unobserved $Z$ conditioned on $X$ using $\theta$
- **M Step**: use observed values plus E-step estimates to derive a better $\theta$

- Guaranteed to find local maximum. Each iteration increases

$$E_{P(Z|X,\theta)}[\log P(X,Z|\theta')]$$
E Step: Use $X$, $\theta$ to Calculate $P(Z|X,\theta)$

- observed $X=$\{F,A,H,N\}
- unobserved $Z=$\{S\}

- How? Bayes net inference problem

$$P(S_k = 1|f_k,a_k,h_k,n_k, \theta) = \frac{P(S_k=1, f_k, a_k, h_k, n_k|\theta)}{P(\text{observed } X) = \sum P(S=1, f_k, a_k, h_k, n_k|\theta) + P(S=0, f_k, a_k, h_k, n_k|\theta)}$$
E Step: Use $X, \theta$ to Calculate $P(Z|X,\theta)$

- observed $X=\{F,A,H,N\}$
- unobserved $Z=\{S\}$

- How? Bayes net inference problem

$$P(S_k = 1|f_k a_k h_k n_k, \theta) = \frac{P(S_k = 1, f_k a_k h_k n_k|\theta)}{P(S_k = 1, f_k a_k h_k n_k|\theta) + P(S_k = 0, f_k a_k h_k n_k|\theta)}$$
EM and estimating $\theta_{s|ij}$

- observed $X=\{F,A,H,N\}$; unobserved $Z=\{S\}$

- E Step: Calculate $P(Z_k|X_k; \theta)$ for each training example, $k$

$$P(S_k = 1|f_ka_kh_kn_k, \theta) = \text{E}[s_k] = \frac{P(S_k = 1, f_ka_kh_kn_k|\theta)}{P(S_k = 1, f_ka_kh_kn_k|\theta) + P(S_k = 0, f_ka_kh_kn_k|\theta)}$$

- M Step: update all relevant parameters.

$$\theta_{s|ij} \leftarrow \frac{\sum_{k=1}^{K} \delta(f_k = i, a_k = j) \text{E}[s_k]}{\sum_{k=1}^{K} \delta(f_k = i, a_k = j)}$$

What was MLE?

$$\theta_{s|ij} = \frac{\sum_{k=1}^{K} \delta(f_k = i, a_k = j, s_k = 1)}{\sum_{k=1}^{K} \delta(f_k = i, a_k = j)}$$
EM and estimating $\theta_{s|i,j}$

- observed $X=\{F,A,H,N\}$; unobserved $Z=\{S\}$

- E Step: Calculate $P(Z_k | X_k; \theta)$ for each training example, $k$

$$P(S_k = 1 | f_k a_k h_k n_k, \theta) = E[s_k] = \frac{P(S_k = 1, f_k a_k h_k n_k | \theta)}{P(S_k = 1, f_k a_k h_k n_k | \theta) + P(S_k = 0, f_k a_k h_k n_k | \theta)}$$

- M Step: update all relevant parameters. For example:

$$\theta_{s|i,j} \leftarrow \frac{\sum_{k=1}^{K} \delta(f_k = i, a_k = j) E[s_k]}{\sum_{k=1}^{K} \delta(f_k = i, a_k = j)}$$

Recall MLE was:

$$\theta_{s|i,j} = \frac{\sum_{k=1}^{K} \delta(f_k = i, a_k = j, s_k = 1)}{\sum_{k=1}^{K} \delta(f_k = i, a_k = j)}$$
Generalizing: EM and estimating $\theta$

- More generally, given observed set $X$, unobserved set $Z$ of boolean values

- **E Step:** Calculate for each training example, $k$ the expected value of each unobserved variable

- **M Step:** Calculate estimates similar to MLE, but replacing each count by its expected count

$$\delta(Y = 1) \rightarrow E_{Z|X,\theta}[Y] \quad \delta(Y = 0) \rightarrow (1 - E_{Z|X,\theta}[Y])$$
Using (partially) unlabeled data to help train naïve Bayes classifier

semi-supervised learning
EM and estimating $\theta$

- **E step:** Calculate for each training example $k$, the expected value of each unobserved variable $Y$

$$E \left[ Y = k \right] = P_{\theta} \left( Y_k | x_1 \ldots x_4 \right)$$

$$= \frac{P_{\theta}(X_1 \ldots X_4 | Y = k) P_{\theta}(Y = k)}{\sum_{j} P_{\theta}(X_1 \ldots X_4 | Y = j) P_{\theta}(Y = j)}$$

Bayes Rule
EM and estimating $\theta$

- Observed set $X$
- Partially unobserved set $Y$ of boolean values

**E step:** Calculate for each training example $k$, the expected value of each unobserved variable $Y$

$$E_{P(Y|X_1...X_N)}[y(k)] = P(y(k) = 1|x_1(k),...x_N(k); \theta) = \frac{P(y(k) = 1) \prod_i P(x_i(k)|y(k) = 1)}{\sum_{j=0}^{1} P(y(k) = j) \prod_i P(x_i(k)|y(k) = j)}$$

**M step:** Calculate estimates similar to MLE, but replacing each count by its expected count
EM and estimating $\theta$

- Observed set $X$
- Partially unobserved set $Y$ of boolean values

**E step:** Calculate for each training example $k$, the expected value of each unobserved variable $Y$

$$E_{P(Y|X_1...X_N)}[y(k)] = P(y(k) = 1|x_1(k),...x_N(k); \theta) = \frac{P(y(k) = 1) \prod_i P(x_i(k)|y(k) = 1)}{\sum_{j=0}^{1} P(y(k) = j) \prod_i P(x_i(k)|y(k) = j)}$$

**M step:** Calculate estimates similar to MLE, but replacing each count by its expected count

$$\theta_{ij|m} = \hat{P}(X_i = j|Y = m) = \frac{\sum_k P(y(k) = m|x_1(k)...x_N(k)) \delta(x_i(k) = j)}{\sum_k P(y(k) = m|x_1(k)...x_N(k))}$$

MLE would be:

$$\hat{P}(X_i = j|Y = m) = \frac{\sum_k \delta((y(k) = m) \land (x_i(k) = j))}{\sum_k \delta(y(k) = m)}$$
EM algorithm — summary

- EM is a general procedure for learning from partly observed data
- Given observed variables $X$, unobserved $Z$ \( (X=\{F,A,H,N\}, Z=\{S\}) \)
- Define \[ Q(\theta'|\theta) = E_{P(Z|X,\theta)}[\log P(X, Z|\theta')] \]

Begin with arbitrary choice for parameters $\theta$

Iterate until convergence:

- **E Step:** Use $X$ and current $\theta$ to calculate $P(Z|X,\theta)$
- **M Step:** Replace current $\theta$ by $\theta \leftarrow \arg\max_{\theta'} Q(\theta'|\theta)$

- Guaranteed to find local maximum. Each iteration increases

\[ E_{P(Z|X,\theta)}[\log P(X, Z|\theta')] \]
What if we have no labeled data at all?

un

semi-supervised learning
Unsupervised clustering

Just extreme case of EM with zero labeled examples…