EM algorithm for t-distribution

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1 Full model and likelihood

Given $Y = (X, W) \in \mathbb{R} \times (0, \infty)$ with joint density

$$f(x, w) = \frac{1}{\sqrt{\pi \nu \sigma^2} 2^{(\nu+1)} \Gamma(\frac{\nu}{2})} w^{\frac{\nu-1}{2}} e^{-\frac{w}{2}\left(1 + \frac{(x-\mu)^2}{\nu\sigma^2}\right)}$$

With location parameter, $\mu \in \mathbb{R}$, scale parameter $\sigma > 0$ and shape parameter $\nu > 0$.

Theorem 1.1. *X has the t-distribution as its marginal density*

Proof. By definition the marginal density of X is given as

$$g(x) = \int f(x, w) dw = \int \frac{1}{\sqrt{\pi \nu \sigma^2} 2^{(\nu+1)/2} \Gamma(\frac{\nu}{2})} w^{\frac{\nu-1}{2}} e^{-\frac{w}{2}\left(1 + \frac{(x-\mu)^2}{\nu\sigma^2}\right)} dw$$

$$= \frac{\Gamma(\frac{\nu+1}{2})}{\sqrt{\pi \nu \sigma^2} 2^{(\nu+1)/2} \Gamma(\frac{\nu}{2}) \left(\frac{1}{2}\left(1 + \frac{(x-\mu)^2}{\nu\sigma^2}\right)\right)^{\left(\frac{\nu+1}{2}\right)}} \int \frac{\frac{1}{2}\left(1 + \frac{(x-\mu)^2}{\nu\sigma^2}\right)^{\left(\frac{\nu+1}{2}\right)}}{\Gamma(\frac{\nu+1}{2})} w^{\frac{\nu-1}{2}} e^{-\frac{w}{2}\left(1 + \frac{(x-\mu)^2}{\nu\sigma^2}\right)} dw$$

$$= \frac{\Gamma(\frac{\nu+1}{2})}{\sqrt{\pi \nu \sigma^2} \Gamma(\frac{\nu}{2}) \left(1 + \frac{(x-\mu)^2}{\nu\sigma^2}\right)^{\left(\frac{\nu+1}{2}\right)}} = \frac{\Gamma(\frac{\nu+1}{2})}{\Gamma(\frac{\nu}{2}) \sqrt{\pi \nu \sigma^2}} \left(1 + \frac{(x-\mu)^2}{\nu\sigma^2}\right)^{-\left(\frac{\nu+1}{2}\right)}$$

$\square$

Consider the likelihood of the full data.

$$\sum_{i=1}^{N} \log\left(f(x_i, w_i)\right) = \sum_{i=1}^{N} \log\left(\frac{1}{\sqrt{\pi \nu \sigma^2} 2^{(\nu+1)} \Gamma(\frac{\nu}{2})} w_i^{\frac{\nu-1}{2}} e^{-\frac{w_i}{2}\left(1 + \frac{(x_i-\mu)^2}{\nu\sigma^2}\right)}\right)$$

$$= \sum_{i=1}^{N} -\frac{1}{2}\log\left(\pi \nu \sigma^2\right) - (\nu+1)\log(2) - \log\left(\Gamma\left(\frac{\nu}{2}\right)\right) + \log(w_i)\left(\frac{\nu-1}{2}\right) - \frac{w_i}{2}\left(1 + \frac{(x_i-\mu)^2}{\nu\sigma^2}\right)$$

$$= -\frac{N}{2}\log\left(\pi \nu \sigma^2\right) - N(\nu+1)\log(2) - N\log\left(\Gamma\left(\frac{\nu}{2}\right)\right) + \sum_{i=1}^{N} \log(w_i)\left(\frac{\nu-1}{2}\right) - \frac{w_i}{2}\left(1 + \frac{(x_i-\mu)^2}{\nu\sigma^2}\right)$$

To get the maximum-likelihood estimator we set the gradient of the likelihood equal to zero. First we calculate the entries

$$\frac{\partial}{\partial \sigma^2} \sum_{i=1}^{N} \log\left(f(x_i, w_i)\right) = -\frac{N}{2\sigma^2} + \sum_{i=1}^{N} \frac{w_i(x_i-\mu)^2}{2\nu\sigma^4} \tag{1}$$

And

$$\frac{\partial}{\partial \mu} \sum_{i=1}^{N} \log\left(f(x_i, w_i)\right) = \sum_{i=1}^{N} \frac{w_i(x_i - \mu)}{\nu \sigma^2} \tag{2}$$

Setting (2) to zero gives

$$\sum_{i=1}^{N} w_i(x_i - \mu) = 0$$

$$\mu = \bar{w}x$$

And from (2) we see

$$0 = -N + \sum_{i=1}^{N} \frac{w_i(x_i - \mu)^2}{\nu \sigma^2}$$

$$\sigma^2 = \frac{1}{\nu N} \sum_{i=1}^{N} w_i(x_i - \mu)^2$$

We are going to need the conditional distribution $W|X$. We see that $W|X$ is $\propto f(x, w)$, whence we see that $W|X \sim \Gamma\left(\frac{\nu+1}{2}, \frac{1}{2}\left(1 + \frac{(x-\mu)^2}{\nu \sigma^2}\right)\right)$. Note also that this implies

$$E\left[W|X\right] = \frac{\frac{\nu+1}{2}}{\frac{1}{2}\left(1 + \frac{(x-\mu)^2}{\nu \sigma^2}\right)}, \qquad E\left[\log\left(W\right)|X\right] = -\log\left(\frac{1}{2}\left(1 + \frac{(x-\mu)^2}{\nu \sigma^2}\right)\right) + \psi\left(\frac{\nu+1}{2}\right)$$

2   The EM-algorithm

To implement the EM-algorithm we calculate the Q-function

$$Q(\theta|\theta') = E_{\theta'}\left[\log\left(f(x, w)\right)\Big| X = x\right]$$

$$= -\frac{1}{2}\log\left(\pi \nu \sigma^2\right) + E_{\theta'}\left[\log\left(w\right)|X = x\right]\left(\frac{\nu-1}{2}\right) - \frac{1}{2}E_{\theta'}\left[w|X = x\right]\left(1 + \frac{(x-\mu)^2}{\nu \sigma^2}\right)$$

Where we have removed the terms that don't depend on σ^2, μ. Differentiating w.r.t. σ^2, μ yields

$$\frac{\partial}{\partial \mu}\left(Q(\theta|\theta')\right) = E_{\theta'}\left[w|X = x\right]\frac{(x-\mu)}{\nu \sigma^2}$$

$$\frac{\partial}{\partial \sigma^2}\left(Q(\theta|\theta')\right) = -\frac{1}{2\sigma^2} + \frac{1}{2}E_{\theta'}\left[w|X = x\right]\frac{(x-\mu)^2}{\nu \sigma^4}$$

Setting them each equal to zero gives

$$\frac{\partial}{\partial \mu}\left(Q(\theta|\theta')\right) = 0$$

$$\hat{\mu} = \frac{\sum_{i=1}^{N} x_i E_{\theta'}\left[w_i|X = x_i\right]}{\sum_{i=1}^{N} E_{\theta'}\left[w_i|X = x_i\right]}$$

And

$$\frac{\partial}{\partial \sigma^2} \left(Q(\theta|\theta') \right) = 0$$

$$N = \sum_{i=1}^{N} E_{\theta'} \left[w_i | X = x_i \right] \frac{(x_i - \mu)^2}{\nu \sigma^2}$$

$$\hat{\sigma}^2 = \frac{1}{N\nu} \sum_{i=1}^{N} E_{\theta'} \left[w_i | X = x_i \right] (x_i - \mu)^2$$

3   The Fisher-information

We find the fisher-information theoretically first

$$\frac{\partial}{\partial \mu^2} \left(Q(\theta|\theta') \right) = -\frac{E_{\theta'} \left[w | X = x \right]}{\nu \sigma^2}$$

$$\frac{\partial}{\partial \mu \sigma^2} \left(Q(\theta|\theta') \right) = -\frac{E_{\theta'} \left[w | X = x \right] (x - \mu)}{\nu \sigma^2}$$

$$\frac{\partial}{\partial (\sigma^2)^2} \left(Q(\theta|\theta') \right) = \frac{1}{2\sigma^4} - E_{\theta'} \left[w | X = x \right] \frac{(x - \mu)^2}{\nu \sigma^6}$$

4   Estimation of ν

To estimate nu we revisit the likelihood of the full data.

$$\sum_{i=1}^{N} \log \left(f(x_i, w_i) \right) = -\frac{N}{2} \log \left(\pi \nu \sigma^2 \right) - N (\nu + 1) \log (2) - N \log \left(\Gamma \left(\frac{\nu}{2} \right) \right)$$

$$+ \sum_{i=1}^{N} \log (w_i) \left(\frac{\nu - 1}{2} \right) - \frac{w_i}{2} \left(1 + \frac{(x_i - \mu)^2}{\nu \sigma^2} \right)$$