Notes on Bayesian Logistic Regression

Max Leung

May 7, 2023

1 Laplace Approximation

$$\begin{aligned} lnf(\boldsymbol{z}) &\approx lnf(\boldsymbol{z}_0) + \overbrace{\nabla lnf(\boldsymbol{z}_0)'}^{\boldsymbol{0}'}(\boldsymbol{z}-\boldsymbol{z}_0) + \frac{1}{2}(\boldsymbol{z}-\boldsymbol{z}_0)'\overbrace{\nabla\nabla lnf(\boldsymbol{z}_0)}^{-\boldsymbol{A}}(\boldsymbol{z}-\boldsymbol{z}_0) \\ &= lnf(\boldsymbol{z}_0) - \frac{1}{2}(\boldsymbol{z}-\boldsymbol{z}_0)'\boldsymbol{A}(\boldsymbol{z}-\boldsymbol{z}_0) \end{aligned}$$

$$\begin{aligned} f(\boldsymbol{z}) &\approx exp(lnf(\boldsymbol{z}_0) - \frac{1}{2}(\boldsymbol{z}-\boldsymbol{z}_0)'\boldsymbol{A}(\boldsymbol{z}-\boldsymbol{z}_0)) \\ &= exp(lnf(\boldsymbol{z}_0))exp(-\frac{1}{2}(\boldsymbol{z}-\boldsymbol{z}_0)'\boldsymbol{A}(\boldsymbol{z}-\boldsymbol{z}_0)) \\ &= f(\boldsymbol{z}_0)exp(-\frac{1}{2}(\boldsymbol{z}-\boldsymbol{z}_0)'\boldsymbol{A}(\boldsymbol{z}-\boldsymbol{z}_0)) \end{aligned}$$

If we approximate $f(.)$ by $N(\boldsymbol{z}_0, \boldsymbol{A}^{-1})$, we have

$$\begin{aligned} &\approx \frac{1}{(2\pi)^{M/2}|\boldsymbol{A}|^{-1/2}} \underbrace{exp\{-\frac{1}{2}(\boldsymbol{z}_0-\boldsymbol{z}_0)'\boldsymbol{A}(\boldsymbol{z}_0-\boldsymbol{z}_0)\}}_{1} exp(-\frac{1}{2}(\boldsymbol{z}-\boldsymbol{z}_0)'\boldsymbol{A}(\boldsymbol{z}-\boldsymbol{z}_0)) \\ &= N(\boldsymbol{z}|\boldsymbol{z}_0, \boldsymbol{A}^{-1}) = q(\boldsymbol{z}) \end{aligned}$$

where $\boldsymbol{z}_0 = arg\ max_{\boldsymbol{z}} lnf(\boldsymbol{z})$ and $\boldsymbol{A} = -\nabla\nabla lnf(\boldsymbol{z}_0)$

2 Bayesian Logistic Regression (Laplace Approximation Approach)

2.1 Posterior Distribution of Parameters

Assume we have prior density $p(\boldsymbol{w}|\boldsymbol{X}) = p(\boldsymbol{w}) = N(\boldsymbol{w}|\boldsymbol{m}_0, \boldsymbol{S}_0)$. Likelihood function is $p(\boldsymbol{t}|\boldsymbol{w}, \boldsymbol{X}) = \prod_{n=1}^{N} p(C_1|\boldsymbol{x}_n; \boldsymbol{w})^{t_n}(1 - p(C_1|\boldsymbol{x}_n; \boldsymbol{w}))^{1-t_n}$ where $p(C_1|\boldsymbol{x}_n; \boldsymbol{w}) = \sigma(\boldsymbol{w}'\boldsymbol{x}_n)$. Posterior density is

$$\begin{aligned} p(\boldsymbol{w}|\boldsymbol{t}, \boldsymbol{X}) &\propto p(\boldsymbol{t}|\boldsymbol{w}, \boldsymbol{X})p(\boldsymbol{w}|\boldsymbol{X}) \\ &= \prod_{n=1}^{N} \sigma(\boldsymbol{w}'\boldsymbol{x}_n)^{t_n}(1 - \sigma(\boldsymbol{w}'\boldsymbol{x}_n))^{1-t_n} N(\boldsymbol{w}|\boldsymbol{m}_0, \boldsymbol{S}_0) \end{aligned}$$

which is not a well known joint density function

$$\begin{aligned} lnp(\boldsymbol{w}|\boldsymbol{t}, \boldsymbol{X}) &= ln[\prod_{n=1}^{N} \sigma(\boldsymbol{w}'\boldsymbol{x}_n)^{t_n}(1 - \sigma(\boldsymbol{w}'\boldsymbol{x}_n))^{1-t_n} N(\boldsymbol{w}|\boldsymbol{m}_0, \boldsymbol{S}_0)] \\ &= \sum_{n=1}^{N}[t_n ln\sigma(\boldsymbol{w}'\boldsymbol{x}_n) + (1-t_n)ln(1 - \sigma(\boldsymbol{w}'\boldsymbol{x}_n))] + ln[N(\boldsymbol{w}|\boldsymbol{m}_0, \boldsymbol{S}_0)] \\ &= \sum_{n=1}^{N}[t_n ln\sigma(\boldsymbol{w}'\boldsymbol{x}_n) + (1-t_n)ln(1 - \sigma(\boldsymbol{w}'\boldsymbol{x}_n))] + ln[\frac{1}{(2\pi)^{D/2}|\boldsymbol{S}_0|^{1/2}} exp\{-\frac{1}{2}(\boldsymbol{w}-\boldsymbol{m}_0)'\boldsymbol{S}_0^{-1}(\boldsymbol{w}-\boldsymbol{m}_0)\}] \\ &= \sum_{n=1}^{N}[t_n ln\sigma(\boldsymbol{w}'\boldsymbol{x}_n) + (1-t_n)ln(1 - \sigma(\boldsymbol{w}'\boldsymbol{x}_n))] + ln[\frac{1}{(2\pi)^{D/2}|\boldsymbol{S}_0|^{1/2}}] - \frac{1}{2}(\boldsymbol{w}-\boldsymbol{m}_0)'\boldsymbol{S}_0^{-1}(\boldsymbol{w}-\boldsymbol{m}_0) \end{aligned}$$

We can approximate $p(\boldsymbol{w}|\boldsymbol{t},\boldsymbol{X})$ by Laplace Approximation. As a result, our posterior follows multivariate normal distribution.

$$p(\boldsymbol{w}|\boldsymbol{t},\boldsymbol{X}) \approx q(\boldsymbol{w}) = N(\boldsymbol{w}|\boldsymbol{w}_{MAP}, \boldsymbol{S}^{-1})$$

where $\boldsymbol{w}_{MAP} = arg\ max_{\boldsymbol{w}} lnp(\boldsymbol{w}|\boldsymbol{t},\boldsymbol{X})$

$$\frac{\partial lnp(\boldsymbol{w}|\boldsymbol{t},\boldsymbol{X})}{\partial \boldsymbol{w}}|_{\boldsymbol{w}_{MAP}} = \boldsymbol{0}$$

$$\frac{\partial \sum_{n=1}^{N}[t_n ln\sigma(\boldsymbol{w}'\boldsymbol{x}_n) + (1-t_n)ln(1-\sigma(\boldsymbol{w}'\boldsymbol{x}_n))] + ln[\frac{1}{(2\pi)^{D/2}|\boldsymbol{S}_0|^{1/2}}] - \frac{1}{2}(\boldsymbol{w}-\boldsymbol{m}_0)'\boldsymbol{S}_0^{-1}(\boldsymbol{w}-\boldsymbol{m}_0)}{\partial \boldsymbol{w}}|_{\boldsymbol{w}_{MAP}} = \boldsymbol{0}$$

$$\boldsymbol{X}'(\boldsymbol{t}-\boldsymbol{p}) - \boldsymbol{S}_0^{-1}(\boldsymbol{w}_{MAP}-\boldsymbol{m}_0) = \boldsymbol{0}$$

where $\boldsymbol{p} = (\sigma(\boldsymbol{w}'_{MAP}\boldsymbol{x}_1), \cdots, \sigma(\boldsymbol{w}'_{MAP}\boldsymbol{x}_D))'$

There is no closed form solution for $\boldsymbol{w}_{MAP}$

$$\begin{aligned}
\boldsymbol{S} &= -\nabla\nabla lnp(\boldsymbol{w}_{MAP}|\boldsymbol{t}) \\
&= -\nabla\nabla\{\sum_{n=1}^{N}[t_n ln\sigma(\boldsymbol{w}'\boldsymbol{x}_n) + (1-t_n)ln(1-\sigma(\boldsymbol{w}'\boldsymbol{x}_n))] + ln[\frac{1}{(2\pi)^{D/2}|\boldsymbol{S}_0|^{1/2}}] - \frac{1}{2}(\boldsymbol{w}-\boldsymbol{m}_0)'\boldsymbol{S}_0^{-1}(\boldsymbol{w}-\boldsymbol{m}_0)\} \\
&= -(-\boldsymbol{X}'\boldsymbol{W}\boldsymbol{X} - \boldsymbol{S}_0^{-1}) \\
&= \boldsymbol{X}'\boldsymbol{W}\boldsymbol{X} + \boldsymbol{S}_0^{-1}
\end{aligned}$$

where $(\boldsymbol{W})_{ii} = \sigma(\boldsymbol{w}'_{MAP}\boldsymbol{x}_i)(1-\sigma(\boldsymbol{w}'_{MAP}\boldsymbol{x}_i))$ and $(\boldsymbol{W})_{ij} = 0$ for $i \neq j$

2.2 Special Case

if $\boldsymbol{m}_0$ is chosen to be $\boldsymbol{w}_{MAP}$ then

$$\boldsymbol{X}'(\boldsymbol{t}-\boldsymbol{p}) - \boldsymbol{S}_0^{-1}(\boldsymbol{w}_{MAP}-\boldsymbol{w}_{MAP}) = \boldsymbol{0}$$

$$\boldsymbol{X}'(\boldsymbol{t}-\boldsymbol{p}) = \boldsymbol{0} \qquad \text{same as FOC of MLE}$$

Thus, $\boldsymbol{w}_{MAP} = \boldsymbol{w}_{MLE}$ in such case, which can be found by Iterated Reweighted Least Squares (IRLS) algorithm.

Additionally, if $\boldsymbol{S}_0$ is chosen to be close to $\boldsymbol{O}^{-1}$. We have

$$\begin{aligned}
\boldsymbol{S} &\approx \boldsymbol{X}'\boldsymbol{W}\boldsymbol{X} + (\boldsymbol{O}^{-1})^{-1} \\
&= \boldsymbol{X}'\boldsymbol{W}\boldsymbol{X}
\end{aligned}$$

Thus,

$$\boldsymbol{S}^{-1} = (\boldsymbol{X}'\boldsymbol{W}\boldsymbol{X})^{-1} = -(-\boldsymbol{X}'\boldsymbol{W}\boldsymbol{X})^{-1} = -(\nabla\nabla p(\boldsymbol{t}|\boldsymbol{w}_{MLE},\boldsymbol{X}))^{-1} = (\underbrace{-\nabla\nabla p(\boldsymbol{t}|\boldsymbol{w}_{MLE},\boldsymbol{X})}_{\boldsymbol{I}(\boldsymbol{w}_{MLE})})^{-1}$$

$\boldsymbol{I}(\boldsymbol{w}_{MLE})^{-1}$ is the asymptotic variance of $\sqrt{D}(\boldsymbol{w}_{MLE} - \boldsymbol{w}_{TRUE})$

Thus, we have $p(\boldsymbol{w}|\boldsymbol{t},\boldsymbol{X}) \approx N(\boldsymbol{w}|\boldsymbol{w}_{MLE}, \boldsymbol{I}(\boldsymbol{w}_{MLE})^{-1})$

2.3 Predictive Distribution

Let $\widetilde{T}$ be the predicted target / dependent variable. Predictive distribution is

$$\begin{aligned}
p(\widetilde{T}=1|\boldsymbol{t},\boldsymbol{X}) &= \int p(\widetilde{T}=1,\boldsymbol{w}|\boldsymbol{t},\boldsymbol{X})\partial\boldsymbol{w} \\
&= \int p(\widetilde{T}=1|\boldsymbol{w},\boldsymbol{t},\boldsymbol{X})p(\boldsymbol{w}|\boldsymbol{t},\boldsymbol{X})\partial\boldsymbol{w} \\
&\approx \int \sigma(\boldsymbol{w}'\boldsymbol{x})q(\boldsymbol{w})\partial\boldsymbol{w}
\end{aligned}$$

Note that $\int \delta(a - \boldsymbol{w}'\boldsymbol{x})\sigma(a)da = \delta(\boldsymbol{w}'\boldsymbol{x} - \boldsymbol{w}'\boldsymbol{x})\sigma(\boldsymbol{w}'\boldsymbol{x}) = 1 \cdot \sigma(\boldsymbol{w}'\boldsymbol{x})$ as $\delta(0) = 1$ and $\delta(a) = 0$ for $\forall a \neq 0$

$$
\begin{aligned}
&= \int \int \delta(a - \boldsymbol{w}'\boldsymbol{x})\sigma(a)da \; q(\boldsymbol{w})\partial\boldsymbol{w} \\
&= \int \int \delta(a - \boldsymbol{w}'\boldsymbol{x})\sigma(a)q(\boldsymbol{w})\partial\boldsymbol{w}da \\
&= \int \sigma(a) \underbrace{\int \delta(a - \boldsymbol{w}'\boldsymbol{x})q(\boldsymbol{w})\partial\boldsymbol{w}}_{p(a)} da
\end{aligned}
$$

$p(a)$'s moments can be evaluated as

$$
\begin{aligned}
\mathbb{E}_p(a) &= \int p(a)a \; da \\
&= \int \int \delta(a - \boldsymbol{w}'\boldsymbol{x})q(\boldsymbol{w})\partial\boldsymbol{w}a \; da \\
&= \int \int \delta(a - \boldsymbol{w}'\boldsymbol{x})q(\boldsymbol{w})a \; da\partial\boldsymbol{w} \\
&= \int \int \delta(a - \boldsymbol{w}'\boldsymbol{x})a \; da \; q(\boldsymbol{w})\partial\boldsymbol{w} \\
&= \int \delta(\boldsymbol{w}'\boldsymbol{x} - \boldsymbol{w}'\boldsymbol{x})\boldsymbol{w}'\boldsymbol{x}q(\boldsymbol{w})\partial\boldsymbol{w} \\
&= \int \boldsymbol{w}'\boldsymbol{x}q(\boldsymbol{w})\partial\boldsymbol{w} \\
&= \mathbb{E}_q(\boldsymbol{w}'\boldsymbol{x}) \\
&= \mathbb{E}_q(\boldsymbol{w})'\boldsymbol{x}
\end{aligned}
$$

$$
\begin{aligned}
Var_p(a) &= \mathbb{E}_p(a^2) - \mathbb{E}_p(a)^2 \\
&= \mathbb{E}_p(a^2 - \mathbb{E}_p(a)^2) \\
&= \int p(a)(a^2 - \mathbb{E}_p(a)^2)da \\
&= \int \int \delta(a - \boldsymbol{w}'\boldsymbol{x})q(\boldsymbol{w})\partial\boldsymbol{w}(a^2 - \mathbb{E}_p(a)^2)da \\
&= \int \int \delta(a - \boldsymbol{w}'\boldsymbol{x})q(\boldsymbol{w})(a^2 - \mathbb{E}_p(a)^2)da\partial\boldsymbol{w} \\
&= \int q(\boldsymbol{w}) \int \delta(a - \boldsymbol{w}'\boldsymbol{x})(a^2 - \mathbb{E}_p(a)^2)da\partial\boldsymbol{w} \\
&= \int q(\boldsymbol{w})\delta(\boldsymbol{w}'\boldsymbol{x} - \boldsymbol{w}'\boldsymbol{x})((\boldsymbol{w}'\boldsymbol{x})^2 - \mathbb{E}_p(\boldsymbol{w}'\boldsymbol{x})^2)\partial\boldsymbol{w} \\
&= \int q(\boldsymbol{w})((\boldsymbol{w}'\boldsymbol{x})^2 - \mathbb{E}_p(\boldsymbol{w}'\boldsymbol{x})^2)\partial\boldsymbol{w} \\
&\approx \int q(\boldsymbol{w})((\boldsymbol{w}'\boldsymbol{x})^2 - \mathbb{E}_q(\boldsymbol{w}'\boldsymbol{x})^2)\partial\boldsymbol{w} \\
&= \mathbb{E}_q((\boldsymbol{w}'\boldsymbol{x})^2 - \mathbb{E}_q(\boldsymbol{w}'\boldsymbol{x})^2) \\
&= Var_q(\boldsymbol{x}'\boldsymbol{w}) \\
&= \boldsymbol{x}'Var_q(\boldsymbol{w})\boldsymbol{x}
\end{aligned}
$$

3 EM Algorithm

$$ln[L(\boldsymbol{\theta})] = ln[p(\boldsymbol{X}|\boldsymbol{\theta})] = ln[\sum_{\boldsymbol{z}} p(\boldsymbol{X}, \boldsymbol{z}|\boldsymbol{\theta})] = ln[\sum_{\boldsymbol{z}} p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})]$$

$$\begin{aligned} ln[L(\boldsymbol{\theta})] - ln[L(\boldsymbol{\theta}_n)] &= ln[\sum_{\boldsymbol{z}} p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})] - ln[p(\boldsymbol{X}|\boldsymbol{\theta}_n)] \\ &= ln[\sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n)\frac{p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})}{p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n)}] - ln[p(\boldsymbol{X}|\boldsymbol{\theta}_n)] \end{aligned}$$

Jensen's Inequality says $f(\sum_i \lambda_i x_i) \geq \sum_i \lambda_i f(x_i)$ if f is concave, $\sum_i \lambda_i = 1$ and $\lambda_i \geq 0$ for $\forall i$. As $ln(.)$ is concave and $p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n)$ is density function, we have

$$\begin{aligned} &\geq \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[\frac{p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})}{p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n)}] - ln[p(\boldsymbol{X}|\boldsymbol{\theta}_n)] \\ &= \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[\frac{p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})}{p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n)}] - ln[p(\boldsymbol{X}|\boldsymbol{\theta}_n)] \cdot 1 \\ &= \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[\frac{p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})}{p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n)}] - ln[p(\boldsymbol{X}|\boldsymbol{\theta}_n)] \cdot \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) \\ &= \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[\frac{p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})}{p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n)}] - \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[p(\boldsymbol{X}|\boldsymbol{\theta}_n)] \\ &= \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) \{ln[\frac{p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})}{p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n)}] - ln[p(\boldsymbol{X}|\boldsymbol{\theta}_n)]\} \\ &= \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[\frac{p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})}{p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n)p(\boldsymbol{X}|\boldsymbol{\theta}_n)}] \end{aligned}$$

Thus,

$$ln[L(\boldsymbol{\theta})] \geq ln[L(\boldsymbol{\theta}_n)] + \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[\frac{p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})}{p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n)p(\boldsymbol{X}|\boldsymbol{\theta}_n)}] =: l(\boldsymbol{\theta}|\boldsymbol{\theta}_n)$$

It can be shown that $ln[L(\boldsymbol{\theta})] = l(\boldsymbol{\theta}|\boldsymbol{\theta}_n)$ when $\boldsymbol{\theta} = \boldsymbol{\theta}_n$

$$\begin{aligned} l(\boldsymbol{\theta}_n|\boldsymbol{\theta}_n) &= ln[L(\boldsymbol{\theta}_n)] + \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[\frac{p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta}_n)p(\boldsymbol{z}|\boldsymbol{\theta}_n)}{p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n)p(\boldsymbol{X}|\boldsymbol{\theta}_n)}] \\ &= ln[L(\boldsymbol{\theta}_n)] + \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[1] \\ &= ln[L(\boldsymbol{\theta}_n)] \end{aligned}$$

Thus, we know that log likelihood function wraps $l(\boldsymbol{\theta}|\boldsymbol{\theta}_n)$ i.e., $ln[L(\boldsymbol{\theta})] \geq l(\boldsymbol{\theta}|\boldsymbol{\theta}_n)$ and $l(\boldsymbol{\theta}|\boldsymbol{\theta}_n)$ touches log likelihood function at $\boldsymbol{\theta}_n$ i.e., $l(\boldsymbol{\theta}_n|\boldsymbol{\theta}_n) = ln[L(\boldsymbol{\theta}_n)]$.

As $ln[L(\boldsymbol{\theta})] \geq l(\boldsymbol{\theta}|\boldsymbol{\theta}_n)$, an increase in $l(\boldsymbol{\theta}|\boldsymbol{\theta}_n)$ implies an increase in $ln[L(\boldsymbol{\theta})]$. $l(\boldsymbol{\theta}|\boldsymbol{\theta}_n)$ stops increasing at its maximum. We pick $\boldsymbol{\theta}_{n+1} = arg\ max_{\boldsymbol{\theta}} l(\boldsymbol{\theta}|\boldsymbol{\theta}_n)$. This guarantees that $ln[L(\boldsymbol{\theta})]$ increases at every step.

$$\begin{aligned} \boldsymbol{\theta}_{n+1} &= arg\ max_{\boldsymbol{\theta}} \{l(\boldsymbol{\theta}|\boldsymbol{\theta}_n)\} \\ &= arg\ max_{\boldsymbol{\theta}} \{ln[L(\boldsymbol{\theta}_n)] + \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[\frac{p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})}{p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n)p(\boldsymbol{X}|\boldsymbol{\theta}_n)}]\} \\ &= arg\ max_{\boldsymbol{\theta}} \{ln[L(\boldsymbol{\theta}_n)] + \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})] - \sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n)p(\boldsymbol{X}|\boldsymbol{\theta}_n)]\} \\ &= arg\ max_{\boldsymbol{\theta}} \{\sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[p(\boldsymbol{X}|\boldsymbol{z}, \boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})]\} \\ &= arg\ max_{\boldsymbol{\theta}} \{\sum_{\boldsymbol{z}} p(\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n) ln[p(\boldsymbol{X}, \boldsymbol{z}|\boldsymbol{\theta})]\} \\ &= arg\ max_{\boldsymbol{\theta}} \{\mathbb{E}_{\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n}[ln[p(\boldsymbol{X}, \boldsymbol{z}|\boldsymbol{\theta})]]\} \end{aligned}$$

$\mathbb{E}_{\boldsymbol{z}|\boldsymbol{X}, \boldsymbol{\theta}_n}$ is the E step. $arg\ max_{\boldsymbol{\theta}}$ is the M step.

4 Bayesian Logistic Regression (Approximate EM Approach)

4.1 Uniform Prior

Posterior density function is

$$\begin{aligned} p(\boldsymbol{\beta}|\boldsymbol{y},\boldsymbol{X}) &\propto L(\boldsymbol{y}|\boldsymbol{\beta},\boldsymbol{X})U(\boldsymbol{\beta}|\boldsymbol{X}) \\ &= L(\boldsymbol{y}|\boldsymbol{\beta},\boldsymbol{X}) \cdot constant \\ &\propto L(\boldsymbol{y}|\boldsymbol{\beta},\boldsymbol{X}) \end{aligned}$$

Uniform prior is not a function of beta.

Thus, posterior mode is the same as maximum likelihood estimate. Log posterior density is

$$ln[p(\boldsymbol{\beta}|\boldsymbol{y},\boldsymbol{X})] \propto ln[L(\boldsymbol{y}|\boldsymbol{\beta},\boldsymbol{X})]$$

Log likelihood function is approximated as negative weighted least squares function locally (see IRLS).

$$\begin{aligned} &\approx -\sum_{i=1}^{N} w_i(z_i - \boldsymbol{x}_i'\boldsymbol{\beta})^2 \\ &\propto -\frac{1}{2}\sum_{i=1}^{N} w_i(z_i - \boldsymbol{x}_i'\boldsymbol{\beta})^2 \end{aligned}$$

where

$$\begin{aligned} z_i &= \boldsymbol{x}_i'\widehat{\boldsymbol{\beta}} + \frac{y_i - p_i}{w_i} \\ w_i &= p_i(1-p_i) \\ p_i &= logistic(\boldsymbol{x}_i'\widehat{\boldsymbol{\beta}}) \end{aligned}$$

$\widehat{\boldsymbol{\beta}}$ is from last step

4.2 Independent Normal / Gaussian Prior

$$\begin{aligned} ln[p(\boldsymbol{\beta}|\boldsymbol{y},\boldsymbol{\mu},\boldsymbol{\Sigma},\boldsymbol{X})] &\propto ln[L(\boldsymbol{y}|\boldsymbol{\beta},\boldsymbol{\mu},\boldsymbol{\Sigma},\boldsymbol{X})N(\boldsymbol{\beta}|\boldsymbol{\mu},\boldsymbol{\Sigma},\boldsymbol{X})] \\ &= ln[L(\boldsymbol{y}|\boldsymbol{\beta},\boldsymbol{X})] + ln[N(\boldsymbol{\beta}|\boldsymbol{\mu},\boldsymbol{\Sigma},\boldsymbol{X})] \\ &\approx -\frac{1}{2}\sum_{i=1}^{N} w_i(z_i - \boldsymbol{x}_i'\boldsymbol{\beta})^2 - \frac{1}{2}\sum_{j=1}^{J}(\frac{(\beta_j - \mu_j)^2}{\sigma_j^2} + ln(\sigma_j^2)) + constant \\ &= -\frac{1}{2}\{\sum_{i=1}^{N}\frac{1}{w_i^{-1}}(z_i - \boldsymbol{x}_i'\boldsymbol{\beta})^2 + \sum_{j=1}^{J}\frac{1}{\sigma_j^2}(\mu_j - 1\cdot\beta_j)^2 + \sum_{j=1}^{J} ln(\sigma_j^2)\} + constant \\ &\approx -\frac{1}{2}\{\sum_{i=1}^{N}\frac{1}{w_i^{-1}}(z_i - \boldsymbol{x}_i'\boldsymbol{\beta})^2 + \sum_{j=1}^{J}\frac{1}{\sigma_j^2}(\mu_j - \boldsymbol{e}_j'\boldsymbol{\beta})^2\} \\ &= -\frac{1}{2}\{(\boldsymbol{z} - \boldsymbol{X}\boldsymbol{\beta})'\boldsymbol{W}(\boldsymbol{z} - \boldsymbol{X}\boldsymbol{\beta}) + (\boldsymbol{\mu} - \boldsymbol{I}_J\boldsymbol{\beta})'\boldsymbol{\Sigma}(\boldsymbol{\mu} - \boldsymbol{I}_J\boldsymbol{\beta})\} \\ &= -\frac{1}{2}(\boldsymbol{z}_* - \boldsymbol{X}_*\boldsymbol{\beta})'\boldsymbol{W}_*(\boldsymbol{z}_* - \boldsymbol{X}_*\boldsymbol{\beta}) \end{aligned}$$

$\boldsymbol{e}_j'$ is the j row of identity matrix

where

$$\begin{aligned} \boldsymbol{z}_* &= \begin{pmatrix} \boldsymbol{z} \\ \boldsymbol{\mu} \end{pmatrix} \\ \boldsymbol{X}_* &= \begin{pmatrix} \boldsymbol{X} \\ \boldsymbol{I}_J \end{pmatrix} \\ \boldsymbol{W}_* &= \begin{pmatrix} \boldsymbol{W} & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{\Sigma} \end{pmatrix} \end{aligned}$$

Thus, original IRLS algorithm can be applied with augmented data ($\boldsymbol{\mu}$ and $\boldsymbol{\Sigma}$ from prior normal distribution) to estimate $\boldsymbol{\beta}$

$$
\begin{aligned}
ln[N(\boldsymbol{\beta}|\boldsymbol{\mu},\boldsymbol{\Sigma},\boldsymbol{X})] &= ln[\prod_{j=1}^{J}\frac{1}{\sqrt{2\pi\sigma_j^2}}exp(-\frac{1}{2}\frac{(\beta_j-\mu_j)^2}{\sigma_j^2})] \\
&= \sum_{j=1}^{J} ln[\frac{1}{\sqrt{2\pi\sigma_j^2}}exp(-\frac{1}{2}\frac{(\beta_j-\mu_j)^2}{\sigma_j^2})] \\
&= \sum_{j=1}^{J}\{ln[1]-ln[(2\pi\sigma_j^2)^{1/2}]+ln[exp(-\frac{1}{2}\frac{(\beta_j-\mu_j)^2}{\sigma_j^2})]\} \\
&= \sum_{j=1}^{J}\{-\frac{1}{2}ln[2\pi\sigma_j^2]-\frac{1}{2}\frac{(\beta_j-\mu_j)^2}{\sigma_j^2}\} \\
&= \sum_{j=1}^{J}\{-\frac{1}{2}ln[2\pi]\}+\sum_{j=1}^{J}\{-\frac{1}{2}ln[\sigma_j^2]-\frac{1}{2}\frac{(\beta_j-\mu_j)^2}{\sigma_j^2}\} \\
&= constant + -\frac{1}{2}\sum_{j=1}^{J}\{ln[\sigma_j^2]+\frac{(\beta_j-\mu_j)^2}{\sigma_j^2}\}
\end{aligned}
$$

4.3 Independent Student-t Prior

$$ln[p(\boldsymbol{\beta}|\boldsymbol{y},\boldsymbol{X})] \propto ln[L(\boldsymbol{y}|\boldsymbol{\beta},\boldsymbol{X})t(\boldsymbol{\beta}|\boldsymbol{X})]$$

Multivariate Student-t density is a product of Multivariate Normal's and Inverse Chi Squares' density after "integrate out"

$$
\begin{aligned}
&= ln[L(\boldsymbol{y}|\boldsymbol{\beta},\boldsymbol{X})\int N(\boldsymbol{\beta}|\boldsymbol{\mu},\boldsymbol{\Sigma},\boldsymbol{X})Inv-\chi^2(\boldsymbol{\Sigma}|\boldsymbol{X})\partial\boldsymbol{\Sigma}] \\
&\approx ln[L(\boldsymbol{y}|\boldsymbol{\beta},\boldsymbol{X})]+ln[N(\boldsymbol{\beta}|\boldsymbol{\mu},\boldsymbol{\Sigma},\boldsymbol{X})]+ln[Inv-\chi^2(\boldsymbol{\Sigma}|\boldsymbol{X})] \\
&\approx -\frac{1}{2}\{\sum_{i=1}^{N}\frac{1}{w_i^{-1}}(z_i-\boldsymbol{x}_i'\boldsymbol{\beta})^2+\sum_{j=1}^{J}\frac{1}{\sigma_j^2}(\mu_j-1\cdot\beta_j)^2+\sum_{j=1}^{J}ln(\sigma_j^2)\}+constant-p(\sigma_j|v_j,s_j) \\
&= -\frac{1}{2}(\boldsymbol{z}_*-\boldsymbol{X}_*\boldsymbol{\beta})'\boldsymbol{W}_*(\boldsymbol{z}_*-\boldsymbol{X}_*\boldsymbol{\beta})-\frac{1}{2}\sum_{j=1}^{J}ln(\sigma_j^2)+constant-p(\sigma_j|v_j,s_j)
\end{aligned}
$$

Gelman et al. (2008, 2013) propose an approximate EM algorithm, in which IRLS and EM algorithm are combined and altered, to estimate $\boldsymbol{\beta}$

1. Use last $\boldsymbol{\beta}$ or initial value to get $\boldsymbol{z}$ and $\boldsymbol{W}$. Use last σ_j^2 or initial value s_j^2 to get $\boldsymbol{\Sigma}$
2. Now we have $\boldsymbol{z}_*$, $\boldsymbol{W}_*$ and $\boldsymbol{X}_*$. We minimize $(\boldsymbol{z}_*-\boldsymbol{X}_*\boldsymbol{\beta})'\boldsymbol{W}_*(\boldsymbol{z}_*-\boldsymbol{X}_*\boldsymbol{\beta})$ to get new $\boldsymbol{\beta}^+$ i.e.,
$$\boldsymbol{\beta}^+=(\boldsymbol{X}_*'\boldsymbol{W}_*\boldsymbol{X}_*)^{-1}(\boldsymbol{X}_*'\boldsymbol{W}_*\boldsymbol{z}_*)$$
We also get $\widehat{Var}(\boldsymbol{\beta}^+)$
3. Approximate E-step: First note that
$$\mathbb{E}[(\beta_j-\mu_j)^2]=Var(\beta_j-\mu_j)+(\mathbb{E}[\beta_j-\mu_j])^2\approx\widehat{Var}(\beta_j^+)+(\beta_j^+-\mu_j)^2$$
Expected value of log posterior density is
$$\mathbb{E}(ln[p(\boldsymbol{\beta}|\boldsymbol{y},\boldsymbol{X})])\approx\sum_{j=1}^{J}\frac{1}{\sigma_j^2}\mathbb{E}[(\mu_j-\beta_j)^2]+\mathbb{E}[-\frac{1}{2}\{\sum_{i=1}^{N}\frac{1}{w_i^{-1}}(z_i-\boldsymbol{x}_i'\boldsymbol{\beta})^2+\sum_{j=1}^{J}ln(\sigma_j^2)\}+constant-p(\sigma_j|v_j,s_j)]$$
Substitute $\mathbb{E}[(\mu_j-\beta_j)^2]$ with $\widehat{Var}(\beta_j^+)+(\beta_j^+-\mu_j)^2$
4. M-step: Maximize approximate expected log posterior density $\mathbb{E}(ln[p(\boldsymbol{\beta}|\boldsymbol{y},\boldsymbol{X})])$ with respect to σ_j^2 and get
$$\sigma_j^2=\frac{\widehat{Var}(\beta_j^+)+(\beta_j^+-\mu_j)^2+v_js_j^2}{1+v_j}$$
5. Repeat step 1 to 4 until convergence of $\boldsymbol{\beta}$

4.3.1 Observation

Without step 3 and 4, the algorithm is the same as that for independent normal prior.

Without step 3 and 4 and data augmentation, the algorithm is the same as IRLS.

Normal and uniform distribution is special cases of Student-t distribution by setting degree of freedom v_j and scale s_j to infinity, respectively. When $v_j = 1$, Student-t distribution is the same as Cauchy distribution.

Gelman et al. (2008) suggest default values of hyper-parameters $\mu_j = 0$, $s_j = 2.5$ and $v_j = 1$ (So, it is Cauchy default prior) for non-intercept.

5 Reference

Bishop, C. M. (2006). Pattern Recognition and Machine Learning. New York :Springer.

Gelman, A., Jakulin, A., Pittau, M. G., & Su., Y.-S. (2008). A Weakly Informative Default Prior Distribution For Logistic And Other Regression Models. Annals of Applied Statistics, 2(4), 1360-1383.

Gelman, A., Carlin, J. B., Stern, H. S., Dunson, D. B., Vehtari, A., & Rubin, D. B. (2013). Bayesian Data Analysis (3rd ed.). Chapman and Hall/CRC. https://doi.org/10.1201/b16018

Borman, S. (2006). The Expectation Maximization Algorithm. A Short Tutorial