

Bayesian Learning  
**Computer Lab 2**

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You are recommended to use R for solving the labs.

You work and submit your labs in pairs, but both of you should contribute equally and understand all parts of your solutions.

**It is not allowed to share exact solutions** with other student pairs.

The submitted lab reports will be verified through URKUND and indications of plagiarism will be investigated by the Disciplinary Board.

**Submit your solutions via LISAM, no later than May 3 at 23:30.**

**Please note the following about the format of the submitted lab report:**

1. The lab report should include all solutions and plots to the stated problems with necessary comments.
  2. Submit the lab report with your code attached to the solution of each sub-problem (1a), 1b),...) in **one** PDF document.
  3. Submit a separate file containing all code.
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**1. Linear and polynomial regression**

The dataset `TempLambohov.txt` contains daily average temperatures (in degree Celsius) at Lambohov, Linköping over the course of the year 2019. The response variable is *temp* and the covariate is

$$time = \frac{\text{the number of days since the beginning of the year}}{365}.$$

A Bayesian analysis of the following quadratic regression model is to be performed:

$$temp = \beta_0 + \beta_1 \cdot time + \beta_2 \cdot time^2 + \varepsilon, \varepsilon \stackrel{iid}{\sim} N(0, \sigma^2).$$

- (a) Use the conjugate prior for the linear regression model. The prior hyperparameters  $\mu_0$ ,  $\Omega_0$ ,  $\nu_0$  and  $\sigma_0^2$  shall be set to sensible values. Start with  $\mu_0 = (-10, 100, -100)^T$ ,  $\Omega_0 = 0.02 \cdot I_3$ ,  $\nu_0 = 3$  and  $\sigma_0^2 = 2$ . Check if this prior agrees with your prior opinions by simulating draws from the joint prior of all parameters and for every draw compute the regression curve. This gives a collection of regression curves; one for each draw from the prior. Does the collection of curves look reasonable? If not, change the prior hyperparameters until the collection of prior regression curves agrees with your prior beliefs about the regression curve.

[Hint: R package `mvtnorm` can be used and your *Inv- $\chi^2$*  simulator of random draws from Lab 1.]

- (b) Write a function that **simulate draws from the joint posterior distribution** of  $\beta_0$ ,  $\beta_1, \beta_2$  and  $\sigma^2$ .

- i. Plot a histogram for each marginal posterior of the parameters.
  - ii. Make a scatter plot of the temperature data and overlay a curve for the posterior median of the regression function  $f(\text{time}) = \mathbb{E}[\text{temp}|\text{time}] = \beta_0 + \beta_1 \cdot \text{time} + \beta_2 \cdot \text{time}^2$ , i.e. the median of  $f(\text{time})$  is computed for every value of  $\text{time}$ . In addition, overlay curves for the 95% equal tail posterior probability intervals of  $f(\text{time})$ , i.e. the 2.5 and 97.5 posterior percentiles of  $f(\text{time})$  is computed for every value of  $\text{time}$ . Does the posterior probability intervals contain most of the data points? Should they?
- (c) It is of interest to locate the  $\text{time}$  with the highest expected temperature (i.e. the  $\text{time}$  where  $f(\text{time})$  is maximal). Let's call this value  $\tilde{x}$ . Use the simulated draws in (b) to simulate from the **posterior distribution of  $\tilde{x}$** . [Hint: the regression curve is a quadratic polynomial. Given each posterior draw of  $\beta_0, \beta_1$  and  $\beta_2$ , you can find a simple formula for  $\tilde{x}$ .]
- (d) Say now that you want to **estimate a polynomial regression of order 8**, but you suspect that higher order terms may not be needed, and you worry about overfitting the data. Suggest a suitable prior that mitigates this potential problem. You do not need to compute the posterior. Just write down your prior. [Hint: the task is to specify  $\mu_0$  and  $\Omega_0$  in a suitable way.]

## 2. Posterior approximation for classification with logistic regression

The dataset `WomenAtWork.dat` contains  $n = 168$  observations on the following eight variables related to women:

Variable	Data type	Meaning	Role
Work	Binary	Whether or not the woman works	Response $y$
Constant	1	Constant to the intercept	Feature
HusbandInc	Numeric	Husband's income	Feature
EducYears	Counts	Years of education	Feature
ExpYears	Counts	Years of experience	Feature
Age	Counts	Age	Feature
NSmallChild	Counts	Number of child $\leq 6$ years in household	Feature
NBigChild	Counts	Number of child $> 6$ years in household	Feature

- (a) Consider the logistic regression model:

$$\Pr(y = 1|\mathbf{x}, \beta) = \frac{\exp(\mathbf{x}^T \beta)}{1 + \exp(\mathbf{x}^T \beta)},$$

where  $y$  equals 1 if the woman works and 0 if she does not.  $\mathbf{x}$  is a 7-dimensional vector containing the seven features (including a 1 to model the intercept).

The goal is to approximate the posterior distribution of the parameter vector  $\beta$  with a multivariate normal distribution

$$\beta|\mathbf{y}, \mathbf{x} \sim N\left(\tilde{\beta}, J_{\mathbf{y}}^{-1}(\tilde{\beta})\right),$$

where  $\tilde{\beta}$  is the posterior mode and  $J(\tilde{\beta}) = -\frac{\partial^2 \ln p(\beta|\mathbf{y})}{\partial \beta \partial \beta^T} \Big|_{\beta=\tilde{\beta}}$  is the negative of the observed Hessian evaluated at the posterior mode. Note that  $\frac{\partial^2 \ln p(\beta|\mathbf{y})}{\partial \beta \partial \beta^T}$  is a  $7 \times 7$  matrix with second derivatives on the diagonal and cross-derivatives

$\frac{\partial^2 \ln p(\beta|\mathbf{y})}{\partial \beta_i \partial \beta_j}$  on the off-diagonal. You can compute this derivative by hand, but we will let the computer do it numerically for you. Calculate both  $\tilde{\beta}$  and  $J(\tilde{\beta})$  by using the `optim` function in R. [Hint: You may use code snippets from my demo of logistic regression in Lecture 6.] Use the prior  $\beta \sim \mathcal{N}(0, \tau^2 I)$ , where  $\tau = 5$ .

Present the numerical values of  $\tilde{\beta}$  and  $J_{\mathbf{y}}^{-1}(\tilde{\beta})$  for the `WomenAtWork` data. Compute an approximate 95% equal tail posterior probability interval for the regression coefficient to the variable `NSmallChild`. Would you say that this feature is of importance for the probability that a woman works?

[Hint: You can verify that your estimation results are reasonable by comparing the posterior means to the maximum likelihood estimates, given by: `glmModel <- glm(Work ~ 0 + ., data = WomenAtWork, family = binomial).`]

- (b) Use your normal approximation to the posterior from (a). Write a function that simulate draws from the posterior predictive distribution of  $\Pr(y = 1|\mathbf{x})$ , where the values of  $\mathbf{x}$  corresponds to a 43-year-old woman, with two children (7 and 10 years old), 12 years of education, 8 years of experience, and a husband with an income of 20. Plot the posterior predictive distribution of  $\Pr(y = 1|\mathbf{x})$  for this woman.

[Hints: The R package `mvtnorm` will be useful. Remember that  $\Pr(y = 1|\mathbf{x})$  can be calculated for each posterior draw of  $\beta$ .]

- (c) Now, consider 11 women which all have the same features as the woman in (b). Rewrite your function and plot the posterior predictive distribution for the number of women, out of these 11, that are working. [Hint: Simulate from the binomial distribution, which is the distribution for a sum of Bernoulli random variables.]

GOOD LUCK!  
BEST, BERTIL