

# Bayesian data analysis – Assignment 7

## General information

- The recommended tool in this course is R (with the IDE R-Studio). You can download R [here](#) and R-Studio [here](#). There are tons of tutorials, videos and introductions to R and R-Studio online. You can find some initial hints from [RStudio Education pages](#).
- Instead of installing R and RStudio on your own computer, see [how to use R and RStudio remotely](#).
- When working with R, we recommend writing the report using R markdown and the provided [R markdown template](#). The template includes the formatting instructions and how to include code and figures.
- Instead of R markdown, you can use other software to make the pdf report, but the same instructions for formatting should be used. These instructions are available also in [the PDF produced from the R markdown template](#).
- Report all results in a single, **anonymous** \*.pdf -file and return it to [peergrade.io](#).
- The course has its own R package `aaltobda` with data and functionality to simplify coding. To install the package just run the following (`upgrade="never"` skips question about updating other packages):
  1. `install.packages("remotes")`
  2. `remotes::install_github("avehtari/BDA_course_Aalto",  
subdir = "rpackage", upgrade="never")`
- Many of the exercises can be checked automatically using the R package `markmyassignment`. Information on how to install and use the package can be found [here](#). There is no need to include `markmyassignment` results in the report.
- Recommended additional self study exercises for each chapter in BDA3 are listed in the course web page.
- We collect common questions regarding installation and technical problems in a course Frequently Asked Questions (FAQ). This can be found [here](#).
- Deadline for all assignments are **Sunday at 23.59**.
- If you have any suggestions or improvements to the course material, please post in the course chat feedback channel, create an issue, or submit a pull request to the public repository! Useful feedback will be thanked with bonus points.

## Information on this assignment

This assignment is related to Chapter 5. The maximum amount of points from this assignment is 9.

**Reading instructions:** Chapter 5 in BDA3, see reading instructions [here](#).

**Grading instructions:** The grading will be done in peergrade. All grading questions and evaluations for assignment 7 can be found [here](#)

**Reporting accuracy:** For posterior statistics of interest, only report digits for which the Monte Carlo standard error (MCSE) is zero. *Example:* If you estimate  $E(\mu) = 1.234$  with  $\text{MCSE}(E(\mu)) = 0.01$ , you should report  $E(\mu) = 1.2$ .

**Installing and using rstan:** See the [Stan demos](#) on how to use Stan in R (or Python) . [jupyter.cs.aalto.fi](http://jupyter.cs.aalto.fi) has working R and RStan environment and is probably the easiest way to use RStan. The Aalto Ubuntu desktops also have the necessary libraries installed. To install Stan on your laptop, see the instructions below and additional answers in [FAQ](#). Recently there have been reports of installation problems with Windows and R 4.0 (see Stan discourse for more), so if you don't succeed in short amount of time, it is probably easier to use [jupyter.cs.aalto.fi](http://jupyter.cs.aalto.fi).

If you use [jupyter.cs.aalto.fi](http://jupyter.cs.aalto.fi), all necessary packages have been pre-installed. In your laptop, install package `rstan`. Installation instructions on Linux, Mac and Windows can be found at <https://github.com/stan-dev/rstan/wiki/RStan-Getting-Started>. Additional useful packages are `loo`, `bayesplot` and `shinystan` (but you don't need these in this assignment). For Python users, `PyStan`, `CmdStanPy`, and `Arviz` packages are useful.

Stan manual can be found at <http://mc-stan.org/documentation/>. From this website, you can also find a lot of other useful material about Stan.

## 1. Linear model: drowning data with Stan (3p)

The provided data `drowning` in the `aaltobda` package contains the number of people drown per year in Finland 1980–2019. A statistician is going to fit a linear model with Gaussian residual model to these data using time as the predictor and number of drownings as the target variable (see the related linear model example for the Kilpisjärvi-temperature data in the example Stan codes). She has two objective questions:

- i) What is the trend of the number of people drown per year? We would plot the histogram of the slope of the linear model.
- ii) What is the prediction for the year 2020? We would plot the histogram of the posterior predictive distribution for the number of people drowning at  $\tilde{x} = 2020$ .

Your task is to fix the Stan code to be able to run this linear regression model.

To access the data, use:

```
> library(aaltobda)
> data("drowning")
```

1. The provided Stan code in Listing ?? given on the next page is almost correct for the given problem. However, there are three mistakes. Find these three mistakes and fix them. Report the original mistakes and your fixes clearly in your report. Include the *full* Stan code in your report. You may find some of the mistakes in the code using Stan syntax checker. If you copy the Stan code to a file ending `.stan` and open it in RStudio (you can also choose from Rstudio menu File->New File->Stan file to create a new Stan file), the editor will show you some syntax errors. More syntax errors might be detected by clicking Check in a bar just on top of the Stan file in RStudio editor. Note that some of the errors in the presented Stan code can be other than syntax errors.
2. The provided broken code does not define any prior for the parameters. In Stan, this corresponds to using a uniform prior. In addition to the three fixes, add a weakly-informative prior  $\text{normal}(0, \sigma_\beta)$  for the slope `beta`. It is very unlikely that the mean number of drownings changes more than 50 % in one year. The approximate historical mean yearly number of drownings is 138. Hence, set  $\sigma_\beta$  so that the following holds for the prior probability for `beta`:  $\Pr(-69 < \text{beta} < 69) = 0.99$ . Determine suitable value for  $\sigma_\beta$  and report the approximate numerical value for it in the report.
3. Using the obtained  $\sigma_\beta$ , add the desired prior in the Stan code. In the report, in a separate section, indicate clearly how you carried out your prior implementation, e.g. “Added line ... in block ...”.
4. In the same way, add a weakly informative prior for the intercept `alpha` and write explanation how did you select the prior.

**Hint!** Example resulting plots for the problem, with the fixes and the desired prior applied, are shown in Figure ?. If you want, you can use these plots as a reference for testing if your modified Stan code produces similar results. However, running the inference and comparing the plots is not required.

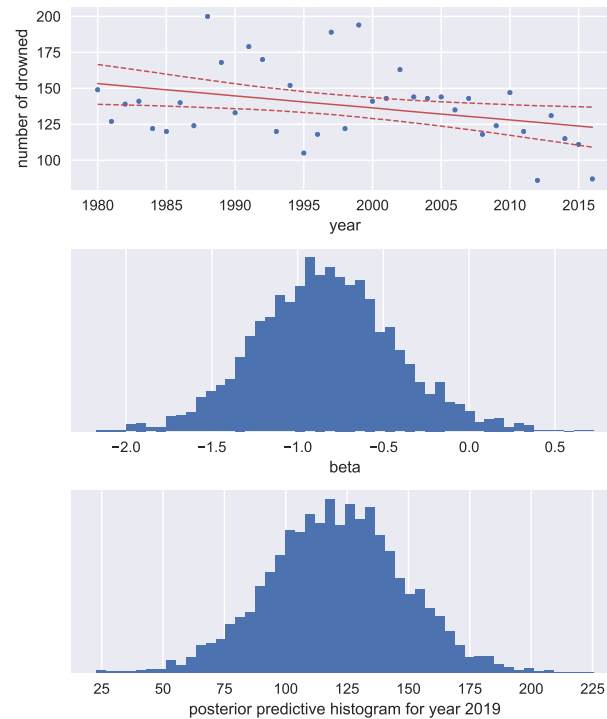


Figure 1: Example plots for the results obtained for problem in the question 1. In the first subplot, the red lines indicate the resulting 5 %, 50 %, and 95 % posterior quantiles for the transformed parameter  $\mu$  at each year.

Listing 1: Broken Stan code for question 1

```

1  data {
2      int<lower=0> N; // number of data points
3      vector[N] x;   // observation year
4      vector[N] y;   // observation number of drowned
5      real xpred;    // prediction year
6  }
7  parameters {
8      real alpha;
9      real beta;
10     real<upper=0> sigma;
11 }
12 transformed parameters {
13     vector[N] mu = alpha + beta*x;
14 }
15 model {
16     y ~ normal(mu, sigma)
17 }
18 generated quantities {
19     real ypred = normal_rng(mu, sigma);
20 }

```

## 2. Hierarchical model: factory data with Stan (3p)

**Note!** Both Assignment 8 and 9 build upon this assignment, hence it is important to get this assignment correct before you start with assignment 8 and 9.

The `factory` data in the `aaltobda` package contains quality control measurements from 6 machines in a factory (units of the measurements are irrelevant here). In the data file, each column contains the measurements for a single machine. Quality control measurements are expensive and time-consuming, so only 5 measurements were done for each machine. In addition to the existing machines, we are interested in the quality of another machine (the seventh machine). To read in the data, just use:

```
> library(aaltobda)
> data("factory")
```

Implement a separate, a pooled, and a hierarchical Gaussian model described in Section 11.6 using Stan. In the pooled model, all the measurements are combined and no distinction is made between the machines. In the separate model, each machine has its own model. Similarly, as in the model described in the book, use the same measurement standard deviation  $\sigma$  for all the groups in the hierarchical model. In the separate model, however, use separate measurement standard deviation  $\sigma_j$  for each group  $j$ . You should use weakly informative priors for all your model.

The provided Stan code in Listing ?? given on the next page is an example the separate model (but with very strange results, why?). This separate model can be summarized mathematically as:

$$\begin{aligned}y_{ij} &\sim N(\mu_j, \sigma_j) \\ \mu_j &\sim N(0, 1) \\ \sigma_j &\sim \text{Inv} - \chi^2(10)\end{aligned}$$

To run stan for that model, simply use:

```
> data("factory")
> sm <- rstan::stan_model(file = "[path to stan model code]")
> stan_data <- list(y = factory,
                   N = nrow(factory),
                   J = ncol(factory))
> model <- rstan::sampling(sm, data = stan_data)
> model
```

Inference for Stan model: 5cbfa723dd8fb382e0b647b3943db079.

4 chains, each with iter=2000; warmup=1000; thin=1;

post-warmup draws per chain=1000, total post-warmup draws=4000.

	mean	se_mean	sd	2.5%	25%	50%
mu[1]	0.11	0.01	0.98	-1.81	-0.56	0.12
mu[2]	0.10	0.01	1.00	-1.86	-0.56	0.10
...						

**Note!** These are *not* results you would expect to turn in in your report. You will need to change the separate model as well.

Using each of the three models with weakly informative priors– separate, pooled, and hierarchical – report, comment and, if applicable, plot histogram for the following distributions:

- i) the posterior distribution of the mean of the quality measurements of the sixth machine.
- ii) the predictive distribution for another quality measurement of the sixth machine.
- iii) the posterior distribution of the mean of the quality measurements of the seventh machine.

The report should (at least) contain:

- a) The plots used to answer question i)-iii) above.
- b) Stan models as model code that use weakly informative priors for all your model.
- c) Each model described with mathematical notation (as is done for the separate model above). Describe in words the difference between the three models.
- d) Include the posterior expectation for  $\mu_1$  with a 90% credibility interval for all three models but using a normal(0, 10) prior for the  $\mu$  parameter(s) and a Gamma(1, 1) prior for the  $\sigma$  parameter(s). In the hierarchical model, use the normal(0, 10) and Gamma(1, 1) as hyper-prior.

**Hint!** See the example Stan-codes [here](#) for the comparison of  $k$  groups with and without the hierarchical structure.

Listing 2: Stan code for a bad seperate model

```
1 data {
2   int<lower=0> N;
3   int<lower=0> J;
4   vector[J] y[N];
5 }
6
7 parameters {
8   vector[J] mu;
9   vector<lower=0>[J] sigma;
10 }
11
12 model {
13   // priors
14   for (j in 1:J){
15     mu[j] ~ normal(0, 1);
16     sigma[j] ~ inv_chi_square(10);
17   }
18
19   // likelihood
20   for (j in 1:J)
21     y[,j] ~ normal(mu[j], sigma[j]);
22 }
23
24 generated quantities {
25   real ypred;
26   // Compute predictive distribution for the first machine
27   ypred = normal_rng(mu[1], sigma[1]);
28 }
```