

# Bayesian data analysis – reading instructions 2

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## Chapter 2 – outline

Outline of the chapter 2

- 2.1 Binomial model (e.g. biased coin flipping)
- 2.2 Posterior as compromise between data and prior information
- 2.3 Posterior summaries
- 2.4 Informative prior distributions (skip exponential families and sufficient statistics)
- 2.5 Gaussian model with known variance
- 2.6 Other single parameter models
  - in this course the normal distribution with known mean but unknown variance is the most important
  - glance through Poisson and exponential
- 2.7 glance through this example, which illustrates benefits of prior information, no need to read all the details (it's quite long example)
- 2.8 Noninformative and weakly informative priors

Laplace's approach for approximating integrals is discussed in more detail in Chapter 4.

R/Python/Matlab demos

- demo2\_1: Binomial model and Beta posterior.
- demo2\_2: Comparison of posterior distributions with different parameter values for the Beta prior distribution.
- demo2\_3: Use samples to plot histogram with quantiles, and the same for a transformed variable.
- demo2\_4: Grid sampling using inverse-cdf method.

## Chapter 2 – most important terms

Find all the terms and symbols listed below. When reading the chapter, write down questions related to things unclear for you or things you think might be unclear for others. See also the additional comments below.

- binomial model
- Bernoulli trial
- exchangeability
- Bin,  $\binom{n}{y}$
- Laplace's law of succession
- think which expectations in eqs. 2.7-2.8
- summarizing posterior inference
- mode, mean, median, standard deviation, variance, quantile
- central posterior interval

- highest posterior density interval / region
- uninformative / informative prior distribution
- principle of insufficient reason
- hyperparameter
- conjugacy, conjugate family, conjugate prior distribution, natural conjugate prior
- nonconjugate prior
- normal distribution
- conjugate prior for mean of normal distribution with known variance
- posterior for mean of normal distribution with known variance
- precision
- posterior predictive distribution
- normal model with known mean but unknown variance
- proper and improper prior
- unnormalized density
- Jeffreys' invariance principle
- note non-uniqueness of noninformative priors for the binomial parameter
- difficulties with noninformative priors
- weakly informative priors

## Integration over Beta distribution

Chapter 2 has example of analysing the ratio of girls born in Paris 1745–1770. Laplace used binomial model and uniform prior which produces Beta distribution as posterior distribution. Laplace wanted to calculate  $p(\theta \geq 0.5)$ , which is obtained as

$$\begin{aligned} p(\theta \geq 0.5) &= \int_{0.5}^1 p(\theta|y, n, M) d\theta \\ &= \frac{493473!}{241945!251527!} \int_{0.5}^1 \theta^y (1 - \theta)^{n-y} d\theta \end{aligned}$$

Note that  $\Gamma(n) = (n - 1)!$ . Integral has a form which is called *incomplete Beta function*. Bayes and Laplace had difficulties in computing this, but nowadays there are several series and continued fraction expressions. For example, betacdf function in Matlab first tries a continued fraction expression and if it diverges, then an alternative approximation. Furthermore usually the normalisation term is computed by computing  $\log(\Gamma(\cdot))$  directly without explicitly computing  $\Gamma(\cdot)$ . Bayes was able to solve integral given small  $n$  and  $y$ . In case of large  $n$  and  $y$ , Laplace used Gaussian approximation of the posterior (more in chapter 4). In this specific case, Matlab's betacdf gives the same results as Laplace's result with at least 3 digit accuracy.

## Numerical accuracy

Laplace calculated

$$p(\theta \geq 0.5|y, n, M) \approx 1.15 \times 10^{-42}.$$

Correspondingly Laplace could have calculated

$$p(\theta \geq 0.5|y, n, M) = 1 - p(\theta \leq 0.5|y, n, M),$$

which in theory could be computed in Matlab with  $\text{betacdf}(0.5, y+1, n-y+1)$ . In practice this fails, due to the limitation in the floating point representation used by the computers. In Matlab the largest floating point number which is smaller than 1 is about  $1-\text{eps}/4$ , where  $\text{eps}$  is about  $2.22 \times 10^{-16}$  (the smallest floating point number larger than 1 is  $1+\text{eps}$ ). Thus the result from  $\text{betacdf}(0.5, y+1, n-y+1)$  will be rounded to 1 and  $1-1=0 \neq 1.15 \times 10^{-42}$ . In these cases it may be useful to choose more suitable version of the next two possibilities:

$$\text{betacdf}(0.5, y+1, n-y+1) = p(\theta \leq 0.5 | y, n, M), \quad (1)$$

or

$$\text{betacdf}(0.5, n-y+1, y+1) = p(\theta \geq 0.5 | y, n, M). \quad (2)$$

### Highest Posterior Density interval

HPD interval is not invariant to reparametrization. Here's an illustrative example:

```
>> r=exp(randn(1000,1));
>> prctile(log(r), [5 95])
ans =
    -1.6497    1.6112
>> log(prctile(r, [5 95]))
ans =
    -1.6496    1.6112
>> hpdi(log(r), 90)
ans =
    -1.6312    1.6634
>> log(hpdi(r, 90))
ans =
    -2.9973    1.2198
```

### Gaussian distribution in more complex models and methods

Gaussian distribution is commonly used in mixture models, hierarchical models, hierarchical prior structures, scale mixture distributions, Gaussian latent variable models, Gaussian processes, Gaussian random Markov fields, Kalman filters, proposal distribution in Monte Carlo methods, etc.

### Predictive distribution

Often the predictive distribution is more interesting than the posterior distribution. The posterior distribution describes the uncertainty in the parameters (like the proportion of red chips in the bag), but the predictive distribution describes also the uncertainty about the future event (like which color is picked next). This difference is important, for example, if we want to what could happen if some treatment is given to a patient.

In case of Gaussian distribution with known variance  $\sigma^2$  the model is

$$y \sim N(\theta, \sigma^2),$$

where  $\sigma^2$  describes aleatoric uncertainty. Using uniform prior the posterior is

$$p(\theta|y) \sim N(\theta|\bar{y}, \sigma^2/n),$$

where  $\sigma^2/n$  described epistemic uncertainty related to  $\theta$ . Using uniform prior the posterior predictive distribution is

$$p(\theta|y) \sim N(\theta|\bar{y}, \sigma^2 + \sigma^2/n),$$

where the uncertainty is sum of epistemic ( $\sigma^2/n$ ) and aleatoric uncertainty ( $\sigma^2$ ).

### **Should we worry about rigged priors?**

Andrew Gelman's blog post answering worries that data analyst would choose a too optimistic prior  
<http://andrewgelman.com/2017/10/04/worry-rigged-priors/>.