

## Handout 13: Hypothesis tests <sup>a</sup>

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**Aim:** To explain, design, and use hypothesis tests in the Bayesian framework

### References:

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- DeGroot, M. H. (2005, Sections 11.5-11.13). Optimal statistical decisions (Vol. 82). John Wiley & Sons
- Robert, C. (2007; Section 5.2(exclude 5.2.6)). The Bayesian choice: from decision-theoretic foundations to computational implementation. Springer Science & Business Media.

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## 1 Set-up of a hypothesis test

**Aim:** Let  $y = (y_1, \dots, y_n)$  generated from the real unknown data-generating process  $y \sim dR(y)$ . Statistician approximates/parametrizes  $dR(\cdot)$  by a statistical model  $dF(y|\theta)$  with unknown  $\theta \in \Theta$ . Then you wish to find useful statements about  $\theta$ : E.g. is there a smaller  $\Theta_* \subseteq \Theta$  where You can restrict the possible values of unknown  $\theta$ ?

*Notation 1.* Let  $y = (y_1, \dots, y_n)$  be a sequence of observables modeled to have been generated from the sampling distribution  $dF(y|\theta)$  labeled by an unknown parameter  $\theta \in \Theta$  following a priori distribution  $d\Pi(\theta)$ ; namely

$$\begin{cases} y|\theta & \sim dF(y|\theta) \\ \theta & \sim d\Pi(\theta) \end{cases} \quad (1)$$

Assume there is interest to test/compare the hypotheses/statements

$$H_0 : \theta \in \Theta_0; \text{ vs. } H_1 : \theta \in \Theta_1 \quad (2)$$

where  $\Theta = \Theta_0 \cup \Theta_1$ , under the Bayesian model (1).

*Note 2.* The pair of hypotheses (2) partitions the overall prior  $d\Pi(\theta)$  (representing overall prior believes about  $\theta$ ) as

$$d\Pi(\theta) = \pi_0 \times d\Pi_0(\theta) + \pi_1 \times d\Pi_1(\theta) \quad (3)$$

where  $\pi_0$ , and  $\pi_1$  describe the prior probabilities of hypotheses  $H_0$  and  $H_1$

$$\pi_0 = \underbrace{P_\Pi(\theta \in \Theta_0)}_{=P_\Pi(H_0)} = \int 1(\theta \in \Theta_0) d\Pi(\theta), \quad \pi_1 = \underbrace{P_\Pi(\theta \in \Theta_1)}_{=P_\Pi(H_1)} = \int 1(\theta \in \Theta_1) d\Pi(\theta),$$

respectively while  $d\Pi_0(\theta) := d\Pi(\theta|\theta \in \Theta_0)$  and  $d\Pi_1(\theta) := d\Pi(\theta|\theta \in \Theta_1)$  are prior distributions with pdf/pmf

$$\pi_0(\theta) := \underbrace{\pi(\theta|\theta \in \Theta_0)}_{=\pi(\theta|H_0)} = \frac{\pi(\theta)1(\theta \in \Theta_0)}{\int 1(\theta \in \Theta_0) d\Pi_0(\theta)}; \quad \text{and} \quad \pi_1(\theta) := \underbrace{\pi(\theta|\theta \in \Theta_1)}_{=\pi(\theta|H_1)} = \frac{\pi(\theta)1(\theta \in \Theta_1)}{\int 1(\theta \in \Theta_1) d\Pi_1(\theta)},$$

describing how the prior mass of  $\theta$  is spread out over the hypotheses  $H_0$  and  $H_1$  respectively. Then the Bayesian hypothesis test is can also be expressed as

$$H_0 : \begin{cases} y|\theta & \sim dF(y|\theta) \\ \theta & \sim d\Pi_0(\theta), \theta \in \Theta_0 \end{cases} \quad \text{vs} \quad H_1 : \begin{cases} y|\theta & \sim dF(y|\theta) \\ \theta & \sim d\Pi_1(\theta), \theta \in \Theta_1 \end{cases} \quad (4)$$

with prior  $\pi_0 = P_\Pi(\theta \in \Theta_0)$  and  $\pi_1 = P_\Pi(\theta \in \Theta_1)$ .

**Question 3.** Which Bayesian model ( $H_0$  or  $H_1$ ) describes ‘better’ the real data generating process?

*Note 4.* In Bayesian framework, hypothesis testing is rather straightforward. All You need to do is to calculate the corresponding posterior probabilities  $P_\Pi(\theta \in \Theta_0|y)$ , and  $P_\Pi(\theta \in \Theta_1|y)$ , and decide between  $H_0$  and  $H_1$ .

## 2 Decision theory perspective

*Note 5.* Bayes hypothesis test (4) can be addressed as a Bayesian statistical decision problem with decision space  $\mathcal{D} = \{\text{accept } H_0, \text{ accept } H_1\}$  or simpler  $\mathcal{D} = \{0, 1\}$ , and under Bayesian model (1). It can be seen as a parametric point inference about the indicator function

$$1_{\Theta_1}(\theta) = \begin{cases} 0 & , \theta \in \Theta_0 \\ 1 & , \theta \in \Theta_1 \end{cases} \quad (5)$$

under Bayesian model (1), prior (3), and a loss function  $\ell(\theta, \delta)$ , with  $\theta \in \Theta$ ,  $\delta \in \mathcal{D}$ ; E.g., the 0 – 1 loss function.

**Theorem 6.** The Bayes estimator of  $1_{\Theta_1}(\theta)$  in (5), under the prior  $d\Pi(\theta)$  in (3) and the  $c_I - c_{II}$  loss function

$$\ell(\theta, \delta) = \begin{cases} 0 & , \text{ if } \theta \in \Theta_0, \delta = 0 \\ 0 & , \text{ if } \theta \notin \Theta_0, \delta = 1 \\ c_{II} & , \text{ if } \theta \notin \Theta_0, \delta = 0 \\ c_I & , \text{ if } \theta \in \Theta_0, \delta = 1 \end{cases} \quad (6)$$

where  $c_I > 0$  and  $c_{II} > 0$  are specified by the researcher is

$$\delta(y) = \begin{cases} 0 & , P_\Pi(\theta \in \Theta_0|y) > \frac{c_{II}}{c_{II}+c_I} \\ 1 & , \text{ otherwise} \end{cases} \quad (7)$$

where  $\{\Theta_0, \Theta_1\}$  constitute a partition for  $\Theta$ , and  $P_\Pi(\theta \in \Theta_0|y) = \int 1(\theta \in \Theta_0) d\Pi(\theta|y)$ .

*Proof.* The posterior expected loss is<sup>1</sup>

$$\begin{aligned} \varrho(\pi, \delta|y) &= E_\Pi(\ell(\theta, \delta)|y) = \int \ell(\theta, \delta) d\Pi(\theta|y) = \int_{\Theta_0} \ell(\theta, \delta) d\Pi(\theta|y) + \int_{\Theta_1} \ell(\theta, \delta) d\Pi(\theta|y) \\ &= \begin{cases} \int_{\Theta_0} 0 d\Pi(\theta|y) + \int_{\Theta_1} c_{II} d\Pi(\theta|y) & , \text{ if } \delta = 0 \\ \int_{\Theta_0} c_I d\Pi(\theta|y) + \int_{\Theta_1} 0 d\Pi(\theta|y) & , \text{ if } \delta = 1 \end{cases} = \begin{cases} c_{II} \int 1(\theta \in \Theta_1) d\Pi(\theta|y) & , \text{ if } \delta = 0 \\ c_I \int 1(\theta \in \Theta_0) d\Pi(\theta|y) & , \text{ if } \delta = 1 \end{cases} \\ &= c_{II} P_\Pi(\theta \notin \Theta_0|y) 1(\delta \in \{0\}) + c_I P_\Pi(\theta \in \Theta_0|y) \end{aligned}$$

<sup>1</sup>Notation:  $\int_{\Theta_j} d\Pi(\theta|y) = \int 1(\theta \in \Theta_j) d\Pi(\theta|y)$

The Bayes rule (estimator) of (5) is  $\delta(y) = 0$  when

$$\varrho(\pi, \delta = 0|y) < \varrho(\pi, \delta = 1|y) \iff c_{\Pi} P_{\Pi}(\theta \notin \Theta_0|y) < c_1 P_{\Pi}(\theta \in \Theta_0|y) \iff P_{\Pi}(\theta \in \Theta_0|y) > \frac{c_{\Pi}}{c_{\Pi} + c_1}$$

The Bayes rule (estimator) of (5) is  $\delta(y) = 1$  when

$$\varrho(\pi, \delta = 0|y) > \varrho(\pi, \delta = 1|y) \iff c_{\Pi} P_{\Pi}(\theta \notin \Theta_0|y) > c_1 P_{\Pi}(\theta \in \Theta_0|y) \iff P_{\Pi}(\theta \in \Theta_0|y) < \frac{c_{\Pi}}{c_{\Pi} + c_1}$$

So  $\varrho(\pi, \delta|y)$  is minimised for (7). □

### 3 Bayes factors perspective

*Note 7.* Hypothesis tests in Bayesian statistics can be addressed by using Bayes factors.

**Definition 8.** The Bayes factor  $B_{01}(y)$  is the ratio of the posterior probabilities of  $H_0$  and  $H_1$  over the ratio of the prior probabilities of  $H_0$  and  $H_1$ .

$$B_{01}(y) = \frac{P_{\Pi}(\theta \in \Theta_0|y) / P_{\Pi}(\theta \in \Theta_0)}{P_{\Pi}(\theta \in \Theta_1|y) / P_{\Pi}(\theta \in \Theta_1)} \quad (8)$$

where

$$P_{\Pi}(\theta \in \Theta_j) = \int 1(\theta \in \Theta_j) d\Pi(\theta); \quad \text{and} \quad P_{\Pi}(\theta \in \Theta_j|y) = \int 1(\theta \in \Theta_j) d\Pi(\theta|y); \quad \text{for } j = 0, 1.$$

**Proposition 9.** For Hypothesis pair (2) and Bayes model (1), where the prior is formed as in (3), the Bayes factor in (8) can be written as

$$B_{01}(y) = \frac{\int_{\Theta_0} f(y|\theta) d\Pi_0(\theta)}{\int_{\Theta_1} f(y|\theta) d\Pi_1(\theta)} = \frac{f_0(y)}{f_1(y)}$$

where  $f_j(y) = \int_{\Theta_j} f(y|\theta) d\Pi_j(\theta)$  is the conditional marginal likelihood (or prior predictive pdf/pmf) given  $H_j$ , for  $j = 0, 1$ .

*Proof.* It results by showing that for  $j = 0, 1$ , it is

$$\begin{aligned} P_{\Pi}(\theta \in \Theta_j|y) &= \int_{\Theta_j} d\Pi(\theta|y) = \int_{\Theta_j} \frac{f(y|\theta) d\Pi(\theta)}{\int_{\Theta} f(y|\theta) d\Pi(\theta)} = \int_{\Theta_j} \frac{f(y|\theta) (\pi_0 \times d\Pi_0(\theta) + \pi_1 \times d\Pi_1(\theta))}{\underbrace{\int_{\Theta} f(y|\theta) d\Pi(\theta)}_{=f(y)}} \\ &= \frac{\pi_0}{f(y)} \int_{\Theta_j} f(y|\theta) d\Pi_0(\theta) + \frac{\pi_1}{f(y)} \int_{\Theta_j} f(y|\theta) d\Pi_1(\theta) = \begin{cases} \frac{\pi_0}{f(y)} \int_{\Theta_0} f(y|\theta) d\Pi_0(\theta) & , \text{if } j = 0 \\ \frac{\pi_1}{f(y)} \int_{\Theta_1} f(y|\theta) d\Pi_1(\theta) & , \text{if } j = 1 \end{cases} \end{aligned}$$

□

*Remark 10.* Obviously,  $B_{10}(y) = 1/B_{01}(y)$

*Remark 11.* Bayes factor  $B_{01}(y)$ :

- ...is the ‘odds in favour of  $H_0$  against  $H_1$  that are given by the data’  $y$ .
- ...evaluate the modification of the odds of  $\Theta_0$  against  $\Theta_1$  due to the observations  $y$ .
- ...is the ratio of the likelihoods, weighted by the conditional priors  $d\Pi_0(\theta)$  and  $d\Pi_1(\theta)$ .

**Proposition 12.** One can write

$$P_{\Pi}(\theta \in \Theta_0|y) = \left[ 1 + \frac{1 - P_{\Pi}(\theta \in \Theta_0)}{P_{\Pi}(\theta \in \Theta_0)} B_{01}(y)^{-1} \right]^{-1} = \left[ 1 + \frac{\pi_1}{\pi_0} B_{01}(y)^{-1} \right]^{-1}$$

where  $\pi_j = P_{\Pi}(\theta \in \Theta_j)$ , for  $j = 0, 1$ , by rearranging (8) (please check).

**Criterion 13.** Consider a hypothesis test  $H_0 : \theta \in \Theta_0$  versus  $H_1 : \theta \in \Theta_1$  as described in (4) with loss function (6), and given a Bayesian model (1). The hypothesis  $H_0$  is accepted when

$$B_{01}(y) > \frac{c_{II} \pi_1}{c_I \pi_0} \quad (9)$$

where  $\pi_j = P_{\Pi}(\theta \in \Theta_j)$ , for  $j = 0, 1$ .

*Proof.* Straightforward result from Definition 8 and Theorem 6. □

**Remark 14.** Eq. 9 shows the duality between loss function and the prior distribution. Different combinations of priors and loss functions may lead to the same result. For instance, for  $c'_{II} = c'_I = 1$ ,  $\pi'_0 = \frac{c_I \pi_0}{c_I \pi_0 + c_{II} \pi_1}$ , and  $\pi'_1 = \frac{c_{II} \pi_1}{c_I \pi_0 + c_{II} \pi_1}$ , we get again (9) !!!

**Criterion 15.** Jeffreys developed a scale to judge the strength of evidence in favor of  $H_0$  or against  $H_0$  brought by the data, outside a true decision-theoretic setting (aka; without the need to specify  $c_I$  and  $c_{II}$  in (9)).

$B_{01}$	$\log_{10}(B_{01})$	Strength of evidence
$(1, +\infty)$	$(0, +\infty)$	<b><math>H_0</math> is supported</b>
$(10^{-1/2}, 1)$	$(-1/2, 0)$	<b>Evidence against <math>H_0</math>: not worth more than a bare</b>
$(10^{-1}, 10^{-1/2})$	$(-1, -1/2)$	<b>Evidence against <math>H_0</math>: substantial</b>
$(10^{-3/2}, 10^{-1})$	$(-3/2, -1)$	<b>Evidence against <math>H_0</math>: strong</b>
$(10^{-2}, 10^{-3/2})$	$(-2, -3/2)$	<b>Evidence against <math>H_0</math>: very strong</b>
$(0, 10^{-2})$	$(-\infty, -2)$	<b>Evidence against <math>H_0</math>: decisive</b>

The precise bounds separating one strength from another are a matter of convention. Note that similar criticism exists in frequentist hypothesis tests with the choice of the significance level  $\alpha = \{0.01, 0.05, 0.1, \dots\}$ .

## 4 Special cases in hypotheses tests

**Definition 16.** Traditionally, hypotheses,  $H_j$ , are categorized as:

- **Single (or point) hypothesis** for  $\theta$  is called the hypothesis  $H_j : \theta \in \Theta_j$  where  $\Theta_j = \{\theta_j\}$  contains a single element, namely when  $\Pi_j(\theta)$  assigns probability one to a specific value for  $\theta$ .
- **Composite hypothesis** for  $\theta$  is called the hypothesis  $H_j : \theta \in \Theta_j$  where  $\Theta_j \subseteq \Theta$  contains many elements. Namely when  $\Pi_j(\theta)$  defines a non-degenerate density  $\pi_j(\theta)$  over  $\Theta_j \subseteq \Theta$ .
- **General alternative hypothesis** for  $\theta$  is called the composite hypothesis  $H_1 : \theta \in \Theta_1$  where  $\Theta_1 = \Theta - \{\theta_0\}$  and  $\theta_0$  a single value. It is often denoted as  $H_1 : \theta \neq \theta_0$  and compared against a single null hypothesis  $H_0 : \theta = \theta_0$ .

We present some special cases of hypothesis tests.

**Case 1. Composite vs Composite** is the hypothesis test:

$$H_0 : \theta \in \Theta_0 \quad \text{vs} \quad H_1 : \theta \in \Theta_1$$

where both  $\Theta_0 \subseteq \Theta$  and  $\Theta_1 \subseteq \Theta$  contain more than one elements. Overall prior can be partitioned as

$$d\Pi(\theta) = \pi_0 \times d\Pi_0(\theta) + \pi_1 \times d\Pi_1(\theta)$$

Then the conditional marginal likelihoods are

$$f_0(y) = \int_{\Theta_0} f(y|\theta) d\Pi_0(\theta); \quad f_1(y) = \int_{\Theta_1} f(y|\theta) d\Pi_1(\theta).$$

**Example.** A composite vs. composite hypothesis is:

$$H_0 : \begin{cases} y_i | \mu, \sigma^2 \stackrel{\text{iid}}{\sim} N(\mu, \sigma^2), i = 1, \dots, n \\ \mu | \sigma^2 \sim N(\mu_0, \sigma^2 \frac{1}{\lambda_0}) \\ \sigma^2 \sim \text{Ga}(a_0, b_0) \end{cases} \quad \text{vs} \quad H_1 : \begin{cases} y_i | \mu \stackrel{\text{iid}}{\sim} T(\mu, 1, k_0), i = 1, \dots, n \\ \mu \sim N(\xi_0, v_0) \end{cases}$$

In  $H_0$ : I consider a sampling model  $y_i \stackrel{\text{iid}}{\sim} N(\mu, \sigma^2)$  with prior  $(\mu, \sigma^2) \sim N(\mu_0, \sigma^2/\lambda_0) \text{IG}(a_0, b_0)$ , and  $\Theta_0 = \{N\} \cup \mathbb{R} \cup (0, \infty)$ . Here  $\mu_0, \lambda_0, a_0, b_0$  are fixed.

In  $H_1$ : I consider a sampling model  $y_i \stackrel{\text{iid}}{\sim} T(\mu, 1, k_0)$  with prior  $(\mu, \sigma^2) \sim N(\mu_0, \sigma^2/\lambda_0) \text{IG}(a_0, b_0)$ , and  $\Theta_1 = \{T\} \cup \mathbb{R}$ . Here  $\mu_0, k_0, \xi_0, v_0$  are fixed.

*Case 2.* **Single vs. General alternative** is the pair of hypotheses

$$H_0 : \theta = \theta_0 \quad \text{vs} \quad H_1 : \theta \neq \theta_0.$$

If  $\theta$  is continuous, the difficulty is that we cannot use a continuous prior for  $d\Pi_0(\theta)$  to conduct a test with point null hypothesis  $H_0 : \theta = \theta_0$  because it would give a prior probability zero for  $\theta = \theta_0$ . To overcome this, we specify the conditional distribution  $d\Pi_0(\theta)$  as a Dirac prior distribution with concentration point at  $\theta_0$ ; namely  $d\Pi_0(\theta) = 1(\theta \in \{\theta_0\}) d\theta$ . The conditional distribution  $d\Pi_1(\theta)$  can be any reasonable distribution  $d\Pi_1(\theta) = d\Pi_1(\theta|\theta \in \Theta_1)$ . Then the overall prior is

$$d\Pi(\theta) = \pi_0 \times 1(\theta \in \{\theta_0\}) d\theta + \pi_1 \times d\Pi_1(\theta|\theta \in \Theta_1) \quad (10)$$

and it is called spike-and-slab. Then the conditional marginal likelihoods are

$$f_0(y) = \int_{\Theta_0} f(y|\theta) d\Pi_0(\theta) = \int_{\{\theta=\theta_0\}} f(y|\theta) 1(\theta \in \{\theta_0\}) d\theta = f(y|\theta_0)$$

$$f_1(y) = \int_{\Theta_1} f(y|\theta) d\Pi_1(\theta) = \int_{\{\theta \neq \theta_0\}} f(y|\theta) d\Pi_1(\theta)$$

**Example.** The standard two side test  $H_0 : \mu = \theta_0$  vs.  $H_1 : \mu \neq \theta_0$ , where the sampling distribution is assumed to be  $y_i \stackrel{\text{iid}}{\sim} N(\mu, \sigma^2)$  with known variance  $\sigma^2$  for  $i = 1, \dots, n$ , is a simple vs. general alternative hypothesis test and can also be formulated as:

$$H_0 : y_i | \theta_0, \sigma_0^2 \stackrel{\text{iid}}{\sim} N(\theta_0, \sigma_0^2), i = 1, \dots, n \quad \text{vs} \quad H_1 : \begin{cases} y_i | \mu, \sigma^2 \stackrel{\text{iid}}{\sim} N(\mu, \sigma^2), i = 1, \dots, n \\ \mu \sim N(\mu_0, \sigma_0^2) \end{cases}$$

Here it is  $\Theta_0 = \{\theta_0\}$ ,  $\Theta_1 = \{\theta \in \mathbb{R} : \theta \neq \theta_0\}$ , while  $\theta_0, \mu_0, \sigma_0^2$  are fixed values.

*Case 3.* **Single vs. Single** is the pair of hypothesis

$$H_0 : \theta = \theta_0 \quad \text{vs} \quad H_1 : \theta = \theta_1$$

where  $\Theta_0 = \{\theta_0\}$  and  $\Theta_1 = \{\theta_1\}$  for some values of  $\theta_0$  and  $\theta_1$ . The hypotheses  $H_0$  and  $H_1$  are single, and hence the corresponding priors can be considered as having a point mass around  $\theta_0$  and  $\theta_1$ . Mathematically,

we assign Dirac prior distributions  $d\Pi_0(\theta) = 1(\theta \in \{\theta_0\})d\theta$  and  $d\Pi_1(\theta) = 1(\theta \in \{\theta_1\})d\theta$ , which imply

$$d\Pi(\theta) = \left( \pi_0 \times 1(\theta \in \{\theta_0\}) + \pi_1 \times 1(\theta \in \{\theta_1\}) \right) d\theta$$

Then the conditional marginal likelihoods are

$$\begin{aligned} f_0(y) &= \int_{\Theta_0} f(y|\theta) d\Pi_0(\theta) = \int_{\{\theta=\theta_0\}} f(y|\theta) 1(\theta \in \{\theta_0\}) d\theta = f(y|\theta_0) \\ f_1(y) &= \int_{\Theta_1} f(y|\theta) d\Pi_1(\theta) = \int_{\{\theta=\theta_1\}} f(y|\theta) 1(\theta \in \{\theta_1\}) d\theta = f(y|\theta_1) \end{aligned}$$

*Note 17.* In this case, Bayes factor is the likelihood ratio of  $H_0$  against  $H_1$  which most statisticians (whether Bayesian or not) view as the odds in favor of  $H_0$  against  $H_1$  that are given by the data.

**Example.** Given the statistical model  $y_i \stackrel{\text{iid}}{\sim} N(\mu, \sigma^2)$  the comparison  $H_0 : \mu = \theta_0$  vs.  $H_1 : \mu = \theta_1$ , is a simple vs. simple hypothesis, where  $\Theta_0 = \{\theta_0\}$ ,  $\Theta_1 = \{\theta_1\}$  are sets with a single elements  $\theta_0 \neq \theta_1$ .

**Example.** The model comparison

$$H_0 : y_i | \phi_0 \stackrel{\text{iid}}{\sim} \text{Nb}(\phi_0, 1) \text{ vs. } H_1 : y_i | \lambda_0 \stackrel{\text{iid}}{\sim} \text{Pn}(\lambda_0)$$

where  $\phi_0 > 0, \lambda_0 > 0$  are known, is a simple vs. simple hypothesis. Here it is  $\Theta_0 = \{\text{Nb}\}$ ,  $\Theta_1 = \{\text{Pn}\}$ .

**Example 18.** Let  $y = (y_1, \dots, y_n)$  a sequence of observables, and assume that  $n = 5$ , and  $y_* = \sum_{i=1}^5 y_i = 3$ . Assume a sampling distribution  $y_i | \theta \stackrel{\text{iid}}{\sim} \text{Br}(\theta)$ , with unknown parameter  $\theta \in [0, 1]$ , a priori following a uniform distribution.

1. By using Jeffreys' scaling rule, perform the following hypothesis test for  $\theta_0 = 1/2$

$$H_0 : \theta = \theta_0 \quad \text{vs} \quad H_1 : \theta \neq \theta_0$$

2. Compute the posterior probability of the NULL hypothesis.

**Solution.** This is a simple vs. general alternative hypothesis. I specify the overall prior with pdf

$$\pi(\theta) = \pi_0 1(\theta = \theta_0) + (1 - \pi_0) U(\theta | 0, 1)$$

for some  $\pi_0 > 0$ . I leave  $\pi_0$  abstract, however the usual choice (but maybe not the best) is  $\pi_0 = 1/2$ .

1. The Bayes factor is

$$B_{01}(y) = \frac{\prod_{i=1}^n \text{Br}(y_i | \theta_0)}{\int_{(0,1)} \prod_{i=1}^n \text{Br}(y_i | \theta) U(\theta | 0, 1) d\theta} = \frac{\theta_0^{y_*} (1 - \theta_0)^{n-y_*}}{\int_{(0,1)} \theta^{y_*} (1 - \theta)^{n-y_*} d\theta} = \frac{\theta_0^{y_*} (1 - \theta_0)^{n-y_*}}{B(y_* + 1, n - y_* + 1)} = \frac{(1/2)^5}{B(4, 3)} = \frac{15}{8}$$

Then  $B_{01}(y) = \frac{15}{8} \approx 2$ , and  $\log_{10}(B_{01}(y)) \approx 0.27$ . According to Jeffreys' scaling rule,  $H_0$  is supported. We can accept the null hypothesis.

2. The posterior probability of  $H_0$  is

$$P_{\Pi}(\theta = \theta_0 | y) = P_{\Pi}(\theta \in \Theta_0 | y) = \left[ 1 + \frac{1 - \pi_0}{\pi_0} B_{01}(y)^{-1} \right]^{-1} = \left[ 1 + \frac{1/2}{1 - 1/2} \left( \frac{15}{8} \right)^{-1} \right]^{-1} = \frac{15}{23} \approx 0.65$$

and hence the posterior distribution tends to support  $H_0$ .

**Example 19.** Let  $y = (y_1, \dots, y_n)$  a sequence of observables. There is interest in performing the following hypothesis test

$$H_0 : \begin{cases} y_i | \phi \sim \text{Nb}(1, \phi); & \phi > 0 \\ \phi \sim \text{Be}(a_0, b_0); & a_0 = 2, b_0 = 2 \end{cases} \quad \text{vs} \quad H_1 : \begin{cases} y_i | \lambda \sim \text{Pn}(\lambda); & \lambda > 0 \\ \lambda \sim \text{Ga}(a_1, b_1); & a_1 = 2, b_1 = 1 \end{cases}$$

1. Perform the test for  $n = 2$ , and  $y_1 = y_2 = 0$ , by using Jeffrey's scaling.
2. Perform the test for  $n = 2$ , and  $y_1 = y_2 = 2$ , by using Jeffrey's scaling.

**Hint-1** Poisson distribution  $x \sim \text{Pn}(\lambda)$  has PMF:  $\text{Pn}(x|\lambda) = \frac{1}{x!} \lambda^x \exp(-\lambda) 1_{\mathbb{N}}(x)$ , where  $\mathbb{N} = \{0, 1, 2, \dots\}$  and  $\lambda > 0$ .

**Hint-2** Negative Binomial distribution  $x \sim \text{Nb}(r, \theta)$  has PMF:  $\text{Nb}(x|r, \theta) = \binom{r+x-1}{r-1} \theta^r (1-\theta)^x 1_{\mathbb{N}}(x)$  with  $\theta \in (0, 1)$ ,  $r \in \mathbb{N} - \{0\}$ , and  $\mathbb{N} = \{0, 1, 2, \dots\}$ .

**Hint-3** Gamma distribution  $x \sim \text{Ga}(a, b)$  has PDF:  $\text{Ga}(x|a, b) = \frac{b^a}{\Gamma(a)} x^{a-1} \exp(-bx) 1_{(0, \infty)}(x)$ , with  $a > 0$  and  $b > 0$ .

**Hint-4** Beta distribution  $x \sim \text{Be}(a, b)$  has PDF:  $\text{Be}(x|a, b) = \frac{1}{B(a, b)} x^{a-1} (1-x)^{b-1} 1_{(0, 1)}(x)$ , with  $a > 0$  and  $b > 0$ .

**Solution.** This is a Composite vs composite hypotheses. The overall a priori distribution  $d\Pi(\theta)$  with  $\theta \in \Theta$  and  $\Theta = \{\text{Nb}\} \times (0, 1) \cup \{\text{Pn}\} \times (0, \infty)$  has density

$$\pi(\theta) = \pi_0 \text{Be}(\phi|a_0, b_0) + \pi_1 \text{Ga}(\lambda|a_1, b_1);$$

where  $\pi_0 = \pi_1 = 0.5$ . Let's compute the Bayes factor

$$\begin{aligned} f_0(y) &= \int \prod_{i=1}^n \text{Nb}(y_i|\phi, 1) \text{Be}(\phi|a_0, b_0) d\phi = \frac{1}{B(a_0, b_0)} \int_0^1 \phi^{n+a_0-1} (1-\phi)^{n\bar{y}+b_0-1} d\phi = \frac{B(n+a_0, n\bar{y}+b_0)}{B(a_0, b_0)} \\ f_1(y) &= \int \prod_{i=1}^n \text{Pn}(y_i|\lambda) \text{Ga}(\lambda|a_1, b_1) d\lambda = \frac{1}{\prod_{i=1}^n y_i!} \frac{b_1^{a_1}}{\Gamma(a_1)} \int_0^\infty \lambda^{n\bar{y}+a_1-1} \exp(-(n+b_1)\lambda) d\lambda \\ &= \frac{\Gamma(n\bar{y}+a_1)}{\Gamma(a_1)} \frac{b_1^{a_1}}{(n+b_1)^{n\bar{y}+a_1}} \frac{1}{\prod_{i=1}^n y_i!} \end{aligned}$$

So the Bayes Factor is

$$B_{01}(y) = \frac{B(n+a_0, n\bar{y}+b_0)}{B(a_0, b_0)} \frac{\Gamma(a_1)}{\Gamma(n\bar{y}+a_1)} \frac{(n+b_1)^{n\bar{y}+a_1}}{b_1^{a_1}} \prod_{i=1}^n y_i!$$

1. Then  $B_{01}(y) = 2.70$ , and  $\log_{10}(B_{01}(y)) \approx 0.43$ . According to Jeffrey's scaling rule,  $H_0$  is supported.
2. Then  $B_{01}(y) = 0.29$ , and  $\log_{10}(B_{01}(y)) \approx -0.53$ . According to Jeffrey's scaling rule, the evidence against  $H_0$  is substantial.

**Example 20.** Let  $y = (y_1, \dots, y_n)$  a sequence of observables. There is interest in performing the following hypothesis test

$$H_0 : y_i | \phi \sim \text{Nb}(\phi, 1); \text{ with } \phi = 1/3 \quad \text{vs} \quad H_1 : y_i | \lambda \sim \text{Pn}(\lambda); \text{ with } \lambda = 2$$

1. Perform the test for  $n = 2$ , and  $y_1 = y_2 = 0$ , by using Jeffreys' scaling.
2. Perform the test for  $n = 2$ , and  $y_1 = y_2 = 2$ , by using Jeffreys' scaling.

**Hint-1** Poisson distribution  $x \sim \text{Pn}(\lambda)$  has PMF:  $\text{Pn}(x|\lambda) = \frac{1}{x!} \lambda^x \exp(-\lambda) 1_{\mathbb{N}}(x)$ , where  $\mathbb{N} = \{0, 1, 2, \dots\}$  and  $\lambda > 0$ .

**Hint-2** Negative Binomial distribution  $x \sim \text{Nb}(r, \theta)$  has PMF:  $\text{Nb}(x|r, \theta) = \binom{r+x-1}{r-1} \theta^r (1-\theta)^x 1_{\mathbb{N}}(x)$  with  $\theta \in (0, 1)$ ,  $r \in \mathbb{N} - \{0\}$ , and  $\mathbb{N} = \{0, 1, 2, \dots\}$ .

**Solution.** This is a simple vs simple hypothesis test. I specify priors  $\pi(\text{Nb}) = \pi(\text{Pn}) = 1/2$ , due to the a priori ignorance about the parametric statistical model, however, we do not really need it now .... The Bayes factor is

$$B_{01}(y) = \frac{f_0(y)}{f_1(y)} = \frac{\prod_{i=1}^n \text{Nb}(y_i|\phi, 1)}{\prod_{i=1}^n \text{Pn}(y_i|\lambda)} = \frac{\phi^n (1-\phi)^{n\bar{y}}}{\lambda^{n\bar{y}} \exp(-n\lambda) / \prod_{i=1}^n y_i!}$$

1. Then  $B_{01}(y) = \exp(4)/9 \approx 6.07$ , and  $\log_{10}(B_{01}(y)) \approx 0.78$ . According to Jeffrey's scaling rule,  $H_0$  is supported.
2. Then  $B_{01}(y) = 4 \exp(4)/729 \approx 0.30$ , and  $\log_{10}(B_{01}(y)) \approx -0.54$ . According to Jeffrey's scaling rule, the evidence against  $H_0$  is substantial.

## Practice

**Question 21.** To practice try to work on the Exercise 67 from the Exercise sheet.