ST308 - Lent term
Bayesian Inference

Kostas Kalogeropoulos

Hypothesis Testing - Prediction - Monte Carlo

Outline

Topics covered: Bayes factors, Lindley's paradox, unit information prior, predictive distribution, Monte Carlo integration

Outline

1. Hypothesis testing

2. Prediction

3. Monte Carlo Integration

Hypothesis Testing problem

- Consider the data $x = (x_1, \ldots, x_n)$.
- Assign model-likelihood $f(x|\theta)$ with some unknown parameters θ.
- (In Bayesian Inference) Assign a prior on θ.
- Consider $H_0 : \theta \in \Theta_0$ and $H_1 : \theta \in \Theta_1$. Use the information from x to choose between them.
- The above can be extended to the case of more than two hypotheses.

Bayes factor

Let $\pi(\theta \in \Theta_0)/\pi(\theta \in \Theta_1)$ and $\pi(\theta \in \Theta_0|x)/\pi(\theta \in \Theta_1|x)$ be the prior and posterior odds of H_0, respectively.

Bayes factor

The Bayes factor in favour of H_0 is the ratio of the corresponding posterior to prior odds

$$B_{01}(x) = \frac{\frac{\pi(\theta \in \Theta_0|x)}{\pi(\theta \in \Theta_1|x)}}{\frac{\pi(\theta \in \Theta_0)}{\pi(\theta \in \Theta_1)}}$$

Note: It is not hard to see that $B_{10}(x) = 1/B_{01}(x)$.

Bayes factor motivation

For the case of simple vs simple hypotheses $H_0 : \theta = \theta_0$ vs $H_1 : \theta = \theta_1$, Bayes factor reduces to the likelihood ratio test, i.e. the most powerful test for this case.

$$B_{10}(x) = \frac{\frac{\pi(\theta_1|x)}{\pi(\theta_0|x)}}{\frac{\pi(\theta_1)}{\pi(\theta_0)}} = \frac{\frac{\frac{1}{m(x)} f(x|\theta_1)\pi(\theta_1)}{\frac{1}{m(x)} f(x|\theta_0)\pi(\theta_0)}}{\frac{\pi(\theta_1)}{\pi(\theta_0)}} = \frac{f(x|\theta_1)}{f(x|\theta_0)}$$

In more general cases the above does not hold but it is still considered as the default criterion for Bayesian hypothesis testing

Bayes factor - interpretation

In terms of interpretation the following guidelines are available

$1 < B_{10}(x) \leq 3$	evidence against H_0 is **poor**
$3 < B_{10}(x) \leq 20$	evidence against H_0 is **substantial**
$20 < B_{10}(x) \leq 150$	evidence against H_0 is **strong**
$B_{10}(x) > 150$	evidence against H_0 is **decisive**

Example: IQ scores

Recall the IQ test example from last week. The prior was the $N(110, 120)$ and the posterior $N(102.8, 48)$.

The student claims it was not his day and his genuine IQ is at least 105. So $H_0 : \theta \geq 105$ vs $H_1 : \theta < 105$.

$$\pi(\theta < 105|x) = \pi\left(Z < \frac{105-102.8}{\sqrt{48}}\right) = \Phi(.318) = .625$$
$$\pi(\theta < 105) = \pi\left(Z < \frac{105-110}{\sqrt{120}}\right) = \Phi(-.456) = .324$$

So the Bayes factor against H_0 is 3.47. Substantial evidence against H_0 (student's claim).

General case

Suppose we want to test $H_0 : \theta = 0$ vs $H_1 : \theta \neq 0$.

Note that for -say- $\theta \in \mathbb{R}$ or $\theta \in [-1, 1]$, $\pi(\theta = 0) = \pi(\theta = 0|x) = 0$. Hence the Bayes factor is indeterminate in such cases.

A more general expression uses the model evidence / marginal likelihood:

$$B_{10}(x) = \frac{\frac{\pi(H_1|x)}{\pi(H_0|x)}}{\frac{\pi(H_1)}{\pi(H_0)}} = \frac{\frac{\pi(H_1|x)f(x)}{\pi(H_1)}}{\frac{\pi(H_0|x)f(x)}{\pi(H_0)}} = \frac{f(x|H_1)}{f(x|H_0)} = \frac{\int_{\Theta_1} f(x|\theta)\pi(\theta)d\theta}{f(x|\theta = 0)}$$

The hypothesis (model) with the higher model evidence is chosen.

Notes on Bayes factors

- No control of type I error probability.
- Compare H_0 with H_1 unlike frequentist inference that focuses on H_0.
- Labels H_0 or H_1 do not matter.
- Except for some specific cases, require proper priors.
- It is easy to extend to more hypotheses.

Bayesian Occam's razor

Bayesian Occam's razor: Models with more parameters (more complex models) will not necessarily have higher marginal likelihood.

Conservation of probability mass: More complex models will handle more complex datasets adequately. But the probabilities over all these datasets will have to sum to one.

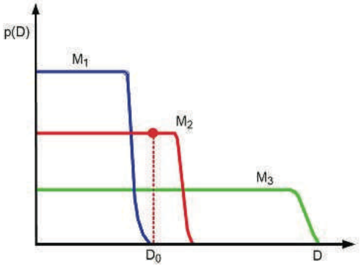

Figure 5.6 A schematic illustration of the Bayesian Occam's razor. The broad (green) curve corresponds to a complex model, the narrow (blue) curve to a simple model, and the middle (red) curve is just right. Based on Figure 3.13 of (Bishop 2006a). See also (Murray and Ghahramani 2005, Figure 2) for a similar plot produced on real data.

Jeffreys-Lindley-Bartlett (Lindley) paradox - example 1

Real data example: A person claimed to possess extrasensory capacities (ESP) and can alter the outcome of a machine that output $0, 1$ with probability $\theta = 0.5$ (H_0). H_1 is $\theta \neq 0.5$.

In 104.490.000 trials, there were 52.263.471 ones.

Jeffreys-Lindley-Bartlett (Lindley) paradox - example 1

Under frequentist inference we reject the null and conclude ESP; p-value $<<$ 0.01.

Bayes factor, under a Uniform$(0, 1)$ prior on θ, favours H_0 therefore rejecting the ESP claim.

Maybe not a paradox. Frequentist testing asks the question is $\theta = 0.5$?

Bayesian testing compares a model with $\theta = 0.5$ and a model with θ drawn uniformly from $(0, 1)$ as to how they explain the data.

Note on p-value: A more careful study of the problem would also check the power and provide a much lower threshold for the p-value.

Jeffreys-Lindley-Bartlett (Lindley) paradox - example 2

Let $y = (y_1, \ldots, y_n)$ iid from the N(θ,1) distribution, and consider testing $H_0 : \theta = 0$ vs $H_1 : \theta \neq 0$.

The Bayes factor in favour of H_0 is

$$B_{01} = \frac{\exp\{-n(\bar{y}_n)^2/2\}}{\int_{-\infty}^{+\infty} \exp\{-n(\bar{y}_n - \theta)^2/2\}\pi(\theta)\,\mathrm{d}\theta}$$

Assume the improper Jeffreys prior $p(\theta) = c$. Then

$$B_{01} = \frac{\exp\{-n(\bar{y}_n)^2/2\}}{c\int_{-\infty}^{+\infty} \exp\{-n(\bar{y}_n - \theta)^2/2\}\,\mathrm{d}\theta} = \frac{\exp\{-n(\bar{y}_n)^2/2\}}{c\sqrt{2\pi/n}}$$

The decision depends on the arbitrary constant c!

Jeffreys-Lindley-(Bartlett) paradox - example 2 (cont'd)

Consider the low informative prior $\mathrm{N}(0, \tau^2)$ for some big τ^2. The Bayes factor is

$$B_{01} = \frac{\exp\{-n(\bar{y}_n)^2/2\}}{\int_{-\infty}^{+\infty} \exp\{-n(\bar{y}_n - \theta)^2/2\}(2\pi\tau^2)^{-1/2} \exp(-\theta^2/2\tau^2)\,\mathrm{d}\theta}$$

As $\tau \to \infty$, $B_{01} \to \infty$ regardless of $\bar{y}_n$ (except if $\bar{y}_n = 0$). So for a near-infinite value of τ^2 we will always choose H_0.

It is therefore clear that more thought should be put on the choice of $\pi(\theta)$ when it come to testing.

If we don't have information we still need to put some information but not too much.

Unit information priors

In the previous example the unit information prior is the $N(\mu_0, 1)$, i.e. putting the same prior variance as the variance of each data point.

The posterior is $N(\mu_n, \tau_n^2)$ with

$$\mu_n = \frac{1}{n+1}(\mu_0 + n\bar{y}), \quad \tau_n^2 = \tfrac{1}{n+1}$$

This prior is like adding one more observation equal to μ_0. In fact σ^2 corresponds to Fisher information from one data point.

Cheat (add information), but as little as possible.

Summary on Bayesian Hypothesis testing

- Use the Bayes factor. In most cases it requires proper priors.

- Bayes factor can be computed in two ways; either can be used. The model evidence is sometimes the only option and can be computationally expensive to compute.

- For testing simple versus simple hypothesis the prior plays no role so any prior can be used.

- For testing hypotheses with the θ of equal dimension, e.g. $H_0 : \theta < 0$ vs $H_1 : \theta \geq 0$, priors with big variance (in some cases even improper priors) are fine.

- But for testing hypotheses of different dimension, e.g. $H_0 : \theta = 0$ vs $H_1 : \theta \neq 0$, such priors may lead to Lindley's paradox. Unit information priors are the recommended option then.

Outline

1. Hypothesis testing
2. Prediction
3. Monte Carlo Integration

Prediction problem

- Consider the data $x = (x_1, \ldots, x_n)$.
- Assign model-likelihood $f(x|\theta)$ with some unknown parameters θ.
- (In Bayesian Inference) Assign a prior on θ.
- Consider a future observation y from the same model $f(y|\theta)$. Provide
  - a point estimate (prediction) of y
  - an interval for y with high probability (prediction interval)
  - choose between two or more hypotheses regarding y, e.g. $y > 0$ or $y \leq 0$.

Sources of uncertainty in prediction

Even under the assumption that the new observation follows the same adopted model there are still two sources of error:

1. Every future value is a random event on its own.
2. The parameters are unknown.

Frequentist inference takes into account 1 but it is not clear what to do for 2 (perhaps a bootstrap approach).

Bayesian Inference handles both 1 and 2 via the predictive distribution

$$f(y|x) = \int f(y|\theta)\pi(\theta|x)d\theta$$

In the presence of several models we can treat the model indicator as part of θ. This is known as model averaging.

Example: Exp-Gamma conjugate family

Let $x = (x_1, \ldots, x_n)$ be a random sample from an Exp(λ). A Gamma(α, β) prior on λ gives the posterior Gamma$(n+\alpha, n\bar{x}+\beta)$.

The predictive distribution (for $y > 0$) is

$$
\begin{aligned}
f(y|x) &= \int \lambda \exp(-\lambda y) \frac{(n\bar{x}+\beta)^{n+\alpha}}{\Gamma(n+\alpha)} \lambda^{n+\alpha-1} \exp(-(n\bar{x}+\beta)\lambda) d\lambda \\
&= \frac{(n\bar{x}+\beta)^{n+\alpha}}{\Gamma(n+\alpha)} \int \lambda^{n+\alpha+1-1} \exp(-(n\bar{x}+\beta+y)\lambda) d\lambda \\
&= \frac{(n\bar{x}+\beta)^{n+\alpha}}{\Gamma(n+\alpha)} \frac{\Gamma(n+\alpha+1)}{(n\bar{x}+\beta+y)^{n+\alpha+1}}
\end{aligned}
$$

Outline

Monte Carlo Integration

Monte Carlo Integral

Let $F(x)$ be a probability distribution and $h(x)$ be a function such that $E_X(h(X)) < \infty$. Also let $x = (x_1, \ldots, x_n)$ be a sample from F. Then

$$E_X(h(X)) = \int_{\mathcal{X}} h(x) dF(x) \approx \frac{1}{n} \sum_{i=1}^{n} h(x_i)$$

Implementation: Draw $x_1, \ldots, x_n$ from F and calculate the integral using the above estimator. The error may become arbitrarily small.

Monte Carlo Integration (cont'd)

- Note that $\int_{\mathcal{X}} h(x)dF(x)$ covers both discrete and continuous RV cases. In the former case the integral is a sum and in the latter we can write

$$\int_{\mathcal{X}} h(x)dF(x) = \int_{\mathcal{X}} h(x)f(x)dx$$

- **Proof:** Direct application of Strong Law of Large numbers:

$$I_n = \frac{1}{n}\sum_{i=1}^{n} h(x_i) \stackrel{a.s.}{\to} \int_{\mathcal{X}} h(x)dF(x) = I$$

- The speed of convergence depends on the variance of I_n

Importance sampler

Suppose that it is difficult to simulate from F (with density f), but it is easy to generate from G (with density g).

Importance sampler

Let $F(x)$ be a probability distribution and $h(x)$ be a function such that $E_X(h(X)) < \infty$. Also let $x = (x_1, \ldots, x_n)$ be a sample from G. Then

$$E_X(h(X)) = \int_{\mathcal{X}} h(x)\frac{f(x)}{g(x)}g(x)dx \approx \frac{1}{n}\sum_{i=1}^{n} h(x_i)\frac{f(x_i)}{g(x_i)}$$

Importance sampler will improve the stability of Monte Carlo integrals if f and g are similar.

Monte Carlo integration in Bayesian Inference

If we identify the posterior distribution and we can simulate from it (directly or via importance sampling) Bayesian inference is straightforward.

- Expectations of functions of the posterior may be accurately approximated. Note that probabilities can be viewed as expectations of indicator functions.

- Percentiles can also be accurately approximated by sorting the simulated posterior draws.

- Posterior draws may be inserted in $f(y|\theta)$. This will provide draws form the predictive distribution.

Percentiles from Expectations

Consider the indicator function $I(\theta \in A)$ that takes the value 1 if $\theta \in A$ and 0 otherwise.

For -say- the median $\theta^{0.5}$ we can use the function $I(\theta < \theta^{0.5})$. Then the value of the following is

$$E_{\theta|x}(I(\theta < \theta^{.5})) = P(\theta < \theta^{0.5}|x) = 0.5$$

To find $\theta^{0.5}$ on needs to solve the following equation

$$E_{\theta|x}(I(\theta < \theta^{.5})) = P(\theta < \theta^{0.5}|x) = 0.5 \tag{1}$$

Percentiles from Expectations (cont'd)

Suppose that you have $n = 100,000$ draws from $\pi(\theta|x)$, Denote by θ_i for $i = 1, \ldots, n$.

Consider the sample median as an estimate $\hat{\theta}^{0.5}$ for $\theta^{0.5}$. What is the value of $E_{\theta|x}(I(\theta < \hat{\theta}^{0.5})$?

$$P(\theta < \hat{\theta}^{0.5}|x) = E_{\theta|x}(I(\theta < \hat{\theta}^{0.5})) \overset{\text{Monte Carlo}}{\approx} \frac{1}{n}\sum_{i=1}^{n} I(\theta_i < \hat{\theta}^{0.5}) = 0.5$$

In other words, $\hat{\theta}^{0.5}$ is a numerical solution to (1). For large n the Monte Carlo error goes to 0.

Reading

J.O. Berger:

Sections 2.4.4, 2.4.4, 4.3.3, 4.3.4 and 4.4.3

Gamerman & Lopes:

Sections 3.1 3.2.1 3.2.2 3.4 5.1 and 5.2