Statistics for Applications

Chapter 8: Bayesian Statistics

The Bayesian approach (1)

- So far, we have studied the frequentist approach of statistics.
- The frequentist approach:
  - Observe data
  - These data were generated randomly (by Nature, by measurements, by designing a survey, etc...)
  - We made assumptions on the generating process (e.g., i.i.d., Gaussian data, smooth density, linear regression function, etc...)
  - The generating process was associated to some object of interest (e.g., a parameter, a density, etc...)
  - This object was unknown but fixed and we wanted to find it: we either estimated it or tested a hypothesis about this object, etc...

The Bayesian approach (2)

- Now, we still observe data, assumed to be randomly generated by some process. Under some assumptions (e.g., parametric distribution), this process is associated with some fixed object.

- We have a **prior belief** about it.

- Using the data, we want to update that belief and transform it into a **posterior belief**.

The Bayesian approach (3)

Example

- Let p be the proportion of woman in the population.
- Sample n people randomly with replacement in the population and denote by $X_1, \ldots, X_n$ their gender (1 for woman, 0 otherwise).
- In the frequentist approach, we estimated p (using the MLE), we constructed some confidence interval for p, we did hypothesis testing (e.g., $H_0 : p = .5$ v.s. $H_1 : p \neq .5$).
- Before analyzing the data, we may believe that p is likely to be close to $1/2$.
- The Bayesian approach is a tool to:
  1. include mathematically our prior belief in statistical procedures.
  2. update our prior belief using the data.

The Bayesian approach (4)

Example (continued)

- Our prior belief about p can be quantified:
- E.g., we are 90% sure that p is between $.4$ and $.6$, 95% that it is between $.3$ and $.8$, etc...
- Hence, we can model our prior belief using a distribution for p, *as if* p was random.
- In reality, the true parameter is not random ! However, the Bayesian approach is a way of modeling our belief about the parameter by doing **as if** it was random.
- E.g., $p \sim \mathcal{B}(a, a)$ (*Beta distribution*) for some $a > 0$.
- This distribution is called the *prior distribution*.

The Bayesian approach (5)

Example (continued)

- In our statistical experiment, $X_1, \ldots, X_n$ are assumed to be i.i.d. Bernoulli r.v. with parameter p **conditionally on** p.
- After observing the available sample $X_1, \ldots, X_n$, we can update our belief about p by taking its distribution conditionally on the data.
- The distribution of p conditionally on the data is called the *posterior distribution*.
- Here, the posterior distribution is

$$\mathcal{B}\left(a + \sum_{i=1}^{n} X_i, a + n - \sum_{i=1}^{n} X_i\right).$$

The Bayes rule and the posterior distribution (1)

- Consider a probability distribution on a parameter space Θ with some pdf $\pi(\cdot)$: the *prior distribution*.

- Let $X_1, \ldots, X_n$ be a sample of n random variables.

- Denote by $p_n(\cdot|\theta)$ the joint pdf of $X_1, \ldots, X_n$ conditionally on θ, where $\theta \sim \pi$.

- Usually, one assumes that $X_1, \ldots, X_n$ are i.i.d. conditionally on θ.

- The conditional distribution of θ given $X_1, \ldots, X_n$ is called the *posterior distribution*. Denote by $\pi(\cdot|X_1, \ldots, X_n)$ its pdf.

The Bayes rule and the posterior distribution (2)

- Bayes' formula states that:

$$\pi(\theta|X_1,\ldots,X_n) \propto \pi(\theta)p_n(X_1,\ldots,X_n|\theta), \quad \forall\theta\in\Theta.$$

- The constant does not depend on θ:

$$\pi(\theta|X_1,\ldots,X_n) = \frac{\pi(\theta)p_n(X_1,\ldots,X_n|\theta)}{\int_\Theta p_n(X_1,\ldots,X_n|t)\,\mathrm{d}\pi(t)}, \quad \forall\theta\in\Theta.$$

The Bayes rule and the posterior distribution (3)

In the previous example:

- $\pi(p) \propto p^{a-1}(1-p)^{a-1}, p \in (0,1)$.

- Given p, $X_1, \ldots, X_n \overset{i.i.d.}{\sim} Ber(p)$, so

$$p_n(X_1, \ldots, X_n | \theta) = p^{\sum_{i=1}^n X_i}(1-p)^{n-\sum_{i=1}^n X_i}.$$

- Hence,

$$\pi(\theta | X_1, \ldots, X_n) \propto p^{a-1+\sum_{i=1}^n X_i}(1-p)^{a-1+n-\sum_{i=1}^n X_i}.$$

- The posterior distribution is

$$\mathcal{B}\left(a + \sum_{i=1}^n X_i, a + n - \sum_{i=1}^n X_i\right).$$

Non informative priors (1)

- Idea: In case of ignorance, or of lack of prior information, one may want to use a prior that is as little informative as possible.
- Good candidate: $\pi(\theta) \propto 1$, i.e., constant pdf on Θ.
- If Θ is bounded, this is the uniform prior on Θ.
- If Θ is unbounded, this does not define a proper pdf on Θ !
- An *improper prior* on Θ is a measurable, nonnegative function $\pi(\cdot)$ defined on Θ that is not integrable.
- In general, one can still define a posterior distribution using an improper prior, using Bayes' formula.

Non informative priors (2)

Examples:

- If $p \sim \mathcal{U}(0,1)$ and given p, $X_1, \dots, X_n \overset{i.i.d.}{\sim} Ber(p)$:
$$\pi(p|X_1, \dots, X_n) \propto p^{\sum_{i=1}^n X_i}(1-p)^{n-\sum_{i=1}^n X_i},$$
i.e., the posterior distribution is
$$\mathcal{B}\left(1+\sum_{i=1}^n X_i, 1+n-\sum_{i=1}^n X_i\right).$$

- If $\pi(\theta) = 1, \forall \theta \in \mathbb{R}$ and given θ, $X_1, \dots, X_n \overset{i.i.d.}{\sim} \mathcal{N}(\theta, 1)$:
$$\pi(\theta|X_1, \dots, X_n) \propto \exp\left(-\frac{1}{2}\sum_{i=1}^n (X_i - \theta)^2\right),$$
i.e., the posterior distribution is
$$\mathcal{N}\left(\bar{X}_n, \frac{1}{n}\right).$$

Non informative priors (3)

- *Jeffreys prior:*

$$\pi_J(\theta) \propto \sqrt{\det I(\theta)},$$

  where $I(\theta)$ is the Fisher information matrix of the statistical model associated with $X_1, \ldots, X_n$ in the frequentist approach (provided it exists).

- In the previous examples:
  - Ex. 1: $\pi_J(p) \propto \frac{1}{\sqrt{p(1-p)}}$, $p \in (0,1)$: the prior is $\mathcal{B}(1/2, 1/2)$.
  - Ex. 2: $\pi_J(\theta) \propto 1$, $\theta \in \mathbb{R}$ is an improper prior.

Non informative priors (4)

- Jeffreys prior satisfies a reparametrization invariance principle: If η is a reparametrization of θ (i.e., $\eta = \phi(\theta)$ for some one-to-one map ϕ), then the pdf $\tilde{\pi}(\cdot)$ of η satisfies:

$$\tilde{\pi}(\eta) \propto \sqrt{\det \tilde{I}(\eta)},$$

where $\tilde{I}(\eta)$ is the Fisher information of the statistical model parametrized by η instead of θ.

Bayesian confidence regions

- For $\alpha \in (0,1)$, a Bayesian confidence region with level α is a random subset $\mathcal{R}$ of the parameter space Θ, which depends on the sample $X_1, \ldots, X_n$, such that:

$$\mathbb{P}[\theta \in \mathcal{R} | X_1, \ldots, X_n] = 1 - \alpha.$$

- Note that $\mathcal{R}$ depends on the prior $\pi(\cdot)$.

- "Bayesian confidence region" and "confidence interval" are two **distinct** notions.

Bayesian estimation (1)

- The Bayesian framework can also be used to estimate the true underlying parameter (hence, in a frequentist approach).
- In this case, the prior distribution does not reflect a prior belief: It is just an artificial tool used in order to define a new class of estimators.
- **Back to the frequentist approach:** The sample $X_1, \dots, X_n$ is associated with a statistical model $(E, (\mathbb{P}_\theta)_{\theta \in \Theta})$.
- Define a distribution (that can be improper) with pdf π on the parameter space Θ.
- Compute the posterior pdf $\pi(\cdot|X_1, \dots, X_n)$ associated with π, seen as a prior distribution.

Bayesian estimation (2)

- *Bayes estimator:*

$$\hat{\theta}^{(\pi)} = \int_{\Theta} \theta \, \mathrm{d}\pi(\theta | X_1, \ldots, X_n) :$$

  This is the *posterior mean*.

- The Bayesian estimator depends on the choice of the prior distribution π (hence the superscript π).

Bayesian estimation (3)

- In the previous examples:
  - Ex. 1 with prior $\mathcal{B}(a,a)$ ($a>0$):

    $$\hat{p}^{(\pi)} = \frac{a + \sum_{i=1}^n X_i}{2a+n} = \frac{a/n + \bar{X}_n}{2a/n+1}.$$

    In particular, for $a = 1/2$ (Jeffreys prior),

    $$\hat{p}^{(\pi_J)} = \frac{1/(2n) + \bar{X}_n}{1/n+1}.$$

  - Ex. 2: $\hat{\theta}^{(\pi_J)} = \bar{X}_n$.
- In each of these examples, the Bayes estimator is consistent and asymptotically normal.
- In general, the asymptotic properties of the Bayes estimator do not depend on the choice of the prior.