Maximum Likelihood Estimation and Bayesian Statistics

Rebecca C. Steorts

Agenda

- Maximum Likelihood Esimation
- Unbiased Estimators

Traditional inference

You are given **data** X and there is an **unknown parameter** you wish to estimate θ

How would you estimate θ?

- Find an unbiased estimator of θ.
- Find the maximum likelihood estimate (MLE) of θ by looking at the likelihood of the data.
- Suppose that $\hat{\theta}$ estimates θ.

Note: $\hat{\theta}$ may depend on the data $x_{1:n} = x_1, \ldots x_n$.

Unbiased Estimator

Recall that $\hat{\theta}$ is an **unbiased estimator** of θ if

$$E[\hat{\theta}] = \theta. \tag{1}$$

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Maximum Likelihood Estimation

For each sample point $x_{1:n}$, let $\hat{\theta}$ be a parameter value at which $p(x_{1:n} \mid \theta)$ attains it's maximum as a function of θ, with $x_{1:n}$ held fixed.

A **maximum likelihood esimator** (MLE) of the parameter θ based on a sample $x_{1:n}$ is $\hat{\theta}$.

Finding the MLE

The solution to the MLE are the possible candidates (θ) that solve

$$\frac{\partial p(x_{1:n} \mid \theta)}{\partial \theta} = 0. \tag{2}$$

The solution to equation 2 are only **possible candidates** for the MLE since the first derivative being 0 is a **necessary condition** for a maximum but not a sufficient one.

Our job is to find a global maximum.

Thus, we need to ensure that we haven't found a local one.

MLE of Normal distribution

Consider

$$X_1, \ldots, X_n \overset{iid}{\sim} \text{Normal}(\theta, 1).$$

Show that the MLE is $\hat{\theta} = \bar{x}$.

MLE of Normal distribution

$$p(x_{1:n} \mid \theta) = (2\pi)^{-n/2} \times \exp\{\frac{-1}{2}\sum_{i=1}^{n}(x_i - \theta)^2\} \tag{3}$$

Consider

$$\log p(x_{1:n}) = -n/2 \log(2\pi) - \frac{1}{2}\sum_{i=1}^{n}(x_i - \theta)^2 \tag{4}$$

MLE of Normal distribution

$$\frac{\partial p(x_{1:n} \mid \theta)}{\partial \theta} = \sum_{i=1}^{n}(x_i - \theta) \tag{5}$$

This implies that

$$\sum_i (x_i - \theta) = 0 \implies \hat{\theta} = \bar{x}.$$

MLE of Normal distribution

Consider

$$\frac{\partial^2 p(x_{1:n} \mid \theta)}{\partial \theta^2} = -n < 0.$$

Thus, our solution is unique (and a global solution).

Exercise

Show that

$$\hat{\theta} = \bar{x}$$

is an unbiased estimator for θ.

Proof.

$$E[\hat{\theta}] = E[\bar{x}] = \frac{1}{n}\sum_i E[x_i] = \frac{1}{n}\sum_i \theta = \theta.$$

Thus, we have showed that the MLE is an unbiased estimator for θ.

Normal-Normal model

Suppose that

$$X_1, \ldots, X_n \overset{iid}{\sim} \text{Normal}(\theta, 1),$$

where we now consider

$$\theta \overset{ind}{\sim} \text{Normal}(\mu, \tau^2).$$

Let $\lambda = 1$ and $\lambda_o = 1/\tau^2$.

Recall that from module 3,

$$\theta \mid x_{1:n} \sim N(M, L^{-1}),$$

where

$$L = n\lambda + \lambda_o$$

and

$$M = \frac{n\lambda\bar{x} + \lambda_o\mu}{n\lambda + \lambda_o}.$$

Normal MLE

Observe that

$$M = \frac{n\lambda\bar{x} + \lambda_o\mu}{n\lambda + \lambda_o} = \frac{n\lambda\hat{\theta} + \lambda_o\mu}{n\lambda + \lambda_o} = \frac{n\lambda}{n\lambda + \lambda_o}\hat{\theta} + \frac{\lambda_o}{n\lambda + \lambda_o}\mu.$$

Thus, we can write the posterior mean as a function of the MLE and the prior mean μ.

Bernoulli-Bayes Estimation

$$X_1, \ldots, X_n \overset{iid}{\sim} \text{Bernoulli}(\theta). \tag{6}$$
$$\theta \sim \text{Beta}(a, b) \tag{7}$$

Note that $Y = \sum_i X_i \sim \textit{Binomial}(n, \theta)$.

Exercise: The MLE for θ is $\bar{x} = y/n$.

Exercise:

$$\theta \mid y \sim \text{Beta}(y + a, n - y + b).$$

Bernoulli-Bayes Estimation

Show that the posterior mean can be written as

$$E[\theta \mid y] = \text{MLE} \times \frac{n}{a+b+n} + \text{priorMean} \times \frac{a+b}{a+b+n},$$

where $\text{MLE} = \bar{x}$ and $\text{priorMean} = \frac{a}{a+b}$.

Bernoulli-Bayes Estimation

Proof:

$$
\begin{aligned}
E[\theta \mid y] &= \frac{y+a}{y+a+n-y+b} = \frac{y+a}{a+n+b} \\
&= \frac{y}{a+b+n} + \frac{a}{a+b+n} \\
&= \frac{y}{n} \times \frac{n}{a+b+n} + \frac{a}{a+b} \times \frac{a+b}{a+b+n} \\
&= \text{MLE} \times \frac{n}{a+b+n} + \text{priorMean} \times \frac{a+b}{a+b+n}
\end{aligned}
$$

Thus, we have written the posterior mean as a linear comboination of the MLE and prior mean with weights being determined by a,b, and n.

Evaluation of Estimators

How do we evaluate estimators? We often use the mean squared error.

$$\text{MSE}(\hat{\theta}) = E_\theta[(\hat{\theta} - \theta)^2].$$

Observe that

$$\text{MSE}(\hat{\theta}) = Var_\theta(\hat{\theta}) + E_\theta[(\hat{\theta} - \theta)^2] = Var_\theta(\hat{\theta}) + \text{Bias}_\theta(\hat{\theta}),$$

where the

$$\text{Bias}_\theta(\hat{\theta}) = E_\theta(\hat{\theta}) - \theta.$$

For a more in depth treatment of MSE and bias, see Section 7.3.1, Casella and Berger, p. 330 - 334.

Binomial MLE

Let

$$X_1, \ldots, X_n \overset{iid}{\sim} \text{Bernoulli}(\theta).$$

Show that the MLE is $\hat{\theta} = \bar{x}$.

Proof: Casella and Berger, Example 7.2.7, page 317-318.

Normal-Normal model

Suppose that

$$X_1, \ldots, X_n \overset{iid}{\sim} \text{Normal}(\theta, \sigma^2),$$

where θ, σ^2 are both unknown.

Show that $(\bar{x}, n^{-1} \sum_i (x_i - \bar{x})^2))$ are the MLE's for (θ, σ^2).

Proof: Casella and Berger, Example 7.2.7, page 317-318.

Invariance property of MLE's

If $\hat{\theta}$ is the MLE of θ, then for any function $g(\theta)$, the MLE of $g(\theta)$ is the MLE of $g(\hat{\theta})$.

Proof: Theorem 7.2.10, Casella and Berger, page 318.

Summary

- Unbiased Estimator
- MLEs
- Examples of MLE's
- MSE