

2. Estimation (Classical)

Network Data Analysis – NDA 2022-2023
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Bibliography

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👉 Chapter 8

- B.2 I. Goodfellow, Y. Bengio, and A. Courville, "Deep learning", MIT Press, 2017.

👉 Chapter 5.4, 5.5

Intro

Statistical Inference is a collection of methods that deal with drawing conclusions from data that are prone to random variation.

Examples

- ▶ Predict the outcome of an election: Use a random sample to poll part of the population about their potential vote.
Randomness from sampling and the uncertainty of vote.
- ▶ Decoding in wireless communications: A message is transmitted to a receiver, but the received message is corrupted with noise (channel and thermal).

We work with **real data**!

Data Analysis

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Data analysis is very much related - but also very different from - probability models.

Let X be a normal random variable with mean $\mu = 100$ and variance $\sigma^2 = 15$. Find the probability that $X > 110$. But, in reality:

- ▶ We do not know what is the distribution of X .
- ▶ Even if we knew it, we do not know the values of μ and σ .

Statistical Inference

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General Setup: There is an unknown quantity θ that we want to estimate. We get some data. From the data we estimate the desired quantity.

There are 2 main approaches:

- ▶ Frequentist (classical) Inference.
- ▶ Bayesian Inference.

Classical...

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- **Frequentist (classical) Inference:** The unknown quantity θ is assumed to be **fixed and deterministic**.
Using data collected, we estimate it by $\hat{\Theta}$, a random variable.

E.g. [Polling] If n is the sample size, let $Y(n)$ be the number of users in the sample, who vote for a certain candidate.

The estimate of the real unknown percentage θ , is $\hat{\Theta} = Y(n)/n$.

...vs Bayesian

- **Bayesian Inference:** The unknown quantity Θ is assumed to be a **random variable**, and we assume an initial guess about its distribution.

After observing the data we update the distribution using Bayes' Rule.

E.g. We want to know if information of 1 *bit* was transmitted. The received signal is $\Theta = 1$ *bit* with probability p , or $\Theta = 0$ *bit* with probability $1 - p$.

Then $\Theta \sim \text{Bernoulli}(p)$. We receive a noisy version X of Θ . To estimate Θ we use X and the prior knowledge over the distribution to update p' .

Point Estimator

Frequentist approach:

A **point estimator** is a function of the **random sample**

$\hat{\Theta} = h(X_1, X_2, \dots, X_n)$ that estimates the unknown quantity θ .

Any function can do? Yes!

But, a good estimator should be close to the true underlying θ that generated the data.

E.g. To estimate the average file-size we can define the point estimator:

$$\hat{\Theta} = \frac{X_1 + X_2 + \dots + X_n}{n}.$$

Sample Mean

The sample mean is a point estimator for the quantity $\theta = \mathbb{E}[X]$,

$$\bar{X} = \frac{X_1 + X_2 + \dots + X_n}{n}.$$

Properties:

- ▶ $\mathbb{E}[\bar{X}] = \mu.$
- ▶ $\text{Var}(\bar{X}) = \frac{\sigma^2}{n}.$
- ▶ **Central Limit Theorem:** The random variable (r.v.)

$$Z_n = \frac{\bar{X} - \mu}{\sigma/\sqrt{n}} = \frac{X_1 + X_2 + \dots + X_n - n\mu}{\sigma\sqrt{n}}$$

converges in distribution to the standard normal r.v. as $n \rightarrow \infty$.

Properties

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- ▶ $\mathbb{E}[\bar{X}] = \mathbb{E}\left[\frac{X_1 + \dots + X_n}{n}\right] = \frac{1}{n}n\mathbb{E}[X_1] = \mu.$
- ▶
$$\begin{aligned} \text{Var}[\bar{X}] &= \mathbb{E}\left[\left(\frac{X_1 + \dots + X_n}{n} - \mu\right)^2\right] = \mathbb{E}\left[\left(\frac{(X_1 - \mu) + \dots + (X_n - \mu)}{n}\right)^2\right] = \\ &= \frac{1}{n^2}\mathbb{E}\left[\left((X_1 - \mu) + \dots + (X_n - \mu)\right)^2\right] = \\ &= \frac{1}{n^2}\mathbb{E}\left[(X_1 - \mu)^2 + \dots + (X_n - \mu)^2 + \sum_{i=1, j>i}^n 2(X_i - \mu)(X_j - \mu)\right] = \\ &= \frac{n}{n^2}\mathbb{E}\left[(X_1 - \mu)^2\right] = \frac{1}{n}\text{Var}(X_1) = \frac{\sigma^2}{n}. \end{aligned}$$

Order Statistics

We can be interested in the largest, smallest, or middle sample value.

Consider a random sample of size n : X_1, X_2, \dots, X_n from a continuous distribution with CDF $F_X(x)$. We order the X_i 's from the smallest to the largest and get the resulting sequence:

$$X_{(1st)}, X_{(2nd)}, \dots, X_{(nth)}$$

Thus we have

$$\begin{aligned} X_{(1st)} &= \min(X_1, X_2, \dots, X_n), \\ X_{(nth)} &= \max(X_1, X_2, \dots, X_n) \end{aligned}$$

👉 We call $X_{(1st)}, X_{(2nd)}, \dots, X_{(nth)}$ the **order statistics** of the random sample, and are interested in their PDFs and CDFs.

Point Estimator Properties

Some Point Estimator Properties

Point Estimator Properties:

- A. Bias
- B. Variance
- C. Mean Squared Error (MSE)
- D. Consistency*

A. Estimator Bias

The **bias of point estimator** $\hat{\Theta} = h(X_1, \dots, X_n)$ is defined by

$$B(\hat{\Theta}) = \mathbb{E}[\hat{\Theta}] - \theta.$$

The bias tells us how far is the estimator from the real value.

☞ We say that $\hat{\Theta}$ is an **unbiased** estimator of θ if

$$B(\hat{\Theta}) = 0, \quad \text{for all possible values of } \theta.$$

Note: **An unbiased estimator is not necessarily a "good" one!**

✎ **Exercise:** Show that $\hat{\Theta}_1 = X_n$ is an unbiased estimator of $\theta = \mathbb{E}[X]$.
Same for the sample mean $\hat{\Theta}_2 = \bar{X}$. Which one is better?

Solve Exercise Bias

Solution: Both the single independent sample $\hat{\Theta}_1$ and the sample mean $\hat{\Theta}_2$ are unbiased:

$$\begin{aligned} B(\hat{\Theta}_1) &= \mathbb{E}[\hat{\Theta}_1] - \mu = \mathbb{E}[X_n] - \mu \\ &= 0 \\ &= \mathbb{E}[\hat{\Theta}_2] - \mu = \mathbb{E}[\bar{X}] - \mu = B(\hat{\Theta}_2). \end{aligned}$$

☞ We suspect that the sample mean is a better estimator than the single random sample. How can we show this?

B. Estimator Variance

Let X_1, \dots, X_n be a random sample, and let θ be an unknown parameter of the distribution that generated it (e.g. the mean).

- ▶ The estimator $\hat{\Theta} = h(X_1, \dots, X_n)$ is a random variable.
- ▶ The **variance** of the estimator


$$\text{Var}(\hat{\Theta}) = \mathbb{E}[(\hat{\Theta} - \mathbb{E}[\hat{\Theta}])^2]$$

strongly depends on the variance of the individual X_i s.

- ▶ The **Standard Error** (SE) is given by

$$\text{SE}(\hat{\Theta}) = \sqrt{\text{Var}(\hat{\Theta})}$$

Exercise Estimator Variance

 **Exercise:** Given a random sample X_1, \dots, X_n generated by a Bernoulli(θ), use $\hat{\Theta}$ to estimate θ : For (a) $\hat{\Theta}_1 = X_n$ and (b) $\hat{\Theta}_2 = \bar{X}$

- ▶ calculate the bias of the estimator $B(\hat{\Theta})$.
- ▶ calculate the variance of the estimator $Var(\hat{\Theta})$.
- ▶ calculate the Standard Error $SE(\hat{\Theta})$.

Solve Exercise

- For the sample mean $\hat{\Theta}$,

$$\hat{\Theta}_1 = X_n, \quad \hat{\Theta}_2 = \bar{X} = \frac{X_1 + \dots + X_n}{n}$$

- For the bias of the estimator,

$$B(\hat{\Theta}_1) = \left(\frac{1}{n} \sum_{i=1}^n \mathbb{E}[X_i] \right) - \theta = 0 = \mathbb{E}[X_n] - \theta = B(\hat{\Theta}_2)$$

- For the variance of the estimator,

$$\text{Var}(\hat{\Theta}_1) = \text{Var}(X_i) = \theta(1 - \theta),$$

$$\text{Var}(\hat{\Theta}_2) = \text{Var}\left(\frac{1}{n} \sum_{i=1}^n X_i\right) = \frac{1}{n^2} \sum_{i=1}^n \text{Var}(X_i) = \frac{\theta(1 - \theta)}{n}.$$

Solve Exercise cont'd

- For the Standard Error of the estimator,

$$SE(\hat{\Theta}_1) = \sqrt{\theta(1-\theta)}, \quad SE(\hat{\Theta}_2) = \sqrt{\frac{\theta(1-\theta)}{n}}.$$

☞ The sample size can determine the accuracy of $\hat{\Theta}$. As $n \rightarrow \infty$, we see that $SE(\hat{\Theta}_2) \rightarrow 0$, but not $SE(\hat{\Theta}_1)$.


C. Mean Squared Error

The **mean squared error** (MSE) of point estimator $\hat{\theta}$ is defined as

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

(Note the difference in definition compared to the $Var(\hat{\theta})$)

Like the bias, this is a measure of distance (error) between the estimator and the real value. A smaller MSE is indicative of a better estimator.

 **Exercise:** Let X_1, \dots, X_n be a random sample from an original distribution with mean $\mathbb{E}[X_i] = \theta$ and variance $Var(X_i) = \sigma^2$. Consider the following two estimators again: $\hat{\theta}_1 = X_n$ and $\hat{\theta}_2 = \bar{X}$.

Which one is better? *Hint:* $MSE(\hat{\theta}_1) > MSE(\hat{\theta}_2)$.

Solve Exercise MSE

Solution: Both the single random sample $\hat{\Theta}_1$ and the sample mean $\hat{\Theta}_2$ are unbiased:

$$MSE(\hat{\Theta}_1) = \mathbb{E}[(\hat{\Theta}_1 - \mu)^2] = \mathbb{E}[(X_n - \mu)^2] = \text{Var}(X_n) = \sigma^2.$$

$$MSE(\hat{\Theta}_2) = \mathbb{E}[(\hat{\Theta}_2 - \mu)^2] = \mathbb{E}[(\bar{X} - \mu)^2] = \text{Var}(\bar{X}) = \frac{\sigma^2}{n}.$$

👉 **With respect to the MSE**, the sample mean is indeed a better estimator than the single random sample, because $MSE(\hat{\Theta}_2) < MSE(\hat{\Theta}_1)$, for $n > 1$.

MSE, Bias and Variance

If $\hat{\Theta}$ is a point estimator for θ ,

$$\begin{aligned} \text{MSE}(\hat{\Theta}) &= \mathbb{E}[(\hat{\Theta} - \theta)^2] = \mathbb{E}[(\hat{\Theta} - \mathbb{E}[\hat{\Theta}] + \mathbb{E}[\hat{\Theta}] - \theta)^2] \\ &= \text{Var}(\hat{\Theta}) + (\mathbb{E}[\hat{\Theta}] - \theta)^2 + 2\mathbb{E}[(\hat{\Theta} - \mathbb{E}[\hat{\Theta}])(\mathbb{E}[\hat{\Theta}] - \theta)] \\ &= \text{Var}(\hat{\Theta}) + B(\hat{\Theta})^2, \end{aligned}$$

where $B(\hat{\Theta}) = \mathbb{E}[\hat{\Theta}] - \theta$ is the bias of $\hat{\Theta}$.

MSE contains a part due to estimator **variance** and a part due to **bias**.


- Bias measures the expected deviation from the true value θ .
- Variance measures the deviation from the expected estimator, due to the particular sample.

☞ Often, these two cannot be minimised simultaneously by the choice of estimator, and there is a **trade-off**.

D. Consistency*

Let $\hat{\Theta}_1, \dots, \hat{\Theta}_n, \dots$ be a sequence of point estimators of θ (e.g. suppose each estimator is calculated with increasing sample size n). We say that $\hat{\Theta}_n$ is a **consistent estimator** of θ , if

$$\lim_{n \rightarrow \infty} P(|\hat{\Theta}_n - \theta| \geq \epsilon) = 0, \quad \text{for all } \epsilon > 0.$$

 **Exercise:** Show that $\hat{\Theta}_n = \bar{X}$ is a consistent estimator for $\mathbb{E}[X_i] = \theta$.
Hint: use Chebyshev's inequality.

👉 If $MSE(\hat{\Theta}_n) = 0$ we can conclude that $\hat{\Theta}_n$ is consistent estimator of θ .

Solve Exercise Consistency*

Solution: Let us denote by $\hat{\Theta}_n = \bar{X}(n)$ the sample mean estimator with $n > 1$ samples. Then:

$$P(|\bar{X} - \theta| \geq \epsilon) \leq \frac{\text{Var}(\bar{X})}{\epsilon^2} = \frac{\sigma^2}{n\epsilon^2}.$$

using Chebyshev's inequality. The righthand side tend to 0 as $n \rightarrow \infty$. □

👉 **The MSE for $\bar{X}(n)$** is equal to σ^2/n , which also tends to 0 as $n \rightarrow \infty$.

Variance Estimator

Point Estimator for Variance

- ✓ We saw that \bar{X} is a reasonable point estimator for the mean.
- 👉 Suppose we want a point estimator for the variance σ^2 . By definition:

$$\sigma^2 = \mathbb{E}[(X - \mu)^2].$$

The reasonable estimator (similar to the mean) is just:

$$\hat{\sigma}^2 = \frac{1}{n} \sum_{k=1}^n (X_k - \mu)^2.$$

This is an unbiased and consistent estimator of σ^2 . However it assumes a known value for the mean μ . In practice this value is unknown and estimated by \bar{X} .

- 📎 **Exercise:** Show that the following estimator has strictly negative bias:

$$\bar{S}^2 = \frac{1}{n} \sum_{k=1}^n (X_k - \bar{X})^2 = \frac{1}{n} \left(-n\bar{X}^2 + \sum_{k=1}^n X_k^2 \right).$$

Solve Exercise Variance Estimator

Solution: We want to calculate the bias

$$\begin{aligned} B(\bar{S}^2) &= \mathbb{E}[\bar{S}^2] - \sigma^2 \\ &= \frac{1}{n} \left(-n\mathbb{E}[\bar{X}^2] + \sum_{k=1}^n \mathbb{E}[X_k^2] \right) - \sigma^2 \\ &= \frac{1}{n} \left(-n\left(\frac{\sigma^2}{n} + \mu^2\right) + \sum_{k=1}^n (\sigma^2 + \mu^2) \right) - \sigma^2 \\ &= \frac{n-1}{n} \sigma^2 - \sigma^2 = -\frac{\sigma^2}{n} < 0. \end{aligned}$$

👉 The bias can be corrected by multiplying $\frac{n}{n-1} \bar{S}^2$.

Sample Variance

Let X_1, \dots, X_n be a random sample with mean $\mathbb{E}[X_i] = \mu < \infty$ and variance $0 < \text{Var}(X_i) = \sigma^2 < \infty$.

The **sample variance** of this random sample is defined as:

$$S^2 = \frac{n}{n-1} \bar{S}^2 = \frac{1}{n-1} \sum_{k=1}^n (X_k - \bar{X})^2 = \frac{1}{n-1} \left(-n\bar{X}^2 + \sum_{k=1}^n X_k^2 \right).$$


The sample variance is an **unbiased estimator** of σ^2 .

The **sample standard deviation** is defined as


$$S = \sqrt{S^2},$$

and is commonly used as an estimator for σ , but is a **biased** one.

Solve Exercise

 **Exercise:** Calculate the sample mean and sample variance for the sample $\{18, 21, 17, 16, 24, 20\}$.

Solve Exercise

 **Exercise:** Calculate the sample mean and sample variance for the sample $\{18, 21, 17, 16, 24, 20\}$.

- ▶ Sample mean

$$\bar{T} = \frac{18 + 21 + 17 + 16 + 24 + 20}{6} = 19,33$$

- ▶ Sample variance

$$S^2 = \frac{\sum_{i=1}^6 (T_i - 19,33)^2}{6 - 1} = 8,67$$

- ▶ Sample standard deviation

$$S = \sqrt{S^2} = \sqrt{8,67} = 2,94$$

Maximum Likelihood

Estimation: A systematic way

- ▶ Our method to propose estimators for mean and variance have been somewhat ad hoc.
- ▶ Is there a systematic way of parameter estimation? Yes!
- ▶ Introducing the Maximum Likelihood Estimation (MLE).

The Likelihood function

Let X_1, \dots, X_n be a random sample from a distribution with a parameter θ . We have observed $X_1 = x_1, \dots, X_n = x_n$.

- ▶ If X_i s are discrete, then the **likelihood function** is defined as

$$L(x_1, \dots, x_n; \theta) = P_{X_1, \dots, X_n}(x_1, \dots, x_n; \theta).$$

- ▶ If X_i s are jointly continuous, then the **likelihood function** is

$$L(x_1, \dots, x_n; \theta) = f_{X_1, \dots, X_n}(x_1, \dots, x_n; \theta).$$

Often, it is easier to work with the **log-likelihood function** given by

$$\ln L(x_1, \dots, x_n; \theta),$$

because if θ^* maximises $L(\bullet; \theta)$ it also maximises $\log L(\bullet; \theta)$.

Maximum Likelihood Estimator

A **maximum likelihood estimate** of θ , shown by $\hat{\theta}_{ML}$, is a value of θ that maximises the likelihood function for the sample values (x_1, \dots, x_n)

$$\hat{\theta}_{ML} = \arg \max L(x_1, \dots, x_n; \theta).$$

The **maximum likelihood estimator (MLE)** of θ , denoted by $\hat{\Theta}_{ML}$ is a random variable $\hat{\Theta}_{ML}(X_1, \dots, X_n)$, whose value when $(X_1, \dots, X_n) = (x_1, \dots, x_n)$ is given by $\hat{\theta}_{ML}$.

MLE alternative

If X_i s are drawn i.i.d. (random sample) we can write:

$$\begin{aligned}\hat{\Theta}_{ML}(x_1, \dots, x_n) &= \arg \max_{\theta} \frac{1}{n} \sum_{i=1}^n \log P_X(x_i; \theta) \\ &= \arg \max_{\theta} \mathbb{E}_{\text{empirical}} [\log P_X(x_i; \theta)] .\end{aligned}$$

An example for MLE

Example: A bag contains 3 balls, some **Red** some **Blue**. We do not know their exact number; the number of **Blue** balls is the unknown parameter θ . Possible values for θ are 0, 1, 2 or 3.

☞ I will choose 4 balls from the bag, using random sampling **with replacement** (I will pick one see the colour and put it back in the bag). The colours in these draws are the r.v.s X_1, X_2, X_3, X_4 , where

$$X_i = \begin{cases} 1 & \text{,if the } i\text{th chosen ball is Blue} \\ 0 & \text{,if the } i\text{th ball is Red} \end{cases}.$$

Then X_i s are i.i.d. and $X_i \sim \text{Bernoulli}(\frac{\theta}{3})$.

After doing the experiment, the following values are observed:
 $x_1 = 1, x_2 = 0, x_3 = 1, x_4 = 1$. (3 balls **Blue** and 1 ball **Red**).

An example for MLE – solution

Questions:

- a) Find the probability of the observed sample,
 $(x_1, x_2, x_3, x_4) = (1, 0, 1, 1)$.
- b) For which value of θ is the observed probability the largest?

An example for MLE – solution

Questions:

- a) Find the probability of the observed sample,
 $(x_1, x_2, x_3, x_4) = (1, 0, 1, 1)$.
- b) For which value of θ is the observed probability the largest?

Answers:

- a) Sample values are i.i.d. $X_i \sim \text{Bernoulli}(\frac{\theta}{3})$

$$P_{X_1 X_2 X_3 X_4}(1, 0, 1, 1) = \left(\frac{\theta}{3}\right)^3 \left(1 - \frac{\theta}{3}\right).$$

- b) The possible values for θ are 0, 1, 2, 3 and the highest probability for the sample is obtained for $\theta^* = 2$.

MLE exercise

Exercise: Find the Maximum Likelihood Estimator (MLE) of θ

1. $X_i \sim \text{Binomial}(m, \theta)$ with observations (x_1, \dots, x_n) .
2. $X_i \sim \text{Exponential}(\theta)$ with observations (x_1, \dots, x_n) .
3. $X_i \sim \mathcal{N}(\theta_1, \theta_2)$ with observations (x_1, \dots, x_n) .

Solution

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☞ Let n be the sample size.

- ▶ Binomial distribution estimator $\text{Binomial}(m, \theta)$

$$\hat{\theta}_{ML} = \frac{1}{mn} \sum_{i=1}^n X_i$$

- ▶ Exponential distribution estimator $\text{Exponential}(\theta)$

$$\hat{\theta}_{ML} = \frac{n}{\sum_{i=1}^n X_i}$$

- ▶ Gaussian distribution estimator $\text{Normal}(\theta_1, \theta_2)$

$$\hat{\theta}_{ML,1} = \frac{1}{n} \sum_{i=1}^n X_i = \bar{X}$$

$$\hat{\theta}_{ML,2} = \frac{1}{n} \sum_{i=1}^n (X_i - \hat{\theta}_{ML,1})^2 = \bar{S}^2$$

Solve exercise*

$$1. \text{ Binomial}(m, \theta) : f_X(x; \theta) = \binom{m}{x} \theta^x (1 - \theta)^{m-x}$$

$$L(x_1, \dots, x_n; \theta) = \left[\prod_{i=1}^n \binom{m}{x_i} \right] \theta^{x_1 + \dots + x_n} (1 - \theta)^{mn - (x_1 + \dots + x_n)}$$

For the maximum likelihood estimate: (let $s = x_1 + \dots + x_n$)

$$\frac{d}{d\theta} L(x_1, \dots, x_n; \theta) = \frac{d}{d\theta} \mathbf{C} \theta^s (1 - \theta)^{mn-s} \Rightarrow \hat{\theta}_{ML} = \frac{s}{nm}.$$

☞ Hence $\hat{\theta}_{ML} = \frac{1}{mn} \sum_{i=1}^n x_i$.

Solve exercise*

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2. Exponential(θ) : $f_X(x; \theta) = \theta \exp(-\theta x) u(x)$

$$L(x_1, \dots, x_n; \theta) = \theta^n \exp(-\theta(x_1 + \dots + x_n))$$

For the maximum likelihood estimate: (let $s = x_1 + \dots + x_n$)

$$\frac{d}{d\theta} \ln L(x_1, \dots, x_n; \theta) = \frac{d}{d\theta} (n \ln(\theta) - \theta s) \Rightarrow \hat{\theta}_{ML} = \frac{n}{s}.$$

☞ Hence $\hat{\theta}_{ML} = \frac{n}{\sum_{i=1}^n x_i}$.

Solve exercise*

2. Normal $\mathcal{N}(\theta_1, \theta_2) : f_X(x; \theta_1, \theta_2) = \frac{1}{\sqrt{2\pi\theta_2}} \exp\left(-\frac{(x-\theta_1)^2}{2\theta_2}\right)$

$$L(x_1, \dots, x_n; \theta) = \frac{1}{(2\pi)^{n/2} \theta_2^{n/2}} \exp\left(-\frac{(x_1 - \theta_1)^2 + \dots + (x_n - \theta_1)^2}{2\theta_2}\right)$$

It is better to work with log-likelihood:

$$\ln L(x_1, \dots, x_n; \theta) = -\frac{n}{2} \ln(2\pi) - \frac{n}{2} \ln(\theta_2) - \frac{1}{2\theta_2} \sum_{i=1}^n (x_i - \theta_1)^2$$

☞ Hence we can maximise over θ_1 and θ_2 separately.

$$\hat{\theta}_{ML,1} = \arg \max \sum_{i=1}^n (x_i - \theta_1)^2. \text{ ((Just the MSE!))}$$

$$\hat{\theta}_{ML,1} = \frac{1}{n} \sum_{i=1}^n x_i \text{ and } \hat{\theta}_{ML,2} = \frac{1}{n} \sum_{i=1}^n (x_i - \hat{\theta}_{1,ML})^2,$$

$$\text{or } \hat{\theta}_{ML,1} = \bar{X}, \text{ and } \hat{\theta}_{ML,2} = \bar{S}^2.$$

Asymptotic Properties of the MLE*

When the sample size becomes large:

- ▶ $\hat{\Theta}_{ML}$ is asymptotically consistent, i.e.

$$\lim_{n \rightarrow \infty} P \left(|\hat{\Theta}_{ML} - \theta| > \epsilon \right) = 0.$$

- ▶ $\hat{\Theta}_{ML}$ is asymptotically unbiased, i.e.

$$\lim_{n \rightarrow \infty} \mathbb{E}[\hat{\Theta}_{ML}] = \theta.$$

- ▶ As n becomes large, $\hat{\Theta}_{ML}$ is approximately a normal random variable. More precisely the r.v.

$$\frac{\hat{\Theta}_{ML} - \theta}{\sqrt{\text{Var}(\hat{\Theta}_{ML})}}$$

converges in distribution to $\mathcal{N}(0, 1)$. See the [CLT](#).

END