

Decision and Estimation in Data Processing

Chapter III. Elements of Estimation Theory

III.1 Introduction

What means “Estimation”?

- ▶ A sender transmits a signal $s_{\Theta}(t)$ which depends on an **unknown** parameter Θ
- ▶ The signal is affected by noise, we receive $r(t) = s_{\Theta}(t) + \text{noise}$
- ▶ We want to **find out** the correct value of the parameter
 - ▶ based on samples from the received signal, or the full continuous signal
 - ▶ available data is noisy \Rightarrow we “estimate” the parameter
- ▶ The found value is $\hat{\Theta}$, **the estimate** of Θ (“estimatul”, rom)
 - ▶ there will always be some estimation error $\epsilon = \hat{\Theta} - \Theta$

What means “Estimation”?

- ▶ Examples:

- ▶ Unknown amplitude of constant signal: $r(t) = A + \text{noise}$, estimate A
- ▶ Unknown phase of sine signal: $r(t) = \cos(2\pi ft + \phi)$, estimate ϕ
- ▶ Even complicated problems:
 - ▶ Record speech signal, estimate/decide what word is pronounced

Estimation vs Decision

- ▶ Consider the following estimation problem:

We receive a signal $r(t) = A + \text{noise}$, estimate A

- ▶ For detection, we have to choose between **two known values** of A :
 - ▶ i.e. A can be 0 or 5 (hypotheses H_0 and H_1)
- ▶ For estimation, A can be anything \Rightarrow we choose between **infinite number of options** for A :
 - ▶ A might be any value in \mathbb{R} , in general

Estimation vs Decision

- ▶ Detection = Estimation constrained to **only a few** discrete options
- ▶ Estimation = Detection with an **infinite number** of options available
- ▶ The statistical methods used are quite similar
 - ▶ In practice, distinction between Estimation and Detections is somewhat blurred
 - ▶ (e.g. when choosing between 1000 hypotheses, do we call it “Detection” or “Estimation”?)

Available data

- ▶ The available data is the received signal $r(t) = s_{\Theta}(t) + \textit{noise}$
 - ▶ it is affected by noise
 - ▶ it depends on the unknown parameter Θ
- ▶ We consider **N samples** from $r(t)$, taken at some sample times t_i

$$\mathbf{r} = [r_1, r_2, \dots, r_N]$$

- ▶ The samples depend on the value of Θ

- ▶ Each sample r_i is a random variable that depends on Θ (and the noise)
 - ▶ Each sample has a distribution that depends on Θ

$$w_i(r_i; \Theta)$$

- ▶ The whole sample vector \mathbf{r} is a N-dimensional random variable that depends on Θ (and the noise)
 - ▶ It has a N-dimensional distribution that depends on Θ

$$w(\mathbf{r}; \Theta)$$

- ▶ Equal to the product of all $w_i(r_i|\Theta)$

$$w(\mathbf{r}|\Theta) = w_1(r_1|\Theta) \cdot w_2(r_2|\Theta) \cdot \dots \cdot w_N(r_N|\Theta)$$

Two types of estimation

- ▶ We consider two types of estimation:
 1. **Maximum Likelihood Estimation (MLE)**: Besides \mathbf{r} , nothing else is known about the parameter Θ , except maybe some allowed range (e.g. $\Theta > 0$)
 2. **Bayesian Estimation**: Besides \mathbf{r} , we know a **prior** distribution $p(\Theta)$ for Θ , which tells us the values of Θ that are more likely than others

II.2 Maximum Likelihood estimation

Maximum Likelihood definition

- ▶ When no distribution is known except \mathbf{r} , we use a method known as **Maximum Likelihood estimation (MLE)**
- ▶ We define the **likelihood** of a parameter value Θ , given the available observations \mathbf{r} as:

$$L(\Theta|\mathbf{r}) = w(\mathbf{r}|\Theta)$$

- ▶ $L(\Theta|\mathbf{r})$ is the likelihood function
- ▶ “The plausibility of a parameter value Θ given some measurements \mathbf{r} = the probability density of generating \mathbf{r} if the true value would be Θ ”
- ▶ Compare with formula in Chapter 2, slide 20
 - ▶ it is the same
 - ▶ here we try to “guess” Θ , there we “guessed” H_i

Maximum Likelihood definition

Maximum Likelihood (ML) Estimation:

- ▶ The estimate $\hat{\Theta}_{ML}$ is **the value that maximizes the likelihood, given the observed data \mathbf{r}**
 - ▶ i.e. the value that maximizes $L(\Theta|\mathbf{r})$, i.e. maximize $w(\mathbf{r}|\Theta)$

$$\hat{\Theta}_{ML} = \arg \max_{\Theta} L(\Theta|\mathbf{r}) = \arg \max_{\Theta} w(\mathbf{r}|\Theta)$$

- ▶ If Θ is allowed to live only in a certain range, restrict the maximization only to that range.

Notations

- ▶ General mathematical notations:
 - ▶ $\arg \max_x f(x)$ = “the value x which maximizes the function $f(x)$ ”
 - ▶ $\max_x f(x)$ = “the maximum value of the function $f(x)$ ”

Maximum Likelihood estimation vs decision

- ▶ Very similar with decision problem!
- ▶ ML decision criterion:
 - ▶ “pick the hypothesis with a higher likelihood”:

$$\frac{L(H_1|r)}{L(H_0|r)} = \frac{w(r|H_1)}{w(r|H_0)} \underset{H_0}{\overset{H_1}{\gtrless}} 1$$

- ▶ ML estimation
 - ▶ “pick the value which maximizes the likelihood”

$$\hat{\Theta}_{ML} = \arg \max_{\Theta} L(\Theta|\mathbf{r}) = \arg \max_{\Theta} w(\mathbf{r}|\Theta)$$

How to solve

- ▶ How to solve the maximization problem?
 - ▶ i.e. how to find the estimate $\hat{\Theta}_{ML}$ which maximizes $L(\Theta|\mathbf{r})$
- ▶ Find maximum by setting derivative to 0

$$\frac{dL(\Theta|\mathbf{r})}{d\Theta} = 0$$

- ▶ We can also maximize the **natural logarithm** of the likelihood function (“log-likelihood function”)

$$\frac{d \ln(L(\Theta))}{d\Theta} = 0$$

Solving procedure

Solving procedure:

1. Find the function

$$L(\Theta|\mathbf{r}) = w(\mathbf{r}|\Theta)$$

2. Set the condition that derivative of $L(\Theta|\mathbf{r})$ or $\ln(L(\Theta|\mathbf{r}))$ is 0

$$\frac{dL(\Theta|\mathbf{r})}{d\Theta} = 0, \text{ or } \frac{d \ln(L(\Theta))}{d\Theta} = 0$$

3. Solve and find the value $\hat{\Theta}_{ML}$
4. Check that second derivative at point $\hat{\Theta}_{ML}$ is negative, to check that point is a maximum
 - ▶ because derivative = 0 for both maximum and minimum points
 - ▶ we'll sometimes skip this, for brevity

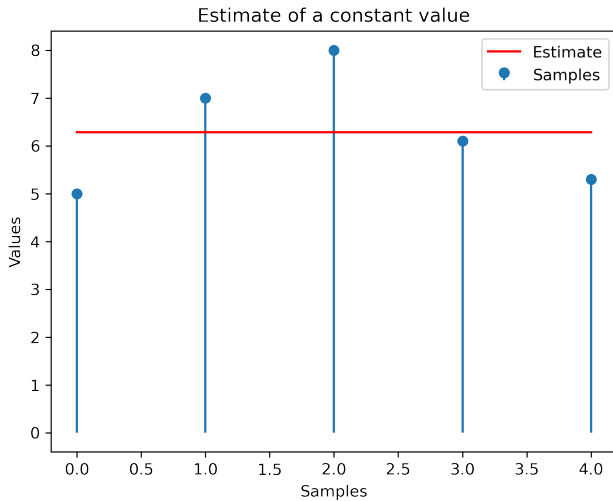
Examples:

- ▶ Estimating a constant signal in gaussian noise:

Find the ML estimate of a constant value $s_{\Theta}(t) = A$ from 5 noisy measurements $r_i = A + \text{noise}$ with values $[5, 7, 8, 6.1, 5.3]$. The noise is AWGN $\mathcal{N}(\mu = 0, \sigma^2)$.

- ▶ Solution: at whiteboard.
- ▶ The estimate \hat{A}_{ML} is the average value of the samples
 - ▶ not surprisingly, what other value would have been more likely?
 - ▶ that's literally what “expected value” means

Numerical simulation



Curve fitting

- ▶ **Estimation = curve fitting**
 - ▶ we're finding the best fitting of $s_{\Theta}(t)$ through the data \mathbf{r}
- ▶ From the previous graphical example:
 - ▶ we have some data \mathbf{r} = some points
 - ▶ we know the shape of the signal = a line (constant A)
 - ▶ we're fitting the best line through the data

General signal in AWGN

- ▶ Consider that the true underlying signal is $s_{\Theta}(t)$
- ▶ Consider **AWGN noise** $\mathcal{N}(\mu = 0, \sigma^2)$.
- ▶ The samples r_i are taken at sample moments t_i
- ▶ The samples r_i have normal distribution with average value $\mu = s_{\Theta}(t_i)$ and variance σ^2
- ▶ Overall likelihood function = product of likelihoods for each sample r_i

$$\begin{aligned} L(\Theta|\mathbf{r}) = w(\mathbf{r}|\Theta) &= \prod_{i=1}^N \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(r_i - s_{\Theta}(t_i))^2}{2\sigma^2}} \\ &= \left(\frac{1}{\sigma\sqrt{2\pi}} \right)^N e^{-\frac{\sum (r_i - s_{\Theta}(t_i))^2}{2\sigma^2}} \end{aligned}$$

General signal in AWGN

- The log-likelihood is

$$\ln(L(\Theta|\mathbf{r})) = \underbrace{\ln\left(\frac{1}{\sigma\sqrt{2\pi}}\right)}_{\text{constant}} - \frac{\sum (r_i - s_{\Theta}(t_i))^2}{2\sigma^2}$$

General signal in AWGN

- ▶ The maximum of the function = the minimum of the exponent

$$\hat{\Theta}_{ML} = \arg \max_{\Theta} L(\Theta|\mathbf{r}) = \arg \min \sum (r_i - s_{\Theta}(t_i))^2$$

- ▶ The term $\sum (r_i - s_{\Theta}(t_i))^2$ is the **squared distance** $d(\mathbf{r}, s_{\Theta})$

$$d(\mathbf{r}, s_{\Theta}) = \sqrt{\sum (r_i - s_{\Theta}(t_i))^2}$$

$$(d(\mathbf{r}, s_{\Theta}))^2 = \sum (r_i - s_{\Theta}(t_i))^2$$

General signal in AWGN

- ▶ ML estimation can be rewritten as:

$$\hat{\Theta}_{ML} = \arg \max_{\Theta} L(\Theta|\mathbf{r}) = \arg \min_{\Theta} d(\mathbf{r}, \mathbf{s}_{\Theta})^2$$

- ▶ ML estimate $\hat{\Theta}_{ML}$ = the value that makes $s_{\Theta}(t_i)$ **closest to the received values \mathbf{r}**
 - ▶ closer = beter fit = more likely
 - ▶ closest = best fit = most likely = maximum likelihood

General signal in AWGN

- ▶ ML estimation in AWGN noise = **minimization of distance**
- ▶ Hey, we had the same interpretation with ML decision!
 - ▶ but for decision, we choose the minimum out of 2 options
 - ▶ here, we choose the minimum out of all possible options
- ▶ Same interpretation applies for all kinds of vector spaces
 - ▶ vectors with N elements, continuous signals, etc
 - ▶ just change the definition of the distance function

General signal in AWGN

Procedure for ML estimation in AWGN noise:

1. Write the expression for the (squared) distance:

$$D = (d(\mathbf{r}, s_{\Theta}))^2 = \sum (r_i - s_{\Theta}(t_i))^2$$

2. We want it minimal, so set derivative to 0:

$$\frac{dD}{d\Theta} = \sum 2(r_i - s_{\Theta}(t_i))\left(-\frac{ds_{\Theta}(t_i)}{d\Theta}\right) = 0$$

3. Solve and find the value $\hat{\Theta}_{ML}$
4. Check that second derivative at point $\hat{\Theta}_{ML}$ is positive, to check that point is a minimum
 - we'll sometimes skip this, for brevity

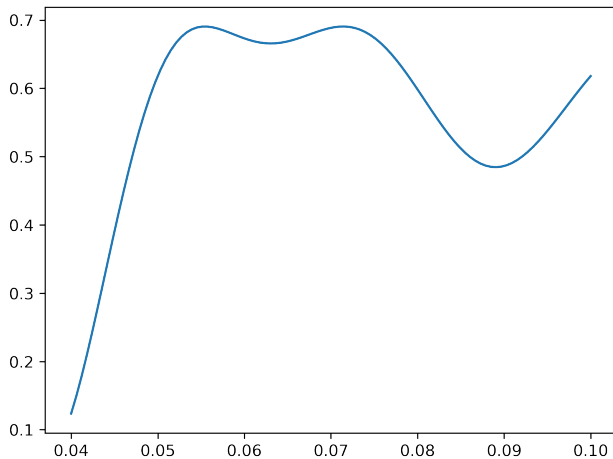
Numerical simulation

Estimating the frequency f of a cosine signal

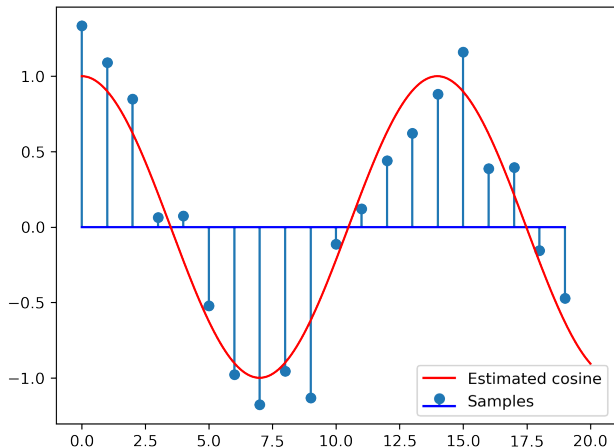
- ▶ Find the Maximum Likelihood estimate of the frequency f of a cosine signal $s_{\Theta}(t) = \cos(2\pi ft_i)$, from 10 noisy measurements $r_i = \cos(2\pi ft_i) + \text{noise}$ with values [...]. The noise is AWGN $\mathcal{N}(\mu = 0, \sigma^2)$. The sample times $t_i = [0, 1, 2, 3, 4, 5, 6, 7, 8, 9]$
- ▶ Solution: at whiteboard.

Numerical simulation

The likelihood function is:



Numerical simulation



Estimating parameters for certain distributions

- ▶ ML estimation can be used to estimate parameters of distributions
- ▶ Suppose we have a set of values r_i , which we model as samples coming from a distribution. How do we find the parameters of that distribution?
- ▶ For now, we consider only one unknown parameter

Estimating the parameters of the normal distribution

- ▶ Assume r_i are samples coming from a normal distribution $\mathcal{N}(\mu, \sigma^2)$
- ▶ The distribution has two parameters: mean μ and standard deviation σ (or variance σ^2)
- ▶ Estimating μ :

Just like estimating a constant signal in AWGN noise of mean 0:

$$\hat{\mu}_{ML} = \frac{1}{N} \sum_{i=1}^N r_i$$

- ▶ Estimating σ^2 :

Can't be formulated as estimating a signal added with AWGN noise, but can still use ML:

$$\hat{\sigma}_{ML} = \arg \max_{\sigma} w(\mathbf{r}|\sigma)$$

Estimating the parameters of the normal distribution

$$\begin{aligned}\hat{\sigma}_{ML} &= \arg \max_{\sigma} w(\mathbf{r}|\sigma) \\ &= \arg \max_{\sigma} \left(\frac{1}{\sigma\sqrt{2\pi}} \right)^N e^{-\frac{\sum (r_i - \mu)^2}{2\sigma^2}} \quad (\text{apply } \ln()) \\ &= \arg \max_{\sigma} \left(-N \ln(\sigma\sqrt{2\pi}) - \frac{\sum (r_i - \mu)^2}{2\sigma^2} \right)\end{aligned}$$

Derivate and set to 0 to obtain the minimum:

$$\begin{aligned}-N \frac{1}{\sigma\sqrt{2\pi}} \sqrt{2\pi} - \frac{\sum (r_i - \mu)^2}{2} (-2) \sigma^{-3} &= 0 \\ -\frac{N}{\sigma} + \frac{\sum (r_i - \mu)^2}{\sigma^3} &= 0 \\ \sigma^2 &= \frac{\sum (r_i - \mu)^2}{N}\end{aligned}$$

Estimating the parameters of the normal distribution

- ▶ Estimated parameters of the normal distribution are identical to the definitions of the mean and variance:

$$\hat{\mu}_{ML} = \frac{1}{N} \sum_{i=1}^N r_i$$
$$\hat{\sigma}_{ML} = \sqrt{\frac{\sum_{i=1}^N (r_i - \mu)^2}{N}}$$

- ▶ Note: estimating σ requires the value of μ
 - ▶ If μ is known, everything is fine
 - ▶ If μ is unknown, we can use $\hat{\mu}_{ML}$ beforehand, but then we're estimating based on another estimate, which is problematic (the estimator is biased, we'll see)

Estimating the parameters of the uniform distribution

- ▶ Assume r_i are samples from a uniform distribution $\mathcal{U}[a, b]$
- ▶ The distribution has two parameters: the limits a și b
- ▶ Estimating a and b :

$$\hat{a}_{ML} = \arg \max_a w(\mathbf{r}|a)$$

$$\hat{b}_{ML} = \arg \max_b w(\mathbf{r}|b)$$

Which means:

$$\hat{a}_{ML} = \min(r_i)$$

$$\hat{b}_{ML} = \max(r_i)$$

- ▶ The interval must contain all the values r_i (otherwise, the likelihood would be 0) but should not extend more than necessary (otherwise, the probability would decrease)

Multiple parameters

- ▶ What if we have more than one parameter?
 - ▶ e.g. unknown parameters are the amplitude, frequency and the initial phase of a cosine:

$$\hat{s}(t) = A \cos(2\pi f t + \phi)$$

- ▶ We can consider the parameter Θ to be a vector:

$$\Theta = [\Theta_1, \Theta_2, \dots, \Theta_M]$$

- ▶ e.g. $\Theta = [\Theta_1, \Theta_2, \Theta_3] = [A, f, \phi]$

Multiple parameters

- ▶ We solve with the same procedure, but instead of one derivative, we have M derivatives
- ▶ We solve the system:

$$\begin{cases} \frac{\partial L}{\partial \Theta_1} = 0 \\ \frac{\partial L}{\partial \Theta_2} = 0 \\ \dots \\ \frac{\partial L}{\partial \Theta_M} = 0 \end{cases}$$

- ▶ sometimes difficult to solve

Gradient Descent

- ▶ How to estimate the parameters Θ in complicated cases?
 - ▶ e.g. in real life applications
 - ▶ usually there are many parameters (Θ is a vector)
- ▶ Typically it is impossible to get the optimal values directly by solving the system
- ▶ Improve them iteratively with **Gradient Descent** algorithm or its variations
- ▶ Gradient Descent is a general method of finding the minimum or maximum of a function

Coborâre după gradient (Gradient Descent)

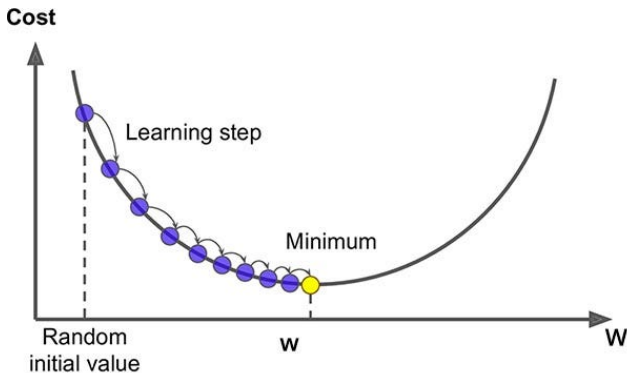


Figure 1: Coborâre după gradient¹

¹Imagine: Quick Guide to Gradient Descent and Its Variants, Sahdev Kansal, Towards Data Science, 2020

Gradient Descent procedure

1. Start with some random parameter values $\Theta^{(0)}$
2. Repeat for each iteration k :
 - 2.1 Compute function $L(\Theta^{(k)}|\mathbf{r})$
 - 2.2 Compute derivatives $\frac{\partial L}{\partial \Theta_i^{(k)}}$ for each Θ_i (“**gradient**”)
 - 2.3 Update all values Θ_i by subtracting the derivative (“**descent**”)

$$\Theta_i^{(k+1)} = \Theta_i^{(k)} - \mu \frac{\partial L}{\partial \Theta_i^{(k)}}$$

► or, in vector form:

$$\Theta^{(k+1)} = \Theta^k - \mu \frac{\partial L}{\partial \Theta^{(k)}}$$

3. Until termination criterion (e.g. parameters don't change much)

Gradient Descent explained

- ▶ The derivative always tells in which direction to advance
- ▶ To find the minimum of a function, subtract the derivative (gradient descent)

$$\Theta^{(k+1)} = \Theta^{(k)} - \mu \frac{\partial L}{\partial \Theta^{(k)}}$$

- ▶ TO find the maximum of a function, add the derivative (gradient ascent)

$$\Theta^{(k+1)} = \Theta^{(k)} + \mu \frac{\partial L}{\partial \Theta^{(k)}}$$

- ▶ The parameter μ is the **learning rate** and is empirically chosen, has a small value
- ▶ GD is sensitive to initial starting point, and can get trapped in local minima
- ▶ Other explanations: at whiteboard
- ▶ Exemplu practic: regresia logistică cu valori 2D

Neural Networks

- ▶ The most prominent example is **Artificial Neural Networks** (a.k.a. Neural Networks, Deep Learning, etc.)
 - ▶ Can be regarded as ML estimation
 - ▶ Use Gradient Descent to update parameters
 - ▶ State-of-the-art applications: image classification/recognition, automated driving etc.
- ▶ More info on neural networks / machine learning:
 - ▶ look up online courses, books
 - ▶ join the IASI AI Meetup

Estimator bias and variance

- ▶ How good is an estimator?
- ▶ An estimator $\hat{\Theta}$ is a **random variable**
 - ▶ can have different values, because it is computed based on the received samples, which depend on noise
 - ▶ example: in lab, try on multiple computers => slightly different results
- ▶ As a random variable, it has:
 - ▶ an average value (expected value): $E \{ \hat{\Theta} \}$
 - ▶ a variance: $E \{ (\hat{\Theta} - \Theta)^2 \}$

Estimator bias and variance

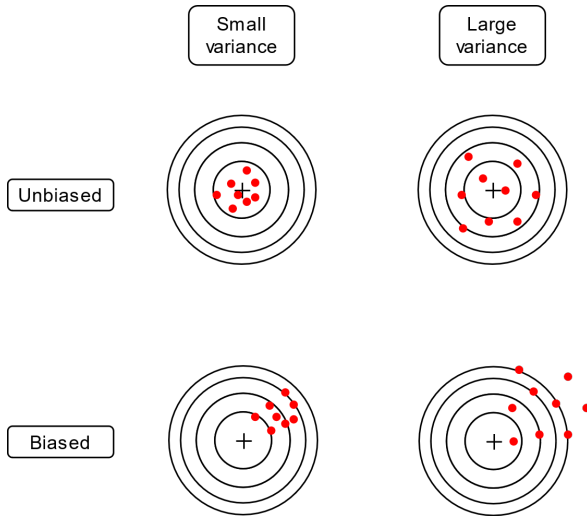


Figure 2: Estimator bias and variance

Estimator bias

- ▶ The **bias** of an estimator $\hat{\Theta}$ = difference between the estimator's average value and the true value

$$Bias = E \{ \hat{\Theta} \} - \Theta$$

- ▶ Estimator is **unbiased** = the average value of the estimator is the true value of Θ

$$E \{ \hat{\Theta} \} = \Theta$$

- ▶ Estimator is **biased** = the average value of the estimator is different from the true value Θ
 - ▶ the difference $E \{ \hat{\Theta} \} - \Theta$ is **the bias** of the estimator

Estimator bias

- ▶ Example: for constant signal A with AWGN noise (zero-mean), ML estimator is $\hat{A}_{ML} = \frac{1}{N} \sum_i r_i$
- ▶ Then:

$$\begin{aligned} E \{ \hat{A}_{ML} \} &= \frac{1}{N} E \left\{ \sum_i r_i \right\} \\ &= \frac{1}{N} \sum_{i=1}^N E \{ r_i \} \\ &= \frac{1}{N} \sum_{i=1}^N E \{ A + \text{noise} \} \\ &= \frac{1}{N} \sum_{i=1}^N A \\ &= A \end{aligned}$$

- ▶ This estimator is unbiased

Estimator bias

- ▶ Example: the estimator of the variance of a normal distribution, using the estimated mean $\hat{\mu}_{ML}$:

$$\hat{\sigma}_{ML}^2 = \frac{\sum_{i=1}^N (r_i - \hat{\mu}_{ML})^2}{N}$$

- ▶ This estimator is **biased**:

$$\begin{aligned} E \left\{ \hat{\sigma}_{ML}^2 \right\} &= E \left\{ \frac{\sum_{i=1}^N (r_i - \hat{\mu}_{ML})^2}{N} \right\} \\ &= \dots \\ &= \frac{N-1}{N} \sigma^2 \end{aligned}$$

where σ^2 is the real variance of the distribution

- ▶ Demonstrație: *Wikipedia* or “*Maximum Likelihood Estimator for Variance is Biased: Proof*”, Dawen Liang, Carnegie Mellon University

The unbiased variance estimator

- ▶ The ML estimator of variance is biased, as it **underestimates** the real variance of the distribution by a factor $(N-1)/N$
- ▶ To obtain an unbiased estimator of the variance, we use:

$$\hat{\sigma}_{ML}^2 = \frac{1}{N-1} \sum_{i=1}^N (r_i - \hat{\mu}_{ML})^2$$

- ▶ The difference: divide to $N - 1$ instead of N
- ▶ Intuition: at whiteboard, with 2 point only; medie este la mijloc; the average is in middle, variance is minimized, so it underestimates the real one

Estimator variance

- ▶ The **variance** of an estimator measures the “spread” of the estimator around its average
 - ▶ that's the definition of variance
- ▶ Unbiased estimators are good, but if the **variance** of the estimator is large, then estimated values can be far from the true value
- ▶ We prefer estimators with **small variance**, even if maybe slightly biased

II.3 Bayesian estimation

Bayesian estimation

- ▶ **Bayesian estimation** considers extra factors alongside $w(\mathbf{r}|\Theta)$ in the estimation:
 - ▶ a prior distribution $w(\Theta)$
 - ▶ possibly some cost function
- ▶ This makes it the estimation version of the MPE and MR decision criteria

Bayesian estimation

- ▶ Conceptually, Bayesian estimation consists of two major steps:
 1. Finding the **posterior distribution** $w(\Theta|\mathbf{r})$
 2. Estimating a value from the distribution, based on a **cost function**

Bayesian estimation

- ▶ We define the **posterior** probability density of Θ , given the known observations \mathbf{r} , using the **Bayes rule**:

$$w(\Theta|\mathbf{r}) = \frac{w(\mathbf{r}|\Theta) \cdot w(\Theta)}{w(\mathbf{r})}$$

- ▶ Explanation of the terms:
 - ▶ Θ is the unknown parameter
 - ▶ \mathbf{r} are the observations that we have
 - ▶ $w(\Theta|\mathbf{r})$ is the probability of a certain value Θ to be the correct one, given our current observations \mathbf{r} ;
 - ▶ $w(\mathbf{r}|\Theta)$ is the likelihood function
 - ▶ $w(\Theta)$ is the **prior distribution** of Θ , i.e. what we know about Θ even in the absence of evidence
 - ▶ $w(\mathbf{r})$ is a scaling constant, which makes the integral of the resulting function be 1 (like for any distribution)

Bayesian estimation

- ▶ With MLE estimation, we only have the term $w(\mathbf{r}|\Theta)$. When viewed as a function of Θ , this is not a distribution of Θ . It's just something we want to maximize.
- ▶ Bayesian estimation, however, uses $w(\Theta|\mathbf{r})$, which **is** the actual probability distribution of the possible values of Θ

Bayes rule

- ▶ The Bayes rule shows that the probability of a value Θ depends on two things:
 1. The observations that we have, via the term $w(\mathbf{r}|\Theta)$
 2. The prior knowledge (or prior belief) about Θ , via the term $w(\Theta)$
 - ▶ (the third term $w(\mathbf{r})$ is considered a constant, and plays no role)
- ▶ Known as “Bayesian estimation”
 - ▶ Thomas Bayes = discovered the Bayes rule
 - ▶ Stuff related to Bayes rule are often named “Bayesian”

The prior distribution

- ▶ The role of the prior distribution $w(\Theta)$ is to express what we know beforehand about Θ
 - ▶ we know beforehand how likely it is to have a certain value
 - ▶ known as *a priori* distribution or *prior* distribution
- ▶ Bayesian estimation takes the prior information into account, alongside the measurements
 - ▶ the estimate will be slightly “moved” towards more likely values

The MAP estimator

- ▶ Suppose we know $w(\Theta|\mathbf{r})$. What is our estimate?
- ▶ Let's pick the value with the highest probability
- ▶ The **Maximum A Posteriori (MAP)** estimator:

$$\hat{\Theta}_{MAP} = \arg \max_{\Theta} w(\Theta|\mathbf{r}) = \arg \max_{\Theta} \{w(\mathbf{r}|\Theta) \cdot w(\Theta)\}$$

- ▶ The MAP estimator chooses Θ as the value where the posterior distribution $w(\Theta|\mathbf{r})$ is maximum
- ▶ The MAP estimator maximizes the likelihood of the observed data **but multiplied with the prior distribution** $w(\Theta)$

The MAP estimator

Image example here

Relation with Maximum Likelihood Estimator

- ▶ The ML estimator:

$$\arg \max w(\mathbf{r}|\Theta)$$

- ▶ The MAP estimator:

$$\arg \max \{w(\mathbf{r}|\Theta) \cdot w(\Theta)\}$$

- ▶ The ML estimator is a particular case of MAP when $w(\Theta)$ is a constant
 - ▶ $w(\Theta) = \text{constant}$ means all values Θ are equally likely
 - ▶ i.e. we don't have a clue where the real Θ might be

Relation with Detection

- ▶ The MPE criterion $\frac{w(r|H_1)}{w(r|H_0)} \underset{H_0}{\overset{H_1}{\gtrless}} \frac{P(H_0)}{P(H_1)}$
- ▶ It can be rewritten as $w(r|H_1) \cdot P(H_1) \underset{H_0}{\overset{H_1}{\gtrless}} w(r|H_0)P(H_0)$
 - ▶ i.e. choose the hypothesis where $w(r|H_i) \cdot P(H_i)$ is maximum
- ▶ **MPE decision criterion:** pick hypothesis which maximizes $w(r|H_i) \cdot P(H_i)$
 - ▶ out of the two possible hypotheses
- ▶ **The MAP estimator:** pick value which maximizes $w(\mathbf{r}|\Theta) \cdot w(\Theta)$
 - ▶ out of all possible values of Θ
- ▶ Same principle!

Cost function

- ▶ Let's find an equivalent for the Minimum Risk criterion. We need an equivalent for the costs C_{ij}
- ▶ The **estimation error** = the difference between the estimate $\hat{\Theta}$ and the true value Θ

$$\epsilon = \hat{\Theta} - \Theta$$

- ▶ The **cost function** $C(\epsilon)$ = assigns a cost to each possible estimation error
 - ▶ when $\epsilon = 0$, the cost $C(0) = 0$
 - ▶ small errors ϵ have small costs
 - ▶ large errors ϵ have large costs

Cost function

- ▶ Usual types of cost functions:

- ▶ Quadratic:

$$C(\epsilon) = \epsilon^2 = (\hat{\Theta} - \Theta)^2$$

- ▶ Uniform (“hit or miss”):

$$C(\epsilon) = \begin{cases} 0, & \text{if } |\epsilon| = |\hat{\Theta} - \Theta| \leq E \\ 1, & \text{if } |\epsilon| = |\hat{\Theta} - \Theta| > E \end{cases}$$

- ▶ Linear:

$$C(\epsilon) = |\epsilon| = |\hat{\Theta} - \Theta|$$

- ▶ Draw them at whiteboard

Cost function

- ▶ The cost function $C(\epsilon)$ is the equivalent of the costs C_{ij} at detection
 - ▶ for detection we only had 4 costs: C_{00} , C_{01} , C_{10} , C_{11}
 - ▶ now we have a cost for all possible estimation errors ϵ
- ▶ The cost function guides which value to choose from $w(\Theta|\mathbf{r})$

The importance of the cost function

- Consider the following posterior distribution

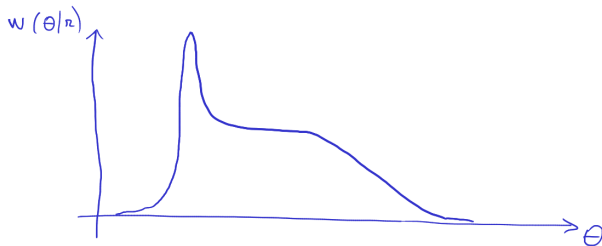


Figure 3: Unbalanced posterior distribution

- Which is the MAP estimate?
- Supposing we have the following cost function, does your estimate change ?:
 - if your estimate $\hat{\Theta}$ is $<$ then the real Θ , you pay 1000\$
 - if your estimate $\hat{\Theta}$ is $>$ then the real Θ , you pay 1\$

The importance of the cost function

- ▶ Choosing one particular value $\hat{\Theta}$ from the distribution of possible values is driven by the cost function
- ▶ The most probable value is not always the best
- ▶ The best value is the one which leads to the smallest average cost

The Bayesian risk

- ▶ The posterior distribution $w(\Theta|\mathbf{r})$ tells us the probability of a certain value $\hat{\Theta}$ to be the correct one of Θ
- ▶ Picking a certain estimate value $\hat{\Theta}$ implies a certain error ϵ
- ▶ The error implies a certain cost $C(\epsilon)$
- ▶ The **risk** = the average cost = $C(\epsilon) \times$ the probability:

$$R = \int_{-\infty}^{\infty} C(\epsilon) w(\Theta|\mathbf{r}) d\Theta$$

The Bayes estimator

- ▶ We need to pick the value $\hat{\Theta}$ which **minimizes the expected cost** R

$$\hat{\Theta} = \arg \min_{\Theta} \int_{-\infty}^{\infty} C(\epsilon) w(\Theta|\mathbf{r}) d\Theta$$

- ▶ To find it, replace $C(\epsilon)$ with its definition and derivate over $\hat{\Theta}$
 - ▶ Attention: derivate with respect to $\hat{\Theta}$, not Θ !

MMSE estimator

- ▶ When the cost function is quadratic $C(\epsilon) = \epsilon^2 = (\hat{\Theta} - \Theta)^2$

$$R = \int_{-\infty}^{\infty} (\hat{\Theta} - \Theta)^2 w(\Theta|\mathbf{r}) d\Theta$$

- ▶ We want the $\hat{\Theta}$ that minimizes R , so we derivate

$$\frac{dR}{d\hat{\Theta}} = 2 \int_{-\infty}^{\infty} (\hat{\Theta} - \Theta) w(\Theta|\mathbf{r}) d\Theta = 0$$

- ▶ Equivalent to

$$\hat{\Theta} \underbrace{\int_{-\infty}^{\infty} w(\Theta|\mathbf{r}) d\Theta}_1 = \int_{-\infty}^{\infty} \Theta w(\Theta|\mathbf{r}) d\Theta$$

- ▶ The **Minimum Mean Squared Error (MMSE)** estimator is

$$\hat{\Theta}_{MMSE} = \int_{-\infty}^{\infty} \Theta \cdot w(\Theta|\mathbf{r}) d\Theta$$

- ▶ **The MMSE estimator:** the estimator $\hat{\Theta}$ is the **average value** of the posterior distribution $w(\Theta|\mathbf{r})$

$$\hat{\Theta}_{MMSE} = \int_{-\infty}^{\infty} \Theta \cdot w(\Theta|\mathbf{r}) d\Theta$$

- ▶ MMSE = “Minimum Mean Squared Error”
 - ▶ average value = sum (integral) of every Θ times its probability $w(\Theta|\mathbf{r})$
- ▶ The MMSE estimator is obtained from the posterior distribution $w(\Theta|\mathbf{r})$ considering the quadratic cost function

The MAP estimator

- ▶ When the cost function is uniform:

$$C(\epsilon) = \begin{cases} 0, & \text{if } |\epsilon| = |\hat{\Theta} - \Theta| \leq E \\ 1, & \text{if } |\epsilon| = |\hat{\Theta} - \Theta| > E \end{cases}$$

- ▶ Keep in mind that $\Theta = \hat{\Theta} - \epsilon$
- ▶ We obtain

$$I = \int_{-\infty}^{\hat{\Theta}-E} w(\Theta|\mathbf{r})d\Theta + \int_{\hat{\Theta}+E}^{\infty} w(\Theta|\mathbf{r})d\Theta$$
$$I = 1 - \int_{\hat{\Theta}-E}^{\hat{\Theta}+E} w(\Theta|\mathbf{r})d\Theta$$

The MAP estimator

- ▶ To minimize C , we must maximize $\int_{\hat{\Theta}-E}^{\hat{\Theta}+E} w(\Theta|\mathbf{r})d\Theta$, the integral around point $\hat{\Theta}$
- ▶ For E a very small, the function $w(\Theta|\mathbf{r})$ is approximately constant, so we pick the point where the function is maximum
- ▶ **The Maximum A Posteriori (MAP) estimator** = the value $\hat{\Theta}$ which maximizes $w(\Theta|\mathbf{r})$

$$\hat{\Theta}_{MAP} = \arg \max_{\Theta} w(\Theta|\mathbf{r}) = \arg \max_{\Theta} \Theta w(\mathbf{r}|\Theta) \cdot w(\Theta)$$

Interpretation

- ▶ The MAP estimator chooses Θ as the value where the posterior distribution is maximum
- ▶ The MMSE estimator chooses Θ as average value of the posterior distribution

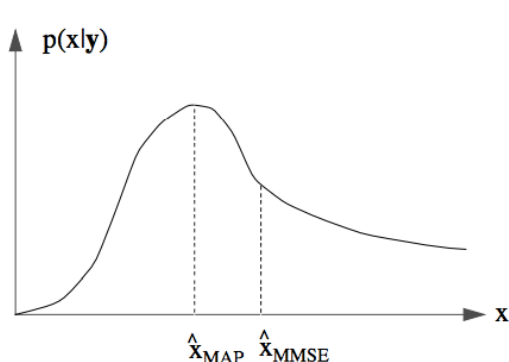


Figure 4: MAP vs MMSE estimators

Relationship between MAP and MMSE

- ▶ The MAP estimator = minimizing the average cost, using the uniform cost function
 - ▶ similar with the MPE decision criteria = MR when all costs are same
- ▶ The MMSE estimator = minimizing the average cost, using the quadratic cost function
 - ▶ similar to MR decision criteria, but more general

Exercise

Exercise: constant value, 3 measurement, Gaussian same σ

- ▶ We want to estimate today's temperature in Sahara
- ▶ Our thermometer reads 40 degrees, but the value was affected by Gaussian noise $\mathcal{N}(0, \sigma^2 = 2)$ (crappy thermometer)
- ▶ We know that this time of the year, the temperature is around 35 degrees, with a Gaussian distribution $\mathcal{N}(35, \sigma^2 = 2)$.
- ▶ Estimate the true temperature using ML, MAP and MMSE estimators

Exercise

Exercise: constant value, 3 measurements, Gaussian same σ

- ▶ What if he have three thermometers, showing 40, 38, 41 degrees

Exercise: constant value, 3 measurements, Gaussian different σ

- ▶ What if the temperature this time of the year has Gaussian distribution $\mathcal{N}(35, \sigma_2^2 = 3)$
 - ▶ different variance, $\sigma_2 \neq \sigma$

General signal in AWGN

- ▶ Consider that the true underlying signal is $s_{\Theta}(t)$
- ▶ Consider AWGN noise $\mathcal{N}(\mu = 0, \sigma^2)$.
- ▶ As in Maximum Likelihood function, overall likelihood function

$$w(\mathbf{r}|\Theta) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{\sum (r_i - s_{\Theta}(t_i))^2}{2\sigma^2}}$$

- ▶ But now this function is also **multiplied with** $w(\Theta)$

$$w(\mathbf{r}|\Theta) \cdot w(\Theta)$$

General signal in AWGN

- ▶ MAP estimator is the argument that maximizes this product

$$\hat{\Theta}_{MAP} = \arg \max w(\mathbf{r}|\Theta)w(\Theta)$$

- ▶ Taking logarithm

$$\begin{aligned}\hat{\Theta}_{MAP} &= \arg \max \ln (w(\mathbf{r}|\Theta)) + \ln (w(\Theta)) \\ &= \arg \max -\frac{\sum (r_i - s_{\Theta}(t_i))^2}{2\sigma^2} + \ln (w(\Theta))\end{aligned}$$

Gaussian prior

- ▶ If the prior distribution is also Gaussian $\mathcal{N}(\mu_{\Theta}, \sigma_{\Theta}^2)$

$$\ln(w(\Theta)) = -\frac{\sum(\Theta - \mu_{\Theta})^2}{2\sigma_{\Theta}^2}$$

- ▶ MAP estimation becomes

$$\hat{\Theta}_{MAP} = \arg \min \frac{\sum(r_i - s_{\Theta}(t_i))^2}{2\sigma^2} + \frac{\sum(\Theta - \mu_{\Theta})^2}{2\sigma_{\Theta}^2}$$

- ▶ Can be rewritten as

$$\hat{\Theta}_{MAP} = \arg \min d(\mathbf{r}, s_{\Theta})^2 + \underbrace{\frac{\sigma^2}{\sigma_{\Theta}^2}}_{\lambda} \cdot d(\Theta, \mu_{\Theta})^2$$

Interpretation

- ▶ MAP estimator with Gaussian noise and Gaussian prior

$$\hat{\Theta}_{MAP} = \arg \min d(\mathbf{r}, s_{\Theta})^2 + \underbrace{\frac{\sigma^2}{\sigma_{\Theta}^2}}_{\lambda} \cdot d(\Theta, \mu_{\Theta})^2$$

- ▶ $\hat{\Theta}_{MAP}$ is close to the expected value μ_{Θ} **and** it makes the true signal close to received data \mathbf{r}
 - ▶ Example: “search for a house that is close to job and close to the Mall”
 - ▶ λ controls the relative importance of the two terms
- ▶ Particular cases
 - ▶ σ_{Θ} very small = the prior is very specific (narrow) = λ large = second term very important = $\hat{\Theta}_{MAP}$ close to μ_{Θ}
 - ▶ σ_{Θ} very large = the prior is very unspecific = λ small = first term very important = $\hat{\Theta}_{MAP}$ close to ML estimation

Applications

- ▶ In general, practical applications:
 - ▶ can use various prior distributions
 - ▶ estimate **multiple parameters** (a vector of parameters)
- ▶ Applications
 - ▶ denoising of signals
 - ▶ signal restoration
 - ▶ signal compression

Sample applications

1. Single object tracking with Kalman filtering

- ▶ estimating an object's position through successive noisy measurements (e.g. consecutive frames in a video)
- ▶ at every new measurement, we have two distributions of the position:
 - ▶ one given by the measurement itself, $w(r|\Theta)$
 - ▶ one predicted based on position and speed from last moment
 - ▶ both are presumed Gaussian, described only through average value and variance
- ▶ the two are combined via the Bayes rule \Rightarrow a more precise distribution $w(\Theta|r)$, also Gaussian
- ▶ the exact position is estimated with MMSE (average value of $w(\Theta|r)$)
- ▶ $w(\Theta|r)$ + speed is used to predict the position at the next time moment

Single object tracking

Single object tracking

Sample applications

2. Constrained Least Squares (CLS) image restoration

- ▶ We have an image I corrupted by noise (additive noise, missing pixels, blurring)

$$I_{noisy} = I_{true} + Z$$

- ▶ We can estimate the original image by solving:

$$\hat{I}_{true} = \underset{I}{\operatorname{argmin}} \|I - I_{zg}\|_2 + \lambda \cdot \|HighPass\{I\}\|_2$$

- ▶ Examples:

- ▶ <https://www.mathworks.com/help/images/deblurring-images-using-a-regularized-filter.html>
- ▶ <https://demonstrations.wolfram.com/ImageRestorationForDegradedImages>
- ▶ Google it

Constrained Least Squares (CLS) image restoration