



Statistical Signal Processing

Lecture 2

chapter 1: parameter estimation

stochastic parameters

- the parameter estimation problem
- Bayes estimation: the MMSE, absolute value and uniform cost functions
- examples: Gaussian mean in Gaussian noise, Poisson process
- vector parameters
- Fischer Information Matrix

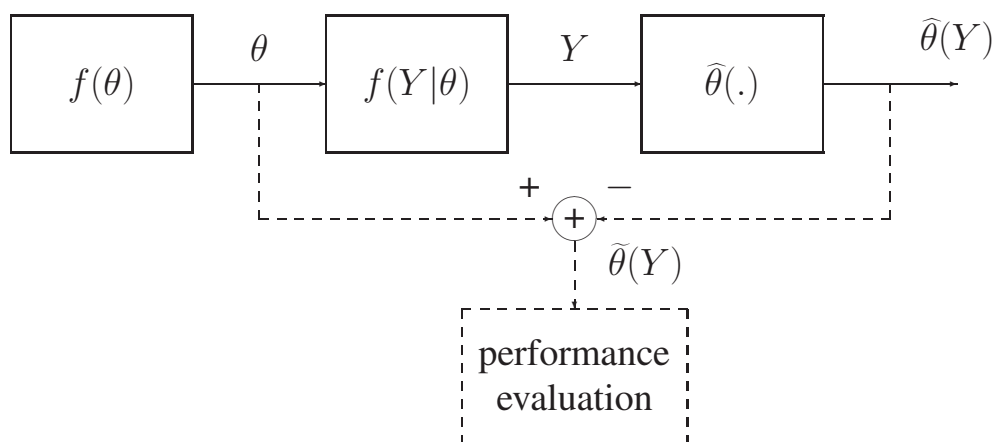


Vector Parameters

$$\bullet \theta = \begin{bmatrix} \theta_1 \\ \vdots \\ \theta_m \end{bmatrix}, \quad \hat{\theta}(Y) = \begin{bmatrix} \hat{\theta}_1(Y) \\ \vdots \\ \hat{\theta}_m(Y) \end{bmatrix}, \quad \tilde{\theta} = \tilde{\theta}(\theta, Y) = \theta - \hat{\theta}(Y)$$

• problem formulation:

- a prior distribution $f_{\boldsymbol{\theta}}(\theta)$
- a conditional distribution $f_{Y|\boldsymbol{\theta}}(Y|\theta)$
- Bayes' rule : joint distribution $f_{Y,\boldsymbol{\theta}}(Y, \theta) = f_{Y|\boldsymbol{\theta}}(Y|\theta)f_{\boldsymbol{\theta}}(\theta)$



Bayes Risk Function

- cost $\mathcal{C}(\theta, \hat{\theta}(Y))$
- $\mathcal{C}(\theta, \hat{\theta}(Y))$ often directly a function of the estimation error $\tilde{\theta}$ and in fact often a function of the length of the estimation error $\|\tilde{\theta}\| = \sqrt{\tilde{\theta}^T \tilde{\theta}} = \sqrt{\sum_{i=1}^n \tilde{\theta}_i^2}$
- We obtain the estimator function $\hat{\theta}(\cdot)$ by minimizing the risk, which is the expected value of the cost:

$$\begin{aligned} \min_{\hat{\theta}(\cdot)} \mathcal{R}(\hat{\theta}(\cdot)) &= \min_{\hat{\theta}(\cdot)} E \mathcal{C}(\theta, \hat{\theta}(Y)) = \min_{\hat{\theta}(\cdot)} E_{\mathbf{Y}, \boldsymbol{\theta}} \mathcal{C}(\theta, \hat{\theta}(Y)) \\ &= \min_{\hat{\theta}(\cdot)} E_{\mathbf{Y}} E_{\boldsymbol{\theta}|\mathbf{Y}} \mathcal{C}(\theta, \hat{\theta}(Y)) = E_{\mathbf{Y}} [\min_{\hat{\theta}(Y)} E_{\boldsymbol{\theta}|\mathbf{Y}} \mathcal{C}(\theta, \hat{\theta}(Y))] \\ &= E_{\mathbf{Y}} [\min_{\hat{\theta}(Y)} \mathcal{R}(\hat{\theta}(Y)|Y)] . \end{aligned}$$

- $\mathcal{R}(\hat{\theta}(\cdot))$ is a weighted average of $\mathcal{R}(\hat{\theta}(Y)|Y)$, weighted by the nonnegative weighting function $f_{\mathbf{Y}}(Y)$. The minimum of $\mathcal{R}(\hat{\theta}(\cdot))$ w.r.t. $\hat{\theta}(\cdot)$ will hence be obtained by minimizing $\mathcal{R}(\hat{\theta}(Y)|Y)$ w.r.t. $\hat{\theta}(Y)$ for every Y .
- again $\mathcal{R}(\hat{\theta}(Y)|Y)$ depends on the posterior distribution $f_{\boldsymbol{\theta}|\mathbf{Y}}(\theta|Y)$.

Optimization w.r.t. Vector Parameters

- $g(\theta) = [g_1(\theta) \cdots g_l(\theta)]$: $1 \times l$ row vector function, its gradient w.r.t. θ :

$$\frac{\partial g(\theta)}{\partial \theta} = \begin{bmatrix} \frac{\partial g(\theta)}{\partial \theta_1} \\ \vdots \\ \frac{\partial g(\theta)}{\partial \theta_m} \end{bmatrix} = \begin{bmatrix} \frac{\partial g_1(\theta)}{\partial \theta_1} & \cdots & \frac{\partial g_l(\theta)}{\partial \theta_1} \\ \vdots & & \vdots \\ \frac{\partial g_1(\theta)}{\partial \theta_m} & \cdots & \frac{\partial g_l(\theta)}{\partial \theta_m} \end{bmatrix} \quad m \times l$$

If $g(\theta)$ is a scalar ($l = 1$), then $\frac{\partial g(\theta)}{\partial \theta}$ is a column vector of the same dimensions as θ .

- in particular: $\frac{\partial \theta^T}{\partial \theta} = \left[\frac{\partial \theta_j}{\partial \theta_i} \right] = [\delta_{ij}] = I_m$
- The gradient operator commutes with linear operations. Let X be $m \times 1$

$$\frac{\partial}{\partial \theta} (\theta^T X) = \left(\frac{\partial \theta^T}{\partial \theta} \right) X = I_m X = X .$$

- Since a scalar equals its transpose, we get

$$\frac{\partial}{\partial \theta} (X^T \theta) = \frac{\partial}{\partial \theta} (\theta^T X) = X$$



Optimization w.r.t. Vector Parameters (2)

- If A is $m \times l$: $\frac{\partial}{\partial \theta} (\theta^T A) = \left(\frac{\partial \theta^T}{\partial \theta} \right) A = I_m A = A$

- scalar case: $(uv)' = u'v + u v'$

- vector case: let $g(\theta)$ and $h(\theta)$ be $l \times 1$. Since

$$g^T(\theta)h(\theta) = (g^T(\theta)h(\theta))^T = h^T(\theta)g(\theta)$$

we get

$$\frac{\partial}{\partial \theta} (g^T(\theta)h(\theta)) = \left(\frac{\partial g^T(\theta)}{\partial \theta} \right) h(\theta) + \left(\frac{\partial h^T(\theta)}{\partial \theta} \right) g(\theta)$$

- Particular application with $g(\theta) = \theta$ and $h(\theta) = A\theta$:

$$\frac{\partial}{\partial \theta} (\theta^T A\theta) = \left(\frac{\partial \theta^T}{\partial \theta} \right) A\theta + \left(\frac{\partial \theta^T A^T}{\partial \theta} \right) \theta = (A + A^T) \theta$$

- When A is symmetric, this gradient reduces to $2A\theta$.



MMSE Criterion: Vector Parameters

- quadratic cost function $\mathcal{C}_{MMSE}(\theta, \hat{\theta}) = \|\tilde{\theta}\|_2^2 = \tilde{\theta}^T \tilde{\theta} = \sum_{i=1}^n \tilde{\theta}_i^2$

- minimizing the conditional Bayes risk :

$$\min_{\hat{\theta}(Y)} \mathcal{R}_{MMSE}(\hat{\theta}(Y)|Y) = \min_{\hat{\theta}(Y)} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} f(\theta|Y) (\theta - \hat{\theta})^T (\theta - \hat{\theta}) d\theta_1 \cdots d\theta_m$$

- extrema:

$$\begin{aligned} \frac{\partial}{\partial \hat{\theta}} \mathcal{R}_{MMSE}(\hat{\theta}|Y) &= \frac{\partial}{\partial \hat{\theta}} \int f(\theta|Y) (\theta - \hat{\theta})^T (\theta - \hat{\theta}) d\theta \\ &= \int f(\theta|Y) \left(\frac{\partial}{\partial \hat{\theta}} (\theta - \hat{\theta})^T (\theta - \hat{\theta}) \right) d\theta = 2 \int f(\theta|Y) (\hat{\theta} - \theta) d\theta = 0 \end{aligned}$$

- or hence $\hat{\theta}(Y) \underbrace{\int f(\theta|Y) d\theta}_{=1} = \int \theta f(\theta|Y) d\theta \Rightarrow \hat{\theta}_{MMSE}(Y) = E(\theta|Y)$

which is again the *mean* of the a posteriori distribution of θ given Y .

- extremum = minimum?

$$\begin{aligned} \text{Hessian} &= \left[\frac{\partial^2}{\partial \hat{\theta}_i \partial \hat{\theta}_j} \mathcal{R}_{MMSE}(\hat{\theta}|Y) \right] = \frac{\partial}{\partial \hat{\theta}} \left(\frac{\partial}{\partial \hat{\theta}} \mathcal{R}_{MMSE}(\hat{\theta}|Y) \right)^T \\ &= 2 \int f(\theta|Y) \left[\frac{\partial \hat{\theta}^T}{\partial \hat{\theta}} - \frac{\partial \theta^T}{\partial \hat{\theta}} \right] d\theta = 2I \int f(\theta|Y) d\theta = 2I > 0 \end{aligned}$$



MMSE Criterion: Vector Parameters (2)

- MMSE estimation commutes over linear transformations: with $\phi = A\theta$

$$\hat{\phi}_{MMSE} = E(\phi|Y) = E(A\theta|Y) = A E(\theta|Y) = A \hat{\theta}_{MMSE}$$

- orthogonality property of MMSE estimators:

$$\hat{\theta}(\mathbf{Y}) = E(\theta|\mathbf{Y}) \text{ iff } E((\theta - \hat{\theta}(\mathbf{Y}))g(\mathbf{Y})) = 0, \forall g(\cdot)$$

where $g(\cdot)$ is a scalar function. Equivalently :

$$E(\hat{\theta}(\mathbf{Y})g(\mathbf{Y})) = E(\theta g(\mathbf{Y})), \forall g(\cdot)$$

which represents an alternative way of defining $E(\theta|\mathbf{Y})$.

- use orthogonality to show optimality: let $\hat{\theta}(Y)$ be any function of Y ,

$$\begin{aligned} E \|\theta - \hat{\theta}(Y)\|_2^2 &= E \|\theta - E(\theta|Y) + E(\theta|Y) - \hat{\theta}(Y)\|_2^2 \\ &= E \|\theta - E(\theta|Y)\|_2^2 + \underbrace{E \|E(\theta|Y) - \hat{\theta}(Y)\|_2^2}_{\geq 0} + 2 \underbrace{E ((\theta - E(\theta|Y))^T (E(\theta|Y) - \hat{\theta}(Y)))}_{=0} \\ &\geq E \|\theta - E(\theta|Y)\|_2^2 \end{aligned}$$

- correlation matrices: $E(\theta - E(\theta|Y))(\theta - E(\theta|Y))^T \leq E(\theta - \hat{\theta})(\theta - \hat{\theta})^T$



MAP Estimators: Vector Parameters

- introduce: a ball centered around θ_o with radius δ

$$\mathcal{B}_\delta(\theta_o) = \{\theta \in \Theta : \|\theta - \theta_o\|_2 \leq \delta\}$$

- Then the natural extension to the vector case of the uniform cost function is

$$\mathcal{C}_{UNIF}(\theta, \hat{\theta}) = \begin{cases} 0, & \theta \in \mathcal{B}_\delta(\hat{\theta}) \\ 1, & \theta \in \Theta \setminus \mathcal{B}_\delta(\hat{\theta}) \end{cases}$$

- The conditional Bayes risk becomes

$$\begin{aligned} \mathcal{R}_{UNIF}(\hat{\theta}(Y)|Y) &= \int_{\Theta} f(\theta|Y) \mathcal{C}_{UNIF}(\theta, \hat{\theta}) d\theta = \int_{\Theta \setminus \mathcal{B}_\delta(\hat{\theta})} f(\theta|Y) d\theta \\ &= \int_{\Theta} f(\theta|Y) d\theta - \int_{\mathcal{B}_\delta(\hat{\theta})} f(\theta|Y) d\theta = 1 - \int_{\mathcal{B}_\delta(\hat{\theta})} f(\theta|Y) d\theta \end{aligned}$$

- The optimization problem $\min_{\hat{\theta}(Y)} \mathcal{R}_{UNIF}(\hat{\theta}(Y)|Y)$ hence leads to

$$\max_{\hat{\theta}(Y)} \int_{\mathcal{B}_\delta(\hat{\theta})} f(\theta|Y) d\theta \approx \text{Vol}(\mathcal{B}_\delta(0)) \max_{\hat{\theta}(Y)} f(\hat{\theta}|Y)$$

the approximation becomes arbitrarily accurate as δ becomes small



MAP Estimators: Vector Parameters (2)

- This leads to the Maximum A Posteriori (likelihood) estimator

$$\hat{\theta}_{MAP}(Y) = \arg \max_{\theta \in \Theta} f(\theta|Y) \quad \text{posterior likelihood}$$

- The same remarks as in the scalar case hold here also. In particular, one may equivalently obtain $\hat{\theta}_{MAP}(Y)$ from the optimization problem

$$\hat{\theta}_{MAP}(Y) = \arg \max_{\theta \in \Theta} \ln f(\theta|Y) \quad \text{posterior log likelihood}$$

- Under certain regularity conditions, $\hat{\theta}_{MAP}(Y)$ can be found from

$$\frac{\partial}{\partial \theta} \ln f(\theta|Y) = 0 = \frac{\partial}{\partial \theta} \ln f(Y|\theta) + \frac{\partial}{\partial \theta} \ln f(\theta)$$

- Also MAP commutes over linear transformations: $\phi = A\theta$ (A invertible)

$$\begin{aligned} \hat{\phi}_{MAP}(Y) &= \arg \max_{\phi} f_{\phi|Y}(\phi|Y) = A \arg \max_{\theta} f_{\phi|Y}(A\theta|Y) \\ &= A \arg \max_{\theta} \frac{1}{|\det A|} f_{\theta|Y}(\theta|Y) = A \hat{\theta}_{MAP}(Y). \end{aligned}$$

This argument can be extended to the case in which $\dim \phi \neq \dim \theta$



Fisher Information Matrix

There exists a lower bound on the correlation matrix of the estimator errors. It is independent of the Bayes estimator (cost) used; it depends only on the posterior distribution. The lower bound is specified in terms of the *information matrix*, which should express in quantitative terms the information carried by the posterior distribution about the parameters θ . For such an information measure, the following properties are desirable:

- The information should increase as the *sensitivity* of $f(\theta|Y)$ to changes in θ increases. Hence, the information should be an increasing function of $\frac{\partial f(\theta|Y)}{\partial \theta}$ or of $\frac{\partial \ln f(\theta|Y)}{\partial \theta}$.
- The information should be *additive* in the sense that it should be the sum of the informations from the prior distribution ($f(\theta)$) and from the data ($f(Y|\theta)$). Furthermore if, given θ , Y_1 and Y_2 are independent ($f(Y_1, Y_2|\theta) = f(Y_1|\theta)f(Y_2|\theta)$), then the informations in Y_1 and Y_2 should add up.
- The information should be positive and should be insensitive to a change of sign of θ .
- The information should be a *deterministic* quantity.



Fisher Information Matrix (2)

- The information matrix is defined as

$$J = E \left(\frac{\partial \ln f(\theta|Y)}{\partial \theta} \right) \left(\frac{\partial \ln f(\theta|Y)}{\partial \theta} \right)^T$$

It can be shown to satisfy all the properties mentioned above.

- The perturbation of Mutual Information (Information Theory) w.r.t. a parameter can be expressed in terms of its Fisher Information.
- With $\frac{\partial \ln f(\theta|Y)}{\partial \theta} = \frac{1}{f(\theta|Y)} \frac{\partial f(\theta|Y)}{\partial \theta}$ we can write the Hessian of $\ln f(\theta|Y)$ as

$$\begin{aligned} \frac{\partial}{\partial \theta} \left(\frac{\partial \ln f(\theta|Y)}{\partial \theta} \right)^T &= \frac{1}{f^2(\theta|Y)} \left[f(\theta|Y) \frac{\partial}{\partial \theta} \left(\frac{\partial f(\theta|Y)}{\partial \theta} \right)^T - \left(\frac{\partial f(\theta|Y)}{\partial \theta} \right) \left(\frac{\partial f(\theta|Y)}{\partial \theta} \right)^T \right] \\ &= \frac{1}{f(\theta|Y)} \frac{\partial}{\partial \theta} \left(\frac{\partial f(\theta|Y)}{\partial \theta} \right)^T - \left(\frac{\partial \ln f(\theta|Y)}{\partial \theta} \right) \left(\frac{\partial \ln f(\theta|Y)}{\partial \theta} \right)^T \end{aligned}$$

- For the expectation of the first term, we get

$$\begin{aligned} E \frac{1}{f(\theta|Y)} \frac{\partial}{\partial \theta} \left(\frac{\partial f(\theta|Y)}{\partial \theta} \right)^T &= \int d\theta \int dY f(Y) \frac{\partial}{\partial \theta} \left(\frac{\partial f(\theta|Y)}{\partial \theta} \right)^T \\ &= \frac{\partial}{\partial \theta} \left(\frac{\partial}{\partial \theta} \int d\theta \int dY f(Y) f(\theta|Y) \right)^T = \frac{\partial}{\partial \theta} \left(\frac{\partial}{\partial \theta} 1 \right)^T = 0 \end{aligned}$$



Fisher Information Matrix (3)

- It follows that we can rewrite the information matrix as

$$J = -E \frac{\partial}{\partial \theta} \left(\frac{\partial \ln f(\theta|Y)}{\partial \theta} \right)^T$$

This expression will often allow us to obtain J more easily.

- Note also that

$$\frac{\partial \ln f(Y, \theta)}{\partial \theta} = \frac{\partial \ln f(\theta|Y)}{\partial \theta} + \underbrace{\frac{\partial \ln f(Y)}{\partial \theta}}_{=0} = \frac{\partial \ln f(\theta|Y)}{\partial \theta}$$

so that as long as derivatives are taken, we can interchange $f(Y, \theta)$ and $f(\theta|Y)$.
Hence

$$\frac{\partial \ln f(Y, \theta)}{\partial \theta} = \frac{\partial \ln f(\theta|Y)}{\partial \theta} = \frac{\partial \ln f(Y|\theta)}{\partial \theta} + \frac{\partial \ln f(\theta)}{\partial \theta}$$

and

$$J = -E \frac{\partial}{\partial \theta} \left(\frac{\partial \ln f(\theta, Y)}{\partial \theta} \right)^T = \underbrace{-E \frac{\partial}{\partial \theta} \left(\frac{\partial \ln f(Y|\theta)}{\partial \theta} \right)^T}_{J_{data}} - \underbrace{E \frac{\partial}{\partial \theta} \left(\frac{\partial \ln f(\theta)}{\partial \theta} \right)^T}_{J_{prior}}$$



Conditions on the Estimator Bias

- The (conditional) *bias* of an estimator $\hat{\theta}(Y)$ of θ is defined as

$$b_{\hat{\theta}}(\theta) = -E_{Y|\theta} \tilde{\theta} = E_{Y|\theta} (\hat{\theta}(Y) - \theta) = E_{Y|\theta} \hat{\theta}(Y) - \theta$$

- An estimator will be called *unbiased* if either

$$E_{\theta} b_{\hat{\theta}}(\theta) = 0 \Leftrightarrow E_{\theta, Y} \tilde{\theta} = 0$$

which means that the unconditional or average bias is zero, or

$$\lim_{\theta \rightarrow \partial\Theta} f(\theta) b_{\hat{\theta}}(\theta) = 0$$

where Θ is the domain for θ and $\partial\Theta$ is its boundary.

- **Lemma 0.1 (Unit Cross Correlation)** *If either condition above is satisfied, then*

$$E \frac{\partial \ln f(Y, \theta)}{\partial \theta} (\hat{\theta} - \theta)^T = I.$$

In words, the cross correlation matrix between $\frac{\partial \ln f(Y, \theta)}{\partial \theta}$ and the estimation error of any unbiased estimator is the identity matrix.



Inner Products

- An inner product $\langle \cdot, \cdot \rangle$ associates a real number $\langle x, y \rangle \in \mathcal{R}$ with two vectors x and y of the vector space \mathcal{V} we are considering, and it has the following properties:

1. *linearity*: $\forall \alpha_1, \alpha_2, \beta_1, \beta_2 \in \mathcal{R}, \forall x, x_1, x_2, y, y_1, y_2 \in \mathcal{V}$:

$$\begin{aligned} \langle \alpha_1 x_1 + \alpha_2 x_2, y \rangle &= \alpha_1 \langle x_1, y \rangle + \alpha_2 \langle x_2, y \rangle \\ \langle x, \beta_1 y_1 + \beta_2 y_2 \rangle &= \langle x, y_1 \rangle \beta_1 + \langle x, y_2 \rangle \beta_2 \end{aligned} \tag{1}$$

2. *symmetry*: $\langle x, y \rangle = \langle y, x \rangle$

3. *non-degeneracy* (of the norm induced by the inner product):

$$\langle x, x \rangle = \|x\|^2 \geq 0. \text{ If } \|x\| = 0, \text{ then } x = 0.$$

- One particular example is a space of random variables with the correlation as inner product: $\langle x, y \rangle = E xy$. Non-degeneracy subtlety:

$$E x^2 = 0 \Rightarrow x = 0 \text{ in m.s.}$$

$x = 0$ “in mean square”. Indeed, $E x^2 = m_x^2 + \sigma_x^2 = 0 \Rightarrow m_x = 0, \sigma_x^2 = 0$. This often (not always) implies $x = 0$ “almost surely” (a.s.) or “almost everywhere” (a.e.) or “with probability 1” (w.p. 1): $\Pr(x = 0) = 1$.



Matrix Inner Products

- We now consider a vector space in which the vectors have multiple components such that the inner product is a real matrix. Example 1: consider a vector space of random vectors with inner product $\langle X, Y \rangle = E XY^T$ where X and Y are column vectors of random variables (not necessarily with the same number of rows).
- Example 2: a vector space in which the “vectors” are $* \times k$ real matrices where k is fixed and $*$ is arbitrary. Inner product: $\langle X, Y \rangle = XY^T$.
- Matrix valued inner products satisfy the following properties, which are natural generalizations of the scalar case.

1. linearity: let $X, X_1, X_2 \in \mathcal{V}$ have m rows and $Y, Y_1, Y_2 \in \mathcal{V}$ have n rows. Then $\forall \alpha_1, \alpha_2 \in \mathcal{R}^{k \times m}, \forall \beta_1, \beta_2 \in \mathcal{R}^{l \times n}$, for any k and l ,

$$\begin{aligned} \langle \alpha_1 X_1 + \alpha_2 X_2, Y \rangle &= \alpha_1 \langle X_1, Y \rangle + \alpha_2 \langle X_2, Y \rangle \\ \langle X, \beta_1 Y_1 + \beta_2 Y_2 \rangle &= \langle X, Y_1 \rangle \beta_1^T + \langle X, Y_2 \rangle \beta_2^T \end{aligned} \quad (2)$$

2. symmetry: $\langle X, Y \rangle = \langle Y, X \rangle^T$

3. non-degeneracy: $\langle X, X \rangle = \|X\|^2 \geq 0$. If $\|X\|^2 = 0$, then $X = 0$.



Schur Complements

- **Lemma 0.2 (Schur Complements)** Let X_1 and X_2 be vectors in a certain vector space with a certain inner product and denote $R_{ij} = \langle X_i, X_j \rangle$, $i, j = 1, 2$ so that $R_{ij} = R_{ji}^T$. Assume that R_{11} is nonsingular. Then, because of property 3 of the inner product (non-degeneracy), we have

$$\begin{aligned} \|X_2 - R_{21}R_{11}^{-1}X_1\|^2 &= \langle X_2 - R_{21}R_{11}^{-1}X_1, X_2 - R_{21}R_{11}^{-1}X_1 \rangle \\ &= R_{22} - 2R_{21}R_{11}^{-1}R_{12} + R_{21}R_{11}^{-1}R_{11}R_{11}^{-1}R_{12} \\ &= R_{22} - R_{21}R_{11}^{-1}R_{12} \geq 0 \end{aligned}$$

with equality iff $X_2 = R_{21}R_{11}^{-1}X_1$.

(matrix version of Cauchy-Schwarz inequality)

- The name for this lemma stems from the following congruence relation

$$\begin{aligned} \left\langle \begin{bmatrix} X_1 \\ X_2 \end{bmatrix}, \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \right\rangle &= \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} = \begin{bmatrix} I & O \\ R_{21}R_{11}^{-1} & I \end{bmatrix} \begin{bmatrix} R_{11} & 0 \\ 0 & R_{22} - R_{21}R_{11}^{-1}R_{12} \end{bmatrix} \begin{bmatrix} I & R_{11}^{-1}R_{12} \\ O & I \end{bmatrix} \\ &= \begin{bmatrix} I \\ R_{21}R_{11}^{-1} \end{bmatrix} R_{11} \begin{bmatrix} I \\ R_{21}R_{11}^{-1} \end{bmatrix}^T + \begin{bmatrix} 0 & 0 \\ 0 & R_{22} - R_{21}R_{11}^{-1}R_{12} \end{bmatrix}. \end{aligned}$$

(block LDU triangular factorization). The matrix $R_{22} - R_{21}R_{11}^{-1}R_{12}$ is called the *Schur complement* of R_{11} within the big matrix on the LHS.