Optimal prediction theory *

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1. Optimal mean square prediction

Let $Y,\ X_1,\ \ldots\ ,\ X_k$ be real random variables in L^2, and $X = (X_1,\ \ldots\ ,\ X_k)'$. We wish to find a function

$$g(X) = g(X_1,\ \ldots\ ,\ X_k)$$

such that

$$\mathsf{E}\left([Y - g(X)]^2 \right) \text{ is minimal.}$$

Given the mean square criterion, we also restrict $g(X)$ to be in L^2 :

$$\mathsf{E}\left[g(X)^2 \right] < \infty .$$

Then it is easy to see that the optimal solution to this problem is

$$g(X) = M(X)$$

where

$$M(X) = \mathsf{E}(Y \mid X) \ .$$

In general, $M(X)$ is a nonlinear function of X. The optimality of $M(X)$ can easily be shown on observing that :

$$\begin{aligned}
\mathsf{E}\left\{ [Y - g(X)]^2 \right\} &= \mathsf{E}\left\{ [Y - \mathsf{E}(Y \mid X) + \mathsf{E}(Y \mid X) - g(X)]^2 \right\} \\
&= \mathsf{E}\left\{ [Y - \mathsf{E}(Y \mid X)]^2 + [\mathsf{E}(Y \mid X) - g(X)]^2 \right. \\
&\quad \left. + 2\,[Y - \mathsf{E}(Y \mid X)]\,[\mathsf{E}(Y \mid X) - g(X)] \right\} \\
&= \mathsf{E}\left\{ [Y - \mathsf{E}(Y \mid X)]^2 \right\} + \mathsf{E}\left\{ [\mathsf{E}(Y \mid X) - g(X)]^2 \right\} \\
&\quad + 2E\left\{ [\mathsf{E}(Y \mid X) - g(X)]\ \mathsf{E}[Y - \mathsf{E}(Y \mid X) \mid X] \right\} \\
&= \mathsf{E}\left\{ [Y - \mathsf{E}(Y \mid X)]^2 \right\} + \mathsf{E}\left\{ [\mathsf{E}(Y \mid X) - g(X)]^2 \right\}
\end{aligned}$$

from which it follows that the optimal solution is

$$g(X) = \mathsf{E}(Y \mid X) \ .$$

The set of random variables

$$M_0 = \left\{ Z : Z = g(X) \text{ is a random variable and } \mathsf{E}\left(Z^2\right) < \infty \right\}$$

is a closed subspace of L^2. $M(X) = \mathsf{E}(Y \mid X)$ can be interpreted as the projection of Y on M_0 :

$$\mathsf{E}(Y \mid X) = P_{M_0} Y.$$

2. Properties of conditional expectations

Let

$$\begin{aligned} Y &= (Y_1, \ldots, Y_q)' , \\ Z &= (Z_1, \ldots, Z_q)' , \\ X &= (X_1, \ldots, X_k) \end{aligned}$$

be random vectors whose components are all in L^2. By definition,

$$\mathsf{E}(Y \mid X) = \begin{bmatrix} \mathsf{E}(Y_1 \mid X) \\ \mathsf{E}(Y_2 \mid X) \\ \vdots \\ \mathsf{E}(Y_q \mid X) \end{bmatrix}$$

and similarly for $\mathsf{E}(Z \mid X)$.

Let $L^2(X)$ be the set of random variables W such that $W = g(X)$ and $\mathsf{E}(W^2) < \infty$.

2.1 Proposition LINEARITY. *Let A an $m \times q$ fixed matrix and b an $m \times 1$ fixed vector. Then*

$$\begin{aligned} \mathsf{E}(AY + b \mid X) &= AE(Y \mid X) + b , \\ \mathsf{E}(Y + Z \mid X) &= \mathsf{E}(Y \mid X) + \mathsf{E}(Z \mid X) . \end{aligned}$$

2.2 Proposition POSITIVITY. *If $Y_i \geq 0$, for $i = 1, \ldots, q$, then*

$$\mathsf{E}(Y_i \mid X) \geq 0 , \quad \text{for} \quad i = 1, \ldots, q .$$

2.3 Proposition MONOTONICITY. *If $Y_i \geq Z_i$, for $i = 1, \ldots, q$, then*

$$\mathsf{E}(Y_i \mid X) \geq \mathsf{E}(Z_i \mid X) , \quad \text{for} \quad i = 1, \ldots, q .$$

2.4 Proposition INVARIANCE.

$$\begin{aligned} \mathsf{E}(Y \mid X) = Y \quad &\Leftrightarrow \quad Y \text{ is a function of } X \\ &\Leftrightarrow \quad \text{there is a function } g(x) \text{ such that } Y = g(X) \\ &\qquad \text{with probability } 1. \end{aligned}$$

2.5 Proposition ORTHOGONALITY. *If $g_1(X) \in L^2$ and $g_2(Y) \in L^2$, then*

$$\mathsf{E}\{g_1(X)[g_2(Y) - \mathsf{E}(g_2(Y) \mid X)]\} = 0 .$$

2.6 Proposition ITERATED CONDITIONINGS LAW. *If W is a random vector such that*

$$L^2(W) \subseteq L^2(X) \ ,$$

then

$$\begin{aligned} \mathsf{E}[\mathsf{E}(Y \mid X) \mid W] &= \mathsf{E}[\mathsf{E}(Y \mid W) \mid X] \\ &= \mathsf{E}(Y \mid W) \ . \end{aligned}$$

2.7 Proposition MEAN SQUARE OPTIMALITY.

$$\mathsf{E}\left[(Y_i - \mathsf{E}(Y_i \mid X))^2\right] = \min_{g_i(X) \in L^2(X)} \mathsf{E}\left[(Y_i - g_i(X))^2\right], \ i = 1, \ \ldots \ , q \, .$$

2.8 Proposition CHARACTERIZATION OF OPTIMALITY BY ORTHOGONALITY. *For any $i = 1, \ \ldots \ , \ q$,*

$$h_i(X) = \mathsf{E}(Y_i \mid X) \Leftrightarrow \mathsf{E}[g(X)(Y_i - h_i(X))] = 0 \ , \ \forall g(X) \in L^2(X) \ .$$

2.9 Definition CONDITIONAL COVARIANCE. *The conditional covariance matrix of Y given X is the matrix*

$$\mathsf{V}(Y \mid X) = \mathsf{E}\left[(Y - \mathsf{E}(Y \mid X))(Y - \mathsf{E}(Y \mid X))' \mid X\right] \ .$$

If we define

$$\varepsilon(X) = Y - \mathsf{E}(Y \mid X) \ ,$$

we see easily that

$$\mathsf{V}[\varepsilon(X)] = \mathsf{E}[\mathsf{V}(Y \mid X)] \ .$$

We can then write

$$Y = \mathsf{E}(Y \mid X) + \varepsilon(X)$$

where $\mathsf{E}(Y \mid X)$ and $\varepsilon(X)$ are uncorrelated.

2.10 Proposition VARIANCE DECOMPOSITION.

$$\begin{aligned} \mathsf{V}(Y) &= \mathsf{V}[\mathsf{E}(Y \mid X)] + \mathsf{V}[\varepsilon(X)] \\ &= \mathsf{V}[\mathsf{E}(Y \mid X)] + \mathsf{E}[\mathsf{V}(Y \mid X)] \ . \end{aligned}$$

3. Linear regression

Consider again the setup of Section 1. We now study the problem of finding a function of the form

$$\begin{aligned} L(X) &= b_0 + b_1 X_1 + \cdots + b_k X_k \\ &= \sum_{i=0}^{k} b_i X_i = b'x \end{aligned}$$

where

$$X_0 = 1,\ b = (b_0,\, b_1,\, \ldots,\, b_k)' \tag{3.1}$$

$$x = (X_0,\, X_1,\, \ldots,\, X_k)', \tag{3.2}$$

such that the mean square prediction error

$$\mathsf{E}\left\{[Y - L(X)]^2\right\} = \mathsf{E}\left[(Y - b'x)^2\right]$$

is minimal. In other words, we wish to minimize (with respect to b) the function

$$\begin{aligned} S(b) &= \mathsf{E}\left\{[Y - b'x]^2\right\} \\ &= \mathsf{E}\left(Y^2\right) - 2b'\mathsf{E}(xY) + b'\mathsf{E}(xx')\, b\,. \end{aligned}$$

It is easy to see that the optimal value of b must satisfy the equation

$$\mathsf{E}[x(Y - b'x)] = 0$$

or

$$\mathsf{E}(xx')\, b = \mathsf{E}(xY)\ .$$

If we write

$$b = \begin{pmatrix} \beta_0 \\ \gamma \end{pmatrix},\ \gamma = \begin{pmatrix} \gamma_1 \\ \vdots \\ \gamma_k \end{pmatrix},\ X = \begin{pmatrix} X_1 \\ \vdots \\ X_k \end{pmatrix},$$

we see that

$$\begin{bmatrix} 1 & \mathsf{E}(X)' \\ \mathsf{E}(X) & \mathsf{E}(XX') \end{bmatrix} \begin{bmatrix} \beta_0 \\ \gamma \end{bmatrix} = \begin{bmatrix} \mathsf{E}(Y) \\ \mathsf{E}(XY) \end{bmatrix},$$

hence

$$\begin{aligned} \beta_0 + \mathsf{E}(X)'\gamma &= \mathsf{E}(Y) && (3.3) \\ \mathsf{E}(Y)\beta_0 + \mathsf{E}(XX')\gamma &= \mathsf{E}(XY) && (3.4) \end{aligned}$$

and

$$\beta_0 = \mathsf{E}(Y) - \mathsf{E}(X)'\gamma .$$

Further, by the basic properties of the expectation operator,

$$\begin{aligned} \mathsf{E}(XX') &= \mathsf{V}(X) + \mathsf{E}(X)\mathsf{E}(X)' , \\ \mathsf{E}(XY) &= \mathsf{C}(X, Y) + \mathsf{E}(X)\mathsf{E}(Y) \end{aligned}$$

where

$$\begin{aligned} \mathsf{V}(X) &= \mathsf{E}\left\{\mathsf{E}[X - \mathsf{E}(X)][X - \mathsf{E}(X)]'\right\} , && (3.5) \\ \mathsf{C}(X, Y) &= \mathsf{E}\left\{[X - \mathsf{E}(X)][Y - \mathsf{E}(Y)]'\right\} . && (3.6) \end{aligned}$$

By the equations (3.3)-(3.6), we then see easily that

$$\begin{aligned} \mathsf{E}(X)\beta_0 + \mathsf{E}(X)\mathsf{E}(X)'\gamma &= \mathsf{E}(X)\mathsf{E}(Y) , \\ \mathsf{E}(X)\beta_0 + \mathsf{V}(X)\gamma + \mathsf{E}(X)\mathsf{E}(X)'\gamma &= \mathsf{C}(X, Y) + \mathsf{E}(X)\mathsf{E}(Y) \end{aligned}$$

hence

$$\mathsf{V}(X)\gamma = \mathsf{C}(X, Y) .$$

Thus,

$$\begin{aligned} \beta_0 &= \mathsf{E}(Y) - \mathsf{E}(X)'\gamma , && (3.7) \\ \mathsf{V}(X)\gamma &= \mathsf{C}(X, Y) . && (3.8) \end{aligned}$$

The function

$$L(X) = \beta_0 + X'\gamma$$

is called the

linear regression of X on Y

or the

affine projection of Y on X. (3.9)

We write

$$L(X) = P_L(Y \mid X) = \beta_0 + X'\gamma$$

where β_0 and γ are any solution of the normal equations:

$$\begin{aligned} \mathsf{V}(X)\gamma &= \mathsf{C}(X, Y) , \\ \beta_0 &= \mathsf{E}(Y) - \mathsf{E}(X)'\gamma . \end{aligned}$$

If we denote by

$$\varepsilon = Y - P_L(Y \mid X)$$

the prediction error, we see easily that:

$$\begin{aligned} \mathsf{E}(\varepsilon) &= 0 , \\ \mathsf{C}(X, \varepsilon) &= 0 . \end{aligned}$$

In the language of Hilbert space theory, we can also write

$$L(X) = P_M Y = P_L(Y \mid X)$$

where

$$M = \overline{sp}\{1, X\} = \overline{sp}\{1, X_1, \ldots, X_k\} .$$

If

$$\det[\mathsf{V}(X)] \neq 0 ,$$

the optimal coefficients β_0 and γ are uniquely defined :

$$\gamma = \mathsf{V}(X)^{-1}\mathsf{C}(X, Y) , \ \beta_0 = \mathsf{E}(Y) - \mathsf{E}(X)'\gamma .$$

4. Properties of the projection operator

Let

$$\begin{aligned} Y &= (Y_1, \ldots, Y_q)' , \\ Z &= (Z_1, \ldots, Z_q)' , \\ X &= (X_1, \ldots, X_k) \end{aligned}$$

be random vectors whose components are all in L^2. By definition,

$$\mathsf{P}_L(Y \mid X) = \begin{bmatrix} \mathsf{P}_L(Y_1 \mid X) \\ \mathsf{P}_L(Y_2 \mid X) \\ \vdots \\ \mathsf{P}_L(Y_q \mid X) \end{bmatrix}$$

We call $\mathcal{L}(X)$ the set of all linear transformations of X.

4.1 Proposition *If* $\det[V(X)] \neq 0$,

$$\begin{aligned} \mathsf{P}_L(Y \mid X) &= \mathsf{E}(Y) + \mathsf{C}(Y, X)\mathsf{V}(X)^{-1}(X - \mathsf{E}(X)) \\ &= [\mathsf{E}(Y) - \mathsf{C}(Y, X)\mathsf{V}(X)^{-1}\mathsf{E}(X)] + \mathsf{C}(Y, X)\mathsf{V}(X)^{-1}X\,. \end{aligned} \tag{4.1}$$

4.2 Proposition LINEARITY. *Let A and B be two fixed matrices of dimensions $n \times q$ and $1 \times n$ respectively. Then*

$$\mathsf{P}_L(AY \mid X) = A\,\mathsf{P}_L(Y \mid X)\,, \tag{4.2}$$

$$\mathsf{P}_L(YB \mid X) = \mathsf{P}_L(Y \mid X)\,B\,, \tag{4.3}$$

$$\mathsf{P}_L(Y + Z \mid X) = \mathsf{P}_L(Y \mid X) + \mathsf{P}_L(Z \mid X)\,. \tag{4.4}$$

4.3 Proposition INVARIANCE.

$$\begin{aligned} \mathsf{P}_L(Y \mid X) = Y &\Leftrightarrow Y \textit{ is a linear function of } X \\ &\Leftrightarrow Y = AX + b \textit{ with probability 1} \end{aligned}$$

where A and b are fixed matrices.

Note that

4.4 Proposition ORTHOGONALITY. *If* $\varepsilon_L(X) = Y - \mathsf{P}_L(Y \mid X)$,

$$\mathsf{C}\big(\varepsilon_L(X),\, X\big) = 0\,. \tag{4.5}$$

4.5 Proposition LAW OF ITERATED PROJECTIONS. *If W is a random vector such that*

$$\mathcal{L}(W) \subseteq \mathcal{L}(X)\,,$$

then

$$\begin{aligned} \mathsf{P}_L[\mathsf{P}_L(Y \mid X) \mid W] &= \mathsf{P}_L[\mathsf{P}_L(Y \mid W) \mid X] \\ &= \mathsf{P}_L(Y \mid W)\,. \end{aligned}$$

In particular, if $X = W$,

$$\mathsf{P}_L[\mathsf{P}_L(Y \mid X) \mid X] = \mathsf{P}_L(Y \mid X) \tag{4.6}$$

4.6 Proposition PROJECTION ON UNCORRELATED VECTORS. *If X and W are uncorrelated, then*

$$\mathsf{P}_L\left(Y \mid X,\, W\right) = \mathsf{P}_L\left(Y \mid X\right) + \mathsf{P}_L\left(Y \mid X\right) - \mathsf{E}(Y)\,. \tag{4.7}$$

4.7 Proposition FRISCH-WAUGH THEOREM.

$$\mathsf{P}_L\left(Y \mid X,\, W\right) = \mathsf{P}_L\left(Y \mid X\right) + \mathsf{P}_L\big(Y \mid W - \mathsf{P}_L\left(W \mid X\right)\big) - \mathsf{E}(Y)\,. \tag{4.8}$$

5. Prediction based on an infinite number of variables

It is possible to generalized the concept of projection to the case where X contains an infinite number of variables

$$X \equiv \overline{X}_{t-1} = \left(X_{t-1},\, X_{t-2}\,,\, \ldots\right) = \left(X_{t-k} : k \geq 1\right). \tag{5.1}$$

Let Y a scalar random variable. If we consider a potentially infinite set I of random variables such that the variables in I have finite second order moments, we can define the set $\mathcal{L}^2(I)$ of linear transformations of a finite set of variables from I. Then we can define $\mathcal{H}(I)$ the smallest set of random variables in L^2 such that $\mathcal{H}(I)$ is closed, i.e. $\mathcal{H}(I)$ satisfies the following condition: if

$$\{Y_n : n \in \mathbb{Z}\} \subseteq \mathcal{H}(I) \tag{5.2}$$

then

$$\mathsf{E}\left[(Y_m - Y_n)^2\right] \longrightarrow 0 \text{ when } m,\, n \longrightarrow \infty \tag{5.3}$$

entails

$$\text{there exists } Y \in \mathcal{H}(I) \text{ such that } \mathsf{E}\big[\,(Y_n - Y)^2\,\big] \underset{n\to\infty}{\longrightarrow} 0\,. \tag{5.4}$$

We call $\mathcal{H}(I)$ the "Hilbert space" generated by I.

5.1 Theorem *There exists a unique random variable $\widehat{Y}_{|t-1} \equiv \mathsf{P}_L(Y \mid I)$ such that*

$$\mathsf{E}\big[\big(Y - \widehat{Y}_{|t-1}\big)^2\big] = \inf_{Z \in \mathcal{H}(I)} \mathsf{E}\big[\big(Y - Z\big)^2\big]\,. \tag{5.5}$$

The operator $\mathsf{P}_L(Y \mid I)$ enjoys properties sated in Propositions **4.2** to **4.7**.

6. Bibliographic notes

On the properties of conditional expectations, see Gouriéroux and Monfort (1995, Appendix B) and Williams (1991).

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