

# Joint Distribution Functions

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# Conditional Distributions

A conditional distribution provides the probability of a random variable, given that it was conditioned on the value of a second random variable.

# Discrete Conditional Distributions

Let  $X$  and  $Y$  be 2 discrete random variables, with a joint distribution function of

$$p_{X,Y}(x, y) = P(X = x, Y = y)$$

The conditional distribution of  $X|Y = y$  is defined as

$$p_{X|Y=y}(x) = \frac{p_{X,Y}(x, y)}{p_Y(y)}$$

# Continuous Conditional Distributions

Let  $X$  and  $Y$  be 2 continuous random variables, with a joint density function of  $f_{X,Y}(x, y)$ . The conditional distribution of  $X|Y = y$  is defined as

$$f_{X|Y=y}(x) = \frac{f_{X,Y}(x, y)}{f_Y(y)}$$

# Bivariate Normal Conditional Distribution

# Multivariate Normal

The normal distribution function can be extended to from univariate ( $n=1$ ), bivariate ( $n=2$ ), to a  $k$ -dimensional normal distribution function:

$$X \sim N_k(\mu, \Sigma)$$

# Multivariate Normal Parameters

$$X = \begin{pmatrix} X_1 \\ \vdots \\ X_k \end{pmatrix} \quad \mu = \begin{pmatrix} \mu_1 \\ \vdots \\ \mu_k \end{pmatrix} \quad \Sigma = \begin{pmatrix} \sigma_1^2 & \sigma_{21} & \cdots & \sigma_{k1} \\ \sigma_{21} & \sigma_2^2 & \cdots & \vdots \\ \vdots & \cdots & \ddots & \vdots \\ \sigma_{k1} & \sigma_{k2} & \cdots & \sigma_k^2 \end{pmatrix}$$

# Multivariate Normal PDF

$$f_X(x) = \det(2\pi\Sigma)^{-1/2} \exp \left\{ -\frac{1}{2}(x - \mu)^T \Sigma^{-1}(x - \mu) \right\}$$



# Marginal Normal Distribution

$$X = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \quad x_1 = \begin{pmatrix} X_1 \\ \vdots \\ X_j \end{pmatrix} \quad x_2 = \begin{pmatrix} X_{j+1} \\ \vdots \\ X_k \end{pmatrix}$$

# Marginal Normal Distribution

$$\mu = \begin{pmatrix} \varpi_1 \\ \varpi_2 \end{pmatrix} \quad \varpi_1 = \begin{pmatrix} \mu_1 \\ \vdots \\ \mu_j \end{pmatrix} \quad \varpi_2 = \begin{pmatrix} \mu_{j+1} \\ \vdots \\ \mu_k \end{pmatrix}$$

# Marginal Normal Distribution

$$\Sigma = \begin{pmatrix} \Sigma_{11} & \Sigma_{21} \\ \Sigma_{12} & \Sigma_{22} \end{pmatrix}$$

# Marginal Normal Distribution

$$\mathcal{X}_1 \sim N_j(\varpi_1, \Sigma_{11})$$

$$\mathcal{X}_2 \sim N_{k-j}(\varpi_2, \Sigma_{22})$$

# Conditional Normal Distribution

$$\mathcal{X}_2 | \mathcal{X}_1 \sim N_j(\varpi_2 + \Sigma_{21} \Sigma_{11}^{-1} (\mathcal{X}_1 - \varpi_1), \Sigma_{22} - \Sigma_{21} \Sigma_{11}^{-1} \Sigma_{12})$$

# Independent Random Variables

Random variables are considered independent of each other if the probability of one variable does not affect the probability of another variable.

# Discrete Independent Random Variables

Let  $X$  and  $Y$  be 2 discrete random variables, with a joint density function of  $p_{X,Y}(x, y)$ .  $X$  is independent of  $Y$  if and only if

$$p_{X,Y}(x, y) = p_X(x)p_Y(y)$$

# Continuous Independent Random Variables

Let  $X$  and  $Y$  be 2 continuous random variables, with a joint density function of  $f_{X,Y}(x, y)$ .  $X$  is independent of  $Y$  if and only if

$$f_{X,Y}(x, y) = f_X(x)f_Y(y)$$



# Matrix Algebra

$$A = \begin{pmatrix} a_1 & 0 \\ 0 & a_2 \end{pmatrix}$$

$$\det(A) = a_1 a_2$$

$$A^{-1} = \begin{pmatrix} 1/a_1 & 0 \\ 0 & 1/a_2 \end{pmatrix}$$

## Example

$$\begin{pmatrix} X \\ Y \end{pmatrix} \sim N_2 \left\{ \begin{pmatrix} \mu_x \\ \mu_y \end{pmatrix}, \begin{pmatrix} \sigma_x^2 & 0 \\ 0 & \sigma_y^2 \end{pmatrix} \right\}$$

Show that  $X \perp Y$  (this will be on the upcoming test!).

# Covariance

Let  $X$  and  $Y$  be 2 random variables with mean  $E(X) = \mu_x$  and  $E(Y) = \mu_y$ , respectively. The covariance of  $X$  and  $Y$  is defined as

$$Cov(X, Y) = E\{(X - \mu_x)(Y - \mu_y)\}$$

$$Cov(X, Y) = E(XY) - \mu_x\mu_y$$

# Covariance

If  $X$  and  $Y$  are independent random variables, then

$$\text{Cov}(X, Y) = 0$$

# Correlation

The correlation of  $X$  and  $Y$  is defined as

$$\rho = \text{Cor}(X, Y) = \frac{\text{Cov}(X, Y)}{\sqrt{\text{Var}(X)\text{Var}(Y)}}$$

# Expectations

Let  $X = (X_1, X_2, \dots, X_n)^T$  be a set of random variables, the expectation of a function  $g(X)$  is defined as

$$E\{g(X)\} = \sum_{x_1 \in X_1} \cdots \sum_{x_n \in X_n} g(X) p(x, \theta)$$

or

$$E\{g(X)\} = \int_{x_1 \in X_1} \cdots \int_{x_n \in X_n} g(X) f(x, \theta) dx_n \cdots dx_1$$

# Expected Value and Variance of Linear Functions

Let  $X_1, \dots, X_n$  and  $Y_1, \dots, Y_m$  be random variables with  $E(X_i) = \mu_i$  and  $E(Y_j) = \tau_j$ . Furthermore, let  $U = \sum_{i=1}^n a_i X_i$  and  $V = \sum_{j=1}^m b_j Y_j$  where  $\{a_i\}_{i=1}^n$  and  $\{b_j\}_{j=1}^m$  are constants. We have the following properties:

- $E(U) = \sum_{i=1}^n a_i \mu_i$
- $Var(U) = \sum_{i=1}^n a_i^2 Var(X_i) + 2 \sum_{i < j} a_i a_j Cov(X_i, X_j)$
- $Cov(U, V) = \sum_{i=1}^n \sum_{j=1}^m a_i b_j Cov(X_i, Y_j)$

# Conditional Expectations

Let  $X_1$  and  $X_2$  be two random variables, the conditional expectation of  $g(X_1)$ , given  $X_2 = x_2$ , is defined as

$$E\{g(X_1)|X_2 = x_2\} = \sum_{x_1} g(x_1)p(x_1|x_2)$$

or

$$E\{g(X_1)|X_2 = x_2\} = \int_{x_1} g(x_1)f(x_1|x_2)dx_1.$$



# Conditional Expectations

Furthermore,

$$E(X_1) = E_{X_2}\{E_{X_1|X_2}(X_1|X_2)\}$$

and

$$Var(X_1) = E_{X_2}\{Var_{X_1|X_2}(X_1|X_2)\} + Var_{X_2}\{E_{X_1|X_2}(X_1|X_2)\}$$