

Introduction to Probability

Lecture 6: Marginals and Joint Distributions

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Experiments often involve **several** random variables, and some of them may **influence** each other.

To this end, we will introduce:

- Joint/Marginal distribution of two (or more) variables
- Independence of two (or more) variables
- Covariance of two variables

For simplicity, we will mainly focus on **discrete** random variables.



Warm-Up Exercise



Example

Let $X_1, X_2 \in \{1, 2, \dots, 6\}$ be two independent rolls of an unbiased die. Let $S := X_1 + X_2$ and $M := \max\{X_1, X_2\}$. List the elements of the event $\{S = 7, M \leq 5\}$ and deduce the probability.

_____ Answer _____

Joint Probability

Joint Probability Mass Function

The **joint probability mass function** of two **discrete** random variables X and Y is the function $p : \mathbb{R}^2 \rightarrow [0, 1]$, defined by:

$$p_{X,Y}(a, b) = \mathbf{P}[X = a, Y = b] \quad \text{for } -\infty < a, b < \infty.$$

Joint Distribution Function

The **joint distribution function** of two (**discrete or continuous**) random variables X and Y is the function $F : \mathbb{R}^2 \rightarrow [0, 1]$, defined by:

$$F_{X,Y}(a, b) = \mathbf{P}[X \leq a, Y \leq b] \quad \text{for } -\infty < a, b < \infty.$$

Marginal Distribution

Given a joint distribution $F_{X,Y}$ of two random variables X, Y , one obtains the **marginal distribution** of X for any a as follows:

$$F_X(a) = \mathbf{P}[X \leq a] = \lim_{b \rightarrow \infty} F_{X,Y}(a, b).$$

Joint Distribution contains (much) more information than the two marginals!



Discrete Example 1

Example

Let $X_1, X_2 \in \{1, 2, \dots, 6\}$ be independent rolls of an unbiased die. Let $S := X_1 + X_2$ and $M := \max\{X_1, X_2\}$. Compute the **joint probability mass function** p of S and M and the **marginal distributions** of S and M .

Answer

| a | b | | | | | | $p_S(a)$ |
|----------|------|------|------|------|------|-------|----------|
| | 1 | 2 | 3 | 4 | 5 | 6 | |
| 2 | 1/36 | 0 | 0 | 0 | 0 | 0 | 1/36 |
| 3 | 0 | 2/36 | 0 | 0 | 0 | 0 | 2/36 |
| 4 | 0 | 1/36 | 2/36 | 0 | 0 | 0 | 3/36 |
| 5 | 0 | 0 | 2/36 | 2/36 | 0 | 0 | 4/36 |
| 6 | 0 | 0 | 1/36 | 2/36 | 2/36 | 0 | 5/36 |
| 7 | 0 | 0 | 0 | 2/36 | 2/36 | 2/36 | 6/36 |
| 8 | 0 | 0 | 0 | 1/36 | 2/36 | 2/36 | 5/36 |
| 9 | 0 | 0 | 0 | 0 | 2/36 | 2/36 | 4/36 |
| 10 | 0 | 0 | 0 | 0 | 1/36 | 2/36 | 3/36 |
| 11 | 0 | 0 | 0 | 0 | 0 | 2/36 | 2/36 |
| 12 | 0 | 0 | 0 | 0 | 0 | 1/36 | 1/36 |
| $p_M(b)$ | 1/36 | 3/36 | 5/36 | 7/36 | 9/36 | 11/36 | 1 |



Discrete Example 2

Example

Suppose an urn contains balls numbered $1, 2, \dots, N$. We draw $1 \leq n \leq N$ balls uniformly and **without replacement** from the urn. Let $X_i \in \{1, 2, \dots, N\}$ be the number of the ball drawn in the i -th step. What is the marginal distribution of X_i ?

Answer

We first compute the **joint distribution**. For distinct a_1, a_2, \dots, a_n ,

Fix i and consider the **marginal distribution** of X_i :



Joint Distributions of Continuous Variables

Definition

Random variables X and Y have a **joint continuous distribution** if for some function $f : \mathbb{R}^2 \rightarrow \mathbb{R}$ and for all numbers $a_1 \leq b_1$ and $a_2 \leq b_2$,

$$\mathbf{P}[a_1 \leq X \leq b_1, a_2 \leq Y \leq b_2] = \int_{a_1}^{b_1} \int_{a_2}^{b_2} f(x, y) dx dy.$$

The function f has to satisfy $f(x, y) \geq 0$ for all x and y , and $\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) dx dy = 1$. We call f the **joint probability density**.

As in one-dimensional case we switch from F to f by **differentiating** (or **integrating**):

$$F(a, b) = \int_{-\infty}^a \int_{-\infty}^b f(x, y) dx dy \quad \text{and} \quad f(x, y) = \frac{\partial^2}{\partial x \partial y} F(x, y)$$



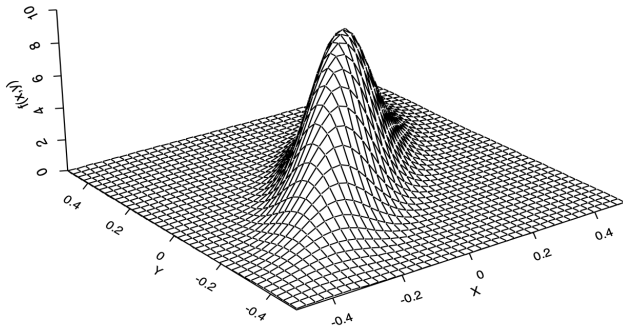
Example of a Joint Distribution of Continuous Random Variables

- Consider the density:

$$f(x, y) = \frac{30}{\pi} \cdot e^{-50x^2 - 50y^2 + 80xy},$$

where $-\infty < x, y < \infty$.

- This is an example of a so-called **bivariate normal probability density function**.



Source: Modern Introduction to Statistics



Dealing with Continuous Variables

Example (1/2)

Suppose that the joint probability density of X and Y is given by

$$f(x, y) = \begin{cases} 2e^{-x}e^{-2y} & \text{for } 0 < x < \infty, 0 < y < \infty, \\ 0 & \text{otherwise.} \end{cases}$$

Compute (i) $\mathbf{P}[X > 1, Y < 1]$ and (ii) $\mathbf{P}[X < Y]$.

Answer _____

(i) We first compute:

$$\mathbf{P}[X > 1, Y < 1] = \int_0^1 \int_1^{\infty} 2e^{-x}e^{-2y} dx dy$$



Dealing with Continuous Variables (cont.)

Example (2/2)

Suppose that the joint probability density of X and Y is given by

$$f(x, y) = \begin{cases} 2e^{-x}e^{-2y} & \text{for } 0 < x < \infty, 0 < y < \infty, \\ 0 & \text{otherwise.} \end{cases}$$

Compute (i) $\mathbf{P}[X > 1, Y < 1]$ and (ii) $\mathbf{P}[X < Y]$.

Answer

(ii) We have:

$$\begin{aligned} \mathbf{P}[X < Y] &= \int_0^{\infty} \int_0^y 2e^{-x}e^{-2y} dx dy \\ &= \frac{1}{3}. \end{aligned}$$

