

# Random vectors I.

(Random vectors, independence, conditional distribution)

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## Probability and Statistics

BIE-PST, WS 2026/27, Lecture 6



# Content

- **Probability theory:**

- ▶ Events, probability, conditional probability, Bayes' Theorem, independence of events.
- ▶ Random variables, distribution function, functions of random variables, characteristics of random variables: expected value, variance, moments, generating function, quantiles, critical values, important discrete and continuous distributions.
- ▶ Random vectors, joint and marginal distributions, functions of random vectors, independence of random variables, conditional distribution, functions of random vectors, covariance and correlation.
- ▶ Markov's and Chebyshev's inequality, weak law of large numbers, strong law of large numbers, Central limit theorem.

- **Mathematical statistics:**

- ▶ Point estimators, sample mean, sample variance, properties of point estimators, Maximum likelihood method.
- ▶ Interval estimators, hypothesis testing, one-sided vs. two-sided alternatives, linear regression, estimators of regression parameters, testing of linear model.

# Recap

- A **random variable**  $X$  is a measurable function, which assigns real values to the outcomes of a random experiment.
- The **distribution** of  $X$  gives the information of the probabilities of its values and is uniquely given by the **distribution function**:

$$F_X(x) = P(X \leq x).$$

- There are two major types of random variables:
  - ▶ **Discrete**, taking only countably many possible values.
  - ▶ **Continuous**, taking uncountably many values from an interval.
- The distribution can be given by:
  - ▶ for discrete distributions by the **probabilities** of possible values  $P(X = x_k)$ .
  - ▶ for continuous distributions by the **density**  $f_X$  for which

$$F_X(x) = \int_{-\infty}^x f_X(t) dt.$$

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Sometimes we can measure **several** random **variables** at once from **one result** of an experiment.

The individual variables can have different distributions and the values of the variables can be strongly mutually interconnected. It is appropriate to **describe** their **distribution together** as the so called **joint distribution**.

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## Definition

Consider two random variables  $X$  and  $Y$  defined on the same probability space  $(\Omega, \mathcal{F}, P)$ . We define their **joint distribution function**  $F_{X,Y}(x, y)$  as

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For  $n$  random variables  $X_1, X_2, \dots, X_n \stackrel{\text{denote}}{=} \mathbf{X}$  we define the joint distribution function as

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The couple  $(X, Y)$  or,  $n$ -tuple  $(X_1, \dots, X_n)$ , is called a **random vector**.

## Example – joint distribution

### Example

Let  $X$  and  $Y$  be random variables with a joint discrete distribution given by the following probabilities:

|                       |   | $x$ |      |      |
|-----------------------|---|-----|------|------|
| $P(X = x \cap Y = y)$ |   | 0.5 | 1    | 2    |
| $y$                   | 2 | 0.3 | 0.06 | 0.04 |
|                       | 1 | 0.4 | 0.15 | 0.05 |

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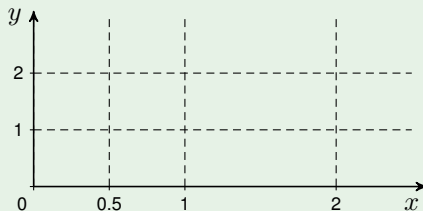
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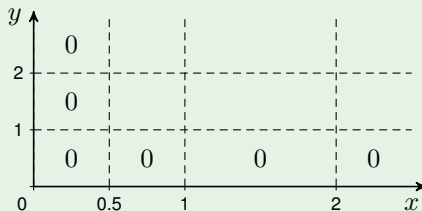
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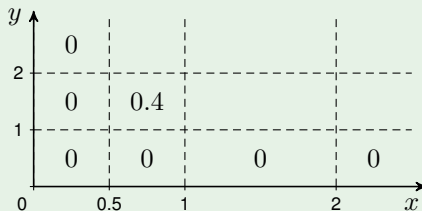
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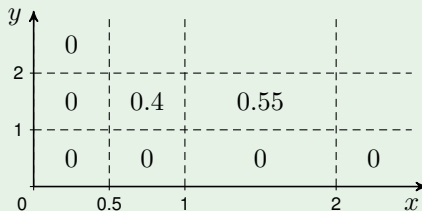
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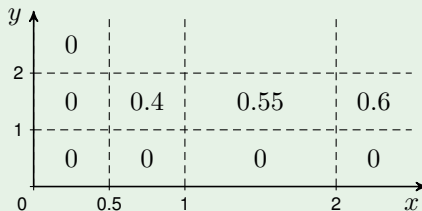
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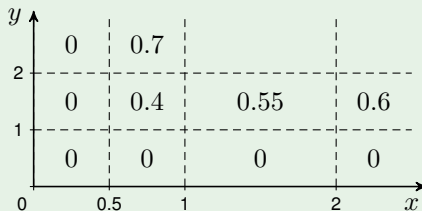
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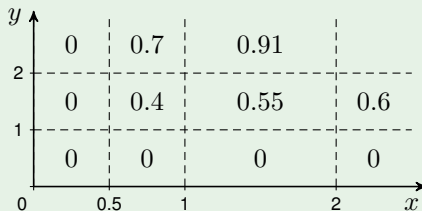
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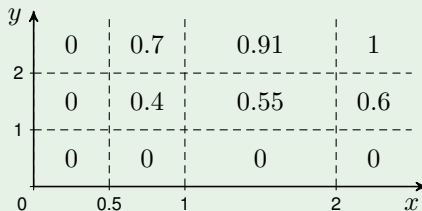
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# Properties of the joint distribution function

The joint distribution function has analogous properties as the distribution function of one variable.

## Theorem

*The joint distribution function  $F_{X,Y}$  of random variables  $X$  and  $Y$  has following properties:*

- i) if  $x_1 < x_2$  and  $y_1 < y_2$  then  $F_{X,Y}(x_1, y_1) \leq F_{X,Y}(x_2, y_2)$ .*

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- ii)  $\forall y \in \mathbb{R}, \lim_{x \rightarrow -\infty} F_{X,Y}(x, y) = 0$       and  
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- iii)  $\forall y \in \mathbb{R}, \lim_{x \rightarrow +\infty} F_{X,Y}(x, y) = F_Y(y)$       and  
 $\forall x \in \mathbb{R}, \lim_{y \rightarrow +\infty} F_{X,Y}(x, y) = F_X(x)$ .

## Proof

Analogously as for the distribution function of one random variable. □

# Vectors of discrete random variables

A **distribution** of random **variables**  $X$  and  $Y$  on the same probability space is described by the **joint distribution function**

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If the variables  $X$  and  $Y$  are **discrete**, it is often useful to describe the distribution by the **joint probabilities** of their values.

## Definition

The **joint probabilities of values** of two discrete random variables  $X$  and  $Y$  is

$$P(X = x \cap Y = y) = P(\{X = x\} \cap \{Y = y\}).$$

Taken as a function of  $x$  and  $y$ , the probabilities are called the **joint probability mass function**.

# Joint probabilities and the joint distribution function

The **joint distribution function** of two discrete random variables  $X$  and  $Y$  is

$$F_{X,Y}(x,y) = P(X \leq x \cap Y \leq y) = \sum_{\{i: x_i \leq x\}} \sum_{\{j: y_j \leq y\}} P(X = x_i \cap Y = y_j)$$

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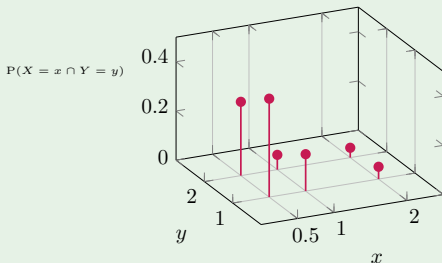
The **normalization condition** follows from the properties of the joint distribution function:

$$\begin{aligned} \sum_i \sum_j P(X = x_i \cap Y = y_j) &= \sum_i P(\{X = x_i\} \cap \bigcup_j \{Y = y_j\}) \\ &= \sum_i P(\{X = x_i\} \cap \{Y \in \mathbb{R}\}) = \sum_i P(X = x_i) \\ &= P(\bigcup_j \{X = x_i\}) = P(\{X \in \mathbb{R}\}) = P(\Omega) = 1. \end{aligned}$$

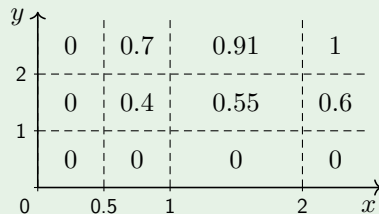
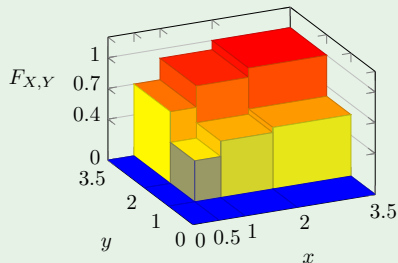
# Joint distribution – visualization

## Example

Joint probabilities



Joint distribution function



# Marginal distribution

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Let  $P(X = x \cap Y = y)$  be the joint probabilities of values of two discrete variables  $X$  and  $Y$ . The **marginal distribution** (or **marginal probabilities**) of a  $X$  is given by

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$$\begin{aligned} P(X = x) &= P(\{X = x\} \cap \{Y \in \mathbb{R}\}) = P(\{X = x\} \cap (\bigcup_j \{Y = y_j\})) = \\ &= P(\bigcup_j (\{X = x\} \cap \{Y = y_j\})) = \sum_j P(\{X = x\} \cap \{Y = y_j\}). \end{aligned}$$



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Find the marginal distribution of  $X$  and  $Y$  separately (find the marginal probabilities  $P(X = x)$  and  $P(Y = y)$ .)

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Random variables forming a countable collection  $X_1, X_2, \dots$  are called independent if all finite  $n$ -tuples  $X_{i_1}, \dots, X_{i_n}$  are independent.

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For discrete random variables we can verify the independence by means of the probabilities of values:

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*Discrete random variables  $X$  and  $Y$  are independent if for all  $x, y \in \mathbb{R}$  the events  $\{X = x\}$  and  $\{Y = y\}$  are independent. Equivalently, if it holds that for all  $x, y \in \mathbb{R}$*

$$P(X = x \cap Y = y) = P(X = x) \cdot P(Y = y).$$

*Random variables  $X_1, \dots, X_n$  are independent if for all  $\mathbf{x} \in \mathbb{R}^n$  it holds that*

$$P(\mathbf{X} = \mathbf{x}) = \prod_{i=1}^n P(X_i = x_i).$$

## Proof

If the condition regarding equalities holds, it must hold also for all inequalities, because they can be rewritten as sums of probabilities of disjoint events.

If the condition regarding inequalities hold, it must hold also for all equalities, because the difference of probabilities of inequalities yields probabilities of equalities. □

# Example – checking independence of random variables

## Example – continuation

Random variables  $X$  and  $Y$  have the following joint and marginal distributions:

| $P(X = x \cap Y = y)$ |   | $x$ |      |      | $P(Y = y)$ |
|-----------------------|---|-----|------|------|------------|
|                       |   | 0.5 | 1    | 2    |            |
| $y$                   | 2 | 0.3 | 0.06 | 0.04 | 0.4        |
|                       | 1 | 0.4 | 0.15 | 0.05 | 0.6        |
| $P(X = x)$            |   | 0.7 | 0.21 | 0.09 |            |

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Are  $X$  and  $Y$  independent?

No, they are not independent because, e.g., for  $x = 0.5$  and  $y = 2$  it holds that

$$0.3 = P(X = 0.5 \cap Y = 2) \neq P(X = 0.5) \cdot P(Y = 2) = 0.7 \cdot 0.4 = 0.28.$$

# Vectors of continuous random variables

The **distribution** of random **variables**  $X$  and  $Y$  on the same probability space is described by the **joint distribution function**

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If the variables  $X$  and  $Y$  are **continuous**, it is often useful to describe the distribution by the **joint probability density**.

## Definition

Two random variables  $X$  and  $Y$  have a **joint (absolutely) continuous** distribution if there exists a **non-negative** function  $f_{X,Y} : \mathbb{R}^2 \rightarrow [0, +\infty)$  such that for all  $x, y \in \mathbb{R}$  it holds

$$F_{X,Y}(x, y) = \int_{-\infty}^y \int_{-\infty}^x f_{X,Y}(u, v) \, du \, dv.$$

The function  $f_{X,Y}$  is called the **joint probability density** of the random variables  $X, Y$  or of the random vector  $(X, Y)$ .

# Properties of continuous random variables

Similarly as in the one-dimensional case it holds that:

- Where the derivative exists:

$$f_{X,Y}(x,y) = \frac{\partial^2 F_{X,Y}}{\partial x \partial y}(x,y).$$

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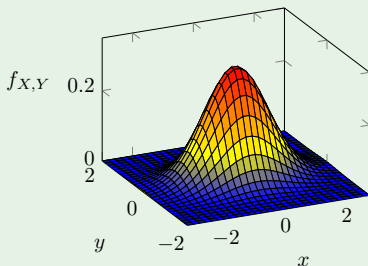
- $P(\{a < X \leq b\} \cap \{c < Y \leq d\}) = \int_c^d \int_a^b f_{X,Y}(x, y) \, dx \, dy.$
- For all  $B$  Borel subset of  $\mathbb{R}^2$  (meaning that  $\{X \in B\}$  is an event)

$$P((X, Y) \in B) = \iint_B f_{X,Y}(x, y) \, dx \, dy.$$

# Joint distribution – visualization

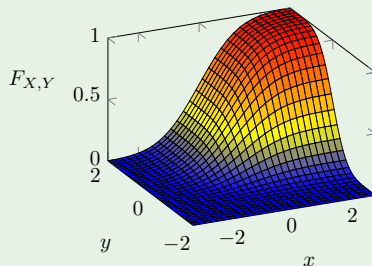
## Example

Joint density



$$f_{X,Y}(x,y) = \frac{1}{\pi} e^{-\frac{x^2}{2} - 2y^2}$$

Joint distribution function



$$F_{X,Y}(x,y) = \int_{-\infty}^y \int_{-\infty}^x \frac{1}{\pi} e^{-\frac{u^2}{2} - 2v^2} du dv$$

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## Proof

We know that:

$$F_X(x) = P(X \leq x) = P(X \leq x \cap Y \in \mathbb{R}) = \int_{-\infty}^x \left( \int_{-\infty}^{+\infty} f_{X,Y}(u, v) \, dv \right) du.$$

The statement of the theorem is obtained by differentiating with respect to  $x$ , or by comparing this formula to the definition of the distribution function of a continuous random variable. The second part is analogous. □

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## Proof

Two random variables  $X$  and  $Y$  are independent if

$$F_{X,Y}(x, y) = F_X(x) \cdot F_Y(y).$$

Taking the derivatives of both sides with respect to both  $x$  and  $y$  yields one implication. Integrating both sides of the equality for densities yields the other direction. □

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## Remark

While verifying the independence of  $X$  and  $Y$  we can use the following.

**Consequence:** If it is possible to **decompose**  $f_{X,Y}$  to

$$f_{X,Y}(x,y) = g(x) \cdot h(y), \quad \forall x, y \in \mathbb{R},$$

where  $g(x)$  and  $h(y)$  are non-negative functions, then the variables  $X$  and  $Y$  are **independent**.

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The statement of the consequence can be formulated for independence of a general random vector  $X_1, \dots, X_n$  too.

## Example – marginal distribution and independence

### Example

Let  $X$  and  $Y$  random variables having the joint probability density

$$f_{X,Y}(x,y) = ye^{-2x} \quad \text{for } x \in [0, +\infty) \text{ and } y \in [0, 2].$$

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**Independence:**

$$ye^{-2x} = f_{X,Y}(x, y) = f_X(x) \cdot f_Y(y) = 2e^{-2x} \cdot \frac{y}{2} = ye^{-2x}.$$

Yes, they are independent!

# Discrete conditional distribution

Now we will study the **distribution** of a random variable  $X$  under the assumption that we **know** the value of the variable  $Y = y$ .

Suppose that we have a partial information about the result of an experiment and we are interested in the change in our prediction.

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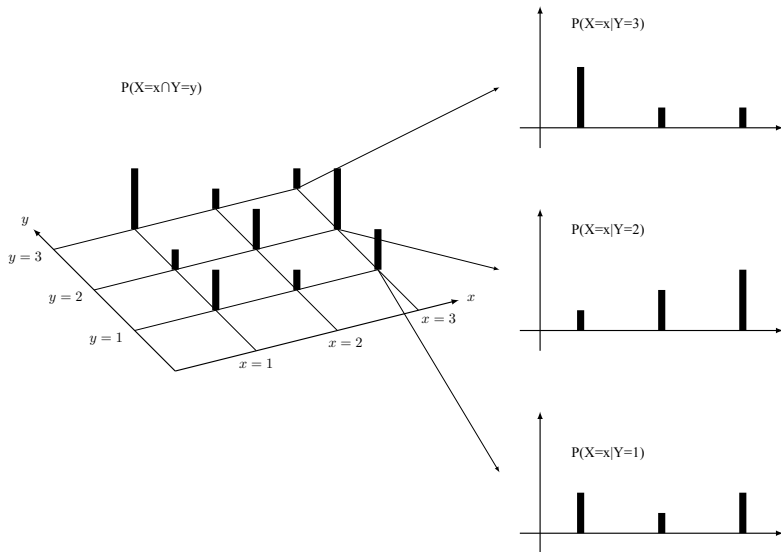
Let  $P(Y = y) > 0$ . Then, the **conditional distribution function**  $F_{X|Y}(\cdot|y)$  of the variable  $X$  given  $Y = y$  is defined as

$$F_{X|Y}(x|y) = P(X \leq x | Y = y).$$

The **conditional probabilities of values** of  $X$  given (under the condition of)  $Y = y$  are given, analogously, by

$$P(X = x | Y = y).$$

# Illustration of conditional probabilities $P(X = x|Y = y)$



# Conditional expectation of a discrete random variable

From the definition it follows that:

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Thus it holds that:

$$E(X|Y = y) = \sum_i x_i P(X = x_i|Y = y) = \sum_i x_i \frac{P(X = x_i \cap Y = y)}{P(Y = y)}.$$

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After taking a limit  $\Delta y \rightarrow 0$  we intuitively obtain the result as

$$P(X \leq x \mid Y = y) = \int_{-\infty}^x \frac{f_{X,Y}(u, y)}{f_Y(y)} \, du.$$

# Continuous conditional distribution

The previous inference lead us to the following formal definition:

## Definition

The **conditional distribution function** of a variable  $X$  given (under the condition of)  $Y = y$  is defined as

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The conditional density is defined accordingly:

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# Conditional expectation of a continuous random variable

Analogously as in the discrete case we define the **conditional expectation** for continuous random variables:

## Definition

Let  $f_Y(y) > 0$ . The expectation of variable  $X$  with density  $f_{X|Y}(x|y)$  is called the **conditional expectation** of  $X$  given  $Y = y$  and is denoted as  $E(X|Y = y)$ .

# Conditional expectation of a continuous random variable

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We compute the conditional expectation for a given value  $y$  as follows:

$$E(X|Y = y) = \int_{-\infty}^{\infty} x f_{X|Y}(x|y) dx = \int_{-\infty}^{\infty} x \frac{f_{X,Y}(x, y)}{f_Y(y)} dx = g(y),$$

where  $g$  is a function which arises from the integration.

# Bayes' Theorem

## Theorem

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*If  $X$  is discrete random variable than we have:*

$$P(X = x|Y = y) = \frac{P(X = x) P(Y = y|X = x)}{\sum_k P(X = k) P(Y = y|X = k)}.$$

# Recap

**Joint distribution function of a random vector  $(X, Y)$ :**

$$F_{X,Y}(x, y) = P(X \leq x \cap Y \leq y).$$

**Discrete random variables  $X$  and  $Y$**

Joint probabilities of values:

$$P(X = x \cap Y = y)$$

**Marginal distribution:**

$$P(X = x) = \sum_{\text{all } y} P(X = x \cap Y = y)$$

$$P(Y = y) = \sum_{\text{all } x} P(X = x \cap Y = y)$$

**Continuous random variables  $X$  and  $Y$**

Joint density:

$$f_{X,Y}(x, y)$$

$$f_X(x) = \int_{-\infty}^{\infty} f_{X,Y}(x, y) dy$$

$$f_Y(y) = \int_{-\infty}^{\infty} f_{X,Y}(x, y) dx$$

**Independence of  $X$  and  $Y$ :**

$$P(X = x \cap Y = y) = P(X = x) P(Y = y) \quad | \quad f_{X,Y}(x, y) = f_X(x) f_Y(y)$$

**Conditional probabilities / density of  $X$  given  $Y = y$ :**

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

**Conditional expectation of  $X$  given  $Y = y$ :**

$$E(X|Y = y) = \sum_x x P(X = x|Y = y) \quad | \quad E(X|Y = y) = \int_{-\infty}^{\infty} x f_{X|Y}(x|y) dx$$