

# Stochastic Processes problems

[https://github.com/bdemeshev/stochastic\\_pro](https://github.com/bdemeshev/stochastic_pro)

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# 1 First step analysis

- 1.1** Biden and Trump alternately throw a fair dice infinite number of times. Biden throws first. The person who obtains the first 6 wins the game.
- a) What is the probability that Biden will win?
  - b) What is expected number of turns?
  - c) What is variance of the number of turns?
  - d) What is expected number of turns given that Biden won?
  - e) Find the transition matrix of this four state Markov chain.
- 1.2** Elon throws an unfair coin until “head” appears. The probability of “head” is  $p \in (0; 1)$ . Let  $N$  be the total number of throws.
- a) Find  $\mathbb{E}(N)$ ,  $\text{Var}(N)$ ,  $\mathbb{E}(N^3)$ ,  $\mathbb{E}(\exp(tN))$ .
  - b) What is the probability than  $N$  will be even?
- 1.3** Alice and Bob throw a fair coin until the sequence  $HTT$  or  $THT$  appears. Alice wins if  $HTT$  appears first, Bob wins if  $THT$  appears first.
- a) Find the probability that Alice wins.
  - b) Find the expected value and variance of the total number of throws.
  - c) Using any open source software find the probability that Alice wins for all possible combinations of three coins sequences for Alice and Bob.
  - d) Now Alice and Bob play the following game. Alice chooses her three coins winning sequence first. Next Bob, knowing the choice of Alice, chooses his three coins winning sequence. Than they throw a fair coin until either of their sequences appears. What is the best strategy for Alice? For Bob? What is the probability that Alice wins this game?
- 1.4** You throw a dice unbounded number of times. If it shows 1, 2 or 3 then the corresponding amount of dollars is added in the pot. If it shows 4 or 5 the game stops and you get the pot with money. If it shows 6 the game ends and you get nothing. Initially the pot is empty.
- a) What is probability that the game will end by 6?
  - b) What is expected duration of the game?
  - c) What is your expected payoff?
  - d) What is your payoff variance?
  - e) Consider variation-A of the game. Rules are the same, but initially the pot contains 100 dollars. How will the answers to questions (a)-(d) change?
  - f) Consider variation-B of the game. Initially the pot is empty. One rule is changed. If the dice shows 5 the content of the pot is burned and the game continues. How will the answers to questions (a)-(d) change?
- 1.5** Boris Johnson throws a fair coin until 1 appears or until he says “quit”. His payoff is the value of the last throw. Boris optimizes his expected payoff. If many strategies gives the same expected payoff he chooses the strategy that minimizes the expected duration of the game.
- a) What is the optimal strategy and the corresponding expected payoff?

- b) What is the expected duration?
- c) How the answers to points (a) and (b) will change if Boris should pay 0.3 dollars for each throw?

**1.6** Winnie-the-Pooh starts wandering from the point  $x = 1$ . Every minute he moves one unit left or one right with equal probabilities.

Let  $T$  be the random moment of time when he reaches  $x = 0$ .

- a) Find the generating function  $g(u) = \mathbb{E}(u^T)$ .
- b) Extract all probabilities  $\mathbb{P}(T = k)$  from the function  $g(u)$ .

**1.7** Gleb Zheglov catches one criminal every day. With probability 0.2 the caught criminal is replaced by  $w$  new criminals. Initially there are  $n$  criminals in the town.

What is the expected time to the ultimate crime eradication in the town?

- a) (4 points) Solve the problem for  $w = 1$  and  $n = 1$ .
- b) (6 points) Solve the problem for arbitrary  $w$  and  $n$ .

**1.8** Consider infinite ladder with steps numbered from 0 to infinity. I start at step 0. Every day with probability  $u$  I go one step up. With probability  $d$  I go one step down. With probability  $1 - u - d$  I stay on the same step.

If I am at step 0 then I stay there with probability  $1 - u$  because it's impossible to go down.

Consider the case  $d > u$ .

What is the probability that I will be at step 0 after  $10^{1000}$  days?

**1.9** I throw a fair die until the sequence 6-2-6 appears. Let  $N$  be the number of throws.

- a) What is the expected value  $\mathbb{E}(N)$ ?
- b) Write down the system of linear equations for the moment generating function of  $N$ . You don't need to solve it!

**1.10** Consider a symmetric random walk  $S_t = S_0 + X_1 + X_2 + \dots + X_t$  where  $(X_t)$  are independent identically distributed and take values  $+1$  or  $-1$  with equal probabilities.

Random time  $T$  is the first moment when we reach the value  $-3$  or  $7$ . Let's denote by  $p_k$  the conditional probability to reach 7 before 3 given that we start at  $S_0 = k$ .

- a) Find  $p_{-3}$  and  $p_7$ .
- b) Find equation on  $p_k, p_{k-1}$  and  $p_{k+1}$  using first step analysis.
- c) Guess the unique solution of this recurrence equation and hence find  $p_0$ .

Now let's denote by  $e_k$  the conditional expected value of  $T$  given that we start at  $S_0 = k$ .

- d) Find  $e_{-3}$  and  $e_7$ .
- e) Find equation on  $e_k, e_{k-1}$  and  $e_{k+1}$  using first step analysis.
- f) Guess the unique solution of this recurrence equation and hence find  $e_0$ .
- g) Generalize the formulas for  $p_0$  and  $e_0$  by replacing  $-3$  and  $7$  by arbitrary  $-a < 0$  and  $b > 0$ .

**1.11** Consider a non-symmetric random walk  $S_t = S_0 + X_1 + X_2 + \dots + X_t$  where  $(X_t)$  are independent identically distributed and take values  $+1$  or  $-1$  with  $\mathbb{P}(X_t = +1) = r$

Random time  $T$  is the first moment when we reach the value  $-3$  or  $7$ . Let's denote by  $p_k$  the conditional probability to reach  $7$  before  $3$  given that we start at  $S_0 = k$ .

- Find  $p_{-3}$  and  $p_7$ .
- Find equation on  $p_k, p_{k-1}$  and  $p_{k+1}$  using first step analysis.
- Guess the unique solution of this recurrence equation and hence find  $p_0$ .

Now let's denote by  $e_k$  the conditional expected value of  $T$  given that we start at  $S_0 = k$ .

- Find  $e_{-3}$  and  $e_7$ .
- Find equation on  $e_k, e_{k-1}$  and  $e_{k+1}$  using first step analysis.
- Guess the unique solution of this recurrence equation and hence find  $e_0$ .
- Generalize the formulas for  $p_0$  and  $e_0$  by replacing  $-3$  and  $7$  by arbitrary  $-a < 0$  and  $b > 0$ .

**1.12** Consider a symmetric random walk  $S_t = X_1 + X_2 + \dots + X_t$  where  $(X_t)$  are independent identically distributed and take values  $+1$  or  $-1$  with equal probabilities. We start at zero,  $S_0 = 0$ .

Let  $N_k$  the number of visits of point  $k$  before the first return of a random walk to  $0$ .

- What is the probability that a random walk will eventually return to  $0$ ?
- What is the probability  $\mathbb{P}(N_k = 0)$ ?
- What is the probability  $\mathbb{P}(N_k = n)$  for arbitrary natural number  $n$ ?
- Compare  $\mathbb{E}(N_2)$  and  $\mathbb{E}(N_{\text{undecillion}})$ .

**1.13** You roll a pair of fair dice infinitely many times.

- What is the probability that you will obtain the sum equal to  $10$  before the sum equal to  $8$ ?
- What is the probability that you will obtain the sum equal to  $10$  before the sum equal to  $8$  but after the sum equal to  $11$ ?

**1.14** How many coin tosses on average you need to obtain  $n$  heads?

**1.15**

**1.16**

**1.17**

## First step into fractal

**1.18** The Cantor set fractal  $C$  is constructed in the following way. We start with unit segment  $I_0 = [0; 1]$ . At the first stage we remove the middle third from the segment. Hence after the first stage we obtain  $I_1 = [0; 1/3] \cup [2/3; 1]$ . At the second stage we remove the middle third from every segment. Hence after the second stage we obtain  $I_2 = [0; 1/9] \cup [2/9; 3/9] \cup [6/9; 7/9] \cup [8/9; 9/9]$ . We continue this process infinitely many times and in the limit we obtain the Cantor set  $C$ , see [https://en.wikipedia.org/wiki/Cantor\\_set](https://en.wikipedia.org/wiki/Cantor_set).

- Find the length of the Cantor set  $C$ .

Now let's choose a point  $X$  in the Cantor set randomly uniformly.

- b) Find  $\mathbb{E}(X)$  and  $\text{Var}(X)$ .
- c) How one may randomly choose a point in the Cantor set using a fair coin?
- d) Find at least one point in the Cantor set that does not the endpoint of any segment.
- e) Let  $F$  the cumulative distribution function of  $X$ . Find the values  $F(1/2)$ ,  $F(1/3)$ ,  $F(1/4)$  and  $F(1/5)$ .

**1.19** The Sierpiński triangle  $S$  is constructed in the following way. We start with an equilateral triangle  $T_0$  with unit sides. At the first stage we subdivide the triangle into four smaller congruent equilateral triangles and remove the central triangle. Hence after the first stage the set  $T_1$  consists of three triangles. At the second stage we subdivide every triangle into four smaller congruent equilateral triangles and remove the central triangle. Hence after the second stage we obtain the set  $T_2$  that consists of nine triangles. We continue this process infinitely many times and in the limit we obtain the Sierpiński triangle  $S$ , see [https://en.wikipedia.org/wiki/Sierpiński\\_triangle](https://en.wikipedia.org/wiki/Sierpiński_triangle).

- a) Find the area of the Sierpiński triangle  $S$ .

Now let's choose a point  $(X, Y)$  in the Sierpiński triangle with vertices  $(0, 0)$ ,  $(1, 0)$  and  $(1/2, \sqrt{3}/2)$  randomly uniformly.

- b) Find  $\mathbb{E}(X)$  and  $\text{Var}(X)$ .
- c) Find  $\mathbb{E}(Y)$  and  $\text{Var}(Y)$ .
- d) Find  $\text{Cov}(X, Y)$ .
- e) How one may randomly choose a point in the Sierpiński triangle using a fair coin?

**1.20**

**1.21**

## 2 Markov chains

**2.1** HSE student lives in two states: "sleep" and "study" and tries to change the state every 1 hour. After the sleep state the student continues sleeping with probability equal to 0.25, otherwise a student starts studying. If the student is studying, the probabilities to continue studying and to start sleeping are equal.

- a) Write down the transition matrix of this Markov chain.
- b) Draw the graph representation.
- c) What is the probability that a Sleeping Student will be a Studying Student after 1 hour? After 2 hours?
- d) We know that initially student is sleeping with probability  $p = \frac{2}{3}$ . Find the probabilities of sleep and study states after 1 and 2 hours.
- e) Find the probabilities of sleep and study states after 20 and 100 hours (do it with **matrix** operations and any soft). Is there any difference and why?

- 2.2** HSE student has three states: pre-coffee, with-coffee and over-coffee. He goes to Jeffrey's each break seeking for a cup of coffee. The line is usually too long, so probability to stay pre-coffee is equal to 60% and to be over-coffee — is zero. Caffeinated students can stay in lines longer, so for with-coffee student the probability to become over-coffee is 20% and to become pre-coffee — 30%. Over-coffee student runs to coffeshop very fast and able to stay over-coffee with  $p = 0.70$  and can suddenly become pre-coffee with  $p = 0.10$ .
- Draw the graph representation of this Markov chain.
  - Write the transition matrix of this Markov chain.
  - What is the probability that morning pre-coffee student will be with-coffee after 1 break? After 3 breaks?
  - What is the probability that morning pre-coffee student will be with-coffee after 1 break? After 3 breaks? After 200 breaks?
- 2.3** Unteachable students in NOTHSE University try to pass the exams. Students cheat successfully and pass the exams with probability 10%. In the case of a failure students are allowed to infinite number of retakes. All students are unteachable so the amount of knowledge is always the same and doesn't depend of the number of retakes.
- Draw the graph representation of this Markov chain.
  - What is the probability to graduate using no more than 5 retakes?
  - What is the probability to graduate eventually?
  - Use **first step analysis** to find the average number of retakes per student in this University.
- 2.4** Every month the real estate Galina agent has two options: to increase her commission and to ask an owner to increase the rent. If the agent has increased the commission, on the next step she increases the commission again with probability  $5/8$ . If she has asked the owner, she decides to increase the commission with probability equal to  $3/4$  on the next step.
- Write the transition matrix of this Markov chain.
  - Draw the graph representation.
  - Use **first step analysis** to find how many steps the agent does between asking the owner to increase the price.
- 2.5** Alice and Bob toss a coin, writing down the results. If the last 3 tosses are Head, Head and Tail, Alice wins. If the last 3 tosses are Tail, Head and Head, Bob wins.
- Is it easy to work with matrix representation in this case?
  - Draw the graph representation. Who is more likely to win the game?
  - Use **first step analysis** to find the probability of Alice's win.
  - Find the probability that the game ends in exactly 4 tosses.
  - Find the expected value and variance of the total number of coin throws in the game.
- 2.6** HSE student has an unusually caring granny who cooks one pie with probability 0.7 every weekend. Granny's pies are so tasty that HSE student can't resist and he gains 1 kilo for each pie eaten. Without pies the student with more than 70 kilos weight loses 1 kilo per week, yeah, he has a lot of studies! At the beginning of the study year student's weight is  $W_0 = 70$  kilos.
- Let  $W_t$  be the weight of the student  $t$  weeks later.

- a) Find the probability  $\mathbb{P}(W_3 \geq 71)$  and expected value  $\mathbb{E}(W_3)$ .
- b) Find the limit weight after infinitely many study weeks  $\lim_{t \rightarrow \infty} W_t$ .
- c) Explain whether the chain  $(W_t)$  has a stationary distribution.

**2.7** The fair price of Sborbank in discrete stock market is somewhere between 100 and 101 rubles. If the price is equal to 100, then the price grows up by 1 ruble with probability  $\frac{9}{10}$ , otherwise it goes down by 1 ruble. If the price is greater than 100, it grows by 1 ruble with probability  $\frac{1}{3}$  or declines by 1 ruble. If the price is lower than 100, it grows by 1 ruble with probability  $\frac{2}{3}$  or declines by 1 ruble.

- a) Draw the graph representation of the corresponding Markov chain.
- b) Do you think this chain has some stationary distribution?
- c) Find the average time for the stock price to fall from 102 rubles to 98 rubles.

Hint: you may to decompose the long path into smaller ones and to use the first step analysis.

**2.8** The hedgehog Melissa starts at the vertex  $A$  of a triangle  $\triangle ABC$ . Each minute she randomly moves to an adjacent vertex with probabilities  $\mathbb{P}(A \rightarrow B) = 0.7$ ,  $\mathbb{P}(A \rightarrow C) = 0.3$ ,  $\mathbb{P}(B \rightarrow C) = \mathbb{P}(B \rightarrow A) = 0.5$ ,  $\mathbb{P}(C \rightarrow B) = \mathbb{P}(C \rightarrow A) = 0.5$ .

- a) What is the probability that she will be in vertex  $B$  after 3 steps?
- b) Write down the transition matrix of this Markov chain.
- c) What proportion of time Melissa will spend in each state in the long run?

**2.9** A Hedgehog starts at the point  $x = 2$  on the real line. Every minute he moves one step left with probability 0.3 or one step right with probability 0.7. There are two exceptions from this rule: the absorbing point  $x = 0$  and the reflecting barrier at  $x = 3$ .

If the Hedgehog reaches the absorbing point  $x = 0$  then he stops moving and stays there. If the Hedgehog reaches the reflecting barrier  $x = 3$  then his next move will be one step left with probability 1.

- a) [2] Write the transition matrix of this Markov chain.
- b) [3] What is the probability that Hedgehog will be at  $x = 1$  after exactly 3 steps?
- c) [5] What is the expected time to reach the absorbing state?

**2.10** Vampire Petr drinks blood of a new victim every day. Unfortunately 20% of the population are vaccinated against vampires. If more than one victim of the last three victims are vaccinated then Petr will be instantaneously cured and will return to the normal life.

For simplicity let's assume that the last three victims were not vaccinated.

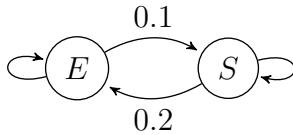
- a) What is the probability that vampire Petr will be cured in the next three days?
- b) How many victims will be bitten by vampire Petr on average?

**2.11** A hedgehog moves at random on the vertices  $A$ ,  $B$ ,  $C$  and  $D$  of a regular tetrahedron (тетраэдр). She start at the vertex  $A$  and every minute changes her position to one of the adjacent vertices with probability  $1/3$  independently of past moves.

- a) Write down the transition matrix of this Markov chain.
- b) What is the expected time of the first return to the starting vertex  $A$ ?



- 2.12** The Cat can be only in two states: Sleeping ( $S$ ) and Eating ( $E$ ). Cat's mood depends only on the previous state. The transition probabilities are given below:



- Compute the missing probabilities on the graph.
  - Write down the transition matrix.
  - Compute  $\mathbb{P}(X_3 = \text{Eating} \mid X_0 = \text{Eating})$ .
- 2.13** Cowboy Joe enters the Epsilon Bar and orders one pint of beer. He drinks it and orders one pint more. And so on and so on and so on... The problem is that the barmaid waters down each pint with probability 0.2 independently of other pints. Joe does not like watered down beer. He will blow the Epsilon Bar to hell if two or more out of the last three pints are watered down. We point out that Joe never drinks less than 3 pints in a bar.

- What is the expected number of pints of beer Joe will drink?

Let  $Y_t$  be the indicator that the pint number  $t$  was watered down. Consider the Markov chain  $S_t = (y_{t-2}, y_{t-1}, y_t)$ . For example,  $S_t = (100)$  means that the pint number  $t - 2$  was watered down while pints number  $t - 1$  and  $t$  are good.

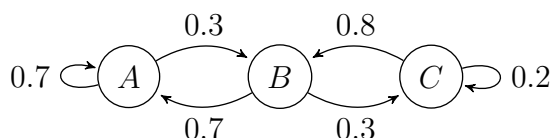
- What are the possible values of  $S_3$  and their probabilities?
  - Write down the transition matrix of this Markov chain.
- 2.14** Pavel Durov starts at the point  $X_0 = 3$  on the real line. Each minute he moves left with probability 0.4 or right with probability 0.6 independently of past moves. The points 0 and 5 are absorbing. If Pavel reaches 0 or 5 he stays there forever. Let  $X_t$  be the coordinate of Pavel after  $t$  minutes.
- Write down the transition matrix of this Markov chain.
  - Calculate the distribution of  $X_7$  [list all values of the random variable  $X_7$  and estimate the probabilities].

Hint: you are free to use python for this problem :)

- 2.15** Consider two identical hedgehogs starting at the vertices  $A$  and  $B$  of a polygon  $ABCD$ . Each minute each hedgehog simultaneously and independently chooses to go clockwise to the adjacent point, to go counter-clockwise to the adjacent point or to stay at his location.

Thus the brotherhood of two brave hedgehogs can be in three states: in one vertex, in two adjacent vertices, in two non-adjacent vertices.

- Draw the graph for the brotherhood Markov chain and calculate all transition probabilities.
  - Write down the transition matrix of the brotherhood Markov chain.
  - What is the probability that they will be in one vertex after 3 steps?
- 2.16** Consider the following Markov chain:



- a) Find the stationary distribution of this Markov chain.

The Markov chain starts at the vertex  $A$ . Let  $N$  be the first moment when the state  $C$  will be reached.

- b) Find the expected value  $\mathbb{E}(N)$ .  
c) Find the variance  $\text{Var}(N)$ .

**2.17** Design a Markov chain with 3 states and unique stationary distribution  $\pi = (0.1, 0.2, 0.7)$ .

**2.18** Consider three games:

Game A: You toss a biased coin with probability 0.48 of  $H$ . You get +1 dollar for  $H$  and -1 dollar for  $T$ .

Game B: If your wellfare is divisible by three you toss a coin that lands on  $H$  with probability 0.09. If your wellfare is not divisible by three you toss a coin that lands on  $H$  with probability 0.74. You get +1 dollar for  $H$  and -1 dollar for  $T$ .

Game C: You toss an unbiased coin. If it lands on  $H$  you play Game A. If it lands on  $T$  you play Game B.

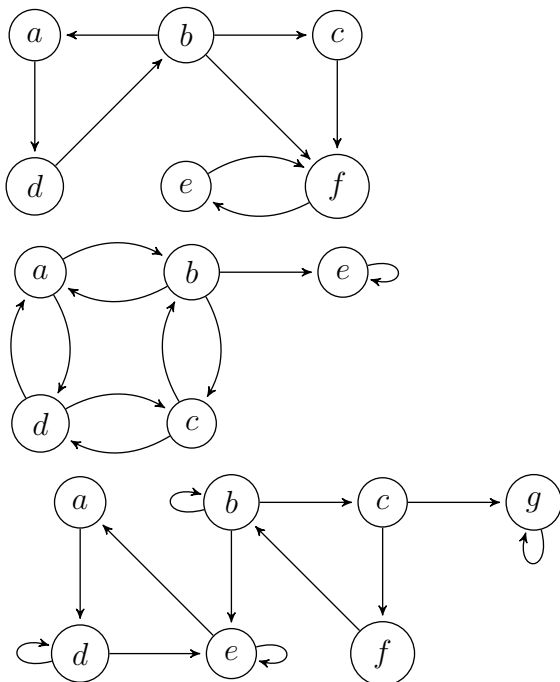
Your initial capital is 10000\$.

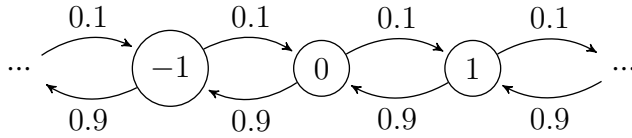
- a) Generate and plot two random trajectories of your wellfare if you play Game A  $10^6$  times.  
b) Generate and plot two random trajectories of your wellfare if you play Game B  $10^6$  times.  
c) Generate and plot two random trajectories of your wellfare if you play Game C  $10^6$  times.

**2.19**

### 3 Classification of states

**3.1** We randomly wander on the graph choosing at each moment of time one of the possible directions. If probabilities are not given we choose equiprobably.





- Split each Markov chain into communicating classes.
- Find the period of every state.
- Classify each state as transient, null-recurrent and positive recurrent.
- For positive recurrent states find the expected return time.
- Find all stationary distributions.

**3.2** A Knight randomly wanders on the chessboard. At each step he randomly chooses one of the possible Knight-moves with equal probabilities.

- Find the stationary distribution.
- Find the expected return time for every square.
- Find the period of every square.

**3.3** Consider the Markov chain with the transition matrix

$$P = \begin{pmatrix} 0.2 & 0.2 & 0 & 0.6 \\ 0.3 & 0.3 & 0.4 & 0 \\ 0 & 0 & 0.1 & 0.9 \\ 0 & 0 & 0.8 & 0.2 \end{pmatrix}.$$

- (3 points) Split the chain in classes and classify them into closed or not closed.
- (2 points) Classify the states into recurrent or transient.
- (5 points) A Hedgehog starts in the state one and moves randomly between states according to the transition matrix.

What is the approximate probability that the Hedgehog will be in the state four after  $10^{2021}$  moves?

**3.4** Consider the Markov chain with the transition matrix

$$P = \begin{pmatrix} 0.2 & 0.2 & 0 & 0.6 & 0 \\ 0.3 & 0.3 & 0.4 & 0 & 0 \\ 0 & 0 & 0.3 & 0.7 & 0 \\ 0 & 0 & 0.8 & 0.2 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}.$$

- (3 points) Split the chain in classes and classify them into closed or not closed.
- (2 points) Classify the states into recurrent or transient.
- (5 points) A Hedgehog starts in the state one and moves randomly between states according to the transition matrix.

What is the approximate probability that the Hedgehog will be in the state four after  $10^{2021}$  moves?

**3.5**

**3.6**

## 4 Generating functions

- 4.1** The MGF (moment generating function) of the random variable  $X$  is given by  $M(t) = 0.3 \exp(2t) + 0.2 \exp(3t) + 0.5 \exp(7t)$ .

Recover the distribution of the random variable  $X$ .

- 4.2** The random variable  $Y$  takes values 1, 2 or 3 with equal probabilities.

Find the MGF of the random variable  $Y$ .

- 4.3** The MGF of the random variable  $W$  has a Taylor expansion that starts with  $M(t) = 1 + 2t + 7t^2 + 20t^3 + \dots$

Find  $\mathbb{E}(W)$ ,  $\text{Var}(W)$ ,  $\mathbb{E}(W^3)$ .

- 4.4** The random variable  $X$  takes non-negative integer values. The generating function  $g(u) = \mathbb{E}(u^X)$  has a Taylor expansion that starts with  $g(u) = 0.1 + 0.2u + 0.15u^2 + \dots$

Find probabilities  $\mathbb{P}(X = 0)$ ,  $\mathbb{P}(X = 1)$ ,  $\mathbb{P}(X = 2)$ .

- 4.5** Random variables  $X_i$  are mutually independent and  $X_i$  has Gamma distribution  $\text{Gamma}(\alpha_i, \beta_i)$ .

I sum up the random number  $N$  of terms,

$$S = X_1 + X_2 + \dots + X_N.$$

The number  $N$  has Poisson distribution  $\text{Pois}(\lambda)$  and is independent of the sequence  $(X_i)$ .

- Find the MGF of  $S$ . You may use the MGF formula for Gamma distribution as known.
- Find  $\mathbb{E}(S)$  and  $\text{Var}(S)$ .

- 4.6** The random variable  $X$  takes non-negative integer values. Its moment generating function is equal to  $M(t) = (2 - \exp(t))^{-7}$ .

- Find the probability generating function  $g(u) = \mathbb{E}(u^X)$ .
- Find  $\mathbb{E}(X)$ ,  $\text{Var}(X)$ ,  $\mathbb{P}(X = 0)$ ,  $\mathbb{P}(X = 1)$ ,  $\mathbb{P}(X = 2)$ .
- Find  $\mathbb{P}(X = k)$ .

- 4.7** The number of players  $N$  who will win the lottery is a random variable with probability mass function  $\mathbb{P}(N = k) = 7 \cdot 0.3^k / 3$  for  $k \geq 1$ . Each player will get a random prize  $X_i \sim U[0; 1]$ . All random variables are independent. Let  $S$  be the sum of all the prizes.

- Find  $\mathbb{E}(S | N)$  and conditional moment generating function  $M_{S|N}(u)$ .
- Find the unconditional moment generating function  $M_S(u)$ .
- What is the probabilistic meaning of  $M_S''(0) - (M_S'(0))^2$ ?

- 4.8** Prince Myshkin throws a fair coin until two consecutive heads appear. Let  $N$  be the number of throws.

Find the moment generating function of  $N$ .

- 4.9** The moment generating function of a random variable  $X$  is  $1/(1 - 2t)$ .

- Find the moment generating function of  $2X$ .

- b) Find the moment generating function of  $X + Y$  where  $X$  and  $Y$  are independent and identically distributed.
- c) Do you remember the sum of geometric progression? Find  $\mathbb{E}(X^{2021})$ .

**4.10** The ultimate goal of this exercise is to prove the good upper bound for tail probability of a normal distribution: if  $X \sim \mathcal{N}(0; \sigma^2)$  then  $\mathbb{P}(X > c) \leq \exp(-c^2/2\sigma^2)$ .

Here are the guiding hints (you free to use not use them):

- a) State the MGF of  $X$ . You may derive it or simply write it if you remember.
- b) Consider  $Y = \exp(uX)$ . Using Markov inequality provide the upper bound for  $\mathbb{P}(Y > \exp(uc))$ .
- c) Prove that  $\mathbb{P}(X > c) \leq MGF_X(u) \exp(-uc)$  for any  $u$ .
- d) Find the value of  $u$  that makes the upper bound as tight as possible.

**4.11** I have an unfair coin with probability of heads equal to  $h \in (0; 1)$ .

- a) Let  $N$  be the number of tails before the first head. Find the MGF of  $N$ .
- b) Let  $S$  be the number of tails before  $k$  heads (not necessary consecutive). Find the MGF of  $S$ .
- c) What is the limit of  $MGF_S(t)$  when  $k \rightarrow \infty$  and  $k \times h \rightarrow 0.5$ ?
- d) What is the limit of  $MGF_S(t)$  when  $k \rightarrow \infty$  and  $k \times (1 - h) \rightarrow 0.5$ ?

**4.12** I have three problems in the home assignment. Time spent on each problem is modelled by independent exponentially distributed random variables with rate  $\lambda$ :  $X_1, X_2, X_3$ .

- a) Find the moment generating function of  $X_i$  and hence the moment generating function of  $S = X_1 + X_2 + X_3$ .
- b) Find  $\mathbb{E}(S^3)$ .
- c) Find the joint density of  $R = X_1/(X_1 + X_2 + X_3)$  and  $S$ .

**4.13** Recognise the distribution family and its parameters by looking at the moment-generating function:

- a)  $0.7 + 0.3 \exp(t)$ ;
- b)  $\exp(2024 \exp(t)) / \exp(2024)$ ;
- c)  $\frac{\exp(3t) - 1}{3t \exp(-2t)}$ ;
- d)  $\exp(6t + 2024t^2)$ ;
- e)  $1/(5t - 1)^{2024}$ .

You may use the table from the article

[https://en.wikipedia.org/wiki/Moment-generating\\_function](https://en.wikipedia.org/wiki/Moment-generating_function).

**4.14** Consider the moment-generating function of a random variable  $X$ :

$$g(t) = \frac{\exp(3t) - 1}{3t \exp(-2t)}.$$

- a) Expand the function  $g(t)$  as Taylor series up to  $t^4$  included.
- b) Find  $\mathbb{E}(X)$ ,  $\mathbb{E}(X^2)$ ,  $\mathbb{E}(X^3)$ ,  $\mathbb{E}(X^4)$ .

**4.15** The moment-generating function of the pair of random variables  $(X, Y)$  is given by  $\exp(6t_1 + 5t_2 + t_1^2 + 20t_2^2 - 2t_1t_2)$ .

Find  $\mathbb{E}(X)$ ,  $\text{Var}(Y)$ ,  $\mathbb{E}(XY)$ .

**4.16**

**4.17**

## 5 Inequalities

**5.1** I have 100 numbers written on small sheets of paper:  $x_1, x_2, \dots, x_{100}$ . The sum of these numbers is 1.

Find the possible values of the sum

$$\frac{x_1}{\sqrt{1-x_1}} + \frac{x_2}{\sqrt{1-x_2}} + \dots + \frac{x_{100}}{\sqrt{1-x_{100}}}.$$

Hint: consider a randomly selected number  $X$  and apply the Jensen's inequality.

**5.2** Ordinary non-random sequences also have alternative limit concept! The real number  $c$  is a Cesaro limit of a sequence  $(a_n)$  if this number is a limit of a sequence of cumulative averages,  $c = \lim \bar{a}_n$ .

- Consider a sequence  $(a_n) = (1, 0, 1, 0, 1, 0, \dots)$ . Does it have ordinary limit? Does it have Cesaro limit?
- Construct an aperiodic sequence that does not have ordinary limit but has Cesaro limit.
- Is it true that any ordinary convergent sequence is also Cesaro-converges?

You now that  $(a_n)$  Cesaro-converges to  $a$  and  $(b_n)$  Cesaro-converges to  $b$ .

- Is it true that  $(a_n + b_n)$  is Cesaro-convergent?
- Is it true that  $(a_n \cdot b_n)$  is Cesaro-convergent?

**5.3**

**5.4**

## 6 Limits

**6.1** Polina loves sweet chestnuts. She has infinite sequence of baskets before her. In the basket number  $n$  there are  $n$  chestnuts in total. Unfortunately only one chestnut in every basket is a sweet one.

She picks chestnuts one by one at random from all the baskets sequentially. First she picks the unique chestnut from the basket number one, then she picks in a random order two chestnuts from the basket number two and so on.

The random variable  $S_t$  indicates whether the chestnut number  $t$  was a sweet one.

- Find  $\lim S_t$  or prove that the limit does not exist.
- Find  $\text{plim } S_t$  or prove that the limit does not exist.

**6.2** Let  $(X_n)$  be independent, each variable  $X_n$  has exponential distribution with rate  $\lambda_n = n$ .

- a) Find the probability limit  $\text{plim } X_n$  or prove that it does not exist.

Let  $(Y_n)$  be independent, each variable  $Y_n$  has exponential distribution with rate  $\lambda_n = n/(n+1)$ .

- b) Find the probability limit  $\text{plim } Y_n$  or prove that it does not exist.

**6.3** Let  $(X_n)$  be independent normally distributed  $\mathcal{N}(5; 10)$ .

- a) Find the probability limit

$$\text{plim } \frac{X_1 + X_2 + \cdots + X_n}{7n}.$$

- b) Find the probability limit

$$\text{plim } \frac{X_1^2 + X_2^2 + \cdots + X_n^2}{7n}.$$

- c) Find the probability limit

$$\text{plim } \ln(X_1^2 + X_2^2 + \cdots + X_n^2) - \ln n.$$

**6.4** Let  $(X_n)$  be independent uniform on  $[0; 1]$ . Let  $Y_n = X_n^2 + X_n^3$ .

- a) Find the probability limit  $\text{plim } V_n$  for

$$V_n = \max\{Y_1, Y_2, \dots, Y_n\}.$$

- b) Find the probability limit  $\text{plim } W_n$  for

$$W_n = \max\{X_1 + Y_1, X_1 + Y_2, \dots, X_1 + Y_n\}.$$

**6.5** Consider the random variable  $X$  and the sequence of random variables  $Y_n$  with  $\mathbb{E}(Y_n) = \frac{1}{n}$  and  $\text{Var}(Y_n) = \frac{\sigma^2}{n}$ . Let  $W_n = X + Y_n$ .

- a) Find the probability limit  $\text{plim } Y_n$ ;  
b) Find the probability limit  $\text{plim } W_n$ .

**6.6** The random variables  $X_i$  are independent and uniformly distributed on  $[0; 1]$ . Let  $Y_n = \min X_1, \dots, X_n$ .

- a) Find the almost sure limit of  $Y_n$ ;  
b) Find the probability limit of  $Y_n$ ;  
c) Find the limiting distribution of  $Y_n$ .

**6.7** Let  $X$  and  $Y$  be independent and uniformly distributed on  $[0; 1]$ . Let  $V_n = n^2 Y \cdot I(X \leq 1/n)$  and  $W_n = Y \cdot I(X > 1/n)$ .

- a) Find  $\text{plim } V_n$  and  $\text{plim } W_n$ .  
b) Does  $(V_n)$  converge in mean squared?  
c) Does  $(W_n)$  converge in mean squared?

**6.8** a) As a warm-up find the limit

$$\lim_{n \rightarrow \infty} \frac{2n^2 + 3n + 6}{5n^2 + 2n + 9}.$$

Now consider the sequence with parameters:

$$X_n = \frac{Ln^2 + 3n + 6}{Rn^2 + 2n + 9}$$

- b) For each value of parameters  $L$  and  $R$  find the limit  $\lim X_n$ .
- c) Find the almost surely limit of  $X_n$  if  $L$  and  $R$  are independent and  $\text{Unif}[0; 1]$ . Does the pointwise limit exist?
- d) Random variables  $L$  and  $Q$  be independent and take values 0 or 1 with equal probabilities. Let  $R = L + Q$ . Find the almost surely limit of  $X_n$  in terms of  $L$  and  $R$ . Does the pointwise limit exist?

**6.9** Consider the sequence  $Y_n = U^n$  with parameter  $U$ .

- a) Find the ordinary limit of  $Y_n$  for all values of  $U$  for which the sequence converges.
- b) Find the almost surely limit of  $Y_n$  if  $U \sim \text{Unif}[0; 1]$ .
- c) What is the probability that  $Y_n$  converges if  $U \sim \text{Unif}[0; 2]$ ?
- d) What is the probability that  $Y_n$  converges if  $U$  takes values  $+1$  or  $-1$  with equal probabilities?
- e) Does  $Y_n$  converges in distribution if  $U$  takes values  $+1$  or  $-1$  with equal probabilities?

**6.10** The random variables  $X_i$  are independent and uniformly distributed on  $[0; 2]$ . Find the probability limit

$$\text{plim}_{n \rightarrow \infty} \max \left\{ \frac{\sum_{i=1}^{10} X_i}{n}, \frac{\sum_{i=1}^n X_i^3}{n+1} \right\}.$$

**6.11** The random variables  $X_i$  are independent and uniformly distributed on  $[0; 1]$ . Find the probability limit

$$\text{plim}_{n \rightarrow \infty} \max \left\{ \frac{\sum_{i=1}^n X_i}{n}, \frac{2 \sum_{i=1}^n X_i^2}{n} \right\}.$$

**6.12** The random variables  $X_i$  are independent and uniformly distributed on  $[0; 2]$ . Find

$$\text{plim}_{n \rightarrow \infty} \frac{(X_1 - \bar{X})^3 + (X_2 - \bar{X})^3 + \dots + (X_n - \bar{X})^3}{n + 2022}.$$

**6.13** Consider the stochastic process  $(X_n)$ , where  $X_0$  is uniform on  $[0; 2]$  and  $X_n = (1 + X_{n-1})/2$ .

- a) Find  $\mathbb{E}(X_n)$  and  $\text{Var}(X_n)$ .
- b) Find the probability limit  $\text{plim } X_n$ .

**6.14** The random variables  $X_i$  are independent and exponentially distributed with rate  $\lambda = 1$ .

- a) Find the probability limit

$$\text{plim} \frac{X_1 + X_2 + X_3 + \dots + X_n}{2n + 7}.$$



b) Find the probability limit

$$\text{plim} \frac{X_1^2 + X_2^2 + X_3^2 + \cdots + X_n^2}{2n + 7}.$$

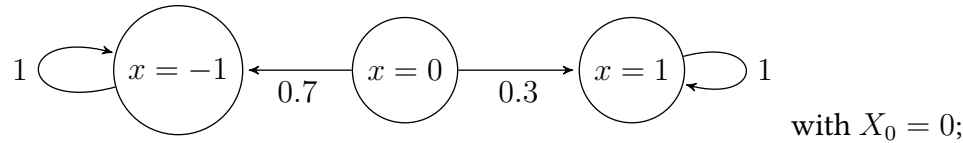
c) Find the probability limit

$$\text{plim} \min\{X_1, X_2, X_3, \dots, X_n\}.$$

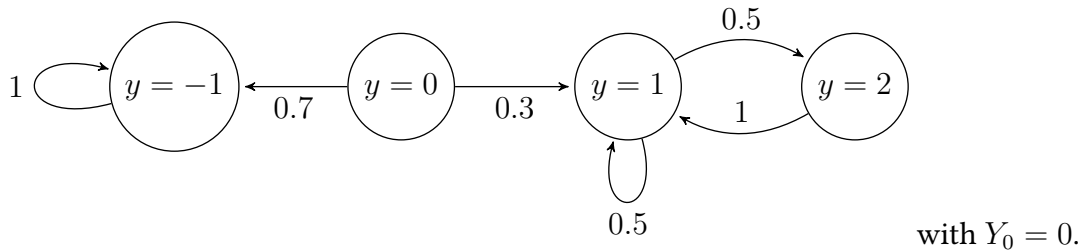
d) Find the probability limit

$$\text{plim} \sqrt[n]{\exp(2X_1 + 2X_2 + \cdots + 2X_n)}.$$

**6.15** Consider two Markov chains,  $(X_t)$  and  $(Y_t)$ :



and



a) Find  $\mathbb{P}(\lim X_n \text{ exists})$  and  $\mathbb{P}(\lim Y_n \text{ exists})$ .

b) Find the limiting distribution of  $(X_n)$  and the limiting distribution of  $(Y_n)$ .

Hint: here you need to calculate all limits  $\lim \mathbb{P}(X_n = k)$ ,  $\lim \mathbb{P}(Y_n = k)$ .

c) Does  $(X_n)$  converges almost surely? In distribution? In probability?

d) Does  $(Y_n)$  converges almost surely? In distribution? In probability?

**6.16**

**6.17**

**6.18**

**6.19**

## 7 Conditional expected value without sigma-algebras

**7.1** We randomly uniformly select a point inside triangle  $A = (6, 0)$ ,  $B = (0, 2)$  and  $O = (0, 0)$ . Let  $(X, Y)$  be coordinates of this random point.

a) Find conditional expected values  $\mathbb{E}(Y | X)$  and  $\mathbb{E}(X | Y)$ .

b) Find conditional variances  $\text{Var}(Y | X)$  and  $\text{Var}(X | Y)$ .

**7.2** The pair of random variables  $X$  and  $Y$  has joint probability density

$$f(x, y) = \begin{cases} x + y, & \text{if } x \in [0; 1], y \in [0; 1]; \\ 0, & \text{otherwise.} \end{cases}$$

- a) Find the marginal densities  $f_X(x)$  and  $f_Y(y)$ .
- b) Find the conditional densities  $f(x | y)$  and  $f(y | x)$ .
- c) Find the conditional expected values  $\mathbb{E}(Y | X)$  and  $\mathbb{E}(X | Y)$ .
- d) Find the conditional variances  $\text{Var}(Y | X)$  and  $\text{Var}(X | Y)$ .

**7.3** The random variables  $X$  and  $Y$  are independent with Poisson distribution with rate  $\lambda = 1$ . Let  $S = X + Y$ .

- a) Find conditional probabilities  $\mathbb{P}(X = x | S = s)$  and  $\mathbb{P}(Y = y | S = s)$ .
- b) Find conditional expected values  $\mathbb{E}(X | S)$  and  $\mathbb{E}(Y | S)$ .
- c) Find conditional variances  $\text{Var}(X | S)$  and  $\text{Var}(Y | S)$ .
- d) How the answers will change if  $X \sim \text{Pois}(\lambda_x)$  and  $Y \sim \text{Pois}(\lambda_y)$ ?

**7.4** Let  $X$  and  $Y$  be independent and exponentially distributed with rate  $\lambda = 1$  and  $S = X + Y$ .

- a) Find conditional densities  $f(x | s)$  and  $f(y | s)$ .
- b) Find conditional expected values  $\mathbb{E}(X | S)$  and  $\mathbb{E}(Y | S)$ .
- c) Find conditional variances  $\text{Var}(X | S)$  and  $\text{Var}(Y | S)$ .
- d) Find  $\text{Cov}(X, Y | S)$  and  $\text{Corr}(X, Y | S)$ .
- e) How the answers will change if  $X \sim \text{Expo}(\lambda_x)$  and  $Y \sim \text{Expo}(\lambda_y)$ ?

**7.5** The random variable  $X$  has Poisson distribution with rate  $\lambda = 1$ . The random variable  $Y$  has uniform distribution on  $[1; 2]$ . Random variables  $X$  and  $Y$  are independent.

Find  $\mathbb{E}(XY | X)$ ,  $\text{Var}(XY + X^3 | X)$ ,  $\text{Cov}(X, Y | X)$ ,  $\text{Cov}(XY, X^2Y | X)$ .

**7.6** The random variables  $X_1$  and  $X_2$  are independent and normally distributed,  $X_1 \sim \mathcal{N}(1; 1)$ ,  $X_2 \sim \mathcal{N}(2; 2)$ . I choose  $X_1$  with probability 0.3 and  $X_2$  with probability 0.7 without knowing their values.

Casino pays me the value  $Y$  that is equal to the chosen random variable.

Let the indicator  $I$  be equal to 1 if I choose  $X_1$  and 0 otherwise.

- a) Express  $Y$  in terms of  $X_1$ ,  $X_2$  and  $I$ .
- b) Find  $\mathbb{E}(Y | I)$ ,  $\text{Var}(Y | I)$ .
- c) Find  $\mathbb{E}(Y)$  and  $\text{Var}(Y)$ .

**7.7** A Hedgehog in the fog starts in  $(0, 0)$  at  $t = 0$  and moves randomly with equal probabilities in four directions (north, south, east, west) by one unit every minute.

Let  $X_t$  and  $Y_t$  be his coordinates after  $t$  minutes and  $S_t = X_t + Y_t$ .

- a) Find  $\mathbb{E}(X_2 | S_2)$ ;
- b) Find  $\text{Var}(X_2 | S_2)$ .

**7.8** Bonnie and Clyde start at the points  $(5, 0)$  and  $(-5, 0)$  of the plane. Each minute each of them simultaneously and independently makes one step in one of the four possible directions (south, north, east, west).

Each of them does  $n$  steps. Let  $X$  be the number of times they will be at the same point.

- a) Estimate the probability  $\mathbb{P}(X \geq 1)$  for  $n = 50$  using  $B = 10000$  simulations.
- b) Estimate  $\mathbb{E}(X)$  and  $\text{Var}(X)$  for  $n = 50$  using  $B = 10000$  simulations.
- c) Plot the estimated value of  $\mathbb{E}(X)$  as a function of  $n$  for  $n$  from 1 to 200 using  $B = 10000$  simulations.

**7.9** Albert Nikolayevich Shiryaev randomly selects a natural number  $N$  from 1 to 7. Let  $Y$  be the remainder after division of  $N$  by 2 and  $X$  be the remainder after division of  $N$  by 3.

- a) Write the joint probability table for  $(X, Y)$ .
- b) Find  $\mathbb{E}(Y | X)$ . Is it linear in  $X$ ?
- c) Find  $\mathbb{E}(X | Y)$ . Is it linear in  $Y$ ?
- d) Find  $\mathbb{E}(\mathbb{E}(Y | X))$  and  $\text{Var}(\mathbb{E}(Y | X))$ .
- e) Find  $\text{Var}(Y | X)$ .
- f) Find  $\mathbb{E}(\text{Var}(Y | X))$ .
- g) Find  $\mathbb{E}(\text{Var}(Y | X)) + \text{Var}(\mathbb{E}(Y | X))$ .

**7.10** Albert Nikolayevich selects a random point uniformly inside a quadrilateral  $ABCD$  where  $A = (0, 0)$ ,  $B = (0, 2)$ ,  $C = (4, 4)$ ,  $D = (4, 0)$ .

- a) Find  $\mathbb{E}(Y | X)$  and  $\mathbb{E}(X | Y)$ .
- b) Find  $\text{Var}(Y | X)$  and  $\text{Var}(X | Y)$ .

Hint: you may use the formula for the variance of uniform distribution :)

**7.11** Albert Nikolayevich selects a random point  $(X, Y)$  with joint probability density

$$f(x, y) = \begin{cases} (3x^2 + 4y^3)/2, & \text{if } x \in [0; 1], y \in [0; 1]; \\ 0, & \text{otherwise.} \end{cases}$$

- a) For the random variable  $x$  find the marginal probability density function  $f(x)$ .
- b) Find the conditional density  $f(y | x)$ .
- c) Find the conditional expected value  $\mathbb{E}(Y | X)$ . Is it linear in  $X$ ?
- d) Find  $\text{Var}(Y | X)$ . Is it constant?
- e) Find  $\mathbb{E}(X)$ ,  $\mathbb{E}(Y)$ ,  $\text{Cov}(X, Y)$  and  $\text{Var}(X)$ .
- f) Find the best linear approximation  $Y^* = \beta_0 + \beta_1 X$  of the random variable  $Y$ .

Hint: Here you should minimize  $\mathbb{E}((Y - Y^*)^2)$  with respect to the true constants  $\beta_0$  and  $\beta_1$ .

**7.12** Consider a fair dice. In the experiment we throw the dice until the first six appears.

- a) Simulate  $B = 100000$  experiments. For every experiment number  $i$  record the total number of throws,  $y_i$ , and the number of even faces appeared,  $x_i$ .
- b) For all values of  $x$  where you have more than 100 records estimate  $\hat{\mu}(x) = \hat{\mathbb{E}}(y_i | x_i = x)$  and  $\hat{v}(x) = \widehat{\text{Var}}(y_i | x_i = x)$ .
- c) Explain intuitively why  $\hat{\mu}(0)$  is less than 3.
- d) Randomly select 100 experiments out of all  $B$  experiments. Draw the scatter plot  $(x_i, y_i)$  for randomly selected experiments. Add the line  $\hat{\mu}(x)$  with bands  $\hat{\mu}(x) \pm 2\sqrt{\hat{v}(x)}$  to the scatter plot.

- e) Is it reasonable to assume that  $\hat{\mu}(x)$  is linear?  
 f) Is it reasonable to assume that  $\hat{v}(x)$  is constant?

No formal tests are required for the last two questions, graphical analysis is sufficient.

**7.13** The joint distribution of vector  $(X, Y)$  is given by  $\mathbb{P}(X = i, Y = j) = 0.1$  for  $1 \leq i \leq j \leq 4$ . Find  $\mathbb{E}(Y | X)$ .

**7.14** The random variable  $X$  is exponentially distributed with parameter  $\lambda$ . The random variable  $Y$  is exponentially distributed with parameter  $1/X$ . Find  $\mathbb{E}(Y | X)$ ,  $\mathbb{E}(Y)$  and  $\text{Var}(Y)$ .

**7.15** In the first bag there balls numbered from 0 to 9, in the second bag there are balls numbered from 1 to 10. One ball was selected from the first bag and one ball from the second one. You will select at random one ball from these two and you will know only its number. Let's denote its number by  $X$  and the number of the other of the two balls by  $Y$ . Find  $\mathbb{E}(Y | X)$ .

**7.16** The random variable  $X$  is uniformly distributed on  $[0; a]$ . Conditionally of  $X$  the random variable  $Y$  is uniformly distributed on  $[0; X]$ . Find  $\mathbb{E}(Y | X)$ ,  $\mathbb{E}(Y)$  and  $\text{Var}(Y)$ .

**7.17**

**7.18**

**7.19**

**7.20**

## 8 Sigma-algebras and measurability

Sigma-algebra generated by discrete random variable  $X$ ,  $\sigma(X)$  — the list of all events that can be stated using  $X$ .

Sigma-algebra generated by arbitrary random variable  $X$ ,  $\sigma(X)$  — the smallest list of events that satisfies two properties:

- The list contains all events of the form  $\{X \leq t\}$ , that means one can compare  $X$  with any number;
- If one takes countably many events from this list and does logical operations (union, complement, intersection) then one will obtain an event from the list.

**8.1** The random variable  $X$  takes values 1, 2 and  $-2$  with equal probabilities.

- Find the sigma-algebra  $\sigma(X)$ .
- How the answer will change if one modifies probability distribution of  $X$ ?
- Find the sigma-algebra  $\sigma(|X|)$ .
- Foma knows  $|X|$  and Yeryoma knows  $X^2$ . What can one say about sigma-algebras that model their knowledge?

**8.2** Experiment may end by one of the six outcomes:

	$X = -1$	$X = 0$	$X = 1$
$Y = 0$	0.1	0.2	0.3
$Y = 1$	0.2	0.1	0.1

- Find explicitly the sigma-algebras  $\sigma(X)$ ,  $\sigma(Y)$ ,  $\sigma(X \cdot Y)$ ,  $\sigma(X^2)$ ,  $\sigma(2X + 3)$ .
- How many elements are there in  $\sigma(X, Y)$ ,  $\sigma(X + Y)$ ,  $\sigma(X, Y, X + Y)$ ?

**8.3** Let's look at the number of possible elements in a sigma-algebra.

- The random variable  $X$  has five possible values. How many events are there in  $\sigma(X)$ ?
- Can a sigma-algebra contain exactly 1000 events? Exactly 1024 events?

Maria throws a coin 100 times and remembers very well all the tosses.

- How many elementary outcomes are there in the probability space  $\Omega$ ?
- How many events are there in a sigma-algebra that models Maria's knowledge?

**8.4** How sigma-algebras  $\sigma(X)$  and  $\sigma(f(X))$  are related? When they are equal?

**8.5** How many different  $\sigma$ -algebras can be created using the set of outcomes  $\Omega$  has three elements? And if  $\Omega$  has four elements?

**8.6** Provide an example of algebra that is not a  $\sigma$ -algebra.

**8.7** Prove a statement or provide a counter-example:

- The intersection of two sigma-algebras is a sigma-algebra.
- If the intersection of two sigma-algebras is a sigma-algebra then one of them is contained in the other one.
- The union of two sigma-algebras is a sigma-algebra.
- If the union of two sigma-algebras is a sigma-algebra then one of them is contained in the other one.

**8.8** Let  $\mathcal{F}$  be some  $\sigma$ -algebra of subsets of  $\Omega$  and  $B \subseteq \Omega$ . Consider the collection of sets  $\mathcal{H} = \{A : A \subseteq B \text{ or } B^c \subseteq A\}$ .

Is  $\mathcal{H}$  a  $\sigma$ -algebra?

**8.9** Будем обозначать количество элементов множества с помощью  $\text{card } A$ . Рассмотрим подмножества натуральных чисел,  $A \subseteq \mathbb{N}$ . Определим для подмножества плотность Чезаро (Cesaro density),

$$\gamma(A) = \lim_{n \rightarrow \infty} \frac{\text{card}(A \cap \{1, 2, 3, \dots, n\})}{n}$$

в тех случаях, когда этот предел существует.

Плотность Чезаро показывает, какую «долю» от всех натуральных чисел составляет указанное подмножество. Обозначим с помощью  $\mathcal{H}$  все подмножества, имеющие плотность Чезаро.

- a) Чему равна плотность Чезаро у нечётных чисел?
- b) Приведите пример множества, у которого не определена доля Чезаро.
- c) Верно ли, что у натуральных чисел, в записи которых присутствует хотя бы одна единица, есть доля? Если да, то чему она равна?
- d) Верно ли, что у натуральных чисел, в записи которых присутствует ровно одна единица, есть доля? Если да, то чему она равна?
- e) Верно ли, что  $\mathcal{H}$  — алгебра? Сигма-алгебра?

**8.10** We throw a fair dice. Let  $Y$  be the indicator of a even score and  $Z$  be the indicator of score bigger than 2.

- a) Find the sigma-algebra  $\sigma(Z)$ .
- b) Find the sigma algebra  $\sigma(Y \cdot Z)$ .
- c) How many elements are there in  $\sigma(Y, Z)$ ?
- d) How are related the  $\sigma$ -algebras  $\sigma(Y \cdot Z)$  and  $\sigma(Y, Z)$ ?

**8.11** We throw a coin infinitely many times. Let  $X_n$  be the indicator that the coin landed on Head at toss number  $n$ . Consider a pack of  $\sigma$ -algebras:  $\mathcal{F}_n := \sigma(X_1, X_2, \dots, X_n)$ ,  $\mathcal{H}_n := \sigma(X_n, X_{n+1}, X_{n+2}, \dots)$ .

- a) For each case provide two examples of  $\sigma$ -algebras that contain the corresponding event
  - (a)  $\{X_{37} > 0\}$ ;
  - (b)  $\{X_{37} > X_{2024}\}$ ;
  - (c)  $\{X_{37} > X_{2024} > X_{12}\}$ ;
- b) Simplify expressions:  $\mathcal{F}_{11} \cap \mathcal{F}_{25}$ ,  $\mathcal{F}_{11} \cup \mathcal{F}_{25}$ ,  $\mathcal{H}_{11} \cap \mathcal{H}_{25}$ ,  $\mathcal{H}_{11} \cup \mathcal{H}_{25}$ .
- c) For each case provide two non-trivial examples (different from  $\Omega$  and  $\emptyset$ ) of an event  $A$  such that
  - (a)  $A \in \mathcal{F}_{2024}$ ;
  - (b)  $A \notin \mathcal{F}_{2025}$ ;
  - (c)  $A \in \mathcal{H}_n$  for all possible  $n$ ;

**8.12** Правда ли равносильны три набора требований к списку множеств  $\mathcal{F}$ ?

Тариф «Классический»:

- a)  $\Omega \in \mathcal{F}$ ;
- b) Если  $A \in \mathcal{F}$ , то  $A^c \in \mathcal{F}$ ;
- c) Если  $A_1, A_2, A_3, \dots \in \mathcal{F}$ , то  $\cup A_i \in \mathcal{F}$ .

Тариф «Перевернутый»:

- a)  $\emptyset \in \mathcal{F}$ ;
- b) Если  $A \in \mathcal{F}$ , то  $A^c \in \mathcal{F}$ ;
- c) Если  $A_1, A_2, A_3, \dots \in \mathcal{F}$ , то  $\cap A_i \in \mathcal{F}$ .

Тариф «Хочу всё»:

- a)  $\Omega \in \mathcal{F}$ ,  $\emptyset \in \mathcal{F}$ ;

- b) Если  $A \in \mathcal{F}$  и  $B \in \mathcal{F}$ , то  $A \setminus B \in \mathcal{F}$ ;
- c) Если  $A_1, A_2, A_3, \dots \in \mathcal{F}$ , то  $\cup A_i \in \mathcal{F}$  и  $\cap A_i \in \mathcal{F}$ .

**8.13** Рассмотрим  $\Omega = [0; 1]$  и набор множества  $\mathcal{F}$  таких, что либо каждое множество не более, чем счётно, либо дополнение к нему не более, чем счётно.

- a) Верно ли, что  $\mathcal{F}$  — алгебра?  $\sigma$ -алгебра?
- b) Придумайте  $B \subset \Omega$ , такое что  $B \notin \mathcal{F}$ .

**8.14** В лесу есть три вида грибов: рыжики, лисички и мухоморы. Попадаются они равновероятно и независимо друг от друга. Маша нашла 100 грибов. Пусть  $R$  — количество рыжиков,  $L$  — количество лисичек, а  $M$  — количество мухоморов среди найденных грибов.

- a) Сколько элементов  $\sigma(R)$ ?
- b) Сколько элементов  $\sigma(R, M)$ ?
- c) Измерима ли  $L$  относительно  $\sigma(R)$ ?
- d) Измерима ли  $L$  относительно  $\sigma(R, M)$ ?
- e) Измерима ли  $L$  относительно  $\sigma(R + M)$ ?
- f) Измерима ли  $L$  относительно  $\sigma(R - M)$ ?

**8.15** Сейчас либо солнечно, либо дождь, либо пасмурно без дождя. Соответственно, множество  $\Omega$  состоит из трёх исходов,  $\Omega = \{\text{солнечно, дождь, пасмурно}\}$ . Джеймс Бонд пойман и привязан к стулу с завязанными глазами, но он может на слух отличать, идёт ли дождь.

- a) Как выглядит  $\sigma$ -алгебра событий, которые различает агент 007?
- b) Как выглядит минимальная  $\sigma$ -алгебра, содержащая событие  $A = \{\text{не видно солнце}\}$ ?
- c) Сколько различных  $\sigma$ -алгебр можно придумать для данного  $\Omega$ ?

**8.16** The random variables  $X_i$  are independent and they take values  $+1$  or  $-1$  with equal probability.

- a) [3] Explicitly list all the events in sigma-algebra  $\sigma(X_1 \cdot X_2)$ .
- b) [3] Pavel says that he knows only whether  $X_1$  and  $X_3$  are equal. How will you describe his knowledge with sigma-algebra?
- c) [4] How many events are in the sigma-algebra  $\sigma(X_1, X_1 + X_2, X_1 + X_2 + X_3)$ ?

**8.17** Vincenzo Peruggia makes attempts to steal the Mona Lisa painting until the first success. Each attempt is successful with probability 0.1.

Let  $X$  be the number of attempts and  $Z = \min\{X, 5\}$ .

- a) (5 points) How many events are in sigma-algebras  $\sigma(Z)$  and  $\sigma(X)$ ?
- b) (5 points) If possible provide an example of events  $A$  and  $B$  such that:  $A \in \sigma(Z)$  but  $A \notin \sigma(X)$ ;  $B \in \sigma(X)$  but  $B \notin \sigma(Z)$ .
- c) (10 points) Find  $\mathbb{E}(Z | X)$  and  $\mathbb{E}(X | Z)$ .

**8.18** Variables  $X_1, X_2, \dots, X_{100}$  are independent and identically distributed with mean 1 and variance 2. Each  $X_i$  has only three possible values: 0, 1, and 2.

- a) (5 points) How many events are in sigma-algebras  $\sigma(X_1, X_2)$  and  $\sigma(X_1 - X_2)$ ?

- b) (5 points) If possible provide an example of events  $A$  and  $B$  such that:  $A \in \sigma(X_1, X_2)$  but  $A \notin \sigma(X_1 - X_2)$ ;  $B \in \sigma(X_1 - X_2)$  but  $B \notin \sigma(X_1, X_2)$ .
- c) (10 points) Find  $\mathbb{E}(X_1 + \dots + X_{100} \mid X_1 + \dots + X_{50})$  and  $\mathbb{E}(X_1 + \dots + X_{50} \mid X_1 + \dots + X_{100})$ .

8.19

8.20

8.21

8.22

## 9 Sigma-algebras and conditional expected value

- 9.1** At time moment  $t = 0$  in the casino there are countably many players with perfect memory. Let's number them as Miss First, Mister Second, etc.

Time is discrete. Random variables  $X_t$  are independent and take values  $+1$  or  $-1$  with equal probabilities. At each moment of time  $t > 0$  everybody gets  $X_t$  roubles and then the player number  $t$  leaves the casino.

The cumulative sum  $S_t = X_1 + \dots + X_t$  reaches its first local maximum at the random time  $T$ . At time  $T + 1$  the dealer calls his friend Black Jack and says «It's time!» They have agreed beforehand on the call time.

Black Jack chases the player number  $T$  and steals all his information before the police can intervene. Let's describe the information of Black Jack by sigma-algebra  $\mathcal{F}_J$  and the information of every player  $t$  at the last moment in casino by  $\mathcal{F}_t$ .

- Which sigma-algebras contain the event  $\{T = 10\}$ ?
- Provide an example of two events from  $\mathcal{F}_J$  that do not enter in neither  $\mathcal{F}_t$ .
- Find conditional expected values  $\mathbb{E}(T \mid \mathcal{F}_J)$ ,  $\mathbb{E}(X_T \mid \mathcal{F}_J)$ ,  $\mathbb{E}(X_{T+1} \mid \mathcal{F}_J)$ .
- Find conditional expected values  $\mathbb{E}(S_{T-1} \mid \mathcal{F}_J)$ ,  $\mathbb{E}(S_T \mid \mathcal{F}_J)$ ,  $\mathbb{E}(S_{T+1} \mid \mathcal{F}_J)$ ,  $\mathbb{E}(S_{T+2} \mid \mathcal{F}_J)$ .

Let's define  $Y_{T-k}$  as

$$Y_{T-k} = \begin{cases} X_{T-k}, & \text{if } T - k > 0; \\ 0, & \text{otherwise.} \end{cases}$$

- Find  $\mathbb{E}(Y_{T-10} \mid \mathcal{F}_J)$ .
- Find conditional expected values  $\mathbb{E}(X_T \mid \mathcal{F}_{10})$ ,  $\mathbb{E}(X_{T+1} \mid \mathcal{F}_{10})$ .
- Find  $\mathbb{E}(T \mid \mathcal{F}_{10})$  and  $\mathbb{E}(S_T \mid \mathcal{F}_{10})$ .

- 9.2** Bad police officers operate in groups of 1, 2 or 3 people with probabilities 0.5, 0.2 and 0.3. If you cross the road in the wrong place, they will catch you and demand a bribe  $X$  of 1, 5 or 10 thousand rubles respectively.

For each of the following cases write down the  $\sigma$ -algebra  $\mathcal{F}$  that models your information and calculate  $\mathbb{E}(X \mid \mathcal{F})$ .

- you can see how many officers are going to stop you;
- they are sitting in the car and you don't know their number;



c) it is dark and you can only say if it is one policeman or more than one.

**9.3** HSE student rolled the dice once. Find the  $\sigma$ -algebras that model the following situations:

- a) she only knows that the dice was rolled once;
- b) she knows the result of the roll;
- c) she observes the result of the roll but she is able to count only up to two.

## 10 Martinales

- *Natural filtration* of a process  $(X_n)$  is given by  $\mathcal{F}_n = \sigma(X_1, X_2, \dots, X_n)$ .
- A process  $(X_n)$  is a *martingale* if  $\mathbb{E}(X_{n+k} \mid X_n, X_{n-1}, \dots, X_1) = X_n$  for all  $k \geq 1$ .
- A process  $(X_n)$  is *adapted* to filtration  $(\mathcal{F}_n)$  if every random variable  $X_n$  is measurable wrt to sigma-algebra  $\mathcal{F}_n$ .
- A process  $(X_n)$  is a *martingale wrt to filtration*  $(\mathcal{F}_n)$  if  $\mathbb{E}(X_{n+k} \mid \mathcal{F}_n) = X_n$ .

**10.1** Consider the sequence  $(X_t)$  of independent identically distributed random variables with mean  $\mathbb{E}(X_t) = 2$  and variance  $\text{Var}(X_t) = 3$ . Let's work with natural filtration  $\mathcal{F}_t = \sigma(X_1, X_2, \dots, X_t)$ . On the base of  $(X_t)$  let's create more sequences:  $S_t = X_1 + X_2 + \dots + X_t$ ,  $W_t = S_t - 2t$  and  $Y_t = W_t^2 - 3t$ .

- a) Is  $(X_t)$  a martingale with respect to  $(\mathcal{F}_t)$ ?
- b) Is  $(S_t)$  a martingale with respect to  $(\mathcal{F}_t)$ ?
- c) Is  $(W_t)$  a martingale with respect to  $(\mathcal{F}_t)$ ?
- d) Is  $(Y_t)$  a martingale with respect to  $(\mathcal{F}_t)$ ?
- e) Is  $(W_t)$  a martingale with respect to  $(\mathcal{F}_{t-1})$ ?
- f) Is  $(W_t)$  a martingale with respect to  $(\mathcal{F}_{t+1})$ ?

**10.2** Vasiliy has found three non-random infinite sequences in his garage:  $a_n = n$ ,  $b_n = -n$  and  $c_n = 0$ . He randomly selects one of these sequences with equal probabilities and hence obtain a sequence of random variables  $(X_n)$ .

- a) What is the distribution of  $X_7$ ?
- b) Find  $\mathbb{E}(X_n)$  and  $\text{Var}(X_n)$ .
- c) Is  $(X_n)$  a Markov chain?
- d) Is  $(X_n)$  a martingale?
- e) Explicitely find the  $\sigma$ -algebra  $\sigma(X_1, X_2, X_3, \dots, X_{1000})$ .
- f) Find the probability that limit of  $(X_n)$  exists.
- g) Does  $\text{plim } X_n$  exist?

**10.3** Consider the sequence  $(X_t)$  of independent identically distributed random variables that take values 0 or 1 with equal probabilities. Let's work with natural filtration  $\mathcal{F}_t = \sigma(X_1, X_2, \dots, X_t)$ . On the base of  $(X_t)$  let's create more sequences:  $S_t = X_1 + X_2 + \dots + X_t$ ,  $W_t = S_t - at$ ,  $M_t = \exp(bS_t)$ .

- a) Is  $(X_t)$  a martingale?
- b) Is  $(S_t)$  a martingale?
- c) For which values of  $a$  the process  $(W_t)$  is a martingale?
- d) For which values of  $b$  the process  $(M_t)$  is a martingale?

**10.4** Consider a well-mixed standard deck of 52 cards. James Bond in an elegant outfit<sup>1</sup> opens cards one by one. Let the sigma-algebra  $(\mathcal{F}_n)$  model his information and  $(X_n)$  be the proportion of Queens in the closed part of the deck after opening  $n$  cards.

- a) Find the marginal distribution of  $X_0$ ,  $X_1$  and  $X_{51}$ .
- b) Find the joint distribution of  $X_{50}$  and  $X_{51}$ .
- c) Is  $(X_n)$  a martingale with respect to  $(\mathcal{F}_n)$ ?

**10.5** If possible create a martingale  $(X_n)$  such that simultaneously  $\mathbb{P}(X_n = 0 \text{ infinitely often}) = 1$  and  $\mathbb{P}(X_n = 1 \text{ infinitely often}) = 1$ .

**10.6** At time  $t = 0$  there is one black and one white ball in the vase. At each moment of time we take out randomly one ball from the vase and put back two balls of the same color. Let  $(W_t)$  be the proportion of white balls in the vase after  $t$  extractions and  $(Q_t)$  be the number of times when white ball was extracted.

- a) What is the distribution of  $W_1$ ? Of  $W_2$ ?
- b) Is  $(W_t)$  a martingale?
- c) Consider a fixed parameter  $p \in (0; 1)$  and the process  $M_t = (t + 1)C_t^{Q_t} p^{Q_t} (1 - p)^{t - Q_t}$ . Is  $(M_t)$  a martingale?
- d) What is the limiting distribution of  $(W_t)$ ?

**10.7** Consider non-random sequence of numbers  $(a_n)$ . How can this sequence be a martingale?

**10.8** Let  $(M_n)$  be a martingale and  $a < b < c < d$ .

- a) Find covariance  $\text{Cov}(M_d - M_c, M_b - M_a)$ .
- b) Are  $(M_d - M_c)$  and  $(M_b - M_a)$  independent?

**10.9** Let  $(M_t)$  be a process adapted to filtration  $(\mathcal{F}_t)$ .

Is it true that in discrete time conditions

$$\mathbb{E}(M_{t+1} \mid \mathcal{F}_t) = M_t$$

and

$$\mathbb{E}(M_{t+k} \mid \mathcal{F}_t) = M_t \text{ for all } k \geq 1$$

are equivalent?

**10.10** Initial wealth of a player is equal to  $W_0 = 1$ . At each moment of time she can bet any proportion of her welfare on the toss of a coin. If she guesses wrong she loses her bet. If she guesses right she gets profit equal to her bet. The coin is not fair lands on head with probability 0.8.

- a) Find the bet that maximises one period log interest rate  $\mathbb{E}(\ln(W_{t+1}/W_t) \mid \mathcal{F}_t)$ .

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<sup>1</sup>Sponsors are wellcome to contact us for product placement!

- b) Assume that the player maximises one period log interest rate every time. Find a constant  $a$  such that  $\ln W_n - an$  is a martingale.

**10.11** For each case provide an example of a process.

- $(X_n)$  is a Markov chain and a martingale.
- $(X_n)$  is a Markov chain but not a martingale.
- $(X_n)$  is a martingale but not a Markov chain.
- $(X_n)$  is neither a Markov chain nor a martingale.

**10.12** Let  $(X_n)$  be a simple symmetric random walk and  $(\mathcal{F}_n)$  its natural filtration.

Find a deterministic (non-random) sequence  $a_n$  such that  $M_n = X_n^3 + a_n X_n$  is a martingale with respect to  $(\mathcal{F}_n)$ .

**10.13** The random variables  $X_i$  are independent and they take values  $+1$  or  $-1$  with equal probability.

- [3] Find  $\mathbb{E}(X_3 \mid X_1, X_2)$ ,  $\mathbb{E}(X_3 \mid X_1 + X_3)$ .
- [3] Find  $\text{Var}(X_3 \mid X_1, X_2, X_3)$ ,  $\text{Var}(X_3 \mid X_1 + X_3)$ .
- [4] Let  $Y_n$  be equal to  $\mathbb{E}(X_1 + \dots + X_{2022} \mid X_1, X_2, \dots, X_n)$ .  
Is the process  $Y_1, Y_2, \dots, Y_{2022}$  a martingale?

**10.14** Let  $S_0 = 0$ ,  $S_t = X_1 + X_2 + \dots + X_t$ . The increments  $X_t$  are independent and identically distributed:

$x$	$-1$	$0$	$1$
$\mathbb{P}(X_t = x)$	$0.2$	$0.2$	$0.6$

- If possible find all constants  $a$  such that  $M_t = S_t + at$  is a martingale.
- If possible find all constants  $b$  such that  $R_t = b^{S_t}$  is a martingale.

**10.15** Let  $X_i$  be independent identically distributed with  $\mathbb{P}(X_i = 1) = 0.9$ ,  $\mathbb{P}(X_i = -1) = 0.1$ .

Find all constants  $a$  and  $b$  such that  $Y_t = a \exp(b \sum_{i=1}^t X_i)$  is a martingale.

**10.16** The random variables  $(Z_t)$  are independent identically distributed with moment generating function given by  $M_Z(u) = 1/(1 - 5u)^3$ .

We define  $X_t$  as  $X_t = \exp(Z_1 + 2Z_2 + 3Z_3 + \dots + tZ_t)$  with  $X_0 = 0$ .

If possible find a martingale of the form  $Y_t = h(t)X_t$  where  $h(\cdot)$  is a non-random function.

**10.17** The process  $(Z_t)$  in discrete time is called *stationary* if it has constant expected value and constant covariances  $\gamma_k$  that do not depend on  $t$ .

$$\begin{cases} \mathbb{E}(Z_t) = \mu; \\ \text{Cov}(Z_t, Z_t) = \gamma_0; \\ \text{Cov}(Z_t, Z_{t+1}) = \gamma_1; \\ \text{Cov}(Z_t, Z_{t+2}) = \gamma_2; \\ \dots \end{cases}$$

- If possible provide an example of a martingale that is not stationary.
- If possible provide an example of a stationary process that is not a martingale.

**10.18** The population starts with one microbe Eve. So the size of the initial generations is  $G_0 = 1$ . After one minute every microbe either dies with probability 0.2, remains alive with probability 0.5 or splits in two copies with probability 0.3. Let  $G_n$  be the size of microbe population after  $n$  minutes.

- Draw a pretty picture of Eve :)
- Find the distribution of  $G_2$ .
- Find a constant  $a$  such that  $M_n = G_n/a^n$  is a martingale.
- Let  $D$  be the event of eventual death of the microbe civilization. Check whether the process  $K_n = \mathbb{E}(I_D \mid G_n, G_{n-1}, \dots, G_0)$  is martingale. Here  $I_D$  is the indicator of the event  $D$ .
- Using first step analysis find  $\mathbb{P}(D)$ .

Hint: you may obtain a quadratic equation for  $\mathbb{P}(D)$ , the smallest root is your friend :)

**10.19** The random variables  $X_n$  are independent and take values  $+1$  with probability 0.7 or  $2$  with probability 0.3. Let  $S_n = X_1 + X_2 + \dots + X_n$  be the cumulative sum.

- Find the constant  $a$  such that  $M_n = S_n - an$  is a martingale.
- Find all constants  $b$  such that  $K_n = \exp(bS_n)$  is a martingale.

**10.20**

## 10.1 Stopping time

Doob's optional stopping time theorem. If  $(M_t)$  is a martingale and  $\tau$  is a stopping time then  $\mathbb{E}(M_\tau) = \mathbb{E}(M_0)$  provided at least one of the following conditions hold:

- $\mathbb{P}(\tau < \infty) = 1$ , the stopped process  $X_t = M_{t \wedge \tau}$  is bounded by some constant.
- $\mathbb{E}(\tau) < \infty$ , the process  $D_t = \mathbb{E}(M_{(t+1) \wedge \tau} - M_{t \wedge \tau} \mid \mathcal{F}_t)$  is bounded by some constant.
- $\mathbb{P}(\tau < \infty) = 1$ , the process  $M_t$  is uniformly integrable, ie

$$\lim_{a \rightarrow \infty} \sup_t \mathbb{E}(M_t \cdot I(M_t > a)) = 0.$$

**10.21** A gambler wins or loses one rouble in each round in the casino with equal probabilities and independently. Let's denote the result of the  $n$ -th round by  $X_n$ .

The gambler starts with initial fortune  $S_0 = 0$ . Let  $S_n = X_1 + X_2 + \dots + X_n$  be the wealth at time  $n$ . She can have negative balance up to  $-a$  roubles.

She quits the casino when she either reaches the target of  $+b$  roubles or the credit limit of  $-a$  roubles.

- Is  $(S_n)$  a martingale?
- Use optional-stopping theorem to find probabilities of reaching  $+b$  or  $-a$ .
- Is  $M_n = S_n^2 - n$  a martingale?
- Find the expected number of rounds before she will stop gambling.

**10.22** A gambler wins or loses one rouble in each round in the casino with unequal probabilities and independently. Let's denote the result of the  $n$ -th round by  $X_n$ ,  $\mathbb{P}(X_n = 1) = p$ ,  $\mathbb{P}(X_n = -1) = q = 1 - p$ .

The gambler starts with initial fortune  $S_0 = 0$ . Let  $S_n = X_1 + X_2 + \dots + X_n$  be the wealth at time  $n$ . She can have negative balance up to  $-a$  roubles.

She quits the casino when she either reaches the target of  $+b$  roubles or the credit limit of  $-a$  roubles.

- a) Is  $(S_n)$  a martingale?
- b) Is  $K_n = (q/p)^{S_n}$  a martingale?
- c) Use optional-stopping theorem to find probabilities of reaching  $+b$  or  $-a$ .
- d) Is  $M_n = S_n - (p - q)n$  a martingale?
- e) Find the expected number of rounds before she will stop gambling.

### 10.23 Famous «ABRACADABRA» problem.

A monkey types randomly letters on a typewriter choosing each time one of the 26 letters with equal probabilities. Let  $T$  be the number of keypresses required to write the word «ABRACADABRA» for the first time.

- a) Organise a casino to calculate  $\mathbb{E}(T)$ .
- b) Organise a casino to calculate  $\mathbb{E}(T^2)$  and hence  $\text{Var}(T)$ .

### 10.24 To survive vampire Boris needs to bite 70 talented students.

These 70 talented students have formed a secret group. They have written their emails on small pieces of paper and have randomly distributed these pieces among them. Each student has exactly one piece of paper with an email<sup>2</sup>.

Initially vampire Boris knows contacts of just two persons from the group. Today he will contact them, drink their blood and get the emails they have. Then vampire Boris will contact new victims and so on.

- a) For  $t \geq 1$  consider the process  $M_t$ , the proportion of non bitten students after the day  $t$ . Is this process a martingale?
- b) Using martingale stopping theorem or otherwise find the probability that vampire Boris will bite all 70 students.

10.25

10.26

10.27

10.28

## 11 Poisson process

The process  $(N_t)$  is called *Poisson process* with intensity  $\lambda$  if

- $N_0 = 0$ ;

<sup>2</sup>The group is so secret that it is possible that a student has his own email on his piece of paper

- **Increments are independent:** If  $t_1 < t_2 < t_3 < \dots < t_k$  then random increments  $N(t_2) - N(t_1)$ ,  $N(t_3) - N(t_2)$ , ... are independent.
- **Increments have Poisson distribution:**

$$N_b - N_a \sim \text{Pois}(\lambda(b - a));$$

Alternative definition. The process  $(N_t)$  is called *Poisson process* with intensity  $\lambda$  if

- $N_0 = 0$ ;
- Increments are independent;
- Increments are stationary:  
The distribution of  $N_b - N_a$  depends only on  $(b - a)$ .
- Probability of observing two or more points in a small interval is negligible:

$$\mathbb{P}(N_{t+\Delta} - N_t > 1) = o(\Delta).$$

- Probability of observing one point is approximately proportional to the length of time interval:

$$\mathbb{P}(N_{t+\Delta} - N_t = 1) = \lambda \Delta + o(\Delta).$$

**11.1** Two cashiers Alice and Bob simultaneously started to service their clients. The service times  $X_a$  and  $X_b$  are independent and exponentially distributed with rates  $\lambda_a = 1$  and  $\lambda_b = 2$ .

- Find the probability  $\mathbb{P}(X_a < X_b)$ .
- Find the density of  $S = X_a + X_b$ .
- Find the density of  $L = \min\{X_a, X_b\}$ .
- Find the density of  $R = \max\{X_a, X_b\}$ .
- Solve all the previous points for general rates  $\lambda_a$  and  $\lambda_b$ .

**11.2** Let  $X_t$  and  $Y_t$  be two independent Poisson processes. Is it true that  $S_t = X_t + Y_t$  is also a Poisson process?

**11.3** Hedgehogs are scattered in a big forest according Poisson process with rate  $\lambda = 1$  per 100 squared meters.

What should be the edge of a square such that the probability of finding a hedgehog there is 0.7?

**11.4** Let  $N_t$  be a Poisson process with rate  $\lambda$ .

- Is the process  $A_t = N_t - \lambda t$  a martingale?
- Is the process  $B_t = A_t^2 - \lambda t$  a martingale?

**11.5** Students arrive in the Grusha café according to the Poisson arrival process  $(X_t)$  with constant rate  $\lambda$ . The probability of no visitors during 5 minutes is 0.05.

- Find the value of  $\lambda$ .
- Find the variance and expected number of arrivals between 5 pm and 8 pm.

c) What is the probability of exactly 5 arrivals between 5 pm and 8 pm?

**11.6** Masha receives on average 10 sms per minute. Sms arrival is well described by the Poisson process.

- a) What is the probability that Masha receives exactly 10 sms in the next 40 seconds?
- b) Masha just received an sms. What is the probability that she will wait more than 2.5 seconds before the next one?
- c) Find the covariance between the number of sms in the first 3 minutes and the number of sms in the first 10 minutes.

**11.7** Taxis arrive to the station according to the Poisson process with rate 1 per 5 minutes. Let  $Y_t$  be the number of taxis that will arrive between 0 and  $t$  minutes.

- a) Sketch the expected value of  $Y_t$  as a function of  $t$ .
- b) Sketch the probability  $\mathbb{P}(Y_t = Y_{60})$  as a function of  $t$ .

**11.8** A company gets fines for non-removal of quadrobics video content. What is the probability that the total amount will exceed two undecillion roubles in 1000 days for each case?

- a) Fines arrive according to Poisson process with rate 1 fine per day and each fine has the size  $10^{33}$  roubles. Fines are summing up without additional penalties.
- b) Initial fine is  $10^5$  roubles but it doubles according to Poisson process with rate 1 doubling per 10 days.

**11.9** Let  $(N_t)$  be a Poisson process with intensity rate 2. Consider the vector  $Y = (N_1, N_2, N_{10})$ .

Find  $\mathbb{E}(Y)$  and covariance matrix  $\text{Var}(Y)$ .

**11.10** Customers order coffee according to Poisson process with rate 1 cup per minute. The owner will close the shop if no one orders a coffee in 7 minutes.

Let  $X$  be the closure time.

Find  $\mathbb{E}(X)$  and  $\text{Var}(X)$ .

**11.11** The arrival of buses at a given stop follows Poisson process with rate 3. The arrival of taxis at same stop follows independent Poisson process with rate 5.

- a) What is the probability that two or more taxis will arrive before next bus?
- b) What is the probability that exactly two taxis will arrive before next bus?

**11.12** Customers order coffee according to Poisson process with rate 1 cup per minute. Let  $N_t$  be the number of orders up to time  $t$ .

Find the probability  $\mathbb{P}(N_t \text{ is even})$ .

**11.13** Arrivals of buses at a stop follow Poisson point process with rate  $\lambda = 2$  buses per hour.

- a) Find the probability that you will wait for the bus more than 30 minutes.
- b) Find the probability to wait for the bus more than 30 minutes, if you have already waited 10 minutes.

**11.14** When light bulb burns out it's immediately replaced by a new similar one. The number of burn-outs during any interval of  $t$  hours has Poisson distribution with parameter  $\lambda t$ .

Find the distribution of the first burn-out time  $Y_1$ . Prove your result.

**11.15** Prove that two definitions of Poisson process are equivalent.

Definition A. The process  $(N_t)$  is called *Poisson process* with intensity  $\lambda$  if

- $N_0 = 0$ ;
- Increments are independent: If  $t_1 < t_2 < t_3 < \dots < t_k$  then random increments  $N(t_2) - N(t_1)$ ,  $N(t_3) - N(t_2)$ , ... are independent.
- Increments have Poisson distribution:

$$N_b - N_a \sim \text{Pois}(\lambda(b - a));$$

Definition B. The process  $(N_t)$  is called *Poisson process* with intensity  $\lambda$  if

- $N_0 = 0$ ;
- Increments are independent;
- Increments are stationary:  
The distribution of  $N_b - N_a$  depends only on  $(b - a)$ .
- Probability of observing two or more points in a small interval is negligible:

$$\mathbb{P}(N_{t+\Delta} - N_t > 1) = o(\Delta).$$

- Probability of observing one point is approximately proportional to the length of time interval:

$$\mathbb{P}(N_{t+\Delta} - N_t = 1) = \lambda\Delta + o(\Delta).$$

**11.16** Class teacher solves three exercises per class on average. Exercise solution times are independent exponentially distributed with the same rate. Class duration is two academic hours.

- Find the probability that only one exercise will be solved during the first academic hour.
- Find the probability that one exercise will be completed during the first academic hour and the second exercise will be completed during the second hour.

**11.17**

## 11.1 Poisson approximation

If  $X \sim \text{Bin}(n, p)$ ,  $Y \sim \text{Pois}(\lambda)$  with  $\lambda = np$  and  $A \subset \mathbb{R}$  then

$$|\mathbb{P}(X \in A) - \mathbb{P}(Y \in A)| \leq \min\{p, np^2\}$$

**11.18** Random variable  $X$  has binomial distribution  $\text{Bin}(n, p = \lambda/n)$ .

- Find  $\mathbb{E}(X)$ .
- Find  $\lim_{n \rightarrow \infty} \text{Var}(X)$ .
- Find  $\lim_{n \rightarrow \infty} \mathbb{P}(X = 0)$ ,  $\lim_{n \rightarrow \infty} \mathbb{P}(X = 1)$ .



d) Find  $\lim_{n \rightarrow \infty} \mathbb{P}(X = k)$ .

**11.19** A manufacturer produces light-bulbs that are packed into boxes of 100. Quality control studies indicate that 0.5% of the light-bulbs produced are defective.

- a) Estimate the probability of no defective light-bulbs in a box using Poisson distribution.
- b) Estimate the probability of two or more defective light-bulbs in a box using Poisson distribution.
- c) Provide bounds for the estimation error in points (a) and (b).

**11.20** The home assignment has three exercises. Alice makes no errors in an exercise with probability 0.9 and one arithmetic error with probability 0.1. The errors in different exercises are independent.

- a) What is the probability that Alice will make exactly two errors in the home assignment?
- b) What is the expected number of errors in Alice home assignment?

The number of errors Bob will make in the home assignment follows Poisson distribution. The expected number of errors per home assignment for Bob and Alice are equal.

- c) What is the rate of Bob's Poisson distribution?
- d) What is the probability that Bob will make exactly two errors?
- e) Solve points (a)-(d) if Alice and Bob write an online test that consists of 40 questions with Alice error probability 0.01 for each question.

**11.21** Clients enter the Café according to Poisson process  $(X_t)$  with intensity  $\lambda = 10$  clients per hour. Let  $(Y_i)$  be the inter-arrival times.

- a) What is the distribution of  $Y_1$ ?
- b) What is the distribution of  $Y_1$  given that  $X_1 = 1$ ?
- c) What is the distribution of  $Y_1$  given that  $X_t = 1$ ?
- d) What is the distribution of  $Y_5$  given that  $X_1 = 12$ ?
- e) What is the density function of  $Y_5$  given that  $X_t = 12$ ?

**11.22**

**11.23**

**11.24**

## 12 Wiener Process

**12.1** Consider a Wiener process  $(W_t)$ .

- a) Find  $\mathbb{E}(W_5)$  and  $\text{Var}(W_5)$ .
- b) Find  $\mathbb{E}(W_t)$  and  $\text{Var}(W_t)$ .
- c) Find  $\mathbb{E}(W_5 \mid W_3)$  and  $\text{Var}(W_5 \mid W_3)$ .
- d) Find  $\mathbb{E}(W_t \mid W_s)$  and  $\text{Var}(W_t \mid W_s)$  for  $s \leq t$ .
- e) Find  $\text{Cov}(W_5, W_3)$  and  $\text{Cov}(W_s, W_t)$ .

- f) Find  $\text{Cov}(W_5, W_3 \mid W_2)$  and  $\text{Cov}(W_s, W_t \mid W_r)$  for  $r \leq s \leq t$ .
- g) Find  $\mathbb{E}(W_5 - 2W_3)$  and  $\text{Var}(W_5 - 2W_3)$ .
- h) Find  $\mathbb{P}(W_5 - 2W_3 > 0)$  and  $\mathbb{P}(W_5 - 2W_3 > 1)$  in terms of standard normal cumulative distribution function.
- i) Find  $\mathbb{E}(W_5 - 2W_3 \mid W_2 = 1)$  and  $\text{Var}(W_5 - 2W_3 \mid W_2 = 1)$ .
- j) Find  $\mathbb{P}(W_5 - 2W_3 > 1 \mid W_2 = 1)$  in terms of standard normal cumulative distribution function.
- k) What is the distribution of random vector  $R = (W_1, W_3, W_5)$ ?
- l) Find the value of  $a$  such that  $W_3 = aW_5 + U$  where  $U$  and  $W_5$  are independent.
- m) Find  $\mathbb{E}(W_3 \mid W_5)$  and  $\text{Var}(W_3 \mid W_5)$ .

**12.2** Consider a Wiener process  $(W_t)$ .

- a) [4] Let  $Y_t = tW_{2t}$ . What is the distribution of  $Y_t - Y_s$  for  $t \geq s$ ? Is  $Y_t$  a Wiener process?
- b) [6] Find a constant  $\alpha$  such that  $M_t = W_t^3 + \alpha t W_t$  is a martingale.

**12.3** Consider a Wiener process  $(W_t)$ . For  $r < s < t < u$  find the following expected values

- a)  $\mathbb{E}((W_u - W_t)^2(W_s - W_r)^2)$ ;
- b)  $\mathbb{E}((W_u - W_s)(W_t - W_r))$ ;
- c)  $\mathbb{E}((W_t - W_r)(W_s - W_r)^2)$ ;
- d)  $\mathbb{E}(W_r W_s W_t)$ ;
- e)  $\mathbb{E}(W_r W_s W_t \mid W_s)$ ;

**12.4** Here  $(W_t)$  is a Wiener process.

- a) Find  $\mathbb{E}(W_5 W_4 \mid W_4)$ ,  $\text{Var}(W_5 W_4 \mid W_4)$ .
- b) Find covariance  $\text{Cov}(W_4 W_5, W_5 W_6)$ .

**12.5** For Wiener process  $(W_t)$  find  $\mathbb{E}(W_1 W_2 W_3)$  and  $\mathbb{E}(W_2 W_3 \mid W_1)$ .

**12.6** Let  $(W_t)$  be the Wiener process.

- a) Is  $(W_t)$  a martingale?
- b) Is  $Q_t = W_t^2 - t$  a martingale?

**12.7** Let  $(W_t)$  be a Wiener process and  $Y_t = W_{4t}/2$ .

- a) Find  $Y_0$ .
- b) What is the distribution of  $Y_t - Y_s$  for  $s \leq t$ ?
- c) Does  $Y_t$  has independent increments?
- d) Is the trajectory of  $(Y_t)$  almost surely continuous?
- e) Is  $(Y_t)$  a Wiener process?
- f) Complete the statement of the theorem: «If  $(W_t)$  is a Wiener process, then  $Y_t = W_{a^2 t} / \dots$  is ...».

**12.8** Let  $(W_t)$  be a Wiener process and

$$Y_t = \begin{cases} 0, & \text{if } t = 0; \\ t \cdot W_{1/t}, & \text{if } t > 0. \end{cases}$$

- a) Find  $Y_0$ .
- b) What is the distribution of  $Y_t - Y_s$  for  $s \leq t$ ?
- c) Does  $Y_t$  has independent increments?
- d) Is the trajectory of  $(Y_t)$  almost surely continuous for  $t > 0$ ?
- e) Is the trajectory of  $(Y_t)$  almost surely continuous at  $t = 0$ ?
- f) Is  $(Y_t)$  a Wiener process?
- g) Complete the statement of the theorem: «If  $(W_t)$  is a Wiener process, then  $Y_t = \begin{cases} 0, & \text{if } t = 0; \\ t \cdot W_{1/t}, & \text{if } t > 0. \end{cases}$  is ...».

**12.9**

**12.10**

## 13 Ito's integral

**13.1** Let  $(W_t)$  be a Wiener process and

$$X_t = \begin{cases} 5, & \text{if } t \in [0; 6) \\ 7, & \text{if } t \geq 6. \end{cases}$$

Let  $J = \int_0^9 X_t dW_t$ .

- a) Express  $J$  without integrals.
- b) Find  $\mathbb{E}(J)$  and  $\text{Var}(J)$ .

Let  $I_t = \int_0^t X_u dW_u$ .

- c) Express  $(I_t)$  without integrals.
- d) Find  $\mathbb{E}(I_t)$ .
- e) Find  $\text{Var}(I_t)$ .
- f) Find  $\int_0^t \mathbb{E}(X_u^2) du$ .
- g) Find  $\text{Cov}(I_3, I_9)$  and  $\text{Cov}(I_s, I_t)$ .
- h) Is  $(I_t)$  a martingale?
- i) Find  $R_t = \int_0^t X_u du$ .
- j) Find  $\mathbb{E}(R_t)$  and  $\text{Var}(R_t)$ .

**13.2** Let  $(W_t)$  be a Wiener process and

$$X_t = \begin{cases} 1, & \text{if } t \in [0; 3) \\ 4W_2, & \text{if } t \geq 3. \end{cases}$$

Let  $J = \int_0^5 X_t dW_t$ .

- a) Express  $J$  without integrals.
- b) Find  $\mathbb{E}(J)$  and  $\text{Var}(J)$ .

Let  $I_t = \int_0^t X_u dW_u$ .

- c) Express  $(I_t)$  without integrals.
- d) Find  $\mathbb{E}(I_t)$ .
- e) Find  $\text{Var}(I_t)$ .
- f) Find  $\int_0^t \mathbb{E}(X_u^2) du$ .
- g) Find  $\text{Cov}(I_2, I_8)$  and  $\text{Cov}(I_s, I_t)$ .
- h) Is  $(I_t)$  a martingale?
- i) Find  $R_t = \int_0^t X_u du$ .
- j) Find  $\mathbb{E}(R_t)$  and  $\text{Var}(R_t)$ .

**13.3** Let  $(W_t)$  be a Wiener process,

$$X_t = \begin{cases} 1, & \text{if } t \in [0; 3) \\ 4W_2, & \text{if } t \geq 3. \end{cases}, \quad Y_t = \begin{cases} 5, & \text{if } t \in [0; 6) \\ 7, & \text{if } t \geq 6. \end{cases}$$

- a) Find  $\text{Cov}(\int_0^5 X_u dW_u, \int_0^5 Y_u dW_u)$ .
- b) Find  $\text{Cov}(\int_0^5 X_u dW_u, \int_0^5 Y_u du)$ .
- c) Find  $\text{Cov}(\int_0^5 X_u du, \int_0^5 Y_u du)$ .

**13.4** Consider Ito process  $X_t$

$$dX_t = \exp(t)W_t dt + \exp(2W_t) dW_t, \quad X_0 = 1.$$

Consider two processes,  $A_t = 1 + t^2 + X_t^3$  and  $B_t = 1 + t^2 + X_t^3 W_t^4$ .

- a) Find  $dA_t$  and  $dB_t$ .
- b) Write the corresponding explicit expressions for  $A_t$  and  $B_t$ :

$$\text{const} + \int_0^t \dots dW_u + \int_0^t \dots du$$

- c) Check whether  $X_t$  is a martingale.

**13.5** Consider the process  $X_t$

$$X_t = tW_t + \int_0^t uW_u^2 dW_u.$$

- a) Find  $\mathbb{E}(X_t)$ ,  $\text{Var}(X_t)$ .
- b) Find  $dX_t$ .
- c) Check whether  $X_t$  is a martingale.

**13.6** Consider  $X_t = \int_0^t W_u^3 dW_u + \int_0^t (W_u^3 + 3W_u u) du - W_t^3 \cdot t$ .

- a) Find  $dX_t$  and the corresponding full form.
- b) Is  $X_t$  a martingale?

**13.7** Consider  $X_t = \exp(-2W_t - 2t)$ .

- a) Find  $dX_t$ . Is  $X_t$  a martingale?
- b) Find  $\mathbb{E}(X_t)$  and  $\text{Var}(X_t)$ .
- c) Find  $\int_0^t X_u dW_u$ .

**13.8** Consider an Ito's process  $I_t = 2022 + W_t t^2 + \int_0^t W_u^3 dW_u + \int_0^t W_u^2 du$ .

- a) Find  $dI_t$  and check whether  $I_t$  is a martingale.
- b) Check whether  $J_t = I_t - \mathbb{E}(I_t)$  is a martingale.

**13.9** Martingales are everywhere :)

Consider the process  $Y_t = \exp(-uW_t)$ .

- a) Find a multiplier  $h(u, t)$  such that  $M_t = h(u, t) \cdot Y_t$  is a martingale.
- b) Find  $dY_t$ ,  $\mathbb{E}(Y_t)$  and  $\text{Var}(Y_t)$ .
- c) Consider  $M_t$  that you have found as a function of  $u$ . Find the Taylor approximation of the function  $M_t(u)$  up to  $u^4$ .
- d) Consider the coefficient before  $u^4$  in the Taylor expansion of  $M_t(u)$ . Is it a martingale?

**13.10** Consider the process  $X_t = \int_0^t W_u^2 dW_u + \int_0^t (W_u^2 + 2W_u u) du - W_t^2 \cdot t$ .

- a) Find  $dX_t$  and the corresponding full form.
- b) Is  $X_t$  a martingale?
- c) Find  $\mathbb{E}(X_t)$ .

**13.11** Consider the stochastic process  $X_t = f(t) \cos(2021W_t)$ .

- a) Find  $dX_t$ .
- b) Find any  $f(t) \neq 0$  such that  $X_t$  is a martingale.
- c) Using  $f(t)$  from the previous point find  $\mathbb{E}(\cos(2021W_t))$ .

**13.12** Let  $Y_t = W_t^3 - 3tW_t$ .

- a) Using Ito's lemma find  $dY_t$ .
- b) Using your previous result find  $\mathbb{E}(Y_t)$  and  $\text{Var}(Y_t)$ .

**13.13** Let  $Y_t = \exp(-aW_t - a^2 t/2)$ .

- a) Using Ito's lemma find  $dY_t$ .
- b) Using your previous result find  $\mathbb{E}(Y_t)$  and  $\text{Var}(Y_t)$ .

**13.14** Once teachers proposed the following problem on the exam: «Let  $S_n$  be a symmetric random walk with  $S_0 = 0$ . Check whether  $S_n^2 - n$  is a martingale».

One student wrongly confused symmetric random walk in discrete time ( $S_n$ ) with Wiener process in continuous time ( $W_t$ ). He proposed the wrong solution: «Let's find  $dS_n$  by Ito's lemma:  $dS_n = 2S_n dS_n - dn + 0.5 \cdot 2(dS_n)^2 = 2S_n dS_n$ . The  $dn$  coefficient is zero, hence  $S_n$  is a martingale».

- a) Provide another example of a function  $h(x, t)$  such that  $h(W_t, t)$  is a martingale in continuous time and  $h(S_n, n)$  is a martingale in discrete time.
- b) Why this coincidence is possible?
- c) Provide an example of a function  $h(x, t)$  such that  $h(W_t, t)$  is a martingale in continuous time but  $h(S_n, n)$  is not a martingale in discrete time.

**13.15**

**13.16**

## 14 Stochastic Differential Equations

**14.1** Let's consider the following system of stochastic differential equations

$$\begin{cases} dX_t = aX_t dt - Y_t dW_t \\ dY_t = aY_t dt + X_t dW_t \end{cases}$$

with initial conditions  $X_0 = x_0$  and  $Y_0 = 0$ .

- a) Find the solution of the form  $X_t = f(t) \cos W_t$  and  $Y_t = g(t) \sin W_t$ .
- b) Prove that for any solution  $D_t = X_t^2 + Y_t^2$  is nonstochastic.

**14.2**

**14.3**

## 15 Binomial asset pricing model

**15.1** Consider two-period binomial model with initial share price  $S_0 = 600$ , Up and down multipliers are  $u = 1.2$ ,  $d = 0.9$ , risk-free interest rate is  $r = 0.05$  per period.

Consider an option that pays you  $X_2 = 100$  at  $T = 2$  if  $S_2 > S_1$  and nothing otherwise.

- a) Find the risk neutral probabilities.
- b) Find the current price  $X_0$  of the asset.
- c) How much shares should I have at  $t = 1$  in the «up» state of the world to replicate the option?

**15.2**

**15.3**

**15.4**

## 16 Black and Scholes model

**16.1** Consider Black and Scholes model with riskless rate  $r$ , volatility  $\sigma$  and initial share price  $S_0$ .

Find the current price  $X_0$  of an option that pays you  $X_2 = S_1^3$  at time  $T = 2$ .

**16.2** Ded Moroz would like to receive  $X_T = S_T^{-1}$  at time  $T$  if  $S_T < 1$  and nothing otherwise.

Assume the framework of Black and Scholes model,  $S_t$  is the share price,  $r$  is the risk free rate,  $\sigma$  is the volatility.

How much Ded Moroz should pay now at  $t = 0$ ?

**16.3** Consider the Black and Scholes model with riskless rate  $r$ , volatility  $\sigma$  and initial share price  $S_0$ .

Find the current price  $X_0$  of an option that pays you one dollar at time  $T = 2$  only if  $S_2 > \exp(3r)S_0$ .

**16.4** In the framework of the Black and Scholes model find the price at  $t = 0$  of an asset that pays  $\min\{M, \ln S_t\}$  at time  $T$ . Here  $S_T$  denotes the price of one share at time  $T$ ,  $M$  – arbitrary constant, specified at the moment of the issue.

**16.5** The price of a share in euros is driven by the equation  $dS = \sigma S dW + \alpha S dt$ , the dollar/euro exchange rate is driven by the equation  $dU = bU dW + cU dt$ .

Find the current price in dollars of a European call option with maturity date  $T$ , strike price  $K$ .

**16.6**

## Lag notation

**16.7** Rewrite the equation  $y_t = 4 + 0.4y_{t-1} + 0.3u_{t-1} + u_t$  using lag operator.

**16.8** Consider the process  $(x_t)$  with  $t \geq 0$  and  $y_t = (1 + L)^t x_t$ . Write  $x_t$  in terms of  $y_t$  using lag operator  $L$ .

**16.9** Let  $(F_n)$  be the sequence of Fibonacci numbers.

- a) Write the recurrence relation of Fibonacci numbers using lag operator.
- b) Simplify the expression  $L^3(1 + L)^3 F_n$ .
- c) Simplify the expression  $L^{13}(1 + L)^{10} F_n$ .
- d) Simplify the fraction

$$\frac{F_{101} + C_5^1 F_{102} + C_5^2 F_{103} + C_5^3 F_{104} + C_5^4 F_{105} + C_5^5 F_{106}}{F_{111}}$$

- e) Simplify the value of  $a$ .

**16.10** Consider the process  $(x_t)$  with integer time  $t$  and  $y_t = x_{-t}$ .

Which reasoning is good and why?

- a)  $Ly_t = Lx_{-t} = x_{-t-1}$ ;
- b)  $Ly_t = y_{t-1} = x_{-t+1}$ ;
- c)  $x_t Ly_t = x_t y_{t-1}$ ;
- d)  $x_t Ly_t = x_{t-1} y_t$ .

## 17 Stationarity

The process  $(u_t)$  is called a white noise if  $\mathbb{E}(u_t) = 0$ ,  $\text{Var}(u_t) = \sigma^2$  and  $\text{Cov}(u_t, u_s) = 0$  for  $t \neq s$ .

The process  $(y_t)$  is called weakly stationary if  $\mathbb{E}(y_t) = \mu$  and  $\text{Cov}(u_t, u_s) = \gamma_{t-s}$ .

The process  $(y_t)$  is called strictly stationary if the distribution law of  $(y_t, y_{t+1}, \dots, y_{t+k})$  does not depend on  $t$  for all  $k$ .

**17.1** The variables  $x_t$  take values 0 or 1 with equal probabilities. The variables  $u_t$  are normal  $\mathcal{N}(0; 1)$ . All variables are independent.

Consider the process  $z_t = x_t(1 - x_{t-2})u_t$ .

- a) Find the covariance  $\text{Cov}(z_t, z_s)$ . Is the process  $z_t$  stationary?
- b) Given that  $z_{100} = 2.3$  find shortest predictive intervals for  $z_{101}$  and  $z_{102}$  with probability of coverage at least 95%.

**17.2** Recall the definition of a martingale, Markov chain and stationary process.

Provide an explicit example for all 8 possible combination of these properties.

**17.3** Each process can be weakly stationary or not, strictly stationary or not.

Provide an explicit example for all four possible combination of these properties.

**17.4** Let  $y_t$  be a stationary process. Check whether the following processes are stationary. For stationary  $(z_t)$  express its autocovariance function in terms of an autocovariance function of  $(y_t)$ .

- a)  $z_t = 2y_t$ ;
- b)  $z_t = y_t + 1$ ;
- c)  $z_t = \Delta y_t$ ;
- d)  $z_t = 2y_t + 3y_{t-1}$ .

**17.5** Let  $u_t$  be a white noise. Consider the equation  $y_t = 2 + 0.5y_{t-1} + u_t$  where  $t \geq 0$  and each  $y_t$  may depend only on  $u_t, u_{t-1}, \dots, u_0$ .

- a) Find  $\mathbb{E}(y_t)$  and  $\text{Var}(y_t)$  and check the stationarity of the process in the following cases:
  - (a)  $y_0 = 0$
  - (b)  $y_0 = 4$
  - (c)  $y_0 = 4 + u_0$
- b) Find initial condition  $y_0$  such that the resulting process is stationary.
- c) In some books and internet sources it is written something like «the process  $y_t = 2 + 0.5y_{t-1} + u_t$  is stationary as  $|0.5| < 1$ ». What is the problem with this statement?

**17.6** I remove odd numbered observations from a stationary process  $(x_t)$  and obtain a new process  $(y_t)$ .

- a) Express the process  $(y_t)$  in terms of the process  $(x_t)$ .
- b) Is the resulting process  $(y_t)$  stationary?
- c) Find the autocovariance function of  $(y_t)$  in terms of the autocovariance function of  $(x_t)$ .

**17.7** Elon Musk observes a stationary process  $(x_t)$  and is very bored. He throws a fair coin every time he observes a next value. If the coin lands on head then he keeps the observed value as the next value of  $(y_s)$ , otherwise he discards the value and does not record it.

- a) Is the resulting process  $(y_t)$  stationary?
- b) Find the autocovariance function of  $(y_t)$  in terms of the autocovariance function of  $(x_t)$ .

**17.8** Consider the process  $(u_t)$  for  $t \geq 0$  where all  $u_t$  are independent and uniformly distributed on  $[-1; 1]$ .

- a) Is the process  $(u_t)$  a white noise?

Let's draw the process  $(u_t)$  and consider a new process  $x_t$  for  $t \geq 1$ . Define  $x_t = 1$  if the segment joining  $u_t$  and  $u_{t-1}$  intersects the abscissa and  $x_t = 0$  otherwise.

- a) Find  $\mathbb{P}(x_t = 1)$ ,  $\mathbb{E}(x_t)$ .
- b) Find  $\text{Cov}(x_t, x_{t+1})$  and  $\text{Cov}(x_t, x_{t+2})$ .
- c) Is  $(x_t)$  stationary? Is it a white noise?

Now let's count the cumulative number of abscissa intersestions,  $s_t = x_1 + x_2 + \dots + x_t$ .

- d) Find  $\mathbb{E}(s_t)$ .
- e) What is the distribution of  $s_t$ ?
- f) Find approximately  $\mathbb{P}(s_{100} > 55)$ .



**17.9** The variables  $x_t$  are independent and take values 0 or 1 with equal probabilities. The variables  $y_t$  are independent and normal  $\mathcal{N}(0; 24)$ . The processes  $(x_t)$  and  $(y_t)$  are independent.

Consider two processes:

$$a_t = x_t(1 - x_{t-1})y_t \quad \text{and} \quad b_t = y_{t-1}y_t.$$

- a) Are  $(a_t)$  identically distributed? And  $(b_t)$ ?
- b) Are  $(a_t)$  independent? And  $(b_t)$ ?
- c) Is  $(a_t)$  a white noise? And  $(b_t)$ ?

**17.10** The variables  $(u_t)$  are independent and identically continuously distributed.

Let's call the time moment  $t$  a turning point («поворотная точка») if it is the local extremum, ie it is higher than both of his neighbors or is lower than both of his neighbors.

Consider the process  $(z_t)$  where  $z_t = 1$  if  $t$  is a turning point and  $z_t = 0$  if not.

- a) Find  $\mathbb{P}(z_t = 1)$  and  $\mathbb{E}(z_t)$ .
- b) Find  $\text{Cov}(z_1, z_2)$ ,  $\text{Cov}(z_1, z_3)$ ,  $\text{Cov}(z_1, z_4)$ .
- c) Is  $(z_t)$  a stationary process?
- d) Represent  $z_t$  in a form  $z_t = \mu + v_t + \alpha_1 v_{t-1} + \alpha_2 v_{t-2}$ , where  $v_t$  is a white noise.
- e) Are  $(v_t)$  in point (d) independent?

Now let's also count the number of observed turning points by  $s_t = z_2 + \dots + z_{t-1}$ . The values  $z_1$  and  $z_t$  do not enter the sum, as we do not count boundary points as turning points.

- a) Find  $\mathbb{E}(s_t)$  and  $\text{Var}(s_t)$ .
- b) Is  $(s_t)$  stationary?

**17.11** The processes  $(a_t)$  and  $(b_t)$  are stationary. The correlation  $\text{Corr}(a_t, b_t) = 0$  for all  $t$ .

Consider the product  $y_t = a_t b_t$  and the sum  $x_t = a_t + b_t$ .

- a) Is the process  $(x_t)$  stationary? Provide a proof or a counter-example.
- b) Is the process  $(y_t)$  stationary? Provide a proof or a counter-example.
- c) How the answers to (a) and (b) will change if  $\text{Corr}(a_t, b_s) = 0$  arbitrary  $t$  and  $s$ .

**17.12**

**17.13**

## Partial correlation

**17.14** We throw a fair dice three time, let's denote the results by  $X_1$ ,  $X_2$  and  $X_3$ . Consider the sums  $L = X_1 + X_2$ ,  $R = X_2 + X_3$  and  $S = X_1 + X_2 + X_3$ .

- a) Intuitively without calculations find the sign of ordinary and partial correlations  $\text{Corr}(L, R)$ ,  $\text{Corr}(L, S)$ ,  $\text{pCorr}(L, R; S)$ ,  $\text{pCorr}(L, S; R)$ ,  $\text{Corr}(X_1, R)$ ,  $\text{pCorr}(X_1, R; S)$ ,  $\text{pCorr}(X_1, R; L)$ ,  $\text{pCorr}(L, R; X_2)$ ,  $\text{pCorr}(L, R; X_1)$ ;
- b) Try to find the exact value of all ordinary and partial calculations intuitively without calculations.
- c) Calculate all the values honestly.

**17.15** The random variable  $Z$  takes values 0 and 1 with equal probabilities. We know the conditional distribution of the vector  $X = (X_1, X_2)$  given  $Z$ :

$$\begin{aligned} \begin{pmatrix} X_1 \\ X_2 \end{pmatrix} \mid Z = 0 &\sim \mathcal{N} \left( \begin{pmatrix} 0 \\ 0 \end{pmatrix}; \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \right) \\ \begin{pmatrix} X_1 \\ X_2 \end{pmatrix} \mid Z = 1 &\sim \mathcal{N} \left( \begin{pmatrix} 1 \\ 1 \end{pmatrix}; \begin{pmatrix} 4 & -1 \\ -1 & 9 \end{pmatrix} \right) \end{aligned}$$

- Find the partial correlation  $\text{pCorr}(X_1, X_2; Z)$ .
- Find the conditional correlation  $\text{Corr}(X_1, X_2 \mid Z)$ .

**17.16** The random vector  $X = (X_1, X_2, X_3)$  has multivariate normal distribution:

$$\begin{pmatrix} X_1 \\ X_2 \\ X_3 \end{pmatrix} \sim \mathcal{N} \left( \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}; \begin{pmatrix} 10 & 1 & -1 \\ 1 & 10 & 2 \\ -1 & 2 & 10 \end{pmatrix} \right).$$

- Find the partial correlation  $\text{pCorr}(X_1, X_2; X_3)$ .
- Find the conditional correlation  $\text{Corr}(X_1, X_2 \mid X_3)$ .

## 18 ARMA

**18.1** Consider stationary  $AR(2)$  model,  $y_t = 2 + 0.3y_{t-1} - 0.02y_{t-2} + u_t$ , where  $(u_t)$  is a white noise with  $\text{Var}(u_t) = 4$ .

The last two observations are  $y_{100} = 2$ ,  $y_{99} = 1$ .

- Find 95% predictive interval for  $y_{102}$ .
- Find the first two values of the autocorrelation function,  $\rho_1, \rho_2$ .
- Find the first two values of the partial autocorrelation function,  $\phi_{11}, \phi_{22}$ .

**18.2** Snegurochka studies a stochastic analog of the Fibonacci sequence

$$y_t = y_{t-1} + y_{t-2} + u_t,$$

where  $(u_t)$  is a white noise process.

- How many non-stationary solutions are there?
- What can you say about the number and the structure of the stationary solutions?
- Can Snëgurochka find two starting constants  $y_0 = c_0$  and  $y_1 = c_1$  in such a way to make a solution stationary?

**18.3** Stochastic process  $X_t$  is defined by  $X_t = 7 + u_t + 0.3u_{t-1}$ , where  $(u_t)$  is a white noise with variance  $\sigma^2$ .

- Is  $(X_t)$  stationary?
- Find the autocorrelation function of  $(X_t)$ .
- Find  $\mathbb{E}(X_{t+2} \mid X_t, X_{t-1}, \dots)$ .

**18.4** Young investor Winnie-the-Crypto compares two trading strategies: buying bitcoins from good bees and from bad bees. Let  $d_t$  be the price difference at day  $t$  (bad minus good). Winnie-the-Crypto would like to test  $H_0: \mathbb{E}(d_t) = 0$  against  $H_a: \mathbb{E}(d_t) \neq 0$  at 5% significance level.

Winnie assumed that  $(d_t)$  can be approximated by a  $MA(1)$  process and estimated the parameters using  $T = 400$  observations,  $\hat{d}_t = 2 + u_t + 0.7u_{t-1}$  with  $\hat{\sigma}_u^2 = 4$ .

- Estimate  $\mathbb{E}(d_t)$ ,  $\text{Var}(d_t)$  and  $\text{Cov}(d_t, d_{t-1})$ .
- Estimate  $\mathbb{E}(\bar{d})$ ,  $\text{Var}(\bar{d})$  and help Winnie by considering  $Z = \frac{\bar{d}-0}{se(\bar{d})}$ .

**18.5** Consider the following stationary process

$$y_t = 1 + 0.5y_{t-2} + u_t + u_{t-1},$$

where random variables  $u_t$  are independent  $\mathcal{N}(0; 4)$ .

- Find the 95% predictive interval for  $y_{101}$  given that  $y_{100} = 2$ ,  $y_{99} = 3$ ,  $y_{98} = 1$ ,  $u_{99} = -1$ .
- Find the point forecast for  $y_{101}$  given that  $y_{100} = 2$ .

**18.6** Consider  $MA(2)$  process given by

$$y_t = 5 + u_t + 2u_{t-1} + 4u_{t-2},$$

where  $(u_t)$  is a white noise with  $\text{Var}(u_t) = \sigma^2$ .

- [1] Find the expected value  $\mathbb{E}(y_t)$ .
- [7] Find the autocorrelation function  $\rho_k = \text{Corr}(y_t, y_{t-k})$ .
- [2] Is the process  $(y_t)$  stationary?

**18.7** Consider  $MA(2)$  process given by

$$y_t = 5 + u_t + 2u_{t-1} + 4u_{t-2},$$

where  $u_t$  are normal independent random variables with  $\text{Var}(u_t) = 4$ .

You know that  $u_{100} = 2$  and  $u_{99} = -1$ .

- [5] Find the 95% predictive interval for  $y_{101}$ .
- [5] Find the 95% predictive interval for  $y_{1000001}$ .

**18.8** The stationary process  $(y_t)$  has autocorrelation function  $\rho_k = 0.2^k$  and expected value 100.

- [7] Find the first two values of the partial autocorrelation function,  $\phi_{11}$  and  $\phi_{22}$ .
- [3] Provide a possible linear recurrence equation for this process. Your equation may include  $y_t$ , its lags and a white noise process  $(u_t)$ .

**18.9** Consider the equation  $y_t = 5 + 2.5y_{t-1} - y_{t-2} + u_t$ , where  $(u_t)$  is a white noise process.

- [3] Find the roots of the corresponding characteristic equation.
- [4] Rewrite the process as  $A(L)(y_t - \mu) = u_t$ . You should explicitly write the lag polynomial  $A(L)$  and the value of  $\mu$ .
- [1] How many non-stationary solutions does the equation have?

- d) [1] How many stationary solutions does the equation have?
- e) [1] How many stationary solutions of the  $MA(\infty)$  form with respect to  $(u_t)$  does the equation have?

**18.10** Consider the difference equation:

$$y_t = 0.7y_{t-1} - 0.12y_{t-2} + u_t,$$

where  $(u_t)$  is a white noise.

- a) How many stationary and non-stationary solutions does the difference equation have?

Consider stationary  $AR(2)$  process that satisfies the difference equation.

- b) Find first two values of autocorrelation function.
- c) Find  $\alpha_1$  and  $\alpha_2$  in  $MA(\infty)$  representation

$$y_t = u_t + \alpha_1 u_{t-1} + \alpha_2 u_{t-2} + \alpha_3 u_{t-3} + \dots$$

**18.11** Consider the process  $y_t = 4 + u_t + u_{t-1} + 2u_{t-2}$ , where  $(u_t)$  is a white noise with variance 16.

- a) Is this process stationary? Explain.
- b) Find the autocorrelation function of this process. Explain the meaning of  $\rho_2$ .
- c) Consider the process  $d_t = \Delta y_t$ . Is it  $ARIMA(p, d, q)$ ? If yes, then find  $p$ ,  $d$  and  $q$ .

**18.12** Consider the stationary  $AR(2)$  process  $y_t = 5 - 0.9y_{t-1} - 0.2y_{t-2} + u_t$ , where  $(u_t)$  is a white noise.

- a) Find the first value of autocorrelation function  $\rho_1$ .
- b) Find the partial autocorrelation function of this process. Explain the meaning of  $\phi_{22}$ .
- c) What is the relationship between values of autocorrelation function  $\rho_{100}$ ,  $\rho_{99}$  and  $\rho_{98}$ .

Hint: values  $\phi_{22}$ ,  $\phi_{33}$  etc may be calculated almost effortlessly :)

**18.13** Random variables  $x_t$  are iid with  $\mathbb{P}(x_t = 0) = \mathbb{P}(x_t = 1) = 0.5$ . Consider the process  $r_t = x_t \cdot x_{t-1} - 0.25$ .

- a) Is  $(r_t)$  stationary?
- b) Elon Musk states that this is  $MA(1)$  that can be rewritten as  $r_t = u_t + \alpha u_{t-1}$ .  
Is Elon Musk right? If yes, then express  $u_t$  using  $x_t$  and its lagged values.

**18.14** The process  $(u_t)$  is a white noise,  $t \in \mathbb{Z}$ . Which of the following equations admit at least one stationary solution?

- a)  $y_t = 1 + u_t + 0.5u_{t-1} + 0.25u_{t-2}$ ;
- b)  $y_t = -2y_{t-1} - 3y_{t-2} + u_t + u_{t-1}$ ;
- c)  $y_t = -0.5y_{t-1} + u_t$ ;
- d)  $y_t = 1 - 1.5y_{t-1} - 0.5y_{t-2} + u_t - 1.5u_{t-1} - 0.5u_{t-2}$ ;
- e)  $y_t = 1 + 0.64y_{t-2} + u_t + 0.64u_{t-1}$ ;
- f)  $y_t = 1 + t + u_t$ ;
- g)  $y_t = 1 + y_{t-1} + u_t$ .

**18.15** The process  $y_t$  is stationary and is generated by equation  $y_t = 1 + 0.5y_{t-1} + u_t$  where  $(u_t)$  is a white noise.

We have 10000 observations.

- What will be the approximate OLS estimates in the regression  $\hat{y}_t = \hat{\beta}_1 + \hat{\beta}_2 y_{t-1}$ ?
- What will be the approximate OLS estimates in the regression  $\hat{y}_t = \hat{\gamma}_1 + \hat{\gamma}_2 y_{t+1}$ ?

**18.16**

## 19 ETS

**19.1** The semi-annual  $y_t$  is modelled by  $ETS(AAA)$  process:

$$\begin{cases} u_t \sim \mathcal{N}(0; 4) \\ s_t = s_{t-2} + 0.1u_t \\ b_t = b_{t-1} + 0.2u_t \\ \ell_t = \ell_{t-1} + b_{t-1} + 0.3u_t \\ y_t = \ell_{t-1} + b_{t-1} + s_{t-2} + u_t \end{cases}$$

- Given that  $s_{100} = 2$ ,  $s_{99} = -1.9$ ,  $b_{100} = 0.5$ ,  $\ell_{100} = 4$  find 95% predictive interval for  $y_{102}$ .
- In this problem particular values of parameters are specified. And how many parameters are estimated in semi-annual  $ETS(AAA)$  model before real forecasting?

**19.2** The  $ETS(AAdN)$  model is given by the system

$$\begin{cases} u_t \sim \mathcal{N}(0; 20) \\ b_t = 0.9b_{t-1} + 0.2u_t \\ \ell_t = \ell_{t-1} + 0.9b_{t-1} + 0.3u_t \\ y_t = \ell_{t-1} + 0.9b_{t-1} + u_t \end{cases}$$

with  $\ell_{100} = 20$  and  $b_{100} = 2$ .

- Find conditional probability  $\mathbb{P}(y_{102} > 30 \mid \ell_{100}, b_{100})$ .
- Approximately find the best point forecast for  $y_{10000}$ .

**19.3** Consider  $ETS(ANN)$  model,

$$\begin{cases} y_t = \ell_{t-1} + u_t \\ \ell_t = \ell_{t-1} + \alpha u_t \\ u_t \sim \mathcal{N}(0; \sigma^2). \end{cases}$$

Let  $\ell_{99} = 50$ ,  $\alpha = 1/2$ ,  $\sigma^2 = 16$ ,  $y_{98} = 48$ ,  $y_{99} = 52$ ,  $y_{100} = 55$ .

Calculate 95% predictive interval for  $y_{101}$ .

**19.4** The semi-annual  $(y_t)$  is modelled by  $ETS(ANA)$  process:

$$\begin{cases} u_t \sim \mathcal{N}(0; 4) \\ s_t = s_{t-2} + 0.1u_t \\ \ell_t = \ell_{t-1} + 0.3u_t \\ y_t = \ell_{t-1} + s_{t-2} + u_t \end{cases}$$

Given that  $s_{100} = 3$ ,  $s_{99} = -2$ ,  $\ell_{100} = 100$  find 95% predictive interval for  $y_{102}$ .

**19.5** The semi-annual  $(y_t)$  is modelled by  $ETS(ANA)$  process:

$$\begin{cases} u_t \sim \mathcal{N}(0; 4) \\ s_t = s_{t-2} + 0.1u_t \\ \ell_t = \ell_{t-1} + 0.3u_t \\ y_t = \ell_{t-1} + s_{t-2} + u_t \\ \ell_0 = 100, s_0 = -3, s_{-1} = 3 \end{cases}$$

Check whether the process  $(y_t)$  is stationary.

**19.6** Consider  $ETS(AAdN)$  model

$$\begin{cases} u_t \sim \mathcal{N}(0; 20) \\ b_t = 0.9b_{t-1} + 0.2u_t \\ \ell_t = \ell_{t-1} + 0.9b_{t-1} + 0.3u_t \\ y_t = \ell_{t-1} + 0.9b_{t-1} + u_t \end{cases}$$

with  $\ell_{100} = 20$  and  $b_{100} = 1$ .

- Find 95% prediction interval for  $y_{102}$ .
- Approximately find the best point forecast for  $y_{10000}$ .

**19.7** Consider  $ETS(AAN)$  model,  $\begin{cases} y_t = \ell_{t-1} + b_{t-1} + u_t \\ \ell_t = \ell_{t-1} + b_{t-1} + \alpha u_t \\ b_t = b_{t-1} + \beta u_t \\ u_t \sim \mathcal{N}(0; \sigma^2). \end{cases}$

Let  $\ell_{100} = 50$ ,  $b_{100} = 2$ ,  $\alpha = 0.4$ ,  $\beta = 0.5$ ,  $\sigma^2 = 16$ .

Calculate one step and two steps ahead 95% predictive intervals.

**19.8**

**19.9**

**19.10**

**19.11**

## 20 GARCH

**20.1** The process  $y_t$  is described by a simple  $GARCH(1, 1)$  model:

$$\begin{cases} y_t = \sigma_t \nu_t \\ \sigma_t^2 = 1 + 0.2y_{t-1}^2 + 0.3\sigma_{t-1}^2 \\ \nu_t \sim \mathcal{N}(0; 1) \end{cases}$$

The variables  $\nu_t$  are independent of past variables  $y_{t-k}$ ,  $\nu_{t-k}$ ,  $\sigma_{t-k}$  for all  $k \geq 1$ . The processes  $y_t$ ,  $\sigma_t^2$  are stationary.

Given  $\sigma_{100} = 1$  and  $\nu_{100} = 0.5$  find 95% predictive interval for  $y_{102}$ .

**20.2** The strictly stationary white noise  $(u_t)$  follows  $ARCH(1)$  model  $\sigma_t^2 = 3 + 0.5u_{t-1}^2$  where  $u_t = \sigma_t\nu_t$  and  $\nu_t \sim \mathcal{N}(0; 1)$ .

- Find 95% prediction interval for  $u_{101}$  given that  $u_{100} = -1$ .
- Find  $\mathbb{E}(u_t)$ ,  $\text{Var}(u_t)$ .
- Find  $\text{Corr}(u_t, u_{t-1})$ ,  $\text{Corr}(u_t^2, u_{t-1}^2)$ .

**20.3** Consider the  $ARCH(1)$  model,  $u_t = \sigma_t\nu_t$ , where  $\nu_t$  are iid  $\mathcal{N}(0; 1)$  and  $\sigma_t^2 = 1 + 0.3u_{t-1}^2$ .

- Find 95% predictive interval for  $u_{101}$  if  $u_{100} = -2$ .
- Find the autocorrelation function of  $r_t = u_t^2$ .

**20.4**

**20.5**

**20.6**

**20.7**

**20.8**

## 21 Method of Moments and maximum likelihood

**21.1** The variables  $X_1, \dots, X_n$  are independent identically distributed with density

$$f(x) = \begin{cases} \lambda \exp(-\lambda(x - \theta)), & \text{if } x \geq \theta \\ 0, & \text{otherwise.} \end{cases}$$

- [5] Find the method of moments estimator of  $\lambda$  for known value  $\theta = 1$  using the first moment.
- [5] Find the method of moments estimator of  $\lambda$  for unknown value  $\theta$  using the first two moments.

**21.2** The variables  $X_1, \dots, X_n$  are independent and normally distributed  $\mathcal{N}(a, 2a)$ .

Find the maximum likelihood estimator of  $a$ .

Hint:  $f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp(-(x - \mu)^2/2\sigma^2)$ .

**21.3** The weight of a fish  $Y_i$  is a discrete random variables with distribution and observed frequencies given in the table

Weight [kg]	1	2	$a$
Probability	$0.2 + 0.1a$	$0.3 - 0.1a$	0.5
Observed frequency	$N_1$	$N_2$	$N_a$

Fish weights  $Y_i$  are independent,  $a > 10$  is unknown.

- Find the method of moments estimator of the parameter  $a$ .
- Find the maximum likelihood estimator of the parameter  $a$ .

- 21.4** The weight of a fish  $Y_i$  is a discrete random variables with distribution and observed frequencies given in the table

Weight [kg]	1	2	4
Probability	$0.2 + a$	$0.3 - a$	0.5
Observed frequency	$N_1$	$N_2$	$N_4$

Fish weights  $Y_i$  are independent.

- [5] Find the maximum likelihood estimator of the parameter  $a$ .
  - [5] Find the method of moments estimator of the parameter  $a$ .
- 21.5** To go to the mountain top I use a gondola lift in the morning. I go back from the top using the same gondola lift in the evening. Cabins are numbered from 1 to  $a$ .  
I have noticed that the absolute difference of cabin numbers of my two trips was 10.
- Estimate  $a$  using maximum likelihood.
  - Estimate  $a$  using method of moments.
- 21.6** Random variables  $X_1, X_2, \dots, X_n$  are independent identically distributed with density

$$f(x_i | \lambda, a) = \frac{\lambda}{2} \exp(-\lambda|x_i - a|).$$

Observed values for  $n = 3$  are  $-3, 1, 11$ .

- Estimate  $\lambda$  using method of moments for fixed  $a = 1$ .
- Estimate  $\lambda$  and  $a$  using maximum likelihood.

**21.7**

**21.8**

**21.9**

## 22 LR, LM and Wald tests

- 22.1** We have two independent random samples  $X_1, X_2, \dots, X_{n_x}$  and  $Y_1, Y_2, \dots, Y_{n_y}$ . The random variables  $X_i$  follow Poisson distribution with intensity rate  $\lambda_x$ , random variables  $Y_i$  follow Poisson distribution with intensity rate  $\lambda_y$ .

We would like to test  $H_0: \lambda_x = \lambda_y$  against  $H_1: \lambda_x \neq \lambda_y$ .

- [3] Find the maximal value of log-likelihood under  $H_0$ .
  - [3] Find the maximal value of log-likelihood under unrestricted model.
  - [2] Construct the likelihood ratio test.
  - [2] Do you reject  $H_0$  if  $n_x = 100, n_y = 200, \sum x_i = 500, \sum y_i = 900$  at significance level 5%?
- 22.2** You observe  $X_1, \dots, X_{400}$  and  $Y_1, \dots, Y_{400}, \bar{X} = 5, \bar{Y} = 6$ . All variables are independent.  
Consider the null hypothesis that all random variables are exponentially distributed with common parameter  $\lambda$  against alternative that parameter is  $\lambda_X$  for every  $X_i$  and  $\lambda_Y$  for every  $Y_j$ .



- a) Estimate common  $\lambda$  using maximum likelihood for the restricted model.
- b) Estimate both  $\lambda_X$  and  $\lambda_Y$  using maximum likelihood in the unrestricted model.
- c) Use LR-test to test the null hypothesis at 5% significance level.

**22.3** Random variables  $X_1, X_2, \dots, X_n$  are independent identically distributed with density

$$f(x_i | \lambda) = \frac{\lambda}{2} \exp(-\lambda|x_i|).$$

For  $n = 100$  I have 40 negative values with sum equal to  $-300$  and 60 positive values with sum equal to 500.

- a) Test the hypothesis  $\lambda = 1$  using LR approach at significance level  $\alpha = 0.01$ .
- b) Test the hypothesis  $\lambda = 1$  using LM approach at significance level  $\alpha = 0.01$ .

**22.4**

**22.5**

**22.6**

## 23 Properties of estimators

**23.1** The variables  $X_1, \dots, X_n$  are independent and uniformly distributed  $\text{Unif}[0; a]$  with  $a > 1$ . We do not observe  $X_i$  directly but we know whether each  $X_i$  is larger than 1. Hence we observe the indicators  $Y_i = I(X_i > 1)$ .

Consider the estimator  $\hat{a} = 1/(1 - \bar{Y})$ .

- a) [5] Is  $\hat{a}$  consistent?
- b) [5] Is  $\hat{a}$  unbiased for  $n = 2$ ?

**23.2** You observe time between taxi arrivals on a stop,  $Y_1, Y_2, \dots, Y_n$ . Assume that  $Y_i$  are independent and exponentially distributed with  $\mathbb{E}(Y_i) = \theta$ , that means the density of each  $Y_i$  is  $f(y) = \exp(-y/\theta)/\theta$  for  $y \geq 0$ . Consider the following estimator of expected value

$$\hat{\theta} = n \cdot \min\{Y_1, Y_2, \dots, Y_n\}$$

- a) [6] Find the probability density function of  $\hat{\theta}$ .
- b) [2] Is  $\hat{\theta}$  unbiased?
- c) [2] Is  $\hat{\theta}$  consistent?

**23.3**

**23.4**

**23.5**

## 24 Fisher information and Cramer – Rao

**24.1** The variables  $X_1, \dots, X_n$  are independent and have Poisson distribution with intensity rate  $\lambda$ . In other words the probability mass function is given by  $\mathbb{P}(X_i = k) = \exp(-\lambda)\lambda^k/k!$ .

- [5] Find theoretical Fisher information for  $\lambda$  contained in the sample.
- [2] Derive the maximum likelihood estimator for  $\lambda$ .
- [3] Does the maximum likelihood estimator attain the Cramer-Rao lower bound for variance?

**24.2** Consider an estimator  $\hat{a}$  with  $\mathbb{E}(\hat{a}) = 0.5a + 3$ . For the given sample size the Fisher information is  $I_F(a) = 400/a^2$ .

- What is the theoretical minimal variance of  $\hat{a}$ ?
- Assume that  $\hat{a}$  attains the minimal variance boundary and is asymptotically normal. Given that  $\hat{a} = 2022$  provide 95% CI for  $a$ .

**24.3** Consider iid sample from bivariate normal distribution,  $\begin{pmatrix} X_i \\ Y_i \end{pmatrix} \sim \mathcal{N}\left(\begin{pmatrix} \theta \\ 2\theta \end{pmatrix}; \begin{pmatrix} 4 & 1 \\ 1 & 9 \end{pmatrix}\right)$ .

Calculate Fischer information for the following cases:

- You observe  $X_1$  only.
- You observe  $X_1, \dots, X_n$ .
- You observe  $X_1, \dots, X_n, Y_1, \dots, Y_n$ .

Hint: the multivariate normal density is  $f(u) = \frac{1}{\sqrt{\det(2\pi\Sigma)}} \exp(-\frac{1}{2}(u - \mu)^T \Sigma^{-1}(u - \mu))$ .

**24.4** Random variables  $X_1, \dots, X_n$  are independent with density  $f(x) = \begin{cases} -\ln(a) \cdot a^x, & \text{if } x \geq 0, \\ 0, & \text{otherwise.} \end{cases}$

- Estimate  $a$  using maximum likelihood.
- Check whether the estimator is unbiased and consistent.
- Check whether the corresponding Cramer-Rao lower bound is attained.

**24.5** Random variables  $X_1, \dots, X_n$  are independent and normally distributed  $\mathcal{N}(1, 1/b)$ .

- Estimate  $b$  using maximum likelihood.
- Does the estimator achieve the Cramer-Rao lower bound?
- Is the estimator consistent?
- Is the estimator unbiased?

**24.6**

**24.7**

**24.8**

## 25 Sufficiency

**25.1** The variables  $X_1, \dots, X_n$  are independent and gamma distributed with density

$$f(x) = \begin{cases} \lambda^\alpha x^{\alpha-1} \exp(-\lambda x) / \Gamma(\alpha), & \text{if } x \geq 0 \\ 0, & \text{otherwise.} \end{cases}$$

- a) [5] Find a sufficient statistic for  $\alpha$  if we know that  $\lambda = 1$ .
- b) [5] Find a two dimensional sufficient statistic for unknown  $\alpha$  and  $\lambda$ .

**25.2** The variables  $X_1, \dots, X_n$  are independent and uniformly distributed on  $[0; 2a]$  for some positive  $a$ .

- a) Find any sufficient statistic for  $a$ .
- b) How the answer will change if  $X_i \sim U[-a; 2a]$ ?

**25.3**

**25.4**

**25.5**

## 26 Solutions

**1.1.**

- a)  $\mathbb{P}(B) = 6/11$ , first step equation for  $p = \mathbb{P}(B)$  is  $p = 1/6 + (5/6)^2 p$  or  $p = 1/6 + 5/6 \cdot (1 - p)$ .
- b)  $\mathbb{E}(N) = 6$ , first step equation for  $m = \mathbb{E}(N)$  is  $m = 1/6 + 5/6(m + 1)$ .
- c)  $\mathbb{E}(N^2) = 66$ ,  $\text{Var}(N) = 30$ , first step equation is  $\mathbb{E}(N^2) = 1/6 + 5/6 \mathbb{E}((N + 1)^2)$ .
- d)  $\mathbb{E}(N \mid B) = 61/11$ . Start by replacing unconditional probabilities on the tree by conditional ones. First step equation for  $\mu = \mathbb{E}(N \mid B)$  is  $\mu = 11/36 + 25/36(\mu + 2)$ .

$$\text{e) } \begin{pmatrix} 0 & 5/6 & 1/6 & 0 \\ 5/6 & 0 & 0 & 1/6 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

**1.2.**

- a)  $\mathbb{E}(N) = 1/p$ ,  $\text{Var}(N) =$ ,  $\mathbb{E}(N^3) =$ ,  $\mathbb{E}(\exp(tN)) =$
- b)  $a = \mathbb{P}(N \in 2 \cdot \mathbb{N})$ ,  $a = (1 - p)(1 - a)$ ,  $a = (1 - p)/(2 - p)$ .

**1.3.**

**1.4.** Let's denote the throws by  $(X_t)$  and the number of throws by  $T$ . Thus the last throw is  $X_T$ .

- a)  $\mathbb{P}(X_T = 6) = 1/3$  as we have three possible endings. One may also sum the probability geometric serie or use first step analysis.

b)  $\mathbb{E}(T) = 0.5 + 0.5(\mathbb{E}(T) + 1)$ ;

c) Let  $\mu = \mathbb{E}(S)$  and  $\gamma = \mathbb{P}(X_T \in \{4, 5\})$ .

$$\mu = \frac{3}{6} \cdot 0 + \frac{1}{6}(\mu + 1 \cdot \gamma) + \frac{1}{6}(\mu + 2 \cdot \gamma) + \frac{1}{6}(\mu + 3 \cdot \gamma)$$

d)

e)

f)

$$\mu_B = \frac{2}{6} \cdot 0 + \frac{1}{6}\mu_B + \frac{1}{6}(\mu + 1 \cdot \beta) + \frac{1}{6}(\mu + 2 \cdot \beta) + \frac{1}{6}(\mu + 3 \cdot \beta),$$

with  $\beta = 1/3$ .

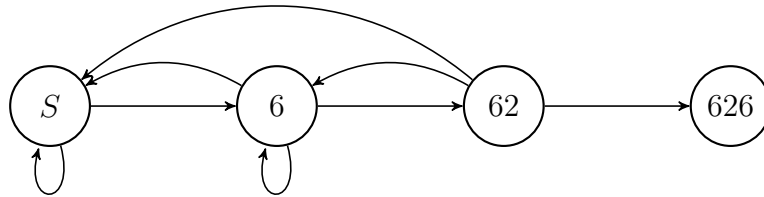
**1.5.**

**1.6.**

**1.7.**

**1.8.**

**1.9.** Let's draw the chain



The system of equations for expected values:

$$\begin{cases} x_s = 1 + \frac{1}{6}x_6 + \frac{5}{6}x_s \\ x_6 = 1 + \frac{1}{6}x_6 + \frac{1}{6}x_{62} + \frac{4}{6}x_s \\ x_{62} = 1 + \frac{1}{6} \cdot 0 + \frac{1}{6}x_6 + \frac{4}{6}x_s \end{cases}$$

The system of equations for moment generating functions:

$$\begin{cases} m_s(t) = \exp(t) \left( \frac{1}{6}m_6(t) + \frac{5}{6}m_s(t) \right) \\ m_6(t) = \exp(t) \left( \frac{1}{6}m_6(t) + \frac{1}{6}m_{62}(t) + \frac{4}{6}m_s(t) \right) \\ m_{62}(t) = \exp(t) \left( \frac{1}{6} \cdot 1 + \frac{1}{6}m_6(t) + \frac{4}{6}m_s(t) \right) \end{cases}$$

**1.10.** Recurrence equation for  $p_k$ :

$$p_k = 0.5p_{k+1} + 0.5p_{k-1}, \text{ with } p_{-a} = 0, p_b = 1;$$

Recurrence equation for  $e_k$ :

$$e_k = 0.5e_{k+1} + 0.5e_{k-1} + 1, \text{ with } e_{-a} = 0, e_b = 0;$$

In general:  $p_0 = a/(a + b)$ ,  $e_0 = ab$ .

**1.11.** Recurrence equation for  $p_k$ :

$$p_k = rp_{k+1} + (1 - r)p_{k-1}, \text{ with } p_{-a} = 0, p_b = 1;$$

Recurrence equation for  $e_k$ :

$$e_k = re_{k+1} + (1 - r)e_{k-1} + 1, \text{ with } e_{-a} = 0, e_b = 0;$$

In general:

**1.12.**

**1.13.**

- a) One may use first step analysis or probability scaling. There 3 options for the sum of 10 and 5 options for the sum of 8. Hence, we scale the answer,  $3/(3 + 5)$ .
- b) First, 11 should be before 10 or 8,  $2/(2 + 3 + 8)$ . Second, 10 should be before 8,  $3/(3 + 5)$ .  
The answer,  $2/(2 + 3 + 8) \cdot 3/(3 + 5)$ .

**1.14.** Let's denote this number by  $e_n$ .

One may consider all the variants from starting point that lead to starting the game anew:  $T$ ,  $HT$ ,  $HHT$ , ... The final term describes the lucky situation of a win without tails.

$$e_n = 1/2(1 + e_n) + 1/4(2 + e_n) + \dots + 1/2^n(n + e_n) + 1/2^n \cdot n.$$

Or one may say, that first one should obtain  $(n - 1)$  heads and then either just one head or restart anew,

$$e_n = e_{n-1} + 0.5 \cdot 1 + 0.5 \cdot (1 + e_n).$$

**1.15.**

**1.16.**

**1.17.**

**1.18.**

- a)  $1 - 1/3 - 2/9 - 4/27 - \dots = 1 - \frac{1/3}{1-2/3} = 0;$

b)  $\mathbb{E}(X) = 1/2$  by symmetry; For the  $\mathbb{E}(X^2)$  we may build an equation using the first step approach

$$\mathbb{E}(X^2) = 0.5 \mathbb{E}((X/3)^2) + 0.5 \mathbb{E}((2/3 + X/3)^2).$$

From this equation one obtains  $\mathbb{E}(X^2) = 3/8$  and hence  $\text{Var}(X) = 1/8$ .

Or one may also use the formula for the variance

$$\text{Var}(X) = \mathbb{E}(\text{Var}(X | Y)) + \text{Var}(\mathbb{E}(X | Y)).$$

Here  $Y = I(X > 1/2)$  indicates whether  $X$  belongs to the left or right side of the fractal.

$$\text{Var}(X | Y) = \text{Var}(X)/9$$

Observe that  $\mathbb{E}(X | Y)$  takes only two values,  $1/6$  or  $5/6$ . And hence  $\text{Var}(\mathbb{E}(X | Y)) = 1/9$ .

$$\text{Var}(X) = \text{Var}(X)/9 + 1/9$$

And, finally  $\text{Var}(X) = 1/8$ .

c) Let's toss the coin infinitely many times. If we observe  $H$  then we choose the left part and if we observe  $T$  then we choose the right part during the stage.

d) Let's go left-right-left-right-...

e)  $F(1/2) = 1/2$ ,  $F(1/3) = 1/2$ ,  $F(1/4) =$ ,  $F(1/5) =$

**1.19.**

a)  $1 - 1/4 - 3/4^2 - 3^2/4^3 - \dots = 1 - \frac{1/4}{1-3/4} = 0$ ;

b)  $\mathbb{E}(X) = 1/2$  by symmetry; For the  $\mathbb{E}(X^2)$  we may build an equation using the first step approach

$$\mathbb{E}(X^2) = 1/3 \mathbb{E}((X/2)^2) + 1/3 \mathbb{E}((1/2 + X/2)^2) + 1/3 \mathbb{E}((1/4 + X/2)^2).$$

c)

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

e) Toss a fair coin infinitely many times. Divide the tosses into pairs. If we observe the pair  $HH$  we choose the left smaller triangle,  $TH$  — the right one,  $HT$  — the upper one,  $TT$  — discard the pair of tosses.

**1.20.**

**1.21.**

**2.1.**

**2.2.**

**2.3.**

**2.4.**

2.5.

2.6.

a)

b)  $\mathbb{E}(W_t) \rightarrow +\infty$ ;

c) No stationary distribution. For stationary distribution  $\mathbb{E}(W_t)$  can't tend to infinity.

2.7.

2.8.

a)  $\mathbb{P}(S_3 = B) = \mathbb{P}(A \rightarrow B \rightarrow A \rightarrow B) + \mathbb{P}(A \rightarrow C \rightarrow A \rightarrow B) + \mathbb{P}(A \rightarrow B \rightarrow C \rightarrow B)$

b)

$$\begin{pmatrix} 0 & 0.7 & 0.3 \\ 0.5 & 0 & 0.5 \\ 0.5 & 0.5 & 0 \end{pmatrix}$$

c)

$$\begin{cases} a = 0.5b + 0.5c \\ b = 0.7a + 0.5c \\ c = 0.3a + 0.5b \\ a + b + c = 1 \end{cases}$$

The solution is  $a = 15/45$ ,  $b = 17/45$ ,  $c = 13/45$ .

2.9.  $\mathbb{P}(X_3 = 1) = 0.3 \cdot 0.7 \cdot 0.3 + 0.7 \cdot 1 \cdot 0.3 = 0.21 + 0.21 = 0.42$  Let's denote  $\tau_j = \min\{t \mid X_t = 0, X_0 = j\}$ ,  $\mu_j = \mathbb{E}(\tau_j)$ .

$$\begin{cases} \mu_0 = 0 \\ \mu_1 = 1 + 0.7\mu_2 \\ \mu_2 = 1 + 0.3\mu_1 + 0.7\mu_3 \\ \mu_3 = \mu_2 + 1 \end{cases}$$

We get  $\mu_2 = 200/9$ .

2.10.

2.11.

2.12.

2.13.

2.14.

2.15.

2.16.

2.17.

2.18.

2.19.

3.1.

3.2.

3.3.

3.4.

3.5.

3.6.

4.1.

4.2.  $M(t) = (\exp(t) + \exp(2t) + \exp(3t))/3$ .

4.3.  $\mathbb{E}(W) = 2$ ,  $\text{Var}(W) = 7 \cdot 2 - 2^2$ ,  $\mathbb{E}(W^3) = 20 \cdot 3!$ .

4.4.  $\mathbb{P}(X = 0) = 0.1$ ,  $\mathbb{P}(X = 1) = 0.2$ ,  $\mathbb{P}(X = 2) = 0.15$ .

4.5.

4.6.  $g(u) = g(\exp(t)) = \mathbb{E}(\exp(tX)) = M(t)$

4.7.

- a) Consider  $N$  as known fixed value,  $\mathbb{E}(S \mid N) = N \mathbb{E}(X_1) = N \cdot 0.5$ . First, let's find moment generating function for  $X_i$ :

$$M_X(u) = \int_0^1 \exp(xu) \cdot 1 \, dx = \frac{\exp(u) - 1}{u};$$

Hence  $M_{S|N}(u) = (M_X(u))^N$  as  $S$  is the sum of  $N$  independent variables.

- b) Random variable  $N$  is discrete,  $M_S(u) = \mathbb{P}(N = 1)(M_X(u))^1 + \mathbb{P}(N = 2)(M_X(u))^2 + \dots = \frac{0.7M_X(u)}{1-0.3M_X(u)}$ .

- c) Moment generating function is used to calculate moments,  $M_S''(0) - (M_S'(0))^2 = \text{Var}(S)$ .

4.8.

4.9.

4.10.

4.11.



a) Moment generating function

$$m_N(t) = \sum_{j=0}^{\infty} \exp(tj)(1-h)^j h = h \sum_{j=0}^{\infty} (\exp(t)(1-h))^j = \frac{h}{1 - \exp(t)(1-h)}$$

b) As  $S = N_1 + N_2 + \dots + N_k$ :

$$m_S(t) = \left( \frac{h}{1 - \exp(t)(1-h)} \right)^k$$

c) 0;

d)

**4.12.**

**4.13.**

**4.14.**

**4.15.**

**4.16.**

**4.17.**

**5.1.**

**5.2.**

- a) Cesaro-limit is  $1/2$ . It's like an average long-term salary.
- b) Split the sequence into groups of two numbers. In each group put one 0 and one 1 in an aperiodic way.
- c) Yes, ordinary convergences implies Cesaro-convergence.
- d) Yes, Cesaro-limit of a sum is a sum of Cesaro-limits.
- e) No. One sequence has 1 at even places, the other sequence has 1 at odd places.

**5.3.**

**5.4.**

**6.1.**

**6.2.**

- a)  $\text{plim } X_n = 0$ ;
- b)  $\text{plim } Y_n$  does not exist.

**6.3.**

- a)  $\text{plim} \frac{X_1 + X_2 + \dots + X_n}{7n} = 5/7;$
- b)  $\text{plim} \frac{X_1^2 + X_2^2 + \dots + X_n^2}{7n} = 5;$
- c)  $\text{plim} \ln(X_1^2 + X_2^2 + \dots + X_n^2) - \ln n = \ln 35.$

**6.4.**

- a)  $\text{plim} \max\{Y_1, Y_2, \dots, Y_n\} = 2;$
- b)  $\text{plim} \max\{X_1 + Y_1, X_1 + Y_2, \dots, X_1 + Y_n\} = X_1 + 2.$

**6.5.**

- a)  $\text{plim} Y_n = 0;$
- b)  $\text{plim} W_n = X.$

**6.6.**

- a)  $\mathbb{P}(\lim Y_n = 0) = 1;$
- b)  $\text{plim} Y_n = 0;$
- c) Limiting distribution is a constant 0.

**6.7.**

- a)  $\text{plim} V_n = 0, \text{plim} W_n = Y;$
- b) The sequence  $V_n$  does not converge in mean squared;
- c)  $W_n$  converges to  $Y$  in mean squared.

**6.8.**

- a)  $2/5;$
- b)  $L/R$  or  $+\infty$  or  $-\infty$  or  $3/2.$
- c) Almost surely limit is  $L/R$ , pointwise limit does not exist.
- d) Pointwise and almost surely limits are  $\frac{2}{5}I(R > 0) + \frac{3}{2}I(R = 0).$

**6.9.**

- a)  $0, 1, +\infty$  or does not exist.
- b) Almost surely limit is 0;
- c)  $1/2;$

- d)  $\mathbb{P}(Y_n \text{ converges}) = 0$ ;  
 e) Yes, as every  $Y_n$  has the same distribution.

**6.10.**

**6.11.**

**6.12.**

$$\begin{aligned} \text{plim} \frac{\sum (X_i - \bar{X})^3}{n + 2022} &= \text{plim} \frac{\sum X_i^3 - 3\bar{X} \sum X_i^2 + 3\bar{X}^2 \sum X_i - \sum \bar{X}^3}{n + 2022} = \\ &= \mathbb{E}(X_1^3) - 3\mathbb{E}(X_1^2) + 3\mathbb{E}(X_1) - 1 = 0; \end{aligned}$$

Note that  $\mathbb{E}(X_1^2) = 4/3$ ,  $\mathbb{E}(X_1^3) = 2$ .

**6.13.** Start with  $X_0$ :  $\mathbb{E}(X_0) = 1$ ,  $\text{Var}(X_0) = 4/12 = 1/3$ .

- a) Expected value is constant,  $\mathbb{E}(X_n) = 0.5 + 0.5 \mathbb{E}(X_{n-1})$ , hence  $\mathbb{E}(X_n) = 1$ . Variance goes to zero,  $\text{Var}(X_n) = 0.25 \text{Var}(X_{n-1})$ .  
 b)  $\text{plim } X_n = 1$

**6.14.**

**6.15.**

**6.16.**

**6.17.**

**6.18.**

**6.19.**

**7.1.**

- a)  $\mathbb{E}(Y | X) = 1 - X/6$  and  $\mathbb{E}(X | Y) = 3 - 1.5X$ .  
 b)  $\text{Var}(Y | X) =$ ,  $\text{Var}(X | Y) =$ .

**7.2.**

a)

$$f(x) = \begin{cases} x + 0.5, & \text{if } x \in [0; 1]; \\ 0, & \text{otherwise.} \end{cases}$$

b)

$$f(x, y) = \begin{cases} (x + y)/(x + 0.5), & \text{if } x \in [0; 1], y \in [0; 1]; \\ 0, & \text{otherwise.} \end{cases}$$

c)

$$\mathbb{E}(Y | X) = \frac{0.5X + 1/3}{X + 0.5}.$$

d)

7.3.

a)

b)  $\mathbb{E}(X | S) = \mathbb{E}(Y | S) = S/2;$

c)

d)

7.4.

a)  $X | S \sim \text{Unif}[0; S], Y | S \sim \text{Unif}[0; S].$

b)  $\mathbb{E}(X | S) = \mathbb{E}(Y | S) = S/2;$

c)  $\text{Var}(X | S) = \text{Var}(Y | S) = S^2/12;$

d)

7.5.  $\mathbb{E}(XY | X) = X \mathbb{E}(Y) = X/2, \text{Var}(XY + X^3 | X) = X^2 \text{Var}(Y) = X^2/12, \text{Cov}(X, Y | X) = 0,$   
 $\text{Cov}(XY, X^2Y | X) = X^3 \text{Var}(Y) = X^3/12$

7.6.

a)  $Y = IX_1 + (1 - I)X_2$

b) Consider  $I$  as known or fixed variable,  $\mathbb{E}(Y | I) = I \mathbb{E}(X_1) + (1 - I) \mathbb{E}(X_2)$ . Note that  $I^2 = I$  and  $(1 - I)^2 = 1 - I$ , hence  $\text{Var}(Y | I) = I \text{Var}(X_1) + (1 - I) \text{Var}(X_2)$ .

c)  $\mathbb{E}(Y) = p\mu_1 + (1 - p)\mu_2$  and  $\text{Var}(Y) = p(1 - p)(\mu_1 - \mu_2)^2 + p\sigma_1^2 + (1 - p)\sigma_2^2$ , where  $p = 0.3$ ,  $\mu_1 = \sigma_1^2 = 1, \mu_2 = \sigma_2^2 = 2$ .

7.7.

7.8.

7.9.

7.10.

7.11.

7.12.

7.13. Joint distribution table of  $X$  and  $Y$  is:

$X/Y$	1	2	3	4
1	0.1	0.1	0.1	0.1
2	0	0.1	0.1	0.1
3	0	0	0.1	0.1
4	0	0	0	0.1

Fixing a certain value of  $X$  we find the conditional expectation of  $Y$ :

$$\mathbb{E}(Y | X) = \begin{cases} \frac{1+2+3+4}{4} = 2.5, & \text{if } x = 1 \\ \frac{2+3+4}{3} = 3, & \text{if } x = 2 \\ \frac{3+4}{2} = 3.5, & \text{if } x = 3 \\ \frac{4}{1} = 4, & \text{if } x = 4 \end{cases}$$

Or, simply,  $\mathbb{E}(Y | X) = 2 + X/2$ .

7.14. Variable  $X$  has exponential distribution, so

$$f_X(x) = \lambda e^{-\lambda x}$$

And we know conditional distribution of  $Y$ :

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

So,

$$\mathbb{E}(Y | X) = \int_{-\infty}^{+\infty} y f_{Y|X}(X, y) dy = \int_0^{+\infty} y \frac{1}{X} e^{-\frac{1}{X}y} dy = (1/X)^{-1} = X.$$

Expected value:

$$\mathbb{E}(Y) = \mathbb{E}(\mathbb{E}(Y | X)) = \mathbb{E}(X) = \int_{-\infty}^{+\infty} x f_X(x) dx = \int_0^{+\infty} x \lambda e^{-\lambda x} dx = \lambda^{-1}$$

Variance:

$$\text{Var}(Y) = \text{Var}(\mathbb{E}(Y | X)) + \mathbb{E}(\text{Var}(Y | X)) = \text{Var}(X) + \mathbb{E}((1/X)^{-2}) = \lambda^{-2} + \mathbb{E}(X^2)$$

We know that  $\mathbb{E}(X^2) = \text{Var}(X) + (\mathbb{E}(X))^2$ , so:

$$\text{Var}(Y) = \lambda^{-2} + \lambda^{-2} + \lambda^{-2} = 3\lambda^{-2}$$

**7.15.** If  $X = 0$  we know that the chosen ball was in the first basket, consequently  $Y$  was in the second one.

$$\mathbb{E}(Y \mid X = 0) = \mathbb{E}(Y \mid Y \text{ from second basket}) = \frac{1 + 2 + \cdots + 10}{10} = 5.5$$

Similarly

$$\mathbb{E}(Y \mid X = 10) = \mathbb{E}(Y \mid Y \text{ from first basket}) = \frac{0 + 1 + \cdots + 9}{10} = 4.5$$

Finally,

$$\mathbb{E}(Y \mid 0 < X < 10) = \frac{1}{2} \mathbb{E}(Y \mid Y \text{ from first basket}) + \frac{1}{2} \mathbb{E}(Y \mid Y \text{ from second basket}) = 0.5(5.5 + 4.5) = 5$$

Answer:

$$\mathbb{E}(Y \mid X) = \begin{cases} 5.5, & \text{if } X = 0 \\ 5, & \text{if } 0 < X < 10 \\ 4.5, & \text{if } X = 10 \end{cases}$$

**7.16.**  $\mathbb{E}(Y \mid X) = X/2$ ,  $\mathbb{E}(Y) = \mathbb{E}(X/2) = a/4$ ,

$$\text{Var}(Y) = \mathbb{E}(\text{Var}(Y \mid X)) + \text{Var}(\mathbb{E}(Y \mid X)) = \mathbb{E}(X^2/12) + \text{Var}(X/2) = \frac{7a^2}{12^2}$$

**7.17.**

**7.18.**

**7.19.**

**7.20.**

**8.1.**

- a)
- b) Sigma-algebras do not depend on probabilities.
- c)  $\sigma(|X|) = \{\emptyset, \Omega, \{|X| = 2\}, \{X = 1\}\}$ .
- d)  $\sigma(|X|) = \sigma(X^2)$ ;

**8.2.**

- a)  $\sigma(X^2) = \{\{X^2 = 1\}, \{X = 0\}, \emptyset, \Omega\}$ ,  $\sigma(2X + 3) = \sigma(X)$
- b)  $\text{card } \sigma(X, Y) = 2^6$ ,  $\text{card } \sigma(X + Y) = 2^4$ ,  $\text{card } \sigma(X, Y, X + Y) = 2^6$ .

**8.3.**

- a)  $2^5$ ;
- b) Only  $2^k$  or infinity;

c)  $2^{100}$ ;

d)  $2^{2^{100}}$ .

**8.4.** In general  $\sigma(f(X)) \subseteq \sigma(X)$ ; If  $f$  is a bijection then  $\sigma(f(X)) = \sigma(X)$ .

**8.5.** In the finite case sigma-algebra corresponds to partitions. We get five sigma-algebras on a set of three elements and 15 sigma-algebras on a set of four elements. These numbers are known as Bell numbers.

**8.6.** Let  $\Omega = \mathbb{N}$ ,  $\mathcal{A}$  contains all finite sets and sets with finite complement.

**8.7.**

a) The intersection of two sigma-algebras is always a sigma-algebra.

b) The intersection of two sigma-algebras is always a sigma-algebra.

c) The union of two sigma-algebras is not always a sigma-algebra.

d)

**8.8.** Yes. This is convenient to draw  $\Omega$  as a segment. With «пескари»  $A \subseteq B$  and «sharks»  $A \supseteq B^c$ .

**8.9.** Разобьем натуральный ряд на пары соседних чисел. Можно так подобрать множества  $A$  и  $B$ , что в каждом из них из каждой пары взято только одно число. Поэтому  $\gamma(A) = \gamma(B) = \frac{1}{2}$ . Подобрать совпадение-несовпадение в паре, можно сделать так, что  $\gamma(A \cap B)$  не существует.

**8.10.**

a)  $\sigma(Z) = \{\{Z = 1\}, \{Z = 0\}, \Omega, \emptyset\}$ .

b)  $\sigma(YZ) = \{\{YZ = 1\}, \{YZ = 0\}, \Omega, \emptyset\}$ .

c)  $2^4$ ;

d)  $\sigma(Y \cdot Z) \subseteq \sigma(Y, Z)$ .

8.11.

8.12. Yes!

8.13. Например,  $B$  — Канторово множество, или, гораздо проще,  $B = [0; 0, 5]$ . Оно само более чем счетно и дополнение к нему более чем счетно.

Набор  $\mathcal{F}$  действительно  $\sigma$ -алгебра.  $\emptyset$  лежит в  $\mathcal{F}$ , так как имеет ноль элементов.

Если  $A$  не более чем счетно, то  $A^c$  лежит в  $\mathcal{F}$ , так как дополнение к  $A^c$  содержит не более чем счетное число элементов.

Если дополнение к  $A$  не более чем счетно, то  $A^c$  лежит в  $\mathcal{F}$ , так как содержит не более чем счетное число элементов.

Проверяем счетное объединение  $\bigcup_i A_i$ . Если среди  $A_i$  встречаются только не более чем счетные, то и их объединение — не более чем счетно. Если среди  $A_i$  встретилось хотя бы одно множество с не более чем счетным дополнением, то  $\bigcup_i A_i$  тоже будет обладать не более чем счетным дополнением, так как объединение не может быть меньше ни одного из объединяемых множеств.

8.14.  $2^{101}, 2^{101 \cdot 51}$ ,

8.15.  $\mathcal{F} = \{\emptyset, \Omega, \{\text{дождь}\}, \{\text{солнечно, пасмурно}\}$ . Всего есть  $1 + 1 + 3 = 5$   $\sigma$ -алгебр.

8.16.

a)  $\sigma(X_1 \cdot X_2) = \{\emptyset, \Omega, \{X_1 X_2 = 1\}, \{X_1 X_2 = -1\}\}$ ;

b)  $\sigma(X_1 = X_3)$ ;

c) Note that  $\sigma(X_1, X_1 + X_2, X_1 + X_2 + X_3) = \sigma(X_1, X_2, X_3)$ , the number of events in sigma-algebra is  $\text{card } \sigma(X_1, X_1 + X_2, X_1 + X_2 + X_3) = 2^8 = 256$ .

8.17.

8.18.

8.19.

8.20.

8.21.

8.22.

9.1.

a)  $\mathcal{F}_J, \mathcal{F}_{11}, \mathcal{F}_{12}, \dots$

b)  $\{T \text{ is divisible by } 2\}, \{T \geq 3, X_{T-2} = 1\}$ .

c)  $\mathbb{E}(T \mid \mathcal{F}_J) = T, \mathbb{E}(X_T \mid \mathcal{F}_J) = 1, \mathbb{E}(X_{T+1} \mid \mathcal{F}_J) = -1$ .

d)  $\mathbb{E}(S_T \mid \mathcal{F}_J) = S_T, \mathbb{E}(S_{T+1} \mid \mathcal{F}_J) = S_T - 1, \mathbb{E}(S_{T+2} \mid \mathcal{F}_J) = S_T - 1$ .

e)  $\mathbb{E}(Y_{T-k} \mid \mathcal{F}_J) = Y_{T-k}$ .



f)  $\mathbb{E}(X_T \mid \mathcal{F}_{10}) = 1, \mathbb{E}(X_{T+1} \mid \mathcal{F}_{10}) = -1.$

g)  $\mathbb{E}(T \mid \mathcal{F}_{10}) = \dots, \mathbb{E}(S_T \mid \mathcal{F}_{10}) = \dots$

## 9.2.

9.3. Here  $\Omega = \{1, 2, 3, 4, 5, 6\}.$

- a)  $\mathcal{F} = \{\emptyset, \Omega\};$
- b)  $\mathcal{F} = 2^\Omega$ , this notation means «all subsets of  $\Omega$ ».
- c)  $\mathcal{F} = \sigma(\{1\}, \{2\})$ , eight events in total;

## 10.1.

- a)  $(X_t)$  is not a martingale with respect to  $(\mathcal{F}_t)$ ;
- b)  $(S_t)$  is not a martingale with respect to  $(\mathcal{F}_t)$ ;
- c)  $(W_t)$  is a martingale with respect to  $(\mathcal{F}_t)$ ;
- d)  $(Y_t)$  is a martingale with respect to  $(\mathcal{F}_t)$ ;
- e)  $(W_t)$  is not a martingale with respect to  $(\mathcal{F}_{t-1})$ ;
- f)  $(W_t)$  is not a martingale with respect to  $(\mathcal{F}_{t+1})$ ;

## 10.2.

- a) What is the distribution of  $X_7$ ?
- b)  $\mathbb{E}(X_n) = 0$  and  $\text{Var}(X_n) = .$
- c) The process  $(X_n)$  is a Markov chain!
- d) The process  $(X_n)$  is not a martingale.
- e)  $\sigma(X_1, X_2, X_3, \dots, X_{1000}) = \sigma(X_1)$
- f)  $\mathbb{P}(\lim X_n \text{ exists}) = 1/3.$
- g)  $\text{plim } X_n$  does not exist.

## 10.3.

- a)  $(X_t)$  is not a martingale;
- b)  $(S_t)$  is not a martingale;
- c)  $a = 0.5;$
- d)  $b = 0$  and  $b = \dots$

## 10.4.

a)  $X_0 = 4/52$ ;  $X_1$  is  $4/51$  with probability  $48/52$  or  $3/51$  with probability  $4/52$ ;  $X_{51}$  is  $1$  with probability  $4/52$  and  $0$  with probability  $48/52$ .

b)

c) With probability  $X_n$  James Bond will pick up a Queen and the current number of closed Queens  $X_n(52 - n)$  will decrease by  $1$ . With probability  $(1 - X_n)$  James Bond will pick up a card different from Queen and the number of closed Queens  $X_n(52 - n)$  will stay the same.

$$\mathbb{E}(X_{n+1} | \mathcal{F}_n) = X_n \left( \frac{X_n(52 - n) - 1}{52 - n - 1} \right) + (1 - X_n) \left( \frac{X_n(52 - n)}{52 - n - 1} \right) = \dots = X_n.$$

Hence the process  $(X_n)$  is a martingale with respect to  $(\mathcal{F}_n)$ .

**10.5.** It is possible.

**10.6.**

a)  $W_1$  is equal to  $1/3$  or  $2/3$  with equal probabilities;  $W_2$  is equal to  $1/4, 2/4, 3/4$

b)  $(W_t)$  is a martingale;

c)  $(M_t)$  is a martingale;

d) The limiting distribution of  $(W_t)$  is uniform on  $[0; 1]$ ;

**10.7.** Only constant non-random sequences are martingales.

**10.8.**  $\text{Cov}(M_d - M_c, M_b - M_a) = 0$ ;

**10.9.** Yes.

**10.10.**

**10.11.**

**10.12.** For example,  $a_n = -3n$ , but one may add any constant.

**10.13.**  $\mathbb{E}(X_3 | X_1, X_2) = \mathbb{E}(X_3) = 0$ ,  $\mathbb{E}(X_3 | X_1 + X_3) = (X_1 + X_3)/2$ ,  $\text{Var}(X_3 | X_1, X_3) = 0$ ,  $\text{Var}(X_3 | X_1 + X_3) = 1 - (X_1 + X_3)^2/4$ .

Посчитаем ожидание и получим  $Y_n = X_1 + X_2 + \dots + X_n$ , the process  $(Y_n)$  is a martingale.

**10.14.**

**10.15.**

$$\begin{aligned} \mathbb{E}(Y_{t+1} | Y_t) &= Y_t \mathbb{E}(e^{bX_{t+1}}) \\ \mathbb{E}(e^{bX_{t+1}}) &= 1 \rightarrow b = 0 \text{ or } b = \ln(1/9) \end{aligned}$$

Trivial solution:  $a = 0$  and any  $b$ .

**10.16.**

**10.17.**

**10.18.**

**10.19.**

**10.20.**

**10.21.**

- a)  $(S_n)$  is a martingale;
- b)  $\mathbb{P}(S_\tau = b) = a/(a + b)$ ;
- c)  $M_n = S_n^2 - n$  is a martingale;
- d)  $\mathbb{E}(\tau) = ab$ ;

**10.22.**

- a)  $(S_n)$  is not a martingale;
- b)  $K_n = (q/p)^{S_t}$  is a martingale;
- c)  $\mathbb{P}(S_\tau = b) = \dots$
- d)  $M_n = S_n - (p - q)n$  is a martingale;
- e)  $\mathbb{E}(\tau) = \dots$

**10.23.**

- a)  $\mathbb{E}(T) = 26^{11} + 26^4 + 26$ .
- b)

**10.24.**

**10.25.**

**10.26.**

**10.27.**

**10.28.**

**11.1.**

- a)  $\mathbb{P}(X_a < X_b) = \lambda_a/(\lambda_a + \lambda_b)$ . There are two possible solutions: double integral and first step analysis.
- b)
- c)

d)

**11.2.** Yes.

**11.3.**

**11.4.**

- a)  $A_t = N_t - \lambda t$  is a martingale;
- b)  $B_t = A_t^2 - \lambda t$  is a martingale;

**11.5.** Let's measure time in minutes.

- a)  $\mathbb{P}(X_5 = 0) = \exp(-5\lambda) = 0.05$ , so  $\lambda = \ln(0.05)/-5 = \ln(20)/5$ .
- b)  $\mathbb{E}(X_{180}) = 180\lambda$ ,  $\text{Var}(X_{180}) = 180\lambda$
- c)  $\mathbb{P}(X_{180} = 5) = \exp(-180\lambda)(180\lambda)^5/5!$

**11.6.**  $\text{Cov}(N_3, N_{10}) = \text{Cov}(N_3, N_3 + (N_{10} - N_3)) = \text{Var}(N_3) = 3\lambda$ .

**11.7.**

**11.8.** Here we may approximate Poisson distribution by normal distribution,  $\mathcal{N}(\lambda t, \lambda t)$ .

**11.9.**

$$\mathbb{E}(Y) = (2, 4, 20), \quad \text{Var}(Y) = \begin{pmatrix} 2 & ? & ? \\ ? & 4 & ? \\ ? & ? & 20 \end{pmatrix}$$

**11.10.**

**11.11.**

**11.12.** Let's denote  $a(t) = \mathbb{P}(N_t \text{ is even})$ .

$$a(t + \Delta) = a(t)(1 - \Delta) + (1 - a(t))\Delta + o(\Delta)$$

Hence we get a differential equation  $a'(t) = 1 - 2a(t)$  with  $a(0) = 1$ . The solution is  $a(t) = (1 + \exp(-2t))/2$ .

**11.13.**

**11.14.**  $Y_1 \sim \text{Expo}(\lambda)$

**11.15.** <https://math.stackexchange.com/questions/3919517/inter-arrival-time>

**11.16.** The rate is  $\lambda = 3/2$  exercises per academic hour.

a)  $\mathbb{P}(X_1 = 1) = \exp(-3/2)(3/2)^1/1!;$

b)  $\mathbb{P}(X_1 = 1, X_2 = 2) = \mathbb{P}(X_1 = 1) \cdot \mathbb{P}(X_2 - X_1 = 1 \mid X_1 = 1) = \exp(-3)(9/4);$

**11.17.**

**11.18.**

a)  $\mathbb{E}(X) = \lambda;$

b)  $\lim_{n \rightarrow \infty} \text{Var}(X) = \lambda;$

c)  $\lim_{n \rightarrow \infty} \mathbb{P}(X = 0) = \exp(-\lambda), \lim_{n \rightarrow \infty} \mathbb{P}(X = 1) = \lambda \exp(-\lambda);$

d)  $\lim_{n \rightarrow \infty} \mathbb{P}(X = k) = \exp(-\lambda)\lambda^k/k!.$

**11.19.**

**11.20.**

**11.21.**

a)  $Y_1 \sim \text{Expo}(\lambda);$

b)  $(Y_1 \mid X_1 = 1) \sim \text{Unif}[0; 1];$

c)  $(Y_1 \mid X_t = 1) \sim \text{Unif}[0; t];$

d)  $(Y_5 \mid X_1 = 12) \sim \text{Beta}(5; 8);$

e)  $(Y_5/t \mid X_t = 12) \sim \text{Beta}(5; 8).$

**11.22.**

**11.23.**

**11.24.**

**12.1.**

a)  $\mathbb{E}(W_5) = 0$  and  $\text{Var}(W_5) = 5.$

b)  $\mathbb{E}(W_t) = 0$  and  $\text{Var}(W_t) = t.$

c)  $\mathbb{E}(W_5 \mid W_3) = W_3$  and  $\text{Var}(W_5 \mid W_3) = 2.$

d)  $\mathbb{E}(W_t \mid W_s) = W_s$  and  $\text{Var}(W_t \mid W_s) = t - s.$

e)  $\text{Cov}(W_5, W_3) = 3$  and  $\text{Cov}(W_s, W_t) = \min\{s, t\}.$

f)  $\text{Cov}(W_5, W_3 \mid W_2) = 1$  and  $\text{Cov}(W_s, W_t \mid W_r) = \min\{s, t\} - r.$

g)  $\mathbb{E}(W_5 - 2W_3) = 0$  and  $\text{Var}(W_5 - 2W_3).$

h)  $\mathbb{P}(W_5 - 2W_3 > 0) = 1/2$  and  $\mathbb{P}(W_5 - 2W_3 > 1).$

i)  $\mathbb{E}(W_5 - 2W_3 \mid W_2 = 1)$  and  $\text{Var}(W_5 - 2W_3 \mid W_2 = 1)$ .

j)  $\mathbb{P}(W_5 - 2W_3 > 1 \mid W_2 = 1)$ .

k)

$$R \sim \mathcal{N} \left( \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}; \begin{pmatrix} 1 & 1 & 1 \\ 1 & 3 & 3 \\ 1 & 3 & 5 \end{pmatrix} \right)$$

l)  $W_3 = 3/5 \cdot W_5 + U$

m)  $\mathbb{E}(W_3 \mid W_5) = 3/5 \cdot W_5$  and  $\text{Var}(W_3 \mid W_5) = \text{Var}(U) = \text{Var}(W_3 - 3/5 W_5)$ .

**12.2.**  $\text{Var}(Y_t - Y_s) = \text{Var}(tW_{2t} - sW_{2s}) = 2t^3 + 2s^3 - 4ts^2$ . We get  $\mathbb{E}(M_{t+u} \mid \mathcal{F}_t) = W_t^3 + 3W_t u + \alpha(t+u)W_t$ . From  $\mathbb{E}(M_{t+u} \mid \mathcal{F}_t) = W_t^3 + \alpha t W_t$  it follows that  $\alpha = -3$ .

**12.3.**

**12.4.**

a)  $\mathbb{E}(W_5 W_4 \mid W_4) = W_4^2$ ,  $\text{Var}(W_5 W_4 \mid W_4) = W_4^2$ ;

b)  $\text{Cov}(W_5 W_4, W_5 W_6) = 40$ ;

**12.5.**

**12.6.**

a)  $(W_t)$  is a martingale;

b)  $Q_t = W_t^2 - t$  is a martingale.

**12.7.**

a)  $Y_0 = 0$ ;

b)  $Y_t - Y_s \sim \mathcal{N}(0; t - s)$ ;

c) yes;

d) yes;

e) yes;

f) If  $(W_t)$  is a Wiener process, then  $Y_t = W_{a^2 t}/a$  is a Wiener process.

**12.8.**

a)  $Y_0 = 0$ ;

b)  $Y_t - Y_s \sim \mathcal{N}(0; t - s)$ ;

c) yes;

d) yes;

e) yes;

f) If  $(W_t)$  is a Wiener process, then  $Y_t = \begin{cases} 0, & \text{if } t = 0; \\ t \cdot W_{1/t}, & \text{if } t > 0. \end{cases}$  is a Wiener process.

**12.9.**

**12.10.**

**13.1.**

**13.2.**

**13.3.**

**13.4.**

**13.5.**

**13.6.**

a)  $dX_t = (W_t^3 - 3W_t^2 \cdot t)dW_t$  (4 points),

$$X_t = X_0 + \int_0^t W_u^3 - 3W_u^2 \cdot u dW_u$$

b) A process is a martingale as in short form  $A_t dt = 0$ .

**13.7.**

a)  $dX_t = -2X_t dW_t$ , this process is a martingale;

b)  $\mathbb{E}(X) = 1$ ,  $\text{Var}(X) = \exp(4t) - 1$ .

c)  $\int_0^t X_u dW_u = \frac{1-X_t}{2}$ .

**13.8.**

**13.9.**

**13.10.**

**13.11.**

a) Let's use Ito's lemma

$$dX_t = f'(t) \cos(2021W_t)dt - 2021f(t) \sin(2021W_t)dW_t + \frac{1}{2}2021^2 f(t) \cos(2021W_t)dt$$

b) To make  $X_t$  a martingale we should kill  $dt$  term.

c) As  $X_t$  is martingale  $\mathbb{E}(X_t) = \mathbb{E}(X_0) = f(0)$ . So  $\mathbb{E}(\cos(2021W_t)) = f(0)/f(t)$ .

**13.12.** Using Ito's lemma  $dY_t = (3W_t^2 - 3t) dW_t + (-3W_t + \frac{1}{2}6W_t) dt = (3W_t^2 - 3t) dW_t$ . Hence,  $Y_t$  is a martingale.  $Y_0 = W_0^3 - 3 \cdot 0W_0 = 0$ .

Now  $\mathbb{E}(Y_t) = \mathbb{E}(Y_0) = 0$  and using Ito's isometry:

$$\text{Var}(Y_t) = \int_0^t \mathbb{E}((3W_s^2 - 3s)^2) ds = \int_0^t 27s^2 + 9s^2 - 18s^2 ds = \int_0^t 18s^2 ds = 6t^3$$

Here we have used the facts that  $\mathbb{E}(W_s^2) = s$  and  $\mathbb{E}(W_s^4) = 3s^2$ .

**13.13.**  $dY_t = -aY_t dW_t$ , so  $Y_t$  is a martingale, and  $\mathbb{E}(Y_t) = Y_0 = 1$ . To find variance one may use Ito's isometry.

**13.14.**

a)  $h(x, t) = x$ ;

b) The coincidence is possible because the first, second and third moments of  $W_t$  and  $S_t$  are the same.

c)  $h(x, t) = x^4 - 6tx^2$ ;

**13.15.**

**13.16.**

**14.1.** Using Ito's lemma we find  $dX_t$  and  $dY_t$

$$\begin{aligned} dX_t &= f'_t(t) \cos W_t dt - f(t) \sin W_t dW_t - 0.5f(t) \cos W_t dt = \\ &= (f'_t(t) - 0.5f(t)) \cos W_t dt - f(t) \sin W_t dW_t \end{aligned}$$

$$\begin{aligned} dY_t &= g'_t(t) \sin W_t dt + g(t) \cos W_t dW_t - 0.5g(t) \sin W_t dt = \\ &= (g'_t(t) - 0.5g(t)) \sin W_t dt + g(t) \cos W_t dW_t \end{aligned}$$

Comparing these expressions with the system we receive:

$$\begin{cases} f'_t(t) - 0.5f(t) = af(t) \\ f(t) = g(t) \\ g'_t(t) - 0.5g(t) = ag(t) \\ g(t) = f(t) \end{cases}$$

The general solution has the form

$$f(t) = g(t) = Ae^{(a+0.5)t}, \quad A \in \mathbb{R}$$

From initial condition we get  $A = x_0$  and

$$f(t) = g(t) = x_0 e^{(a+0.5)t}$$



Answer:

$$\begin{aligned} X_t &= x_0 + x_0 \int_0^t a e^{(a+0.5)u} \cos W_u du - x_0 \int_0^t e^{(a+0.5)t} \sin W_u dW_u \\ Y_t &= x_0 \int_0^t a e^{(a+0.5)u} \sin W_u du + x_0 \int_0^t e^{(a+0.5)t} \cos W_u dW_u \end{aligned}$$

Now we use Ito's lemma once again:

$$\begin{aligned} dD_t &= 2X_t dX_t + 2Y_t dY_t = 2X_t((f'_t(t) - 0.5f(t)) \cos W_t dt - f(t) \sin W_t dW_t) + \\ &\quad + 2Y_t((g'_t(t) - 0.5g(t)) \sin W_t] dt + g(t) \cos W_t dW_t) = \\ &= 2f(t)(f'_t(t) - 0.5f(t)) \cos^2 W_t dt - f^2(t) \cos W_t \sin W_t dW_t + \\ &\quad + 2f(t)(f'_t(t) - 0.5f(t)) \sin^2 W_t dt + f^2(t) \cos W_t \sin W_t dW_t = \\ &= 2f(t)(f'_t(t) - 0.5f(t)) dt = 2af^2(t) dt \end{aligned}$$

$$D_t = D_0 + \int_0^t 2ax_0 e^{(2a+1)u} du = x_0^2 + \frac{2ax_0}{2a+1} (e^{(2a+1)t} - 1)$$

14.2.

14.3.

15.1.

- a)  $p_u^* = p_d^* = 1/2$ ;
- b)  $X_1^u = X_1^d = (0.5 \cdot 100 + 0.5 \cdot 0)/1.05$ , hence  $X_0 = 50/1.05^2 \approx 45.35$ ;
- c)  $\alpha = X_2^{uu} - X_2^{ud} / (S_2^{uu} - S_2^{ud}) = 100/216 \approx 0.46$ ;

15.2.

15.3.

15.4.

16.1.

$$\begin{aligned} X_0 &= \exp(-2r) \mathbb{E}_*(X_2) \\ X_2 &= S_1^3 = S_0^3 \exp(3r) \exp(3\sigma W_1^* - 9\sigma^2/2) \\ X_0 &= S_0^3 \exp(r) \exp(3\sigma^2) \end{aligned}$$

16.2.

16.3.

16.4.

$$X_0 = \mathbb{E}_{\bar{p}}(\exp(-rT)X_T \mid \mathcal{F}_0)$$

16.5. We need to find a price of the classic European option in dollars, while stock prices are in euros.

16.6.

16.7.

$$(1 - 0.4L)y_t = 4 + (1 + 0.3L)u_t$$

16.8.  $x_t = (1 - L)^t y_t$

16.9. Recall that  $F_n = L(1 + L)F_n$ , hence  $F_n = L^k(1 + L)^k F_n$  or  $F_{n+k} = (1 + L)^k F_n$  and  $a = 1$ .

16.10.

- a) false;
- b) true;
- c) true;
- d) false.

17.1.

17.2.

17.3.

- a)  $u_t \sim \mathcal{N}(0; 1)$  and independent;
- b)  $u_t \sim \mathcal{N}(0; 1)$  for  $t > 1$ ,  $u_1$  takes values  $-1$  or  $1$  with probability  $1/2$ . All  $(u_t)$  are independent.
- c) Variables  $u_t$  are independent and identically distributed with infinite  $\mathbb{E}(u_t)$ .
- d)  $u_t \sim \mathcal{N}(t; 1)$  and independent.

17.4.

- a) stationary,  $\gamma_k^z = 4\gamma_k^y$ .
- b) stationary,  $\gamma_k^z = \gamma_k^y$ .
- c) stationary;
- d) stationary;

17.5.

- a)
- b) Process  $(y_t)$  is stationary for  $y_0 = 4 + \frac{2}{\sqrt{3}}u_0$ .
- c) Expression  $y_t = 2 + 0.5y_{t-1} + u_t$  is only an equation. There are infinitely many stochastic processes that satisfy this equation. Most of them are non-stationary, but it has a stationary solution.

17.6.

- a)  $y_t = x_{2t}$ ;

b) Yes,  $(y_t)$  is stationary.

c)

**17.7.**

a) The process  $(y_t)$  is stationary.

b)

**17.8.**

a)  $\mathbb{P}(x_t = 1) = \mathbb{E}(x_t) = 1/2$ ;

b)  $\text{Cov}(x_t, x_s) = 0$  for  $t \neq s$ ;

c) The process  $(x_t)$  is stationary but not a white noise as  $\mathbb{E}(x_t) \neq 0$ .

d)  $\mathbb{E}(s_t) = t/2$ ;

e)  $s_t \sim \text{Bin}(t, 1/2)$ ;

f) Use the central limit theorem.

**17.9.**

a)  $(a_t)$  are identically distributed;  $(b_t)$  are identically distributed.

b)  $(a_t)$  are dependent, ie if  $a_t \neq 0$  then  $a_{t-1} = a_{t+1} = 0$ ;  $(b_t)$  are dependent.

c)  $(a_t)$  is a white noise;  $(b_t)$  is a white noise.

**17.10.**

a)  $\mathbb{P}(z_t = 1) = \mathbb{E}(z_t) = 2/3$ ;

b)  $\text{Cov}(z_1, z_2) = \text{Cov}(z_1, z_3) = \text{Cov}(z_1, z_4) = 0$ ;

c)  $(z_t)$  is stationary;

d)

e)

f)  $\mathbb{E}(s_t) = (t - 2) \cdot 2/3$ ,  $\text{Var}(s_t) = (16t - 29)/90$ ;

g)  $(s_t)$  is not stationary;

**17.11.**

a) The process  $(x_t)$  may not be stationary;

b) The process  $(y_t)$  may not be stationary;

c) The process  $(x_t)$  is stationary, but  $(y_t)$  may not.

17.12.

17.13.

17.14.

17.15. Projections:  $\tilde{X}_1 = X_1 + Z$ ;  $\tilde{X}_2 = X_2 + Z$ ;  $\mathbb{E}(X_i|Z) = 1 - Z$ ;  $\text{Cov}(X_i, Z) = -1/4$ ;  
Variable  $Z$  has Bernoulli distribution, hence  $\mathbb{E}(Z) = 1/2$  и  $\text{Var}(Z) = 1/4$ ;

$$\begin{aligned}\text{pCorr}(X_1, X_2; Z) &= \frac{-1/2}{12.5} = -\frac{1}{\sqrt{50}} \\ \text{Corr}(X_1, X_2|Z) &= -Z/6\end{aligned}$$

17.16.

18.1.

18.2.

- a) Infinitely many non-stationary solutions.
- b)  $\lambda^2 - \lambda - 1 = 0$ ,  $\lambda = (1 \pm \sqrt{5})/2$ ; there is exactly one stationary solution, this solution can not be represented as  $MA(\infty)$  with respect to  $(u_t)$ .
- c) No;

18.3.

18.4.

18.5.

- a) Let's denote by  $x$  all available information,

$$x = \begin{pmatrix} y_{100} \\ y_{99} \\ y_{98} \\ u_{99} \end{pmatrix}$$

Let's use  $t = 100$ :

$$y_{100} = 1 + 0.5y_{98} + u_{100} + u_{99}$$

Using all available information we obtain  $u_{100} = 1.5$  and hence

$$y_{101} | x \sim \mathcal{N}(1 + 0.5y_{99} + u_{100}; 4)$$

- b) Here we work with true betas:

$$\mathbb{E}(y_{101} | y_{100}) = \mu_y + \frac{\text{Cov}(y_{100}, y_{101})}{\text{Var}(y_{100})}(y_{100} - \mu_y)$$

**18.6.**

- a)  $\mathbb{E}(y_t) = 5$
- b)  $\rho_3 = \rho_4 = \dots = 0$
- c) The process is stationary.

**18.7.**

- a)
- b) Here past information is not useful,  $\mathbb{E}(y_t) = 5$ ,  $\text{Var}(y_t) = 4 \cdot (1 + 2^2 + 4^2) = 84$ .

$$[5 - 1.96\sqrt{84}; 5 + 1.96\sqrt{84}]$$

**18.8.**

- a)  $\phi_{11} = \rho_1 = 0.2$ ,  $\phi_{22} = 0$
- b) Possible equation is  $y_t = 0.2y_{t-1} + u_t$ . Another possibility is  $y_t = 5y_{t-1} + u_t$ . In the second case the stationary solution will be forward-looking and not  $MA(\infty)$  with respect to  $(u_t)$ .

**18.9.**

- a)  $\lambda_1 = 2$ ,  $\lambda_2 = 0.5$ , here the roots of the lag polynomial are exactly the same.
- b)  $(1 - 2L)(1 - 0.5L)(y_t + 10) = u_t$
- c) The equation has infinitely many non-stationary solutions.
- d) The equation has unique stationary solution.
- e) The equation has no stationary solutions that are  $MA(\infty)$  with respect to  $(u_t)$ .

**18.10.**

- a) [2 points]  $\lambda_1 = 0.3$ ,  $\lambda_2 = 0.4$ , one stationary solution, infinitely many non-stationary solutions.
- b) [6 points]: [2 points] for the system + [2 points] for  $\rho_1$  + [2 points] for  $\rho_2$ .

$$\begin{cases} \gamma_1 = 0.7\gamma_0 - 0.12\gamma_1 \\ \gamma_2 = 0.7\gamma_1 - 0.12\gamma_0. \end{cases}$$

$$\rho_1 = 70/112 = 0.625, \quad \rho_2 = 49/112 - 0.12 = 0.3175$$

- c) [2 points]

$$\alpha_1 = 0.7, \quad \alpha_2 = 0.37$$

**18.11.**

- a) Yes, the process is stationary, that is  $MA(2)$  process.

b)  $\rho_3 = \rho_4 = \dots = 0$

c)  $d_t = u_t + u_{t-1} + 2u_{t-2} - u_{t-1} - u_{t-2} - 2u_{t-3}$ , hence  $d_t \sim ARIMA(0, 0, 3)$ .

**18.12.**

a)

b)  $\phi_{11} = \rho_1$ ,  $\phi_{22} = -0.2$ ,  $\phi_{33} = \phi_{44} = \dots = 0$ . The partial correlation  $\phi_{22}$  measures how will  $y_t$  on average react to the unit change of  $y_{t-2}$  given fixed  $y_{t-1}$ .

c)  $\rho_{100} = -0.9\rho_{99} - 0.2\rho_{98}$

**18.13.**

**18.14.**

a)  $y_t = 1 + u_t + 0.5u_{t-1} + 0.25u_{t-2}$  admits a stationary solution.

b)  $y_t = -2y_{t-1} - 3y_{t-2} + u_t + u_{t-1}$

c)  $y_t = -0.5y_{t-1} + u_t$  admits a stationary solution.

d)  $y_t = 1 - 1.5y_{t-1} - 0.5y_{t-2} + u_t - 1.5u_{t-1} - 0.5u_{t-2}$

e)  $y_t = 1 + 0.64y_{t-2} + u_t + 0.64u_{t-1}$  admits a stationary solution.

f)  $y_t = 1 + t + u_t$  does not admit a stationary solution.

g)  $y_t = 1 + y_{t-1} + u_t$  does not admit a stationary solution.

**18.15.**  $\hat{\beta}_1 \approx \hat{\gamma}_1 \approx 1$  and  $\hat{\beta}_2 \approx \hat{\gamma}_2 \approx 0.5$  as estimates can be recovered from sample autocovariance function and sample mean.

**18.16.**

**19.1.**

**19.2.**

**19.3.**

**19.4.**

**19.5.** The process is not stationary as  $\mathbb{E}(y_1) = 3$  and  $\mathbb{E}(y_2) = -3$ .

**19.6.**

a)

$$y_{102} = \ell_{100} + (0.9 + 0.9^2)b_{100} + (0.3 + 0.18)u_{101} + u_{102}$$

$$(y_{102} \mid y_1, \dots, y_{100}) \sim \mathcal{N}(21.71, 24.608)$$

The interval

$$[21.71 - 1.96 \cdot 4.96; 21.71 + 1.96 \cdot 4.96]$$

b)

$$\lim_{h \rightarrow \infty} \mathbb{E}(y_{100+h} \mid y_1, \dots, y_{100}) = \ell_{100} + (0.9 + 0.9^2 + \dots)b_{100} = 20 + 9 \cdot 1$$

**19.7.**

**19.8.**

**19.9.**

**19.10.**

**19.11.**

**20.1.**

**20.2.**

a) [4 points]

$$\sigma_{101}^2 = 3 + 0.5(-1)^2 = 3.5$$

$$(u_{101} \mid \sigma_{101}) \sim \mathcal{N}(0; \sigma_{101}^2)$$

$$[-1.96\sqrt{3.5}; +1.96\sqrt{3.5}]$$

b) [3 points] [1 point] for  $\mathbb{E}(u_t)$  and [2 points] for  $\text{Var}(u_t)$  The process  $(u_t)$  is a white noise, hence

$$\mathbb{E}(u_t) = 0.$$

$$\sigma_u^2 = 3 + 0.5 \cdot \sigma_u^2$$

c) [3 points]: [1 point] for  $\text{Corr}(u_t, u_{t-1})$  and [2 points] for  $\text{Corr}(u_t^2, u_{t-1}^2)$  The process  $(u_t)$  is a white noise, hence

$$\text{Corr}(u_t, u_{t-1}) = 0.$$

$$u_t^2 = 3 + 0.5u_{t-1}^2 + (u_t^2 - \sigma_t^2)$$

We notice that  $r_t = u_t^2 - \sigma_t^2$  is a white noise, hence  $u_t^2$  is an  $AR(1)$  process. Hence,  $\text{Corr}(u_t^2, u_{t-1}^2) = 0.5$ .

20.3.

20.4.

20.5.

20.6.

20.7.

20.8.

**21.1.** Let's observe that we may decompose  $X_i$  as a sum  $X_i = Y_i + \theta$ , where  $Y_i \sim \text{Expo}(\lambda)$ . Hence,  $\mathbb{E}(X_i) = 1/\lambda + \theta$ ,  $\text{Var}(X_i) = \text{Var}(Y_i) = 1/\lambda^2$  and  $\mathbb{E}(X_i^2) = 1/\lambda^2 + (1/\lambda + \theta)^2$ . There is an alternative solution with direct integration:

$$\mathbb{E}(X_i) = \int_{\theta}^{+\infty} x f(x) dx, \quad \mathbb{E}(X_i^2) = \int_{\theta}^{+\infty} x^2 f(x) dx.$$

a) Solving  $1/\hat{\lambda} + 1 = \bar{X}$  we obtain  $\hat{\lambda} = 1/(\bar{X} - 1)$ .

b) Solving for  $\hat{\lambda}$  and  $\hat{\theta}$  the system

$$\begin{cases} 1/\hat{\lambda} + \hat{\theta} = \bar{X} \\ 1/\hat{\lambda}^2 + (1/\hat{\lambda} + \hat{\theta})^2 = M_2 \text{ with } M_2 = \sum X_i^2/n \end{cases}$$

we obtain

$$\hat{\lambda} = \frac{1}{\sqrt{M_2 - \bar{X}^2}}, \quad \hat{\theta} = \bar{X} - \sqrt{M_2 - \bar{X}^2}$$

**21.2.** The log-likelihood function is equal to

$$\ell(a) = \sum_{i=1}^n \left( (-0.5) \ln(4\pi) - 0.5 \ln a - (x_i - a)^2/4a \right).$$

The equation  $\ell'(a) = 0$  may be simplified to

$$n\hat{a}^2 + 2n\hat{a} - \sum X_i^2 = 0$$

Hence,

$$\hat{a} = \frac{-2n \pm \sqrt{4n^2 + 4n \sum X_i^2}}{2n}$$

We choose the root  $\hat{a} > 0$  as  $\text{Var}(X_i) = 2a > 0$ .

$$\hat{a} = \sqrt{1 + \sum X_i^2/n} - 1$$

Just for fun. In the case  $X_i \sim \mathcal{N}(a, ka)$  the equation would be

$$n\hat{a}^2 + kn\hat{a} - \sum X_i^2 = 0$$



And

$$\hat{a} = \frac{-nk + \sqrt{k^2 n^2 + 4n \sum X_i^2}}{2n}.$$

**21.3.**

**21.4.**

a)

$$\begin{aligned} L &= \text{const}(0.2 + a)^{N_1}(0.3 - a)^{N_2}0.5^{N_3} \\ \ell &= \text{const} + N_1 \ln(0.2 + a) + N_2 \ln(0.3 - a) + N_3 \ln 0.5 \\ \frac{\partial \ell}{\partial a} &= \frac{N_1}{0.2 + a} - \frac{N_2}{0.3 - a} \\ \hat{a}_{ML} &= \frac{0.3N_1 - 0.2N_2}{N_1 + N_2} \end{aligned}$$

We see that  $\partial \ell / \partial a$  decreases as  $a$  increases, so  $\hat{a}_{ML}$  is indeed the point of maximum.

b)

$$\begin{aligned} \mathbb{E}(Y_i) &= (0.2 + a) + 2(0.3 - a) + 4 \cdot 0.5 = 2.8 - a \\ \bar{Y} &= \frac{N_1 + 2N_2 + 4N_4}{N_1 + N_2 + N_4} \\ \hat{a}_{MM} &= 2.8 - \frac{N_1 + 2N_2 + 4N_4}{N_1 + N_2 + N_4} \end{aligned}$$

**21.5.**

**21.6.**

**21.7.**

**21.8.**

**21.9.**

**22.1.**

a) Under  $H_0$  we have  $X_i \sim \text{Pois}(\lambda)$ ,  $Y_i \sim \text{Pois}(\lambda)$ .

$$\ell(\lambda) = \sum_{i=1}^{n_x} (-\lambda + X_i \ln \lambda - \ln(X_i!)) + \sum_{i=1}^{n_y} (-\lambda + Y_i \ln \lambda - \ln(Y_i!))$$

The score function is

$$\text{score}(\lambda) = \ell'(\lambda) = \sum_{i=1}^{n_x} (-1 + X_i/\lambda) + \sum_{i=1}^{n_y} (-1 + Y_i/\lambda).$$

The estimator is  $\hat{\lambda} = (\sum X_i + \sum Y_i)/(n_x + n_y)$ .

$$\max \ell_R = -\hat{\lambda}(n_x + n_y) + \left( \sum X_i + \sum Y_i \right) \ln \hat{\lambda} - \sum \ln X_i! - \sum \ln Y_i!$$

b) In unrestricted model we have two independent estimators,

$$\hat{\lambda}_x = \bar{X}, \quad \hat{\lambda}_y = \bar{Y}$$

$$\max \ell_{UR} = -\hat{\lambda}_x n_x + \sum X_i \ln \hat{\lambda}_x + \sum Y_i \ln \hat{\lambda}_y - \sum \ln X_i! - \sum \ln Y_i!$$

c)

$$LR = 2(\max \ell_{UR} - \max \ell_R) = 2 \sum X_i (\ln \hat{\lambda}_x - \ln \hat{\lambda}) + 2 \sum Y_i (\ln \hat{\lambda}_y - \ln \hat{\lambda})$$

d) Unrestricted model has two parameters, restricted model has one parameter, hence we use chi-squared distribution with  $2 - 1 = 1$  degree of freedom,  $LR_{\text{crit}} = 3.84$ . We calculate estimates,  $\hat{\lambda}_x = 5$ ,  $\hat{\lambda}_y = 4.5$ ,  $\hat{\lambda} = 14/3$ .

$$LR = 1000(\ln 5 - \ln(14/3)) + 1800(\ln 4.5 - \ln(14/3)) \approx 3.5$$

We do not reject  $H_0$ .

**22.2.**

**22.3.**

**22.4.**

**22.5.**

**22.6.**

**23.1.**  $\mathbb{E}(Y_i) = \mathbb{P}(X_i > 1) = (a - 1)/a = p$ .

a) The estimator is consistent as

$$\text{plim } \hat{a} = \frac{1}{1 - \text{plim } \bar{Y}} = \frac{1}{1 - \frac{a-1}{a}} = a$$

b) For  $n = 2$  we have the positive probability  $p^2$  that  $\bar{Y} = 1$ . Hence with positive probability  $\hat{a}$  is not defined. The value  $\mathbb{E}(\hat{a})$  does not exist for  $n = 2$ .

**23.2.**

a)

$$\mathbb{P}(\hat{\theta} > y) = \mathbb{P}(Y_1 > y/n)^n = (\exp(-y/n\theta))^n = \exp(-y/\theta)$$

Hence  $\hat{\theta}$  has exponential distribution with rate  $1/\theta$  and probability density function

$$f(t) = \begin{cases} \exp(-t/\theta)/\theta, & \text{if } t \geq 0, \\ 0, & \text{otherwise.} \end{cases}$$

b) The estimator is unbiased as

$$\mathbb{E}(\hat{\theta}) = 1/(1/\theta) = \theta.$$

c) The estimator is non consistent as its distribution does not depend on  $n$ .

23.3.

23.4.

23.5.

24.1.

a) The log-likelihood function is equal to

$$\ell(\lambda) = \sum_{i=1}^n (-\lambda + X_i \ln \lambda - \ln(X_i!))$$

The score function is

$$\text{score}(\lambda) = \ell'(\lambda) = \sum_{i=1}^n (-1 + X_i/\lambda).$$

And

$$\ell''(\lambda) = \sum_{i=1}^n (-X_i/\lambda^2).$$

Fisher information is

$$I_F = -\mathbb{E}(\ell''(\lambda)) = \sum \mathbb{E}(X_i)/\lambda^2 = n\lambda/\lambda^2 = n/\lambda.$$

b) Solving  $\ell' = 0$  we obtain

$$\hat{\lambda} = \bar{X}$$

c) Rewrite  $\ell'(\lambda)$  using  $\hat{\lambda}$ . Be careful! Do not confound  $\lambda$  and  $\hat{\lambda}$ .

$$\text{score}(\lambda) = \ell'(\lambda) = -n + n\hat{\lambda}/\lambda.$$

Hence the score function is linear function of  $\hat{\lambda}$ ,  $\text{Corr}(\text{score}(\lambda), \hat{\lambda}) = 1$  and the Cramer-Rao bound is attained.

One may also find  $\mathbb{E} \hat{\lambda} = \lambda$ ,  $\text{Var}(\hat{\lambda}) = \lambda/n$  and explicitly check that the general bound

$$\text{Var}(\hat{\lambda}) \geq 1/I_F$$

is attained as equality in our case

$$\lambda/n = 1/(n/\lambda).$$

24.2.

24.3.

24.4.

24.5.

24.6.

24.7.

**24.8.**

**25.1.** We do not need the formula for  $\Gamma(\alpha)$  here.

a) For known  $\lambda = 1$  the likelihood is

$$L = \left( \prod X_i \right)^{\alpha-1} \frac{1}{\Gamma(\alpha)} \cdot \exp\left(-\sum X_i\right).$$

If we optimize this function for  $\alpha$  the optimal  $\hat{\alpha}$  will depend only on  $\prod X_i$ . Hence  $\prod X_i$  is a sufficient statistic for  $\alpha$ . There are many other sufficient statistics,  $\sum \ln X_i$  is another example.

b) Now the likelihood is

$$L = \left( \prod X_i \right)^{\alpha-1} \frac{1}{\Gamma(\alpha)} \lambda^\alpha \exp\left(-\lambda \sum X_i\right).$$

If we optimize this function for  $\alpha$  and  $\lambda$  the optimal point will depend only on  $\prod X_i$  and  $\sum X_i$ . Hence  $\left( \prod X_i, \sum X_i \right)$  is a two dimensional sufficient statistic for  $(\alpha, \lambda)$ .

**25.2.**

**25.3.**

**25.4.**

**25.5.**

## 27 Sources of wisdom

[Buz+15] Nazar Buzun et al. “Stochastic Analysis in Problems, part 1 (in Russian).” In: *arXiv preprint arXiv:1508.03461* (2015). URL: <https://arxiv.org/abs/1508.03461>.