

# ICEF master program. Maths for economists. Exam collection.

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# 1 2008-2009

## 1.1 Exam, 12.01.2009

Final exam consists of the two parts: A and B. Part A lasts for 110 minutes. Upon completion of that part the papers will be collected and the students will have 10 minutes break. Part B lasts for 70 minutes. Students should answer eight of the following nine questions: six from Part A and two from Part B. Points will be deducted for the insufficient explanation within your answers.

Part A. Answer all SIX questions of this section. Each question is worth 10 points.

- 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  $\mathbb{E}(Y | X)$ .
- 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  $\text{Var}(Y)$ .
- Let  $Y_t = W_t^3 - 3tW_t$ .
  - Using Ito's lemma find  $dY_t$ .
  - Using your previous result find  $\mathbb{E}(Y_t)$  and  $\text{Var}(Y_t)$ .
- Using a current value Hamiltonian maximize the integral

$$\int_0^2 e^{-t} \left( x - \frac{5}{2}x^2 - 2y^2 \right) dt$$

subject to the conditions  $\dot{x} = y - x/2$ ,  $x(0) = 0$ ,  $x(2)$  is free. Find  $x$ ,  $y$ ,  $\mu$ .

- Solve the bounded control problem

$$\int_0^T e^{-rt} (1 - u)x dt \rightarrow \max$$

, subject to  $\dot{x} = xu$ ,  $x(0) = 1$ ,  $0 \leq u \leq 1$ , where  $0 < r < 1$ .

- Consider the following optimization problem

$$\sum_0^\infty u(a_t) \rightarrow \max$$

, subject to  $\sum_0^\infty a_t \leq s$ ,  $s > 0$ ,  $a_t \geq 0$ .

- Show that if  $u(a)$  is increasing and strictly concave this problem has no solution

- (b) What happens if the sum in the maximization problem is changed to  $\sum_0^\infty \delta^t u(a_t)$ , where  $0 < \delta < 1$ ?

Part B. Answer two questions out of the three from this section. Each question is worth 20 points. Part B lasts for 70 minutes.

7. In the framework of the Black and Scholes model find the price at  $t = 0$  of an asset that pays  $\max\{0, \ln S_T\}$  at time  $T$ , where  $S_T$  denotes the price of one share at time  $T$ .
8. 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.
9. Consider the profit-maximizing problem for a representative competitive firm

$$\int_0^\infty (p - wn(t))q(t)e^{-rt} dt \rightarrow \max$$

, subject to (\*)  $\dot{x} = x(1 - x) - q$ , where the state variable  $x(t)$  represents a renewable stock resource (fish) that evolves according to the equation (\*) and  $q(t) = 2\sqrt{x(t)n(t)}$  is the extraction rate. Here  $n(y)$  is a labor effort with a constant wage rate  $w$ . The price of fish is assumed to be constant and equal  $p$ . The optimization problem is to choose  $n(t)$  to maximize the discounted profits,  $0 < r < 1$ .

- (a) Derive necessary conditions
- (b) Draw the phase diagram for this problem with the fish stock and the multiplier labeled on the axes
- (c) Show that if  $p/w$  is sufficiently large the fish stock will be driven to zero, while  $p/w$  is low there is a steady-state with a positive stock

## 1.2 Exam, 12.01.2009, solutions

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

2. 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:

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

3. 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  $\mathbb{E}(W_s^4) = 3s^2$ .

4.

5.

6.

7.

8. 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:

$$\begin{aligned} X_t &= x_0 + x_0 \int_0^t ae^{(a+0.5)u} \cos W_u du - x_0 \int_0^t e^{(a+0.5)t} \sin W_u dW_u \\ Y_t &= x_0 \int_0^t ae^{(a+0.5)u} \sin W_u du + x_0 \int_0^t e^{(a+0.5)t} \cos W_u dW_u \end{aligned}$$

Now we use Ito's lemma once again:

$$\begin{aligned} dD_t &= 2X_t dX_t + 2Y_t dY_t = 2X_t((f'_t(t) - 0.5f(t)) \cos W_t dt - f(t) \sin W_t dW_t) + \\ &\quad + 2Y_t((g'_t(t) - 0.5g(t)) \sin W_t dt + g(t) \cos W_t dW_t) = \\ &= 2f(t)(f'_t(t) - 0.5f(t)) \cos^2 W_t dt - f^2(t) \cos W_t \sin W_t dW_t + \\ &\quad + 2f(t)(f'_t(t) - 0.5f(t)) \sin^2 W_t dt + f^2(t) \cos W_t \sin W_t dW_t = \\ &= 2f(t)(f'_t(t) - 0.5f(t)) dt = 2af^2(t) dt \end{aligned}$$

$$D_t = D_0 + \int_0^t 2ax_0 e^{(2a+1)u} du = x_0^2 + \frac{2ax_0}{2a+1} (e^{(2a+1)t} - 1)$$

### 1.3 Retake, ????.2009

Final exam consists of the two parts: A and B. Part A lasts for 110 minutes. Upon completion of that part the papers will be collected and the students will have 10 minutes break. Part B lasts for 70 minutes. Students should answer eight of the following nine questions: six from Part A and two from Part B. Points will be deducted for the insufficient explanation within your answers.

Part A. Answer all SIX questions of this section. Each question is worth 10 points.

1. In the first bag there balls numbered from 0 to 9, in the second bag there are balls numbered from 1 to 10. Two balls were selected. You know that one ball was selected from the first bag and one 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  $\mathbb{E}(Y | X)$
2. The random variable  $X$  is uniformly distributed on  $[0; a]$ . The random variable  $Y$  is uniformly distributed on  $[0; X]$ .  
Find  $\mathbb{E}(Y | X)$ ,  $\mathbb{E}(Y)$  and  $\text{Var}(Y)$ .
3. Let  $Y_t = \exp\left(-aW_t - \frac{a^2}{2}t\right)$ .  
(a) Using Ito's lemma find  $dY_t$

(b) Using your previous result find  $\mathbb{E}(Y_t)$  and  $\text{Var}(Y_t)$

4. Find extremals for the integral  $\int_0^1 (\frac{1}{2}\dot{x}^2 + x\dot{x} + x) dt$  when  $x(0) = 0$  and  $x(1)$  is chosen freely.
5. Solve the bounded control problem  $\int_0^2 (2x - 3u) dt \rightarrow \max$ , subject to  $\dot{x} = x + u$ ,  $x(0) = 5$ ,  $0 \leq u \leq 2$ , where  $x(2)$  is free.
6. Consider the following optimization problem: maximize  $\sum_0^\infty \beta^t u(c_t)$ , subject to  $c_t + k_{t+1} = f(k_t)$ ,  $0 < \beta < 1$ , where both the utility function  $u(t)$  and the production function  $f(k)$  have the standard properties of monotonicity and strict concavity. Let the state variable be  $k$  and denote the next period value of  $k$  as  $k'$ . Substitute  $c = f(k) - k'$  into utility function and write down the Bellman equation.

Using the formal differentiation of the Bellman equation with respect to  $k$  under the sign of max, and drawing FOC from Bellman equation, exclude the value function and find the equation which combines the values of  $u'$  and  $f'$  at the adjacent time periods.

Part B. Answer two questions out of the three from this section. Each question is worth 20 points. Part B lasts for 70 minutes.

7. 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  $T$ , where  $S_T$  denotes the price of one share at time  $T$ ,  $M$  – arbitrary constant, specified at the moment of the issue.
8. 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  $K$ .
9. Consider the profit-maximizing problem for a representative competitive firm  $\int_0^\infty (p - c(x(t)))q(t)e^{-rt} dt \rightarrow \max$ , subject to (\*)  $\dot{x} = 1 - x - q$ , where the state variable  $x(t) < 1$  represents a nonrenewable stock resource (oil) that depletes according to the equation (\*) and  $q(t)$  is the extraction rate. Here  $c(x)$  is a cost function of the extraction that is defined by  $c(x) = e^{-x}$ . The price of oil is assumed to be constant and equal  $p$  where  $1/e < p < 1$ . The optimization problem is to choose  $q(t)$  to maximize the discounted profits,  $0 < r < 1$ .

(a) Derive necessary conditions.

(b) Prove that the steady-state exists and is unique.

## 1.4 Retake, ????.2010-solutions

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

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

Similarly

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

Finally,

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

Answer:

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

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

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

3.  $dY_t = -aY_t dW_t$ , so  $Y_t$  is a martingale, and  $\mathbb{E}(Y_t) = Y_0 = 1$ . To find variance one may use Ito's isometry.

4.

$$X_0 = \mathbb{E}_{\tilde{P}}(\exp(-rT) X_T | \mathcal{F}_0)$$

5. We need to find a price of the classic European option in dollars, while stock prices are in euros.

## 2 2009-2010

### 2.1 Exam, 14.01.2010

Final exam consists of the two parts: A and B. Part A lasts for 120 minutes. Upon completion of that part the papers will be collected and the students will have 10 minutes break. Part B lasts for 60 minutes. Students should answer eight of the following eight questions: six from Part A and two from Part B. Points will be deducted for the insufficient explanation within your answers.

Part A. Answer all SIX questions of this section. Each question is worth 10 points.

1. The joint distribution of the random vector  $(X, Y)$  is given by its p.d.f

$$f(x, y) = \begin{cases} ce^{x-y}, & \text{for } 0 \leq x, y \leq 1 \\ 0, & \text{otherwise} \end{cases}$$

where  $c$  is a normalization constant. Find  $\mathbb{E}(X | Y)$ .

2. Let  $Y_t = W_t^3 - tW_t^4$ . Find  $\mathbb{E}(Y_t)$  and  $\text{Var}(Y_t)$ . You don't have to use Ito Lemma here.

3. Let  $X_n$  be a discrete time stochastic process that converges in probability to a random number  $X$  as  $n \rightarrow \infty$ . Does this condition imply that  $X_n$  converges to  $X$  in mean? Almost surely? In distribution? Support at least one of your answers with a proof or counterexample. Give a definition for each type of convergence.

4. Seek to optimize the integral  $\int_0^{\frac{\ln 2}{2}} (4u - u^2 - x - 3x^2) dt$  subject to the conditions  $\dot{x} = u + x$ ,  $x(0) = 5/8$ ,  $x(\frac{\ln 2}{2})$  is free. Find  $x, u, \lambda$ . What kind of optimum did you find?

5. Solve the bounded control problem  $\int_0^1 (2 - 5t)u dt$ , subject to  $\dot{x} = 2x + 4te^{2t}u$ ,  $x(0) = 0$ ,  $x(1) = e^2$ ,  $-1 \leq u \leq 1$ .

6. Consider the following optimization problem: maximize  $\sum_0^\infty (\frac{3}{4})^t \ln c_t$ , subject to  $c_t + k_{t+1} = \sqrt{k_t}$ ,  $k_0 > 0$ . Let the state variable be  $k$  and denote the next period value of  $k$  as  $k'$ .

(a) Write down the Bellman equation for the value function  $V(k)$

(b) Using method of undetermined coefficients find  $V(k)$

(c) Find the optimal policy function  $k' = h(k)$

Part B. Answer both questions from this section. Each question is worth 20 points. Part B lasts for 60 minutes.

7. Let  $X_t$  be a stochastic process such that  $dX_t = \frac{X_\infty - X_t}{\tau} dt + \sigma dW_t$ , where  $X_\infty$  and  $\tau$  are non-random constants,  $W_t$  is a Wiener process, and let  $\tilde{Y}_t = X_t e^{t/\tau}$ .



- (a) Use Ito Lemma to find both differential and integral expressions for  $Y_t$  and use them to express  $X_t$  (a.s.) in terms of  $X_\infty$ ,  $X_0$ ,  $\tau$ ,  $\sigma$  and  $t$ . Here  $X_0$  is the value of  $X_t$  at time  $t = 0$ .
- (b) Find  $\mathbb{E}(X_t)$  and  $\text{Var}(X_t)$ . Sketch the graph of  $\mathbb{E}(X_t)$  as a function of  $t$  for  $X_\infty = 1$ ,  $\tau = 1$ , and  $X_0 = 0, 1$ , and  $2$ . Plot a possible trajectory of  $X_t$  in each case. Is there any name or names associated with  $X_t$ ?
8. Utility  $U(C, P) = U_1(C) + U_2(P)$  increases with the consumption  $C$  and decreases with the level of pollution  $P$ . For  $C > 0$ ,  $P > 0$  it is known that  $U'_1 > 0$ ,  $U''_1 < 0$ ,  $U'_2 < 0$  and  $U''_2 < 0$ . It is known that  $\lim_{C \rightarrow 0} U'_1(C) = \infty$  and  $\lim_{P \rightarrow 0} U'_2(P) = 0$ . Consumption lies within the range  $0 \leq C \leq \bar{C}$ . Consumption contributes to pollution, while pollution control reduces it; moreover environment absorbs pollution at a constant rate  $b > 0$ . Pollution dynamics is governed by equation  $\dot{P} = C^2 - (C^*)^2 - bP$  in which the first two terms represent the net contribution to the pollution flow, where  $0 < C^* < \bar{C}$ . Consider the problem of maximizing the discounted ( $r > 0$ ) utility stream  $\int_0^\infty e^{-rt} U(C, P) dt \rightarrow \max$  subject to  $\dot{P} = C^2 - (C^*)^2 - bP$ ,  $P(0) = P_0 > 0$ ,  $P \geq 0$ ,  $0 \leq C \leq \bar{C}$ .
- (a) Derive necessary conditions, using the current value Hamiltonian.
- (b) Sketch the phase diagram for this problem with the pollution and the consumption labeled on the axes.
- (c) Find the condition under which the steady state solution  $(P_s, C_s)$  exists and  $0 < C_s < \bar{C}$ .
- (d) Explore the stability of the steady state. Hint. You may find the return to the variables  $(P, m)$  easier for solving that part.

## 2.2 Exam-solutions

1. The probability density should integrate to one, so from  $\int_0^1 \int_0^1 f(x, y) dx dy = 1$  we infer the value of  $c$ ,  $c = e/(e-1)^2$ .  
Using the formula  $f(x | y) = f(x, y)/f(y)$  we obtain  $f(x | y) = e^x/(e-1)$ .  
We obtain marginal density,  $f(y) = \int_0^1 f(x, y) dx = e^{1-y}/(e-1)$  and hence the conditional density  $f(x | y) = e^x/(e-1)$ . As one may notice it does not depend on  $y$ . The reason is that the random variables  $X$  and  $Y$  are independent and  $f(x, y) = f_X(x)f_Y(y)$ . So we may expect that  $\mathbb{E}(X | Y) = \mathbb{E}(X)$ .  
And *coup de grâce*

$$\mathbb{E}(X | Y) = \int_0^1 x f(x | Y) dx = 1/(e-1)$$

2.  $\mathbb{E}(Y_t) = \mathbb{E}(W_t^3 - tW_t^4) = \mathbb{E}(W_t^3) - \mathbb{E}(tW_t^4) = \mathbb{E}(W_t^3) - t\mathbb{E}(W_t^4) = 0 - 3t^3 = -3t^3$ , as  
 $\mathbb{E}(W_t^3) = \frac{3(3-1)}{2} \int_0^t \mathbb{E}(W_s^{3-2}) ds = 0$   
 $\mathbb{E}(W_t^4) = \frac{4(4-1)}{2} \int_0^t \mathbb{E}(W_s^{4-2}) ds = 6 \int_0^t s ds = 3t^2$   
 $\text{Var}(Y_t) = \mathbb{E}(Y_t^2) - (\mathbb{E}(Y_t))^2$   
 $\mathbb{E}(Y_t^2) = \mathbb{E}(W_t^3 - tW_t^4)^2 = \mathbb{E}(W_t^6 - 2tW_t^7 + t^2W_t^8) = \mathbb{E}(W_t^6) - 2t\mathbb{E}(W_t^7) + t^2\mathbb{E}(W_t^8) = 15t^3 + 105t^6$ ,  
as  $\mathbb{E}(W_t^5) = \frac{5(5-1)}{2} \int_0^t \mathbb{E}(W_s^{5-2}) ds = 0$   
 $\mathbb{E}(W_t^6) = \frac{6(6-1)}{2} \int_0^t \mathbb{E}(W_s^{6-2}) ds = 15 \int_0^t 3s^2 ds = 15t^3$   
 $\mathbb{E}(W_t^7) = \frac{7(7-1)}{2} \int_0^t \mathbb{E}(W_s^{7-2}) ds = 0$   
 $\mathbb{E}(W_t^8) = \frac{8(8-1)}{2} \int_0^t \mathbb{E}(W_s^{8-2}) ds = 105t^4$   
 $\text{Var}(Y_t) = \mathbb{E}(Y_t^2) - (\mathbb{E}(Y_t))^2 = 15t^3 + 105t^6 - (-3t^3)^2 = 15t^3 + 96t^6$

- 3.
- 4.
- 5.
- 6.
- 7.

$$\begin{aligned} dY_t &= \frac{1}{\tau} X_t e^{\frac{t}{\tau}} dt + e^{\frac{t}{\tau}} dX_t = \frac{1}{\tau} X_t e^{\frac{t}{\tau}} dt + \frac{X_\infty - X_t}{\tau} e^{\frac{t}{\tau}} dt + \sigma e^{\frac{t}{\tau}} dW_t = \\ &= \frac{X_\infty}{\tau} e^{\frac{t}{\tau}} dt + \sigma e^{\frac{t}{\tau}} dW_t \end{aligned}$$

$$Y_t = Y_0 + \int_0^t \frac{X_\infty}{\tau} e^{\frac{u}{\tau}} du + \int_0^t \sigma e^{\frac{u}{\tau}} dW_u = X_0 + X_\infty(e^{\frac{t}{\tau}} - 1) + \int_0^t \sigma e^{\frac{u}{\tau}} dW_u$$

$$X_t = e^{-\frac{t}{\tau}} Y_t = e^{-\frac{t}{\tau}} (X_0 + X_\infty(e^{\frac{t}{\tau}} - 1) + \int_0^t \sigma e^{\frac{u}{\tau}} dW_u) = X_0 e^{-\frac{t}{\tau}} + X_\infty(1 - e^{-\frac{t}{\tau}}) + \int_0^t \sigma e^{\frac{u-t}{\tau}} dW_u$$

$$\mathbb{E}(X_t) = X_0 e^{-\frac{t}{\tau}} + X_\infty(1 - e^{-\frac{t}{\tau}})$$

$$\text{Var}(X_t) = \text{Var}\left(\int_0^t \sigma e^{\frac{u-t}{\tau}} dW_u\right) = \int_0^t \mathbb{E}(\sigma e^{\frac{u-t}{\tau}})^2 du = \int_0^t \sigma^2 e^{\frac{2u-2t}{\tau}} du = \frac{\tau \sigma^2}{2} (1 - e^{-\frac{2t}{\tau}})$$

### 3 2010-2011

#### 3.1 Exam, 12.01.2011

Notation:  $W_t$  is the standard Wiener process.

Part A (10 points each problem). Time allowed: 120 minutes.

1. The joint probability density function of  $X$  and  $Y$  is given by

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

Find  $\mathbb{E}(Y | X)$  in terms of  $X$ , find the probability density function of  $\mathbb{E}(Y | X)$

2. Consider the process  $X_t = \int_0^t s W_s dW_s$ . Find  $\mathbb{E}(X_t)$ ,  $\text{Var}(X_t)$ ,  $\text{Cov}(X_t, W_t)$
3. The process  $Y_t$  is given by  $Y_t = 2W_t + 5t$ . The stopping time  $\tau$  is given by  $\tau = \min\{t \mid Y_t^2 = 100\}$ . Find the distribution of the random variable  $Y_\tau$  and the expected value  $\mathbb{E}(\tau)$ .

Hint: you may find the martingales  $a^{Y_t}$  and  $Y_t - f(t)$  useful

4. Find  $\mathbb{P}(W_2 - W_1 > 2)$
5. In the framework of Black and Scholes model find the price of an asset which gives you the payoff of 1 rubble only if the final price  $S_t$  is at least two times bigger than the initial price  $S_0$  of the asset.
6. Consider the free end problem, where  $T > 0$  is not given

$$\int_0^T (\dot{x}^2 - x + 1) dt \rightarrow \text{extr}$$

At the left end  $x(0) = 0$  Find the optimal  $T$  value and the extremal. Check that you solved the optimality problem or show the opposite.

Part B (20 points each problem). Time allowed: 60 minutes.

7. Consider the stochastic differential equation

$$dX_t = (\sqrt{1 + X_t^2} + 0.5X_t)dt + \sqrt{1 + X_t^2}dW_t, \quad X_0 = 0$$

- Suppose that  $Y_t$  is another process that depends only on  $X_t$ , i.e.  $Y_t = f(X_t)$ . Find  $dY$  using the Ito's lemma.
- Find such function  $f$  that the term before  $dW$  in  $dY$  is constant.
- Find  $X_t$
- Sketch  $\mathbb{P}(X_t > 0)$  as the function of  $t$ .

8. Consider the neoclassical optimal growth model

$$\int_0^\infty e^{-rt} \left( \bar{U} - \frac{1}{c(t)} \right) dt \rightarrow \max$$

subject to  $\dot{k} = A \ln(1 + k) - c - \delta k$ , where  $A > r > \delta > 0$ ,  $k(0) = k_0$ ,  $\bar{U} > 0$ .

- Derive necessary conditions, using the current value Hamiltonian
- Sketch the phase diagram for this problem with the capital intensity and consumption labeled on the horizontal and vertical axes, respectively
- Check that the steady state solution exists. Provide explanation.
- Explore the stability of the steady state, using the Jacobian
- Why are you sure the found growth path maximizes the discounted stream of utility?

### 3.2 Exam-solutions

- Let's start,  $f(x) = \int_0^1 f(x, y) dy = x + 1/2$  for  $x \in [0; 1]$ . The conditional density,  $f(y | x) = f(x, y)/f(x) = (x + y)/(x + 1/2)$  for  $x$  and  $y$  in  $[0; 1]$ .

The conditional expected value:

$$\mathbb{E}(Y | X) = \int_0^1 y f(y | X) dy = \frac{3X + 2}{6X + 3} = \frac{1}{2} + \frac{1}{12X + 6}$$

We also need to find the density of  $\hat{Y} = \frac{3X+2}{6X+3}$ .

Let's first find the probability distribution function:

$$F_{\hat{Y}}(t) = \mathbb{P}(\hat{Y} \leq t) = \mathbb{P}\left(\frac{1}{2} + \frac{1}{12X + 6} \leq t\right) = \mathbb{P}\left(X \geq \frac{2 - 3t}{6t - 3}\right) = 1 - F_X(a),$$

where  $a = \frac{2-3t}{6t-3}$  and  $F_X(a) = \int_0^a f(t) dt$ .

Take the derivative with respect to  $t$  to obtain:

$$f_{\hat{Y}}(t) = -f_X(a) \frac{da}{dt} = -\left(\frac{2-3t}{6t-3} + \frac{1}{2}\right) \frac{-3}{(6t-3)^2}$$

2. First,  $\mathbb{E}(X_t) = 0$ . Using Ito's isometry:

$$\text{Var}(X_t) = \int_0^t \mathbb{E}(s^2 W_s^2) ds = \int_0^t s^3 ds = t^4/4$$

Again using Ito's isometry:

$$\text{Cov}(X_t, W_t) = \text{Cov}\left(\int_0^t s W_s dW_s, \int_0^t 1 dW_s\right) = \int_0^t \mathbb{E}(s W_s \cdot 1) ds = 0$$

3. First we find distribution of  $Y_\tau$ :

$$\begin{array}{cc} Y_\tau & -10 & 10 \\ \hline & p & 1-p \end{array}$$

We introduce  $Z_t = a^{Y_t}$ . To make  $Z_t$  martingale we should eliminate  $dt$  part in  $dZ_t$ . Hence  $\ln a = -2.5$ . And  $Z_t = e^{-2.5Y_t}$  is a martingale.

$$\begin{array}{cc} Z_\tau & e^{25} & e^{-25} \\ \hline & p & 1-p \end{array}$$

From Doob's theorem:  $\mathbb{E}(Z_\tau) = Z_0 = 1$ . And we obtain  $p$  from linear equation

$$pe^{25} + (1-p)e^{-25} = 1$$

The process  $R_t = Y_t - 5t$  is a martingale. By Doob's theorem  $\mathbb{E}(R_\tau) = R_0 = 0$ , but

$$\mathbb{E}(R_\tau) = \mathbb{E}(Y_\tau) - 5\mathbb{E}(\tau)$$

So,

$$\mathbb{E}(\tau) = \mathbb{E}(Y_{\tau})/5 = -2p + 2(1-p) = 2 - 4p$$

4. We know that  $W_2 - W_1 \sim \mathcal{N}(0; 1)$ , therefore

$$\mathbb{P}(W_2 - W_1 > 2) = 1 - \Phi(2) = 1 - 0.9772 = 0.0228$$

5.

$$X_T = \begin{cases} 1 & \text{if } \frac{S_T}{S_0} > 2, \\ 0 & \text{otherwise} \end{cases}$$

So,

$$X_0 = e^{-rT} E_{\tilde{\mathbb{P}}}(X_T | \mathcal{F}_0) = e^{-rT} \tilde{\mathbb{P}}\left(\frac{S_T}{S_0} > 2 \mid \mathcal{F}_0\right) = e^{-rT} \tilde{\mathbb{P}}\left(\left(\exp\left(r - \frac{\sigma^2}{2}\right)T + \sigma \tilde{W}_T\right) > 2 \mid \mathcal{F}_0\right)$$

$$\sigma \tilde{W}_T > \ln 2 - \left(r - \frac{\sigma^2}{2}\right)T \Rightarrow \tilde{W}_T > \frac{\ln 2 - \left(r - \frac{\sigma^2}{2}\right)T}{\sigma}$$

We want standard normal distribution of  $\tilde{W}_T$ , so we standardize by  $\sqrt{T}$ :

$$\frac{\tilde{W}_T}{\sqrt{T}} > \frac{\ln 2 - \left(r - \frac{\sigma^2}{2}\right)T}{\sigma \sqrt{T}}$$

So,

$$X_0 = e^{-rT} \tilde{\mathbb{P}} \left( \frac{\tilde{W}_T}{\sqrt{T}} > \frac{\ln 2 - \left(r - \frac{\sigma^2}{2}\right) T}{\sigma \sqrt{T}} \right) = e^{-rT} \left( 1 - \Phi \left( \frac{\ln 2 - \left(r - \frac{\sigma^2}{2}\right) T}{\sigma \sqrt{T}} \right) \right)$$

### 3.3 Retake, ??01.2011

Answer all SIX questions of this section. Each question is worth 10 points.

1. The joint distribution of the random vector  $(X, Y)$  is given by its p.d.f

$$f(x, y) = \begin{cases} ce^{x-y}, & \text{for } 0 \leq x, y \leq 1 \\ 0, & \text{otherwise} \end{cases}$$

where  $c$  is a normalization constant. Find  $\mathbb{E}(X | Y)$ .

2. Let  $Y_t = W_t^3 - tW_t^4$ . Find  $\mathbb{E}(Y_t)$  and  $\text{Var}(Y_t)$ . You don't have to use Ito Lemma here.
3. Let  $X_n$  be a discrete time stochastic process that converges in probability to a random number  $X$  as  $n \rightarrow \infty$ . Does this condition imply that  $X_n$  converges to  $X$  in mean? Almost surely? In distribution? Support at least one of your answers with a proof or counterexample. Give a definition for each type of convergence.
4. Solve the calculus of variations problem to optimize the integral  $\int_{1/2}^1 \sqrt{1 + \dot{x}^2}/x dt \rightarrow \max$  subject to the conditions  $x(1/2) = \sqrt{3}/2$ ,  $x(1) = 1$ . Justify your answer referring to the sufficiency conditions. What kind of extremum did you find?
5. Let  $x(t)$  represent the revenue of a firm. The fraction of it, namely  $xu(t)$ , where  $0 \leq u \leq 1$ , is spent on investments allowing the revenue to grow according to the rule  $\dot{x} = \alpha xu$  with  $\alpha = \text{const} > 0$ .

Another fraction of the revenue  $\beta x$ ,  $\beta = \text{const} > 0$  serves to reimburse the costs. Maximize the profit of the firm over the finite time horizon

$$\int_0^T (1 - \beta - u)x dt \rightarrow \max$$

subject to  $\dot{x} = \alpha xu$ ,  $x(0) = x_0$ ,  $0 \leq u \leq 1$ .

6. Consider the following «cake-eating» problem: maximize

$$\sum_0^\infty \beta^t \ln c_t$$

subject to  $W_{t+1} = W_t - c_t$ ,  $W_t \leq W$ ,  $W > 0$ ,  $0 < \beta < 1$ . Let the state variable be  $W$  and denote the next period value of  $W$  as  $W'$ .

- (a) Write down the Bellman equation for the value function  $V(W)$
- (b) Using method of undetermined coefficients find  $V(W)$
- (c) Find the optimal policy function  $c = h(W)$

Part B. Answer both questions from this section. Each question is worth 20 points. Part B lasts for 60 minutes.

7. Let  $X_t$  be a stochastic process such that  $dX_t = \frac{X_\infty - X_t}{\tau} dt + \sigma dW_t$ , where  $X_\infty$  and  $\tau$  are non-random constants,  $W_t$  is a Wiener process, and let  $\tilde{Y}_t = X_t e^{t/\tau}$ .

- (a) Use Ito Lemma to find both differential and integral expressions for  $Y_t$  and use them to express  $X_t$  (a.s.) in terms of  $X_\infty$ ,  $X_0$ ,  $\tau$ ,  $\sigma$  and  $t$ . Here  $X_0$  is the value of  $X_t$  at time  $t = 0$ .
- (b) Find  $\mathbb{E}(X_t)$  and  $\text{Var}(X_t)$ . Sketch the graph of  $\mathbb{E}(X_t)$  as a function of  $t$  for  $X_\infty = 1$ ,  $\tau = 1$ , and  $X_0 = 0, 1$ , and  $2$ . Plot a possible trajectory of  $X_t$  in each case. Is there any name or names associated with  $X_t$ ?
8. Consider the profit maximizing problem over the infinite time horizon

$$\int_0^\infty e^{-rt}(2\sqrt{K} - cI) dt \rightarrow \max$$

where  $K$  is capital,  $I$  is investment,  $c = \text{const}$  is the unit cost of investment,  $r$  is discount rate. Let  $K(0) = K_0 > 0$ . The capital changes under the investment equation  $\dot{K} = I - bK$ , where  $b > 0$  is the depreciation rate. Investment is bounded  $0 \leq I \leq \bar{I}$ . Suppose the parameters of the problem satisfy conditions

$$K_0 < \frac{1}{c^2(r+b)^2} < \frac{\bar{I}}{b}$$

- (a) Derive necessary conditions, using the current value Hamiltonian
- (b) Does the steady-state solution(s)  $(K_s, I_s)$  exist? Explain. If your answer is positive explore its stability.

### 3.4 Retake-solutions

1. Let's go:

$$f(x, y) = \begin{cases} ce^{(x-y)}, & 0 \leq x, y \leq 1 \\ 0, & \text{else} \end{cases}$$

First, we need to find constant  $c$ .

$$1 = \int_0^1 \int_0^1 (ce^{x-y}) dx dy = \int_0^1 (-ce^{x-y}) \Big|_0^1 dx = \int_0^1 (-ce^{x-1} + ce^x) dx = -ce^{x-1} + ce^x \Big|_0^1 = -c + ce + \frac{c}{e} - c = 1$$

From this simple equation we get  $c = \frac{e}{(e-1)^2}$

So the problem now looks like:

$$f(x, y) = \begin{cases} \frac{e}{(e-1)^2} e^{(x-y)}, & 0 \leq x, y \leq 1 \\ 0, & \text{else} \end{cases}$$

$$\mathbb{E}(X | Y) = \int_0^1 x f(x | y) dx, \text{ where } f(x | y) = \frac{f(x, y)}{f(y)}$$

$$f(y) = \int_0^1 f(x, y) dx = \frac{e}{(e-1)^2} (e^{1-y} - e^{-y})$$

$$f(x | y) = \frac{e^x}{e-1}$$

$$\mathbb{E}(X | Y) = \int_0^1 \frac{xe^x}{e-1} dx = \frac{1}{e-1} \int_0^1 x de^x = \frac{1}{e-1} (xe^x - e^x) \Big|_0^1 = \frac{1}{e-1}$$

So the final answer will be  $\mathbb{E}(X | Y) = \frac{1}{e-1}$

2.  $\mathbb{E}(Y_t) = \mathbb{E}(W_t^3 - tW_t^4) = \mathbb{E}(W_t^3) - \mathbb{E}(tW_t^4) = \mathbb{E}(W_t^3) - t\mathbb{E}(W_t^4) = 0 - 3t^3 = -3t^3$ , as
- $$\mathbb{E}(W_t^3) = \frac{3(3-1)}{2} \int_0^t \mathbb{E}(W_s^{3-2}) ds = 0$$
- $$\mathbb{E}(W_t^4) = \frac{4(4-1)}{2} \int_0^t \mathbb{E}(W_s^{4-2}) ds = 6 \int_0^t s ds = 3t^2$$
- $$\text{Var}(Y_t) = \mathbb{E}(Y_t^2) - (\mathbb{E}(Y_t))^2$$

$$\begin{aligned}\mathbb{E}(Y_t^2) &= \mathbb{E}(W_t^3 - tW_t^4)^2 = \mathbb{E}(W_t^6 - 2tW_t^7 + t^2W_t^8) = \mathbb{E}(W_t^6) - 2t\mathbb{E}(W_t^7) + t^2\mathbb{E}(W_t^8) = \\ &= 15t^3 + 105t^6, \\ \text{as } \mathbb{E}(W_t^5) &= \frac{5(5-1)}{2} \int_0^t \mathbb{E}(W_s^{5-2}) ds = 0 \\ \mathbb{E}(W_t^6) &= \frac{6(6-1)}{2} \int_0^t \mathbb{E}(W_s^{6-2}) ds = 15 \int_0^t 3s^2 ds = 15t^3 \\ \mathbb{E}(W_t^7) &= \frac{7(7-1)}{2} \int_0^t \mathbb{E}(W_s^{7-2}) ds = 0 \\ \mathbb{E}(W_t^8) &= \frac{8(8-1)}{2} \int_0^t \mathbb{E}(W_s^{8-2}) ds = 105t^4 \\ \text{Var}(Y_t) &= \mathbb{E}(Y_t^2) - (\mathbb{E}(Y_t))^2 = 15t^3 + 105t^6 - (-3t^3)^2 = 15t^3 + 96t^6\end{aligned}$$

3.

### 3.5 Reretake, 08.02.2011

#### Stochastic calculus part

- (10 pts) The joint density of random variables  $X$  and  $Y$  is given by  $f(x, y) = x + y$  for  $x \in [0; 1]$  and  $y \in [0; 1]$ . Find  $\mathbb{E}(Y | X)$  and  $\text{Var}(Y | X)$
- (10 pts) The random variables  $X_i$  are independent and uniformly distributed on  $[0; 2011]$ . We define  $Y_n = (X_1 \cdot X_2 \cdot \dots \cdot X_n)^{1/n}$ . In what sense does the sequence  $Y_n$  converge? What is the limit? Find the expected value and the variance of the limit.
- (10 pts) Let  $W_1(t)$  and  $W_2(t)$  be two independent Wiener processes. Consider  $Y_t = aW_1(t) + \sqrt{1 - a^2}W_2(t)$ . Is  $Y_t$  a Wiener process?
- (20 pts) Consider the Vasicek interest rate model,  $dR_t = a(b - R_t) dt + s dW_t$ , where  $a, b$  and  $s$  are positive constants.
  - Using the substitution  $Y_t = e^{at} R_t$  find the solution of the stochastic differential equation;
  - Find  $\mathbb{E}(R_t)$  and  $\text{Var}(R_t)$ .

### 3.6 Reretake, 08.02.2011, solution

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- Consider  $R_n = \ln Y_n$ , then  $R_n$  is the average of  $\ln X_1, \dots, \ln X_n$ . By the law of large numbers  $R_n$  converges to  $\mathbb{E}(\ln X_1)$  in probability and almost surely.
- Yes,  $Y_t$  is a Wiener process. We just check all properties: independence of increments, stationarity of increments,  $Y_0 = 0$ , continuity of path, normality of increments.
- Start with Ito's lemma:

$$dY_t = ae^{at} R_t dt + e^{at} dR_t = ae^{at} R_t dt + e^{at} (a(b - R_t) dt + s dW_t) = e^{at} (ab dt + s dW_t)$$

So,

$$Y_t = Y_0 + \int_0^t e^{au} ab du + \int_0^t s e^{au} dW_u;$$

## 4 2011-2012

### 4.1 Retake, 03.02.2012

Section A. 10 points for each problem.

- Solve the bounded control problem with the free end value where  $T > 1$  is specified in advance but  $x(T)$  is not.

$$\int_0^T (x - u) dt \rightarrow \max, x(0) = 1$$

$x' = u$ ,  $0 \leq u \leq x$ . What guarantees that a maximizer would be found?

- Two stochastic processes are defined by the system of SDE with the Brownian motions  $W_{1t}$ ,  $W_{2t}$  independent of each other

$$\begin{cases} dX_t = (2 + 5t + X_t)dt + 3dW_{1t} \\ dY_t = 4Y_t dt + 8Y_t dW_{1t} + 6dW_{2t} \end{cases}$$

Calculate  $d(X_t Y_t)$

- Find the value of the constant  $a$  such that the process  $X_t = W_t^3 - a \int_0^t W_s ds$  is a martingale.
- The process  $Y_t$  is given by  $Y_t = 2W_t + 5t$ . The stopping time  $\tau$  is given by  $\tau = \min\{t \mid Y_t^2 = 100\}$ . Find the distribution of the random variable  $Y_\tau$  and the expected value  $\mathbb{E}(\tau)$ .

Hint: you may find the martingales  $a^{Y_t}$  and  $Y_t - f(t)$  useful

- What is the expected value and variance of  $W_t^2$  for  $t > s$  given that  $W_s = x$ ?
- In the framework of Black and Scholes model find the price at the time 0 of an asset which gives you the payoff  $\max\{\ln(S_t), 0\}$  at the time  $t$ . Here  $S_t$  is the price of the underlying asset.

Section B. 20 points for each problem.

- The goal of this exercise is to solve the SDE

$$dX_t = \frac{1}{X_t} dt + X_t dW_t$$

with initial condition  $X_0 = 1$ .

- Apply the Ito's lemma to the process  $Y_t = \exp(f(t) + g(W_t))X_t^2$
  - Find non-constant functions  $f$  and  $g$  such that the coefficient before  $dW_t$  in the expression for  $dY_t$  is zero.
  - Find  $X_t$ . The final expression may contain a Riemann integral of some stochastic process.
- A typical firm with the production function  $x = f(l)$  in an economy employs 1 unit of the capital paying for it  $\bar{r}$ . There are  $n$  identical firms in this economy where  $n(t)$  is a function of time. Let the output of a firm be  $x(t)$ . Then the aggregate supply equals  $nx$ . Assuming that the market is in the equilibrium we use the inverse demand function  $p(nx)$ , where  $p'(y) < 0$ . Equation defining the dynamics of labor is given by  $\frac{dl}{dt} = a(w - \bar{w})$ , where  $a > 0$  and  $\bar{w}$  is some equilibrium wage rate. The growth (or fall) in number of firms is governed by the equation  $\frac{dn}{dt} = b(px - \bar{w}l - \bar{r})$ , where  $b > 0$ . Write down the system of ODE for the unknowns  $l(t)$ ,  $n(t)$ , using the first-order condition for the profit-maximizing firm, find and classify the steady-state solutions (if any exist). Production function is twice differentiable and concave everywhere.

## 4.2 Retake-solutions

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$$d(X_t Y_t) = 0 dt + X_t dY_t + Y_t dX_t + \frac{1}{2} dX_t dY_t$$

Here  $W_{1t}$  and  $W_{2t}$  are independent and  $dW_{1t} dW_{2t} = 0$ .

- Using Ito-Doebelin lemma,  $dW_t^3 = 3W_t^2 dW_t + \frac{1}{2} 6W_t dt$ . Hence,

$$dX_t = 3W_t^2 dW_t + (3 - a)W_t dt$$



Ito's integral is always a martingale, so  $a = 3$ .

4. The distribution of  $Y_\tau$  is given by the table

$y$	-10	10
$\mathbb{P}(Y_\tau = y)$	$1 - p$	$p$

First we find two martingales,  $Z_t = Y_t - 5t$ , and  $X_t = \exp(-2.5Y_t)$ . Here Ito's lemma is useful.

According to Doob's theorem  $\mathbb{E}(X_t) = X_0 = 1$  and we have an equation for  $p$ :

$$p \cdot \exp(-25) + (1 - p) \cdot \exp(25) = 1$$

We use once again Doob's theorem,  $\mathbb{E}(Z_t) = Z_0 = 0$ , so

$$\mathbb{E}(Y_\tau - 5\tau) = 0$$

The value of  $\mathbb{E}(\tau)$  may be calculated as  $\mathbb{E}(\tau) = \mathbb{E}(Y_\tau)/5 = \frac{10p-10(1-p)}{5}$ .

5. Let's first consider the unconditional version of the problem.

$$E(W_t^2) = E((W_t - W_0)^2) = \text{Var}(W_t - W_0) + E(W_t - W_0)^2 = t - 0 = t$$

$$\text{Var}(W_t^2) = E(W_t^4) - E(W_t^2)^2 = E(W_t^4) - t^2$$

In order to compute  $\mathbb{E}(W_t^4)$  we use the following formula:

$$E(W_t^k) = \frac{k(k-1)}{2} \int_0^t E(W_s^{k-2}) ds$$

So,

$$E(W_t^4) = 6 \int_0^t E(W_s^2) ds = 6 \int_0^t s ds = 3t^2 \Rightarrow \text{Var}(W_t^2) = 3t^2 - t^2 = 2t^2$$

However we know that  $W_s = x$ . Using the properties of Wiener process we may assume that the timer is started again from 0. So we define  $W'_{t'} = W_{t'+s} - x$ .

So,

$$\mathbb{E}(W_t^2 | W_s = x) = \mathbb{E}((W'_{t'} + x)^2) = \mathbb{E}(W'^2_{t'} + 2xW'_{t'} + x^2) = t' + x^2 = (t - s) + x^2$$

And

$$\begin{aligned} \text{Var}(W_t^2 | W_s = x) &= \text{Var}((W'_{t'} + x)^2) = \text{Var}(W'^2_{t'} + 2xW'_{t'} + x^2) = \\ &= \text{Var}(W'^2_{t'}) + 4x^2 \text{Var}(W'_{t'}) + 0 = 2(t - s)^2 + 4x^2(t - s) \quad (1) \end{aligned}$$

## 5 2012-2013

### 5.1 Midterm, 13.11.2012

1. (25 points) Solve the calculus of variations problem (use necessary conditions)

$$\int_0^{\pi/2} (x^2 + \dot{x}^2 - x\dot{x} + 4x \cos^2 t) dt \rightarrow \text{extr},$$

where  $x(0) = -6/5$ ,  $x(\pi/2) = -4/5$ .

What kind of a sufficient condition is applicable to this problem and why?

2. (25 points) Solve the control problem with the free end value

$$\int_0^T (-u^2/2 - x) dt \rightarrow \max,$$

where  $x(0) = x_0 > 0$ ,  $x(T)$  is unknown,  $\dot{x} = u^2x$ .

Can you apply any of the sufficiency theorems to prove that the maximizer has been found? Why we are sure in the validity of the solution?

3. (20 points) Consider an optimal growth problem  $\sum_{t=0}^{\infty} \frac{1}{5^t} \ln c_t \rightarrow \max$ , subject to  $k_{t+1} = k_t^{7/8} - c_t$ ,  $k(0) = k_0 > 0$ .

(a) State the Bellman equation

(b) Use the iteration method to find the first two iterations of the value function. Set  $V_0(k) = 0$ .

(c) Use the guess-and-verify method to find the value function.

4. (30 points) Consider a profit-maximizing firm over the infinite horizon planning period

$$\int_0^{\infty} (pf(K, I) - cK - gI)e^{-rt} dt \rightarrow \max,$$

subject to  $\dot{K} = I - \delta K$ ,  $K(0) = K_0 > 0$ .

The production function  $f(K, I) = (1 - \alpha I^2) \ln K$ , where parameter  $\alpha$  is so small that  $f$  takes only positive values within the reasonable values of the gross investment rate  $I$  which can take any sign (investment/disinvestment). Moreover, the production function is concave everywhere. Using the current value Hamiltonian derive the system of differential equations in  $K(t)$  and  $I(t)$ . Prove that the steady-state solution exists. By calculating the Jacobian at the equilibrium prove that  $(K_s, I_s)$  is the saddle point. All exogenous parameters in this model are positive.

## 5.2 Exam, 10.01.2013

### Optimal control part.

- [10 points] Solve the optimal control problem  $\int_0^1 (x + u) dt \rightarrow \max$  subject to  $\dot{x} = -x + u + t$ ,  $x(0) = 0$ ,  $x(1)$  is free, and  $0 \leq u \leq 1$ .
- [10 points] Consider an intertemporal utility maximization problem over the finite horizon in discrete time  $t = 1, \dots, T$ . The utility is  $u(c) = \ln c$ , the initial wealth is  $w$  and if the remaining wealth at time  $t$  was  $w_t$ , then by the beginning of the next period it becomes  $w_{t+1} = (1+r)(w_t - c_t)$ , where  $r$  is the discount rate and  $c_t$  is the consumption. To find the maximum value of the utility stream one can use the finite version of the Bellman equation written in the form  $V_t(w) = \max\{u(c) + V_{t+1}((1+r)(w - c))\}$  where the function within the braces is maximized over the values of  $0 \leq c \leq w$ . It is important to note that the value function  $V_t$  is the maximum value of the utility stream from time  $t$  onwards.

(a) [3 points] Let  $V_T = \ln w$ . Find  $V_{T-1}$ .

(b) [7 points] Try to verify the conjecture that  $V_t = \gamma_t \ln(1+r) + (T-t+1) \ln \frac{w}{T-t+1}$  where  $\gamma_t$  is some (unknown) function of time.

3. [20 points] A spill of toxic substance should be cleaned up by a company. If a cleanup rate is  $u(t)$ , then the area of the spill shrinks by the law  $x(t) = x_0 - \int_0^t u(s) ds$ , where  $x_0$  is the initial area. According to the government contract by the time  $T$  (and not earlier) the area of the spill should be reduced to  $x_T$ , where  $x_T < x_0$ . Clearly  $u(t) \geq 0$ , and by technology requirement  $u(t) \leq \bar{u}$ , where  $\bar{u} > (x_0 - x_T)/T$ . Costs of cleaning are directly proportional to  $u(t)$ . Let the unit costs equal  $c > 0$  and the costs are discounted with the discount rate  $r > 0$ .
  - (a) [5 points] Formulate the minimization problem with the bounded control. Hint: this is a fixed endpoints problem.
  - (b) [15 points] By using the current value Hamiltonian set the system of equations and solve it.

**Stochastic calculus part.** Here  $W_t$  always denotes the standard Wiener process.

4. [10 points] Waves are arriving on the seashore. The sizes of the waves are independent uniform on  $[0; 1]$  random variables  $X_i$ . If the size of  $i$ -th wave is greater than the size of its neighboring waves,  $X_i > \max\{X_{i-1}, X_{i+1}\}$ , then we call it a «high» wave. Let  $H_i$  be the indicator of the «high» waves:  $H_i = 1$  if  $X_i > \max\{X_{i-1}, X_{i+1}\}$  and  $H_i = 0$  otherwise. Find  $\mathbb{E}(X_i | H_i)$  and  $\mathbb{E}(H_i | X_i)$
5. [10 points] Find  $\mathbb{E}(W_s \cdot W_t)$  and  $\mathbb{E}(W_r \cdot W_s \cdot W_t)$  where  $r < s < t$ .
6. [10 points] Consider the process  $X_t = \int_0^t s^2 W_s dW_s$ . Find  $\mathbb{E}(X_t)$ ,  $\text{Var}(X_t)$ ,  $\text{Cov}(X_t, W_t)$
7. [10 points] In the framework of Black and Scholes model find the price at the time 0 of an asset which gives you the payoff  $\ln(S_T)$  at the time  $T$ . Here  $S_t$  is the price of the underlying asset at time  $t$ .
8. [20 points] The goal of this exercise is to solve the SDE

$$dX_t = -9X_t^2(1 - X_t)dt + 3X_t(1 - X_t)dW_t, \quad X_0 = 1/2$$

- (a) Using Ito's lemma find  $dY_t$  for the process  $Y_t = f(X_t)$
- (b) Find such a function  $f()$  that the term before  $dt$  in  $dY_t$  is zero
- (c) Obtain a simple differential equation for  $Y_t$ . It should not contain  $X_t$ .
- (d) Solve the stochastic differential equation for  $Y_t$
- (e) Express  $X_t$  as a function of  $W_t$  and  $t$ .

### 5.3 exam 10.01.2013-hints

1.  $\mathbb{E}(H_i | X_i) = X_i^2$ ,

$$\mathbb{E}(X_i | H_i = 1) = \mathbb{E}(X_i | X_i \text{ is the biggest of three waves}) = \frac{3}{4}$$

$$\mathbb{E}(X_i | H_i = 0) = \frac{1}{2} \mathbb{E}(X_i | X_i \text{ is the smallest of three waves}) + \frac{1}{2} \mathbb{E}(X_i | X_i \text{ is the median of three waves})$$

$$\mathbb{E}(X_i | H_i) = (3 + 3H_i)/8$$

2.  $\mathbb{E}(W_s \cdot W_t) = s$  and

Let's introduce deltas:  $D_1 = W_s - W_r$  and  $D_2 = W_t - W_s$ . The bonus of this notation is that  $D_1, D_2$  and  $W_r$  are independent random variables. And

$$\mathbb{E}(W_r \cdot (W_r + D_1) \cdot (W_r + D_1 + D_2)) = \mathbb{E}(W_r^3 + W_r^2 D_1 + W_r^2 D_2 + W_r^2 D_1 + W_r D_1^2 + W_r D_1 D_2) = 0 + 0 + 0 + 0 + 0 + 0.$$

3.  $\mathbb{E}(X_t) = 0$ ,  $\text{Var}(X_t) = t^6/6$ ,  $\text{Cov}(X_t, W_t) = 0$   
 4.  $C_0 = e^{-rT}(\ln S_0 + (r - \sigma^2/2)T)$   
 5. Equation for  $f$  has the form  $f''(x)(1-x) - 2f'(x) = 0$ . Use the substitution  $f'(x) = h(x)$ . This ordinary differential equation has many solutions, one of them is  $f(x) = 1/(1-x)$ . We may take any function  $f$  that makes initial stochastic differential equation less difficult, so we take  $f(x) = 1/(1-x)$ , and  $Y_t = 1/(1-X_t)$ .

And

$$dY_t = 3X_t/(1-X_t) dW_t$$

We may notice that  $X_t/(1-X_t) = 1/(1-X_t) - 1 = Y_t - 1$ , so

$$dY_t = 3(Y_t - 1) dW_t$$

We use the substitution  $Z_t = Y_t - 1$ , so  $dZ_t = 3Z_t dW_t$  and then the substitution  $Q_t = \ln Z_t$ .

## 5.4 Retake, 08.02.2013

**Stochastic calculus part.** Here  $W_t$  denotes standard Wiener process

- (10 points) Random variables  $X$  and  $Y$  are jointly normal with zero expected values, unit variances and correlation  $\rho$ . Find  $\mathbb{E}(Y | X)$  and  $\mathbb{E}(Y^2 | X)$
- (10 points) Consider the processes  $X_t = \int_0^t s^3 W_s dW_s$  and  $Y_t = \int_0^t W_s dW_s$ . Find  $\mathbb{E}(X_t)$ ,  $\text{Var}(X_t)$ ,  $\text{Cov}(X_t, Y_t)$
- (10 points) The stochastic process  $Y_t$  is given by equation  $Y_t = W_t^4 - 6tW_t^2 + 3t^2$ . Find  $dY_t$  and  $\mathbb{E}(Y_7 | Y_2)$
- (20 points) Consider the stochastic differential equation

$$dX_t = X_t dt + X_t dW_t, \quad X_0 = 1$$

(a) Solve this stochastic differential equation

(b) Let  $\tau = \inf_{t>0} \{t : X_t \geq R\}$ . Find  $\mathbb{E}(\tau)$  applying the optional stopping theorem to the process  $W_t$ .

**Optimal control part.**

- (10 points) Solve the optimal control problem:  $\int_0^1 u^2 dt \rightarrow \min$ , subject to  $\dot{x} = x + u$ ,  $x(0) = 1$ .
- (10 points) Consider a maximization problem over the finite horizon in discrete time  $t = 1, \dots, T$ :

$$\sum_{t=1}^T \left( \frac{t^3}{3} + \frac{t^2}{2} \right) a_t^2 \rightarrow \max$$

subject to constraint  $\sum_{t=1}^T a_t = c, a_t \geq 0$ .

By introducing  $w_t = \sum_{i=1}^t a_i$  reduce that problem to dynamic programming (3 points) and solve it (7 points).

7. (20 points) Consider the profit-maximizing problem for a representative competitive firm

$$\int_0^\infty (p - c(x(t)))q(t)e^{-rt} dt \rightarrow \max$$

subject to (\*)  $\dot{x} = 1 - x - q$ , where the state variable  $x(t) < 1$  represents a nonrenewable stock resource (oil) that depletes according to the equation (\*) and  $q(t)$  is the extraction rate. Here  $c(x)$  is a cost function of the extraction that is defined by  $c(x) = e^{-x}$ . The price of oil is assumed to be constant and equal  $p$  where  $1/e < p < 1$ . The optimization problem is to choose  $q(t)$  to maximize the discounted profits,  $0 < r < 1$ .

(a) (10 points) Derive necessary conditions.

(b) (10 points) Prove that the steady-state exists.

## 5.5 retake — short hints

1. First we decompose  $Y$  as  $Y = aX + bZ$ , where  $Z$  is independent from  $X$  and has unit variance. To obtain  $a$  and  $b$  we make system:

$$\begin{cases} \text{Var}(Y) = a^2 \text{Var}(X) + b^2 \text{Var}(Z) = 1 \\ \text{Cov}(Y, X) = a \text{Cov}(X, X) = \rho \end{cases}$$

So,  $a = \rho$  and  $b = \sqrt{1 - \rho^2}$ . The variable  $Y$  is decomposed as  $Y = \rho X + \sqrt{1 - \rho^2}Z$ . Then

$$\mathbb{E}(Y | X) = \mathbb{E}(\rho X + \sqrt{1 - \rho^2}Z | X) = \rho X + 0$$

And

$$\mathbb{E}(Y^2 | X) = \mathbb{E}(\rho^2 X^2 + (1 - \rho^2)Z^2 + 2\rho\sqrt{1 - \rho^2}XZ | X) = \rho^2 X^2 + (1 - \rho^2) \cdot 1 + 2 \cdot 0$$

2.  $\mathbb{E}(X_t) = \mathbb{E}(Y_t) = 0$ , for variance and covariance we use isometry property

$$\text{Var}(X_t) = \text{Var}\left(\int_0^t s^3 W_s dW_s\right) = \int_0^t \mathbb{E}(s^3 W_s)^2 ds = \int_0^t s^7 ds = \frac{t^8}{8}$$

$$\text{Cov}(X_t, Y_t) = \text{Cov}\left(\int_0^t s^3 W_s dW_s, \int_0^t W_s dW_s\right) = \int_0^t \mathbb{E}(s^3 W_s^2) ds = \int_0^t s^4 ds = \frac{t^5}{5}$$

3. Calculate  $dY_t$ . We observe that  $dY_t = (4W_t^3 - 12tW_t) dW_t$ , so  $Y_t$  is a martingale and  $\mathbb{E}(Y_7 | Y_2) = Y_2$ .
4. Use the substitution  $Y_t = \ln X_t$ . Then, using Ito's lemma we obtain:

$$dY_t = \frac{1}{X_t} dX_t - \frac{1}{2X_t^2} (dX_t)^2$$

Initial SDE gives us  $dX_t = X_t dt + X_t dW_t$ , so we can compute also  $(dX_t)^2$  and plug it in the  $dY_t$ .

$$dX_t^2 = (X_t dt + X_t dW_t)^2 = X_t^2 dt$$

Recall that  $dW_t \cdot dW_t = dt$ ,  $dW_t \cdot dt = 0$  and  $dt \cdot dt = 0$

Plugging in we get:

$$dY_t = \frac{X_t dt + X_t dW_t}{X_t} - \frac{X_t^2 dt}{2X_t^2} = dt + dW_t - \frac{dt}{2} = dW_t + \frac{dt}{2}$$

The full form for  $Y_t$ :

$$Y_t = Y_0 + \int_0^t dW_s + \int_0^t \frac{ds}{2} = Y_0 + W_t + \frac{t}{2} = \ln X_t$$

Now we are ready to write the solution:

$$X_t = e^{Y_0} e^{W_t} e^{\frac{t}{2}} = X_0 e^{W_t + \frac{t}{2}}$$

## 6 2013-2014

### 6.1 Stochastic calculus homework

1. Let  $X$  and  $Y$  be independent exponentially distributed with parameter  $\lambda$ . Find  $\mathbb{E}(X + Y \mid X - Y)$ .
2. Let  $S_n$  be symmetric random walk with  $S_0 = 2013$ . The stopping time  $\tau$  is the first moment when  $|S_n|$  reaches the value 2014 or the value 2000. Find  $\mathbb{E}(\tau S_\tau)$ .  
Hint: You may construct a martingale of the form  $M_n = S_n^3 - f(n)S_n$  for some function  $f$ .
3. Conditional variance is defined as  $\text{Var}(Y \mid X) = \mathbb{E}(Y^2 \mid X) - (\mathbb{E}(Y \mid X))^2$ . Find  $\text{Var}(W_s \mid W_t)$ .  
Hint: do not forget two cases,  $t > s$  and  $s < t$ . You may find inversion property of the Wiener process useful.
4. Let  $f$  be a real function such that  $f''$  is continuous. Find all such functions  $f$  that  $X_t = \exp(\alpha t)f(W_t)$  is a martingale.
5. Solve the stochastic differential equation

$$dX_t = (X_t/t + t)dt + 2\sqrt{tX_t}dW_t$$

Hint: You may suppose without a proof that the solution has the form  $X_t = f(t)g(W_t)$ .

6. In the framework of Black and Scholes model find the price of the asset, which pays you  $S_T$  at the fixed moment of time  $T > 1$  if  $S_{T-1} > 1$  and 0 otherwise.

### 6.2 Solution for stochastic calculus homework

Author: Vladimir Shmarov

#### Problem 1.

Denote  $\xi = X + Y$  and  $\eta = X - Y$ .

Then we are gonna find  $\mathbb{E}(\xi \mid \eta)$ .

Since  $X \sim \text{Expo}(\lambda)$ , it has a nice density:  $p_X(u) = \lambda e^{-\lambda u} \cdot I_{\{u \geq 0\}}$ .

Similarly,  $p_Y(v) = \lambda e^{-\lambda v} \cdot I_{\{v \geq 0\}}$ .

Since  $X$  and  $Y$  are independent, the vector  $(X, Y)$  has a two-dimensional density, which equals to the product of densities of  $X$  and  $Y$ , i.e.

$$p_{(X,Y)}(u, v) = I_{\{u \geq 0, v \geq 0\}} \lambda^2 e^{-\lambda(u+v)}$$

We have  $X = X(\xi, \eta) = \frac{\xi+\eta}{2}$  and  $Y = Y(\xi, \eta) = \frac{\xi-\eta}{2}$ .

$$\text{Then } J = \begin{vmatrix} \frac{\partial X}{\partial \xi} & \frac{\partial X}{\partial \eta} \\ \frac{\partial Y}{\partial \xi} & \frac{\partial Y}{\partial \eta} \end{vmatrix} = \begin{vmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} \end{vmatrix} = -\frac{1}{2}.$$

Therefore

$$p_{(\xi,\eta)}(s, t) = p_{(X,Y)}\left(\frac{s+t}{2}, \frac{s-t}{2}\right) \cdot |J| = \frac{\lambda^2}{2} I_{\{s+t \geq 0\}} I_{\{s-t \geq 0\}} e^{-\lambda s} = \frac{\lambda^2}{2} I_{\{s \geq |t|\}} e^{-\lambda s}$$

is a density of a vector  $(\xi, \eta)$ .

Further,

$$p_\eta(t) = \int_{\mathbb{R}} p_{(\xi,\eta)}(s, t) ds = \frac{\lambda e^{-\lambda|t|}}{2}$$

Then the conditional density is

$$p_{(\xi|\eta)}(s | t) = \frac{p_{(\xi,\eta)}(s, t)}{p_\eta(t)} = \lambda e^{-\lambda(s-|t|)} \cdot I_{\{s-|t| \geq 0\}}$$

And finally, denoting  $z = s - |t|$ , we get

$$\begin{aligned} \mathbb{E}(\xi | \eta) &= \int_{\mathbb{R}} s \cdot p_{(\xi|\eta)}(s | t) ds \Big|_{t=\eta} = \int_{\mathbb{R}} (z + |t|) \cdot \lambda e^{-\lambda z} \cdot I_{\{z \geq 0\}} dz \Big|_{t=\eta} = \\ &= \int_{\mathbb{R}} z \cdot \lambda e^{-\lambda z} \cdot I_{\{z \geq 0\}} dz \Big|_{t=\eta} + |t| \int_{\mathbb{R}} \lambda e^{-\lambda z} \cdot I_{\{z \geq 0\}} dz \Big|_{t=\eta} = \left( \frac{1}{\lambda} + |t| \right) \Big|_{t=\eta} = \frac{1}{\lambda} + |\eta| \quad (2) \end{aligned}$$

(the first integral is just the expectation of exponential distribution with parameter  $\lambda$ , and the second is  $|t|$  times the integral of the density, which equals 1)

**Answer:**  $\mathbb{E}(X + Y | X - Y) = \frac{1}{\lambda} + |X - Y|$

**Problem 2 – part 1 of 2.**

At first,  $S_n = S_0 + \sum_{i=1}^n \varepsilon_i$ , where  $\{\varepsilon_i\}$  is the sequence of independent random variables with  $\mathbb{P}(\varepsilon_i = -1) = \mathbb{P}(\varepsilon_i = 1) = \frac{1}{2}$ . Also denote  $\mathcal{F}_n = \sigma(\varepsilon_1, \dots, \varepsilon_n)$ .

Observe that  $\tau$  is really a stopping time, because at each moment of time we precisely know, are we in one of the points  $\{2000, 2014\}$  or not.

Let's prove that  $\mathbb{E}(\tau) < \infty$  (which will also imply that  $\mathbb{P}(\tau = +\infty) = 0$ ).

We shall obviously reach  $\tau$  after any 14 consecutive steps in one direction. Then

$$\begin{aligned} P(\tau \geq 14n) &\leq \mathbb{P}(\text{At least one of } \varepsilon_1, \dots, \varepsilon_{14} \text{ equals } -1) \times \dots \times \mathbb{P}(\text{At least one of } \varepsilon_{14(n-1)+1}, \dots, \varepsilon_{14n} \text{ equals } -1) \\ &= (1 - 2^{-14})^n = q^n \quad (3) \end{aligned}$$

where  $q < 1$ .

Then

$$E(\tau) = \sum_{n=1}^{+\infty} P(\tau \geq n) \leq 14 \sum_{n=0}^{+\infty} P(\tau \geq 14n + 1) \leq 14 \sum_{n=0}^{\infty} q^n = 14 \cdot 2^{14} < \infty$$

as required.

The sequence  $\{S_t\}$  is a martingale w.r.t. filtration  $\{\mathcal{F}_n\}$ , because it is obviously  $\{\mathcal{F}_t\}$ -adapted, has a finite (zero) expectation and

$$E(S_{t+1} | \mathcal{F}_t) = E(S_t + \varepsilon_{t+1} | \mathcal{F}_t) = S_t + E(\varepsilon_{t+1} | \mathcal{F}_t) = S_t$$

Further,  $S_{\min\{t, \tau\}}$  is bounded in  $t$ : it always lies between 2000 and 2014. The Doob's theorem conditions are satisfied, which means that

$$E(S_\tau) = S_0 = 2013$$

But  $E(S_\tau) = 2000 \cdot \mathbb{P}(S_\tau = 2000) + 2014 \cdot \mathbb{P}(S_\tau = 2014)$ , which after the substitution  $E(S_\tau) = 2013$  gives us

$$\mathbb{P}(S_\tau = 2000) = \frac{1}{14} \text{ and } \mathbb{P}(S_\tau = 2014) = \frac{13}{14}$$

Further, let's prove that the sequence  $\{S_t^3 - 3tS_t\}$  is a  $\{\mathcal{F}_t\}$ -martingale. At first, it is obviously adapted and  $|\mathbb{E}(S_t^3 - 3tS_t)| < \infty$

Then

$$\begin{aligned} \mathbb{E}(S_{t+1}^3 - 3(t+1)S_{t+1} | \mathcal{F}_t) &= \mathbb{E}((S_t + \varepsilon_{t+1})^3 - 3(t+1)(S_t + \varepsilon_{t+1}) | \mathcal{F}_t) = \\ &= \mathbb{E}\left(S_t^3 + 3S_t^2 \underline{\varepsilon_{t+1}} + 3(\underline{\varepsilon_{t+1}^2} - 1)S_t - 3tS_t + \underline{\varepsilon_{t+1}^3} - 3(t+1)\underline{\varepsilon_{t+1}} | \mathcal{F}_t\right) = S_t^3 - 3tS_t \quad (4) \end{aligned}$$

(the underlined terms are going out after taking conditional expectation;  $(\varepsilon_{t+1}^2 - 1)$  goes out even without it)

Denote  $X_t = S_t^3 - 3tS_t$ .

For  $t \geq \tau$  we have  $|X_{\min\{t+1, \tau\}} - X_{\min\{t, \tau\}}| = 0$ , and for  $t < \tau$  we have

$|X_{\min\{t+1, \tau\}} - X_{\min\{t, \tau\}}| = |X_{t+1} - X_t| = |3S_t^2 \varepsilon_{t+1} - (3t+2)\varepsilon_{t+1}| \leq 3 \times 2014^2 + 3\tau + 2$ , which expectation is bounded by the finite number  $3 \times 2014^2 + 2 + 3E(\tau)$ .

Then, the overall expectation  $E(|X_{\min\{t+1, \tau\}} - X_{\min\{t, \tau\}}|) \leq 3 \times 2014^2 + 2 + 3E(\tau)$  for every  $t$ , i.e. is bounded in  $t$ .

### Problem 2 – part 2 of 2.

Then again, the conditions of the Doob's theorem are satisfied, i.e.

$$\mathbb{E}(X_\tau) = X_0 = 2013^3$$

But also  $\mathbb{E}(X_\tau) = \mathbb{E}(S_\tau^3) - 3\mathbb{E}(\tau S_\tau)$ , i.e.

$$\mathbb{E}(\tau S_\tau) = \frac{1}{3} (\mathbb{E}(S_\tau^3) - 2013^3) = \frac{1}{3} \left( \frac{1}{14} 2000^3 + \frac{13}{14} 2014^3 - 2013^3 \right) = 13 \times 2009 = 26117$$

**Answer:**  $\mathbb{E}(\tau S_\tau) = 26117$ .

### Problem 3.

Case 1. Let  $s \geq t$ .



Then

$$\begin{aligned}\mathbb{E}(W_s^2 | W_t) &= \mathbb{E}(W_t^2 + 2W_t(W_s - W_t) + (W_s - W_t)^2 | W_t) = \\ &= W_t^2 + 2W_tE(W_s - W_t) + E((W_s - W_t)^2) = W_t^2 + (s - t)\end{aligned}$$

Further,

$$\mathbb{E}(W_s | W_t) = W_t + \mathbb{E}(W_s - W_t | W_t) = W_t$$

Then we have  $\text{Var}(W_s | W_t) = \mathbb{E}(W_s^2 | W_t) - \mathbb{E}(W_s | W_t)^2 = (s - t)$ .

Case 2. Let  $s < t$ .

By the inverse property,  $V_t = tW_{\frac{1}{t}}$  is also a standard Wiener process.

From the case 1 we have

$$\frac{1}{s} - \frac{1}{t} = \text{Var}\left(V_{\frac{1}{s}} | V_{\frac{1}{t}}\right) = \text{Var}\left(\frac{1}{s}W_s | \frac{1}{t}W_t\right) = \frac{1}{s^2} \text{Var}\left(W_s | \frac{1}{t}W_t\right) = \frac{1}{s^2} \text{Var}(W_s | W_t)$$

the last equation is because obviously  $\sigma(W_t) = \sigma(\frac{1}{t}W_t)$ .

Then  $\text{Var}(W_s | W_t) = s - \frac{s^2}{t}$ .

Summing up these two cases, we get the

$$\textbf{Answer: } \text{Var}(W_s | W_t) = \max\left\{s - t, s - \frac{s^2}{t}\right\}$$

**Problem 4.**

Let  $g(t, W_t) = X_t = e^{\alpha t} f(W_t)$ , then  $g_t = \alpha g$ ,  $g_{W_t} = e^{\alpha t} f'(W_t)$  and  $g_{W_t W_t} = e^{\alpha t} f''(W_t)$ .

By the Ito's lemma we have

$$\begin{aligned}dX_t &= \alpha X_t dt + e^{\alpha t} f'(W_t) dW_t + \frac{1}{2} e^{\alpha t} f''(W_t) dt = \\ &= e^{\alpha t} \left( \alpha f(W_t) + \frac{1}{2} f''(W_t) \right) dt + e^{\alpha t} f'(W_t) dW_t\end{aligned}$$

Therefore

$$X_t = f(0) + \int_0^t e^{\alpha u} \left( \alpha f(W_u) + \frac{1}{2} f''(W_u) \right) du + \int_0^t e^{\alpha u} f'(W_u) dW_u$$

The last term in the right-hand side is a martingale, so  $X_t$  is a martingale if and only if the coefficient near  $dt$  equals zero for all  $t$ , i.e.

$$\alpha f(W_t) + \frac{1}{2} f''(W_t) = 0 \quad \text{a.s.}$$

which (together with continuity of  $f''$ ) implies

$$\alpha f(x) + \frac{1}{2} f''(x) = 0 \quad \forall x$$

We know how to solve the linear differential equations, so I will not go into details and I'll just write the answer.

**Answer:** If  $\alpha < 0$ , then  $f(x) = C_1 e^{t\sqrt{-2\alpha}} + C_2 e^{-t\sqrt{-2\alpha}}$ , where  $C_1, C_2$  are any real constants;  
if  $\alpha = 0$ , then  $f(x) = C_1 x + C_2$ ;  
if  $\alpha > 0$ , then  $f(x) = C_1 \cos(t\sqrt{2\alpha}) + C_2 \sin(t\sqrt{2\alpha})$

**Problem 5 – part 1 of 2.**

Assume for simplicity that  $X_t = f(t)g(W_t)$ , where  $f$  and  $g$  are kinda nice functions (defined on  $[0, +\infty)$  and continuously differentiable the required number of times on this interval; right-differentiable at zero, of course).

By the Itô's lemma we have

$$dX_t = \left( f'(t)g(W_t) + \frac{1}{2}f(t)g''(W_t) \right) dt + f(t)g'(W_t)dW_t$$

Substituting this into the condition of the problem and separating the parts with  $dt$  and  $dW_t$  we get

$$\begin{cases} f'(t)g(W_t) + \frac{1}{2}f(t)g''(W_t) = \frac{f(t)}{t}g(W_t) + t & (1) \\ f(t)g'(W_t) = 2\sqrt{tf(t)g(W_t)} & (2) \end{cases}$$

Both equations are satisfied for every  $t > 0$  almost surely.

*Step 1.* Let's prove that  $f(t) \neq 0$  if  $t > 0$ . Indeed, if  $f(t_0) = 0$ , (1) gives us

$$f'(t_0)g(W_{t_0}) = t_0 \quad \text{a.s.}$$

so

$$g(W_{t_0}) = \frac{t_0}{f'(t_0)} \quad \text{a.s.}$$

But  $g$  is continuous, so this gives us

$$g(x) \equiv C = \text{Const}$$

But then (2) gives

$$X_t \equiv 0 \quad \text{a.s.}$$

which does not satisfy the condition of the problem.

Therefore,  $f(t) \neq 0$ , when  $t \neq 0$ .

Now (2) can be transformed into

$$\frac{f(t)}{4t}g'(W_t)^2 = g(W_t) \quad (3)$$

*Step 2.*  $g'(x)$  cannot be zero in any interval.

Suppose that  $g'(x) = 0$  for all  $x \in (a, b)$ . From (3) we have  $g(x) = 0$  almost everywhere at  $(a, b)$  (because  $\mathbb{P}(W_t \in (a, b)) \neq 0$  for  $t > 0$ ), and also  $g'(x) = 0$  at  $(a, b)$ . But substituting these values to (1) provides us contradiction.

Let  $A = \{x \in \mathbb{R} \mid g'(x) \neq 0\}$ . Since  $g'$  is continuous and is not identical zero (from the step 2), the

set  $A$  has a positive Lebesgue measure; therefore  $\mathbb{P}(W_t \in A) \neq 0$  for all  $t > 0$ .

**Problem 5 – pat 2 of 2.**

Now fix some  $t_0 > 0$ . From (3) we have that almost everywhere in the event  $\{W_{t_0} \in A\}$  the equality

$$\frac{g(W_{t_0})}{g'(W_{t_0})^2} = \frac{f(t_0)}{4t_0}$$

holds. Then for almost all  $x \in A$  we have  $\frac{g(x)}{g'(x)^2} = \frac{f(t_0)}{4t_0}$ . Now fix any other  $t_1 > 0$ .

We have that almost everywhere in  $A$  the equality  $\frac{g(x)}{g'(x)^2} = \frac{f(t_1)}{4t_1}$  holds. Since  $A$  has a positive measure, we have

$$\frac{f(t_0)}{4t_0} = \frac{f(t_1)}{4t_1}$$

i.e.  $f(t) = Ct$  for all  $t > 0$  and some  $C = \text{Const.}$  From the continuity  $\boxed{f(t) = Ct \text{ for all } t \geq 0}$

Substitute this to (1):

$$Cg(W_t) + \frac{1}{2}Ctg''(W_t) = Cg(W_t) + t$$

$$g''(W_t) = \frac{2}{C} \quad (4)$$

(4) holds almost everywhere, but since  $g''$  is continuous, we have  $\boxed{g''(x) \equiv \frac{2}{C}}$

Then  $g'(x) = \frac{2x}{C} + D$  and  $g(x) = \frac{x^2}{C} + Dx + E$  for some constants  $D, E$ .

From (3) we have

$$g(x) = \frac{f(t)}{4t}g'(x)^2 = \frac{C}{4}g'(x)^2$$

Substitute the values of  $g'(x)$  and  $g(x)$ :

$$\frac{x^2}{C} + Dx + E = \frac{C}{4} \left( \frac{2x}{C} + D \right)^2$$

$$\frac{x^2}{C} + Dx + E = \frac{x^2}{C} + Dx + \frac{CD^2}{4}$$

which gives us  $E = \frac{CD^2}{4}$  and  $g(x) = (Ax + B)^2$ , where  $A^2 = \frac{1}{C}$  and  $2AB = D$ .

**Answer:**  $X_t = t(W_t + C)^2$  for some constant  $C$ .

(in our notation this constant equals  $\frac{B}{A}$ )

**REMARK.** Precisely speaking, this is not a correct answer, because  $\sqrt{tX_t}$  is always positive, so (2) does not always hold, because the left side of (2), which is  $2t(W_t + C)$ , can be negative with nonzero probability. In other words, we solved similar, but different equation

$$dX_t = \left( \frac{X_t}{t} + t \right) dt \pm 2\sqrt{tX_t}dW_t$$

and the original problem has no solutions of the type  $f(t)g(W_t)$ .

**Problem 6 – part 1 of 4.**

The risky asset  $S_t$  satisfies the stochastic differential equation

$$dS_t = \mu S_t dt + \sigma S_t dW_t$$

which implies

$$S_t = S_0 \exp \left( t \left( \mu - \frac{\sigma^2}{2} \right) + \sigma W_t \right)$$

The risk-free asset satisfies the equation

$$dB_t = r B_t dt$$

which implies

$$B_t = B_0 e^{rt}$$

Let  $X_t$  be our self-financing portfolio at time  $t$ , which contains  $\Delta_t$  shares of the risky asset.

The total amount of money in the risky asset is  $\Delta_t$ , in the risk-free asset –  $(X_t - \Delta_t S_t)$ .

Therefore

$$dX_t = \Delta_t dS_t + r(X_t - \Delta_t S_t) dt$$

Let  $\tilde{W}_t = \frac{\mu-r}{\sigma}t + W_t$ , and  $\tilde{P}$  is the probability measure, w.r.t. which  $\tilde{W}_t$  is a standard Wiener process (the existence of such measure is the statement of Girsanov's theorem).

In class we explicitly derived that

$$e^{-rt} X_t = X_0 + \int_0^t \Delta_u e^{-ru} \sigma S_u d\tilde{W}_u$$

The last term is a  $\tilde{P}$ -martingale, which means that

$$\mathbb{E}_{\tilde{P}} (e^{-rT} X_T \mid \mathcal{F}_0) = X_0 \quad (1)$$

Now recall that

$$X_T = S_T I_{\{S_{T-1} > 1\}}$$

so we need to calculate

$$\mathbb{E}_{\tilde{P}}(S_T I_{\{S_{T-1} > 1\}}) = \iint_{u>0, v>1} u \cdot \tilde{p}_{(S_T, S_{T-1})}(u, v) du dv$$

where  $\tilde{p}_{(S_T, S_{T-1})}$  is a two-dimensional density of a corresponding vector w.r.t. measure  $\tilde{P}$ .

**Problem 6 – part 2 of 4.**

But

$$\iint_{u>0, v>1} u \cdot \tilde{p}_{(S_T, S_{T-1})}(u, v) du dv = \int_1^{+\infty} \left( \int_0^{+\infty} u \cdot \tilde{p}_{(S_T, S_{T-1})}(u, v) du \right) dv = \int_1^{+\infty} \tilde{p}_{S_{T-1}}(v) \cdot E_{\tilde{P}}(S_T \mid S_{T-1} = v) dv$$

Further,

$$S_{T-1} = S_0 \exp \left( (T-1) \left( \mu - \frac{\sigma^2}{2} \right) + \sigma W_{T-1} \right) = S_0 \exp \left( (T-1) \left( r - \frac{\sigma^2}{2} \right) + \sigma \tilde{W}_{T-1} \right)$$

which means that with notation  $A(x) = S_0 \exp \left( (T-1) \left( r - \frac{\sigma^2}{2} \right) + \sigma x \right)$  we have

$$\tilde{p}_{\tilde{W}_{T-1}}(x) = \tilde{p}_{S_{T-1}}(A(x)) \cdot \sigma A(x)$$

We have  $x = \sigma^{-1} \left( \ln \left( \frac{A(x)}{S_0} \right) - (T-1) \left( r - \frac{\sigma^2}{2} \right) \right)$ . Therefore

$$\tilde{p}_{S_{T-1}}(v) = \frac{1}{\sigma v} \cdot \frac{1}{\sqrt{2\pi(T-1)}} \exp \left( -\frac{1}{2\sigma^2(T-1)} \left( \ln(v) - \left( \ln(S_0) + (T-1) \left( r - \frac{\sigma^2}{2} \right) \right) \right)^2 \right) \quad (2)$$

Very ugly expression! Let's believe most of those terms will cancel out.

Now

$$S_T = S_0 \exp \left( T \left( r - \frac{\sigma^2}{2} \right) + \sigma \tilde{W}_T \right) = S_{T-1} \cdot \exp \left( r - \frac{\sigma^2}{2} + \sigma \left( \tilde{W}_T - \tilde{W}_{T-1} \right) \right)$$

and  $\left( \tilde{W}_T - \tilde{W}_{T-1} \right)$  is independent of the  $\sigma$ -algebra  $\sigma(S_{T-1}) \subseteq \mathcal{F}_{T-1}$ .

Then

$$\begin{aligned} \mathbb{E}_{\tilde{P}}(S_T \mid S_{T-1} = v) &= \mathbb{E}_{\tilde{P}} \left( S_{T-1} \cdot \exp \left( r - \frac{\sigma^2}{2} + \sigma \left( \tilde{W}_T - \tilde{W}_{T-1} \right) \right) \mid S_{T-1} = v \right) = \\ &= v \cdot \exp \left( r - \frac{\sigma^2}{2} \right) \mathbb{E}_{\tilde{P}} \left( \exp \left( \sigma \left( \tilde{W}_T - \tilde{W}_{T-1} \right) \right) \right) \end{aligned} \quad (3) \quad (5)$$

Further, if  $\xi \sim \mathcal{N}(0, 1)$ , then

$$\mathbb{E}(e^{\sigma\xi}) = \frac{1}{\sqrt{2\pi}} \int_{\mathbb{R}} e^{-\frac{x^2}{2} + \sigma x} dx = e^{\frac{\sigma^2}{2}} \cdot \frac{1}{\sqrt{2\pi}} \int_{\mathbb{R}} e^{-\frac{(x-\sigma)^2}{2}} dx = e^{\frac{\sigma^2}{2}}$$

which gives us

$$\mathbb{E}_{\tilde{P}}(S_T \mid S_{T-1} = v) = v \cdot \exp \left( r - \frac{\sigma^2}{2} \right) \exp \left( \frac{\sigma^2}{2} \right) = ve^r \quad (4)$$

which, I think, is a very nice formula (especially if we compare it with (2)).

#### **Problem 6 – part 3 of 4.**

Taking (2) and (4), we have

$$\begin{aligned} &\int_1^{+\infty} \tilde{p}_{S_{T-1}}(v) \cdot E_{\tilde{P}}(S_T \mid S_{T-1} = v) dv = \\ &= e^r \int_1^{+\infty} \frac{1}{\sigma} \cdot \frac{1}{\sqrt{2\pi(T-1)}} \exp \left( -\frac{1}{2\sigma^2(T-1)} \left( \ln(v) - \left( \ln(S_0) + (T-1) \left( r - \frac{\sigma^2}{2} \right) \right) \right)^2 \right) dv = \\ &= e^r \int_0^{+\infty} e^s \cdot \frac{1}{\sqrt{2\pi\sigma^2(T-1)}} \exp \left( -\frac{1}{2\sigma^2(T-1)} \left( s - \left( \ln(S_0) + (T-1) \left( r - \frac{\sigma^2}{2} \right) \right) \right)^2 \right) ds \end{aligned} \quad (6)$$

We substituted  $s = \ln(v)$ . Of course,  $dv = e^s ds$ .

Denote also  $B = \ln(S_0) + (T - 1) \left( r - \frac{\sigma^2}{2} \right)$ .

Then our integral equals

$$\begin{aligned}
& e^r \int_0^{+\infty} \frac{1}{\sqrt{2\pi\sigma^2(T-1)}} \exp \left( -\frac{s^2 - 2Bs - 2\sigma^2(T-1)s + B^2}{2\sigma^2(T-1)} \right) ds = \\
& = \exp \left( r - \frac{B^2}{2\sigma^2(T-1)} + \frac{(B + \sigma^2(T-1))^2}{2\sigma^2(T-1)} \right) \int_0^{+\infty} \frac{1}{\sqrt{2\pi\sigma^2(T-1)}} \exp \left( -\frac{(s - B - \sigma^2(T-1))^2}{2\sigma^2(T-1)} \right) ds = \\
& = \exp \left( r - \frac{B^2}{2\sigma^2(T-1)} + \frac{(B + \sigma^2(T-1))^2}{2\sigma^2(T-1)} \right) \cdot \tilde{P}(\eta > -(B + \sigma^2(T-1))) \quad (7)
\end{aligned}$$

where  $\eta \sim \mathcal{N}(0, \sigma^2(T-1))$ . The integral magically turns into the probability, because under the integral there is a well-known density.

Therefore our integral finally equals

$$\begin{aligned}
& \exp \left( r + \frac{(B + \sigma^2(T-1))^2 - B^2}{2\sigma^2(T-1)} \right) \cdot \tilde{P} \left( \frac{\eta}{\sigma\sqrt{T-1}} > -\frac{B + \sigma^2(T-1)}{\sigma\sqrt{T-1}} \right) = \\
& = \exp \left( r + B + \frac{\sigma^2(T-1)}{2} \right) \Phi \left( \frac{B + \sigma^2(T-1)}{\sigma\sqrt{T-1}} \right) = e^{\ln(S_0) + rT} \cdot \Phi \left( \frac{\ln(S_0) + (T-1) \left( r + \frac{\sigma^2}{2} \right)}{\sigma\sqrt{T-1}} \right) \quad (8)
\end{aligned}$$

where  $\Phi(x)$  is a distribution function of a standard normal random value,  $\Phi(x) = \int_{-\infty}^x \frac{1}{\sqrt{2\pi}} \exp \left( -\frac{t^2}{2} \right) dt$ .

#### Problem 6 – part 4 of 4.

And now I'll finish this huge problem.

We had

$$\begin{aligned}
X_0 = e^{-rT} E_{\tilde{P}} \left( S_T I_{\{S_{T-1} > 1\}} \right) & = e^{-rT} \cdot e^{\ln(S_0) + rT} \Phi \left( \frac{\ln(S_0) + (T-1) \left( r + \frac{\sigma^2}{2} \right)}{\sigma\sqrt{T-1}} \right) = \\
& = S_0 \Phi \left( \frac{\ln(S_0) + (T-1) \left( r + \frac{\sigma^2}{2} \right)}{\sigma\sqrt{T-1}} \right) \quad (9)
\end{aligned}$$

This is our answer.

**Answer:** The price of our asset equals

$$S_0 \cdot \Phi \left( \frac{\ln(S_0) + (T-1) \left( r + \frac{\sigma^2}{2} \right)}{\sigma\sqrt{T-1}} \right)$$

where  $\Phi(x)$  is a distribution function of a standard normal random value,  $\Phi(x) = \int_{-\infty}^x \frac{1}{\sqrt{2\pi}} \exp \left( -\frac{t^2}{2} \right) dt$

### 6.3 Exam, 17.01.2014

#### Optimal control part

1. [10 points] A collector of wine is told by a doctor that he is going to die in  $T$  years and he develops a consumption plan that maximizes the utility of consumption of wine over remaining lifetime. At present the stock of wine equals  $w(0) = w_0 > 0$ . It will be consumed fully by time  $T$ , that is  $w(T) = 0$ . The utility function is  $U(c) = c$ , where  $c$  is consumption of wine. The stock of wine follows the rule  $w(t) = w_0 - \int_0^t c(s) ds$ . Consumption is bounded  $0 \leq c \leq \bar{c}$ , where  $\bar{c} > w_0/T$ .

State the dynamic optimization problem, if the discount rate is  $r > 0$ . Introduce the current value Hamiltonian for that problem. Write down the first-order conditions. Solve the system of equations.

2. [10 points] Consider the following optimization problem: maximize  $\sum_{t=0}^{\infty} 0.75^t \ln c_t$ , subject to  $c_t + k_{t+1} = \sqrt{k_t}$ , where  $k_0 > 0$ . Let the state variable be  $k$  and denote the next period value of  $k$  as  $k'$ .

- (a) Write down the Bellman equation for the value function  $V(k)$
- (b) Using the method of undetermined coefficients find  $V(k)$
- (c) Find the optimal policy function  $k' = h(k)$

3. [20 points] Consider the nonlinear system of differential equations

$$\begin{cases} \dot{x} = -y + ax(x^2 + y^2) \\ \dot{y} = x + ay(x^2 + y^2) \end{cases}$$

where  $a$  is a parameter.

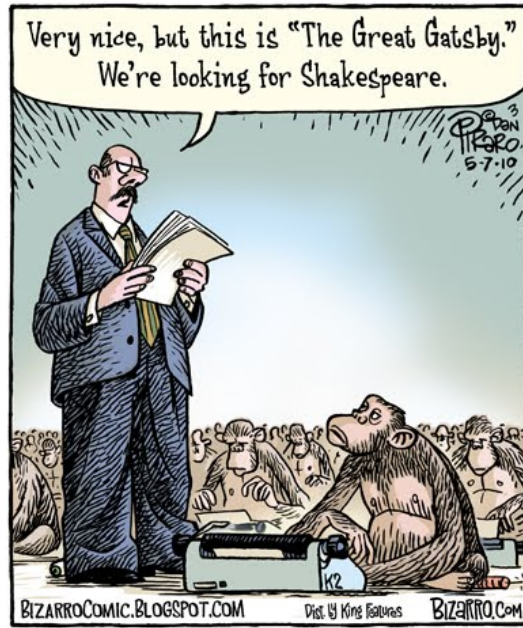
- (a) [5 points] Linearize the system and classify the steady-state solution
- (b) [10 points] Restore the nonlinear system and by changing the Cartesian into the polar coordinates show that the system becomes

$$\begin{cases} \dot{r} = ar^3 \\ \dot{\theta} = 1 \end{cases}$$

- (c) [5 points] Solve this system and draw the phase diagram for  $a < 0$ ,  $a = 0$ ,  $a > 0$ .

#### Stochastic calculus part

Here  $W_t$  always denotes the standard Wiener process.



1. [10 points] It is known that  $\text{Var}(X) = 16$ ,  $\text{Var}(Y) = 9$ ,  $\text{Cov}(X, Y) = -1$ ,  $\mathbb{E}(X) = \mathbb{E}(Y) = 0$ . Let's denote  $\hat{Y} = \mathbb{E}(Y | X)$  and  $\hat{X} = \mathbb{E}(X | Y)$ . It is also known that  $\mathbb{E}(\hat{X}^2) = 4$  and  $\mathbb{E}(\hat{Y}^2) = 1$ . Find  $\text{Var}(\hat{Y})$ ,  $\text{Cov}(\hat{X}, Y)$ ,  $\text{Cov}(\hat{Y}, Y)$ .
2. [10 points] Let's consider a Wiener process with drift,  $X_t = W_t + \mu t$ .
  - (a) Find a non-trivial martingale of the form  $M_t = e^{\beta X_t}$
  - (b) Let  $\tau$  be a stopping time, the first moment when  $X_t$  hits 2 or  $-1$ . Find the probability  $\mathbb{P}(X_\tau = 2)$

You may assume without proof that some version of Doob's theorem may be applied here.

3. [10 points] Is  $X_t = \cos W_t$  a martingale? If not, find any non-zero function  $f(t)$  such that  $Y_t = f(t)X_t$  is a martingale. Find the variance of  $Y_t$ .  
Hint: You may use the fact that  $\mathbb{E}(\cos W_t) = e^{-t/2}$ .
4. [10 points] In the framework of Black and Scholes model find the price at the time 0 of an asset which gives you the payoff  $S_T^2$  at the time  $T$ . Here  $S_t$  is the price of the underlying asset at time  $t$ .
5. [20 points] Consider the following stochastic differential equation

$$dX_t = -0.5e^{-2X_t}dt + e^{-X_t}dW_t,$$

with deterministic initial value  $X_0$ .

- (a) Is  $X_t$  a martingale?
- (b) Using the substitution  $Y_t = f(X_t)$  solve this differential equation. Hint: try to find a function  $f$  such that the term before  $dt$  cancels out.
- (c) Sketch the possible path of the process  $X_t$
- (d) Using basic facts about Wiener process find the limit  $\lim_{t \rightarrow \infty} \mathbb{P}(X_t \geq a)$  for all values of the parameter  $a$ .

## 6.4 marking scheme

1. 3 pts:

$$\text{Var}(\hat{Y}) = \mathbb{E}(\hat{Y}^2) - (\mathbb{E}(\hat{Y}))^2 = 1 - 0^2 = 1$$



3 pts:

$$\text{Cov}(\hat{X}, Y) = \mathbb{E}(\mathbb{E}(X | Y)Y) - \mathbb{E}(\hat{X}) \mathbb{E}(Y) = \mathbb{E}(\mathbb{E}(YX | Y)) - \mathbb{E}(X) \mathbb{E}(Y) = \text{Cov}(X, Y)$$

4 pts:

$$\text{Cov}(\hat{Y}, Y) = \dots = \text{Cov}(\hat{Y}, \hat{Y})$$

2.  $M_t = e^{-2\mu X_t}$  5 pts, probability — 5 pts,  $p = \frac{1 - \exp(2\mu)}{\exp(-4\mu) - \exp(2\mu)}$   
 3.  $X_t$  is not a martingale — 1 pt,

$$dY_t = \cos W_t f'(t) dt + f(t)(-\sin W_t dW_t + \frac{1}{2}(-\cos W_t) dt)$$

We obtain simple differential equation  $f'(t) - f(t)/2 = 0$ , we choose any solution, for example,  $f(t) = e^{t/2}$ .

$Y_t = e^{t/2} X_t$  or proportional — 4 pts, variance — 5 pts

$$\text{Var}(Y_t) = \mathbb{E}(Y_t^2) - (\mathbb{E}(Y_t))^2$$

We note that  $Y_t$  is a martingale by construction, so  $\mathbb{E}(Y_t) = Y_0 = 1$ .

So,  $\mathbb{E}(e^{t/2} \cos W_t) = 1$ . Hence  $\mathbb{E}(\cos W_t) = e^{-t/2}$ .

Let's recall from middle school that  $\cos^2 W_t = \frac{1 + \cos 2W_t}{2}$ .

We also note that  $2W_t \sim \mathcal{N}(0; 4t)$  and  $W_{4t} \sim \mathcal{N}(0; 4t)$ . In any expectation we may safely replace  $2W_t$  by  $W_{4t}$ .

$$\mathbb{E}(Y_t^2) = \mathbb{E}(e^t \cos^2 W_t) = \mathbb{E}\left(e^t \frac{1 + \cos 2W_t}{2}\right) = \frac{e^t}{2} + \frac{e^t}{2} \mathbb{E}(\cos 2W_t)$$

Where  $\mathbb{E}(\cos 2W_t) = \mathbb{E}(\cos(W_{4t})) = e^{-4t/2} = e^{-2t}$ .

Finally we obtain,

$$\text{Var}(Y_t) = (e^t + e^{-t} - 2)/2$$

4. Pricing formula — 2 pts, risk-neutral substitution — 2 pts, calculations — 6 pts.

Using the pricing formula  $X_0 = \mathbb{E}_{\mathbb{P}}[e^{-rT} X_T]$ :

$$X_0 = \mathbb{E}_{\mathbb{P}}[\exp(-rT) X_T] = \exp(-rT) \mathbb{E}_{\mathbb{P}}[S_T^2]$$

We substitute  $S_T = S_0 \exp((r - \sigma^2/2)T + \sigma \tilde{W}_T)$ :

$$\begin{aligned} X_0 &= \exp(-rT) \mathbb{E}_{\mathbb{P}} \left[ S_0^2 \exp(2(r - \sigma^2/2)T + 2\sigma \tilde{W}_T) \right] = \\ &= S_0^2 \exp(-rT) \exp(2(r - \sigma^2/2)T) \mathbb{E}_{\mathbb{P}} \left[ e^{2\sigma \tilde{W}_T} \right] \quad (10) \end{aligned}$$

We use the fact that  $\mathbb{E}[\exp(aW_t)] = \exp(a^2 t/2)$ , so:

$$X_0 = S_0^2 e^{-rT} \exp(2(r - \sigma^2/2)T) \exp(4\sigma^2 T/2) = S_0^2 \exp((2r + \sigma^2)T)$$

5. (a)  $X_t$  is not a martingale — 1 pt  
 (b) use of Ito's formula — 5 pts, equation  $f' = f$  — 5 pts, solution  $X_t = \ln(W_t + e^{X_0})$ . — 5 pts  
 (c) Key features: “jiggly” — 1 pt, blows down to minus infinity in finite time — 2 pts

(d) The limit is zero.

## 6.5 Retake, 08.02.2014

### Stochastic calculus part

1. [10 points] Is  $X_t = \sin W_t$  a martingale? If not, find any non-zero function  $f(t)$  such that  $Y_t = f(t)X_t$  is a martingale. Find the expected value  $\mathbb{E}(X_t)$
2. [10 points] In the framework of Black and Scholes model find the price of the asset, which pays you  $S_2/S_1$  at the fixed moment of time  $T = 2$
3. [10 points] Let  $\tau$  be a stopping time, the first moment when  $W_t$  hits 2 or  $-1$ .
  - (a) Find the probability  $\mathbb{P}(W_\tau = 2)$
  - (b) Find a martingale of the form  $X_t = W_t^2 + f(t)$ .
  - (c) Find  $\mathbb{E}(\tau)$
4. [10 points] The joint distribution of the random vector  $(X, Y)$  is given by its probability density function

$$f(x, y) = \begin{cases} ce^{x-y}, & \text{for } 0 \leq x, y \leq 1 \\ 0, & \text{otherwise} \end{cases}$$

where  $c$  is a normalization constant. Find  $\mathbb{E}(X | Y)$ .

5. [20 points] 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) Ignoring the initial conditions find solution of the form  $X_t = f(t) \cos W_t$  and  $Y_t = g(t) \sin W_t$
- (b) Modify your solution to take into account the initial conditions
- (c) Prove that for any solution  $D_t = X_t^2 + Y_t^2$  is nonstochastic

## 6.6 Answers and hints

1.  $f(t) = e^{t/2}$  or proportional,  $\mathbb{E}(X_t) = 0$ .
2. Using the pricing formula  $X_0 = \mathbb{E}_{\tilde{\mathbb{P}}} [e^{-rT} X_T]$ :

$$X_0 = \mathbb{E}_{\tilde{\mathbb{P}}} [\exp(-rT) X_T] = \exp(-2r) \mathbb{E}_{\tilde{\mathbb{P}}} [S_2/S_1]$$

We substitute  $S_T = S_0 \exp((r - \sigma^2/2)T + \sigma \tilde{W}_T)$ :

$$\begin{aligned} X_0 &= \exp(-2r) \mathbb{E}_{\tilde{\mathbb{P}}} [\exp(r - \sigma^2/2 + \sigma \tilde{W}_2 - \sigma \tilde{W}_1)] = \\ &= \exp(-2r) \exp(r - \sigma^2/2) \mathbb{E}_{\tilde{\mathbb{P}}} [\exp(\sigma \tilde{W}_2 - \sigma \tilde{W}_1)] \quad (11) \end{aligned}$$

The distribution of  $\tilde{W}_2 - \tilde{W}_1$  is similar to the distribution of  $\tilde{W}_1$  and is  $N(0; 1)$ . So, we simplify:

$$X_0 = \exp(-2r) \exp(r - \sigma^2/2) \mathbb{E}_{\tilde{\mathbb{P}}} [\exp(\sigma \tilde{W}_1)]$$

We use the fact that  $\mathbb{E}[\exp(aW_t)] = \exp(a^2t/2)$ , so:

$$X_0 = \exp(-2r) \exp(r - \sigma^2/2) \exp(\sigma^2/2) = \exp(-r)$$

3. Using Doob's theorem,  $\mathbb{E}(W_\tau) = 0$ , so  $\mathbb{P}(W_\tau = 2) = 1/3$ . Using Ito's lemma or otherwise  $X_t = W_t^2 - t$  is a martingale, so  $\mathbb{E}(X_\tau) = 0$  and  $\mathbb{E}(\tau) = 2$ .
4.  $\mathbb{E}(X | Y) = \int_0^1 xf(x | Y) dx$ . Here  $f(x, y)$  maybe factored, so  $X$  and  $Y$  are independent, and  $\mathbb{E}(X | Y) = \text{const.}$
5. See the solution of problem 8 from exam of 2008-2009 [on page 5](#)

## 7 2014-2015

### 7.1 Practice problems

These problems were not graded.

1. An enemy submarine is somewhere on the number line. The initial coordinate of the submarine is some unknown integer number. It is moving at some constant integer speed (units per minute).  
You can launch a torpedo each minute at any integer on the number line. If the the submarine is there, you hit it and it sinks. You have infinite number of torpedoes. You must sink this enemy sub.
  - (a) Draw a picture of number line and the submarine. Just for fun!
  - (b) Devise a strategy that is guaranteed to eventually hit the enemy submarine
2. Compare the power of two sets:  $A = \mathbb{Q}$  – the set of all rational numbers,  $B = \mathbb{Q}^2$  – the set of all possible pairs of rational numbers.
3. Using the fact that the Borel  $\sigma$ -algebra  $\mathcal{B}$  is the smallest  $\sigma$ -algebra containing all subsets of the form  $(-\infty; t]$  show that  $\mathbb{N} \in \mathcal{B}$ .
4. Let  $\Omega = \mathbb{R}$ . Find explicitly the smallest  $\sigma$ -algebra which contains the sets  $A = [0; 1]$  and  $B = [10; 100]$ .
5. Let  $X$  be uniform on  $[0; 1]$  and  $Y = 1_{X < 0.7} + 1_{X > 0.1}$ . Describe the  $\sigma$ -algebra  $\sigma(Y)$ . How many events  $\sigma(Y)$  contains? Is the set  $\sigma(X)$  countable?
6. How many different  $\sigma$ -algebras one may construct if  $\Omega$  contains three elements? Four?
7. We throw a coin infinite number of times. Let's define the sequence of random variables  $X_n$  such that  $X_n$  is equal to 1, if the result of  $n$ -th throw is tail, and 0 otherwise. We also define a bunch 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) Give two non-trivial (other than  $\Omega$  and  $\emptyset$ ) examples of event  $A$ , such that  $A \in \mathcal{F}_{2014}$ .
  - (b) Give two non-trivial examples of event  $A$ , such that  $A \notin \mathcal{F}_{2014}$ .
  - (c) Give two non-trivial examples of event  $A$ , such that  $A$  belongs to every  $\mathcal{H}_n$ .
  - (d) Which  $\sigma$ -algebras contains the event  $A = \{X_{37} > 0\}$ ?
  - (e) Which  $\sigma$ -algebras contains the event  $B = \{X_{37} > X_{2014}\}$ ?
  - (f) Which  $\sigma$ -algebras contains the event  $C = \{X_{37} > X_{2014} > X_{12}\}$ ?
  - (g) Simplify where possible:  $\mathcal{F}_{11} \cap \mathcal{F}_{25}$ ,  $\mathcal{F}_{11} \cup \mathcal{F}_{25}$ ,  $\mathcal{H}_{11} \cap \mathcal{H}_{25}$ ,  $\mathcal{H}_{11} \cup \mathcal{H}_{25}$ .
8. Veniamin throws a coin until three consecutive tails appear. Let the random variable  $T$  be the number of throws. Let  $\mathcal{F}_T$  be the  $\sigma$ -algebra of all events distinguishable by Veniamin.

- (a) Provide two non-trivial (not equal to  $\Omega$  or  $\emptyset$ ) examples of event  $A$  such that  $A \in \mathcal{F}_T$  but  $A \notin \sigma(T)$
- (b) Provide two non-trivial (not equal to  $\Omega$  or  $\emptyset$ ) examples of event  $A$  such that  $A \in \sigma(T)$
- (c) Is it true, that  $\sigma(T) \subset \mathcal{F}_T$ ?

## 7.2 Practice-solutions

- 1.
2. The set  $A$  and  $B$  have the same power.
- 3.
4. The  $\sigma$ -algebra contains  $8 = 2^3$  events: all combinations of  $A$ ,  $B$  and  $\mathbb{R}/(A \cup B)$ .
5.  $\sigma(Y) = \{\emptyset, \Omega, \{Y = 1\}, \{Y = 2\}\}$ ,  $\sigma(X)$  is not countable.

## 7.3 Hometask

1. Researcher Veniamin throws a fair dice until 6 appears. Let denote by  $T$  the total number of throws and by  $N$  the number of throws when 5 appeared. Find  $\mathbb{E}(N | T)$ ,  $\text{Var}(N | T)$ ,  $\mathbb{E}(N)$ ,  $\text{Var}(N)$  and  $\mathbb{E}(T | N)$ .
2. It is  $25^\circ\text{C}$  in Australia today. Each day the temperature goes one degree up or down with equal probability. Each day I will put the sum equal to the temperature in my piggy bank. So today I will put 25 roubles. I will stop my investment strategy when the temperature will reach  $15^\circ\text{C}$  or  $30^\circ\text{C}$  for the first time.



What will be the expected value of my account in my piggy bank?

3. Veniamin and Varvara are managers of two gladiators-vampires teams. Veniamin has 4 gladiators-vampires with initial strengths 1, 2, 3 and 4. Varvara has 3 gladiators-vampires with initial strengths 1, 3 and 5.

The competition between two teams is organised as a sequence of rounds. In each round two gladiators-vampires (one from each team) will meet and fight to the death. Varvara always selects the best gladiator from her team to fight in the next round.

When the gladiators of strengths  $a$  and  $b$  meet the first will win with probability  $a/(a+b)$ , the second — with probability  $b/(a+b)$ . The gladiators are vampires, so the strength of the winner will become  $a+b$ .

- (a) Let's denote by  $\tau$  the number of the final round. What is the maximum value of  $\tau$ ?
- (b) Let's denote by  $X_t$  the total strength of the Veniamin's team. Is  $X_t$  a martingale?
- (c) What is best strategy for Veniamin? What is the probability that Veniamin's team will win?
4. Consider the processes  $X_t = \int_0^t (sW_s)^3 dW_s$  and  $Y_t = \int_0^t W_s dW_s$ . Find  $\mathbb{E}(X_t)$ ,  $\text{Var}(X_t)$ ,  $\text{Cov}(X_t, Y_t)$
5. The process  $X_t$  is given by

$$dX_t = tW_t e^{W_t} dt + \sin(tW_t) dW_t, \quad X_0 = 1$$

Using Ito-Doebelin lemma find  $Z_0$  and  $dZ_t$  if  $Z_t = X_t^2 + t \cos(X_t)$

6. Solve the stochastic differential equation:

$$dX_t = X_t(1 - X_t) dt + X_t dW_t, \quad X_0 = 1$$

Some hints: you may find the substitution  $Y_t = \ln X_t$  useful.

7. In the framework of Black and Scholes model find the price at  $t = 0$  of the asset, which pays you 1\$ if  $S_{T-1} > 1$  and 0 otherwise. Here  $S_t$  denotes the price of a share at time  $t$ . The payment is made at the fixed moment of time  $T > 1$ .

## 7.4 Hometask-solution

1. If the total number of throws is  $T$  then the last throw has value 6. Each of the preceding  $(T - 1)$  throws may have a value from 1 to 5. So if  $T$  is considered fixed, then  $N$  has binomial distribution with  $n = T - 1$  and  $p = 1/5$ . It follows that  $\mathbb{E}(N | T) = \frac{T-1}{5}$  and  $\text{Var}(N | T) = \frac{4(T-1)}{25}$ .

Using tower property of conditional expectation

$$\mathbb{E}(N) = \mathbb{E}(\mathbb{E}(N | T)) = \mathbb{E}\left(\frac{T-1}{5}\right) = \frac{\mathbb{E}(T) - 1}{5}$$

Here  $T$  is geometric with  $p = 1/6$ , so  $\mathbb{E}(T) = 6$  and  $\mathbb{E}(N) = 1$ .

We use the following decomposition of variance:

$$\begin{aligned} \text{Var}(N) &= \mathbb{E}(\text{Var}(N | T)) + \text{Var}(\mathbb{E}(N | T)) = \\ &= \mathbb{E}\left(\frac{4(T-1)}{25}\right) + \text{Var}\left(\frac{T-1}{5}\right) = (\text{Var}(T-1) + 4\mathbb{E}(T-1))/25 \quad (12) \end{aligned}$$

As  $T$  is geometric  $\text{Var}(T) = (1-p)/p^2 = 30$ . And, hence,  $\text{Var}(N) = 2$ .

If  $N$  is fixed, then the total time  $T$  is equal to the following sum: from start to first five, from first five to second five, ..., from  $N$ -th five to six, so  $\mathbb{E}(T | N) = aN + b$ . From the properties of geometric distribution,  $b = 5$  (no five) and  $a = 5$  (no six).

2.  $X_0 = 25$ ,  $X_{t+1} = X_t + D_{t+1}$  is a martingale. The random variable  $X_\tau$  can take only the values 30 and 15. Applying the Doob's theorem we get  $\mathbb{E}(X_\tau) = 25$  and, hence,  $\mathbb{P}(X_\tau = 15) = 1/3$ .

Using the second martingale,  $X_t^2 - t$  and again Doob's theorem,  $\mathbb{E}(X_\tau^2) - \mathbb{E}(\tau) = X_0^2 = 625$ , and  $\mathbb{E}(\tau) = 50$ .

Using the third martingale,  $M_t = \sum_{i=0}^t X_i - 25(t+1)$ . Here we have  $(t+1)$  as there are  $(t+1)$  terms in  $\sum_{i=0}^t X_i$ . Using Doob's theorem,  $\mathbb{E}(M_\tau) = M_0 = 0$ , and, finally,  $\mathbb{E}(\sum_{i=0}^\tau X_i) = 25 \cdot 51 = 1275$ .

3.  $\tau \in \{3, 4, 5, 6\}$ ,  $X_t$  is a martingale. The random variable  $X_\tau$  can take only two values, 0 or  $1 + 2 + 3 + 4 + 1 + 3 + 5 = 19$ . According to the Doob's theorem,  $\mathbb{E}(X_\tau) = X_0 = 10$ . And hence  $\mathbb{P}(\text{Veniamin wins}) = \mathbb{P}(X_\tau = 19) = 10/19$ . The strategy does not matter.
4.  $\mathbb{E}(X_t) = 0$ ,  $\text{Var}(X_t) = 3t^{10}/2$ , and  $\text{Cov}(X_t, Y_t) = t^6/2$ .

The expected value

$$\mathbb{E}(W_t^{2k}) = t^k \cdot 1 \cdot 3 \cdot 5 \cdot \dots \cdot (2k-1)$$

may be useful with Ito's isometry.

5.

$$dZ_t = [\cos X_t + 2X_t t W_t e^{W_t} - t^2 W_t e^{W_t} \sin X_t + \sin^2(t W_t) - 0.5t \cos X_t \sin^2(t W_t)] dt + [\sin(t W_t)(2X_t - t \sin(X_t))] dW_t \quad (13)$$

6. Using the substitution  $Y_t = \ln X_t$  we obtain equation  $dY_t = (0.5 - X_t) dt + dW_t$ . And  $\ln X_t + \int_0^t X_s ds = 0.5t + W_t$ .

We exponentiate and then take integral

$$\int_0^t X_s ds = \ln \left( 1 + \int_0^t \exp(0.5s + W_s) ds \right)$$

Differentiate to obtain

$$X_t = \frac{\exp(0.5t + W_t)}{1 + \int_0^t \exp(0.5s + W_s) ds}$$

7.

$$X_0 = e^{-rT} F \left( \frac{\ln S_0 - (\sigma^2/2 - r)(T - 1)}{\sigma \sqrt{T - 1}} \right),$$

where  $F()$  is the cumulative probability function for standard normal distribution.

## 7.5 Exam, 27.12.2014

### Optimal control part

1. (10 points) Consider the nonlinear system of DE

$$\begin{cases} \dot{x}_1 = e^{x_1+x_2} - x_2 \\ \dot{x}_2 = -x_1 + x_1 x_2 \end{cases}$$

Determine the points of rest of the system, classify their type and stability and draw the local phase diagram at each of them with the found eigenvectors.

2. (10 points) Solve the optimal control problem

$$\int_0^T [pK(t) - wK(t) - cI^2(t)] dt \rightarrow \max$$

subject to  $\dot{K}(t) = I(t)$ ,  $K(0) = K_0 > 0$ ,  $K(T)$  not given,  $p > w > 0$ ,  $c > 0$ .

Also show that  $K(t) > 0$  for  $t \in [0; T]$  and  $\dot{K}(T) = 0$  (4 points for that part).

3. (20 points) Consider the optimal problem for the infinite horizon

$$\int_0^\infty e^{-rt} \left[ -\frac{1}{2}u^2 + xu - \frac{1}{2}x^2 \right] dt \rightarrow \max$$

subject to  $\dot{x} = u$ ,  $x(0) = x_0 > 0$  and  $1 < r < 2$ .

(a) (5 points) Write down the system of equations based on the current value Hamiltonian

(b) (3 points) Is the integrand a concave or a strictly concave function?

(c) (5 points) Reduce the necessary conditions down to a pair of linear DE involving only  $x$  and  $\lambda$

- (d) (3 points) Find all steady-states of the system
- (e) (4 points) Classify them

### Stochastic calculus part

Here  $W_t$  always denotes the standard Wiener process.

1. [10 points] Let  $\tau$  denote the first moment of time when  $|W_t| = 100$ .
  - (a) What is the distribution of  $W_\tau$ ?
  - (b) Are  $W_\tau$  and  $\tau$  independent?
  - (c) Assuming that some version of Doob's theorem may be applied find  $\mathbb{E}(e^{-2\tau})$ .

Hint: maybe  $\exp(2W_t - 2t)$  will help?

2. [10 points] The random variables  $X_1, X_2, \dots, X_n, \dots$  are independent uniformly distributed on  $[0; 1]$ . I am summing them until the first  $X_i$  greater than 0.5 is added. After this term I stop. Let's denote by  $S$  the total sum and by  $N$  — the number of terms added. Find  $\mathbb{E}(S | N)$ ,  $\text{Var}(S | N)$ ,  $\mathbb{E}(S)$

Hints: If  $U$  is uniform on  $[a; b]$  then  $\text{Var}(U) = (b - a)^2/12$ . If  $G$  has geometric distribution (the number of throws to get the first success) then  $\mathbb{E}(G) = 1/p$  where  $p$  is the probability of success.

3. [10 points] Find  $\text{Var} \left( \int_0^t W_s ds \right)$ .

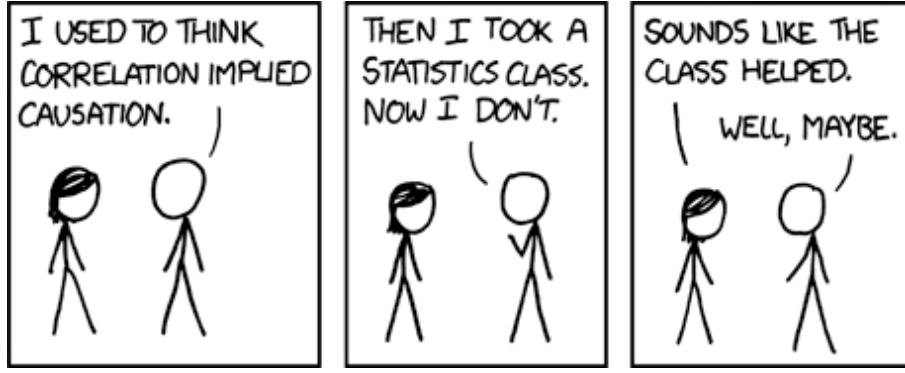
You may use the following guiding steps:

- (a) Find  $d(tW_t)$  in short and full form
  - (b) Find  $\mathbb{E} \left( 2tW_t \int_0^t s dW_s \right)$
  - (c) Find  $\mathbb{E} \left( \left( \int_0^t s dW_s \right)^2 \right)$
  - (d) Find  $\mathbb{E} \left( \int_0^t W_s ds \right)$
  - (e)  $(a - b)^2 = a^2 - 2ab + b^2$  :
4. [10 points] The risk-free interest rate is equal to 0.1. The volatility of the share is equal to  $\sigma = 1$ . You have an option to receive 1\$ two years later if the percentage change of price of the share,  $S_t$ , during the first year is less than during the second year. Assume the framework of the Black and Scholes model. What is the fair price of this option?
  5. [20 points] Solve the stochastic differential equation

$$dX_t = t dt + X_t dW_t, \quad X_0 = 1$$

You may use the following guiding steps:

- (a) Solve a less difficult stochastic differential equation,  $dY_t = -Y_t dW_t, Y_0 = 1$
- (b) Find  $dA_t$ , where  $A_t = X_t Y_t$
- (c) Find any deterministic function  $f(t)$  such that  $d(f(t)A_t)$  contains neither  $X_t$  nor  $A_t$
- (d) Using full form of  $d(f(t)A_t)$  find  $X_t$ . It may depend on some integrals :



## 7.6 Exam, 27.12.2014 - solution

1.  $W_\tau$  takes values 100 and  $-100$  with equal probabilities. Yes, independent.  $\mathbb{E}(e^{-2\tau}) = \frac{2}{e^{200} + e^{-200}}$
2.  $\mathbb{E}(S | N) = 0.25N + 0.5$ ,  $\text{Var}(S | N) = 0.25N/12$ ,  $\mathbb{E}(N) = 1/p = 2$ ,  $\mathbb{E}(S) = \mathbb{E}(\mathbb{E}(S | N)) = 1$ . One may also find the variance,  $\text{Var}(S) = 1/8 + 1/24 = 1/6$ .
3. By hints:

(a)  $d(tW_t) = t dW_t + W_t dt$

(b) Using Ito's isometry:

$$\begin{aligned} \mathbb{E} \left( 2tW_t \int_0^t s dW_s \right) &= 2t \mathbb{E} \left( \int_0^t 1 dW_s \int_0^t s dW_s \right) = 2t \text{Cov} \left( \int_0^t 1 dW_s, \int_0^t s dW_s \right) = \\ &= 2t \int_0^t \mathbb{E}(1 \cdot s) ds = t^3 \quad (14) \end{aligned}$$

(c)  $\mathbb{E} \left( \left( \int_0^t s dW_s \right)^2 \right) = t^3/3$  using Ito's isometry

(d)  $\mathbb{E} \left( \int_0^t W_s ds \right) = 0$

(e)  $\text{Var} \left( \int_0^t W_s ds \right) = t^3/3$

4. Event  $\left\{ \frac{S_1 - S_0}{S_0} < \frac{S_2 - S_1}{S_1} \right\}$  simplifies to  $S_1^2 < S_0 S_2$  and further simplifies to  $2\tilde{W}_1 - \tilde{W}_2 < 0$ .  
And

$$X_0 = e^{-0.2} \tilde{P}(2\tilde{W}_1 - \tilde{W}_2 < 0) = e^{-0.2}/2$$

5. By steps:

(a) Using the substitution  $U_t = \ln Y_t$ , one obtains

$$dU_t = -dW_t - \frac{1}{2}dt$$

And the solution  $Y_t = \exp(-W_t - t/2)$

(b) As  $A_t = X_t Y_t$  we have:

$$dA_t = X_t dY_t + Y_t dX_t + \frac{1}{2} 2dX_t dY_t$$



Finally

$$dA_t = Y_t(t - X_t)dt$$

(c)

$$d(f(t)A_t) = f'(t)A_t dt + f(t)dA_t = f'(t)X_t Y_t dt + f(t)Y_t(t - X_t)dt$$

To kill  $X_t$  in this expression we need to find a function  $f$  such that  $f'(t) - f(t) = 0$ . For example,  $f(t) = e^t$ .

(d) From previous point we have

$$d(e^t A_t) = e^t Y_t t dt$$

And

$$e^t A_t = e^0 A_0 + \int_0^t e^s Y_s s ds$$

From initial condition  $A_0 = 1$  and finally

$$X_t = \frac{1 + \int_0^t s \exp(-W_s + s/2) ds}{\exp(-W_t + t/2)}$$

## 8 2015-2016

### 8.1 Stochastic calculus homework

- Find the expected value of  $\mathbb{E}(\exp(aW_t))$ ,  $\mathbb{E}(1_{W_t \leq b})$ ,  $\mathbb{E}(\exp(aW_t) \cdot 1_{W_t \leq b})$  and  $\mathbb{E}(W_t 1_{W_t \leq b})$ . Naturally, you may use the standard normal cumulative distribution function  $F$  in your answer
- It is known that  $\mathbb{E}(Y | X) = 0$ . Which of the following quantities must be zero:  $\mathbb{E}(Y)$ ?  $\mathbb{E}(X)$ ?  $\text{Cov}(X, Y)$ ?  $\text{Cov}(X^2, Y)$ ?  $\text{Cov}(X, Y^2)$ ? Prove or provide a counter-example.
- Alisa and Bob throw a fair coin until either the sequence THTH or the sequence HTHH appears. Alisa wins if the sequence THTH appears first and Bob wins if the sequence HTHH appears first.

(a) What is the probability that Alisa will win?

(b) What is the expected duration of the game in tosses?

Hint: you may introduce a martingale from lecture or solve this problem without martingales at all

- Consider the process  $Y_t = \exp(2W_t - 2t)$ .

(a) Find  $dY_t$

(b) Find  $\int_0^t Y_u dW_u$

(c) Find  $\mathbb{E}(Y_t)$  and  $\text{Var}(Y_t)$

- Consider stochastic differential equation

$$dX_t = (a - bX_t)dt + c dW_t, \quad X_0 = x_0$$

(a) Solve this differential equation<sup>1</sup>.

(b) Find  $\mathbb{E}(X_t)$  and  $\text{Var}(X_t)$

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<sup>1</sup>The answer may contain an Ito integral that cannot be simplified.

6. In the framework of Black and Scholes model find the price at  $t = 0$  of the classic European call option by calculating corresponding expected value.  
European call option with strike price  $K$  is the right to buy at time  $t$  one share at price  $K$ . So, at time  $t$  it pays you  $S_t - K$  if  $S_t > K$  and zero otherwise.

## 8.2 Stochastic calculus homework – Solution

1. Let's remark that  $W_t \sim \mathcal{N}(0; t)$  and  $Z = W_t/\sqrt{t} \sim \mathcal{N}(0; 1)$ .

$$\mathbb{E}(\exp(aW_t)) = \mathbb{E}(\exp(a\sqrt{t}Z)) = \int_{-\infty}^{\infty} \exp(a\sqrt{t}z)f(z)dz = e^{a^2t/2}$$

$$\mathbb{E}(1_{W_t \leq b}) = F(b/\sqrt{t}), \mathbb{E}(\exp(aW_t) \cdot 1_{W_t \leq b}) = \dots, \mathbb{E}(W_t 1_{W_t \leq b}) = \dots$$

2. Short answers:

(a)  $\mathbb{E}(Y) = \mathbb{E}(\mathbb{E}(Y | X)) = 0$ .

(b) The value  $\mathbb{E}(X)$  can be non-zero, counterexample:  $X \sim N(42; 42)$ ,  $Y = 0 = \text{const.}$

(c)  $\text{Cov}(Y, f(X)) = \mathbb{E}(f(X)Y) - \mathbb{E}(Y)\mathbb{E}(f(X)) = \mathbb{E}(f(X)Y)$ .

$$\mathbb{E}(f(X)Y) = \mathbb{E}(\mathbb{E}(f(X)Y | X)) = \mathbb{E}(f(X)\mathbb{E}(Y | X)) = \mathbb{E}(0) = 0$$

So,  $\text{Cov}(Y, X) = \text{Cov}(Y, X^2) = 0$

(d)  $\text{Cov}(X, Y^2)$  may be non-zero. Let  $Y$  take the values  $-1, 1, -2$  and  $2$  with equal probability. And  $X = Y^2$ . In this case  $\text{Cov}(X, Y^2) = \text{Var}(X) > 0$ .

3. Let's denote the moment of time when the sequences  $A$  and  $B$  appear by  $N_A$  and  $N_B$  correspondingly. The game ends at moment  $N = \min\{N_A, N_B\}$ .

We need to find  $p_A = \mathbb{P}(N = N_A)$ ,  $p_B = \mathbb{P}(N = N_B)$  and  $\mathbb{E}(N)$ . We have one equation,  $p_A + p_B = 1$  so we need two more equations:

We build them from nothing :)

$$\begin{cases} \mathbb{E}(N_A) = \mathbb{E}(N) + \mathbb{E}(N_A - N) \\ \mathbb{E}(N_B) = \mathbb{E}(N) + \mathbb{E}(N_B - N) \end{cases}$$

Here  $\mathbb{E}(N_A) = 16 + 4 = 20$ ,  $\mathbb{E}(N_B) = 16 + 2 = 18$ .

Or

$$\begin{cases} \mathbb{E}(N_A) = \mathbb{E}(N) + p_A \mathbb{E}(N_A - N | N = N_A) + p_B \mathbb{E}(N_A - N | N = N_B) \\ \mathbb{E}(N_B) = \mathbb{E}(N) + p_A \mathbb{E}(N_B - N | N = N_A) + p_B \mathbb{E}(N_B - N | N = N_B) \end{cases}$$

$$\begin{cases} \mathbb{E}(N_A) = \mathbb{E}(N) + p_B \mathbb{E}(N_A - N | N = N_B) \\ \mathbb{E}(N_B) = \mathbb{E}(N) + p_A \mathbb{E}(N_B - N | N = N_A) \end{cases}$$

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Based on [http://projecteuclid.org/download/pdf\\_1/euclid.aop/1176994578](http://projecteuclid.org/download/pdf_1/euclid.aop/1176994578)

There is also a solution using Markov chains.

### 8.3 Exam, 12.01.2016

#### Stochastic calculus part

Here  $W_t$  always denotes the standard Wiener process.

1. [10 points] You throw a fair coin until «head» appears. Let's denote the result of the first toss by  $Y_1$  (0 for tail and 1 for head) and the total number of throws by  $N$ . Find  $\mathbb{E}(Y_1 | N)$ ,  $\text{Var}(Y_1 | N)$  and  $\mathbb{E}(N | Y_1)$
2. [10 points] Consider  $\tau$ , the first moment of time when the standard Wiener process will touch the barrier  $4y^2 = x + 1$ , or formally,  $\tau = \inf\{t \mid t \geq 0, |W_t| = 0.5\sqrt{t+1}\}$ . Find  $\mathbb{E}(\tau)$ .  
Hint: you may find the process  $M_t = W_t^2 - t$  useful, you may also suppose that technical conditions of Doob's theorem are satisfied

3. [10 points] Let

$$Y_t = \exp\left(-6t^3 + \int_0^t f(s) dW_s\right),$$

where  $f$  is some deterministic function.

- (a) Using Ito's lemma find  $dY_t$
  - (b) Find at least one function  $f$  such that  $Y_t$  is a martingale
4. [10 points] The risk-free interest rate is equal to 0.1. The volatility of the share is equal to  $\sigma = 1$ . You have an option to receive 1\$ two years later if the price growth during the second year is higher than 5%. Assume the framework of the Black and Scholes model. What is the fair price of this option?
  5. [20 points] Consider the stochastic differential equation

$$dX_t = X_t^3 dt + X_t^2 dW_t,$$

- (a) Apply Ito's lemma to  $Y_t = f(X_t)$
- (b) Find all the functions  $f$  that makes  $Y_t$  a martingale
- (c) Find all the solutions of the stochastic differential equation
- (d) Find the solution such that  $X_0 = 2$ .
- (e) Find the probability that the sample path of  $X_t$  will be continuous for  $t \in [0; \infty)$

#### Optimal control part

6. (10 points) Given the system of differential equations

$$\begin{cases} \dot{x} = \sin(x + y) \\ \dot{y} = \sin(x - y) \end{cases}$$

explore the behavior of its solutions in the neighborhood of the 2 points:  $A(\pi, \pi)$  and  $B(3\pi/2, 3\pi/2)$ . Draw the phase portraits near  $A$  and  $B$  based on the knowledge of their eigenvalues, eigenvectors where possible.

7. (10 points) Solve the bounded control problem: maximize

$$\int_0^1 (2x - u^2/2) dt$$

subject to constraints  $\dot{x} = u - x + t^2$ ,  $x(0) = 0$ ,  $-1 \leq u \leq 0$ . Verify that the maximizer has been found by applying one of the sufficient conditions.

8. (20 points) Solve so-called “limit pricing problem”. A homogeneous product is produced by a dominant firm along with the “competitive fringe” consisting of the  $x(t)$  identical firms ( $x$  is a continuous variable). Demand on good is given by  $f(p) \in C^2$ , where  $p(t)$  is the price,  $f'(p) < 0$  for  $p > 0$ . Let the dominant firm has a constant returns to scale technology with the marginal costs  $c = \text{const} > 0$ . Then  $(p - c)f(p)$  is a strictly concave function. The problem of the firm is to maximize the discounted stream of profits

$$\int_0^\infty e^{-rt}(p - c)(f(p) - x) dt$$

(each fringe firm produces only one unit of good) subject to constraint  $\dot{x} = k(p - \bar{p})$  where  $k$  is some number,  $\bar{p}$  is the equilibrium price and  $r > 0$ . Also  $x(0) = x_0$ .

- Application of the current value Hamiltonian is required here. Derive the system of the first-order conditions.
- By eliminating the Lagrange multiplier reduce the system to 2 equations with respect to  $(x, p)$ . Check that  $H_{pp} < 0$ .
- Show that if the dominant firm operates at the price level  $\bar{p} = c$  then the fringe firms supply the entire market in the equilibrium.
- Let the equilibrium price  $\bar{p}$  be slightly above  $c$ . By evaluating the derivative  $\frac{\partial x^s}{\partial \bar{p}}$  at  $\bar{p} = c$  show that the dominant firm's market share becomes positive if  $\bar{p}$  is slightly above  $c$  ( $x^s$  is the equilibrium number of the fringe firms).

## 8.4 Solution, exam 12.01.2016

1. If we know the value  $N$  then we know the value of  $Y_1$ , so  $\text{Var}(Y_1 | N) = 0$  and

$$\mathbb{E}(Y_1 | N) = \begin{cases} 0, & \text{if } N > 1; \\ 1, & \text{if } N = 1 \end{cases}$$

$$\mathbb{E}(N | Y_1) = \begin{cases} 1, & \text{if } Y_1 = 1; \\ 1 + 2, & \text{if } Y_1 = 0 \end{cases}$$

Or, simply,  $\mathbb{E}(N | Y_1) = 3 - 2Y_1$

2. We check that  $M_t$  is a martingale:  $dM_t = -dt + 2W_t dW_t + \frac{1}{2}2 dt = 2W_t dW_t$ . And we apply Doob's theorem:

$$\mathbb{E}(W_\tau^2 - \tau) = \mathbb{E}(M_\tau) = \mathbb{E}(M_0) = 0$$

So,  $\mathbb{E}(W_\tau^2) = \mathbb{E}(\tau)$

From the definition of  $\tau$ ,  $W_\tau^2 = (\tau + 1)/4$ . We get the equation

$$\mathbb{E}(\tau) = \mathbb{E}(\tau + 1)/4$$

And  $\mathbb{E}(\tau) = 1/3$

Based on <http://www-stat.wharton.upenn.edu/~shepp/publications/14.pdf>.

3. Let's write the process  $Y_t$  as  $Y_t = \exp(Z_t)$  where  $Z_t = -6t^3 + \int_0^t f(s) dW_s$ . So,  $dY_t = \exp(Z_t) dZ_t + \frac{1}{2} \exp(Z_t) (dZ_t)^2$ .

We find  $dZ_t$ :

$$dZ_t = -18t^2 dt + f(t) dW_t$$

So,  $(dZ_t)^2 = f^2(t) dt$  and

$$dY_t = \exp(Z_t)(-18t^2 dt + f(t) dW_t) + \frac{1}{2} \exp(Z_t) f^2(t) dt$$

To cancel the term before  $dt$  one should have

$$-18t^2 + \frac{1}{2} f^2(t) = 0$$

Possible solutions are  $f(t) = 6t$  and  $f(t) = -6t$

4. We should find the discounted expected price:

$$X_0 = e^{-2r} \tilde{\mathbb{P}}(S_2/S_1 > 1.05) = e^{-2r} \tilde{\mathbb{P}}(\exp((r - \sigma^2/2) + \sigma(\tilde{W}_2 - \tilde{W}_1)) > 1.05)$$

We remark that  $\tilde{W}_2 - \tilde{W}_1 \sim N(0; 1)$  under  $\tilde{\mathbb{P}}$ . So

$$X_0 = e^{-2r} \tilde{\mathbb{P}}(N(0; 1) > (\ln 1.05 - r + \sigma^2/2)/\sigma) = e^{-2r} F((r - \sigma^2/2 - \ln 1.05)/\sigma) = e^{-0.2} F(-0.45)$$

5. Step by step

(a) Apply Ito's lemma:

$$dY_t = f'(X_t) dX_t + \frac{1}{2} f''(X_t) (dX_t)^2 = f' \cdot (X_t^3 dt + X_t^2 dW_t) + \frac{1}{2} f'' \cdot X_t^4 dt$$

(b) To cancel the term before  $dt$  the following condition must be satisfied

$$f' \cdot X_t^3 + \frac{1}{2} f'' \cdot X_t^4 = 0$$

Let's denote  $f'$  by  $g$ , so  $g + g' \cdot x/2 = 0$ . This equation may be solved by separation of variables:

$$-2 \frac{dx}{x} = \frac{dg}{g}$$

The general solution is  $g(x) = cx^{-2}$ , so the general solution for  $f$  is

$$f(x) = c_1 x^{-1} + c_2$$

(c) To find all the solutions we use the simplest possible  $f$ ,  $f(x) = x^{-1}$ . In this case

$$dY_t = 0 dt + f' \cdot X_t^2 dW_t = -dW_t$$

So,  $Y_t = Y_0 - W_t$  and

$$X_t = \frac{1}{c - W_t}$$

- (d) If  $X_0 = 2$  than  $X_t = 1/(0.5 - W_t)$
- (e) The probability that  $W_t$  will forever stay below 0.5 is zero, so the probability that  $X_t$  will have continuous sample path for all  $t$  is also zero.

## 8.5 Retake, 15.02.2016

### Stochastic calculus part

Here  $W_t$  always denotes the standard Wiener process.

- [10 points] You throw a fair coin infinite number of times. Let's denote the result of the second toss by  $Y_2$  (0 for tail and 1 for head) and the number of throws to get the first «head» by  $N$ . Find  $\mathbb{E}(Y_2 | N)$ ,  $\text{Var}(Y_2 | N)$  and  $\mathbb{E}(N | Y_2)$
- [10 points] The process  $Y_t$  is given by  $Y_t = 2W_t + 5t$ . The stopping time  $\tau$  is given by  $\tau = \min\{t \mid Y_t^2 = 100\}$ . Find the distribution of the random variable  $Y_\tau$  and the expected value  $\mathbb{E}(\tau)$ .  
Hint: you may find the martingales  $a^{Y_t}$  and  $Y_t - f(t)$  useful
- [10 points] Let  $X_0 = 2016$  and  $dX_t = 2t dt + t^2 dW_t$ . Find  $\mathbb{E}(X_t)$  and  $\text{Var}(X_t)$ .
- [10 points] The risk-free interest rate is equal to 0.1. The volatility of the share is equal to  $\sigma = 1$ . The price of a share at  $t = 0$  is  $S_0 = 100$ . You have an option to receive 1\$ **two** years later if the price of the share after **one** year is more than 105. Assume the framework of the Black and Scholes model. What is the fair price of this option?
- [20 points] Consider the stochastic differential equation

$$dX_t = 8W_t^2 X_t dt + 4W_t X_t dW_t, \text{ where } X_0 = 1$$

- Apply Ito's lemma to  $Y_t = \ln X_t$
- Find the solution of the initial stochastic differential equation

### Optimal control part

- Find extremals that provide the highest or lowest values of the following integral

$$J(y) = \int_1^e \left[ \frac{1}{2} x(y')^2 + \frac{2yy'}{x} - \frac{y^2}{x^2} \right] dx$$

with the boundary values  $y(1) = 1$ ,  $y(e) = 2$ .

- (10 points) Find the extremal(s).
  - (10 points) Let  $\tilde{y}(x)$  be the extremal you have found. Let  $h(x) \in C^1$  and  $h(1) = h(e) = 0$  ( $h(x)$  is not identically zero). Prove that  $J(\tilde{y} + h) - J(\tilde{y}) > 0$ .
- Consider Ramsey's model. Maximize the integral  $I = \int_0^\infty [u(c) - B] dt$  subject to  $\dot{k} = f(k) - c - \delta k$ ,  $k(0) = k_0$ . Function  $u(c)$  monotonically increases and tends to  $B$  at the infinity, moreover  $I$  converges.

- (5 points) Derive Ramsey's Law  $\frac{d}{dt} u'(c) = u'(c)[\delta - f'(k)]$ .
- (5 points) Let

$$u(c) = \begin{cases} 2c - \frac{c^2}{B}, & \text{for } c \leq B \\ B, & \text{otherwise} \end{cases}$$

Production function  $f(k) = \alpha k$  and  $\alpha > \delta$ . Find the optimal solutions  $c^*, k^*$ . Do these solutions necessarily have an economic sense?

8. (10 points) Solve the problem on the bounded optimal control  $\int_0^T (1 - \beta - u)x dt \rightarrow \max$ , subject to  $\dot{x} = \alpha x u$ ,  $x(0) = x_0$ ,  $0 \leq u \leq 1$ . In this problem  $\alpha > 0$  and  $0 < \beta < 1$ .

## 8.6 Retake, solution

1.

$$\mathbb{E}(Y_2 | N) = \begin{cases} 0.5, & \text{if } N = 1; \\ 1, & \text{if } N = 2; \\ 0, & \text{if } N > 2; \end{cases}$$

$$\text{Var}(Y_2 | N) = \begin{cases} 0.25, & \text{if } N = 1; \\ 0, & \text{if } N > 1; \end{cases}$$

$$\mathbb{E}(N | Y_2) = \begin{cases} 0.5 \cdot 1 + 0.5 \cdot (2 + 1/0.5), & \text{if } Y_2 = 0 \\ 0.5 \cdot 1 + 0.5 \cdot 2, & \text{if } Y_2 = 1 \end{cases}$$

2. We find that

$$X_t = 2016 + t^2 + \int_0^t u^2 dW_u$$

So  $\mathbb{E}(X_t) = 2016 + t^2$  and  $\text{Var}(X_t) = t^5/5$ .

## 9 2016-2017

### 9.1 Hometask

1. Consider the two independent Brownian motions,  $(W_t)$  and  $(V_t)$ . Which of the following processes is Brownian motion:

(a)  $Z_t = \frac{1}{2}W_t + \frac{1}{2}V_t$

(b)  $Q_t = \frac{1}{\sqrt{2}}W_t + \frac{1}{\sqrt{2}}V_t$

2. Let  $Y_t = \int_0^t (W_u + u)^2 dW_u$ . Find  $\mathbb{E}(Y_t)$  and  $\text{Var}(Y_t)$ .
3. James Bond plays in a casino. At every bet he wins one pound with probability 0.5, loses one pound with probability 0.4 or wins nothing with probability 0.1. His initial fortune is  $X_0 = 10$  pounds. He stops playing if he goes bankrupt or if he achieves the fortune of 300 pounds (airline ticket price from London to Moscow).

(a) Find the constant  $a$  such that  $M_t = a^{X_t}$  is a martingale.

(b) What is the probability that James Bond will win enough to buy the ticket?

4. Let  $R_t$  be the exchange rate at time  $t$ . We suppose that  $dR_t = \mu R_t dt + \sigma R_t dW_t$ . Consider the inverse exchange rate  $I_t = 1/R_t$ . Find the expression for  $dI_t$ . The expression should not contain  $R_t$ .
5. It is known that  $M_t$  is a martingale. We also know that in short-hand notation  $(dM_t)^2 = dt$ . What can we say about the process  $Y_t = M_t^2 - t + 2017$ ?

6. Solve the stochastic differential equation

$$dX_t = \frac{-1}{1-t} X_t dt + dW_t, \quad X_0 = 0 \quad (15)$$

You may use or not use the following hints:

- (a) The correct answer will contain the integral  $\int_0^t \frac{1}{1-u} dW_u$  that cannot be simplified.
- (b) Solve the ordinary differential equation

$$dY_t = \frac{-1}{1-t} Y_t dt, \quad Y_0 = 1 \quad (16)$$

- (c) Represent  $X_t$  as  $X_t = Y_t \cdot Z_t$  and find the equation for  $dZ_t$ . Find the expression for  $Z_t$ .
7. Consider the framework of the Black and Scholes model. Let  $\mathbb{P}$  be the original probability measure and  $\tilde{\mathbb{P}}$  be the risk-neutral probability measure. Provide an example of three events  $A$ ,  $B$  and  $C$  such that  $\mathbb{P}(A) > \tilde{\mathbb{P}}(A)$ ,  $\mathbb{P}(B) < \tilde{\mathbb{P}}(B)$ ,  $\mathbb{P}(C) = \tilde{\mathbb{P}}(C)$ .
8. Consider the framework of the Black and Scholes model. The asset pays you 1 dollar at fixed time  $T$  if and only if the price of a share  $S_T$  is above the strike-price  $K$ . Find the current price  $X_0$  of this asset.

## 9.2 ht, solution

Solution by Anastasia Andreeva:

1. (a)

$$Z_t = \frac{1}{2} W_t + \frac{1}{2} V_t$$

$\text{Var}(Z_t - Z_s) = \text{Var}[0.5 \cdot (W_t - W_s + V_t - V_s)] = \frac{1}{4} \text{Var}(W_t - W_s) + \frac{1}{4} \text{Var}(V_t - V_s) = \frac{1}{2}(t-s)$   
 Thus,  $Z_t - Z_s \sim \mathcal{N}(0, \frac{t-s}{2})$ , therefore,  $Z_t$  is not a Brownian motion.

(b)

$$Q_t = \frac{1}{\sqrt{2}} W_t + \frac{1}{\sqrt{2}} V_t$$

Let's check all the conditions:

- i.  $Q_0 = \frac{1}{\sqrt{2}}(W_0 + V_0) = 0$
- ii.  $\mathbb{P}(Q_t \text{ trajectory is continuous}) = 1$  since  $W_t$  and  $V_t$  correspond to this condition
- iii.  $Q_t - Q_s = \frac{1}{\sqrt{2}}(W_t - W_s) + \frac{1}{\sqrt{2}}(V_t - V_s)$  is independent on  $\mathcal{F}_s$  since  $W_t - W_s$  and  $V_t - V_s$  are independent on  $\mathcal{F}_s$
- iv.  $\mathbb{E}(Q_t - Q_s) = \frac{1}{\sqrt{2}} \mathbb{E}(W_t - W_s) + \frac{1}{\sqrt{2}} \mathbb{E}(V_t - V_s) = 0$   
 $\text{Var}(Q_t - Q_s) = \text{Var}\left(\frac{1}{\sqrt{2}} \cdot (W_t - W_s + V_t - V_s)\right) = \frac{1}{2} \text{Var}(W_t - W_s) + \frac{1}{2} \text{Var}(V_t - V_s) = t - s$  Thus,  $Q_t - Q_s \sim \mathcal{N}(0, t - s)$
- v.  $Q_t$  is measurable relative to  $\mathcal{F}_t$

Thus,  $Q_t$  is a Brownian motion.



2.

$$Y_t = \int_0^t (W_u + u)^2 dW_u$$

$Y_t$  is a martingale because it is a stochastic integral, so  $\mathbb{E}(Y_t) = \mathbb{E}(Y_0) = 0$ .

$$\mathbb{E}(W_u^4) = 3u^2, \mathbb{E}(W_u^2) = u, \mathbb{E}(W_u^3) = \mathbb{E}(W_u) = 0$$

$$\begin{aligned} \text{Var}(Y_t) &= \int_0^t \mathbb{E}(W_u + u)^4 du = \int_0^t \mathbb{E}(W_u^4 + 4W_u^3u + 6W_u^2u^2 + 4W_uu^3 + u^4) du = \\ &= \int_0^t (3u^2 + 6u^3 + u^4) du = u^3 + \frac{3u^4}{2} + \frac{u^5}{5} \Big|_0^t = t^3 + \frac{3t^4}{2} + \frac{t^5}{5} \quad (17) \end{aligned}$$

3. (a)  $\mathbb{E}(M_{t+1} | \mathcal{F}_t) = \mathbb{E}(a^{X_{t+1}} | \mathcal{F}_t) = 0.5a^{X_{t+1}} + 0.4a^{X_t-1} + 0.1a^{X_t} = a^{X_t}(0.5a + 0.4a^{-1} + 0.1)$   
 $0.5a + 0.4a^{-1} + 0.1 = 1 \Rightarrow a^2 - 1.8a + 0.8 = 0 \Rightarrow a_1 = 1, a_2 = 0.8$   
 $a \neq 1$  otherwise  $M_t = 1$  for all  $t$ . So,  $a = 0.8$ .

- (b) James Bond will get 300 with probability  $p$  and lose all money with probability  $(1 - p)$ .  
 $\tau$  is the stopping moment (win or lose).

According to Doob's theorem,  $\mathbb{E}(M_\tau) = \mathbb{E}(M_0) = 0.8^{10}$ .

At the same time  $\mathbb{E}(M_\tau) = \mathbb{E}(0.8^{X_\tau}) = p \cdot 0.8^{300} + (1 - p) \cdot 0.8^0 = 0.8^{10}$

Then  $p = \frac{1 - 0.8^{10}}{1 - 0.8^{300}} \approx 0.89$

Thus, the answer is 89%.

4. I will use the Ito's formula:

$$(dR_t)^2 = \sigma^2 R_t^2 dt$$

$$\begin{aligned} dI_t &= -\frac{1}{R_t^2} dR_t + \frac{1}{R_t^3} (dR_t)^2 = -\frac{1}{R_t^2} (\mu R_t dt + \sigma R_t dW_t) + \frac{\sigma^2}{R_t} dt = \\ &= \frac{1}{R_t} ((\sigma^2 - \mu) dt - \sigma dW_t) = I_t ((\sigma^2 - \mu) dt - \sigma dW_t) \quad (18) \end{aligned}$$

5.

$$dY_t = 2M_t dM_t - dt + \frac{1}{2} 2 dt = 2M_t dM_t$$

Since  $M_t$  is a martingale  $dM_t = A_t dW_t$ . So  $dY_t = 2M_t A_t dW_t$ .

Since the expression does not include  $dt$ ,  $Y_t$  is a martingale.

6.

$$dX_t = -\frac{1}{1-t} X_t dt + dW_t, X_0 = 0$$

(a)

$$dY_t = -\frac{1}{1-t} Y_t dt, Y_0 = 1$$

$$\frac{dY_t}{Y_t} = -\frac{dt}{1-t}$$

$$\ln|Y_t| = \ln|1-t| + C_0$$

$$Y_t = C(1-t), Y_0 = C = 1 \Rightarrow Y_t = 1-t$$

(b)

$$\begin{aligned}
X_t &= Y_t Z_t \\
dX_t &= -\frac{X_t}{1-t} dt + dW_t = Z_t dY_t + Y_t dZ_t = -\frac{Z_t Y_t}{1-t} dt + Y_t dZ_t = -\frac{X_t}{1-t} dt + (1-t) dZ_t \\
dW_t &= (1-t) dZ_t \Rightarrow dZ_t = \frac{dW_t}{1-t} \Rightarrow Z_t = Z_0 + \int_0^t \frac{dW_u}{1-u}
\end{aligned}$$

(c)

$$\begin{aligned}
X_t &= Y_t Z_t = (1-t) \left( Z_0 + \int_0^t \frac{dW_u}{1-u} \right), X_0 = 0 = Z_0 \\
X_t &= (1-t) \int_0^t \frac{dW_u}{1-u}
\end{aligned}$$

7.  $W_t$  is a Brownian motion for  $P$ .  $Y_t = W_t + \frac{\mu-r}{\sigma}t$  is a Brownian motion for  $\tilde{P}$ .

If  $\mu > r$ , then  $Y_t > W_t$  and  $\tilde{\mathbb{P}}(Y_t > 0) = \mathbb{P}(W_t > 0) = \mathbb{P}(Y_t > \mu t) < \mathbb{P}(Y_t > 0)$ .

If  $\mu < r$ , then  $Y_t < W_t$  and  $\tilde{\mathbb{P}}(Y_t > 0) > \mathbb{P}(Y_t > 0)$ .

If  $\mu = r$ , then  $W_t = Y_t$  and  $\mathbb{P}(W_t > 0) = \tilde{\mathbb{P}}(W_t > 0)$ .

8.

$$X_T = \begin{cases} 1, & \text{if } S_T > K \\ 0, & \text{otherwise} \end{cases}$$

$$X_0 = e^{-rT} \mathbb{E}_{\tilde{P}}(X_T \mid \mathcal{F}_0) = e^{-rT} \tilde{\mathbb{P}}(S_T > K \mid \mathcal{F}_0) = e^{-rT} \tilde{\mathbb{P}}(S_0 e^{(r-0.5\sigma^2)T + \sigma \tilde{W}_T} > K \mid \mathcal{F}_0)$$

$$\tilde{W}_T > \frac{\ln \frac{K}{S_0} - \left(r - \frac{\sigma^2}{2}\right) T}{\sigma}$$

Further, we standardize  $\tilde{W}_T$ :

$$\frac{\tilde{W}_T}{\sqrt{T}} > \frac{\ln \frac{K}{S_0} - \left(r - \frac{\sigma^2}{2}\right) T}{\sigma \sqrt{T}}$$

Thus,

$$X_0 = e^{-rT} \tilde{P} \left( \frac{\tilde{W}_T}{\sqrt{T}} > \frac{\ln \frac{K}{S_0} - \left(r - \frac{\sigma^2}{2}\right) T}{\sigma \sqrt{T}} \right) = e^{-rT} \left( 1 - \Phi \left( \frac{\ln \frac{K}{S_0} - \left(r - \frac{\sigma^2}{2}\right) T}{\sigma \sqrt{T}} \right) \right)$$

### 9.3 exam, 10.01.2017

#### Stochastic calculus part

Here  $W_t$  always denotes the standard Wiener process.

1. (10 points) You throw a standard fair die  $n$  times. Let  $X$  be the number of «fives» in the first  $(n-1)$  throws and  $Y$  — the number of «fives» in the last  $(n-1)$  throws.

For  $n \geq 3$  calculate  $\mathbb{E}(Y \mid X)$ ,  $\mathbb{E}(X \mid Y)$ ,  $\text{Var}(Y \mid X)$ .

2. (10 points) Find a constant  $b$  such that  $Y_t = \int_0^t W_u^3 du + bW_t^5$  is a martingale.

3. (10 points) The process  $X_t$  evolves according to the formula

$$X_t = 1 - t + (1 - t) \int_0^t \frac{1}{1 - u} dW_u$$

- (a) Is  $X_t$  a martingale?
  - (b) Find  $\mathbb{E}(X_t)$ ,  $\text{Var}(X_t)$  and  $\text{Cov}(W_t, X_t)$
  - (c) Draw  $\mathbb{E}(X_t)$  and  $\text{Var}(X_t)$  as functions of  $t$
  - (d) Draw two possible trajectories of  $X_t$
4. (10 points) Find the price of the «Asset-or-nothing» call option at time  $t = 0$  in the framework of Black and Scholes model. The risk-free interest rate is equal to  $r$ . The volatility of the share is equal to  $\sigma$ . The current share price is  $S_0$ . The «Asset-or-nothing» call option pays you at fixed time  $T$  the sum  $S_T$  if  $S_T$  is higher than the strike price  $K$  or nothing otherwise.  
Hint: the correct answer will contain the normal cumulative distribution function  $F(\cdot)$ .
5. (20 points) Interest rate evolves according to the stochastic differential equation

$$dr_t = -\lambda(r_t - c) dt + \sigma dW_t$$

where  $r_0$ ,  $c$ ,  $\lambda$  and  $\sigma$  are some positive constants.

Solve this stochastic differential equation.

You may use or not use the following hints:

- (a) Obtain a stochastic differential equation for  $X_t = r_t - c$ .
- (b) Solve the ordinary differential equation  $dY_t = -\lambda Y_t dt$ ,  $Y_0 = 1$
- (c) Represent  $X_t$  as  $X_t = Y_t \cdot Z_t$  and find the equation for  $dZ_t$ .
- (d) Solve the equation for  $Z_t$ .
- (e) The correct answer for  $r_t$  will contain an Ito's integral that cannot be simplified.

### Optimal control part

6. (10 points) Solve the bounded control problem:

$$\int_0^T (u - x)^2 dt \rightarrow \min$$

subject to  $\dot{x} = \frac{1}{2}(u - x)$ ,  $x(0) = 1$ ,  $|u| \leq 1$ ,  $T > 0$ .

7. (10 points) Find the extremals for the calculus of variations problem:

$$\int_0^1 \frac{1}{2} \dot{x}^2 + x \dot{x} + x dt$$

when both endpoint values  $x(0)$  and  $x(1)$  can be chosen freely.

8. (20 points) Costs of the farmer's production  $C(x, y)$  depends on the output  $y(t)$  and the fertility of soil  $x(t)$  by the formula  $C = y^2 + \frac{1}{\sqrt{x}}$ . This industry is perfectly competitive and the price of the harvest per unit is  $p$ . Fertility changes over time by the dynamic law  $\dot{x} = B - \alpha y$ , where  $p\alpha > 2B > 0$ , and  $x(0) > 0$ . Constant  $B$  is defined by the government subsidy. Profit of the firm is discounted with the rate  $r > 0$ .

- (a) Write down the problem of maximizing the stream of discounted profit over the infinite time horizon.
- (b) Write down the system of first order conditions using the current value Hamiltonian. Draw the phase portrait in  $(x, y)$  coordinate system, in which  $x$  – axis is drawn horizontally. Find the steady-state  $(x_s, y_s)$  if it exists, classify it using Jacobian. With the help of the arrows provide the sketch of the dynamic paths of the system.
- (c) Find the sign of  $\partial x_s / \partial p$ . What justification of this sign can you provide from the economic point of view?

## 9.4 exam, solution

1.

$$\mathbb{E}(Y | X) = \frac{n-2}{n-1}X + \frac{1}{6}$$

$$\mathbb{E}(X | Y) = \frac{n-2}{n-1}Y + \frac{1}{6}$$

2. Take  $dY_t$ , kill term before  $dt$ ,  $b = -0.1$ .

$$dY_t = (W_t^3 + 10bW_t^3) dt + 5bW_t^4 dW_t$$

3. The process  $X_t$  is not a martingale as  $\mathbb{E}(X_t) = 1 - t$ .

$$\text{Var}(X_t) = (1-t)^2 \mathbb{E}(I^2) = (1-t)^2 \int_0^t \frac{1}{(1-u)^2} du = t(1-t)$$

$$\text{Cov}(W_t, X_t) = (1-t) \cdot \left( \int_0^t dW_u \cdot \int_0^t \frac{1}{1-u} dW_u \right) = (1-t) \mathbb{E} \left( \int_0^t \frac{1}{1-u} du \right) = (t-1) \ln(1-t)$$

4.

$$X_0 = e^{-rT} \tilde{\mathbb{E}}(S_T \cdot 1_{S_T > K})$$

5.

$$dX_t = dr_t = -\lambda X_t dt + \sigma dW_t$$

Solving ODE we obtain  $Y_t = e^{-\lambda t}$ .

$$dX_t = Y_t dZ_t + Z_t dY_t + dY_t dZ_t$$

Equation for  $Z_t$ :

$$dZ_t = e^{\lambda t} \sigma dW_t$$

Just recover the full form:

$$Z_t = Z_0 + \sigma \int_0^t e^{\lambda u} dW_u$$

Finally,

$$r_t = e^{-\lambda t} \left( r_0 - c + \sigma \int_0^t e^{\lambda u} dW_u \right) + c$$

## 10 2017-2018

### 10.1 Hometask

1. Let  $Y = 1_{W_3 \leq 2}$ . Find  $\mathbb{E}(W_5 \cdot Y)$ ,  $\text{Var}(W_5 \cdot Y)$ ,  $\text{Cov}(W_5, Y)$ ,  $\text{Cov}(W_5, W_5 \cdot Y)$ .
2. At time  $n = 0$  I have one apples and one banana. At each moment of time I choose one of all my fruits randomly with equal probabilities. I eat it and buy two more of the same kind. For example, if I choose banana I will eat it and buy two bananas more. I repeat the process of choosing, eating and buying fruits indefinitely. Let  $A_n$  and  $B_n$  be the number of apples and bananas after  $n$  rounds.
  - (a) Find non-trivial function  $f$  such that  $M_n = f(n) \cdot A_n$  is a martingale.
  - (b) Let  $\tau$  be the moment when the first banana is chosen. Assuming that Doob's theorem is applicable find  $\mathbb{E}(1/(\tau + 2))$ .
3. Find all constants  $a$  such that  $Y_t = 42 + W_t^7 + a \int_0^t W_u^5 du + \int_0^t u^2 \cos W_u dW_u$  is a martingale. Find  $\mathbb{E}(Y_t)$ .
4. Consider the framework of the Black and Scholes model. The asset pays you 1 dollar at fixed time  $T$  if and only if

$$\frac{S_T}{S_{T/2}} > \frac{S_{T/2}}{S_0}.$$

Find the current price  $X_0$  of this asset.

5. Solve the stochastic differential equation and find  $\mathbb{E}(X_t)$  and  $\text{Var}(X_t)$

$$dX_t + aX_t dt = bdt + cdW_t;$$

You are free to use or not to use the following guiding steps:

- (a) Find  $dY_t$  for  $Y_t = \exp(\gamma t)X_t$ ;
- (b) Find the value of  $\gamma$  such that in  $dY_t$  the term before  $dt$  is non-random.
- (c) Solve the equation for  $Y_t$  and then find  $X_t$ ;
- (d) Do not forget about  $\mathbb{E}(X_t)$  and  $\text{Var}(X_t)$ .

### 10.2 Hometask soltuion

Solution by Evgeny Zalyubovsky

1.

$$\begin{aligned}\mathbb{E}(W_5 \cdot Y) &= \mathbb{E}(W_5 \mid W_3 \leq 2) = \mathbb{E}(W_5 - W_3 \mid W_3 \leq 2) + \mathbb{E}(W_3 \mid W_3 \leq 2) = 0 + \int_{-\infty}^2 x \frac{e^{-x^2/6}}{\sqrt{6\pi}} dx = \\ &= \frac{1}{2\sqrt{6\pi}} \left( \int_{+\infty}^0 e^{-z/6} dz + \int_0^4 e^{-z/6} dz \right) = -\frac{\sqrt{6}}{2\sqrt{\pi}} (1 + e^{-4/6} - 1) = -\sqrt{\frac{3}{2\pi}} e^{-2/3}\end{aligned}$$

$$\begin{aligned}
\text{Var}(W_5 \cdot Y) &= \mathbb{E}(W_5^2 \cdot Y) - (\mathbb{E}(W_5 \cdot Y))^2 = \mathbb{E}((W_5 - W_3)^2 \mid W_3 \leq 2) + \\
&+ 2 \mathbb{E}(W_5 \cdot (W_5 - W_3) \mid W_3 \leq 2) + \mathbb{E}(W_3^2 \mid W_3 \leq 2) - \frac{3e^{-4/3}}{2\pi} = 3 \mathbb{E}((W_5 - W_3)^2) + \\
&+ 2 \mathbb{E}(W_3 \cdot (W_5 - W_3) \mid W_3 \leq 2) + \int_{-\infty}^2 x^2 \frac{e^{-x^2/6}}{\sqrt{6\pi}} dx - \frac{3e^{-4/3}}{2\pi} = \\
&= 3 (\text{Var}(W_5 - W_3) + (\mathbb{E}(W_5 - W_3))^2) + 2 \mathbb{E}(W_3 \mid W_3 \leq 2) \mathbb{E}(W_5 - W_3) + \\
&+ \frac{1}{\sqrt{6\pi}} \left( - \int_0^{+\infty} x^2 e^{-x^2/6} dx + \int_0^2 x^2 e^{-x^2/6} dz \right) - \frac{3e^{-4/3}}{2\pi} = 3 \cdot (2+0) + 0 - \frac{1}{\sqrt{6\pi}} \int_2^{+\infty} x^2 e^{-x^2/6} dx - \\
&- \frac{3e^{-4/3}}{2\pi} = 6 - \frac{3e^{-4/3}}{2\pi} - \frac{1}{\sqrt{6\pi}} \int_2^{+\infty} x^2 e^{-x^2/6} dx,
\end{aligned}$$

where

$$\begin{aligned}
-\frac{1}{\sqrt{6\pi}} \int_2^{+\infty} x^2 e^{-x^2/6} dx &= \frac{1}{\sqrt{6\pi}} \int_2^{+\infty} 3x \left( -\frac{x}{3} e^{-x^2/6} \right) dx = \left( \frac{3x e^{-x^2/6}}{\sqrt{6\pi}} \right) \Big|_2^{+\infty} - \frac{1}{\sqrt{6\pi}} \int_2^{+\infty} 3e^{-x^2/6} dx \\
&= -\frac{e^{-2/3}}{\sqrt{\pi/6}} - 3 + 3\Phi \left( 2/\sqrt{3} \right) \Rightarrow
\end{aligned}$$

$$\Rightarrow \text{Var}(W_5 \cdot Y) = 6 - \frac{3e^{-4/3}}{2\pi} - \frac{e^{-2/3}}{\sqrt{\pi/6}} - 3 + 3\Phi \left( 2/\sqrt{3} \right) = 3 - \frac{3e^{-4/3}}{2\pi} - \frac{e^{-2/3}}{\sqrt{\pi/6}} + 3\Phi \left( \sqrt{4/3} \right)$$

$$\begin{aligned}
\text{Cov}(W_5, Y) &= \mathbb{E}((W_5 - \mathbb{E}(W_5)) (Y - \mathbb{E}(Y))) = \mathbb{E}(W_5 (Y - \mathbb{P}(W_3 \leq 2))) = \\
&= \mathbb{E}(W_5 \cdot Y) - \Phi \left( \sqrt{4/3} \right) \mathbb{E}(W_5) = -\sqrt{\frac{3}{2\pi}} e^{-2/3} - 0 = -\sqrt{\frac{3}{2\pi}} e^{-2/3}
\end{aligned}$$

$$\begin{aligned}
\text{Cov}(W_5, W_5 \cdot Y) &= \mathbb{E}(W_5 (W_5 \cdot Y - \mathbb{E}(W_5 \cdot Y))) = \mathbb{E}(W_5^2 \cdot Y) - \mathbb{E}(W_5 \cdot Y) \mathbb{E}(W_5) = \\
&= \text{Var}(W_5 \cdot Y) + (\mathbb{E}(W_5 \cdot Y))^2 - 0 = 3 - \frac{e^{-2/3}}{\sqrt{\pi/6}} + 3\Phi \left( \sqrt{4/3} \right)
\end{aligned}$$

$$\begin{aligned}
\mathbb{E}(W_5 \cdot Y) &= -\sqrt{\frac{3}{2\pi}} e^{-2/3}; \text{Var}(W_5 \cdot Y) = 3 - \frac{3e^{-4/3}}{2\pi} - \frac{e^{-2/3}}{\sqrt{\pi/6}} + 3\Phi \left( \sqrt{4/3} \right); \text{Cov}(W_5, Y) = \\
&= -\sqrt{\frac{3}{2\pi}} e^{-2/3}; \text{Cov}(W_5, W_5 \cdot Y) = 3 - \frac{e^{-2/3}}{\sqrt{\pi/6}} + 3\Phi \left( \sqrt{4/3} \right).
\end{aligned}$$

2. Consider a function  $f$  such that

$$\mathbb{E}(M_{n+k} \mid \mathcal{F}_n) = M_n. \tag{19}$$

Obviously, as  $A_n$  is always finite, so are  $f(n)$  and  $\mathbb{E}(M_n)$ . Moreover,  $A_n$  is always adapted to  $\mathcal{F}_n$  while  $f(n)$  is a constant, so  $M_n$  is also always adapted to  $\mathcal{F}_n$ . Therefore, condition (19) is both necessary and sufficient for  $M_n$  to be a martingale. Before using that to obtain  $f(n)$ ,

let's derive a formula for  $\mathbb{E}(A_{n+k} \mid \mathcal{F}_n)$ :

$$\begin{aligned}\mathbb{E}(A_{n+1} \mid \mathcal{F}_n) &= A_n + \frac{A_n}{A_n + B_n} = A_n + \frac{A_n}{A_0 + B_0 + n} = A_n + \frac{A_n}{2 + n} = \frac{n+3}{n+2} A_n \Rightarrow \\ &\Rightarrow \mathbb{E}(A_{n+k} \mid \mathcal{F}_n) = \mathbb{E}(\mathbb{E}(A_{n+k} \mid \mathcal{F}_{n+k-1}) \mid \mathcal{F}_n) = \mathbb{E}\left(\frac{(n+k-1)+3}{(n+k-1)+2} A_{n+k-1} \mid \mathcal{F}_n\right) = \\ &= \frac{(n+k-1)+3}{(n+k-1)+2} \cdot \mathbb{E}(A_{n+k-1} \mid \mathcal{F}_n) = \dots = \mathbb{E}(A_n \mid \mathcal{F}_n) \cdot \prod_{i=0}^{k-1} \frac{n+i+3}{n+i+2} = \frac{n+k+2}{n+2} A_n.\end{aligned}$$

$$\begin{aligned}(19) \Rightarrow \mathbb{E}(M_{n+k} \mid \mathcal{F}_n) &= \mathbb{E}(f(n+k) \cdot A_{n+k} \mid \mathcal{F}_n) = f(n+k) \frac{n+k+2}{n+2} A_n = M_n = f(n) A_n \Rightarrow \\ &\Rightarrow f(n+k) \frac{n+k+2}{n+2} = f(n) \Rightarrow f(n) = \frac{1}{n+2}\end{aligned}$$

First, note that  $A_n + B_n = n + 2 \forall n$ , so if  $\frac{1}{n+2} A_n$  is a martingale, then so are  $1 - \frac{1}{n+2} B_n$  and  $\frac{1}{n+2} B_n$ . What is more,  $\tau = \min_n \{n \mid B_n = 2\} \Rightarrow B_\tau = 2 \forall \tau$ . According to Doob's theorem, we have that  $\mathbb{E}(\frac{B_\tau}{\tau+2}) = \mathbb{E}(\frac{B_0}{0+2}) = \frac{1}{2}$ , but  $\mathbb{E}(\frac{B_\tau}{\tau+2}) = \mathbb{E}(\frac{2}{\tau+2}) = 2 \mathbb{E}(\frac{1}{\tau+2})$ , hence  $\mathbb{E}(\frac{1}{\tau+2}) = \frac{1}{4}$ .

3.  $dY_t = 7W_t^6 dW_t + \frac{1}{2} 42W_t^5 dt + aW_t^5 dt + t^2 \cos W_t dW_t = (7W_t^6 + t^2 \cos W_t) dW_t + (21 + a)W_t^5 dt \Rightarrow$  in order to have no terms with  $dt$ , we need that  $21 + a = 0 \Leftrightarrow a = -21$ .

As for the ultimate question, due to  $Y_t$  being a martingale,  $\mathbb{E}(Y_t) = Y_0 = 42$ .

4.

$$\begin{aligned}X_0 &= B_0 \tilde{\mathbb{E}}\left(\frac{X_T}{B_T} \mid \mathcal{F}_0\right) = B_0 \tilde{\mathbb{E}}\left(\frac{1_{S_0 S_T > S_{T/2}^2}}{B_0 e^{rT}} \mid \mathcal{F}_0\right) = e^{-rT} \tilde{\mathbb{P}}(S_0 S_T > S_{T/2}^2 \mid \mathcal{F}_0) = \\ &= e^{-rT} \tilde{\mathbb{P}}\left(S_0^2 e^{(\mu - \sigma^2/2)T + \sigma W_T} > S_0^2 e^{(\mu - \sigma^2/2)T + 2\sigma W_{T/2}} \mid \mathcal{F}_0\right) = e^{-rT} \tilde{\mathbb{P}}(e^{W_T} > e^{2W_{T/2}} \mid \mathcal{F}_0) = \\ &= e^{-rT} \tilde{\mathbb{P}}\left(\tilde{W}_T + \frac{\mu - r}{\sigma} T > 2\tilde{W}_{T/2} + \frac{\mu - r}{\sigma} T \mid \mathcal{F}_0\right) = e^{-rT} \tilde{\mathbb{P}}(\tilde{W}_T > 2\tilde{W}_{T/2}) = \\ &= e^{-rT} \tilde{\mathbb{P}}(\tilde{W}_T - \tilde{W}_{T/2} > \tilde{W}_{T/2}) = e^{-rT} \tilde{\mathbb{P}}(\mathcal{N}(0, T/2) > \mathcal{N}(0, T/2)) = \frac{1}{2} e^{-rT}\end{aligned}$$

5.

$$\begin{aligned}dY_t &= \exp(\gamma t) dX_t + \gamma \exp(\gamma t) X_t dt + \gamma \exp(\gamma t) dX_t dt = \\ &= \exp(\gamma t) ((b - aX_t) dt + c dW_t) + \gamma \exp(\gamma t) X_t dt = \\ &= c \exp(\gamma t) dW_t + \exp(\gamma t) (b - aX_t + \gamma X_t) dt\end{aligned}$$

That term will be constant iff  $(a - \gamma)X_t \equiv 0 \Leftrightarrow \gamma = a$ .

$$\begin{aligned}dY_t &= c \exp(at) dW_t + b \exp(at) dt \Rightarrow \\ \Rightarrow Y_t &= X_0 + c \int_0^t \exp(au) dW_u + b \int_0^t \exp(au) du \Rightarrow \\ \Rightarrow X_t &= \exp(-at) \left( X_0 + c \int_0^t \exp(au) dW_u + b \int_0^t \exp(au) du \right)\end{aligned}$$

$$\begin{aligned}
\mathbb{E}(X_t) &= \exp(-at) \left( X_0 + b \int_0^t \exp(au) du \right) + c \exp(-at) \mathbb{E} \left( \int_0^t \exp(au) dW_u \right) = \\
&= X_0 \exp(-at) + \frac{b}{a} \\
\text{Var}(X_t) &= \mathbb{E}(X_t^2) - (\mathbb{E}(X_t))^2 = \\
&= \mathbb{E} \left( \left( \int_0^t \exp(au) dW_u \right)^2 \right) = \\
&= \int_0^t \mathbb{E}(\exp(2au)) du = \\
&= \frac{\exp(2at)}{2a}
\end{aligned}$$

### 10.3 Exam 2017-12-29

#### 10.3.1 Dynamic optimization

1. [10 points] Consider a system of differential equations

$$\begin{cases} \dot{x} = -2y + x(x^2 + y^2 - 1); \\ \dot{y} = 2x + y(x^2 + y^2 - 1). \end{cases}$$

- (a) [5 points] Check that  $(0, 0)$  is the only point of rest of this system. Change the variables from the Cartesian to the polar  $(r, \varphi)$ . Rewrite the system in the polar coordinates.
  - (b) [5 points] Draw two time paths of the system for  $r_0 > 1$ , where  $r_0$  is the radius of the initial point and for  $0 < r_0 < 1$ . Justify your sketch. What if  $r_0 = 1$ ?
2. [10 points] Solve the calculus of variations problem

$$\int_1^2 \left( \frac{2y^2}{x^2} + (y')^2 \right) dx \rightarrow \max / \min$$

with the fixed endpoints  $y(1) = 0, y(2) = \frac{7}{2}$ .

Hint: for solving Euler's equation try to find solutions in the form of  $x^a$ . Check all available second-order conditions.

3. [20 points] Road construction costs minimization.

Let the terrain profile be represented by the function

$$y(t) = \begin{cases} 3 - 3|t|, & \text{if } |t| \leq 1 \\ 0, & \text{otherwise.} \end{cases}$$

The contractor minimizes the excavation costs given by the formula

$$\int_{-c}^c (x(t) - y(t))^2 dt,$$

where  $x(t)$  is the road profile we need to find,  $c > 2$  and  $[-c, c]$  — road section where the excavation takes place ( $c$  is not set). Allowable grade of the road satisfies  $|\dot{x}| \leq 1$ .



- (a) [5 points] Form Hamiltonian and derive first-order conditions taking into account that multiplier  $\lambda$  satisfies transversality conditions  $\lambda(-c) = \lambda(c) = 0$ .
- (b) [15 points] Find  $x(t)$  on the section  $[-c, c]$ .

### 10.3.2 Stochastic Calculus

Standard Wiener process is denoted by  $W_t$ .

- [10 points] Let  $Y$  be equal to 1 if  $W_2 > 0$  and 0 otherwise.  
Find  $\mathbb{E}(Y \mid W_1)$ ,  $\text{Var}(Y \mid W_1)$ ,  $\mathbb{E}(Y \mid W_1^2)$ .
- [10 points] James Bond flips a biased coin until the sequence Head-Tail-Head-Tail appears. The probability of «Head» is equal to  $p$ . Using Doog's theorem and an appropriate martingale find the expected number of coin flips.
- [10 points] The process  $X_t$  is given by

$$X_t = 2017 + t^2 W_t^2 + \int_0^t u dW_u$$

- Find  $dX_t$ ;
  - Is  $X_t$  a martingale?
  - Find  $\mathbb{E}(X_t)$ .
- [10 points] Consider the framework of the Black and Scholes model. You agreed with Warren Buffett that at fixed time  $T$  he will pay you the strange sum

$$X_T = \ln S_T \cdot \ln S_{T/2},$$

where  $S_t$  is the price of a share.

What is the non-arbitrage price  $X_0$  of this agreement?

- [20 points] Solve the stochastic differential equation

$$dY_t = (Y_t^3 - Y_t) dt + Y_t^2 dW_t$$

You are free to use or not to use the following guiding steps:

- [5 points] Consider  $Z_t = Y_t^n$  and find  $dZ_t$ ;
- [3 points] Find a constant  $n$  such that the term before  $dW_t$  in  $dZ_t$  is non-random.
- [2 points] Write down the equation for  $dZ_t$  in terms of  $t$  and  $Z_t$  only: you should get rid of  $Y_t$ .
- [8 points] Solve the equation for  $dZ_t$ .  
Hint: It's just the particular case of the equation in your hometask :) Do you remember? Multiply  $Z_t$  by some exponent :)
- [2 points] Finally, find  $Y_t$ .

### 10.4 Exam, solution

- 

$$\mathbb{E}(Y \mid W_1) = \mathbb{P}(W_2 > 0 \mid W_1) = \mathbb{P}(W_2 - W_1 > -W_1 \mid W_1) = 1 - F(-W_1) = F(W_1)$$

$$\text{Var}(Y \mid W_1) = F(W_1)(1 - F(W_1))$$

$$\mathbb{E}(Y \mid W_1^2) = \mathbb{P}(W_2 > 0 \mid W_1^2) = 0.5F(-|W_1|) + 0.5F(|W_1|) = 0.5$$

2. We organise a casino. Each entrant brings one dollar into the casino. And bets all his fortune every time. Each player bets on head, tail, head and then tail consecutively. To make the fortune of each player a martingale we will pay him  $1/p$  if he guesses head correctly and  $1/(1-p)$  if he guesses tail correctly.

The total wealth of all players,  $S_t$ , is not a martingale because  $\mathbb{E}(S_t) = t$ . But the process  $M_t = S_t - t$  is a martingale. Let  $\tau$  be the first moment when the sequence HTHHT appears.

We note that  $M_0 = 0$  and  $M_\tau = \frac{1}{p} \frac{1}{1-p} + \frac{1}{p} \frac{1}{1-p} \frac{1}{p} \frac{1}{1-p} - \tau$ .

According to Doob's theorem  $\mathbb{E}(M_\tau) = \mathbb{E}(M_0) = 0$ .

So

$$\mathbb{E}(\tau) = \frac{1}{p} \frac{1}{1-p} + \frac{1}{p} \frac{1}{1-p} \frac{1}{p} \frac{1}{1-p}$$

- 3.

$$dX_t = (2tW_t^2 + t^2) dt + (2t^2W_t + t) dW_t$$

$X_t$  is not a martingale because the term before  $dt$  is not zero.

$$\mathbb{E}(X_t) = 2017 + \mathbb{E}(t^2W_t^2) = 2017 + t^3$$

- 4.

$$X_0 = \exp(-rT) \tilde{\mathbb{E}}(X_T \mid \mathcal{F}) = \dots = \exp(-rT) (\ln^2 S_0 + \frac{3}{2} \ln S_0 (r - \sigma^2/2)T + (r - \sigma^2/2)^2 T^2/2 + \sigma^2 T/2)$$

- 5.

$$dZ_t = n(Y_t^{n+2} - Y_t^n + \frac{n-1}{2} Y_t^{n+2}) dt + nY_t^{n+1} dW_t$$

There are two values of  $n$ ,  $n = 0$  and  $n = -1$ . The value  $n = 0$  is useless. Consider  $n = -1$ .

$$dZ_t = Z_t dt - dW_t$$

Let's introduce  $X_t = e^{-t} Z_t$ :

$$dX_t = \dots = -\exp(-t) dW_t$$

So

$$Y_t = e^{-t} \frac{1}{1/Y_0 - \int_0^t \exp(-u) dW_u}$$

## 11 Some junk

### 11.1 Problems

1. Let  $Y_t = W_t + \mu t$ . Find all constants  $b$  such that  $Z_t = e^{bY_t}$  is a martingale.

### 11.2 Solutions

1. Using Ito's lemma

$$dZ_t = e^{bY_t} b \left( dW_t + \mu dt + \frac{1}{2} b dt \right)$$

So  $b = 0$  and  $b = -2\mu$  are ok.

## 12 2018-2019

### 12.1 Stochastic calculus: home assignment

1. I throw a fair die until first six appears. Let's denote the total number of throws by  $X$  and the number of odd integers thrown by  $Y$ .

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

2. Let  $X_t = \exp(-\alpha t) \left(1 + \int_0^t \exp(\alpha u) dW_u\right)$ .

(a) Simplify the expression  $X_t + \alpha \int_0^t X_u du$ .

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

3. Today the price of a share is  $S_0 = 100$  roubles. Each day the price  $S_t$  goes up by one rouble with probability  $p \in (0; 1)$  or by two roubles with probability  $1 - p$ .

(a) Find a number  $a$  such that  $M_t = a^{S_t}$  is a martingale.

(b) Let  $\tau$  be the first moment of time when the price will be greater or equal to 200 roubles. Find  $\mathbb{E}(\tau)$ .

4. In the framework of Black and Scholes model find the price at time  $t = 0$  of an asset that pays you at time  $T$  the amount

$$X_T = \min\{S_T, S_T^2\}.$$

5. Consider the stochastic differential equation

$$dX_t = 2W_t \exp(-X_t) dW_t + 2t \exp(-2X_t) dt$$

Find at least one solution of the form  $X_t = h(f(W_t) + g(t))$ .

### 12.2 Exam

#### Optimal Control

1. Search costs for a good  $c$  are uniformly distributed on the segment  $c \in [0; z]$ . Every consumer forms her expectation about the reservation price on this good while solving the minimization problem

$$\pi(R) = p(R) + \sigma(R)c \min_{R>0},$$

where  $R$  is the reservation price,  $p(R)$  is the market price of the good,  $\sigma(R)$  — the length of search for this good.

- (a) (6 points) Assume the problem is solved, then  $R$  is the function depending on  $c$ . Prove that  $d\pi/dc = \sigma$ .
- (b) (7 points) Let the monopolistic producer solve the problem of setting the optimal price

$$\int_0^z pX(\pi, c) dc \rightarrow \max,$$

where  $\pi$  satisfies the original equation and reservation price is optimal. Form the Hamiltonian to derive the first-order conditions for the optimal control problem, where  $\pi$  is the state variable,  $\sigma$  the control variable and  $X$  is the demand on good.

- (c) (7 points) Let  $X = \alpha - \beta\pi^2 + \gamma c$ , where  $\alpha > 0$ ,  $\beta > 0$  and  $\gamma$  are fixed parameters. Use the Hamiltonian system derived earlier to show that  $\gamma > 0$ .

2. (10 points) Find the steady-state solutions of the system of differential equations:

$$\begin{cases} \dot{x} = \ln(2 + xy - x - y); \\ \dot{y} = e^{2x+3y-5} - 1 \end{cases}.$$

On the portrait plot the equilibrium points, sketch the paths after finding the eigenvalues and eigenvectors of the linearized system.

3. (10 points) Solve the calculus of variations problem with the free-end value

$$\int_0^{\pi/2} ((y')^2 - 2yy' + y^2 - 2y' \cos^2 x) dx \rightarrow \max / \min, \quad y(0) = 0.$$

Check the sufficiency condition in order to classify the extremal.

## Stochastic Calculus

Standard Wiener process is denoted by  $W_t$ .

4. [10 points] Consider a well-shuffled deck of 52 cards. You open the cards one by one until the second King appears. Calculate the unconditional probability that
- the next card will be Queen of Diamonds;
  - the next card will be King of Diamonds.

Hint: a good martingale may be very useful here :)

5. [10 points] Find  $\mathbb{E}(W_{2019}^3 | W_{2018})$  and  $\mathbb{E}(W_{2018}^3 | W_{2019})$ .
6. [10 points] Suppose  $X_t$  satisfies the stochastic differential equation

$$dX_t = 2018X_t dt + X_t^{2019} dW_t$$

Determine constants  $a$ ,  $b$  and  $c$  such that  $Y_t = \exp(aX_t^b + ct)$  is a martingale.

7. [10 points] Consider the framework of the Black and Scholes model. The asset  $X$  will pay you one share at fixed time  $T$  if  $S_T > 2S_{T/2}$ , where  $S_t$  is the price of a share. What is the non-arbitrage price  $X_0$  of this asset?
8. [20 points] Consider the stochastic differential equation

$$dY_t = (2Y_t/t + 3(t^4 Y_t)^{1/3}) dt + 3(tY_t)^{2/3} dW_t, \quad Y_0 = 0.$$

- [15 points] Solve the stochastic differential equation.
- [5 points] Find  $\mathbb{E}(Y_t)$  and  $\text{Var}(Y_t)$ .

You are free to use or not to use the following guiding steps:

- [5 points] Suppose that  $Y_t = g(W_t)h(t)$ . Find  $dY_t$ .
- [5 points] By looking at the term before  $dW_t$  provide the equations for  $g(W_t)$  and  $h(t)$ .
- [5 points] Find  $g(W_t)$  and  $h(t)$  and check your solution.

## 12.3 Solution, stochastic calculus part

1. Non-martingale solution: let's bet not on the next card, but on the last one. At every moment of time we have the same information about the next and the last cards. But for last card the probability is always  $1/52$ .

Martingale solution. Consider the martingale studied in the lectures:  $M_n$  – indicator whether the Queen of Diamonds is still in the remaining part of the deck divided by the number of remaining cards. And stopping time,  $\tau$  – moment of the second King plus one. Doob's theorem is satisfied as  $\tau \leq 52$ . So  $\mathbb{E}(M_\tau) = \mathbb{E}(M_0) = 1/52$ .

2. Use the decomposition  $W_{2019}^3 = (W_{2018} + (W_{2019} - W_{2018}))^3$ . For the second question first use inversion.

$$\mathbb{E}(W_{2019}^3 | W_{2018}) = W_{2018}^3 + 3W_{2018}$$

$$\mathbb{E}(W_{2018}^3 | W_{2019}) = 2018^3 ((W_{2019}/2019)^3 + 3W_{2019}/(2018 \cdot 2019^2))$$

3. Use Ito's lemma. Do not forget that  $dX_t$  also contains  $dt$  term.

$$c + 0.5ab(abX_t^{2b-2+4038} + (b-1)X_t^{b-2+4038} + 4036X_t^b) = 0$$

Solutions are:  $c = 0, a = 0$ , any  $b$ ;  $c = 0, b = 0$ , any  $a$ ;  $b = -4036, a = 1, c = -0.5ab(b-1)$ .

- 4.

$$e^{-rT} \mathbb{E}^*(S_T \cdot 1_{S_T > 2S_{T/2}})$$

- 5.

$$Y_t = W_t^3 t^2$$

$$\mathbb{E}(Y_t) = 0; \text{Var}(Y_t) = t^4 \mathbb{E}(W_t^6) = 15t^7$$

## 13 2019-2020

### 13.1 Exam, 2019-12-23

#### Optimal Control

1. Consider a profit maximization problem when a perfectly competitive firm spends  $u(t)$  on advertising:

$$\int_0^\infty e^{-rt} (Px(t) - u(t)) dt \rightarrow \max,$$

where  $x(t)$  is the share of the market,  $P$  – price of sales per unit time,  $r > 0$  – the discount rate. Maximization is subject to  $\dot{x} = u(1-x) - x/2$ ,  $x_0 \geq 0$  and  $0 \leq u \leq 1$ .

(a) (5 points) Using current value Hamiltonian state the system of first-order conditions.

(b) (15 points) Find the bounds on price  $P_{\min} < P < P_{\max}$  for which the steady-state solution  $(x_s, u_s)$  with  $x_s < 1$  and  $u_s < 1$  exists and find it. Draw in  $(x, u)$ -plane the paths of most rapid approach to steady-state for  $x_s \neq x_0$ .

2. (10 points) Consider a problem in discrete time

$$\sum_{t=0}^{\infty} \beta^t U(c_t) \rightarrow \max$$

with respect to  $c_t$  subject to  $k_{t+1} = \sqrt{k_t - c_t}$ , where  $k_0$  is given and  $0 < \beta < 1$ . Suppose there is a constant  $\delta > 0$  such that  $U(c) \leq \delta c$  for all  $c \geq 0$ .

- (a) Write down Bellman's equation for this problem.
- (b) Prove that under assumption that Bellman's equation has a unique solution the value function of the problem satisfies the estimate  $V(k) \leq \delta k + C$  for some  $C > 0$  and provide lower bound for  $C$ .
3. (10 points) Solve bounded control problem  $\int_0^4 (u^2 + x) dt \rightarrow \min$  subject to  $dx/dt = u$ ,  $x(0) = 0$  and  $|u| \leq 1$ .

## Stochastic Calculus

Standard Wiener process is denoted by  $W_t$ .

1. [10 points] Find a function  $f(t)$  such that  $M_t = \exp(W_t^2/(1+2t))/f(t)$  is a martingale.
2. [10 points] Find the limit of  $X_n$  in mean squared when  $n$  tends to infinity:

$$X_n = \sum_{i=1}^n (W_{ti/n} - W_{t(i-1)/n})^3$$

3. [10 points] In the framework of the Black and Scholes model find the price at  $t = 0$  of an asset that pays  $X_T = S_T^2/S_{T/2}$  at time  $T$ . Here  $S_t$  denotes the price of one share at time  $t$ .
4. [10 points] Solve the following stochastic differential equation.

$$dX_t = \frac{X_t}{t-1} dt + dW_t, \quad X_0 = 0$$

Hint: the solution has the form  $X_t = a(t) \cdot \int_0^t b(u) dW_u$  for some deterministic functions  $a(t)$  and  $b(t)$ . You only need to find  $a(t)$  and  $b(t)$  :)

5. [20 points] Let  $\tau$  be the first moment of time when the Wiener process  $W_t$  touches the line  $y(t) = 10 - t$ .

The goal of this exercise is to find  $\mathbb{E}(\tau)$  and  $\text{Var}(\tau)$ .

You are free to use or not to use the following hints:

- (a) Check whether the process  $R_t = \exp(\sigma W_t - \sigma^2 t/2)$  is a martingale.
- (b) Apply the Doob's theorem and find the function  $m(\lambda) = \mathbb{E}(\exp(-\lambda\tau))$ . You don't need to check all the conditions of the Doob's theorem.
- (c) Find  $m'(0)$ , find  $m''(0)$ .
- (d) Find  $\mathbb{E}(\tau)$ ,  $\text{Var}(\tau)$  using  $m'(0)$  and  $m''(0)$ . You can do the last point without any previous point.

## 13.2 Stochastic calculus, hints and solutions

1. Using Ito's lemma take  $dM_t$ . And obtain expression of the form  $dM_t = A_t dt + B_t dW_t$ . If  $M_t$  is a martingale then  $A_t = 0$ . I believe you can be attentive and obtain the equation  $f'/f = 1/(1+2t)$ .
2. We check that  $\mathbb{E}(X_n) = 0$ ,  $\text{Var}(X_n) \rightarrow 0$ , so the limit of  $X_n$  in mean squared is zero.
3. Just calculate  $\mathbb{E}_*(\exp(-rT)X_T)$ .

4. Let's denote  $X_t = a(t)Y_t$ . We note that  $dY_t = b(t)dW_t$ . No second order terms as  $dt dY_t = 0$ . By Ito's Lemma

$$dX_t = a'(t)Y_t dt + a(t)dY_t = X_t a'(t)/a(t) dt + a(t)b(t)dW_t$$

Hence we get the system

$$\begin{cases} a'(t)/a(t) = 1/(t-1), \\ a(t)b(t) = 1 \end{cases}$$

5.  $m'(\lambda) = \mathbb{E}(-\tau \exp(-\lambda\tau))$ , so  $m'(0) = \mathbb{E}(-\tau)$ , by the same reasoning  $m''(0) = \mathbb{E}(\tau^2)$ .

## 14 2020-2021

### 14.1 Exam, 2020-12-29

Short rules: online with proctoring, 120 minutes, A4 cheat sheet and calculator are allowed.

1. (10 points) Ded Moroz would like to receive  $K$  roubles at time  $T = 2$  if  $S_2 < 0.5S_1$  and zero 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  $t = 0$ ?

2. (10 points) Simplify as much as possible the integral

$$\int_0^t \exp(-W_u - u/2) dW_u.$$

3. (10 points) The process  $Y_t$  is defined by

$$dY_t = W_t^2 dt + W_t dW_t, \quad Y_0 = 0.$$

(a) (6 points) Find  $\mathbb{E}(Y_t)$ ,  $\mathbb{E}(Y_t W_t)$ ,  $\mathbb{E}(Y_t W_t^2)$ .

(b) (4 points) Find  $\text{Var}(Y_t)$ .

4. (10 points) Find at least one solution of the stochastic differential equation

$$dR_t = 4R_t dt + 7dW_t, \quad R_0 = 1.$$

You are free to use the following steps:

- Solve deterministic equation  $dQ_t = 4Q_t dt$ .
  - Now you need to «remove» this deterministic solution  $Q_t$  from  $R_t$ . To accomplish this goal represent  $R_t$  as  $R_t = Q_t B_t$  and find a very simple equation for  $B_t$ .
  - Solve the equation for  $B_t$ .
  - Finalize your solution.
5. (10 points) The variables  $X$  and  $Y$  are independent and are exponentially distributed with mean 1. Let  $L = \min\{X, Y\}$  and  $R = \max\{X, Y\}$ . Find  $\mathbb{E}(L | R)$  and  $\mathbb{E}(R | L)$ .

Be brave!! One more problem is waiting to kill you!! The final boss of this game!!

6. (20 points) Consider a process  $S_t = Z_1 + Z_2 + \dots + Z_t$  with  $S_0 = 0$ . Increments  $Z_t$  are identically distributed and take values  $(-1)$  and  $1$  with equal probabilities. Let  $\tau$  be the first moment of time when  $|S_t| = 100$ .

- Find  $f(\lambda)$  such that  $M_t = f(\lambda)^t \exp(\lambda S_t)$  is a martingale.
- Are  $S_\tau$  and  $\tau$  independent?
- Using Doob's optional stopping time theorem obtain  $q(\lambda) = \mathbb{E}(f(\lambda)^\tau)$ .
- By explicitly finding  $G(f) = \mathbb{E}(f^\tau)$  or otherwise find  $G'(1)$ .
- Express  $\mathbb{E}(\tau)$  in terms of  $G'(1)$ .

Hint: you may not check technical conditions of Doob's optional stopping time theorem.

## 14.2 Marking scheme, exam 2020-12-29

- formula for  $S_t$  with  $W_t^*$  and  $r = 1$  point formula for  $X_0$  with  $\mathbb{E}^* = 1$  points from expectation to  $K \exp()$   $\mathbb{P}^*(event) = 4$  points from  $\mathbb{P}^*(event)$  to normal cdf = 4 points
- guessed answer = 2 points, guess check = 8 points
- three expected values = 2 points \* 3 = 6 points, variance = 4 points
- 4a = 2 points, 4b = 3 points, 4c = 3 points, 4d = 2 points
- joint density of min and max = 4 points,  $\mathbb{E}(\min | \max) = 3$  points  $\mathbb{E}(\max | \min) = 3$  points
- $f(\lambda) = 2/(\exp(\lambda) + \exp(-\lambda))$ .
  - Yes. Possible argument: if you multiply  $S_t$  by  $(-1)$  the distribution of  $\tau$  will be unaffected, but  $S_\tau$  will be multiplied by  $(-1)$ .
  - $G'(1) = \mathbb{E}(\tau f^{\tau-1}) = \mathbb{E}(\tau)$ .

## 15 2021 Fall

### 15.1 Exam, 2021-12-21

- (10 points) Ded Moroz would like to receive one share at time  $T$  if  $S_T > S_{T/2}$  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  $t = 0$ ?
- (10 points) Let  $X_0 = 0.2021$ . Next values of  $X_t$  and  $Y_t$  are defined recursively. The filtration is given by  $\mathcal{F}_t = \sigma(X_0, \dots, X_t)$ .  
The random variable  $Y_t$  given  $\mathcal{F}_{t-1}$  has Bernoulli distribution with  $\mathbb{P}(Y_t = 1 | \mathcal{F}_{t-1}) = X_{t-1}$ .  
And  $X_t = (Y_t + X_{t-1})/2$ .
  - Check whether  $X_t$  is a martingale.
  - The sequence  $(X_t)$  converges almost surely (you don't need to prove this). What is the distribution of the limit?
- (10 points) Consider two integrals:  $I_t = \int_0^t W_u^2 dW_u$  and  $J_t = \int_0^t W_u^2 du$ .
  - Find  $\mathbb{E}(I_t)$  and  $\mathbb{E}(J_t)$ .
  - Find  $\text{Var}(I_t)$  and  $\text{Var}(J_t)$ .



4. (10 points) You pick up cards one by one from a well shuffled deck of 52 cards. Let  $X_i$  be an indicator variable, equal to one if the card number  $i$  is a Queen, and zero otherwise. Let  $Y_i = \mathbb{E}(X_{52} \mid X_1, X_2, \dots, X_i)$ . Find the covariance  $\text{Cov}(Y_{50}, Y_{51})$ .
5. (10 points) Imagine the share price satisfies the equation

$$dS_t = S_t dt + \sqrt{S_t} dW_t, \quad S_0 = 1.$$

Find all transformations  $Y_t = h(S_t)$  such that  $Y_t$  is a martingale.

6. (20 points) Consider two stopping times:  $U = \min\{t \mid W_t = 2\}$  and  $D = \min\{t \mid W_t = -1\}$ . The ultimate goal of this problem is to find  $M(s) = \mathbb{E}(e^{-sU} \mid U < D)$  and explain how to obtain  $\mathbb{E}(U \mid U < D)$  and  $\text{Var}(U \mid U < D)$ .

You may use or not use the following guiding steps.

- (a) (3 points) Is  $W_t$  a martingale? Using optional stopping time theorem find  $\mathbb{P}(U < D)$ .
- (b) (3 points) Is  $\exp(aW_t - a^2t/2)$  a martingale? State the equation that follows from optional stopping time theorem.
- (c) (3 points) From the equation obtained previously get a system of two equations by considering two values of  $a$ :  $a = \sqrt{2s}$  and  $a = -\sqrt{2s}$ .
- (d) (5 points) Find  $\mathbb{E}(e^{-sU} \cdot I(U < D))$  where  $I$  is indicator of the corresponding event.
- (e) (3 points) Find the function  $M(s) = \mathbb{E}(e^{-sU} \mid U < D)$ .
- (f) (3 points) Explain how to find  $\mathbb{E}(U \mid U < D)$  and  $\text{Var}(U \mid U < D)$  using  $M(s)$ . (You don't need to do actual calculations).

You may not check technical conditions of Doob's optional stopping time theorem.

## 15.2 Marking scheme, 2021-12-21

1. One dollar and not one share has been considered: -3 points. The random variable  $S_T$  present in final answer: -5 points. Variables  $S_T$  and indicator assumed independent: -3 points.
2. 2a = 5 points, 2b = 5 points.
3.  $\mathbb{E}(I_t) = 2$  points,  $\mathbb{E}(J_t) = 3$  points,  $\text{Var}(I_t) = 2$  points,  $\text{Var}(J_t) = 3$  points.
4.
  - Possible values of  $Y_{51}$ : 2 points;
  - Possible values of  $Y_{50}$ : 2 points;
  - Table of probabilities: 3 points;
  - $\mathbb{E}(Y_{51})$ : 1 point;
  - $\mathbb{E}(Y_{50})$ : 1 point;
  - Covariance: 1 point.
5.
  - correct differential equation for  $h$ : 6 points;
  - solution of differential equation: 4 points;
  - common error, 1/2 instead of 2: -2 points.
6. Points assigned in the text.

## 16 2022 Fall

### 16.1 Exam, 2022-12-29

Rules: 120 minutes, A4 cheat sheet and calculator are ok,  $W_t$  denotes a Wiener process, 10 points for each problem.

1. Consider  $X_t = \exp(-2W_t - 2t)$ .
  - (a) Find  $dX_t$ . Write the corresponding full form. Is  $X_t$  a martingale?
  - (b) Find  $\mathbb{E}(X_t)$  and  $\text{Var}(X_t)$ .
  - (c) Find  $\int_0^t X_u dW_u$ .
2. Let  $(W_t)$  be 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  $\mathbb{E}(W_5 W_4 W_3 \mid W_4)$ ,  $\text{Var}(W_5 W_4 W_3 \mid W_4)$ .
3. Winnie-the-Pooh starts at zero of the real line. Every minute he moves left by one with probability 0.2, right by one with probability 0.2 or does not move and eats a honey-pot with probability 0.6.  
 Let  $X_t$  be the coordinate of Winnie at time  $t$ . Rabbit's hole has x-coordinate 6 and Owl lives at  $(-4)$ , let  $\tau$  be the first moment when Winnie visits Owl or Rabbit,  $\tau = \min\{t \mid X_t = 6 \text{ or } X_t = -4\}$ .
  - (a) Is  $X_t$  a martingale?
  - (b) Find a constant  $a$  such that  $Y_t = X_t^2 - at$  is a martingale.
  - (c) Find  $\mathbb{P}(X_\tau = 6)$  and  $\mathbb{E}(\tau)$ .

Hint: you don't need to check technical conditions of Doob's optional stopping theorem in point (c).

4. Consider the Vasicek interest rate model

$$dR_t = (0.05 - R_t)dt + dW_t, \quad R_0 = 0.07.$$

- (a) Write the same models in full form with integrals.
- (b) Let  $b_t = \mathbb{E}(R_t)$ . Find  $b_t$  and sketch it.

Hint: to find  $b_t$  take expected value of both sides of the full form and solve the ordinary differential equation.

5. Consider two-period binomial model with initial share price  $S_0 = 600$ , Up and down multipliers are  $u = 1.2$ ,  $d = 0.8$ , 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 «down» state of the world to replicate the option?
6. Consider Black and Scholes model in continuous time with risk-free interest rate  $r$ , volatility  $\sigma$ , initial share price  $S_0$  and exponential growth rate of expected share price  $\mu$ .
  - (a) Let's denote by  $\mathbb{P}$  the real probability and by  $\mathbb{P}^*$  the risk-neutral probability. Find  $\mathbb{P}(S_2 > S_1)$  and  $\mathbb{P}^*(S_2 > S_1)$ .
  - (b) An option pays you the sum  $X_2 = \sqrt{S_1}$  at  $T = 2$ . Find the non-arbitrage price  $X_0$  of the option.

Hint: the answers may contain the standard normal cumulative distribution function  $F(\cdot)$ .

## 16.2 Marking scheme, 2022-12-29

1. Process  $X_t$  is a martingale as

$$dX_t = -2 \exp(-2W_t - 2t) dW_t.$$

Full form:

$$X_t = 1 + \int_0^t (-2) \exp(-2W_u - 2u) dW_u,$$

Hence,  $\mathbb{E}(X_t) = 1$ . Use Ito's isometry for variance:

$$\text{Var}(X_t) = \int_0^t \mathbb{E}((-2)^2 \exp(-4W_u - 4u)) du = \int_0^t 4 \exp(4u) du = \exp(4t) - 1.$$

$$\int_0^t \exp(-2W_u - 2u) dW_u = \frac{1}{2} - \frac{1}{2} \exp(-2W_t - 2t).$$

Marking: 3 points for  $dX_t$ , 1 point for martingale, 1 point for full form, 1 point for  $\mathbb{E}(X_t)$ , 2 points for variance and 2 points for integral.

2. 2 points for each expected value, 3 points for each variance:  $\mathbb{E}(W_5 W_4 \mid W_4) = W_4^2$ ,  $\text{Var}(W_5 W_4 \mid W_4) = W_4^2$ .

For point (b) remark that  $W_5 = W_4 + X$  and  $W_3 = \frac{3}{4}W_4 + Y$ , where  $X, Y$  and  $W_4$  are independent normal with  $\text{Var}(X) = 1$ ,  $\text{Var}(Y) = 3 - \frac{9}{4} = \frac{3}{4}$ .

$$\mathbb{E}(W_5 W_4 W_3 \mid W_4) = \frac{3}{4} W_4^3, \text{Var}(W_5 W_4 W_3 \mid W_4) = \frac{21}{16} W_4^4 + \frac{3}{4} W_4^2.$$

3. Process  $X_t$  is a martingale (2 points); for  $\alpha = 0.4$  (3 points)  $Y_t = X_t^2 - 0.4t$  is a martingale. Using Doob's theorem and two martingales we get two equations,  $\mathbb{E}(X_\tau) = X_0 = 0$ ,  $\mathbb{E}(X_\tau^2) = 0.4 \mathbb{E}(\tau)$ .

Hence,  $\mathbb{P}(X_\tau = 6) = 0.4$  (2 points) and  $\mathbb{E}(\tau) = 60$  (3 points).

4. 2 points for full form

$$R_t = 0.07 + \int_0^t (0.05 - R_u) du + W_t.$$

Integral equation for  $b_t$ :

$$b_t = 0.07 + \int_0^t (0.05 - b_u) du$$

Differential equation:

$$b'_t = 0.05 - b_t$$

And  $b_t = 0.05 + 0.02 \exp(-t)$ .

To find  $b_t$  one may also solve the SDE and take the expectation.

Marking: 6 points for  $b_t$  and 2 points for a sketch.

5. 2 points for probabilities  $p_u^* = 5/8$ ,  $p_d^* = 3/8$ ; 4 points for

$$X_0 = 100 \cdot \frac{5}{8} \cdot \frac{1}{(1+r)^2} \approx 56.7$$

4 points for

$$\alpha = \frac{X_2^{du} - X_2^{dd}}{S_2^{du} - S_2^{dd}} = \frac{100}{192} \approx 0.52$$

6. 2 points for each probability, 6 points for  $X_0$ ;

$$\mathbb{P}(S_2 > S_1) = F\left(\frac{\mu}{\sigma} - \frac{\sigma}{2}\right), \quad \mathbb{P}^*(S_2 > S_1) = F\left(\frac{r}{\sigma} - \frac{\sigma}{2}\right);$$

$$X_0 = \sqrt{S_0} \exp(-3r/2 - \sigma^2/8);$$

## 17 2023 Fall

### 17.1 Exam, 2023-12-27

Rules: 120 minutes, A4 cheat sheet and calculator are ok,  $(W_t)$  denotes a Wiener process.

- [10 points] Winnie-the-Pooh starts at zero of the real line. Every minute he moves left by one with probability 0.2, right by one with probability 0.8. Let  $X_t$  be the coordinate of Winnie at time  $t$ .

The stopping time  $\tau$  is the first moment when Winnie visits  $(-4)$  or  $6$ ,  $\tau = \min\{t \mid X_t = 6 \text{ or } X_t = -4\}$ .

(a) [5] Find all martingales of the form  $M_t = \exp(bX_t)$  where  $b$  is a constant.

(b) [5] Using Doob's theorem or otherwise find  $\mathbb{P}(X_\tau = 6)$ .

Hint: You may not check all the conditions of the Doob's theorem.

- [10 points] Consider the process  $dX_t = W_t dW_t + W_t dt$  with  $X_0 = 2024$ .

(a) [3] Find  $\mathbb{E}(X_t)$ . Is  $(X_t)$  a martingale?

(b) [3] Find  $dY_t$  for  $Y_t = X_t W_t$ .

(c) [4] Find  $\mathbb{E}(Y_t)$ .

- [10 points] Solve the stochastic differential equation

$$dX_t = (2X_t + 1)dt + 2\sqrt{X_t}dW_t, \quad X_0 = 1.$$

You are free to use or to completely ignore the following hints:

(a) [3] Simplify the equation using substitution  $Y_t = \sqrt{X_t}$ .

(b) [7] Solve the simplified equation using substitution  $Z_t = h(t)Y_t$  with reasonable choice of  $h$ .

- [10 points] Consider the process  $Y_t = \int_0^t \text{sign}(\cos u) dW_u$ .

(a) [5] Find the covariance  $\text{Cov}(Y_{2024\pi}, W_{2024\pi})$ .

(b) [5] Is  $(Y_t)$  a Wiener process?

Hint:  $\text{sign } c = 1$  if  $c > 0$ ,  $\text{sign } c = -1$  if  $c < 0$  and  $0$  otherwise.

- [10 points] You have two correlated Wiener processes,  $(A_t)$  and  $(B_t)$ , with  $\text{Corr}(A_t - A_s, B_t - B_s) = \rho$  for all  $t > s$ .

Split the time interval  $[0; t]$  into  $n$  small segments of equal length. Let  $\Delta_i^A$  be the increment of the Wiener process  $(A_t)$  on the  $i$ -th small segment, i.e.  $\Delta_i^A = A(it/n) - A((i-1)t/n)$ . Let  $\Delta_i^B$  be the increment of the Wiener process  $(B_t)$  on the  $i$ -th small segment.

Consider the sum of cross-products,  $S_n = \sum_{i=1}^n \Delta_i^A \Delta_i^B$ .

(a) [3] Find  $\mathbb{E}(S_n)$ .

(b) [5] Find  $\lim_{n \rightarrow \infty} \text{Var}(S_n)$ .

- (c) [2] Find the mean square limit of  $(S_n)$ .
- (d) [1] How would you write the limit in (c) using short hand notation with  $dA_t$  and  $dB_t$ ?
6. [10 points] Consider Black and Scholes model in continuous time with risk-free interest rate  $r$ , volatility  $\sigma$ , initial share price  $S_0$  and exponential growth rate of expected share price  $\mu$ . An option  $A$  pays you 1 dollar at fixed time moment  $T$  if  $S_T/S_{T/2} > S_{T/2}/S_0$  and 0 otherwise. Find the non-arbitrage price  $X_0$  of the option  $A$ .  
Hint: the answer may contain the standard normal cumulative distribution function  $F(\cdot)$ .

## 17.2 Marking scheme, 2023-12-27

1. [10 points]

- (a) [5] Let's denote  $X_t - X_{t-1}$  by  $Z_t$ . The process  $(X_t)$  should be a martingale,

$$\mathbb{E}(\exp(bX_t + bZ_{t+1}) \mid \mathcal{F}_t) = \exp(bX_t).$$

We obtain an equation [+2 points]

$$\mathbb{E}(\exp(bZ_{t+1})) = 1.$$

That is  $0.8 \exp(b) + 0.2 \exp(-b) = 1$  [+2 points] and  $b = -2 \ln 2$  or  $b = 0$ .

- (b) [5] From Doob's theorem we have  $\mathbb{E}(M_\tau) = 1$ . The equation for  $p = \mathbb{P}(X_\tau = 6)$  is

$$p \exp(-12 \ln 2) + (1 - p) \exp(-8 \ln 2) = 1.$$

Hint: You may not check all the conditions of the Doob's theorem.

2. [10 points]

- (a) [3]

$$\mathbb{E}(X_t) = 2024 + \mathbb{E}\left(\int_0^t W_u dW_u\right) + \int_0^t \mathbb{E}(W_u) du = 2024.$$

However  $(X_t)$  is not a martingale as it has non-zero  $dt$  term.

- (b) [3]

$$d(X_t W_t) = W_t dX_t + X_t dW_t + 0.5 \cdot 2 dW_t dX_t = W_t^2 dW_t + W_t^2 dt + X_t dW_t + W_t dt$$

- (c) [4]

$$\mathbb{E}(X_t W_t) = 0 + \int_0^t \mathbb{E}(W_u^2 + W_u) du = t^2/2.$$

3. [10 points]

- (a) [3] Using Ito's lemma we obtain

$$dY_t = 0.5 X_t^{-0.5} dX_t - 0.125 X_t^{-1.5} (dX_t)^2 = X_t^{0.5} dt + dW_t$$

Hence, the equation for  $Y_t$  is  $dY_t = Y_t dt + dW_t$ .

- (b) [7] Using Ito's lemma once again we obtain

$$dZ_t = h'(t) Y_t dt + h(t) dY_t = (h'(t) Y_t + h(t) Y_t) dt + h(t) dW_t.$$

If we choose  $h'(t) = -h(t)$  then the  $dt$  term will be zero. Let's do so,  $h(t) = \exp(-t)$ . For  $Z_t = \exp(-t)Y_t$  we have  $dZ_t = \exp(-t)dW_t$ .

$$Z_t = Z_0 + \int_0^t \exp(-u)dW_u$$

From  $X_0 = 1$  we get  $Z_0 = 1$ . Finally,

$$X_t = Y_t^2 = \exp(2t)Z_t^2 = \exp(2t) \left( 1 + \int_0^t \exp(-u)dW_u \right)^2.$$

4. (a) [5] One way to find  $\text{Cov}(Y_{2024\pi}, W_{2024\pi})$  is to use Ito's isometry,

$$\text{Cov}\left(\int_0^t A_u dW_u, \int_0^t 1 dW_u\right) = \int_0^t \mathbb{E}(\text{sign}(\cos u)) du$$

The value  $2024\pi$  contains 1012 full  $2\pi$  periods. Hence the integral is zero.

- (b) [5] Yes,  $(Y_t)$  is a Wiener process.

5. [10 points]

- (a) [3]

$$\mathbb{E}(S_n) = n \mathbb{E}(\Delta_i^A \Delta_i^B) = n \text{Cov}(\Delta_i^A, \Delta_i^B) = n\rho(t-0)/n = \rho t$$

- (b) [5]

$$\lim_{n \rightarrow \infty} \text{Var}(S_n) = 0.$$

- (c) [2] The random sequence  $(S_n)$  tends to  $\rho t$  in mean square and in probability.

- (d) [1]  $dA_t dB_t = \rho dt$ .

6. [10 points] Recall that  $S_t = S_0 \exp((r - \sigma^2/2)t + \sigma W_t^*)$ . The event

$$B = \{S_T/S_{T/2} > S_{T/2}/S_0\}$$

may be written as  $B = \{W_T^* > 2W_{T/2}^*\}$  [5 points].

Hence,

$$X_0 = \exp(-rT) \mathbb{P}^*(W_T^* > 2W_{T/2}^*) = \exp(-rT)/2.$$