

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Electrical Engineering & Computer Science
6.041/6.431: Probabilistic Systems Analysis
(Final Exam | Spring 2009)

Problem 1: True or False (2pts. each, 18 pts. total)

No partial credit will be given for individual questions in this part of the quiz.

- a. Let $\{X_n\}$ be a sequence of i.i.d random variables taking values in the interval $[0, 0.5]$. Consider the following statements:
- (A) If $\mathbf{E}[X_n^2]$ converges to 0 as $n \rightarrow \infty$ then X_n converges to 0 in probability.
 - (B) If all X_n have $\mathbf{E}[X_n] = 0.2$ and $\text{var}(X_n)$ converges to 0 as $n \rightarrow \infty$ then X_n converges to 0.2 in probability.
 - (C) The sequence of random variables Z_n , defined by $Z_n = X_1 \cdot X_2 \cdots X_n$, converges to 0 in probability as $n \rightarrow \infty$.

Which of these statements are **always** true? Write **True** or **False** in each of the boxes below.

A:	B:	C:
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- b. Let X_i ($i = 1, 2, \dots$) be i.i.d. random variables with mean 0 and variance 2; Y_i ($i = 1, 2, \dots$) be i.i.d. random variables with mean 2. Assume that all variables X_i, Y_j are independent. Consider the following statements:
- (A) $\frac{X_1 + \dots + X_n}{n}$ converges to 0 in probability as $n \rightarrow \infty$.
 - (B) $\frac{X_1^2 + \dots + X_n^2}{n}$ converges to 2 in probability as $n \rightarrow \infty$.
 - (C) $\frac{X_1 Y_1 + \dots + X_n Y_n}{n}$ converges to 0 in probability as $n \rightarrow \infty$.

Which of these statements are **always** true? Write **True** or **False** in each of the boxes below.

A:	B:	C:
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- c. We have i.i.d. random variables $X_1 \dots X_n$ with an unknown distribution, and with $\mu = \mathbf{E}[X_i]$. We define $M_n = (X_1 + \dots + X_n)/n$. Consider the following statements:
- (A) M_n is a maximum-likelihood estimator for μ , irrespective of the distribution of the X_i 's.
 - (B) M_n is a consistent estimator for μ , irrespective of the distribution of the X_i 's.
 - (C) M_n is an asymptotically unbiased estimator for μ , irrespective of the distribution of the X_i 's.

Which of these statements are **always** true? Write **True** or **False** in each of the boxes below.

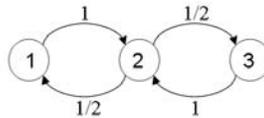
A:	B:	C:
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Problem 2: Multiple Choice (4 pts. each, 24 pts. total)

Clearly circle the appropriate choice. **No partial credit** will be given for individual questions in this part of the quiz.

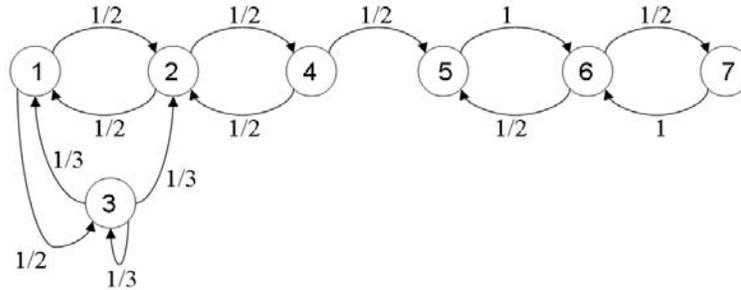
- a. Earthquakes in Sumatra occur according to a Poisson process of rate $\lambda = 2/\text{year}$. Conditioned on the event that exactly two earthquakes take place in a year, what is the probability that both earthquakes occur in the first three months of the year? (for simplicity, assume all months have 30 days, and each year has 12 months, i.e., 360 days).
- (i) $1/12$
 - (ii) $1/16$
 - (iii) $64/225$
 - (iv) $4e^{-4}$
 - (v) There is not enough information to determine the required probability.
 - (vi) None of the above.
- b. Consider a continuous-time Markov chain with three states $i \in \{1, 2, 3\}$, with dwelling time in each visit to state i being an exponential random variable with parameter $\nu_i = i$, and transition probabilities p_{ij} defined by the graph



What is the long-term expected fraction of time spent in state 2?

- (i) $1/2$
- (ii) $1/4$
- (iii) $2/5$
- (iv) $3/7$
- (v) None of the above.

c. Consider the following Markov chain:



Starting in state 3, what is the steady-state probability of being in state 1?

- (i) 1/3
- (ii) 1/4
- (iii) 1
- (iv) 0
- (v) None of the above.

d. Random variables X and Y are such that the pair (X, Y) is uniformly distributed over the trapezoid A with corners $(0, 0)$, $(1, 2)$, $(3, 2)$, and $(4, 0)$ shown in Fig. 1:

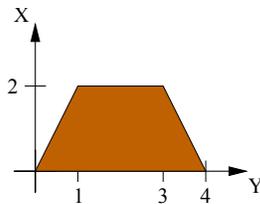


Figure 1: $f_{X,Y}(x, y)$ is constant over the shaded area, zero otherwise.

i.e.

$$f_{X,Y}(x, y) = \begin{cases} c, & (x, y) \in A \\ 0, & \text{else.} \end{cases}$$

We observe Y and use it to estimate X . Let \hat{X} be the least mean squared error estimator of X given Y . What is the value of $\text{var}(\hat{X} - X|Y = 1)$?

- (i) 1/6
- (ii) 3/2
- (iii) 1/3
- (iv) The information is not sufficient to compute this value.
- (v) None of the above.

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- e. $X_1 \dots X_n$ are i.i.d. normal random variables with mean value μ and variance v . Both μ and v are unknown. We define $M_n = (X_1 + \dots + X_n)/n$ and

$$V_n = \frac{1}{n-1} \sum_{i=1}^n (X_i - M_n)^2$$

We also define $\Phi(x)$ to be the CDF for the standard normal distribution, and $\Psi_{n-1}(x)$ to be the CDF for the t-distribution with $n-1$ degrees of freedom. Which of the following choices gives an exact 99% confidence interval for μ for all $n > 1$?

- (i) $[M_n - \delta\sqrt{\frac{V_n}{n}}, M_n + \delta\sqrt{\frac{V_n}{n}}]$ where δ is chosen to give $\Phi(\delta) = 0.99$.
 - (ii) $[M_n - \delta\sqrt{\frac{V_n}{n}}, M_n + \delta\sqrt{\frac{V_n}{n}}]$ where δ is chosen to give $\Phi(\delta) = 0.995$.
 - (iii) $[M_n - \delta\sqrt{\frac{V_n}{n}}, M_n + \delta\sqrt{\frac{V_n}{n}}]$ where δ is chosen to give $\Psi_{n-1}(\delta) = 0.99$.
 - (iv) $[M_n - \delta\sqrt{\frac{V_n}{n}}, M_n + \delta\sqrt{\frac{V_n}{n}}]$ where δ is chosen to give $\Psi_{n-1}(\delta) = 0.995$.
 - (v) None of the above.
- f. We have i.i.d. random variables X_1, X_2 which have an exponential distribution with unknown parameter θ . Under hypothesis H_0 , $\theta = 1$. Under hypothesis H_1 , $\theta = 2$. Under a likelihood-ratio test, the rejection region takes which of the following forms?
- (i) $R = \{(x_1, x_2) : x_1 + x_2 > \xi\}$ for some value ξ .
 - (ii) $R = \{(x_1, x_2) : x_1 + x_2 < \xi\}$ for some value ξ .
 - (iii) $R = \{(x_1, x_2) : e^{x_1} + e^{x_2} > \xi\}$ for some value ξ .
 - (iv) $R = \{(x_1, x_2) : e^{x_1} + e^{x_2} < \xi\}$ for some value ξ .
 - (v) None of the above.

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Problem 3 (12 pts. total)

Aliens of two races (blue and green) are arriving on Earth independently according to Poisson process distributions with parameters λ_b and λ_a respectively. The Alien Arrival Registration Service Authority (AARSA) will begin registering alien arrivals soon.

Let T_1 denote the time AARSA will function until it registers its first alien. Let G be the event that the first alien to be registered is a green one. Let T_2 be the time AARSA will function until at least one alien of both races is registered.

(a) (4 points.) Express $\mu_1 = \mathbf{E}[T_1]$ in terms of λ_g and λ_b . **Show your work.**

(b) (4 points.) Express $p = \mathbf{P}(G)$ in terms of λ_g and λ_b . **Show your work.**

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(c) (4 points.) Express $\mu_2 = \mathbf{E}[T_2]$ in terms of λ_g and λ_b . **Show your work.**

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Problem 4 (18 pts. total)

Researcher Jill is interested in studying employment in technology firms in Dilicon Valley. She denotes by X_i the number of employees in technology firm i and assumes that X_i are independent and identically distributed with mean p . To estimate p , Jill randomly interviews n technology firms and observes the number of employees in these firms.

(a) (6 points.) Jill uses

$$M_n = \frac{X_1 + \cdots + X_n}{n}$$

as an estimator for p . Find the limit of $\mathbf{P}(M_n \leq x)$ as $n \rightarrow \infty$ for $x < p$. Find the limit of $\mathbf{P}(M_n \leq x)$ as $n \rightarrow \infty$ for $x > p$. **Show your work.**

(b) (6 points.) Find the smallest n , the number of technology firms Jill must sample, for which the Chebyshev inequality yields a guarantee

$$\mathbf{P}(|M_n - p| \geq 0.5) \leq 0.05.$$

Assume that $\text{var}(X_i) = v$ for some constant v . State your solution as a function of v . **Show your work.**

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- (c) (6 points.) Assume now that the researcher samples $n = 5000$ firms. Find an approximate value for the probability

$$\mathbf{P}(|M_{5000} - p| \geq 0.5)$$

using the Central Limit Theorem. Assume again that $\text{var}(X_i) = v$ for some constant v . Give your answer in terms of v , and the standard normal CDF Φ . **Show your work.**

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Problem 5 (12 pts. total)

The RandomView window factory produces window panes. After manufacturing, 1000 panes were loaded onto a truck. The weight W_i of the i -th pane (in pounds) on the truck is modeled as a random variable, with the assumption that the W_i 's are independent and identically distributed.

- (a) (6 points.) Assume that the measured weight of the load on the truck was 2340 pounds, and that $\text{var}(W_i) \leq 4$. Find an approximate 95 percent confidence interval for $\mu = \mathbf{E}[W_i]$, using the Central Limit Theorem (you may use the standard normal table which was handed out with this quiz). **Show your work.**

- (b) (6 points.) Now assume instead that the random variables W_i are i.i.d, with an exponential distribution with parameter $\theta > 0$, i.e., a distribution with PDF

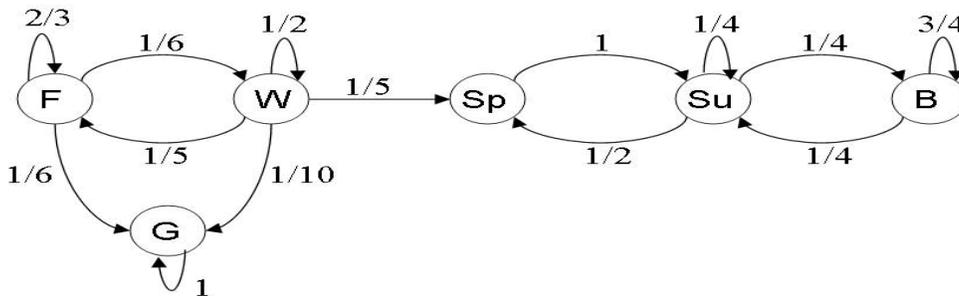
$$f_W(w; \theta) = \theta e^{-\theta w}$$

What is the maximum likelihood estimate of θ , given that the truckload has weight 2340 pounds? **Show your work.**

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Problem 6 (21 pts. total)

In Alice's Wonderland, there are six different seasons: Fall (F), Winter (W), Spring (Sp), Summer (Su), Bitter Cold (B), and Golden Sunshine (G). The seasons do not follow any particular order, instead, at the beginning of each day the Head Wizard assigns the season for the day, according to the following Markov chain model:



Thus, for example, if it is Fall one day then there is $1/6$ probability that it will be Winter the next day (note that it is possible to have the same season again the next day).

(a) (4 points.) For each state in the above chain, identify whether it is recurrent or transient. **Show your work.**

(b) (4 points.) If it is Fall on Monday, what is the probability that it will be Summer on Thursday of the same week? **Show your work.**

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(c) (4 points.) If it is Spring today, will the chain converge to steady-state probabilities? If so, compute the steady-state probability for each state. If not, explain why these probabilities do not exist. **Show your work.**

(d) (5 points.) If it is Fall today, what is the probability that Bitter Cold will never arrive in the future? **Show your work.**

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- (e) (5 points.) If it is Fall today, what is the expected number of days till either Summer or Golden Sunshine arrives for the first time? **Show your work.**

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Problem 7 (12 pts. total)

A newscast covering the final baseball game between Sed Rox and Y Nakee becomes noisy at the crucial moment when the viewers are informed whether Y Nakee won the game.

Let a be the parameter describing the actual outcome: $a = 1$ if Y Nakee won, $a = -1$ otherwise. There were n viewers listening to the telecast. Let Y_i be the information received by viewer i ($1 \leq i \leq n$). Under the noisy telecast, $Y_i = a$ with probability p , and $Y_i = -a$ with probability $1 - p$. Assume that the random variables Y_i are independent of each other.

The viewers as a group come up with a joint estimator

$$Z_n = \begin{cases} 1 & \text{if } \sum_{i=1}^n Y_i \geq 0, \\ -1 & \text{otherwise.} \end{cases}$$

(a) (6 points.)

Find $\lim_{n \rightarrow \infty} \mathbf{P}(Z_n = a)$ assuming that $p > 0.5$ and $a = 1$. **Show your work.**

(b) (6 points.) Find $\lim_{n \rightarrow \infty} \mathbf{P}(Z_n = a)$, assuming that $p = 0.5$ and $a = 1$. **Show your work.**

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