

## PRACTICE MIDTERM EXAM

CSC 412 - WINTER 2023

*University of Toronto*

Exam duration: **2 x 50 minutes**

Please check that your exam has **12 pages**, including this one. The total possible number of points is 100.

Read the following instructions carefully:

1. Exam is closed book and internet. You can use an optional A4 aid sheet - double-sided.
2. If a question asks you to do some calculations, you must **show your work** for full credit.
3. Conceptual questions do not require long answers.
4. You will write your answers to each question in the space provided on the exam sheet. If you require additional paper, simply raise your hand.
5. After solving each question, you should write your answers immediately. Do not wait last minute to write them all at once.
6. Do not share the exam with anyone or in any platform!
7. Lastly, enjoy the problems!!!

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The University of Toronto’s [Code of Behaviour on Academic Matters](#) outlines the behaviours that constitute academic misconduct, the processes for addressing academic offences, and the penalties that may be imposed. You are expected to be familiar with the contents of this document.

Potential offences include, but are not limited to:

- Working together to answer questions.
- Looking at someone else’s answers.
- Letting someone else look at your answers.
- Sharing or posting the exam questions.
- Discussing answers or the exam questions with anyone else in or outside the course.
- Misrepresenting your identity or having someone else complete your exam.

Prior to beginning this exam, you must attest that you will follow the Code of Behaviour on Academic Matters and will not commit academic misconduct in the completion of this exam. Affirm your agreement to this by rewriting the following statement:

*I, \_\_\_\_\_ (your full name), \_\_\_\_\_ (your student number),  
agree to fully abide to the Code of Behaviour on Academic Matters. I will not commit academic  
misconduct, and am aware of the penalties that may be imposed if I commit an academic offence.*

**You must fill in the above statement by hand, with your name and student number, for your exam to be marked. Failing to do so will be considered as “absent in exam”.** All suspected cases of academic dishonesty will be investigated following the procedures outlined in the Code of Behaviour on Academic Matters.

**1. Maximum likelihood estimation and unnormalised models - 10 pts.** Consider a model for three binary random variables  $(x_1, x_2, x_3)$ ,

$$p_\theta(x_1, x_2, x_3) \propto \exp\{\theta x_1 x_2 + \theta x_2 x_3\}, \quad x_i \in \{0, 1\}.$$

1. What is the sufficient statistics of this exponential family?
2. Compute the partition function  $Z(\theta)$  and the derivative of  $A(\theta) = \log Z(\theta)$ .
3. Verify that for the sample  $\{(1, 1, 1), (1, 1, 1), (1, 1, 0), (0, 1, 1), (0, 1, 0)\}$  the maximum likelihood is  $\hat{\theta} = \ln(3)$ . You will not need a calculator for this computation.
4. Compute the joint distribution  $p_{\hat{\theta}}(x_1, x_2, x_3)$  corresponding to this MLE.

**2. Graphical models - 16 pts.** *No explanation needed, just your answers.*

(a) (4 pts) Draw the DAG corresponding to the following factorization of a joint distribution:

$$p(A, B, C, D, E) = P(A)P(B|A)P(C|A)P(D|B, C)P(E|B)$$

(b) (4 pts) Draw the Markov Random Field that corresponds to the following factorization.

$$p(A, B, C, D, E, F) \propto \phi_{A,B,F}(A, B, F)\phi_{B,C,D}(B, C, D)\phi_{D,E,F}(D, E, F)\phi_{B,D,F}(B, D, F)$$

(c) (4 pts) Write the variables that belong to the Markov blanket of node 3 in the Figure 1.

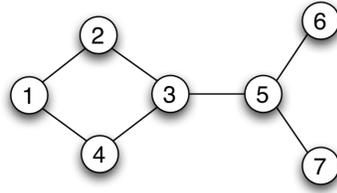


Fig 1: Simple MRF

- (d) (4 pts) Belief propagation algorithm is run on a tree graph to compute the marginal of a node  $x$ .
- How many passes in which direction is sufficient to compute the marginal of  $x$ , given that we choose  $x$  to be the root?
  - How many passes in which direction is sufficient to compute the marginal of  $x$ , given that we choose a root that is not the node  $x$ ?

Here, the direction is either from leaves to root or from root to leaves, and a single pass refers to passing all messages pointing to one direction (either from root to leaves or from leaves to root).

**3. Decision Theory - 5 pts.** Imagine we are running a nuclear power plant that is undergoing a malfunction. We have two options: A) Vent the core, and B) do nothing.

Our current beliefs are that the amount of radiation in the core is uniform between 10 and 20 units, i.e.

$$\text{variant 1: } R|\text{vent} \sim U(10, 20)$$

If we do nothing, there is a  $X\%$  chance that no radiation will be released, and a  $(1 - X)\%$  that 100 units of radiation will be released.

For what range of probabilities  $X$  would venting the core release less radiation in expectation?

**4. Simple Monte Carlo - 12 pts.** Imagine we have a rain prediction model that outputs samples of

$$P(R_1, R_2, \dots, R_T | \text{measurements})$$

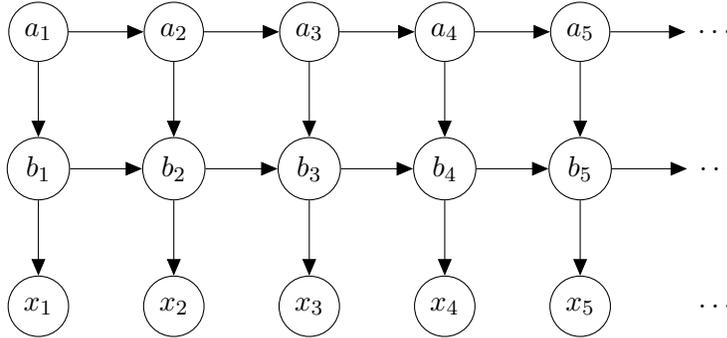
where each  $R_i$  is the predicted probability of rain  $i$  days ahead.

Given a set of  $N$  i.i.d. samples from this joint predictive distribution:

$$(4.1) \quad \begin{aligned} r_1^{(1)}, r_2^{(1)}, \dots, r_T^{(1)} &\sim P(R_1, R_2, \dots, R_T | \text{measurements}) \\ r_1^{(2)}, r_2^{(2)}, \dots, r_T^{(2)} &\sim P(R_1, R_2, \dots, R_T | \text{measurements}) \\ &\vdots \\ r_1^{(N)}, r_2^{(N)}, \dots, r_T^{(N)} &\sim P(R_1, R_2, \dots, R_T | \text{measurements}) \end{aligned}$$

1. **[3 points]** Write an unbiased estimator for the probability that it rains every day for the next  $T$  days. You might want to use the notation  $I(\text{statement})$  which takes value 1 if the statement is true, and 0 if it is false.
2. **[3 points]** What is the variance of this estimator as a function of  $N$ ?
3. **[3 points]** Write an unbiased estimator for the probability that it rains on day 3.
4. **[3 points]** Write an unbiased estimator for the probability that it rains on day 3 given that it rained on day 4.

5. HMM Question - 12 pts. Given the following DAG:



1. [2 points] Write the factorized joint distribution implied by this DAG. Don't be afraid to add extra brackets or parentheses to avoid ambiguity.

$$p(a_1, a_2, \dots, a_T, b_1, b_2, \dots, b_T, x_1, x_2, \dots, x_T) =$$

2. If each variable  $a_i$  can take one of  $K_a$  states, each variable  $b_i$  can take one of  $K_b$  states, and each variable  $x_i$  can take one of  $K_a$  states:

- [2 points] How many states can this set of variables take on?
- [2 points] How many parameters are required to parameterize the joint distribution  $p(a_1, a_2, \dots, a_T, b_1, b_2, \dots, b_T, x_1, x_2, \dots, x_T)$ , again assuming the factorization given by the DAG above? Note that this factorization does not imply that the factors at each time share any parameters. Also recall that for a categorical variable with  $K$  settings, only  $K - 1$  parameters are required.

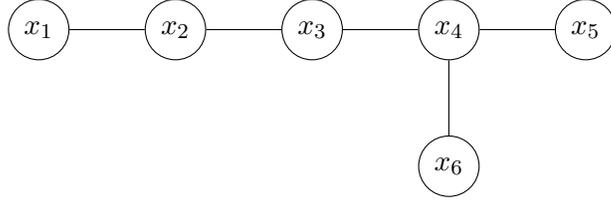
3. [1 point] Is  $x_1 \perp x_2$ ?
4. [1 point] Is  $x_1 \perp x_2 | b_1$ ?
5. [1 point] Is  $x_1 \perp x_2 | b_2$ ?
6. [1 point] Is  $a_1 \perp a_3 | a_2$ ?
7. [1 point] Is  $b_1 \perp b_3 | b_2$ ?
8. [1 point] Is  $b_1 \perp b_3 | a_2, b_2$ ?

**6. Markov chains and their stationary distributions - 15 pts.** Consider a simple two-state Markov chain  $x_0, x_1, x_2, \dots$  with  $x_t \in \{1, 2\}$  given by transition matrix

$$A = \begin{bmatrix} 2/3 & 1/3 \\ 1/2 & 1/2 \end{bmatrix}.$$

1. Find the stationary distribution  $\pi = (\pi_1, 1 - \pi_1)$  of this Markov chain. The stationary distribution is given as the solution to the vector equation  $A^\top \pi = \pi$ .
2. Denote  $p_t = \mathbb{P}(x_t = 1)$ . Find the expression for  $p_{t+1}$  in terms of  $p_t$ .
3. Show that  $p_t$  converges to  $\pi_1$  as  $t \rightarrow \infty$ . You may want to use the fact that for  $|q| < 1$  it holds that  $\sum_{i=0}^{t-1} q^i = \frac{1-q^t}{1-q}$ .
4. Find the exact expression for the distance  $|\pi_1 - p_t|$  in terms of  $t$  and  $p_0$  to get a quantification of how quickly the Markov chain will converge to its stationary distribution.
5. Use the Metropolis-Hastings algorithm that uses this Markov chain to generate draws from the uniform distribution on  $\{1, 2\}$ .

**7. Belief propagation - 20 pts.** Given the following graph of binary variables:



With  $x_4$  being selected as root, having observed  $\bar{x}_6 = 1$ , and given the following potentials:

$\psi_{\text{even}}(x_i) = \begin{pmatrix} 1 \\ 3 \end{pmatrix}$  the node potential for all  $x_i$  where  $i$  is even

$\psi_{\text{odd}}(x_i) = \begin{pmatrix} 4 \\ 2 \end{pmatrix}$  The node potential for all  $x_i$  where  $i$  is odd

$\psi_{i,j}(x_i, x_j) = \begin{bmatrix} 5 & 1 \\ 1 & 5 \end{bmatrix}$  for all  $i, j$

1. (7 points) Calculate the message from 6 to 4:  $m_{6 \rightarrow 4}(x_4)$

2. (7 points) Given the normalized message  $m_{3 \rightarrow 4}(x_3) = \begin{pmatrix} 0.55 \\ 0.45 \end{pmatrix}$  calculate  $m_{4 \rightarrow 5}(x_5)$

3. (6 points) Calculate  $p(x_5 | \bar{x}_6)$

**8. Miscellaneous - 10 pts.**

- (a) (2 pts) Describe the Markov blanket of a set of variables  $A$ . Write the variables that belong to the Markov blanket of node 2 in the Figure 2.

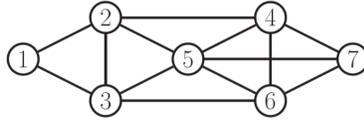


Fig 2: Simple MRF

- (b) (2 pts) Identify all maximal and maximum cliques in the Figure 2.
- (c) (2 pts) Describe the connection between belief propagation and variable elimination on trees.
- (d) (2 pts) Compare the methods Metropolis-Hasting algorithm vs rejection sampling in terms of i) the proposal densities used ii) dependencies among the samples produced.
- (e) (2 pts) In a classification problem over two classes  $\mathcal{C}_1$  and  $\mathcal{C}_2$ , we are minimizing the misclassification error. Figure 3 shows the joint distributions. What is the decision rule that

minimizes misclassification error (no derivation needed).

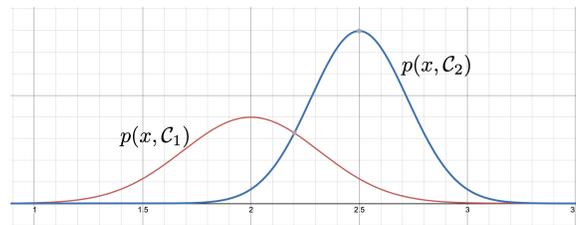


Fig 3: Decision theory