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**Problem Set 1: Probability, Statistics and Inference**


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**Exercise 1** (source: Minka). *My neighbor has two children. Assuming that the gender of a child is like a coin flip, it is most likely, a priori, that my neighbor has one boy and one girl, with probability 1/2. The other possibilities—two boys or two girls—both have probabilities 1/4.*

- *Suppose I ask him whether he has any boys, and he says yes. What is the probability that one child is a girl?*
- *Now suppose that instead of asking him, I happen to see one of his children run by, and it happens to be a boy. What is the probability that the other child is a girl?*

**Exercise 2.** *Show that  $\mathbb{E}\{\text{var}(u|v)\} + \text{var}(\mathbb{E}\{u|v\}) = \text{var}(u)$*

**Exercise 3** (source: Murphy). *The normalization constant for a zero mean Gaussian is given by*

$$Z = \int_a^b \exp\left(-\frac{x^2}{2\sigma^2}\right) dx \quad (1)$$

where  $a = -\infty$  and  $b = \infty$ . *To compute this, consider its square*

$$Z^2 = \int_a^b \int_a^b \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right) dx dy \quad (2)$$

*Then, change variables from cartesian  $(x, y)$  to polar  $(r, \theta)$  using  $x = r \cos \theta$  and  $y = r \sin \theta$ . Since  $dx dy = r dr d\theta$ , and  $\cos^2 \theta + \sin^2 \theta = 1$ , we have*

$$Z^2 = \int_0^{2\pi} \int_0^\infty r \exp\left(-\frac{r^2}{2\sigma^2}\right) dr d\theta \quad (3)$$

*Evaluate the integral and hence show  $Z = \sqrt{\sigma^2 2\pi}$ . Hint: consider the derivative of the integrand.*

**Exercise 4** (source: Murphy). *We say that two random variables are pairwise independent if*

$$p(X_2|X_1) = p(X_2) \quad (4)$$

*and hence*

$$p(X_2, X_1) = p(X_1)p(X_2|X_1) = p(X_1)p(X_2) \quad (5)$$

*We say that  $n$  random variables are mutually independent if*

$$p(X_i|X_S) = p(X_i), \quad \forall S \subseteq \{1, \dots, n\} \setminus \{i\} \quad (6)$$

and hence

$$p(X_{1:n}) = \prod_{i=1}^n p(X_i) \quad (7)$$

Show that pairwise independence between all pairs of variables does not necessarily imply mutual independence. Hint: consider the event space  $\Omega = \{1, 2, 3, 4\}$  where the probability of getting each of the four numbers is  $1/4$ . Consider the set of events  $A = \{1, 2\}$ ,  $B = \{1, 3\}$  and  $C = \{1, 4\}$ . What is the probability of each event? To show pairwise independence, consider the events  $A \cap B$ ,  $B \cap C$  and  $A \cap C$  corresponding to the probability of getting an element which belongs to both subsets. Then consider the probability of the intersection  $A \cap B \cap C$

**Exercise 5** (source: Koller). After your yearly checkup, the doctor has bad news and good news. The bad news is that you tested positive for a serious disease and that the test is 99% accurate (i.e the probability of testing positive given that you have the disease is .99 as is the probability of testing negative given that you don't have the disease). The good news is that this is a rare disease striking only on in 10,000 people. What are the chances that you actually have the disease?

**Exercise 6** (source: CB). The exponential family has interesting properties that are useful in machine learning. Show that each of the following families is an exponential family

- normal family with either parameter  $\mu$  or  $\sigma$  known
- Gamma family with either parameter  $\alpha$  or  $\beta$  known or both unknown
- Beta family with either parameter  $\alpha$  or  $\beta$  known or both unknown
- Poisson family
- negative binomial family with  $r$  known,  $0 < p < 1$ .

**Exercise 7** (source: CB). A man with  $n$  keys wants to open his door and tries the keys at random. Exactly one key will open the door. Find the mean number of trials if

- unsuccessful keys are not eliminated from further selections
- unsuccessful keys are eliminated

**Exercise 8** (source: CB). Let the number of chocolate chips in a certain type of cookie have a Poisson distribution. We want the probability that a randomly chosen cookie has at least two chocolate chips to be greater than .99. Find the smallest value of the mean of the distribution that ensures this probability.

**Exercise 9.** The Maximum likelihood estimator (MLE) which is often denoted as  $\hat{\theta}(\mathbf{x})$  is the parameter value at which the likelihood function  $L(\theta|\mathbf{x})$  attains its maximum as a function of  $\theta$  with  $\mathbf{x}$  fixed. If the likelihood function is differentiable, possible candidates for the MLE are the values of  $(\theta_1, \dots, \theta_k)$  that solve

$$\frac{\partial}{\partial \theta_i} L(\theta|\mathbf{x}) = 0 \quad (8)$$

Let  $X_1, \dots, X_n$  be i.i.d Bernoulli( $p$ ). Then the likelihood function is

$$L(p|\mathbf{x}) = \prod_{i=1}^n p^{x_i} (1-p)^{1-x_i} = p^y (1-p)^{n-y},$$

where  $y = \sum x_i$ . Compute the MLE.

**Exercise 10.** Let  $X_1, \dots, X_n$  be i.i.d normal random variables with fixed variance. I.e,  $X_i \sim \mathcal{N}(\theta, 1)$ . Give the expression of the likelihood function. Then compute the MLE. Set the derivative to zero and prove that you have a maximum.

**Exercise 11.** To verify that a function of two variables  $H(\theta_1, \theta_2)$  has a local maximum at  $(\hat{\theta}_1, \hat{\theta}_2)$ , it must be shown that the following three conditions hold:

- First order partial derivatives must vanish

$$\frac{\partial}{\partial \theta_1} H(\theta_1, \theta_2) \Big|_{\theta_1=\hat{\theta}_1, \theta_2=\hat{\theta}_2} = 0, \quad \text{and} \quad \frac{\partial}{\partial \theta_2} H(\theta_1, \theta_2) \Big|_{\theta_1=\hat{\theta}_1, \theta_2=\hat{\theta}_2} = 0 \quad (9)$$

- At least one second order partial derivative is negative

$$\left| \frac{\partial^2}{\partial \theta_1^2} H(\theta_1, \theta_2) \right|_{\theta_1=\hat{\theta}_1, \theta_2=\hat{\theta}_2} < 0, \quad \text{or} \quad \left| \frac{\partial^2}{\partial \theta_2^2} H(\theta_1, \theta_2) \right|_{\theta_1=\hat{\theta}_1, \theta_2=\hat{\theta}_2} < 0 \quad (10)$$

- The Jacobian of the second-order partial derivatives is positive

$$\begin{vmatrix} \frac{\partial^2}{\partial \theta_1^2} H(\theta_1, \theta_2) & \frac{\partial^2}{\partial \theta_1 \partial \theta_2} H(\theta_1, \theta_2) \\ \frac{\partial^2}{\partial \theta_1 \partial \theta_2} H(\theta_1, \theta_2) & \frac{\partial^2}{\partial \theta_2^2} H(\theta_1, \theta_2) \end{vmatrix} \Big|_{\theta_1=\hat{\theta}_1, \theta_2=\hat{\theta}_2} \quad (11)$$

$$= \frac{\partial^2}{\partial \theta_1^2} H(\theta_1, \theta_2) \frac{\partial^2}{\partial \theta_2^2} H(\theta_1, \theta_2) - \left( \frac{\partial^2}{\partial \theta_1 \partial \theta_2} H(\theta_1, \theta_2) \right)^2 \Big|_{\theta_1=\hat{\theta}_1, \theta_2=\hat{\theta}_2} > 0 \quad (12)$$

Compute the normal MLE when both the mean and the variance are unknown. Then show that your estimator is a local maximum.

**Exercise 12** (source: Jeffrey Miller, Harvard). We consider an uncalibrated sensor from which we acquire data  $X \sim \text{Uniform}(0, \theta)$  for some unknown  $\theta > 0$ . I.e

$$p(x|\theta) = \begin{cases} 1/\theta & \text{if } 0 < x < \theta \\ 0 & \text{otherwise} \end{cases} \quad (13)$$

$$= \frac{1}{\theta} I_{0, \theta}(x) \quad (14)$$

where  $I_{(0, \theta)}(x)$  is the indicator function which equals 1 when  $0 < x < \theta$  and 0 otherwise. We acquire samples  $D = (x_1, \dots, x_n)$ . We would like to estimate the underlying parameter to characterize the distribution.

- Write down the likelihood function for  $p(D|\theta)$ . Find the maximum likelihood estimator for  $\theta$ . As above, prove that your estimator is indeed the MLE.
- We now consider the following prior distribution on  $\theta$ .

$$p(\theta) = \alpha \beta^\alpha \theta^{-\alpha-1} I_{\beta, \infty}(\theta) \quad (15)$$

which is known as a Pareto distribution. Plot the prior densities corresponding to the parameters  $(\alpha, \beta) = \{(0.1, 0.1), (2.0, 0.1), (1.0, 2.0)\}$

- We still assume that the data follows a uniform distribution ( $X_1, \dots, X_n \sim \text{Uniform}(0, \theta)$ ) but we consider uncertainty on the parameter which we encode through the Pareto distribution, i.e.  $\theta \sim \text{Pareto}(\alpha, \beta)$ . Write down the posterior distribution  $p(\theta|D)$ . Does it belong to a family of distribution you know?
- Using the posterior from the previous point, derive the MAP for  $\theta$ .

- The square loss is defined as  $L(\theta, \hat{\theta})$ . For the Pareto posterior, what estimator of  $\theta$  minimizes the posterior expected loss (i.e. the posterior loss averaged over all possible values of  $\theta$ )? Simplify your answer as much as possible. How does it compare to the MLE? What about the MAP?
- Suppose the data you observe is given by  $D = \{0.7, 1.3, 1.7\}$ . Plot the density of the posterior distribution of  $\theta$  for each of the three Pareto priors used in the second point. For each of those three priors, what is the MAP estimator? What estimator minimizes the posterior expected loss?