

Final Review Sheet Answers

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Spring 2019

The proofs/calculations of most exercises here are omitted. Again, refer to your notes if unsure; all of the theoretical results have been discussed in lecture notes or in the textbook.

1 Fundamental Techniques

1. *Rules of probability:*

$$\text{Conditional probability/Bayes' Rule: } P(A|B) = \frac{P(AB)}{P(B)} = \frac{P(A)P(B|A)}{P(B)}$$

$$\text{DeMorgan's Laws: } P(\{A \cup B\}^c) = 1 - P(A^c \cap B^c),$$

$$P(\{A \cap B\}^c) = 1 - P(A^c \cup B^c) = 1 - (P(A^c) + P(B^c) - P(A^c B^c))$$

2. *Constant and variable parts of densities:*

$$X \sim \text{Gamma}(4, 6); \int_0^\infty 5x^3 e^{-6x} dx = 5\left(\frac{\Gamma(3)}{6^4}\right)$$

3. *Independence and dependence:*

To check that two events A, B are independent, we might check that $P(AB) = P(A)P(B)$, or equivalently, $P(A) = P(A|B)$.

For two variables to be independent, in the discrete case, we must show that $P(X = x, Y = y) = P(X = x)P(Y = y)$. In the continuous case, we may show that $f_X(x, y) = f_X(x)f_Y(y)$, **and** that the support of X and Y do not depend on each other (i.e., for all (x, y) , we have that $f_{X,Y}(x, y) > 0$ if and only if $f_X(x) > 0$ and $f_Y(y) > 0$.)

An easy way to show that two variables are dependent is to find x, y such that $P(Y = y) > 0$ but $P(Y = y|X = x) = 0$. The idea is to find a value of X that makes a particular value of Y impossible. (A similar result holds in the continuous case.)

4. *Working with densities:*

(a) The CDF of X is given by $F_X(x) = \int_{-\infty}^x f_X(t)dt$. By the fundamental theorem of calculus, it follows that $f_X(x) = F'_X(x)$.

(b) $f_X(x) = \int_{-\infty}^{\infty} f_{X,Y}(x, y)dy$

(c) $f_{X|Y}(x|y) = f_{X,Y}(x, y)/f_Y(y)$. Note this does not necessarily require the marginal density of X , f_X , to calculate!

2 Relationships Between Distributions

1. cX , where $X \sim \text{Exp}(\lambda)$, $c > 0$:

$\text{Exp}(\frac{\lambda}{c})$. The methods we have used include using the CDF of X , using the change of variable method, and using the MGF of X and properties of MGFs.

2. Consider $X = U_{(3)}$ and $Y = U_{(7)}$, the 3rd and 7th order statistics of 10 iid Unif $(0, 1)$ RVs. What is the distribution of X/Y ?

We proved in lecture that for this type of example (ratio of joint Uniform $(0,1)$ order statistics, where the numerator is the smaller one), the resulting distribution is a Beta. In particular, this example follows the Beta $(3,4)$ distribution.

3. $X^2 + Y^2$, where X, Y are independent standard Normal. What is $\sqrt{X^2 + Y^2}$?

Exp $(\frac{1}{2})$; standard Rayleigh

4. $2X + 3Y$, where X, Y independent Normal (μ, σ^2) . What if X, Y are bivariate normal with correlation $\rho = 0.6$?

$2X + 3Y \sim \mathcal{N}(5\mu, 13\sigma^2)$ if $\rho = 0$; $2X + 3Y \sim \mathcal{N}(5\mu, (13 + 7.2)\sigma^2)$ if $\rho = 0.6$

5. Consider each of the following common discrete distributions: Poisson, Binomial, Geometric, and Hypergeometric. For which of these is the sum of two independent RVs a known distribution? Under what conditions?

Excluding the degenerate cases (e.g., $p = 0$ or $p = 1$), this holds for the first 3 distributions. For Binomial, the p values must be the same, in which case the n 's are added; for the Geometric the result is Negative Binomial provided the p values are the same.

3 Symmetry

1. Under some conditions, we can quickly recognize the expectation of a random variable X to be zero. What are they?

The distribution/density of X must be symmetric about the origin, and $\mathbb{E}(|X|) < \infty$; i.e. the expectation must be defined.

2. Find the probability that the last ace in a standard, well-shuffled deck is at position 47 or greater.

Using symmetry between the front and back of the deck, this answer is

$$1 - P(\text{no aces in first 6}) = 1 - \frac{\binom{4}{0} \binom{48}{6}}{\binom{52}{6}}$$

3. You and I each roll a fair n sided die. Without using a summation, find the probability your roll is strictly greater than mine.

$P(X < Y) = P(X > Y)$, and $P(X < Y) + P(X > Y) + P(X = Y) = 1$. Therefore,

$$P(X > Y) = \frac{1 - \frac{1}{n}}{2}$$

4. Let X, Y be independent $\mathcal{N}(0, \sigma^2)$ random variables. Without using Φ , find $P(X + 2Y > 0, X > 0)$. What is the reason behind this answer?

Using the rotational symmetry of the joint distribution of (X, Y) ,

$$P(X + 2Y > 0, X > 0) = \frac{\frac{\pi}{2} + \arctan(\frac{1}{2})}{2\pi}$$

5. Let X_1, X_2, \dots, X_n be identically distributed, exchangeable variables such that their sum is always a constant. Find $\text{Corr}(X_i, X_j)$ for $i \neq j$.

$\text{Corr}(X_i, X_j) = -1/(n - 1)$.

4 To Infinity, and Beyond

1. Let $X \sim \text{Geom}(p)$ on $\{1, 2, \dots\}$. It is not easy to directly find $\mathbb{E}(X)$ using the formula $\sum_{x=1}^{\infty} xP(X=x)$. We have shown three alternate methods for finding this expectation; what are they?

The three methods are (i) the tail sum formula for expectations of discrete RVs, (ii) using the MGF of a Geometric, and (iii) conditioning on the result of the first toss.

2. Two players simultaneously toss coins which land heads with probabilities p_1 and p_2 respectively. They continue until exactly one player's coin lands heads; that player is the winner. Show that the probability Player 1 wins is $\frac{p_1 q_2}{p_1 q_2 + q_1 p_2}$.

Hint: write this out as a sequence of tosses. For the first player to win on the n^{th} toss, what has to happen?

3. Find $\mathbb{E}(X(X-1))$ for $X \sim \text{Pois}(\mu)$.

Using the function rule, we observe that this value is μ^2 .

4. Let Y have density $f_Y(y) = \frac{\lambda}{2} e^{-\lambda|y|}$, for $y \in \mathbb{R}$. With little computation, find $\mathbb{E}(|Y|)$ and $\mathbb{E}(Y)$.

If we look at the graph of the density of Y , or through the change-of-variable formula, we observe that $|Y| \sim \text{Exp}(\lambda)$. Thus $\mathbb{E}(|Y|) = \frac{1}{\lambda}$, and $\mathbb{E}(Y) = 0$ by symmetry.

5 Could You Rephrase That?

1. Suppose there are $3n$ people in a room, divided into groups of 3. What is the chance that there is at least one group where two members share the same birthday?

$$1 - \left(\frac{364 \cdot 363}{365^2} \right)^n$$

2. Continued from (a): Approximate this chance for large n .

We use a Poisson approximation, with $p = P(\text{shared b-day in group}) = 1 - \frac{364 \cdot 363}{365^2}$. Then this probability from (a) is approximately $1 - e^{-np}$ for large n .

3. Let $X \sim \text{Gamma}(r, \lambda)$, where r is an integer. Use what we know about the Poisson process to obtain the CDF of X .

$$\begin{aligned} P(X < t) &= P(N_t \geq r) \\ &= 1 - P(N_t < r) \\ &= 1 - \sum_{k=0}^{r-1} e^{-\lambda t} \frac{(\lambda t)^k}{k!} \end{aligned}$$

4. Let X be an arbitrary random variable with an invertible CDF F_X . What is the random variable formed by $F_X(X)$?

Let $Z = F_X(X)$. Then,

$$\begin{aligned} F_Z(z) &= P(Z \leq z) \\ &= P(F_X(X) \leq z) \\ &= P(F_X^{-1}(F_X(X)) \leq F_X^{-1}(z)) \\ &= P(X \leq F_X^{-1}(z)) \\ &= F_X(F_X^{-1}(z)) \\ &= z, \quad z \in [0, 1] \end{aligned}$$

We conclude that $Z \sim \text{Unif}(0,1)$.

6 Some Useful Results

1. Let $X \sim \text{Pois}(\mu)$, $Y \sim \text{Pois}(\lambda)$, $X \perp Y$. What is the distribution of $X + Y$? (Hint: use the binomial theorem, $(x + y)^n = \sum_{k=0}^n \binom{n}{k} x^k y^{n-k}$.) $X + Y \sim \text{Pois}(\mu + \lambda)$
2. Use Markov's Inequality to derive Chebyshev's Inequality. See pg. 191 – 192 in Pitman's *Probability*.
3. Let $X \sim \text{Exp}(\lambda_X)$, $Y \sim \text{Exp}(\lambda_Y)$. What is $P(X < Y)$? $\frac{\lambda_X}{\lambda_X + \lambda_Y}$
4. Find the distribution of $\min\{X_1, X_2, \dots, X_n\}$, where the X_i 's are independent $\text{Exp}(\lambda)$ variables.
Let M denote the minimum. Then $M \sim \text{Exp}(n\lambda)$. Note this result generalizes to the case where the rates are all different; you simply add the rate parameters.
5. Suppose cars and trucks arrive at a bridge according to independent Poisson processes with rates λ_c and λ_r per minute respectively. Given that n vehicles arrive in t minutes, what is the distribution of $N_{c,t}$, the number of cars to arrive by time t ?

The easiest way to proceed here is using the conditional probability rule. We find that $N_{c,t} | N_t = n \sim \text{Binom}(n, \frac{\lambda_c}{\lambda_c + \lambda_r})$.