

## STA2603 Distribution Theory II

Always specify the domain of the function!

Always specify the parameters when identifying the distribution!

### Study Unit 2

Frequency Function (discrete) = density function (continuous). Distribution function is CDF.

#### Discrete Random Variables

Distribution	Mass function $p_X(k)$	$M_X(t)$ mgf	Mean & Variance
Bernoulli $ber(p)$	$\begin{cases} p^k (1-p)^{1-k} & k = 0; 1 \\ 0 & \text{elsewhere} \end{cases}$	$(1-p + pe^t)$	$\begin{aligned} \mu_X &= p \\ \sigma_X^2 &= p(1-p) \end{aligned}$
Binomial $b(n; p)$	$\begin{cases} \binom{n}{x} p^x (1-p)^{n-x} & x = 0; 1; \dots; n \\ 0 & \text{elsewhere} \end{cases}$	$(1-p + pe^t)^n$	$\begin{aligned} \mu_X &= np \\ \sigma_X^2 &= np(1-p) \end{aligned}$
Geometric $geo(p)$	$\begin{cases} (1-p)^{x-1} p, & x = 1; 2; 3; \dots \\ 0 & \text{elsewhere} \end{cases}$	$\frac{pe^t}{1 - (1-p)e^t}$	$\begin{aligned} \mu_X &= \frac{1}{p} \\ \sigma_X^2 &= \frac{1-p}{p^2} \end{aligned}$
Negative Binomial $nb(r; p)$	$\begin{cases} \binom{k-1}{r-1} p^r (1-p)^{k-r}, & k = 1; 2; \dots \\ 0 & \text{elsewhere} \end{cases}$	$\left[ \frac{pe^t}{1 - (1-p)e^t} \right]^r$	$\begin{aligned} \mu_X &= \frac{r}{p} \\ \sigma_X^2 &= \frac{r(1-p)}{p^2} \end{aligned}$
Poisson $Po(\lambda)$	$\begin{cases} \frac{\lambda^k}{k!} e^{-\lambda}, & k = 0; 1; \dots \\ 0 & \text{elsewhere} \end{cases}$	$e^{\lambda(e^t - 1)}$	$\begin{aligned} \mu_X &= \lambda \\ \sigma_X^2 &= \lambda \end{aligned}$

1.  $p_X(x_i) \geq 0$
2.  $\sum_{x=0}^{\infty} p_X(x) = 1$

#### Bernoulli Random Variables

Indicator random variable  $I_A(\omega) = \begin{cases} 1 & \omega \in A \\ 0 & \text{otherwise} \end{cases}$

$$p_X(x) = \begin{cases} 1-p & \text{if } x=0 \\ p & \text{if } x=1 \\ 0 & \text{otherwise} \end{cases}$$

$$F_X(x) = \begin{cases} 0 & \text{if } x < 0 \\ 1-p & \text{if } 0 < x < 1 \\ 1 & \text{if } x > 1 \end{cases}$$

## Binomial Distribution

The sum of independent Bernoulli variables is a binomial random variable.

To prove binomial probabilities sums to 1. Use finite binomial series expansion:

$$\begin{aligned}
 (a+b)^n &= a^n + \binom{n}{1} a^{n-1}b + \binom{n}{2} a^{n-2}b^2 + \dots + \binom{n}{n-1} a^{n-(n-1)}b^{n-1} + \binom{n}{n} a^{n-n}b^n \\
 &= (a+b)^n = a^n + \binom{n}{1} a^{n-1}b + \binom{n}{2} a^{n-2}b^2 + \dots + b^n \\
 &= \sum_{x=0}^n \binom{n}{x} a^{n-x} b^x
 \end{aligned}$$

and therefore it is a series expansion of  $[(1-p) + p]^n$

## Geometric Distribution

To prove that geometric distribution sums to 1, use Taylor series at  $x=0$

$$\begin{aligned}
 (1-p)^{-1} &= 1 + \frac{(-1)}{1!} (-p) + \frac{(-1)(-1-1)}{2!} (-p)^2 + \frac{(-1)(-1-1)(-1-2)}{3!} (-p)^3 + \dots \\
 &= 1 + p + p^2 + p^3 + p^4 + \dots \\
 p \sum_{x=1}^{\infty} (1-p)^{x-1} &= p \sum_{r=0}^{\infty} (1-p)^r \\
 &= p \left[ 1 + (1-p) + (1-p)^2 + (1-p)^3 + \dots \right] \\
 &= p (1 - (1-p))^{-1} \\
 &= \frac{p}{p} \\
 &= 1
 \end{aligned}$$

**Negative Binomial Distribution**

A negative binomial random variable can be expressed as the sum of  $r$  independent geometric variables.

**Hypergeometric distribution**

$$pX(x) = \begin{cases} \frac{\binom{r}{x} \binom{n-r}{m-x}}{\binom{n}{m}} & \text{if } x = 0, 1, 2, \dots, n \\ 0 & \text{otherwise} \end{cases}$$

**Poisson Distribution**

To show it is a frequency function:

$$e^\lambda = 1 + \lambda + \frac{\lambda^2}{2!} + \frac{\lambda^3}{3!} + \frac{\lambda^4}{4!} + \dots$$

$$= \sum_{x=0}^{\infty} \frac{\lambda^x}{x!}$$

$$\sum_{x=0}^{\infty} \frac{\lambda^x}{x!} e^{-\lambda} = e^\lambda e^{-\lambda} = 1.$$

Poisson distribution can be used to approximate binomial distribution, if  $n$  is large and  $p$  is small.

**Continuous Random Variables**

1.  $F_X(x)$  is a non-decreasing function
2.  $\lim_{x \rightarrow -\infty} F_X(x) = 0$
3.  $\lim_{x \rightarrow \infty} F_X(x) = 1$
4.  $F_X(x)$  is everywhere continuous

$$P(a < X < b) = \int_a^b f_X(x) dx$$

1.  $f_X(x) \geq 0$  and
2.  $\int_{-\infty}^{\infty} f_X(x) dx = 1$

$$P(a < X < b) = P(a \leq X \leq b) = P(a \leq X < b) = P(a < X \leq b)$$

The  $p$ th quantile:  $F(x_p) = p$  or  $P(X \leq x_p) = p$  and  $x_p = F^{-1}(p)$

## Exponential Density

## Gamma Density

Gamma function  $\Gamma(a) = \int_0^{\infty} x^{a-1} e^{-x} dx$  Properties  $\Gamma(\alpha + 1) = \alpha \Gamma(\alpha)$   $\Gamma(\frac{1}{2}) = \sqrt{\pi}$   $c^n \Gamma(n) = \int_0^{\infty} x^{n-1} e^{-\frac{x}{c}} dx$   
 $\Gamma(2) = 1$

If  $\alpha = 1$  then it becomes exponential density

If  $\lambda = 1$  then it is a one parameter gamma density

$$\begin{aligned} \int_{-\infty}^{\infty} \frac{\lambda^\alpha}{\Gamma(\alpha)} t^{\alpha-1} e^{-\lambda t} dt &= \frac{\lambda^\alpha}{\Gamma(\alpha)} \int_0^{\infty} t^{\alpha-1} e^{-\lambda t} dt \\ &= \frac{\lambda^\alpha}{\Gamma(\alpha)} \int_0^{\infty} t^{\alpha-1} e^{-t/\frac{1}{\lambda}} dt \\ &= \frac{\lambda^\alpha}{\Gamma(\alpha)} \Gamma(\alpha) \left(\frac{1}{\lambda}\right)^\alpha \\ &= 1. \end{aligned}$$

## Normal (Gaussian) distribution

## Beta Density

Beta function:  $B(m, n) = \int_0^1 x^{m-1} (1-x)^{n-1} dx$  or  $B(m, n) = \int_0^{\infty} \frac{x^{n-1}}{(1+x)^{m+n}} dx$

To prove density function:

For  $0 < x < 1$  and  $m > 0, n > 0$

$$\begin{aligned} \int_0^1 \frac{1}{B(m, n)} x^{m-1} (1-x)^{n-1} dx &= \frac{1}{B(m, n)} B(m, n) \\ &= 1. \end{aligned}$$

$$\begin{aligned} B(m+1; n+1) &= \frac{m\Gamma(m) n\Gamma(n)}{(m+n+1)\Gamma(m+n+1)} \\ &= \frac{mn}{(m+n+1)(m+n)} \times \frac{\Gamma(m)\Gamma(n)}{\Gamma(m+n)} \\ &= \frac{mn}{(m+n+1)(m+n)} B(m; n). \end{aligned}$$

### Different characteristics of the beta function

Characteristic	Comment	Proof / Examples	Ref no
Type 1 beta function $\int_0^1 x^{m-1} (1-x)^{n-1} dx$ $= B(m; n)$	Recognize and use beta integral in integration	$\int_0^1 x^5 (1-x)^6 dx$ $= \int_0^1 x^{6-1} (1-x)^{7-1} dx$ $= B(6; 7)$	B1
Symmetry with respect to the parameters $m > 0; n > 0$	$B(m; n) = B(n; m)$		B2
Relationship between beta and gamma functions	$m > 0; n > 0$ <b>Numerical value for any beta function</b>	$B(m; n) = \frac{\Gamma(m)\Gamma(n)}{\Gamma(m+n)}$	B4
Changing the limits of the integral from $\int_0^1 \dots$ to $\int_0^{\infty} \dots$	$\int_0^{\infty} \frac{x^{n-1}}{(1+x)^{m+n}} dx$ $= B(m; n)$ which is a type 2 beta function	$\int_0^{\infty} \frac{x^3}{(1+x)^5} dx$ $= \int_0^{\infty} \frac{x^{4-1}}{(1+x)^{4+1}} dx$ $= B(4; 1)$	

## Functions of random Variables

Standard normal CDF =  $\Phi(X)$     Standard normal density =  $\phi(X)$

**Proposition A:** if  $X \sim N(\mu, \sigma^2)$  and  $Y = aX + b$ , then  $Y \sim N(a\mu + b, a^2\sigma^2)$

### PROPOSITION B

Let  $X$  be a continuous random variable with density  $f(x)$  and let  $Y = g(X)$  where  $g$  is a differentiable, strictly monotonic function on some interval  $I$ . Suppose that  $f(x) = 0$  if  $x$  is not in  $I$ . Then  $Y$  has the density function

$$f_Y(y) = f_X(g^{-1}(y)) \left| \frac{d}{dy} g^{-1}(y) \right|$$

for  $y$  such that  $y = g(x)$  for some  $x$ , and  $f_Y(y) = 0$  if  $y \neq g(x)$  for any  $x$  in  $I$ . Here  $g^{-1}$  is the inverse function of  $g$ ; that is,  $g^{-1}(y) = x$  if  $y = g(x)$ . ■

### PROPOSITION C

Let  $Z = F(X)$ ; then  $Z$  has a uniform distribution on  $[0, 1]$ .

#### Proof

$$P(Z \leq z) = P(F(X) \leq z) = P(X \leq F^{-1}(z)) = F(F^{-1}(z)) = z$$

This is the uniform cdf. ■

### PROPOSITION D

Let  $U$  be uniform on  $[0, 1]$ , and let  $X = F^{-1}(U)$ . Then the cdf of  $X$  is  $F$ .

#### Proof

$$P(X \leq x) = P(F^{-1}(U) \leq x) = P(U \leq F(x)) = F(x) \quad \blacksquare$$

$$[N(0, 1)]^2 \sim \chi_1^2$$

$$\text{Weibull density: } \frac{\beta}{\alpha^\beta} x^{\beta-1} e^{-\left(\frac{x}{\alpha}\right)^\beta}$$

## Study Unit 3: Joint Distributions

### Discrete Random Variables

$$p_{XY}(x, y) = P(X = x, Y = y)$$

$$1. \quad p_{X,Y}(x, y) \geq 0 \quad \text{for all } (x, y) \in \mathbb{R}^2$$

$$2. \quad \sum_{x=0}^{n_1} \sum_{y=0}^{n_2} p_{X,Y}(x, y) = 1$$

### Continuous Random Variables

Marginal density.

$$1. \quad f_{X,Y}(x, y) \geq 0 \quad \text{for all } (x, y) \in \mathbb{R}^2$$

$$2. \quad \int \int_S f_{X,Y}(x, y) dy dx = 1$$

$$f_{X,Y}(x; y) = \frac{\partial^2}{\partial x \partial y} F_{X,Y}(x; y).$$

$$f_X(x) = \int_{-\infty}^{\infty} f_{X,Y}(x; v) dv \quad \text{for all } x \in \mathbb{R}$$

$$f_Y(y) = \int_{-\infty}^{\infty} f_{X,Y}(u; y) du \quad \text{for all } y \in \mathbb{R}$$

### Marginals sum to 1

Joint cumulative distribution.

$$\begin{aligned} F_{X,Y}(x; y) &= P(X < x; Y < y) \\ &= \int_{-\infty}^y \int_{-\infty}^x f_{X,Y}(u; v) du dv \end{aligned}$$

### Independent Random variables

Independent if  $F(x, y) = F_X(x)F_Y(y)$

Two discrete random variables will be independent if their joint mass function factors.

### Conditional Distributions

Discrete:

The law of total probability.  $p_X(x) = \sum_y p_{X|Y}(x|y)p_Y(y)$

Continuous:

The law of total probability.  $f_Y(y) = \int_{-\infty}^{\infty} f_{Y|X}(y|x)f_X(x) dx$