Elementary Probability Review Continued
DATA 5600, Spring 2022

This is a review of elementary probability that will be useful for our study of regression analysis. It is based on coverage Wooldridge (2004).

The **cumulative distribution function** (**CDF**) of the random variable X is:

$$F(X) = P(X \leq x)$$

For discrete random variables it is obtained by summing the PDF over all values x_j such that $x_j \leq x$.

For a continuous random variable, $F(X)$ is the area under the PDF, $f(x)$ to the left of x.

Because it is a probability, $0 \leq F(X) \leq 1$.

If $x_1 < x_2$ then $P(X \leq x_1) \leq P(X \leq x_2)$, that is $F(x_1) \leq F(x_2)$.

Two important properties of CDFs that are useful for computing probabilities are the following:

- For and number c, $P(X > c) = 1 - F(c)$
- For any numbers a and b, $P(a \leq X \leq b) = F(b) - F(a)$

For continuous random variables the inequalities in probability statements are not strict:

$$P(X \geq c) = P(> c)$$

$$\begin{aligned} P(a < X < b) &= P(a \leq X \leq b) \\ &= P(a \leq X < b) \\ &= P(a < X \leq b) \end{aligned}$$

Let X and Y be discrete random variables. Then for (X, Y) a **joint distribution** which is fully described by the **joint probability density function** of (X, Y):

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

X and Y are said to be independent if, and only if:

$$f_{XY}(x, y) = f_X(x) f_Y(y) \quad \text{for every } x \text{ and } y$$

where f_X is the PDF of the random variable X, and f_Y is the PDF of random variable Y.

f_X and f_Y are referred to as the **marginal probability density functions**.

The discrete case is the easiest to grok. If X and Y are discrete and independent then

$$P(X = x, Y = y) = P(X = x)P(Y = y)$$

Note: If X and Y are independent then finding the joint PDF only requires knowledge of $P(X = x)$ and $P(Y = y)$

Example: Consider a basketball player shooting two free throws. Let X be the Bernoulli random variable equal to 1 if he makes the first free throw, and 0 otherwise. Let Y be the Bernoulli random variable equal to 1 if he makes the second free throw. Suppose that he is an 80% free throw shooter, so that $P(X = 1) = P(Y = 1) = 0.80$. What is the probability of making both free throws?

If X and Y are independent: $P(X = 1, Y = 1) = P(X = 1)P(Y = 1) = (0.8)(0.8) = 0.64$. Thus, a 64% chance of making both.

Independence is often reasonable in more complicated situations. In the airline example, suppose that n is the number of reservations booked. For each $i = 1, 2, \ldots, n$ let Y_i denote the Bernoulli random variable indicating whether or not customer i shows up for the flight.

Let θ again denote the probability of success (showing up for the reservation). Each $Y_i \sim$ Bernoulli(θ).

The variable of primary interest is the total number of customers showing up out of the n reservations: call this X.

$$X = Y_1 + Y_2 + \ldots + Y_n$$

Assume that $P(Y_i = 1) = \theta$ for every Y_i, and further that they Y_i are independent. Then X has a **binomial distribution**, which we write in shorthand as: $X \sim$ Binomial(n, θ). The binomial PDF is the following:

$$f(x) = \binom{n}{x}\theta^x(1-\theta)^{n-x} \quad \text{for } x = 0, 1, 2, \ldots, n$$

Note: $\binom{n}{x} = \frac{n!}{x!(n-x)!}$, and is read as "n choose x".

Example: If the flight has 100 seats and $n = 120$ and $\theta = 0.85$ then:

$$P(X > 100) = P(X = 101) + P(X = 102) + \ldots + P(X = 120)$$

In econometrics we are usually interested in how one variable Y is related to one or more other variables. For now, consider only one such variable X. What we can know about how X affects Y is contained in the **conditional distribution** of Y given X. This information is summarized in the **conditional probability distribution function**:

$$f_{Y|X}(y|x) = \frac{f_{XY}(x, y)}{f_X(x)}$$

In the discrete case: $f_{Y|X}(y|x) = P(Y = y|X = x)$, which we read as the probability that $Y = y$ given that $X = x$.

If X and Y are independent, then the knowledge of X tells us nothing about Y:

$$\begin{aligned} f_{Y|X}(y|x) &= f_Y(y) \quad \text{and} \\ f_{X|Y}(x|y) &= f_X(x) \end{aligned}$$

Example: Free throw shooting again. Assume the conditional PDF is given by the following:

$f_{Y|X}(1|1) = 0.85$, and $f_{Y|X}(0|1) = 0.15$.

$f_{Y|X}(1|0) = 0.70$, and $f_{Y|X}(0|0) = 0.30$.

These are not independent. The probability of making the second free throw depends on whether or not the first free throw was made. We can calculate $P(X = 1, Y = 1)$ if we know $P(X = 1)$. Assume the probability of making the first free throw is $P(X = 1) = 0.80$. Then:

$$\begin{aligned} P(X = 1, Y = 1) &= P(Y = 1|X = 1) \times P(X = 1) \\ &= (0.85) \times (0.80) \\ &= 0.68 \end{aligned}$$

The **expected value** is a measure of central tendency. It is one of the most important probabilistic concepts in econometrics. If X is a random variable the **expected value** (or expectation) of X, denoted $E(X)$ and sometimes μ, is a weighted average of all possible values of X. The weights are determined by the PDF.

Consider the case of a discrete random variable. Let $f(x)$ denote the PDF of X. The expected value of X is the weighted average:

$$E(X) = x_1 f(x_1) + x_2 f(x_2) + \ldots + x_k f(x_k) = \sum_{j=1}^{k} x_j f(x_j)$$

Example: Suppose X takes on the values -1, 0, and 2 with probabilities $\frac{1}{8}$, $\frac{1}{2}$, $\frac{3}{8}$. Then

$$E(X) = (-1)(\frac{1}{8}) + (0)(\frac{1}{2}) + (2)(\frac{3}{8}) = \frac{5}{8}$$

Note: $E(X)$ can take on values that are not even possible outcomes of X.

If X is a continuous random variable then

$$E(X) = \int_{-\infty}^{\infty} x f(x) dx$$

This is still interpreted as a weighted average.

Given a random variable X and a function $g(\cdot)$, we can create a new random variable $g(X)$. For example, if X is a random variable, then so is X^2 or $log(X)$ (for $x > 0$).

The expected value of $g(X)$ is given by

$$E[g(X)] = \sum_{j=1}^{k} g(x_j) f_X(x_j)$$

or

$$E[g(X)] = \int_{-\infty}^{\infty} g(x) f_X(x) dx$$

Example: For the random variable above let $g(X) = X^2$. Then

$$E(X^2) = (-1)^2(\frac{1}{8}) + (0)^2(\frac{1}{2}) + (2)^2(\frac{3}{8}) = \frac{13}{8}$$

Note: $E[g(X)] \neq g[E(X)]$.

Properties of Expected Values:

Property E1: For any constant c, $E(c) = c$.

Property E2: For any constants a and b, $E(aX + b) = aE(X) + b$.

Property E3: If $a_1, a_2, \ldots, a_n$ are constants and $X_1, X_2, \ldots, X_n$ are random variables then:

- $E(a_1X_1 + a_2X_x + \ldots + a_nX_n) = a_1E(X_1) + a_2E(X_2) + \ldots + a_nE(X_n)$
- Or $E(\sum_{i=1}^{n} a_iX_i) = \sum_{i=1}^{n} a_iE(X_i)$
- A special case is when each $a_i = 1$ so that $E(\sum_{i=1}^{n} E(X_i)) = \sum_{i=1}^{n} E(X_i)$, or in other words the expected value of a sum, is the sum of the expected values.

Example: Expected revenue at a pizzeria. X_1, X_2, and X_3 are the number of small, medium, and large pizzas sold during the day. Suppose $E(X_1) = 25$, $E(X_2) = 57$, and $E(X_3) = 40$. Prices are \$5.50 for a small, \$7.60 for a medium, and \$9.15 for a large. Then expected revenue is the following

$$\begin{aligned} E(5.50X_1 + 7.60X_2 + 9.15X_3) &= 5.50E(X_1) + 7.60E(X_2) + 9.15E(X_3) \\ &= 5.50(25) + 7.60(57) + 9.15(40) \\ &= 936.70 \end{aligned}$$

The outcome on any given day will differ from this, but this is the expected revenue.

If $X \sim \text{Binomial}(n, \theta)$ then $E(X) = n\theta$. The expected number of successes in n Bernoulli trials is $n\theta$. We can see this by writing

$$X = Y_1 + Y_2 + \ldots + Y_n \quad \text{where each } Y_i \sim \text{Bernoulli}(\theta)$$

Then

$$\begin{aligned} E(X) &= \sum_{i=1}^{n} E(Y_i) \\ &= \sum_{i=1}^{n} \theta \\ &= n\theta \end{aligned}$$

Example: Consider the airline problem with $n = 120$ and $\theta = 0.85$. Then $E(X) = n\theta = 120(0.85) = 102$, which is too many.

The **median** is another measure of central tendency. If X is continuous then the median is the value m such that one–half of the area under the PDF is to the left of m, and one–half is to the right of m.

If X is discrete and takes on an odd number of finite values, the median is obtained by ordering the possible outcomes of X and selecting the middle value.

Example: For the sample $\{-4, 0, 2, 8, 10, 13, 17\}$ the median is 8.

If X takes on an even number of values, then the median is the average of the two middle values.

Example: For the sample $\{-5, 3, 9, 17\}$ the median is $\frac{3+9}{2} = 6$.

For a random variable let $E(X) = \mu$. There are various ways to measure how far X is from its expected value. One of the simplest is the squared distance:

$$(X - \mu)^2$$

This eliminates the sign, which corresponds with our intuitive notion of a distance measure. It treats values above and below μ symmetrically.

The **variance** is defined as follows:

$$Var(X) = E[(X - \mu)^2]$$

The variance is sometimes denoted by σ_X^2 or just σ^2 when the random variable is understood to be X.

Note:

$$\begin{aligned} \sigma^2 &= E(X^2 - 2X\mu + \mu^2) \\ &= E(X^2) - 2\mu^2 + \mu^2 \\ &= E(X^2) - \mu^2 \end{aligned}$$

Example: If $X \sim$ Bernoulli(θ) we know that $E(X) = \theta$. Since $X^2 = X$ it follows that $E(X^2) = \theta$. Then $Var(X) = E(X^2) - \mu^2 = \theta - \theta^2 = \theta(1-\theta)$.

Properties of variance:

> **Property VAR1:** $Var(X) = 0$ if, and only if for every c such that $P(X = c) = 1$, in which case $E(X) = c$.
>
> **Property VAR2:** For constants a and b $Var(aX + b) = a^2 Var(X)$.

The **standard deviation** is related to the variance as follows: $sd(X) = \sqrt{Var(x)}$. The standard deviation is often denoted σ_x or just σ.

Properties of the standard deviation:

> **Property SD1:** For a constant c, $sd(c) = 0$.
>
> **Property SD2:** For constants a and b $sd(aX + b) = |a| sd(X)$.

Given a random variable X, we can define a new random variable Z by

$$Z = \frac{X - \mu}{\sigma}$$

or $Z = aX + b$ where $a = \frac{1}{\sigma}$ and $b = \frac{-\mu}{\sigma}$. Then $E(Z) = aE(X) + b = \frac{\mu}{\sigma} - \frac{\mu}{\sigma} = 0$.

The variance is $Var(Z) = a^2 Var(X) = \frac{\sigma^2}{\sigma^2} = 1$. Thus the new random variable has $\mu = 0$ and $\sigma^2 = 1$. This is known as **standardizing** a random variable.

Example: Suppose $E(X) = 2$ and $Var(X) = 9$ then $Z = \frac{X-2}{3}$.

While the joint distribution completely describes the relationship between two random variables it is often useful to have a summary measure of how, on average, two random variables vary with one another.

The **covariance** is defined as follows:

$$Cov(X, Y) = E[(X - \mu_X)(Y - \mu_Y)]$$

The covariance is often denoted by σ_{XY}. If $\sigma XY > 0$ then on average when X is above its mean Y is also above its mean. If $\sigma_{XY} < 0$ then on average when X is above its mean Y is below its mean, and vice versa.

Note:

$$\begin{aligned} Cov(X, Y) &= E[(X - \mu_X)(Y - \mu_Y)] \\ &= E[(X - \mu_X)Y] \\ &= E(XY) - \mu_X \mu_Y \end{aligned}$$

Properties of covariance:

> **Property COV1:** If X and Y are independent then $Cov(X, Y) = 0$. Note: the converse is not true. Zero $Cov(X, Y)$ does not imply independence.
>
> **Property COV2:** For any constants a_1, b_2, a_2, and b_2 $Cov(a_1X + b_1, a_2Y + b_2) = a_1a_2Cov(X, Y)$.
>
> **Property COV3:** $|Cov(X, Y)| \leq sd(X)sd(Y)$.

Note: property COV2 suggests that $Cov(X, Y)$ depends upon how the random variables are measured, not only on how strongly they are related. In other words, scale matters for $Cov(X, Y)$.

The **correlation coefficient** is defined as

$$Corr(X, Y) = \frac{Cov(X, Y)}{sd(X)sd(Y} = \frac{\sigma_{XY}}{\sigma_X \sigma_Y}$$

The correlation coefficient is sometimes denoted by ρ_{XY}.

Properties of correlation:

> **Property CORR1:** $-1 \leq Corr(X, Y) \leq 1$.
>
> **Property CORR2:** For constants a_1, b_1, a_2, and b_2 with $a_1a_2 > 0$ $Corr(a_1X + b_1, a_2Y + b_2) = Corr(X, Y)$. If $a_1a_2 < 0$ then $Corr(a_1X + b_1, a_2Y + b_2) = -Corr(X, Y)$.

With covariance and correlation defined we state further properties of the variance:

> **Property VAR3:** For constants a and b, $Var(aX + bY) = a^2Var(X) + b^2Var(Y) + 2abCov(X, Y)$.
>
> **Property VAR4:** If $\{X_1, X_2, \ldots, X_n\}$ are pairwise uncorrelated and $\{a_i : i = 1, \ldots, n\}$ are constants then $Var(\sum\limits_{i=1}^{n} a_iX_i) = \sum\limits_{i=1}^{n} a_i^2 Var(X_i)$.

The **conditional mean** is defined as follows:

$$E(Y|x) = \sum_{j=1}^{m} y_j f_{Y|X}(y_j|x)$$

Example: Let (X, Y) represent the population of all working individuals, where X is years of education and Y is hourly wages. Then $E(Y|X = 12)$ is the average hourly wage for all the people in the population with 12 years of education (roughly high school education). $E(Y|X = 16)$ is the average hourly wage for all people with 16 years of education.

A typical situation in econometrics will look like the following:

$$E(WAGE|EDUC) = 1.05 + 0.45EDUC$$

If this linear relationship holds then for 8 years of education the expected hourly wage is $1.05 + 0.45(8) = 4.65$ of \$4.65 per hour.

Properties of conditional expectations:

> **Property CE1:** $E[c(X)|X] = c(X)$ for any function $c(X)$. In other words, functions act as constants. For example, $E[X^2|X] = X^2$. If we know X we also know X^2.
>
> **Property CE2:** For funtions $a(X)$ and $b(X)$, $E[a(X)Y + b(X)|X] = a(X)E(Y|X) + b(X)$. For example, consider the random variable $XY + 2X^2$. $E(XY + 2X^2|X) = XE(Y|X) + 2X^2$.
>
> **Property CE3:** If X and Y are independent then $E(Y|X) = E(Y)$.
>
> **Property CE4:** $E[E(Y|X)] = E(Y)$. This is known as the Law of Iterated Expectations.
>
> **Property CE5:** $E(Y|X) = E[E(Y|X, Z)|X]$.
>
> **Property CE6:** If $E(Y|X) = E(Y)$ then $Cov(X, Y) = 0$ and $Corr(X, Y) = 0$.

The **conditional variance** is defined as follows:

$$Var(Y|X = x) = E(Y^2|X) - [E(Y|X)]^2$$

Properties of conditional variance:

> **Property CV1:** If X and Y are independent then $Var(Y|X) = Var(Y)$.

The **normal probability density function** is defined as follows:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp \frac{-(X-\mu)^2}{2\sigma^2}, \quad \text{for } -\infty < x < \infty$$

where $E(X) = \mu$ and $Var(X) = \sigma^2$. When is a random variable is normally distributed we write $X \sim N(\mu, \sigma^2)$.

A special case is the **standard normal distribution**, which is defined as follows:

$$\phi(z) = \frac{1}{\sqrt{2\pi}} \exp \frac{-z^2}{2}, \quad \text{for } -\infty < z < \infty$$

The standard normal cumulative distribution function is denoted by $\Phi(z) = P(Z \leq z)$. Using some basic facts from probability we arrive at the following helpful formulas:

$$P(Z > z) = 1 - \Phi(z)$$
$$P(Z < -z) = P(Z > z)$$
$$P(a \leq Z \leq b) = \Phi(b) - \Phi(a)$$

Properties of the normal distribution:

Property NORMAL1: If $X \sim N(\mu, \sigma^2)$ then $\frac{(X-\mu)}{\sigma} \sim N(0,1)$.

Property NORMAL2: If $X \sim N(\mu, \sigma^2)$ then $aX + b \sim N(a\mu + b, a^2\sigma^2)$.

Property NORMAL3: If X and Y are jointly normally distributed, then they are independent if, and only if $Cov(X,Y) = 0$.

Property NORMAL4: Any linear combination of independent, identically distributed normal random variables has a normal distribution.

Example: Let X_i for $i = 1, 2, \text{and}, 3$, be independent random variables distributed as $N(\mu, \sigma^2)$. Define $W = X_1 + 2X_2 - 3X_3$. Then W is normally distributed. We can solve for the mean and variance as follows:

$$E(W) = E(X_1) + 2E(X_2) - 3E(X_3) = \mu + 2\mu - 3\mu = 0$$
$$Var(W) = Var(X_1) + 4Var(X_2) + 9Var(X_3) = 16\sigma^2$$

The **chi–square distribution** is obtained directly from independent, standard normal random variables. Let Z_i, $i = 1, 2, \ldots, n$, be independent random variables, each distributed as standard normal. Define a new random variable as the sum of the squares of the individual Z_i:

$$X = \sum_{i=1}^{n} Z_i^2$$

The new random variable X has a **chi–square distribution** with n **degrees of freedom**. This is often written as $X \sim \chi^2_n$.

The t **distribution** is a workhorse in classical statistics and econometrics. A t distribution is obtained from a standard normal and a chi–square random variable. Let Z have a standard normal distribution and let X have a chi-square distribution with n degrees of freedom. Also assume that Z and X are independent. Then the following random variable

$$T = \frac{Z}{\sqrt{Z/n}}$$

has a t distribution with n degrees of freedom. This is denoted by $T \sim t_n$. The t distribution gets its degrees of freedom from the chi–square random variable.

Another important distribution for statistics and econometrics is the F **distribution**. To define an F random variable, let $X_1 \sim \chi^2_{k_1}$ and $X_2 \sim \chi^2_{k_2}$ and assume that X_1 and X_2 are independent. Then, the random variable

$$F = \frac{X_1/k_1}{X_2/k_2}$$

has an F distribution with (k_1, k_2) degrees of freedom. We denote this as $F \sim F_{k_1,k_2}$. The order of the degrees of freedom is important. k_1 is the *numerator degrees of freedom* and k_2 is the *denominator degrees of freedom*.