Mathematical Statistics I

Chapter 6: Distributions Derived from the Normal Distribution

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1 χ^2 distributions

Introduction

- This material comes primarily from Rice (2007, Chapter 6).

- Here, we introduce several important distributions that arise from transformations applied to normal distributions.

- Many of these distributions form the basis of traditional statistical inference procedures that are taught in introductory statistics courses.

- They are very useful in practice due to the central limit theorem: with enough observations, the limiting behavior of nearly all distributions is normal, so distributions that come from the normal distribution arise in practice as well.

χ^2_ν Distribution

- The first distribution we will consider is the χ^2_1 (Chi-square with 1 degree of freedom).

Definition: χ^2_1 distribution
If Z is a standard normal random variable, then $X = Z^2$ is called the chi-square distribution with 1 degree of freedom.

- We typically use the notation $X \sim \chi^2_1$ (in LaTeX: `\chi`).

The pdf of χ^2_1
Let X follow a χ^2_1 distribution. Then, the pdf of X is given by

$$f_X(x) = \frac{1}{\sqrt{2\pi}} x^{-1/2} e^{-x/2}.$$

Proof. There are a few ways to show this is the case, and was one of the early examples we saw in Chapter 2. For practice, we repeat this example here.

- By definition, X has the same distribution of Z^2, where Z is a standard normal.

- Recall the standard normal density is:

$$\phi(z) = \frac{1}{\sqrt{2\pi}}e^{-z^2/2}$$

- Using the CDF method, we write

$$\begin{aligned}
F_X(x) &= P(X \leq x) \\
&= P(Z^2 \leq x) \\
&= P(-\sqrt{x} \leq Z \leq \sqrt{x}) \\
&= P(Z \leq \sqrt{x}) - P(Z \leq -\sqrt{x}) \\
&= \Phi(\sqrt{x}) - \Phi(-\sqrt{x}),
\end{aligned}$$

- Where $\Phi(z)$ is the cdf of Z.

- Taking the derivative of both sides of the equation, the chain rule gives us

$$\begin{aligned}
f_X(x) &= \frac{1}{2}x^{-1/2}\phi(\sqrt{x}) + \frac{1}{2}x^{-1/2}\phi(-\sqrt{x}) \\
&= x^{-1/2}\phi(\sqrt{x}),
\end{aligned}$$

- where the last step is a result of the symmetry of $\phi(x)$, noting $\phi(-x) = \phi(x)$ for all $x \in \mathbb{R}$.

- Thus, replacing $\phi(\sqrt{x})$ with the definition,

$$f_X(x) = \frac{1}{\sqrt{2\pi}}x^{-1/2}e^{-x/2}$$

$\square$

- In Chapter 2, we previously noted that that $f_X(x)$ is an example of a Gamma distribution.

- Specifically, the *kernel* of the Gamma density is x raised to some power, and e raised to some multiple of x:

$$f_{\text{Gamma}}(x) \propto x^{\alpha-1}e^{-\lambda x}.$$

- Thus, ignoring the constant for a moment, if $\alpha = 1/2$, $\lambda = 1/2$, then the pdf of $X \sim \chi_1^2$ is just this Gamma density:

$$f_X(x) \propto x^{-1/2}e^{-x/2} = x^{\alpha-1}e^{-\lambda x}.$$

- Since both functions are proper probability density functions, they have to integrate to one, so the normalizing constant *must* be the same.

- This is also easily verified. The normalizing constant of the Gamma distribution is $\lambda^\alpha/\Gamma(\alpha)$.

- With our specific values of $\lambda = \alpha = 1/2$, and recalling that $\Gamma(1/2) = \sqrt{\pi}$,

$$\frac{1}{\sqrt{2\pi}} = \frac{(1/2)^{(1/2)}}{\Gamma(1/2)} = \frac{\lambda^\alpha}{\Gamma(\alpha)}$$

MGF of χ_1^2

We previously derived the MGF of a Gamma(α, λ) distribution: $M(t) = \big(\lambda/(\lambda - t)\big)^\alpha$. Thus, the MGF of a Chi-square(1) distribution is

$$M(t) = (1 - 2t)^{-1/2}, \quad t < 1/2.$$

Definition

If $U_1, U_2, \ldots, U_n$ are n independent χ_1^2 random variables, then

$$V = U_1 + U_2 + \ldots + U_n$$

then the distribution of V is called the Chi-square distribution with n degrees of freedom, denoted χ_n^2.

- There are a few different ways of deriving the pdf of a χ_n^2 random variable. Here, we will use the MGF uniqueness theorem.

- Let $M_i(t)$ denote the MGF of U_i, where $U_i \sim \chi_1^2$. Then, due to independence,

$$M_V(t) = M_{\sum_i U_i}(t) = \prod_{i=1}^n M_i(t) = \big(M_t(t)\big)^n = (1 - 2t)^{-n/2}$$

- Compare this to the Gamma MGF: $M(t) = \big(\lambda/(\lambda - t)\big)^\alpha$. Then, setting $\lambda = 1/2$, $\alpha = n/2$, we see that V has a Gamma$(n/2, 1/2)$ distribution.

- Thus, the pdf of V is given by:

$$f_V(v) = \frac{1}{2^{n/2}\Gamma(n/2)} v^{(n/2)-1} e^{-v/2}.$$

- The expected value and variance of the χ_n^2 distribution can easily be found then by using the fact that it is a special case of a Gamma distribution.

2 The t and F distributions

The Student's t distributions

The Student's t distribution

If $Z \sim N(0, 1)$ and $U \sim \chi_n^2$, and Z and U are independent, then the distribution of T, where

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

is called the Student's t distribution (or simply the t distribution) with n degrees of freedom, which is often denoted t_n
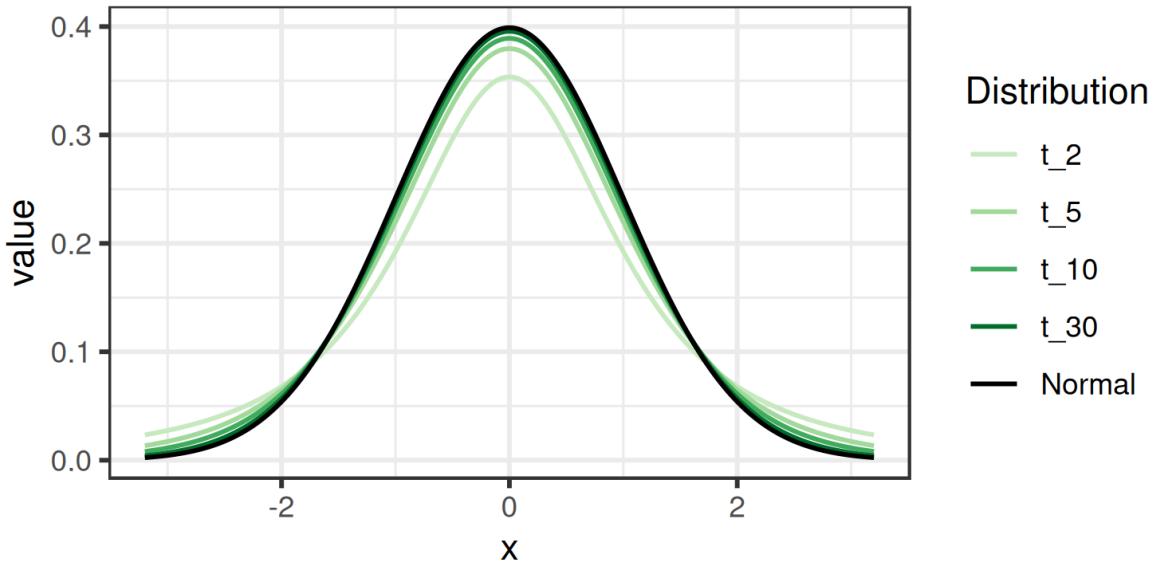
- Students often forget the make sure that Z and U in the definition of the t distribution are independent.

- The t distribution is the distribution used to perform the famed "t-test".

The density of the t_n distribution

The pdf of the t distribution with n degrees of freedom is:

$$f(t) = \frac{\Gamma\big((n + 1)/2\big)}{\sqrt{n\pi}\Gamma(n/2)} \left(1 + \frac{t^2}{n}\right)^{-(n+1)/2}$$

- The derivation of the pdf of a t distribution is a good practice exercise.

- Recall it is defined as the ratio of two independent random variables; in Chapter 3, we derived a formula for computing densities of random variables of this form.

- Note that $f(t) = f(-t)$, and so f is symmetric about zero.

- It also has a bell-curve shape similar to a normal distribution.

- You can see as $n \to \infty$, the t_n distribution converges to the standard normal (e.g., use Slutsky's theorem, good practice).

The F distributions

3   Sampling Distributions

The sample mean

- In what follows, we'll assume that we are taking samples $X_1, X_2, \ldots, X_n$ from a larger population.

- These samples can be repeated experiments, or repeated observations. However, we will assume in general that the samples are independent and identically distributed, unless stated otherwise.

- *For the remainder of the chapter*, we will also assume $X_i \sim N(\mu, \sigma^2)$ for all i.

- As a reminder from earlier chapters, linear combinations of independent normal random variables are also normally distributed. Thus, if $X_1, X_2, \ldots, X_n$ are iid normal, then $\bar{X}_n$ is also normally distributed.

Sampling distribution of the mean
If X_i are iid $N(\mu, \sigma^2)$, then $\bar{X}_n$ is normal, with

$$E\left[1/n \sum_i X_i \right] = (1/n) \sum_i \mu = \mu,$$

$$\operatorname{Var}\!\left(1/n \sum_i X_i\right) = 1/n^2 \sum_i \sigma^2 = \sigma^2/n.$$

Thus, $\bar{X}_n \sim N(\mu, \sigma^2/n)$.

Lemma 6.1: Independent Normal RVs

Let X and Y be normally distributed random variables. Then X and Y are independent, *if and only if*

$$\operatorname{Cov}(X, Y) = 0.$$

- The above statement can be proved using the factorization theorem, and considering the MGF or pdf of a bivariate normal distribution.

- Recall that for most distributions, independence implies $\operatorname{Cov}(X, Y) = 0$, but not the other way around.

- It turns out that the normal distribution is the only distribution that has this property.

Theorem 6.1: Independence of Deviations

Let $X_1, \ldots, X_n$ be iid $N(\mu, \sigma^2)$ random variables. Then, $\bar{X}_n$ is independent of the vector of random variables called the *deviations*, $\left(X_i - \bar{X}_n\right)_{i=1}^n$.

Proof. First, note that $\bar{X}_n$ is normally distributed. Using Lemma 6.1, all we need to do is argue that the deviations are normally distributed, and that the covariance between $\bar{X}_n$ and $X_i - \bar{X}_n$ is zero. Because $\bar{X}_n$ and X_i are both normally distributed, then for all i, $X_i - \bar{X}_n$ is just a linear combination of normally distributed random variables, and as a result is also normally distributed. Using the bilinearity of covariance,

$$
\begin{aligned}
\operatorname{Cov}(\bar{X}_n, X_i - \bar{X}_n) &= \operatorname{Cov}(\bar{X}_n, X_i) - \operatorname{Cov}(\bar{X}_n, \bar{X}_n) \\
&= \operatorname{Cov}\!\left(\sum_{j=1}^n \frac{1}{n} X_j, X_i\right) - \operatorname{Cov}\!\left(\sum_{i=1}^n \frac{1}{n} X_i, \sum_{j=1}^n \frac{1}{n} X_j\right) \\
&= \frac{1}{n}\operatorname{Cov}(X_i, X_i) - \sum_{i=1}^n \sum_{j=1}^n \frac{1}{n^2}\operatorname{Cov}(X_i, X_j) \\
&= \frac{\sigma^2}{n} - \frac{1}{n^2} \sum_{i=j}^n \operatorname{Cov}(X_i, X_j) \\
&= \frac{\sigma^2}{n} - \frac{1}{n^2}(n\sigma^2) = 0.
\end{aligned}
$$

Thus, by Lemma 6.1, $\bar{X}_n$ is independent of $X_i - \bar{X}_n$ for all i. $\qquad\square$

Corollary 6.1

If the X_i are iid $N(\mu, \sigma^2)$, then $\bar{X}_n$ is independent of the sample variance S^2, defined by

$$S^2 = \frac{1}{n-1} \sum_{i=1}^n (X_i - \bar{X}_n)^2.$$

Proof. First recall from one of our homework problems that S^2 is an unbiased estimate of σ^2: $E[S^2] = \sigma^2$ (Note that this does not require the assumption that the X_i are normally distributed, just that they are independent and identically distributed with finite variance $\operatorname{Var}(X_i) = \sigma^2 < \infty$.)
From Theorem 6.1, if the X_i are normally distributed, then $\bar{X}_n$ is independent of the vector $\left(X_i - \bar{X}_n\right)_{i=1}^n$. Because S^2 is just a function of $\left(X_i - \bar{X}_n\right)_{i=1}^n$, we can immediate conclude that $\bar{X}_n$ is independent of S^2. $\qquad\square$

Theorem 6.2

If the X_i are iid normal, then $(n-1)S^2/\sigma^2$ has a chi-square distribution with $n-1$ degrees of freedom.

Proof. First recall how we defined the χ_n^2 distribution. First, if we square a standard normal $Z \sim N(0,1)$, then $Z^2 \sim \chi_1^2$. Then, the sum of n χ_1^2 random variables is how we define a χ_n^2 random variable, i.e., if $Z_i \overset{iid}{\sim} N(0,1)$, then $Z_1^2 + \ldots + Z_n^2 \sim \chi_n^2$. Thus, because $E[X_i] = \mu$, $\text{Var}(X_i) = \sigma^2$ for all i,

$$\left(\frac{X_i - \mu}{\sigma}\right) \sim N(0,1),$$

and therefore

$$\frac{1}{\sigma^2}\sum_{i=1}^n (X_i - \mu)^2 = \sum_{i=1}^n \left(\frac{X_i - \mu}{\sigma}\right)^2 \sim \chi_n^2.$$

Now we will expand this same sum by adding and subtracting $\bar{X}_n$:

$$\frac{1}{\sigma^2}\sum_{i=1}^n (X_i - \mu)^2 = \frac{1}{\sigma^2}\sum_{i=1}^n \left((X_i - \bar{X}_n) + (\bar{X}_n - \mu)\right)^2.$$

From above, we already know this entire expression results in a random variable with a χ_n^2 distribution. We can now manipulate the right hand side to get the distribution of $(n-1)S^2/\sigma$, which was our original goal. We will now expand the square, and note that $\sum_{i=1}^n (X_i - \bar{X}) = 0$ to simplify:

$$\frac{1}{\sigma^2}\sum_{i=1}^n (X_i - \mu)^2 = \frac{1}{\sigma^2}\sum_{i=1}^n (X_i - \bar{X}_n)^2 + \left(\frac{\bar{X}_n - \mu}{\sigma/\sqrt{n}}\right)^2$$

$$V = (n-1)S^2/\sigma^2 + U,$$

where $U \sim \chi_1^2$, since it is the result of squaring a standard normal random variable, and $V \sim \chi_n^2$. Importantly, U is a function of $\bar{X}_n$, which was shown to be independent of S^2 in Corollary 6.1. As a result, we can use the identity for the MGF of the sum of independent random variables: $M_V(t) = M_{(n-1)S^2/\sigma^2} M_U(t)$. For the values of t for which it is defined, we can then solve for the MGF of $(n-1)S^2/\sigma^2$, which uniquely determines the distribution of the random variable. As a reminder, the MGF of a χ_n^2 random variable is $M(t) = (1-2t)^{-n/2}$. Thus,

$$\begin{aligned} M_{(n-1)S^2/\sigma^2} &= M_V(t)/M_U(t) \\ &= \frac{(1-2t)^{-n/2}}{(1-2t)^{-1/2}} \\ &= (1-2t)^{-(n-1)/2}, \end{aligned}$$

which is the MGF of a χ_{n-1}^2 random variable. $\qquad\square$

Theorem 6.3: t distribution

Let X_i be iid Normal(μ, σ^2) random variables, and let $\bar{X}_n$ and S^2 denote the sample mean and variance, respectively. Then,

$$\frac{\bar{X}_n - \mu}{S/\sqrt{n}} \sim t_{n-1}.$$

Proof. The proof is straightforward application of Theorem 6.2, and the definition of the t distribution with n degrees of freedom. We will rewrite the expression as follows:

$$\frac{\bar{X}_n - \mu}{S/\sqrt{n}} = \frac{\left(\frac{\bar{X}_n - \mu}{\sigma/\sqrt{n}}\right)}{\sqrt{S^2/\sigma^2}}$$

The numerator is a $N(0, 1)$ random variable. By Corollary 6.1, the numerator is independent of the denominator. The denominator is a the square root of an independent random variable with χ^2_{n-1}, divided by its degrees of freedom $(n - 1)$:

$$\frac{(n-1)S^2}{\sigma^2(n-1)}.$$

By the definition of the t distribution, the ratio has a t_{n-1} distribution. $\qquad\square$

Proof.

Final Comments

- The identity in Theorem 6.3 provides the theoretical justification for a one-sample t-test. The justification for a two-sample t-test is derived in a similar way.

- Theorem 6.3 relies on the X_i coming from a normal population, then this distribution is exact. The normal distribution arises in a large number of real-world applications.

- In practice, however, the t-test is often used even when the samples X_i do not come from a normal distribution.

- The justification of this practice can heuristically be justified by the central limit theorem: Even if the X_i are not normally distributed, $\bar{X}_n - \mu$ will be approximately normally distributed, with even relatively small n.

- Note, however, that the limiting distribution of the statistic in Theorem 6.3 is normal, not t. This can be shown with Slutsky's Theorem, noting that $S_n^2 \xrightarrow{p} \sigma^2$ (see CLT example in Chapter 5 slides.)

- In practice, the t distribution is often used because it has heavier tails than the normal distribution, and thus leads to conservative estimates of the distribution of the statistic in Theorem 6.3. Simulation studies suggest this approximation is quite good, even when there are large deviations from normality.

The F distributions (ommited earlier)

- The F distribution is often used as the null-distribution for hypothesis test.

- Used regularly in ANOVA, testing overall significance in a multiple regression model, and comparing population variances.

Definition: F-distribution
Let U and V be independent chi-square random variables with m and n degrees of freedom, respectively. The distribution of

$$W = \frac{U/m}{V/n}$$

is called the F distribution with m and n degrees of freedom, denoted $F_{m,n}$.

Density of the F distribution
If $W \sim F_{m,n}$, then the density of W is given by

$$f(w) = \frac{\Gamma\big((m+n)/2\big)}{\Gamma(m/2)\Gamma(n/2)} \left(\frac{m}{n}\right)^{m/2} w^{m/2-1}\left(1 + \frac{m}{n}w\right)^{-(m+n)/2}.$$

- Note that W is just the ratio of two independent random variables, so this can be derived using results from Chapter 3 on the density of the ratio of two independent random variables. This is a good practice exercise.

- It can be shown that the square of a t_n random variable follows an $F_{1,n}$ distribution.

Acknowledgments

References

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