

Testing of Hypotheses

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1 Introduction

Consider a coin that looks normal, but may or may not be fair – i.e., the probability that it comes up heads when tossed may or may not be $\frac{1}{2}$. How can we ascertain whether it is indeed fair? If we toss it a hundred times, and heads appear exactly fifty times out of these hundred tosses, then we may *feel* sure that it is a fair coin. However, even a fair coin does not always give a perfectly fifty-fifty results every time. And a biased coin may in fact give a fifty-fifty result once in a while. Statistical testing of hypotheses deals with making formal tests of such claims using the theory of probability and statistics.

For instance, in this example, let X be a random variable associated with the result of a single toss of the given coin – let X be 1 if the result is heads and 0 if the result is tails. If θ is the (unknown) probability of heads, then we have $f(1) = \theta$ and $f(0) = 1 - \theta$, where $f(x)$ is the probability mass function of X . Thus, we see that

the probability distribution of X has a known type¹, but depends on an unknown parameter θ . That is, if the value of θ were given, it would completely determine the probability distribution of X .

Now, suppose we suspect that the coin is biased, and has a higher probability for heads – i.e., that $\theta > 0.5$. We wish to test this *hypothesis*, which we may denote as $H_1: \theta > 0.5$. We mean to test this *against* the hypothesis that the coin is fair – i.e., that $\theta = 0.5$. This hypothesis can be denoted as $H_0: \theta = 0.5$. We call H_0 the *null hypothesis* and H_1 the *alternative hypothesis*.

In order to test these hypotheses, we can conduct an experiment of tossing the coin a fixed n number of times and observing the result each time – or equivalently, of noting the value of X each time. Thus, we get n different values of X , say, X_1, X_2, \dots, X_n (each one being either 0 or 1). In other words, we have a sample $(X_1, X_2, \dots, X_n)^2$ from the population defined by the random variable X .

The question now is, how can we decide from the results of the experiment whether the coin is fair or not? As we noted earlier, an exact fifty-fifty distribution cannot be expected from a fair coin, and at the same time, such a result is possible, if rare, even in the case of a biased coin. So we must allow for a margin of error, luck, or chance in the final result. For instance, we may decide that even if the number of heads obtained is up to 60% of the total number of tosses, the coin may still be fair – but that if the number of heads is above 60%, then it is most likely not fair. Such a choice is certainly arbitrary. But, firstly, there is no theory that can tell us exactly what the cut-off should be. And secondly, what truly matters is how certain we can be of the results of the test, after we choose a particular cut-off (or some other criterion). Measuring this amount of certainty and the probabilities of errors is the real essence of this subject – since all we can control is the amount of certainty we have about the results we obtain.

Since X is 1 when the result is heads and 0 otherwise, the sum $X_1 + X_2 + \dots + X_n$ is exactly the number of heads. Recall that we have decided to declare the coin to be fair if the percentage of heads obtained is at most 60% – and biased if it is more than 60%. The first case is equivalent to having $\sum_{i=1}^n \frac{X_i}{n} \leq 0.6$, that is, $\bar{X} \leq 0.6$, where \bar{X} is the sample mean. And therefore the second case is equivalent to having $\bar{X} > 0.6$. Thus, we will *accept the null hypothesis* H_0 if $\bar{X} \leq 0.6$ and we will *reject the*

¹Here, $X \sim B(1, \theta)$ – a special case of the binomial distribution (i.e., with $n = 1$), called the Bernoulli distribution.

²Written in this form, (X_1, X_2, \dots, X_n) denotes the as yet unknown value of the sample, which we are considering *before* having conducted the experiment – thus, (X_1, \dots, X_n) is a (multidimensional) random variable. After conducting the experiment, however, we will obtain *particular* values x_1, \dots, x_n of these random variables, and thus we will have a *sample point* (x_1, \dots, x_n) . The set of all possible sample points is exactly the *sample space* associated with this experiment. This subtle difference in notation is not new – we usually use X (and other upper case letters) to denote the random variable and x (or corresponding lower case letters) to denote a possible *value* taken by the random variable.

null hypothesis H_0 (and accept the alternative hypothesis H_1) if $\bar{X} > 0.6$. This is an example of what is formally called a *statistical test*.

To summarise what we have so far, a coin is given, which we suspect to be biased. To express this mathematically, we associate a random variable X with the coin, which takes value 1 with probability θ – the probability of heads in a single toss – and 0 with probability $1 - \theta$ (which indicates tails in a single toss). The hypothesis we wish to test³ is $H_1: \theta > 0.5$, against the null hypothesis $H_0: \theta = 0.5$. The test that we have decided to use is: Compute the the sample mean \bar{x} , and if $\bar{x} > 0.6$, then we reject the null hypothesis H_0 and accept the alternative hypothesis H_1 (note that here we write \bar{x} since we are talking about the *value* of the sample mean obtained after conducting the experiment).

As mentioned earlier, there is no way to fully justify the decision to use 0.6 as the cut-off instead of some other number. What we can do is measure the probability that our test will give us an erroneous result. What does this mean? Remember that while in reality the coin may be fair, there is still a possibility (however small) that in a particular sequence of tosses, a large number of heads is obtained. If this occurs in our experiment, we will reject H_0 and accept H_1 – thus committing an error, although we have no means of detecting it. Another possibility is that the coin is actually biased, but by a similar accident of chance, the number of heads obtained is nearly 50%. Then we will accept H_0 and reject H_1 – which is another type of error, which again we cannot detect. Thus we have the following.

	H_0 is True	H_0 is False
Accept H_0	No error	Type II error
Reject H_0	Type I error	No error

Note. Carefully note the distinction between the *statement* that a hypothesis “is true” and the *decision* to “accept” the hypothesis. The hypothesis’ being true (or not) is a fact of reality which, by definition, we cannot know in practice (otherwise there would be no need for any statistical test). On the other hand, accepting (or rejecting) the hypothesis is a decision we make based on a pre-decided rule (namely the hypothesis test) – which is not a statement about reality, but an *action*.

Thus, we wish to compute the probabilities of the two errors – Type I and Type II – in our example. Since Type I error is *rejecting* H_0 when H_0 is *true*, what we want is $P[\text{Reject } H_0 \mid H_0 \text{ True}]$. But we reject H_0 only if $\bar{X} > 0.6$. And H_0 is true only if $\theta = 0.5$. Thus, the probability of Type I error, which we shall denote by α , is $\alpha = P[\bar{X} > 0.6 \mid \theta = 0.5]$. It is not hard to see that given the distribution

³It is a convention that the hypothesis we form and wish to establish is taken as the *alternative* hypothesis H_1 , rather than the *null* hypothesis H_0 . The latter is to be thought of as a default belief, that is to be *refuted* by our experiment. And if we fail to refute this – i.e., if we fail to prove the alternative hypothesis – then it does not usually mean that we strongly believe the null hypothesis. It means only that we have *not* succeeded in proving our claim. This is in keeping with the basic scientific principle that the onus of proof is on the one making the claim.

of X as stated earlier, the random variable $\sum_{i=1}^n X$ follows the binomial distribution $B(n, \theta)$. If $\theta = 0.5$ (i.e., if H_0 is true), then $\sum_{i=1}^n X \sim B(n, 0.5)$. And therefore, $P[\bar{X} > 0.6] = P[\sum X > 0.6n]$, which can be computed in the usual way, given the value of n , the number of tosses. For example, if $n = 10$, then $\alpha = P(\sum X > 6) = \left(\binom{10}{7} + \cdots + \binom{10}{10}\right)(0.5)^{10} \approx 0.17$. That is, the probability of Type I error in our test when $n = 10$ is $\alpha = 0.17$. This probability is known as the *level of significance* of the test. Any particular value of $K(\theta)$ at a given value of θ is called the *power of the test* at that point.

More generally, the probability of rejecting H_0 is a function of the parameter θ . In order to compute α , the level of significance, we have taken $\theta = 0.5$, which is the case when H_0 is true. If we find the probability of rejecting H_0 for an arbitrary value of θ , we get the *power function of the test*, $K(\theta) = P[\text{Reject } H_0 \mid \theta]$. Thus, in our example, $\alpha = K(0.5)$ ⁴.

As the result of the test is entirely based on whether the sample point obtained satisfies a certain criterion or not (in our case, whether $\bar{x} > 0.6$ or not), we call the set of all sample points that satisfy the criterion as the *critical region*. In other words, the critical region is that subset C of the sample space such that we reject H_0 and accept H_1 if $(X_1, \dots, X_n) \in C$. The statistical test is therefore completely determined by specifying the critical region.

1.1 Definitions

Definition 1.1. A *statistical hypothesis* is a claim about the probability distribution of one or more populations (random variables). The hypothesis is *simple* if it completely specifies the distribution, and *composite* otherwise.

Definition 1.2. A *statistical test* of a hypothesis is a rule, stated in terms of a sample, that prescribes whether the hypothesis is to be rejected or accepted, based on the value of the sample point obtained. The *critical region* of the test is the region of the sample space such that if the sample point lies in it, the hypothesis is rejected.

Thus, we may also say that a statistical test is the specification of a subset of the sample space as the critical region, and the prescription that the hypothesis be rejected if the sample point obtained is in this region.

⁴In general, the significance level α is the *maximum* probability of rejecting H_0 when it is true. In our example, H_0 is a *simple hypothesis* where θ takes a particular value (and H_1 is a *composite hypothesis*, where θ lies in a range of values). Therefore in our example, there is only one way in which H_0 could be true and correspondingly there is only one probability of rejecting it when it is true. If H_0 were a composite hypothesis (for example, $\theta \leq 0.5$), then for each possible value of θ that makes H_0 true, we would get a different value of the power $K(\theta)$, and then α would be taken as the maximum (or supremum) of these values.

Definition 1.3. The *power function* K of a test is the probability that the sample point falls in the critical region of the test. If H_0 is the null hypothesis of the test, then K is the probability of rejecting H_0 . The value of the power function at a particular point (a particular assignment of values to the unknown parameter(s)) is the *power* of the test at that point.

Definition 1.4. The *level of significance* of a test is the size of the critical region of the test – that is, the significance level is the supremum/maximum probability of rejecting the null hypothesis H_0 when H_0 is true.

1.2 Solved Problems

1. X has a pdf of the form $f(x; \theta) = \theta x^{\theta-1}$, $0 < x < 1$, where $\theta > 0$. To test the simple hypothesis $H_0: \theta = 1$ against the alternative simple hypothesis $H_1: \theta = 2$, it is decided to use a random sample (X_1, X_2) of size $n = 2$ with the critical region as $C = \{(x_1, x_2) \mid x_1 x_2 \geq \frac{3}{4}\}$. Compute the power function $K(\theta)$ and the significance level α of the test.

Solution. We know that the power function $K(\theta)$ is the probability of rejecting the null hypothesis, which is the probability that $(X_1, X_2) \in C$. Thus, according to the definition of C given in the question,

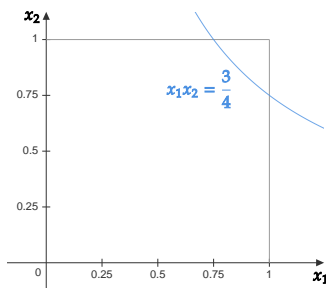
$$K(\theta) = P\left(X_1 X_2 \geq \frac{3}{4}\right).$$

Since (X_1, X_2) is a sample, X_1 and X_2 are independent, and therefore, the joint pdf of the sample is

$$\begin{aligned} g(x_1, x_2; \theta) &= f(x_1; \theta) f(x_2; \theta) \\ &= \theta^2 (x_1 x_2)^{\theta-1}, \quad 0 < x_1, x_2 < 1. \end{aligned}$$

Thus,

$$\begin{aligned} K(\theta) &= P\left(X_1 X_2 \geq \frac{3}{4}\right) \\ &= \int_{x_1=3/4}^1 \int_{x_2=3/4x_1}^1 \theta^2 (x_1 x_2)^{\theta-1} dx_2 dx_1 \\ &= \theta^2 \int_{x_1=3/4}^1 x_1^{\theta-1} \left[\frac{x_2^\theta}{\theta} \right]_{3/4x_1}^1 dx_1 \\ &= \theta \int_{x_1=3/4}^1 x_1^{\theta-1} - \frac{1}{x_1} \left(\frac{3}{4}\right)^\theta dx_1 \\ &= 1 - \left(\frac{3}{4}\right)^\theta \left[1 - \theta \log \frac{3}{4}\right]. \end{aligned}$$



Now the significance level is obtained by evaluating the power function at the parameter point where the null hypothesis H_0 is true, that is at $\theta = 1$. Therefore, the significance level is

$$\begin{aligned}\alpha &= K(1) \\ &= \frac{1}{4} + \frac{3}{4} \log \frac{3}{4} \\ &\approx 0.034.\end{aligned}$$

2. Let (X_1, X_2) be a random sample of size 2 from the distribution having pdf $f(x; \theta) = \frac{1}{\theta} e^{-x/\theta}$, $x > 0$, where $\theta > 0$. We reject $H_0: \theta = 2$ and accept $H_1: \theta = 1$ if the observed value (x_1, x_2) of the sample is such that

$$\frac{f(x_1; 2)f(x_2; 2)}{f(x_1; 1)f(x_2; 1)} \leq \frac{1}{2}.$$

Find the significance level of the test and the power of the test when H_1 is true.

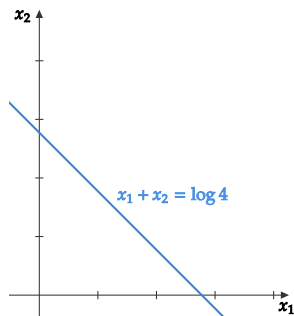
Solution. The critical region is defined by

$$\begin{aligned}\frac{f(x_1; 2)f(x_2; 2)}{f(x_1; 1)f(x_2; 1)} &\leq \frac{1}{2} \iff \\ \frac{1}{4} \times \frac{e^{-\frac{x_1+x_2}{2}}}{e^{-(x_1+x_2)}} &\leq \frac{1}{2} \iff \\ e^{\frac{x_1+x_2}{2}} &\leq 2 \iff \\ x_1 + x_2 &\leq \log 4.\end{aligned}$$

Now, $g(x_1, x_2; \theta) = \frac{1}{\theta^2} e^{-\frac{x_1+x_2}{\theta}}$, $x_1, x_2 > 0$.

The power function is

$$\begin{aligned}K(\theta) &= \frac{1}{\theta^2} \int_0^{\log 4} \int_0^{\log 4 - x_1} e^{-\frac{x_1+x_2}{\theta}} dx_2 dx_1 \\ &= \frac{1}{\theta} \int_0^{\log 4} e^{-\frac{x_1}{\theta}} \left[1 - e^{-\frac{x_1 - \log 4}{\theta}} \right] dx_1 \\ &= \frac{1}{\theta} \int_0^{\log 4} e^{-\frac{x_1}{\theta}} - 4^{-\frac{1}{\theta}} dx_1 \\ &= 1 - 4^{-\frac{1}{\theta}} + 4^{-\frac{1}{\theta}} \log 4^{-\frac{1}{\theta}}.\end{aligned}$$



Then the significance level is

$$\begin{aligned}\alpha &= K(2) \quad [\because H_0: \theta = 2] \\ &= \frac{1}{2} + \frac{1}{2} \log \frac{1}{2} \\ &\approx 0.15.\end{aligned}$$

H_1 is true when $\theta = 1$. Thus, the power of the test when H_1 is true is

$$K(1) = \frac{3}{4} + \frac{1}{4} \log \frac{1}{4} \approx 0.4.$$

3. The life length of a tyre in miles, X , is normally distributed with mean θ and standard deviation 5000. Past experience indicates that $\theta = 30,000$. The manufacturer claims that the tyres made by a new procedure have $\theta > 30,000$ and it is very likely that $\theta = 35,000$. Check the claim by testing $H_0: \theta \leq 30,000$ against $H_1: \theta > 30,000$. Observe n independent values of X , say x_1, x_2, \dots, x_n and reject H_0 if and only if $\bar{x} > c$. Determine n and c so that the power function $K(\theta)$ has values $K(30,000) = 0.01$ and $K(35,000) = 0.98$.

Solution. $K(\theta) = P[\bar{X} > c \mid \theta]$ (where \bar{X} is the sample mean⁵).

Since $X \sim N(\theta, 5000^2)$, the sample mean $\bar{X} \sim N\left(\theta, \frac{5000^2}{n}\right)$. Therefore, $Z = \frac{\bar{X} - \theta}{5000/\sqrt{n}} \sim N(0, 1)$.

$$\begin{aligned}K(30,000) &= 0.01 \implies \\ P[\bar{X} > c \mid \theta = 30000] &= 0.01 \implies \\ P\left[Z > \frac{c - 30000}{5000/\sqrt{n}}\right] &= 0.01 \implies \\ P\left[Z \leq \frac{c - 30000}{5000/\sqrt{n}}\right] &= 0.99 \implies \\ \frac{c - 30000}{5000/\sqrt{n}} &= 2.33\end{aligned} \tag{1}$$

⁵Here we write \bar{X} because it is a random variable, not the particular value \bar{x} obtained after the experiment.

$$\begin{aligned}
P[\bar{X} > c \mid \theta = 35000] &= 0.98 \implies \\
P\left[Z > \frac{c - 35000}{5000/\sqrt{n}}\right] &= 0.98 \implies \\
P\left[Z \leq \frac{c - 35000}{5000/\sqrt{n}}\right] &= 0.98 \implies \\
\frac{c - 35000}{5000/\sqrt{n}} &= 2.06
\end{aligned} \tag{2}$$

From (1) and (2), $n = 19.2 \approx 19$ and $c = 32653.8$.

1.3 Exercises

1. Let X have a Poisson distribution with mean θ . Test the simple hypothesis $H_0: \theta = 0.5$ against the composite hypothesis $\theta < 0.5$ by using a sample (X_1, \dots, X_{12}) of size 12. Reject H_0 if and only if the observed value of $Y = X_1 + \dots + X_{12} \leq 2$. Find the powers $K(\frac{1}{2})$, $K(\frac{1}{3})$, $K(\frac{1}{4})$, $K(\frac{1}{6})$, and $K(\frac{1}{12})$. What is the significance level of the test?
2. Let Y have a binomial distribution with parameters n and p . We reject $H_0: p = \frac{1}{2}$ and accept $H_1: p > \frac{1}{2}$ if $Y \geq c$. Find n and c to give a power function $K(p)$ which is such that $K(\frac{1}{2}) = 0.1$ and $K(\frac{2}{3}) = 0.95$, approximately.
3. Let $X \sim U[0, \theta]$. Test $H_0: \theta = 1$ against $H_1: \theta = 2$ using a sample (X_1, X_2) of size 2, by rejecting H_0 if either $\bar{X} > 0.75$ or at least one of X_1 and X_2 is greater than 1. Compute $K(1)$ and $K(2)$.

2 Chi-Square Tests

In Section 1, we considered the problem of determining if a given coin was fair or biased. Now imagine that the same question is asked about a given six-sided die. Again, we can test the hypothesis that the die is fair, by throwing it n times and observing the distribution of the resulting outcomes. Now, however, we have not two but six different classes into which the outcomes are divided⁶ – namely the number of appearances of 1, the number of appearances of 2, ..., the number of appearances of 6. Let these numbers be denoted by x_1, x_2, \dots, x_6 . We also have the probabilities p_1, p_2, \dots, p_6 for the occurrence of the respective faces 1, 2, ..., 6 of the

⁶Recall that in the case of a coin, the two classes are number of heads and number of tails – and given the total number of tosses, it is enough to specify just one of these, say, the number of heads obtained.

die in each throw. In the case of a fair die, each of these would be $p_i = \frac{1}{6}$. Since n is the total number of throws, we expect that each observed number x_i should be more or less equal to np_i . For instance, if we throw the die 60 times, then if the die is fair, each face should appear roughly 10 times. Therefore the difference $x_i - np_i$ between the observed and expected number of appearances is a measure of how *false* our hypothesis is likely to be. Therefore we need to design a test that uses these deviations to estimate the probability of the truth or falsehood of the hypothesis.

Firstly, observe that $x_6 = n - (x_1 + \dots + x_5)$, so that we only need to consider x_1, \dots, x_5 . The sample (X_1, X_2, \dots, X_5) has what is known as the multinomial distribution⁷ with parameters n, p_1, \dots, p_5 . Then if we define

$$Q_5 = \frac{(X_1 - np_1)^2}{np_1} + \frac{(X_2 - np_2)^2}{np_2} + \frac{(X_3 - np_3)^2}{np_3} + \frac{(X_4 - np_4)^2}{np_4} + \frac{(X_5 - np_5)^2}{np_5} + \frac{(X_6 - np_6)^2}{np_6},$$

$Q_5 \sim \chi_5^2$ approximately for large n (i.e., in the limiting case where $n \rightarrow \infty$).

Now the test is as follows. Select a value c , and reject the hypothesis that the die is fair if $Q_5 \geq c$. What should be the ideal value of c ? That depends on the significance level of the test. What we can do therefore, is to *set* a desired significance level α and select c such that $P(Q_5 \geq c) = \alpha$. This value of c can be obtained from the chi-square.

The chi-square test in general can therefore be described as follows. Given k classes C_1, C_2, \dots, C_k , to test the hypothesis H_0 that the probability distribution of these classes is p_1, p_2, \dots, p_k respectively (where $p_1 + \dots + p_k = 1$), we conduct n trials and observe the frequencies X_1, X_2, \dots, X_k of the respective classes (so that $X_1 + X_2 + \dots + X_k = n$). Now define

$$Q_{k-1} = \sum_{i=1}^k \frac{(X_i - np_i)^2}{np_i}.$$

Then the chi-square test with significance level α is to reject H_0 if $Q_{k-1} \geq c$, where c is the value such that $P[Q_{k-1} \geq c] = \alpha$. Common values of α are 0.05 and 0.01, written as 5% and 1% respectively.

2.1 Solved Problems

1. A six-sided die is thrown 60 times and the observed frequencies of the faces 1, 2, ..., 6 are 13, 19, 11, 8, 5, 4 respectively. Test whether the die is fair, at 5%

⁷The multinomial distribution is a generalisation of the binomial distribution – the multinomial distribution with only two parameters n and p_1 is exactly $B(n, p_1)$.

level of significance.

Solution. Here, we have number of classes $k = 6$, and theoretical probabilities $p_1 = p_2 = \dots = p_6 = \frac{1}{6}$ (since a fair die must have equally likely outcomes), so that $np_i = 10$, $i = 1, 2, \dots, 10$. Then,

$$\begin{aligned} Q_5 &= \sum_{i=1}^5 \frac{(x_i - np_i)^2}{np_i} \\ &= \frac{(13 - 10)^2}{10} + \frac{(19 - 10)^2}{10} + \frac{(11 - 10)^2}{10} + \frac{(8 - 10)^2}{10} + \frac{(5 - 10)^2}{10} + \frac{(4 - 10)^2}{10} \\ &= 15.6. \end{aligned}$$

But $\chi_5^2 = 11.1$ at 5% level of significance. Thus, $Q_5 > \chi_5^2$, which means that **we reject the hypothesis that the die is fair.**

2. The Mendelian theory of genetics of crossing two types of peas states that the probabilities of classification of the four resulting types are $\frac{9}{16}$, $\frac{3}{16}$, $\frac{3}{16}$, and $\frac{1}{16}$ respectively. If, from 160 independent observations, the observed frequencies of these classifications are 86, 35, 26, 13 respectively, test whether the data is consistent with the theory with $\alpha = 0.01$.

Solution. Here, $k = 4$, $n = 160$, and $np_1 = 90$, $np_2 = 30$, $np_3 = 30$, $np_4 = 10$. Therefore,

$$\begin{aligned} Q_3 &= \frac{(86 - 90)^2}{90} + \frac{(35 - 30)^2}{30} + \frac{(26 - 30)^2}{30} + \frac{(13 - 10)^2}{10} \\ &= 2.44 < 11.345 = \chi_3^2 \end{aligned}$$

at 1% level of significance (since $\alpha = 0.01$).

Thus, we **accept** the hypothesis – i.e, the data is consistent with Mendelian theory.

2.2 Exercises

1. The table below lists the observed results of $n = 120$ independent throws of a die.

Face	1	2	3	4	5	6
Frequency	a	20	20	20	20	$40 - a$

For what values of a would the hypothesis that the die is unbiased be rejected at 0.025 level of significance in a chi-square test?

2. A manufacturer of lightbulbs claims that the lightbulbs produced fall into five categories A, B, C, D, and E by quality, from highest to lowest, and that the percentages of lightbulbs in these five categories are 15, 25, 35, 20, and 5 respectively. A contractor who purchases a large number of the lightbulbs tests the claim by taking a random sample of 30 lightbulbs and observes that the numbers of lightbulbs that fall in the categories A, B, C, D, and E are 3, 6, 9, 7, and 5 respectively. Test whether the manufacturer is speaking the truth, using a chi-square test
- (i) at 5% significance level;
- (ii) at 1% significance level.

Appendices

A Critical Values of χ^2

D.f	Significance level		
	5%	1%	0.1%
1	3.841	6.635	10.828
2	5.991	9.210	13.816
3	7.815	11.345	16.266
4	9.488	13.277	18.467
5	11.070	15.086	20.515
6	12.592	16.812	22.458
7	14.067	18.475	24.322
8	15.507	20.090	26.124
9	16.919	21.666	27.877
10	18.307	23.209	29.588