

## Chapter 3

# Probability and simulation (solutions to exercises)

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## 3.1 Concrete items

### |||| Exercise 3.1 Concrete items

A construction company receives concrete items for a construction. The length of the items are assumed reasonably normally distributed. The following requirements for the length of the elements are made

$$\mu = 3000 \text{ mm.}$$

The company samples 9 items from a delivery which are then measured for control. The following measurements (in mm) are found:

3003	3005	2997	3006	2999	2998	3007	3005	3001
------	------	------	------	------	------	------	------	------

- a) Compute the following three statistics: the sample mean, the sample standard deviation and the standard error of the mean, and what are the interpretations of these statistics?

### |||| Solution

From the data we get the sample mean and sample standard deviation

$$\bar{x} = 3002.33\text{mm and } s = 3.708\text{mm.}$$

```
x <- c(3003, 3005, 2997, 3006, 2999, 2998, 3007, 3005, 3001)
mean(x)

[1] 3002

sd(x)

[1] 3.708
```

From Definition 3.7, we get the standard error of the mean as

$$SE_{\bar{x}} = \frac{3.708}{\sqrt{9}} = 1.236.$$

The interpretations of these are:

$\bar{x} = 3002.33$  The best estimate we can make of the true mean length of such concrete items

$s = 3.708$  The population of concrete item lengths has a standard deviation estimated at 3.7. We estimate the average deviation from the mean for concrete items to be 3.7 mm. So most concrete items will be within the range of approximately  $\pm 7.4$  mm of the mean

$SE_{\bar{x}} = 1.236$  All of the following are versions of the same story given by this number:

- The standard deviation of the sampling distribution of the sample mean (seen as a random variable) is (estimated at) 1.24
- And also: The standard deviation of the sampling distribution of the difference between sample mean and the population mean (seen as a random variable) is (estimated at) 1.24
- So from sample to sample (of size  $n = 9$ ) the sample mean will be different. And the size of these differences, that is, the difference between the sample mean and the true population mean is on average 1.24
- The sample mean is on average 1.24 away from the target: the population mean
- The error we will make on average in using the sample mean for estimating the population mean is 1.24

|||| **Remark 3.1**

Please, think about the difference between the story told by  $s$  and the story told by  $SE_{\bar{x}}$  (both are estimated standard deviations, but for two VERY different concepts).

- b) In a construction process, 5 concrete items are joined together to a single construction with a length which is then the complete length of the 5 concrete items. It is very important that the length of this new construction is within 15 m plus/minus 1 cm. How often will it happen that such a construction will be more than 1 cm away from the 15 m target (assume that the population mean concrete item length is  $\mu = 3000$  mm and that the population standard deviation is  $\sigma = 3$ )?

## ||| Solution

Let  $Y$  denote the length of the joined construction. So

$$Y = \sum_{i=1}^5 X_i,$$

where  $X_i$  is the length of a randomly selected concrete item. So using the rules for mean and variance calculations from Section 2.7, we can find that

$$E(Y) = \sum_{i=1}^5 E(X_i) = \sum_{i=1}^5 3000 = 5 \cdot 3000 = 15000,$$

and

$$V(Y) = \sum_{i=1}^5 V(X_i) = \sum_{i=1}^5 9 = 5 \cdot 9 = 45.$$

We can also state that, since the concrete item distribution is a normal

$$X_i \sim N(\mu, \sigma^2), \quad i = 1, \dots, 5,$$

then the sum of five (independent) of such will be normal (Theorem 2.40), so

$$Y \sim N(15000, 45).$$

(Actually, the normality result is expressed in Theorem 3.3 for the sample mean, however, the sum is just a simple scaling of the mean, so then the normality also holds for the sum) So we can now find the answer to the question

$$P(|Y - 15000| > 10) = 2 \cdot P\left(\frac{Y - 15000}{\sqrt{45}} > 10/\sqrt{45}\right) = 2 \cdot P(Z > 1.4907) = 0.136.$$

```
2*(1-pnorm(15010, mean=15000, sd=sqrt(45)))
```

```
[1] 0.136
```

```
2*pnorm(-1.4907)
```

```
[1] 0.136
```

In between 13 and 14 cases out of 100 the joined construction is beyond 1 cm away from the target – maybe a new supplier should be considered!

c) Find the 95% confidence interval for the mean  $\mu$ .

### ||| Solution

Since the 97.5%-quantile,  $t_{0.975}$  of the  $t$ -distribution with 8 degrees of freedom equals  $t_{0.975} = 2.306$  (found in R as: `qt(0.975, 8)`), we get

$$3002.33 \pm 2.306 \cdot \frac{3.708}{\sqrt{9}} \Leftrightarrow [2999.5; 3005.2].$$

Or everything in R:

```
x <- c(3003, 3005, 2997, 3006, 2999, 2998, 3007, 3005, 3001)
mean(x)

[1] 3002

sd(x)

[1] 3.708

qt(0.975, 8)

[1] 2.306

t.test(x)

One Sample t-test

data: x
t = 2429, df = 8, p-value <2e-16
alternative hypothesis: true mean is not equal to 0
95 percent confidence interval:
 2999 3005
sample estimates:
mean of x
 3002
```

- d) Find the 99% confidence interval for  $\mu$ . Compare with the 95% one from above and explain why it is smaller/larger!

### ||| Solution

Since the 99.5%-quantile,  $t_{0.995}$  of the  $t$ -distribution with 8 degrees of freedom equals  $t_{0.995} = 3.355$  (found in R as: `qt(0.995, 8)`), we get

$$3002.33 \pm 3.335 \cdot \frac{3.708}{\sqrt{9}} \Leftrightarrow [2998.2; 3006.5].$$

Or everything in R:

```
qt(0.995, 8)
[1] 3.355

t.test(x, conf.level=0.99)

One Sample t-test

data: x
t = 2429, df = 8, p-value <2e-16
alternative hypothesis: true mean is not equal to 0
99 percent confidence interval:
 2998 3006
sample estimates:
mean of x
 3002
```

It makes good sense that the 99% confidence interval becomes larger than the 95% one, as the consequence of wanting to be more confident on capturing the true mean  $\mu$  will make us having to state a larger interval.

- e) Find the 95% confidence intervals for the variance  $\sigma^2$  and the standard deviation  $\sigma$ .

## ||| Solution

We use the formula for the variance confidence interval

$$\left[ \frac{(n-1)s^2}{\chi_{1-\alpha/2}^2}; \frac{(n-1)s^2}{\chi_{\alpha/2}^2} \right].$$

where the quantiles come from a  $\chi^2$ -distribution with  $\nu = n - 1 = 8$  degrees of freedom

$$\begin{aligned} \left[ \frac{(n-1)s^2}{\chi_{1-\alpha/2}^2}; \frac{(n-1)s^2}{\chi_{\alpha/2}^2} \right] &= \left[ \frac{8 \cdot 3.708^2}{\chi_{0.975}^2}; \frac{8 \cdot 3.708^2}{\chi_{0.025}^2} \right] = \left[ \frac{8 \cdot 13.75}{17.535}; \frac{8 \cdot 13.75}{2.180} \right] \\ &= [6.273; 50.465]. \end{aligned}$$

And for the standard deviation:

$$\left[ \sqrt{6.273}; \sqrt{50.465} \right] = [2.50; 7.10].$$

In R:

```
qchisq(c(0.975,0.025), 8)
[1] 17.53  2.18

c(8*13.75/qchisq(0.975, 8), 8*13.75/qchisq(0.025, 8))
[1]  6.273 50.465

sqrt(c(8*13.75/qchisq(0.975, 8), 8*13.75/qchisq(0.025, 8)))
[1] 2.505 7.104
```

- f) Find the 99% confidence intervals for the variance  $\sigma^2$  and the standard deviation  $\sigma$ .



## ||| Solution

$$\left[ \frac{8 \cdot 13.75}{21.955}, \frac{8 \cdot 13.75}{1.344} \right] = [5.010; 81.820].$$

And for the standard deviation:

$$\left[ \sqrt{5.010}, \sqrt{81.820} \right] = [2.24; 9.05].$$

In R:

```
qchisq(c(0.995,0.005), 8)
```

```
[1] 21.955 1.344
```

```
c(8*13.75/qchisq(0.995, 8), 8*13.75/qchisq(0.005, 8))
```

```
[1] 5.01 81.82
```

```
sqrt(c(8*13.75/qchisq(0.995, 8), 8*13.75/qchisq(0.005, 8)))
```

```
[1] 2.238 9.045
```

## 3.2 Aluminum profile

### |||| Exercise 3.2 Aluminum profile

The length of an aluminum profile is checked by taking a sample of 16 items whose length is measured. The measurement results from this sample are listed below, all measurements are in mm:

180.02	180.00	180.01	179.97	179.92	180.05	179.94	180.10
180.24	180.12	180.13	180.22	179.96	180.10	179.96	180.06

From data is obtained:  $\bar{x} = 180.05$  and  $s = 0.0959$ .

It can be assumed that the sample comes from a population which is normal distributed.

- a) A 90%-confidence interval for  $\mu$  becomes?

### |||| Solution

Since the 95%-quantile,  $t_{0.95}$  of the  $t$ -distribution with 15 degrees of freedom equals  $t_{0.95} = 1.753$  (found in R as: `qt(0.95, 15)`), we get

$$180.05 \pm 1.753 \cdot \frac{0.0959}{\sqrt{16}} = [180.00, 180.10].$$

Or everything in R:

```
x <- c(180.02, 180.00, 180.01, 179.97, 179.92, 180.05, 179.94, 180.10,
180.24, 180.12, 180.13, 180.22, 179.96, 180.10, 179.96, 180.06)
mean(x)

[1] 180.1

sd(x)

[1] 0.09592

qt(0.95, 15)

[1] 1.753

t.test(x, conf.level=0.9)

One Sample t-test

data: x
t = 7509, df = 15, p-value <2e-16
alternative hypothesis: true mean is not equal to 0
90 percent confidence interval:
 180.0 180.1
sample estimates:
mean of x
 180.1
```

b) A 99%-confidence interval for  $\sigma$  becomes?

### ||| Solution

We use the formula for the variance confidence interval

$$\left[ \frac{(n-1)s^2}{\chi_{1-\alpha/2}^2}; \frac{(n-1)s^2}{\chi_{\alpha/2}^2} \right],$$

where the quantiles come from a  $\chi^2$ -distribution with  $\nu = n - 1 = 15$  degrees of freedom

$$\left[ \frac{(n-1)s^2}{\chi_{1-\alpha/2}^2}; \frac{(n-1)s^2}{\chi_{\alpha/2}^2} \right] = \left[ \frac{15 \cdot 0.0092}{\chi_{0.995}^2}; \frac{15 \cdot 0.0092}{\chi_{0.005}^2} \right] = \left[ \frac{15 \cdot 0.0092}{32.801}; \frac{15 \cdot 0.0092}{4.601} \right] \\ = [0.00421; 0.02999].$$

And for the standard deviation:

$$\left[ \sqrt{0.00421}; \sqrt{0.02999} \right] = [0.065; 0.173].$$

In R:

```
qchisq(p=c(0.995,0.005), df=15)
[1] 32.801 4.601

c(15*0.0092/qchisq(p=0.995,df=15), 15*0.0092/qchisq(p=0.005,df=15))
[1] 0.004207 0.029994

sqrt(c(15*0.0092/qchisq(p=0.995,df=15), 15*0.0092/qchisq(p=0.005,df=15)))
[1] 0.06486 0.17319
```

## 3.3 Concrete items (hypothesis testing)

### |||| Exercise 3.3 Concrete items (hypothesis testing)

This is a continuation of Exercise 1, so the same setting and data is used (read the initial text of it).

- a) To investigate whether the requirement to the mean is fulfilled (with  $\alpha = 5\%$ ), the following hypothesis should be tested

$$H_0 : \mu = 3000$$

$$H_1 : \mu \neq 3000.$$

Or similarly asked: what is the evidence against the null hypothesis?

### |||| Solution

This is a one-sample situation. In R it could be handled by:

```
x <- c(3003,3005,2997,3006,2999,2998,3007,3005,3001)
t.test(x, mu=3000)

One Sample t-test

data:  x
t = 1.9, df = 8, p-value = 0.1
alternative hypothesis: true mean is not equal to 3000
95 percent confidence interval:
 2999 3005
sample estimates:
mean of x
 3002
```

from which the answer can be seen. One could also explicitly do it as

$$t_{\text{obs}} = \frac{3002.333 - 3000}{3.708/\sqrt{9}} = 1.885.$$

And then find the  $p$ -value as (using a  $t$ -distribution with  $\nu = 8$  degrees of freedom)

$$2 * P(T > 1.885) = 0.096.$$

(in R as:  $2*(1-pt(1.885,8))$ ). So although there is a weak evidence against the null, cf. the  $p$ -value interpretation table in Section 3.1, when using an  $\alpha$  of 0.05 the null hypothesis is not rejected, but must be accepted.

- b) What would the level  $\alpha = 0.01$  critical values be for this test, and what are the interpretation of these?

### ||| Solution

The critical values would be  $\pm t_{0.995} = \pm 3.355$ :

```
qt(p=0.995, df=8)
```

```
[1] 3.355
```

This means that, in a new experiment, the standardized difference between the data and the null hypothesis, also called  $t_{\text{obs}}$ , must be either larger than 3.355 or smaller than  $-3.355$  to lead to a significant result of the experiment.

- c) What would the level  $\alpha = 0.05$  critical values be for this test (compare also with the values found in the previous question)?

### ||| Solution

The critical values would be  $\pm t_{0.975} = \pm 2.306$ :

```
qt(p=0.975, df=8)
```

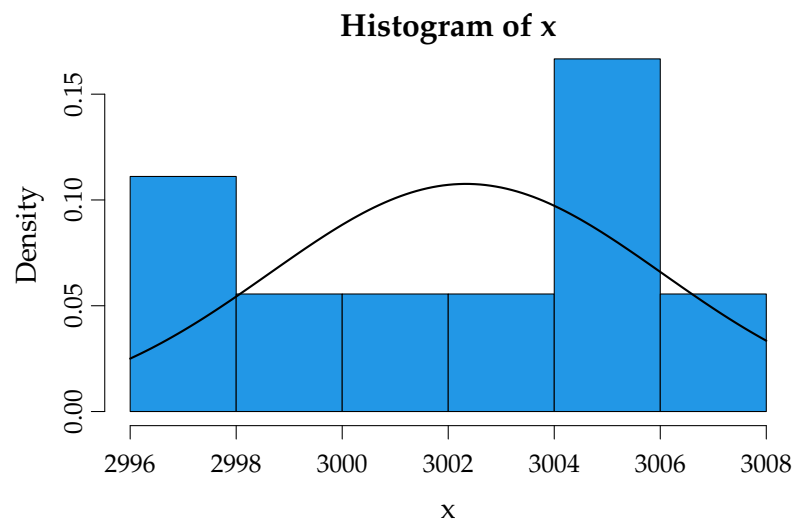
```
[1] 2.306
```

This means that, again in a new experiment, it is easier to detect an effect with significance level  $\alpha = 0.05$  than on level  $\alpha = 0.01$ .

- d) Investigate, by some plots, whether the data here appears to be coming from a normal distribution (as assumed until now)?

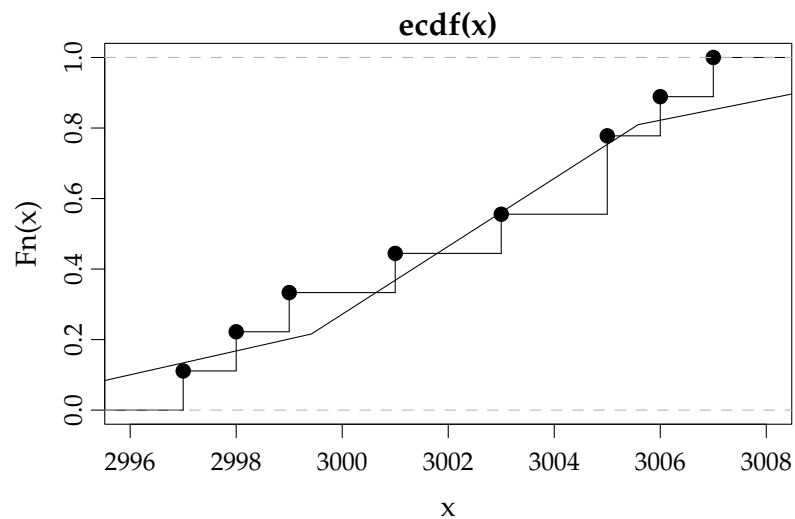
### ||| Solution

```
x=c(3003,3005,2997,3006,2999,2998,3007,3005,3001)
hist(x, freq=F, col = 4)
xp <- seq(2996, 3008, 0.1)
lines(xp, dnorm(xp, mean(x), sd(x)), lwd = 2)
```



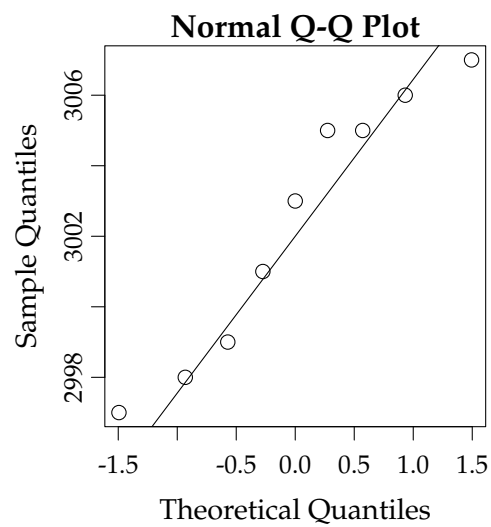
## ||| Solution

```
plot(ecdf(x), verticals = TRUE)
xp <- seq(0.9*min(x), 1.1*max(x), length.out = 100)
lines(xp, pnorm(xp, mean(x), sd(x)))
```



## ||| Solution

```
qqnorm(x)
qqline(x)
```

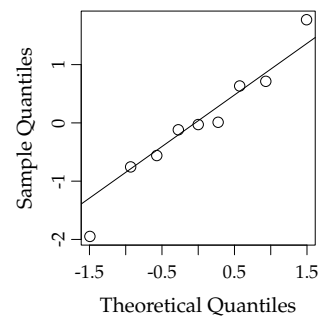
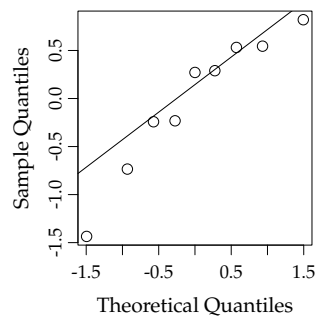
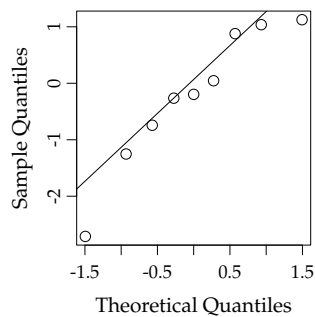
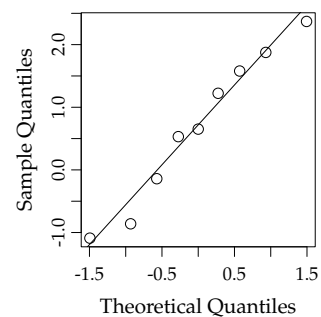
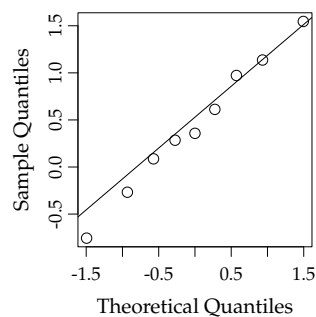
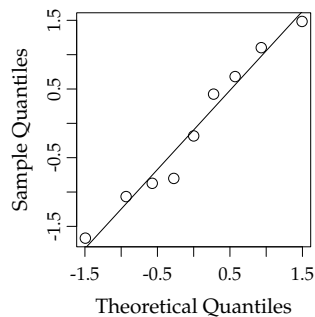
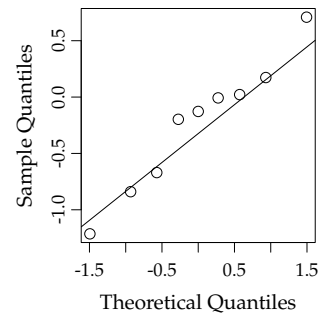
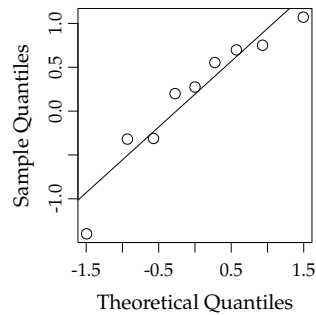
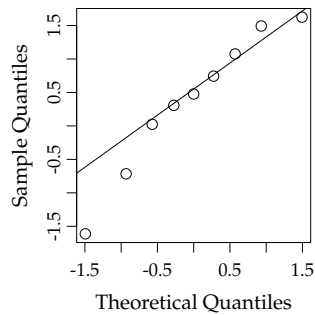




## ||| Solution

Compare with 9 simulated ones

```
par(mfrow = c(3, 3))
for (i in 1:9){
  xr <- rnorm(9)
  qqnorm(xr, main="")
  qqline(xr)
}
```



### ||| Solution

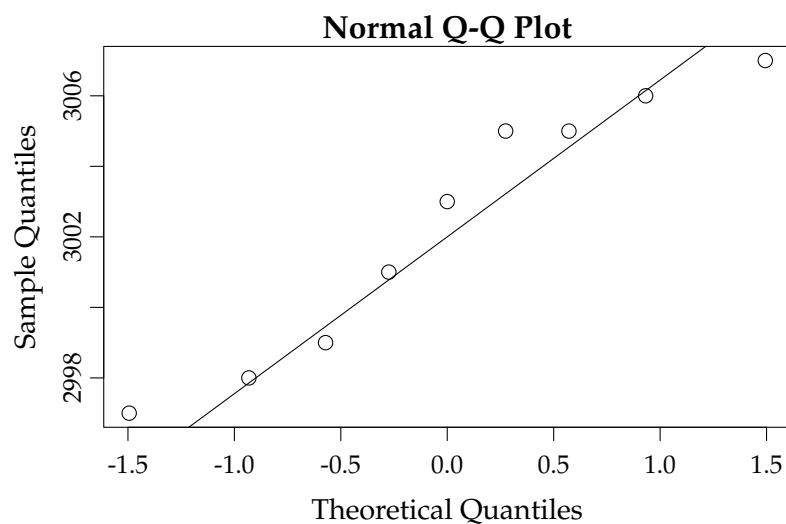
The nine data points do not differ more from the line than what truly normally distributed samples of size  $n = 9$  do, so we cannot falsify the normality assumption (Did we prove normality?...no, we accept that they are normal distributed (like when we accept the null hypothesis)).

- e) Assuming that you, maybe among different plots, also did the normal q-q plot above, the question is now: What exactly is plotted in that plot? Or more specifically: what are the  $x$ - and  $y$ -coordinates of e.g. the two points to the lower left in this plot?

### ||| Solution

Let us look at the Normal q-q plot again:

```
qqnorm(x)
qqline(x)
```



The  $y$ -coordinates of the nine points from left to right in the plot are the ordered observations  $x_{(1)}, \dots, x_{(9)}$ :

```
sort(x)
```

```
[1] 2997 2998 2999 3001 3003 3005 3005 3006 3007
```

||| **Solution**

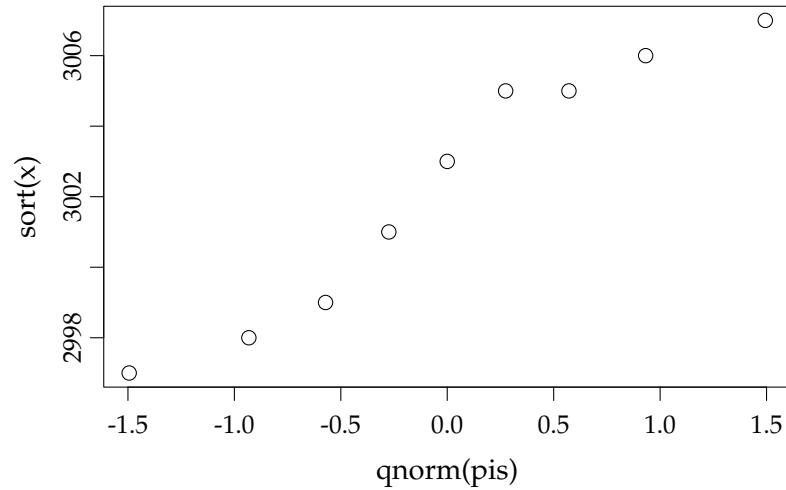
The  $x$ -coordinates are quantiles from the standard normal distribution. Method 3.42 tell us exactly which quantiles, that are used by R (in the current case there is less than  $n = 10$  observations):

$$p_i = \frac{i - 3/8}{9 + 1/4}, i = 1, \dots, 9$$

```
is <- 1:9
pis <- (is-3/8)/(9+1/4)
qnorm(pis)

[1] -1.4942 -0.9320 -0.5716 -0.2744  0.0000  0.2744  0.5716  0.9320
[9]  1.4942

plot(qnorm(pis), sort(x))
```



## 3.4 Aluminum profile (hypothesis testing)

### |||| Exercise 3.4 Aluminium profile (hypothesis testing)

We use the same setting and data as in Exercise 2, so read the initial text of it.

- a) Find the evidence against the following hypothesis:

$$H_0 : \mu = 180.$$

### |||| Solution

First we compute the observed  $t$ -statistic

$$t_{\text{obs}} = \frac{180.05 - 180}{0.0959/\sqrt{16}} = 2.085,$$

and the  $p$ -value is

$$p\text{-value} = 2 \cdot P(T > 2.085) = 2 \cdot 0.0273 = 0.055.$$

```
2*(1-pt(2.085, 15))
```

```
[1] 0.05457
```

Or in completely solve by R:

```
x <- c(180.02, 180.00, 180.01, 179.97, 179.92, 180.05, 179.94, 180.10,
180.24, 180.12, 180.13, 180.22, 179.96, 180.10, 179.96, 180.06)
t.test(x, mu=180)
```

```
One Sample t-test
```

```
data: x
t = 2.1, df = 15, p-value = 0.05
alternative hypothesis: true mean is not equal to 180
95 percent confidence interval:
 180.0 180.1
sample estimates:
mean of x
 180.1
```

■ Hence there is *weak evidence against*  $H_0$ , cf. Table 3.1.

b) If the following hypothesis test is carried out

$$H_0 : \mu = 180,$$

$$H_1 : \mu \neq 180.$$

What are the level  $\alpha = 1\%$  critical values for this test?

### |||| Solution

The critical values are the 0.005 and 0.995 quantiles of the  $t$ -distribution with  $\nu = n - 1 = 15$  degrees of freedom,  $\pm t_{0.995} = \pm 2.947$ :

```
qt(p=0.995, df=15)
```

```
[1] 2.947
```

c) What is the 99%-confidence interval for  $\mu$ ?

### |||| Solution

The formula gives

$$180.05 \pm t_{0.995} \frac{0.0959}{\sqrt{16}} = [179.98; 180.12].$$

```
t.test(x, mu=180, conf.level=0.99)

One Sample t-test

data: x
t = 2.1, df = 15, p-value = 0.05
alternative hypothesis: true mean is not equal to 180
99 percent confidence interval:
 180.0 180.1
sample estimates:
mean of x
 180.1
```

d) Carry out the following hypothesis test

$$H_0 : \mu = 180,$$

$$H_1 : \mu \neq 180,$$

using  $\alpha = 5\%$ .

### |||| Solution

We already found the  $p$ -value = 0.055 above, and as this is larger than  $\alpha$  we cannot reject the null hypothesis of  $\mu = 180$ .

## 3.5 Transport times

### |||| Exercise 3.5 Transport times

A company, MM, selling items online wants to compare the transport times for two transport firms for delivery of the goods. To compare the two companies recordings of delivery times on a specific route were made, with a sample size of  $n = 9$  for each firm. The following data were found:

Firm A:  $\bar{y}_A = 1.93$  d and  $s_A = 0.45$  d,

Firm B:  $\bar{y}_B = 1.49$  d and  $s_B = 0.58$  d.

note that d is the SI unit for days. It is assumed that data can be regarded as stemming from normal distributions.

a) We want to test the following hypothesis

$$H_0 : \mu_A = \mu_B$$

$$H_1 : \mu_A \neq \mu_B$$

What is the  $p$ -value, interpretation and conclusion for this test (at  $\alpha = 5\%$  level)?

### |||| Solution

This is the independent samples (non-directional)  $t$ -test (Welch) in Method 3.49 (or Method 3.51). We first find the  $t$ -test statistic

$$t_{\text{obs}} = \frac{1.93 - 1.49}{\sqrt{0.45^2/9 + 0.58^2/9}} = 1.8,$$

and then the degrees of freedom

$$\nu = \frac{\left(\frac{0.45^2}{9} + \frac{0.58^2}{9}\right)^2}{\frac{(0.45^2/9)^2}{8} + \frac{(0.58^2/9)^2}{8}} = 15.0,$$

and the  $p$ -value is then found to

$$2 \cdot P(T > 1.8) = 0.0922,$$

using a  $t$ -distribution with 15.0 degrees of freedom. So even though, according to Table 3.1, there is weak evidence against the null hypothesis, when we use  $\alpha = 0.05$  we cannot reject the null hypothesis of the two firms being equally fast. In R it can be found as

```

ms <- c(1.93, 1.49)
vs <- c(0.45^2, 0.58^2)
ns <- c(9,9)
t_obs <- (ms[1]-ms[2])/sqrt(vs[1]/ns[1]+vs[2]/ns[2])
nu <- ((vs[1]/ns[1]+vs[2]/ns[2])^2)/
((vs[1]/ns[1])^2/(ns[1]-1)+(vs[2]/ns[2])^2/(ns[2]-1))
t_obs

[1] 1.798

nu

[1] 15.07

2*(1-pt(t_obs,nu))

[1] 0.09222

```

b) Find the 95% confidence interval for the mean difference  $\mu_A - \mu_B$ .

### ||| Solution

We need the degrees of freedom - we found that number above:  $\nu = 15.0$ . Since the relevant  $t$ -quantile then is, using  $\nu = 15.0$ ,

```

qt(p=0.975, df=15.0)

[1] 2.131

```

$$t_{0.975} = 2.131,$$

the confidence interval becomes

$$1.93 - 1.49 \pm 2.131 \sqrt{0.45^2/9 + 0.58^2/9}.$$

Which becomes



```
1.93-1.49 +c(-1,1)*qt(0.975,15.0)*sqrt(0.45^2/9+0.58^2/9)
[1] -0.08156  0.96156
```

Hence the answer is:  $[-0.082; 0.962]$ .

- c) What is the power of a study with  $n = 9$  observations in each of the two samples of detecting a potential mean difference of 0.4 between the firms (assume that  $\sigma = 0.5$  and that we use  $\alpha = 0.05$ )?

### ||| Solution

```
power.t.test(n = 9, delta = 0.4, sd = 0.5, sig.level = 0.05)
```

```
Two-sample t test power calculation
```

```
      n = 9
  delta = 0.4
     sd = 0.5
sig.level = 0.05
  power = 0.3578
alternative = two.sided
```

```
NOTE: n is number in *each* group
```

So the power is only 0.36 - not nearly good enough for a reasonable study.

- d) What effect size (mean difference) could be detected with  $n = 9$  observations in each of the two samples with a power of 0.8 (assume that  $\sigma = 0.5$  and that we use  $\alpha = 0.05$ )?

## ||| Solution

```
power.t.test(n = 9, power = 0.8, sd = 0.5, sig.level = 0.05)
```

```
Two-sample t test power calculation
```

```
      n = 9
  delta = 0.7035
      sd = 0.5
sig.level = 0.05
  power = 0.8
alternative = two.sided
```

```
NOTE: n is number in *each* group
```

So a potential mean difference of 0.70 is detectable with probability 0.8 by such a study.

- e) How large a sample size (from each firm) would be needed in a new investigation, if we want to detect a potential mean difference of 0.4 between the firms with probability 0.90, that is with power=0.90 (assume that  $\sigma = 0.5$  and that we use  $\alpha = 0.05$ )?

## ||| Solution

```
power.t.test(power = 0.90, delta = 0.4, sd = 0.5, sig.level = 0.05)
```

```
Two-sample t test power calculation
```

```
      n = 33.83
  delta = 0.4
     sd = 0.5
sig.level = 0.05
  power = 0.9
alternative = two.sided
```

```
NOTE: n is number in *each* group
```

So  $n = 34$  in each sample would do the job!

## 3.6 Cholesterol

### |||| Exercise 3.6 Cholesterol

In a clinical trial of a cholesterol-lowering agent, 15 patients' cholesterol (in mmol/L) has been measured before treatment and 3 weeks after starting treatment. Data are listed in the following table:

Patient	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Before	9.1	8.0	7.7	10.0	9.6	7.9	9.0	7.1	8.3	9.6	8.2	9.2	7.3	8.5	9.5
After	8.2	6.4	6.6	8.5	8.0	5.8	7.8	7.2	6.7	9.8	7.1	7.7	6.0	6.6	8.4

The following is run in R:

```
x1 <- c(9.1, 8.0, 7.7, 10.0, 9.6, 7.9, 9.0, 7.1,
        8.3, 9.6, 8.2, 9.2, 7.3, 8.5, 9.5)
x2 <- c(8.2, 6.4, 6.6, 8.5, 8.0, 5.8, 7.8, 7.2,
        6.7, 9.8, 7.1, 7.7, 6.0, 6.6, 8.4)
t.test(x1, x2)
```

Welch Two Sample t-test

```
data: x1 and x2
t = 3.3, df = 27, p-value = 0.003
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 0.4637 1.9630
sample estimates:
mean of x mean of y
 8.600     7.387
```

```
t.test(x1, x2, pair=TRUE)
```

Paired t-test

```
data: x1 and x2
t = 7.3, df = 14, p-value = 0.000004
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 0.8588 1.5678
```

```
sample estimates:
mean of the differences
      1.213
```

- a) Can there, based on these data be demonstrated a significant decrease in cholesterol levels with  $\alpha = 0.001$ ?

### |||| Solution

This is clearly a *paired* setting so only the results from the last of the R-calls are relevant, where we can read off the results:

The (non-directional)  $p$ -value is 0.00000367, so there is very strong evidence against the null hypothesis, and we can beyond any reasonable doubts conclude that the mean cholesterol level has decreased after the 3 weeks.

## 3.7 Pulse

### |||| Exercise 3.7 Pulse

13 runners had their pulse measured at the end of a workout and 1 minute after again and we got the following pulse measurements:

Runner	1	2	3	4	5	6	7	8	9	10	11	12	13
Pulse end	173	175	174	183	181	180	170	182	188	178	181	183	185
Pulse 1min	120	115	122	123	125	140	108	133	134	121	130	126	128

The following was run in R:

```
Pulse_end <- c(173,175,174,183,181,180,170,182,188,
              178,181,183,185)
Pulse_1min <- c(120,115,122,123,125,140,108,133,134,
               121,130,126,128)
mean(Pulse_end)

[1] 179.5

mean(Pulse_1min)

[1] 125

sd(Pulse_end)

[1] 5.19

sd(Pulse_1min)

[1] 8.406

sd(Pulse_end-Pulse_1min)

[1] 5.768
```

- a) What is the 99% confidence interval for the mean pulse drop (meaning the drop during 1 minute from end of workout)?

## ||| Solution

We use the paired sample  $t$ -test version of the confidence interval (see Section 3.2.3) with  $s_{\text{dif}} = 5.768$ ,  $n = 13$  and 12 degrees of freedom for the  $t$ -quantile  $t_{0.005}$ :

```
qt(p=0.995, df=12)
[1] 3.055
```

Or in completely in R:

```
Pulse_end <- c(173,175,174,183,181,180,170,182,188,178,181,183,185)
Pulse_1min <- c(120,115,122,123,125,140,108,133,134,121,130,126,128)

t.test(Pulse_end, Pulse_1min, paired=TRUE, conf.level = 0.99)

Paired t-test

data: Pulse_end and Pulse_1min
t = 34, df = 12, p-value = 3e-13
alternative hypothesis: true difference in means is not equal to 0
99 percent confidence interval:
 49.58 59.35
sample estimates:
mean of the differences
          54.46
```

So, the answer is:

$$54.46 \pm 3.054 \cdot \frac{5.768}{\sqrt{13}} = [49.58; 59.35].$$

- b) Consider now the 13 pulse end measurements (first row in the table). What is the 95% confidence interval for the standard deviation of these?

## ||| Solution

Using 3.19 we find the 95% confidence interval for the variance to

$$\frac{12 \cdot 5.18998^2}{\chi_{0.975}^2} < \sigma^2 < \frac{12 \cdot 5.18998^2}{\chi_{0.025}^2},$$

which then for the standard deviation becomes

$$\sqrt{\frac{12 \cdot 5.18998^2}{23.34}} < \sigma < \sqrt{\frac{12 \cdot 5.18998^2}{4.40}}.$$

Or in R:

```
t.test(Pulse_end, Pulse_1min, paired=TRUE, conf.level = 0.95)

Paired t-test

data: Pulse_end and Pulse_1min
t = 34, df = 12, p-value = 3e-13
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 50.98 57.95
sample estimates:
mean of the differences
          54.46

sqrt(12*var(Pulse_end)/qchisq(0.975,12))

[1] 3.722

sqrt(12*var(Pulse_end)/qchisq(0.025,12))

[1] 8.567
```

So, the answer is that we accept that  $\sigma \in [3.72; 8.57]$  or we could write  $3.72 < \sigma < 8.57$ .



## 3.8 Foil production

### |||| Exercise 3.8 Foil production

In the production of a certain foil (film), the foil is controlled by measuring the thickness of the foil in a number of points distributed over the width of the foil. The production is considered stable if the mean of the difference between the maximum and minimum measurements does not exceed 0.35 mm. At a given day, the following random samples are observed for 10 foils:

Foil	1	2	3	4	5	6	7	8	9	10
Max. in mm ( $y_{\max}$ )	2.62	2.71	2.18	2.25	2.72	2.34	2.63	1.86	2.84	2.93
Min. in mm ( $y_{\min}$ )	2.14	2.39	1.86	1.92	2.33	2.00	2.25	1.50	2.27	2.37
Max-Min ( $D$ )	0.48	0.32	0.32	0.33	0.39	0.34	0.38	0.36	0.57	0.56

The following statistics may potentially be used

$$\bar{y}_{\max} = 2.508, \bar{y}_{\min} = 2.103, s_{y_{\max}} = 0.3373, s_{y_{\min}} = 0.2834, s_D = 0.09664.$$

a) What is a 95% confidence interval for the mean difference?

### |||| Solution

The 95% confidence interval is given by:

```
(2.508 - 2.103) + c(-1, 1) * qt(0.975, df=10-1) * 0.09664 / sqrt(10)
```

```
[1] 0.3359 0.4741
```

The confidence interval contains those values of the mean difference that we believe in based on the data. Notice that the CI contains  $\mu_D = 0.35$ , hence we know that we will not reject the null hypothesis  $H_0 = 0.35$ , which is the next question.

b) How much evidence is there that the mean difference is different from 0.35? State the null hypothesis,  $t$ -statistic and  $p$ -value for this question.

## ||| Solution

The  $t$ -statistic is found using Method 9:

$$t_{\text{obs}} = \frac{(2.508 - 2.103) - 0.35}{0.09664/\sqrt{10}} = 1.80.$$

```
(tobs <- ((2.508 - 2.103) - 0.35) / (0.09664 / sqrt(10)))  
[1] 1.8
```

The  $p$ -value for this assessment is

$$p\text{-value} = 2 \cdot P(T > t_{\text{obs}}) = 0.1054.$$

where  $T$  has a  $t$ -distribution with 9 degrees of freedom:

```
2 * pt(abs(tobs), df=10-1, lower.tail=FALSE)  
[1] 0.1054
```

According to Table 3.1 there is little or no evidence that against the null hypothesis that  $\mu_D = 0.35$ .

## 3.9 Course project

### |||| Exercise 3.9 Course project

At a specific education it was decided to introduce a project, running through the course period, as a part of the grade point evaluation. In order to assess whether it has changed the percentage of students passing the course, the following data was collected:

	Before introduction of project	After introduction of project
Number of students evaluated	50	24
Number of students failed	13	3
Average grade point $\bar{x}$	6.420	7.375
Sample standard deviation $s$	2.205	1.813

- a) As it is assumed that the grades are approximately normally distributed in each group, the following hypothesis is tested:

$$H_0 : \mu_{\text{Before}} = \mu_{\text{After}}$$

$$H_1 : \mu_{\text{Before}} \neq \mu_{\text{After}}$$

The test statistic, the  $p$ -value and the conclusion for this test become?

### |||| Solution

The (Welch)  $t$ -test statistic for this setup is found using Method :

$$t = \frac{6.42 - 7.375}{\sqrt{2.205^2/50 + 1.813^2/24}} = -1.97.$$

From the  $t$ -distribution with  $\nu = 54.4$  we can find that the (non-directional)  $p$ -value is

$$2 \cdot P(T > 1.97) = 0.054.$$

```
2*(1-pt(1.97, 54.4))
```

```
[1] 0.05394
```

In R we could do it by the following:

```
ms <- c(6.42, 7.375)
vs <- c(2.205^2, 1.813^2)
ns <- c(50, 24)
t_obs <- (ms[1]-ms[2])/sqrt(vs[1]/ns[1]+vs[2]/ns[2])
nu <- ((vs[1]/ns[1]+vs[2]/ns[2])^2)/
((vs[1]/ns[1])^2/(ns[1]-1)+(vs[2]/ns[2])^2/(ns[2]-1))
t_obs

[1] -1.973

nu

[1] 54.39
```

On a 5% level we cannot conclude a significant difference in the grade point means before and after.

b) A 99% confidence interval for the mean grade point difference is?

### ||| Solution

We need the degrees of freedom - we found that number above:  $\nu = 54.4$ . Since the relevant  $t$ -quantile then is, using  $\nu = 54.4$ ,

```
qt(p=0.995, df=54.4)
```

```
[1] 2.669
```

Hence  $t_{0.995} = 2.669$ , and the confidence interval becomes

$$6.42 - 7.375 \pm 2.669 \sqrt{2.205^2/50 + 1.813^2/24},$$

Which is:

```
6.42-7.375+c(-1,1)*qt(0.995,54.4)*sqrt(2.205^2/50 + 1.813^2/24)
```

```
[1] -2.2468 0.3368
```

and the answer is: we accept that the mean difference in the interval  $[-2.247; 0.337]$ .

- c) A 95% confidence interval for the grade point standard deviation after the introduction of the project becomes?

### ||| Solution

The confidence interval formula for a sample variance is used WITH the square-root applied to everything:

$$\frac{\sqrt{(n-1) \cdot s^2}}{\sqrt{\chi_{0.975}^2}} < \sigma < \frac{\sqrt{(n-1) \cdot s^2}}{\sqrt{\chi_{0.025}^2}},$$

so

$$\frac{\sqrt{23 \cdot 1.813^2}}{\sqrt{38.076}} < \sigma_{\text{After}} < \frac{\sqrt{23 \cdot 1.813^2}}{\sqrt{11.689}}.$$

The values found in R:

```
sqrt(23*1.813^2)/sqrt(qchisq(0.975,23))
```

```
[1] 1.409
```

```
sqrt(23*1.813^2)/sqrt(qchisq(0.025,23))
```

```
[1] 2.543
```

So the answer is, that we accept that  $\sigma_{\text{After}} \in [1.41; 2.54]$ .

## 3.10 Concrete items (sample size)

### |||| Exercise 3.10 Concrete items (sample size)

This is a continuation of Exercise 1, so the same setting and data is used (read the initial text of it).

- a) A study is planned of a new supplier. It is expected that the standard deviation will be approximately 3, that is,  $\sigma = 3$  mm. We want a 90% confidence interval for the mean value in this new study to have a width of 2 mm. How many items should be sampled to achieve this?

#### |||| Solution

We use the sample size formula (Method 3.63) with wanted margin of error  $ME = 1$  (as the width of the confidence interval is twice the margin of error)

$$n = \left( \frac{z_{0.95}\sigma}{ME} \right)^2 = \left( \frac{1.645 \cdot 3}{1} \right)^2 = 24.35.$$

(in R: `qnorm(0.95)` to get  $z_{0.95} = 1.645$ ). Hence the answer becomes: at least 25.

- b) Answer the sample size question above but requiring the 99% confidence interval to have the (same) width of 2 mm.

#### |||| Solution

The same formula as above:

$$n = \left( \frac{z_{0.995}\sigma}{ME} \right)^2 = \left( \frac{2.576 \cdot 3}{1} \right)^2 = 59.72.$$

(using R: `qnorm(0.995)` to get  $z_{0.995} = 2.576$ ). Hence the answer becomes: at least 60.

- c) (Warning: This is a difficult question about a challenging abstraction - do not worry, if you do not make this one) For the two sample sizes found in the two previous questions find the probability that the corresponding confidence interval in the future study will actually be more than 10% wider than planned for (still assuming and using that the population variance is  $\sigma^2 = 9$ ).

### ||| Solution

The random width of the confidence interval is due to the randomly changing sample variance in the formula for the (random) half width of the interval

$$\text{'Half width of CI'} = t_{1-\alpha/2} \frac{S}{\sqrt{n}}.$$

The (sampling) distribution of the variance estimator,  $S$ , is a  $\chi^2$ -distribution, as stated in Section 3.1.6 (around Equation (3-17)). Thus: let  $S^2$  be the variance of a sample of size  $n$  from a normal distribution with variance  $\sigma^2 = 3^2 = 9$ . Then

$$\chi^2 = \frac{(n-1) \cdot S^2}{9},$$

is a stochastic variable following the  $\chi^2$ -distribution with  $v = n - 1$  degrees of freedom.

### ||| Solution

So, as the wanted margin error was  $ME = 1$ , we are asked to first find with  $\alpha = 0.10$  and  $n = 25$ , and hence  $t_{0.95} = 1.711$  (in R `qt(0.95, 24)`)

$$\begin{aligned} P(\text{'Half width of CI'} > 1.1) &= P\left(t_{0.95} \cdot \frac{S}{\sqrt{n}} > 1.1\right) \\ &= P\left(t_{0.95}^2 \cdot \frac{S^2}{n} > 1.1^2\right) \\ &= P\left(t_{0.95}^2 \cdot \frac{9 \cdot \chi^2}{24 \cdot 25} > 1.1^2\right) \\ &= P\left(\chi^2 > \frac{1.1^2 \cdot 24 \cdot 25}{t_{0.95}^2 \cdot 9}\right) \\ &= P(\chi^2 > 27.56) \\ &= 0.28. \end{aligned}$$

```
qt(0.95, 24)
[1] 1.711

1.1^2*25*24/(qt(0.95, 24)^2*9)
[1] 27.56

1-pchisq(1.1^2*25*24/(qt(0.95, 24)^2*9), 24)
[1] 0.2791
```

Therefore in almost 30% of cases an experiment planned for a 90%  $ME = 1$  would actually end up with a confidence interval of half width more than 1.1.

For the 99% case, and  $n = 60$  the same computation gives:

```
qt(p=0.995, df=59)
[1] 2.662

1.1^2*60*59/(qt(p=0.995, df=59)^2*9)
[1] 67.18

1 - pchisq(q=1.1^2*60*59/(qt(0.995, 59)^2*9), df=59)
[1] 0.2174
```

So in this case it only happens in 22% of the cases. In the next part of this topic we will learn how we can plan experiments such that we are more in control of the risk of the experiments not really meeting our needs.

- d) Now a new experiment is to be planned. In the first part above, given some wanted margin of error (ME) a sample size of  $n = 25$  was found. What are each of the probabilities that an experiment with  $n = 25$  will detect effects corresponding to ("end up significant for")  $\mu_1 = 3001, 3002, 3003$  respectively? Assume that we use the typical  $\alpha = 0.05$  level and that  $\sigma = 3$ ?



### |||| Solution

We can only solve this by the in-built `power.t.test` function in R. If we specify everything but the power - it will compute the power for us. With e.g.  $\mu_1 = 3001$ , we have that  $\mu_0 - \mu_1 = -1$ , so in the R-function the `delta` should be set to either 1 or  $-1$ . And in fact one can insert a list of the three relevant deltas to get the three answers by a single call to R:

```
power.t.test(n = 25, delta = 1:3, sd = 3, sig.level = 0.05,
type = c("one.sample"))
```

```
One-sample t test power calculation
```

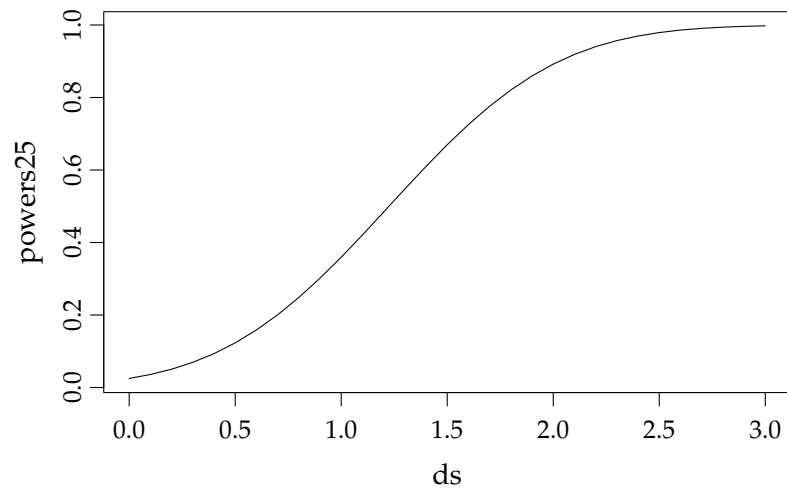
```
      n = 25
  delta = 1, 2, 3
      sd = 3
sig.level = 0.05
  power = 0.3595, 0.8920, 0.9977
alternative = two.sided
```

So the three probabilities are 0.36, 0.89 and 0.998. A difference of 1 would not be reasonably detectable by this experiment but a difference of 2 has a high probability of being detected and even more so for 3.

### |||| Solution

A plot of all possible powers for all possible effect sizes could now easily be made:

```
ds = seq(0, 3, 0.1)
powers25 <- power.t.test(n = 25, delta = ds, sd = 3, sig.level = 0.05,
type = c("one.sample"))$power
plot(ds, powers25, type = "l")
```



- e) One of the sample size computation above led to  $n = 60$  (it is not so important how/why). Answer the same question as above using  $n = 60$ .

### ||| Solution

```
power.t.test(n = 60, delta = 1:3, sd = 3, sig.level = 0.05,  
type = c("one.sample"))
```

```
One-sample t test power calculation
```

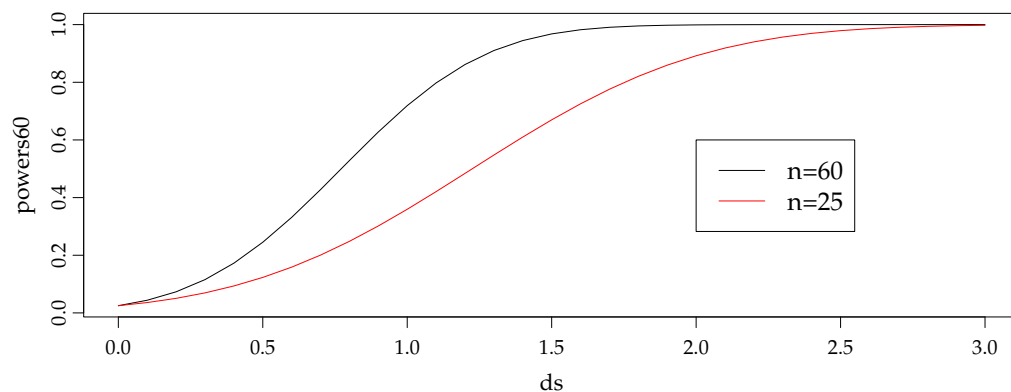
```
      n = 60  
  delta = 1, 2, 3  
     sd = 3  
sig.level = 0.05  
  power = 0.7190, 0.9991, 1.0000  
alternative = two.sided
```

So the three probabilities are 0.72, 0.999 and 1.00000. A difference of 1 would still not be reasonably detectable by this experiment but a difference of 2 and 3 has extremely high power.

### ||| Solution

A plot of all possible powers for all possible effect sizes could now easily be made:

```
ds = seq(0, 3, 0.1)
powers60 <- power.t.test(n = 60, delta = ds, sd = 3, sig.level = 0.05,
type = c("one.sample"))$power
plot(ds, powers60, type = "l")
lines(ds, powers25, col="red")
legend(2,0.6,c("n=60", "n=25"), col=c("black", "red") , lty=c(1,1))
```



- f) What sample size would be needed to achieve a power of 0.80 for an effect of size 0.5?

### ||| Solution

The approximate sample size formula, Method 3.47, is only formally given for one-sided tests, so at first sight again we have no formulas for this (as we test two-sided here). However, in fact the formula also works nicely for the two-sided case, substituting  $z_{1-\alpha}$  by  $z_{1-\alpha/2}$ , as the only error that is made would be the left hand tail of the rejection area, cf. the power plots on page 46, which essentially is zero for relevant effect sizes. So IF we use this adapted (and no-where stated) formula we would get:

$$n = \left( 3 \cdot \frac{z_{0.8} + z_{0.975}}{0.5} \right)^2 = 282.6.$$

```
(3*(qnorm(p=0.8)+qnorm(p=0.975))/0.5)^2
```

```
[1] 282.6
```

However, it would actually be (slightly) better to simply use the R-function again as the R-function does not rely on any normal approximation of the more correct *t*-distributions:

```
power.t.test(power = 0.8, delta = 0.5, sd = 3, sig.level = 0.05,  
type = c("one.sample"))
```

```
One-sample t test power calculation
```

```
      n = 284.5  
delta = 0.5  
      sd = 3  
sig.level = 0.05  
      power = 0.8  
alternative = two.sided
```

This would lead to  $n = 285$ . So 0.5 is an effect size that it would be pretty expensive to be able to detect.

- g) Assume that you only have the finances to do an experiment with  $n = 50$ . How large a difference would you be able to detect with probability 0.8 (i.e. Power = 0.80)?

**||| Solution**

```
power.t.test(n = 50, power = 0.8, sd = 3, sig.level = 0.05,  
type = c("one.sample"))
```

```
One-sample t test power calculation
```

```
      n = 50  
  delta = 1.213  
      sd = 3  
sig.level = 0.05  
  power = 0.8  
alternative = two.sided
```

The answer is 1.21, so a true alternative mean of 2998.8 (or smaller) or 3001.2 (or larger) would be detected by this experiment with probability 0.80