

# Applied statistics (spring term 2019)

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# 1 Estimating parameters

## 1.1 Confidence and tolerance intervals

In statistical analysis we want to estimate a population from a random sample. This is called interference about the parameter. Random samples are used to provide information about parameters in an underlying population distribution. Rather than estimating the full shape of the underlying distribution, we usually focus on one or two parameters.

We want the error distribution to be centered on zero. Such an estimator is called unbiased. An biased estimator tends to have negative/positive errors, i.e. it usually underestimates/overestimates the parameter that is being estimated.

We also want error distribution to be tightly concentrated on zero, i.e. to have a small spread.

A good estimator should have a small bias and small standard error. These two criteria can be combined with into single value called the estimator's mean squared error. Most estimators that we will consider are unbiased, the spread of the error distribution is most important.

### Definition 1.1 (Standard error)

The standard error (SE) of an estimator  $\hat{\theta}$  of a parameter  $\theta$  is defined to be its standard deviation.

### ■ Example 1.2

Standard error of the mean:

- Bias ( $\mu$  error) = 0, i.e.  $E(\hat{\theta}) = \theta$
- When population standard deviation is known:  $SE = \frac{\sigma}{\sqrt{n}}$
- When population standard deviation is unknown:  $SE = \frac{s}{\sqrt{n}}$

Do not confuse SD (sample standard deviation) ( $\rightarrow$  one sample) and SE (standard deviation of the sample mean  $\bar{x}$ ) ( $\rightarrow$  error from hypothetical samples)!

### Definition 1.3 (Confidence interval for $\mu$ with known $\sigma$ )

We can be  $(1 - \alpha) \cdot 100\%$  confident that the estimate for  $\mu$  will be in the interval

$$\bar{x} - z_{\alpha/2} \frac{\sigma}{\sqrt{n}} < \mu < \bar{x} + z_{\alpha/2} \frac{\sigma}{\sqrt{n}}$$

Common exact values of  $z_{\alpha/2}$  with critical values from normal distribution:

confidence	value of $z_{\alpha/2}$
90%	1.645
95%	1.96
99%	2.575

**Definition 1.4 (Confidence interval for  $\mu$  when  $\sigma$  is unknown)**

If we simply replace  $\sigma$  by its sample variance the confidence level will be lower than 95%. When the sample size is large, the confidence level is close to 95% but the confidence level can be much lower if the sample size is small.

Critical value comes from the STUDENTS t distribution. The value of  $t_{\alpha/2}$  depends on the sample size through the use of degrees of freedom. The confidence interval is

$$\bar{x} - t_{\alpha/2} \frac{s}{\sqrt{n}} < \mu < \bar{x} + t_{\alpha/2} \frac{s}{\sqrt{n}}$$

Consider estimation of a population mean,  $\mu$ , from a random sample of size  $n$ . A confidence interval will be of the form  $\bar{x} \pm t_{\alpha/2} \frac{s}{\sqrt{n}}$ . If we want our estimate to be within  $k$  of  $\mu$ , then we need  $n$  to be large enough so that  $t_{\alpha/2} \frac{s}{\sqrt{n}} < k$ . For 95% confidence interval if  $n$  is reasonably large the t-value in the inequality will be approximately 1.96:  $1.96 \frac{s}{\sqrt{n}} < k$  that can be re-written as  $n > \left(\frac{1.96s}{k}\right)^2$ . In practice, it is best to increase  $n$  a little over this value in case the sample deviation was wrongly guessed.

**■ Example 1.5**

If we expect that a particular type of measurement will have a standard deviation of about 8, and we want to estimate its mean,  $\mu$ , to within 2 of its correct value with probability 0.95, the sample size should be:

$$n > \left(\frac{1.96 \cdot 8}{2}\right)^2 = 61.5$$

This suggests a sample size of at least 62. The more accurate trial-and-error method using a t-value would give a sample size of 64.

The sample proportion of successes is denoted by  $\hat{p}$  and is an estimate of  $p$ . The estimation error is  $\hat{p} - p$ .

$$\hat{p} = \frac{\text{number of successes in sample}}{\text{sample size}}$$

A 95% confidence interval is<sup>1</sup>  $\hat{p} \pm 2 \cdot \sqrt{\frac{p(1-p)}{n}}$

**■ Example 1.6**

In a random sample of  $n = 36$  values, there were  $x = 17$  successes. We estimate the population proportion  $\hat{p}$  with  $\hat{p} = \frac{17}{36} = 0.472$ . A 95% confidence interval for  $\hat{p}$  is  $0.472 \pm 0.166$ . We are therefore 95% confident that the population of successes is between 30.6% and 63.8%. A sample size of  $n = 36$  is clearly too small to give a very accurate estimate.

If the sample size  $n$  is small or  $\hat{p}$  is close to either 0 or 1, this normal approximation is inaccurate and the confidence level for the interval can be considerably less than 95%. Classical theory recommends to use the confidence interval for  $\hat{p}$  only when  $n > 30$ ,  $n\hat{p} > 5$  and  $n(1 - \hat{p}) > 5$ .

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<sup>1</sup>To get the correct result, you would have to multiply by 1.96 instead of 2. You can also use 2 for a quick calculation.

### Annotation (z-value or t-value?)

- If you know the variance of the population, then you should use the z-value from normal distribution.
- If you don't know the variance of the population or the population is non-normal, then you should formally always use the t-value.
- For most non-normal population distributions, the distribution of the sample mean becomes close to normal when the sample size increases (Central Limit Theorem)
- Even for relatively small samples, the distributions are virtually the same. Therefore, it is common to approximate the t-distribution using normal distribution for sufficiently large samples (e.g.  $n > 30$ ).

### Definition 1.7 (Tolerance interval)

A  $(1 - \alpha) \cdot 100\%$  tolerance interval for  $\gamma \cdot 100\%$  of the measurements in a normal population is given by  $\bar{x} \pm Ks$  where  $K$  is a tolerance factor. Tolerance limits are the endpoints of the tolerance interval.

Do not mix up with confidence intervals! We focus on  $\gamma$  (a certain percentage of measurements) rather than on a population parameter.

If we knew  $\mu$  and  $\sigma$  then the tolerance factor  $K$  is 1. Otherwise the tolerance factor depends on the level of confidence,  $\gamma$  and the sample size  $n$ .

### ■ Example 1.8

A corporation manufactures field rifles. To monitor the process, an inspector randomly selected 50 firing pins from the production line. The sample mean  $\bar{x}$  for all observations is 0.9958 inch and standard deviation  $s$  is 0.0333. Assume that the distribution of pin lengths is normal. Find a 95% tolerance interval for 90% of the firing pin lengths.

Given  $n = 50$ ,  $\gamma = 0.9$  and  $\alpha = 0.05$ , work out  $K$  (you can either use a special table or MATLAB function).  $K = 1.996$ . The 95% tolerance interval is (0.9293, 1.0623). Approximately 95 of 100 similarly constructed tolerance intervals will contain 90% of the firing pin lengths in the population.

## 1.2 Maximum Likelihood Estimate

### Definition 1.9 (likelihood function)

If random variables have joint probability  $p(x_1, \dots, x_n | \theta)$  then the function  $L(\theta | x_1, \dots, x_n) = p(x_1, \dots, x_n | \theta)$  is called the likelihood function of  $\theta$ .

The likelihood function tells the probability of getting the data that were observed if the parameter value was really  $\theta$ .

### Definition 1.10 (maximum likelihood estimate)

The maximum likelihood estimate of a parameter  $\theta$  is the value that maximizes the likelihood function  $L(\theta | x_1, \dots, x_n) = p(x_1, \dots, x_n | \theta)$ .

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In practice they maximize the logarithm of the likelihood function and solve the following equation:

$$\frac{d \log L(\theta|x_1, \dots, x_n)}{d\theta}$$

The following formula can find an approximate numerical value for the standard error of almost any maximum likelihood estimator:

$$SE(\hat{\theta}) \approx \sqrt{-\frac{1}{l''(\hat{\theta})}}$$

For the 95% confidence interval we can write:

$$\hat{\theta} - 1.96 \cdot SE(\hat{\theta}) < \theta < \hat{\theta} + 1.96 \cdot SE(\hat{\theta})$$

For the 90% confidence interval we can write:

$$\hat{\theta} - 1.645 \cdot SE(\hat{\theta}) < \theta < \hat{\theta} + 1.645 \cdot SE(\hat{\theta})$$

### ■ Example 1.11

The probability density function (PDF) of exponential distribution is

$$\text{PDF} = \begin{cases} \lambda e^{-\lambda x} & x \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

We want to estimate the parameter  $\lambda$ .

Likelihood function	$L(\lambda x_1, \dots, x_n) = \lambda^n e^{-\lambda \sum x_i}$
log-likelihood function	$l(\lambda x_1, \dots, x_n) = n \log(\lambda) - \lambda \sum x_i$
MLE	$l'(\lambda x_1, \dots, x_n) = \frac{n}{\lambda} - \sum x_i \stackrel{!}{=} 0 \Rightarrow \hat{\lambda} = \frac{1}{\bar{x}}$
Standard error	$SE(\hat{\lambda}) = \sqrt{-\frac{1}{l''(\hat{\lambda})}} = \frac{\hat{\lambda}}{\sqrt{n}} = \frac{1}{\sqrt{n\bar{x}}}$ where $l''(\lambda) = -\frac{n}{\lambda^2}$
95% confidence interval	$\frac{1}{\bar{x}} \pm 1.96 \cdot \frac{1}{\sqrt{n\bar{x}}}$

Lets assume that the mean time between failures of 199 air-conditioners is  $\bar{x} = 90.92$  hours. The MLE for the estimated failure rate  $\lambda$  is  $\frac{1}{\bar{x}} = 0.0110$  failure per hour.

$\Rightarrow$  95% confidence interval for the failure rate:

$$\frac{1}{\bar{x}} \pm 1.96 \cdot \frac{1}{\sqrt{n\bar{x}}} \Rightarrow \lambda \in [0.00974, 0.01253]$$

Given a sample, we can estimate two unknown parameters in a probability distribution, for example, estimate parameters  $\mu$  and  $\sigma$  in a normal distribution.

**Definition 1.12 (likelihood function for two parameters)**

If random variables have joint probability  $p(x_1, \dots, x_n | \theta, \varphi)$  then the function  $L(\theta, \varphi | x_1, \dots, x_n) = p(x_1, \dots, x_n | \theta, \varphi)$  is called the likelihood function of  $\theta$  and  $\varphi$ .

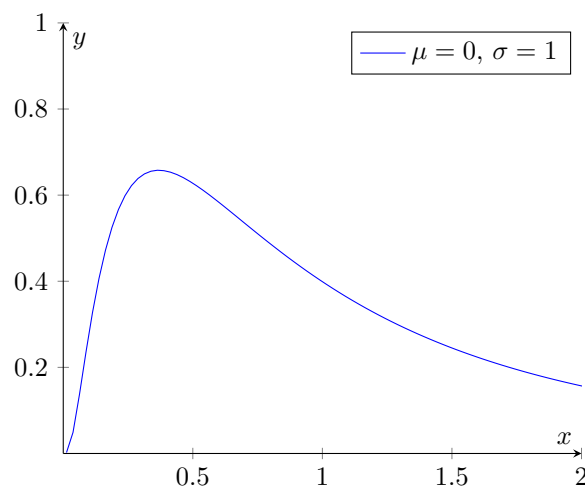
The likelihood function is maximised at a turning point of the likelihood function and could therefore be found by setting the partial derivatives of  $L(\theta, \varphi)$  with respect to  $\theta$  and  $\varphi$  to zero.

There are two important properties of the maximum likelihood estimator  $\hat{\theta}$  of a parameter  $\theta$  based on a random sample of size  $n$  from a distribution with a probability function  $p(x_1, \dots, x_n | \theta)$ :

- Asymptotically unbiased:  $E(\hat{\theta}) \rightarrow \theta$  when  $n \rightarrow \infty$
- Asymptotically has a normal distribution:  $\hat{\theta} \rightarrow$  normal distribution when  $n \rightarrow \infty$  that can be used to generate confidence intervals.
- Maximum likelihood estimators have low mean squared error if the sample size is large enough. MLE can be heavily biased for small samples!

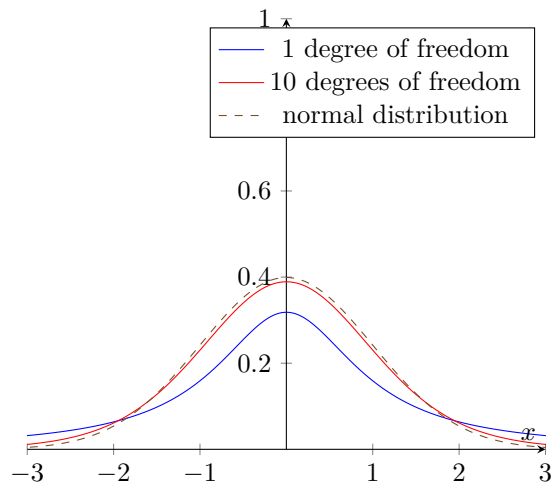
### 1.3 Continuous distributions

The lognormal distribution is used in situations where values are positively skewed, for example, for financial analysis of stock prices. Note that the uncertain variable can increase without limits but cannot take negative values.

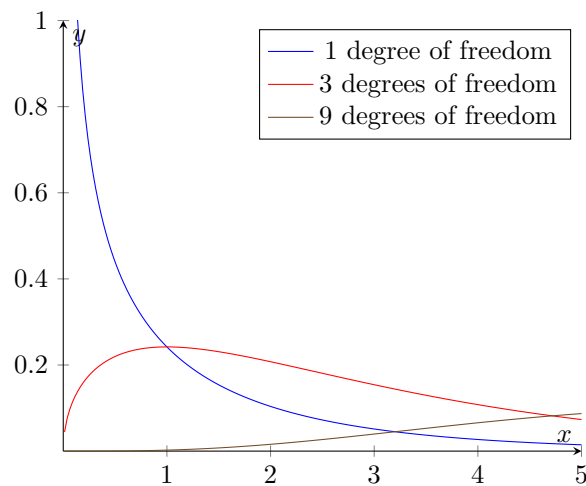


In the beta distribution the uncertain variable is a random value between 0 and positive value. The distribution is frequently used for estimating the proportions and probabilities (i.e. values between 0 and 1). The shape of the distribution is specified by two positive parameters.

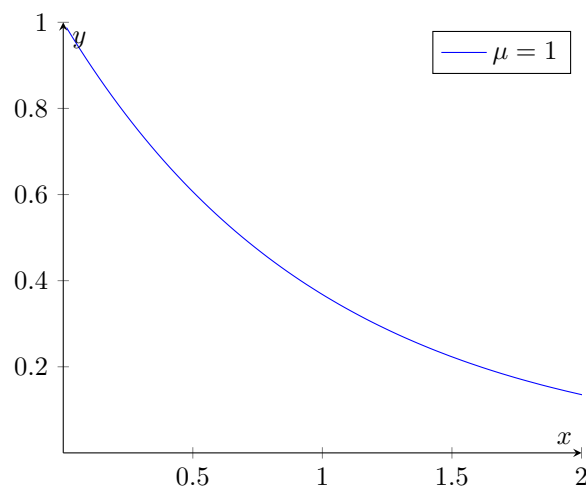
The STUDENTS t distribution is the most widely used distribution in confidence intervals and hypothesis testing. The distribution can be used to estimate the mean of a normally distributed population when the sample size is small. The t distribution comes to approximate the normal distribution as the degrees of freedom (or sample size) increases.



The chi-square distribution is usually used for estimating the variance in a normal distribution.



In a homogeneous POISSON process with a rate  $\lambda$  events per unit time, the time until the first event happens has a distribution called an exponential distribution. All exponential distributions have their highest probability density at  $x = 0$  and steadily decrease as  $x$  increases.

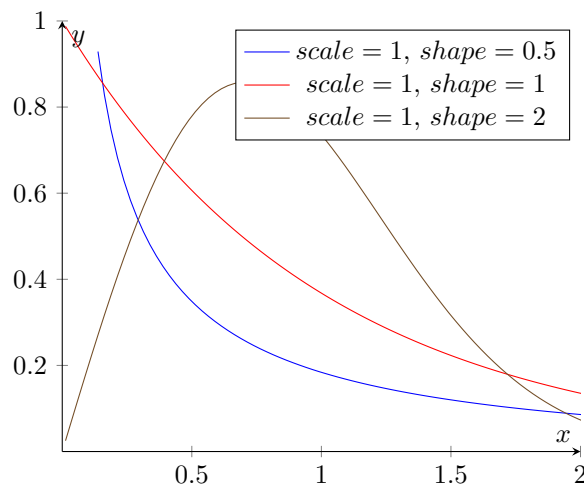




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The WEIBULL distribution can be used as a model for items that either deteriorate or improve over time. It's basic version has two parameters: shape and scale.



- $shape > 1$ : the hazard function is increasing so the item becomes less reliable as it gets older.
- $shape < 1$ : the hazard function is decreasing so the item becomes more reliable as it gets older.
- $shape = 1$ : the hazard function is constant so the lifetime distribution becomes exponential.

The survival function (probability of surviving until a particular time) is  $R(t) = 1 - F(t)$ . The hazard rate function (failure rate) is worked out by the formula:

$$\begin{aligned} h(t) &= \frac{f(t)}{1 - F(t)} \\ &= \frac{f(t)}{R(t)} \end{aligned}$$

where  $f(t)$  and  $F(t)$  are PDF and CDF of the distribution.

The hazard function describes how an item ages where  $t$  affects its risk of failure. This constant hazard function in the exponential distribution corresponds to the POISSON process without memory, i.e. the chance of failing does not depend on what happened before and how long the item has already survived.

## 2 Hypothesis testing

There are two types of questions in statistical inference:

- **Parameter estimation:** What parameter values would be consistent with the sample data?
- **Hypothesis testing:** Are the sample data consistent with some statement about the parameters?

The Null Hypothesis  $H_0$  often specifies a single value for the unknown parameter such as " $\alpha = \dots$ ". It is a default value that can be accepted as holding if there is no evidence against it. A researcher often collects data with the express hope of disproving the null hypothesis.

If the null hypothesis is not true, we say that the alternative hypothesis  $H_A$  holds. If the data are not consistent with the null hypothesis, then we can conclude that the alternative hypothesis must be true. Either the null hypothesis or the alternative hypothesis must be true.

### ■ Example 2.1

The data show the number of operating hours between successive failures of air-conditioning equipment in ten aircrafts. The sample of 199 values is a test statistic. We can test the manufacturer's claim that the rate of failures is no more than one per 110 hours of use.

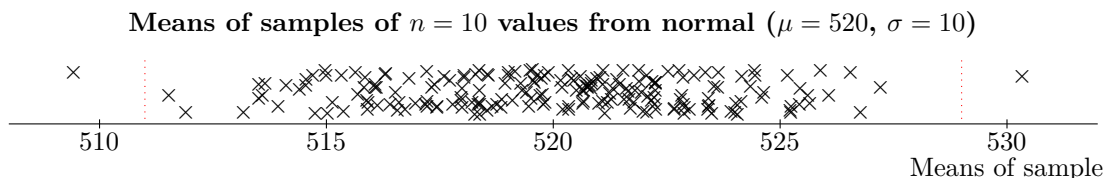
$$H_0 : \lambda \leq \frac{1}{100} \text{ (claim of a manufacturer)}$$
$$H_A : \lambda > \frac{1}{100}$$

This can be simplified:

$$H_0 : \lambda = \frac{1}{100} \text{ (claim of a manufacturer)}$$
$$H_A : \lambda > \frac{1}{100}$$

### 2.1 The p-value (probability value)

In an industrial process some measurement is normally distributed with standard deviation  $\sigma = 10$ . Its mean should be  $\mu = 520$ , but can differ a little bit. Samples of  $n = 10$  measurements are regularly collected as part of quality control. If a sample had  $\bar{x} = 529$ , does the process need to be adjusted?



From the 200 simulated samples above (MONTE CARLO simulation), it seems very unlikely that a sample mean of 529 would have been recorded if  $\mu = 520$ . There is strong evidence that the industrial process no longer has a mean of  $\mu = 520$  and needs to be adjusted.

**Definition 2.2 (p-value)**

A p-value describes the **evidence against**  $H_0$ . A p-value is evaluated from a random sample so it has a distribution in the same way that a sample mean has a distribution.

p-value	Interpretation
over 0.1	no evidence that $H_0$ does not hold
between 0.05 and 0.1	very weak evidence that $H_0$ does not hold
between 0.01 and 0.05	moderately strong evidence that $H_0$ does not hold
under 0.01	strong evidence that $H_0$ does not hold

**Example 2.3 (normal distribution with known  $\sigma$ , one-tailed test)**

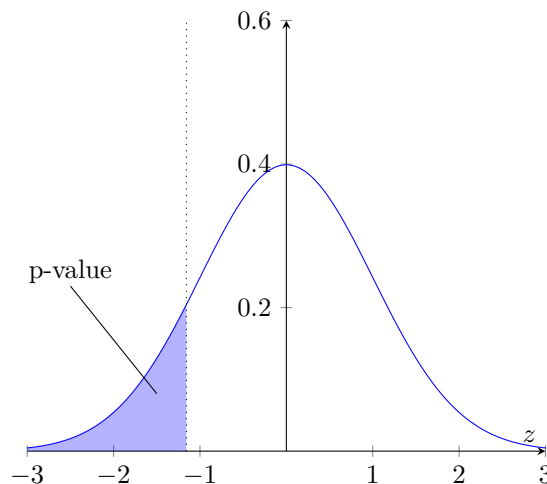
We are given a random sample of  $n = 30$  with  $\bar{x} = 16.8$ . Does the population have mean  $\mu = 18.3$  and standard deviation  $\sigma = 7.1$ , or is the mean now lower than 18.3?

$$H_0 : \mu = 18.3$$

$$H_A : \mu < 18.3$$

The p-value can be evaluated using the statistical distance of 16.8 from 18.3 (a z statistic).

$$z = \frac{\bar{x} - 18.3}{\underbrace{\frac{7.1}{\sqrt{30}}}_{\text{standard error}}} = -1.157$$



$$\text{p-value} = P(z \leq -1.157) = 0.124$$

The p-value is reasonably large, meaning that a sample mean as low as 16.8 would not be unusual if  $\mu = 18.3$ , so there is no evidence against  $H_0$ .

### Annotation

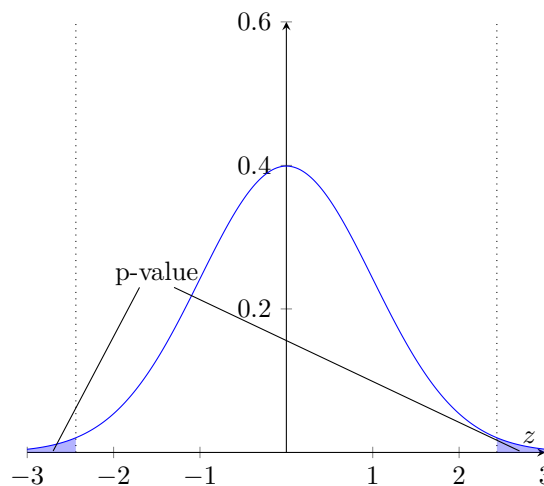
To compute the p-value you can use

$$\text{p-value} = \text{CDF}(\text{NormalDistribution}(0,1), -1.157)$$

### ■ Example 2.4 (normal distribution with known $\sigma$ , two-tailed test)

Companies test their products to ensure that the amount of active ingredient is within some limits. However the chemical analysis is not precise and repeated measurements of the same specimen usually differ slightly. One type of analysis gives results that are normally distributed with a mean that depend on the actual product being tested and standard deviation 0.0068 grams per litre. A product is tested three times with the following concentrations of the active ingredient: 0.8403, 0.8363, 0.8447 grams per litre. are the data consistent with the target concentration of 0.85 grams per litre?

null hypothesis	$H_0: \mu = 0.85$
alternative hypothesis	$H_A: \mu \neq 0.85$
test statistic	$\bar{x} = 0.8404, z = \frac{0.8404 - 0.85}{\frac{0.0068}{\sqrt{3}}} = -2.437, P(z \leq -2.437) = 0.00741$
p-value	$2 \cdot 0.00741 = 0.0148$
p-value interpretation	There is moderately strong evidence that the true concentration is not 0.85.



### ■ Example 2.5 (normal distribution with unknown $\sigma$ , one-tailed test)

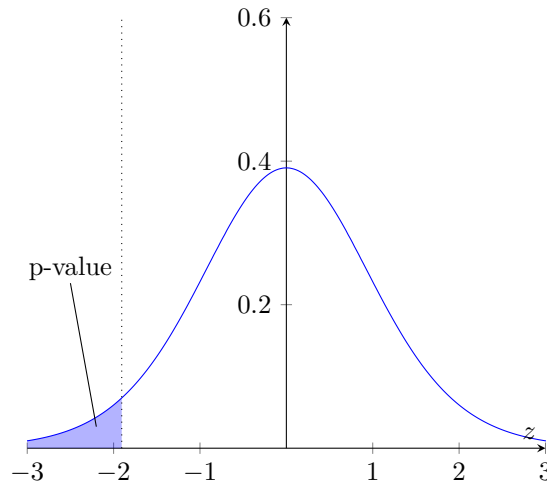
Both cholesterol and saturated fats are often avoided by people who are trying to lose weight or reduce their blood cholesterol level. Cooking oil made from soybeans has little cholesterol and has been claimed to have only 15% saturated fat. A clinician believes that the saturated fat content is greater than 15% and randomly samples 13 bottles of soybean cooking oil for testing with the following percentage saturated fat: 15.2, 12.4, 15.4, 13.5, 15.9, 17.1, 16.9, 14.3, 19.1, 18.2, 15.5,

## 2. Hypothesis testing

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16.3, 20.0.

null hypothesis	$H_0: \mu = 15$
alternative hypothesis	$H_A: \mu > 15$
T-test for $\mu$	$\bar{x} = 16.138$ , $t = \frac{16.138 - 15}{\frac{2.154}{\sqrt{13}}} = 1.906$ , $P(t \geq 1.906) = 0.040$ (t-distribution with 12 degrees of freedom)
p-value interpretation	Since this is below 0.05, we conclude that there is moderately strong evidence that the mean saturated fat content of the oils is higher than the claimed 15%.



A hypothesis test is based on two competing hypotheses about the value of a parameter  $\theta$ .

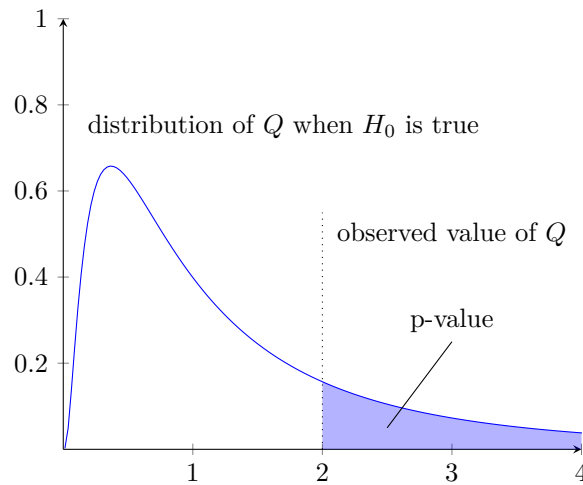
Null hypothesis  $H_0: \theta = \theta_0$

Alternative hypothesis (one-tailed test)  $H_A: \theta > \theta_0$

The hypothesis test is based on a test statistic that is some function of the data values:

$$Q = g(x_1, \dots, x_n | \theta_0)$$

whose distribution is fully known when  $H_0$  is true (i.e. when  $\theta_0$  is the true parameter value). We evaluate the test statistic to assess whether it is unusual enough to throw doubt on the null hypothesis.



**Theorem 2.6**

P-values close to zero throw doubt on the null hypothesis.

## 2.2 The significance level

**Definition 2.7 (significance level)**

The significance level is the probability of wrongly concluding that  $H_0$  does not hold when it actually does.

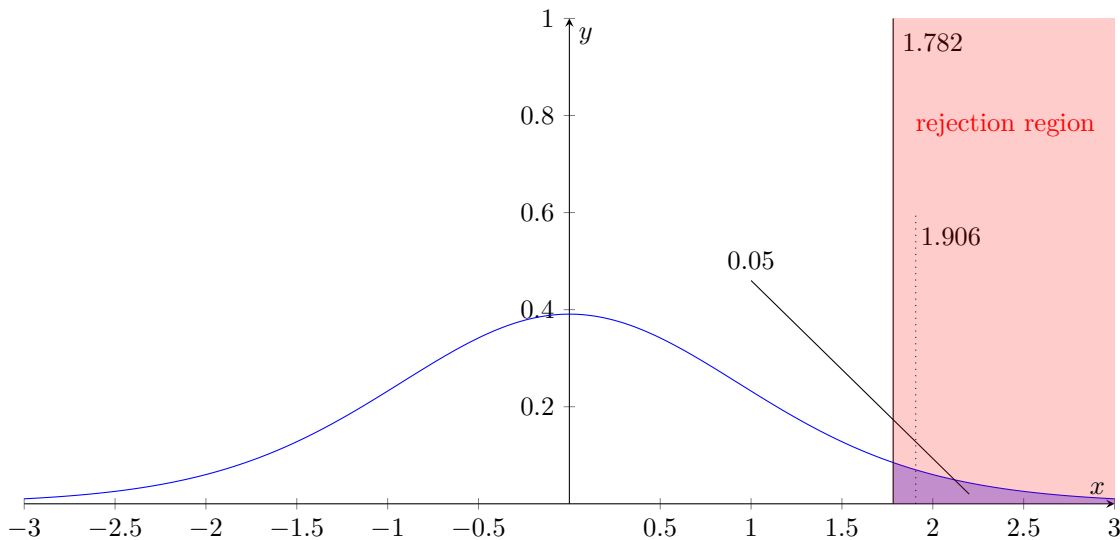
- **One-tailed test:** For example, it may be acceptable to have a 5% chance of concluding that  $\theta < \theta_0$  when actually  $\theta = \theta_0$ . This means a significance level (tail area of the test statistic's distribution) of this test is  $\alpha = 0.05$ .
- **Two-tailed test:** Values at both tails of the distribution of the test statistic result in rejection of  $H_0$ , so the corresponding tail areas should each have area  $\frac{\alpha}{2}$  for a test with significance level  $\alpha$ .

■ **Example 2.8**

Cooking oil made from soybeans has little cholesterol and has been claimed to have only 15% saturated fat. A clinician believes that the saturated fat content is greater than 15% and randomly samples 13 bottles of soybean cooking oil for testing: 15.2, 12.4, 15.4, 13.5, 15.9, 17.1, 16.9, 14.3, 19.1, 18.2, 15.5, 16.3, 20.0.

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Null hypothesis	$H_0: \mu = 15$
Alternative hypothesis	$H_A: \mu > 15$
A significance level of $\alpha = 0.05$ means that the clinician is willing to wrongly conclude that the saturated fat content is over 15% when it really is 15% with probability 0.05.	
t-statistic	$t = \frac{\bar{x}-15}{\frac{s}{\sqrt{13}}} = 1.906$
rejection region	$P(T > 1.782) = 0.05$ (t distribution with 12 degrees of freedom)
Conclusion	$t$ lies in the rejection region so $H_0$ is rejected at the 5% significance level.



### Definition 2.9 (Type 1 + 2 error)

The Type 1 error is the significance level of the test. The decision rule is usually defined to make the significance level 5% or 1%.

The Type 2 error is wrongly accepting  $H_0$  when it is false.

Instead of the probability of a Type 2 error, it is common to use the power of a test, defined as one minus the probability of a Type 2 error. The power of a test is the probability of correctly rejecting  $H_0$  when it is false.

		Decision	
		accept $H_0$	reject $H_0$
Truth	$H_0$ is true		significance level = $P(\text{Type 1 error})$
	$H_0$ is false	$P(\text{Type 2 error})$	Power = $1 - P(\text{Type 2 error})$

## 2. Hypothesis testing

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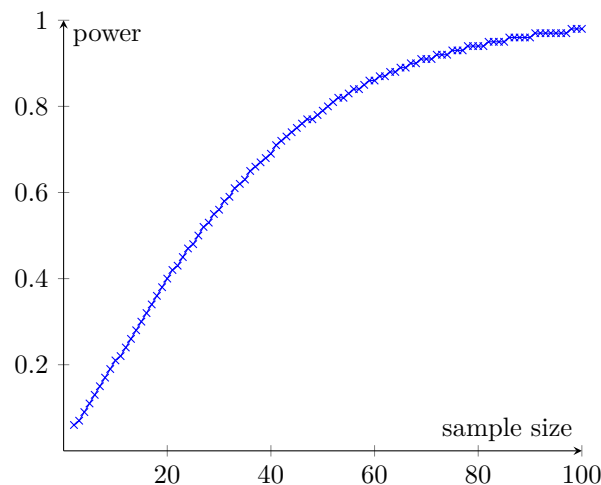
Computer software can provide the p-value for a hypothesis test at 5% or 1% significance level (Type 1 error).

It is clearly desirable to use a test whose power is as close to 1 as possible. There are three different ways to increase the power:

- **Increase the significance level:** If the critical value for the test is adjusted, increasing the probability of a Type 1 error decreases the probability of a Type 2 error and therefore increase the power.
- **Use a different decision rule:** For example, in a test about the mean of a normal population, a decision rule based on the sample median has lower power than a decision rule based on the sample mean.
- **Increase the sample size:** By increasing the amount of data on which we base our decision about whether to accept or reject  $H_0$ , the probabilities of making errors can be reduced.

When the significance level is fixed, increasing the sample size is therefore usually the only way to improve the power.

Ideally there should be a trade-off between low significance level (Type 1 error) and high power. The desired power of the test is usually 0.8. The power of a test is not a single value since the alternative hypothesis allows for a range of different parameter values. It is represented by a power function that can be graphed against the possible parameter values. MATLAB `sampsizepwr` can compute the sample size to obtain a particular power for a hypothesis test, given the parameter value of the alternative hypothesis.



There are a many number of statistical tests for assessing normality: SHAPIRO-WILK test, KOLMOGOROV-SMIRNOV test, JACQUE-BERA test, etc. The SHAPIRO-WILK test ( $n < 50$ ) can be used to verify whether data come from a normal distribution:

$H_0$ : sample data are not significantly different than a normal population.

$H_A$ : sample data are significantly different than a normal population.

P-value  $> 0.05$  mean the data are normal

P-value  $< 0.05$  mean the data are not normal

MONTE CARLO simulations proved the efficiency of SHAPIRO-WILK test. It s preferable that normality



is assessed visually as well! The KOLMOGOROV-SMIRNOV non-parametric test ( $n > 50$ ) examines if scores are likely to follow some distribution in some population (not necessarily normal).

### 2.3 Likelihood ratio test

In some cases we need to perform a hypothesis test to compare two models: big "general" model ( $M_B$ ) and small "simple" model ( $M_S$ ) nested into the bigger model.

$H_0$ :  $M_S$  fits the data

$H_A$ :  $M_S$  does not fit the data and  $M_B$  should be used instead.

We need to verify if  $M_B$  fits the data significantly better.

- **Measure how well a model fits the data:** The fit of any model can be described by the maximum possible likelihood for that model:

$$L(M) = \max\{P(\text{data}|\text{model})\}$$

Calculate the maximum likelihood estimates for all unknown parameters and insert them into the likelihood function.

- **Work out the likelihood ratio:**

$$R = \frac{L(M_B)}{L(M_S)} \geq 1$$

Big values of  $R$  suggests that  $M_S$  does not fit as well as  $M_B$ .

- **Work out log of likelihood ratio:**

$$\log(R) = l(M_B) - l(M_S) \geq 0$$

Big values of  $R$  suggests that  $M_S$  does not fit as well as  $M_B$ .

#### ■ Example 2.10

There are a number of defective items on a production line in 20 days that follow  $\text{POISSON}(\lambda)$  distribution: 1, 2, 3, 4, 2, 3, 2, 5, 5, 2, 4, 3, 5, 1, 2, 4, 0, 2, 2, 6.

$M_S$ : the sample comes from  $\text{POISSON}(2)$

$M_B$ : the sample comes from  $\text{POISSON}(\lambda)$

#### ■ Example 2.11

Clinical records give the survival time for 30 people: 9.73, 5.56, 4.28, 4.87, 1.55, 6.20, 1.08, 7.17, 28.65, 6.10, 16.16, 9.92, 2.40, 6.19. In a clinical trial of a new drug treatment 20 people had survival times of: 22.07, 12.47, 6.42, 8.15, 0.64, 20.04, 17.49, 2.22, 3.00. Is there any difference in survival times for those using the new drug?

$M_S$ : Both examples come from the same exponential( $\lambda$ ) distribution.

$M_B$ : The first sample comes from exponential( $\lambda_1$ ) and the second sample from exponential( $\lambda_2$ ).

**Definition 2.12**

If the data come from  $L(M_S)$ , and  $L(M_B)$  has  $k$  more parameters than  $L(M_S)$  then

$$\begin{aligned} X^2 &= 2\log(R) \\ &= 2(l(M_B) - l(M_S)) \\ &\approx \chi^2(k \text{ degrees of freedom}) \end{aligned}$$

The main steps for the likelihood ratio test are:

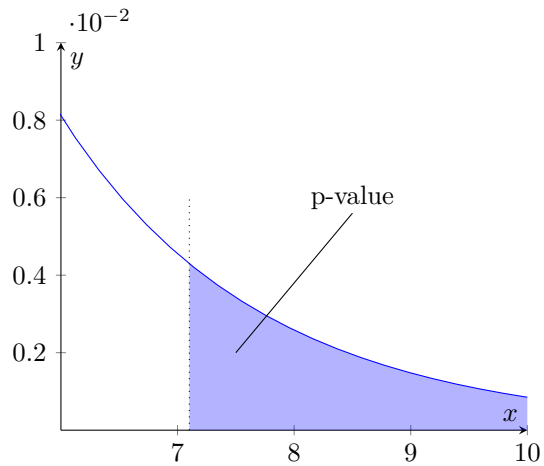
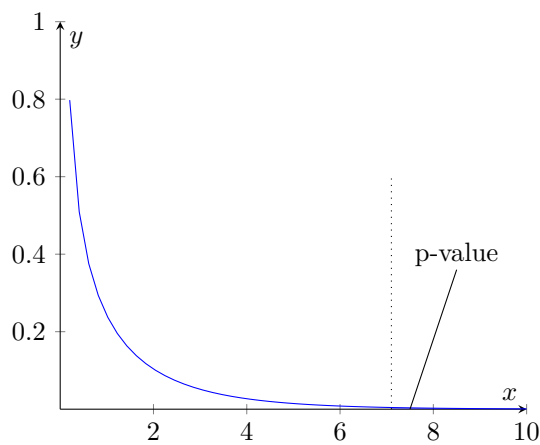
1. Work out maximum likelihood estimates of all unknown parameters in  $M_S$ .
2. Work out maximum likelihood estimates of all unknown parameters in  $M_B$ .
3. Evaluate the test statistic:  $\chi^2 = 2(l(M_B) - l(M_S))$
4. The degrees of freedom for the test are the difference between the numbers of unknown parameters in two models. The p-value for the test is the upper tail probability of the  $\chi^2(k \text{ degrees of freedom})$  distribution given the test statistic.
5. Interpret the p-value: small values give evidence that the null hypothesis ( $M_S$  model) does not hold.

**■ Example 2.13**

There are a number of defective items on a production line in 20 days that follow  $\text{POISSON}(\lambda)$  distribution: 1, 2, 3, 4, 2, 3, 2, 5, 5, 2, 4, 3, 5, 1, 2, 4, 0, 2, 2, 6.

## 2. Hypothesis testing

	null hypothesis	$H_0: \lambda = 2$ small model $M_S$
	alternative hypothesis	$H_A: \lambda \neq 2$ big model $M_B$
	log-likelihood for the Poisson distribution	$l(\lambda) = \left(\sum_{i=1}^{20} x_i\right) \log(\lambda) - n\lambda$
$M_B$	MLE for the unknown parameter	$\hat{\lambda} = \frac{\sum x_i}{n} = 2.9$
	Maximum possible value for the log-likelihood	$l(M_B) = 58 \log(2.9) - 20 \cdot 2.9 = 3.7532$
$M_S$	MLE for the unknown parameter	no unknown parameter
	Maximum possible value for the log-likelihood	$l(M_S) = 58 \log(2) - 20 \cdot 2 = 0.2025$
	Likelihood ratio test	$\chi^2 = 2(l(M_B) - l(M_S)) = 7.101$
It should be compared to $\chi^2$ (1 degree of freedom) since the difference in unknown parameters is equal to 1.		
	p-value	The p-value is 0.008 (the upper tail probability above 7.101)
	Interpreting p-value	The p-value is very small and we can conclude that there is strong evidence that $M_B$ fits the data better than $M_S: \lambda \neq 2$ .



A two-sample t-test should be used to compare group means when you have independent samples. A paired t-test is needed when each sampled item in one group is associated with an item sampled from the other group.

## 2.4 Two-sample t-test

We can carry out a hypothesis test to verify if the two means are equal:

$H_0: \mu_1 = \mu_2$

$H_A: \mu_1 \neq \mu_2$  (The corresponding one-tailed alternative also holds.)

### Definition 2.14

If  $\bar{x}_1$  and  $\bar{x}_2$  come from  $\text{Normal}(\mu_1, \sigma)$  and  $\text{Normal}(\mu_2, \sigma)$  with sample sizes  $n_1$  and  $n_2$  then

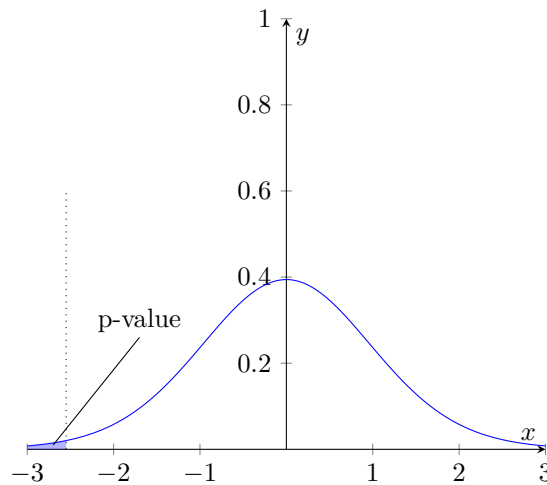
$$T = \frac{\bar{x}_1 - \bar{x}_2}{\text{SE}(\bar{x}_1 - \bar{x}_2)} \approx t(n_1 + n_2 - 2 \text{ degrees of freedom})$$

provided  $\mu_1 = \mu_2$ . For relatively large sample sizes (Central Limit Theorem) we can use Z-test instead of t-test.

### ■ Example 2.15

A botanist is interested in comparing the growth response of dwarf pea stems to two different levels of the hormone indoleacetic acid (IAA). The botanist measured the growth of pea stem segments in millimetres for  $0.5 \cdot 10^{-4}$  IAA level: 0.8, 1.8, 1.0, 0.1, 0.9, 1.7, 1.0, 1.4, 0.9, 1.2, 0.5 and for  $10^{-4}$  IAA level: 1.0, 1.8, 0.8, 2.5, 1.6, 1.4, 2.6, 1.9, 1.3, 2.0, 1.1, 1.2. Test whether the larger hormone concentration results in greater growth of the pea plants.

independent samples	$n_x = 11, n_y = 12$
Null hypothesis	$H_0: \mu_x = \mu_y$
Alternative hypothesis	$H_A: \mu_x < \mu_y$
The <u>pooled estimate</u> assumes that the variance is the same in both groups	$s^2 = \frac{10s_x^2 + 11s_y^2}{21} = 0.2896$
test statistic	$t = \frac{1.027 - 1.6}{\sqrt{0.2896(\frac{1}{11} + \frac{1}{12})}} = -2.5496$
p-value for 21 degrees of freedom in t-distribution	$P(t \leq -2.5496) = 0.0093$
Interpretation	There is very strong evidence that the mean growth of the peas is higher at the higher hormone concentration.



### Annotation (pooled variance)

In statistics, pooled variance (also known as combined, composite, or overall variance) is a method for estimating variance of several different populations when the mean of each population may be different, but one may assume that the variance of each population is the same. The numerical estimate resulting from the use of this method is also called the pooled variance.

Under the assumption of equal population variances, the pooled sample variance provides a higher precision estimate of variance than the individual sample variances. This higher precision can lead to increased statistical power when used in statistical tests that compare the populations, such as the t-test.

$$s^2 = \frac{\sum_{i=1}^k (n_i - 1) s_i^2}{\sum_{i=1}^k (n_i - 1)}$$

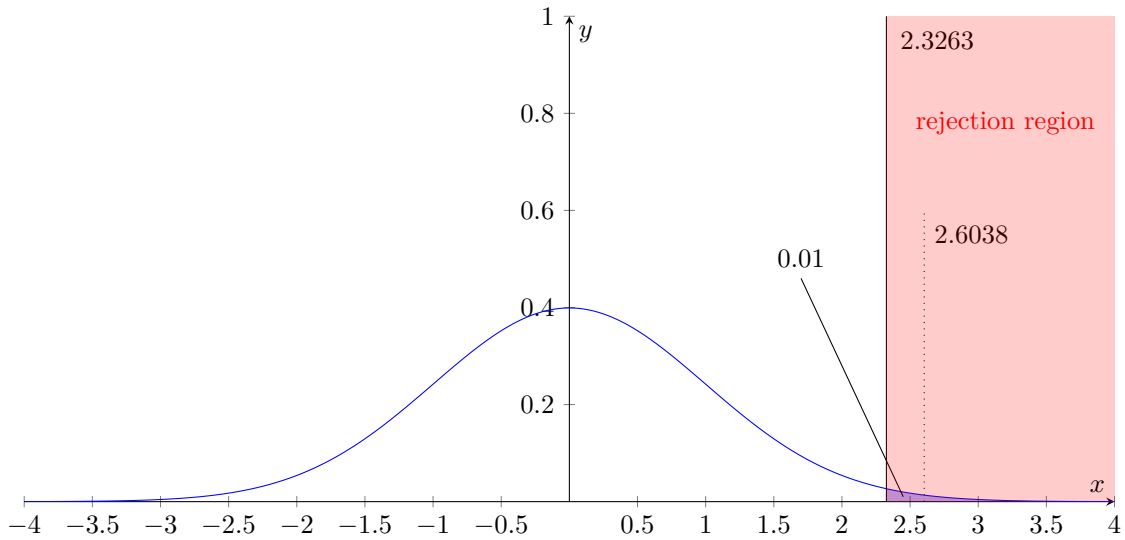
Adapted from [https://en.wikipedia.org/wiki/Pooled\\_variance](https://en.wikipedia.org/wiki/Pooled_variance).

### ■ Example 2.16 (from MATLAB session)

When you sign in to your Facebook account, you are granted access to more than 1 million relying party (RP) websites. RP websites were categorized as server-flow or client-flow websites. Of the 40 server-flow sites studied, 20 were found to be vulnerable to impersonation attacks. Of the 54 client-flow sites, 41 were found to be vulnerable to impersonation attacks. Do these results indicate that a client-flow website is more likely to be vulnerable to an attack than a server-flow website? Test using  $\alpha = 0.01$ .

## 2. Hypothesis testing

Null hypothesis	$H_0: p_{server} = p_{client} \Rightarrow \frac{20}{40} = \frac{41}{54}$
Alternative hypothesis	$H_A: p_{server} < p_{client}$
pooled sample proportion	$p = \frac{40 \cdot \frac{20}{40} + 54 \cdot \frac{41}{54}}{40 + 54} = 0.6489$
test statistic	$z = \frac{p_{client} - p_{server}}{\sqrt{0.6489(\frac{1}{40} + \frac{1}{54})}} = 2.6038$
rejection region for $\alpha = 0.01$	$\text{norminv}(0.01) = 2.3268$
Interpretation	$z$ lies in the rejection region so $H_0$ is rejected.



### 2.5 Paired t-test

Testing whether two paired measurements  $X$  and  $Y$  have equal means is done in terms of the difference  $D = Y - X$ . The hypothesis

$$H_0: \mu_x = \mu_y$$

$$H_A: \mu_x \neq \mu_y$$

can be re-written as

$$H_0: \mu_d = 0$$

$$H_A: \mu_d \neq 0.$$

This can reduce the paired data set to a univariate data set of differences. The hypothesis can be assigned using t-test:

$$t = \frac{\bar{d} - 0}{\frac{s_d}{\sqrt{n}}}$$

Z-test can be used for relatively large sample sizes.

#### ■ Example 2.17

A researcher studying congenital heard disease wants to compare the development of cyanotic children with normal children. Among the measurement of interest is the age at which the children

## 2. Hypothesis testing

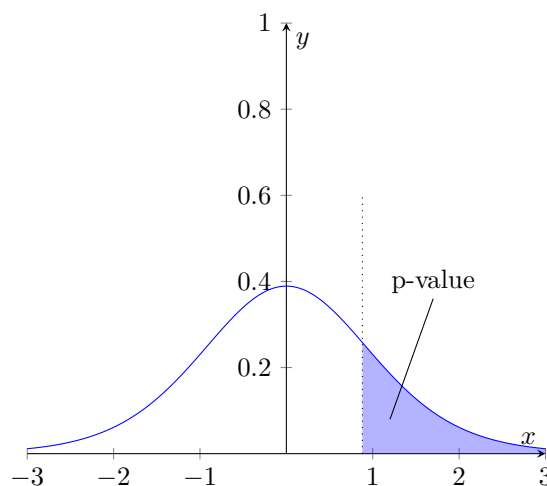
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speak their first word.

pair of siblings	cyanotic sibling	normal sibling	difference
1	11.8	9.8	2.0
2	20.8	16.5	4.3
3	14.5	14.5	0.0
4	9.5	15.2	-5.7
5	13.5	11.8	1.7
6	22.6	12.2	10.4
7	11.1	15.2	-4.1
8	14.9	15.6	-0.7
9	16.5	17.2	-0.7
10	16.5	10.5	6.0

The researcher wants to test whether cyanotic children speak their first word later on average than children without the disease.

Null hypothesis	$H_0: \mu_d = 0$
Alternative hypothesis	$H_A: \mu_d > 0$
test statistic	$t = \frac{\bar{d}-0}{\frac{s_d}{\sqrt{n}}} = 0.8802$
Interpretation	The p-value is well above zero (0.1997), so there is no evidence that the cyanotic children learn to speak later.



### ■ Example 2.18

The blood pressure of 15 college-aged woman was measured before starting to take the pill and

## 2. Hypothesis testing

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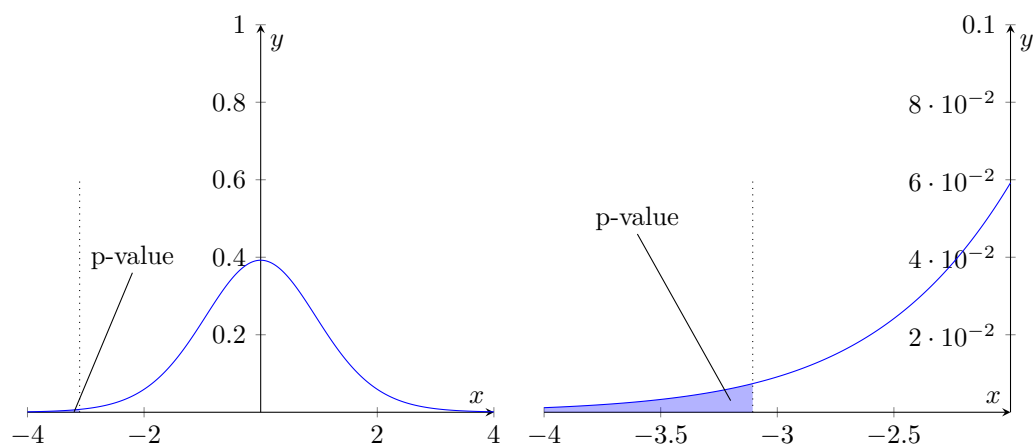
after 6 months of use.

subject	blood pressure	
	before pill	after pill
1	70	68
2	80	72
3	72	62
4	76	70
5	76	58
6	76	66
7	72	68
8	78	52
9	82	64
10	64	72
11	74	74
12	92	60
13	74	74
14	68	72
15	84	74

A two-tailed test is used as the pill might either increase or decrease blood pressure.

Null hypothesis	$H_0: \mu_d = 0$
Alternative hypothesis	$H_A: \mu_d \neq 0$
test statistic	$t = \frac{\bar{d}-0}{\frac{s_d}{\sqrt{n}}} = -3.1054$
Interpretation	The p-value (0.0072) is very small that gives strong evidence that the blood pressure has changed. The negative t-value suggests that the blood pressure has decreased.





## 3 Bootstrapping

### 3.1 A word of warning

The limitation of the bootstrap is the assumption that the distribution of the data represented by one sample is an accurate estimate of the population distribution. If the sample does not reflect the population distribution, then the random sampling performed in the bootstrap procedure may add another level of sampling error, resulting in inaccurate statistical estimations.

It is important to get quality data that accurately reflects the population being sampled. The smaller the original sample, the less likely it is to accurately represent the entire population.

We use bootstrap if

- we have a small but representative random sample or
- we have a not-normal distribution or aren't sure about it.

### 3.2 Why to use it?

In normal population the mean  $\mu$  is the parameter that is most often estimated. But other parameters are possible too:

- standard deviation
- interquartile range (upper quartile - lower quartile)
- median
- other percentiles (e.g. upper quartile)

These parameters can be estimated using the corresponding summary statistic from a random sample, but the error distribution may be difficult to obtain theoretically.

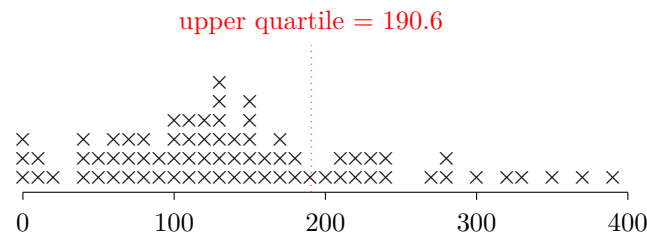
Resampling techniques are normally used to estimate parameters and confidence intervals from sample data when parametric test assumptions are not met or for small samples from non-normal distributions.

- non-parametric bootstrap
- parametric bootstrap
- Jackknife
- permutation tests

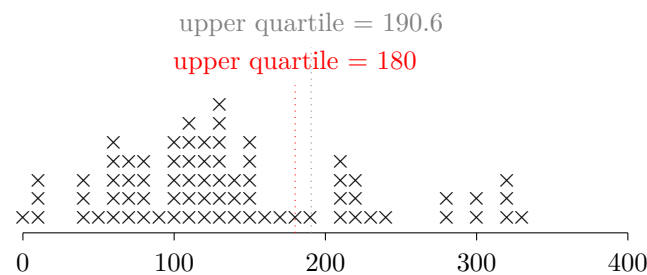
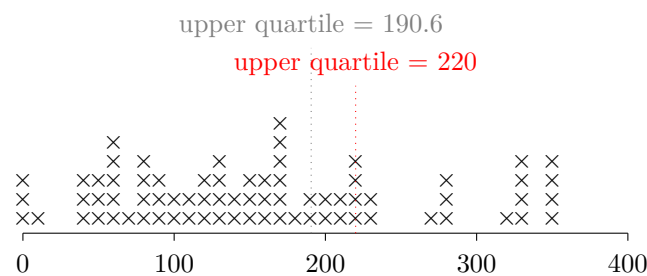
Non-parametric bootstrap means that only a random sample is known and no prior knowledge on the population density function.

#### ■ Example 3.1

Monthly rainfall in Dodoma, Tanzania has a skew distribution in some months. The distribution of a sample is provided below.



If a normal distribution does not seem a reasonable model, an alternative is to treat the actual sample as the "population" for the simulation and take random samples with replacement from this sample. Such samples are called bootstrap samples. A simulation with these bootstrap samples can again show the error distribution and provide approximate values for the bias and standard error.



### 3.3 Bootstrap distribution

The standard error of a statistic is the standard deviation of the sample statistic. The standard error can be calculated as the standard deviation of the sampling distribution.

Bootstrap sample is a random sample taken with replacement from the original sample, of the same size as the original sample. A bootstrap statistic is the statistic computed on a bootstrap sample. A bootstrap distribution is the distribution of many bootstrap statistics. The standard error of a statistic can be estimated using the standard deviation of the bootstrap distribution.

Let  $\hat{\theta}$  a statistic calculated from a sample ( $\hat{\theta} = \bar{x}$ ). We draw  $r$  observations with replacement to create a bootstrap sample and calculate the statistic  $\hat{\theta}^*$  for this sample.

- **bootstrap standard error:** the sample standard deviation of the bootstrap distribution:

$$SE_b = \sqrt{\frac{\sum (\hat{\theta}_b^* - \bar{\theta}^*)^2}{B - 1}}$$

where  $B$  is the number of bootstrap replications (usually  $B > 10000$ )

### 3. Bootstrapping

- **bootstrap bias:**  $\bar{\theta}^* - \hat{\theta}$
- **bootstrap confidence intervals:** bootstrap percentile interval, t confidence interval with bootstrap standard error, bootstrap t-interval, etc.

#### 3.4 Bootstrap methods

Name	calculate	repeat	get distribution	confidence interval
Bootstrap percentile CI or EFRON method	$\hat{\theta}_b^*$	$B$ times	$\left\{ \hat{\theta}_b^* \right\}_{b=1}^B$	$[q_{\alpha/2}, q_{1-\alpha/2}]$
Bootstrap CI - bootstrap t	$\frac{\hat{\theta}_b^* - \hat{\theta}}{SE(\hat{\theta}_b^*)}$	$B$ times	$\left\{ \frac{\hat{\theta}_b^* - \hat{\theta}}{SE(\hat{\theta}_b^*)} \right\}_{b=1}^B$	$[\hat{\theta} - SE(\hat{\theta}) \cdot q_{1-\alpha/2}, \hat{\theta} - SE(\hat{\theta}) \cdot q_{\alpha/2}]$
Bootstrap CI symmetric t-percentile	$\frac{\hat{\theta}_b^* - \hat{\theta}}{SE(\hat{\theta}_b^*)}$	$B$ times	$\left\{ \frac{\hat{\theta}_b^* - \hat{\theta}}{SE(\hat{\theta}_b^*)} \right\}_{b=1}^B$	$[\hat{\theta} - SE(\hat{\theta}) \cdot q_{1-\alpha}, \hat{\theta} + SE(\hat{\theta}) \cdot q_{1-\alpha}]$
Bootstrap CI HALL method	$\hat{\theta}_b^* - \hat{\theta}$	$B$ times	$\left\{ \hat{\theta}_b^* - \hat{\theta} \right\}_{b=1}^B$	$[\hat{\theta} - q_{1-\alpha/2}, \hat{\theta} - q_{\alpha/2}]$

**Bootstrap using t CI - not recommended**

$$\hat{\theta} \pm t_{\alpha/2} \cdot SE_b$$

Bootstrap standard error is the sample standard deviation of the bootstrap distribution

$$SE_b = \sqrt{\frac{\sum (\hat{\theta}_b^* - \bar{\theta}^*)^2}{B - 1}}$$

where  $B$  is the number of bootstrap replications (usually  $B > 10000$ ). The bootstrap bias is  $\bar{\theta}^* - \hat{\theta}$ . It can be useful when the standard error is difficult to derive. **It has a poor performance when distributions are highly skewed.**

#### Bootstrap percentile CI or Elfron method

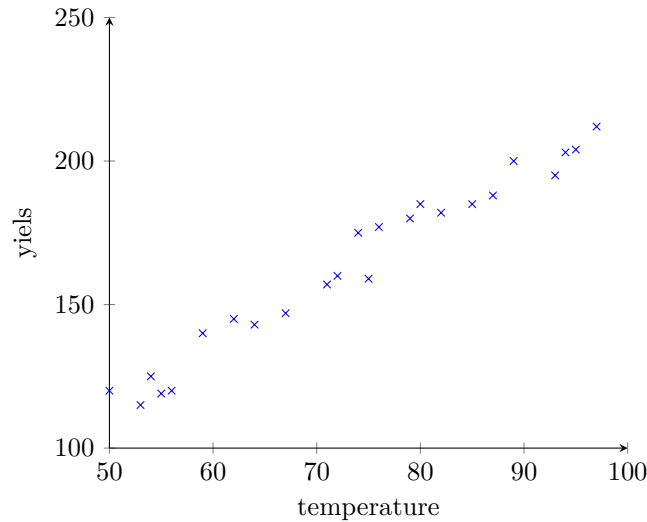
For a 90% confidence interval keep the middle 90%, leaving 5% in each tail and 5% in the head. The 90% confidence interval boundaries would be the 5th percentile and the 95th percentile. In case we have 10000 bootstrap replications:  $\theta_1^* \leq \theta_2^* \leq \dots \leq \theta_{10000}^*$  the 90% confidence interval is  $[\theta_{500}^*, \theta_{9500}^*]$ .

- **Advantages:** A very intuitive and easy to implement method. Can also outperform some other bootstrap CI methods for skewed distributions.
- **Disadvantages:** Can be too narrow for small samples.

## 4 Linear models (Simple linear regression)

### ■ Example 4.1

Suppose a chemical reaction produces higher yields of a product, the higher the ambient temperature



Simple linear regression is what we can use to investigate if a relationship between two variables exists when we don't know about the underlying process. We model a linear relationship between two variables and

- (a) quantify this pattern before
- (b) testing if we can believe it

### 4.1 Structure of simple linear regression models

#### Definition 4.2 (simple linear regression)

For  $n$  observed data pairs  $\{(x_i, Y_i) \mid i = 1, \dots, n\}$  simple linear regression assumes we have the relationship

$$Y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$$

$Y$  is called the respose variable and  $x$  the explanatory variable.  $\beta_0$  and  $\beta_1$  are model parameters.  $\varepsilon_i$  are error terms (spread around the regression line) and crucially, we assume  $\varepsilon_i \stackrel{i.i.d}{\sim} \text{Normal}(0, \sigma)$  in simple linear regression.

**Definition 4.3 (alternative representations for simple linear regression models)**

(a) algebraic notation:

$$\begin{aligned} Y_1 &= \beta_0 + \beta_1 x_1 + \varepsilon_1 \\ Y_2 &= \beta_0 + \beta_1 x_2 + \varepsilon_2 \\ &\vdots \\ Y_n &= \beta_0 + \beta_1 x_n + \varepsilon_n \end{aligned}$$

(b) Matrix notation:

$$Y = \beta X + \varepsilon$$

Because of the error term  $\varepsilon$ , the response  $Y$  is a random variable. So,  $Y_i = E(Y_i) + \varepsilon_i = \beta_0 + \beta_1 x_i + \varepsilon_i$  and thus  $E(Y_i) = \beta_0 + \beta_1 x_i$ . This leads to the following notation

(c) Random variable notation:

$$\begin{aligned} Y_i &\overset{i.i.d}{\sim} \text{Normal}(\beta_0 + \beta_1 x_i, \sigma) \\ Y &\sim \text{Normal}(X\beta, \mathbb{1}\sigma) \end{aligned}$$

Since the mean of the response is a linear function of the explanatory variables, there are often called simple linear models.

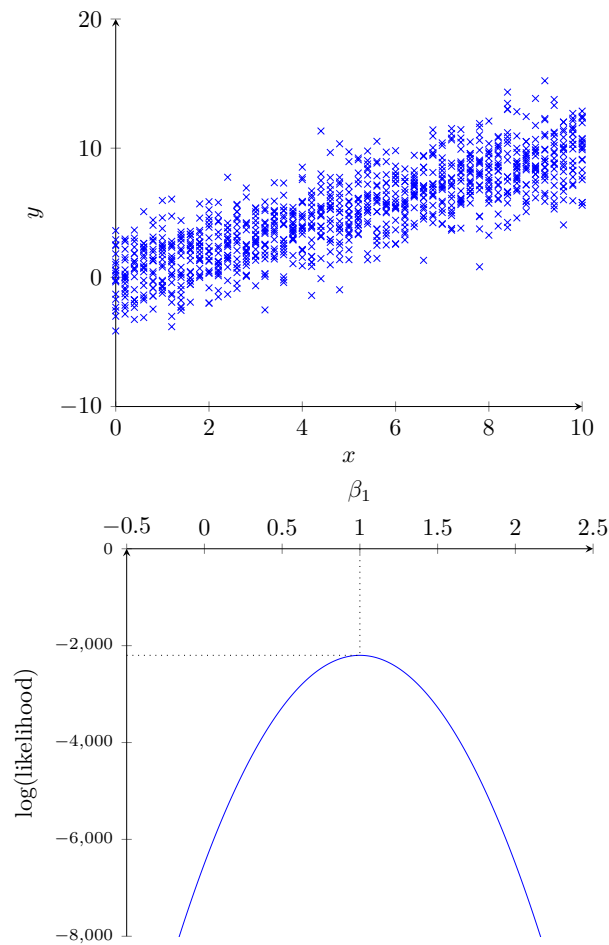
Given data, we want to estimate the parameters of the model. In this course, we always use Maximum Likelihood Estimation (MLE). That means, we find parameter values that maximise the likelihood of our model. The likelihood for an simple linear model is

$$L(\beta | X) = \prod_{i=1}^n f_{\text{Normal}}(Y_i, \mu = \beta_0 + \beta_1 x_i, \sigma)$$

where  $f_{\text{Normal}}$  is the PDF for the normal distribution with mean  $\mu = \beta_0 + \beta_1 x_i$  and standard deviation  $\sigma$  evaluated at  $Y_i$ . For linear models, it has been shown that MLE is equivalent to Ordinary Least Squares (OLS). For linear models exact equations for these parameter estimates exist

$$\begin{aligned} \hat{\beta} &= (X^T X)^{-1} X^T Y \\ \hat{\sigma}^2 &= \frac{1}{n-2} (Y - X\hat{\beta})^T (Y - X\hat{\beta}) \end{aligned}$$

Fitted values for the response are:  $\hat{Y} = X\hat{\beta}$



In  $Y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$ , assuming we know  $\beta_0 = 0$  and  $\sigma$ , we can see that the likelihood is maximal for  $\beta_1 = 1$ . Seeming plausible given the data on the left.

## 4.2 Assumptions of simple linear models

All statistical models make assumptions. Linear models are no exception. They assume, most importantly:

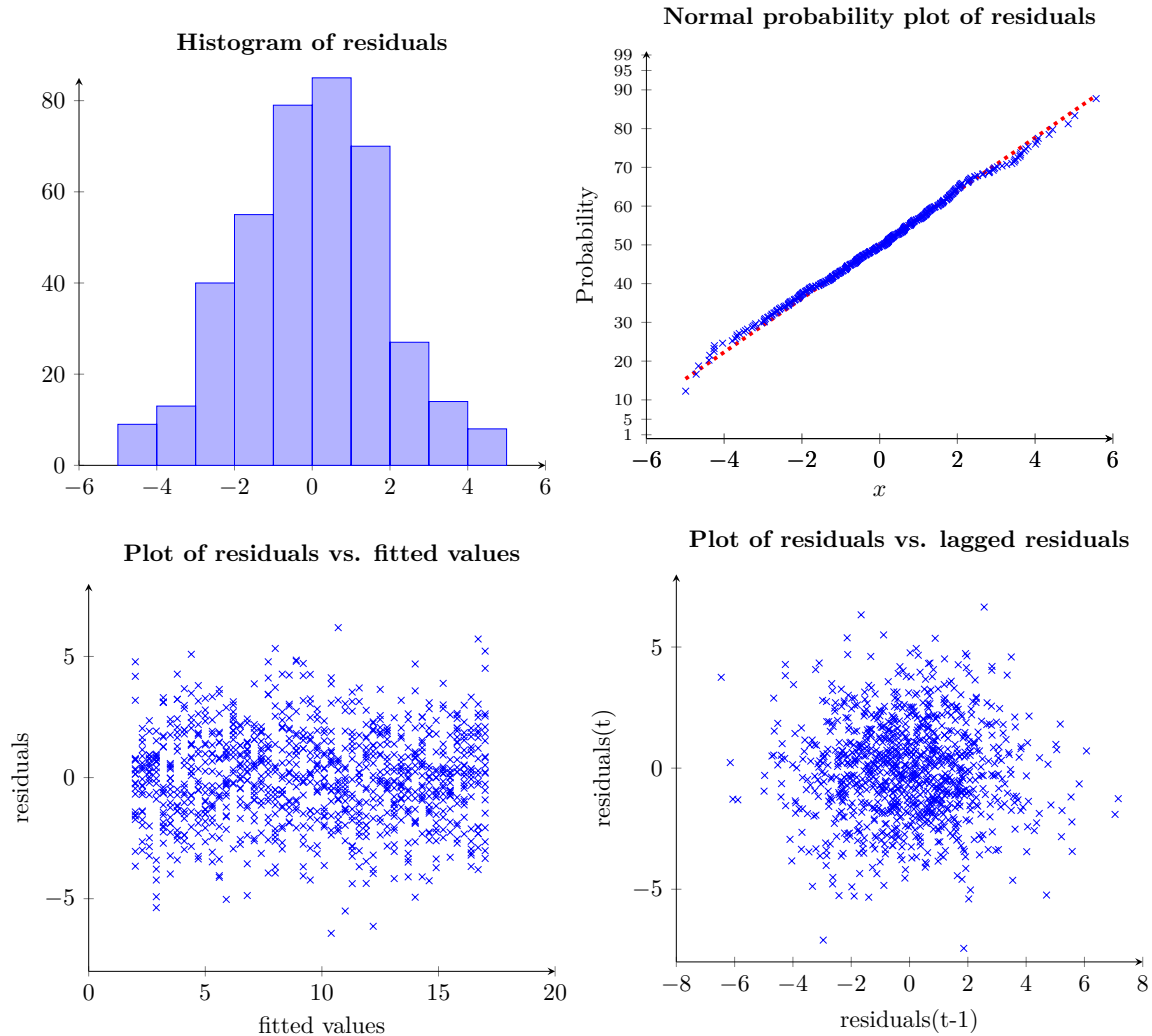
- **Linearity:** response variable is a linear combination of the explanatory variables
- **Normality:** errors follow a normal distribution
- **Constant error variance (homoscedasticity):** variance of the response variable (or errors) does not depend on the value of the explanatory variables. If this assumption is invalid it's called heteroscedasticity.
- **Independence:** the errors are uncorrelated (ideally statistically independent). This means that the response variable observations are conditionally independent. Need this for the product in the likelihood function.
- **Weak exogeneity:** the explanatory variables can be treated as fixed values, rather than random variables.

#### 4. Linear models (Simple linear regression)

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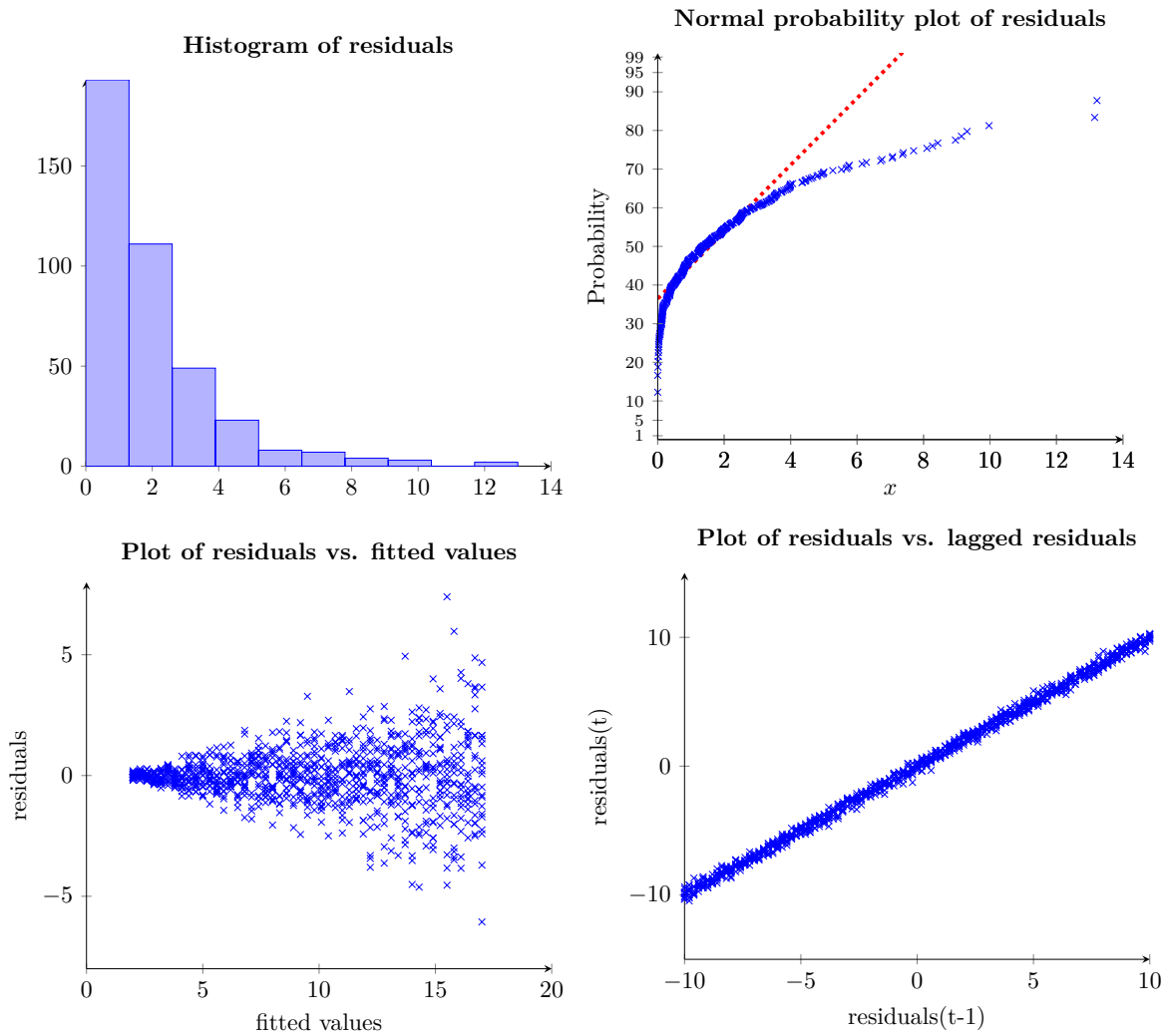
It is important to check that the most important assumptions hold (approximately) when fitting linear models to data.

To check if the model assumptions hold, we look at the errors, or residuals:  $\varepsilon = Y - X\hat{\beta}$ . Hypothesis testing on residuals is possible, but we will focus on residual plots for model checking. Perfect residual plots look like this:



The following residual plots gone wrong. Note that these plots are not all from the same data.





### 4.3 Hypothesis testing on simple linear model parameters

How to test if the  $x_i$ s contribute information for the prediction of  $Y$  in  $Y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$ ? One way of doing this is to test the hypothesis that  $Y$  does not change as the explanatory  $x$  changes. In other words, we test the hypothesis

$$H_0: \beta_1 = 0$$

$$H_A: \beta_1 \neq 0$$

Fortunately, 'math boffins' have found that  $\hat{\beta}_1$  follows a normal distribution with mean  $\beta_1$  and standard error

$$\sigma_{\hat{\beta}_1} = \frac{\sigma}{\sqrt{SS_{xx}}} \approx \frac{s}{\sqrt{SS_{xx}}}$$

where  $SS_{xx} = \sum (x_i - \bar{x})^2$  and  $s^2 = \frac{\sum (Y_i - \hat{Y}_i)^2}{n-2}$ . Since  $\sigma$  is usually unknown, we need to use a STUDENT's t-test on

$$t = \frac{\hat{\beta}_1 - \text{hypothesised value}}{\frac{s}{\sqrt{SS_{xx}}}}$$

#### 4. Linear models (Simple linear regression)

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with degrees of freedom based on the number of data points and model parameters. In practice, software will do this for us!

As an alternative for inference on parameter estimates, we can also compute confidence intervals. The  $(1 - \alpha)100\%$  confidence interval for the gradient  $\beta_1$  is

$$\hat{\beta}_1 \pm t_{\alpha/2} s_{\hat{\beta}_1}$$

where  $s_{\hat{\beta}_1} = \frac{s}{\sqrt{SS_{xx}}}$  and  $t_{\alpha/2}$  is based on  $n - 2$  degrees of freedom.  $t_{\alpha/2}$  is obtained from the STUDENT's t-distribution in the usual way. Some statistical software provides these values by default, but often (e.g. in MATLAB), only the standard errors for parameter estimates are provided.

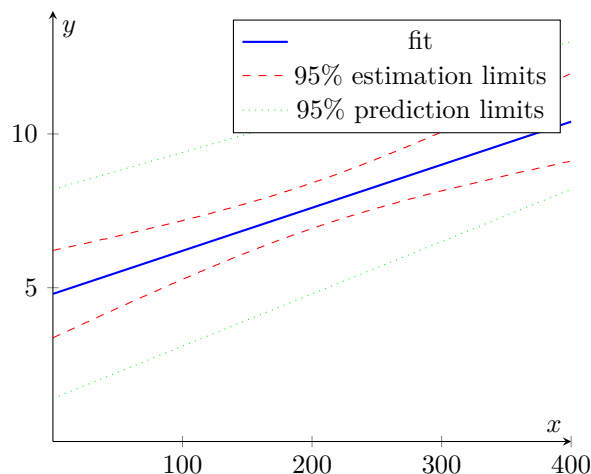
#### 4.4 Estimation and prediction for simple linear models

##### Definition 4.4 (estimation)

Estimation: estimate mean value of  $Y$  over many data points

##### Definition 4.5 (prediction)

Prediction: predict  $Y$  for a particular value of  $x$ . This leads to higher error bounds (add error in mean to variation around mean).



Be careful with predictions far away from mean of explanatory variable or outside of region covered by data.

It's good practise to always check the fit visually<sup>2</sup>. Looking at residual plots is also useful.

##### Definition 4.6 (Coefficient of Determination)

The Coefficient of Determination,  $R^2$ , is defined as

$$R^2 = \frac{SS_{yy} - SSE}{SS_{yy}}$$

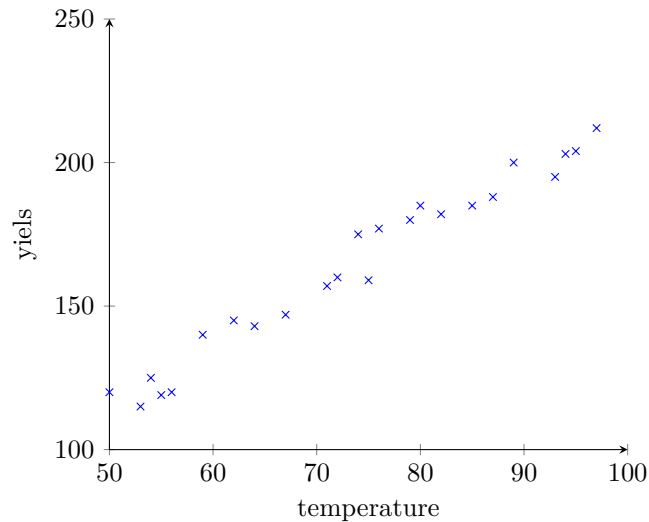
where  $SS_{yy} = \sum(Y_i - \bar{Y})^2$  and  $SSE = \sum(Y_i - \hat{Y}_i)^2$ .  $R^2$  can be interpreted as the proportion of the variance in the response variable that is explained by (or attributed to) the explanatory variable. There are other measures, similar to  $R^2$  and there are a few issues making it problematic for assessing goodness of fit. We'll revisit this later in the course.

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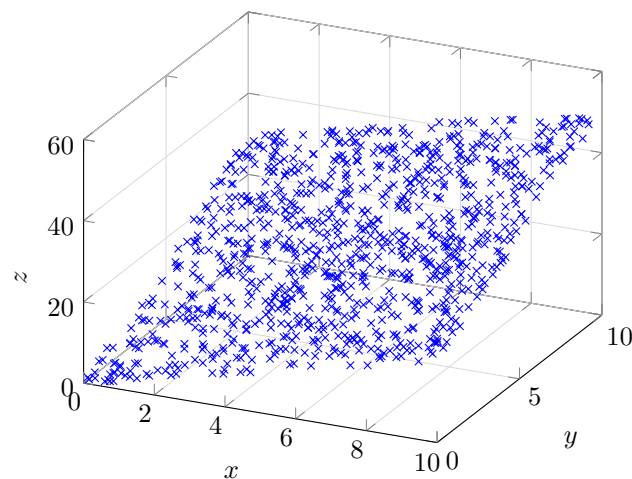
<sup>2</sup>If you don't believe that have a look at [https://en.wikipedia.org/wiki/Anscombe%27s\\_quartet](https://en.wikipedia.org/wiki/Anscombe%27s_quartet)

## 5 Linear models (Multiple linear regression)

Last lecture we've looked at simple linear regression ( $Y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$ )



This lecture we'll look at multiple linear regression (more than one predictor)



### 5.1 Structure of multiple linear regression models

Good news: simple linear models are a special case of multiple linear regression and with minor extensions everything we've looked at so far still applies. For  $p$  predictors and data tuples  $\{(x_{1i}, x_{2i}, \dots, x_{pi}, Y_i) \mid i = 1, \dots, n\}$ , we assume the relationship

$$Y_i = \beta_0 + \sum_{j=1}^p \beta_j x_{ji} + \varepsilon_i$$

As before, we assume  $\varepsilon_i \stackrel{i.i.d}{\sim} \text{Normal}(0, \sigma)$ .

The matrix notation,  $Y = X\beta + \varepsilon$ , now becomes very convenient:

$$Y = \begin{pmatrix} Y_1 \\ \vdots \\ Y_n \end{pmatrix} \quad X = \begin{pmatrix} 1 & x_{11} & \dots & x_{p1} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & x_{1n} & \dots & x_{pn} \end{pmatrix} \quad \beta = \begin{pmatrix} \beta_0 \\ \vdots \\ \beta_p \end{pmatrix} \quad \varepsilon = \begin{pmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_n \end{pmatrix}$$

As before, the random variable notation is

$$Y_i \stackrel{i.i.d}{\sim} \text{Normal} \left( \beta_0 + \sum_{j=1}^p \beta_j x_{ji}, \sigma \right)$$

$$Y \sim \text{Normal}(X\beta, \mathbb{1}\sigma)$$

Model fitting using Maximum Likelihood Estimation (MLE) proceeds in the same way as for simple linear models seen before and is equivalent to Ordinary Least Squares (OLS) fitting. The likelihood function is given by

$$L(\beta | X) = \prod_{i=1}^n f_{\text{Normal}} \left( Y_i, \mu = \beta_0 + \sum_{j=1}^p \beta_j x_{ji}, \sigma \right)$$

where  $f_{\text{Normal}}$  is the PDF for the normal distribution evaluated at  $Y_i$ . The exact equations for parameter MLEs are

$$\hat{\beta} = (X^T X)^{-1} X^T Y$$

$$\hat{\sigma}^2 = \frac{1}{n - (p + 1)} (Y - X\hat{\beta})^T (Y - X\hat{\beta}) \quad (1)$$

Fitted values for the response are:  $\hat{Y} = X\hat{\beta}$ . Parameter estimates for one explanatory variable describe the relationship between this variable and the response variable when all other explanatory variables are held fixed.

## 5.2 Assumptions of linear models

The assumptions for multiple linear regression models are the same as for simple linear models:

- **Linearity:** response variable is a linear combination of the explanatory variables
- **Normality:** errors follow a normal distribution
- **Homoscedasticity:** variance of the response variable (or errors) is constant.
- **Independence:** the errors are uncorrelated (ideally statistically independent).
- **Weak exogeneity:** the explanatory variables can be treated as fixed values, rather than random variables.

However, there is one important addition:

- **Lack of perfect multicollinearity:** if two explanatory variables are perfectly correlated, we can not solve the equation for parameter estimates (eq. (1)). Some (but not perfect!) correlation between explanatory variables may be permissible.

### 5.3 Hypothesis testing on linear model parameters

### 5.4 Model selection

#### 5.4.1 Hypothesis tests on model parameters

#### 5.4.2 $R^2$ and adjusted $R^2$

#### 5.4.3 F-test on linear models

#### 5.4.4 Quality measures based on the likelihood

#### 5.4.5 Likelihood-ratio test for nested models

### 5.5 Automated or standardised model selection strategies

## 6 Model building

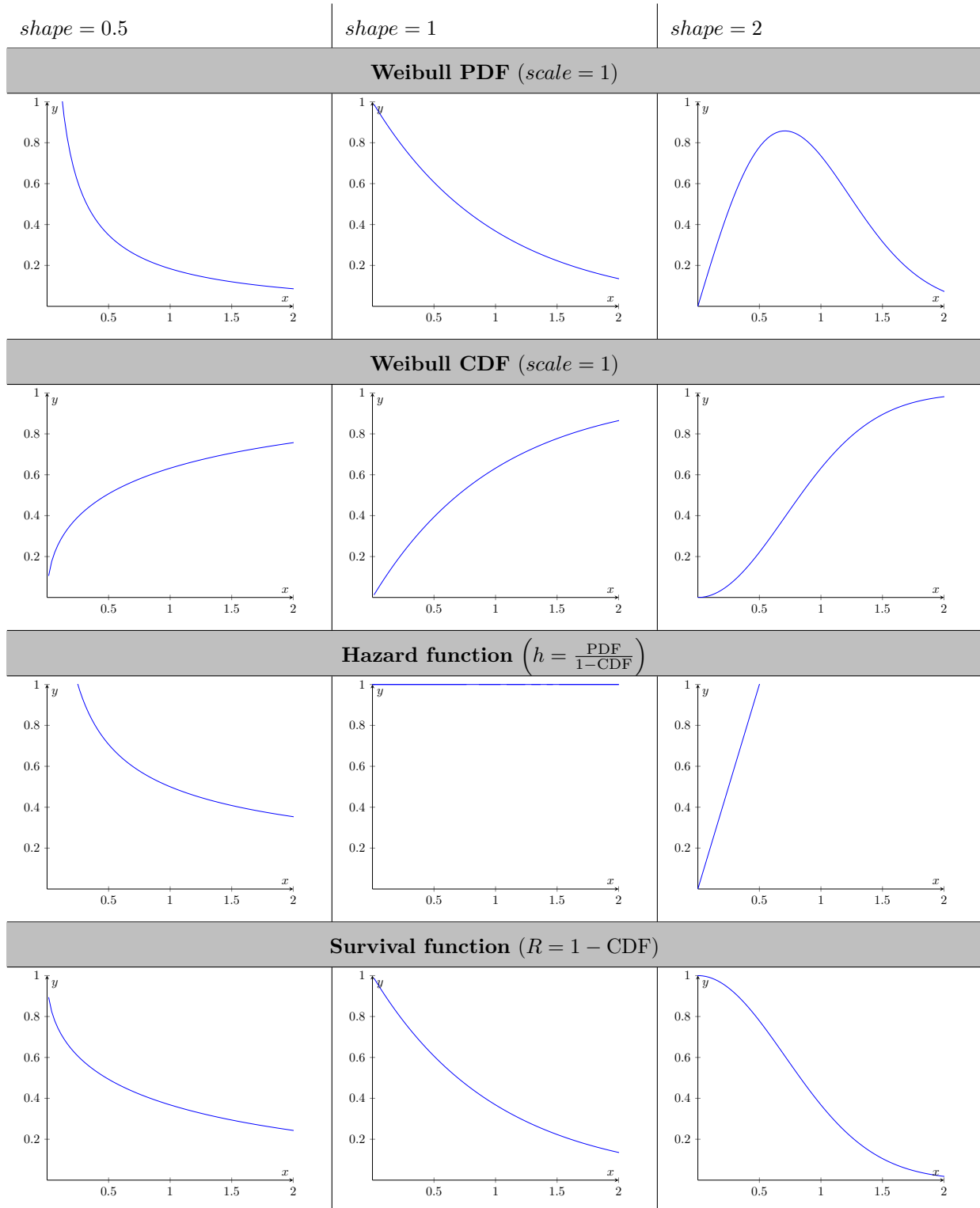
## **7 Experimental design and ANOVA**

## 8 Generalised linear models



## 9 Appendix

### 9.1 Weibulls Distribution - Graphs



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