

1 R Tutorial

1.1 Loading Data

```

1 # loading csv files
2 data <- read.table("whatever.csv", sep=";", header=T)
3
4 # csv files can be stored with (almost) any kind of file ending, e.g.:
5 data <- read.table("whatever.dat", sep=";", header=T)
6 data <- read.table("whatever.txt", sep=";", header=T)

```

2 Probability And Statistics

2.1 Probability Models for Measurement Data

2.1.1 Random Variables

Random Variables												
Definition	$X : \Omega \longrightarrow W_x$											
Example	<p>A Coin is thrown three times, head and tails is observed:</p> $\Omega = \{hhh, hht, htt, hth, ttt, tth, thh, tht\}$ <p>Total number of heads $W_x = \{0, 1, 2, 3\}$</p> <p>Total number of tails $W_x = \{0, 1, 2, 3\}$</p> <p>Number of heads minus tails $W_x = \{-3, -1, 1, 3\}$</p>											
Probability Mass Function												
Definition	The probability distribution of a discrete random variable: $P(X = x)$											
Example	<table><tr><td>x</td><td>0</td><td>1</td><td>2</td><td>3</td></tr><tr><td>$P(X = x)$</td><td>$\frac{1}{8}$</td><td>$\frac{3}{8}$</td><td>$\frac{3}{8}$</td><td>$\frac{1}{8}$</td></tr></table>	x	0	1	2	3	$P(X = x)$	$\frac{1}{8}$	$\frac{3}{8}$	$\frac{3}{8}$	$\frac{1}{8}$	
x	0	1	2	3								
$P(X = x)$	$\frac{1}{8}$	$\frac{3}{8}$	$\frac{3}{8}$	$\frac{1}{8}$								

2.1.2 Probability Distributions

Cumulative Density Function (cdf)	
Definition	$F(x) = P(X \leq x)$
Properties	$P(a < X \leq b) = F(b) - F(a)$ $0 \leq F(x) \leq 1$ $P(X = a) = F(a) - F(a) = 0$

Probability Density Function (pdf)	
Definition	$f(x) = \frac{dF(x)}{dx}$
Properties	$f(x) \geq 0$ $P(a < X \leq b) = F(b) - F(a) = \int_a^b f(x)dx$ $\int_{-\infty}^{\infty} f(x)dx = 1$

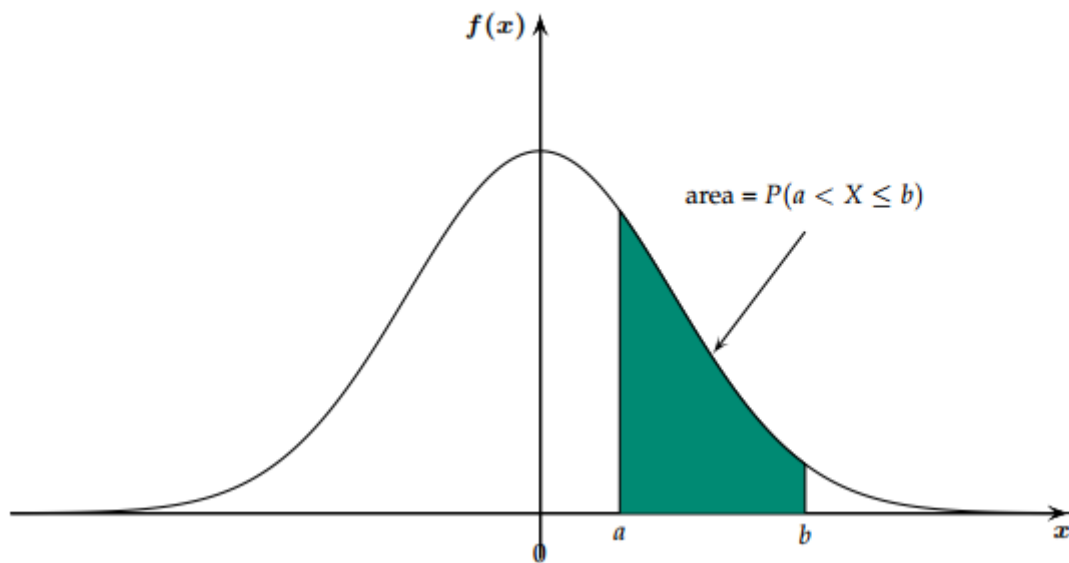


Figure 1: Probability density of a random variable and the probability of measuring a value from (a,b]

2.1.3 Summary Statistics of Continuous Distributions

Expected Value, Variance and Quantile	
Expected value	Discrete: $E(X) = \sum_i x_i P(X = x_i)$ Continuous: $E(X) = \mu_X = \int_{-\infty}^{\infty} x \cdot f(x)dx$
Variance	$\text{Var}(X) = \sigma_x^2 = E((X - E(X))^2) = \int_{-\infty}^{\infty} (x - E(X))^2 \cdot f(x)dx$
Quantile	$P(X \leq q(\alpha)) = \alpha$ $F(q(\alpha)) = \alpha \Leftrightarrow q(\alpha) = F^{-1}(\alpha)$ <i>Note: When you're asked for the 50%-quantile, that means $\alpha = 50\%$, and you must find $q(0.5)$</i>
Example Body Length	If $\alpha=0.75$ and the corresponding quantile is $q(\alpha)=182.5\text{cm}$ then 75% of the persons is shorter or equal 182.5cm.

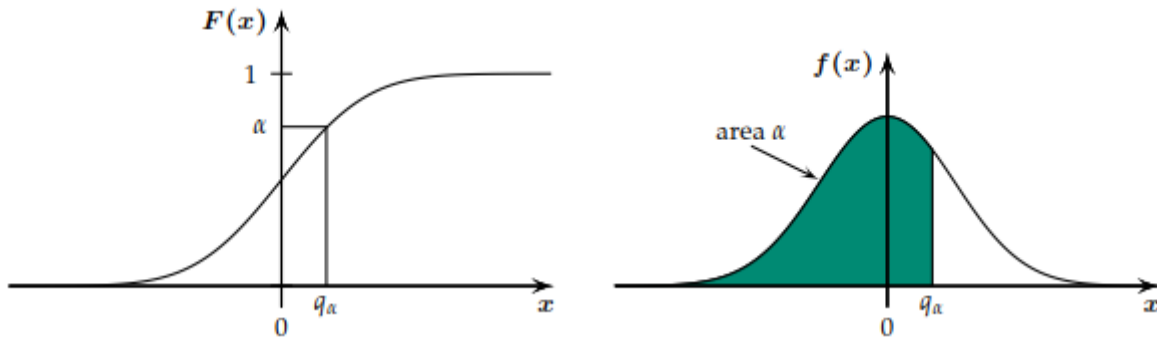


Figure 2: Quantiles

2.1.4 Important Distributions

2.1.4.1 Uniform Distribution

Theory	Code Example
$f(x) = \begin{cases} \frac{1}{b-a} & a \leq x \leq b \\ 0 & \text{otherwise} \end{cases}$ $F(x) = \begin{cases} 0 & x < a \\ \frac{x-a}{b-a} & a \leq x \leq b \\ 1 & x > b \end{cases}$ $E(x) = \frac{a+b}{2}$ $\text{Var}(x) = \frac{(b-a)^2}{12}$ $\sigma_x = \frac{b-a}{\sqrt{12}}$	<pre> 1 # value of the probability density function Uniform([1, 10]) at the position x = 5 2 duniform(x=5, min=1, max=10) [1] 0.1111111 3 4 5 # P(X <= 5) 6 punif(q=5, min=1, max=10) [1] 0.4444444 7 8 9 # P(1.2 < X <= 4.8) 10 punif(4.8, 1, 10) - punif(1.2, 1, 10) [1] 0.4 11 12 13 # 5 uniformly distributed random values in Uniform([1, 10]) 14 runif(5,min=1,max=10) [1] 1.061933 6.484813 5.928334 8.459887 8.852405 15 16 17 # TODO: ADD MORE HERE </pre>

2.1.4.2 Exponential Distribution

Theory	Code Example
$f(x) = \begin{cases} \lambda \cdot e^{-\lambda \cdot x} & x \geq 0 \\ 0 & \text{otherwise} \end{cases}$ $F(x) = \begin{cases} 1 - \lambda \cdot e^{-\lambda \cdot x} & x \geq 0 \\ 0 & \text{otherwise} \end{cases}$ $E(x) = \frac{1}{\lambda}$ $\text{Var}(x) = \frac{1}{\lambda^2}$ $\sigma_x = \frac{1}{\lambda}$	<pre> 1 # P(0 <= X <= 4) of X ~ Exp(3) pexp(4, rate=3) 2 [1] 0.9999939 3 4 5 # TODO: ADD MORE HERE </pre>

2.1.4.3 Normal Distribution

Theory	Code Example
$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$ $F(x) = \int_{-\infty}^x f(y) dy$ $E(x) = \mu$ $\text{Var}(x) = \sigma^2$ $\sigma_x = \sigma$	<pre> 1 # X~N(u, sigma^2) --> X~N(100,15^2) 2 # In R we compute P(X>130) as 1 - P(X<=130) 3 1-pnorm(130, mean=100, sd=15) 4 [1] 0.02275013 5 6 #P(85<=X<=115) 7 pnorm(115, mean=100, sd=15)-pnorm(85, mean=100, 8 sd=15) 9 [1] 0.6826895 10 # TODO: ADD MORE HERE </pre>

2.1.4.4 Linear Transformation of Random Variables

Properties of Linear Transformation of a Random Variable	
Definition	<p>For $Y = a + bX$ the following apply</p> <p>(i) $E(Y) = a + bE(X)$</p> <p>(ii) $\text{Var}(Y) = b^2\text{Var}(X)$, $\sigma_Y = b \sigma_X$</p> <p>(iii) α - Quantile of $Y = q_Y(\alpha) = a + bq_X(\alpha)$</p> <p>(iv) $f_Y(y) = \frac{1}{ b }f_X(\frac{y-a}{b})$</p>
Summary Statistics of S_n and \bar{X}_n	
Summary Statistics of Sample Total S_n	$E(S_n) = E(X_1 + X_2 + \dots + X_n) = \sum_{i=1}^n E(X_i) = n\mu$ $\text{Var}(S_n) = \sum_{i=1}^n \text{Var}(X_i) = n\text{Var}(X_i)$ $\sigma(S_n) = \sqrt{n}\sigma_X$
Summary Statistics of Sample Mean \bar{X}_n	$E(\bar{X}_n) = E\left(\frac{X_1+X_2+\dots+X_n}{n}\right) = \frac{1}{n} \sum_{i=1}^n E(X_i) = \frac{1}{n}nE(X_i) = \mu$ $\text{Var}(\bar{X}_n) = \frac{1}{n^2} \sum_{i=1}^n \text{Var}(X_i) = \frac{1}{n^2}n\sigma_X^2 = \frac{\sigma_X^2}{n}$ <p>Standard Error</p> $\sigma(\bar{X}_n) = \frac{\sigma_X}{\sqrt{n}}$

2.1.4.5 Distributions of S_n and \bar{X}_n

Theory	Code Example
<p>1. For $X_i \in \{0, 1\}$, we have</p> $S_n \sim \text{Bin}(n, \pi) \text{ with } \pi = P(X_i = 1)$ <p>2. For $X_i \sim \text{Pois}(\lambda)$, we have</p> $S_n \sim \text{Pois}(n\lambda)$ <p>3. For $X_i \sim N(\mu, \sigma^2)$</p> $S_n \sim N(n\mu, n\sigma^2) \text{ and } \bar{X}_n \sim N(\mu, \frac{\sigma_X^2}{n})$	<pre> 1 What is the probability that among 10000 tosses 2 of a fair coin, heads would appear in 3 maximum 5100 cases? 4 #Approximated: X~N(5000,2500) 5 pnorm(5100,5000,sqrt(2500)) 6 [1] 0.9772499 7 8 # "True Result": X~Bin(10000,0.5) 9 pbinom(5100,10000,0.5) 10 [1] 0.9777871 </pre>

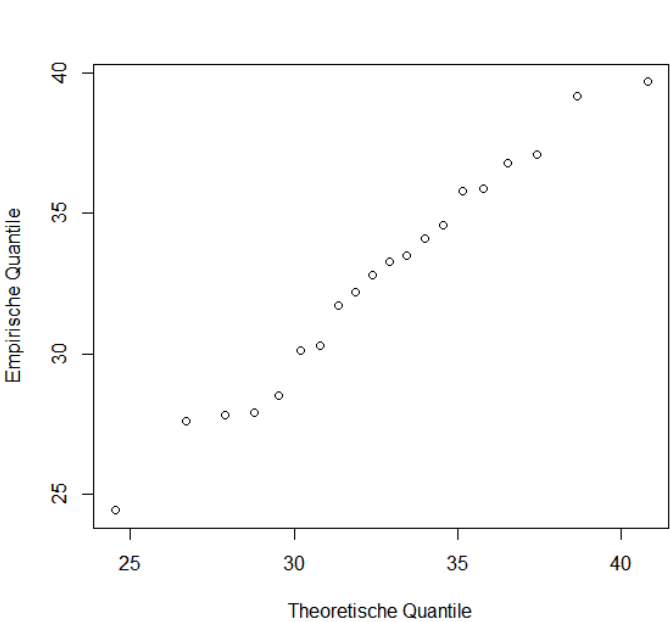
2.2 Statistics for Measurement Data

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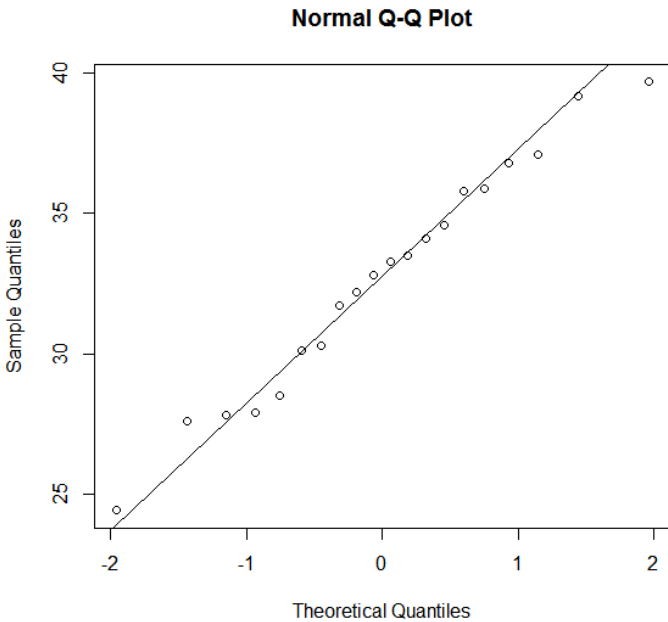
2.2.1 Assess the Normal Distribution Assumption

2.2.1.1 Q-Q Plot

Theory	Code Example
<div>1. For$\alpha_k = \frac{k-0.5}{n}$with $k = 1, \dots, n$calculate the corresponding theoretical quantiles of the model distribution$q(\alpha_k) = F^{-1}(\alpha_k)$</div> <div>2. Determine the empirical α_k-quantiles,$x_{(1)} < x_{(2)} < \dots < x_{(n)}$</div> <div>3. Plot the empirical quantiles x_k on the y-axis against the theoretical quantiles $q(\alpha_k)$ on the x-axis.</div>	<pre>1 x <- c(24.4, 27.6, 27.8, 27.9, 28.5, 30.1, 30.3, 2 31.7, 32.2, 32.8, 33.3, 33.5, 34.1, 34.6, 3 35.8, 35.9, 36.8, 37.1, 39.2, 39.7) 4 5 alpha_k <- (seq(1, length(x), by=1)-0.5)/length(x) 6 7 quantile_th <- qnorm(alpha_k, mean=mean(x), sd=sd(x)) 8 9 quantile_emp <- sort(x) 10 #image qqplot 11 qqplot(quantile_th, quantile_emp, xlab="Theoretische Quantile", ylab = "Empirische Quantile") 12 13 #image qqnorm;qqline 14 qqnorm(x);qqline(x)</pre>



(a) qqplot()



(b) qqnorm();qqline()

k	$x_{(k)}$	$\alpha_k = (k - 0.5)/n$	q_{α_k} for $\mathcal{N}(32.7, 4.15^2)$	$\Phi^{-1}(\alpha_k)$
1	24.4	0.0250	24.5	-1.96
2	27.6	0.075	26.7	-1.44
3	27.8	0.125	27.9	-1.15
4	27.9	0.175	28.8	-0.935
5	28.5	0.225	29.5	-0.755
6	30.1	0.275	30.2	-0.600
7	30.3	0.325	30.8	-0.453
8	31.7	0.375	31.3	-0.319
9	32.2	0.425	31.9	-0.189
10	32.8	0.475	32.4	-0.0627
11	33.3	0.525	32.9	0.0627
12	33.5	0.575	33.4	0.189
13	34.1	0.625	34.0	0.319
14	34.6	0.675	34.5	0.454
15	35.8	0.725	35.1	0.598
16	35.9	0.775	36.0	0.755
17	36.8	0.825	36.5	0.935
18	37.1	0.875	37.4	1.15
19	39.2	0.925	38.6	1.44
20	39.7	0.975	40.8	1.96

```

1 #x(k) are the measured values N(u,sigma^2)
2 x <- c(24.4, 27.6, 27.8, 27.9, 28.5, 30.1, 30.3,
3     31.7, 32.2, 32.8, 33.3, 33.5, 34.1, 34.6, 35.8,
4     35.9, 36.8, 37.1, 39.2, 39.7)
5 mean(x)
6 [1] 32.665
7 sd(x)
8 [1] 4.149734
9 #N(32.7, 4.15)
10 #a_k = (k-0.5)/n = qnorm(q_ak, 32.7, 4.15)
11 pnorm(24.5, 32.7, 4.15)
12 [1] 0.02408285
13 pnorm(32.4, 32.7, 4.15)
14 [1] 0.4711859
15 pnorm(35.8, 32.7, 4.15)
16 [1] 0.7724646
17 pnorm(40.8, 32.7, 4.15)
18 [1] 0.9745195
19 #q_ak for N(32.7, 4.15) = qnorm(a_k, 32.7, 4.15)
20 qnorm(0.025, 32.7, 4.15)
21 [1] 24.56615
22 qnorm(0.475, 32.7, 4.15)
23 [1] 32.43977
24 qnorm(0.725, 32.7, 4.15)
25 [1] 35.1807
26 qnorm(0.975, 32.7, 4.15)
27 [1] 40.83385
28 #phi^{-1}(a_k)
29 qnorm(0.025)
30 [1] -1.959964
31 qnorm(0.475)
32 [1] -0.06270678
33 qnorm(0.725)
34 [1] 0.5977601
35 qnorm(0.975)
36 [1] 1.959964

```

2.2.2 Parameter Estimation for Continuous Probability Distributions

Method of Moments (not unbiased)

1. We consider our data measurements x_1, x_2, \dots, x_n as realization of random variables X_1, X_2, \dots, X_n originating from the same known distribution.

2. We calculate the expected value $E(X)$ and solve the equation for the unknown parameter that we intend to estimate.

3. We replace the expected value with its counterpart, the empirical mean value and obtain an estimate of the unknown parameter. A method of moments estimate of the standard deviation is the empirical standard deviation.

$$\mu = E(X) \Rightarrow \hat{\mu} = \bar{x}_n = \frac{x_1 + x_2 + \dots + x_n}{n} = \frac{653.3}{20} = 32.7$$

$$\sigma^2 = E(X^2) - E(X)^2 = E(X^2) - \mu^2$$

$$\hat{\mu}^2 + \hat{\sigma}^2 = \frac{1}{n} \sum_{i=1}^n x_i^2$$

$$\hat{\sigma}^2 = \frac{\sum_{i=1}^n (x_i - \bar{x}_n)^2}{n}$$

$$\hat{\sigma}^2 = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \hat{\mu})^2} = \sqrt{\frac{1}{20} \sum_{i=1}^{20} (x_i - 32.7)^2} = 4.04$$

Method of Maximum Likelihood

We have n observations that are i.i.d.

For a discrete probability distribution: probability that these n observations (events) actually have occurred can be expressed as follows

$$X_1 = x_1, X_2 = x_2, \dots, X_n = x_n$$

$$P[(X_1 = x_1) \cap (X_2 = x_2) \cap \dots \cap (X_n = x_n)] = P[X_1 = x_1] \cdot P[X_2 = x_2] \cdot \dots \cdot P[X_n = x_n] = \prod_{i=1}^n P[X_i = x_i]$$

<p>Probability that the n independent random variables x_1, x_2, \dots, x_n are observed, depends on parameter θ, which we wish to estimate. Therefore the Likelihood function is given by $L(\theta)$ where $P[X_i = x_i \theta]$ denotes probability mass function that value x_i has been observed, given the parameter value θ.</p> <p>Idea of Maximum Likelihood : estimate the parameter θ in such a way that the likelihood is maximized, that is, that it makes the observed data most likely or most probable.</p> <p>Continuous probability distributions : with probability density function $f(x; \theta)$. Probability, that each observation x_i falls into its corresponding interval $[x_i, x_i + dx_i]$:</p> <p>Infinitesimal intervals dx_i do not depend on the parameter value θ : we omit them in the likelihood function</p> <p>If assumed probability density function $f(x_i; \theta)$ and parameter value of θ are correct, we expect a high probability for the actually observed data to occur : maximization of $L(\theta)$</p>	$L(\theta) = P[X_1 = x_1 \theta] \cdot P[X_2 = x_2 \theta] \cdot \dots \cdot P[X_n = x_n \theta] = \prod_{i=1}^n P[X_i = x_i \theta]$ $\prod_{i=1}^n f(x_i; \theta) dx_i$ $\prod_{i=1}^n f(x_i; \theta)$
Example: Maximum Likelihood for Exponential Distribution	
Let X_1, X_2, \dots, X_n i.i.d. $\sim \text{Exp}(\lambda)$, that is	$f(x_i; \lambda) = \lambda e^{-\lambda x_i}$
Likelihood function for a given data set x_1, x_2, \dots, x_n is given by	$L(\lambda) = \prod_{i=1}^n \lambda e^{-\lambda x_i}$
Log likelihood function is	$\log(L(\lambda)) = n \log(\lambda) - \lambda \sum_{i=1}^n x_i$
If we calculate the derivative of the log likelihood function with respect to λ and set it equal to 0, then we obtain	$\frac{d \log(L(\lambda))}{d\lambda} = \frac{n}{\lambda} - \sum_{i=1}^n x_i \stackrel{!}{=} 0$
The maximum likelihood estimate $\hat{\lambda}$ thus corresponds to the solution of the previous equation	$\hat{\lambda} = \frac{n}{\sum_{i=1}^n x_i} = \frac{1}{\bar{x}}$

2.2.3 Statistical Tests and Confidence Interval for Normally Distributed Data

z-Test (σ_x known)	
1. Model:	X_1, \dots, X_n i.i.d. $\sim N(\mu, \sigma_X^2)$, σ_X known
2. Null hypothesis:	$H_0: \mu = \mu_0$
Alternative:	$H_A: \mu \neq \mu_0$ (or $<$ or $>$)
3. Test statistic:	$Z = \frac{(\bar{X}_n - \mu_0)}{\sigma_{\bar{X}_n}} = \frac{(\bar{X}_n - \mu_0)}{\sigma_{X_n}/\sqrt{n}} = \frac{\sqrt{n}(\bar{X}_n - \mu_0)}{\sigma_{X_n}} = \frac{\text{observed} - \text{expected}}{\text{standard error}}$
Null distribution (assuming H_0 is true):	$Z \sim N(0, 1)$
4. Significance level:	α
5. Rejection region for the test statistic:	$K = (-\infty, z_{\frac{\alpha}{2}}] \cup [z_{1-\frac{\alpha}{2}}, \infty)$ with $H_A: \mu \neq \mu_0$, $K = (-\infty, z_{\alpha}]$ with $H_A: \mu < \mu_0$, $K = [z_{1-\alpha}, \infty)$ with $H_A: \mu > \mu_0$
where	$z_{\frac{\alpha}{2}} = \Phi^{-1}(\alpha/2)$

6. Test decision:	Check whether the observed value of the test statistic falls into the rejection region.
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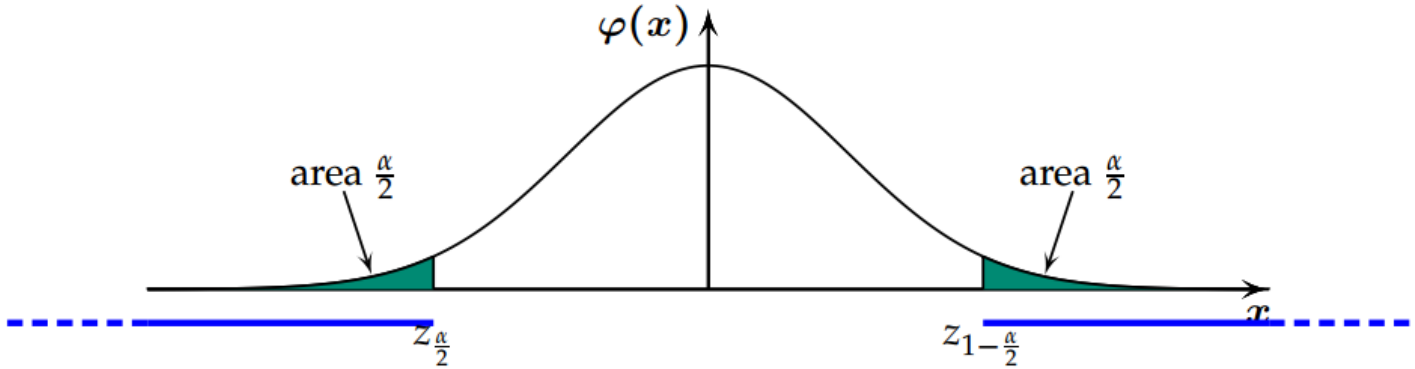


Figure 4: z-Test: Rejection Region

z-Test (σ_x known): Example	
Measurement of fusion heat:	The empirical mean value of $n = 13$ measurements is 80.02. From previous measurements the standard deviation is $\sigma_X = 0.01$. Is a fusion heat of exactly $80.00 \frac{\text{g}}{\text{cal}}$ plausible?
1. Model:	X_1, \dots, X_n i.i.d. $\sim N(\mu, \sigma_X^2)$, $\sigma_X = 0.01$ known, $n = 13$
2. Null hypothesis:	$H_0: \mu = \mu_0 = 80.00$
Alternative:	$H_A: \mu \neq \mu_0$
3. Test statistic:	$Z = \frac{\sqrt{n}(\bar{X}_n - \mu_0)}{\sigma_{X_n}}$
Null distribution (assuming H_0 is true):	$Z \sim N(0, 1)$
4. Significance level:	$\alpha = 0.05$ (commonly used α -level)
5. Rejection region for the test statistic:	$K = (-\infty, z_{\frac{\alpha}{2}}] \cup [z_{1-\frac{\alpha}{2}}, \infty)$ with $H_A: \mu \neq \mu_0$
Given $\alpha = 0.05$, R yields the following 2.5% quantile of the standard normal distribution.	$\begin{array}{l} 1 \parallel \text{qnorm}(0.025) \\ 2 \parallel [1] \quad -1.959964 \end{array}$
The following rejection region for the test statistic results	$z_{\frac{\alpha}{2}} = \Phi^{-1}(\alpha/2) = \Phi^{-1}(0.025) = -1.96$ $K = (-\infty, -1.96] \cup [1.96, \infty)$
6. Test decision:	Hence the value for the statistics is
	$z = \frac{\sqrt{n}(\bar{X}_n - \mu_0)}{\sigma_{X_n}} = \frac{\sqrt{13}(80.02 - 80.00)}{0.01} = 7.211$
Remarks: Standardizing is in principle unnecessary because of technical aid of computer software.	Therefore the observed value falls into the rejection region.
3. Test statistic: (not standardized)	The mean value of the measurements
	$T: \bar{X}_n$

Null distribution (assuming H_0 is true):	$T \sim N(\mu_0, \frac{\sigma_X^2}{n}) = N(80, \frac{0.01^2}{13})$
5. Rejection region for the test statistic: (not standardized) Given $\alpha = 0.05$, R yields the following 2.5% quantile of the standard normal distribution.	$K = (-\infty, c_u] \cup [c_o, \infty)$ with $H_A : \mu \neq \mu_0$ <pre> 1 qnorm(0.025, 80.0, 0.01/sqrt(13)) 2 [1] 79.99456 3 qnorm(0.975, 80.0, 0.01/sqrt(13)) 4 [1] 80.00544 </pre>
In this way, we obtain the rejection region for the test statistic:	$K = (-\infty, 79.99] \cup [80.01, \infty)$

t-Test (σ_x unknown)	
1. Model:	X_1, \dots, X_n i.i.d. $\sim N(\mu, \sigma_X^2)$, σ_X is estimated by $\hat{\sigma}_X$
2. Null hypothesis:	$H_0: \mu = \mu_0$
Alternative:	$H_A: \mu \neq \mu_0$ (or $<$ or $>$)
3. Test statistic:	$T = \frac{\sqrt{n}(\bar{X}_n - \mu_0)}{\hat{\sigma}_X} = \frac{\text{observed} - \text{expected}}{\text{estimated standard error}}$
Null distribution (assuming H_0 is true):	$T \sim t_{n-1}$
4. Significance level:	α
5. Rejection region for the test statistic:	$K = (-\infty, t_{n-1; \frac{\alpha}{2}}] \cup [t_{n-1; 1-\frac{\alpha}{2}}, \infty)$ with $H_A : \mu \neq \mu_0$, $K = (-\infty, t_{n-1; \alpha}]$ with $H_A : \mu < \mu_0$, $K = [t_{n-1; 1-\alpha}, \infty)$ with $H_A : \mu > \mu_0$
6. Test decision:	Check whether the observed value of the test statistic falls into the rejection region.
Example	
1. Model:	X_1, \dots, X_n i.i.d. $\sim N(\mu, \sigma_X^2)$, σ_X is estimated, $\hat{\sigma}_X = 0.024$
2. Null hypothesis:	$H_0: \mu = \mu_0 = 80.00$
Alternative:	$H_A: \mu \neq \mu_0$
3. Test statistic:	$T = \frac{\sqrt{n}(\bar{X}_n - \mu_0)}{\hat{\sigma}_X}$
Null distribution (assuming H_0 is true):	$T \sim t_{n-1}$
4. Significance level:	$\alpha = 0.05$
5. Rejection region for the test statistic: We determine the value by means of R , where $\alpha = 0.05$ and $n = 13$.	$K = (-\infty, t_{n-1; \frac{\alpha}{2}}] \cup [t_{n-1; 1-\frac{\alpha}{2}}, \infty)$ with $H_A : \mu \neq \mu_0$, $t_{n-1; 1-\frac{\alpha}{2}} = t_{12; 0.975} = 2.179$ <pre> 1 qt(0.975, 12) 2 [1] 2.178813 </pre>
The rejection region of the test statistic thus is given by	$K = (-\infty, -2.179] \cup [2.179, \infty)$
6. Test decision:	On the basis of $n = 13$ measurements, we find

	$\bar{x} = 80.02$ and $\hat{\sigma}_X = 0.024$ Hence, the realized value of the test statistic is $t = \frac{\sqrt{n}(\bar{X}_n - \mu_0)}{\hat{\sigma}_X} = \frac{\sqrt{13}(80.02 - 80.00)}{0.024} = 3.00$ The observed value falls into the rejection region. Therefore, the null hypothesis is rejected at 5% level.
<p>The t-test directly performed in R using the function <code>t.test()</code></p> <p>Remarks:</p> <p>(i) The observed value of the test statistic is 3.12. Assuming the null hypothesis is true, then the test statistic follows a t-distribution with $df = 12$ degrees of freedom.</p> <p>(ii) The observed mean value of the data is 80.02. A 95% confidence interval for the true mean is [80.006, 80.035].</p> <p>(iii) The R functions <code>qt(p,df)</code> calculates the quantile from the probability density and the degrees of freedom and <code>pt(q,df)</code> calculates the probability density from the quantile and the degrees of freedom.</p> <p>(iv) The confidence interval for measurement data consists of the values μ, for which the corresponding statistical test does not reject the null hypothesis.</p>	<pre> 1 x <- c(79.98, 80.04, 80.02, 80.04, 80.03, 2 80.03, 80.04, 79.97, 80.05, 80.03, 3 80.02, 80.00, 80.02) 4 5 t.test(x, alternative = "two.sided", 6 mu = 80.00, conf.level = 0.95) 7 8 ## 9 ## One Sample t-test 10 ## 11 ## data: x 12 ## t = 3.1246, df = 12, p-value = 0.008779 13 ## alternative hypothesis: true mean is not 14 ## equal to 80 15 ## 95 percent confidence interval: 16 ## 80.00629 80.03525 17 ## sample estimates: 18 ## mean of x 19 ## 80.02077 20 21 qt(0.975,12) 22 [1] 2.178813 23 pt(2.178813,12) 24 [1] 0.975 25 qt(0.5,12) 26 [1] 0.0 27 pt(0.0,12) 28 [1] 0.5 </pre>
P-Value	
<p>The p-value is the probability that the test statistic will take on a value that is at least as extreme (with respect to the alternative hypothesis) as the observed value of the statistic when the null hypothesis H_0 is true.</p> <p>In R we compute the one-sided and the two sided p-value as follows:</p> <p>These p-values are evidence against the null hypothesis at 5% level. Whereas the two-sided value is statistically significant at the 5% value.</p>	<p>For the one-sided alternative hypothesis $H_A: \mu > \mu_0$, the p-value can be calculated as follows - the observed value of the statistics is $t = \frac{\sqrt{n}(\bar{X}_n - \mu_0)}{\hat{\sigma}_X} = 3.1246$:</p> <p>$p\text{-value} = P(T > t) = P(T > 3.1246) = 0.00439$ For the two-sided alternative hypothesis $H_A: \mu \neq \mu_0$, the p-value can be calculated as follows (the observed value of the test statistics is $t = \frac{\sqrt{n} \bar{X}_n - \mu_0 }{\hat{\sigma}_X}$):</p> <p>$p\text{-value} = 2 \cdot P(T > t)$</p> <pre> 1 ## one-sided p-value 2 1-pt(3.1246, df=12) 3 [1] 0.004389739 4 ## two-sided p-value 5 2*(1-pt(3.1246, df=12)) 6 [1] 0.008779477 </pre>

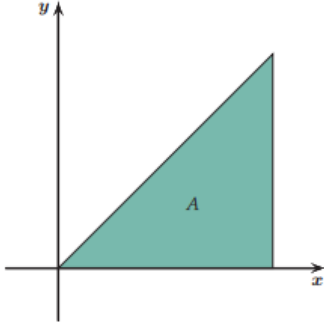
<p>p-value and Statistical Test</p> <ol style="list-style-type: none"> 1. Reject H_0 if $p\text{-value} \leq \alpha$ 2. Retain H_0 if $p\text{-value} > \alpha$ <p>The <i>p-value</i> is the <i>smallest level of significance</i> that would lead to rejection of the null hypothesis H_0 with the given data.</p>	<p>The <i>p-value</i> quantifies how significant an alternative is:</p> <p>$p\text{-value} \approx 0.05$: weakly significant, "."</p> <p>$p\text{-value} \approx 0.01$: weakly significant, "**"</p> <p>$p\text{-value} \approx 0.001$: weakly significant, "***"</p> <p>$p\text{-value} \leq 10^{-4}$: weakly significant, "****"</p>
--	--

2.3 Joint Distributions

2.3.1 Joint, Marginal and Conditional Distributions

Discrete Joint Probability Distribution																																									
The Joint Probability Distribution of X and Y is defined by the following distributions:				$P(X = x, Y = y), x \in W_x, y \in W_y$																																					
Marginal Distributions are single distributions $P(X = x)$ of X and $P(Y = y)$ of Y . They can be calculated based on their joint distribution: Joint distribution of (X, Y) starting from the marginal distribution of X and Y is only possible for independent X and Y . Then it holds:				$P(X = x) = \sum_{y \in W_y} P(X = x, Y = y), x \in W_x$ $P(X = x, Y = y) = P(X = x) \cdot P(Y = y), x \in W_x, y \in W_y$																																					
Conditional probability of X given $Y = y$ is defined as: The marginal distributions then can be expressed as follows:				$P(X = x Y = y) = \frac{P(X=x, Y=y)}{P(Y=y)}$ $P(X = x) = \sum_{y \in W_y} P(X = x Y = y)P(Y = y), x \in W_x$																																					
Conditional Expected Value of Y given $X = x$ is defined as:				$E[Y X = x] = \sum_{y \in W_y} y \cdot P(Y = y X = x)$																																					
Example																																									
<table><tr><th>X\ Y</th><th>1</th><th>2</th><th>3</th><th>4</th><th>Σ</th></tr><tr><th>1</th><td>0.080</td><td>0.015</td><td>0.003</td><td>0.002</td><td>0.100</td></tr><tr><th>2</th><td>0.050</td><td>0.350</td><td>0.050</td><td>0.050</td><td>0.500</td></tr><tr><th>3</th><td>0.030</td><td>0.060</td><td>0.180</td><td>0.030</td><td>0.300</td></tr><tr><th>4</th><td>0.001</td><td>0.002</td><td>0.007</td><td>0.090</td><td>0.100</td></tr><tr><th>Σ</th><td>0.161</td><td>0.427</td><td>0.240</td><td>0.172</td><td>1</td></tr></table>				X\ Y	1	2	3	4	Σ	1	0.080	0.015	0.003	0.002	0.100	2	0.050	0.350	0.050	0.050	0.500	3	0.030	0.060	0.180	0.030	0.300	4	0.001	0.002	0.007	0.090	0.100	Σ	0.161	0.427	0.240	0.172	1	$P(X = 3, Y = 4) = 0.030 \text{ or } P(X = 3 \cup Y = 4) = 0.030$ $P(X = 3) = P(X = 3, Y = 1) + P(X = 3, Y = 2) + P(X = 3, Y = 3) + P(X = 3, Y = 4) = 0.030 + 0.060 + 0.180 + 0.030 = 0.300$ $P(Y = 2 X = 4) = \frac{P(Y=2, X=4)}{P(X=4)} = \frac{0.002}{0.1} = 0.02$ $P(X = Y) = P(X = 1, Y = 1) + P(X = 2, Y = 2) + P(X = 3, Y = 3) + P(X = 4, Y = 4) = 0.700$ If random variables are independent it must hold that $P(X = x, Y = y) = P(X = x) \cdot P(Y = y)$ From the marginal distribution follows $P(X = 1) \cdot P(Y = 2) = 0.100 \cdot 0.427 = 0.043$ and this is not equal to $P(X = 1, Y = 2) = 0.15$ X and Y are not independent	
X\ Y	1	2	3	4	Σ																																				
1	0.080	0.015	0.003	0.002	0.100																																				
2	0.050	0.350	0.050	0.050	0.500																																				
3	0.030	0.060	0.180	0.030	0.300																																				
4	0.001	0.002	0.007	0.090	0.100																																				
Σ	0.161	0.427	0.240	0.172	1																																				

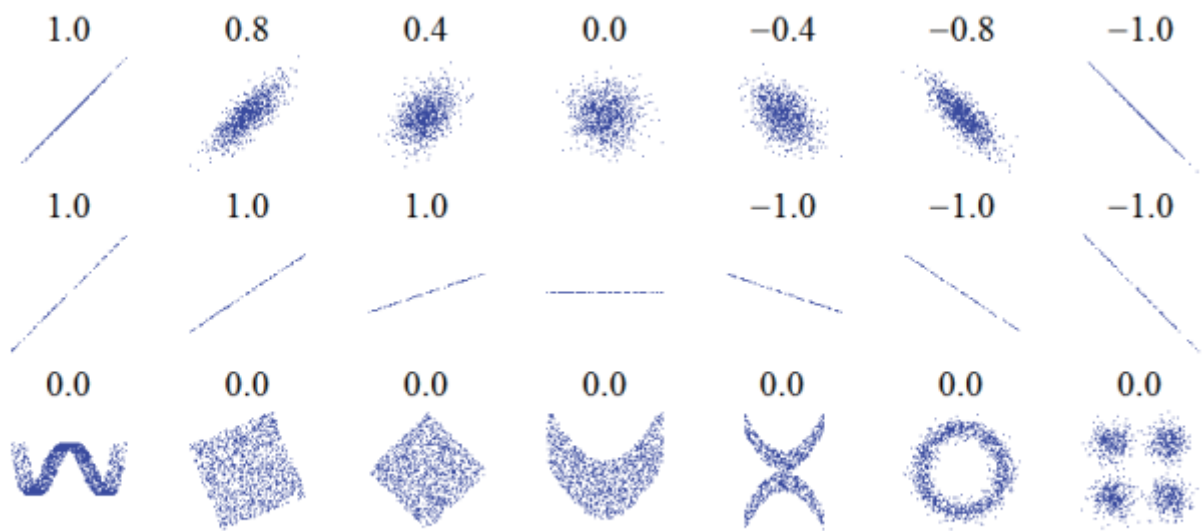
Joint Density Function	
The probability that the joint random variable (X, Y) lies in a two-dimensional region A , i.e., $A \subset \mathbb{R}^2$, is given by	$P((X, Y) \in A) = \iint_A f_{X,Y}(x, y) dx dy$

The (bivariate) joint density function needs to satisfy	$\iint_{\mathbb{R}} f_{X,Y}(x,y) dx dy = 1$
X and Y are only independent if	$f_{X,Y}(x,y) = f_X(x) \cdot f_Y(y), x, y \in \mathbb{R}$
Marginal Density	$f_X(x) = \int_{-\infty}^{\infty} f_{X,Y}(x,y) dy, f_Y(y) = \int_{-\infty}^{\infty} f_{X,Y}(x,y) dx$
Conditional Probability	$f_{Y X=x}(y) = f_Y(y X=x) = \frac{f_{X,Y}(x,y)}{f_X(x)}$
X and Y are only independent if the following apply:	$f_{Y X=x}(y) = f_Y(y)$ resp. $f_{X Y=y}(x) = f_X(x)$
Conditional Expected Value of a continuous random variable Y given $X = x$	$E[Y X=x] = \int_{-\infty}^{\infty} y \cdot f_{Y X=x}(y) dy$
Example	
<p>Two machines with exponentially distributed life expectancy $X \sim \text{Exp}(\lambda_1)$ and $Y \sim \text{Exp}(\lambda_2)$, where X and Y are independent. $f_X(x) = \lambda_1 e^{-\lambda_1 x}$ and $f_Y(y) = \lambda_2 e^{-\lambda_2 y}$</p> 	<p>Due to independence: $f_{X,Y}(x,y) = \lambda_1 e^{-\lambda_1 x} \lambda_2 e^{-\lambda_2 y}$</p> $P(Y < X) = \int_0^{\infty} \left(\int_0^x \lambda_1 e^{-\lambda_1 x} \lambda_2 e^{-\lambda_2 y} dy \right) dx$ $P(Y < X) = \int_0^{\infty} \lambda_1 e^{-\lambda_1 x} (1 - e^{-\lambda_2 x}) dx = \frac{\lambda_2}{\lambda_1 + \lambda_2}$

2.3.2 Covariance and Correlation

Covariance and Correlation	
Covariance	$Cov(X,Y) = E[(X - \mu_X)(Y - \mu_Y)] = E[XY] - E[X]E[Y]$
X, Y independent	$E[XY] = E[X]E[Y]$
	$Cov(X,X) = E[(X - \mu_X)(X - \mu_X)] = E[(X - \mu_X)^2] = Var(X)$
Sum of Variances	$Var\left(\sum_{i=1}^n X_i\right) = Cov\left(\sum_{i=1}^n X_i, \sum_{i=1}^n X_i\right) = \sum_{i=1}^n Var(X_i) + 2 \sum_{i < j} Cov(X_i, X_j)$
2 Random Variables	$Var(X+Y) = Cov(X+Y, X+Y) = Var(X) + Var(Y) + 2Cov(X,Y)$
If all X_i are independent	$Var(X_1 + X_2 + \dots + X_n) = Var(X_1) + \dots + Var(X_n)$
Correlation	$Cor(X,Y) = \rho_{XY} = \frac{Cov(X,Y)}{\rho_X \rho_Y}$ where $-1 \leq Cor(X,Y) \leq 1$
Measure for strength and direction of the <i>linear dependency</i> between X and Y .	$Cor(X,Y) = +1$ if $Y = a + bX$ for $a \in \mathbb{R}$ and $b > 0$ $Cor(X,Y) = -1$ if $Y = a + bX$ for $a \in \mathbb{R}$ and $b < 0$

X and Y linear independent	$ Cor(X,Y) = 1$ means perfect linear relationship between X and Y.
	$Cor(X,Y) = 0$ means X and Y are uncorrelated.
	$Cor(X,Y) = 0$ (and thus $Cov(X,Y) = 0$)



If $Cor(X,Y) = 0$, then X and Y may still exhibit (non-linear) dependency.

Figure 5: Correlations

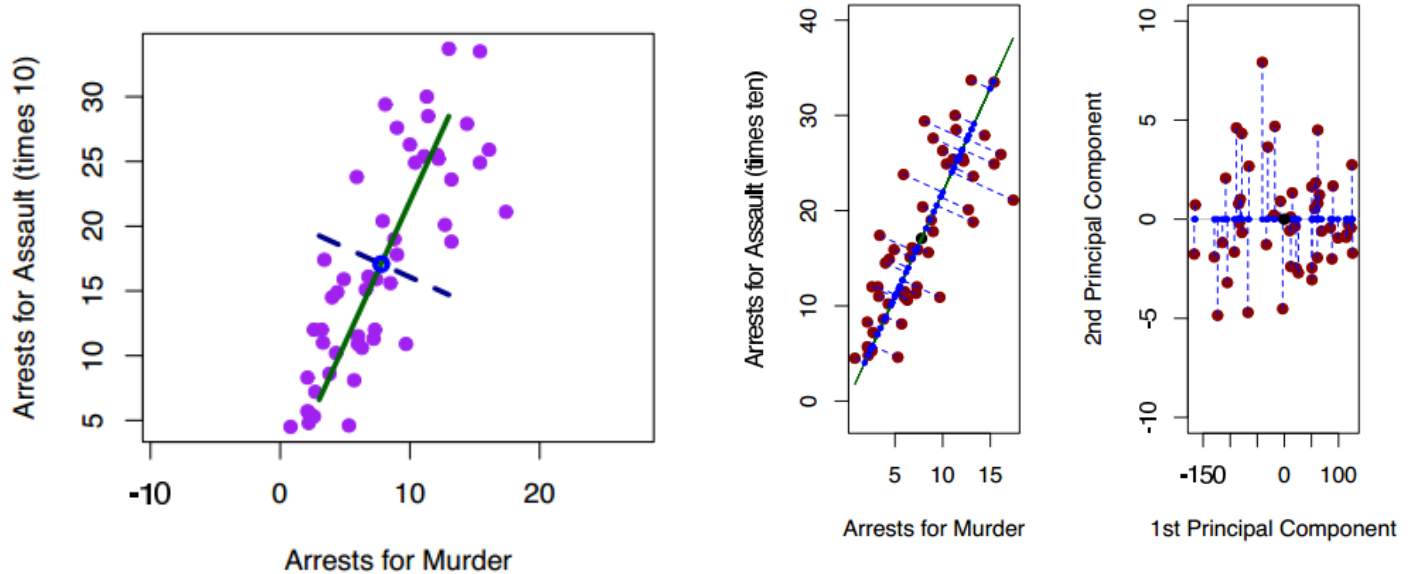
2.3.3 Bivariate Normal Distribution

Bivariate Normal Distribution	
Expected values and variances of the marginal distribution	μ_X, σ_X^2 and μ_Y, σ_Y^2
Covariance between X and Y	$Cov(X,Y) = \rho_{XY}\sigma_X\sigma_Y$
Joint Density	$f_{X,Y}(x,y) = \frac{1}{2\pi\sqrt{det(\Sigma)}}exp\left(-\frac{1}{2}(x-\mu_X,y-\mu_Y)\Sigma^{-1}\begin{pmatrix}x-\mu_X\\y-\mu_Y\end{pmatrix}\right)$
Covariance Matrix	$\Sigma = \begin{pmatrix}Cov(X,X) & Cov(X,Y)\\Cov(Y,X) & Cov(Y,Y)\end{pmatrix} = \begin{pmatrix}\sigma_X^2 & \rho_{XY}\sigma_X\sigma_Y\\ \rho_{XY}\sigma_X\sigma_Y & \sigma_Y^2\end{pmatrix}$

2.3.4 Principal Component Analysis (PCA)

PCA is a popular approach for deriving a low-dimensional set of features from a large set of variables. PCA is a technique for reducing the dimension of a $n \times p$ data matrix X where n corresponds to the number of observations and p to the number of variables.

2.3.4.1 Example: USArrests

Assault versus Murder Rate, US, 1973

(a) The data vary the most along the first principal component (b) Counter Clockwise Rotation that 1. PC coincides with x-axis

Figure 6: 1st and 2nd Principal Component

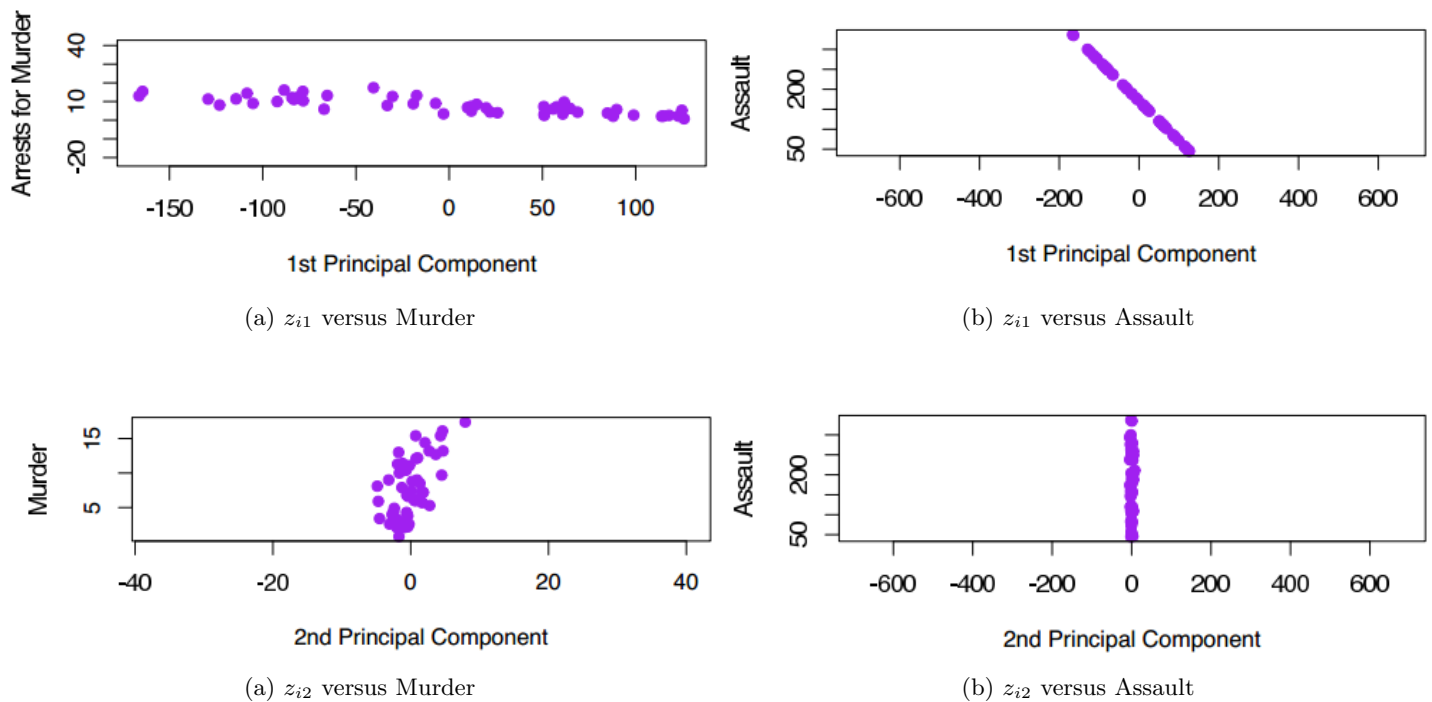


Figure 8: The fact that the 2nd principal component scores are much closer to zero indicates that this component captures far less information as the 1st principal component.

Theory	Code Example
$Z_1 = -0.0419126(\text{Murder} - \overline{\text{Murder}}) - 0.9991213(\text{Assault} - \overline{\text{Assault}})$ $\phi_{11} = -0.0419126$ and $\phi_{21} = -0.9991213$ are the <i>principal component loadings</i> The idea is that every that out of every linear combination of Murder and Assault sucht that $\phi_{11}^2 + \phi_{21}^2 = 1$ and $\text{Var}(\phi_{11})(\text{Murder} - \overline{\text{Murder}}) + \phi_{21}(\text{Assault} - \overline{\text{Assault}})$ is maximized. <code>prcomp()</code> centers the variables to have mean zero. This corresponds to how the first principal component is defined. $z_{i1} = -0.0419126(\text{Murder} - \overline{\text{Murder}}) - 0.9991213(\text{Assault} - \overline{\text{Assault}})$ The values of z_{i1}, \dots, z_{n1} are known as <i>principal component scores</i> , seen in the right-hand panel in Figure 6. $z_{i1} > 0$ indicates a state with below-average arrests for murder and below average for assault. A negative score suggests the opposite. $Z_2 = 0.9991213(\text{Murder} - \overline{\text{Murder}}) - 0.0419126(\text{Assault} - \overline{\text{Assault}})$	<pre> 1 #First principal component 2 pr.out <- prcomp(USArrests[,c("Murder", "Assault")]) 3 pr.out\$rotation[,1] 4 5 ## Murder Assault 6 ## -0.0419126 -0.9991213 7 8 #principal component scores (z_i1 to z_in) 9 pr.out <- prcomp(USArrests[,c("Murder", "Assault")]) 10 head(pr.out\$x) 11 12 ## PC1(z_i1) PC2(z_i2) 13 ## Alabama -65.40950 2.6728663 14 ## Alaska -92.25166 -1.6559620 15 ## Arizona -123.14478 -4.8535831 16 ## Arkansas -19.26551 0.2047123 17 ## California -105.19832 -3.1999471 18 ## Colorado -33.21549 -1.2812733 19 20 #Second principal component 21 pr.out <- prcomp(USArrests[,c("Murder", "Assault")]) 22 pr.out\$rotation[,2] 23 24 ## Murder Assault 25 ## 0.9991213 -0.0419126 </pre>

With two-dimensional data, such as in our USArrests example, we can construct at most two principal components. However, if we had other variables, such as Rape, then additional components could be constructed.

2.3.4.2 PCA and Covariance Matrix

The covariance matrix of two random variables X and Y is defined as

$$\Sigma = \begin{pmatrix} \text{Cov}(X, X) & \text{Cov}(X, Y) \\ \text{Cov}(Y, X) & \text{Cov}(Y, Y) \end{pmatrix} = \begin{pmatrix} \sigma_X^2 & \text{Cov}(X, Y) \\ \text{Cov}(Y, X) & \sigma_Y^2 \end{pmatrix}$$

Since Z_1 and Z_2 are required to be uncorrelated, this implies for their covariance matrix Σ to have vanishing off diagonal elements. Therefore the covariance has to be diagonalized. This can be done with by a rotation matrix Φ so that

$$\begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix} = (X - \mu_X, Y - \mu_Y) \begin{pmatrix} \phi_{11} & \phi_{12} \\ \phi_{21} & \phi_{22} \end{pmatrix} = \begin{pmatrix} \phi_{11}(X - \mu_X) & \phi_{12}(Y - \mu_Y) \\ \phi_{21}(X - \mu_X) & \phi_{22}(Y - \mu_Y) \end{pmatrix}$$

and

$$\begin{pmatrix} \text{Cov}(Z_1, Z_1) & \text{Cov}(Z_1, Z_2) \\ \text{Cov}(Z_2, Z_1) & \text{Cov}(Z_2, Z_2) \end{pmatrix} = \begin{pmatrix} \sigma_{Z_1}^2 & 0 \\ 0 & \sigma_{Z_2}^2 \end{pmatrix}$$

The rotation matrix Φ needs to satisfy the condition $\phi_{11}^2 + \phi_{21}^2 = 1$ and $\phi_{12}^2 + \phi_{22}^2 = 1$ It is straightforward to generalize the case of $p = 2$ to an arbitrary p .

2.3.4.3 Proportion of Variance Explained by Principal Components

Theory	Code Example
<p>There is an information loss of the given data by projecting the observations onto the first few principal components. Therefore we want to know the <i>proportion of variance explained (PVE)</i>. The <i>total variance</i> is defined as</p> $\sum_{j=1}^p \text{Var}(X_j) = \sum_{j=1}^p \frac{1}{n} \sum_{i=1}^n x_{ij}^2$ <p>and the variance of the mth principal component is</p> $\frac{1}{n} \sum_{i=1}^n z_{im}^2 = \frac{1}{n} \sum_{i=1}^n \left(\sum_{j=1}^p \phi_{jm} x_{ij} \right)^2$ <p>Therefore the PVE by the mth principal component is given by</p> $\frac{\sum_{i=1}^n \left(\sum_{j=1}^p \phi_{jm} x_{ij} \right)^2}{\sum_{j=1}^p \sum_{i=1}^n x_{ij}^2}$	<pre> 1 pr.out <- prcomp(USArrests[,c("Murder", "Assault")], scale=FALSE) 2 pr.var <- pr.out\$sdev^2 3 pve <- pr.var/sum(pr.var) 4 pve 5 6 7 ## [1] 0.9990292327 0.0009707673 8 9 ## Most of the information of the data about the arrests for Murder and Assault is contained in the first principal component. </pre>

3 Regression Analysis

3.1 Simple Linear Regression

TO DO: Chapter 5

...

3.1.1 Estimating the Coefficients

Theory	Code Example
<p>Estimation of response variable Y based on a predictor variable X.</p> $Y \simeq \beta_0 + \beta_1 X$	<pre> 1 lm(Y ~ X, data=someData) </pre>

Source code:	Output:
<pre> 1 advertising <- read.csv("../Data/Advertising.csv") 2 model <- lm(sales ~ TV, data=advertising) 3 summary(model) </pre>	<pre> 1 ## 2 ## Call: 3 ## lm(formula = sales ~ TV, data = Advertising) 4 ## 5 ## Residuals: 6 ## Min 1Q Median 3Q Max 7 ## -8.3860 -1.9545 -0.1913 2.0671 7.2124 8 ## 9 ## Coefficients: 10 ## Estimate Std. Error t value Pr(> t) 11 ## (Intercept) 7.032594 0.457843 15.36 <2e-16 ** 12 ## TV 0.047537 0.002691 17.67 <2e-16 *** 13 ## --- 14 ## Signif. codes: 15 ## 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 16 ## 17 ## Residual standard error: 3.259 on 198 degrees 18 ## of freedom 19 ## Multiple R-squared: 0.6119, Adjusted R-squared 20 ## : 0.6099 21 ## F-statistic: 312.1 on 1 and 198 DF, p-value: 22 ## < 2.2e-16 </pre>
Interpretation of output:	
TO DO: interpretation here	

3.2 Residual Analysis

TO DO: Chapter 6

3.3 Multiple Linear Regression

TO DO: Chapter 7

3.4 Linear Model Selection

TO DO: Chapter 8

4 Classification

4.1 Logistic Regression

TO DO: Chapter 10

4.2 Decision Trees

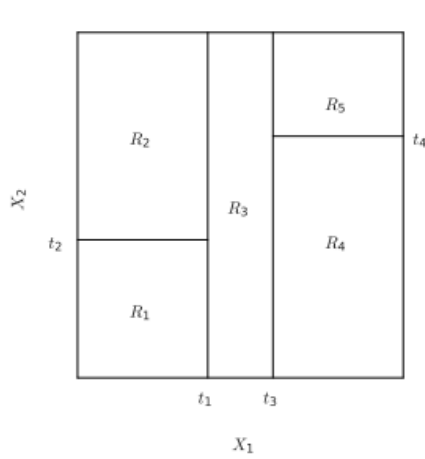
Decision trees are applied to both, classification and regression. TO DO: Chapter 11

4.2.1 Classification Trees

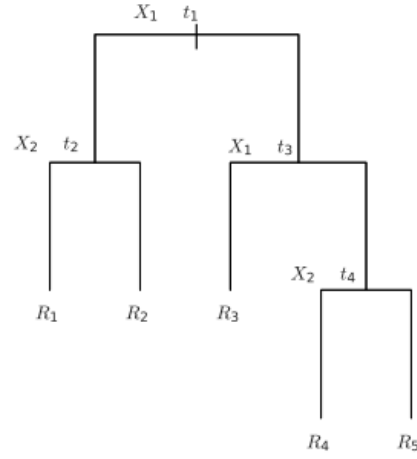
4.2.1.1 Binary Splitting

In binary splitting, a training set is used to split up the predictor domain into regions which contain data for which the response variable belongs to the same class. By **binary** it is meant that a region is split into **two** subregions (i.e. “is a predictor less or greater than a threshold value?” → yes/no).

Theory	Code Example
<p>Algorithm:</p> <ol style="list-style-type: none"> 1. Initialise the set of regions $\mathcal{R} = R$ by the predictor domain R 2. Choose the optimal region R in \mathcal{R} and the optimal predictor X_i such that a binary split of R with respect to X $R_1 = \{\vec{x} \in R x_i > t\} \quad \text{and} \quad R_2 = \{\vec{x} \in R x_i \leq t\}$ gives the highest gain in purity (for some threshold t). 3. Replace R in \mathcal{R} with R_1 and R_2 and return to 2. <p>The iteration is stopped if the current splitting fulfils a pre-defined stopping criterion.</p>	<pre> 1 require(tree) 2 #default controls 3 tc = tree.control(nobs = 303, mincut = 5, 4 minsize = 10, mindev = 0.01) 5 6 #grow tree 7 tree.model = tree(AHD~MaxHR+Age, data = heart, 8 control = tc) 9 10 #plot tree and label splits 11 plot(tree.model) 12 text(tree.model, cex=0.8) 13 14 #plot partition (only for two predictor case) 15 partition.tree(tree.model) 16 points(Age~MaxHR, data = heart, col = cols[label 17], pch=20) </pre>



(a) Example regions resulting from binary splitting



(b) Example decision tree resulting from binary splitting

4.2.1.2 Node Purity

Notation:

Variable	Description
Y	Response variable
K	Levels (categories) of the response variable
T	The decision tree
M	Amount of terminal nodes
\hat{p}_{mk}	proportion of the training data in region m from level k

Purity Measures:

Classification error rate	$E_m(T) = 1 - \max_k (\hat{p}_{mk})$
---------------------------	--------------------------------------

Gini index	$G_m(T) = \sum_{k=1}^K \hat{p}_{mk} \cdot (1 - \hat{p}_{mk})$
Cross-entropy	$D_m(T) = - \sum_{k=1}^K \hat{p}_{mk} \cdot \log(\hat{p}_{mk})$

Code example: Cross Entropy and Gini measures in R

```

1 require(tree)
2 # deviance or cross entropy
3 tree.model = tree(AHD~MaxHR+Age, data = heart, split = "deviance")
4 plot(tree.model)
5 text(tree.model, cex=0.8)
6 partition.tree(tree.model)
7 points(Age~MaxHR, data = heart, col = cols[label], pch=20)
8
9 # Gini index
10 tc = tree.control(303, mincut = 5, minsize = 60, mindev = 0.01)
11 tree.model = tree(AHD~MaxHR+Age, data = heart, split = "gini", control = tc)
12 plot(tree.model)
13 text(tree.model, cex=0.8)
14 partition.tree(tree.model)
15 points(Age~MaxHR, data = heart, col = cols[label], pch=20)

```

4.3 Random Forests

TO DO: Chapter 12

5 Time Series Analysis

5.1 Introduction to Time Series

TO DO: Chapter 13

5.2 Mathematical Models for Time Series

TO DO: Chapter 14

5.3 Forecasting ime Series

TO DO: Chapter 15

6 Idiotenseite

6.1 Dreiecksformeln

Cosinussatz

$$c^2 = a^2 + b^2 - 2 \cdot a \cdot b \cdot \cos \gamma$$

Sinussatz

$$\frac{a}{\sin \alpha} = \frac{b}{\sin \beta} = \frac{c}{\sin \gamma} = 2r = \frac{u}{\pi}$$

Pythagoras beim Sinus

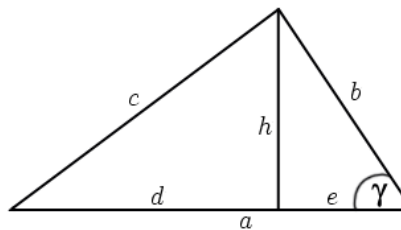
$$\sin^2(b) + \cos^2(b) = 1 \quad \tan(b) = \frac{\sin(b)}{\cos(b)}$$

$$\sin \beta = \frac{b}{a} = \frac{\text{Gegenkathete}}{\text{Hypotenuse}}$$

$$\cos \beta = \frac{c}{a} = \frac{\text{Ankathete}}{\text{Hypotenuse}}$$

$$\tan \beta = \frac{c}{b} = \frac{\text{Gegenkathete}}{\text{Ankathete}}$$

$$\cot \beta = \frac{c}{b} = \frac{\text{Ankathete}}{\text{Gegenkathete}}$$



6.2 Funktionswerte für Winkelargumente

deg	rad	sin	cos	tan	deg	rad	sin	cos	deg	rad	sin	cos	deg	rad	sin	cos
0°	0	0	1	0	90°	$\frac{\pi}{2}$	1	0	180°	π	0	-1	270°	$\frac{3\pi}{2}$	-1	0
30°	$\frac{\pi}{6}$	$\frac{1}{2}$	$\frac{\sqrt{3}}{2}$	$\frac{\sqrt{3}}{3}$	120°	$\frac{2\pi}{3}$	$\frac{\sqrt{3}}{2}$	$-\frac{1}{2}$	210°	$\frac{7\pi}{6}$	$-\frac{1}{2}$	$-\frac{\sqrt{3}}{2}$	300°	$\frac{5\pi}{3}$	$-\frac{\sqrt{3}}{2}$	$\frac{1}{2}$
45°	$\frac{\pi}{4}$	$\frac{\sqrt{2}}{2}$	$\frac{\sqrt{2}}{2}$	1	135°	$\frac{3\pi}{4}$	$\frac{\sqrt{2}}{2}$	$-\frac{\sqrt{2}}{2}$	225°	$\frac{5\pi}{4}$	$-\frac{\sqrt{2}}{2}$	$-\frac{\sqrt{2}}{2}$	315°	$\frac{7\pi}{4}$	$-\frac{\sqrt{2}}{2}$	$\frac{\sqrt{2}}{2}$
60°	$\frac{\pi}{3}$	$\frac{\sqrt{3}}{2}$	$\frac{1}{2}$	$\sqrt{3}$	150°	$\frac{5\pi}{6}$	$\frac{1}{2}$	$-\frac{\sqrt{3}}{2}$	240°	$\frac{4\pi}{3}$	$-\frac{\sqrt{3}}{2}$	$-\frac{1}{2}$	330°	$\frac{11\pi}{6}$	$-\frac{1}{2}$	$\frac{\sqrt{3}}{2}$

6.3 Periodizität

$$\cos(a + k \cdot 2\pi) = \cos(a) \quad \sin(a + k \cdot 2\pi) = \sin(a) \quad (k \in \mathbb{Z})$$

6.4 Quadrantenbeziehungen

$$\begin{aligned} \sin(-a) &= -\sin(a) & \cos(-a) &= \cos(a) \\ \sin(\pi - a) &= \sin(a) & \cos(\pi - a) &= -\cos(a) \\ \sin(\pi + a) &= -\sin(a) & \cos(\pi + a) &= -\cos(a) \\ \sin\left(\frac{\pi}{2} - a\right) &= \sin\left(\frac{\pi}{2} + a\right) = \cos(a) & \cos\left(\frac{\pi}{2} - a\right) &= -\cos\left(\frac{\pi}{2} + a\right) = \sin(a) \end{aligned}$$

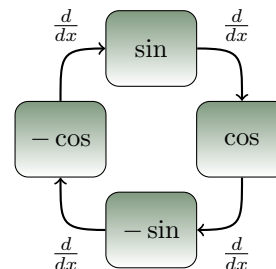
6.6 Additionstheoreme

$$\begin{aligned} \sin(a \pm b) &= \sin(a) \cdot \cos(b) \pm \cos(a) \cdot \sin(b) \\ \cos(a \pm b) &= \cos(a) \cdot \cos(b) \mp \sin(a) \cdot \sin(b) \\ \tan(a \pm b) &= \frac{\tan(a) \pm \tan(b)}{1 \mp \tan(a) \cdot \tan(b)} \end{aligned}$$

6.8 Produkte

$$\begin{aligned} \sin(a) \sin(b) &= \frac{1}{2}(\cos(a - b) - \cos(a + b)) \\ \cos(a) \cos(b) &= \frac{1}{2}(\cos(a - b) + \cos(a + b)) \\ \sin(a) \cos(b) &= \frac{1}{2}(\sin(a - b) + \sin(a + b)) \end{aligned}$$

6.5 Ableitungen



6.7 Doppel- und Halbwinkel

$$\begin{aligned} \sin(2a) &= 2 \sin(a) \cos(a) \\ \cos(2a) &= \cos^2(a) - \sin^2(a) = 2 \cos^2(a) - 1 = 1 - 2 \sin^2(a) \\ \cos^2\left(\frac{a}{2}\right) &= \frac{1 + \cos(a)}{2} \quad \sin^2\left(\frac{a}{2}\right) = \frac{1 - \cos(a)}{2} \end{aligned}$$

6.9 Euler-Formeln

$$\begin{aligned} \sin(x) &= \frac{1}{2j}(e^{jx} - e^{-jx}) & \cos(x) &= \frac{1}{2}(e^{jx} + e^{-jx}) \\ e^{x+jy} &= e^x \cdot e^{jy} = e^x \cdot (\cos(y) + j \sin(y)) \\ e^{j\pi} &= e^{-j\pi} = -1 \end{aligned}$$

6.10 Summe und Differenz

$$\begin{aligned}\sin(a) + \sin(b) &= 2 \cdot \sin\left(\frac{a+b}{2}\right) \cdot \cos\left(\frac{a-b}{2}\right) \\ \sin(a) - \sin(b) &= 2 \cdot \sin\left(\frac{a-b}{2}\right) \cdot \cos\left(\frac{a+b}{2}\right)\end{aligned}$$

$$\begin{aligned}\cos(a) + \cos(b) &= 2 \cdot \cos\left(\frac{a+b}{2}\right) \cdot \cos\left(\frac{a-b}{2}\right) \\ \cos(a) - \cos(b) &= -2 \cdot \sin\left(\frac{a+b}{2}\right) \cdot \sin\left(\frac{a-b}{2}\right) \\ \tan(a) \pm \tan(b) &= \frac{\sin(a \pm b)}{\cos(a) \cos(b)}\end{aligned}$$

6.12 Ableitungen elementarer Funktionen S436

Funktion	Ableitung	Funktion	Ableitung
C (Konstante)	0	$\sec x$	$\frac{\sin x}{\cos^2 x}$
x	1	$\sec^{-1} x$	$\frac{-\cos x}{\sin^2 x}$
x^n ($n \in \mathbb{R}$)	nx^{n-1}	$\arcsin x$ ($ x < 1$)	$\frac{1}{\sqrt{1-x^2}}$
$\frac{1}{x}$	$-\frac{1}{x^2}$	$\arccos x$ ($ x < 1$)	$-\frac{1}{\sqrt{1-x^2}}$
$\frac{1}{x^n}$	$-\frac{n}{x^{n+1}}$	$\arctan x$	$\frac{1}{1+x^2}$
\sqrt{x}	$\frac{1}{2\sqrt{x}}$	$\operatorname{arccot} x$	$-\frac{1}{1+x^2}$
$\sqrt[n]{x}$ ($n \in \mathbb{R}, n \neq 0, x > 0$)	$\frac{1}{n\sqrt[n]{x^{n-1}}}$	$\operatorname{arcsec} x$	$\frac{1}{x\sqrt{x^2-1}}$
e^x	e^x	$\operatorname{arccossec} x$	$-\frac{1}{x\sqrt{x^2-1}}$
e^{bx} ($b \in \mathbb{R}$)	be^{bx}	$\sinh x$	$\cosh x$
a^x ($a > 0$)	$a^x \ln a$	$\cosh x$	$\sinh x$
a^{bx} ($b \in \mathbb{R}, a > 0$)	$ba^{bx} \ln a$	$\tanh x$	$\frac{1}{\cosh^2 x}$
$\ln x$	$\frac{1}{x}$	$\coth x$ ($x \neq 0$)	$-\frac{1}{\sinh^2 x}$
$\log_a x$ ($a > 0, a \neq 1, x > 0$)	$\frac{1}{x} \log_a e = \frac{1}{x \ln a}$	$\operatorname{Arsinh} x$	$\frac{1}{\sqrt{1+x^2}}$
$\lg x$ ($x > 0$)	$\frac{1}{x} \lg e \approx \frac{0.4343}{x}$	$\operatorname{Arcosh} x$ ($x > 1$)	$\frac{1}{\sqrt{x^2-1}}$
$\sin x$	$\cos x$	$\operatorname{Artanh} x$ ($ x < 1$)	$\frac{1}{1-x^2}$
$\cos x$	$-\sin x$	$\operatorname{Arcoth} x$ ($ x > 1$)	$-\frac{1}{x^2-1}$
$\tan x$ ($x \neq (2k+1)\frac{\pi}{2}, k \in \mathbb{Z}$)	$\frac{1}{\cos^2 x} = \sec^2 x$	$[f(x)]^n$ ($n \in \mathbb{R}$)	$n[f(x)]^{n-1} f'(x)$
$\cot x$ ($x \neq k\pi, k \in \mathbb{Z}$)	$\frac{-1}{\sin^2 x} = -\operatorname{cosec}^2 x$	$\ln f(x)$ ($f(x) > 0$)	$\frac{f'(x)}{f(x)}$

6.11 Einige unbestimmte Integrale S1074

$\int dx = x + C$	$\int x^\alpha dx = \frac{x^{\alpha+1}}{\alpha+1} + C, x \in \mathbb{R}^+, \alpha \in \mathbb{R} \setminus \{-1\}$
$\int \frac{1}{x} dx = \ln x + C, x \neq 0$	$\int e^x dx = e^x + C$
$\int a^x dx = \frac{a^x}{\ln a} + C, a \in \mathbb{R}^+ \setminus \{1\}$	$\int \sin x dx = -\cos x + C$
$\int \cos x dx = \sin x + C$	$\int \frac{dx}{\sin^2 x} = -\cot x + C, x \neq k\pi \text{ mit } k \in \mathbb{Z}$
$\int \frac{dx}{\cos^2 x} = \tan x + C, x \neq \frac{\pi}{2} + k\pi \text{ mit } k \in \mathbb{Z}$	$\int \sinh x dx = \cosh x + C$
$\int \cosh x dx = \sinh x + C$	$\int \frac{dx}{\sinh^2 x} = -\coth x + C, x \neq 0$
$\int \frac{dx}{\cosh^2 x} = \tanh x + C$	$\int \frac{dx}{ax+b} = \frac{1}{a} \ln ax+b + C, a \neq 0, x \neq -\frac{b}{a}$
$\int \frac{dx}{a^2x^2+b^2} = \frac{1}{ab} \arctan \frac{b}{a}x + C, a \neq 0, b \neq 0$	$\int \frac{dx}{a^2x^2-b^2} = \frac{1}{2ab} \ln \left \frac{ax-b}{ax+b} \right + C, a \neq 0, b \neq 0, x \neq \pm \frac{b}{a}$
$\int \sqrt{a^2x^2+b^2} dx = \frac{x}{2} \sqrt{a^2x^2+b^2} + \frac{b^2}{2a} \ln(ax + \sqrt{a^2x^2+b^2}) + C, a \neq 0, b \neq 0$	$\int \sqrt{a^2x^2-b^2} dx = \frac{x}{2} \sqrt{a^2x^2-b^2} - \frac{b^2}{2a} \ln ax + \sqrt{a^2x^2-b^2} + C, a \neq 0, b \neq 0, a^2x^2 \geq b^2$
$\int \sqrt{b^2-a^2x^2} dx = \frac{x}{2} \sqrt{b^2-a^2x^2} + \frac{b^2}{2a} \arcsin \frac{a}{b}x + C, a \neq 0, b \neq 0, a^2x^2 \leq b^2$	$\int \frac{dx}{\sqrt{a^2x^2-b^2}} = \frac{1}{a} \ln(ax + \sqrt{a^2x^2+b^2}) + C, a \neq 0, b \neq 0$
$\int \frac{dx}{\sqrt{a^2x^2-b^2}} = \frac{1}{a} \ln ax + \sqrt{a^2x^2-b^2} + C, a \neq 0, b \neq 0, a^2x^2 > b^2$	$\int \frac{dx}{\sqrt{b^2-a^2x^2}} = \frac{1}{a} \arcsin \frac{a}{b}x + C, a \neq 0, b \neq 0, a^2x^2 < b^2$
Die Integrale $\int \frac{dx}{X}, \int \sqrt{X} dx, \int \frac{dx}{\sqrt{X}}$ mit $X = ax^2 + 2bx + c, a \neq 0$ werden durch die Umformung $X = a(x + \frac{b}{a})^2 + (c - \frac{b^2}{a})$ und die Substitution $t = x + \frac{b}{a}$ in die oberen 4 Zeilen transformiert.	$\int \frac{x dx}{X} = \frac{1}{2a} \ln X - \frac{b}{a} \int \frac{dx}{X}, a \neq 0, X = ax^2 + 2bx + c$
$\int \sin^2 ax dx = \frac{x}{2} - \frac{1}{4a} \cdot \sin 2ax + C, a \neq 0$	$\int \cos^2 ax dx = \frac{x}{2} + \frac{1}{4a} \cdot \sin 2ax + C, a \neq 0$
$\int \sin^n ax dx = -\frac{\sin^{n-1} ax \cos ax}{na} + \frac{n-1}{n} \int \sin^{n-2} ax dx, n \in \mathbb{N}, a \neq 0$	$\int \cos^n ax dx = \frac{\cos^{n-1} ax \sin ax}{na} + \frac{n-1}{n} \int \cos^{n-2} ax dx, n \in \mathbb{N}, a \neq 0$
$\int \frac{dx}{\sin ax} = \frac{1}{a} \ln \left \tan \frac{ax}{2} \right + C, a \neq 0, x \neq k\frac{\pi}{a} \text{ mit } k \in \mathbb{Z}$	$\int \frac{dx}{\cos ax} = \frac{1}{a} \ln \left \tan \left(\frac{ax}{2} + \frac{\pi}{4} \right) \right + C, a \neq 0, x \neq \frac{\pi}{2a} + k\frac{\pi}{a} \text{ mit } k \in \mathbb{Z}$
$\int \tan ax dx = -\frac{1}{a} \ln \cos ax + C, a \neq 0, x \neq \frac{\pi}{2a} + k\frac{\pi}{a} \text{ mit } k \in \mathbb{Z}$	$\int \cot ax dx = \frac{1}{a} \ln \sin ax + C, a \neq 0, x \neq k\frac{\pi}{a} \text{ mit } k \in \mathbb{Z}$
$\int x^n \sin ax dx = -\frac{x^n}{a} \cos ax + \frac{n}{a} \int x^{n-1} \cos ax dx, n \in \mathbb{N}, a \neq 0$	$\int x^n \cos ax dx = \frac{x^n}{a} \sin ax - \frac{n}{a} \int x^{n-1} \sin ax dx, n \in \mathbb{N}, a \neq 0$
$\int x^n e^{ax} dx = \frac{1}{a} x^n e^{ax} - \frac{n}{a} \int x^{n-1} e^{ax} dx, n \in \mathbb{N}, a \neq 0$	$\int e^{ax} \sin bx dx = \frac{e^{ax}}{a^2+b^2} (a \sin bx - b \cos bx) + C, a \neq 0, b \neq 0$
$\int e^{ax} \cos bx dx = \frac{e^{ax}}{a^2+b^2} (a \cos bx + b \sin bx) + C, a \neq 0, b \neq 0$	$\int \ln x dx = x(\ln x - 1) + C, x \in \mathbb{R}^+$
$\int x^\alpha \cdot \ln x dx = \frac{x^{\alpha+1}}{(\alpha+1)^2} [(\alpha+1) \ln x - 1] + C, x \in \mathbb{R}^+, \alpha \in \mathbb{R} \setminus \{-1\}$	