

Chapter 13

Anova and Elements of Statistical Design

*****anova.tex*****

In chapter 5 we introduced procedures for comparing means of two populations. However many real life experiments involve more than two populations. For example, an experimenter may be interested in comparing the test scores of students taught by several different methods.

At first glance it seems that we can apply t -test on all possible pairs of means. This “solution” would not be good since the probability of the error of first type for such procedure is unduly large.

The appropriate procedure for testing hypotheses of equality of several means is analysis of variances (ANOVA). ANOVA is probably one of the most frequently used statistical procedures and its reasoning is applicable in many other seemingly different problems.

The rationale of ANOVA is very simple. The variability between sample means is compared to the variability within the populations.

13.1 One-way analysis of variance

Suppose we are interested in testing the equality of means μ_1, \dots, μ_k belonging to the populations $\mathcal{P}_1, \dots, \mathcal{P}_k$. From the i th population \mathcal{P}_i we take a sample

$$y_{i1}, y_{i2}, \dots, y_{in_i},$$

of size n_i . We model y_{ij} as

$$y_{ij} = \mu_i + \epsilon_{ij}, \quad 1 \leq i \leq k, \quad 1 \leq j \leq n_i. \quad (13.1)$$

The assumptions underlying the one-way ANOVA are the following:

- (i) All populations are assumed to be normal;
- (ii) The variance in all populations is the same;
- (iii) different samples are independent;

That can be expressed by the requirement that all ϵ_{ij} in (13.1) are iid $N(0, \sigma^2)$.

		Population			
		1	2	...	k
Population Means	Population	μ_1	μ_2	...	μ_k
	Common Standard Deviation	σ	σ	...	σ

If the sample sizes are the same, i.e. $n_1 = n_2 = \dots = n_k$, then the ANOVA is called balanced. It is often the case that many experiments are designed as balanced ANOVA. During the treatment it may happen that experimental unit is lost, leading to the unbalanced case.

In terms of the model (13.1) the null hypothesis is

$$H_0 : \mu_1 = \mu_2 = \dots = \mu_k, \quad (13.2)$$

And the alternative is

$$H_1 : (H_0)^c \quad (\text{or} \quad \mu_i \neq \mu_j, \text{ for at least one pair } i, j. \quad (13.3)$$

One can parameterize the means μ_i as $\mu_i = \mu + \tau_i$. An alternative (and sometimes preferred) form of the hypothesis H_0 is:

$$H_0 : \tau_1 = \tau_2 = \dots = \tau_k = 0 \quad (13.4)$$

The alternative is H_1 : Not all τ_i s are equal to 0, of course.

The parameter μ is called *the grand mean* and $\mu = \frac{1}{k} \sum_{i=1}^k \mu_i$, and τ_i is the *effect of i-th population (treatment)*. We also assume that $\sum \tau_i = 0$, for balanced designs. It is needed to ensure uniqueness of the decomposition $\mu_i = \mu + \tau_i$. For unbalanced designs the condition is more complicated.

Fundamental ANOVA Identity

$$\sum_{i=1}^k \sum_{j=1}^n (y_{ij} - \bar{y})^2 = n \sum_{i=1}^k (\bar{y}_i - \bar{y})^2 + \sum_{i=1}^k \sum_{j=1}^n (y_{ij} - \bar{y}_i)^2. \quad (13.5)$$

SST = SSTR + SSE.

Why ANOVA when we are dealing with means?

Test the homogeneity of variances first!

There are several procedures that test for fulfillment of the ANOVA condition of homoscedascity. A reasonably sensitive and simple test is Cochran's test applicable if the design is balanced.

Reject hypotheses that k populations have the same mean if $G = \frac{s_{max}^2}{s_1^2 + \dots + s_k^2}$ is large. The table below gives the critical values for $\alpha = 0.05$ and n sample size in balanced design.

$\nu = n - 1$	1	2	3	4	5	6	7	10	36	144
k	0.9985	0.9750	0.9392	0.9057	0.8772	0.8534	0.8332	0.7880	0.6602	0.5813
	0.9669	0.8709	0.7977	0.7457	0.7071	0.6771	0.6530	0.6025	0.4748	0.4031
	0.9065	0.7679	0.6841	0.6287	0.5896	0.5598	0.5365	0.4884	0.3720	0.3093

4. Effects of THC on Activity in Rats. The nucleus accumbent is a forebrain structure that has been shown to be involved in locomotor activity in rats. Systemic administrations of low doses of tetrahydrocannabinol (THC, the major active ingredient in marijuana) is known to increase locomotor activity, whereas high doses lead to a decrease in activity. In an attempt to examine whether THC is acting within the nucleus accumbens to produce its effects on activity, Conti and Musty (1984) bilaterally injected either a placebo, or 0.1, 0.5, 1, or 2 micrograms (μg) of THC into the nucleus accumbens of rats. The investigators recorded the activity level of animals before and after the injection. Activity was recorded by placing the animal in a test chamber and suspending the chamber on rubber mounts. The vibrations of the chamber as the animal moved around were transduced by an accelerometer and converted to activity units, which were read off a meter. These units, then, were arbitrary, a point that will become relevant when we consider transformations. Conti and Musty took as their dependent variable the rat's activity for 10 minutes after the injection as a proportion of the rat's activity in the 10 minutes before the injection. Since animals generally decrease their activity as they become accustomed to an apparatus, most ratios were less than 1. However, it was expected that those rats with intermediate levels of THC would decrease their activity less (exhibit a higher postinjection \div preinjection ratio) than would those with either low or high levels. (Intermediate levels were expected to lead to the greatest activity, because very low doses should be insufficient to produce an effect and high doses should lead to decreases in activity.)

	Control	0.1 μ g	0.5 μ g	1 μ g	2 μ g	All Groups
	30	60	71	33	36	
	27	42	50	78	27	
	52	48	38	71	60	
	38	52	59	58	51	
	20	28	65	35	29	
	26	93	58	35	29	
	8	32	74	46	24	
	41	46	67	32	17	
	49	63	61		50	
	49	44			53	
Total	340	508	543	388	381	2160
Mean	34.00	50.80	60.33	48.50	38.10	45.96
S.D.	14.30	18.39	11.07	18.32	14.46	17.62
n	10	10	9	8	10	47

4. Animal diet. In 1968, Koch and Sen ('Some aspects of the statistical analysis of the mixed model', *Biometrics*, 24, 27-48), examined the results of experiments undertaken at the Department of Pathology, Duke University Medical Centre, North Carolina by Dr N. Kaufmann and Dr J. V. Klavins. In one of their experiments, 16 animals were randomly placed into one of two groups - an experimental group which received ethionine in their diets, and a control group. The liver of each animal was divided into two parts, one of which was treated with radioactive iron and oxygen, and the other with radioactive iron and nitrogen. The data consist of the amount of iron absorbed by the variously treated liver portions; in the table the treatments are denoted by EO (ethionine-oxygen), EN (ethionine- nitrogen), CO (control-oxygen) and CN (control-nitrogen).

Pair	EO	EN	CO	CN
1	38.43	31.47	36.09	32.53
2	36.09	29.89	34.01	27.73
3	34.49	34.50	36.54	29.51
4	37.44	38.86	39.87	33.03
5	35.53	32.69	33.38	29.88
6	32.35	32.69	36.07	29.29
7	31.54	31.89	35.88	31.53
8	33.37	33.26	34.17	30.16

Analyze these data to see whether there are significant differences in the amounts of iron absorbed in livers subjected to the four treatments.

Sol.

ANALYSIS OF VARIANCE ON C5

SOURCE	DF	SS	MS	F	P
C6	3	131.19	43.73	8.62	0.000
ERROR	28	142.09	5.07		
TOTAL	31	273.28			

NBA Players. In the 1993 basketball players in the NBA from the four ACC schools were analyzed: Duke, North Carolina, North Carolina State, and Georgia Tech. Below are their 1993 season's PPG (points per game).

	Duke	UNC	NCSU	GT
	7.5	5.5	16.9	7.9
	8.7	6.2	4.5	7.8
	7.1	13.0	10.5	14.5
	18.2	9.7	4.4	6.1
		12.9	4.6	4.0
		5.9	18.7	14.0
		1.9	8.7	
			15.8	

Formulate the question.

[Ans. $F = 0.41$. H_0 not rejected. Basketball players from these four schools are likely to score equal amounts regardless where they attended college.]

Insects. Some colors are more attractive to insects than others. In an experiment aimed at determining the best color for attracting cereal leaf beetles, six boards in each of four colors were placed in a field of oats in July. The following table gives data on the number of cereal leaf beetles trapped. (Modified from M. C. Wilson and R. E. Shadé, "Relative attractiveness of various luminescent colors to the cereal leaf beetle and the meadow spittle-bug," *Journal of Economic Entomology*, 60 (1967), pp. 578-580.)

Board color	Insects trapped					
Lemon Yellow	45	59	48	46	38	47
White	21	12	14	17	13	17
Green	37	32	15	25	39	41
Blue	16	11	20	21	14	7

(a) Make a plot of the counts of insects trapped against board color (space the four colors equally on the horizontal axis). Compute the mean count for each color, add the means to your plot, and connect the means with line segments.
(b) Based on the data, state your conclusions about the attractiveness of these colors to the beetles.
(c) Does it make sense to speak of a positive or negative association between board color and insect count?

```
> yellow_scan()
1: 45 59 48 46 38 47
7:
> white_scan()
1: 21 12 14 17 13 17
7:
> green_scan()
1: 37 32 15 25 39 41
7:
> blue_scan()
1: 16 11 20 21 14 7
7:
> data_cbind(yellow, white, green, blue)
> data
     yellow white green blue
[1,]    45    21    37    16
[2,]    59    12    32    11
[3,]    48    14    15    20
[4,]    46    17    25    21
[5,]    38    13    39    14
[6,]    47    17    41     7

> Anova(data,r=2)

  Source  SS      df      MS      F      p
  -----
  Treat   4218.46  3      1406.15  30.55   0
  Error   920.5    20     46.02
  Total   5138.96  23
  -----
  RootMSE= 6.78      R-squared= 0.82
  -----
```

Nematodes. Some varieties of nematodes (roundworms that live in the soil and are frequently so small they are invisible to the naked eye) feed on the roots of lawn grasses and crops such as strawberries and tomatoes. This pest, which is particularly troublesome in warm climates, can be treated by the application of nematocides. However, because of size of the worms, it is very difficult to measure the effectiveness of these pesticides directly. To compare four nematocides, the yields of equal-size plots of one variety of tomatoes were collected. The data (yields in pounds per plot) are shown in the table.

Nematocide A	Nematocide B	Nematocide C	Nematocide D
18.6	18.7	19.4	19.0
18.4	19.0	18.9	18.8
18.4	18.9	19.5	18.6
18.5	18.5	19.1	18.7
17.9		18.5	

One-way ANOVA was run and MINITAB output is given below.

ANALYSIS OF VARIANCE ON YIELD

SOURCE	DF	SS	MS	F	P
BRAND	3	1.3094	0.4365	5.20	0.013
ERROR	14	1.1750	0.0839		
TOTAL	17	2.4844			

INDIVIDUAL 95 PCT CI'S FOR MEAN
BASED ON POOLED STDEV

LEVEL	N	MEAN	STDEV	-----+-----+-----+-----+-----+-----
1	5	18.360	0.270	(-----*-----)
2	4	18.775	0.222	(-----*-----)
3	5	19.080	0.402	(-----*-----)
4	4	18.775	0.171	(-----*-----)

-----+-----+-----+-----+-----+-----

POOLED STDEV = 0.290 18.20 18.55 18.90 19.25

- (a) Write a statistical model for ANOVA and state H_0 and H_1 in terms of your model.
- (b) What is your decision if $\alpha = 0.05$?
- (c) For what values of α your decision will be different than that in (b)?

Maternal behavior in rats. To investigate maternal behavior of laboratory rats, researchers separated the rat pup from the mother and record the time required for the mother to retrieve the pup. The study was run with 5, 20 and 35 day old pups, six in each group. The pups were moved to a fixed distance from the mother and the time of retrieval (in seconds) was recorded.

5 days	15	10	25	15	20	18
20 days	30	15	20	25	23	20
35 days	40	35	50	43	45	40

Run a One-way ANOVA on the data and state your conclusions.

Density of bricks. An experiment was run to determine whether four specific firing temperatures affect the density of a certain type of brick. The experiment led to the following data.

Temperature	Density					
100	21.8	21.9	21.7	21.7	21.6	21.7
125	21.7	21.4	21.5	21.4		
150	21.9	21.8	21.8	21.8	21.6	21.5
175	21.9	21.7	21.8	21.4		

(a) Does the firing temperature affect the density of the bricks?
 (b) Compare the means using Duncan's multiple range test.

Chemist. A chemist wishes to test the effect of four chemical agents on the strength of a particular type of cloth. Because there might be variability from one bolt to another, the chemist decides to use a randomized block design, with the bolts of cloth considered as blocks. She selects five bolts and applies all four chemicals in random order to each bolt. The resulting tensile strengths follow. Analyze the data and draw appropriate conclusions.

Chemical	Bolt				
	1	2	3	4	5
1	73	68	74	71	67
2	73	67	75	72	70
3	75	68	78	73	68
4	73	71	75	75	69

Oscilloscope. An experiment is conducted to study the influence of operating temperature and three types of face-plate glass in the light output of an oscilloscope tube. The following data are collected.

Glass Type	Temperature		
	100	125	150
1	580	1090	1392
	568	1087	1380
	570	1085	1386
2	550	1070	1328
	530	1035	1312
	579	1000	1299
3	546	1045	867
	575	1053	904
	599	1066	889

Fertilizer. It has been shown that the fertilizer magnesium ammonium phosphate, $MgNH_4PO_4$, is an effective supplier of the nutrients necessary for plant growth. The compounds supplied by this fertilizer are highly soluble in water, allowing the fertilizer to be applied directly on the soil surface or mixed with the growth substrate during the potting process. A study on the "Effect of Magnesium Ammonium Phosphate on Height of Chrysanthemums" was conducted at George Mason University in 1980 to determine a possible optimum level of fertilization, based on the enhanced vertical growth response of the chrysanthemums. Forty chrysanthemums seedlings were divided into 4 groups each containing 10 plants. Each was planted in a similar pot containing a uniform growth medium. To each group of plants an increasing concentration of $MgNH_4PO_4$, measured in grams per bushel, was added. The 4 groups of plants were grown under uniform conditions in a greenhouse for a period of four weeks. The treatments and the respective changes in heights, measured in centimeters, are shown in the following table:

Treatment			
50 gm/bu	100 gm/bu	200 gm/bu	400 gm/bu
13.2	16.0	7.8	21.0
12.4	12.6	14.4	14.8
12.8	14.8	20.0	19.1
17.2	13.0	15.8	15.8
13.0	14.0	17.0	18.0
14.0	23.6	27.0	26.0
14.2	14.0	19.6	21.1
21.6	17.0	18.0	22.0
15.0	22.2	20.2	25.0
20.0	24.4	23.2	18.2

can we conclude at the 0.05 level of significance that different concentration of $MgNH_4PO_4$, affect the average attained height of chrysanthemums?

Repeated measures design. Seven patients each underwent three different methods of kidney dialysis (Daugirdas, 1982). The following values were obtained for weight change in kilograms between dialysis sessions:

Patient	Treatment 1	Treatment 2	Treatment 3
1	2.90	2.97	2.67
2	2.56	2.45	2.62
3	2.88	2.76	1.84
4	2.73	2.20	2.33
5	2.50	2.16	1.27
6	3.18	2.89	2.39
7	2.83	2.87	2.39

(i) Test the null hypothesis that there is no difference in mean weight change among treatments.

13.2 SPLUS program

Explanation of the program and use

Sharp Willies. After loosing the contract with Sherwood Rascals, Sharp Willie, an arrow producing enterprise, has sent a number of employees to four educational institutions for technical training. The company hoped that the training would improve employee productivity and product quality. At the end of program Sharp Willie tested 40 graduates. The scores are:

Program A:	95 88 90 99 89 93 95 97 85 90
Program B:	92 88 80 75 67 78 92 80 77 69
Program C:	85 81 86 91 78 81 86 90 75 83
Program D:	98 65 74 82 90 62 75 85 70 82

Fill-in the ANOVA table and test that all programs are the same at $\alpha = 1\%$.

```
Analysis of variance on score
Source      SS      df      MS      F
program      382.3
error
total      3367.9
```

Elasticity of Billiard Balls. The billiard balls are made under three different conditions: Ten batches of melted plastic were prepared.(These are 10 blocks of material.) Each batch is divided into 3 equal portions. One portion was chosen at random and set aside as a control. The second portion was chosen at random from the remaining two, and was mixed with additive A. The third portion was mixed with additive B. In this way, the experimenters hoped to balance out any variations in the plastic from batch to batch. Elasticity was measured on a scale from 0 to 100, with higher number representing greater elasticity (desirable property).

Batch	Control	Additive A	Additive B
1	51	75	39
2	45	89	43
3	49	73	51
4	66	84	34
5	53	66	54
6	41	85	43
7	58	73	42
8	56	71	37
9	60	78	37
10	63	65	44

Source	DF	SS	MS	F	P
batch	9	82.30	9.14	0.12	0.999
additive	2	5654.87	2827.43	36.62	0.000
Error	18	1389.80	77.21		
Total	29	7126.97			

```

> Anova <-
function(data, factors = "Treat", repeat = "Error", r = 3)
{
  out <- list()
  out$means <- apply(data, 2, mean.na)
  out$data <- data
  out$fit <- matrix(out$means, nrow = dim(data)[1], ncol = dim(data)[2],
                     byrow = T, dimnames = dimnames(data))
  out$fit <- out$fit + 0 * data
  out$res <- data - out$fit
  out$grand <- mean.na(data)
  out$ngroup <- apply(!is.na(data), 2, sum)
  out$sstr <- sum.na((out$fit - out$grand)^2)
  out$sse <- sum.na(out$res^2)
  out$sst <- sum.na((data - out$grand)^2)
  out$dftr <- (dim(data)[2] - 1)
  out$dfe <- (sum(!is.na(data)) - dim(data)[2])
  out$dft <- sum(!is.na(data)) - 1
  out$mstr <- out$sstr/out$dftr
  out$mse <- out$sse/out$dfe
  out$F <- out$mstr/out$mse
  out$p <- 1 - pf(out$F, out$dftr, out$dfe)
  cat("\n-----\n")
  cat("Source", "SS", "df", "MS", "F", "p", sep = "\t")
  cat("\n-----\n")
  cat(factors, round(out$sstr, r), round(out$dftr, r), round(out$mstr, r),
      round(out$F, r), round(out$p, r + 1), "\n", sep = "\t")
  cat(repeat, round(out$sse, r), round(out$dfe, r), round(out$mse, r),
      "\n", sep = "\t")
  cat("Total", round(out$sst, r), round(out$dft, r), "\n", sep = "\t")
  cat("-----\n")
  cat("RootMSE=", round(sqrt(out$mse), r), "\t R-squared=", round(out$sstr/out$sst, r), "\n")
  cat("-----\n")
  invisible(out)
}

```

13.2.1 Scheffe's method for comparison of contrasts

In ANOVA only testable linear combinations of means are contrasts. That means that only hypotheses of the form $H_0 : \sum c_i \mu_i = 0$ can be tested, where $\underline{c} = (c_1, \dots, c_a)$ is a vector that satisfies $\sum_{i=1}^a n_i c_i = 0$, for n_i being the cell sample sizes. If the design is balanced, i.e. $n_1 = n_2 = \dots = n_a$ then the requirement for \underline{c} is $\sum c_i = 0$.

For a balanced ANOVA with $a = 5$ the following linear combinations are contrasts.

Hypothesis H_0	Linear Combination	Vector \underline{c}
$\mu_1 = \mu_3$	$\mu_1 - \mu_3 = 0$	$(1, 0, -1, 0, 0)$
$\mu_1 + \mu_2 = \mu_3 + \mu_4$	$\mu_1 + \mu_2 - \mu_3 - \mu_4 = 0$	$(1, 1, -1, -1, 0)$
$\mu_1 = \frac{\mu_4 + \mu_5}{2}$	$\mu_1 - \frac{1}{2}\mu_4 - \frac{1}{2}\mu_5 = 0$	$(1, 0, 0, -\frac{1}{2}, -\frac{1}{2})$

```

#First Version of Scheffe
> Scheffe
function(data, contrast, alpha = 0.05, r = 3)
{
  means <- apply(data, 2, mean.na)
  fit <- matrix(means, nrow = dim(data)[1], ncol = dim(data)[2], byrow =
    T, dimnames = dimnames(data))
  fit <- fit + 0 * data
  res <- data - fit
  ngroup <- apply(!is.na(data), 2, sum)
  if((contrast %*% ngroup)[1, 1] != 0)
    stop("The contrast is", " untestable for this design.", (
      contrast %*% ngroup)[1, 1])
  sse <- sum.na(res^2)
  dfe <- (sum(!is.na(data)) - dim(data)[2])
  mse <- sse/dfe
  Cu <- (contrast %*% means)[1, 1]
  SCu <- sqrt(mse * sum(contrast^2/ngroup))
  Salp <- SCu * sqrt((dim(data)[2] - 1) * qf(1 - alpha, dim(data)[2] - 1,
    dfe))
  cat("\n Cu=", round(Cu, r), " SCu=", round(SCu, r), " Salp=", round(
    Salp, r), "\n")
  cat("\n", 100 * (1 - alpha), "% confidence interval is:(", round(Cu -
    Salp, r), ",", round(Cu + Salp, r), ")\n")
  if(abs(Cu) < Salp) {
    cat("\n The contrast is tested to be 0 at the level", alpha,
      "\n")
  }
  else {
    cat("\n The contrast is tested not to be 0 at the level", alpha,
      "\n")
  }
}
>

```

Notation in the S-plus program:

$$Cu = c_1 \bar{y}_1 + \Phi c_2 \bar{y}_2 + \dots + c_a \bar{y}_a.$$

$$SCu = \sqrt{MSE \sum_{i=1}^a (c_i^2/n_i)}, \text{ where } n_i \text{ are cell sample sizes.}$$

$$Salp = SCu \sqrt{(a-1) F_{a-1, N-a, \alpha}}$$

The Tensile Strength. The tensile strength of synthetic fiber used to make cloth for men's shirts is of interest to manufacturer. It is suspected that the strength is affected by the percentage of cotton in the fiber. Five levels of cotton percentage are of interest, 15 percent, 20 percent, 25 percent, 30 percent, and 35 percent. Five observations are taken at each level of cotton percentage. The table below describes measurements.

	15 %	20 %	25 %	30 %	35 %
obs 1	7	12	14	19	7
obs 2	7	17	18	25	10
obs 3	15	12	18	22	11
obs 4	11	18	19	19	15
obs 5	9	18	19	23	11

The ANOVA for the problem is

Source	SS	df	MS	F	P
Treat	475.76	4	118.94	14.757	0
Error	161.2	20	8.06		

Total 636.96 24

RootMSE= 2.839 R-squared= 0.747

Test the hypothesis $H_0 : \mu_1 + \mu_3 = \mu_4 + \mu_5$. at the level $\alpha = 0.01$.

```
> data
  15 % 20 % 25 % 30 % 35 %
obs 1    7   12   14   19    7
obs 2    7   17   18   25   10
obs 3   15   12   18   22   11
obs 4   11   18   19   19   15
obs 5    9   18   19   23   11

> Scheffe(data, c(1,0,1,-1,-1), alpha=0.01)

Cu= -5  SCu= 2.539  Salp= 10.69

99 % confidence interval is:( -15.69 , 5.69 )

The contrast is tested to be 0 at the level 0.01
```

1. **Beetles.** The following data were extracted from the more extensive study by Sokal and Karten¹ The data represent mean dry weights (in mg) of three genotypes of beetles, *Tribolium castaneum*, reared at density of 20 beetles per gram of flour. The four series of experiments represent replications.

Series	Genotypes		
	++	+b	bb
1	0.958	0.986	0.925
2	0.971	1.051	0.952
3	0.927	0.891	0.829
4	0.971	1.010	0.955

1. Test whether the genotypes differ in mean dry weight. Take $\alpha = 0.01$.

The following partial ANOVA table may be useful for the test.

Source	SS	df	MS	F	P
Geno	0.01	2	-----	-----	-----
Error	0.026	9	-----	-----	-----
Total	0.035	11			

2. What assumptions are needed for ANOVA?

Beetles. The following data were extracted from the more extensive study by Sokal and Karten² The data represent mean dry weights (in mg) of three genotypes of beetles, *Tribolium castaneum*, reared at density of 20 beetles per gram of flour. The four series of experiments represent replications.

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	++	+b	bb
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¹Sokal, R. and Karten, I. (1964). Competition among genotypes in *Tribolium castaneum* at varying densities and gene frequencies (the black locus). *Genetics*, **49** 195-211.

²Sokal, R. and Karten, I. (1964). Competition among genotypes in *Tribolium castaneum* at varying densities and gene frequencies (the black locus). *Genetics*, **49** 195-211.

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Geno	0.01	2	-----	-----	-----
Error	0.026	9	-----		
Total	0.035	11			

2. What assumptions are needed for ANOVA?

Bees. The data for this problem are taken from Park (1932)³ who investigated changes in the concentration of nectar in the honey sac of the bee. Syrup of approximately 40% concentration was fed to the bees. The concentration in their honey sacs was determined upon their arrival at the hive. The decreases recorded in the table are classified according to date, both day (September, 1931) and time of day being differentiated. The question to be answered is this: Were significant differences introduced by changes in the time of gathering the data, or may the six groups be considered random samples from a homogeneous population?

	3	3	3	10	11	12
	10:20	11:10	2:20	4:00	1:10	10:30
	1.1	1.0	0.6	-1.6	1.1	2.5
	1.0	0.6	0.3	0.8	0.5	0.6
	0.9	1.0	-0.1	2.1	2.2	1.1
	1.1	0.4	0.0	1.1	1.1	0.6
	0.9	0.4	1.5	0.6	0.4	1.8
	1.1	0.9	0.9	0.6	-2.0	0.6
	0.6	0.6	0.3	0.6	1.4	1.2
	0.5	0.4	0.2	0.2	-0.4	1.2
	0.5	1.1	0.4	0.8	2.4	0.4
	0.7	0.7	0.4	0.6	0.0	1.0

ANALYSIS OF VARIANCE ON syrup

SOURCE	DF	SS	MS	F	P
time	5	2.538	0.508	0.93	0.470
ERROR	54	29.515	0.547		
TOTAL	59	32.052			

INDIVIDUAL 95 PCT CI'S FOR MEAN BASED ON POOLED STDEV

LEVEL	N	MEAN	STDEV	-----+-----+-----+-----
1	10	0.8400	0.2459	(-----*-----)
2	10	0.7100	0.2726	(-----*-----)
3	10	0.4500	0.4649	(-----*-----)
4	10	0.5800	0.9175	(-----*-----)
5	10	0.6700	1.2936	(-----*-----)
6	10	1.1000	0.6429	(-----*-----)

POOLED STDEV = 0.7393 0.00 0.50 1.00 1.50

Clover Varieties. Six plots each of five varieties of Clover were planted at the Danbury Experiment Station in North Carolina. Yields in tons per acre were as follows:

³Park, W. (1932). Studies on the change in nectar concentration produced by the honeybee, *Apis mellifera*. Part I: Changes that occur between the flower and the hive. Iowa Agricultural Experiment Station Research Bulletin No 151, 1932.

Variety	Yield
Spanish	2.79, 2.26, 3.09, 3.01, 2.56, 2.82
Evergreen	1.93, 2.07, 2.45, 2.20, 1.86, 2.44
Commercial Yellow	2.76, 2.34, 1.87, 2.55, 2.80, 2.21
Madrid	2.31, 2.30, 2.49, 2.26, 2.69, 2.17
Wisconsin A46	2.39, 2.05, 2.68, 2.96, 3.04, 2.60

The following MINITAB output is obtained:

```
MTB > oneway c1 c2;
SUBC> fisher.
```

ANALYSIS OF VARIANCE ON C1

SOURCE	DF	SS	MS	F	P
C2	4	1.2784	0.3196	3.53	0.020
ERROR	25	2.2619	0.0905		
TOTAL	29	3.5403			

BASED ON POOLED STDEV

LEVEL	N	MEAN	STDEV	-----+-----+-----+-----	(-----*-----)
1	6	2.7550	0.3052	-----+-----+-----+-----	(-----*-----)
2	6	2.1583	0.2510	-----+-----+-----+-----	(-----*-----)
3	6	2.4217	0.3549	-----+-----+-----+-----	(-----*-----)
4	6	2.3700	0.1884	-----+-----+-----+-----	(-----*-----)
5	6	2.6200	0.3671	-----+-----+-----+-----	(-----*-----)

POOLED STDEV = 0.3008 2.10 2.40 2.70

FISHER'S multiple comparison procedure

```
Nominal level = 0.0500
Family error rate = 0.268
Individual error rate = 0.0500
```

Critical value = 2.060

Intervals for (mean of column group) - (mean of row group)

	1	2	3	4
2	0.2389			
	0.9544			
3	-0.0244	-0.6211		
	0.6911	0.0944		
4	0.0273	-0.5694	-0.3061	
	0.7427	0.1461	0.4094	
5	-0.2227	-0.8194	-0.5561	-0.6077
	0.4927	-0.1039	0.1594	0.1077

(i) Test the hypothesis that the mean yields for the five clover varieties are the same. Take $\alpha = 5\%$. What happens if your α is 1%.

(ii) Which means are different at 5% level?
 (iii) Is the hypothesis $H_0 : 3(\mu_1 + \mu_5) = 2(\mu_2 + \mu_3 + \mu_4)$ a contrast? Why? If yes, test it against the two sided alternative, at $\alpha = 5\%$ level.

Promiscuity at Duke. Many students criticize the Greek fraternity and sorority systems for their loose sexual

attitudes, so Katie, Joshua, and Anna⁴ decided to conduct a study that would compare the levels of promiscuity among Greek and non-Greek men and women. Based on their experiences at Duke University so far, Katie, Joshua, and Anna agreed with the prevalent view that Greek students are generally more promiscuous than non-Greeks (independents), and that men are generally more promiscuous than women in this campus. In order to conduct a statistical analysis, they defined “promiscuity” as the number of different people that particular subject at least kissed on the lips this semester. The data (given in the table) have been tested by the two-way ANOVA procedure.

	men	women
greek	1 1 2 2 6	1 1 0 3 2
	4 1 1 1 2	1 1 2 1 1
	7 8 3 4 1	2 0 7 2 1
	1 4 3 3 4	4 5 1 2 3
independent	2 2 1 1 1	1 1 1 0 5
	1 1 5 8 2	1 3 2 5 2
	1 8 6 2 2	2 1 2 4 1
	6 0 0 0 1	1 0 0 1 1

MTB > anova prom = greek gender greek*gender

Factor	Type	Levels	Values
greek	fixed	2	1 2
gender	fixed	2	1 2

Analysis of Variance for prom

Source	DF	SS	MS	F
greek	1	2.812	2.812	-----
gender	1	15.313	15.313	-----
greek*gender	1	0.112	0.112	-----
Error	76	310.150	4.081	
Total	79	328.388		

- (i) Explain what type of statistical analysis the above table refers to.
- (ii) What can you say about the effect of interaction `greek*gender`.
- (iii) Test for significance of factor `greek`. Use $\alpha = 0.1$.
- (iv) Test for significance of factor `gender`. Use $\alpha = 0.1$.
- (v) Explain in words your findings.

Beautify me!.

Marketing research contractors.

A marketing research consultant evaluated the effects of fee schedule (Factor A), scope of work (Factor B), and type of supervisory control (Factor C) on the quality of work performed under contract by independent marketing research agencies. The factor levels in the study were as follows.

A fee level	i=1 high
	i=2 average
	i=3 low
B scope	j=1 all contract work performed in the house
	j=2 some work subcontracted out
C supervis	k=1 local supervisors
	k=2 traveling supervisors only

The quality of the work performed was measured by an index taking into account several characteristics of the quality.

Data:

⁴Katie Anderson, Joshua Smith, and Anna Wulfsberg: Promiscuity at Duke, STA110E Project, Fall 1995.

```

#-----#
#      k=1          k=2
#      j=1      j=2      j=1      j=2
#-----#
MTB > set c1
DATA> 124.3  115.1    112.7  88.2
DATA> 120.6  119.9    110.2  96.0
DATA> 120.7  115.4    113.5  96.4
DATA> 122.6  117.3    108.6  90.1
DATA>
DATA> 119.3  117.2    113.6  92.7
DATA> 118.9  114.4    109.1  91.1
DATA> 125.3  113.4    108.9  90.7
DATA> 121.4  120.0    112.3  87.9
DATA>
DATA> 90.9   89.9     78.6   58.6
DATA> 95.3   83.0     80.6   63.5
DATA> 88.8   86.5     83.5   59.8
DATA> 92.0   82.7     77.1   62.3
DATA> end
MTB > set c2
DATA> 1 1  1 1
DATA>
DATA> 2 2  2 2
DATA>
DATA> 3 3  3 3
DATA> end
MTB > set c3
DATA> 1 2  1 2
DATA>
DATA> 1 2  1 2
DATA>
DATA> 1 2  1 2
DATA> end
MTB > set c4
DATA> 1 1  2 2
DATA>
DATA> 1 1  2 2

```

```

DATA> 1 1 2 2
DATA> 1 1 2 2
DATA> 1 1 2 2
DATA>
DATA> 1 1 2 2
DATA> end
MTB > names c1 'qual' c2 'fee' c3 'scope' c4 'suprv'
MTB > anova qual = fee|scope|suprv

```

Factor	Type	Levels	Values
fee	fixed	3	1 2 3
scope	fixed	2	1 2
suprv	fixed	2	1 2

Analysis of Variance for qual

Source	DF	SS	MS	F	P
fee	2	10044.3	5022.1	679.34	0.000
scope	1	1834.0	1834.0	248.08	0.000
suprv	1	3832.4	3832.4	518.40	0.000
fee*scope	2	1.6	0.8	0.11	0.898
fee*suprv	2	0.8	0.4	0.05	0.948
scope*suprv	1	574.8	574.8	77.75	0.000
fee*scope*suprv	2	3.9	2.0	0.27	0.767
Error	36	266.1		7.4	
Total	47	16557.9			

```
MTB > anova qual = fee scope suprv scope*suprv
```

Factor	Type	Levels	Values
fee	fixed	3	1 2 3
scope	fixed	2	1 2
suprv	fixed	2	1 2

Analysis of Variance for qual

Source	DF	SS	MS	F	P
fee	2	10044.3	5022.1	774.14	0.000
scope	1	1834.0	1834.0	282.70	0.000
suprv	1	3832.4	3832.4	590.75	0.000
scope*suprv	1	574.8	574.8	88.60	0.000
Error	42	272.5		6.5	
Total	47	16557.9			

SINGERS

singers.dat file contains heights of singers in New Your Choral Society.

```
attach("/daub4/local/brani/pub/datasets/.Data")
```

```

#-----
> !ls
93cars.dat      attachme      bass2.dat      fruitfly.dat      televisions.doc
93cars.doc       basepath.dat   blank.doc      fruitfly.doc      tenor1.dat
airport.dat      basepath.info  cigarettes.dat  singers.dat      tenor2.dat
airport.doc      basketball.dat cigarettes.doc  sop1.dat        ushighway1.dat
alto1.dat        basketball.doc fishcatch.dat  sop2.dat        ushighway1.doc
alto2.dat        bass1.dat     fishcatch.doc  televisions.dat ushighway2.dat

#-----
> sop1_scan("sop1.dat")
> sop1
[1] 64 62 66 65 60 61 65 66 65 63 67 65 62 65 68 65 63 65 62 65 66 62 65 63 65
[26] 66 65 62 65 66 65 61 65 66 65 62

#-----
> sop2_scan("sop2.dat")
> sop2
[1] 63 67 60 67 66 62 65 62 61 62 66 60 65 65 61 64 68 64 63 62 64 62 64 65 60
[26] 65 70 63 67 66

#-----
> alto1_scan("alto1.dat")
> alto1
[1] 65 62 68 67 67 63 67 66 63 72 62 61 66 64 60 61 66 66 66 62 70 65 64 63 65
[26] 69 61 66 65 61

#-----
> alto2_scan("alto2.dat")
> alto2
[1] 70 65 65 65 64 66 64 70 63 70 64 63 67 65 63 66 66 64 64 70 70 66 66 66 69
[26] 67 65

#-----
> tenor1_scan("tenor1.dat")
> tenor1
[1] 69 72 71 66 76 74 71 66 68 67 70 65 72 70 68 64 73 66 68 67 64 63 64 67 66
[26] 68

#-----
> tenor2_scan("tenor2.dat")
> tenor2
[1] 68 73 69 71 69 76 71 69 71 66 69 71 71 71 69 70 69 68 70 68 69

#-----
> bass1_scan("bass1.dat")
> bass1
[1] 72 70 72 69 73 71 72 68 68 71 66 68 71 73 73 70 68 70 75 68 71

#-----
> bass2_scan("bass2.dat")
> bass2
[1] 72 75 67 75 74 72 72 74 72 74 70 66 68 75 68 70 72 67 70 70

```

Descriptive Statistics

```

> summary(sop1)
Min. 1st Qu. Median Mean 3rd Qu. Max.

```

```

60   62.75      65 64.25      65   68
> summary(sop1)[4]-mean(sop1)
Mean
0

> Eda.shape
function(x)
{
  par(mfrow = c(2, 2))
  hist(x)
  boxplot(x)
  iqd <- summary(x)[5] - summary(x)[2]
  plot(density(x, width = 2 * iqd), xlab = "x", ylab = "", type = "l")
  qqnorm(x)
  qqline()
}

> Eda.shape(sop1)
> #Figure 1.

> HH_c(sop1, sop2, alto1, alto2, tenor1, tenor2, bass1, bass2)
> voices_rep(c("S1", "S2", "A1", "A2", "T1", "T2", "B1", "B2"),
+ c(length(sop1),length(sop2), length(alto1), length(alto2), length(tenor1)
+ , length(tenor2), length(bass1), length(bass2)) )
> voices_factor(voices)
> # making data frame
> HH.df_data.frame(voices, HH)
> HH.df
  voices HH
1      S1 64
2      S1 62
3      S1 66
.
.
.
209      B2 72
210      B2 67
211      B2 70
212      B2 70

> length(c(sop1, sop2, alto1, alto2))
[1] 123
> length(HH)
[1] 212
> gen_rep(c("F", "M"), c(123, 212-123))
> gen_factor(gen)
> GEN.df_data.frame(gen, HH)

> par(mfrow=c(2,2))
> plot.design(GEN.df)
> plot.factor(GEN.df)
> plot.design(HH.df)
> plot.factor(HH.df)
> #Figure 2.

```

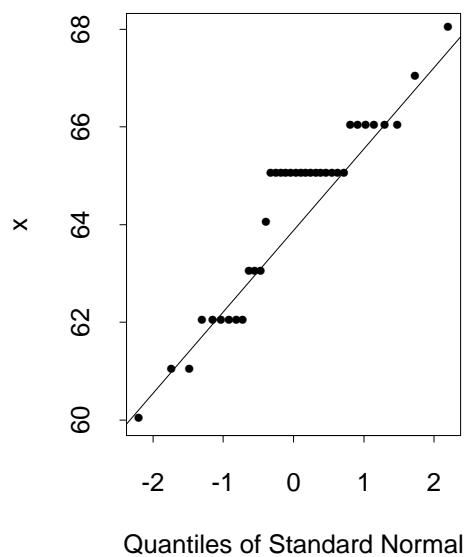
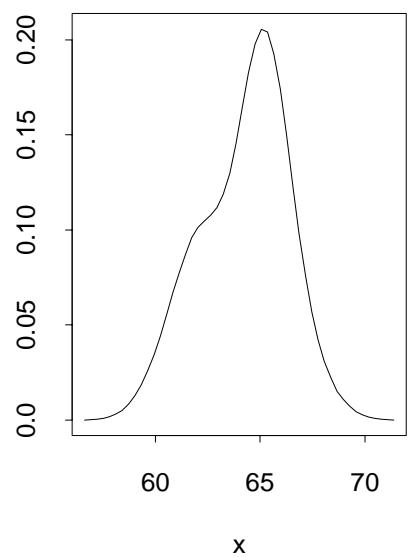
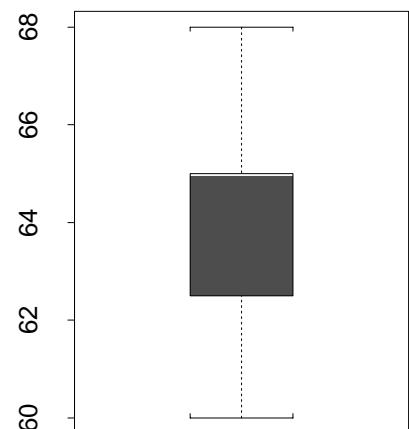
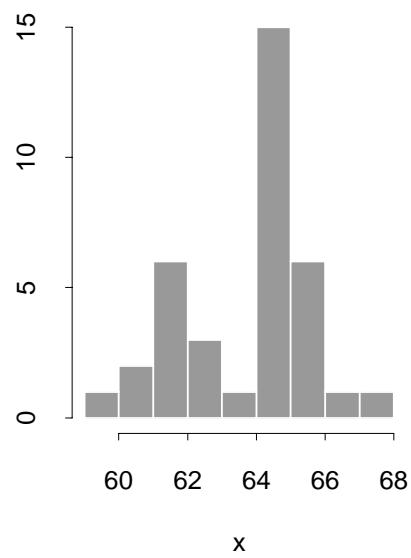


Figure 13.1: Eda.shape for `sop1` data set

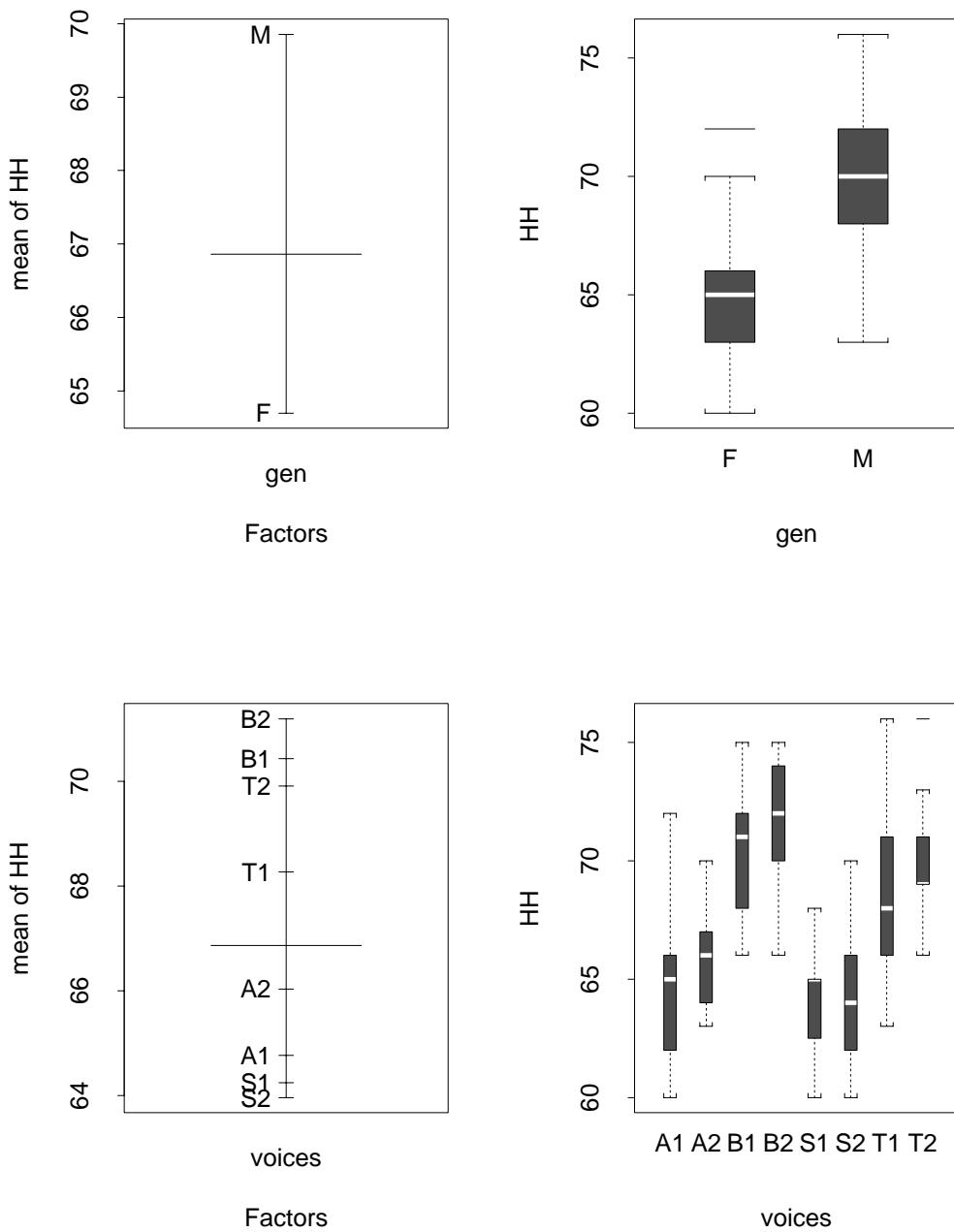


Figure 13.2: Design and Factorplots for GEN and HH data frames

Inference

```

> t.test(c(sop1, sop2, alto1, alto2),
+         c(tenor1, tenor2, bass1, bass2), alternative="less")

  Standard Two-Sample t-Test

data: c(sop1, sop2, alto1, alto2) and c(tenor1, tenor2, bass1, bass2)
t = -13.8275, df = 210, p-value = 0
alternative hypothesis: true difference in means is less than 0
95 percent confidence interval:
NA -4.538845
sample estimates:
mean of x mean of y
64.69919 69.85393

Model:  $y_{ij} = \mu_i + \epsilon_{ij} = \mu + \tau_i + \epsilon_{ij}, j = 1, \dots, J_i; i = 1, \dots, I.$ 

> aov.HH_aov(HH ~ voices, HH.df)
> summary(aov.HH)
      Df Sum of Sq  Mean Sq  F Value Pr(F)
voices      7  1553.681 221.9544 34.16352     0
Residuals 204  1325.352   6.4968

> fitted.values(aov.HH)
  1     2     3     4     5     6     7     8     9     10    11    12    13
64.25 64.25 64.25 64.25 64.25 64.25 64.25 64.25 64.25 64.25 64.25 64.25
.
.
.
71.19048 71.19048 71.19048 71.19048 71.19048 71.19048 71.19048 71.19048
207      208      209      210      211      212
71.19048 71.19048 71.19048 71.19048 71.19048 71.19048
> Eda.shape(resid(aov.HH))
> #Figure 3.

> coef(aov.HH)
(Intercept) voices1 voices2 voices3 voices4 voices5 voices6
  67.35168 0.6351852 1.675573 1.028263 -0.7711376 -0.5613139 0.2137135
voices7
  0.3647265

> contrasts(HH.df$voices)
 [,1] [,2] [,3] [,4] [,5] [,6] [,7]
A1   -1   -1   -1   -1   -1   -1   -1
A2    1   -1   -1   -1   -1   -1   -1
B1    0    2   -1   -1   -1   -1   -1
B2    0    0    3   -1   -1   -1   -1
S1    0    0    0    4   -1   -1   -1
S2    0    0    0    0    5   -1   -1
T1    0    0    0    0    0    6   -1
T2    0    0    0    0    0    0    7

> as.vector(coef(aov.HH)) %*% t(as.matrix(cbind(rep(1,8),contrasts(HH.df$voices))))
      A1      A2      B1      B2      S1      S2      T1      T2
[1,] 64.76667 66.03704 70.42857 71.19048 64.25 63.96667 68.26923 69.90476

```

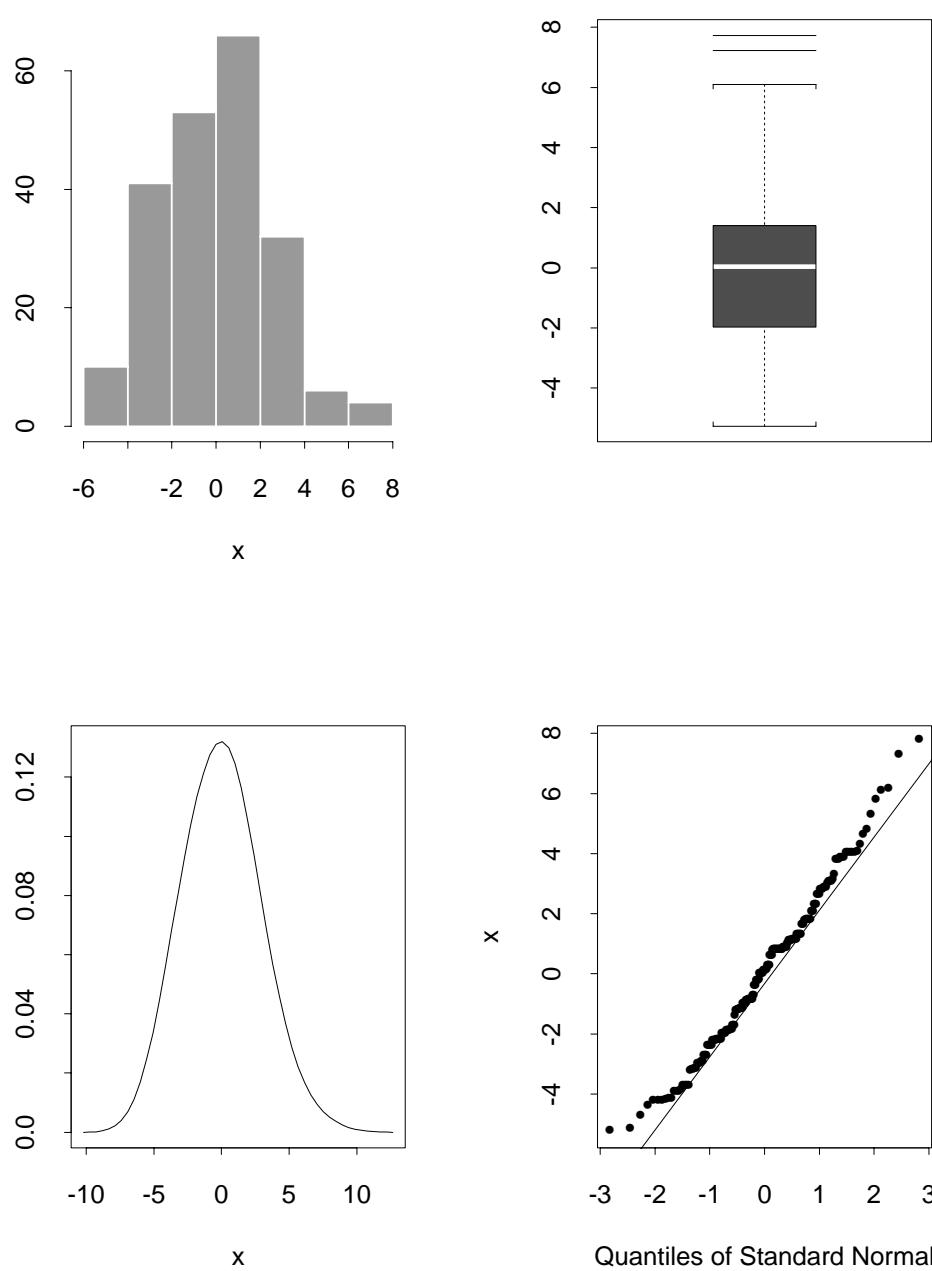


Figure 13.3: `Eda.shape` for the residuals

Pairwise Comparisons

```

> Scheffe
function(data, contrast, alpha = 0.05, r = 3)
{
  means <- apply(data, 2, mean.na)
  cat("\n means:", means, "\n")
  fit <- matrix(means, nrow = dim(data)[1], ncol = dim(data)[2], byrow =
    T, dimnames = dimnames(data))
  fit <- fit + 0 * data
  res <- data - fit
  ngroup <- apply(!is.na(data), 2, sum)
  if((contrast %*% ngroup)[1, 1] != 0)
    stop("The contrast is", " untestable for this design.", (
      contrast %*% ngroup)[1, 1])
  cat("\n ngroup:", ngroup, "\n")
  sse <- sum.na(res^2)
  dfe <- (sum(!is.na(data)) - dim(data)[2])
  mse <- sse/dfe
  C <- (contrast %*% means)[1, 1] #dim(C) <- NULL
  cat("\n C=", round(C, r), "\n")
  SC <- sqrt(mse * sum(contrast^2/ngroup))
  Salp <- SC * sqrt((dim(data)[2] - 1) * qf(1 - alpha, dim(data)[2] - 1,
    dfe))
  cat("\n C=", round(C, r), " SC=", round(SC, r), " Salp=", round(Salp, r
    ), "\n")
  cat("\n", 1 - alpha, "*100% confidence interval is:(", round(C - Salp,
    r), ", ", round(C + Salp, r), ") \n")
  if(abs(C) < Salp) {
    cat("\n The contrast is tested to be 0 at the level", alpha,
      "\n")
  }
  else {
    cat("\n The contrast is tested not to be 0 at the level", alpha,
      "\n")
  }
}

> cont_c(1/36, 1/30, -1/30, -1/27, -1/26, -1/21, 1/21, 1/21)
> Scheffe(data, cont)

means: 64.25 63.966666666667 64.766666666667 66.037037037037 68.2692307692308
       69.9047619047619 70.4285714285714 71.1904761904762

ngroup: 36 30 30 27 26 21 21 21

C= 0.101
C= 0.101  SC= 0.059  Salp= 0.222
0.95 *100% confidence interval is:( -0.12 , 0.323 )

The contrast is tested to be 0 at the level 0.05

```

$$\begin{aligned}
, &= c_1\mu_1 + \dots + c_I\mu_I \\
\sum c_i n_i &= 0, \quad \sum n_i = N. \\
C &= c_1\bar{y}_1 + \dots + c_I\bar{y}_I.
\end{aligned}$$

$$SC = \sqrt{MSE \sum_{i=1}^I (c_i^2/n_i)}$$

$$S_\alpha = SC \sqrt{(I-1)F_{\alpha, I-1, N-I}}$$

Conf. Int: $[C - S_{alpha}, C + S_\alpha]$

Singers in the trellis library

The Trellis library is a collection of functions and datasets for creating Trellis displays which have multiple panels arranged in a regular grid-like structure. Each panel graphs a subset of the data. All panels in a Trellis display contain the same type of graph. Graph types include histograms, scatter plots, dot plots, contour plots, wireframe plots and 3-d point clouds. The data subsets for each panel are chosen in a regular manner conditioning on continuous or discrete variables in the data, thus providing a coordinated series of views of high dimensional data. The Trellis functions include control over axes and aspect ratio and contain *banking* computations that let the data select the aspect ratio.

To access the functions in the library correctly you must attach it with the `first=T` argument to library set, i.e.

```
> library(trellis, first=T)
> library(help="trellis")
```

After attaching the library, start a graphics device using the `trellis.device` function e.g.

```
> trellis.device(motif)
```

This will set appropriate graphics parameters for the specified device.

There is a collection of example functions in the library that illustrate its capabilities. See the `trellis.examples` help file.

`singer`: Data frame giving the heights of singers in the New York Choral Society. Components are named `height` (inches) and `voice.part`.

```
> singer
  height voice.part
1      64  Soprano 1
2      62  Soprano 1
3      66  Soprano 1
4      65  Soprano 1
.
.
.
232     72      Bass 2
233     71      Bass 2
234     74      Bass 2
235     75      Bass 2

> boxplot(height ~ voice.part, data=singer, xlab="Height (inches) ")
> #Figure 4.

> qqmath(height ~ qnorm | voice.part, data=singer)
> qqmath(log(height) ~ qnorm | voice.part, data=singer)
> #Figure 5.

> qqmath(height ~ qnorm | voice.part, data=singer, aspect=1, layout=c(4,2), strip.name=FALSE,
  prepanel = prepanel.qqmathline, panel=function(x,y){
    panel.grid()
    panel.qqmathline(y)
    panel.qqmath(x,y)
  },
  xlab = "Unit Normal Quantile"
)
> #Figure 6.
```

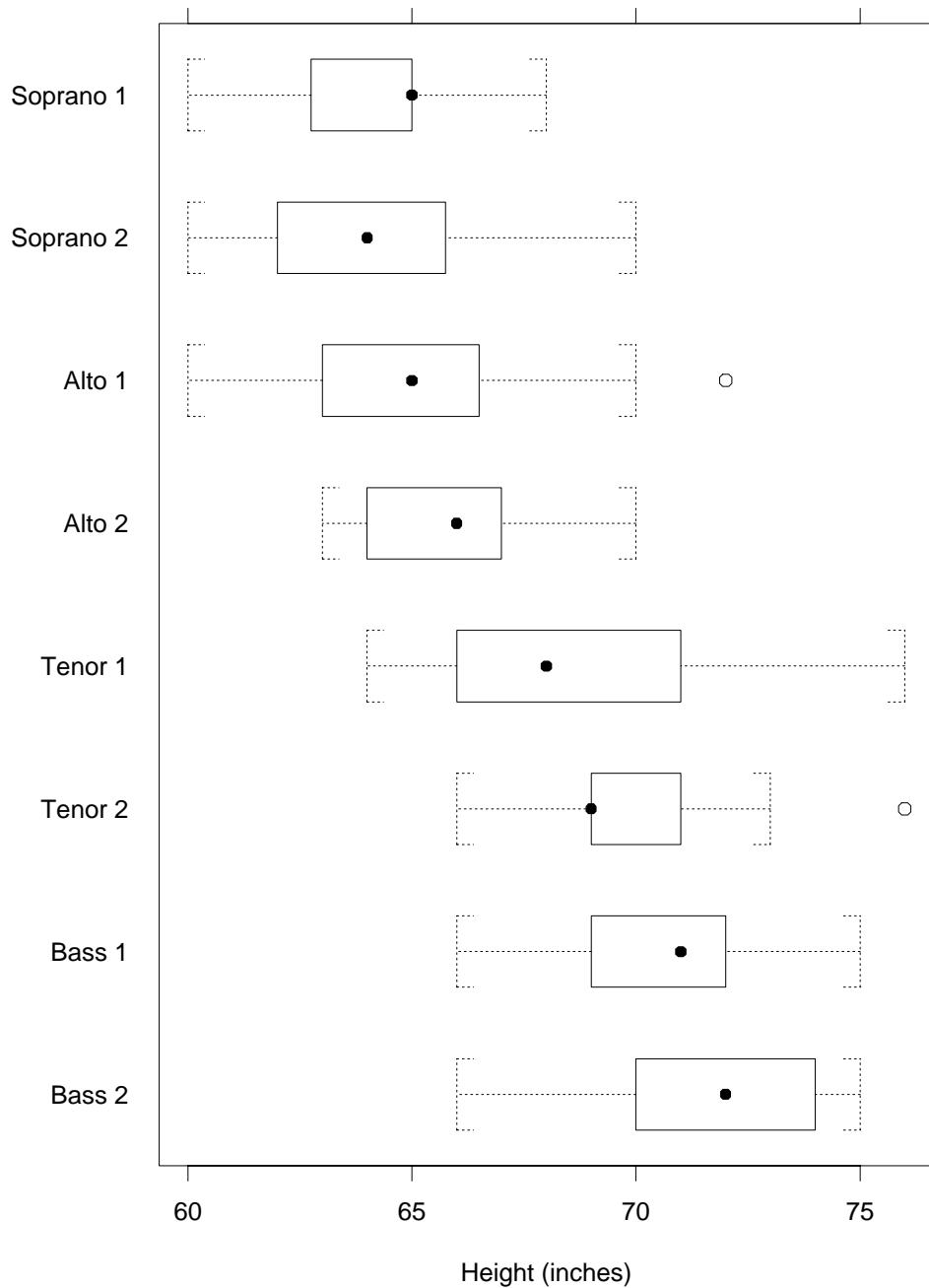


Figure 13.4: A boxplot showing heights of members of a choral group, arranged according to the part they sing.

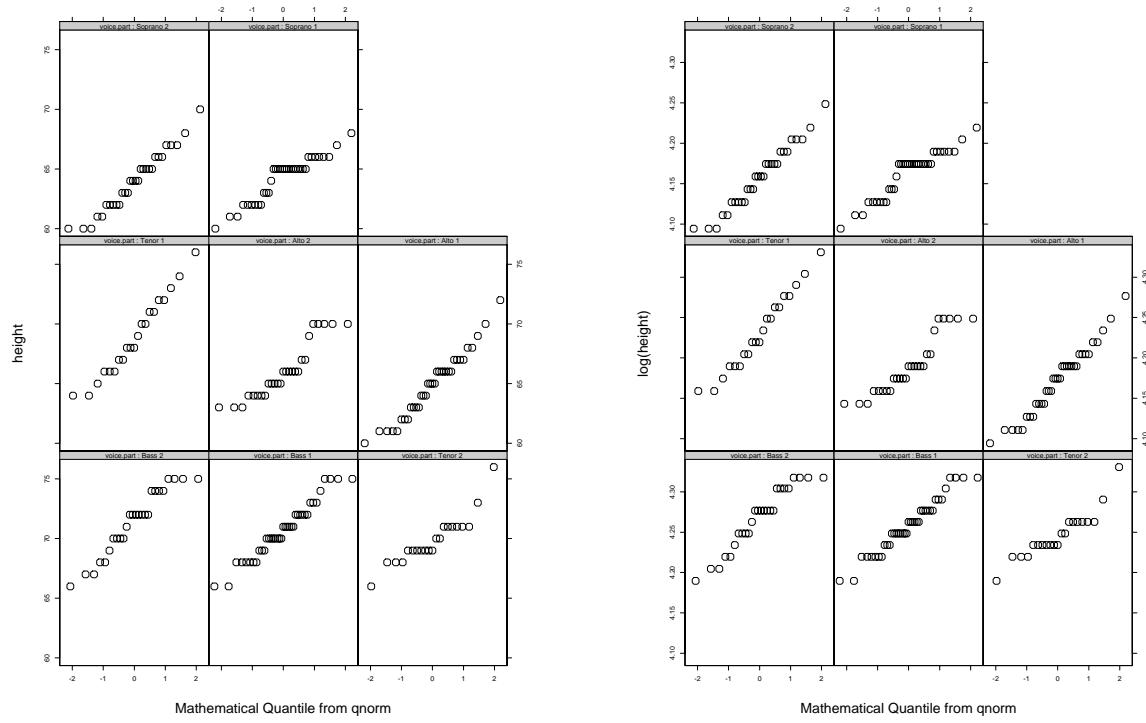


Figure 13.5: Mathematical quantiles: responses height (left panel) and $\log(\text{height})$ (right panel).

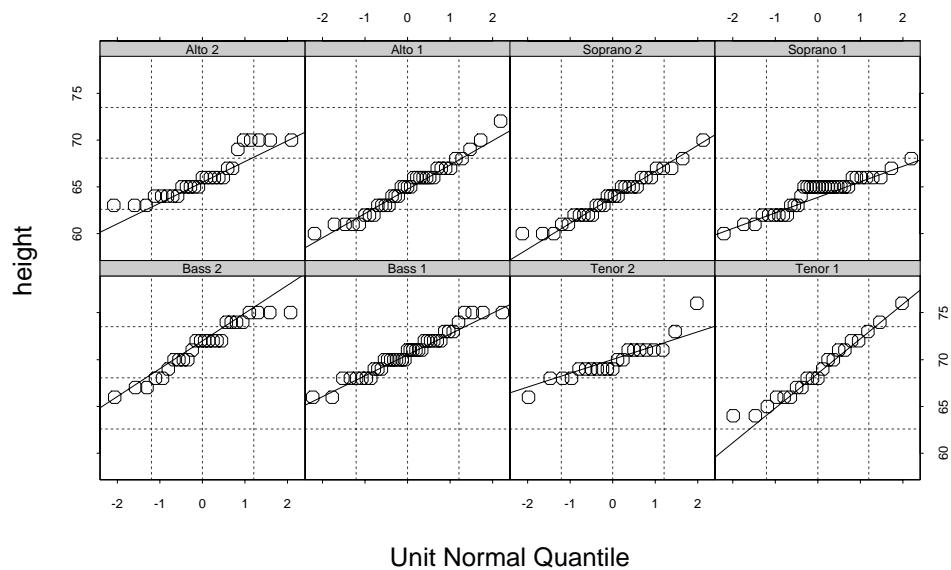


Figure 13.6: Improved display of `qqmath`.