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## DAY 2. A beginners guide to solving biological problems in R

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Course material:  
<http://logic.sysbiol.cam.ac.uk/teaching/Rcourse/>

Original slides by Ian Roberts and Robert Stojnić

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### Day 1 review

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1. Introduction to R and its environment
  - Running R from the command line
  - Rstudio
  - Creating and calculating with vectors
  - Loading packages
2. Data structures
  - Data frames, factors, matrices, lists
3. Data analysis example
  - reading from and writing to files
4. Programming techniques
  - manipulating data frames, looping, if statements
5. Statistics
  - distributions, tests, linear models

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### Day 2 Schedule

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1. Writing scripts
  - Building scripts for routine analysis
  - Script automation using R batch mode
2. Extending R with customized functions
  - Learn how to write your own R functions
3. Advanced data analysis and basic R graphics
  - Integrate data from different sources and analyze
4. More on R graphics
  - Produce publication quality charts

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Writing custom scripts & running R batch mode analysis

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## The R scripting language

### Scripting

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- A script is a series of instructions that when executed sequentially automates a task
  - A script is a good solution to a repetitive problem
- The art of good script writing is
  - understanding exactly what you want to do
  - expressing the steps as concisely as possible
  - making use of error checking
  - including descriptive comments
- R is a powerful scripting language, and embodies aspects found in most standard programming environments
  - procedural statements
  - loops
  - functions
  - conditional branching
- Scripts may be written in any standard text editor, e.g. notepad, gedit, kate
  - RGui (Mac and Windows) has a built-in text editor

## An example script

### Scripting

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- Colony forming assays provide a measure of cellular proliferation. They are used as read outs for various biological systems
  - A well controlled study may involve multiple samples, treatments and controls (probably replicated).
  - This produces a lot of 'count' data, ideally suited to routine script processing
- Encapsulating the analysis into an R script requires a clear understanding of the problem and data structure

## CFA experimental design Scripting

- Expression of gene X may prevent cells from proliferating in high concentrations of compound Z. The theory is tested by knocking down gene X and growing cells in varying concentrations of compound Z.
  - Three repeat runs (same cell line)
    - Gene X knockdown --> KdX
    - Scramble gene X knockdown control --> ScX
    - Control (transfect empty vector) --> CnX
  - 4 concentrations of compound Z
    - High (HZ), Medium (MZ), Low (LZ), None (OZ)
  - The experiment is replicated over 3 successive weeks
    - Run1 (R1), Run2 (R2) and Run3 (R3)
  - 108 counts in total

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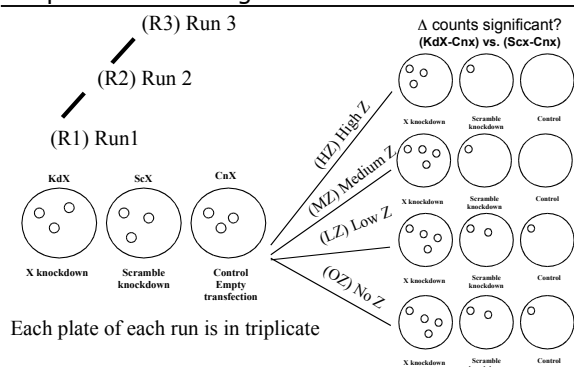
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## Colony forming assay experimental design




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## Preparing the calculation(s) Scripting

- We need to make barplots of counts for the KDX-CNX and SCX-CNX for each concentration of Z.
- We will group the repeat runs & replicates, and take an average.
- A Wilcoxon Rank Sum test will tell us whether there is a significant level of protection for KDX in concentrations of Z
- We'll add in some data quality checks
  - Boxplots of repeat runs
  - Variance within replicates

We can copy & paste lines of code into a blank text document, try them out and keep the ones that work!

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## Importing data

### Scripting

[illegible]

Fine for humans, bad for R

[illegible]

### Factors

Response

We will create a data frame of factors  
 > comprising Run, Plate, Treatment, Replicate  
 The response variable is counts.

We have 3 spreadsheets of data

- Run1counts.csv
- Run2counts.csv
- Run3counts.csv

We will need to write a procedure that reads in the data  
Note that our script will require a consistent data format

## Prepare for raw data

### Script walkthrough 1

- Open a blank text document, and prepare to write this script
- The data is contained in three files:
  - 11\_CFA\_Run1Counts.csv
  - 11\_CFA\_Run2Counts.csv
  - 11\_CFA\_Run3Counts.csv
- Load in the data and concatenate it into a single data frame

```
# load in the data from the three runs into three separate data frames t1,
# t2, t3
t1 = read.csv("11_CFA_Run1Counts.csv")
t2 = read.csv("11_CFA_Run2Counts.csv")
t3 = read.csv("11_CFA_Run3Counts.csv")

# concatenate the three data frames into a single data frame
colony = rbind(t1, t2, t3)

# (or use one of the loops from yesterday...)
```

Example code:  
11\_CFAcountData.R

## Import raw data

### Script walkthrough 2

- Data is by default read in as factors, i.e. all input strings are enumerated and stored as numbers
- The three separate data frame have no indication of which number they came from. We will add a column indicating this:

```
# add the missing Run column - factors are stored as numbers !
runNum <- factor( rep( 1:3, each=36 ), labels=c("Run1", "Run2", "Run3") )
colony <- cbind( "Run" = runNum, colony )

# reorder factor levels in their natural order (instead of alphabetical)
colony$Treatment <- factor(colony$Treatment, c("OZ", "LZ", "MZ", "HZ"))
colony$Plate <- factor(colony$Plate, c("KDX", "SCX", "CNX"))

# show the full table
colony
```

## The tapply function a brief digression

- Assume we have the following data for heights of 5 males and females:

```
data <- data.frame(gender=c("Male", "Male", "Female",  
  "Female", "Female"), height=c(6, 6.1, 5.8, 6, 5.95))
```

| gender   | height |
|----------|--------|
| 1 Male   | 6.00   |
| 2 Male   | 6.10   |
| 3 Female | 5.80   |
| 4 Female | 6.00   |
| 5 Female | 5.95   |
- By calling `mean()` on the height column we can get the average of all 5 people, but how do we get average separately for males and females?
- `tapply()` lets us do exactly this
  - It applies a function to grouped data:
- `tapply( data$height, data$gender, mean )`  
data groups function

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## Undertake data analysis Script walkthrough 3

- We need the means of the triplicate counts for each Run
  - Broken down by plate type (KDX,SCX,CNX) and Z treatment concentration (OZ,LZ,MZ,HZ)

```
### Part 2. Investigating data ###  
tapply(colony$Count, list(colony$Run, colony$Plate,  
  colony$Treatment), mean)
```

We can plot a graph of this. It gives us the variation in counts per run

```
par(mar=c(4,2,2,2))  
boxplot(Count~Run*Plate*Treatment, las=2, cex=0.2,  
  data=colony)
```

Better still, lets plot a grouped bar chart of mean counts per plate type per Z treatment

```
barplot(tapply(colony$Count, list(colony$Plate,  
  colony$Treatment), mean), beside=T)
```

```
## OZ  
Run1 98.33333 129.6667 108.3333  
Run2 180.33333 206.0000 186.6667  
Run3 282.33333 288.6667 265.6667  
  
## LZ  
Run1 75.0000 53.0000 21.66667  
Run2 136.3333 103.6667 32.00000  
Run3 157.0000 180.6667 46.66667  
  
## MC  
Run1 29.66667 6.333333 0.3333333  
Run2 47.00000 11.66667 2.0000000  
Run3 73.00000 17.33333 3.666667  
  
## HZ  
Run1 6.333333 1.333333 0.3333333  
Run2 12.000000 0.333333 0.0000000  
Run3 18.666667 0.333333 0.0000000
```

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## Summarize & save the analysis Script walkthrough 4

- We need a reshaped, background corrected, table of results on which to perform our tests
- for clarity where possible use dollar (\$) notation (work only with data frames)

```
### Part 3. Summarizing data ###  
result <- tapply(colony$Count, list(colony$Treatment, colony$Plate), mean)  
result <- data.frame(result) # result of tapply is matrix, convert to dataframe  
result  
  
# calculate kdx and scx values after background correction  
kdx = result$KDX - result$CNX  
scx = result$SCX - result$CNX  
  
result <- cbind(kdx, scx)  
# remove the OZ entry  
result <- result[-1,]  
barplot(result, beside=T)
```

-ve subscripts  
mean 'delete'

```
wilcox.test(result[,1], result[,2], paired=T)  
cor.test(result[,1], result[,2], paired=T)  
write.csv(result, "CFRresults.csv")
```

We can plot the results as a barchart, and undertake an appropriate two sample classical test

We find that the difference in means is not significant (would expect observation to occur 1:4 times), and that the scramble and knockdown counts have a 90% correlation

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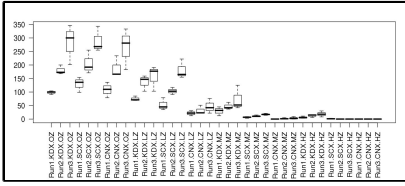
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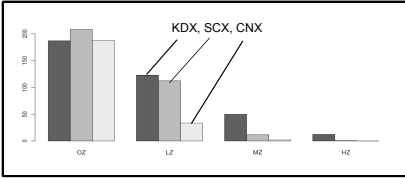
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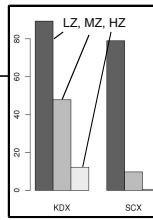
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Boxplot shows variation in replicates. Run 3 had greatest count variation.



Bar chart shows run average counts of various plate types in different Z treatments. KDX is the only plate type that had growth in high Z.



Bar chart shows KDX had greater viability in Z compared to SCX. Treatments are Low, Medium and High.

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```
> wilcox.test(result[,1],result[,2],paired=TRUE)

Wilcoxon signed rank test

data: result[, 1] and result[, 2]
V = 6, p-value = 0.25
alternative hypothesis: true location shift is not equal to 0
```

```
> cor.test(result[,1],result[,2],paired=TRUE)

Pearson's product-moment correlation

data: result[, 1] and result[, 2]
t = 2.5584, df = 1, p-value = 0.2372
alternative hypothesis: true correlation is not equal to 0
sample estimates:
cor
0.9313792
```

Would expect to see trend 1 in 4 times. There is a 93% correlation between the knockdown of gene X and scramble control and cell counts response when grown in compound Z.

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## Script steps review

### Script walkthrough 5

- Excel formatted data needs to be exported as comma separated values text (or tab!)
- Get the data into R
  - `read.csv()` ... to assign the data to an object
- Produce exploratory plots
  - `boxplot()`
  - `barplot()`
- Undertake statistical tests
  - `cor.test()`
    - Spearman's rank correlation test
  - `wilcox.test()`
    - Wilcoxon test with two sets of paired data ... Mann-Whitney U test
- Write out the results
  - `write.csv()`
    - exports data as comma separated list
  - `save.image()`
    - could also save the R environment after analysis (we didn't do this)

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## Exercise

### Colony forming assay script

- Enter the text of the count data script, and save the file.
  - To run the count data script in R, type
  - `source("filename")` # the script is available as 11\_countData.R
- Each step of the script is executed, and the results displayed.
- We need to export the graphical output to a file, and the R objects also need to be saved.
  - Modify the script as follows:  
Section 3, line directly after **apply** command insert:  

```
jpeg(file="fig1.jpg",width=1600,height=800,res=150)
par(oma=c(4,2,2,2))
... <boxplot commands in middle> ...
dev.off()
jpeg(file="fig2.jpg",width=675,height=900,res=150)
... <barplot commands in middle> ...
dev.off()
```

  
Section 4, line directly after **result** command insert:  

```
jpeg(file="fig3.jpg",width=1600,height=800,res=150)
... <barplot commands in middle> ...
dev.off()
```

## Batch processing R scripts

### Scripting

- Scripts can be run without ever launching R, using R CMD batch mode.

quit R and type the following in a linux terminal

```
R CMD BATCH --no-restore 11_CFAcountData.R
```

or if you write all of graphical output to files:

```
Rscript 11_CFAcountData.R (works only with recent R versions)
```

User functions

## 2

## Introducing ... User functions

- All R commands are functions.
- Functions perform calculations, possibly involving several arguments, then return a value to the calling statement.
- The calculation maybe any process, might or might not have return value
  - It need not be arithmetic
- User functions extend the capabilities of R by adapting or creating new tasks that are tailored to your specific requirements.
- User functions are a special kind of object

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## Defining a new function

- Parts of function definition: name, arguments, procedural steps, return value

```
sqXplusX <- function(x){  
  x^2 + x  
}
```
- **sqXplusX** is the function name
- **x** is the single argument to this function and it exists only within the function
- everything between brackets { } are procedural steps
- the **last** calculated value is the function return value
- after defining the function, we can use it:

```
> sqXplusX(10)  
[1] 110
```

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## Named and default arguments

- Example of function with more than one named argument:

```
powXplusX <- function(x, power=2){  
  x^power + x  
}
```
- Now we have two arguments. The second argument has a default value of 2.
- Arguments without default value are required, those with default values are optional.

```
> powXplusX(10)  
[1] 110  
> powXplusX(10, 3)  
[1] 1010
```

arguments matched based on **position**

```
> powXplusX(x=10, power=3)  
[1] 1010
```

arguments matched based on **name**

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## Assignments with arguments

### User functions

```
sqXplusX <- function(x){  
  x^2 + x  
}
```

You can use a blank document in gedit, nedit or other text editor to hold these commands for you, then copy / paste the instructions into R

- Now try this ...

```
a <- matrix(1:100, ncol=10, byrow=T) # make some dummy data  
b <- sqXplusX(a) # transform a by sqXplusX, assign result to b  
b # to view the result  
• sqXplusX user function is now an R object, check its arguments and  
  list it in the current workspace  
> args(sqXplusX)  
> ls()  
> sqXplusX
```

Don't add brackets to see the definition of sqXplusX

## Assigned or anonymous ...

### User functions

- Functions may be assigned a name, or anonymously created within an operation
  - Anonymous functions are really useful in `apply()` style procedures

```
apply(object, margin, function)
```

- E.g. I have a 10 x 10 matrix and want to square each item, and add the item to itself

```
a <- matrix(1:100, ncol=10, byrow=T)  
a # to view new object  
apply(a, c(1,2), function(x) x^2+x)
```

x is transiently assigned each item of a, and this is passed as an argument to the anonymous function

1 means by rows, 2 means by columns [1<sup>st</sup> or 2<sup>nd</sup> margin]  
c(1,2) means do both rows and columns

## Functions occupy their own space

### User functions

- Objects created in functions are not available to the general environment unless returned.
  - they are said to be out of scope
    - Scope relates to the accessibility of an object.
- A function can only return one object.
- Custom functions disappear when R sessions end, unless the function object is saved in an Rdata file or sourced from a script.
  - A really useful function could be added to your .Rprofile file, and would always be ready for you at launch
- You could also make a package
  - Beyond the scope of the beginners course!!!!

## Script / function tips

### User functions

- If your script repeats the same style command more than twice, you should consider writing a function
- Writing functions makes your code more easily understandable because they encapsulate a procedure into a well-defined boundary with consistent input/output
- Functions should not be longer than one-to-two screens of code, keep functions clean and simple
- Look at other functions to get ideas for how to write your own ...
  - Display function code by entering the function's name without brackets.

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## File commands for extending scripts & user functions

Generic file commands

```
dir(...,pattern="txt")
```

Retrieve working directory file listing filtered by pattern. Note pattern is a regular expression, not a shell wildcard

```
glob2rx("*.*txt")
```

Changes wildcards to regular expressions!

```
unlink(...)
```

Remove (permanently) a file from system

```
system(...)
```

Execute a shell command from within R

Result can not be coerced to an object, only available to linux R

```
> glob2rx("*.*txt")  
[1] "^.*\\.txt$"
```

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## Text manipulation for extending scripts & user functions

- Text manipulation and file name mangling ... that's a technical term
- ```
grep( pattern, object )
  - If pattern is not found, grep returns a 0 length object.
    - Test for null with is.null()

```
sub( pattern, replacement, object )  
gsub( pattern, replacement, object )
  - Sub replaces first occurrence only, gsub does them all.

```
cat( "...", file=... )
  - Outputs text to a file, or prints it on screen if file=""
    - cat requires "\n" to be given for new lines ... try ...

```
cat("Hello World!") ; cat("Hello World!",sep="\n") ; cat("Hello  
World!",sep="\n",file="world.txt")
  - cat is extremely useful for writing scripts or generating reports on-the-fly
```


```


```


```

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- Your code should report errors if inconsistency is detected.

```
stop(...)
```

- Stops execution of a function and reports a custom error message

```
is.family(...)
```

- Functions that can be used to test for a variety of conditions place them inside `if` structures to check that all is well

```
if( !is.numeric(x) ){ stop ("Non numeric value entered.  Cannot
  continue.") }
```

If the object `x` is non numeric (e.g. Text has been entered when numbers were required), then stop execution and report message

The is.family

[illegible]

- Centigrade to Fahrenheit conversion is given by

- $F = \frac{9}{5} C + 32$

- Write a function that converts between temperatures.

- The function will need two named arguments

- temperature ( $t$ ) is numeric

- *units (unit)* is character

- They will need default values, e.g  $t=0$ ,  $unit="c"$

- The function should report an appropriate error if inappropriate values are given

```
if( !is.numeric(t) ) { .... }
```

```
if( !(unit %in% c("c","f")) ){...}
```

- The function should print out the temperature in F if given in C, and vice versa

Functions with named arguments are defined with the following syntax

```
myFunc<-function(arg=defaultValue,...)
```

- Why not add a third scale?

$$K = C + 273.15$$

Example code:  
12 convTemp.B

- It is difficult to write large chunks of code, instead start with something that works and build upon it

- E.g. to solve the temperature conversion exercise:

- start with the function `powXplusX` (from some slides ago)

- modify the argument names

- delete the old code, for now just print out the input arguments

- save the function file, load it into R and try it out

- now add the two lines for input checking from the previous slide

- try it out, see if passing a character for temperature gives the expected error

- now try to convert C into F and print out the result

- when that works, add the conversion from F to C

- If you get stuck, call us to help you !

## Temperature conversion script

convTemp<-function(t=0,unit="c"){ # convTemp is defined as a new user function requiring two arguments, t and unit, the default values are 0 and "c", respectively.

```
  if( !is.numeric(t) ){
    stop("Non numeric temperature entered") # Exception error if character given for
    temperature
  }
  if(! (unit %in% c("c","f","k"))){
    stop("Unrecognized temperature unit. \n Enter either (c)entigrade, (f)ahrenheit
    or (k)elvin") # Exception error if unrecognized units entered
  }
  # Conversion for centigrade
  if(unit=="c"){
    fTemp <- 9/5 * t + 32
    kTemp <- t + 273.15
    output <- paste(t,"C is: \n",fTemp,"F \n",kTemp,"K \n")
    cat(output)
  }
  # Conversion for Fahrenheit
  if(unit=="f"){
    cTemp <- 5/9 * (t-32)
    kTemp <- cTemp + 273.15
    output <- paste(t,"F is: \n",cTemp,"C \n",kTemp,"K \n")
    cat(output)
  }
  # Conversion for Kelvin
  if(unit=="k"){
    cTemp <- t - 273.15
    fTemp <- 9/5 * cTemp + 32
    output <- paste(t,"K is: \n",cTemp,"C \n",fTemp,"F \n")
    cat(output)
  }
}
```

Example code:  
12\_convTemp.R

Units must be entered  
in quotes, as it's a  
character object

"\n" -> puts text on a new line

## Advanced data processing

### 3

## Combining data from multiple sources *Gene clustering example*

- R has powerful functions to combine heterogeneous data into a single data set
- Gene clustering example data:
  - five sets of differentially expressed genes from various experimental conditions
  - file with names of experimentally verified genes
- Gene clustering exercise:
  - 1.combine this dataset into a single table and cluster to see which conditions are similar
  - 2.repeat the clustering but only on a subset of experimentally verified genes

## Combining gene tables

- input files have two columns: gene names and fold change
- we want to combine all five tables into a single table, with 0 for missing values

|         |         |         |         |         |         |         |         |         |         |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| LPR2    | 3.5795  | Psa     | 3.8529  | lola    | 3.0121  | lola    | 3.3019  | brat    | 5.2812  |
| fs(1yh  | 3.1376  | vmd     | 3.6457  | CG31368 | 2.8063  | CG6919  | 2.9965  | ct      | 4.828   |
| CG6954  | 2.7482  | ct      | 3.201   | Kr-h1   | 2.7262  | CG31368 | 2.817   | CG31163 | 4.3345  |
| Psa     | 2.7012  | fs(1yh  | 3.1489  | svp     | 2.7005  | CG5149  | 2.7675  | LPR2    | 3.6882  |
| zfh2    | 2.6247  | bld     | 3.1229  | miub    | 2.6475  | Kr-h1   | 2.7647  | vmd     | 3.6666  |
| Fur1    | 2.4413  | zfh2    | 2.6421  | CG5149  | 2.5248  | TER94   | 2.6286  | zfh2    | 3.5314  |
| ct      | 2.3804  | RhoB7B  | 2.6022  | run     | 2.4759  | lma     | 2.5748  | pros    | 3.4307  |
| S       | 2.3674  | pros    | 2.5679  | lma     | 2.4302  | CG11153 | 2.4795  | Psa     | 3.3968  |
| rux     | 2.3574  | CG1124  | 2.5475  | CG6954  | 2.4235  | run     | 2.3631  | fs(1yh  | 3.3869  |
| RhoB7B  | 2.26    | S       | 2.5404  | CG11153 | 2.3845  | CG14888 | 2.0938  | CG31241 | 2.9973  |
| CG14889 | 2.1735  | pc      | 2.5111  | Awd     | 2.2295  | S       | -2.0243 | HmgZ    | 2.9226  |
| pc      | 2.1421  | Fur1    | 2.43    | CG6919  | 2.1324  | rux     | -2.0668 | Fur1    | 2.7469  |
| jms     | 2.0882  | PHDP    | 2.304   | CG14888 | 2.087   | pc      | -2.3437 | RhoB7B  | 2.7189  |
| Kr-h1   | -2.0447 | CG31241 | 2.2802  | Psa     | -2.0276 | corto   | -2.5596 | pc      | 2.6543  |
| CG5149  | -2.1521 | rux     | 2.2232  | rux     | -2.093  | fs(1yh  | -2.6211 | Toll-7  | 2.6161  |
| lma     | -2.2102 | CG14889 | 2.1752  | fs(1yh  | -2.141  | brat    | -2.9904 | rux     | 2.5975  |
| CG14888 | -2.4346 | CG31163 | 2.1608  | CG1124  | -2.155  | brat    | -3.3404 | CG14889 | 2.3054  |
| CG31368 | -2.4793 | HmgZ    | 2.0795  | Fur1    | -2.1588 | ct      | -4.4947 | S       | 2.2304  |
| Trim9   | -2.616  | svp     | -2.0404 | S       | -2.2539 | zfh2    | -4.4947 | CG1124  | 2.0216  |
| Awd     | -3.0395 | TER94   | -2.1807 | corto   | -2.2618 | CG6954  | -4.7244 | Kr-h1   | -2.1439 |
|         |         | cg113   | -2.3481 | pc      | -2.3017 |         |         | lma     | -2.1793 |
|         |         | off413  | -2.4404 | CG14889 | -2.4393 |         |         | CG5149  | -2.1892 |
|         |         | brat    | -2.7256 | zfh2    | -2.5884 |         |         | run     | -2.2194 |
|         |         | CG31368 | -2.7293 | HmgZ    | -3.6328 |         |         | Trim9   | -2.251  |
|         |         | miub    | -2.9055 | bld     | -3.7627 |         |         | off413  | -2.3821 |
|         |         | Awd     | -3.1413 | brat    | -3.7716 |         |         | bld     | -3.0293 |
|         |         | lola    | -3.6892 |         |         |         |         | CG6919  | -3.3719 |

## Gene clustering

### Script walkthrough 1

- To make the big table we first need to find out all the genes present in at least one of the files
- Make sure not to use factors in read.delim()

```
# start with an empty collection of genes
genes <- c()
for( fileNum in 1:5 ){
  # load in files 13_DiffGenes1.tsv ...
  t <- read.delim(paste("13_DiffGenes", fileNum, ".tsv", sep=""),
    as.is=TRUE, header=FALSE)

  # label the input columns to help code readability
  names(t) <- c("gene", "expression")
  genes <- union(genes, t$gene)
}

# for tidiness order our genes by name
genes <- sort(genes)

genes # show all genes
```

when loading in character data use **as.is=T** to prevent it being converted to factors!

union() is a set operation, combines two vectors by eliminating duplicates. There are also intersect() and setdiff()

Example code:  
13\_geneClustering.R

## Gene clustering

### Script walkthrough 2

- Using the complete list of genes, we can create the big table and fill in the values:

```
# make the destination table [rows = unique genes, cols = file numbers]
values <- matrix(0, nrow=length(genes), ncol=5)
rownames(values) <- genes # name the rows with the complete gene names

for(fileNum in 1:5){
  # read in the file again
  t <- read.delim(paste("13_DiffGenes", fileNum, ".tsv", sep=""),
    as.is=T, header=F)
  names(t) <- c("gene", "expression")

  # match the names of the genes to the rows in our big table
  index <- match(t$gene, rownames(values))
  # copy the expression levels
  values[index, fileNum] <- t$expression
}
```

we use index to pick the rows in such way that they match the gene order in the input file

match() returns the index of first argument in the second, i.e. index of input file genes in the big table

### Script walkthrough 3

- ```
heatmap(values, scale="none", col = cm.colors(256))
```

Heatmap showing the expression of 15 genes across five samples (3, 4, 1, 2, 5). The genes are listed on the right: CCL4, CCL4L1, CCL4L2, CCL4L3, CCL4L4, CCL4L5, CCL4L6, CCL4L7, CCL4L8, CCL4L9, CCL4L10, CCL4L11, CCL4L12, CCL4L13, CCL4L14, CCL4L15. The heatmap shows varying levels of expression, with sample 3 generally showing higher expression than sample 5. A dendrogram on the left indicates the hierarchical clustering of the samples.

## Script walkthrough 4

- citation
- Segal et al, Development 2001
- Krejci et al, Development 2002

## Script walkthrough 5

- ```
# redo the heatmap by using just the genes in the experimentally verified set
is.experimental <- rownames(values) %in% experim.genes
heatmap(values[ is.experimental, ], scale="none", col = cm.colors(256))
```

[illegible]

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## Gene clustering review

- We load in the five tables twice - first to collect gene names, then to load expression values
- Based on expression table (values) we construct a clustered heatmap first on the whole set of genes, then on a selected subset
- Go through the code, try it out it and understand it
- Try answering the following questions:
  - what is `rownames(values)` ?
  - why is `rownames(values)[index]` and `t$gene` giving the same output?
  - what is the difference between `rownames(values) %in% experim.genes` and `experim.genes %in% rownames(values)`

Example code:  
13\_geneClustering.R

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## Graphics

### 4

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## Starting out with R graphics

### Graphics

- R provides several mechanisms for producing graphical output
  - Functionality depends on the level at which the user seeks interaction with R
    - graphics systems, packages, devices & engines
- High level graphics
  - Functions compute an appropriate chart based up on the information provided. Optional arguments may tailor the chart as required
    - Interaction is at traditional graphics system level. The user isn't required to know much about anything
- Low level graphics
  - The user interacts with the drawing device to build up a picture of the chart piece by piece.
    - This fine granular control is only required if you seek to do something exceptional
- R graphics produces plots using a painter's model
  - Elements of the graph are added to the canvas one layer at a time, and the picture built up in levels. Lower levels are obscured by higher levels, allowing for blending, masking and overlaying of objects.

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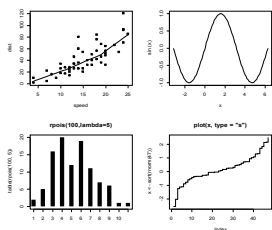
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## High level vs. Low level plotting Graphics



High level plotting  
**example (plot)**

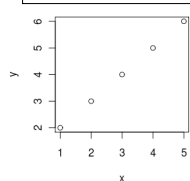


Low level plotting  
(Scotland by blighty package)

## Essential plotting - plot()

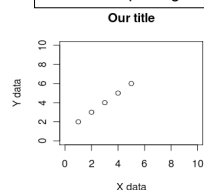
- `plot()` is the main function for plotting, it takes x,y values to plot and also lots of graphical parameters (see **?par** for all of them)

default plotting



```
x <- 1:5
y <- 2:6
plot(x,y)
```

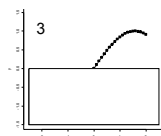
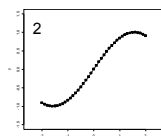
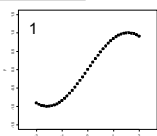
custom plotting



```
x <- 1:5
y <- 2:6
plot(x,y, xlab="X data", ylab="Y
data", xlim=c(0,10), ylim=c(0,10),
main="Our title")
```

## R graphics uses a painter's model

```
x <- seq(-2, 2, 0.1)
y <- sin(x)
```



```
plot(y~x, ylim=c(-1.5,1.5),
xlim=c(-2.5,2.5),
col="red", pch=16, cex=1.4)
```

```
lines(y~x, ylim=c(-1.5,1.5),
xlim=c(-2.5,2.5), col="blue",
lty=1,lwd=2)
```

```
rect(-2.5,0,2.5,-1.5,
col="white", border="white")
```

xlim, ylim = axis limits  
col = line colour  
pch = plotting character [example (points)]  
cex = character expansion [scaling factor]

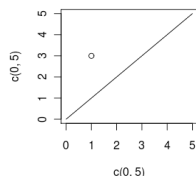
lty = line type  
lwd = line width  
rect = rectangle

Example code:  
14\_painterModel.R



## Plotting x,y data - plot(), points(), lines()

- **plot()** is used to start a new plot, accepts x,y data, but also data from some objects (like linear regression). Use the parameter **type** to draw points, lines, etc (see **?plot**)
- **points()** is used to add points to an existing plot
- **lines()** is used to add lines to an existing plot



```
plot(c(0, 5), c(0, 5), type="l") # draw as line from (0,0) to (5,5)
points(1, 3) # add a point at 1,3
```

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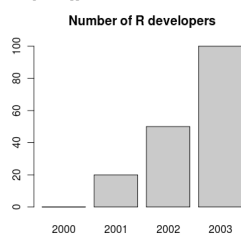
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## Making bar plots - barplot()

- visualizing a vector of data can be done with bar plots, using function **barplot()**



```
data <- c("2000"=0, "2001"=20, "2002"=50, "2003"=100)
barplot(data, main="Number of R developers")
```

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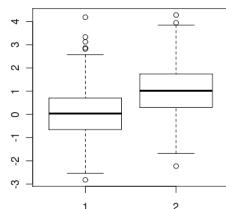
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## Making box plots - boxplot()

- when a spread of data needs to be visualised, we can use boxplots with function **boxplot()**



```
data1 <- rnorm(1000, mean=0)
data2 <- rnorm(1000, mean=1)
boxplot(data1, data2)
```

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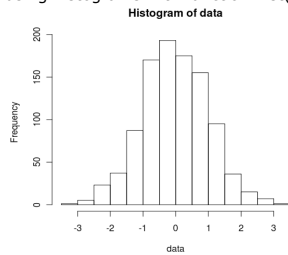
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## Making histograms - hist()

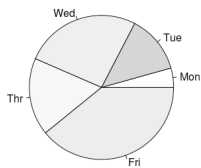
- when we need to look at the distribution of data, we can visualize it using histograms with function `hist()`



```
data <- rnorm(1000)
hist(data)
```

## Pie charts - pie()

- to visualise percentages or parts of a whole we can use pie charts with function `pie()`



```
data <- c("Mon"=1, "Tue"=3, "Wed"=6, "Thr"=4, "Fri"=9)
pie(data)
```

## Typical plotting workflow

- Set the plot layout and style - `par()`
  - Set the number of plots you want per page
  - Set the outer margins of the figure region
    - The distance between the edge of the page and the figure region, or between adjacent plots if there are multiple figures per page
  - Set the inner margins of the plot
    - The distance between the plot axes and the labels & titles
  - Set the styles for the plot
    - Colours, fonts, line styles and weights
- Draw the plot - `plot(x, y, ...)`

## Setting graphics layout and style - par()

- par()** Top level graphics function
- parameter specifies various page settings. These are inherited by subordinate functions, if no other styles are set.
    - Specific colours and styles may be set globally with **par**, but changed ad hoc in plotting commands
    - The global setting will remain unchanged, and reused in future plotting calls.
  - par** sets the size of page and figure margins
    - Margin spacing is in 'lines'
  - par** is responsible for controlling the number of figures that are plotted on a page
  - par** may set global colouring of axes, text, background, foreground, line styles (solid/dashed), if figures should be boxed or open etc. etc.

type **par()** to get a list of top down settings which may be set globally

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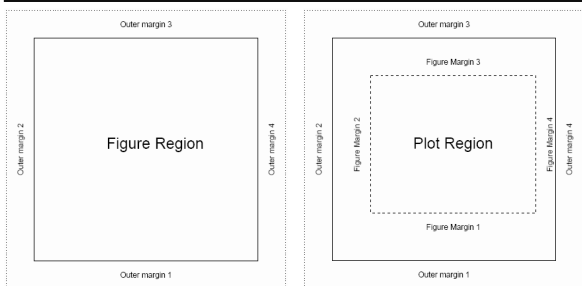
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## Page settings with par Graphics



```
par(mfrow=c(1,1))  
one figure on page  
par(oma=c(2,2,2,2))  
equal outer margins
```

```
par(mar=c(5,4,4,2))  
Sets space for x & y labels, a main title, and a thin margin on the right
```

Numbering: bottom, left, top, right

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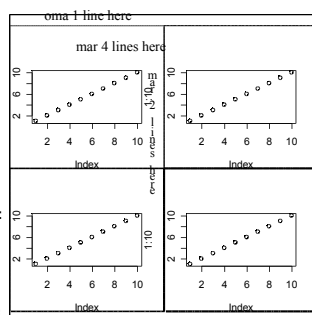
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## Page layout plot exercise Graphics

- ```
par(mfrow=c(2,2))  
• 2 x 2 figures per page  
par(oma=c(1,0,1,0))  
• 1 line spacing top and bottom  
par(mar=c(4,2,4,2))  
• 4 lines at bottom & top  
• 2 lines left & right  
par(bg="lightblue",fg="darkgrey")  
• light blue background  
• dark grey spots  
par(pch=16,cex=1.4)  
• Large circles for spots  
• Execute 4 times with different colors:  
plot(1:10)  
box("figure",lty=3,col="blue")  
• Draw a blue dashed line around plot  
box("outer",lty=1,lwd=3,  
col="green")  
• Draw a green solid line around figure
```



See how the figure margins overlap  
Using painter's model

15\_parExample.R

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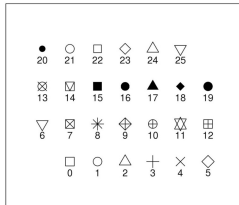
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## Plotting characters for plot() size and orientation

**pch=** ...  
Sets one of the 26 standard plotting character used.  
Can also use characters, such as "."  
**cex=** ...  
Character expansion. Sets the scaling factor of the printing character  
**las=** ...  
Axes label style. 1 normal, 2 rotated 90°  
4 styles (0-3)

26 standard plotting characters



## Plotting characters exercise Graphics

```
xCounter<-1
yCounter<-1
plotChar<-0

plot(NULL, xlim=c(0,8),
      ylim=c(0,5), xaxt="n",
      yaxt="n", ylab="", xlab=""
      ,main="26 standard plotting
      characters")

while (plotChar < 26){
  if(xCounter < 7){
    xCounter <- xCounter+1
  } else {
    xCounter <- 1
    yCounter <- yCounter+1
  }

  points(xCounter,yCounter,pch=plotChar,
         cex=2)
  text(xCounter,(yCounter-0.3),plotChar)
  plotChar <- plotChar+1
}
```

**16\_plottingChars.R**

X-Y coordinates,  
Plotting character index counter

Sets up an empty plotting area.  
Axis scale limits, xlim, ylim  
Don't draw axis ticks, xaxt, yaxt="n"  
Don't annotate axis, xlab, ylab=""  
Set a main title, main

We want to print the characters in a  
7 x 4 grid. The if statement sets up  
the character plotting coordinates  
such that each time x = 7, make it 1  
again and increment the y axis by 1 at  
the same time

While loop counts up to 25  
(0 to 25 = 26 iterations)  
And cycles through each pch  
available

## Annotating the plot

- plot accepts main title, subtitle, X label, Y label as standard arguments
- ```
plot(x, y, main="...", sub="...", xlab="...", ylab="...")
mtext(text="...", side=...)
```
- allows text to be written directly into the margin of a plot
- ```
text(x,y,labels="...")
```
- allows text to be written in the plot at x,y
- ```
legend(x,y, legend=...)
```
- produces a legend for the plot

## Appreciating drawing coordinates

- How do we know where to place items within the plot region when building up our customized graphs?
- Most of the time we can specify X,Y coordinates.
  - R calculates sensible pixel coordinates of plots from the data we provide. We don't need to worry about pixels, centimetre distances etc.
- `locator(...)`
  - Returns x,y coordinates from a mouse click within a plot
  - good for working out where to place legend items
- `identify(...)`
  - provides an id tag for the closest plotted point to a mouse click
  - useful if you want to label points on a chart
- `xy.coords(...)`
  - translates x,y coordinates into pixel coordinates
- Margin spacing is in lines
  - The exact distance is a factor of font family, style and size
  - Text may appear bunched or squashed if sufficient distance is not left between the axes and the caption

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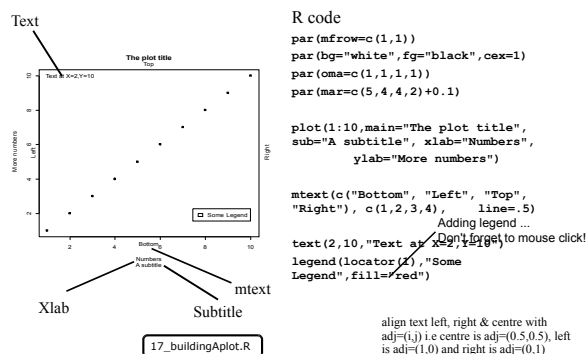
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## Building up a plot Graphics



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## Plots with custom axes Graphics

- R `plot` doesn't support multiple Y axis by default
    - You have to make additional axes yourself!
  - Adding custom axis
- ```
axis(side=, at=, labels=, ...)
```
- If you want to specify custom axes, make sure you turn off the automatic axes in the plot / points call
- ```
plot( ..., axes=F)
```

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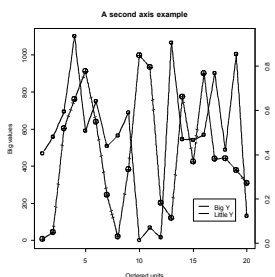
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## Adding a second Y axis

### Graphics



#### The trick

1. plot first Y series
2. use `par(new=T)` to overlay a second figure region
3. plot second series without axes
4. `axis(side=4, ...)` to add second Y axis
5. `mtext(side=4, ...)` to label second Y

## Example: The second Y series

### Graphics

```
x1<-1:20
y1<-sample(1000,20)
y2<-runif(20)
y2axis<-seq(0,1,.2)
```

Demo data

```
par(mar=c(4,4,4,4))
```

Set up equivalent figure margins

```
plot(x1,y1,type="p",pch=10,cex=2,col="red",
     main="A second axis example",
     ylab="Big values",ylim=c(0,1100),
     xlab="Ordered units")
points(x1,y1,type="l",lty=3,lwd=2,col="green")
```

Plot and label first Y series

Connect dots with a line

```
par(new=T)
```

Overlay a second plot region

```
plot(x1,y2,type="p",pch=20,cex=2,col="black",axes=FALSE,bty="n",xlab="",ylab="")
points(x1,y2,type="l",lty=2,lwd=2,col="grey")
```

Plot second Y series, but suppress labels

```
axis(side=4,at=pretty(y2axis))
mtext("Little values",side=4,line=2.5)
```

Anotate second Y axis

```
legend(15,0.2,c("Big Y","Little Y"),lty=1,lwd=2,col=c("green","grey"))
```

Add legend, note X,Y is on second Y axis scale

## Use of colour in R

### Graphics

- Colour is usually expressed as a hexadecimal code of Red, Green, and Blue counterparts
  - No good for humans.
- R supports numerous colour palettes which are available through several "colour" functions.
  - `colours()` # get inbuilt names of known colours
    - RGB primaries may take on a decimal intensity value of 0 to 255
      - 255 is #FF in hexadecimal
        - White is #FF FF FF
        - Black is #00 00 00
  - `rgb()` # converts red green blue intensities to colour
    - Strangely, likes decimalized intensities (ie. 0 is black, 1 is white)

```
> rgb(1,1,1)
[1] "FFFFFF"

> par(mfrow=c(2,2))
> plot(1:10,col="#FF00FF")
> plot(1:10,col=rgb(1,0,1))
> plot(1:10,col="magenta")
```

## Colour Ramps & Palettes Graphics

- Heatmaps use colour depth to convey data values. Cold colours are typically low values, and light colours are high state values. This is a colour ramp.

- R supports numerous graded colour charts. Specify *n*, to set the number of gradations required in the palette

```
rainbow(n)
```

heat.colors(n)

terrain.colors(n)

topo.colors (n)

cm.colors(n)



19\_colourCharts.R

You can specify a user defined palette of indexed colours:

```
palette(rainbow(7)) # creates 7 indexed colours (1:7) based on
                    # rainbow palette R O Y G B I V !!!
```

Colour packages: RColorBrewer  
Graphics

- This add on package provides a series of well defined colour palettes. The colours in these palettes are selected to permit maximum visual discrimination
- Access the RColorBrewer library functions ...

```
library("RColorBrewer")
```

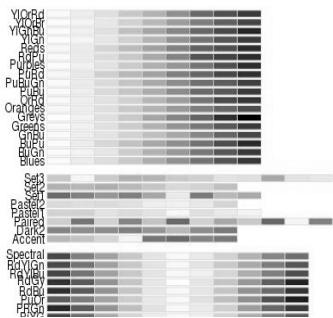
- Check out the available palettes

```
display.brewer.all(n=NULL, type="all", select=NULL, exact.n=TRUE)
```

- Define your own palette based on one of RColorBrewers'

```
myCol<-brewer.pal(n,"...") # n=number of colours, "..." is the palette name
```

## RColorBrewer named palettes



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## Saving plots to files

- Unless specified, R plots all graphics to the screen
- To send plots to a file, you need to set up an appropriate graphics device ...

```
postscript(file="a_name.ps", ...)
```

```
pdf(file="_.pdf", ...)
```

```
jpeg(file="_.jpg", ...)
```

```
png(file="_.png", ...)
```

- Each graphics device will have a specific set of arguments that dictate characteristics of the outputted file
  - `height=`, `width=`, `horizontal=`, `res=`, `paper=`
    - Top tip: jpeg, A4 @ 300 dpi, portrait, size in pixels
    - `jpg(file="my_Figure.jpg", height=3510, width=2490, res=300)`
    - Postscript & pdf work in inches by default, A4 = 8.3" x 11.7"

- Graphics devices need closing when printing is finished

```
dev.off()
```

for example:

```
png("tenPoints.png", width=300, height=300)
plot(1:10)
dev.off()
```

## Thoughts when plotting to a file

### Graphics

- Its very tempting to send all graphical output to a pdf file. Caution!
  - For high resolution publication quality images you need postscript. Set up postscript file capture with the following function

```
postscript("a_file.ps", paper="a4")
```

- postscript images can be converted to JPEG using ghostscript (free to download) for low resolution lab book photos and talks
- PDF images will grow too large for acrobat to render if plots contain many data points (e.g. Affymetrix MA plots)
- Automatically send multiple page outputs to separate image files using `...file="somename%02d.jpg"`
- Don't forget to close graphics devices (i.e. the file) by using
  - `dev.off()`

## Plotting exercise

### Graphics

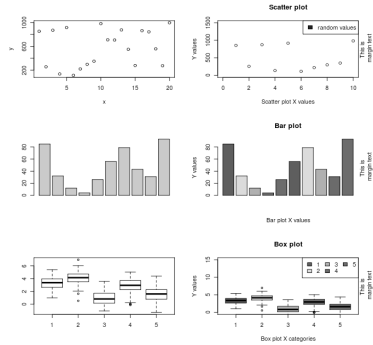
- Exercise:
  - Make a full A4 page figure comprising of 6 plots: 2 each of XY plot (`plot()`), barchart (`barplot()`) and box plots (`boxplot()`)
  - The two version of each plots should consist of: the default plot and a customised plot (change for instance colours, range, captions...)
  - Output the completed 6-panel figure to: screen, jpeg, postscript and pdf file
- Suggested route to solution:
  1. Generate some plotting data appropriate for each type of plot
  2. Write the code to produce the six plots, once plotting the data by using default plotting, one with some customisations you want
  3. To output the plot to screen, jpeg, postscript and pdf you will need to redo the plot multiple times - create a function to do a plotting and call it by redirecting graphical output to screen, jpeg file, postscript file and pdf file

20\_6PanelPlotScript.R



## 6 Panel plots exercise

### Graphics



## References

- Official documentation on:
  - <http://cran.r-project.org/manuals.html>
- A good repository of R recipes:
  - Quick-R: <http://www.statmethods.net/>
- Don't forget that many packages come with tutorials (vignettes)
- Website of this course:
  - <http://logic.sysbiol.cam.ac.uk/teaching/Rcourse/>
- R forums (stackoverflow & official):
  - <http://stackoverflow.com/questions/tagged/r>
  - <http://news.gmane.org/gmane.comp.lang.r.general>
- Plenty of textbooks to choose from, comprehensive list + reviews:
  - <http://www.r-project.org/doc/bib/R-books.html>

Thanks for your attention!

**END OF COURSE**