Lock5 with R

a companion to

Statistics: Unlocking the Power of Data

Randall Pruim and Lana Park

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0.1 Getting Started With RStudio

RStudio

RStudio provides an integrated development environment (IDE) for R that makes R much easier to use. It is freely available from http://rstudio.com in versions for Macintosh, PC, or Linux. RStudio server provides access to RStudio via a web browser. We will generally assume that RStudio is being used throughout. Although most things can be done without RStudio as well, our descriptions may apply only to RStudio.

Loading packages

R is divided up into packages. A few of these are loaded every time you run R, but most have to be selected. This way you only have as much of R as you need.

In the Packages tab in RStudio, check the boxes next to the following packages to load them:

- Lock5withR (data sets and utilities to accompany the text)
- mosaic (a package from Project MOSAIC)
- mosaicData (Project MOSAIC data sets)

You can also load these packages with the following commands:

require-packages

```
require(Lock5withR)
require(mosaic)
require(mosaicData)
```

We will always assume that these three packages have been loaded.

Using R as a calculator

Notice that RStudio divides its world into four panels. Several of the panels are further subdivided into multiple tabs. The console panel is where we type commands that R will execute.

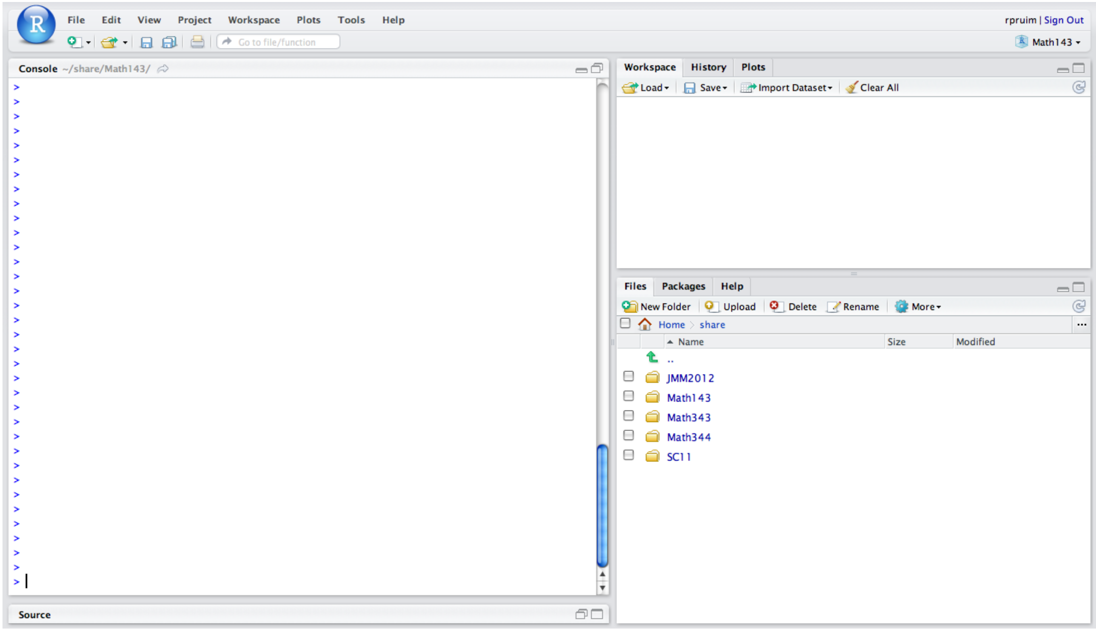


Figure 1: Welcome to RStudio.

R can be used as a calculator. Try typing the following commands in the console panel.

arithmetic2

```
5 + 3

[1] 8

15.3 * 23.4

[1] 358

sqrt(16)

[1] 4
```

You can save values to named variables for later reuse

variables2

```
product = 15.3 * 23.4       # save result
product                     # show the result

[1] 358

product <- 15.3 * 23.4      # <- is assignment operator, same as =
product

[1] 358
```

```
15.3 * 23.4 -> newproduct   # -> assigns to the right
newproduct

[1] 358

.5 * product                # half of the product

[1] 179

log(product)                # (natural) log of the product

[1] 5.88

log10(product)              # base 10 log of the product

[1] 2.55

log(product, base = 2)      # base 2 log of the product

[1] 8.48
```

The semi-colon can be used to place multiple commands on one line. One frequent use of this is to save and print a value all in one go:

variables-semi2

```
15.3 * 23.4 -> product; product    # save result and show it

[1] 358
```

0.2 Getting Help in RStudio

The RStudio help system

There are several ways to get RStudio to help you when you forget something. Most objects in packages have help files that you can access by typing something like:

help-questionmark

```
?bargraph
?histogram
?HELPrct
```

You can search the help system using

help-GR

```
help.search("Grand Rapids")  # Does R know anything about Grand Rapids?
```

This can be useful if you don't know the name of the function or data set you are looking for.

History

If you know you have done something before, but can't remember how, you can search your history. The history tab shows a list of recently executed commands. There is also a search bar to help you find things from longer ago.

Error messages

When things go wrong, R tries to help you out by providing an error message. If you can't make sense of the message, you can try copying and pasting your command and the error message and sending to me in an email. One common error message is illustrated below.

error-message

```
fred <- 23
frd

Error in eval(expr, envir, enclos):  object 'frd' not found
```

The object `frd` is not found because it was mistyped. It should have been `fred`. If you see an "object not found" message, check your typing and check to make sure that the necessary packages have been loaded.

0.3 Four Things to Know About R

Computers are great for doing complicated computations quickly, but you have to speak to them on their terms. Here are few things that will help you communicate with R.

1. R is case-sensitive

   If you mis-capitalize something in R it won't do what you want.

2. Functions in R use the following syntax:

   function-syntax

   ```
   functionname(argument1, argument2, ...)
   ```

   - The arguments are always *surrounded by (round) parentheses* and *separated by commas*.

     Some functions (like `data()`) have no required arguments, but you still need the parentheses.

   - If you type a function name without the parentheses, you will see the *code* for that function – which probably isn't what you want at this point.

3. TAB completion and arrows can improve typing speed and accuracy.

   If you begin a command and hit the TAB key, R will show you a list of possible ways to complete the command. If you hit TAB after the opening parenthesis of a function, it will show you the list of arguments it expects. The up and down arrows can be used to retrieve past commands.

4. If you get into some sort of mess typing (usually indicated by extra '+' signs along the left edge), you can hit the escape key to get back to a clean prompt.

0.4 Data in R

Data in Packages

Most often, data sets in R are stored in a structure called a **data frame**. There are a number of data sets built into R and many more that come in various add on packages. The Lock5withR package, for example, contains all the data sets from our text book. In the book, data set names are printed in bold text.

You can see a list of them using

datasets

```
data(package = "Lock5withR")
```

You can find a longer list of all data sets available in any loaded package using

```
data()
```

The HELPrct data set

The HELPrct data frame from the mosaicData package contains data from the Health Evaluation and Linkage to Primary Care randomized clinical trial. You can find out more about the study and the data in this data frame by typing

HELPrcthelp

```
?HELPrct
```

Among other things, this will tell us something about the subjects in this study:

> Eligible subjects were adults, who spoke Spanish or English, reported alcohol, heroin or cocaine as their first or second drug of choice, resided in proximity to the primary care clinic to which they would be referred or were homeless. Patients with established primary care relationships they planned to continue, significant dementia, specific plans to leave the Boston area that would prevent research participation, failure to provide contact information for tracking purposes, or pregnancy were excluded.
>
> Subjects were interviewed at baseline during their detoxification stay and follow-up interviews were undertaken every 6 months for 2 years.

It is often handy to look at the first few rows of a data frame. It will show you the names of the variables and the kind of data in them:

headHELP

```
head(HELPrct)
```

```
  age anysubstatus anysub cesd d1 daysanysub dayslink drugrisk e2b female    sex g1b
1  37            1    yes   49  3        177      225        0  NA      0   male yes
2  37            1    yes   30 22          2       NA        0  NA      0   male yes
3  26            1    yes   39  0          3      365       20  NA      0   male  no
4  39            1    yes   15  2        189      343        0   1      1 female  no
5  32            1    yes   39 12          2       57        0   1      0   male  no
```

```
6  47            1    yes    6  1         31      365        0  NA      1 female  no
  homeless i1 i2 id indtot linkstatus link   mcs  pcs pss_fr racegrp satreat sexrisk
1   housed 13 26  1     39          1  yes 25.11 58.4      0   black      no       4
2 homeless 56 62  2     43         NA <NA> 26.67 36.0      1   white      no       7
3   housed  0  0  3     41          0   no  6.76 74.8     13   black      no       2
4   housed  5  5  4     28          0   no 43.97 61.9     11   white     yes       4
5 homeless 10 13  5     38          1  yes 21.68 37.3     10   black      no       6
6   housed  4  4  6     29          0   no 55.51 46.5      5   black      no       5
  substance treat
1   cocaine   yes
2   alcohol   yes
3    heroin    no
4    heroin    no
5   cocaine    no
6   cocaine   yes
```

That's plenty of variables to get us started with exploration of data.

Using your own data

From Excel or Google to R

So far we have been using data that lives in R packages. This has allowed us to focus on things like how to make plots and create numerical summaries without worrying too much about the data themselves. But if you are going to do any of your own statistical analyses, then you will need to import your own data into R and have some tools for manipulating the data once it is there.

Excel or Google spreadsheets are reasonable tools for entering (small) data sets by hand and doing basic data tidying (organizing) and cleaning (correcting errors). This section describes how to get data from a spreadsheet into R.

While you are still in the spreadsheet

If you are creating your own data in a spreadsheet with the intent of bringing into R (or some other statistical package) for analysis, it is important that you design your spreadsheet appropriately. For most data sets this will mean

1. The first row should contain variables names.

   These should be names that will work well in R. This usually means they will be relatively short and avoid spaces and punctuation.

2. Each additional row corresponds to a case/observational unit.

3. Each column corresponds to a variable.

4. There is **nothing** else in the spreadsheet.

   Do not include notes to yourself, plots, numerical summaries, etc. These things can be kept in a separate worksheet, another file, your lab notebook, just not in the worksheet you are going to export.

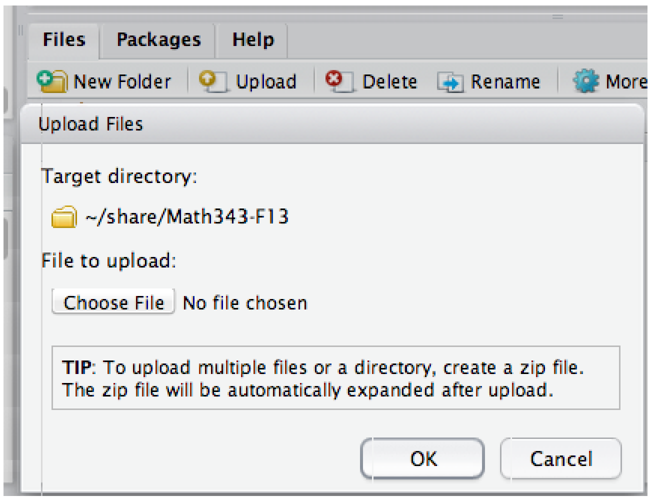
Exporting to csv

The comma separated values (csv) format has become a standard way of transferring data between programs. Both Google and Excel can export to this format, and R can import from this format. Once your dataare ready to go, export them to csv. Give the file a good name, and remember where you have put it.

Uploading the data (RStudio server only)

To get the data from your computer onto the server, you need to **upload** the data. (You can skip this step if you are working with a local copy of RStudio.) Uploading transfers a copy of your data from your computer onto the server (the "cloud"). This is like uploading pictures to Facebook so you can later use them in posts or as a cover photo or tag your friends or whatever else once the photo is on Facebook.

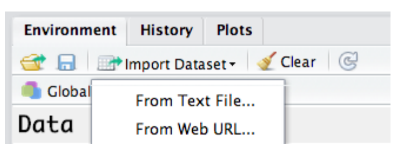
To upload the data, go to the **Files** tab and click on **Upload**:



A window will pop up prompting you to browse to the file's location on your computer. Choose the file and it will upload to the server. You should see it appear in your file menu.

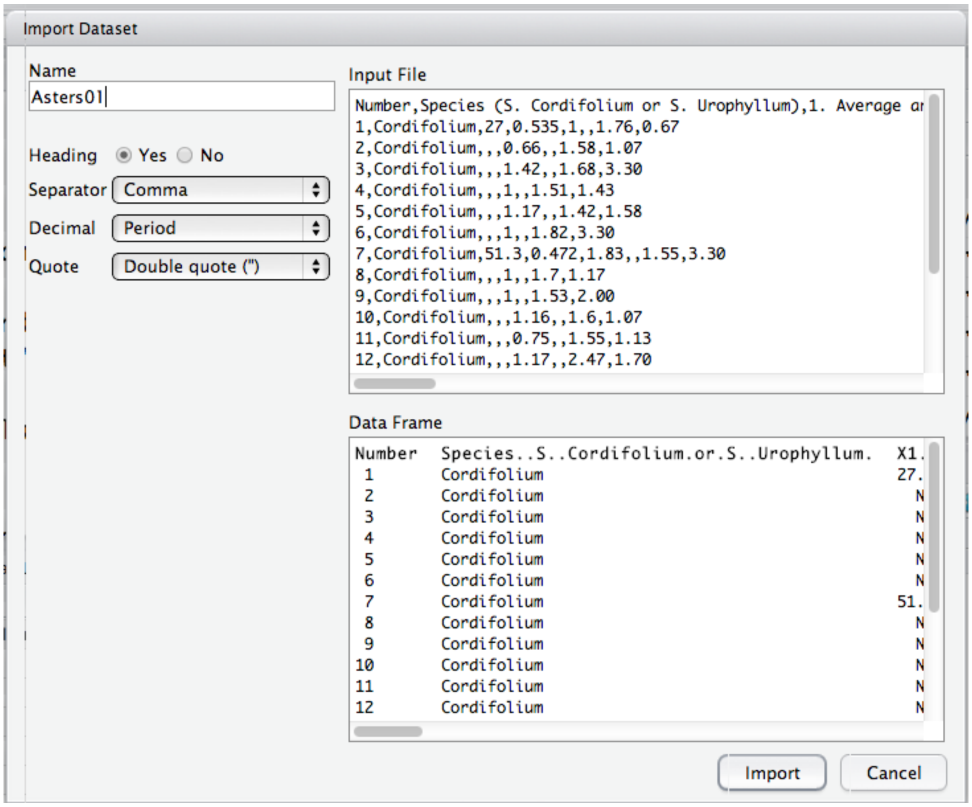
Importing the data into R

Now that the file is on the server, you can import it into R. This takes place in the **Environment** tab. Once there, choose **Import Dataset** and then **From Text File...**.



The instructions are pretty clear from there, but here are some things to watch for:

- The default name for the data set is taken from the file name. If you used a very long file name, you will probably want to shorten this down. (But don't call it `Data` or something too generic either.) If the data are from the asters you have been tagging, perhaps call it `Asters`. If you are working with multiple data sets that deal with asters, add a bit more detail, perhaps `Asters01` or some such thing.
- Be sure to select to use your first line as variable names (Heading = Yes).



The data set should now be ready for use in R.

A shortcut for Google Spreadsheets

The new `googlesheets` package provides a number of utilities for reading and writing between R and Google sheets. At the time of this writing, it is in active development and available via github.

Using R commands to read a data file

Even if you primarily use the RStudio interface to import data, it is good to know about the command line methods since these are required to import data into scripts, RMarkdown, and Rnw files. CSV files (and a few other types of files as well) can be read with

```
someData <- read.file("file.csv")
```

This can be used to read data directly from a URL as well. For example, here is some data from the US Census Bureau:

```
Population <- read.file(
  "https://www.census.gov/popest/data/national/totals/2012/files/NST_EST2012_ALLDATA.csv"
)


Loading required namespace:  RCurl
Reading data with read.csv()


dim(Population)
```



```
[1] 57 46

head(Population, 4)

  Sumlev Region Division State              Name CENSUS2010POP ESTIMATESBASE2010
1     10      0        0     0     United States     308745538         308747508
2     20      1        0     0 Northeast Region      55317240          55317245
3     20      2        0     0   Midwest Region      66927001          66927489
4     20      3        0     0     South Region     114555744         114557147
  POPESTIMATE2010 POPESTIMATE2011 POPESTIMATE2012 NPOPCHG_2010 NPOPCHG_2011 NPOPCHG_2012
1       309326225       311587816       313914040       578717      2261591      2326224
2        55376926        55597646        55761091        59681       220720       163445
3        66972135        67145089        67316297        44646       172954       171208
4       114853800       116022230       117257221       296653      1168430      1234991
  BIRTHS2010 BIRTHS2011 BIRTHS2012 DEATHS2010 DEATHS2011 DEATHS2012 NATURALINC2010
1     987836    3977039    3953593     598716    2490976    2513173         389120
2     160353     644224     631961     108678     465661     466970          51675
3     210660     839312     825776     141184     580842     580718          69476
4     373379    1503557    1510568     235600     956673     970844         137779
  NATURALINC2011 NATURALINC2012 INTERNATIONALMIG2010 INTERNATIONALMIG2011
1        1486063        1440420               189597               775528
2         178563         164991                48282               211281
3         258470         245058                24794               100624
4         546884         539724                71591               282102
  INTERNATIONALMIG2012 DOMESTICMIG2010 DOMESTICMIG2011 DOMESTICMIG2012 NETMIG2010
1               885804               0               0               0     189597
2               221546          -38396         -161531         -220968       9886
3               111790          -49082         -184696         -185118     -24288
4               337769           86302          325546          353879     157893
  NETMIG2011 NETMIG2012 RESIDUAL2010 RESIDUAL2011 RESIDUAL2012 Rbirth2011 Rbirth2012
1     775528     885804            0            0            0       12.8       12.6
2      49750        578        -1880        -7593        -2124       11.6       11.4
3     -84072     -73328         -542        -1444         -522       12.5       12.3
4     607648     691648          981        13898         3619       13.0       13.0
  Rdeath2011 Rdeath2012 RNATURALINC2011 RNATURALINC2012 RINTERNATIONALMIG2011
1       8.02       8.04            4.79            4.61                  2.50
2       8.39       8.39            3.22            2.96                  3.81
3       8.66       8.64            3.85            3.65                  1.50
4       8.29       8.32            4.74            4.63                  2.44
  RINTERNATIONALMIG2012 RDOMESTICMIG2011 RDOMESTICMIG2012 Rnetmig2011 Rnetmig2012
1                  2.83             0.00             0.00       2.498      2.8323
2                  3.98            -2.91            -3.97       0.897      0.0104
3                  1.66            -2.75            -2.75      -1.254     -1.0907
4                  2.90             2.82             3.03       5.264      5.9298
```

Many web sites provide data in csv format. Here some examples:

- `http://www.census.gov/` (Census Bureau data)
- `http://www.ncdc.noaa.gov/data-access` (NOAA Weather and climate data)
- `http://www.gapminder.org/data/` (Gapminder data)
- `http://introcs.cs.princeton.edu/java/data/` has a number of data sets, some in csv format, collected from other places on the internet.
- `http://www.exploredata.net/Downloads` has data from WHO, a genome expression study, and a microbiome study.

But be aware that some of these files might need to be cleaned up a bit before they are usable for statistics. Also, some internet files are very large and may take a while to download. Many sites will give an indication of the size of the data set so you know what you are in for. The better sites will include links to a code book (a description of all the variables, units used, how and when the data were collected, and any other information relevant to interpreting the data). Such a document is available for the population data loaded above. You can find it at `http://www.census.gov/popest/data/national/totals/2012/files/NST-EST2012-alldata.pdf`

Missing Data

The `na.strings` argument can be used to specify codes for missing values. The following can be useful, for example:

```
someData <- read.file('file.csv', na.strings = '.')
someData <- read.file('file.csv', na.strings = '-')
```

because SAS uses a period (`.`) to code missing data, and some csv exporters use '`-`'. By default R reads these as string data, which forces the entire variable to be of character type instead of numeric.

Importing Other Kinds of Data

Many R packages provide the ability to load data from special data files. If you have data in some other format, there may well be a package that makes it easy to load your data into R. For example, several packages (including `readxl`) provide the ability to read data directly from Excel files without first saving the data as a csv file. If you make frequent use of Excel spreadsheets, you may find this convenient. `rdrop2` provides the ability to manage data with Dropbox. And the `foreign` package provides functions to read data from a wide range of other statistical packages. But since these typically all know how to read and write csv files, learning a workflow that goes through CSV is a broadly applicable skill.

0.5 The Most Important Template

Most of what we will do in this chapter makes use of a single R template:

$$\boxed{}\,(\,\boxed{} \sim \boxed{}\,,\ \texttt{data} = \boxed{}\,)$$

It is useful if we name the slots in this template:

$$\boxed{\texttt{goal}}\,(\,\boxed{\texttt{y}} \sim \boxed{\texttt{x}}\,,\ \texttt{data} = \boxed{\texttt{mydata}}\,)$$

Actually, there are some variations on this template:

```
### Simpler version -- for just one variable
goal(~x, data = mydata)
### Fancier version:
goal(y ~ x | z, data = mydata)
### Unified version:
goal(formula, data = mydata)
```

To use the template (we'll call it the formula template because there is always a formula involved), you just need to know what goes in each slot. This can be determined by asking yourself two questions:

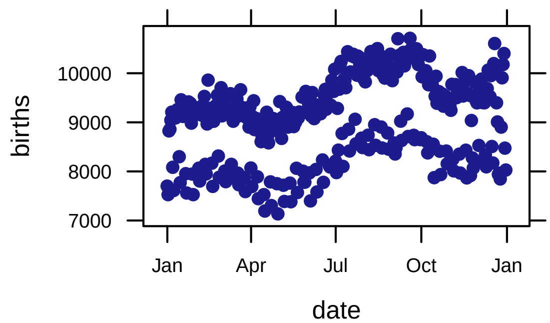
1. What do you want R to do?

    - this determines what function to use (goal).

2. What must R know to do that?

    - this determines the inputs to the function
    - for describing data, must must identify *which data frame* and *which variable(s)*.

Let's try an example. Suppose we want to make this plot



1. What is our goal?

    Our goal is to make a scatter plot. The function that does this is called `xyplot()`. That takes care of the first slot.

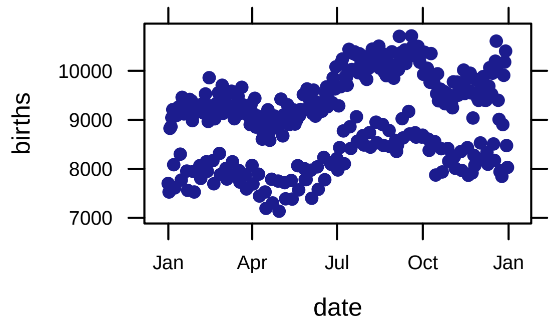
2. What does R need to know to do this?

    It needs to know what data set to use, and which varialbes to use on the x and y axes. These data are in the `Births78` data set in the `mosaicData` package. Let's take a quick look at the data:

    births-head
    ```
    require(mosaicData)  # load the package that contains our data set
    head(Births78)

            date births dayofyear  wday
    1 1978-01-01   7701         1   Sun
    2 1978-01-02   7527         2   Mon
    3 1978-01-03   8825         3  Tues
    4 1978-01-04   8859         4   Wed
    5 1978-01-05   9043         5 Thurs
    6 1978-01-06   9208         6   Fri
    ```

    We want the date on the x-axis and the number of births on the y axis, so the full command is

    births-scatterplot
    ```
    xyplot(births ~ date, data = Births78)
    ```



This same template can be used for a wide variety of graphical and numerical summaries. For example, to compute the mean number of births, we can change `xyplot()` to `mean()` and provide `births` but not `date`:

```
mean(~births, data = Births78)

[1] 9132
```

Notice that when there is only one variable, it goes on the right side of the wiggle (code~).

We'll see more examples of this template as we go along.

0.6 Manipulating your data

Creating a subset

The `filter()` command can be used to create subsets. The population data set we downloaded has population for states and various other regions. If we just want the states, we can select the items where the `State` variable is greater than 0. (Notice the double equals for testing equality.)

filter

```
States <- filter(Population, State > 0)
dim(States)

[1] 52 46
```

That two states too many. We can scan the list to see what else is in there.

extra-states

```
States$name

NULL
```

The two extras are Washington, DC and Peurto Rico.

Choosing specific columns

filter() chooses rows from a data frame. select() selects columns. This can be handy if you have a data set with many more variables than you are interested in. Let's pick just a handful from the Population data set.

select

```
States2 <- select(States, Name, POPESTIMATE2010, POPESTIMATE2011, POPESTIMATE2012)
```

Dropping Variables

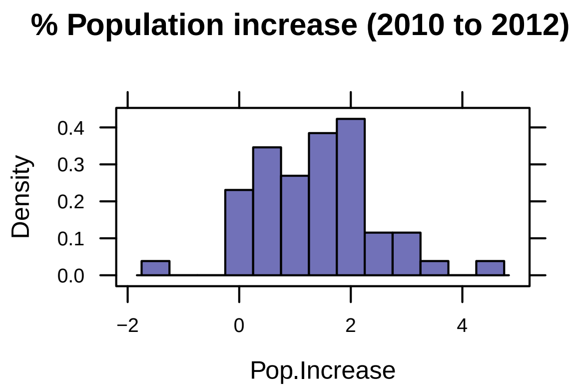
Sometimes it is easier to think about dropping variables. We can use select() for this as well:

```
iris2 <- select(iris, -Sepal.Width, -Sepal.Length)  # the minus sign means drop
head(iris2, 3)


  Petal.Length Petal.Width Species
1          1.4         0.2  setosa
2          1.4         0.2  setosa
3          1.3         0.2  setosa
```

Creating new variables

We can add a new variable to data set using mutate():

```
head(iris, 3)


  Sepal.Length Sepal.Width Petal.Length Petal.Width Species
1          5.1         3.5          1.4         0.2  setosa
2          4.9         3.0          1.4         0.2  setosa
3          4.7         3.2          1.3         0.2  setosa


iris3  <- mutate(iris,
                   Sepal.Ratio = Sepal.Length / Sepal.Width,
                   Petal.Ratio = Petal.Length / Petal.Width )
head(iris3, 3)


  Sepal.Length Sepal.Width Petal.Length Petal.Width Species Sepal.Ratio Petal.Ratio
1          5.1         3.5          1.4         0.2  setosa        1.46         7.0
2          4.9         3.0          1.4         0.2  setosa        1.63         7.0
3          4.7         3.2          1.3         0.2  setosa        1.47         6.5


States3 <- mutate(States2,
                   Pop.Increase = 100 * (POPESTIMATE2012 - POPESTIMATE2010)/POPESTIMATE2010 )
histogram( ~ Pop.Increase, data = States3, width = 0.5,
                          main = "% Population increase (2010 to 2012)")
```



Generally, it is a good idea to keep raw data (like `Sepal.Length` and `Sepal.Width` in your data file, but let R do the computation of derived variables for you. Among other advantages, if you ever fix an error in a `Sepal.Length` measurement, you don't have to worry about remembering to also recompute the ratio. Futhermore, your R code documents how the derived value was computed.

Saving Data

`write.csv()` can be used to save data from R into csv formatted files. This can be useful for exporting to some other program.

writingData

```
write.csv(iris3, "iris3.csv")
```

Data can also be saved in native R format. Saving data sets (and other R objects) using `save()` has some advantages over other file formats:

- Complete information about the objects is saved, including attributes.
- Data saved this way takes less space and loads much more quickly.
- Multiple objects can be saved to and loaded from a single file.

The downside is that these files are only readable in R.

savingData

```
save(iris3, file = "iris3.rda")  # the traditional file extension is rda for R native data.
load("iris3.rda")  # loads previously saved data
```

For more on importing and exporting data, especially from other formats, see the *R Data Import/Export* manual available on CRAN.

Merging datasets

The `fusion1` data frame in the `fastR` package contains genotype information for a SNP (single nucleotide polymorphism) in the gene *TCF7L2*. The `pheno` data frame contains phenotypes (including type 2 diabetes case/control status) for an intersecting set of individuals. We can merge these together to explore the association between genotypes and phenotypes using `merge()`.


```
require(fastR)
head(fusion1, 3)
```

```
     id     marker markerID allele1 allele2 genotype Adose Cdose Gdose Tdose
1  9735 RS12255372        1       3       3       GG     0     0     2     0
2 10158 RS12255372        1       3       3       GG     0     0     2     0
3  9380 RS12255372        1       3       4       GT     0     0     1     1
```

```
head(pheno, 3)
```

```
    id     t2d  bmi sex  age smoker chol waist weight height   whr sbp dbp
1 1002    case 32.9   F 70.8 former 4.57 112.0   85.6    161 0.987 135  77
2 1009    case 27.4   F 53.9  never 7.32  93.5   77.4    168 0.940 158  88
3 1012 control 30.5   M 53.9 former 5.02 104.0   94.6    176 0.933 143  89
```

```
# merge fusion1 and pheno keeping only id's that are in both
fusion1m <- merge(fusion1, pheno, by.x = "id", by.y = "id", all.x = FALSE, all.y = FALSE)
head(fusion1m, 3)
```

```
    id     marker markerID allele1 allele2 genotype Adose Cdose Gdose Tdose     t2d  bmi
1 1002 RS12255372        1       3       3       GG     0     0     2     0    case 32.9
2 1009 RS12255372        1       3       3       GG     0     0     2     0    case 27.4
3 1012 RS12255372        1       3       3       GG     0     0     2     0 control 30.5
  sex  age smoker chol waist weight height   whr sbp dbp
1   F 70.8 former 4.57 112.0   85.6    161 0.987 135  77
2   F 53.9  never 7.32  93.5   77.4    168 0.940 158  88
3   M 53.9 former 5.02 104.0   94.6    176 0.933 143  89
```

In this case, since the values are the same for each data frame, we could collapse `by.x` and `by.y` to `by` and collapse `all.x` and `all.y` to `all`. The first of these specifies which column(s) to use to identify matching cases. The second indicates whether cases in one data frame that do not appear in the other should be kept (`TRUE`) or dropped (filling in `NA` as needed) or dropped from the merged data frame.

Now we are ready to begin our analysis.

fusion1-xtabs

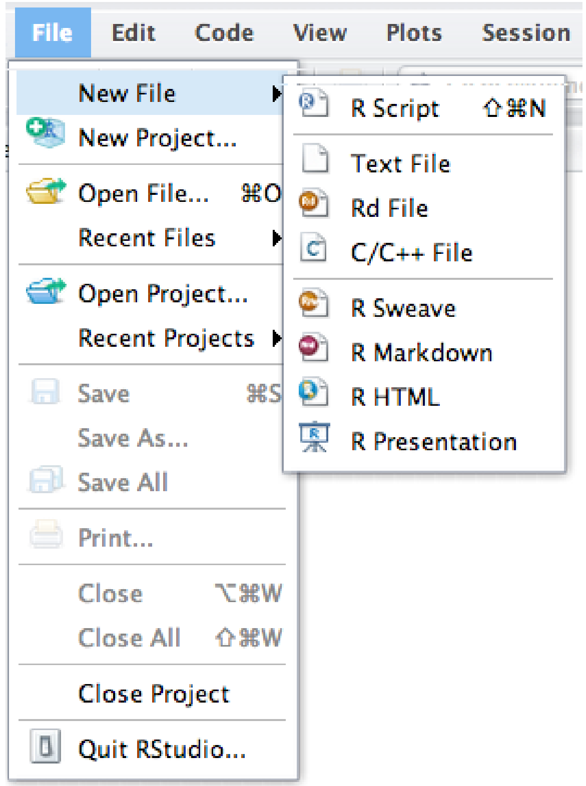
```
tally(~t2d + genotype, fusion1m)
```

```
         genotype
t2d        GG  GT  TT
  case    737 375  48
  control 835 309  27
```

0.7 Using R Markdown

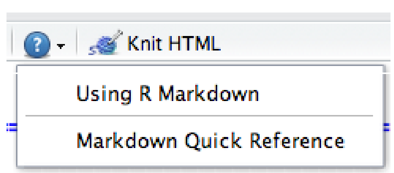
Although you can export plots from RStudio for use in other applications, there is another way of preparing documents that has many advantages. RStudio provides several ways to create documents that include text, R code, R output, graphics, even mathematical notation all in one document. The simplest of these is R Markdown.

To create a new R Markdown document, go to “File”, “New”, then “R Markdown”:

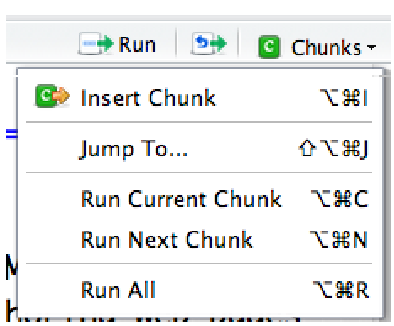


When you do this, a file editing pane will open with a template inserted. If you click on "Knit HTML", RStudio will turn this into an HTML file and display it for you. Give it a try. You will be asked to name your file if you haven't already done so. If you are using the RStudio server in a browser, then your file will live on the server ("in the cloud") rather than on your computer.

If you look at the template file you will see that the file has two kinds of sections. Some of this file is just normal text (with some extra symbols to make things bold, add in headings, etc.) You can get a list of all of these mark up options by selecting the "Mardown Quick Reference" in the question mark menu.



The second type of section is an R code chunk. These are colored differently to make them easier to see. You can insert a new code chunk by selecting "Insert Chunk" from the "Chunks" menu:



(You can also type ```{r} to begin and ``` to end the code chunk if you would rather type.) You can put any R code in these code chunks and the results (text output or graphics) as well as the R code will be displayed in your HTML file.

There are options to do things like (a) run R code without displaying it, (b) run R code without displaying the output, (c) controling size of plots, etc., etc. But for starting out, this is really all you need to know.

R Markdown files must be self-contained

R Markdown files do not have access to things you have done in your console. (This is good, else your document would change based on things not in the file.) This means that you must explicitly load data, and require packages *in the R Markdown file* in order to use them. In this class, this means that most of your R Markdown files will have a chunk near the beginning that includes

```
require(mosaic)  # load the mosaic package
require(Lock5withR)  # get data sets from the book
```

The `mosaic` package provides some templates that are available if you choose "from template" when creating an RMarkdown file in RStudio. Among other things, this will insert the code required to load the `mosaic` package, change some default settings, and include a reminder to load any additional packages you will be using.

Output formats

RStudio makes it easy to generate HTML, PDF, or Word documents from your RMarkdown. Just remember that if you edit any of these files after you generate them with RMarkdown, then you will need to redo those edits if you ever go back and change the RMarkdown file, but if you change the RMarkdown file, one click will generate the new HTML, PDF, or Word document. (There are even ways to get it to generate all three in one go; see the `render()` function in the `rmarkdown` package.) So it is best to keep you editing to the RMarkdown document as much as possible.

0.8 Statistics: Answering Questions With Data

This is a course primarily about statistics, but what exactly is *statistics*? In other words, what is this course about?[1]

Here are some definitions of statistics from other people:

- a collection of procedures and principles for gaining information in order to make decisions when faced with uncertainty (J. Utts [**?**]),
- a way of taming uncertainty, of turning raw data into arguments that can resolve profound questions (T. Amabile [**?**]),
- the science of drawing conclusions from data with the aid of the mathematics of probability (S. Garfunkel [**?**]),
- the explanation of variation in the context of what remains unexplained (D. Kaplan [**?**]),

[1] As we will see, the words *statistic* and *statistics* get used in more than one way. More on that later.

- the mathematics of the collection, organization, and interpretation of numerical data, especially the analysis of a population's characteristics by inference from sampling (American Heritage Dictionary [**?**]).

Here's a simpler definition:

Statistics is the science of answering questions with data.

This definition gets at two important elements of the longer definitions above:

Data – the raw material

Data are the raw material for doing statistics. We will learn more about different types of data, how to collect data, and how to summarize data as we go along.

Information – the goal

The goal of doing statistics is to gain some information or to make a decision – that is, to answer some question.

Statistics is useful because it helps us answer questions like the following: [2]

- Which of two treatment plans leads to the best clinical outcomes?
- Are men or women more successful at quitting smoking? And does it matter which smoking cessation program they use?
- Is my cereal company complying with regulations about the amount of cereal in its cereal boxes?

In this sense, statistics is a science – a method for obtaining new knowledge.Our simple definition is light on describing the context in which this takes place. So let's add two more important aspects of statistics.

Uncertainty – the context

The tricky thing about statistics is the uncertainty involved. If we measure one box of cereal, how do we know that all the others are similarly filled? If every box of cereal were identical and every measurement perfectly exact, then one measurement would suffice. But the boxes may differ from one another, and even if we measure the same box multiple times, we may get different answers to the question *How much cereal is in the box?*

So we need to answer questions like *How many boxes should we measure?* and *How many times should we measure each box?* Even so, there is no answer to these questions that will give us absolute certainty. So we need to answer questions like *How sure do we need to be?*

Probability – the tool

In order to answer a question like *How sure do we need to be?*, we need some way of measuring our level of certainty. This is where mathematics enters into statistics. Probability is the area of mathematics that deals with reasoning about uncertainty.

[2] The opening pages of each chapter of our book include many more questions.

0.9 A First Example: The Lady Tasting Tea

There is a famous story about a lady who claimed that tea with milk tasted different depending on whether the milk was added to the tea or the tea added to the milk. The story is famous because of the setting in which she made this claim. She was attending a party in Cambridge, England, in the 1920s. Also in attendance were a number of university dons and their wives. The scientists in attendance scoffed at the woman and her claim. What, after all, could be the difference?

All the scientists but one, that is. Rather than simply dismiss the woman's claim, he proposed that they decide how one should *test* the claim. The tenor of the conversation changed at this suggestion, and the scientists began to discuss how the claim should be tested. Within a few minutes cups of tea with milk had been prepared and presented to the woman for tasting.

Let's take this simple example as a prototype for a statistical study. What steps are involved?

1. Determine the question of interest.

   Just what is it we want to know? It may take some effort to make a vague idea precise. The precise questions may not exactly correspond to our vague questions, and the very exercise of stating the question precisely may modify our question. Sometimes we cannot come up with any way to answer the question we really want to answer, so we have to live with some other question that is not exactly what we wanted but is something we can study and will (we hope) give us some information about our original question.

   In our example this question seems fairly easy to state: Can the lady tell the difference between the two tea preparations? But we need to refine this question. For example, are we asking if she *always* correctly identifies cups of tea or merely if she does better than we could do ourselves (by guessing)?

2. Determine the **population**.

   Just who or what do we want to know about? Are we only interested in this one woman or women in general or only women who claim to be able to distinguish tea preparations?

3. Select **measurements**.

   We are going to need some data. We get our data by making some measurements. These might be physical measurements with some device (like a ruler or a scale). But there are other sorts of measurements too, like the answer to a question on a form. Sometimes it is tricky to figure out just what to measure. (How do we measure happiness or intelligence, for example?) Just how we do our measuring will have important consequences for the subsequent statistical analysis. The recorded values of these measurements are called **variables** (because the values vary from one individual to another).

   In our example, a measurement may consist of recording for a given cup of tea whether the woman's claim is correct or incorrect.

4. Determine the **sample**.

   Usually we cannot measure every individual in our population; we have to select some to measure. But how many and which ones? These are important questions that must be answered. Generally speaking, bigger is better, but it is also more expensive. Moreover, no size is large enough if the sample is selected inappropriately.

   Suppose we gave the lady one cup of tea. If she correctly identifies the mixing procedure, will we be convinced of her claim? She might just be guessing; so we should probably have her taste more than one cup. Will we be convinced if she correctly identifies 5 cups? 10 cups? 50 cups?

   What if she makes a mistake? If we present her with 10 cups and she correctly identifies 9 of the 10, what will we conclude? A success rate of 90% is, it seems, much better than just guessing, and anyone can make a mistake now and then. But what if she correctly identifies 8 out of 10? 80 out of 100?

   And how should we prepare the cups? Should we make 5 each way? Does it matter if we tell the woman that there are 5 prepared each way? Should we flip a coin to decide even if that means we might end up with 3 prepared one way and 7 the other way? Do any of these differences matter?

5. Make and record the measurements.

   Once we have the design figured out, we have to do the legwork of data collection. This can be a time-consuming and tedious process. In the case of the lady tasting tea, the scientists decided to present her with ten cups of tea which were quickly prepared. A study of public opinion may require many thousands of phone calls or personal interviews. In a laboratory setting, each measurement might be the result of a carefully performed laboratory experiment.

6. Organize the data.

   Once the data have been collected, it is often necessary or useful to organize them. Data are typically stored in spreadsheets or in other formats that are convenient for processing with statistical packages. Very large data sets are often stored in databases.

   Part of the organization of the data may involve producing graphical and numerical summaries of the data. These summaries may give us initial insights into our questions or help us detect errors that may have occurred to this point.

7. Draw conclusions from data.

   Once the data have been collected, organized, and analyzed, we need to reach a conclusion. Do we believe the woman's claim? Or do we think she is merely guessing? How sure are we that this conclusion is correct?

   Eventually we will learn a number of important and frequently used methods for drawing inferences from data. More importantly, we will learn the basic framework used for such procedures so that it should become easier and easier to learn new procedures as we become familiar with the framework.

8. Produce a report.

   Typically the results of a statistical study are reported in some manner. This may be as a refereed article in an academic journal, as an internal report to a company, or as a solution to a problem on a homework assignment. These reports may themselves be further distilled into press releases, newspaper articles, advertisements, and the like. The mark of a good report is that it provides the essential information about each of the steps of the study.

   As we go along, we will learn some of the standard terminology and procedures that you are likely to see in basic statistical reports and will gain a framework for learning more.

At this point, you may be wondering who the innovative scientist was and what the results of the experiment were. The scientist was R. A. Fisher, who first described this situation as a pedagogical example in his 1925 book on statistical methodology [**?**]. Fisher developed statistical methods that are among the most important and widely used methods to this day, and most of his applications were biological.

0.10 Coins and Cups

You might also be curious about how the experiment came out. How many cups of tea were prepared? How many did the woman correctly identify? What was the conclusion?

Fisher never says. In his book he is interested in the method, not the particular results. But let's suppose we decide to test the lady with ten cups of tea. We'll flip a coin to decide which way to prepare the cups. If we flip a head, we will pour the milk in first; if tails, we put the tea in first. Then we present the ten cups to the lady and have her state which ones she thinks were prepared each way.

It is easy to give her a score (9 out of 10, or 7 out of 10, or whatever it happens to be). It is trickier to figure out what to do with her score. Even if she is just guessing and has no idea, she could get lucky and get quite a few correct – maybe even all 10. But how likely is that?

Let's try an experiment. I'll flip 10 coins. You guess which are heads and which are tails, and we'll see how you do.

⋮

Comparing with your classmates, we will undoubtedly see that some of you did better and others worse.

Now let's suppose the lady gets 9 out of 10 correct. That's not perfect, but it is better than we would expect for someone who was just guessing. On the other hand, it is not impossible to get 9 out of 10 just by guessing. So here is Fisher's great idea: Let's figure out how hard it is to get 9 out of 10 by guessing. If it's not so hard to do, then perhaps that's just what happened, so we won't be too impressed with the lady's tea tasting ability. On the other hand, if it is really unusual to get 9 out of 10 correct by guessing, then we will have some evidence that she must be able to tell something.

But how do we figure out how unusual it is to get 9 out of 10 just by guessing? We'll learn another method later, but for now, let's just flip a bunch of coins and keep track. If the lady is just guessing, she might as well be flipping a coin.

So here's the plan. We'll flip 10 coins. We'll call the heads correct guesses and the tails incorrect guesses. Then we'll flip 10 more coins, and 10 more, and 10 more, and .... That would get pretty tedious. Fortunately, computers are good at tedious things, so we'll let the computer do the flipping for us using a tool in the `mosaic` package. This package is already installed in our RStudio server. If you are running your own installation of R you can install `mosaic` using the following command:

install-mosaic

```
install.packages("mosaic")
```

The `rflip()` function can flip one coin

flip1coin

```
require(mosaic)
rflip()
```

```
Flipping 1 coin [ Prob(Heads) = 0.5 ] ...

H

Number of Heads: 1 [Proportion Heads: 1]
```

or a number of coins

flip10coins

```
rflip(10)
```

```
Flipping 10 coins [ Prob(Heads) = 0.5 ] ...

H T H H T T T H T H

Number of Heads: 5 [Proportion Heads: 0.5]
```

and show us the results.

Typing `rflip(10)` a bunch of times is almost as tedious as flipping all those coins. But it is not too hard to tell R to `do()` this a bunch of times.

```
do(2) * rflip(10)
```

```
   n heads tails prop
1 10     6     4  0.6
2 10     2     8  0.2
```

Let's get R to `do()` it for us 10,000 times and make a table of the results.

```
Flips <- do(10000) * rflip(10)
tally(~heads, data = Flips)
```

```
   0    1    2    3    4    5    6    7    8    9   10
   5  102  467 1203 2048 2470 2035 1140  415  108    7
```

```
tally(~heads, data = Flips, format = "percent")
```

```
    0     1     2     3     4     5     6     7     8     9    10
 0.05  1.02  4.67 12.03 20.48 24.70 20.35 11.40  4.15  1.08  0.07
```

```
tally(~heads, data = Flips, format = "proportion")
```

```
     0      1      2      3      4      5      6      7      8      9     10
0.0005 0.0102 0.0467 0.1203 0.2048 0.2470 0.2035 0.1140 0.0415 0.0108 0.0007
```

You might be surprised to see that the number of correct guesses is exactly 5 (half of the 10 tries) only 25% of the time. But most of the results are quite close to 5 correct. 67% of the results are 4, 5, or 6, for example. And 1% of the results are between 3 and 7 (inclusive). But getting 8 correct is a bit unusual, and getting 9 or 10 correct is even more unusual.

So what do we conclude? It is possible that the lady could get 9 or 10 correct just by guessing, but it is not very likely (it only happened in about 1.2% of our simulations). So *one of two things must be true*:

- The lady got unusually "lucky", or
- The lady is not just guessing.

Although Fisher did not say how the experiment came out, others have reported that the lady correctly identified all 10 cups! [**?**]

This same reasoning can be applied to answer a wide range of questions that have a similar form. For example, the question of whether dogs can smell cancer could be answered essentially the same way (although it would be a bit more involved than preparing tea and presenting cups to the Lady).

1 Collecting Data

1.1 The Structure of Data

Cases and Variables

Data sets in R are usually stored as **data frames** in a rectangular arrangement with rows corresponding to observational units and columns corresponding to variables. A number of data sets are built into R and its packages. The package for our text is `Lock5withR` which comes with a number of data sets.

```
require(Lock5withR)  # Tell R to use the package for our text book
data(StudentSurvey)  # load the StudentSurvey data set
```

Imagine data as a 2-dimensional structure (like a spreadsheet).

- Rows correspond to **observational units** (people, animals, plants, or other objects we are collecting data about).
- Columns correspond to **variables** (measurements collected on each observational unit).
- At the intersection of a row and a column is the **value** of the variable for a particular observational unit.

Observational units go by many names, depending on the kind of thing being studied. Popular names include subjects, individuals, and cases. Whatever you call them, it is important that you always understand what your observational units are.

Let's take a look at the data frame for the Student Survey example in the text. If we type the name of the data set, R will display it in its entirety for us. However, `StudentSurvey` is a larger data set, so it is more useful to look at some sort of summary or subset of the data.

Table 1.1

```r
head(StudentSurvey)  # first six cases of the data set
```

Table1.1

```
       Year Gender Smoke   Award HigherSAT Exercise TV Height Weight Siblings BirthOrder
1    Senior      M    No Olympic      Math       10  1     71    180        4          4
2 Sophomore      F   Yes Academy      Math        4  7     66    120        2          2
3 FirstYear      M    No   Nobel      Math       14  5     72    208        2          1
4    Junior      M    No   Nobel      Math        3  1     63    110        1          1
5 Sophomore      F    No   Nobel    Verbal        3  3     65    150        1          1
6 Sophomore      F    No   Nobel    Verbal        5  4     65    114        2          2
  VerbalSAT MathSAT  SAT  GPA Pulse Piercings    Sex
1       540     670 1210 3.13    54         0   Male
2       520     630 1150 2.50    66         3 Female
3       550     560 1110 2.55   130         0   Male
4       490     630 1120 3.10    78         0   Male
5       720     450 1170 2.70    40         6 Female
6       600     550 1150 3.20    80         4 Female
```

We can easily classify variables as either **categorical** or **quantitative** by studying the result of `head()`, but there are some summaries of the data set which reveal such information.

Data1.1

```r
str(StudentSurvey)  # structure of the data set
```

```
'data.frame': 362 obs. of  18 variables:
 $ Year      : Factor w/ 5 levels "","FirstYear",..: 4 5 2 3 5 5 2 5 3 2 ...
 $ Gender    : Factor w/ 2 levels "F","M": 2 1 2 2 1 1 1 2 1 1 ...
 $ Smoke     : Factor w/ 2 levels "No","Yes": 1 2 1 1 1 1 1 1 1 ...
 $ Award     : Factor w/ 3 levels "Academy","Nobel",..: 3 1 2 2 2 2 3 3 2 2 ...
 $ HigherSAT : Factor w/ 3 levels "","Math","Verbal": 2 2 2 2 3 3 2 2 3 2 ...
 $ Exercise  : num  10 4 14 3 3 5 10 13 3 12 ...
 $ TV        : int  1 7 5 1 3 4 10 8 6 1 ...
 $ Height    : int  71 66 72 63 65 65 66 74 61 60 ...
 $ Weight    : int  180 120 208 110 150 114 128 235 NA 115 ...
 $ Siblings  : int  4 2 2 1 1 2 1 1 2 7 ...
 $ BirthOrder: int  4 2 1 1 1 2 1 1 2 8 ...
 $ VerbalSAT : int  540 520 550 490 720 600 640 660 550 670 ...
 $ MathSAT   : int  670 630 560 630 450 550 680 710 550 700 ...
 $ SAT       : int  1210 1150 1110 1120 1170 1150 1320 1370 1100 1370 ...
 $ GPA       : num  3.13 2.5 2.55 3.1 2.7 3.2 2.77 3.3 2.8 3.7 ...
 $ Pulse     : int  54 66 130 78 40 80 94 77 60 94 ...
 $ Piercings : int  0 3 0 0 6 4 8 0 7 2 ...
 $ Sex       : Factor w/ 2 levels "Female","Male": 2 1 2 2 1 1 1 2 1 1 ...
```

```r
summary(StudentSurvey)  # summary of each variable
```

```
        Year      Gender   Smoke         Award       HigherSAT       Exercise
          :  2   F:169   No :319   Academy: 31          :  7   Min.   : 0.0
 FirstYear: 94   M:193   Yes: 43   Nobel  :149   Math  :205   1st Qu.: 5.0
 Junior   : 35                     Olympic:182   Verbal:150   Median : 8.0
 Senior   : 36                                                Mean   : 9.1
 Sophomore:195                                                3rd Qu.:12.0
                                                              Max.   :40.0
                                                              NA's   :1
       TV            Height          Weight        Siblings       BirthOrder      VerbalSAT
 Min.   : 0.0   Min.   :59.0   Min.   : 95   Min.   :0.00   Min.   :1.00   Min.   :390
```

```
 1st Qu.: 3.0   1st Qu.:65.0   1st Qu.:138   1st Qu.:1.00   1st Qu.:1.00   1st Qu.:550
 Median : 5.0   Median :68.0   Median :155   Median :1.00   Median :2.00   Median :600
 Mean   : 6.5   Mean   :68.4   Mean   :160   Mean   :1.73   Mean   :1.83   Mean   :594
 3rd Qu.: 9.0   3rd Qu.:71.0   3rd Qu.:180   3rd Qu.:2.00   3rd Qu.:2.00   3rd Qu.:640
 Max.   :40.0   Max.   :83.0   Max.   :275   Max.   :8.00   Max.   :8.00   Max.   :800
 NA's   :1      NA's   :7      NA's   :5                    NA's   :3
    MathSAT          SAT            GPA            Pulse          Piercings          Sex
 Min.   :400   Min.   : 800   Min.   :2.00   Min.   : 35.0   Min.   : 0.00   Female:169
 1st Qu.:560   1st Qu.:1130   1st Qu.:2.90   1st Qu.: 62.0   1st Qu.: 0.00   Male  :193
 Median :610   Median :1200   Median :3.20   Median : 70.0   Median : 0.00
 Mean   :609   Mean   :1204   Mean   :3.16   Mean   : 69.6   Mean   : 1.67
 3rd Qu.:650   3rd Qu.:1270   3rd Qu.:3.40   3rd Qu.: 77.8   3rd Qu.: 3.00
 Max.   :800   Max.   :1550   Max.   :4.00   Max.   :130.0   Max.   :10.00
                              NA's   :17                     NA's   :1
```

```
inspect(StudentSurvey)  # summary of each variable
```

```
categorical variables:
       name  class levels   n missing                                 distribution
1      Year factor      5 362       0 Sophomore (53.9%), FirstYear (26%) ...
2    Gender factor      2 362       0 M (53.3%), F (46.7%)
3     Smoke factor      2 362       0 No (88.1%), Yes (11.9%)
4     Award factor      3 362       0 Olympic (50.3%), Nobel (41.2%) ...
5 HigherSAT factor      3 362       0 Math (56.6%), Verbal (41.4%),  (1.9%)
6       Sex factor      2 362       0 Male (53.3%), Female (46.7%)

quantitative variables:
         name   class min     Q1 median     Q3  max    mean      sd   n missing
1    Exercise numeric   0    5.0    8.0   12.0   40    9.05   5.741 361       1
2          TV integer   0    3.0    5.0    9.0   40    6.50   5.584 361       1
3      Height integer  59   65.0   68.0   71.0   83   68.42   4.079 355       7
4      Weight integer  95  138.0  155.0  180.0  275  159.80  31.619 357       5
5    Siblings integer   0    1.0    1.0    2.0    8    1.73   1.179 362       0
6  BirthOrder integer   1    1.0    2.0    2.0    8    1.83   1.124 359       3
7   VerbalSAT integer 390  550.0  600.0  640.0  800  594.19  74.176 362       0
8     MathSAT integer 400  560.0  610.0  650.0  800  609.44  68.490 362       0
9         SAT integer 800 1130.0 1200.0 1270.0 1550 1203.63 121.285 362       0
10        GPA numeric   2    2.9    3.2    3.4    4    3.16   0.398 345      17
11      Pulse integer  35   62.0   70.0   77.8  130   69.57  12.205 362       0
12  Piercings integer   0    0.0    0.0    3.0   10    1.67   2.173 361       1
```

Here are some more summaries:

Data1.1b

```
nrow(StudentSurvey)  # number of rows
```

```
[1] 362
```

```
ncol(StudentSurvey)  # number of columns
```

```
[1] 18
```

```
dim(StudentSurvey)  # number of rows and columns
```

```
[1] 362  18
```

Many of the datasets in R have useful help files that describe the data and explain how they were collected or give references to the original studies. You can access this information for the `AllCountries` data set by typing

```
?StudentSurvey
```
Data1.1c

We'll learn how to make more customized summaries (numerical and graphical) soon. For now, it is only important to observe how the organization of data in R reflects the observational units and variables in the data set.

This is important if you want to construct your own data set (in Excel or a google spreadhseet, for example) that you will later import into R. You want to be sure that the structure of your spread sheet uses rows and columns in this same way, and that you don't put any extra stuff into the spread sheet. It is a good idea to include an extra row at the top which names the variables. Take a look at Chapter 0 to learn how to get the data from Excel into R.

Categorical and Quantitative Variables

categorical variable a variable that places observational units into one of two or more categories (examples: color, sex, case/control status, species, etc.)

These can be further sub-divided into ordinal and nominal variables. If the categories have a natural and meaningful order, we will call them **ordered** or **ordinal** variables. Otherwise, they are **nominal** variables.

quantitative variable a variable that records measurements along some scale (examples: weight, height, age, temperature) or counts something (examples: number of siblings, number of colonies of bacteria, etc.)

Quantitative variables can be **continuous** or **discrete**. Continuous variables can (in principle) take on any real-number value in some range. Values of discrete variables are limited to some list and "in-between values" are not possible. Counts are a good example of discrete variables.

Investigating Variables and Relationships between Variables

```
head(AllCountries)
```
Data1.2

```
         Country Code LandArea Population Energy Rural Military Health HIV Internet
1    Afghanistan  AFG   652230     29.021     NA  76.0      4.4    3.7  NA      1.7
2        Albania  ALB    27400      3.143   2088  53.3       NA    8.2  NA     23.9
3        Algeria  ALG  2381740     34.373  37069  34.8     13.0   10.6 0.1     10.2
4 American Samoa  ASA      200      0.066     NA   7.7       NA     NA  NA       NA
5        Andorra  AND      470      0.084     NA  11.1       NA   21.3  NA     70.5
6         Angola  ANG  1246700     18.021  10972  43.3       NA    6.8 2.0      3.1
  Developed BirthRate ElderlyPop LifeExpectancy   CO2  GDP  Cell Electricity  kwhPerCap
1        NA      46.5        2.2           43.9 0.025  501  37.8          NA       <NA>
2         1      14.6        9.3           76.6 1.313 3678 141.9        1747 Under 2500
3         1      20.8        4.6           72.4 3.233 4495  92.4         971 Under 2500
4        NA        NA         NA             NA    NA   NA    NA          NA       <NA>
5        NA      10.4         NA             NA 6.528   NA  77.2          NA       <NA>
6         1      42.9        2.5           47.0 1.351 4423  46.7         202 Under 2500
```

```
inspect(AllCountries)
```

```
categorical variables:
       name   class levels   n missing                                  distribution
1   Country  factor    213 213       0 Afghanistan (0.5%), Albania (0.5%) ...
2      Code  factor    211 213       0  (1.4%), AFG (0.5%), ALB (0.5%) ...
3 kwhPerCap ordered      3 135      78 Under 2500 (54.1%), Over 5000 (30.4%) ...

quantitative variables:
             name   class      min       Q1   median       Q3      max     mean       sd
1        LandArea integer   2.0000 1.08e+04 94080.00 4.46e+05 1.64e+07 6.08e+05 1.77e+06
2      Population numeric   0.0200 7.73e-01     5.61 2.06e+01 1.32e+03 3.15e+01 1.24e+02
3          Energy integer 159.0000 5.25e+03 17478.00 5.25e+04 2.28e+06 8.63e+04 2.80e+05
4           Rural numeric   0.0000 2.29e+01    40.40 6.32e+01 8.96e+01 4.21e+01 2.44e+01
5        Military numeric   0.0000 3.80e+00     5.85 1.22e+01 2.93e+01 8.28e+00 6.14e+00
6          Health numeric   0.7000 8.00e+00    11.30 1.44e+01 2.61e+01 1.12e+01 4.37e+00
7             HIV numeric   0.1000 1.00e-01     0.40 1.30e+00 2.59e+01 1.98e+00 4.44e+00
8        Internet numeric   0.2000 5.65e+00    22.80 4.81e+01 9.05e+01 2.90e+01 2.63e+01
9       Developed integer   1.0000 1.00e+00     1.00 3.00e+00 3.00e+00 1.76e+00 8.91e-01
10      BirthRate numeric   8.2000 1.21e+01    19.40 2.89e+01 5.35e+01 2.20e+01 1.07e+01
11     ElderlyPop numeric   1.0000 3.40e+00     5.40 1.16e+01 2.14e+01 7.47e+00 5.07e+00
12 LifeExpectancy numeric  43.9000 6.28e+01    71.90 7.60e+01 8.28e+01 6.89e+01 1.02e+01
13            CO2 numeric   0.0226 6.18e-01     2.74 7.02e+00 4.91e+01 5.09e+00 6.73e+00
14            GDP numeric 192.1238 1.25e+03  4408.84 1.24e+04 1.05e+05 1.13e+04 1.68e+04
15           Cell numeric   1.2385 5.92e+01    93.70 1.21e+02 2.06e+02 9.11e+01 4.48e+01
16    Electricity numeric  35.6844 8.00e+02  2237.51 5.82e+03 5.13e+04 4.11e+03 5.83e+03
     n missing
1  213       0
2  212       1
3  136      77
4  213       0
5   98     115
6  187      26
7  145      68
8  199      14
9  135      78
10 197      16
11 191      22
12 196      17
13 198      15
14 173      40
15 201      12
16 135      78


AllCountries[86, ]


   Country Code LandArea Population Energy Rural Military Health HIV Internet Developed
86 Iceland  ISL   100250      0.317   5255   7.7      0.1   13.1 0.3     90.5         3
   BirthRate ElderlyPop LifeExpectancy  CO2   GDP Cell Electricity kwhPerCap
86      15.2       11.7           81.3 7.02 39617  110       51259 Over 5000
```

Using Data to Answer a Question

response variable a variable we are trying to predict or explain

explanatory variable a variable used to predict or explain a response variable

1.2 Sampling from a Population

Samples from Populations

population the collection of animals, plants, objects, etc. that we want to know about

sample the (smaller) set of animals, plants, objects, etc. about which we have data

parameter a number that describes a population or model.

statistic a number that describes a sample.

Much of statistics centers around this question:

> *What can we learn about a population from a sample?*

Sampling Bias

Often we are interested in knowing (approximately) the value of some parameter. A statistic used for this purpose is called an **estimate**. For example, if you want to know the mean length of the tails of lemurs (that's a *parameter*), you might take a sample of lemurs and measure their tails. The mean length of the tails of the lemurs in your sample is a *statistic*. It is also an *estimate*, because we use it to estimate the parameter.

Statistical estimation methods attempt to

- reduce **bias**, and
- increase **precision**.

bias the systematic tendency of sample estimates to either overestimate or underestimate population parameters; that is, a *systematic tendency to be off in a particular direction*.

precision the measure of how close estimates are to the thing being estimated (called the **estimand**).

Simple Random Sample

Sampling is the process of selecting a sample. Statisticians use **random samples**

- to avoid (or at least reduce) **bias**, and
- so they can quantify **sampling variability** (the amount samples differ from each other), which in turn allows us to quantify precision.

The simplest kind of random sample is called a **simple random sample** (aren't statisticians clever about naming things?). A simple random sample is equivalent to putting all individuals in the population into a big hat, mixing thoroughly, and selecting some out of the hat to be in the sample. In particular, in a simple random sample, *every individual has an equal chance to be in the sample*, in fact, every subset of the population of a fixed size has an equal chance to be in the sample.

Other sampling methods include

convenience sampling using whatever individuals are easy to obtain

This is usually a terrible idea. If the convenient members of the population differ from the inconvenient members, then the sample will not be representative of the population.

volunteer sampling using people who volunteer to be in the sample

This is usually a terrible idea. Most likely the volunteers will differ in some ways from the non-volunteers, so again the sample will not be representative of the population.

systematic sampling sampling done in some systematic way (every tenth unit, for example).

This can sometimes be a reasonable approach.

stratified sampling sampling separately in distinct sub-populations (called *strata*)

This is more complicated (and sometimes necessary) but fine as long as the sampling methods in each stratum are good and the analysis takes the sampling method into account.

Example 1.15

```
sample(AllCountries, 5)
```

Example1.15

```
              Country Code LandArea Population Energy Rural Military Health HIV Internet
211      Yemen, Rep.  YEM   527970     22.917   7478  69.4       NA    4.3  NA      1.6
168       Seychelles  SEY      460      0.087     NA  45.7      3.1   10.1  NA     39.0
2            Albania  ALB    27400      3.143   2088  53.3       NA    8.2  NA     23.9
123 Marshall Islands  MHL      180      0.060     NA  28.9       NA   14.6  NA      3.7
68             Gabon  GAB   257670      1.448   2073  15.0       NA    6.6 5.3      6.2
    Developed BirthRate ElderlyPop LifeExpectancy  CO2   GDP   Cell Electricity
211         1      36.8        2.4           62.9 1.03    NA  46.09         219
168        NA      17.8         NA           73.2 7.84 10825 135.90          NA
2           1      14.6        9.3           76.6 1.31  3678 141.93        1747
123        NA        NA         NA             NA 1.87  3015   7.03          NA
68          1      27.3        4.3           60.4 1.70  8643 106.94         922
     kwhPerCap orig.id
211 Under 2500     211
168       <NA>     168
2   Under 2500       2
123       <NA>     123
68  Under 2500      68
```

1.3 Experiments and Observational Studies

Confounding Variables

Table 1.2

```
head(LifeExpectancyVehicles, 10)
```

Table1.2

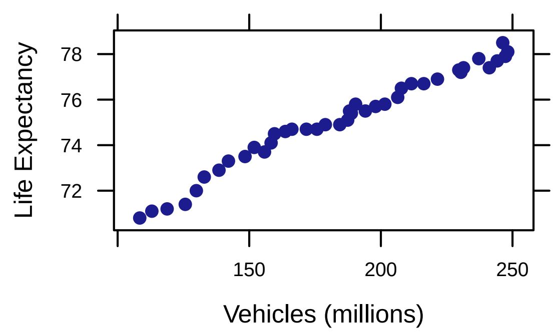
```
   Year LifeExpectancy Vehicles
1  1970           70.8      108
2  1971           71.1      113
```

```
3   1972            71.2       119
4   1973            71.4       126
5   1974            72.0       130
6   1975            72.6       133
7   1976            72.9       138
8   1977            73.3       142
9   1978            73.5       148
10  1979            73.9       152

Sub <- filter(LifeExpectancyVehicles, Year%%4 == 2)
Sub

   Year LifeExpectancy Vehicles
1  1970            70.8       108
2  1974            72.0       130
3  1978            73.5       148
4  1982            74.5       160
5  1986            74.7       176
6  1990            75.4       189
7  1994            75.7       198
8  1998            76.7       212
9  2002            77.3       230
10 2006            77.7       244
```

Figure 1.2

```
xyplot(LifeExpectancy ~ Vehicles, xlab = "Vehicles (millions)", ylab = "Life Expectancy",
       data = LifeExpectancyVehicles)
```

Figure1.2



Observational Studies vs. Experiments

Statisticians use the word experiment to mean something very specific. *In an **experiment**, the researcher determines the values of one or more (explanatory) variables*, typically by random assignment. If there is no such assignment by the researcher, the study is an **observational study**.

2 Describing Data

In this chapter we discuss graphical and numerical summaries of data.

2.1 Categorical Variables

Let us investigate categorical variables in R by taking a look at the data set for the One True Love survey. Notice that the data set is not readily available in our textbook's package. However, the authors do provide us with the necessary information to create our own data spreadsheet (in either Excel or Google) and import it into R. (See Chapter 0 for instructions.)

Data2.1

```
OneTrueLove <- read.file("OneTrueLove.csv")
```

```
Reading data with read.csv()
```

Alternatively, we can read from a URL like this

Data2.1b

```
OneTrueLove2 <- read.file("https://raw.githubusercontent.com/rpruim/Lock5withR/master/Book/OneTrueLove.csv")
```

```
Reading data with read.csv()
```

One Categorical Variable

From the dataset we named as `OneTrueLove`, we can use the `prop()` function to quickly find **proportions**.

proportion

```
prop(~Response, data = OneTrueLove)
```

```
Agree
 0.28
```

Table 2.1

We can also tabulate the categorical variable to display the *frequency* by using the `tally()` function. The default in tallying is to not include the row totals, or column totals when there are two variables. These are called marginal totals and if you want them, you can change the default.

Table2.1

```
tally(~Response, margin = TRUE, data = OneTrueLove)
```

```
     Agree   Disagree Don't know      Total 
       735       1812         78       2625 
```

Example 2.3

To find the proportion of responders who *disagree* or *don't know*, we can use the `level=` argument in the function to find proportions.

Example2.3

```
prop(~Response, level = "Disagree", data = OneTrueLove)
```

```
Disagree 
    0.69 
```

```
prop(~Response, level = "Don't know", data = OneTrueLove)
```

```
Don't know 
    0.0297 
```

Further, we can also display the *relative frequencies*, or **proportions** in a table.

Example2.3b

```
tally(~Response, format = "proportion", margin = TRUE, data = OneTrueLove)
```

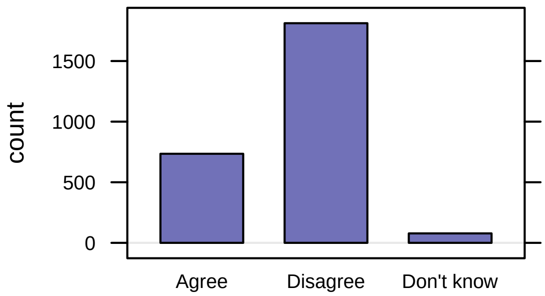
```
     Agree   Disagree Don't know      Total 
    0.2800     0.6903     0.0297     1.0000 
```

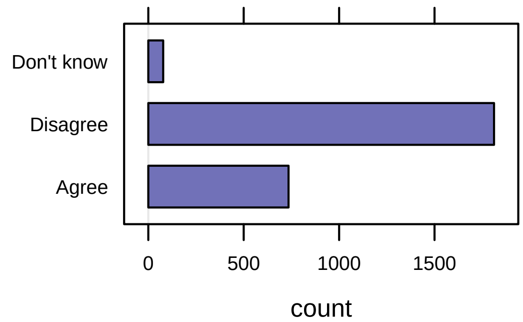
Figure 2.1

R provides many different chart and plot functions, including *bar charts* and *pie charts*, to visualize counts or proportions. Bar charts, also known as bar graphs, are a way of displaying the distribution of a categorical variable.

Figure2.1

```
bargraph(~Response, data = OneTrueLove)
bargraph(~Response, data = OneTrueLove, horizontal = TRUE)
```





Two Categorical Variables: Two-Way Tables

Often, it is useful to compute cross tables for two (or more) variables. We can again use `tally()` for several ways to investigate a two-way table.

Table 2.3

```
tally(~Response + Gender, data = OneTrueLove)
```

Table2.3

```
            Gender
Response      Female Male
  Agree          363  372
  Disagree      1005  807
  Don't know      44   34
```

Table 2.4

```
tally(~Response + Gender, margins = TRUE, data = OneTrueLove)
```

Table2.4

```
            Gender
Response      Female Male Total
  Agree          363  372   735
  Disagree      1005  807  1812
  Don't know      44   34    78
  Total         1412 1213  2625
```

Example 2.5

Similar to one categorical variable, we can use the `prop()` function to find the proportion of two variables. The first line results in the proportion of females who agree and the proportion of males who agree. The second line shows the proportion who agree that are female and the proportion who disagree that are female. The third results in the proportion of all the survey responders that are female.

Example2.5

```
prop(Response ~ Gender, data = OneTrueLove)

Agree.Female   Agree.Male
       0.138        0.142

prop(Gender ~ Response, data = OneTrueLove)

     Female.Agree   Female.Disagree Female.Don't know
           0.1383            0.3829            0.0168

prop(~Gender, data = OneTrueLove)

Female
 0.538
```

See though that because we have multiple levels of each variable, this process can become quite tedious if we want to find the proportions for all of the levels. Using the tally function a little differently will result in these proportions.

Example2.5b

```
tally(Response ~ Gender, data = OneTrueLove)

            Gender
Response     Female Male
  Agree         363  372
  Disagree     1005  807
  Don't know     44   34

tally(~Response | Gender, data = OneTrueLove)

            Gender
Response     Female Male
  Agree         363  372
  Disagree     1005  807
  Don't know     44   34

tally(Gender ~ Response, data = OneTrueLove)

        Response
Gender   Agree Disagree Don't know
  Female   363     1005         44
  Male     372      807         34

tally(~Gender | Response, data = OneTrueLove)

        Response
Gender   Agree Disagree Don't know
  Female   363     1005         44
  Male     372      807         34
```

Notice that (by default) some of these use counts and some use proportions. Again, we can change the format.

Example2.5c

```
tally(~Gender, format = "percent", data = OneTrueLove)

Female   Male
  53.8   46.2
```

Example 2.6

Example2.6

```
tally(~Gender + Award, margin = TRUE, data = StudentSurvey)

       Award
Gender  Academy Nobel Olympic Total
  F          20    76      73   169
  M          11    73     109   193
  Total      31   149     182   362
```

Also, we can arrange the table differently by converting it to a data frame.

Example2.6b

```
as.data.frame(tally(~Gender + Award, data = StudentSurvey))

  Gender   Award Freq
1      F Academy   20
2      M Academy   11
3      F   Nobel   76
4      M   Nobel   73
5      F Olympic   73
6      M Olympic  109
```

Example2.6c

```
prop(~Award, level = "Olympic", data = StudentSurvey)

Olympic
  0.503
```

Example 2.7

To calculate the difference of certain statistics, we can use the `diff()` function. Here we use it to find the difference in proportions, but it can be used for means, medians, and etc.

Example2.7

```
diff(prop(Award ~ Gender, level = "Olympic", data = StudentSurvey))
```

```
Olympic.M
   0.0994
```

We will continue more with proportions in Chapter 3.

Figure 2.2

A way to look at multiple groups simultaneously is by using *comparative plots* such as a *segmented bar chart* or *side-by-side bar chart*. We use the `groups` argument for this. What `groups` does depends a bit on the type of graph. Using `groups` with `histogram()` doesn't work so well because it is difficult to overlay histograms.[1] Density plots work better for this.

Notice the addition of `groups=` (to group), `stack=` (to segment the graph), and `auto.key=TRUE` (to build a simple legend so we can tell which groups are which).

Figure2.2

```
bargraph(~Award, groups = Gender, stack = TRUE, auto.key = TRUE, data = StudentSurvey)
```

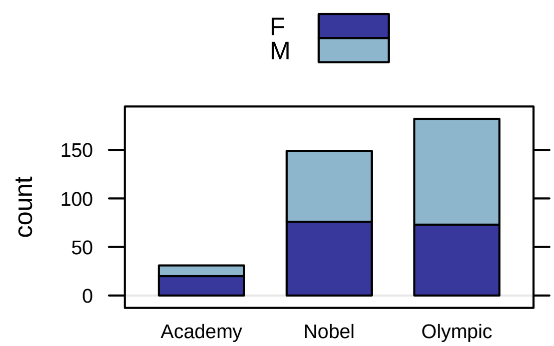
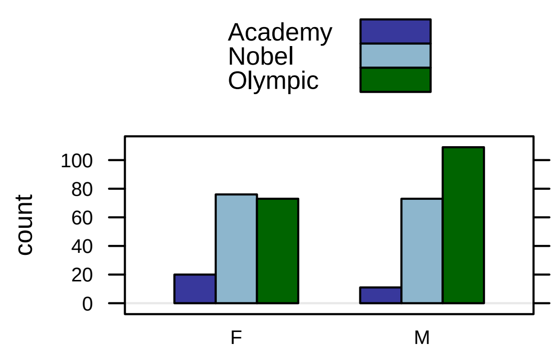


Figure2.2b

```
bargraph(~Gender, groups = Award, auto.key = TRUE, data = StudentSurvey)
```



[1] The `mosaic` function `histogram()` does do something meaningful with `groups` in some situations.

2.2 One Quantitative Variable: Shape and Center

The distribution of a variable answers two questions:

- *What values* can the variable have?
- *With what frequency* does each value occur?

  Again, the frequency may be described in terms of counts, proportions (often called relative frequency), or densities (more on densities later).

A distribution may be described using a table (listing values and frequencies) or a graph (e.g., a histogram) or with words that describe general features of the distribution (e.g., symmetric, skewed).

The Shape of a Distribution

Table 2.14

```
MammalLongevity
```

Table2.14

```
         Animal Gestation Longevity
1        baboon       187        20
2    bear,black       219        18
3  bear,grizzly       225        25
4    bear,polar       240        20
5        beaver       122         5
6       buffalo       278        15
7         camel       406        12
8           cat        63        12
9    chimpanzee       231        20
10     chipmunk        31         6
11          cow       284        15
12         deer       201         8
13          dog        61        12
14       donkey       365        12
15     elephant       645        40
16          elk       250        15
17          fox        52         7
18      giraffe       425        10
19         goat       151         8
20      gorilla       257        20
21   guinea pig        68         4
22 hippopotamus       238        25
23        horse       330        20
24     kangaroo        42         7
25      leopard        98        12
26         lion       100        15
27       monkey       164        15
28        moose       240        12
29        mouse        21         3
30      opposum        15         1
31          pig       112        10
32         puma        90        12
```

```
33       rabbit     31    5
34   rhinoceros    450   15
35     sea lion    350   12
36        sheep    154   12
37     squirrel     44   10
38        tiger    105   16
39         wolf     63    5
40        zebra    365   15
```

Statisticians have devised a number of graphs to help us see distributions visually. The general syntax for making a graph of one variable in a data frame is

```
plotname(~variable, data = dataName)
```

In other words, there are three pieces of information we must provide to R in order to get the plot we want:

- The kind of plot (`histogram()`, `bargraph()`, `densityplot()`, `bwplot()`, etc.)
- The name of the variable
- The name of the data frame this variable is a part of.

This should look familiar from the previous section.

Figure 2.6

Let's make a *dot plot* of the variable Longevity in the `MammalLongevity` data set for a quick and simple look at the distribution. We use the syntax provided above with two additional arguments to make the figure look the way we want it to. The next few sections will explain a few of the different arguments available for plots in R.

Figure2.6

```
dotPlot(~Longevity, width = 1, cex = 0.35, data = MammalLongevity)
```

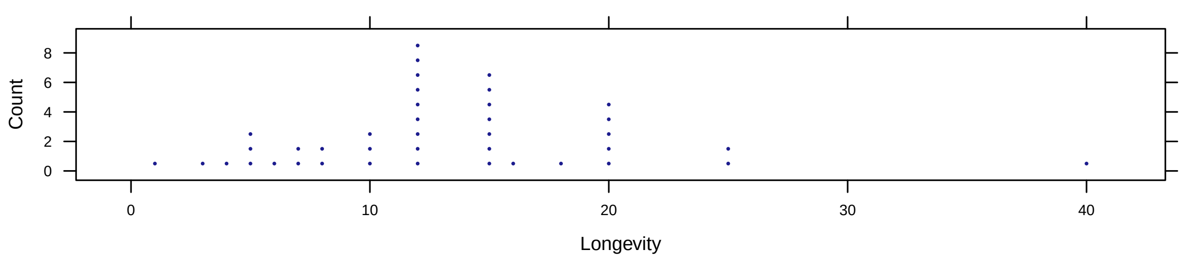


Table 2.15

Although `tally()` works with quantitative variables as well as categorical variables, this is only useful when there are not too many different values for the variable.

Table2.15

```
tally(~Longevity, margin = TRUE, data = MammalLongevity)
```

```
    1     3     4     5     6     7     8    10    12    15    16    18    20    25    40
    1     1     1     3     1     2     2     3     9     7     1     1     5     2     1
Total
   40
```

Sometimes, it is more convenient to group them into bins. We just have to tell R what the bins are. For example, suppose we wanted to group together by 5.

Table2.15b

```
binned.long <- cut(MammalLongevity$Longevity, breaks = c(0, 5, 10, 15, 20, 25, 30, 35, 40))
tally(~binned.long)  # no data frame given because it is not in a data frame
```

```
  (0,5]  (5,10] (10,15] (15,20] (20,25] (25,30] (30,35] (35,40]
      6       8      16       7       2       0       0       1
```

Suppose we wanted to group the 1s, 10s, 20s, etc. together. We want to make sure then that 10 is with the 10s, so we should add another argument.

Table2.15c

```
binned.long2 <- cut(MammalLongevity$Longevity, breaks = c(0, 10, 20, 30, 40, 50), right = FALSE)
tally(~binned.long2)  # no data frame given because it is not in a data frame
```

```
 [0,10) [10,20) [20,30) [30,40) [40,50)
     11      21       7       0       1
```

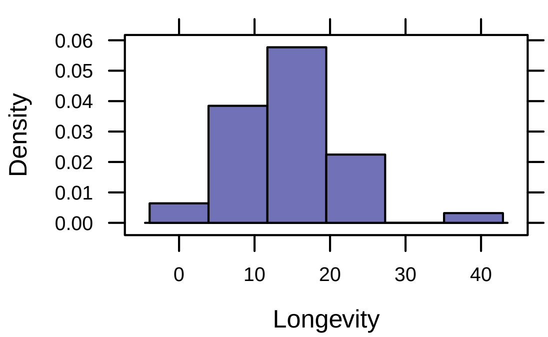
We won't use this very often however, since seeing this information in a histogram is typically more useful.

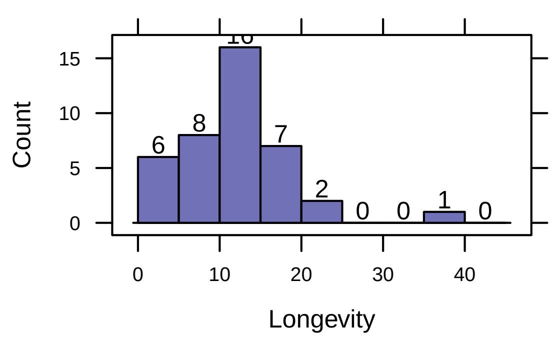
Figure 2.7

Histograms are a way of displaying the distribution of a quantitative variable.

Figure2.7

```
histogram(~Longevity, data = MammalLongevity)
histogram(~Longevity, width = 5, type = "count", center = 2.5, label = TRUE, data = MammalLongevity)
```

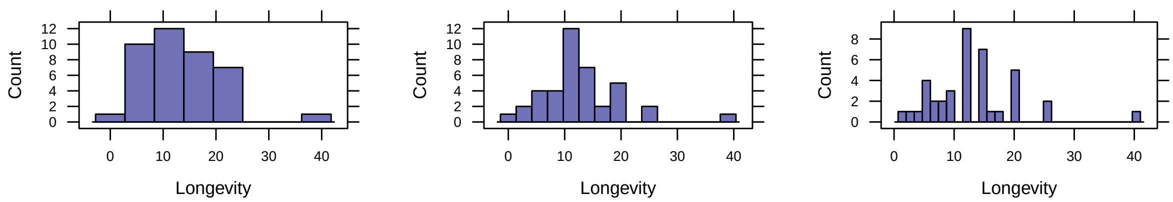




We can control the (approximate) number of bins using the `nint` argument, which may be abbreviated as `n`. The number of bins (and to a lesser extent the positions of the bins) can make a histogram look quite different.

Figure2.7b

```
histogram(~Longevity, type = "count", data = MammalLongevity, n = 8)
histogram(~Longevity, type = "count", data = MammalLongevity, n = 15)
histogram(~Longevity, type = "count", data = MammalLongevity, n = 30)
```



We can also describe the bins in terms of center and width instead of in terms of the number of bins. This is especially nice for count or other integer data.

Figure2.7c

```
histogram(~Longevity, type = "count", data = MammalLongevity, width = 10)
histogram(~Longevity, type = "count", data = MammalLongevity, width = 5)
histogram(~Longevity, type = "count", data = MammalLongevity, width = 2)
```

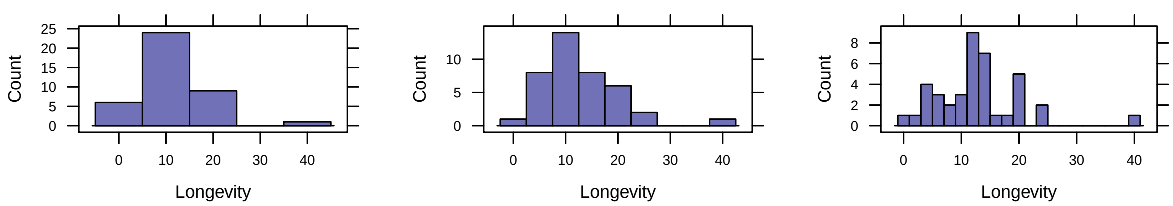
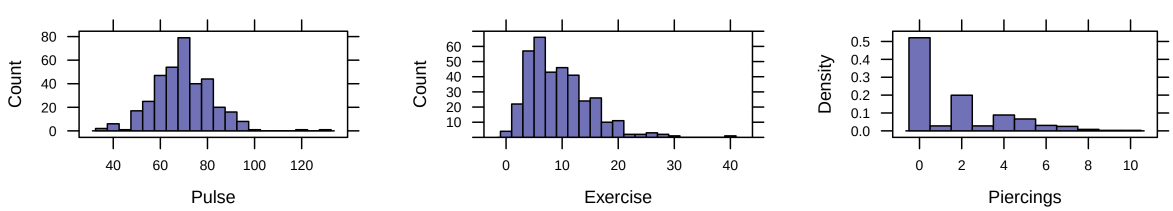


Figure 2.8

The various options available for the `histogram()` function enable us to replicate Figure 2.8, some including centering, adding counts, labels, and limit to the y-axis (similar for x-axis).

Figure2.8

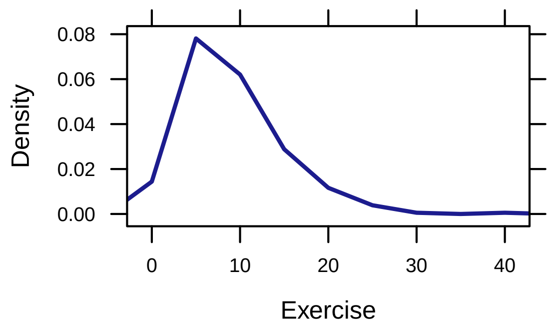
```
histogram( ~ Pulse, type = "count", width = 5, data = StudentSurvey)
histogram( ~ Exercise, type = "count", width = 2, center = 2,
          right = FALSE, ylim = c(0, 70), data = StudentSurvey)
histogram( ~ Piercings, width = 1, data = StudentSurvey)
```



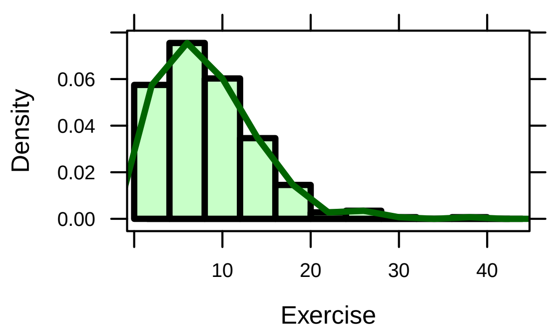
Sometimes a **frequency polygon** provides a more useful view. The only thing that changes is `histogram()` becomes `freqpolygon()`.

freqpolygon

```
freqpolygon(~Exercise, width = 5, data = StudentSurvey)
```



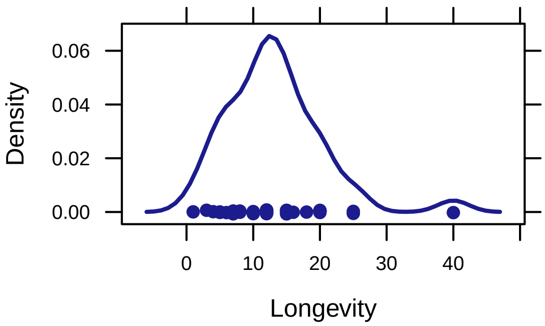
What is a frequency polygon? The picture below shows how it is related to a histogram. The frequency polygon is just a dot-to-dot drawing through the centers of the tops of the bars of the histogram.

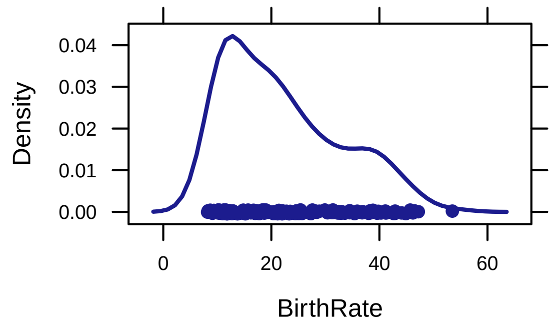


R also provides a "smooth" version called a density plot; just change the function name from `histogram()` to `densityplot()`.

densityplot

```
densityplot(~Longevity, data = MammalLongevity)
densityplot(~BirthRate, data = AllCountries)
```





If we make a histogram (or any of these other plots) of our data, we can describe the overall shape of the distribution. Keep in mind that the shape of a particular histogram may depend on the choice of bins. Choosing too many or too few bins can hide the true shape of the distribution. (When in doubt, make more than one histogram.)

Here are some words we use to describe shapes of distributions.

symmetric The left and right sides are mirror images of each other.

skewed The distribution stretches out farther in one direction than in the other. (We say the distribution is skewed toward the long tail.)

uniform The heights of all the bars are (roughly) the same. (So the data are equally likely to be anywhere within some range.)

unimodal There is one major "bump" where there is a lot of data.

bimodal There are two "bumps".

outlier An observation that does not fit the overall pattern of the rest of the data.

The Center of a Distribution

Recall that a statistic is a number computed from data. The **mean** and the **median** are key statistics which describe the center of a distribution. We can see through Example 2.11 that numerical summaries are computed using the same template as graphical summaries.

Note that the example asks about subsets of `ICUAdmissions`–specifically about 20-year-old and 55-year-old patients. In this case, we can manipulate the data (to name a new data set) with the subset command. Here are some examples.

1. Select only the males from the `ICUAdmissions` data set.

subset

```
head(ICUAdmissions, 2)

  ID Status Age Sex Race Service Cancer Renal Infection CPR Systolic HeartRate Previous
1  8      0  27   1    1       0      0     0         1   0      142        88        0
2 12      0  59   0    1       0      0     0         0   0      112        80        1
  Type Fracture PO2 PH PCO2 Bicarbonate Creatinine Consciousness status    sex  race
1    1        0   0  0    0           0          0             1  Lived Female White
2    1        0   0  0    0           0          0             1  Lived   Male White
  service cancer renal infection cpr previous      type pO2low pO2 pHlow pH pCO2hi pCO2
```

```
1 Medical      No     No        Yes  No        No Emergency      No   Hi     No Hi      No  Low
2 Medical      No     No         No  No       Yes Emergency      No   Hi     No Hi      No  Low
  bicarbonateLow bicarbonate creatinineHi creatinine consciousness
1              No          Hi           No         Low     Conscious
2              No          Hi           No         Low     Conscious

tally(~sex, data = ICUAdmissions)


Female   Male
    76    124

ICUMales <- subset(ICUAdmissions, sex == "Male")  # notice the double =
tally(~sex, data = ICUMales)


Female   Male
     0    124
```

2. Select only the subjects over 50:

```
ICUOld <- subset(ICUAdmissions, Age > 50)
```

subset2

The `subset()` function can use any condition that evaluates to TRUE or FALSE for each row (case) in the data set.

Example 2.11

```
ICU20 <- subset(ICUAdmissions, Age == "20")
mean(~HeartRate, data = ICU20)


[1] 82.2


median(~HeartRate, data = ICU20)


[1] 80


ICU55 = subset(ICUAdmissions, Age == "55")
mean(~HeartRate, data = ICU55)


[1] 108


median(~HeartRate, data = ICU55)


[1] 106
```

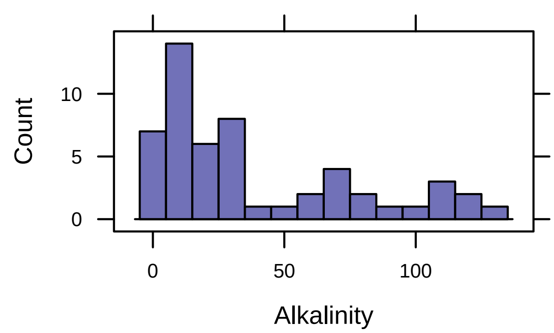
Example2.11

Resistance

Figure 2.10

Figure2.10

```
head(FloridaLakes)

  ID         Lake Alkalinity  pH Calcium Chlorophyll AvgMercury NumSamples MinMercury
1  1    Alligator        5.9 6.1     3.0         0.7       1.23          5       0.85
2  2        Annie        3.5 5.1     1.9         3.2       1.33          7       0.92
3  3       Apopka      116.0 9.1    44.1       128.3       0.04          6       0.04
4  4 Blue Cypress       39.4 6.9    16.4         3.5       0.44         12       0.13
5  5        Brick        2.5 4.6     2.9         1.8       1.20         12       0.69
6  6       Bryant       19.6 7.3     4.5        44.1       0.27         14       0.04
  MaxMercury ThreeYrStdMercury AgeData
1       1.43              1.53       1
2       1.90              1.33       0
3       0.06              0.04       0
4       0.84              0.44       0
5       1.50              1.33       1
6       0.48              0.25       1

histogram(~Alkalinity, width = 10, type = "count", data = FloridaLakes)
```



Example 2.14

Example2.14

```
mean(~Alkalinity, data = FloridaLakes)

[1] 37.5

median(~Alkalinity, data = FloridaLakes)

[1] 19.6
```


2.3 One Quantitative Variable: Measures of Spread

In the previous section, we investigated center summary statistics. In this section, we will cover some other important statistics.

Example 2.15

```
summary(April14Temps)
```

Example2.15

```
      Year        DesMoines      SanFrancisco
 Min.   :1995   Min.   :37.2   Min.   :48.7
 1st Qu.:1999   1st Qu.:44.4   1st Qu.:51.3
 Median :2002   Median :54.5   Median :54.0
 Mean   :2002   Mean   :54.5   Mean   :54.0
 3rd Qu.:2006   3rd Qu.:61.3   3rd Qu.:55.9
 Max.   :2010   Max.   :74.9   Max.   :61.0
```

```
favstats(~DesMoines, data = April14Temps)  # some favorite statistics
```

```
  min   Q1 median   Q3  max mean   sd  n missing
 37.2 44.4   54.5 61.3 74.9 54.5 11.7 16       0
```

```
favstats(~SanFrancisco, data = April14Temps)
```

```
  min   Q1 median   Q3 max mean   sd  n missing
 48.7 51.3     54 55.9  61   54 3.38 16       0
```

Standard Deviation

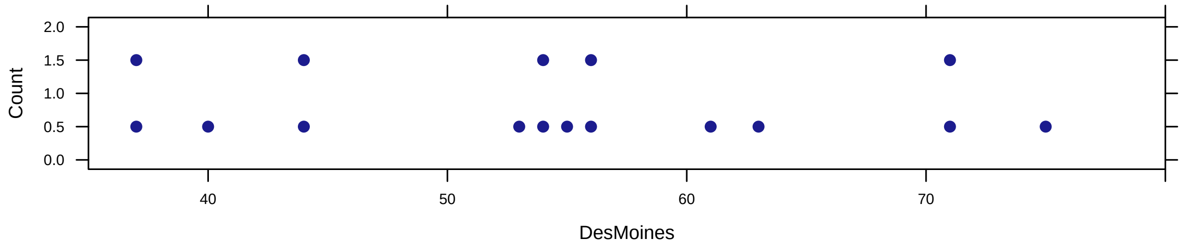
The density plots of the temperatures of Des Moines and San Francisco reveal that Des Moines has a greater *variability* or *spread*.

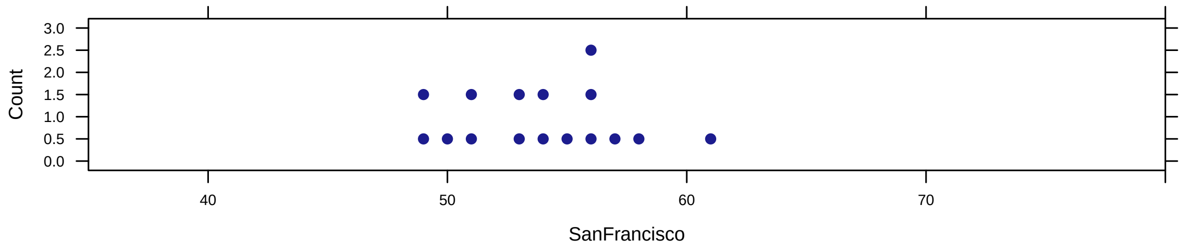
Figure 2.18

The `cex` argument controls "character expansion" and can be used to make the plotting "characters" larger or smaller by specifying the scaling ratio. `xlim` sets the limits for the x-axis.

Figure2.18

```
dotPlot(~DesMoines, width = 1, cex = 0.25, xlim = c(35, 80), data = April14Temps)
dotPlot(~SanFrancisco, width = 1, cex = 0.35, xlim = c(35, 80), data = April14Temps)
```





Example 2.16

Although both `summary()` and `favstats()` calculate the **standard deviation** of a variable, we can also use `sd()` to find just the standard deviation.

standard-deviation

```
sd(~DesMoines, data = April14Temps)

[1] 11.7

sd(~SanFrancisco, data = April14Temps)

[1] 3.38

var(~DesMoines, data = April14Temps)  # variance = sd^2

[1] 138
```

Example 2.17

To see that the distribution is indeed symmetric and approximately bell-shaped, you can use the argument `fit` to overlay a "normal" curve.

Example2.17

```
histogram(~Pulse, fit = "normal", data = StudentSurvey)
mean <- mean(~Pulse, data = StudentSurvey)
mean

[1] 69.6
```

```
sd <- sd(~Pulse, data = StudentSurvey)
sd
```

```
[1] 12.2
```

```
mean - 2 * sd
```

```
[1] 45.2
```

```
mean + 2 * sd
```

```
[1] 94
```

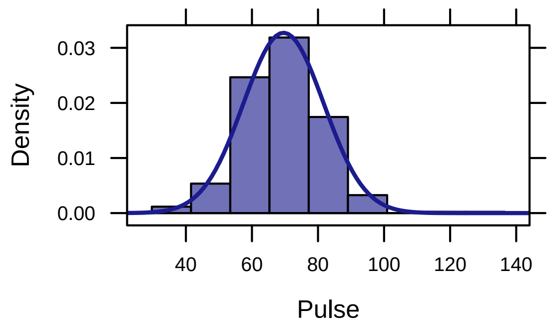
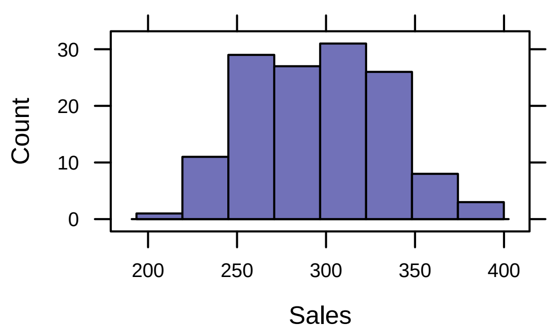


Figure 2.20

```
histogram(~Sales, type = "count", data = RetailSales)
```

Figure2.20



Example 2.18

```
mean <- mean(~Sales, data = RetailSales)
mean
```
Example2.18

```
[1] 296
```

```
sd <- sd(~Sales, data = RetailSales)
sd
```

```
[1] 38
```

```
mean - 2 * sd
```

```
[1] 220
```

```
mean + 2 * sd
```

```
[1] 372
```

Example 2.19

Z-scores can be computed as follows:

Example2.19

```
(204 - mean(~Systolic, data = ICUAdmissions))/sd(~Systolic, data = ICUAdmissions)
```

```
[1] 2.18
```

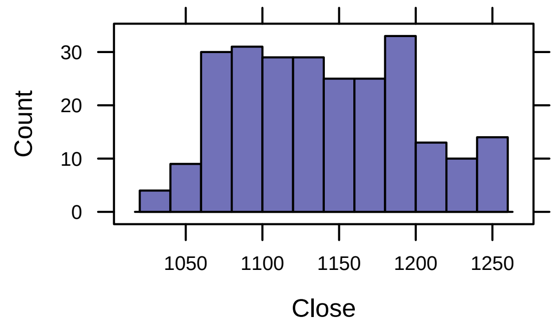
```
(52 - mean(~HeartRate, data = ICUAdmissions))/sd(~HeartRate, data = ICUAdmissions)
```

```
[1] -1.75
```

Percentiles

Figure 2.21

```
histogram(~Close, type = "count", width = 20, center = 10, data = SandP500)
```
Figure2.21



Example 2.20

The text uses a histogram to estimate the **percentile** of the daily closing price for the S&P 500 but we can also find the exact percentiles using the `quantile()` function.

Example2.20

```
quantile(SandP500$Close, probs = seq(0, 1, 0.25))

  0%  25%  50%  75% 100%
1023 1095 1137 1183 1260

quantile(SandP500$Close, probs = seq(0, 1, 0.9))

  0%  90%
1023 1217
```

Five Number Summary

We have already covered many different functions which results in the **five number summary** but `fivenum()` is most direct way to obtain in the five number summary.

Example 2.21

Example2.21

```
fivenum(~Exercise, data = StudentSurvey)
```

Example 2.22

Example2.22

```
fivenum(~Longevity, data = MammalLongevity)

[1]  1.0  8.0 12.0 15.5 40.0
```

```
min(~Longevity, data = MammalLongevity)

[1] 1

max(~Longevity, data = MammalLongevity)

[1] 40

range(~Longevity, data = MammalLongevity)  # subtract to get the numerical range value

[1]  1 40

iqr(~Longevity, data = MammalLongevity)  # interquartile range

[1] 7.25
```

Note the difference in the quartile and IQR from the textbook. This results because there are several different methods to determine the quartile.

Example 2.23

Example2.23

```
fivenum(~DesMoines, data = April14Temps)

[1] 37.2 44.4 54.5 62.0 74.9

fivenum(~SanFrancisco, data = April14Temps)

[1] 48.7 51.2 54.0 56.0 61.0

range(~DesMoines, data = April14Temps)

[1] 37.2 74.9

diff(range(~DesMoines, data = April14Temps))

[1] 37.7

range(~SanFrancisco, data = April14Temps)

[1] 48.7 61.0

diff(range(~SanFrancisco, data = April14Temps))

[1] 12.3
```



```
iqr(~DesMoines, data = April14Temps)

[1] 16.9

iqr(~SanFrancisco, data = April14Temps)

[1] 4.6
```

2.4 Outliers, Boxplots, and Quantitative/Categorical Relationships

Detection of Outliers

Generally, outliers are considered to be values

- less than $Q_1 - 1.5 \cdot (IQR)$, and
- greater than $Q_3 + 1.5 \cdot (IQR)$.

Example 2.25

Example2.25

```
fivenum(~Longevity, data = MammalLongevity)

[1]  1.0  8.0 12.0 15.5 40.0

iqr(~Longevity, data = MammalLongevity)

[1] 7.25

8 - 1.5 * 7.25

[1] -2.88

15.5 + 1.5 * 7.25

[1] 26.4

subset(MammalLongevity, Longevity > 26.375)

     Animal Gestation Longevity
15 elephant       645        40
```

There is no function in R that directly results in outliers because practically, there is no one specific formula for such a determination. However, a boxplot will indirectly reveal outliers.

Boxplots

A way to visualize the five number summary and outliers for a variable is to create a boxplot.

Example 2.26

Example2.26

```
favstats(~Longevity, data = MammalLongevity)

 min Q1 median   Q3 max mean   sd  n missing
   1  8     12 15.2  40 13.2 7.24 40       0

bwplot(~Longevity, data = MammalLongevity)
```

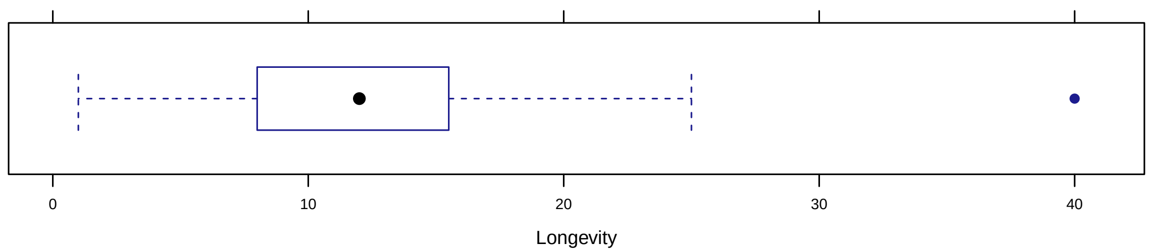
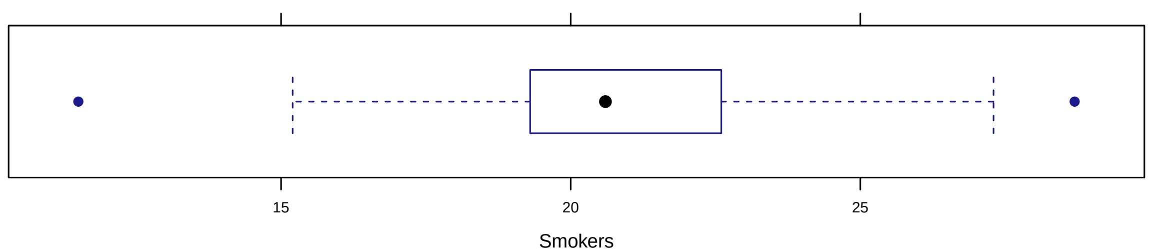


Figure 2.32

Figure2.32

```
bwplot(~Smokers, data = USStates)
```



Example 2.27

We can similarity investigate the *Smokers* variable in `USStates`.

Example2.27

```
fivenum(~Smokers, data = USStates)

[1] 11.5 19.3 20.6 22.6 28.7
```


The boxplot reveals two outliers. To identify them, we can again use `subset()` for smokers greater or less than the *whiskers* of the boxplot.

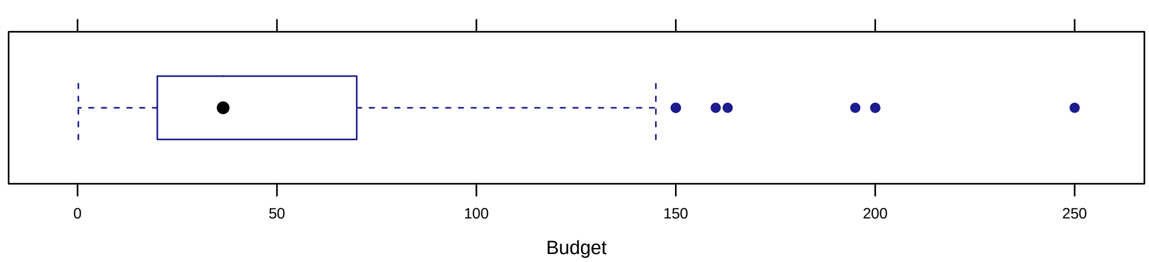
Example2.27b

```
subset(USStates, Smokers < 15)


   State HouseholdIncome  IQ McCainVote Region ObamaMcCain Population EighthGradeMath
44  Utah           55619 101      0.629      W           M       2.42             279
   HighSchool   GSP FiveVegetables Smokers PhysicalActivity Obese College NonWhite
44         91 36758           22.1    11.5             83.1  21.2      31     12.1
   HeavyDrinkers Pres2008
44           2.9   McCain


subset(USStates, Smokers > 28)


      State HouseholdIncome   IQ McCainVote Region ObamaMcCain Population EighthGradeMath
17 Kentucky           38694 99.4      0.575     MW           M       4.14             274
   HighSchool   GSP FiveVegetables Smokers PhysicalActivity Obese College NonWhite
17       81.8 33666           16.8    28.7             70.1  28.6    22.6      9.4
   HeavyDrinkers Pres2008
17           2.7   McCain
```

Figure 2.33

Figure2.33

```
bwplot(~Budget, data = HollywoodMovies2011)
```



Example 2.28

Example2.28

```
subset(HollywoodMovies2011, Budget > 225)


                                       Movie LeadStudio RottenTomatoes AudienceScore
30 Pirates of the Caribbean:\nOn Stranger Tides     Disney             34            61
   Story  Genre TheatersOpenWeek BOAverageOpenWeek DomesticGross ForeignGross WorldGross
30 Quest Action             4155             21697           241          803       1044
   Budget Profitability OpeningWeekend
30    250          4.18           90.2


head(HollywoodMovies2011)
```

```
                                     Movie       LeadStudio RottenTomatoes
1                                Insidious             Sony             67
2                     Paranormal Activity 3       Independent             68
3                              Bad Teacher       Independent             44
4 Harry Potter and the Deathly Hallows Part 2       Warner Bros             96
5                              Bridesmaids Relativity Media             90
6                          Midnight in Paris             Sony             93
  AudienceScore         Story   Genre TheatersOpenWeek BOAverageOpenWeek DomesticGross
1            65 Monster Force  Horror             2408              5511          54.0
2            58 Monster Force  Horror             3321             15829         103.7
3            38        Comedy  Comedy             3049             10365         100.3
4            92       Rivalry Fantasy             4375             38672         381.0
5            77       Rivalry  Comedy             2918              8995         169.1
6            84          Love Romance              944              6177          56.2
  ForeignGross WorldGross Budget Profitability OpeningWeekend
1         43.0         97    1.5         64.67          13.27
2         98.2        202    5.0         40.38          52.57
3        115.9        216   20.0         10.81          31.60
4        947.1       1328  125.0         10.62         169.19
5        119.3        288   32.5          8.87          26.25
6         83.0        139   17.0          8.19           5.83
```

One Quantitative and One Categorical Variable

The formula for a `lattice` plot can be extended to create multiple panels (sometimes called **facets**) based on a “condition”, often given by another variable. This is another way to look at multiple groups simultaneously. The general syntax for this becomes

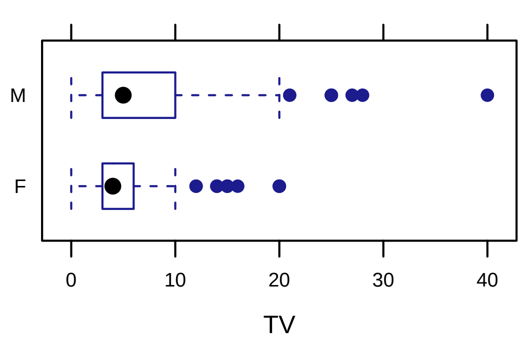
```
plotname(~variable | condition, data = dataName)
```

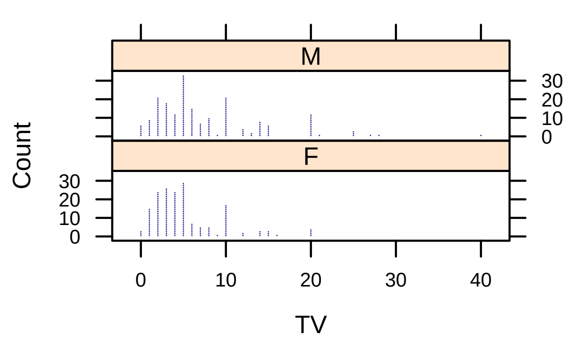
Figure 2.34

Depending on the type of plot, you will want to use conditioning.

Figure2.34

```
bwplot(Gender ~ TV, data = StudentSurvey)
dotPlot(~TV | Gender, layout = c(1, 2), width = 1, cex = 1, data = StudentSurvey)
```

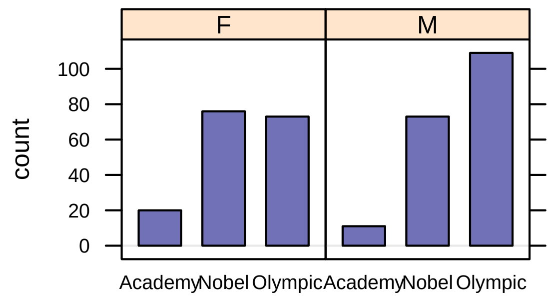




We can do the same thing for bar graphs.

Figure2.34b

```
bargraph(~Award | Gender, data = StudentSurvey)
```



This graph should be familiar as we have plotted these variables together previously. Here we used different panels, but before, in 2.1, we had used grouping. Note that we can combine grouping and conditioning in the same plot.

Example 2.31

Example2.31

```
favstats(~TV | Gender, data = StudentSurvey)
diffmean(~TV | Gender, data = StudentSurvey)
```

2.5 Two Quantitative Variables: Scatterplot and Correlation

Example 2.32

Example2.32

```
ElectionMargin

   Year  Candidate Approval Margin Result
1  1940  Roosevelt       62   10.0    Won
2  1948     Truman       50    4.5    Won
3  1956 Eisenhower       70   15.4    Won
4  1964    Johnson       67   22.6    Won
5  1972      Nixon       57   23.2    Won
6  1976       Ford       48   -2.1   Lost
7  1980     Carter       31   -9.7   Lost
8  1984     Reagan       57   18.2    Won
9  1992 G.H.W.Bush       39   -5.5   Lost
10 1996    Clinton       55    8.5    Won
11 2004   G.W.Bush       49    2.4    Won
```

Visualizing a Relationship between Two Quantitative Variables: Scatterplots

The most common way to look at two quantitative variables is with a scatterplot. The `lattice` function for this is `xyplot()`, and the basic syntax is

```
xyplot(yvar ~ xvar, data = dataName)
```

Notice that now we have something on both sides of the ~ since we need to tell R about two variables.

Example 2.33

```
xyplot(Margin ~ Approval, data = ElectionMargin)
```

Example2.33

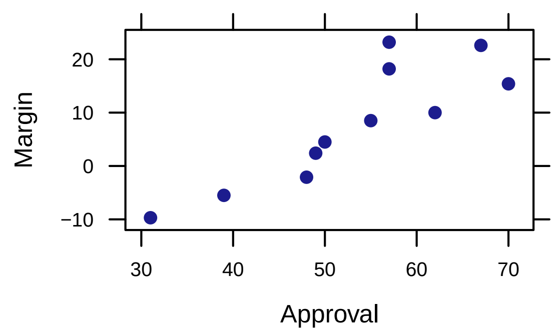
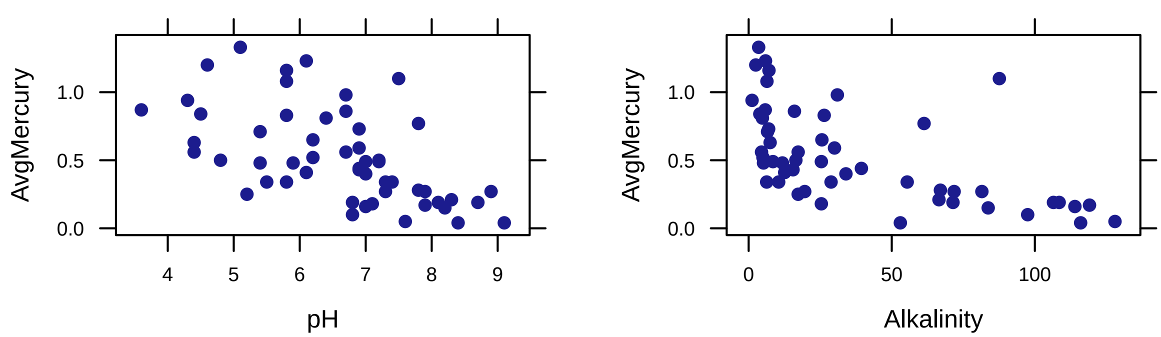
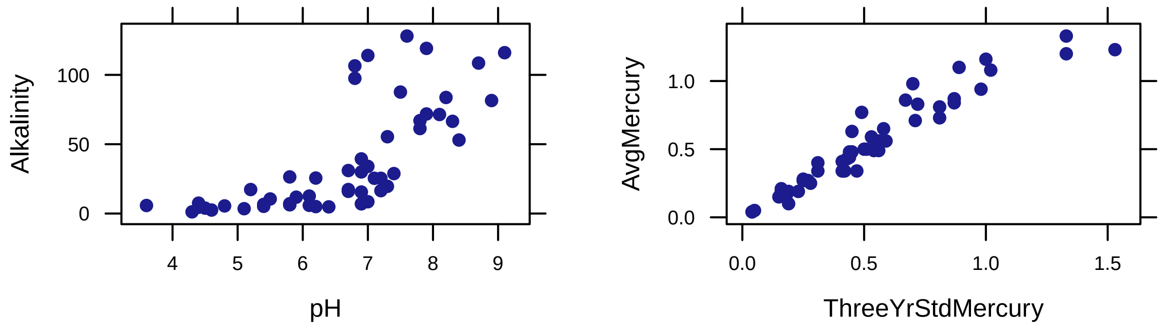


Figure 2.49

```
xyplot(AvgMercury ~ pH, data = FloridaLakes)
xyplot(AvgMercury ~ Alkalinity, data = FloridaLakes)
xyplot(Alkalinity ~ pH, data = FloridaLakes)
xyplot(AvgMercury ~ ThreeYrStdMercury, data = FloridaLakes)
```

Figure2.49





Summarizing a Relationship between Two Quantitative Variables: Correlation

Another key numerical statistic is the **correlation**–the correlation is a measure of the strength and direction of the relationship between two quantitative variables.

Table2.30

```
cor(Margin ~ Approval, data = ElectionMargin)

[1] 0.863

cor(AvgMercury ~ pH, data = FloridaLakes)

[1] -0.575

cor(AvgMercury ~ Alkalinity, data = FloridaLakes)

[1] -0.594

cor(Alkalinity ~ pH, data = FloridaLakes)

[1] 0.719

cor(AvgMercury ~ ThreeYrStdMercury, data = FloridaLakes)

[1] 0.959
```

Table 2.31

Table2.31

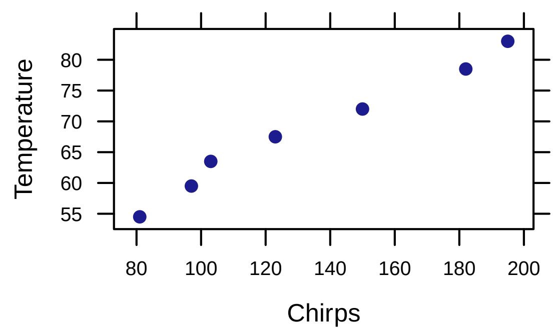
```
CricketChirps

  Temperature Chirps
1        54.5     81
```

```
2         59.5      97
3         63.5     103
4         67.5     123
5         72.0     150
6         78.5     182
7         83.0     195
```

Figure 2.50

```
xyplot(Temperature ~ Chirps, data = CricketChirps)
```

Figure2.50



Example 2.35

```
cor(Temperature ~ Chirps, data = CricketChirps)

[1] 0.991
```

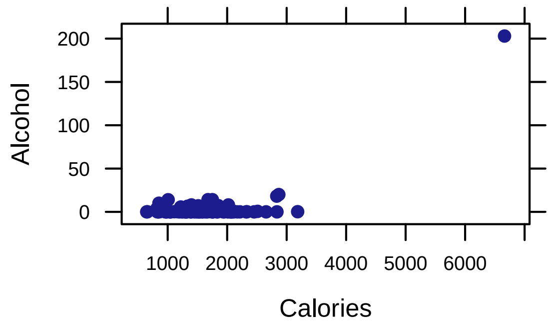
Example2.35

Example 2.38

Further, using the `subset()` function again, we can investigate the correlation between variables with some restrictions.

Example2.38

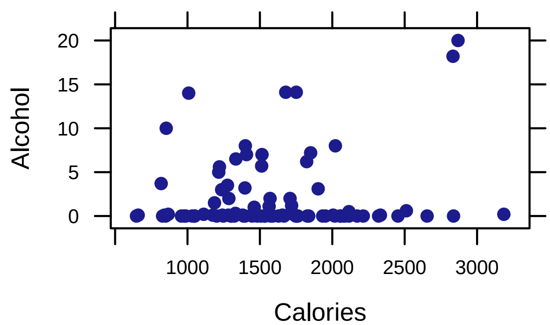
```
xyplot(Alcohol ~ Calories, data = subset(NutritionStudy, Age > 59))
cor(Alcohol ~ Calories, data = subset(NutritionStudy, Age > 59))

[1] 0.72
```



And now we omit the outlier

Example2.38b

```
NutritionStudy60 = subset(NutritionStudy, Age > 59)
xyplot(Alcohol ~ Calories, data = subset(NutritionStudy60, Alcohol < 25))
cor(Alcohol ~ Calories, data = subset(NutritionStudy60, Alcohol < 25))

[1] 0.145
```

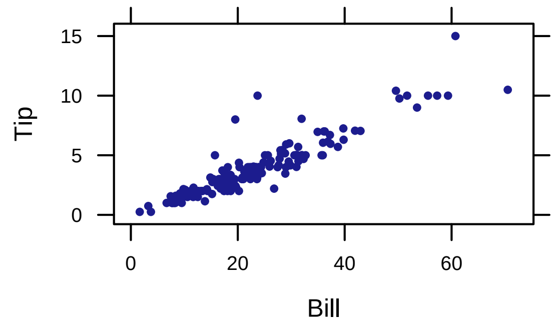


2.6 Two Quantitative Variables: Linear Regression

Figure 2.63

```
xyplot(Tip ~ Bill, cex = 0.5, data = RestaurantTips)
```

Figure2.63

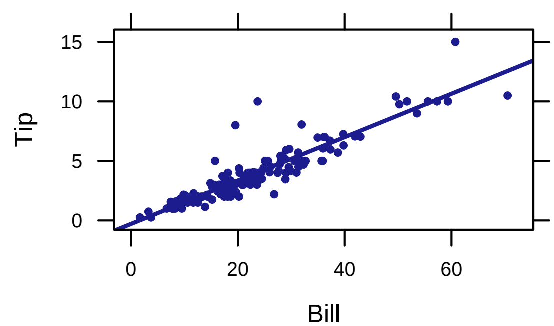


Example 2.39

When the relationship between variables is sufficiently *linear*, you may be able to predict the value of a variable using the other variable. This is possible by fitting a *regression line*. To plot this in R, all we need to do is add an additional argument, `type = c("p", "r")`, to the xyplot.

Example2.39

```
xyplot(Tip ~ Bill, cex = 0.5, type = c("p", "r"), data = RestaurantTips)
cor(Tip ~ Bill, data = RestaurantTips)

[1] 0.915
```



The equation for the regression line, or the *prediction equation* is

$$\widehat{\text{Response}} = a + b \cdot \text{Explanatory}$$

So now, we need to find the values for a, the intercept, and b, the slope using the function to fit linear models.

Example 2.41

Example2.41

```
lm(Tip ~ Bill, data = RestaurantTips)
```



```
Call:
lm(formula = Tip ~ Bill, data = RestaurantTips)

Coefficients:
(Intercept)         Bill
     -0.292        0.182


coef(lm(Tip ~ Bill, data = RestaurantTips))  # just show me the coefficients


(Intercept)        Bill
     -0.292       0.182
```

This results in the equation

$$\widehat{\text{Tip}} = -0.292 + 0.182 \cdot \text{Bill}$$

With this equation, one can predict the tip for different bill amounts.

Example2.41b

```
Tip.Fun <- makeFun(lm(Tip ~ Bill, data = RestaurantTips))  # make a function of the linear model
Tip.Fun(Bill = 59.33)  # predicted tip when bill is $59.33


   1
10.5


Tip.Fun(Bill = 9.52)


   1
1.44


Tip.Fun(Bill = 23.7)


   1
4.03
```

An important aspect of the linear regression is the difference between the prediction and actual observation. This is called the **residual**, defined

$$\text{residual} = \text{observed response} - \text{predicted response}$$

Example 2.42

Example2.42

```
Resid.a <- 10 - 10.51  # predicted tip from Example 2.41
Resid.a


[1] -0.51


Resid.b <- 1 - 1.44
Resid.b
```

```
[1] -0.44

Resid.c <- 10 - 4.02
Resid.c

[1] 5.98
```

Example 2.43

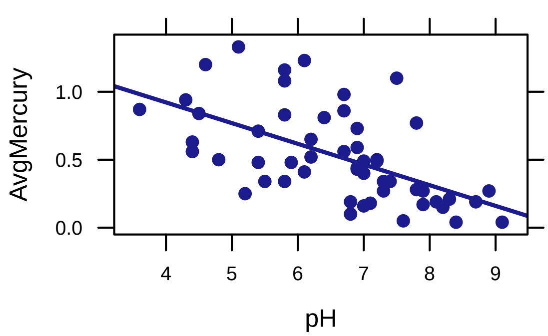
```
Elect.mod <- lm(Margin ~ Approval, data = ElectionMargin)
resid(lm(Margin ~ Approval, data = ElectionMargin))

     1      2      3      4      5      6      7      8      9     10     11
-5.323 -0.796 -6.608  3.099 12.055 -5.725  0.880  7.055 -1.604 -0.974 -2.060
```

Example2.43

Example 2.45

```
lm(AvgMercury ~ pH, data = FloridaLakes)

Call:
lm(formula = AvgMercury ~ pH, data = FloridaLakes)

Coefficients:
(Intercept)           pH
      1.531       -0.152

xyplot(AvgMercury ~ pH, type = c("p", "r"), data = FloridaLakes)
```

Example2.45




```
Mer.Fun <- makeFun(lm(AvgMercury ~ pH, data = FloridaLakes))
Mer.Fun(pH = 7.5)  # predicted mercury level at 7.5 pH
```

Example2.45b


```
    1
0.389

Resid <- 1.1 - 0.388  # residual at 7.5 pH
Resid

[1] 0.712
```

Example 2.46

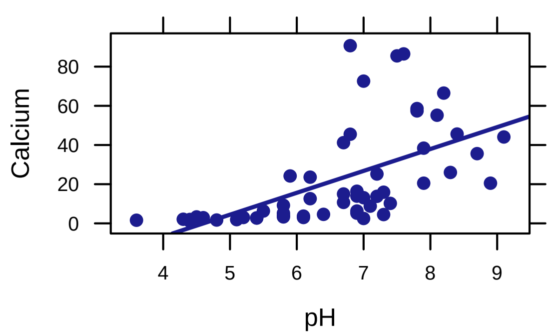
```
Cal.Fun <- makeFun(lm(Calcium ~ pH, data = FloridaLakes))
Cal.Fun

function (pH, ..., transform = function (x)
x)
return(transform(predict(model, newdata = data.frame(pH = pH),
    ...)))
<environment: 0x7fe5f00980a0>
attr(,"coefficients")
(Intercept)          pH
      -51.4        11.2
```

Example2.46

Figure 2.68

```
xyplot(Calcium ~ pH, type = c("p", "r"), data = FloridaLakes)
```

Figure2.68



3 Confidence Intervals

3.1 Sampling Distributions

The key idea in this chapter is the notion of a sampling distribution. Do not confuse it with the population (what we would like to know about) or the sample (what we actually have data about). If we could repeatedly sample from a population, and if we computed a statistic from each sample, the distribution of those statistics would be the sampling distribution. Sampling distributions tell us how things vary from sample to sample and are the key to interpreting data.

Variability of Sample Statistics

Example 3.4

Example3.4

```
head(StatisticsPhD)
```

```
                     University    Department FTGradEnrollment
1             Baylor University    Statistics               26
2             Boston University Biostatistics               39
3              Brown University Biostatistics               21
4      Carnegie Mellon University    Statistics               39
5 Case Western Reserve University    Statistics               11
6       Colorado State University    Statistics               14
```

```
mean(~FTGradEnrollment, data = StatisticsPhD)  # mean enrollment in original population
```

```
[1] 53.5
```

Example 3.5

To select a random sample of a certain size in R, we can use the `sample()` function.

Example3.5

```
sample10 <- sample(StatisticsPhD, 10)
sample10
```

```
                         University    Department FTGradEnrollment orig.id
49            University of Chicago    Statistics              109      49
17             Iowa State University    Statistics              145      17
35     Southern Methodist University    Statistics               21      35
29         Oklahoma State University    Statistics               22      29
14      George Washington University    Statistics                9      14
52            University of Florida    Statistics               68      52
44 University of California - Davis    Statistics               34      44
1                 Baylor University    Statistics               26       1
15               Harvard University Biostatistics              70      15
82                  Yale University    Statistics               36      82
```

```
x.bar <- mean(~FTGradEnrollment, data = sample10)
x.bar  # mean enrollment in sample10
```

```
[1] 54
```

Note that this sample has been assigned a name to which we can refer back to find the mean of that particular sample.

Example3.5b

```
mean(~FTGradEnrollment, data = sample(StatisticsPhD, 10))  # mean enrollment in another sample
```

```
[1] 55.7
```

Figure 3.1

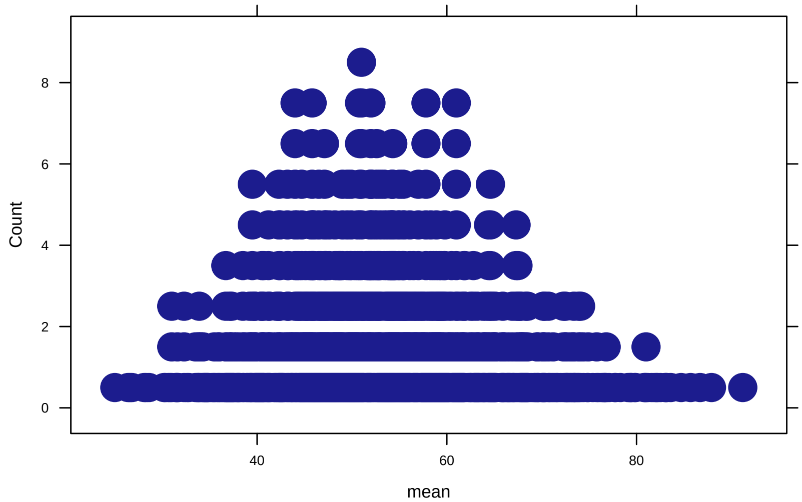
We should check that that our sample distribution has an appropriate shape:

Figure3.1

```
# Now we'll do it 1000 times
Sampledist <- do(1000) * mean(~FTGradEnrollment, data = sample(StatisticsPhD, 10))
head(Sampledist, 3)
```

```
  mean
1 52.9
2 52.0
3 40.4
```

```
dotPlot(~mean, width = 0.005, data = Sampledist)
```

In many (but not all) situations, the sampling distribution is

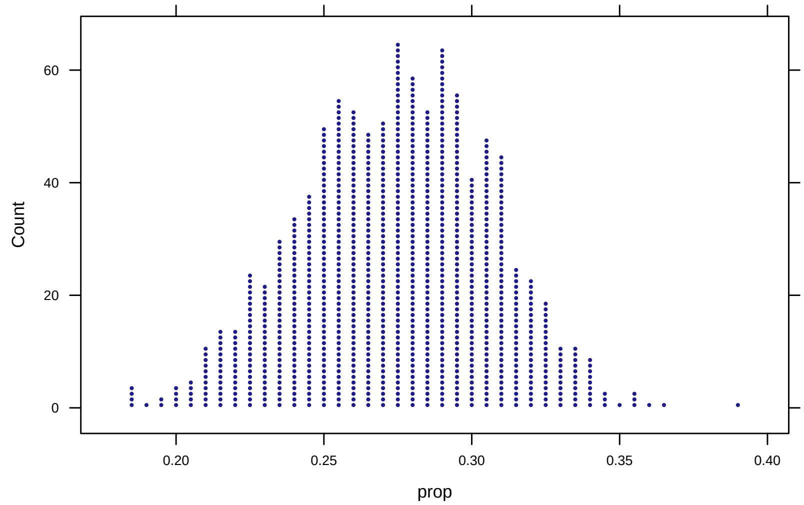
- unimodal,
- symmetric, and
- bell-shaped (The technical phrase is "approximately normal".)

Example 3.6

This time we don't have data, but instead we have a summary of the data. We can however, still simulate the sample distribution by using the `rflip()` function.

Example3.6

```
Sampledist.deg <- do(1000) * rflip(200, 0.275)  # 1000 samples, each of size 200 and proportion 0.275
head(Sampledist.deg, 3)

    n heads tails  prop
1 200    47   153 0.235
2 200    57   143 0.285
3 200    56   144 0.280

dotPlot(~prop, width = 0.005, data = Sampledist.deg)
```



Measuring Sampling Variability: The Standard Error

The standard deviation of a sampling distribution is called the **standard error**, denoted SE.

The standard error is our primary way of measuring how much variability there is from sample statistic to sample statistic, and therefore how precise our estimates are.

Example 3.7

Calculating the SE is the same as calculating the standard deviation of a sampling distribution, so we use `sd()`.

Example3.7

```
SE <- sd(~mean, data = Sampledist)
SE  # sample from Example 3.5

[1] 11.4

SE2 <- sd(~prop, data = Sampledist.deg)
SE2  # sample from Example 3.6

[1] 0.0316
```

The Importance of Sample Size

Example 3.9

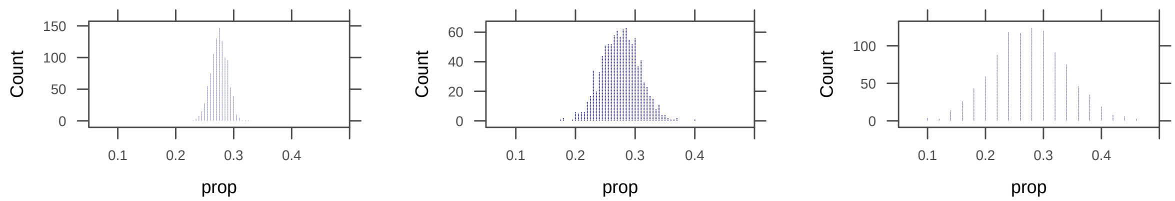
Example3.9

```
Sampledist.1000 <- do(1000) * rflip(1000, 0.275)  # 1000 samples, each of size 1000 and proportion 0.275
Sampledist.200 <- do(1000) * rflip(200, 0.275)  # 1000 samples, each of size 200 and proportion 0.275
Sampledist.50 <- do(1000) * rflip(50, 0.275)  # 1000 samples, each of size 50 and proportion 0.275
```

Figure 3.3

Figure3.3

```
dotPlot(~prop, width = 0.005, xlim = c(0.05, 0.5), data = Sampledist.1000)
dotPlot(~prop, width = 0.005, xlim = c(0.05, 0.5), data = Sampledist.200)
dotPlot(~prop, width = 0.005, xlim = c(0.05, 0.5), data = Sampledist.50)
```



3.2 Understanding and Interpreting Confidence Intervals

Interval Estimates and Margin of Error

An **interval estimate** gives a range of plausible values for a population parameter.

This is better than a single number (also called a point estimate) because it gives some indication of the precision of the estimate.

One way to express an interval estimate is with a point estimate and a **margin of error**.

We can convert margin of error into an interval by adding and subtracting the margin of error to/from the statistic.

Example 3.12

Example3.12

```
p.hat <- 0.42                    # sample proportion
MoE <- 0.03                      # margin of error
p.hat - MoE                      # lower limit of interval estimate

[1] 0.39

p.hat + MoE                      # upper limit of interval estimate

[1] 0.45
```

Example 3.13

```
p.hat <- 0.54                    # sample proportion
MoE <- 0.02                      # margin of error
p.hat - MoE                      # lower limit of interval estimate
```

```
[1] 0.52
```

```
p.hat + MoE                      # upper limit of interval estimate
```

```
[1] 0.56
```

Example3.13

```
p.hat <- 0.54
MoE <- 0.1
p.hat - MoE
```

```
[1] 0.44
```

```
p.hat + MoE
```

```
[1] 0.64
```

Example3.13b

Confidence Intervals

A confidence interval for a parameter is an interval computed from sample data by a method that will capture the parameter for a specified proportion of all samples

1. The probability of correctly containing the parameter is called the coverage rate or **confidence level**.
2. So 95% of 95% confidence intervals contain the parameter being estimated.
3. The margins of error in the tables above were designed to produce 95% confidence intervals.

Example 3.14

```
x.bar <- 61.5            # given sample mean
SE <- 11                 # given estimated standard error
MoE <- 2 * SE; MoE       # margin of error for 95% CI
```

```
[1] 22
```

```
x.bar - MoE              # lower limit of 95% CI
```

Example3.14


```
[1] 39.5

x.bar + MoE                # upper limit of 95% CI

[1] 83.5
```

Understanding Confidence Intervals

Example 3.15

Example3.15

```
SE <- 0.03
p1 <- 0.26
p2 <- 0.32
p3 <- 0.2
MoE <- 2 * SE
```

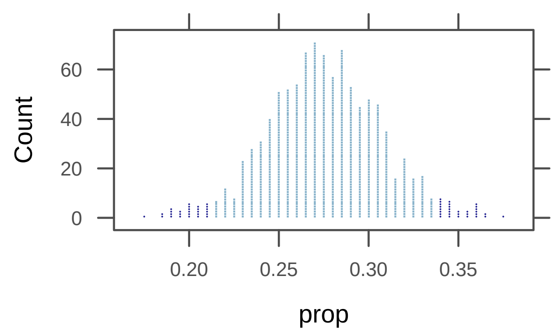
Example3.15b

```
p1 - MoE

[1] 0.2

p1 + MoE

[1] 0.32

p2 - MoE

[1] 0.26

p2 + MoE

[1] 0.38

p3 - MoE

[1] 0.14

p3 + MoE

[1] 0.26
```

Figure 3.12

Figure3.12

```
p <- 0.275
SE <- 0.03
MoE <- 2 * SE
p - MoE

[1] 0.215

p + MoE

[1] 0.335

dotPlot(~prop, width = 0.005, groups = (0.215 <= prop & prop <= 0.335), data = Sampledist.deg)
```



Notice how we defined groups in this dotplot. We are grouping proportions that less than 0.215 and more than 0.335.

Figure 3.13

We can create the data needed for plots like Figure 3.13 using `CIsim()`.

Figure3.13

```
CIsim(200, samples = 3, rdist = rbinom, args = list(size = 1, prob = 0.275), method = binom.test,
    method.args = list(success = 1), verbose = FALSE, estimand = 0.275)
```

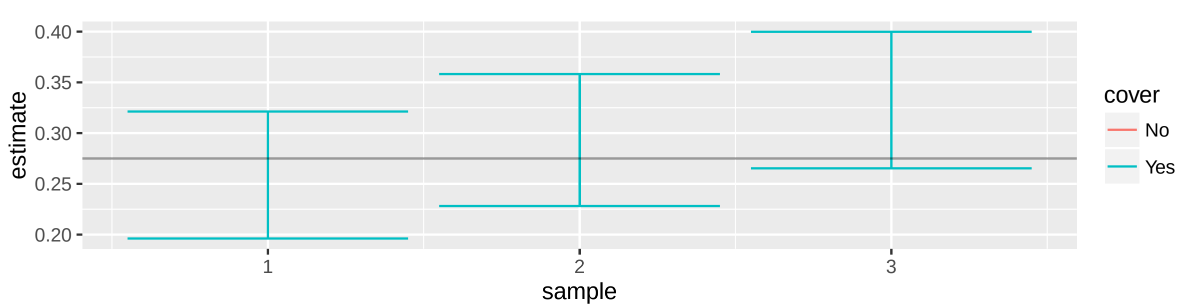
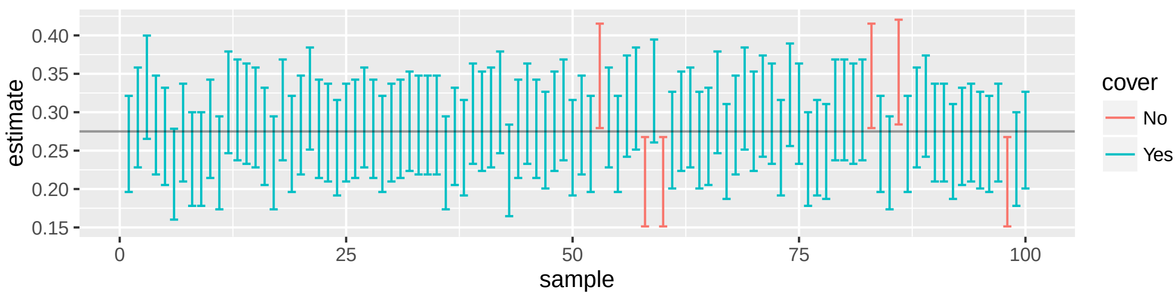


Figure3.13b

```
CIsim(200, samples = 100, rdist = rbinom, args = list(size = 1, prob = 0.275), method = binom.test,
    method.args = list(success = 1), verbose = FALSE, estimand = 0.275)
```



Interpreting Confidence Intervals

Example 3.16

Example3.16

```
x.bar <- 27.655
SE <- 0.009
MoE <- 2 * SE
x.bar - MoE

[1] 27.6

x.bar + MoE

[1] 27.7
```

Example 3.17

Example3.17

```
diff.x <- -1.915
SE <- 0.016
MoE <- 2 * SE
diff.x - MoE

[1] -1.95

diff.x + MoE

[1] -1.88
```

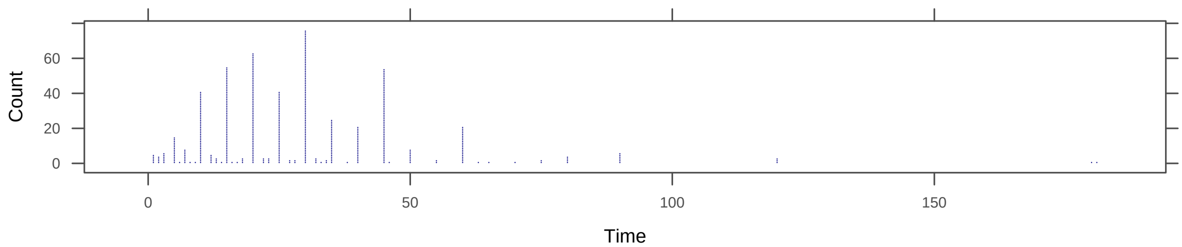
3.3 Constructing Bootstrap Confidence Intervals

Here's the clever idea: We don't have the population, but we have a sample. Probably the sample it similar to the population in many ways. So let's sample from our sample. We'll call it **resampling** (also called **bootstrapping**). We want samples the same size as our original sample, so we will need to sample with replacement. This means that we may pick some members of the population more than once and others not at all. We'll do this many times, however, so each member of our sample will get its fair share. (Notice the similarity to and difference from sampling from populations in the previous sections.)

Figure 3.14

Figure3.14

```
dotPlot(~Time, width = 1, data = CommuteAtlanta)
```



Bootstrap Samples

Table 3.7

The computer can easily do all of the resampling by using the `resample()`.

Table3.7

```
mean(~Time, data = resample(CommuteAtlanta))  # mean commute time in one resample

[1] 30.1

mean(~Time, data = resample(CommuteAtlanta))  # mean commute time in another resample

[1] 30.9

mean(~Time, data = resample(CommuteAtlanta))

[1] 28.3
```


Bootstrap Distribution

Figure 3.16

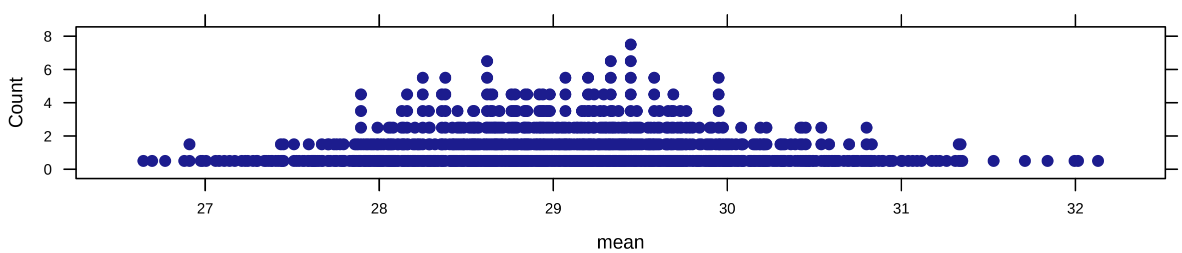
The example below uses data from 500 Atlanta commuters.

Figure3.16

```
# Now we'll do it 1000 times
Bootstrap <- do(1000) * mean(~Time, data = resample(CommuteAtlanta))
head(Bootstrap, 3)
```

```
    mean
1 27.006
2 28.354
3 28.362
```

```
# We should check that that our bootstrap distribution has an appropriate shape:
dotPlot(~mean, width = 0.005, data = Bootstrap)
```



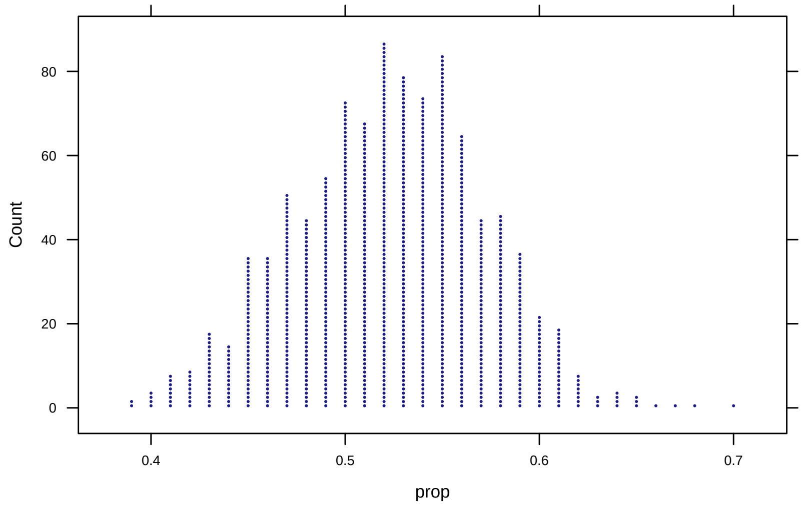
Example 3.19

Example3.19

```
BootP <- do(1000) * rflip(100, 0.52)
head(BootP, 3)
```

```
    n heads tails prop
1 100    49    51 0.49
2 100    45    55 0.45
3 100    61    39 0.61
```

```
dotPlot(~prop, width = 0.01, data = BootP)
```



Example 3.20

Variables can be created in R using the `c()` function then collected into a data frame using the `data.frame()` function.

Example3.20

```
Laughter <- data.frame(NumLaughs = c(16, 22, 9, 31, 6, 42))
mean(~NumLaughs, data = Laughter)

[1] 21
```

Example3.20b

```
mean(~NumLaughs, data = resample(Laughter))

[1] 25.5

mean(~NumLaughs, data = resample(Laughter))

[1] 20.8

mean(~NumLaughs, data = resample(Laughter))

[1] 19.7
```

Estimating Standard Error Based on a Bootstrap Distribution

Example 3.21

Since the shape of the bootstrap distribution from Example 3.19 looks good, we can estimate the standard error.

Example3.21

```
SE <- sd(~prop, data = BootP)
SE
```

```
[1] 0.0485
```

95 % Confidence Interval Based on a Bootstrap Standard Error

Example 3.22

We can again use the standard error to compute a 95% confidence interval.

Example3.22

```
x.bar <- mean(~Time, data = CommuteAtlanta); x.bar
```

```
[1] 29.1
```

```
SE <- sd( ~ mean, data = Bootstrap ); SE        # standard error
```

```
[1] 0.902
```

```
MoE <- 2 * SE; MoE                              # margin of error for 95% CI
```

```
[1] 1.8
```

```
x.bar - MoE                                     # lower limit of 95% CI
```

```
[1] 27.3
```

```
x.bar + MoE                                     # upper limit of 95% CI
```

```
[1] 30.9
```

Example3.22b

```
p.hat <- 0.52
SE <- sd(~prop, data = BootP)
SE
```

```
[1] 0.0485
```

```
MoE <- 2 * SE
MoE
```

```
[1] 0.097
```

```
p.hat - MoE

[1] 0.423

p.hat + MoE

[1] 0.617
```

The steps used in this example get used in a wide variety of confidence interval situations.

1. Compute the statistic from the original sample.
2. Create a bootstrap distribution by resampling from the sample.
   (a) same size samples as the original sample
   (b) with replacement
   (c) compute the statistic for each sample

   The distribution of these statistics is the bootstrap distribution
3. Estimate the standard error SE by computing the standard deviation of the bootstrap distribution.
4. 95% CI is
$$\text{statistic} \pm 2SE$$

3.4 Bootstrap Confidence Intervals Using Percentiles

Confidence Intervals Based on Bootstrap Percentiles

Example 3.23

Another way to create a 95% confidence interval is to use the middle 95% of the bootstrap distribution. The `cdata()` function can compute this for us as follows:

Example3.23

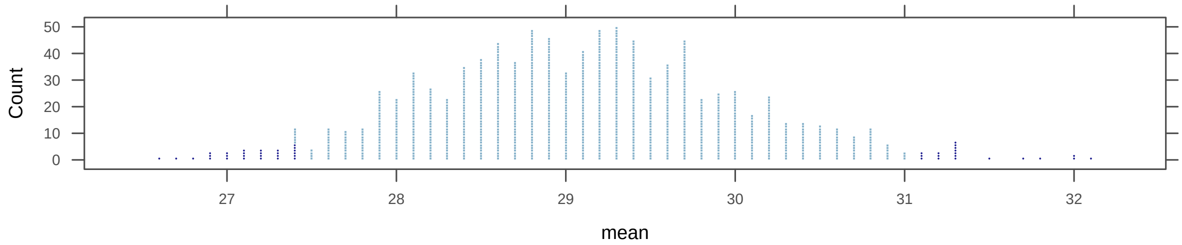
```
cdata(~mean, 0.95, data = Bootstrap)

     low       hi central.p
   27.41    30.89      0.95
```

This is not exactly the same as the interval of the original sample, but it is pretty close.

Figure 3.22

Figure3.22

```
dotPlot(~mean, width = 0.1, groups = (27.43 <= mean & mean <= 31.05), data = Bootstrap)
```



Notice the `groups=` for marking the confidence interval.

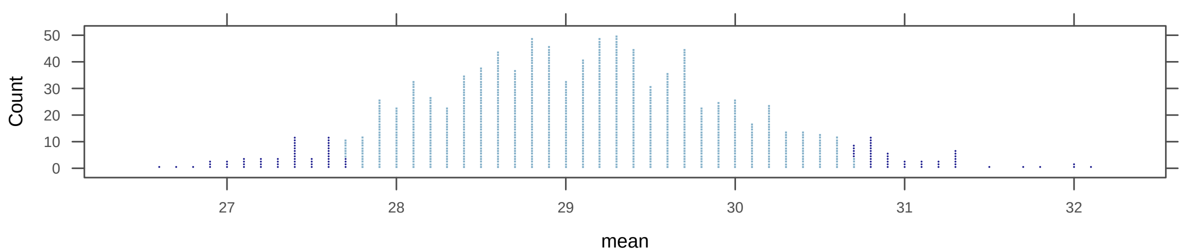
Example 3.24

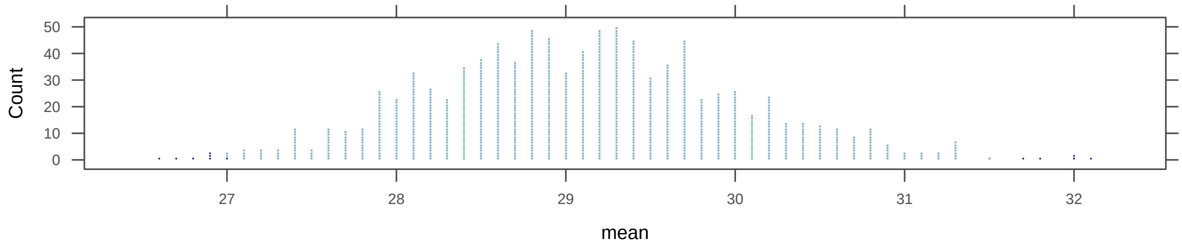
One advantage of this method is that it is easy to change the confidence level.

To make a 90% and 99% confidence interval, we use the middle 90% and 99% of the sample distribution instead.

Example3.24

```
cdata(~mean, 0.9, data = Bootstrap)

     low       hi central.p
    27.7     30.6       0.9

dotPlot(~mean, width = 0.1, groups = (27.7 <= mean & mean <= 30.71), data = Bootstrap)
cdata(~mean, 0.99, data = Bootstrap)

     low       hi central.p
   26.91    31.53      0.99

dotPlot(~mean, width = 0.1, groups = (26.98 <= mean & mean <= 31.63), data = Bootstrap)
```



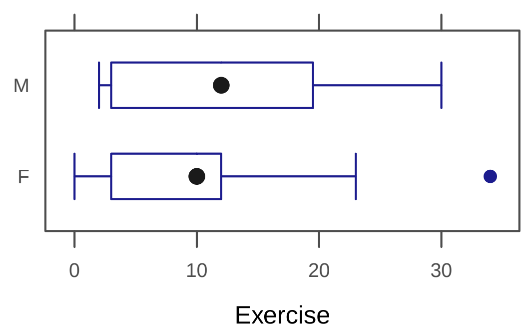


Finding Confidence Intervals for Many Different Parameters

Figure 3.24

```
bwplot(Gender ~ Exercise, data = ExerciseHours)
```

Figure3.24



Example 3.25

```
head(ExerciseHours)

  Year Gender Hand Exercise TV Pulse Pierces
1    4      M    l       15  5    57       0
2    2      M    l       20 14    70       0
3    3      F    r        2  3    70       2
4    1      F    l       10  5    66       3
5    1      M    r        8  2    62       0
6    1      M    r       14 14    62       0

favstats(~Exercise | Gender, data = ExerciseHours)

  Gender min Q1 median   Q3 max mean   sd  n missing
1      F   0  3     10 12.0  34  9.4 7.41 30       0
2      M   2  3     12 19.2  30 12.4 8.80 20       0

stat <- diffmean(Exercise ~ Gender, data = ExerciseHours)
stat
```

Example3.25

```
diffmean
       3
```

Example3.25b

```
BootE <- do(3000) * diffmean(Exercise ~ Gender, data = resample(ExerciseHours))
head(BootE, 3)
```

```
   diffmean
1 6.6000000
2 0.3694581
3 1.6029412
```

Example3.25c

```
cdata(~diffmean, 0.95, data = BootE)
```

```
      low        hi central.p
    -1.47      7.63      0.95
```

```
dotPlot(~diffmean, width = 0.25, cex = 0.75, groups = (-1.717 <= M & M <= 7.633), xlab = "Difference in mean",
    data = BootE)
```

```
Error in eval(expr, envir, enclos):  object 'M' not found
```

Example3.25d

```
SE <- sd(~diffmean, data = BootE)
SE
```

```
[1] 2.34
```

```
stat - 2 * SE
```

```
diffmean
   -1.67
```

```
stat + 2 * SE
```

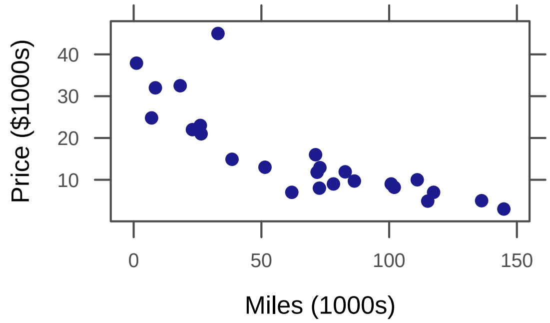
```
diffmean
    7.67
```

Figure 3.26

Figure3.26

```
xyplot(Price ~ Miles, ylab = "Price ($1000s)", xlab = "Miles (1000s)", data = MustangPrice)
cor(Price ~ Miles, data = MustangPrice)
```

```
[1] -0.825
```



Example 3.26

```
BootM <- do(5000) * cor(Price ~ Miles, data = resample((MustangPrice)))
head(BootM, 3)
```

Example3.26

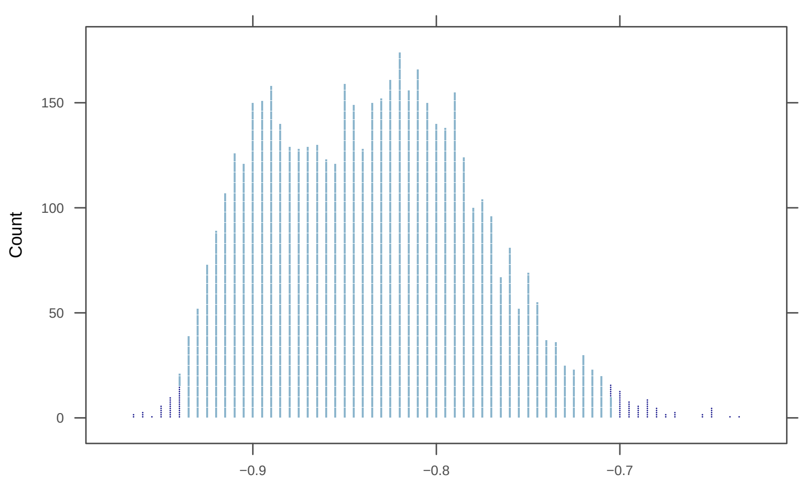
```
         cor
1 -0.7804073
2 -0.8045040
3 -0.8130291
```

Example3.26b

```
cdata(~cor, 0.98, data = BootM)
```

```
     low       hi central.p
  -0.937   -0.701     0.980
```

```
dotPlot(~cor, width = 0.005, groups = (-0.94 <= cor & cor <= -0.705), xlab = "r", data = BootM)
```



Another Look at the Effect of Sample Size

Example 3.27

```
BootP400 <- do(1000) * rflip(400, 0.52)
head(BootP400, 3)
```

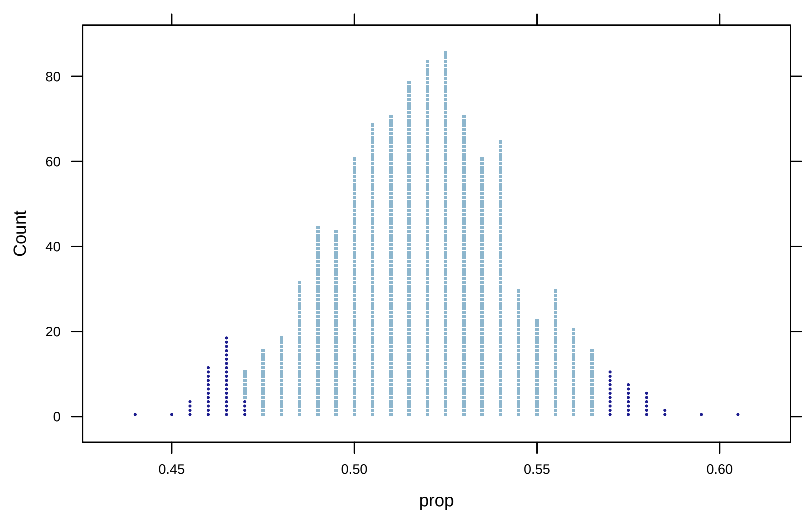
Example3.27

```
    n heads tails   prop
1 400   205   195 0.5125
2 400   214   186 0.5350
3 400   214   186 0.5350
```

```
cdata(~prop, 0.95, data = BootP400)
```

```
      low        hi central.p
   0.4675    0.5700    0.9500
```

```
dotPlot(~prop, width = 0.005, groups = (0.472 <= prop & prop <= 0.568), data = BootP400)
```



One Caution on Constructing Bootstrap Confidence Intervals

Example 3.28

```
median(~Price, data = MustangPrice)
```

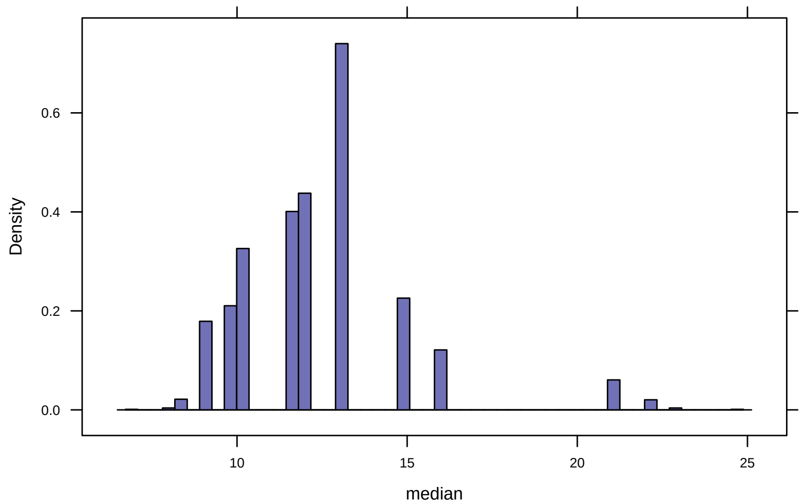
Example3.28

```
[1] 11.9
```

```
Boot.Mustang <- do(5000) * median(~Price, data = resample(MustangPrice))
head(Boot.Mustang, 3)
```

```
  median
1   11.8
2   14.9
3   10.0
```

```
histogram(~median, n = 50, data = Boot.Mustang)
```



This time the histogram does not have the desired shape. There are two problems:

1. The distribution is not symmetric. (It is right skewed.)
2. The distribution has spikes and gaps.

   Since the median must be an element of the sample when the sample size is 25, there are only 25 possible values for the median (and some of these are *very* unlikely.

Since the bootstrap distribution does not look like a normal distribution (bell-shaped, symmetric), we cannot safely use our methods for creating a confidence interval.

4 Hypothesis Tests

4.1 Introducing Hypothesis Tests

The 4-step outline

The following 4-step outline is a useful way to organize the ideas of hypothesis testing.

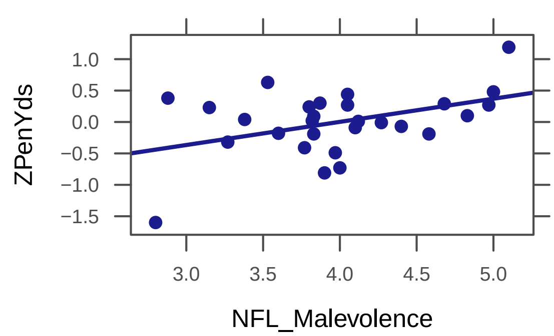
1. State the Null and Alternative Hypotheses
2. Compute the Test Statistic
   The test statistic is a number that summarizes the evidence
3. Determine the p-value (from the Randomization Distribution)
4. Draw a conclusion

Null and Alternative Hypotheses

Figure 4.1

```
xyplot(ZPenYds ~ NFL_Malevolence, type = c("p", "r"), data = MalevolentUniformsNFL)
```

Figure4.1



4.2 Measuring Evidence with P-values

Randomization distributions are a bit like bootstrap distributions except that instead of resampling from our sample (in an attempt to approximate resampling from the population), we need to sample from a situation in which our null hypothesis is true.

P-values from Randomization Distributions

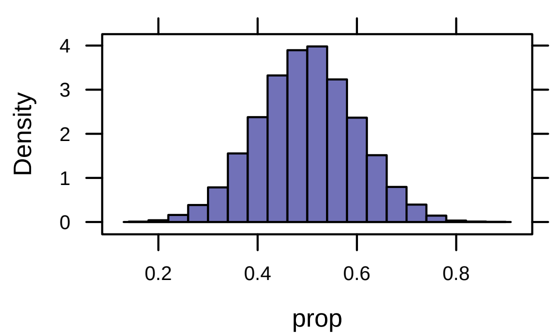
Example 4.13

Testing one proportion.

1. H_0: $p = 0.5$
   H_a: $p > 0.5$
2. Test statistic: $\hat{p} = 16/25$ (the sample proportion)
3. We can simulate a world in which $p = 0.5$ using `rflip()`:

Example4.13

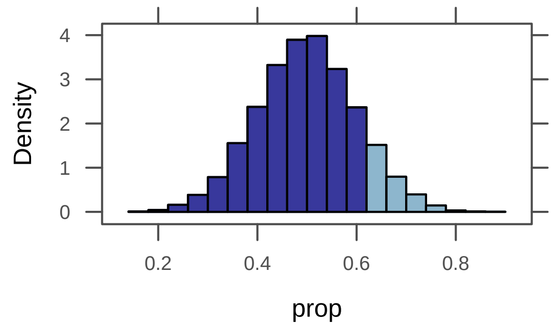
```
Randomization.Match <- do(10000) * rflip(25, 0.5)  # 25 because n = 25
head(Randomization.Match)

   n heads tails prop
1 25    16     9 0.64
2 25    18     7 0.72
3 25    10    15 0.40
4 25    13    12 0.52
5 25    13    12 0.52
6 25    12    13 0.48

histogram(~prop, width = 0.04, data = Randomization.Match)
```



Here we find the proportion of the simulations which resulted in 16 or more matches out of 25, or 0.64 or greater, for the p-value.

Example4.13b

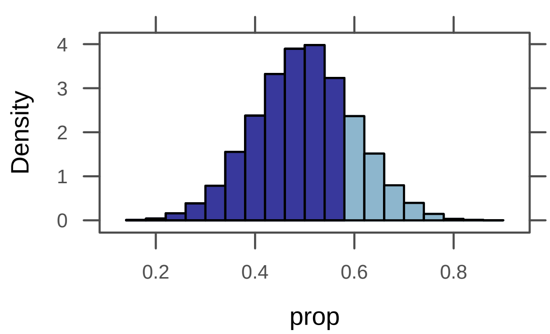
```
prop(~(prop >= 0.64), data = Randomization.Match)  # 16/25

 TRUE
0.116

histogram(~prop, width = 0.04, groups = (prop >= 0.64), data = Randomization.Match)
```

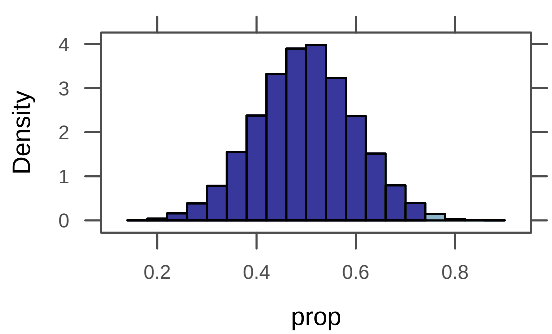


Example 4.15

Example4.15

```
prop(~(prop >= 0.6), data = Randomization.Match)  # 15/25

TRUE
0.21

prop(~(prop >= 0.76), data = Randomization.Match)  # 19/25

  TRUE
0.0076

histogram(~prop, width = 0.04, groups = (prop >= 0.6), data = Randomization.Match)
histogram(~prop, width = 0.04, groups = (prop >= 0.76), data = Randomization.Match)
```





Example 4.16

Example4.16

```
prop(~(prop >= 0.88), data = Randomization.Match)  # 22/25

 TRUE
1e-04
```

```
histogram(~prop, width = 0.04, v = c(0.88), data = Randomization.Match)
```

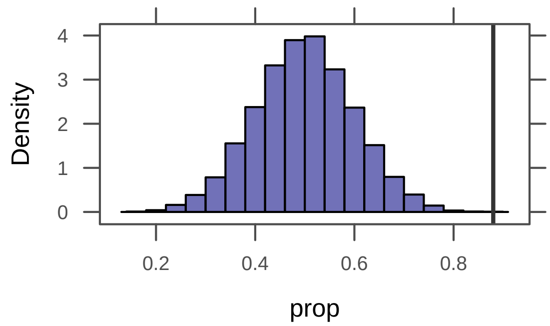
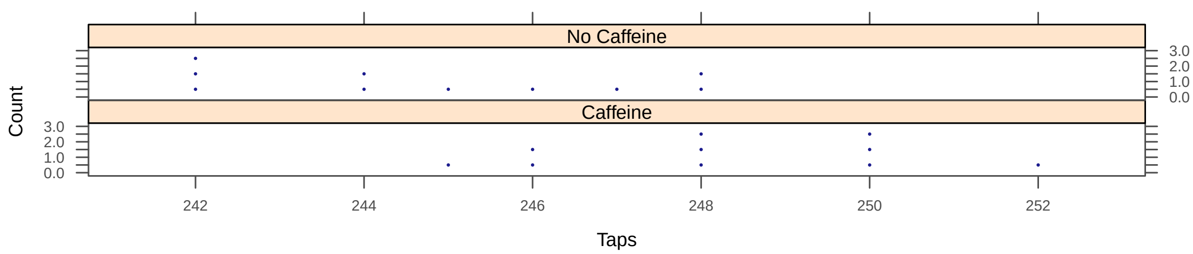


Figure 4.10

Figure4.10

```
dotPlot(~Taps | Group, layout = c(1, 2), width = 1, cex = 0.3, data = CaffeineTaps)
```



Example 4.18

Testing two means.

Example4.18

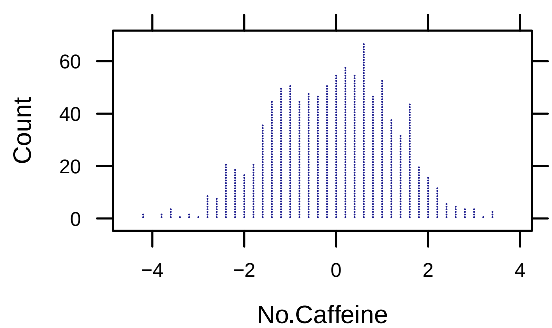
```
mean(Taps ~ Group, data = CaffeineTaps)

   Caffeine No Caffeine
        248         245

diff(mean(Taps ~ Group, data = CaffeineTaps))

No Caffeine
       -3.5
```

1. H_0: $\mu_1 = \mu_2$
   H_a: $\mu_1 > \mu_2$

2. Test statistic: $\bar{x}_1 - \bar{x}_2 = 3.5$ (the difference in sample means)
3. We simulate a world in which $\mu_1 = \mu_2$ or $\mu_1 - \mu_2 = 0$:

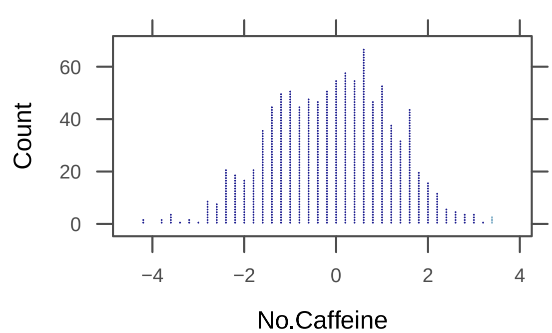
Example4.18b

```
Randomization.Caff <- do(1000) * ediff(mean(Taps ~ shuffle(Group), data = CaffeineTaps))
head(Randomization.Caff, 3)

  V1 No.Caffeine
1 NA        -1.1
2 NA        -1.3
3 NA        -2.1

dotPlot(~No.Caffeine, width = 0.2, data = Randomization.Caff)
```



Example4.18c

```
prop(~(No.Caffeine >= 3.5), data = Randomization.Caff)

 TRUE
0.003

dotPlot(~No.Caffeine, width = 0.2, groups = (No.Caffeine >= 3.5), data = Randomization.Caff)
```



P-values and the Alternative Hypothesis

Example 4.19

Testing one proportion.

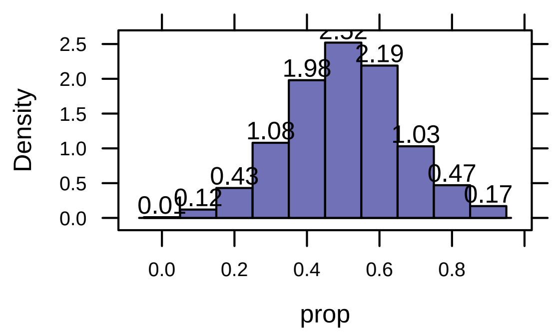
1. H_0: $p = 0.5$
   H_a: $p > 0.5$

2. Test statistic: $\hat{p} = 0.8, 0.6, 0.4$ (the sample proportion of 8/10, 6/10, 4/10 heads)

3. We simulate a world in which $p = 0.5$:

Example4.19

```
RandomizationDist <- do(1000) * rflip(10, 0.5)  # 10 because n = 10
head(RandomizationDist)

   n heads tails prop
1 10     2     8  0.2
2 10     5     5  0.5
3 10     5     5  0.5
4 10     4     6  0.4
5 10     4     6  0.4
6 10     7     3  0.7

histogram(~prop, label = TRUE, width = 1/10, data = RandomizationDist)
```



Example4.19b

```
prop(~(prop >= 0.8), data = RandomizationDist)

 TRUE
0.042

prop(~(prop >= 0.6), data = RandomizationDist)

 TRUE
0.369

prop(~(prop >= 0.4), data = RandomizationDist)

 TRUE
0.825
```

Example 4.20

Testing one proportion.

1. H_0: $p = 0.5$
   H_a: $p \neq 0.5$
2. Test statistic: $\hat{p} = 0.8$ (the sample proportion of 8/10 heads)
3. We use the simulated world in which $p = 0.5$:

Example4.20

```
prop(~ (prop >= 0.8), data = RandomizationDist)

 TRUE
0.042

prop(~ (prop <= 0.2), data = RandomizationDist)

TRUE
0.05
```

Example4.20b

```
# a 2-sided p-value is the sum of the values above
prop(~(prop <= 0.2 | prop >= 0.8), data = RandomizationDist)

 TRUE
0.092

# We can also approximate the p-value by doubling one side
2 * prop(~prop >= 0.8, data = RandomizationDist)

 TRUE
0.084
```

4.3 Determining Statisical Significance

Less Formal Statistical Decisions

Example 4.27

Testing two means.

Example4.27

```
head(Smiles)


  Leniency Group
1      7.0 smile
2      3.0 smile
3      6.0 smile
4      4.5 smile
5      3.5 smile
6      4.0 smile


mean(Leniency ~ Group, data = Smiles)
```

```
neutral   smile
   4.12    4.91

diff(mean(Leniency ~ Group, data = Smiles))

smile
0.794
```

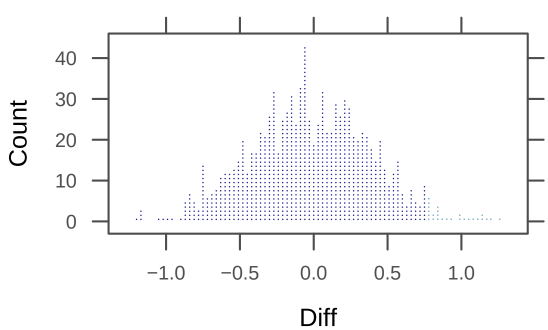
1. H_0: $\mu_1 = \mu_2$
   H_a: $\mu_1 \neq \mu_2$
2. Test statistic: $\bar{x}_1 - \bar{x}_2 = 0.79$ (the difference in sample means)
3. We simulate a world in which $\mu_1 = \mu_2$:

Example4.27b

```
Randomization.Smiles <- do(1000) * diff(mean(Leniency ~ shuffle(Group), data = Smiles))
head(Randomization.Smiles, 3)

       smile
1  0.1176471
2  0.1176471
3 -0.2647059
```

Example4.27c

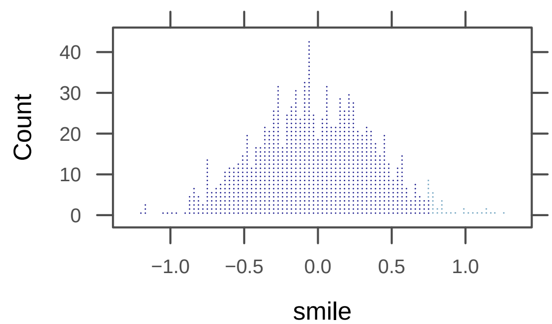
```
prop(~ (smile <= -0.79 | smile >= 0.79), data = Randomization.Smiles)

 TRUE
0.055

2 * prop(~ smile >= 0.79, data = Randomization.Smiles )

 TRUE
0.052

dotPlot(~ smile, width = 0.03, cex = 0.5, groups = (smile >= 0.79),
        xlab = "Diff", data = Randomization.Smiles)
```



Now we find the p-value to test a difference of 0.76:

Example4.27d

```
prop(~(smile <= -0.76 | smile >= 0.76), data = Randomization.Smiles)

 TRUE
0.069

2 * prop(~smile >= 0.76, data = Randomization.Smiles)

 TRUE
0.062

dotPlot(~smile, width = 0.03, cex = 0.5, groups = (smile >= 0.76), data = Randomization.Smiles)
```



4.4 Creating Randomization Distributions

In order to use these methods to estimate a p-value, we must be able to generate a randomization distribution. In the case of a test with null hypothesis claiming that a proportion has a particular value (e.g, H_0: $p = 0.5$), this is pretty easy. If the population has proportion 0.50, we can simulate sampling from that proportion by flipping a fair coin. If the proportion is some value other than 0.50, we simply flip a coin that has the appropriate probability of resulting in heads. So the general template for creating such a randomization distribution is

```
do(1000) * rflip(n, hypothesized_proportion)
```

where `n` is the size of the original sample.

In other situations, it can be more challenging to create a randomization distribution because the null hypothesis does not directly specify all of the information needed to simulate samples.

- H_0: $p_1 = p_2$

  This would be simple *if* we new the value of p_1 and p_2 (we could use `rflip()` twice, once for each group),

- H_0: μ = some number

  Just knowing the mean does not tell us enough about the distribution. We need to know about its shape. (We might need to know the standard deviation, for example, or whether the distribution is skewed.)

- H_0: $\mu_1 \neq \mu_2$ some number.

  Now we don't know the common mean and we don't know the things mentioned in the previous example either.

So how do we come up with randomization distribution?

The main criteria to consider when creating randomization samples for a statistical test are:

- Be consistent with the null hypothesis.

  If we don't do this, we won't be testing our null hypothesis.

- Use the data in the original sample.

  With luck, the original data will shed light on some aspects of the distribution that are not determined by null hypothesis.

- Reflect the way the original data were collected.

Randomization Test for a Difference in Proportions: Cocaine Addiction

Data 4.7

Data 4.7 in the text describes some data that are not in a data frame. This often happens when a data set has only categorical variables because a simple table completely describes the distributions involved. Here's the table from the book:[1]

	Relapse	No Relapse
Lithium	18	6
Placebo	20	4

Here's one way to create the data in R:

Section4.4b

```
Cocaine <- rbind(
  do(18) * data.frame( treatment = "Lithium", response = "Relapse"),
  do(6)  * data.frame( treatment = "Lithium", response = "No Relapse"),
  do(20) * data.frame( treatment = "Placebo", response = "Relapse"),
  do(4)  * data.frame( treatment = "Placebo", response = "No Relapse")
  )
```

Example 4.29

Testing two proportions.

Example4.29

```
tally(response ~ treatment, data = Cocaine)

            treatment
response     Lithium Placebo
  Relapse         18      20
  No Relapse       6       4
```

[1] The book includes data on an additional treatment group which we are omitting here.

```
prop(response ~ treatment, data = Cocaine)

Relapse.Lithium Relapse.Placebo
          0.375           0.417

diff(prop(response ~ treatment, data = Cocaine))

Relapse.Placebo
         0.0417
```

1. H_0: $p_1 = p_2$

   H_a: $p_1 < p_2$

2. Test statistic: $\hat{p}_1 = \hat{p}_2$ (the difference in sample proportions)

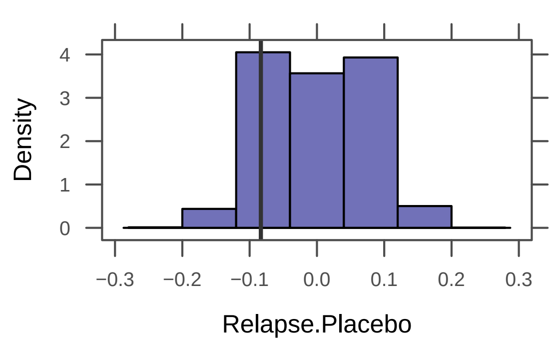
3. We simulate a world in which $p_1 = p_2$ or $p_1 - p_2 = 0$:

Example4.29b

```
Randomization.Coc <- do(5000) * diff(prop(response ~ shuffle(treatment), data = Cocaine))
head(Randomization.Coc)

  Relapse.Placebo
1      0.00000000
2      0.00000000
3     -0.04166667
4      0.00000000
5      0.08333333
6     -0.08333333
```

Example4.29c

```
prop(~(Relapse.Placebo < -0.0833), data = Randomization.Coc)

 TRUE
0.142

histogram(~Relapse.Placebo, data = Randomization.Coc, v = c(-0.0833), width = 0.08)
```



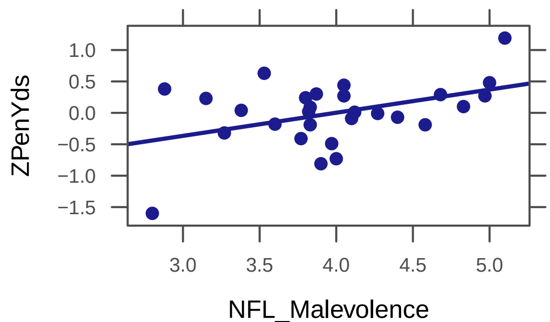
Randomization Test for a Correlation: Malevolent Uniforms and Penalties

Example 4.31

Testing correlation.

Example4.31

```
xyplot(ZPenYds ~ NFL_Malevolence, type = c("p", "r"), data = MalevolentUniformsNFL)
cor(ZPenYds ~ NFL_Malevolence, data = MalevolentUniformsNFL)

[1] 0.43
```



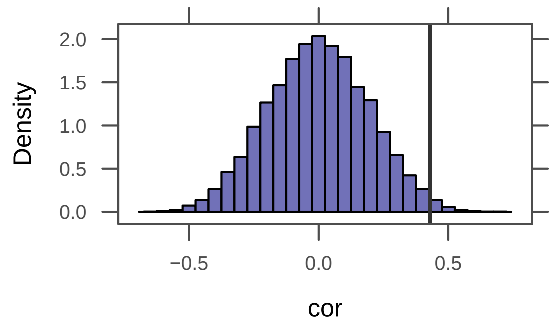
1. H_0: $\rho = 0$
   H_a: $\rho > 0$
2. Test statistic: $r = 0.43$ (the sample correlation)
3. We simulate a world in which $\rho = 0$:

Example4.31b

```
Randomization.Mal <-
  do(10000) * cor(NFL_Malevolence ~ shuffle(ZPenYds), data = MalevolentUniformsNFL)
head(Randomization.Mal)

          cor
1  0.40316055
2 -0.49992479
3  0.04493107
4  0.26963865
5 -0.33415748
6  0.07458544
```

Example4.32c

```
prop(~(cor > 0.43), data = Randomization.Mal)

  TRUE
0.0108

histogram(~cor, v = c(0.43), width = 0.05, data = Randomization.Mal)
```



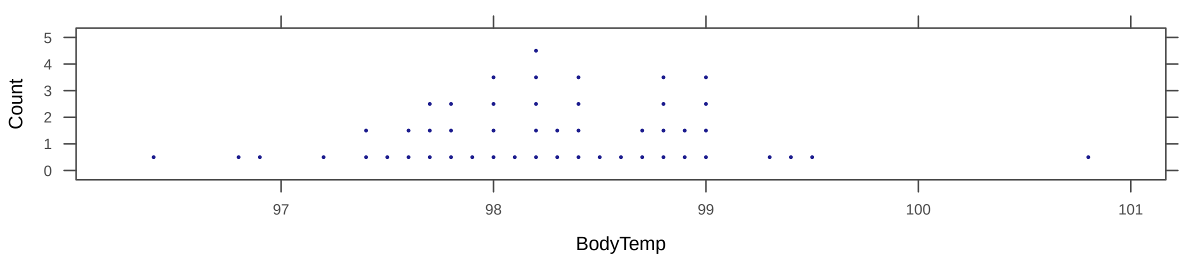
Randomization Test for a Mean: Body Temperature

Example 4.33

Testing one mean.

Example4.33

```
mean(~BodyTemp, data = BodyTemp50)

[1] 98.3

dotPlot(~BodyTemp, v = c(98.26), width = 0.1, cex = 0.2, data = BodyTemp50)
```



1. H_0: $\mu = 98.6$

   H_a: $\mu \neq 98.6$

2. Test statistic: $\bar{x} = 98.26$ (the sample mean)

   Notice that the test statistic differs a bit from 98.6

   Example4.33b

   ```
   98.6 - mean(~BodyTemp, data = BodyTemp50)

   [1] 0.34
   ```

   But might this just be random variation? We need a randomization distribution to compare against.

3. If we resample, the mean will not be 98.6. But we shift the distribution a bit, then we will have the desired mean while preserving the shape of the distribution indicated by our sample. We simulate a world in which $\mu = 98.6$:

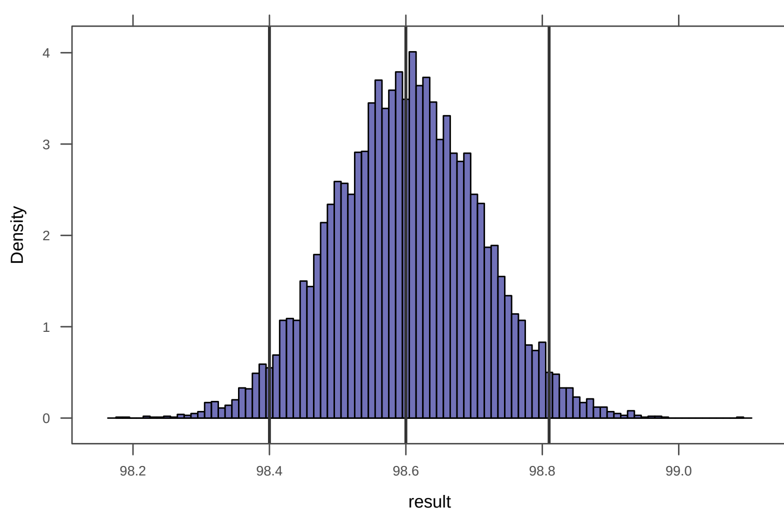
Example4.33c

```
Randomization.Temp <- do(10000) * (mean(~BodyTemp, data = resample(BodyTemp50)) + 0.34)
head(Randomization.Temp, 3)

  result
1 98.524
2 98.588
3 98.668

mean(~result, data = Randomization.Temp)

[1] 98.60053

cdata(~result, 0.95, data = Randomization.Temp)

      low        hi central.p
    98.39     98.81      0.95
```

From this we can estimate the p-value:

Example4.33d

```
prop(~abs(result - 98.6) > 0.34, data = Randomization.Temp)

  TRUE
0.0018

histogram(~result, width = 0.01, v = c(98.4, 98.6, 98.81), data = Randomization.Temp)
```



How do we interpret this (estimated) p-value of 0? Is it impossible to have a sample mean so far from 98.6 if the true population mean is 98.6? No. This merely means that we didn't see any such cases *in our 10000 randomization samples*. We might estimate the p-value as $p < 0.001$. Generally, to more accurately estimate small p-values, we must use many more randomization samples.

Example 4.33: A different approach

An equivalent way to do the preceding test is based on a different way of expressing our hypotheses.

1. H_0: $\mu - 98.6 = 0$
   H_a: $\mu - 98.6 \neq 0$
2. Test statistic: $\bar{x} - 98.6 = -0.34$
3. We we create a randomization distribution centered at $\mu - 98.6 = 0$:

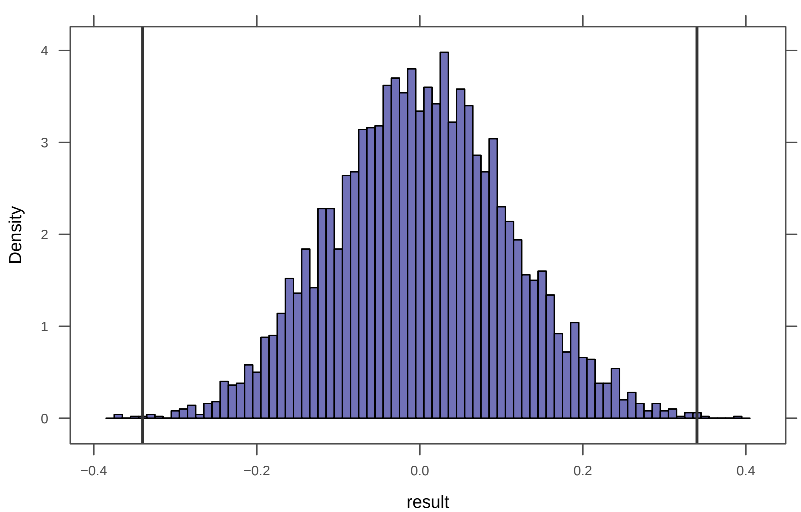
Example4.33e

```
Randomization.Temp2 <- do(5000) * (mean(~BodyTemp, data = resample(BodyTemp50)) - 98.26)
head(Randomization.Temp2, 3)

  result
1 -0.044
2 -0.138
3  0.056

mean(~result, data = Randomization.Temp2)

[1] 0.0015444
```

From this we can estimate the p-value:

Example4.33f,

```
prop(~abs(result) > 0.34, data = Randomization.Temp2)

  TRUE
0.0016

histogram(~result, width = 0.01, v = c(0.34, -0.34), data = Randomization.Temp2)
```



Often there are multiple ways to express the same hypothesis test.

4.5 Confidence Intervals and Hypothesis Tests

If your randomization distribution is centered at the wrong value, then it isn't simulating a world in which the null hypothesis is true. This would happen, for example, if we got confused about randomization vs. bootstrapping.

Randomization and Bootstrap Distributions

Figure 4.32

Figure4.32

```
Boot.Temp <- do(5000) * mean(~BodyTemp, data = resample(BodyTemp50))
head(Boot.Temp, 3)
```

```
    mean
1 98.184
2 98.248
3 98.328
```

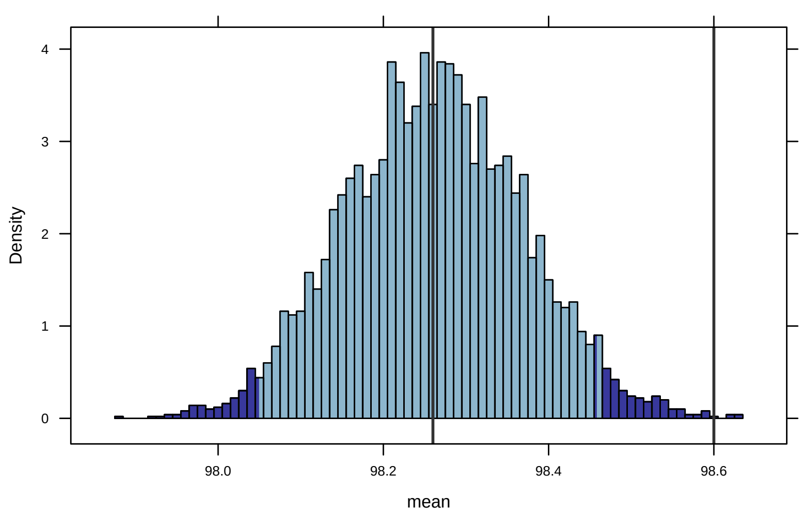
```
mean(~mean, data = Boot.Temp)
```

```
[1] 98.26156
```

```
cdata(~mean, 0.95, data = Boot.Temp)
```

```
      low        hi central.p
 98.05600  98.46805   0.95000
```

```
histogram(~mean, width = 0.01, v = c(98.26, 98.6), groups = (98.05 <= mean & mean <= 98.46),
    data = Boot.Temp)
```



Notice that the distribution is now centered at our test statistic instead of at the value from the null hypothesis.

Example 4.35

1. H_0: $\mu = 98.4$

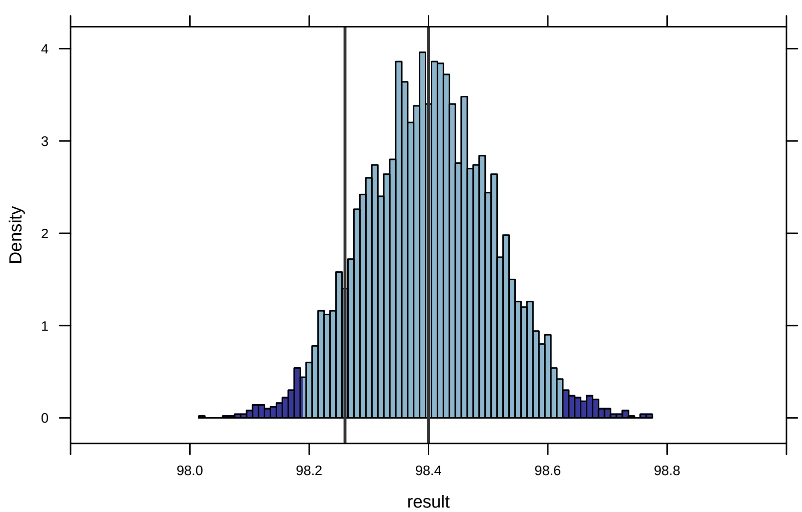
   H_a: $\mu \neq 98.4$

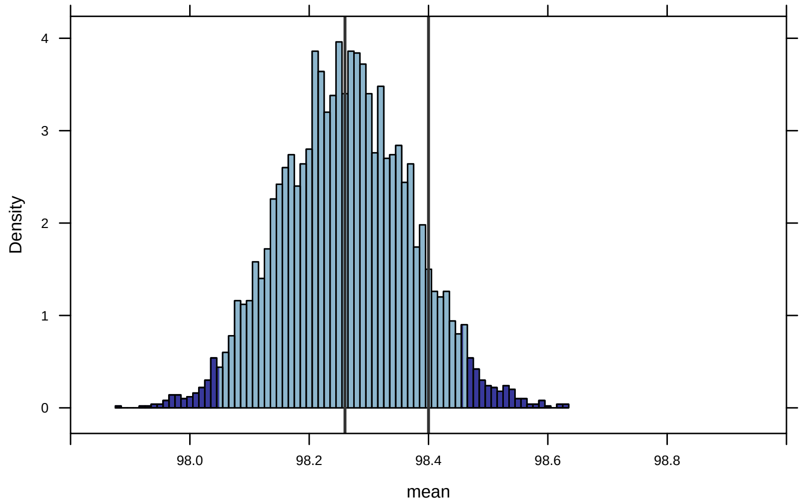
2. Test statistic: $\bar{x} = 98.26$ (the sample mean)

3. We simulate a world in which $\mu = 98.4$:

Example4.35

```
Randomization.Temp3 <- do(5000) * (mean(~BodyTemp, data = resample(BodyTemp50)) + 0.14)
head(Randomization.Temp3, 3)

  result
1 98.324
2 98.388
3 98.468

mean(~result, data = Randomization.Temp3)

[1] 98.40156

cdata(~result, 0.95, data = Randomization.Temp3)

      low        hi central.p
 98.19600  98.60805   0.95000

histogram(~result, width = 0.01, v = c(98.26, 98.4), groups = (98.19 <= result & result <=
    98.62), xlim = c(97.8, 99), data = Randomization.Temp3)  # randomization
histogram(~mean, width = 0.01, v = c(98.26, 98.4), groups = (98.05 <= mean & mean <= 98.46),
    xlim = c(97.8, 99), data = Boot.Temp)  # bootstrap
```




Density
mean
0
1
2
3
4
98.0
98.2
98.4
98.6
98.8

5 Approximating with a Distribution

5.1 Normal Distributions

Density Curves

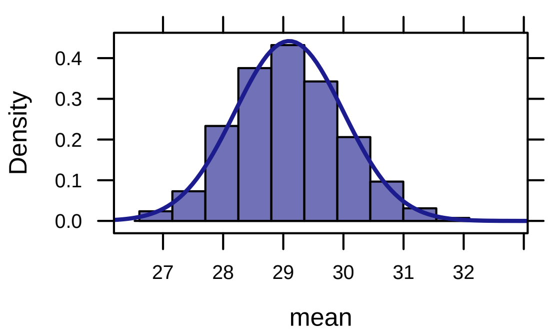
Example 5.1

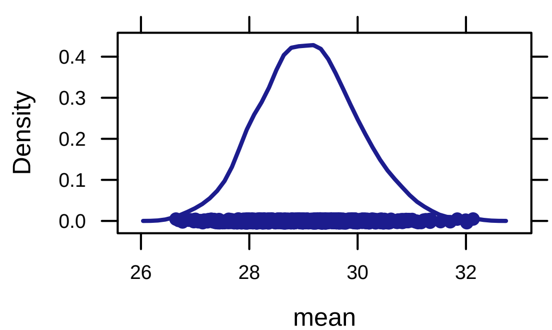
Example5.1

```
Bootstrap <- do(1000) * mean(~Time, data = resample(CommuteAtlanta))
head(Bootstrap, 3)
```

```
  mean
1 29.2
2 30.0
3 28.4
```

```
histogram(~mean, density = TRUE, data = Bootstrap)
densityplot(~mean, data = Bootstrap)
```





Example5.1b

```
prop(~(mean <= 30), data = Bootstrap)  # proportion less than 30 min
```



```
 TRUE
0.825

prop(~(mean >= 31), data = Bootstrap)  # proportion greater than 31 min

 TRUE
0.029

prop(~(mean >= 30 & mean <= 31), data = Bootstrap)  # proportion between 30 and 31 min

 TRUE
0.146
```

Normal Distributions

Normal distributions

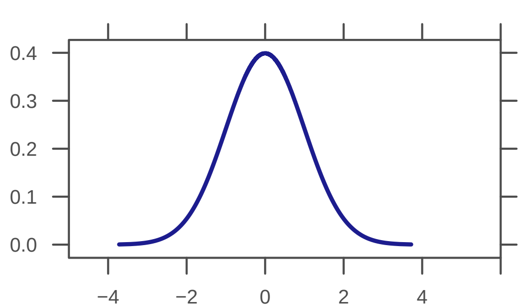
- are symmetric, unimodel, and bell-shaped
- can have any combination of mean and standard deviation (as long as the standard deviation is positive)
- satisfy the 68–95–99.7 rule:
  Approximately 68% of any normal distribution lies within 1 standard deviation of the mean.
  Approximately 95% of any normal distribution lies within 2 standard deviations of the mean.
  Approximately 99.7% of any normal distribution lies within 3 standard deviations of the mean.

Many naturally occurring distributions are approximately normally distributed. Normal distributions are also an important part of statistical inference. The `plotDist()` function can be used to plot many common distributions.

Figure 5.5

```
plotDist("norm", mean = 0, sd = 1, xlim = c(-5, 6))
plotDist("norm", mean = 2, sd = 1, col = "red", add = TRUE)
```

Figure5.5



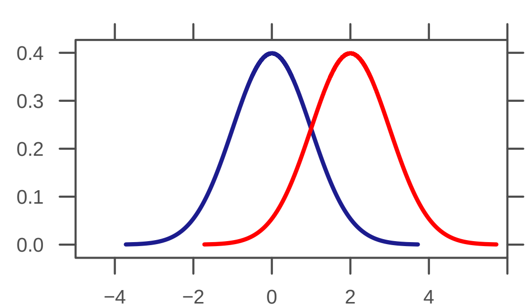
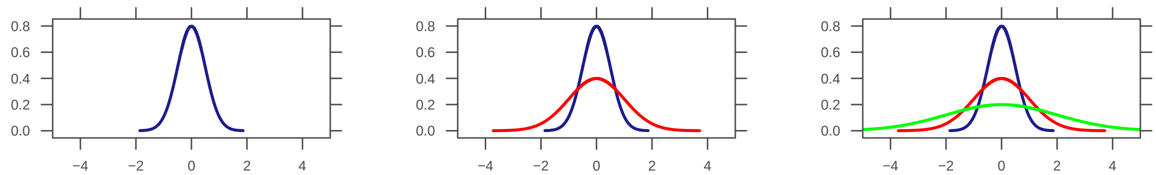


Figure5.5b

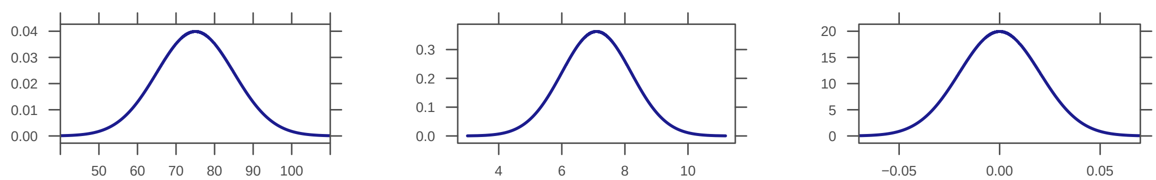
```
plotDist("norm", mean = 0, sd = 0.5, xlim = c(-5, 5))
plotDist("norm", mean = 0, sd = 1, add = TRUE, col = "red")
plotDist("norm", mean = 0, sd = 2, add = TRUE, col = "green")
```



Example 5.2

Example5.2

```
plotDist("norm", mean = 75, sd = 10, xlim = c(40, 110))
plotDist("norm", mean = 7.1, sd = 1.1, xlim = c(2.7, 11.5))
plotDist("norm", mean = 0, sd = 0.02, xlim = c(-0.07, 0.07))
```



Finding Normal Probabilities and Percentiles

The two main functions we need for working with normal distributions are `pnorm()` and `qnorm()`. `pnorm()` computes the proportion of a normal distribution below a specified value:

$$\texttt{pnorm(x, mean = } \mu \texttt{, sd = } \sigma \texttt{)} = \Pr(X \le x)$$

when $X \sim \text{Norm}(\mu, \sigma)$.

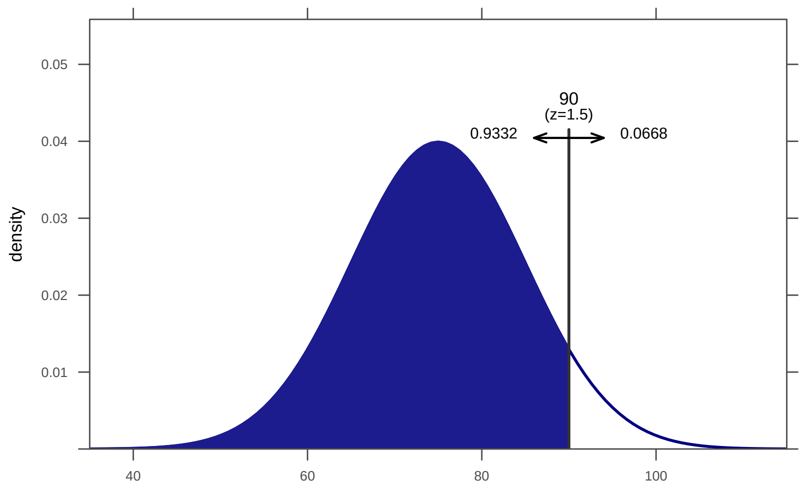
We can obtain arbitrary probabilities using `pnorm()`

Example 5.3

Example5.3

```
pnorm(90, 75, 10, lower.tail = FALSE)  # proportion of scores above 90

[1] 0.0668

xpnorm(90, 75, 10, lower.tail = FALSE)
```

```
If X ~ N(75,10), then

P(X <= 90) = P(Z <= 1.5) = 0.9332
P(X >  90) = P(Z >  1.5) = 0.0668
[1] 0.0668
```



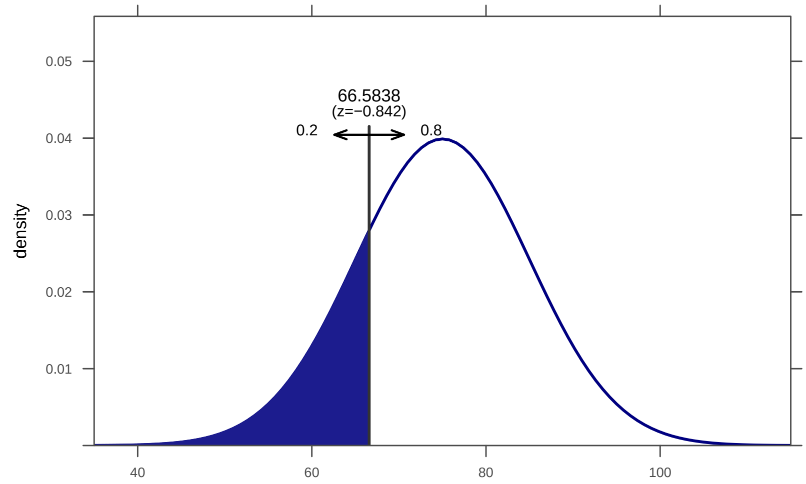
The `xpnorm()` function gives a bit more verbose output and also gives you a picture. Notice the `lower.tail = FALSE`. This is added because the default for `pnorm()` and `xpnorm()` finds the lower tail, not the upper tail. However, we can also subtract the proportion of the lower tail from 1 to find the the proportion of the upper tail.

Example 5.4

`qnorm()` goes the other direction: You provide the quantile (percentile expressed as a decimal) and R gives you the value.

Example5.4

```
qnorm(0.2, 75, 10)  # 20th percentile in Norm(75, 10)

[1] 66.6

xqnorm(0.2, 75, 10)

P(X <= 66.5837876642709) = 0.2
P(X >  66.5837876642709) = 0.8
[1] 66.6
```



Standard Normal N(0,1)

Because probabilities in a normal distribution depend only on the number of standard deviations above and below the mean, it is useful to define Z-scores (also called standardized scores) as follows:

$$Z\text{-score} = \frac{\text{value} - \text{mean}}{\text{standard deviation}}$$

If we know the population mean and standard deviation, we can plug those in. When we do not, we will use the mean and standard deviation of a random sample as an estimate.

Z-scores provide a second way to compute normal probabilities.

Example 5.5

Example5.5

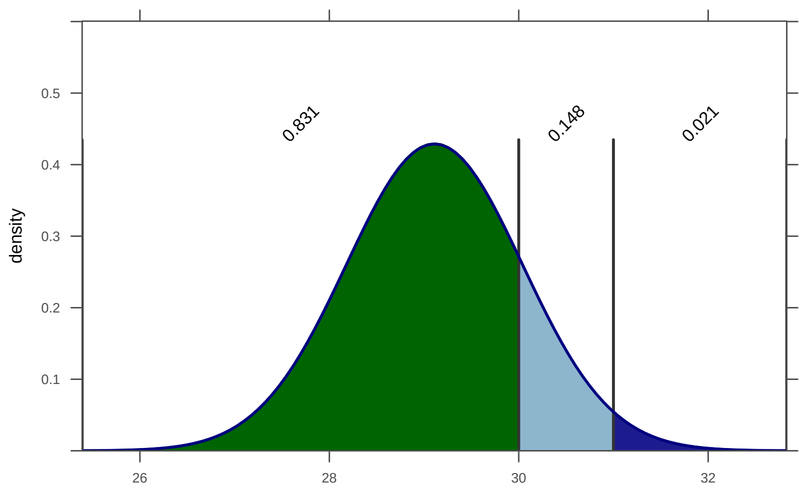
```
z30 <- (30 - 29.11) / 0.93; z30  # z-score for 30 min

[1] 0.957

z31 <- (31 - 29.11) / 0.93; z31  # z-score for 31 min

[1] 2.03

xpnorm(c(30, 31), 29.11, 0.93)   # original normal distribution proportion between 30 and 31 min


If X ~ N(29.11,0.93), then

P(X <= 30) = P(Z <= 0.957) = 0.8307
  P(X <= 31) = P(Z <= 2.032) = 0.9789
P(X >  30) = P(Z >  0.957) = 0.1693
  P(X >  31) = P(Z >  2.032) = 0.0211
[1] 0.831 0.979
```

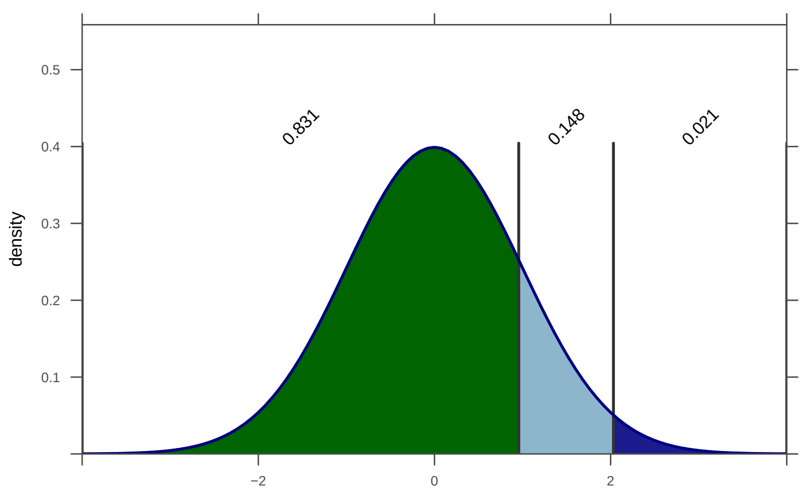
```
xpnorm(c(z30, z31))            # standardized distribution proportion between 30 and 31 min
```

```
If X ~ N(0,1), then

P(X <= 0.956989247311829) = P(Z <= 0.957) = 0.8307
  P(X <= 2.03225806451613) = P(Z <= 2.032) = 0.9789
P(X >  0.956989247311829) = P(Z >  0.957) = 0.1693
  P(X >  2.03225806451613) = P(Z >  2.032) = 0.0211
[1] 0.831 0.979
```

```
pnorm(z31) - pnorm(z30)
```

```
[1] 0.148
```

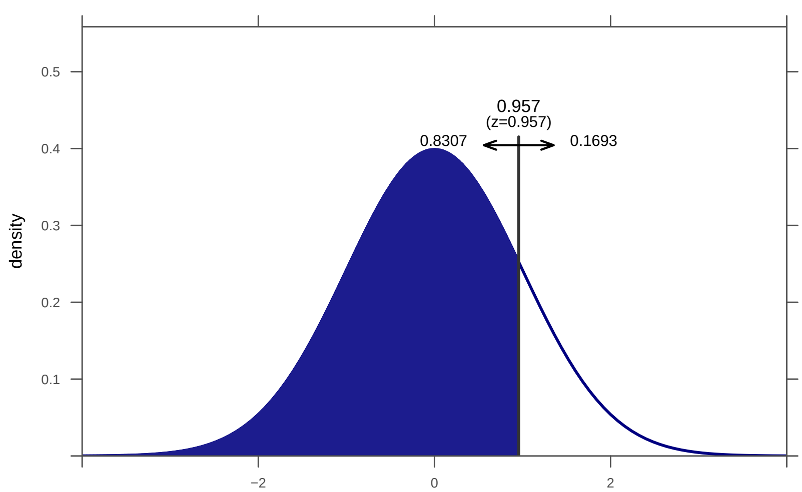


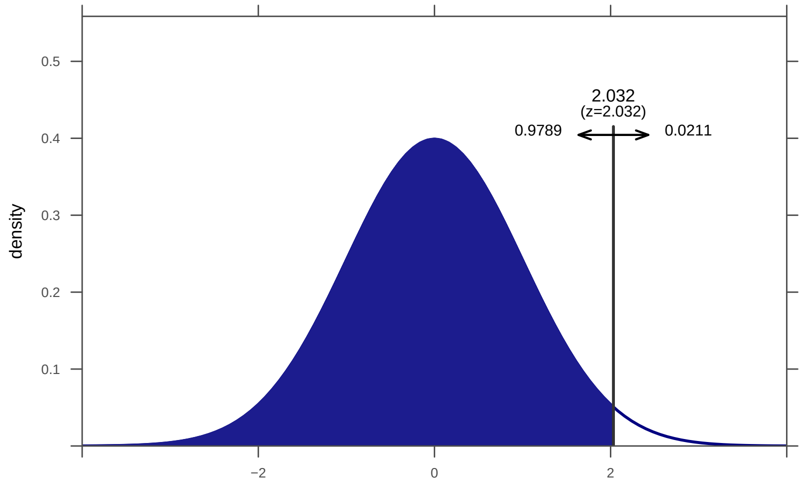


Example5.5b

```
xpnorm(0.957)                    # proportion with z-score below 0.957
```

```
If X ~ N(0,1), then

P(X <= 0.957) = P(Z <= 0.957) = 0.8307
P(X >  0.957) = P(Z >  0.957) = 0.1693
[1] 0.831

xpnorm(2.032, lower.tail = FALSE)  # proportion with z-score above 2.032

If X ~ N(0,1), then

P(X <= 2.032) = P(Z <= 2.032) = 0.9789
P(X >  2.032) = P(Z >  2.032) = 0.0211
[1] 0.0211

pnorm(30, 29.11, 0.93)

[1] 0.831

pnorm(31, 29.11, 0.93, lower.tail = FALSE)

[1] 0.0211
```





Example 5.6

```
z <- qnorm(0.2)
z
```

Example5.6

```
[1] -0.842
```

```
75 + z * 10
```

```
[1] 66.6
```

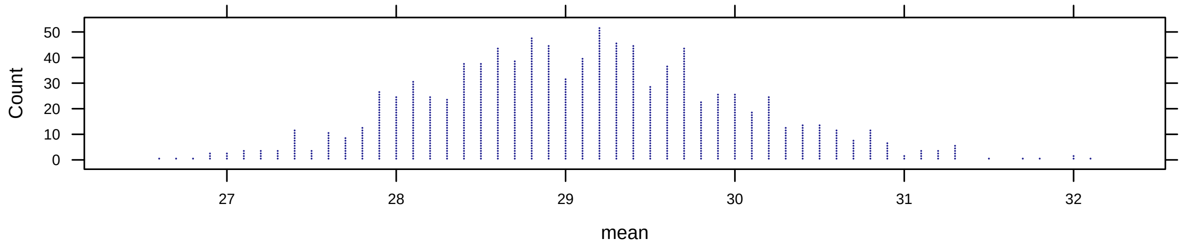
5.2 Confidence Intervals and P-values Using Normal Distributions

Confidence Intervals Based on a Normal Distribution

Example 5.7

```
Bootstrap <- do(1000) * mean(~Time, data = resample(CommuteAtlanta))
dotPlot(~mean, width = 0.1, data = Bootstrap)
```

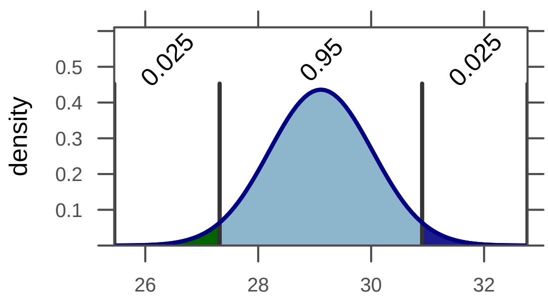
Example5.7



Example5.7b

```
xqnorm(c(0.025, 0.975), 29.11, 0.915)  # 95% confidence interval for the normal distribution
```

```
P(X <= 27.3166329541458) = 0.025
  P(X <= 30.9033670458542) = 0.975
P(X >  27.3166329541458) = 0.975
  P(X >  30.9033670458542) = 0.025
[1] 27.3 30.9
```



Example5.7c

```
qnorm(0.005, 29.11, 0.915)  # lower endpoint for 99% confidence interval
```

```
[1] 26.8
```

```
qnorm(0.995, 29.11, 0.915)  # upper endpoint for 99% confidence interval
```

```
[1] 31.5
```

```
qnorm(0.05, 29.11, 0.915)  # lower endpoint for 90% confidence interval
```

```
[1] 27.6
```

```
qnorm(0.95, 29.11, 0.915)  # upper endpoint for 90% confidence interval
```

```
[1] 30.6
```

Example 5.8

```
qnorm(0.005, 13.1, 0.2)  # lower endpoint for 99% confidence interval
```

Example5.8

```
[1] 12.6
```

```
qnorm(0.995, 13.1, 0.2)  # upper endpoint for 99% confidence interval
```

```
[1] 13.6
```

P-values Based on a Normal Distribution

Example 5.9

```
Randomization.Temp <- do(10000) * (mean(~BodyTemp, data = resample(BodyTemp50)) + 0.34)
histogram(~mean, width = 0.025, fit = "normal", data = Randomization.Temp)
```

Example5.9

```
Error in tmp[subset]:  object of type 'closure' is not subsettable
```

Example5.9b

```
pnorm(98.26, 98.6, 0.1066)
```

```
[1] 0.000713
```

```
2 * pnorm(98.26, 98.6, 0.1066)
```

```
[1] 0.00143
```

Example5.9c

```
z <- (98.26 - 98.6)/0.1066
z
```

```
[1] -3.19
```

```
pnorm(z)
```

```
[1] 0.000713
```

```
2 * pnorm(z)
```

```
[1] 0.00143
```


Example 5.10

```
pnorm(0.66, 0.65, 0.013, lower.tail = FALSE)                Example5.10

[1] 0.221
```

6 Inference for Means and Proportions

6.1 Distribution of a Sample Proportion

When sampling distributions, bootstrap distributions, and randomization distributions are well approximated by normal distributions, and when we have a way of computing the standard error, we can use normal distributions to compute confidence intervals and p-values using the following general templates:

- confidence interval:

$$\text{statistic} \pm \text{critical value} \cdot SE$$

- hypothesis testing:

$$\text{test statistic} = \frac{\text{statistic} - \text{null parameter}}{SE}$$

Example 6.1

Example6.1

```
SE <- sqrt(0.25 * (1 - 0.25)/50)
SE

[1] 0.0612

SE <- sqrt(0.25 * (1 - 0.25)/200)
SE

[1] 0.0306

SE <- sqrt(0.4 * (1 - 0.4)/50)
SE

[1] 0.0693
```

How Large a Sample Size is Needed?

Figure 6.2

Figure6.02

```
P.05 <- do(2000) * rflip(50, 0.05)
dotPlot(~prop, width = 0.02, cex = 25, data = P.05)
P.10 <- do(2000) * rflip(50, 0.1)
dotPlot(~prop, width = 0.02, cex = 15, data = P.10)
P.25 <- do(2000) * rflip(50, 0.25)
dotPlot(~prop, width = 0.02, cex = 10, data = P.25)
P.50 <- do(2000) * rflip(50, 0.5)
dotPlot(~prop, width = 0.02, cex = 5, data = P.50)
P.90 <- do(2000) * rflip(50, 0.9)
dotPlot(~prop, width = 0.02, cex = 10, data = P.90)
P.99 <- do(2000) * rflip(50, 0.99)
dotPlot(~prop, width = 0.02, cex = 25, data = P.99)
```

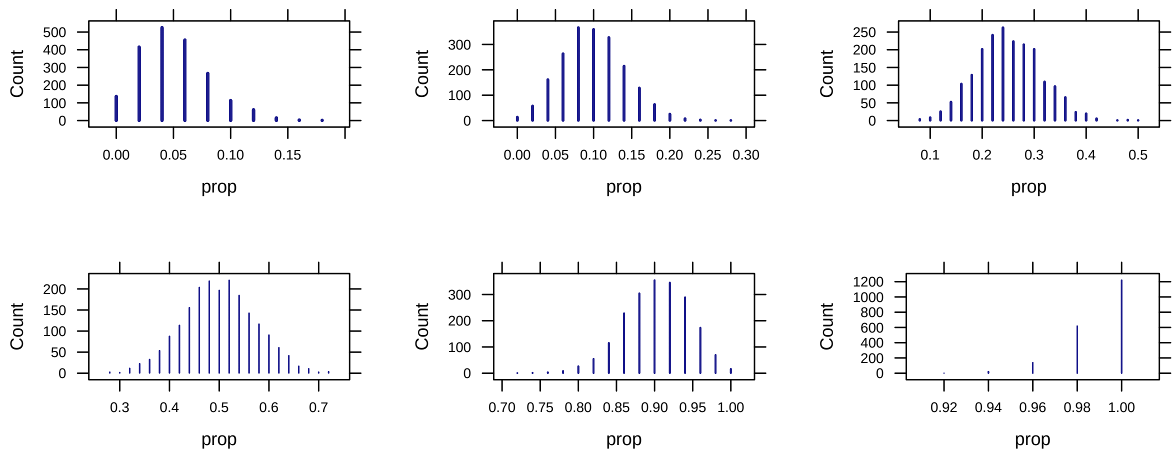
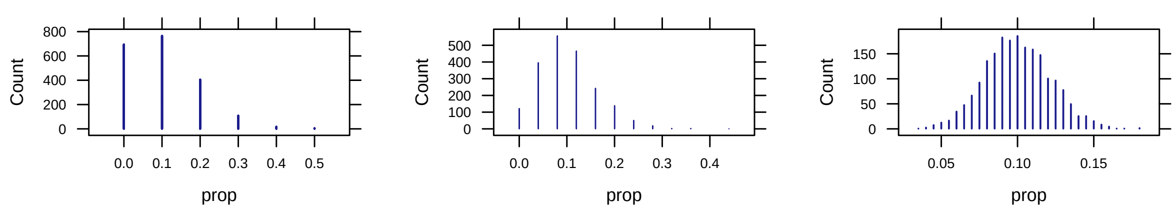


Figure 6.3

Figure6.03

```
n10 <- do(2000) * rflip(10, 0.1)
dotPlot(~prop, width = 0.1, cex = 25, data = n10)
n25 <- do(2000) * rflip(25, 0.1)
dotPlot(~prop, width = 0.04, cex = 10, data = n25)
n200 <- do(2000) * rflip(200, 0.1)
dotPlot(~prop, width = 0.005, cex = 5, data = n200)
```

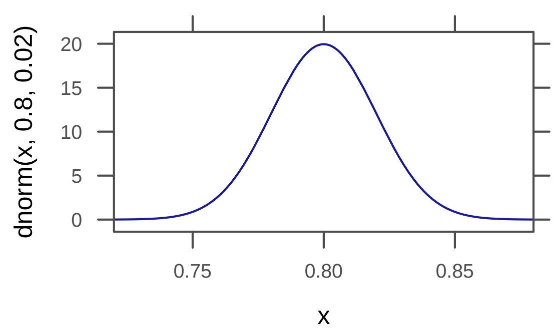


Example 6.2

```
p.hat <- 0.80; p.hat                                                    Example6.2

[1] 0.8

p.hat * 400              # check >= 10

[1] 320

(1 - p.hat) * 400        # check >= 10

[1] 80

SE <- sqrt(.80 * .20 / 400); SE

[1] 0.02
```

Figure 6.4

```
plotFun(dnorm(x, 0.8, 0.02) ~ x, x.lim = c(0.72, 0.88))                 Figure6.4
```



6.2 Confidence Interval for a Single Proportion

Confidence Interval for a Single Proportion

Example 6.3

```
p.hat <- 52/100; p.hat                                                  Example6.3
```

```
[1] 0.52

SE <- sqrt(p.hat * (1 - p.hat) / 100); SE    # est. SE

[1] 0.05

p.hat - 1.96 * SE                            # lower end of CI

[1] 0.422

p.hat + 1.96 * SE                            # upper end of CI

[1] 0.618
```

R can automate finding the confidence interval. Notice the `correct = FALSE` in the second line. The default for the proportion test includes a continuity correction for more accurate results. You can perform the test without the correction for answers closer to the ones in the textbook.

Example6.3b

```
confint(prop.test(52, 100))

     p lower upper level
1 0.52 0.418  0.62  0.95

confint(prop.test(52, 100, correct = FALSE))

     p lower upper level
1 0.52 0.423 0.615  0.95
```

Example 6.4

Example6.4

```
p.hat <- 0.28; p.hat

[1] 0.28

SE <- sqrt(p.hat * (1 - p.hat) / 800); SE    # est. SE

[1] 0.0159

p.hat - 1.96 * SE                            # lower end of CI

[1] 0.249

p.hat + 1.96 * SE                            # upper end of CI
```

```
[1] 0.311

confint(prop.test(224, 800))              # 224 = 0.28 * 800

     p lower upper level
1 0.28 0.249 0.313  0.95
```

Example6.4b

```
p.hat <- 0.82; p.hat

[1] 0.82

SE <- sqrt(p.hat * (1 - p.hat) / 800); SE    # est. SE

[1] 0.0136

p.hat - 1.96 * SE                         # lower end of CI

[1] 0.793

p.hat + 1.96 * SE                         # upper end of CI

[1] 0.847

confint(prop.test(656, 800))              # 656 = 0.82 * 800

     p lower upper level
1 0.82 0.791 0.846  0.95
```

Determining Sample Size for Estimating a Proportion

Example 6.5

Example6.5

```
z.star <- qnorm(0.995)
z.star  # critical value for 99% confidence

[1] 2.58

p.hat <- 0.28
p.hat

[1] 0.28

n <- ((z.star/0.01)^2) * p.hat * (1 - p.hat)
n
```

```
[1] 13376
```

Example 6.6

```
z.star <- qnorm(0.975)
z.star  # critical value for 95% confidence
```

Example6.6

```
[1] 1.96
```

```
p.hat <- 0.5
p.hat
```

```
[1] 0.5
```

```
n <- ((z.star/0.03)^2) * p.hat * (1 - p.hat)
n
```

```
[1] 1067
```

6.3 Test for a Single Proportion

Example 6.7

1. H_0: $p = 0.20$
   H_a: $p < 0.20$
2. Test statistic: $\hat{p} = 0.19$ (the sample approval rating)
3. Test for a single proportion:

Example6.7

```
p.hat <- 0.19
p.hat
```

```
[1] 0.19
```

```
p <- 0.2
p
```

```
[1] 0.2
```

```
p * 1013  # check >= 10
```

```
[1] 203
```

```
(1 - p) * 1013  # check >= 10
```

```
[1] 810
```

```
SE <- sqrt(p * (1 - p)/1013)
SE

[1] 0.0126

z <- (p.hat - p)/SE
z

[1] -0.796

pnorm(z)

[1] 0.213
```

Again, R can automate the test for us.

Example6.7b

```
prop.test(192, 1013, alt = "less", p = 0.2)  # 192 = 0.19 * 1013


1-sample proportions test with continuity correction

data:  192 out of 1013
X-squared = 0.6, df = 1, p-value = 0.2
alternative hypothesis: true p is less than 0.2
95 percent confidence interval:
 0.000 0.211
sample estimates:
   p
0.19
```

Notice the "less" for the alternative hypothesis because this is a lower tail alternative.

Example 6.8

Example6.8

```
p.hat <- 66/119; p.hat

[1] 0.555

p <- 1/3; p

[1] 0.333

p * 119                    # check >= 10

[1] 39.7

(1 - p) * 119              # check >= 10

[1] 79.3
```

```
SE <- sqrt(p * (1 - p) / 119); SE

[1] 0.0432

z <- (p.hat - p) / SE; z

[1] 5.12

pnorm(z)                  # large side (rounded)

[1] 1

1 - pnorm(z)              # small side (less rounding)

[1] 1.52e-07

2 * (1 - pnorm(z))        # p-value = 2 * small side

[1] 3.04e-07

prop.test(66, 119, p = 1/3)


1-sample proportions test with continuity correction

data:  66 out of 119
X-squared = 30, df = 1, p-value = 5e-07
alternative hypothesis: true p is not equal to 0.333
95 percent confidence interval:
 0.461 0.645
sample estimates:
    p
0.555
```

Example 6.9

Example6.9

```
p.hat <- 8/9
p.hat

[1] 0.889

p <- 0.5
p

[1] 0.5

p * 9  # check >= 10
```

```
[1] 4.5
```

```
Randomization <- do(1000) * rflip(9, 0.5)
head(Randomization, 3)
```
Example6.9b

```
  n heads tails      prop
1 9     6     3 0.6666667
2 9     6     3 0.6666667
3 9     2     7 0.2222222
```

```
prop(~(prop >= p.hat), data = Randomization)
```

```
 TRUE
0.023
```

6.4 Distribution of a Sample Mean

Computing the Standard Error

Example 6.10

```
SE <- 32000/sqrt(100)
SE
```
Example6.10

```
[1] 3200
```

```
SE <- 32000/sqrt(400)
SE
```

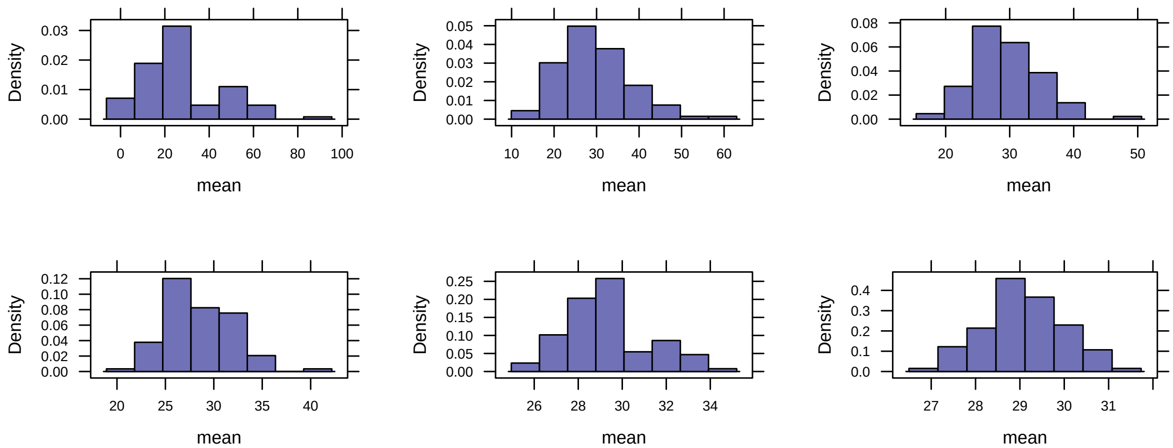
```
[1] 1600
```

How Large a Sample Size is Needed?

Figure 6.6

```
n1 <- do(100) * mean(~Time, data = resample(CommuteAtlanta, 1))
histogram(~mean, data = n1)
n5 <- do(100) * mean(~Time, data = resample(CommuteAtlanta, 5))
histogram(~mean, data = n5)
n15 <- do(100) * mean(~Time, data = resample(CommuteAtlanta, 15))
histogram(~mean, data = n15)
n30 <- do(100) * mean(~Time, data = resample(CommuteAtlanta, 30))
histogram(~mean, data = n30)
```
Figure6.06

```
n125 <- do(100) * mean(~Time, data = resample(CommuteAtlanta, 125))
histogram(~mean, data = n125)
n500 <- do(100) * mean(~Time, data = resample(CommuteAtlanta, 500))
histogram(~mean, data = n500)
```



The t-Distribution

If we are working with one quantitative variable, we can compute confidence intervals and p-values using the following standard error formula:

$$SE = \frac{\sigma}{\sqrt{n}}$$

Once again, there is a small problem: we won't know σ. So we will estimate σ using our data:

$$SE \approx \frac{s}{\sqrt{n}}$$

Unfortunately, the distribution of

$$\frac{\overline{x} - \mu}{s/\sqrt{n}}$$

does not have a normal distribution. Instead the distribution is a bit "shorter and fatter" than the normal distribution. The correct distribution is called the t-distribution with $n-1$ degrees of freedom. All t-distributions are symmetric and centered at zero. The smaller the degrees of freedom, the shorter and fatter the t-distribution.

Example 6.11

Example6.11

```
df <- 50 - 1
df

[1] 49

SE <- 10.5/sqrt(50)
SE

[1] 1.48
```


Example6.11b

```
df <- 8 - 1
df
```

```
[1] 7
```

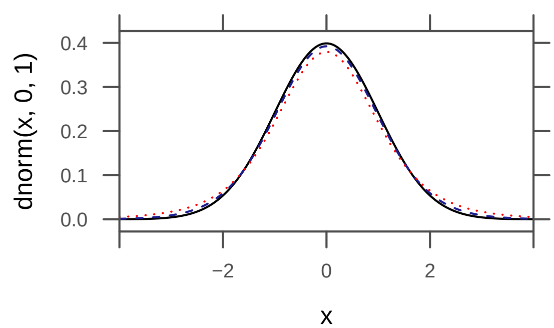
```
SE <- 1.25/sqrt(8)
SE
```

```
[1] 0.442
```

Figure 6.8

Figure6.08

```
plotFun(dnorm(x, 0, 1) ~ x, x.lim = c(-4, 4), col = "black")
plotFun(dt(x, df = 15) ~ x, add = TRUE, lty = 2)
plotFun(dt(x, df = 5) ~ x, add = TRUE, lty = 3, col = "red")
```



Example 6.12

Example6.12

```
qt(0.975, df = 15)
```

```
[1] 2.13
```

```
pt(1.5, df = 15, lower.tail = FALSE)
```

```
[1] 0.0772
```

Similar to the normal distribution, the function for t-distribution is set to find probability of the lower tail.

Example6.12b

```
qnorm(0.975)
```

```
[1] 1.96

pnorm(1.5, lower.tail = FALSE)

[1] 0.0668
```

Figure 6.9

Figure6.09

```
plotFun(dt(x, df = 15) ~ x, x.lim = c(-4, 4))
plotDist("t", params = list(df = 15), type = c("h", "l"), groups = (-2.131 < x & x < 2.131),
    lty = 1)
ladd(grid.text("2.131", 2.1, 0.1, default.units = "native", hjust = 0))
```

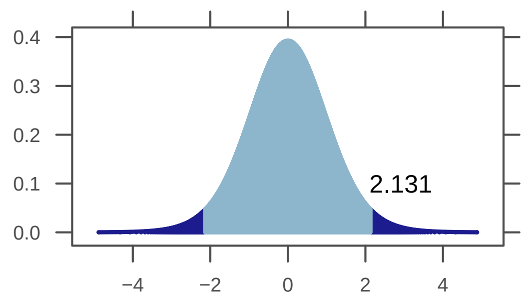
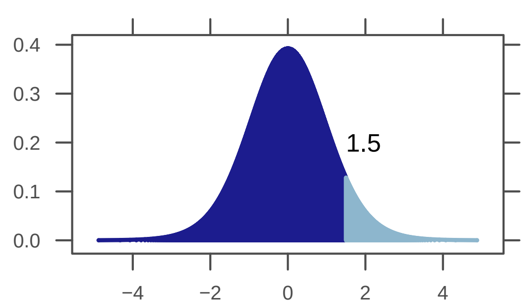


Figure6.09b

```
plotFun(dt(x, df = 15) ~ x, x.lim = c(-4, 4))
plotDist("t", params = list(df = 15), type = c("h", "l"), groups = x > 1.5, lty = 1)
ladd(grid.text("1.5", 1.5, 0.2, default.units = "native", hjust = 0))
```



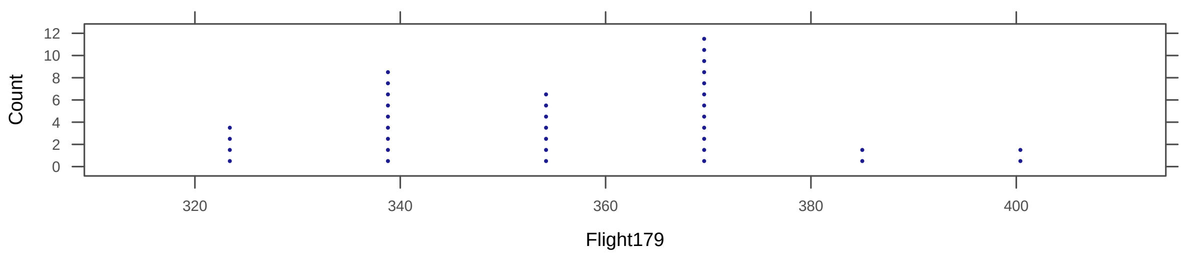
6.5 Confidence Interval for a Mean Using the t-Distribution

Confidence Interval for a Mean Using the t-Distribution

Example 6.13

Example6.13

```
head(Flight179, 3)

        Date Flight179 Flight180        MDY
1 01/05/2010       368       308 2010-01-05
2 01/15/2010       370       292 2010-01-15
3 01/25/2010       354       290 2010-01-25

dotPlot(~Flight179, cex = 0.5, data = Flight179)  # to check for normality
```



RStudio can do all of the calculations for you if you give it the raw data:

Example6.13b

```
favstats(~Flight179, data = Flight179)

 min  Q1 median  Q3 max mean   sd  n missing
 330 342    358 370 407  358 20.2 36       0

t.test(~Flight179, data = Flight179)


One Sample t-test

data:  data$Flight179
t = 100, df = 40, p-value <2e-16
alternative hypothesis: true mean is not equal to 0
95 percent confidence interval:
 351 365
sample estimates:
mean of x
      358
```

You can also zoom in just the information you want:

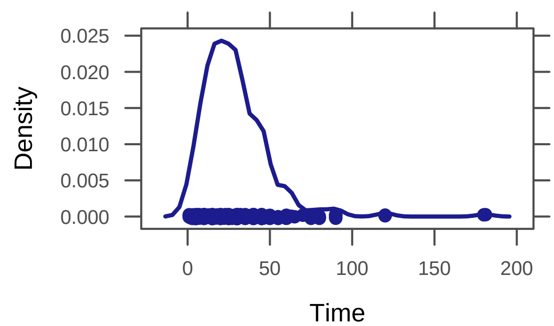
Example6.13c

```
confint(t.test(~Flight179, data = Flight179))

  mean of x lower upper level
1       358   351   365  0.95
```

Example 6.14

Example6.14

```
head(CommuteAtlanta, 3)

     City Age Distance Time Sex
1 Atlanta  19       10   15   M
2 Atlanta  55       45   60   M
3 Atlanta  48       12   45   M

densityplot(~Time, data = CommuteAtlanta)  # to check for normality
```



Example6.14b

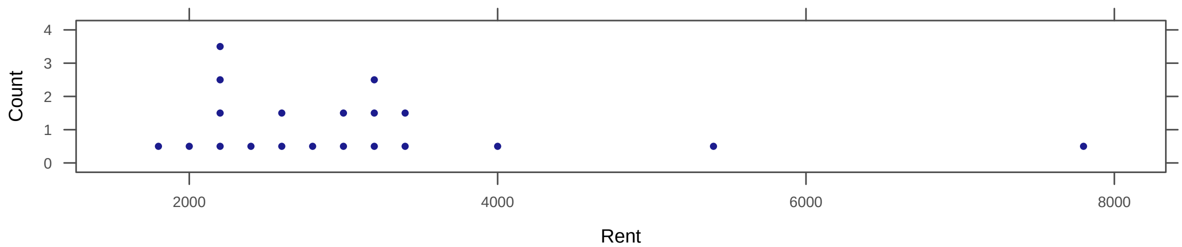
```
favstats(~Time, data = CommuteAtlanta)

 min Q1 median Q3 max mean   sd   n missing
   1 15     25 40 181 29.1 20.7 500       0

confint(t.test(~Time, conf.level = 0.99, data = CommuteAtlanta))

  mean of x lower upper level
1      29.1  26.7  31.5  0.99

confint(t.test(~Time, conf.level = 0.95, data = CommuteAtlanta))

  mean of x lower upper level
1      29.1  27.3  30.9  0.95
```


Example 6.15

```
head(ManhattanApartments, 3)                                              Example6.15
```

```
  Rent
1 2275
2 5495
3 2250
```

```
dotPlot(~Rent, width = 200, cex = 0.3, data = ManhattanApartments)  # to check for normality
```




```
                                                                          Example6.15b
Boot.Rent <- do(1000) * mean(~Rent, data = resample(ManhattanApartments))
head(Boot.Rent, 3)
```

```
     mean
1 3625.45
2 3504.75
3 2762.50
```

```
favstats(~mean, data = Boot.Rent)
```

```
    min       Q1  median       Q3     max     mean       sd    n missing
 2470.2 2934.125 3130.35 3344.063 4196.85 3152.336 294.5866 1000       0
```

```
cdata(~mean, 0.95, data = Boot.Rent)
```

```
      low        hi central.p
 2659.314  3807.577     0.950
```

Determining Sample Size for Estimating a Mean

Example 6.16

```
n <- (1.96 * 20.18/2)^2                                                   Example6.16
n
```

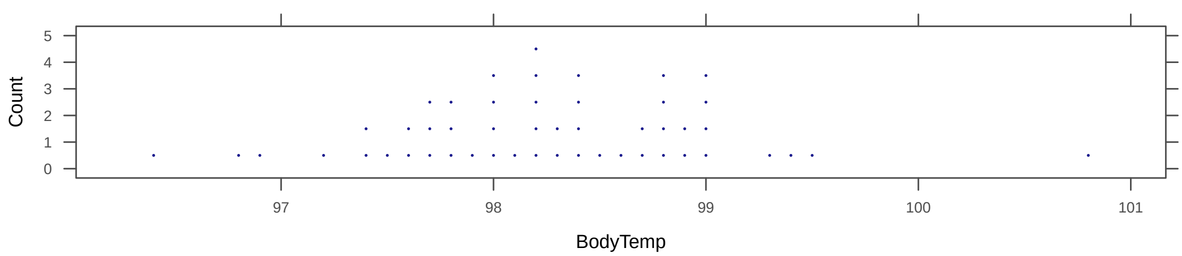
```
[1] 391
```

6.6 Test for a Single Mean

Example 6.17

Example6.17

```
head(BodyTemp50)

  BodyTemp Pulse Gender    Sex
1     97.6    69      0 Female
2     99.4    77      1   Male
3     99.0    75      0 Female
4     98.8    84      1   Male
5     98.0    71      0 Female
6     98.9    76      1   Male

dotPlot(~BodyTemp, cex = 0.15, width = 0.1, data = BodyTemp50)  # to check for normality
```



Example6.17b

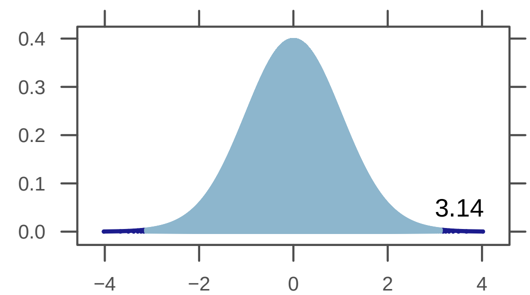
```
favstats(~BodyTemp, data = BodyTemp50)

  min   Q1 median   Q3 max mean    sd  n missing
 96.4 97.8   98.2 98.8 101 98.3 0.765 50       0

t.test(~BodyTemp, mu = 98.6, data = BodyTemp50)


One Sample t-test

data:  data$BodyTemp
t = -3, df = 50, p-value = 0.003
alternative hypothesis: true mean is not equal to 98.6
95 percent confidence interval:
 98.0 98.5
sample estimates:
mean of x
     98.3
```

```
pval(t.test(~BodyTemp, mu = 98.6, data = BodyTemp50))  # to find the p-value directly

p.value
0.00285
```

Figure 6.17

Figure6.17

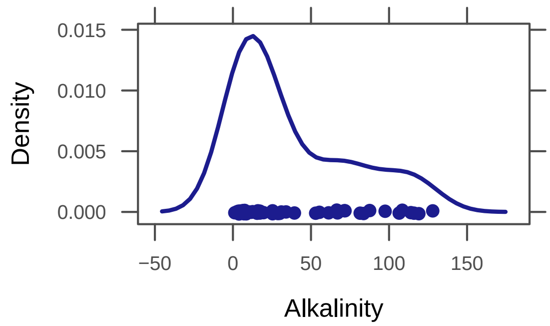
```
plotFun(dt(x, df = 49) ~ x, x.lim = c(-4, 4))
plotDist("t", params = list(df = 49), type = c("h", "l"), groups = (-3.14 < x & x < 3.14),
    lty = 1)
ladd(grid.text("3.14", 3, 0.05, default.units = "native", hjust = 0))
```



Example 6.18

Example6.18

```
head(FloridaLakes, 3)

  ID      Lake Alkalinity  pH Calcium Chlorophyll AvgMercury NumSamples MinMercury
1  1 Alligator        5.9 6.1     3.0         0.7       1.23          5       0.85
2  2     Annie        3.5 5.1     1.9         3.2       1.33          7       0.92
3  3    Apopka      116.0 9.1    44.1       128.3       0.04          6       0.04
  MaxMercury ThreeYrStdMercury AgeData
1       1.43              1.53       1
2       1.90              1.33       0
3       0.06              0.04       0

densityplot(~Alkalinity, data = FloridaLakes)  # to check for normality
```

Example6.18b

```
favstats(~Alkalinity, data = FloridaLakes)

 min  Q1 median   Q3 max mean   sd  n missing
 1.2 6.6   19.6 66.5 128 37.5 38.2 53       0

t.test(~Alkalinity, alt = "greater", mu = 35, data = FloridaLakes)


One Sample t-test

data:  data$Alkalinity
t = 0.5, df = 50, p-value = 0.3
alternative hypothesis: true mean is greater than 35
95 percent confidence interval:
 28.7  Inf
sample estimates:
mean of x
     37.5
```

Notice the "greater" for the alternative hypothesis.

6.7 Distribution of Differences in Proportions

Example 6.19

Example6.19

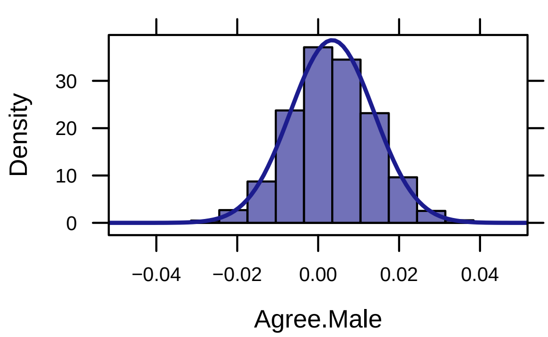
```
OneTrueLove <- read.file("OneTrueLove.csv")

Reading data with read.csv()

head(OneTrueLove)

  Gender Response
1   Male    Agree
2   Male    Agree
3   Male    Agree
```

```
4   Male    Agree
5   Male    Agree
6   Male    Agree

tally(Response ~ Gender, format = "count", margins = TRUE, data = OneTrueLove)

            Gender
Response     Female Male
  Agree         363  372
  Disagree     1005  807
  Don't know     44   34
  Total        1412 1213

prop(Response ~ Gender, data = OneTrueLove)

Agree.Female   Agree.Male
       0.138        0.142

diff(prop(Response ~ Gender, data = OneTrueLove))

Agree.Male
   0.00343
```

Figure 6.20

```
Boot.Love <- do(5000) * diff(prop(Response ~ Gender, data = resample(OneTrueLove)))
head(Boot.Love, 3)

    Agree.Male
1 -0.022857143
2 -0.008380952
3 -0.014857143

histogram(~Agree.Male, fit = "normal", data = Boot.Love)
```

Figure6.20



Example 6.20

```
SE <- sqrt(0.257 * (1 - 0.257)/1412 + 0.307 * (1 - 0.307)/1213)
SE
```

Example6.20

```
[1] 0.0176
```

6.8 Confidence Interval for a Difference in Proportions

Data 6.3

```
success <- c(158, 109)
n <- c(444, 922)
```

Data6.3

Example 6.21

```
success <- c(158, 109)
n <- c(444, 922)
prop.test(success, n, conf.level = 0.9)
```

Example6.21

```
2-sample test for equality of proportions with continuity correction

data:  success out of n
X-squared = 100, df = 1, p-value <2e-16
alternative hypothesis: two.sided
90 percent confidence interval:
 0.195 0.281
sample estimates:
prop 1 prop 2
 0.356  0.118
```

6.9 Test For a Difference in Proportions

Data 6.4

```
SplitSteal <- rbind(
  do(187) * data.frame(agegroup = "Under40", decision = "Split"),
  do(195) * data.frame(agegroup = "Under40", decision = "Steal"),
  do(116) * data.frame(agegroup = "Over40",  decision = "Split"),
  do(76)  * data.frame(agegroup = "Over40",  decision = "Steal")
  )
```

Data6.4

Example 6.22

```
prop(decision ~ agegroup, data = SplitSteal)  # sample prop within each group
```
Example6.22

```
Split.Under40  Split.Over40
        0.326         0.202
```

```
prop(~decision, data = SplitSteal)  # pooled proportion
```

```
Split
0.528
```

Example 6.23

```
diff <- diff(prop(decision ~ agegroup, data = SplitSteal))
diff
```
Example6.23

```
Split.Over40
      -0.124
```

```
prop.test(decision ~ agegroup, data = SplitSteal)
```

```
2-sample test for equality of proportions with continuity correction

data:  tally(decision ~ agegroup)
X-squared = 6, df = 1, p-value = 0.01
alternative hypothesis: two.sided
95 percent confidence interval:
 -0.2040 -0.0253
sample estimates:
prop 1 prop 2
 0.490  0.604
```

6.10 Distribution of Differences in Means

Figure 6.21

```
BootE <- do(2000) * diff(mean(Exercise ~ Gender, data = resample(ExerciseHours)))
head(BootE, 3)
```
Figure6.21

```
          M
1 3.0993590
2 0.7708333
3 1.6761905
```

```
histogram(~M, width = 0.5, fit = "normal", data = BootE)
```

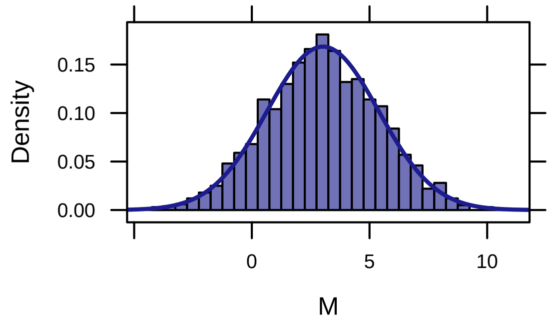
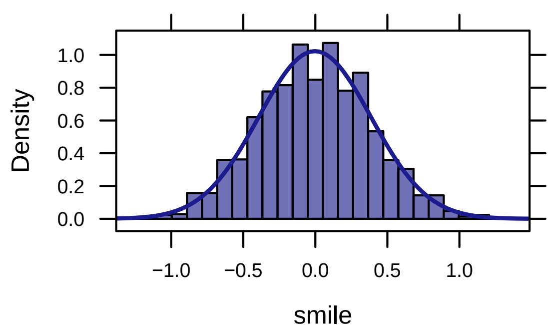


Figure6.21b

```
Random.Smiles <- do(2000) * diff(mean(Leniency ~ shuffle(Group), data = Smiles))
head(Random.Smiles, 3)
```

```
        smile
1  0.05882353
2  0.20588235
3 -0.14705882
```

```
histogram(~smile, n = 24, , fit = "normal", data = Random.Smiles)
```



The t-Distribution

Example 6.24

Example6.24

```
favstats(Exercise ~ Gender, data = ExerciseHours)
```

```
  Gender min Q1 median   Q3 max mean   sd  n missing
1      F   0  3     10 12.0  34  9.4 7.41 30       0
2      M   2  3     12 19.2  30 12.4 8.80 20       0
```

```
SE <- sqrt(8.8^2/20 + 7.41^2/30)
SE
```

```
[1] 2.39
```

```
favstats(Leniency ~ Group, data = Smiles)
```

```
    Group min  Q1 median   Q3 max mean   sd  n missing
1 neutral 2.0 3.0   4.00 4.88   8 4.12 1.52 34       0
2   smile 2.5 3.5   4.75 5.88   9 4.91 1.68 34       0
```

```
SE <- sqrt(1.68^2/34 + 1.52^2/34)
SE
```

```
[1] 0.389
```

6.11 Confidence Interval for a Difference in Means

Example 6.26

Example6.26

```
head(CommuteStLouis)
```

```
       City Age Distance Time Sex
1 St. Louis  52       10   20   M
2 St. Louis  21       35   40   F
3 St. Louis  23       40   45   F
4 St. Louis  38        0    2   M
5 St. Louis  26       15   25   M
6 St. Louis  46        7   12   M
```

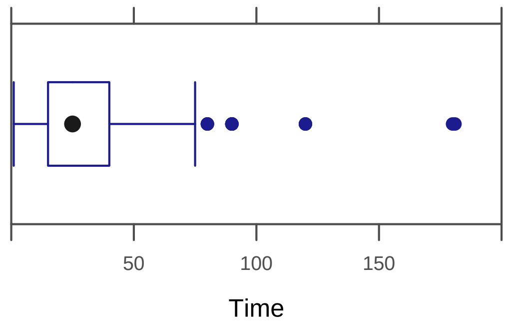
```
favstats(~Time, data = CommuteStLouis)
```

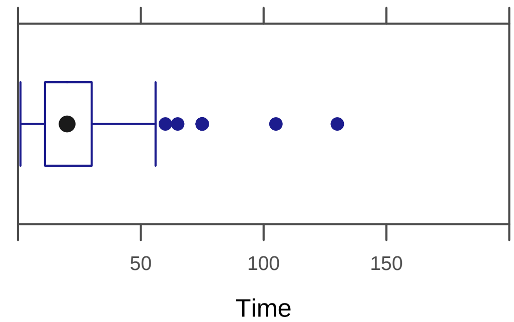
```
 min   Q1 median Q3 max mean   sd   n missing
   1 11.5     20 30 130   22 14.2 500       0
```

```
favstats(~Time, data = CommuteAtlanta)
```

```
 min Q1 median Q3 max mean   sd   n missing
   1 15     25 40 181 29.1 20.7 500       0
```

```
bwplot(~Time, xlim = c(0, 200), data = CommuteAtlanta)  # to check for normality
bwplot(~Time, xlim = c(0, 200), data = CommuteStLouis)  # to check for normality
```





Example6.26b

```
confint(t.test(CommuteAtlanta$Time, CommuteStLouis$Time, conf.level = 0.9))
```

```
  mean of x mean of y lower upper level
1      29.1        22  5.29  8.99   0.9
```

6.12 Test for a Difference in Means

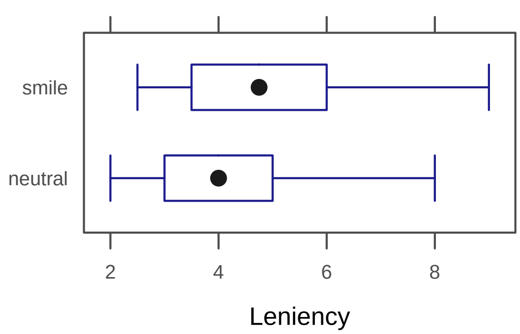
Example 6.27

Example6.27

```
head(Smiles, 3)
```

```
  Leniency Group
1        7 smile
2        3 smile
3        6 smile
```

```
bwplot(Group ~ Leniency, data = Smiles)  # to check for normality
```



Example6.27b

```
t.test(Leniency ~ Group, alt = "less", data = Smiles)
```

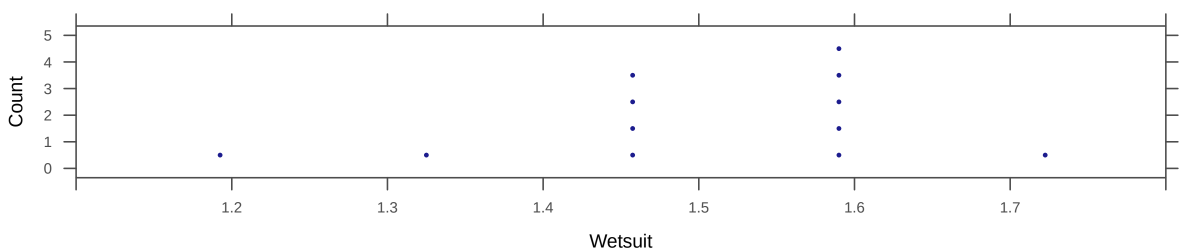
```
Welch Two Sample t-test

data:  Leniency by Group
t = -2, df = 70, p-value = 0.02
alternative hypothesis: true difference in means is less than 0
95 percent confidence interval:
   -Inf -0.145
sample estimates:
mean in group neutral   mean in group smile
                 4.12                  4.91
```

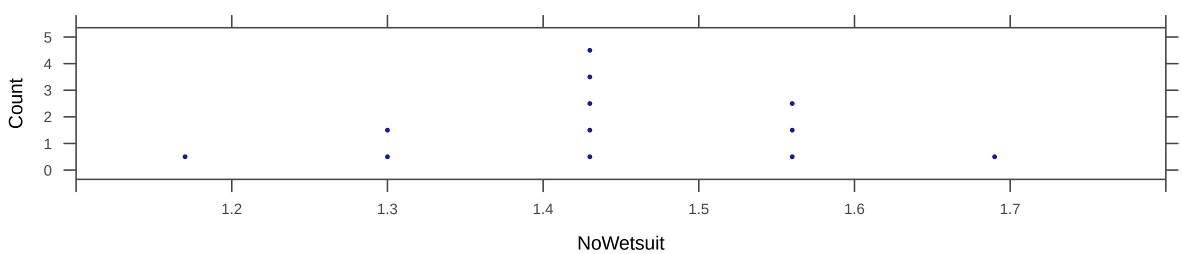
6.13 Paired Difference in Means

Example 6.28

Example6.28

```
head(Wetsuits, 3)


  Wetsuit NoWetsuit Gender       Type    Sex
1    1.57      1.49      F    swimmer Female
2    1.47      1.37      F triathlete Female
3    1.42      1.35      F    swimmer Female


dotPlot(~Wetsuit, xlim = c(1.1, 1.8), cex = 0.25, data = Wetsuits)  # to check for normality
dotPlot(~NoWetsuit, xlim = c(1.1, 1.8), cex = 0.25, data = Wetsuits)  # to check for normality
```





Example6.28b

```
t.test(Wetsuits$Wetsuit, Wetsuits$NoWetsuit)
```

```
Welch Two Sample t-test

data:  Wetsuits$Wetsuit and Wetsuits$NoWetsuit
t = 1, df = 20, p-value = 0.2
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -0.0399  0.1949
sample estimates:
mean of x mean of y
     1.51      1.43
```

Example 6.29

```
head(Wetsuits, 3)
```

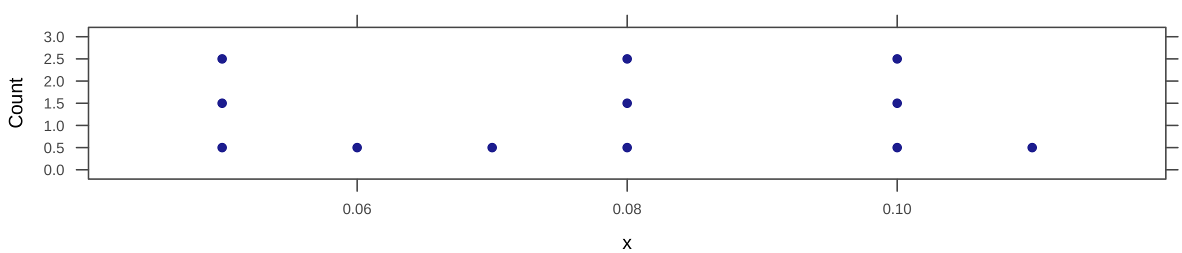
Example6.29

```
  Wetsuit NoWetsuit Gender       Type    Sex
1    1.57      1.49      F    swimmer Female
2    1.47      1.37      F triathlete Female
3    1.42      1.35      F    swimmer Female
```

```
t.test(Wetsuits$Wetsuit, Wetsuits$NoWetsuit, paired = TRUE)
```

```
Paired t-test

data:  Wetsuits$Wetsuit and Wetsuits$NoWetsuit
t = 10, df = 10, p-value = 9e-08
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 0.0637 0.0913
sample estimates:
mean of the differences
                 0.0775
```

```
dotPlot(Wetsuits$Wetsuit - Wetsuits$NoWetsuit, width = 0.01, cex = 0.3)
```



Example 6.30

```
confint(t.test(Wetsuits$Wetsuit, Wetsuits$NoWetsuit, paired = TRUE))
```

Example6.30

```
  mean of the differences  lower  upper level
1                  0.0775 0.0637 0.0913  0.95
```

```
confint(t.test(~(Wetsuit - NoWetsuit), data = Wetsuits))
```

```
  mean of x  lower  upper level
1    0.0775 0.0637 0.0913  0.95
```

7 Chi-Squared Tests for Categorical Variables

Goodness of fit tests test how well a distribution fits some hypothesis.

7.1 Testing Goodness-of-Fit for a Single Categorical Variable

Example 7.1

```
tally(~Answer, format = "proportion", data = APMultipleChoice)
```

Example7.1

```
    A     B     C     D     E 
0.212 0.225 0.198 0.195 0.170 
```

Chi-square Statistic

The **Chi-squared test statistic**:

$$\chi^2 = \sum \frac{(\text{observed} - \text{expected})^2}{\text{expected}}$$

There is one term in this sum *for each cell in our data table*, and

- observed = the tally in that cell (a count from our raw data)
- expected = the number we would "expect" if the percentages followed our null hypothesis exactly. (Note: the expected counts might not be whole numbers.)

Example 7.5

You could calculate the chi-square statistic manually but of course, R can automate this whole process for us if we provide the data table and the null hypothesis. Notice that to use `chisq.test()`, you must enter the data like `answer <- c(85, 90, 79, 78, 68)`. The default null hypothesis is that all the probabilities are equal.

Example7.5

```
head(APMultipleChoice)
```

```
  Answer
1      B
2      B
3      D
4      A
5      E
6      D
```

```
answer <- c(85, 90, 79, 78, 68)
chisq.test(answer)
```

```
Chi-squared test for given probabilities

data:  answer
X-squared = 3, df = 4, p-value = 0.5
```

Chi-square Distribution

The `chisq()` function can be used to calculate a chi-squared statistic from one of three kinds of input: from the result of `chisq.test()`, from a table of counts, as produced by `tally()`, or from a formula and data frame that could have been the input to `tally()`.

```
chisq(sex ~ substance, data = HELPrct)
```

```
X.squared
     2.03
```

```
chisq(tally(sex ~ substance, data = HELPrct))
```

```
X.squared
     2.03
```

```
chisq(chisq.test(tally(sex ~ substance, data = HELPrct)))
```

```
X.squared
     2.03
```

Figure 7.2

Figure7.02

```
chisq.sample <- do(1000) * chisq(~resample(toupper(letters[1:5]), 400))
histogram(~X.squared, data = chisq.sample)
```

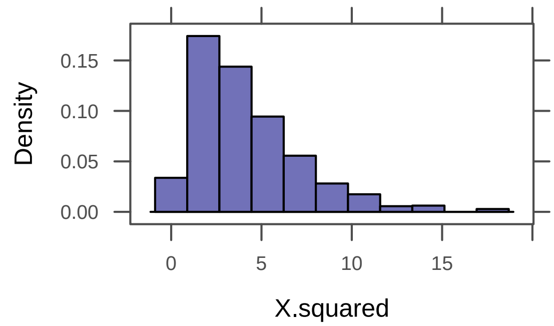
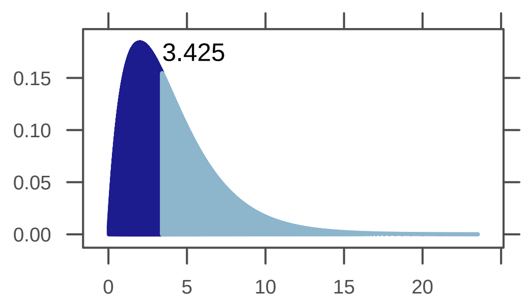



Figure 7.3

```
plotDist("chisq", params = list(df = 4), type = c("h", "l"), groups = x > 3.425, lty = 1)
ladd(grid.text("3.425", 3.425, 0.175, default.units = "native", hjust = 0))
```

Figure7.03



Our test statistic will be large when the observed counts and expected counts are quite different. It will be small when the observed counts and expected counts are quite close. So we will reject when the test statistic is large. To know how large is large enough, we need to know the sampling distribution.

If H_0 is true and the sample is large enough, then the sampling distribution for the Chi-squared test statistic will be approximately a Chi-squared distribution.

- The **degrees of freedom** for this type of goodness of fit test is one less than the number of cells.
- The approximation gets better and better as the sample size gets larger.

The mean of a Chi-squared distribution is equal to its degrees of freedom. This can help us get a rough idea about whether our test statistic is unusually large or not.

Example 7.6

1. H_0: $p_w = 0.54$, $p_b = 0.18$, $p_h = 0.12$, $p_a = 0.15$, $p_o = 0.01$;
   H_a: At least one p_i is not as specified.

2. Observed count: $w = 780$, $b = 117$, $h = 114$, $a = 384$, $o = 58$
3. Chi-squared test:

Example7.6

```
jury <- c(780, 117, 114, 384, 58)
chisq.test(jury, p = c(0.54, 0.18, 0.12, 0.15, 0.01))


Chi-squared test for given probabilities

data:  jury
X-squared = 400, df = 4, p-value <2e-16

xchisq.test(jury, p = c(0.54, 0.18, 0.12, 0.15, 0.01))  # to list expected counts


Chi-squared test for given probabilities

data:  x
X-squared = 400, df = 4, p-value <2e-16

 780.00   117.00   114.00   384.00    58.00
(784.62) (261.54) (174.36) (217.95) ( 14.53)
[  0.027] [ 79.880] [ 20.895] [126.509] [130.051]
<-0.16>  <-8.94>  <-4.57>  <11.25>  <11.40>

key:
observed
(expected)
[contribution to X-squared]
<residual>
```

Notice in this example, we need to tell R what the null hypothesis is.

How unusual is it to get a test statistic at least as large as ours? We compare to a Chi-squared distribution with 4 degrees of freedom. The mean value of such a statistic is 4, and our test statistic is much larger, so we anticipate that our value is extremely unusual.

Goodness-of-Fit for Two Categories

When there are only two categories, the Chi-squared goodeness of fit test is equivalent to the 1-proportion test. Notice that `prop.test()` uses the count in one category and total but that `chisq.test()` uses cell counts.

Example 7.8

Example7.8

```
prop.test(84, 200)



1-sample proportions test with continuity correction

data:  84 out of 200
X-squared = 5, df = 1, p-value = 0.03
alternative hypothesis: true p is not equal to 0.5
```



```
95 percent confidence interval:
 0.351 0.492
sample estimates:
   p
0.42


chisq.test(c(84, 116), p = c(0.5, 0.5))



Chi-squared test for given probabilities

data:  c(84, 116)
X-squared = 5, df = 1, p-value = 0.02


binom.test(84, 200)





data:  84 out of 200
number of successes = 80, number of trials = 200, p-value = 0.03
alternative hypothesis: true probability of success is not equal to 0.5
95 percent confidence interval:
 0.351 0.492
sample estimates:
probability of success
                  0.42
```

Although all three tests test the same hypotheses and give similar p-values (in this example), the binomial test is generally used because

- The binomial test is exact for all sample sizes while the Chi-squared test and 1-proportion test are only approximate, and the approximation is poor when sample sizes are small.
- The binomial test and 1-proportion test also produce confidence intervals.

7.2 Testing for an Association Between Two Categorical Variables

Example 7.9

```
OneTrueLove <- read.file("OneTrueLove.csv")                    Example7.9

Reading data with read.csv()

tally(~Response, format = "proportion", data = OneTrueLove)


     Agree   Disagree Don't know
    0.2800     0.6903     0.0297
```

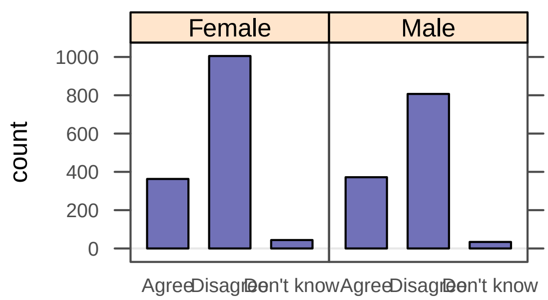
```
tally(~Response + Gender, format = "proportion", margin = TRUE, data = OneTrueLove)
```

```
            Gender
Response     Female   Male  Total
  Agree      0.1383 0.1417 0.2800
  Disagree   0.3829 0.3074 0.6903
  Don't know 0.0168 0.0130 0.0297
  Total      0.5379 0.4621 1.0000
```

Figure 7.4

```
bargraph(~Response | Gender, type = "count", data = OneTrueLove)
```

Figure7.04



Chi-square Test for Association

Example 7.10

```
head(WaterTaste, 3)
```

Example7.10

```
  Gender Age Class UsuallyDrink FavBotWatBrand Preference First      Second    Third
1      F  18     F     Filtered      DEER PARK       CABD  Fiji SamsChoice Aquafina
2      F  18     F          Tap           NONE       CABD  Fiji SamsChoice Aquafina
3      F  18     F          Tap      DEER PARK       CADB  Fiji SamsChoice      Tap
    Fourth    Sex
1      Tap Female
2      Tap Female
3 Aquafina Female
```

```
water <- tally(~UsuallyDrink + First, data = WaterTaste)
water
```

```
            First
UsuallyDrink Aquafina Fiji SamsChoice Tap
    Bottled        14   15          8   4
    Filtered        4   10          9   3
    Tap             7   16          7   3
```


Example7.10b

```
water <- rbind(c(14, 15, 8, 4), c(11, 26, 16, 6))  # to combine Tap and Filtered
water

     [,1] [,2] [,3] [,4]
[1,]   14   15    8    4
[2,]   11   26   16    6

colnames(water) <- c("Aquafina", "Fiji", "SamsChoice", "Tap")  # add column names
rownames(water) <- c("Bottled", "Tap/Filtered")  # add row names
water

             Aquafina Fiji SamsChoice Tap
Bottled            14   15          8   4
Tap/Filtered       11   26         16   6
```

Example7.10c

```
xchisq.test(water)


Pearson's Chi-squared test

data:  x
X-squared = 3, df = 3, p-value = 0.4

 14.00    15.00     8.00     4.00
(10.25)  (16.81)  ( 9.84)  ( 4.10)
[1.3720] [0.1949] [0.3441] [0.0024]
< 1.171> <-0.441> <-0.587> <-0.049>

 11.00    26.00    16.00     6.00
(14.75)  (24.19)  (14.16)  ( 5.90)
[0.9534] [0.1354] [0.2391] [0.0017]
<-0.976> < 0.368> < 0.489> < 0.041>

key:
observed
(expected)
[contribution to X-squared]
<residual>
```

Special Case for a 2 x 2 Table

There is also an exact test that works only in the case of a 2×2 table (much like the binomial test can be used instead of a goodness of fit test if there are only two categories). The test is called **Fisher's Exact Test**.

In this case we see that the simulated p-value from the Chi-squared Test is nearly the same as the exact p-value from Fisher's Exact Test. This is because Fisher's test is using mathematical formulas to compute probabilities of *all* randomizations – it is essentially the same as doing infinitely many randomizations!

Note: For a 2×2 table, we could also use the method of 2-proportions (`prop.test()`, manual resampling, or formula-based). The approximations based on the normal distribution will be poor in the same situations where the Chi-squared test gives a poor approximation.

Example 7.11

```
SplitStealTable <- rbind(c(187, 195), c(116, 76))
SplitStealTable
```

Example7.11

```
     [,1] [,2]
[1,]  187  195
[2,]  116   76
```

```
colnames(SplitStealTable) <- c("Split", "Steal")
rownames(SplitStealTable) <- c("Younger", "Older")
SplitStealTable
```

```
        Split Steal
Younger   187   195
Older     116    76
```

Example7.11b

```
fisher.test(SplitStealTable)
```

```
Fisher's Exact Test for Count Data

data:  SplitStealTable
p-value = 0.01
alternative hypothesis: true odds ratio is not equal to 1
95 percent confidence interval:
 0.435 0.907
sample estimates:
odds ratio
     0.629
```

```
xchisq.test(SplitStealTable)
```

```
Pearson's Chi-squared test with Yates' continuity correction

data:  x
X-squared = 6, df = 1, p-value = 0.01

 187.00   195.00
(201.65) (180.35)
 [0.99]   [1.11]
<-1.03>  < 1.09>

 116.00    76.00
(101.35) ( 90.65)
 [1.97]   [2.21]
< 1.46>  <-1.54>
```

```
key:
observed
(expected)
[contribution to X-squared]
<residual>
```

To use the test for proportions as done in Example 6.23,

Example7.11c

```
SplitStealData <- rbind(
  do(187) * data.frame(agegroup = "Under40", decision = "Split"),
  do(195) * data.frame(agegroup = "Under40", decision = "Steal"),
  do(116) * data.frame(agegroup = "Over40",  decision = "Split"),
  do(76)  * data.frame(agegroup = "Over40",  decision = "Steal")
  )
```

Example7.11d

```
prop.test(decision ~ agegroup, data = SplitStealData)



2-sample test for equality of proportions with continuity correction

data:  tally(decision ~ agegroup)
X-squared = 6, df = 1, p-value = 0.01
alternative hypothesis: two.sided
95 percent confidence interval:
 -0.2040 -0.0253
sample estimates:
prop 1 prop 2
 0.490  0.604
```

8 ANOVA to Compare Means

8.1 Analysis of Variance

- Two variables: categorical explanatory and quantitative response
  - Can be used in either experimental or observational designs.
- Main Question: Does the population mean response depend on the (treatment) group?
  - H_0: the population group means are all the equal ($\mu_1 = \mu_2 = \cdots \mu_k$)
  - H_a: the population group means are not all equal
- If categorical variable has only 2 values, we already have a method: 2-sample t-test
  - ANOVA allows for 3 or more groups (sub-populations)
- F statistic compares within group variation (how different are individuals in the same group?) to between group variation (how different are the different group means?)
- ANOVA assumes that each group is normally distributed with the same (population) standard deviation.
  - Check normality with normal quantile plots (of residuals)
  - Check equal standard deviation using 2:1 ratio rule (largest standard deviation at most twice the smallest standard deviation).

Null and Alternative Hypotheses

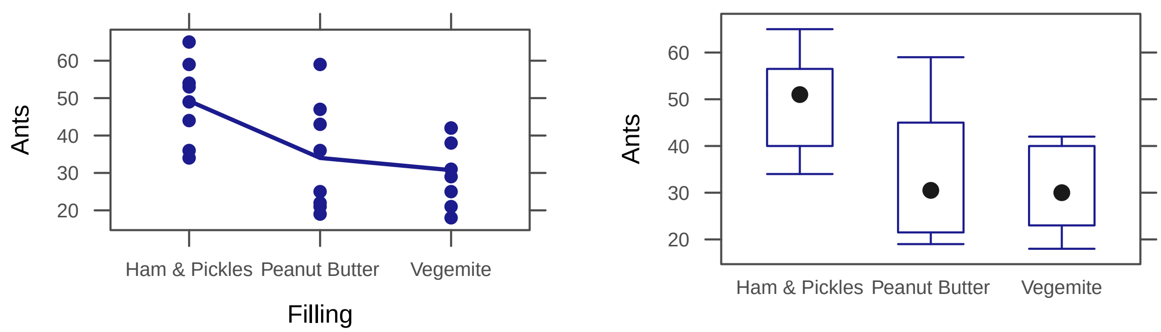
Example 8.1

```
favstats(Ants ~ Filling, data = SandwichAnts)
```

Example8.1

```
        Filling min   Q1 median   Q3 max mean    sd n missing
1 Ham & Pickles  34 42.0   51.0 55.2  65 49.2 10.79 8       0
2 Peanut Butter  19 21.8   30.5 44.0  59 34.0 14.63 8       0
3      Vegemite  18 24.0   30.0 39.0  42 30.8  9.25 8       0
```

Example8.1b
```
xyplot(Ants ~ Filling, SandwichAnts, type = c("p", "a"))
bwplot(Ants ~ Filling, SandwichAnts)
```



Partitioning Variability

Example 8.3

Example8.3
```
Ants.Model <- lm(Ants ~ Filling, data = SandwichAnts)
anova(Ants.Model)

Analysis of Variance Table

Response: Ants
          Df Sum Sq Mean Sq F value Pr(>F)
Filling    2   1561     780    5.63  0.011 *
Residuals 21   2913     139
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

The p-value listed in this output is the p-value for our null hypothesis that the mean population response is the same in each treatment group. In this case we would reject the null hypothesis at the $\alpha = 0.05$ level.

In the next section we'll look at this test in more detail, but notice that if you know the assumptions of a test, the null hypothesis being tested, and the p-value, you can generally interpret the results even if you don't know all the details of how the test statistic is computed.

The F-Statistic

The ANOVA test statistic (called F) is based on three ingredients:

1. how different the group means are (between group differences)
2. the amount of variability within each group (within group differences)
3. sample size

Each of these will be involved in the calculation of F.

Figure 8.3

```
Rand.Ants <- do(1000) * anova(lm(Ants ~ shuffle(Filling), data = SandwichAnts))
tally(~(F >= 5.63), data = Rand.Ants)
```

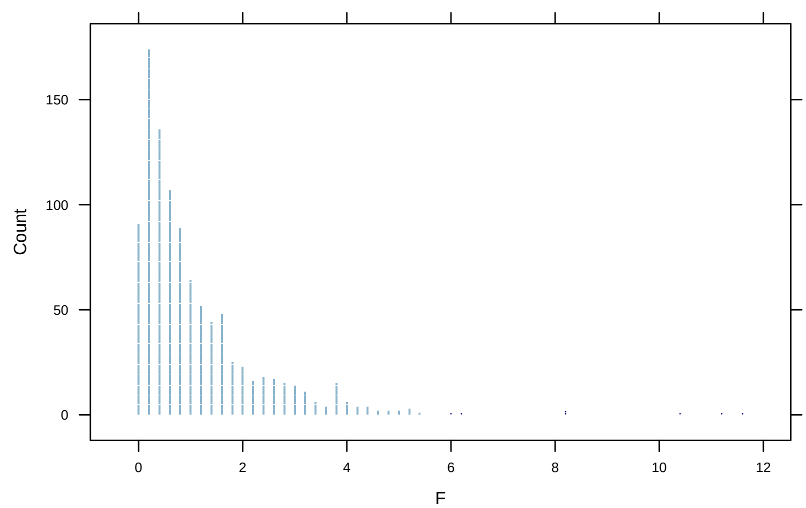
Figure8.3

```
 TRUE FALSE  <NA>
    7   993  1000
```

```
prop(~(F >= 5.63), data = Rand.Ants)
```

```
 TRUE
0.007
```

```
dotPlot(~F, width = 0.2, groups = (F <= 5.63), data = Rand.Ants)
```



The F-distribution

Under certain conditions, the F statistic has a known distribution (called the F distribution). Those conditions are

1. The null hypothesis is true (i.e., each group has the same mean)
2. Each group is sampled from a normal population
3. Each population group has the same standard deviation

When these conditions are met, we can use the F-distribution to compute the p-value without generating the randomization distribution.

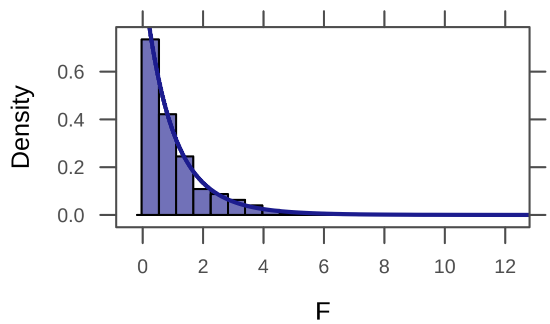
- F distributions have two parameters – the degrees of freedom for the numerator and for the denominator. In our example, this is 2 for the numerator and 7 for the denominator.

- When H_0 is true, the numerator and denominator both have a mean of 1, so F will tend to be close to 1.
- When H_0 is false, there is more difference between the groups, so the numerator tends to be larger. This means we will reject the null hypothesis when F gets large enough.
- The p-value is computed using `pf()`.

Figure 8.4

```
histogram(~F, width = 4/7, center = 0.25, data = Rand.Ants)
plotDist("f", df1 = 2, df2 = 21, add = TRUE)
```

Figure8.4



More Examples of ANOVA

Example 8.5

```
head(StudentSurvey, 3)
```

Example8.5

```
       Year Gender Smoke   Award HigherSAT Exercise TV Height Weight Siblings BirthOrder
1    Senior      M    No Olympic      Math       10  1     71    180        4          4
2 Sophomore      F   Yes Academy      Math        4  7     66    120        2          2
3 FirstYear      M    No   Nobel      Math       14  5     72    208        2          1
  VerbalSAT MathSAT  SAT  GPA Pulse Piercings    Sex
1       540     670 1210 3.13    54         0   Male
2       520     630 1150 2.50    66         3 Female
3       550     560 1110 2.55   130         0   Male
```

```
favstats(~Pulse, data = StudentSurvey)
```

```
 min Q1 median   Q3 max mean   sd   n missing
  35 62     70 77.8 130 69.6 12.2 362       0
```

```
favstats(Pulse ~ Award, data = StudentSurvey)
```

```
    Award min   Q1 median Q3 max mean   sd   n missing
1 Academy  42 64.5     71 76  95 70.5 12.4  31       0
2   Nobel  40 65.0     72 80 130 72.2 13.1 149       0
3 Olympic  35 60.0     68 74  96 67.3 11.0 182       0
```

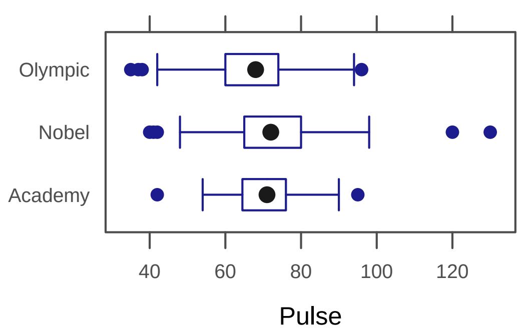
```
anova(lm(Pulse ~ Award, StudentSurvey))
```

```
Analysis of Variance Table

Response: Pulse
           Df Sum Sq Mean Sq F value  Pr(>F)
Award       2   2047    1024     7.1 0.00094 ***
Residuals 359  51729     144
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Figure 8.5

```
bwplot(Award ~ Pulse, data = StudentSurvey)
```

Figure8.5



ANOVA Calculations

- Between group variability: $G = \texttt{groupMean} - \texttt{grandMean}$

  This measures how different a group is from the overall average.

- Within group variability: $E = \texttt{response} - \texttt{groupMean}$

  This measures how different and individual is from its group average. E stands for "error", but just as in "standard error" it is not a "mistake". It is simply measure how different an individual response is from the model prediction (in this case, the group mean).

  The individual values of E are called **residuals**.

Example 8.6

Let's first compute the grand mean and group means.

Example8.6

```
SandwichAnts
```

```
   Butter       Filling      Bread Ants Order
1      no      Vegemite        Rye   18    10
2      no Peanut Butter        Rye   43    26
3      no Ham & Pickles        Rye   44    39
4      no      Vegemite  Wholemeal   29    25
5      no Peanut Butter  Wholemeal   59    35
6      no Ham & Pickles  Wholemeal   34     1
7      no      Vegemite Multigrain   42    44
8      no Peanut Butter Multigrain   22    36
9      no Ham & Pickles Multigrain   36    32
10     no      Vegemite      White   42    33
11     no Peanut Butter      White   25    34
12     no Ham & Pickles      White   49    13
13     no      Vegemite        Rye   31    14
14     no Peanut Butter        Rye   36    31
15     no Ham & Pickles        Rye   54    20
16     no      Vegemite  Wholemeal   21    19
17     no Peanut Butter  Wholemeal   47    38
18     no Ham & Pickles  Wholemeal   65     5
19     no      Vegemite Multigrain   38    21
20     no Peanut Butter Multigrain   19    22
21     no Ham & Pickles Multigrain   59     8
22     no      Vegemite      White   25    41
23     no Peanut Butter      White   21    16
24     no Ham & Pickles      White   53    23
```

```
mean(Ants, data = SandwichAnts)  # grand mean
```

```
[1] 38
```

```
mean(Ants ~ Filling, data = SandwichAnts)  # group means
```

```
Ham & Pickles Peanut Butter      Vegemite
         49.2          34.0          30.8
```

And add those to our data frame

Example8.6b

```
SA <- transform(SandwichAnts, groupMean = c(30.75, 34, 49.25, 30.75, 34, 49.25, 30.75, 34,
    49.25, 30.75, 34, 49.25, 30.75, 34, 49.25, 30.75, 34, 49.25, 30.75, 34, 49.25, 30.75, 34,
    49.25))
SA <- transform(SA, grandMean = rep(38, 24))
SA
```

```
   Butter       Filling      Bread Ants Order groupMean grandMean
1      no      Vegemite        Rye   18    10      30.8        38
2      no Peanut Butter        Rye   43    26      34.0        38
3      no Ham & Pickles        Rye   44    39      49.2        38
4      no      Vegemite  Wholemeal   29    25      30.8        38
5      no Peanut Butter  Wholemeal   59    35      34.0        38
6      no Ham & Pickles  Wholemeal   34     1      49.2        38
```

```
7      no       Vegemite Multigrain   42    44        30.8         38
8      no Peanut Butter Multigrain   22    36        34.0         38
9      no Ham & Pickles Multigrain   36    32        49.2         38
10     no       Vegemite      White   42    33        30.8         38
11     no Peanut Butter      White   25    34        34.0         38
12     no Ham & Pickles      White   49    13        49.2         38
13     no       Vegemite        Rye   31    14        30.8         38
14     no Peanut Butter        Rye   36    31        34.0         38
15     no Ham & Pickles        Rye   54    20        49.2         38
16     no       Vegemite  Wholemeal   21    19        30.8         38
17     no Peanut Butter  Wholemeal   47    38        34.0         38
18     no Ham & Pickles  Wholemeal   65     5        49.2         38
19     no       Vegemite Multigrain   38    21        30.8         38
20     no Peanut Butter Multigrain   19    22        34.0         38
21     no Ham & Pickles Multigrain   59     8        49.2         38
22     no       Vegemite      White   25    41        30.8         38
23     no Peanut Butter      White   21    16        34.0         38
24     no Ham & Pickles      White   53    23        49.2         38
```

Example8.6c

```
SA <- transform(SA, M = groupMean - grandMean)
SA <- transform(SA, E = Ants - groupMean)
SA
```

```
   Butter       Filling      Bread Ants Order groupMean grandMean     M      E
1      no       Vegemite        Rye   18    10        30.8         38 -7.25 -12.75
2      no Peanut Butter        Rye   43    26        34.0         38 -4.00   9.00
3      no Ham & Pickles        Rye   44    39        49.2         38 11.25  -5.25
4      no       Vegemite  Wholemeal   29    25        30.8         38 -7.25  -1.75
5      no Peanut Butter  Wholemeal   59    35        34.0         38 -4.00  25.00
6      no Ham & Pickles  Wholemeal   34     1        49.2         38 11.25 -15.25
7      no       Vegemite Multigrain   42    44        30.8         38 -7.25  11.25
8      no Peanut Butter Multigrain   22    36        34.0         38 -4.00 -12.00
9      no Ham & Pickles Multigrain   36    32        49.2         38 11.25 -13.25
10     no       Vegemite      White   42    33        30.8         38 -7.25  11.25
11     no Peanut Butter      White   25    34        34.0         38 -4.00  -9.00
12     no Ham & Pickles      White   49    13        49.2         38 11.25  -0.25
13     no       Vegemite        Rye   31    14        30.8         38 -7.25   0.25
14     no Peanut Butter        Rye   36    31        34.0         38 -4.00   2.00
15     no Ham & Pickles        Rye   54    20        49.2         38 11.25   4.75
16     no       Vegemite  Wholemeal   21    19        30.8         38 -7.25  -9.75
17     no Peanut Butter  Wholemeal   47    38        34.0         38 -4.00  13.00
18     no Ham & Pickles  Wholemeal   65     5        49.2         38 11.25  15.75
19     no       Vegemite Multigrain   38    21        30.8         38 -7.25   7.25
20     no Peanut Butter Multigrain   19    22        34.0         38 -4.00 -15.00
21     no Ham & Pickles Multigrain   59     8        49.2         38 11.25   9.75
22     no       Vegemite      White   25    41        30.8         38 -7.25  -5.75
23     no Peanut Butter      White   21    16        34.0         38 -4.00 -13.00
24     no Ham & Pickles      White   53    23        49.2         38 11.25   3.75
```

As we did with variance, we will square these differences:

Example8.6d

```
SA <- transform(SA, M2 = (groupMean - grandMean)^2)
SA <- transform(SA, E2 = (Ants - groupMean)^2)
SA
```

```
   Butter       Filling      Bread Ants Order groupMean grandMean      M      E    M2
1      no      Vegemite        Rye   18    10      30.8        38 -7.25 -12.75  52.6
2      no Peanut Butter        Rye   43    26      34.0        38 -4.00   9.00  16.0
3      no Ham & Pickles        Rye   44    39      49.2        38 11.25  -5.25 126.6
4      no      Vegemite  Wholemeal   29    25      30.8        38 -7.25  -1.75  52.6
5      no Peanut Butter  Wholemeal   59    35      34.0        38 -4.00  25.00  16.0
6      no Ham & Pickles  Wholemeal   34     1      49.2        38 11.25 -15.25 126.6
7      no      Vegemite Multigrain   42    44      30.8        38 -7.25  11.25  52.6
8      no Peanut Butter Multigrain   22    36      34.0        38 -4.00 -12.00  16.0
9      no Ham & Pickles Multigrain   36    32      49.2        38 11.25 -13.25 126.6
10     no      Vegemite      White   42    33      30.8        38 -7.25  11.25  52.6
11     no Peanut Butter      White   25    34      34.0        38 -4.00  -9.00  16.0
12     no Ham & Pickles      White   49    13      49.2        38 11.25  -0.25 126.6
13     no      Vegemite        Rye   31    14      30.8        38 -7.25   0.25  52.6
14     no Peanut Butter        Rye   36    31      34.0        38 -4.00   2.00  16.0
15     no Ham & Pickles        Rye   54    20      49.2        38 11.25   4.75 126.6
16     no      Vegemite  Wholemeal   21    19      30.8        38 -7.25  -9.75  52.6
17     no Peanut Butter  Wholemeal   47    38      34.0        38 -4.00  13.00  16.0
18     no Ham & Pickles  Wholemeal   65     5      49.2        38 11.25  15.75 126.6
19     no      Vegemite Multigrain   38    21      30.8        38 -7.25   7.25  52.6
20     no Peanut Butter Multigrain   19    22      34.0        38 -4.00 -15.00  16.0
21     no Ham & Pickles Multigrain   59     8      49.2        38 11.25   9.75 126.6
22     no      Vegemite      White   25    41      30.8        38 -7.25  -5.75  52.6
23     no Peanut Butter      White   21    16      34.0        38 -4.00 -13.00  16.0
24     no Ham & Pickles      White   53    23      49.2        38 11.25   3.75 126.6
         E2
1  162.5625
2   81.0000
3   27.5625
4    3.0625
5  625.0000
6  232.5625
7  126.5625
8  144.0000
9  175.5625
10 126.5625
11  81.0000
12   0.0625
13   0.0625
14   4.0000
15  22.5625
16  95.0625
17 169.0000
18 248.0625
19  52.5625
20 225.0000
21  95.0625
22  33.0625
23 169.0000
24  14.0625
```

And then add them up (SS stands for “sum of squares”)

Example8.6e

```
SST <- sum(~((Ants - grandMean)^2), data = SA)
SST
```

```
[1] 4474
```

```
SSM <- sum(~M2, data = SA)
SSM  # also called SSG


[1] 1561


SSE <- sum(~E2, data = SA)
SSE


[1] 2913
```

8.2 Pairwise Comparisons and Inference After ANOVA

Using ANOVA for Inferences about Group Means

We can construct a confidence interval for any of the means by just taking a subset of the data and using `t.test()`, but there are some problems with this approach. Most importantly,

> We were primarily interested in comparing the means across the groups. Often people will display confidence intervals for each group and look for "overlapping" intervals. But this is not the best way to look for differences.

Nevertheless, you will sometimes see graphs showing multiple confidence intervals and labeling them to indicate which means appear to be different from which. (See the solution to problem 15.3 for an example.)

Example 8.7

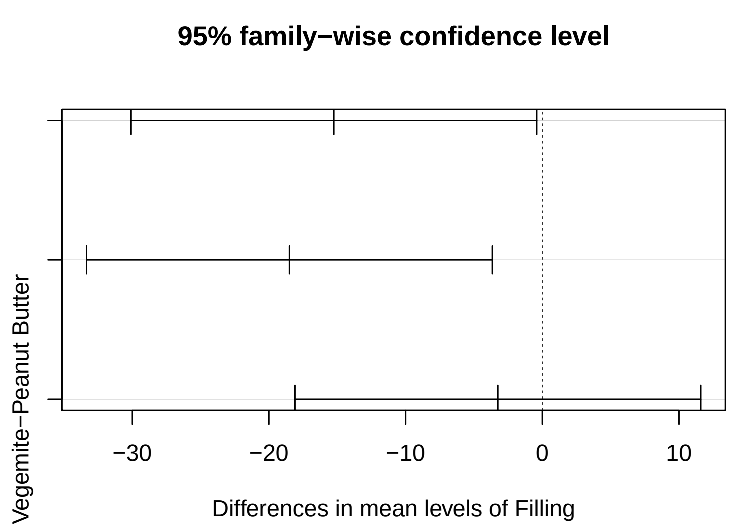
Example8.7

```
anova(Ants.Model)


Analysis of Variance Table

Response: Ants
          Df Sum Sq Mean Sq F value Pr(>F)
Filling    2   1561     780    5.63  0.011 *
Residuals 21   2913     139
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1


MSE <- 138.7
mean(Ants ~ Filling, data = SandwichAnts)


Ham & Pickles Peanut Butter      Vegemite
         49.2          34.0          30.8


mean <- 34
t.star <- qt(0.975, df = 21)
t.star
```

```
[1] 2.08

mean - t.star * (sqrt(MSE)/sqrt(8))

[1] 25.3

mean + t.star * (sqrt(MSE)/sqrt(8))

[1] 42.7
```

Example8.7b

```
TukeyHSD(Ants.Model)


  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = x)

$Filling
                              diff   lwr    upr p adj
Peanut Butter-Ham & Pickles -15.25 -30.1 -0.407 0.043
Vegemite-Ham & Pickles      -18.50 -33.3 -3.657 0.013
Vegemite-Peanut Butter       -3.25 -18.1 11.593 0.847


plot(TukeyHSD(Ants.Model))
```



Example 8.8

Example8.8

```
MSE <- 138.7
mean(Ants ~ Filling, data = SandwichAnts)
```

```
Ham & Pickles Peanut Butter      Vegemite
         49.2          34.0          30.8
```

```
diff.mean <- (30.75 - 49.25)
t.star <- qt(0.975, df = 21)
t.star
```

```
[1] 2.08
```

Example8.8b

```
diff.mean - t.star * (sqrt(MSE * (1/8 + 1/8)))
```

```
[1] -30.7
```

```
diff.mean + t.star * (sqrt(MSE * (1/8 + 1/8)))
```

```
[1] -6.25
```

Example 8.9

Example8.9

```
MSE <- 138.7
mean(Ants ~ Filling, data = SandwichAnts)
```

```
Ham & Pickles Peanut Butter      Vegemite
         49.2          34.0          30.8
```

```
diff.mean <- (30.75 - 34)
```

Example8.9b

```
t <- diff.mean/sqrt(MSE * (1/8 + 1/8))
t
```

```
[1] -0.552
```

```
pt(t, df = 21) * 2
```

```
[1] 0.587
```

Lots of Pairwise Comparisons

Example 8.10

Example8.10

```
head(TextbookCosts)
```

```
           Field Books Cost
1  SocialScience     3   77
2 NaturalScience     2  231
3 NaturalScience     1  189
4  SocialScience     6   85
5 NaturalScience     1  113
6     Humanities     9  132
```

```
Books.Model <- lm(Cost ~ Field, data = TextbookCosts)
anova(Books.Model)
```

```
Analysis of Variance Table

Response: Cost
          Df Sum Sq Mean Sq F value Pr(>F)
Field      3  30848   10283    4.05  0.014 *
Residuals 36  91294    2536
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
summary(Books.Model)
```

```
Call:
lm(formula = Cost ~ Field, data = TextbookCosts)

Residuals:
   Min     1Q Median     3Q    Max
-77.60 -35.30  -4.95  36.90 102.70

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)             94.6       15.9    5.94  8.3e-07 ***
FieldHumanities         25.7       22.5    1.14   0.2613
FieldNaturalScience     76.2       22.5    3.38   0.0017 **
FieldSocialScience      23.7       22.5    1.05   0.2996
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 50.4 on 36 degrees of freedom
Multiple R-squared:  0.253,Adjusted R-squared:  0.19
F-statistic: 4.05 on 3 and 36 DF,  p-value: 0.014
```

Example8.10b

```
TukeyHSD(Books.Model)
```

```
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = x)
```

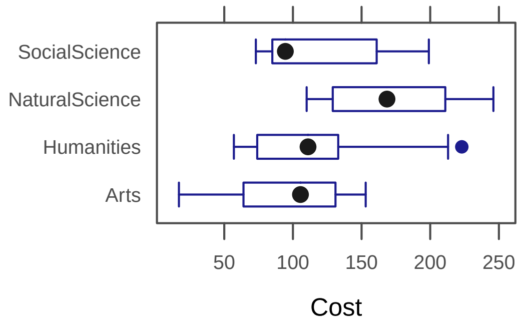


```
$Field
                              diff    lwr    upr p adj
Humanities-Arts               25.7  -35.0  86.35 0.667
NaturalScience-Arts           76.2   15.5 136.85 0.009
SocialScience-Arts            23.7  -37.0  84.35 0.720
NaturalScience-Humanities     50.5  -10.2 111.15 0.131
SocialScience-Humanities      -2.0  -62.7  58.65 1.000
SocialScience-NaturalScience -52.5 -113.2   8.15 0.110
```

Figure 8.8

```
bwplot(Field ~ Cost, data = TextbookCosts)
```

Figure8.8



9 Inference for Regression

9.1 Inference for Slope and Correlation

Simple Linear Model

$$Y = \beta_0 + \beta_1 x + \epsilon \qquad \text{where } \epsilon \sim \mathsf{Norm}(0, \sigma).$$

In other words:

- The mean response for a given predictor value x is given by a linear formula

$$\text{mean response} = \beta_0 + \beta_1 x$$

- The distribution of all responses for a given predictor value x is normal.
- The standard deviation of the responses is the same for each predictor value.

One of the goals in simple linear regression is to estimate this linear relationship – that is to estimate the intercept and the slope.

Of course, there are lots of lines. We want to determine the line that fits the data best. But what does that mean?

The usual method is called the **method of least squares** and chooses the line that has the *smallest possible sum of squares of residuals*, where residuals are defined by

$$\text{residual} = \text{observed response} - \text{predicted response}$$

For a line with equation $y = b_0 + b_1 x$, this would be

$$e_i = y_i - (b_0 + b_1 x)$$

Simple calculus (that you don't need to know) allows us to compute the best b_0 and b_1 possible. These best values define the least squares regression line. Fortunately, statistical software packages do all this work for us. In R, the command that does this is `lm()`.

Example 9.1

```
lm(Price ~ PPM, data = InkjetPrinters)
```

Example9.1

```
Call:
lm(formula = Price ~ PPM, data = InkjetPrinters)

Coefficients:
(Intercept)          PPM
      -94.2         90.9
```

You can get terser output with

Example9.1b

```
coef(lm(Price ~ PPM, data = InkjetPrinters))
```

```
(Intercept)         PPM
      -94.2        90.9
```

You can also get more information with

Example9.1c

```
msummary(lm(Price ~ PPM, data = InkjetPrinters))
```

```
            Estimate Std. Error t value Pr(>|t|)
(Intercept)    -94.2       56.4   -1.67  0.11209
PPM             90.9       19.5    4.66  0.00019 ***

Residual standard error: 58.5 on 18 degrees of freedom
Multiple R-squared:  0.547,Adjusted R-squared:  0.522
F-statistic: 21.7 on 1 and 18 DF,  p-value: 0.000193
```

So our regression equation is

$$\widehat{\text{Price}} = -94.222 + 90.878 \cdot \text{PPM}$$

For example, this suggests that the average price for inkjet printers that print 3 pages per minute is

$$\widehat{\text{Price}} = -94.222 + 90.878 \cdot 3.0 = 178.412$$

Inference for Slope

Figure 9.1

Figure9.1

```
xyplot(Price ~ PPM, data = InkjetPrinters, type = c("p", "r"))
```

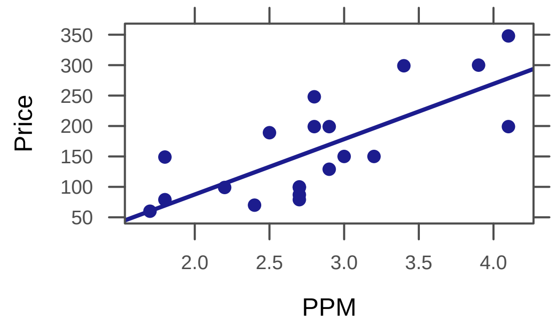
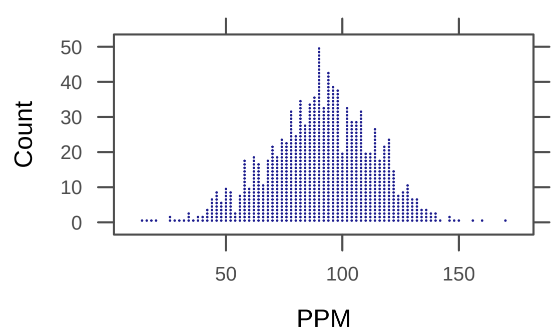



Figure 9.2

Figure9.2

```
Boot.Ink <- do(1000) * lm(Price ~ PPM, data = resample(InkjetPrinters))
favstats(~PPM, data = Boot.Ink)

  min   Q1 median  Q3 max mean   sd    n missing
 14.5 76.7   91.5 107 170 90.7 22.8 1000       0

dotPlot(~PPM, width = 2, data = Boot.Ink)
Rand.Ink <- do(1000) * lm(Price ~ shuffle(PPM), data = InkjetPrinters)
favstats(~PPM, data = Rand.Ink)

Error in eval(expr, envir, enclos):  object 'PPM' not found

dotPlot(~PPM, width = 2, data = Rand.Ink)

Error in eval(expr, envir, enclos):  object 'PPM' not found
```



Example 9.2

Example9.2

```
msummary(lm(Price ~ PPM, data = InkjetPrinters))
```

```
            Estimate Std. Error t value Pr(>|t|)
(Intercept)    -94.2       56.4   -1.67  0.11209
PPM             90.9       19.5    4.66  0.00019 ***

Residual standard error: 58.5 on 18 degrees of freedom
Multiple R-squared:  0.547,Adjusted R-squared:  0.522
F-statistic: 21.7 on 1 and 18 DF,  p-value: 0.000193
```

```
confint(lm(Price ~ PPM, data = InkjetPrinters), "PPM")
```

```
    2.5 % 97.5 %
PPM  49.9    132
```

Example 9.3

Example9.3

```
head(RestaurantTips)
```

```
  Bill   Tip Credit Guests Day Server PctTip CreditCard
1 23.7 10.00      n      2 Fri      A   42.2         No
2 36.1  7.00      n      3 Fri      B   19.4         No
3 32.0  5.01      y      2 Fri      A   15.7        Yes
4 17.4  3.61      y      2 Fri      B   20.8        Yes
5 15.4  3.00      n      2 Fri      B   19.5         No
6 18.6  2.50      n      2 Fri      A   13.4         No
```

```
summary(lm(Tip ~ Bill, data = RestaurantTips))
```

```
Call:
lm(formula = Tip ~ Bill, data = RestaurantTips)

Residuals:
   Min     1Q Median     3Q    Max
-2.391 -0.489 -0.111  0.284  5.974

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -0.29227    0.16616   -1.76    0.081 .
Bill         0.18221    0.00645   28.25   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.98 on 155 degrees of freedom
Multiple R-squared:  0.837,Adjusted R-squared:  0.836
F-statistic:  798 on 1 and 155 DF,  p-value: <2e-16
```

```
confint(lm(Tip ~ Bill, data = RestaurantTips), "Bill", level = 0.9)
```

```
       5 %  95 %
Bill 0.172 0.193
```

Example 9.4

1. H_0: $\beta_1 = 0$; H_a: $\beta_1 \neq 0$
2. Test statistic: $b_1 = 0.0488$ (sample slope)
3. t-test for slope:

Example9.4

```
msummary(lm(PctTip ~ Bill, data = RestaurantTips))

            Estimate Std. Error t value Pr(>|t|)
(Intercept)  15.5096     0.7396    21.0   <2e-16 ***
Bill          0.0488     0.0287     1.7    0.091 .

Residual standard error: 4.36 on 155 degrees of freedom
Multiple R-squared:  0.0183,Adjusted R-squared:  0.012
F-statistic: 2.89 on 1 and 155 DF,  p-value: 0.0911
```

t-Test for Correlation

Example 9.5

Example9.5

```
summary(lm(CostBW ~ PPM, data = InkjetPrinters))


Call:
lm(formula = CostBW ~ PPM, data = InkjetPrinters)

Residuals:
   Min     1Q Median     3Q    Max
-2.138 -0.729 -0.337  0.532  3.807

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)    8.683      1.284    6.76  2.5e-06 ***
PPM           -1.552      0.444   -3.50   0.0026 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.33 on 18 degrees of freedom
Multiple R-squared:  0.405,Adjusted R-squared:  0.372
F-statistic: 12.2 on 1 and 18 DF,  p-value: 0.00257
```

Example 9.6

Example9.6

```
msummary(lm(PctTip ~ Bill, data = RestaurantTips))

            Estimate Std. Error t value Pr(>|t|)
(Intercept)  15.5096     0.7396    21.0   <2e-16 ***
Bill          0.0488     0.0287     1.7    0.091 .
```

```
Residual standard error: 4.36 on 155 degrees of freedom
Multiple R-squared:  0.0183,Adjusted R-squared:  0.012
F-statistic: 2.89 on 1 and 155 DF,  p-value: 0.0911
```

Coefficient of Determination: R-squared

Example 9.7

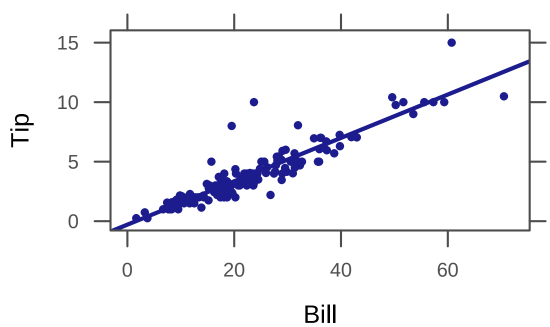
```
msummary(lm(Price ~ PPM, data = InkjetPrinters))
```
Example9.7

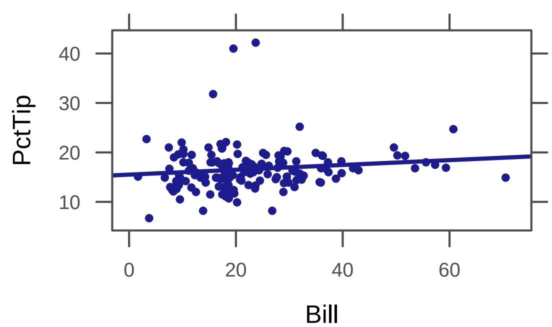
```
            Estimate Std. Error t value Pr(>|t|)
(Intercept)    -94.2       56.4   -1.67  0.11209
PPM             90.9       19.5    4.66  0.00019 ***

Residual standard error: 58.5 on 18 degrees of freedom
Multiple R-squared:  0.547,Adjusted R-squared:  0.522
F-statistic: 21.7 on 1 and 18 DF,  p-value: 0.000193
```

Checking Conditions for a Simple Linear Model

Example 9.9

```
xyplot(Tip ~ Bill, data = RestaurantTips, type = c("p", "r"), cex = 0.5)
xyplot(PctTip ~ Bill, data = RestaurantTips, type = c("p", "r"), cex = 0.5)
```
Example9.9





9.2 ANOVA for Regression

Partitioning Variability

We can also think about regression as a way to analyze the variability in the response. This is a lot like the ANOVA tables we have seen before. This time:

$$SST = \sum (y - \overline{y})^2$$
$$SSE = \sum (y - \hat{y})^2$$
$$SSM = \sum (\hat{y} - \overline{y})^2$$
$$SST = SSM + SSE$$

As before, when SSM is large and SSE is small, then the model ($\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x$) explains a lot of the variability and little is left unexplained (SSE). On the other hand, if SSM is small and SSE is large, then the model explains only a little of the variability and most of it is due to things not explained by the model.

Example 9.10

Example9.10

```r
summary(lm(Calories ~ Sugars, data = Cereal))
```

```
Call:
lm(formula = Calories ~ Sugars, data = Cereal)

Residuals:
   Min     1Q Median     3Q    Max 
-36.57 -25.28  -2.55  17.80  51.81 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)   88.920     10.812    8.22  6.0e-09 ***
Sugars         4.310      0.927    4.65  7.2e-05 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 26.6 on 28 degrees of freedom
Multiple R-squared:  0.436,Adjusted R-squared:  0.416 
F-statistic: 21.6 on 1 and 28 DF,  p-value: 7.22e-05
```

```r
anova(lm(Calories ~ Sugars, data = Cereal))
```

```
Analysis of Variance Table

Response: Calories
          Df Sum Sq Mean Sq F value  Pr(>F)    
Sugars     1  15317   15317    21.6 7.2e-05 ***
Residuals 28  19834     708                    
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

F-Statistic

- $MSM = SSM/DFM = SSM/(\text{number of groups} - 1)$
- $MSE = SSE/DFE = SSE/(n - \text{number of groups})$

MS stands for "mean square"

Our test statistic is

$$F = \frac{MSM}{MSE}$$

Example 9.11

```
SSM <- 15317
MSM <- SSM/(2 - 1)
MSM
```

Example9.11

```
[1] 15317
```

```
SSE <- 19834
MSE <- SSE/(30 - 2)
MSE
```

```
[1] 708
```

Example9.11b

```
F <- MSM/MSE
F
```

```
[1] 21.6
```

```
pf(F, 1, 28, lower.tail = FALSE)
```

```
[1] 7.22e-05
```

Example 9.12

```
summary(lm(Calories ~ Sodium, data = Cereal))
```

Example9.12

```

Call:
lm(formula = Calories ~ Sodium, data = Cereal)

Residuals:
   Min      1Q Median      3Q     Max
-47.39 -22.92  -8.01  18.75  76.23

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  103.759     18.868    5.50  7.1e-06 ***
Sodium         0.137      0.081    1.69      0.1
---
```



```
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 33.8 on 28 degrees of freedom
Multiple R-squared:  0.0922,Adjusted R-squared:  0.0598
F-statistic: 2.84 on 1 and 28 DF,  p-value: 0.103


anova(lm(Calories ~ Sodium, data = Cereal))


Analysis of Variance Table

Response: Calories
          Df Sum Sq Mean Sq F value Pr(>F)
Sodium     1   3241    3241    2.84    0.1
Residuals 28  31909    1140
```

The percentage of explained variability is denoted r^2 or R^2:

$$R^2 = \frac{SSM}{SST} = \frac{SSM}{SSM + SSE}$$

Example 9.13

The summary of the linear model shows us the **coefficient of determination** but we can also find it manually.

Example9.13

```
SSM <- 15317
SST <- SSM + 19834
R2 <- SSM/SST
R2


[1] 0.436


rsquared(lm(Calories ~ Sugars, data = Cereal))


[1] 0.436
```

Example9.13b

```
SSM <- 3241
SST <- SSM + 31909
R2 <- SSM/SST
R2


[1] 0.0922


rsquared(lm(Calories ~ Sodium, data = Cereal))


[1] 0.0922
```

Computational Details

Example 9.15

Again, the summary of the linear model gives us the standard deviation of the error but we can calculate it manually.

Example9.15

```
SSE <- 31909
SD <- sqrt(SSE/(30 - 2))
SD
```

```
[1] 33.8
```

Example 9.16

Example9.16

```
favstats(~Sodium, data = Cereal)
```

```
 min  Q1 median  Q3 max mean   sd  n missing
   5 184    217 251 408  220 77.4 30       0
```

```
SE <- SD/(77.4 * sqrt(30 - 1))  # SD from Example 9.15
SE
```

```
[1] 0.081
```

9.3 Confidence and Prediction Intervals

Interpreting Confidence and Prediction Intervals

It may be very interesting to make predictions when the explanatory variable has some other value, however. There are two ways to do this in R. One uses the `predict()` function. It is simpler, however, to use the `makeFun()` function in the `mosaic` package, so that's the approach we will use here.

Prediction intervals

1. are much wider than confidence intervals
2. are very sensitive to the assumption that the population normal for each value of the predictor.
3. are (for a 95% confidence level) a little bit wider than

   $$\hat{y} \pm 2SE$$

   where SE is the "residual standard error" reported in the summary output.

   > The prediction interval is a little wider because it takes into account the uncertainty in our estimated slope and intercept as well as the variability of responses around the true regression line.

Example 9.18

First, let's build our linear model and store it.

Example9.18

```
ink.model <- lm(Price ~ PPM, data = InkjetPrinters)
summary(ink.model)
```

```

Call:
lm(formula = Price ~ PPM, data = InkjetPrinters)

Residuals:
   Min     1Q Median     3Q    Max 
-79.38 -51.40  -3.49  43.85  87.76 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)    -94.2       56.4   -1.67  0.11209    
PPM             90.9       19.5    4.66  0.00019 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 58.5 on 18 degrees of freedom
Multiple R-squared:  0.547,Adjusted R-squared:  0.522 
F-statistic: 21.7 on 1 and 18 DF,  p-value: 0.000193
```

Now let's create a function that will estimate values of `Price` for a given value of `PPM`:

Example9.18b

```
Ink.Price <- makeFun(ink.model)
```

We can now input a PPM and see what our least squares regression line predicts for the price:

Example9.18c

```
Ink.Price(PPM = 3)  # estimate Price when PPM is 3.0
```

```
  1 
178 
```

R can compute two kinds of confidence intervals for the response for a given value

1. A confidence interval for the *mean response* for a *given explanatory value* can be computed by adding `interval = 'confidence'`.

   Example9.18d

   ```
   Ink.Price(PPM = 3, interval = "confidence")
   ```

   ```
     fit lwr upr
   1 178 150 207
   ```

2. An interval for an *individual response* (called a prediction interval to avoid confusion with the confidence interval above) can be computed by adding `interval = 'prediction'` instead.

Example9.18e

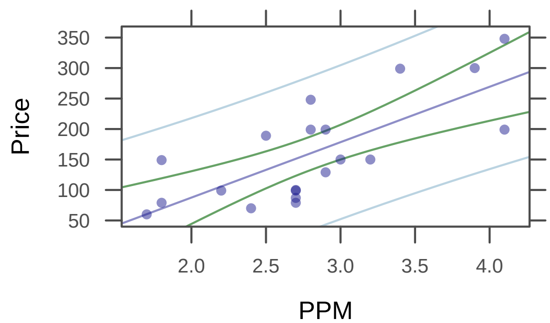
```
Ink.Price(PPM = 3, interval = "prediction")

  fit  lwr upr
1 178 52.1 305
```

Figure 9.13

The figure below shows the confidence (dotted) and prediction (dashed) intervals as bands around the regression line.

Figure9.13

```
xyplot(Price ~ PPM, data = InkjetPrinters, panel = panel.lmbands, cex = 0.6, alpha = 0.5)
```



As the graph illustrates, the intervals are narrow near the center of the data and wider near the edges of the data. It is not safe to extrapolate beyond the data (without additional information), since there is no data to let us know whether the pattern of the data extends.

10 Multiple Regression

10.1 Multiple Predictors

Multiple Regression Model

Example 10.1

```
lm(Price ~ PPM + CostBW, data = InkjetPrinters)
```

Example10.1

```

Call:
lm(formula = Price ~ PPM + CostBW, data = InkjetPrinters)

Coefficients:
(Intercept)          PPM       CostBW
       89.2         58.1        -21.1
```

```
Ink.Price <- makeFun(lm(Price ~ PPM + CostBW, data = InkjetPrinters))
Ink.Price(PPM = 3, CostBW = 3.7)
```

```
  1
185
```

Testing Individual Terms in a Model

Example 10.2

```
msummary(lm(Price ~ PPM + CostBW, data = InkjetPrinters))
```

Example10.2

```
            Estimate Std. Error t value Pr(>|t|)
(Intercept)    89.20      95.74    0.93    0.365
PPM            58.10      22.79    2.55    0.021 *
```

```
CostBW        -21.13       9.34   -2.26    0.037 *

Residual standard error: 52.8 on 17 degrees of freedom
Multiple R-squared:  0.652,Adjusted R-squared:  0.611
F-statistic: 15.9 on 2 and 17 DF,  p-value: 0.000127
```

Example 10.3

```
msummary(lm(Bodyfat ~ Weight + Height, data = BodyFat))
```

Example10.3

```
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  71.4825    16.2009    4.41  2.7e-05 ***
Weight        0.2316     0.0238    9.72  5.4e-16 ***
Height       -1.3357     0.2589   -5.16  1.3e-06 ***

Residual standard error: 5.75 on 97 degrees of freedom
Multiple R-squared:  0.494,Adjusted R-squared:  0.484
F-statistic: 47.4 on 2 and 97 DF,  p-value: 4.48e-15
```

Example 10.4

```
msummary(lm(Bodyfat ~ Weight + Height + Abdomen, data = BodyFat))
```

Example10.4

```
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -56.1329    18.1372   -3.09  0.00258 **
Weight       -0.1756     0.0472   -3.72  0.00033 ***
Height        0.1018     0.2444    0.42  0.67775
Abdomen       1.0747     0.1158    9.28  5.3e-15 ***

Residual standard error: 4.2 on 96 degrees of freedom
Multiple R-squared:  0.733,Adjusted R-squared:  0.725
F-statistic:   88 on 3 and 96 DF,  p-value: <2e-16
```

ANOVA for a Multiple Regression Model

Example 10.6

```
Mod0 <- lm(Price ~ 1, data = InkjetPrinters)
Mod1 <- lm(Price ~ PPM, data = InkjetPrinters)
Mod2 <- lm(Price ~ PPM + CostBW, data = InkjetPrinters)
anova(Mod0, Mod1)
```

Example10.6

```
Analysis of Variance Table

Model 1: Price ~ 1
Model 2: Price ~ PPM
```



```
  Res.Df    RSS Df Sum of Sq    F  Pr(>F)
1     19 136237
2     18  61697  1     74540 21.8 0.00019 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1


anova(Mod0, Mod2)


Analysis of Variance Table

Model 1: Price ~ 1
Model 2: Price ~ PPM + CostBW
  Res.Df    RSS Df Sum of Sq    F  Pr(>F)
1     19 136237
2     17  47427  2     88809 15.9 0.00013 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Example 10.7

```
Mod0 <- lm(Price ~ 1, data = InkjetPrinters)
Mod1 <- lm(Price ~ PhotoTime + CostColor, data = InkjetPrinters)
msummary(Mod1)


            Estimate Std. Error t value Pr(>|t|)
(Intercept)  371.892     66.892    5.56  3.5e-05 ***
PhotoTime      0.104      0.366    0.28   0.7804
CostColor    -18.732      5.282   -3.55   0.0025 **

Residual standard error: 67.9 on 17 degrees of freedom
Multiple R-squared:  0.426,Adjusted R-squared:  0.358
F-statistic:  6.3 on 2 and 17 DF,  p-value: 0.00899


anova(Mod0, Mod1)


Analysis of Variance Table

Model 1: Price ~ 1
Model 2: Price ~ PhotoTime + CostColor
  Res.Df    RSS Df Sum of Sq   F Pr(>F)
1     19 136237
2     17  78264  2     57973 6.3  0.009 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Example10.7

Example 10.8

```
rsquared(lm(Price ~ PPM + CostBW, data = InkjetPrinters))
```

Example10.8

```
[1] 0.652

rsquared(lm(Price ~ PhotoTime + CostColor, data = InkjetPrinters))

[1] 0.426
```

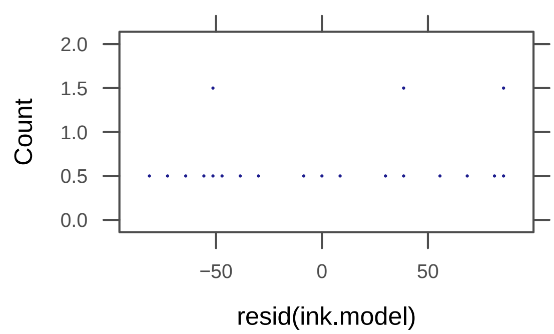
10.2 Checking Conditions for a Regression Model

Histogram/Dotplot/Boxplot of Residuals

Example 10.12

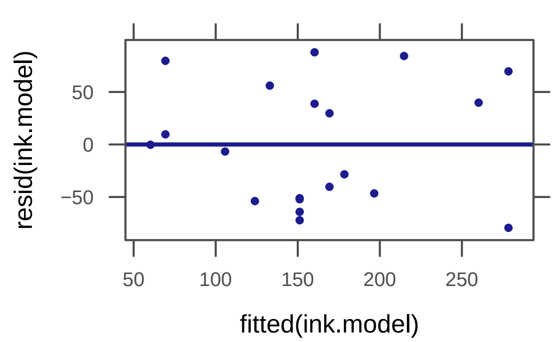
```
ink.model <- lm(Price ~ PPM, data = InkjetPrinters)
dotPlot(~resid(ink.model), cex = 0.05, nint = 40)
```

Example10.12




```
xyplot(resid(ink.model) ~ fitted(ink.model), type = c("p", "r"), cex = 0.5)
```

Example10.12b



Checking Conditions for a Multiple Regression Model

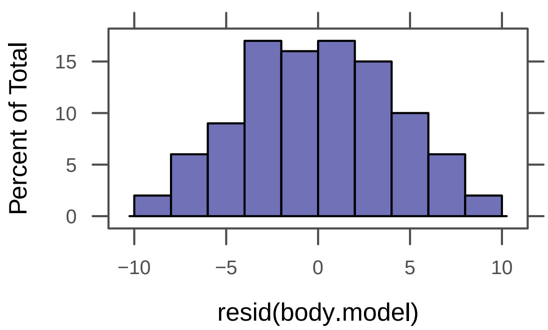
Example 10.13

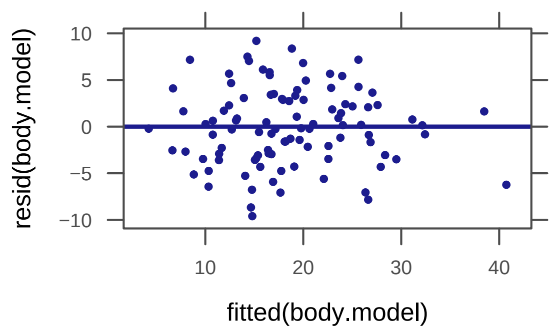
```
body.model <- lm(Bodyfat ~ Weight + Abdomen, data = BodyFat)
msummary(body.model)
```

Example10.13

```
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -48.7785     4.1810  -11.67  < 2e-16 ***
Weight       -0.1608     0.0310   -5.19  1.2e-06 ***
Abdomen       1.0441     0.0892   11.71  < 2e-16 ***

Residual standard error: 4.18 on 97 degrees of freedom
Multiple R-squared:  0.733,Adjusted R-squared:  0.727
F-statistic:  133 on 2 and 97 DF,  p-value: <2e-16
```

```
histogram(~resid(body.model), breaks = 10)
xyplot(resid(body.model) ~ fitted(body.model), type = c("p", "r"), cex = 0.5)
```





10.3 Using Multiple Regression

Choosing a Model

Example 10.14

```
msummary(lm(Bodyfat ~ Weight + Height + Abdomen + Age + Wrist, data = BodyFat))
```

Example10.14

```
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -24.9416    20.7741   -1.20   0.2329
Weight       -0.0843     0.0589   -1.43   0.1555
Height        0.0518     0.2385    0.22   0.8286
Abdomen       0.9676     0.1304    7.42  5.1e-11 ***
Age           0.0774     0.0487    1.59   0.1152
Wrist        -2.0580     0.7289   -2.82   0.0058 **

Residual standard error: 4.07 on 94 degrees of freedom
```

```
Multiple R-squared:  0.754,Adjusted R-squared:  0.741
F-statistic: 57.7 on 5 and 94 DF,  p-value: <2e-16


msummary(lm(Bodyfat ~ Weight + Abdomen + Age + Wrist, data = BodyFat))


            Estimate Std. Error t value Pr(>|t|)
(Intercept) -21.0611    10.5281   -2.00   0.0483 *
Weight       -0.0761     0.0447   -1.70   0.0923 .
Abdomen       0.9507     0.1040    9.14  1.1e-14 ***
Age           0.0785     0.0482    1.63   0.1062
Wrist        -2.0690     0.7235   -2.86   0.0052 **

Residual standard error: 4.05 on 95 degrees of freedom
Multiple R-squared:  0.754,Adjusted R-squared:  0.744
F-statistic: 72.8 on 4 and 95 DF,  p-value: <2e-16
```

Example 10.15

```
msummary(lm(Bodyfat ~ Weight + Abdomen + Wrist, data = BodyFat))


            Estimate Std. Error t value Pr(>|t|)
(Intercept) -28.7531     9.4938   -3.03  0.00316 **
Weight       -0.1236     0.0343   -3.61  0.00049 ***
Abdomen       1.0449     0.0872   11.98  < 2e-16 ***
Wrist        -1.4659     0.6272   -2.34  0.02151 *

Residual standard error: 4.09 on 96 degrees of freedom
Multiple R-squared:  0.747,Adjusted R-squared:  0.739
F-statistic: 94.6 on 3 and 96 DF,  p-value: <2e-16
```

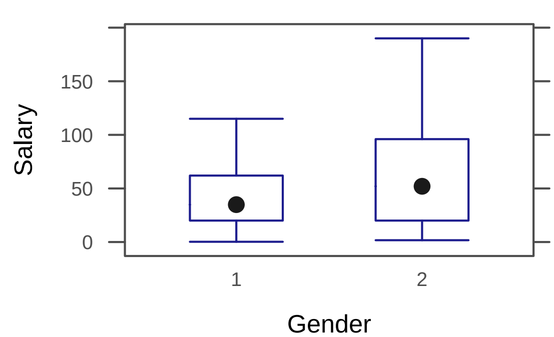
Example10.15

Categorical Variables

Figure 10.9

```
bwplot(Salary ~ Gender, horizontal = FALSE, data = SalaryGender)
```

Figure10.9



Example 10.16

```
msummary(lm(Salary ~ Gender, data = SalaryGender))
```
Example10.16

```
            Estimate Std. Error t value Pr(>|t|)
(Intercept)     41.6        5.8    7.18  1.3e-10 ***
Gender          21.8        8.2    2.66   0.0092 **

Residual standard error: 41 on 98 degrees of freedom
Multiple R-squared:  0.0672,Adjusted R-squared:  0.0577
F-statistic: 7.06 on 1 and 98 DF,  p-value: 0.00918
```

Example 10.17

```
msummary(lm(Salary ~ PhD, data = SalaryGender))
```
Example10.17

```
            Estimate Std. Error t value Pr(>|t|)
(Intercept)    33.86       4.52    7.50    3e-11 ***
PhD            47.85       7.23    6.61    2e-09 ***

Residual standard error: 35.3 on 98 degrees of freedom
Multiple R-squared:  0.309,Adjusted R-squared:  0.302
F-statistic: 43.8 on 1 and 98 DF,  p-value: 1.98e-09
```

```
confint(lm(Salary ~ PhD, data = SalaryGender))
```

```
            2.5 % 97.5 %
(Intercept)  24.9   42.8
PhD          33.5   62.2
```

Accounting for Confounding Variables

Example 10.18

```
msummary(lm(Salary ~ Gender + PhD + Age, data = SalaryGender))
```
Example10.18

```
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   -6.955     10.836   -0.64  0.52253
Gender        11.094      6.707    1.65  0.10136
PhD           36.431      7.253    5.02  2.4e-06 ***
Age            0.847      0.232    3.65  0.00042 ***

Residual standard error: 32.8 on 96 degrees of freedom
Multiple R-squared:  0.415,Adjusted R-squared:  0.397
F-statistic: 22.7 on 3 and 96 DF,  p-value: 3.31e-11
```

Association between Explanatory Variables

Example 10.19

```
msummary(lm(Final ~ Exam1 + Exam2, data = StatGrades))
```

Example10.19

```
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   30.895      7.997    3.86  0.00034 ***
Exam1          0.447      0.161    2.78  0.00773 **
Exam2          0.221      0.176    1.26  0.21509

Residual standard error: 6.38 on 47 degrees of freedom
Multiple R-squared:  0.525,Adjusted R-squared:  0.505
F-statistic:   26 on 2 and 47 DF,  p-value: 2.51e-08
```

Figure 10.10

```
xyplot(Final ~ Exam1, type = c("p", "r"), data = StatGrades)
xyplot(Final ~ Exam2, type = c("p", "r"), data = StatGrades)
xyplot(Exam2 ~ Exam1, type = c("p", "r"), data = StatGrades)
```

Figure10.10