StatPREP: Data-driven statistics

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Chapter 1

Teaching Data-driven Statistics

Description, prediction, decision

Large and growing student interest in computer science and statistics. That growing interest is not simply a matter of new subjects receiving attention or of transient employment opportunities. The interest reflects systemic changes in the technical infrastructure of life and work in the US and the world due to the emergence of ubiquitous computing. Among other things, computing has led to an explosion in the availability of data and to the ability to explore systems at a greater level of complexity and a finer level of detail. Since computers always work with a mathematical representation of the world, the ability to construct and interpret such representations (aka "modeling") is now a core part of research, commercial, industrial, medical, social, and government activities. Mathematical skills, particularly in applied math and statistics, are essential here.

1. Wrangling
2. Visualization
3. Statistical description
4. Prediction

1.1 Pocket guide to StatPREP commands

See `Essential_statprep_command.key`. Maybe put a copy of it here, or a full-page version.

Chapter 2

Data and Presentations

Here is a very general, dictionary definition of "data"

> factual information (as measurements or statistics) used as a basis for reasoning, discussion, or calculation – Merriam-Webster dictionary

Let's re-organize this definition into three components: raw facts; calculation; reasoning and discussion. These three components translate into three broad classes of data:

1. **Non-tabular data** which can be any record, be it in the form of notes from interviews, photographs, sound and signal recordings, readings from lab instruments, documents, medical records, etc. These are the "facts" in the dictionary definition.
2. **Tabular data**, a spreadsheet-like organization, which is by far the most widely used for statistical calculation.
3. **Data presentations**, that is, data formatted in a way to be more-or-less directly accessible to human perception, discussion, and reasoning. One of the most useful forms of data presentation is graphics, but there are others.

We'll be mainly concerned with the calculations by which tabular data is transformed into presentations. The tabular format for data provides a standard that makes it straightforward to perform many of the calculations, allows different software tools to interoperate, and provides the mean to combine data from different sources in creative and flexible ways.

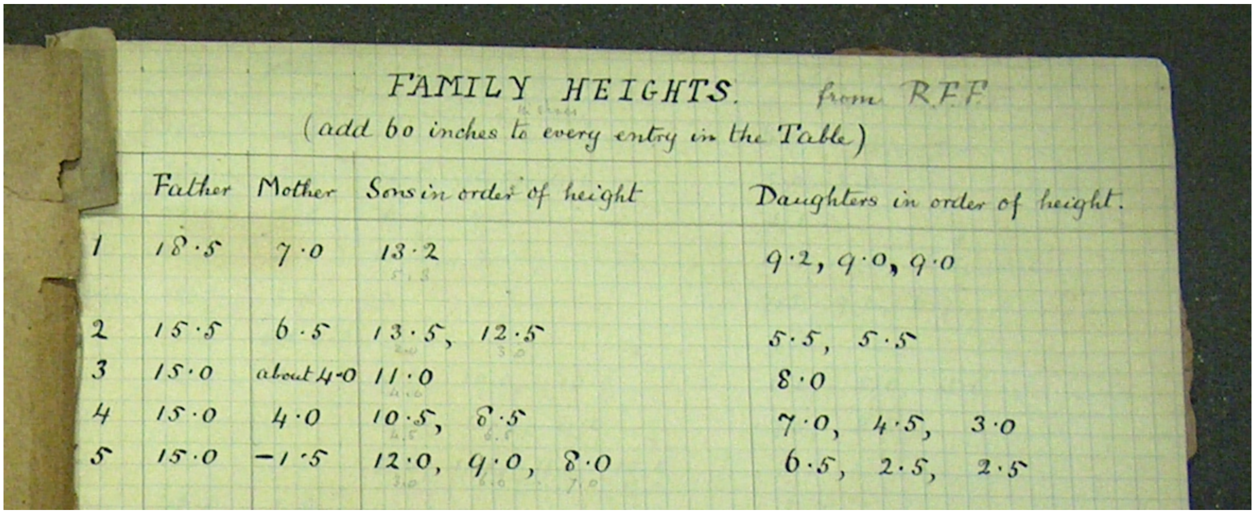
2.1 Non-tabular data

As an example of non-tabular data, consider the records from one of the earliest statistical projects, Francis Galton's investigation in the 1880s of the heritability of biological traits. Records of Galton's collection of data on the heights of adult children and their parents are contained in Galton's notebook, a portion of which is displayed in Figure 1.

Figure 1: *Part of a page from Francis Galton's notebook.*

You can imagine how Galton might have collected these data, going from house to house in London, tacking a yardstick to a wall, and having the various members of the family stand in front of the ruler to measure their heights. A yardstick isn't a suitable length to measure height from the floor to the head, so perhaps Galton positioned the yardstick at a height of 5 feet above the floor and recorded the number of extra inches above that. So recording a daughter with a height of 9.2 means that her actual height was 5 ft 9.2 inches, or 69.2 inches.

Galton's notebook is neatly organized, but it's raw data, not in the kind of tabular form used in statistical calculations.



FAMILY HEIGHTS. from RFF

(add 60 inches to every entry in the Table)

	Father	Mother	Sons in order of height	Daughters in order of height.
1	18·5	7·0	13·2	9·2, 9·0, 9·0
2	15·5	6·5	13·5, 12·5	5·5, 5·5
3	15·0	about 4·0	11·0	8·0
4	15·0	4·0	10·5, 8·5	7·0, 4·5, 3·0
5	15·0	−1·5	12·0, 9·0, 8·0	6·5, 2·5, 2·5

Figure 2.1:

2.2 Tabular data

Tabular data is organized as a rectangular array. There are two coordinates to a rectangle, and similarly there are two coordinates to tabular data:

1. Rows, also called “cases” or “units of observation.”
2. Columns, also called “variables”

Here’s one possible organization of the height measurements in Galton’s notebook rendered into a tabular form:

```
## PhantomJS not found. You can install it with webshot::install_phantomjs(). If it is installed, pleas
```

Figure 2: *Galton’s notebook observations translated to a tabular form.*

2.3 Data presentations

You can page through the Galton data table but it is very hard to draw conclusions from the table itself. *Data presentations* show data in a manner better suited for interpretation by people. The proper design of the presentation depends on its *purpose*: what aspect of the data you wish to emphasize. There can be very different presentations of the same data for different purposes.

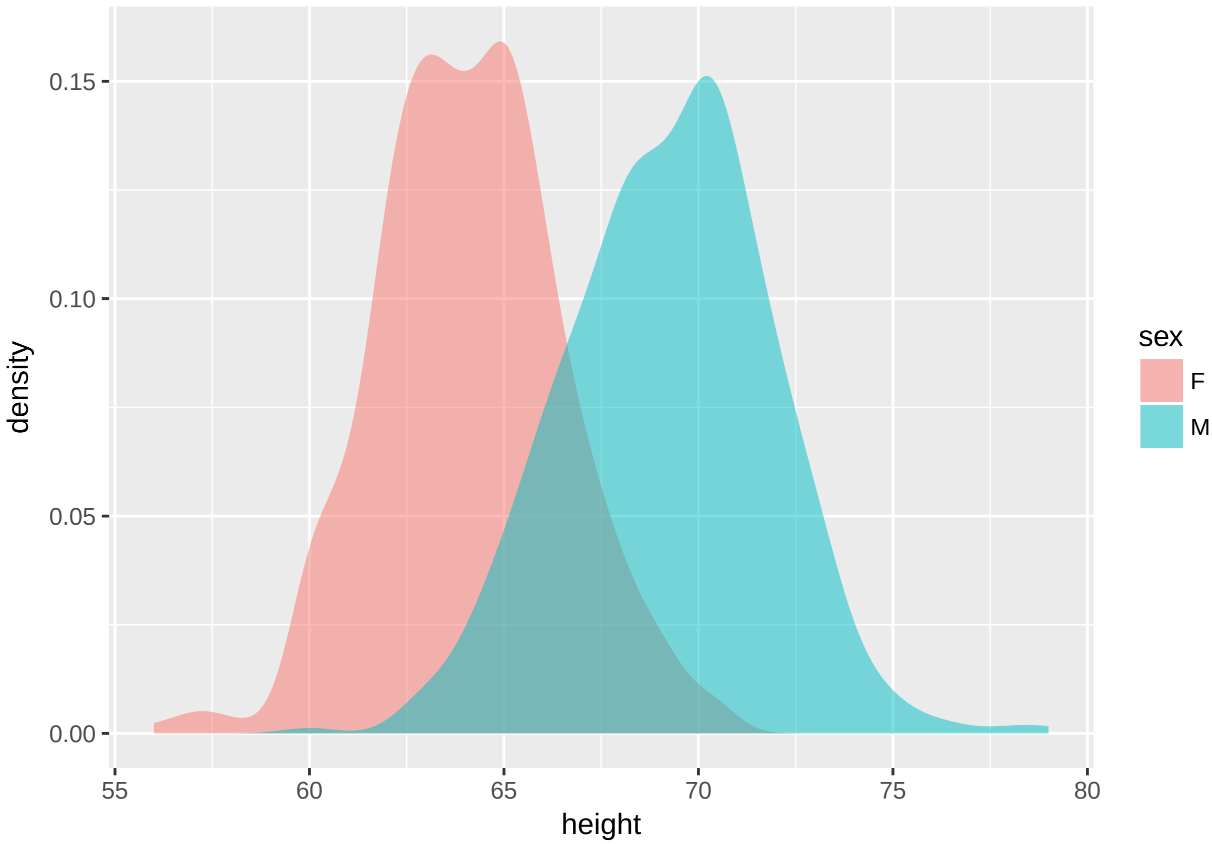


Figure 3: *A graphical presentation of Galton's data for the purpose of comparing heights by sex.*

Presentations often are numerical in form, such as this report of the means and standard deviations of the heights of the girls and boys in Galton's data.

```
##   sex        m        s
## 1   F 64.11016 2.370320
## 2   M 69.22882 2.631594
```

Or, consider this rather more technical presentation on the difference in mean heights between the sexes:

```
##    estimate statistic       p.value  conf.low conf.high
## 1 -5.118656 -30.66182 1.042115e-141 -5.446293 -4.791018
```

Much of what we teach in intro stats is about familiarizing students with a variety of forms of data presentations and how to draw conclusions from them.

Chapter 3

Data Frames

something here

3.1 Rows and columns

Data tables are organized into rows and columns.

- Each row is a *unit of observation.*
- Each column is a *variable.*

3.1.1 Unit of observation

The *unit of observation* is the kind of thing each row corresponds to in the real world. In Figure 2, the unit of observation is a child. Galton recorded heights of 898 children in his notebook so there are 898 rows in the data table.

In a properly arranged data table, every row is about the same sort of observational unit. If you have different types of observational units, they should be in different tables. For instance, you might have a table giving the address of each family. That should not be intermixed with the table where the unit of observation is a child. Instead, it would be in a separate table where the unit of observaton is a family.

3.1.2 Variables

Each column of a data table is a *variable.* The individual entries in the column are *values* of the variable. The word "variable" reflects that the values vary from row-to-row.

In the Galton table, there are six different variables:

1. An ID for the family.
2. The family's father's height. (inches)
3. The family's mother's height. (inches)
4. The sex of the child.
5. The child's height. (inches)
6. The number of children in the family.

In properly arranged tabular data, the value for any particular variable is the *same kind of thing* for every observational unit. For instance, the `father` variable is the height of the father in inches. Values of the `sex` variable are always "F" or "M".

3.2 Kinds of values

Data tables are composed of two main types of variables:

1. **Quantitative**: a number.
2. **Categorical**: a label, typically written using characters.

In the Galton data table, the `sex` variable is categorical and consists of the labels `"F"` and `"M"`. The other variables are quantitative. But note that the `family` variable, although expressed as numbers, is actually a categorical variable: all that matters about the values in `family` is that they are distinct. The order is of no particular meaning; we can't say that family 4 is in between families 2 and 5.

Quantitative variables typically represent some real-world quantity such as height, age, blood pressure, etc. Such real-world quantities often have *units*, e.g. inches, years, millimeters of mercury (mmHg).

In a properly organized data table, the units of the quantitative variable are *not* part of the value; they are implicit. A good reason for this is that in properly organized data, the a variable's unit should be the same in every row. This is part of what it means that all the values are *the same kind of thing*.

For a categorical variable, the set of possible values of the variables are called the *levels* of the variable. In the Galton `sex` variable, the set consists of `"F"` and `"M"`.

3.2.1 Missing data

In both quantitative and categorical values are sometimes *missing*. Historically, such missingness was often denoted with a special numerical value such as `-999` or with a special level such as `"missing"`. This is a poor practice, since it's easy to mistakenly treat those values as if they were non-missing. Instead, a special token is used to indicate missing data: `NA`.

3.3 The codebook

How are you to know what are the physical units of a quantitative variable or the legitimate levels of a categorical variable? This information is contained in a *codebook* associated with the data table. Codebook can take the form of an actual book, a text file, a spreadsheet, a PDF document, etc.

Many of the data tables we will be working with have codebooks available through the R `help()` system. For instance, the following command chunk will display the codebook for the `Galton` data table:

3.4 Tables and files

Data tables are typically stored as computer files. There are many formats for such files in use. One popular file format is called *CSV* (comma-separated values). The particular file format does not really matter, so long as you can find the appropriate software to read the file. Similarly, the physical location of the file does not really matter, so long as you have access to it.

3.4.1 Loading data

When using statistical software, data tables are "read in" to the software. This is often called *loading* the data table. The R statistical software has a standard representation of a data table, called a "data frame." There are several widely used implementations of data frames and so you may see referenced to `data.frame`, `tibble`, etc.

In general, a first step in using data is to load the data from a file into a data frame. Almost always, the data frame is given a name by which the table can be referred.

The following command chunk has two commands. The first reads in a small data table from a file on the internet, creating a data frame given the name `Baseball`. The second causes the data frame to be printed.

```
## # A tibble: 14 x 3
##    Team         Wins BattingAvg
##    <chr>       <int>      <dbl>
##  1 New York       97      0.285
##  2 Toronto        87      0.284
##  3 Baltimore      70      0.277
##  4 Boston         86      0.269
##  5 Tampa Bay      61      0.255
##  6 Cleveland      78      0.280
##  7 Detroit        95      0.274
##  8 Chicago        90      0.280
##  9 Kansas City    62      0.271
## 10 Minnesota      96      0.287
## 11 Los Angeles    89      0.274
## 12 Texas          80      0.278
## 13 Seattle        78      0.272
## 14 Oakland        93      0.260
```

3.4.2 R-package data

Many of the data tables we will use in these notes have already been loaded into R by instructing R to use a *library* or *package* containing the data. This is the case with the `Galton` example, which comes from the `mosaicData` package.

For the present, you don't need to be concerned with how to load R-package data. It will be done for you. But do remember that somewhere there is a computer file containing the data and that it is being loaded in to R with software appropriate for that format of file.

3.5 Textbook data

Recall the distinction between tabular data and a *presentation* constructed from the data. Textbooks are oriented to the human reader and, naturally, they tend to use forms indended for the human reader. Thus, much of the "data" in textbooks is in the form of presentations such as the cross-tabulation in Figure 1.

Figure 1: *A data presentation from the open source textbook "Intro Stat with Simulation and Randomization" ISRS.*

A stickler might argue that the table in Figure 1 can be construed as a data table, but for our purpose here, let's take a pragmatic approach to defining what constitutes the sorts of data used in data science. In particular, these notes will focus on data that contain many rows and are available in machine-readable form. Or, stated another way, we'll work with data *before* they have been aggregated into the sort of presentation seen in Figure 1.

It's easy to imagine what the disaggregated data table that underlies this presentation might look like: perhaps this one where the unit of observation is a person:

patient	accupuncture	pain	date	technician
A2322	control	yes	2014-03-15	Audrey

patient	accupuncture	pain	date	technician
A2397	treatment	yes	2014-03-17	Audrey
A3213	treatment	no	2014-03-17	Bill
B8732	treatment	no	2014-03-18	Audrey
C6920	control	yes	2014-03-18	Bill
⋮	⋮	⋮	⋮	⋮

Figure 2: *What the underlying data from Figure 1 might have looked like, presented as a data table.*

By learning the tools to work with data tables, you can easily create presentations like the cross-tabulation in Figure 1. But you also have the ability to explore other possible explanations for the variation in pain, such as the effectiveness of the technician or the day of the week.

3.6 Example

Figure 3 shows a style of presentation common in intro stats textbooks.

Figure 3: *A textbook presentation of data (Source: 2016 GAISE College Report)*

The data are almost in tabular form. Does it matter that the variables are arranged as rows rather than columns? Not in any mathematical sense, but it is a violation of the standard format for data, which means that the data will be (slightly) more difficult to work with: you'll have to transform them to the standard before performing calculations.

The textbook provides a brief description of the data, including an explanation of the meaning of the variables and their units, and an indication of the source. Since data tables are usually stored as a computer file, such descriptive information is stored in an auxilliary file called a "codebook."

Note that the variable names — `Duration (seconds)` and `Distance (meters)` — include the units. This is appropriate in a data presentation. But the data table from which this presentation originates should not include the units; that information can be placed in the codebook.

Figure 4 shows two imagined data-table forms for the honeybee data. The left form has included the units — seconds and meters. In the left table, the two variables are actually categorical, not numeric. Look closely at the printed table. Under the variable name, it includes a brief description of the type of variable. `chr` stands for "character", which is to say that the variables in the left table are being stored as character strings. The table on the right properly presents the values as numeric. (The notation `dbl` refers to a particular internal format for the numbers, a "double-precision-floating point number". You will also see, from time to time, `int`, which indicates that the number is stored in computer integer format. In your calculations, you don't need to worry about which type of storage format is used for numerical data.)

Improper form

Proper form

duration	distance
0.40 sec	200 m
0.45 sec	250 m
0.95 sec	500 m
1.30 sec	950 m

1.1 Migraine and acupuncture. A migraine is a particularly painful type of headache, which patients sometimes wish to treat with acupuncture. To determine whether acupuncture relieves migraine pain, researchers conducted a randomized controlled study where 89 females diagnosed with migraine headaches were randomly assigned to one of two groups: treatment or control. 43 patients in the treatment group received acupuncture that is specifically designed to treat migraines. 46 patients in the control group received placebo acupuncture (needle insertion at nonacupoint locations). 24 hours after patients received acupuncture, they were asked if they were pain free. Results are summarized in the contingency table below.[47]

		Pain free		
		Yes	No	Total
Group	Treatment	10	33	43
	Control	2	44	46
	Total	12	77	89

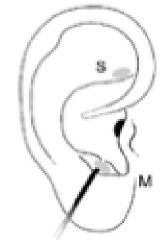


Figure from the original paper displaying the appropriate area (M) versus the inappropriate area (S) used in the treatment of migraine attacks.

Figure 3.1:

Duration (seconds)	0.40	0.45	0.95	1.30	2.00	3.10	4.10
Distance (meters)	200	250	500	950	1950	3500	4300

Figure 3.2:

In a study of honeybees, Seeley (2010) observed that scout bees do a "waggle dance" to help communicate the distance to a new nest site to bees back in the original nest. The table shows the distance to the new site (in meters) and duration of the dance (in seconds) recorded for

Figure 3.3:

duration	distance
0.40	200
0.45	250
0.95	500
1.30	950

Improper form

duration	distance
0.40 sec	200 m
0.45 sec	250 m
0.95 sec	500 m
1.30 sec	950 m

Proper form

duration	distance
0.40	200
0.45	250
0.95	500
1.30	950

Figure 4: *Two possible ways of arranging the honeybee data in a data table. The left one is awkward: the variables are categorical even though they represent physical quantities. The right table properly has quantitative variables: their values are numbers. The physical meaning for the number is described in the codebook, which here takes the form of descriptive text in the book.*

Chapter 4

Organizing stats

Much emphasis in stats courses is given to the arithmetic involved in calculating statistics such as the mean and standard deviation. This might be a valid way to introduce concepts, but in data science the computation of the statistic itself is a trivial (but essential!) part of the overall work. The difficult part is keeping track of the results so that they can be presented and so that they can play a role in additional calculations.

For instance, presenting the mean with its confidence interval involves computing these statistics: the mean, the standard deviation, n. Glueing them together into the confidence interval requires more operations: addition, subtraction, division, square roots, and (for very small n) looking up a value from the t-distribution.

Such a complicated sequence of operations makes a good example for an introductory programming course. Even the programming involved in storing a confidence interval (a pair of numbers) exercises substantial programming skills.

Keeping the whole process in mind, even when using familiar tools such as paper and pencil, imposes a substantial cognitive load and distracts from the main objective: drawing meaningful conclusions from data. Our objective here is to streamline the process so that we can think about how to use statistics rather than how to calculate statistics.