Reproducible Research: Concepts and Ideas

Reproducible Research

Roger D. Peng, Associate Professor of Biostatistics
Johns Hopkins Bloomberg School of Public Health

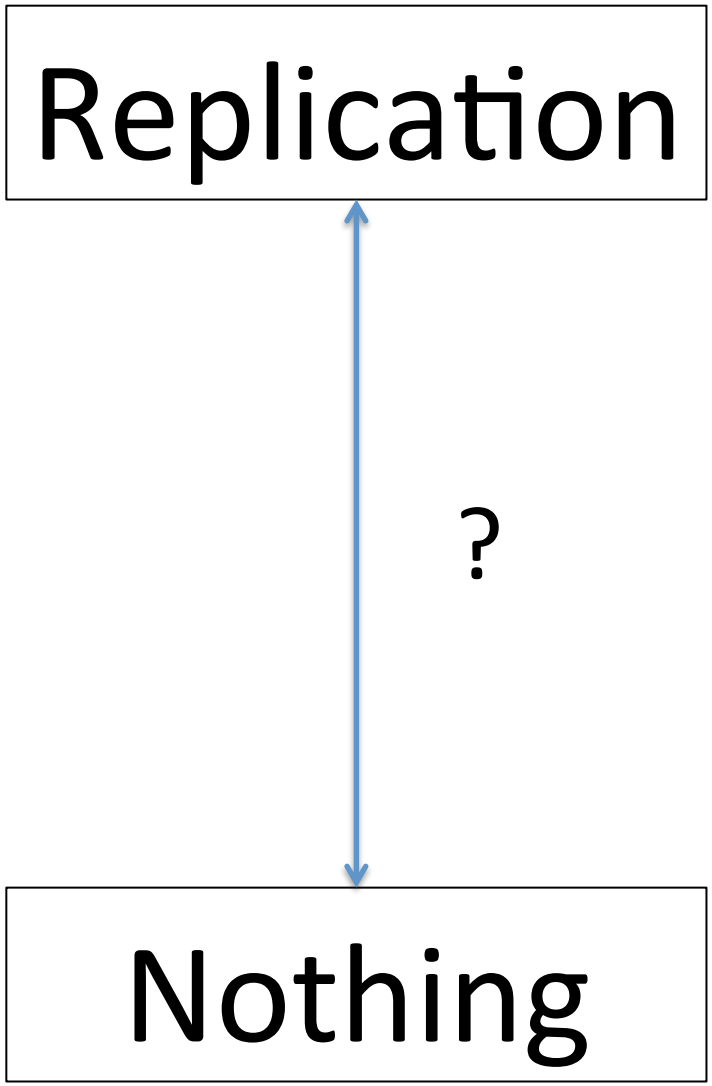
Replication

- The ultimate standard for strengthening scientific evidence is replication of findings and conducting studies with independent
  - Investigators
  - Data
  - Analytical methods
  - Laboratories
  - Instruments
- Replication is particularly important in studies that can impact broad policy or regulatory decisions

What's Wrong with Replication?

- Some studies cannot be replicated
  - No time, opportunistic
  - No money
  - Unique
- Reproducible Research: Make analytic data and code available so that others may reproduce findings

How Can We Bridge the Gap?



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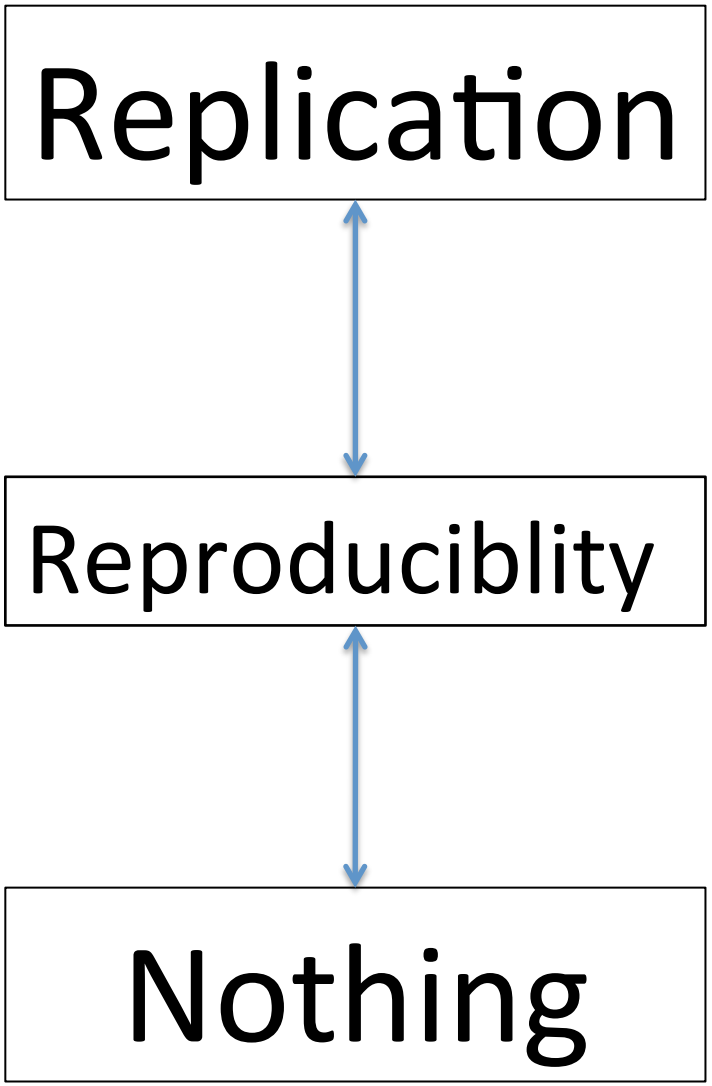


Why Do We Need Reproducible Research?

- New technologies increasing data collection throughput; data are more complex and extremely high dimensional
- Existing databases can be merged into new "megadatabases"
- Computing power is greatly increased, allowing more sophisticated analyses
- For every field "X" there is a field "Computational X"

Example: Reproducible Air Pollution and Health Research

- Estimating small (but important) health effects in the presence of much stronger signals
- Results inform substantial policy decisions, affect many stakeholders
  - EPA regulations can cost billions of dollars
- Complex statistical methods are needed and subjected to intense scrutiny

Internet-based Health and Air Pollution Surveillance System (iHAPSS)

iHAPSS
Internet-based Health & Air Pollution Surveillance System

ABOUT iHAPSS

iHAPSS is an internet system for monitoring the effects of air pollution on mortality and morbidity in the United States.

iHAPSS is funded by the Health Effects Institute (HEI). It provides published material, software and data to monitor the association between air pollution and mortality and morbidity.

iHAPSS is developed and maintained by the Department of Biostatistics at the Johns Hopkins Bloomberg School of Public Health.

PUBLICATIONS

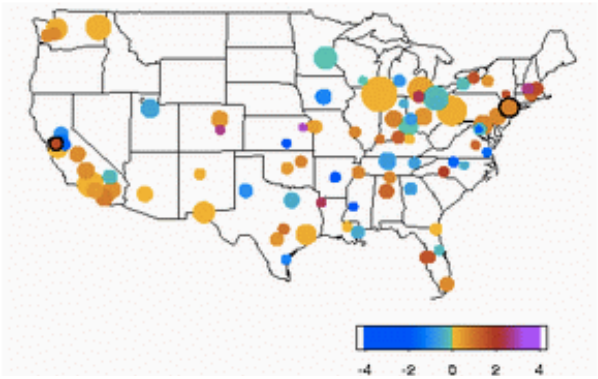
Current and previous publications and reports.

SOFTWARE

Tools for data analysis.

DATA

Air pollution and meteorological data for 108 U.S. cities 1987–2000.

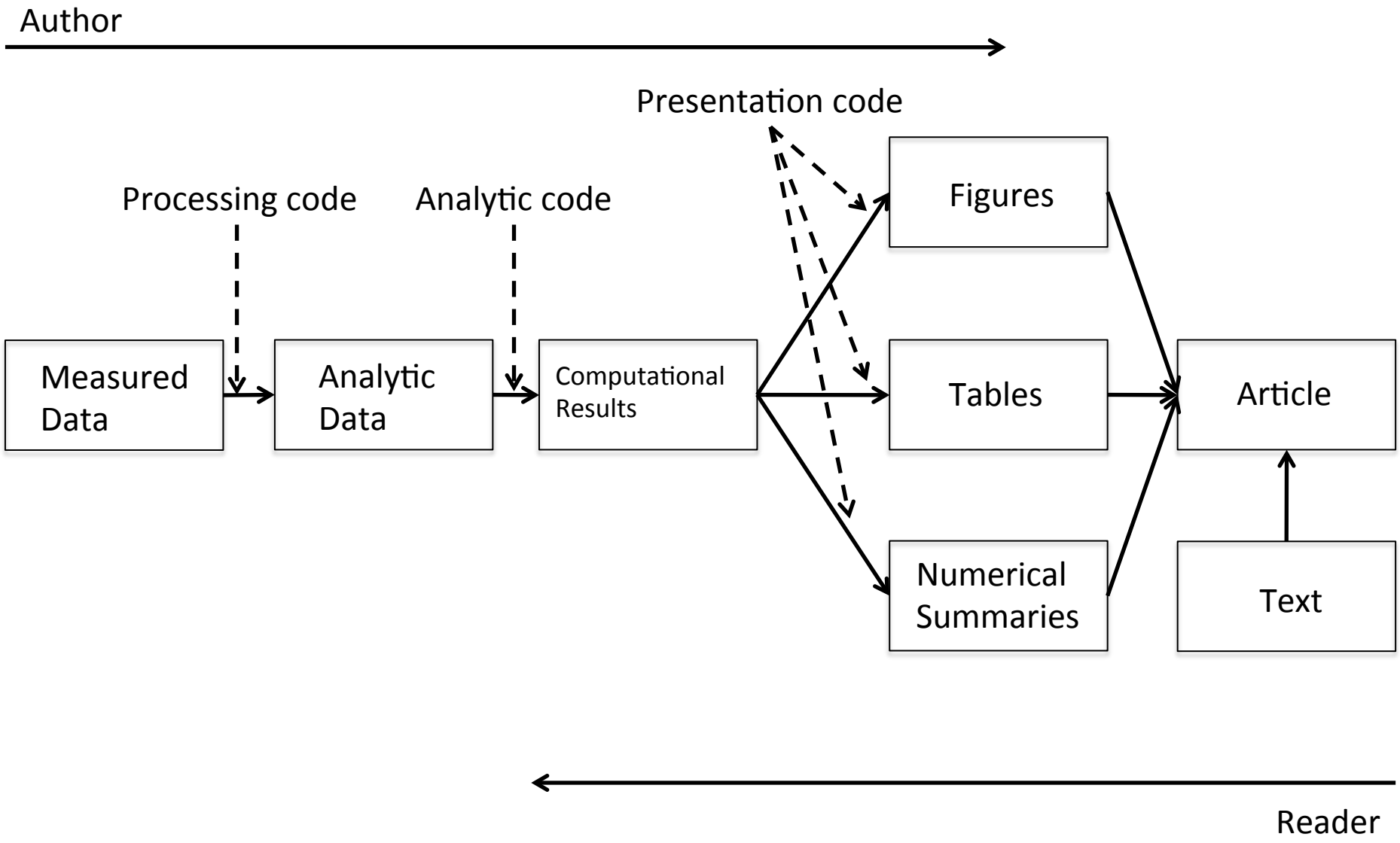


http://www.ihapss.jhsph.edu

Research Pipeline

Reader

Research Pipeline



Recent Developments in Reproducible Research

Data Replication & Reproducibility

PERSPECTIVE

Reproducible Research in Computational Science

Roger D. Peng

Computational science has led to exciting new developments, but the nature of the work has exposed limitations in our ability to evaluate published findings. Reproducibility has the potential to serve as a minimum standard for judging scientific claims when full independent replication of a study is not possible.

Recent Developments in Reproducible Research

The Duke Saga

Recent Developments in Reproducible Research

REPORT BRIEF MARCH 2012

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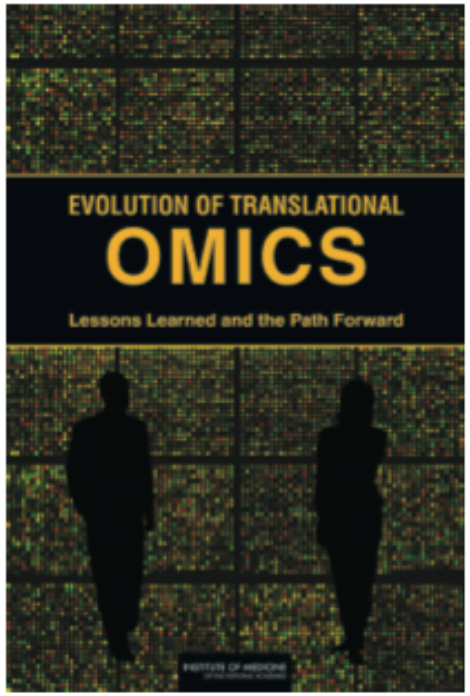
For more information visit www.iom.edu/translationalomics

Evolution of Translational Omics

Lessons Learned and the Path Forward



The IOM Report

In the Discovery/Test Validation stage of omics-based tests:

- **Data/metadata** used to develop test should be made publicly available
- The **computer code** and fully specified computational procedures used for development of the candidate omics-based test should be made sustainably available
- "Ideally, the computer code that is released will **encompass all of the steps of computational analysis**, including all data preprocessing steps, that have been described in this chapter. All aspects of the analysis need to be transparently reported."

What do We Need?

- Analytic data are available
- Analytic code are available
- Documentation of code and data
- Standard means of distribution

Who are the Players?

- Authors
  - Want to make their research reproducible
  - Want tools for RR to make their lives easier (or at least not much harder)
- Readers
  - Want to reproduce (and perhaps expand upon) interesting findings
  - Want tools for RR to make their lives easier

Challenges

- Authors must undertake considerable effort to put data/results on the web (may not have resources like a web server)
- Readers must download data/results individually and piece together which data go with which code sections, etc.
- Readers may not have the same resources as authors
- Few tools to help authors/readers (although toolbox is growing!)

In Reality…

- Authors
  - Just put stuff on the web
  - (Infamous) Journal supplementary materials
  - There are some central databases for various fields (e.g. biology, ICPSR)
- Readers
  - Just download the data and (try to) figure it out
  - Piece together the software and run it

Literate (Statistical) Programming

- An article is a stream of **text** and **code**
- Analysis code is divided into text and code "chunks"
- Each code chunk loads data and computes results
- Presentation code formats results (tables, figures, etc.)
- Article text explains what is going on
- Literate programs can be **weaved** to produce human-readable documents and **tangled** to produce machine-readable documents

Literate (Statistical) Programming

- Literate programming is a general concept that requires
  1. A documentation language (human readable)
  2. A programming language (machine readable)
- Sweave uses LaTeX and R as the documentation and programming languages
- Sweave was developed by Friedrich Leisch (member of the R Core) and is maintained by R core
- Main web site: `http://www.statistik.lmu.de/~leisch/Sweave`

Sweave Limitations

- Sweave has many limitations
- Focused primarily on LaTeX, a difficult to learn markup language used only by weirdos
- Lacks features like caching, multiple plots per chunk, mixing programming languages and many other technical items
- Not frequently updated or very actively developed

Literate (Statistical) Programming

- knitr is an alternative (more recent) package
- Brings together many features added on to Sweave to address limitations
- knitr uses R as the programming language (although others are allowed) and variety of documentation languages
  - LaTeX, Markdown, HTML
- knitr was developed by Yihui Xie (while a graduate student in statistics at Iowa State)
- See http://yihui.name/knitr/

Summary

- Reproducible research is important as a **minimum standard**, particularly for studies that are difficult to replicate
- Infrastructure is needed for **creating** and **distributing** reproducible documents, beyond what is currently available
- There is a growing number of tools for creating reproducible documents

Structure of a Data Analysis

Part 1

Roger D. Peng, Associate Professor of Biostatistics
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Steps in a data analysis

- Define the question
- Define the ideal data set
- Determine what data you can access
- Obtain the data
- Clean the data
- Exploratory data analysis
- Statistical prediction/modeling
- Interpret results
- Challenge results
- Synthesize/write up results
- Create reproducible code

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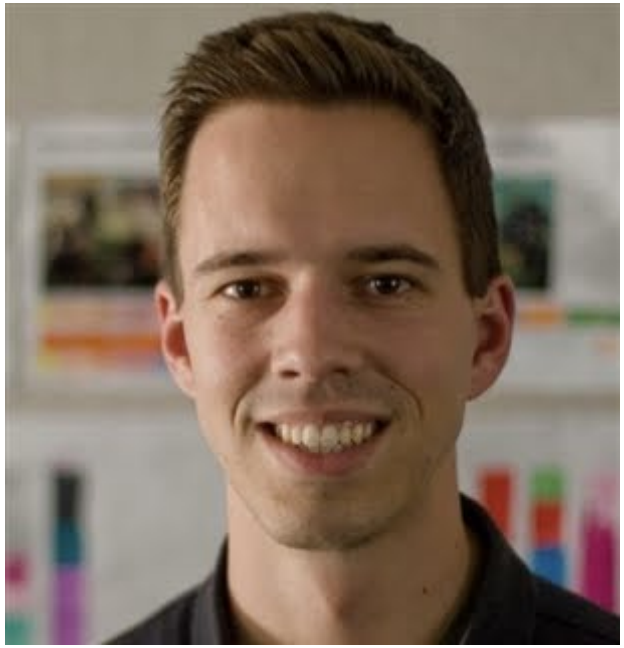
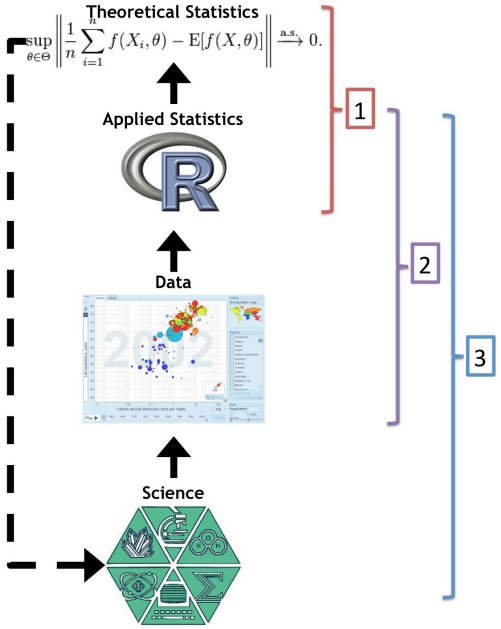
The key challenge in data analysis

"Ask yourselves, what problem have you solved, ever, that was worth solving, where you knew all of the given information in advance? Where you didn't have a surplus of information and have to filter it out, or you had insufficient information and have to go find some?"



Dan Myer, Mathematics Educator

Defining a question



1. Statistical methods development
2. Danger zone!!!
3. Proper data analysis

An example

Start with a general question

Can I automatically detect emails that are SPAM that are not?

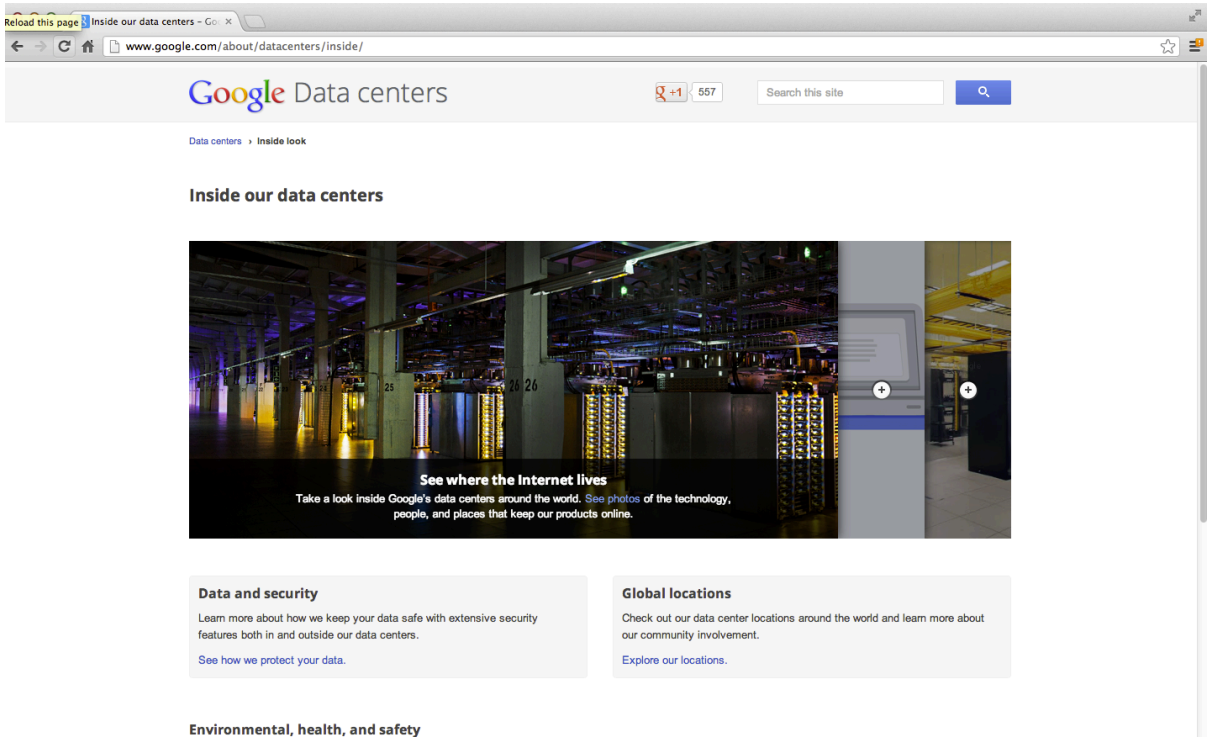
Make it concrete

Can I use quantitative characteristics of the emails to classify them as SPAM/HAM?

Define the ideal data set

- The data set may depend on your goal
  - Descriptive - a whole population
  - Exploratory - a random sample with many variables measured
  - Inferential - the right population, randomly sampled
  - Predictive - a training and test data set from the same population
  - Causal - data from a randomized study
  - Mechanistic - data about all components of the system

Our example

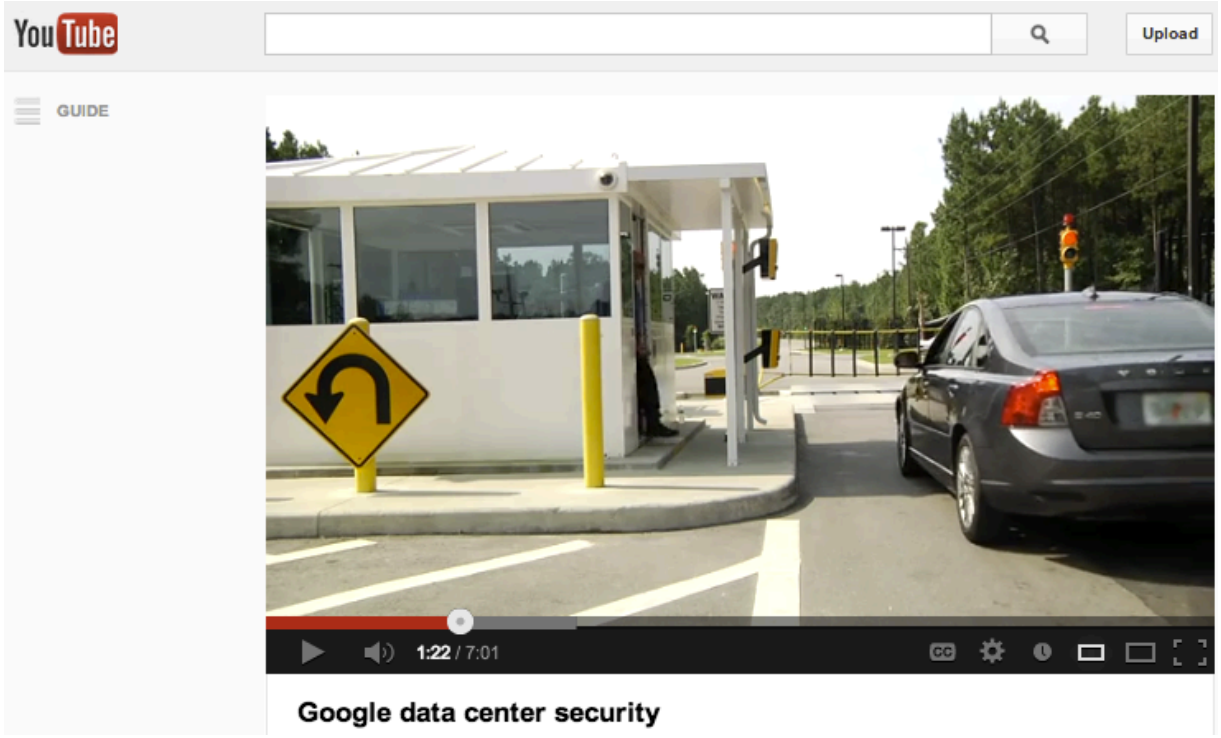


http://www.google.com/about/datacenters/inside/

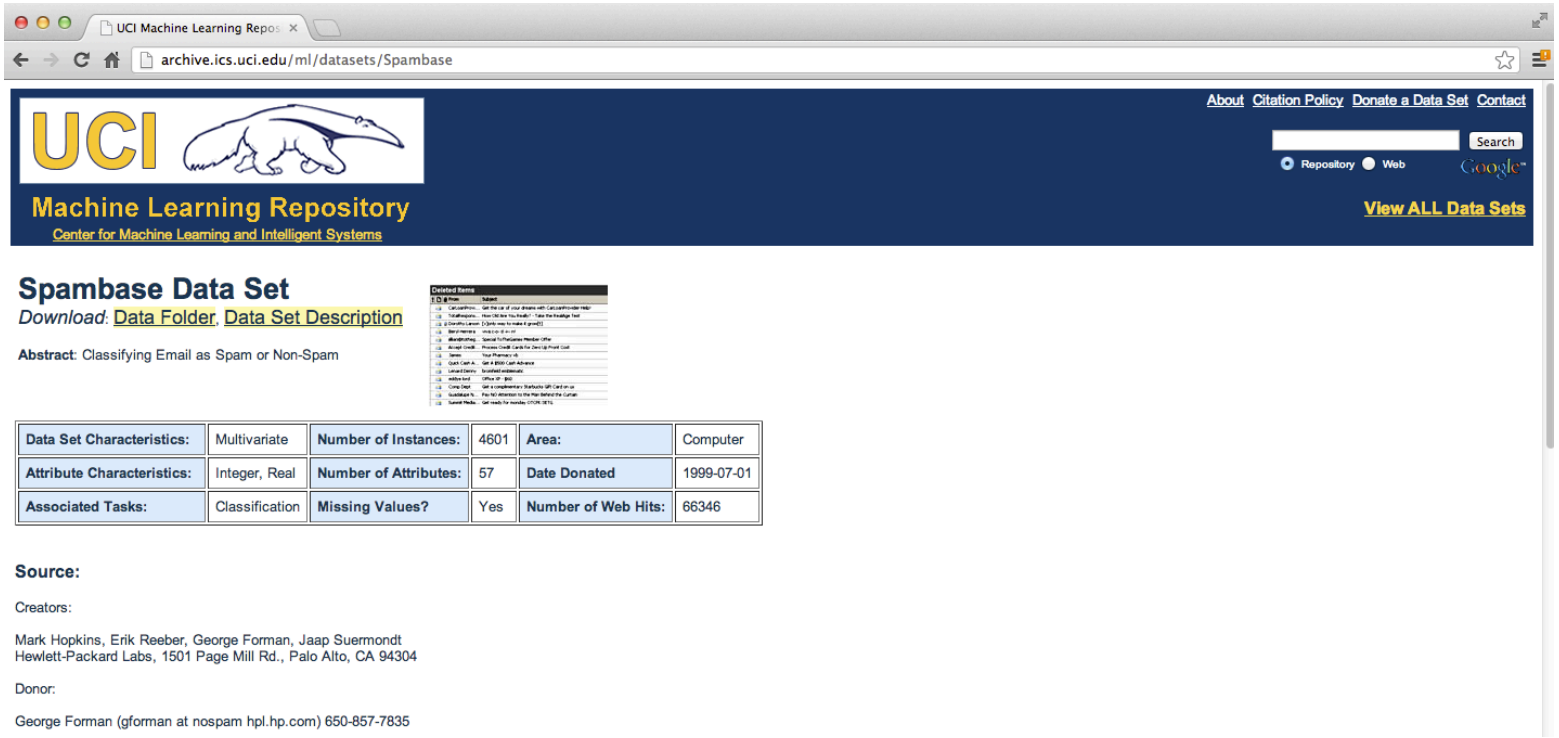
Determine what data you can access

- Sometimes you can find data free on the web
- Other times you may need to buy the data
- Be sure to respect the terms of use
- If the data don't exist, you may need to generate it yourself

Back to our example



A possible solution

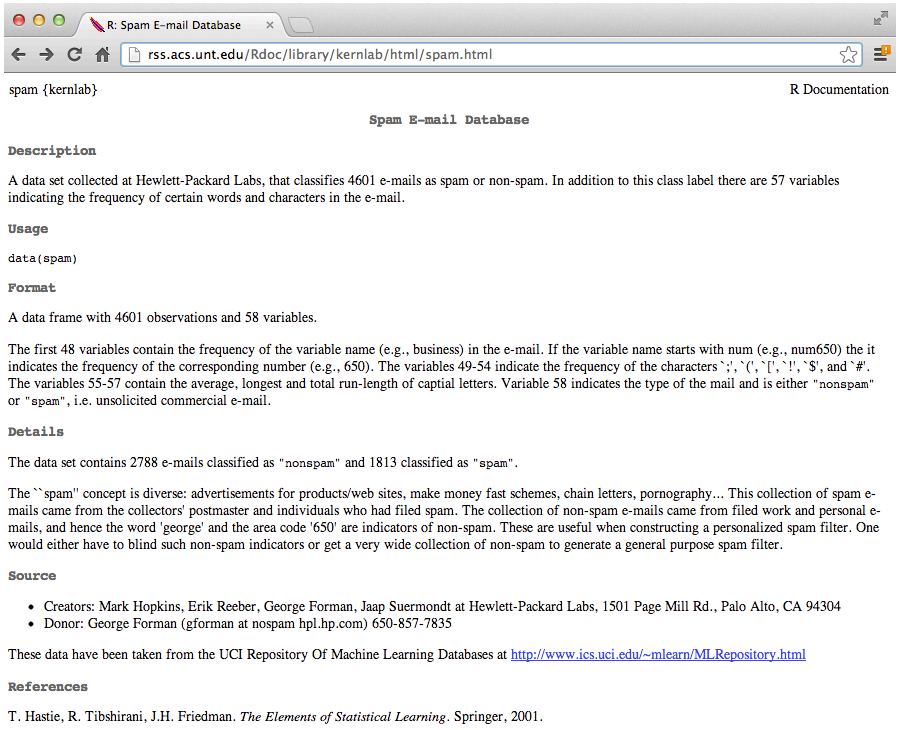


http://archive.ics.uci.edu/ml/datasets/Spambase

Obtain the data

- Try to obtain the raw data
- Be sure to reference the source
- Polite emails go a long way
- If you will load the data from an internet source, record the url and time accessed

Our data set



R: Spam E-mail Database

rss.acs.unt.edu/Rdoc/library/kernlab/html/spam.html

spam {kernlab} R Documentation

Spam E-mail Database

Description

A data set collected at Hewlett-Packard Labs, that classifies 4601 e-mails as spam or non-spam. In addition to this class label there are 57 variables indicating the frequency of certain words and characters in the e-mail.

Usage

```
data(spam)
```

Format

A data frame with 4601 observations and 58 variables.

The first 48 variables contain the frequency of the variable name (e.g., business) in the e-mail. If the variable name starts with num (e.g., num650) the it indicates the frequency of the corresponding number (e.g., 650). The variables 49-54 indicate the frequency of the characters `;', `(', `[', `!', `$', and `#'. The variables 55-57 contain the average, longest and total run-length of captial letters. Variable 58 indicates the type of the mail and is either `"nonspam"` or `"spam"`, i.e. unsolicited commercial e-mail.

Details

The data set contains 2788 e-mails classified as `"nonspam"` and 1813 classified as `"spam"`.

The ``spam'' concept is diverse: advertisements for products/web sites, make money fast schemes, chain letters, pornography... This collection of spam e-mails came from the collectors' postmaster and individuals who had filed spam. The collection of non-spam e-mails came from filed work and personal e-mails, and hence the word 'george' and the area code '650' are indicators of non-spam. These are useful when constructing a personalized spam filter. One would either have to blind such non-spam indicators or get a very wide collection of non-spam to generate a general purpose spam filter.

Source

- Creators: Mark Hopkins, Erik Reeber, George Forman, Jaap Suermondt at Hewlett-Packard Labs, 1501 Page Mill Rd., Palo Alto, CA 94304
- Donor: George Forman (gforman at nospam hpl.hp.com) 650-857-7835

These data have been taken from the UCI Repository Of Machine Learning Databases at http://www.ics.uci.edu/~mlearn/MLRepository.html

References

T. Hastie, R. Tibshirani, J.H. Friedman. *The Elements of Statistical Learning*. Springer, 2001.

http://search.r-project.org/library/kernlab/html/spam.html

Clean the data

- Raw data often needs to be processed
- If it is pre-processed, make sure you understand how
- Understand the source of the data (census, sample, convenience sample, etc.)
- May need reformating, subsampling - record these steps
- **Determine if the data are good enough** - if not, quit or change data

Our cleaned data set

```
# If it isn't installed, install the kernlab package with install.packages()
library(kernlab)
data(spam)
str(spam[, 1:5])
```

```
'data.frame':   4601 obs. of  5 variables:
 $ make   : num  0 0.21 0.06 0 0 0 0 0 0.15 0.06 ...
 $ address: num  0.64 0.28 0 0 0 0 0 0 0 0.12 ...
 $ all    : num  0.64 0.5 0.71 0 0 0 0 0 0.46 0.77 ...
 $ num3d  : num  0 0 0 0 0 0 0 0 0 0 ...
 $ our    : num  0.32 0.14 1.23 0.63 0.63 1.85 1.92 1.88 0.61 0.19 ...
```

http://search.r-project.org/library/kernlab/html/spam.html

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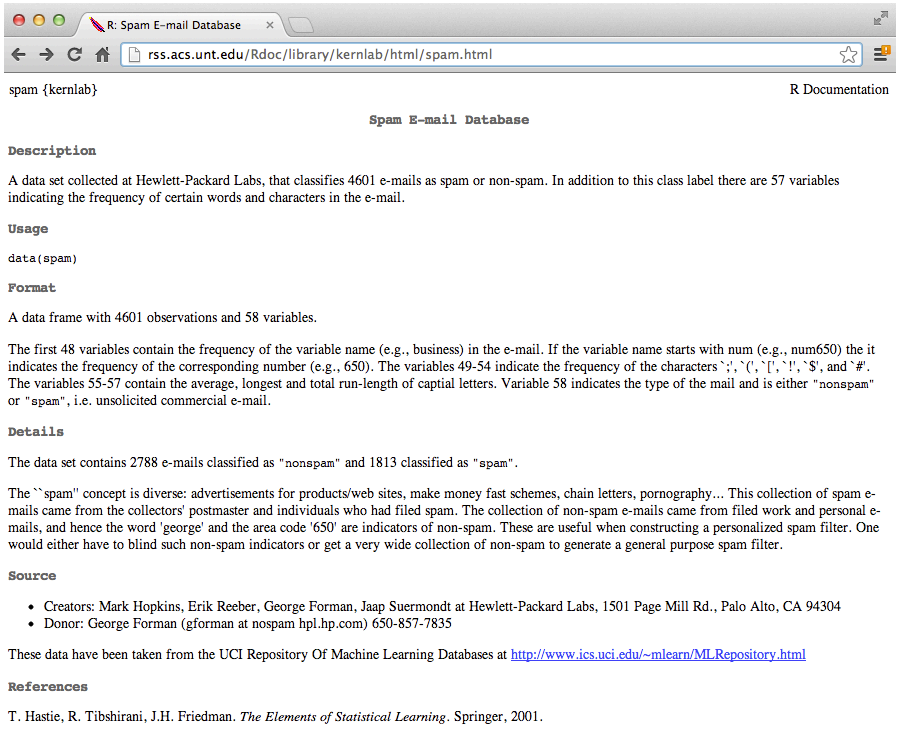

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http://search.r-project.org/library/kernlab/html/spam.html

Subsampling our data set

We need to generate a test and training set (prediction)

```
# If it isn't installed, install the kernlab package
library(kernlab)
data(spam)
# Perform the subsampling
set.seed(3435)
trainIndicator = rbinom(4601, size = 1, prob = 0.5)
table(trainIndicator)
```

```
## trainIndicator
##    0    1
## 2314 2287
```

```
trainSpam = spam[trainIndicator == 1, ]
testSpam = spam[trainIndicator == 0, ]
```

Exploratory data analysis

- Look at summaries of the data
- Check for missing data
- Create exploratory plots
- Perform exploratory analyses (e.g. clustering)

Names

```
names(trainSpam)
```

```
##  [1] "make"              "address"           "all"
##  [4] "num3d"             "our"               "over"
##  [7] "remove"            "internet"          "order"
## [10] "mail"              "receive"           "will"
## [13] "people"            "report"            "addresses"
## [16] "free"              "business"          "email"
## [19] "you"               "credit"            "your"
## [22] "font"              "num000"            "money"
## [25] "hp"                "hpl"               "george"
## [28] "num650"            "lab"               "labs"
## [31] "telnet"            "num857"            "data"
## [34] "num415"            "num85"             "technology"
## [37] "num1999"           "parts"             "pm"
## [40] "direct"            "cs"                "meeting"
## [43] "original"          "project"           "re"
## [46] "edu"               "table"             "conference"
## [49] "charSemicolon"     "charRoundbracket"  "charSquarebracket"
## [52] "charExclamation"   "charDollar"        "charHash"
## [55] "capitalAve"        "capitalLong"       "capitalTotal"
## [58] "type"
```

Head

```
head(trainSpam)
```

```
##    make address  all num3d  our over remove internet order mail receive
## 1  0.00    0.64 0.64     0 0.32 0.00   0.00        0  0.00 0.00    0.00
## 7  0.00    0.00 0.00     0 1.92 0.00   0.00        0  0.00 0.64    0.96
## 9  0.15    0.00 0.46     0 0.61 0.00   0.30        0  0.92 0.76    0.76
## 12 0.00    0.00 0.25     0 0.38 0.25   0.25        0  0.00 0.00    0.12
## 14 0.00    0.00 0.00     0 0.90 0.00   0.90        0  0.00 0.90    0.90
## 16 0.00    0.42 0.42     0 1.27 0.00   0.42        0  0.00 1.27    0.00
##    will people report addresses free business email  you credit your font
## 1  0.64   0.00      0         0 0.32        0  1.29 1.93   0.00 0.96    0
## 7  1.28   0.00      0         0 0.96        0  0.32 3.85   0.00 0.64    0
## 9  0.92   0.00      0         0 0.00        0  0.15 1.23   3.53 2.00    0
## 12 0.12   0.12      0         0 0.00        0  0.00 1.16   0.00 0.77    0
## 14 0.00   0.90      0         0 0.00        0  0.00 2.72   0.00 0.90    0
## 16 0.00   0.00      0         0 1.27        0  0.00 1.70   0.42 1.27    0
##    num000 money hp hpl george num650 lab labs telnet num857 data num415
## 1       0  0.00  0   0      0      0   0    0      0      0 0.00      0
## 7       0  0.00  0   0      0      0   0    0      0      0 0.00      0
## 9       0  0.15  0   0      0      0   0    0      0      0 0.15      0
## 12      0  0.00  0   0      0      0   0    0      0      0 0.00      0
## 14      0  0.00  0   0      0      0   0    0      0      0 0.00      0
```

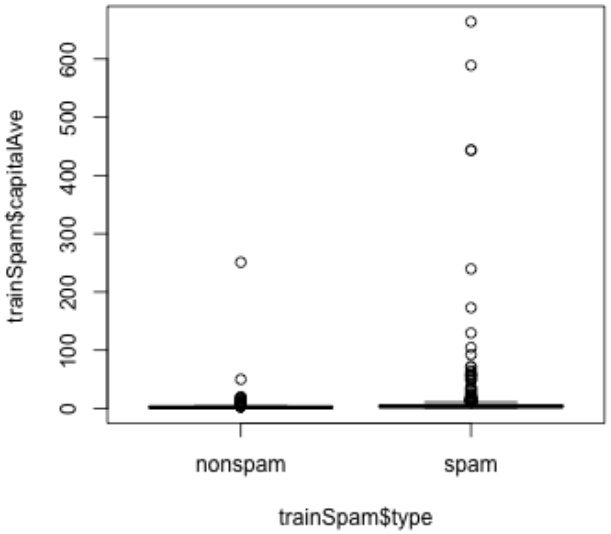
Summaries

```
table(trainSpam$type)
```

```
##
## nonspam    spam
##    1381     906
```

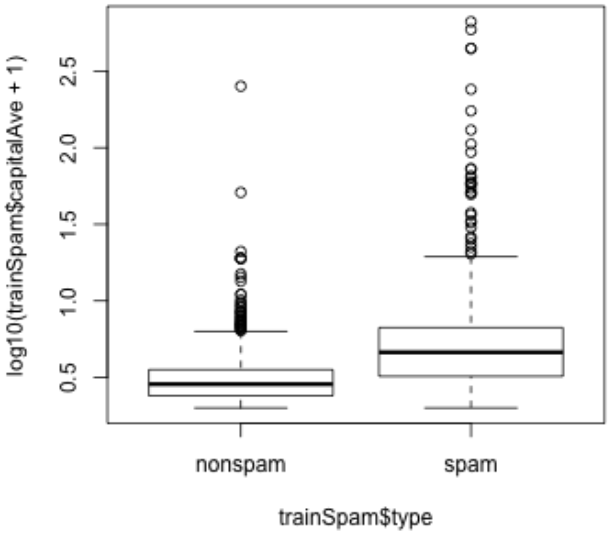
Plots

```
plot(trainSpam$capitalAve ~ trainSpam$type)
```



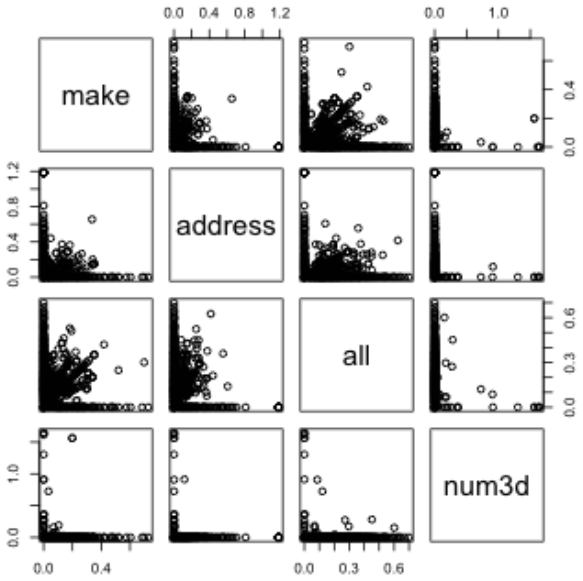
Plots

```
plot(log10(trainSpam$capitalAve + 1) ~ trainSpam$type)
```



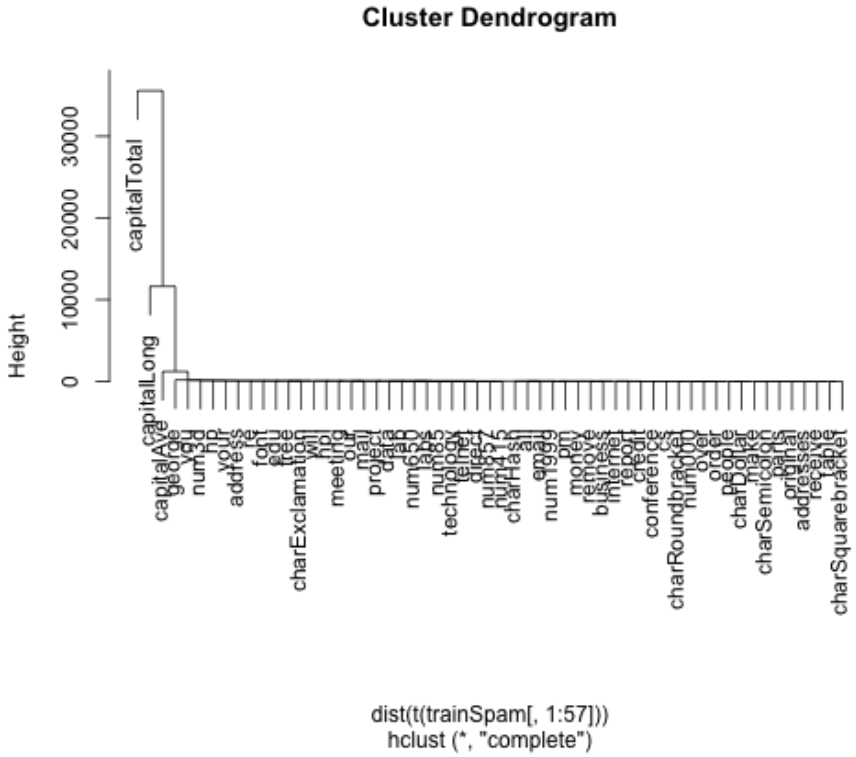
Relationships between predictors

```
plot(log10(trainSpam[, 1:4] + 1))
```



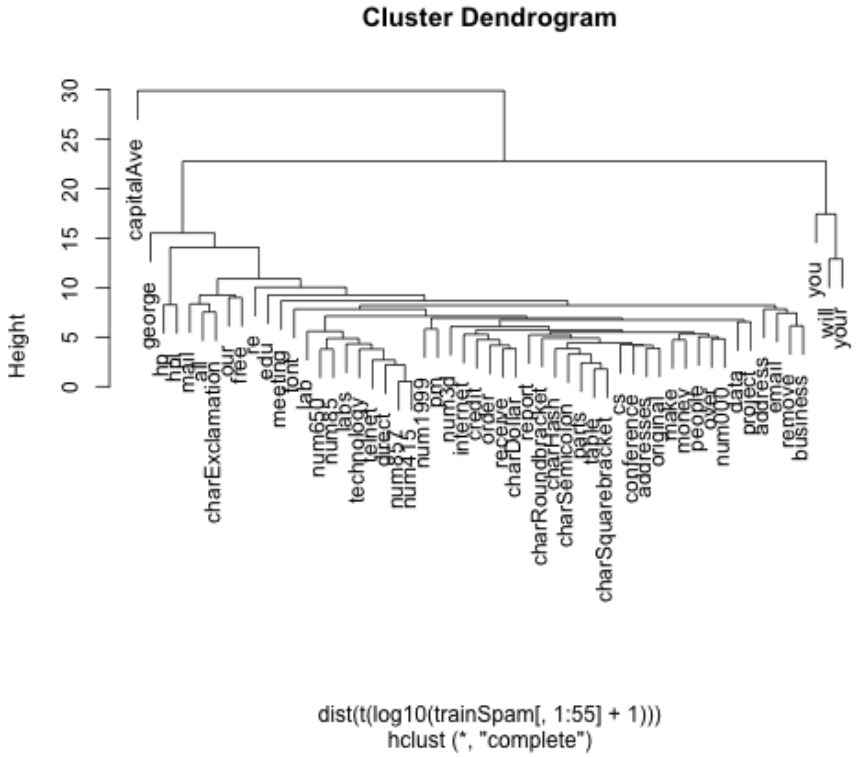
Clustering

```
hCluster = hclust(dist(t(trainSpam[, 1:57])))
plot(hCluster)
```



New clustering

```
hClusterUpdated = hclust(dist(t(log10(trainSpam[, 1:55] + 1))))
plot(hClusterUpdated)
```



Statistical prediction/modeling

- Should be informed by the results of your exploratory analysis
- Exact methods depend on the question of interest
- Transformations/processing should be accounted for when necessary
- Measures of uncertainty should be reported

Statistical prediction/modeling

```
trainSpam$numType = as.numeric(trainSpam$type) - 1
costFunction = function(x, y) sum(x != (y > 0.5))
cvError = rep(NA, 55)
library(boot)
for (i in 1:55) {
    lmFormula = reformulate(names(trainSpam)[i], response = "numType")
    glmFit = glm(lmFormula, family = "binomial", data = trainSpam)
    cvError[i] = cv.glm(trainSpam, glmFit, costFunction, 2)$delta[2]
}

## Which predictor has minimum cross-validated error?
names(trainSpam)[which.min(cvError)]


## [1] "charDollar"
```

Get a measure of uncertainty

```
## Use the best model from the group
predictionModel = glm(numType ~ charDollar, family = "binomial", data = trainSpam)

## Get predictions on the test set
predictionTest = predict(predictionModel, testSpam)
predictedSpam = rep("nonspam", dim(testSpam)[1])

## Classify as `spam' for those with prob > 0.5
predictedSpam[predictionModel$fitted > 0.5] = "spam"
```

Get a measure of uncertainty

```
## Classification table
table(predictedSpam, testSpam$type)
```

```
##
## predictedSpam nonspam spam
##       nonspam    1346  458
##       spam         61  449
```

```
## Error rate
(61 + 458)/(1346 + 458 + 61 + 449)
```

```
## [1] 0.2243
```

Interpret results

- Use the appropriate language
  - describes
  - correlates with/associated with
  - leads to/causes
  - predicts
- Give an explanation
- Interpret coefficients
- Interpret measures of uncertainty

Our example

- The fraction of charcters that are dollar signs can be used to predict if an email is Spam
- Anything with more than 6.6% dollar signs is classified as Spam
- More dollar signs always means more Spam under our prediction
- Our test set error rate was 22.4%

Challenge results

- Challenge all steps:
  - Question
  - Data source
  - Processing
  - Analysis
  - Conclusions
- Challenge measures of uncertainty
- Challenge choices of terms to include in models
- Think of potential alternative analyses

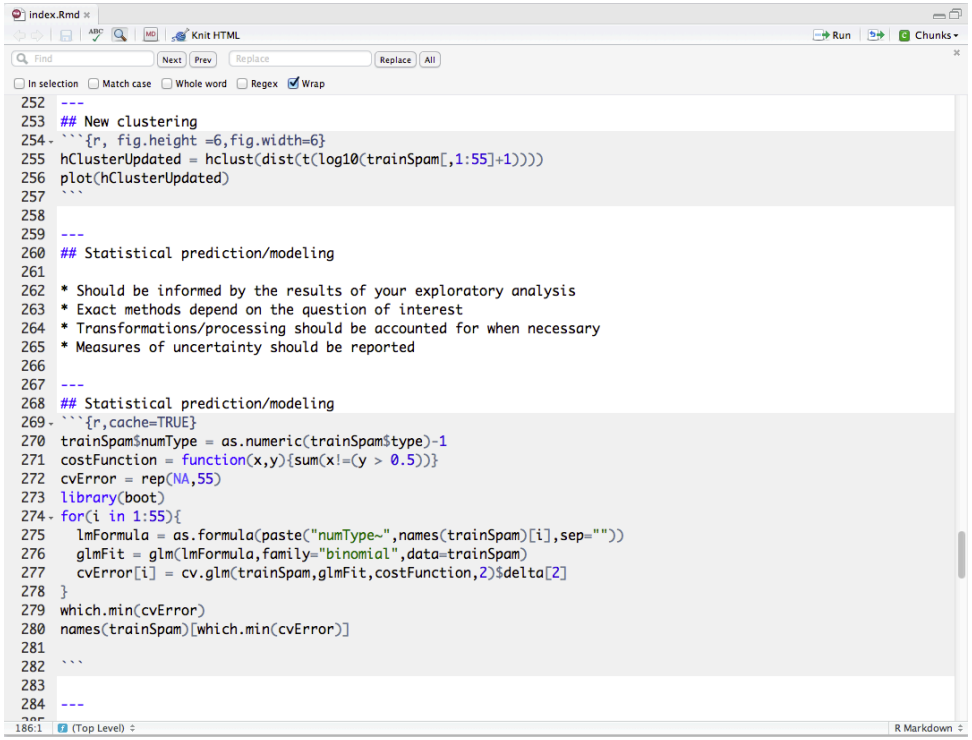
Synthesize/write-up results

- Lead with the question
- Summarize the analyses into the story
- Don't include every analysis, include it
  - If it is needed for the story
  - If it is needed to address a challenge
- Order analyses according to the story, rather than chronologically
- Include "pretty" figures that contribute to the story

In our example

- Lead with the question
  - Can I use quantitative characteristics of the emails to classify them as SPAM/HAM?
- Describe the approach
  - Collected data from UCI -> created training/test sets
  - Explored relationships
  - Choose logistic model on training set by cross validation
  - Applied to test, 78% test set accuracy
- Interpret results
  - Number of dollar signs seems reasonable, e.g. "Make money with Viagra $ $ $ $!"
- Challenge results
  - 78% isn't that great
  - I could use more variables
  - Why logistic regression?

Create reproducible code



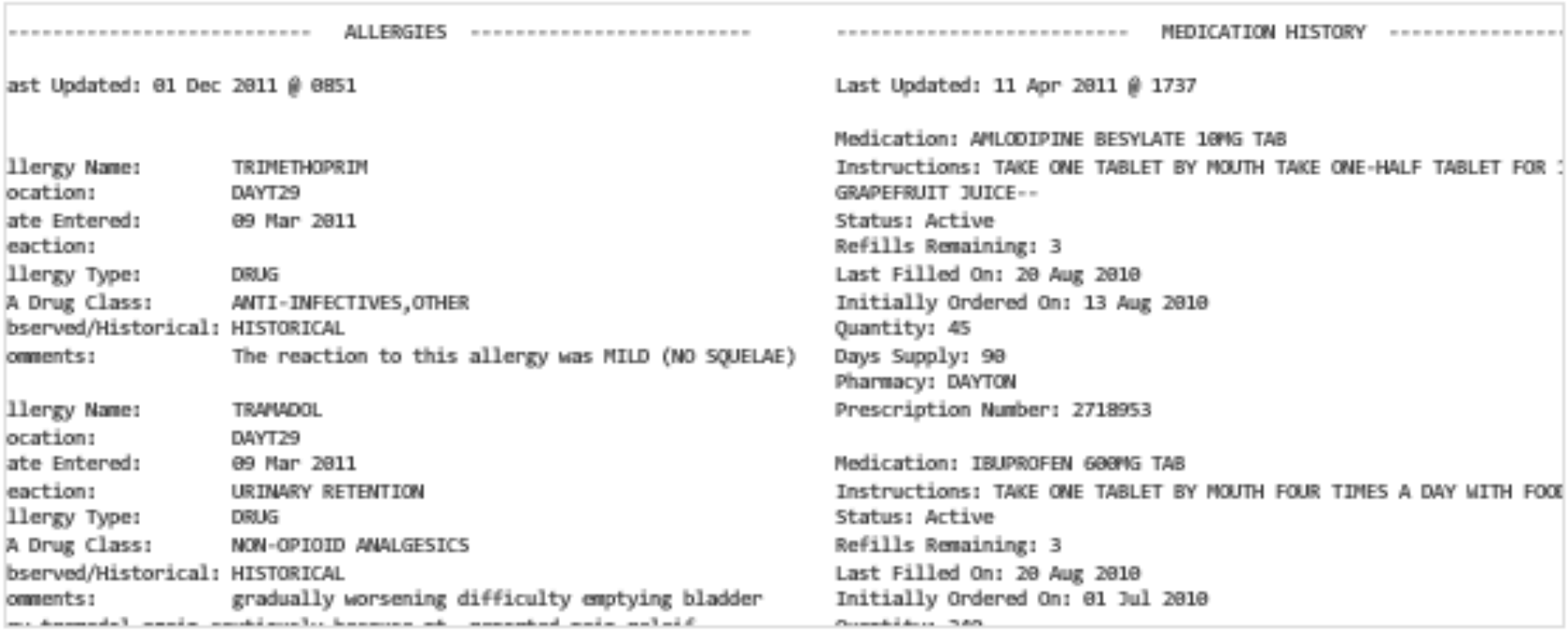
Organizing a Data Analysis

Roger D. Peng, Associate Professor of Biostatistics
Johns Hopkins Bloomberg School of Public Health

Data analysis files

- Data
  - Raw data
  - Processed data
- Figures
  - Exploratory figures
  - Final figures
- R code
  - Raw / unused scripts
  - Final scripts
  - R Markdown files
- Text
  - README files
  - Text of analysis / report

Raw Data



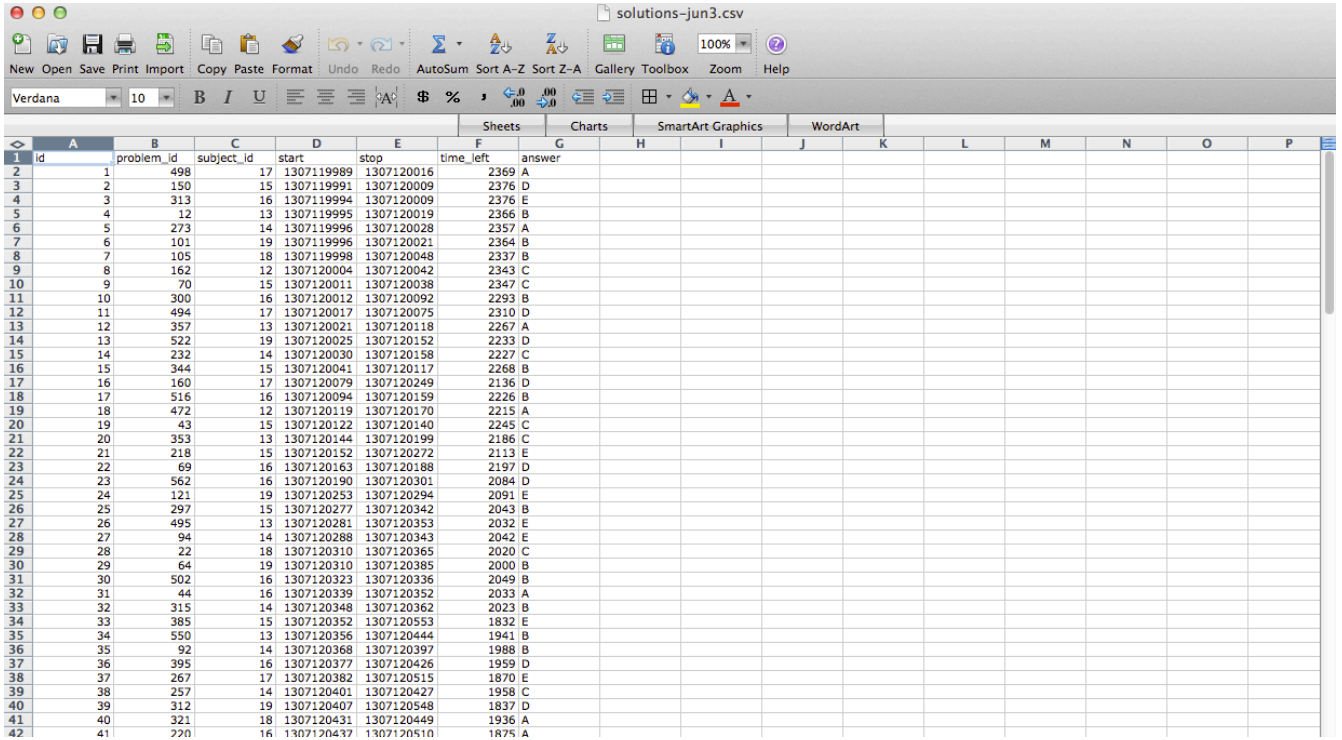
```
--------------------------   ALLERGIES   -------------------------      --------------------------   MEDICATION HISTORY   ----------------

ast Updated: 01 Dec 2011 @ 0851                                        Last Updated: 11 Apr 2011 @ 1737

                                                                       Medication: AMLODIPINE BESYLATE 10MG TAB
llergy Name:        TRIMETHOPRIM                                       Instructions: TAKE ONE TABLET BY MOUTH TAKE ONE-HALF TABLET FOR
ocation:            DAYT29                                             GRAPEFRUIT JUICE--
ate Entered:        09 Mar 2011                                        Status: Active
eaction:                                                               Refills Remaining: 3
llergy Type:        DRUG                                               Last Filled On: 20 Aug 2010
A Drug Class:       ANTI-INFECTIVES,OTHER                              Initially Ordered On: 13 Aug 2010
bserved/Historical: HISTORICAL                                         Quantity: 45
omments:            The reaction to this allergy was MILD (NO SQUELAE) Days Supply: 90
                                                                       Pharmacy: DAYTON
llergy Name:        TRAMADOL                                           Prescription Number: 2718953
ocation:            DAYT29
ate Entered:        09 Mar 2011                                        Medication: IBUPROFEN 600MG TAB
eaction:            URINARY RETENTION                                  Instructions: TAKE ONE TABLET BY MOUTH FOUR TIMES A DAY WITH FOOD
llergy Type:        DRUG                                               Status: Active
A Drug Class:       NON-OPIOID ANALGESICS                              Refills Remaining: 3
bserved/Historical: HISTORICAL                                         Last Filled On: 20 Aug 2010
omments:            gradually worsening difficulty emptying bladder    Initially Ordered On: 01 Jul 2010
```

- Should be stored in your analysis folder
- If accessed from the web, include url, description, and date accessed in README

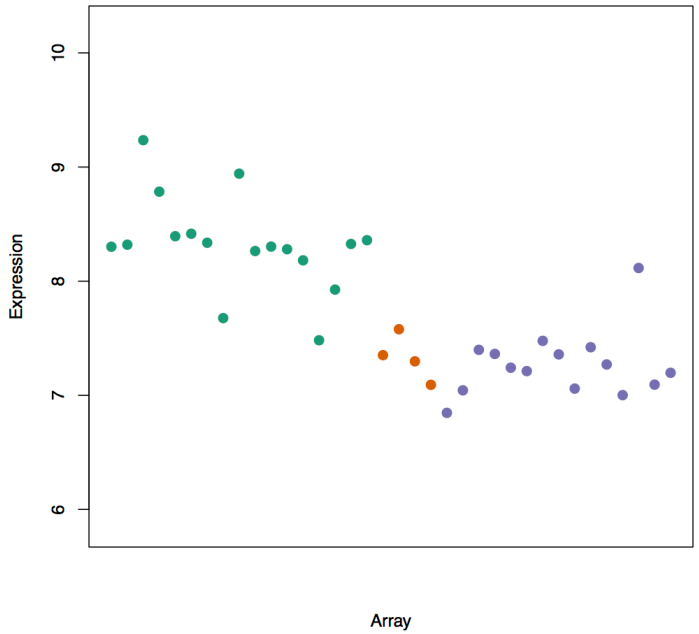
Processed data



	A	B	C	D	E	F	G
1	id	problem_id	subject_id	start	stop	time_left	answer
2	1	498	17	1307119989	1307120016	2369	A
3	2	150	15	1307119991	1307120009	2376	D
4	3	313	16	1307119994	1307120009	2376	E
5	4	12	13	1307119995	1307120019	2366	B
6	5	273	14	1307119996	1307120028	2357	A
7	6	101	19	1307119996	1307120021	2364	B
8	7	105	18	1307119998	1307120048	2337	B
9	8	162	12	1307120004	1307120042	2343	C
10	9	70	15	1307120011	1307120038	2347	C
11	10	300	16	1307120012	1307120092	2293	B
12	11	494	17	1307120017	1307120075	2310	D
13	12	357	13	1307120021	1307120118	2267	A
14	13	522	19	1307120025	1307120152	2233	D
15	14	232	14	1307120030	1307120158	2227	C
16	15	344	15	1307120041	1307120117	2268	B
17	16	160	17	1307120079	1307120249	2136	D
18	17	516	16	1307120094	1307120159	2226	B
19	18	472	12	1307120119	1307120170	2215	A
20	19	43	15	1307120122	1307120140	2245	C
21	20	353	13	1307120144	1307120199	2186	C
22	21	218	15	1307120152	1307120272	2113	E
23	22	69	16	1307120163	1307120188	2197	D
24	23	562	16	1307120190	1307120301	2084	D
25	24	121	19	1307120253	1307120294	2091	E
26	25	297	15	1307120277	1307120342	2043	B
27	26	495	13	1307120281	1307120353	2032	E
28	27	94	14	1307120288	1307120343	2042	E
29	28	22	18	1307120310	1307120365	2020	C
30	29	64	19	1307120310	1307120385	2000	B
31	30	502	16	1307120323	1307120336	2049	B
32	31	44	16	1307120339	1307120352	2033	A
33	32	315	14	1307120348	1307120362	2023	B
34	33	385	15	1307120352	1307120553	1832	E
35	34	550	13	1307120356	1307120444	1941	B
36	35	92	14	1307120368	1307120397	1988	B
37	36	395	16	1307120377	1307120426	1959	D
38	37	267	17	1307120382	1307120515	1870	E
39	38	257	14	1307120401	1307120427	1958	C
40	39	312	19	1307120407	1307120548	1837	D
41	40	321	18	1307120431	1307120449	1936	A
42	41	220	16	1307120437	1307120510	1875	A

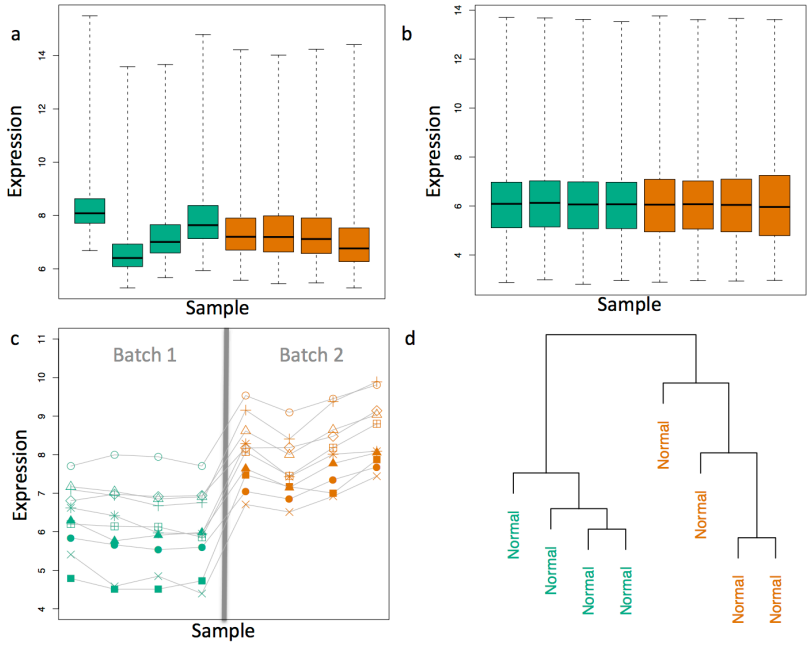
- Processed data should be named so it is easy to see which script generated the data.
- The processing script - processed data mapping should occur in the README
- Processed data should be tidy

Exploratory figures



- Figures made during the course of your analysis, not necessarily part of your final report.
- They do not need to be "pretty"

Final Figures



- Usually a small subset of the original figures
- Axes/colors set to make the figure clear
- Possibly multiple panels

Raw scripts

```r
source("regmodel.R")

dp <- ddm[, c("group", "pm25_0", "pm25_1", "symfree0", "symfree1")]
dp$p_id <- row.names(dp)

fitx0 <- lm(pm25_1 ~ pm25_0 + age + no2_0 + pm10_0, data = subset(ddm, group == 0
fitx1 <- lm(pm25_1 ~ ns(pm25_0, 2) + age + no2_0 + pm10_0, data = subset(ddm, gro

fity0 <- glm(cbind(symfree1, 14-symfree1) ~ symfree0 + age + factor(gender), data
fity1 <- glm(cbind(symfree1, 14-symfree1) ~ symfree0 + age + factor(gender), data

y10 <- predict(fity0, subset(ddm, group == 1), type = "response") * 14
y01 <- predict(fity1, subset(ddm, group == 0), type = "response") * 14
p10 <- predict(fitx0, subset(ddm, group == 1))
p01 <- predict(fitx1, subset(ddm, group == 0))

yy <- data.frame(p_id = as.integer(c(names(y10), names(y01))),
                 symfree00 = c(y10, y01))
pp <- data.frame(p_id = as.integer(c(names(p10), names(p01))),
                 pm25_00 = c(p10, p01))

m <- merge(dp, yy, by = "p_id")
mm <- merge(m, pp, by = "p_id")
```

- May be less commented (but comments help you!)
- May be multiple versions
- May include analyses that are later discarded

Final scripts

```
49  ###############################################################
50  ## Main 'pgibbs()' function
51
52
53  pgibbs <- function(gibbsState,
54                     maxit = 80000,
55                     verbose = TRUE,
56                     dbfile = "statepgibbs",
57                     deleteCache = FALSE,
58                     singleAgeCat = TRUE,
59                     sigmaE = NULL,
60                     delta = NULL) {
61          library(MASS)
62
63          ## Setup database of results
64          if(file.exists(dbfile)) {
65                  if(deleteCache) {
66                          message("removing existing cache file")
67                          file.remove(dbfile)
68                  }
69                  else
70                          stop(sprintf("cache file '%s' already exists", dbfile))
71          }
```

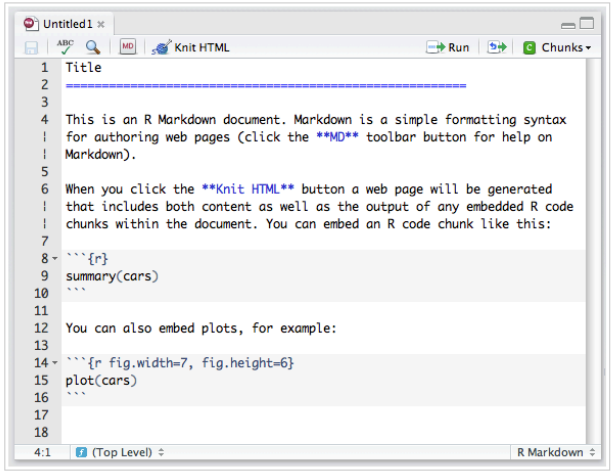
- Clearly commented
  - Small comments liberally - what, when, why, how
  - Bigger commented blocks for whole sections
- Include processing details
- Only analyses that appear in the final write-up

R markdown files

R Markdown Documents

To work with R Markdown (.Rmd) files in RStudio you first need to ensure that the knitr package (version 0.5 or later) in installed.

To create a new R Markdown file, go to **File | New |** and select **R Markdown**. A new file is create with a default template to get you oriented:

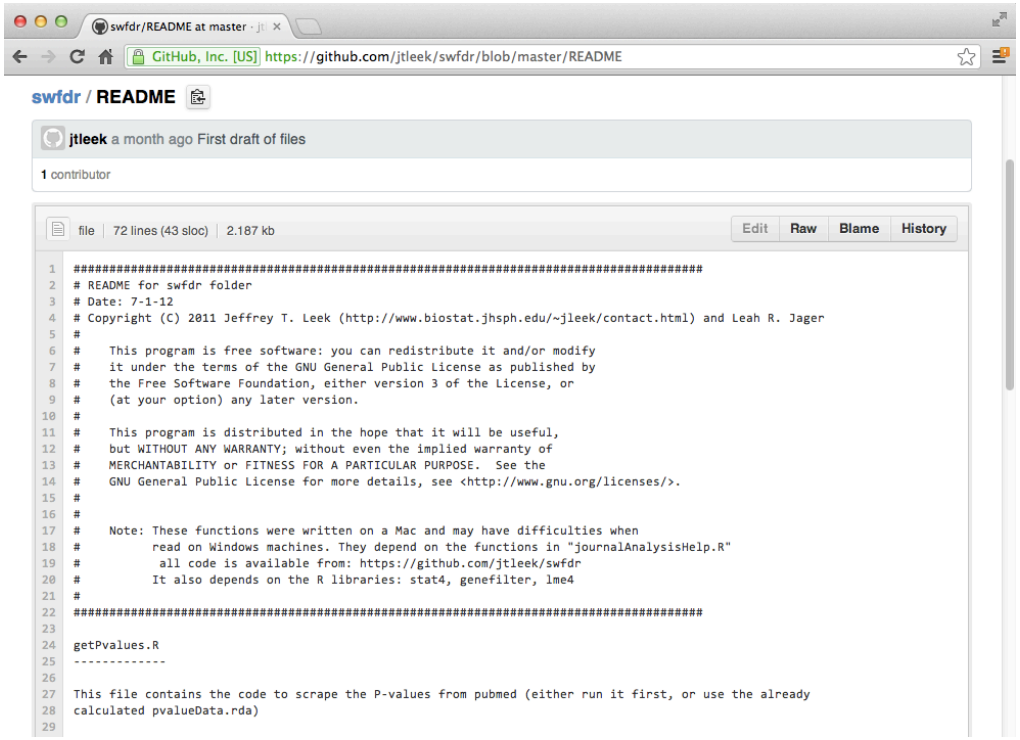


Note that the toolbar provides some useful tools for working with R Markdown:

- **Quick Reference** — Click the **MD** toolbar button to open a quick reference guide for Markdown.
- **Knit HTML** — Click to knit the current document to HTML, see the **Knitting to HTML** section below for more details.
- **Run** — Run the current line or selection of lines in the console. This allows running R code inside a code chunk similar to a normal R source file.
- **Chunks** — The chunks menu provides assistance with inserting, running, and chunk navigation. See the **Chunk Menu and Options** section below for more details.

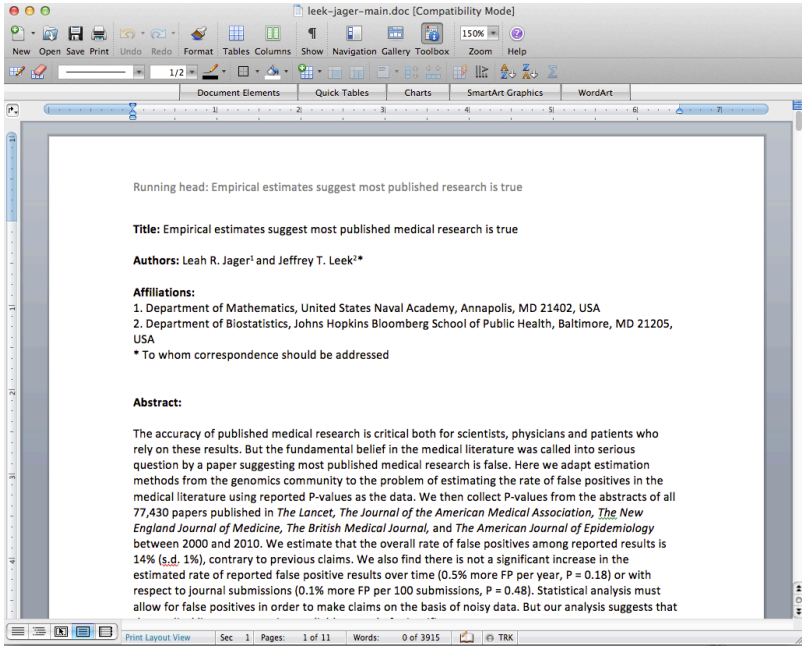
- R markdown files can be used to generate reproducible reports
- Text and R code are integrated
- Very easy to create in Rstudio

Readme files



- Not necessary if you use R markdown
- Should contain step-by-step instructions for analysis
- Here is an example https://github.com/jtleek/swfdr/blob/master/README

Text of the document



- It should include a title, introduction (motivation), methods (statistics you used), results (including measures of uncertainty), and conclusions (including potential problems)
- It should tell a story
- *It should not include every analysis you performed*
- References should be included for statistical methods

Further resources

- Information about a non-reproducible study that led to cancer patients being mistreated: The Duke Saga Starter Set
- Reproducible research and Biostatistics
- Managing a statistical analysis project guidelines and best practices
- Project template - a pre-organized set of files for data analysis