

# Steps toward reproducible research

Karl Broman

Biostatistics & Medical Informatics, UW–Madison

`kbroman.org`

`github.com/kbroman`

`@kwbroman`

Course web: [kbroman.org/AdvData](https://kbroman.org/AdvData)



Karl -- this is very interesting,  
however you used an old version of  
the data (n=143 rather than n=226).

I'm really sorry you did all that  
work on the incomplete dataset.

Bruce

The results in Table 1 don't seem to correspond to those in Figure 2.

Where did we get this data file?

Why did I omit those samples?

Which image goes with which experiment?

How did I make that figure?

In what order do I run these scripts?



“Your script is now giving an error.”

“The attached is similar to the code we used.”

Reproducible

vs.

Replicable

Reproducible

vs.

Correct

[kbroman.org/steps2rr](http://kbroman.org/steps2rr)

A little bit reproducible  
is better than not reproducible.

A little bit open  
is better than not open.

Strive to make each project  
a bit better organized than the last.

# Organize your project

File organization and naming  
are powerful weapons against chaos.

— Jenny Bryan

# Organize your project

Your closest collaborator is you six months ago,  
but you don't reply to emails.

(paraphrasing **Mark Holder**)



# Organize your project

Have sympathy for your future self.

# Organize your project

RawData/  
DerivedData/

Python/  
R/  
Ruby/

Analysis/  
Figures/

Notes/  
Refs/

ReadMe.txt  
ToDo.txt  
Makefile

# Chaos

AimeeNullSims/	Deuterium/	Ping/
AimeeResults/	ExtractData4Gary/	Ping2/
AnnotationFiles/	FromAimee/	Ping3/
Brian/	GoldStandard/	Ping4/
Chr6_extrageno/	HumanGWAS/	Play/
Chr6_segdis/	Insulin/	Prdm9/
ChrisPlaisier/	Int2_for_Mark/	RBM_PlasmaUrine_2012-03-08/
Code4Aimee/	Islet_2011-05/	Slco1a6/
CompAnnot/	MappingProbes/	StudyLineupMethods/
CondScans/	MultiProbes/	kidney_chr6.R
D20_2012-02-14/	NewMap/	pck2_suc1a2.R
D20_cellcycle/	Notes/	penalties.txt
D20corr/	NullSims/	transeQTL4Lude/
Data4Aimee/	NullSims_2009-09-10/	
Data4Tram/	PepIns_2012-02-09/	

# Choose good names for things

betw_tissue_corr.R	expr_scatterplot_allprobes.R	gve_similarity_alltissues.R
coatcolor_lod.R	expr_scatterplots_dup.R	gve_similarity.R
colors.R	expr_scatterplots_mix.R	gve_supp.R
cover_fig.R	expr_scatterplots_swap.R	insulin_lod.R
eqtl_counts_10.R	expr_swaps.R	local_eqtl_locations.R
eqtl_counts.R	func.R	my_plot_map.R
eve_hist.R	genotype_plates.R	my_plot_scanone.R
eve_scheme.R	gve_hist.R	sex_vs_X.R
eve_similarity.R	gve_new.R	xchr_fig.R
eve_similarity_supp.R	gve.R	xist_and_y.R
expr_corr_dup.R	gve_scheme.R	
expr_corr_mix.R	gve_similarity_2ndbest.R	

# Choose good names for things

fig1.png

fig10.png

fig2.png

fig3.png

fig4.png

fig5.png

fig6.png

fig7.png

fig8.png

fig9.png

# Choose good names for things

- ▶ Machine readable
  - No spaces
  - No special characters except `_` and `-`
- ▶ Human readable
  - Explain the contents
- ▶ Consistent
  - Name similar files in a similar way
- ▶ Make use of computer's sorting
  - pad numbers with 0's (e.g., 01, 02, ...)
  - start with general grouping, then more specific
  - dates like 2019-05-14


## PUBLIC SERVICE ANNOUNCEMENT:

OUR DIFFERENT WAYS OF WRITING DATES AS NUMBERS CAN LEAD TO ONLINE CONFUSION. THAT'S WHY IN 1988 ISO SET A GLOBAL STANDARD NUMERIC DATE FORMAT.

THIS IS *THE* CORRECT WAY TO WRITE NUMERIC DATES:

2013-02-27

THE FOLLOWING FORMATS ARE THEREFORE DISCOURAGED:

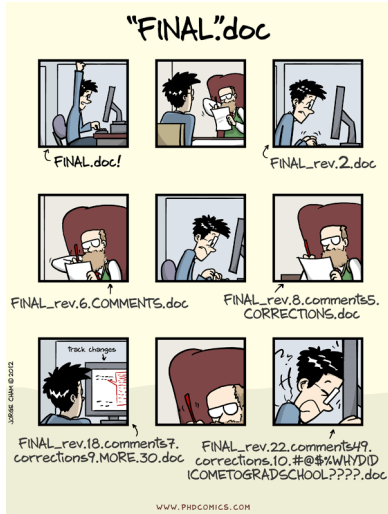
02/27/2013 02/27/13 27/02/2013 27/02/13  
20130227 2013.02.27 27.02.13 27-02-13  
27.2.13 2013.II.27.  $27\frac{1}{2}$ -13 2013.158904109  
MMXIII-II-XXVII MMXIII  $\frac{\text{LVII}}{\text{CCCLXV}}$  1330300800  
 $((3+3) \times (111+1) - 1) \times 3 / 3 - 1 / 3^3$  2013  
10/11011/1101 02/27/20/13  $\begin{matrix} 2 & 3 & 1 & 4 \\ 0 & 1 & 2 & 3 & 7 \\ & 5 & 6 & 7 & 8 \end{matrix}$  

# Choose good names for things

```
0_vcf2db.R  
1_prep_genotype.R  
2_prep_pheno_clin.R  
2_prep_pheno_otu.R  
3_prep_covar.R  
4_prep_analysis_pheno_clin.R  
4_prep_analysis_pheno_otu.R  
5_scans.R  
6_grab_peaks.R  
7_find_nearby_peaks.R
```



# No “final” in file names



# No “final” in file names

```
Deprecated/  
ReadMe.txt  
adipose_int1_final.RData  
adipose_int2_final.RData  
adipose_mlratio_final.RData  
adipose_mlratio_nqrnk_final.RData  
adipose_prcomp.RData  
aligned_geno_with_pmap.RData  
batches_final.RData  
batches_raw_final.RData  
cpl_final.RData  
d2o_final.RData  
gastroc_int1_final.RData  
gastroc_int2_final.RData  
gastroc_mlratio_final.RData  
gastroc_mlratio_nqrnk_final.RData  
gastroc_prcomp.RData  
hypo_int1_final.RData  
hypo_int2_final.RData  
hypo_mlratio_final.RData  
hypo_mlratio_final_old.RData  
hypo_mlratio_nqrnk_final.RData  
hypo_mlratio_nqrnk_final_old.RData  
hypo_omit.RData  
hypo_prcomp.RData  
islet_int1_final.RData  
islet_int2_final.RData  
islet_mlratio_final.RData  
islet_mlratio_nqrnk_final.RData  
islet_prcomp.RData  
kidney_int1_final.RData  
kidney_int2_final.RData  
kidney_mlratio_final.RData  
kidney_mlratio_nqrnk_final.RData  
kidney_prcomp.RData  
lipomics_final_rev2.RData  
liverTG_final.RData  
liver_int1_final.RData  
liver_int2_final.RData  
liver_mlratio_final.RData  
liver_mlratio_nqrnk_final.RData  
liver_prcomp.RData  
mirna_final.RData  
necropsy_final_rev2.RData  
plasmaurine_final_rev.RData  
pmark.RData  
rbm_final.RData
```

# No “final” in file names

```
Deprecated/  
ReadMe.txt  
adipose_int1_final.RData  
adipose_int2_final.RData  
adipose_mlratio_final.RData  
adipose_mlratio_nqrnk_final.RData  
adipose_prcomp.RData  
aligned_geno_with_pmap.RData  
batches_final.RData  
batches_raw_final.RData  
cpl_final.RData  
d2o_final.RData  
gastroc_int1_final.RData  
gastroc_int2_final.RData  
gastroc_mlratio_final.RData  
gastroc_mlratio_nqrnk_final.RData  
gastroc_prcomp.RData  
hypo_int1_final.RData  
hypo_int2_final.RData  
hypo_mlratio_final.RData  
hypo_mlratio_final_old.RData  
hypo_mlratio_nqrnk_final.RData  
hypo_mlratio_nqrnk_final_old.RData  
hypo_omit.RData  
hypo_prcomp.RData  
islet_int1_final.RData  
islet_int2_final.RData  
islet_mlratio_final.RData  
islet_mlratio_nqrnk_final.RData  
islet_prcomp.RData  
kidney_int1_final.RData  
kidney_int2_final.RData  
kidney_mlratio_final.RData  
kidney_mlratio_nqrnk_final.RData  
kidney_prcomp.RData  
lipomics_final_rev2.RData  
liverTG_final.RData  
liver_int1_final.RData  
liver_int2_final.RData  
liver_mlratio_final.RData  
liver_mlratio_nqrnk_final.RData  
liver_prcomp.RData  
mirna_final.RData  
necropsy_final_rev2.RData  
plasmaurine_final_rev.RData  
pmark.RData  
rbm_final.RData
```

# Choose good names for things

```
batches_raw_v1.rds
batches_v1.rds
clinical_cpl_v2.rds
clinical_d2o_v2.rds
clinical_lipomics_v4.rds
clinical_liverTG_v2.rds
clinical_mirna_v2.rds
clinical_necropsy_v4.rds
clinical_plasmaurine_v3.rds
clinical_rbm_v2.rds
Deprecated/
geneexpr_int1_adipose_v2.rds
geneexpr_int1_gastroc_v2.rds
geneexpr_int1_hypo_v2.rds
geneexpr_int1_islet_v2.rds
geneexpr_int1_kidney_v2.rds
geneexpr_int1_liver_v2.rds
geneexpr_int2_adipose_v2.rds
geneexpr_int2_gastroc_v2.rds
geneexpr_int2_hypo_v2.rds
geneexpr_int2_islet_v2.rds
geneexpr_int2_kidney_v2.rds
geneexpr_int2_liver_v2.rds
geneexpr_mlratio_adipose_v2.rds
geneexpr_mlratio_gastroc_v2.rds
geneexpr_mlratio_hypo_v1.rds
geneexpr_mlratio_hypo_v2.rds
geneexpr_mlratio_islet_v2.rds
geneexpr_mlratio_kidney_v2.rds
geneexpr_mlratio_liver_v2.rds
geneexpr_mlratio_nqrank_adipose_v2.rds
geneexpr_mlratio_nqrank_gastroc_v2.rds
geneexpr_mlratio_nqrank_hypo_v1.rds
geneexpr_mlratio_nqrank_hypo_v2.rds
geneexpr_mlratio_nqrank_islet_v2.rds
geneexpr_mlratio_nqrank_kidney_v2.rds
geneexpr_mlratio_nqrank_liver_v2.rds
geneexpr_omit_hypo.rds
geneexpr_prcomp_adipose_v2.rds
geneexpr_prcomp_gastroc_v2.rds
geneexpr_prcomp_hypo_v2.rds
geneexpr_prcomp_islet_v2.rds
geneexpr_prcomp_kidney_v2.rds
geneexpr_prcomp_liver_v2.rds
geno_aligned_w_pmap.rds
geno_pmark.rds
ReadMe.txt
```

# Document your work

- ▶ What is all of this stuff?
- ▶ What was your analysis process?

→ ReadMe files

# Organizing data in spreadsheets

	A	B	C	D	E	F	G
1	1MIN						
2			Normal			Mutant	
3	B6	146.6	138.6	155.6	166	179.3	186.9
4	BTBR	245.7	240	243.1	177.8	171.6	188.1
5							
6	5MIN						
7			Normal			Mutant	
8	B6	333.6	353.6	408.8	450.6	474.4	423.8
9	BTBR	514.4	610.6	597.9	412.1	447.4	446.5

# Organizing data in spreadsheets

	A	B	C	D
1	ttt_min	strain	mutation	response
2	1	B6	normal	146.6
3	1	B6	normal	138.6
4	1	B6	normal	155.6
5	1	B6	mutant	166
6	1	B6	mutant	179.3
7	1	B6	mutant	186.9
8	1	BTBR	normal	245.7
9	1	BTBR	normal	240
10	1	BTBR	normal	243.1
11	1	BTBR	mutant	177.8
12	1	BTBR	mutant	171.6
13	1	BTBR	mutant	188.1
14	5	B6	normal	333.6
15	5	B6	normal	353.6

# Organizing data in spreadsheets

- ▶ Make it a rectangle
- ▶ Individual measurements as rows; variables as columns
- ▶ Single header row
- ▶ One item per cell
- ▶ No empty cells
- ▶ No calculations in the raw data
- ▶ No highlighting or coloring as data



“What the heck is ‘FAD\_NAD SI 8.3\_3.3G’?”

# Metadata

- ▶ Create a data dictionary
  - Explain each column
  - Include different versions of the variable names (compact vs descriptive)
  - Units
  - Allowable values
- ▶ The metadata are data
  - Make it a rectangle

# Data dictionary

	A	B	C	D
1	name	plot_name	group	description
2	mouse	Mouse	demographic	Animal identifier
3	sex	Sex	demographic	Male (M) or Female (F)
4	sac_date	Date of sac	demographic	Date mouse was sacrificed
5	partial_inflation	Partial inflation	clinical	Indicates if mouse showed partial pancreatic inflation
6	coat_color	Coat color	demographic	Coat color, by visual inspection
7	crumblers	Crumblers	clinical	Indicates if mouse stored food in their bedding
8	diet_days	Days on diet	clinical	Number of days on high-fat diet

# Everything with a script

If you do something once,  
you'll do it 1000 times.

# Reproducible reports

## Gough project diagnostics

Karl Broman, 3 March 2014

### Combine genotypes and phenotypes

I've combined the initial genotypes (using the re-clustered genotypes for plates 14-16) with the well-behaved portion of the re-run genotypes. I'm focusing on 36813 markers that are informative (though, as we'll see, there are still a lot of badly behaved and basically non-informative markers that need to be removed). I've combined data on replicate samples, to give one set of genotype calls for each sample.

There are 1497 genotyped mice and 1464 phenotyped mice. All of the mice in the phenotype data have genotypes, but there are 33 genotyped mice with no phenotypes, including 3 Gough mice and 30 F2 progeny.

# Reproducible reports

## Gough project diagnostics

```
Karl 25 I've combined the initial genotypes (using the re-clustered genotypes
26 for plates 14-16) with the well-behaved portion of the re-run
Co 27 genotypes. I'm focusing on `r totmar(g)` markers that are informative
28 (though, as we'll see, there are still a lot of badly behaved and
I've 29 basically non-informative markers that need to be removed).
the v 30 I've combined data on replicate samples, to give one set of genotype
infor 31 calls for each sample.
infor 32
give 33 There are `r nind(g)` genotyped mice and `r nrow(phe)` phenotyped
34 mice. All of the mice in the phenotype data have genotypes, but there
Ther 35 are `r sum(is.na(match(gid, pid)))` genotyped mice with no phenotypes,
data 36 including `r sum(g$pheno$gen[which(is.na(match(gid, pid)))]==0)`
mice 37 Gough mice and `r sum(g$pheno$gen[which(is.na(match(gid, pid)))]==2)`
38 F2 progeny.
```

# Automate the process (GNU Make)

```
R/analysis.html: R/analysis.Rmd Data/cleandata.csv  
    cd R;R -e "rmarkdown::render('analysis.Rmd')"
```

```
Data/cleandata.csv: R/prepData.R RawData/rawdata.csv  
    cd R;R CMD BATCH prepData.R
```

```
RawData/rawdata.csv: Python/xls2csv.py RawData/rawdata.xls  
    Python/xls2csv.py RawData/rawdata.xls > RawData/rawdata.csv
```

# Automate the process (GNU Make)

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R/analysis.html: R/analysis.Rmd Data/cleandata.csv  
    cd R;R -e "rmarkdown::render('analysis.Rmd')"
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```

```
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```

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```

```
Python/xls2csv.py RawData/rawdata.xls > RawData/rawdata.csv
```

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```

```
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```

```
RawData/rawdata.csv: Python/xls2csv.py RawData/rawdata.xls
```

```
Python/xls2csv.py RawData/rawdata.xls > RawData/rawdata.csv
```

# Fancier example

```
FIG_DIR = Figs

mypaper.pdf: mypaper.tex ${FIG_DIR}/fig1.pdf ${FIG_DIR}/fig2.pdf
    pdflatex mypaper

# One line for both figures
${FIG_DIR}/%.pdf: R/%.R
    cd R;R CMD BATCH $(<F)

# Use "make clean" to remove the PDFs
clean:
    rm *.pdf Figs/*.pdf
```

# How do you use make?

- ▶ If you name your make file `Makefile`, then just go into the directory containing that file and type `make`
- ▶ If you name your make file `something.else`, then type `make -f something.else`
- ▶ Actually, the commands above will build the **first** target listed in the make file. So I'll often include something like the following.

```
all: target1 target2 target3
```

Then typing `make all` (or just `make`, if `all` is listed first in the file) will build all of those things.

- ▶ To build a specific target, type `make target`. For example, `make Figs/fig1.pdf`

# Write modular code

- ▶ Modular code is easier to understand, maintain, and reuse.
- ▶ Turn repeated code into functions
- ▶ Combine useful functions into a package or module

# Keeping track of versions

- ▶ Google drive / Dropbox / Box
- ▶ Version numbers in file names
- ▶ Formal version control (e.g., git/GitHub)
  - Browse changes
  - Try new things without fear of breaking what works
  - Jump to the state of the project at any time point
  - Merge simultaneous changes from multiple people

## Version control (git/GitHub)

Public

kbroman / **Talk\_MAGIC**

Unwatch 1

Star 0

Fork 0

Talk for MAGIC workshop in Cambridge, UK, 12 June 2013 — Edit

97 commits

1 branch

0 releases

1 contributor

branch: master

**Talk\_MAGIC**

Greatly simplify the public domain stuff in the ReadMe

**kbroman** authored 15 days ago      latest commit: f1777ef192

<b>Figs</b>	Add crazy table from preCC paper	4 months ago
<b>Perl</b>	Add lines_of_code_by_version.csv to repository	4 months ago
<b>R</b>	Another fix regarding map expansion in B-way RIL by setting at k=0	4 months ago
<b>.gitignore</b>	Add lines_of_code_by_version.csv to repository	4 months ago
<b>Makefile</b>	Revise Readme to link to version for web	4 months ago
<b>ReadMe.md</b>	Greatly simplify the public domain stuff in the ReadMe	15 days ago
<b>magic.tex</b>	Fix two slight bugs in slides:	4 months ago

ReadMe.md

## Talk for **MAGIC Workshop** in Cambridge, UK

These are slides for a talk I will give at the [Workshop on MAGIC-type populations](#) in Cambridge, UK, on 12 June 2013.

The PDF is [here](#).

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To the extent possible under law, [Karl Broman](#) has waived all copyright and related or neighboring rights to "[MAGIC design and other topics](#)". This work is published from: United States.

Public Domain

Code

Issues

Pull Requests

Wiki

Pulse

Graphs

Network

Settings

HTTPS clone URL

https://github.com/

You can clone with [HTTPS](#), [SSH](#), or [Subversion](#).

Clone on Desktop

Download ZIP

# Version control (git/GitHub)

PUBLIC kbroman / Talk\_MAGIC

Unwatch 1 Star 0 Fork 0

Talk for MAGIC workshop in Cambridge, UK, 12 June 2013 — Edit

97 commits 1 branch 0 releases 1 contributor


Code Issues 0

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magic.tex	Fix two slight bugs in slides:	4 months ago

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 PUBLIC DOMAIN





# Version control (git/GitHub)

PUBLIC kbroman / Talk\_MAGIC



Unwatch 1 Star 0 Fork 0

branch: master - Talk\_MAGIC / Commits









Sep 27, 2013

-  **Greatly simplify the public domain stuff in the ReadMe**  
kbroman authored 15 days ago [f1777eef192](#) Browse code
-  **Fix url in ReadMe.md file**  
kbroman authored 15 days ago [06515023f9](#) Browse code

Jun 17, 2013


-  **Another fix regarding map expansion in 8-way RIL by selfing at k=0**  
kbroman authored 4 months ago [2000482f2c](#) Browse code
-  **Fix two slight bugs in slides:** XXX  
- 8-way RIL by selfing: map expansion = 1 at k=0  
- Slight repair to definition of 3-pt coincidence  
kbroman authored 4 months ago [51d40a9ceb](#) Browse code

Jun 10, 2013

-  **Change one page number**  
kbroman authored 4 months ago [e0e0600615](#) Browse code
-  **Add missing paren**  
kbroman authored 4 months ago [f4975dee6e](#) Browse code
-  **who's -> who is**  
kbroman authored 4 months ago [886f20f098](#) Browse code
-  **rubbish -> bad**  
kbroman authored 4 months ago [e6fbf2f647](#) Browse code
-  **Add link to R/qtl page**  
kbroman authored 4 months ago [4edf3e8676](#) Browse code
-  **Revise slide re analysis issues**  
kbroman authored 4 months ago [14ebb1eeb5](#) Browse code
-  **Italicize 'de novo'**  
kbroman authored 4 months ago [45dd04b4c7](#) Browse code
-  **replace plain right arrow with fat arrow**  
kbroman authored 4 months ago [8bbe305d6c](#) Browse code

# Version control (git/GitHub)

PUBLIC

 kbroman / Talk\_MAGIC

Unwatch

1

Star

0

Fork

0


Fix two slight bugs in slides:

Browse code

- 8-way RIL by selfing: map expansion = 1 at k=0

- Slight repair to definition of 3-pt coincidence

master

 kbroman authored 4 months ago

1 parent e0e0608 commit 51d4aa9ceb104bbf26e0cbe105a5c7f8dc02a832

Showing 2 changed files with 5 additions and 3 deletions.

Show Diff Stats

6

R/map\_expansion\_func.R

View file @ 51d4aa9

... -25,8 +25,10 @@ mesibA4 <- function(k)

25 25 #####

26 26 # Eight-way

27 27 #####

28 -meself8 <- function(k)

29 - 4 - (((1)/(2)))^(k-2)

28 +meself8 <- function(k) {

29 + if(k==0) return(1)

30 + 4 - (((1)/(2)))^(k-2)

31 +}

30 32

31 33 mesibX8 <- function(k)

32 34 (((14)/(3)) - (((30 + 14\*sqrt(5))/(15))) \* (((1+sqrt(5))/(4)))^k - (((30 - 14\*sqrt(5))/(15))) \* (((1-sqrt(5))/(4)))^k))

2

magic.tex

View file @ 51d4aa9

... -636,7 +636,7 @@

636 636

637 637 \hspace{20mm} {\color{myblue} = \mathsf{Pr}\{\text{rec'n in 23} \} \}

638 638 \ \text{rec'n in 12}} /

639 - Pr{\text{rec'n in 12}}}}\$

639 + Pr{\text{rec'n in 23}}}}\$

640 640


641 641 \item

642 642 No interference { \color{myblue} = 1 }

39

# Version control (git/GitHub)

28		-meself8 <- function(k)
29		- 4 - (((1)/(2)))^(k-2)
	28	+meself8 <- function(k) {
	29	+ if(k==0) return(1)
	30	+ 4 - (((1)/(2)))^(k-2)
	31	+}
30	32	
31	33	mesibX8 <- function(k)
32	34	((14)/(3)) - (((30 + 14*sqrt(5))/(15))) ,

2 		magic.tex
...	...	@@ -636,7 +636,7 @@
636	636	
637	637	\hspace{20mm} {\color{myblue} = \$\mathsf{Pr}('\$
638	638	\ \text{rec'n in 12}) /
639		- Pr(\text{rec'n in 12}))\$}
	639	+ Pr(\text{rec'n in 23}))\$}
640	640	

# Backups

- ▶ Multiple places, including off-site
- ▶ Automatic

# License your software

Pick a license, any license

– Jeff Atwood

# Share your stuff

## ► Code

- GitHub / BitBucket
- Zenodo (archival, with DOIs)

## ► Data

- Domain-specific repository (e.g., dbGAP)
- General repository (e.g., github, figshare, zenodo, datadryad)
- Institutional repository

# Summary

1. Organize your project
2. Choose good names for things
3. Document what's what
4. Organize data as a rectangle
5. Metadata is data
6. Everything with a script
7. Even better: reproducible reports
8. Automate the process (GNU Make)
9. Write modular code (functions and packages)
10. Use version control (git/GitHub)
11. License your software
12. Share your data and code