



# Bayesian Statistics and Bayesian Cognitive Modeling (BayesCog)

## Part I

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[https://github.com/lei-zhang/BayesCog\\_Part1](https://github.com/lei-zhang/BayesCog_Part1)

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lei-zhang.net  
@lei\_zhang\_lz



# Schedule

## Part 1

04.05: 9:30-13:30

11.05: 9:30-13:30

18.05: 9:30-13:30

25.05: 9:30-13:30

## Part 2

10.06: 9:30-13:30 (different date!)

15.06: 9:30-13:30

22.06: 9:30-13:30

29.06: 9:30-13:30

## Statistical modeling

Introduction

R Basics

Probability Basics

Bayes' theorem

MCMC and Stan

Single-Parameter Model – Binomial Model

Multiple-Parameter Model – Linear Regression

Inference, Posterior Predictive Check

## Cognitive modeling

Reinforcement Learning Model

Hierarchical Models

Optimizing Stan Codes

Model Comparison

Stan Style Tip and Debugging

Model-Based fMRI

Capstone Project: Delay Discounting Task

# About me: Dr. Lei Zhang

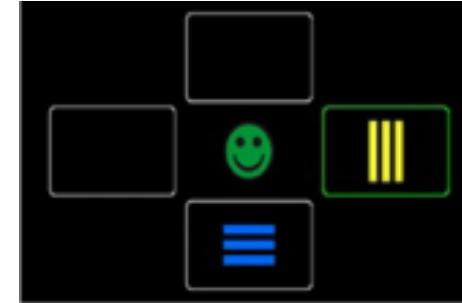
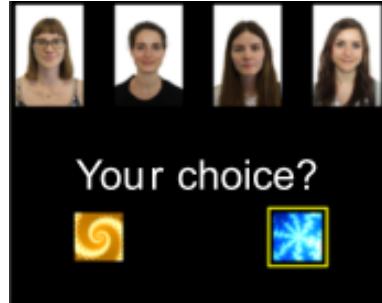
- Current: Postdoc @ [SCAN-Unit](#), w/ [Claus Lamm](#) 
- Ph.D. Cognitive computational neuroscience, w/ [Jan Gläscher](#) 
- M.Sc. Cognitive neuroscience 
- B.Sc. Psychology 
- My journey through computational modeling
  - Started with MLE (@fminsearch in Matlab)
  - Switched to Bayesian: first JAGS, then Stan



# My research:

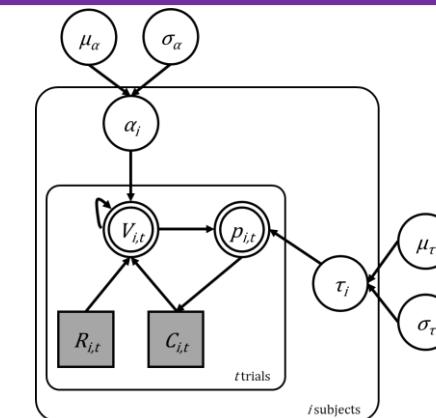
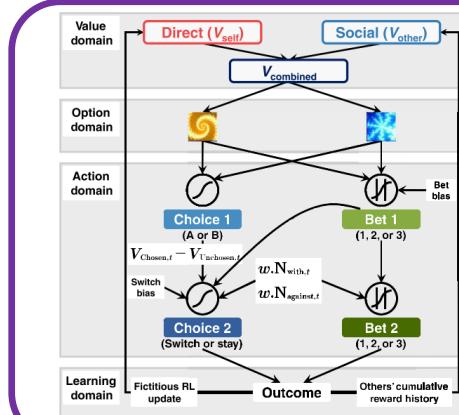
- I ask people to make decisions

Computation



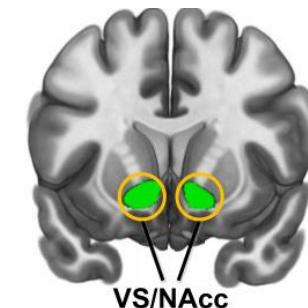
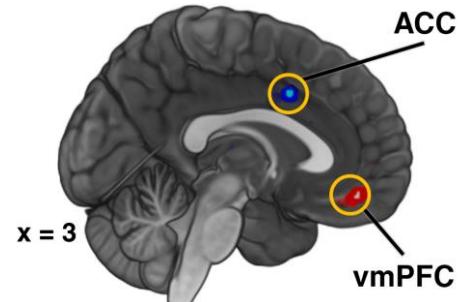
- I build computational models

Algorithm



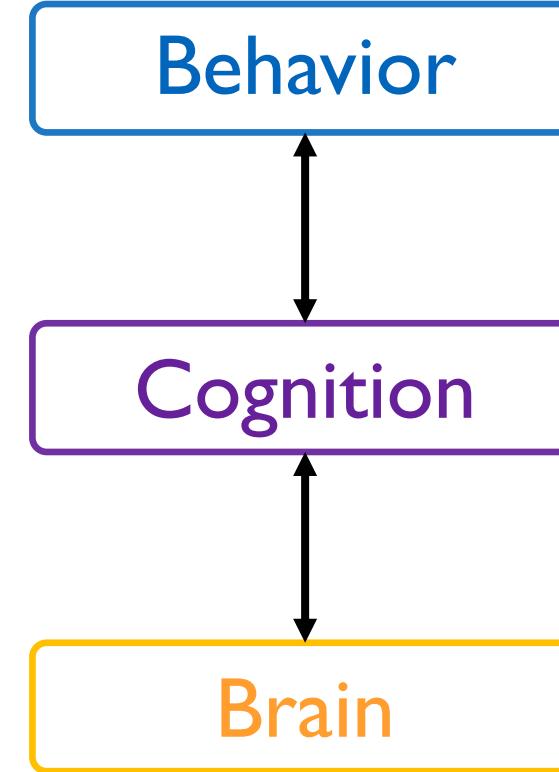
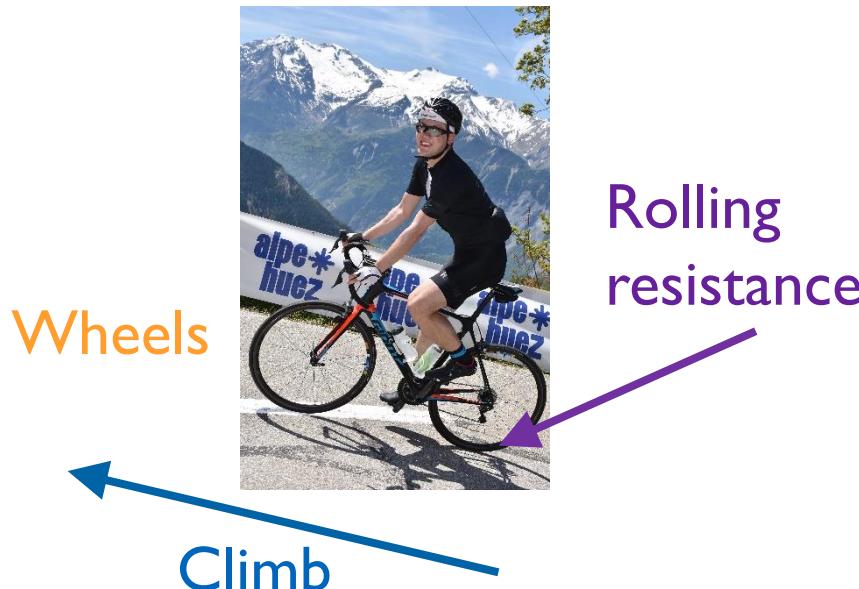
- I examine neural mechanisms

Implementation



# Influential perspective: Marr's 3 levels of analysis

LEVELS		
<b>Computation</b>	1	why (problem)
<b>Algorithm</b>	2	what (rules)
<b>Implementation</b>	3	how (physical)



David Marr, (1982)

# Goal of this course

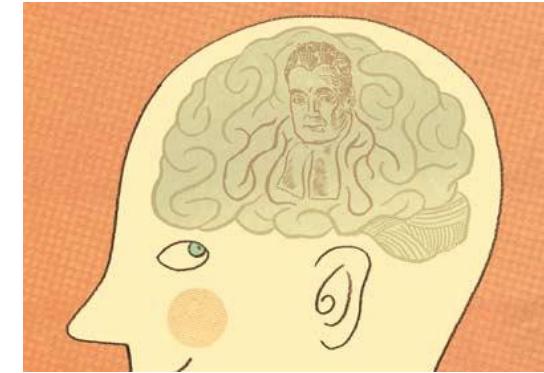
- Practical R programming
- Practical model-building in Stan, model diagnostics
- (Enough) theory to ground you
- Be comfortable to use R/Stan for your own work: model building/estimating/testing/validating, and/or model-based fMRI/EEG



# Goal of this course

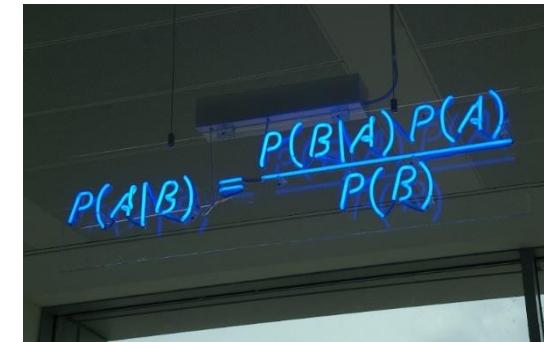
This course is NOT about...

- ... Bayes in the brain (e.g. predictive coding)
- ... Bayesian statistics to supersede classic statistics



However, Bayesian statistics offer great tools to analyze cognitive processes!

- Construct cognitive models
- Estimate posterior distributions of parameters
- Compare models: which is the best one, given the data
- Perform model-based analysis, e.g. model-based fMRI/EEG/eye-movement


$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

# A clear goal depends on knowledge & expectations

What is your experience with...

- Statistics?
- R? (and / or Matlab?)
- Cognitive Modeling?

You would like to...

- gain knowledge of Bayesian stats?
- be able to read “computational modeling” section in papers?
- write your own model?



**Richard McElreath**  
@rlmcelreath



I say this a lot, bc I am also confused quite often.



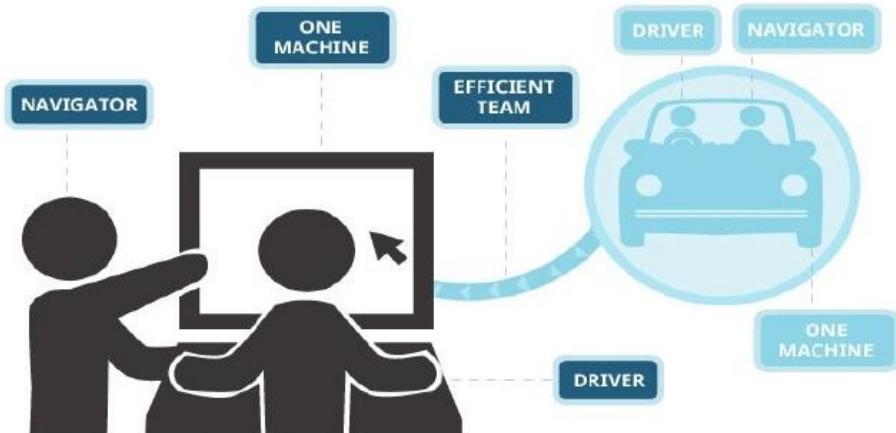
**Anna Jacobson** @AnnaChingChing · Feb 21

"If you are confused, it is only because you are trying to understand." -  
@rlmcelreath in Statistical Rethinking

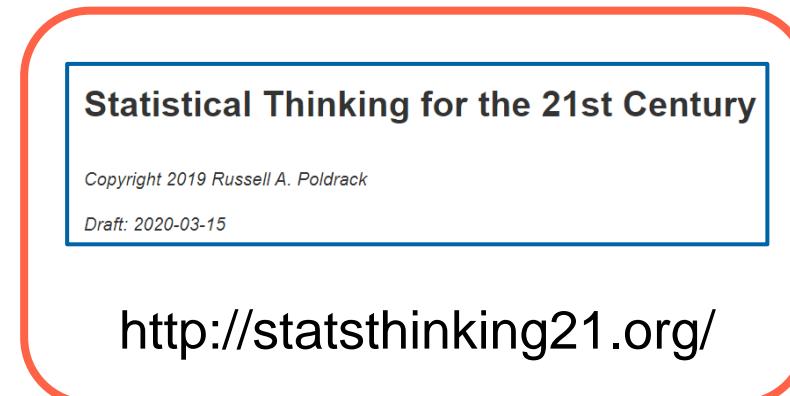
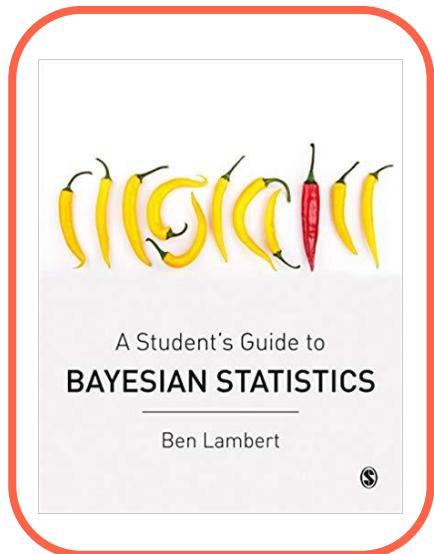
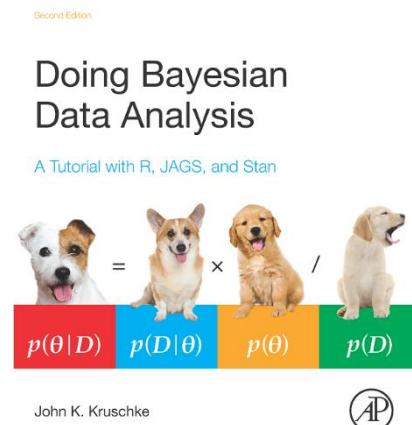
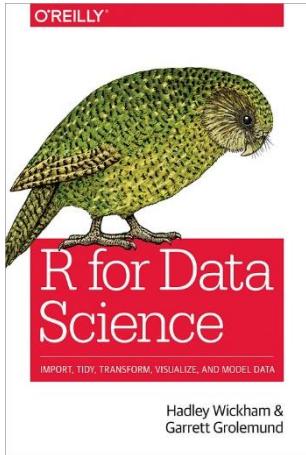
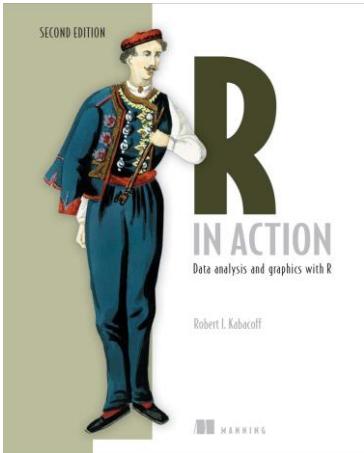
# How to Get the **Most** out of the course

- Workshop structure: interleaved theory/demo + exercise
- Work in pairs: Talk to each other & help each other
- Ask questions
- Try the exercises

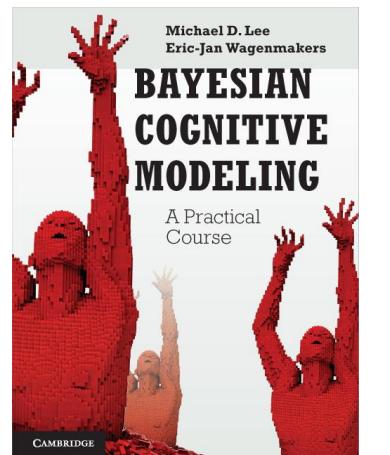
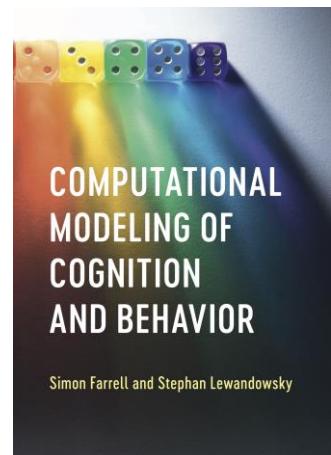
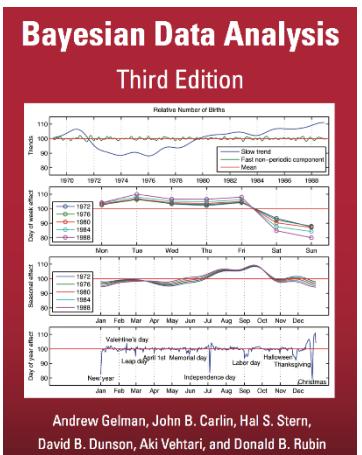
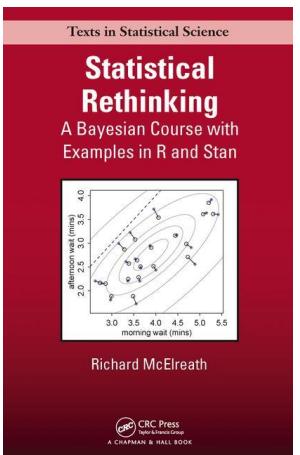
## PAIR PROGRAMMING



# Resources



<https://www.datacamp.com/>



<https://jasp-stats.org/>

# Resources

## Ten simple rules for the computational modeling of behavioral data

Robert C Wilson<sup>1,2†\*</sup>, Anne GE Collins<sup>3,4†\*</sup>

<https://elifesciences.org/articles/49547>

## Trial-by-trial data analysis using computational models

Nathaniel D. Daw

August 27, 2009

<http://www.princeton.edu/~ndaw/d10.pdf>

## Computational modelling of social cognition and behaviour—a reinforcement learning primer

Patricia L Lockwood , Miriam C Klein-Flügge

*Social Cognitive and Affective Neuroscience*, nsaa040,  
<https://doi.org/10.1093/scan/nsaa040>

<https://doi.org/10.1093/scan/nsaa040>

## Using reinforcement learning models in social neuroscience: frameworks, pitfalls and suggestions of best practices

Lei Zhang , Lukas Lengersdorff, Nace Mikus, Jan Gläscher, Claus Lamm [Author Notes](#)

*Social Cognitive and Affective Neuroscience*, Volume 15, Issue 6, June 2020, Pages 695–707, <https://doi.org/10.1093/scan/nsaa089>

<https://doi.org/10.1093/scan/nsaa089>

Now let's **begin!**

# BASICS OF R PROGRAMMING



# R Basics

cognitive model  
statistics  
computing

- R
  - a programming language for statistical computing
  - R has its own user interface
  - freely available on Windows, Mac, and Linux



- R Studio
  - integrated development environment (IDE) for R
  - a more sophisticated R-friendly editor, with helpful syntax highlight



script editor

The screenshot shows the RStudio interface with several panes:

- Script Editor:** Top-left pane containing R code for generating three plots (g1, g2, g3) using ggplot2. The code defines a theme (myconfig) and adds it to each plot.
- Environment:** Top-right pane showing the Global Environment. It displays a message "Environment is empty".
- Console:** Bottom-left pane showing the R startup message and basic usage instructions.
- File/Pkg/Img/etc.:** Bottom-right pane showing the System Library, listing various R packages with their descriptions and versions.

```
21 # -----
22 library(ggplot2)
23
24 myconfig <- theme_bw(base_size = 20) +
25   theme(panel.grid.major = element_blank(),
26         panel.grid.minor = element_blank(),
27         panel.background = element_blank() )
28
29 ## normal distribution
30 # dnorm
31 g1 <- ggplot(data.frame(x = c(-5, 5)), aes(x)) +
32   stat_function(fun = dnorm, args = list(mean = 0, sd = 1), size = 3, colour = 'black')
33 g1 <- g1 + myconfig
34 print(g1)
35
36 # pnorm
37 g2 <- ggplot(data.frame(x = c(-5, 5)), aes(x)) +
38   stat_function(fun = pnorm, args = list(mean = 0, sd = 1), size = 3)
39 g2 <- g2 + myconfig
40 print(g2)
41
42 # qnorm
43 g3 <- ggplot(data.frame(x = c(0, 1)), aes(x)) +
44   stat_function(fun = qnorm, args = list(mean = 0, sd = 1), size = 3)
45 g3 <- g3 + myconfig
46 print(g3)
```

Name	Description	Version
abind	Combine Multidimensional Arrays	1.4-3
assertthat	Easy pre and post assertions.	0.1
base64enc	Tools for base64 encoding	0.1-3
BayesFactor	Computation of Bayes Factors for Common Designs	0.912-2
BH	Boost C++ Header Files	1.60-0.1
bitops	Bitwise Operations	1.0-6
boot	Bootstrap Functions (Originally by Angelo Canty for S)	1.3-17
broom	Convert Statistical Analysis Objects into Tidy Data Frames	0.4.1
Cairo	R graphics device using cairo graphics library for creating high-quality bitmap (PNG, JPEG, TIFF), vector (PDF, SVG, PostScript) and display (X11 and Win32) output	1.5-9
car	Companion to Applied Regression	2.1-1
caTools	Tools: moving window statistics, GIF, Base64, ROC AUC, etc.	1.17.1
class	Functions for Classification	7.3-14
cluster	"Finding Groups in Data": Cluster Analysis Extended Rousseeuw et al.	2.0.3
coda	Output Analysis and Diagnostics for MCMC	0.18-1
codetools	Code Analysis Tools for R	0.2-14
colorspace	Color Space Manipulation	1.2-6
compiler	The R Compiler Package	3.2.3
coplot	Visualization of a correlation matrix	0.73
cubature	Adaptive multivariate integration over hypercubes	1.1-2
curl	A Modern and Flexible Web Client for R	0.9.6
Data.Analytic.and.Graphic.Data.and.Functions	Data Analytic and Graphic Data and Functions	1.22

environment/  
command history

file/pkg/img/  
etc.

console

# Know your R

```
>R.version
```

```
platform      x86_64-w64-mingw32  
arch          x86_64  
os            mingw32  
system        x86_64, mingw32  
status  
major         3  
minor         5.1  
year          2018  
month         07  
day           02  
svn rev       74947  
language      R  
version.string R version 3.5.1 (2018-07-02)  
nickname      Feather Spray
```

# R Console as a Calculator

## Addition and Subtraction

```
> 3+2  
[1] 5
```

```
> 3-2  
[1] 1
```

## Multiplication and Division

```
> 3*2  
[1] 6
```

```
> 3/2  
[1] 1.5
```

## Exponents in R

```
> 3^2  
[1] 9
```

```
> 2^3  
[1] 8
```

## Constants in R

```
> pi  
[1] 3.141593
```

```
> exp(1) base of the natural logarithm  
[1] 2.718282
```

# Special values

## Infinite Values

```
> Inf  
[1] Inf
```

```
> 1+Inf  
[1] Inf
```

## Machine Epsilon

```
> .Machine$double.eps  
[1] 2.220446e-16
```

```
> 0>.Machine$double.eps  
[1] FALSE
```

## Empty Values

```
> NULL  
NULL
```

```
> 1+NULL  
numeric(0)
```

## Missing Values

```
> NA  
[1] NA
```

```
> 1+NA  
[1] NA
```

# Storing and manipulating variables

Define objects `x` and `y` with values of 3 and 2, respectively:

```
> x=3  
> y=2
```

Some calculations with the defined objects `x` and `y`:

```
> x+y  
[1] 5
```

```
> x*y  
[1] 6
```

Warning: R is case sensitive, so `x` and `X` are not the same object.

# Basic R functions

## Combine

```
> c(1,3,-2)  
[1] 1 3 -2
```

```
> c("a","a","b","b","a")  
[1] "a" "a" "b" "b" "a"
```

## Sum and Mean

```
> sum(c(1,3,-2))  
[1] 2
```

```
> mean(c(1,3,-2))  
[1] 0.6666667
```

## Variance and Std. Dev.

```
> var(c(1,3,-2))  
[1] 6.333333
```

```
> sd(c(1,3,-2))  
[1] 2.516611
```

## Minimum and Maximum

```
> min(c(1,3,-2))  
[1] -2
```

```
> max(c(1,3,-2))  
[1] 3
```

# Basic R functions (cont.)

Define objects `x` and `y`:

```
> x=c(1,3,4,6,8)  
> y=c(2,3,5,7,9)
```

Calculate the correlation:

```
> cor(x,y)  
[1] 0.988765
```

Calculate the covariance:

```
> cov(x,y)  
[1] 7.65
```

Combine as columns

```
> cbind(x,y)  
      x  y  
[1, ] 1  2  
[2, ] 3  3  
[3, ] 4  5  
[4, ] 6  7  
[5, ] 8  9
```

Combine as rows

```
> rbind(x,y)  
      [,1] [,2] [,3] [,4] [,5]  
x     1     3     4     6     8  
y     2     3     5     7     9
```

# Basic Commands

```
getwd()
setwd('E:/teaching/BayesCog_Wien/')
dir() # folders/files in the wd
ls() # anything in the environment/workspace
print('Hello World!')
cat('Hello', 'World!')
paste0('C:/', 'Group1')
help(func)
? func # and Google!
a <- 5
a = 5
head(d) # first 6 entries
tail(d) # last 6 entries
save(varname, file = "pathname/varname.RData")
load("pathname/varname.RData")
rm(list = ls())
q()
```

# RStudio - Shortcuts

cognitive model  
statistics  
**computing**

Ctrl + L: clean console

Ctrl + Shift + N: create a new script

↑: command history

Ctrl(hold) + ↑: command history with certain starts

Ctrl + Enter: execute selected codes (in a script)

# Editor (WIN general) - Shortcuts

cognitive model  
statistics  
computing

Ctrl + home/Pos: go to the very top of a script

Ctrl + end/Ende: go to the very end of a script

Shift(hold) + ↑/↓: select line(s)

Ctrl(hold) + ←/→: select word(s)

# Data Classes

numeric: 1.1 2.0

integer: 1 2 3

character / string: "hello world!"

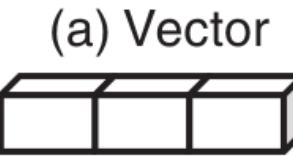
logical: TRUE FALSE

factors: "male" / "female"

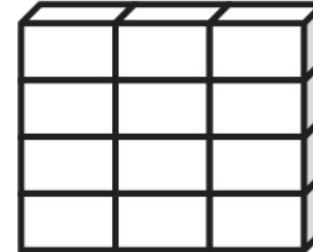
(complex: 1+2i)

# Data Types

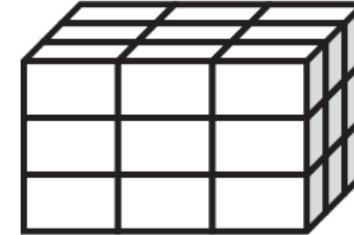
cognitive model  
statistics  
computing



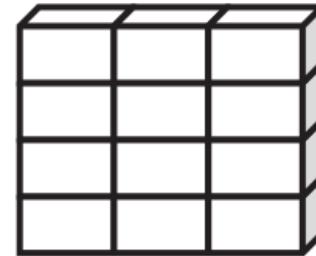
(b) Matrix



(c) Array



(d) Data frame



Columns can be different modes

(e) List

Vectors  
Arrays  
Data frames  
Lists

# Exercise I

cognitive model  
statistics  
computing

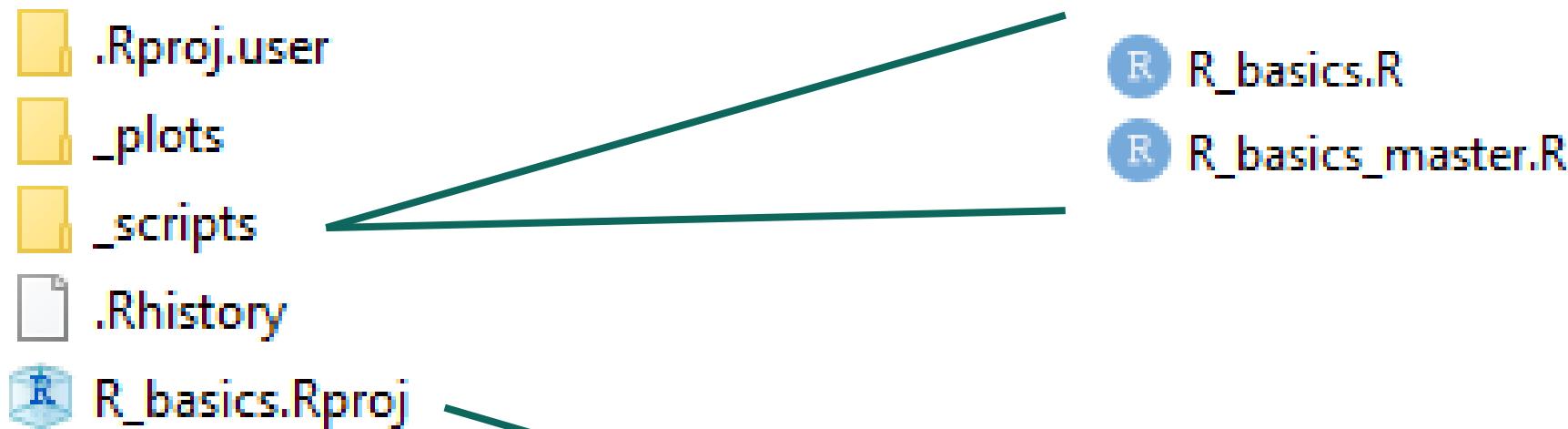
.../01.R\_basics/\_scripts/R\_basics.R

up to “Control Flow”

**TASK:** practise basic R commands and data type

**TIP:** `class()`, `str()`

# Side note: folder structure



click this to start each exercise,  
then no need to set directory

# Logical Operators

Operator	Summary
<	Less than
>	Greater than
<=	Less than or equal to
>=	Greater than or equal to
==	Equal to
!=	Not equal to
!x	NOT x
x y	x OR y
x&y	x AND y

# Control Flow

- **if-else**

```
if (cond) {  
    ..statement..  
}
```

```
if (cond) {  
    ..statement..  
} else {  
    ..statement..  
}
```

```
if (cond) {  
    ..statement..  
} else if (cond) {  
    ..statement..  
} else {  
    ..statement..  
}
```

- **for-loop**

```
for ( j in 1:J ) {  
    ..statement..  
}
```

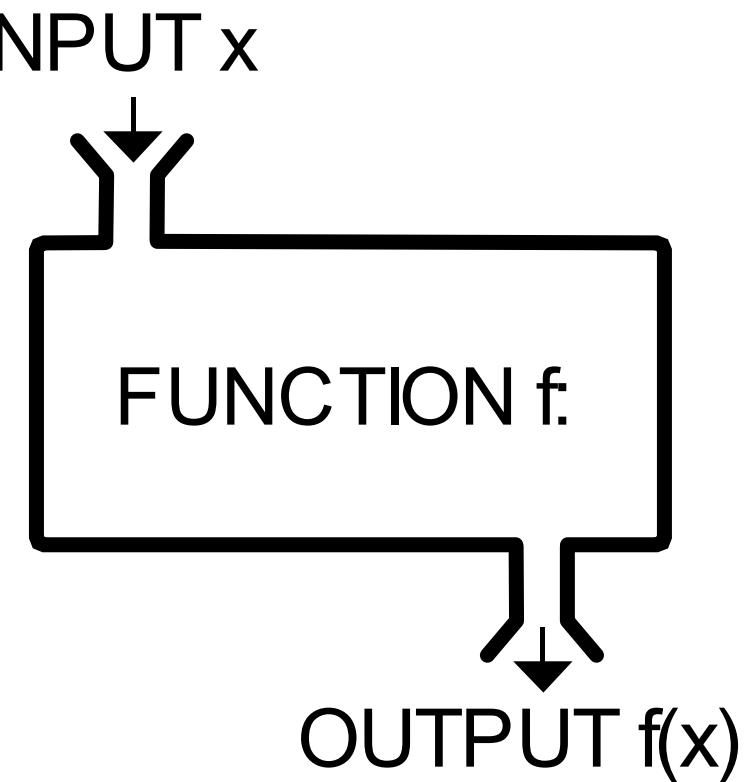
```
for ( j in 1:J ) {  
    for ( k in 1:K ) {  
        ..statement..  
    }  
}
```

# Functions

cognitive model  
statistics  
computing

The operation(s) to obtain some quantity, based on another quantity.

- built-in functions
- external functions (packages)
- user-defined functions



# User-defined Function

```
funname <- function (input_arges) {  
  .. function body ..  
  .. function body ..  
  return(output_arges)  
}
```

$$sem = \sqrt{\frac{s^2}{n - 1}}$$

```
sem <- function(x) {  
  sqrt( var(x,na.rm=TRUE) / (length(na.omit(x))-1) )  
}
```

# Exercise II

cognitive model  
statistics  
computing

.../01.R\_basics/\_scripts/R\_basics.R

**TASK:** practise control flow and user-defined function

# Exercise II

- Generate a random number between 0 and 1
- Compare it against 1/3 and 2/3
- Print the random number and its position relative to 1/3 and 2/3.

```
# if-else
t <- runif(1) # random number between 0 and 1
if (t <= 1/3) {
  cat("t =", , ", t <= 1/3. \n")
} else if () {
  cat("t =", t, ", t > 2/3. \n")
} else {
  cat("t =", t, ", 1/3 < t <= 2/3. \n")
}
```

Example outcome:

t = 0.895 , t > 2/3.

- Get the name of each month
- Print it one by one

```
# for-loop
month_name <- format(ISOdate(2018,1:12,1), "%B")
for (j in 1:length(month_name) ) {
  cat()
}
```

```
The month is January
The month is February
The month is March
The month is April
The month is May
The month is June
The month is July
The month is August
The month is September
The month is October
The month is November
The month is December
```

# Packages in R

R packages are collections of functions and data sets developed by the community, to make your life a lot easier!

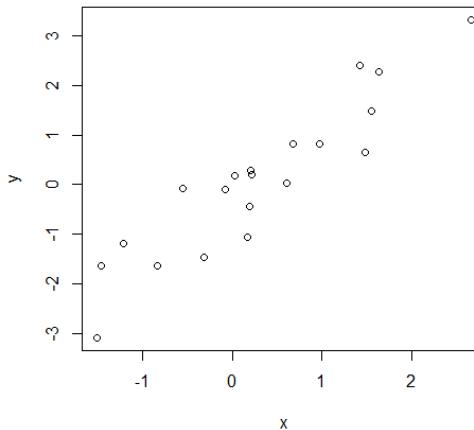
```
install.packages('ggplot2')
library(ggplot2)
detach('package:ggplot2')
```

# Visualization

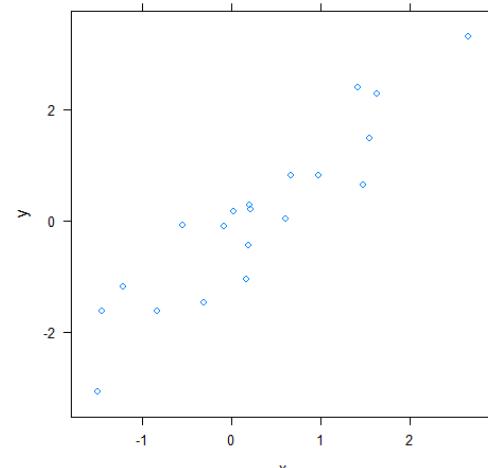
cognitive model  
statistics  
computing

- **built-in** plotting functions – first attempt / quick look / exploratory
- **{lattice}** – making nicer, similar to basic plotting functions (takes lm formulae)
- **{ggplot2}** – making nicer, a layering philosophy

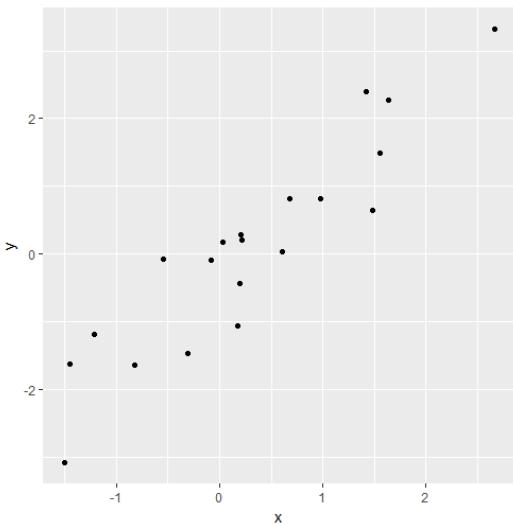
`plot(x,y)`



`lattice::xyplot(y~x)`



`ggplot2::qplot(x,y)`

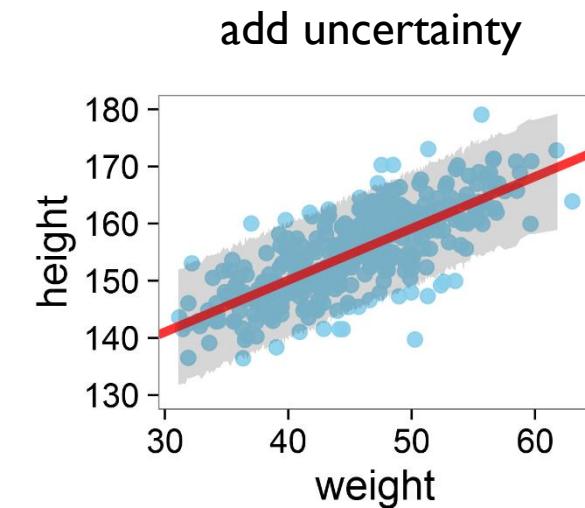
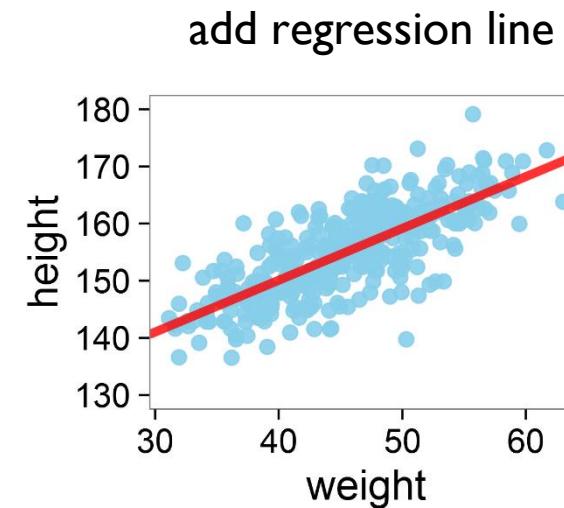
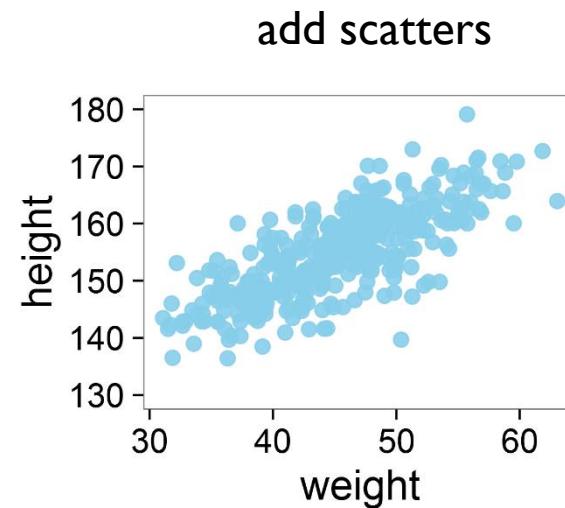
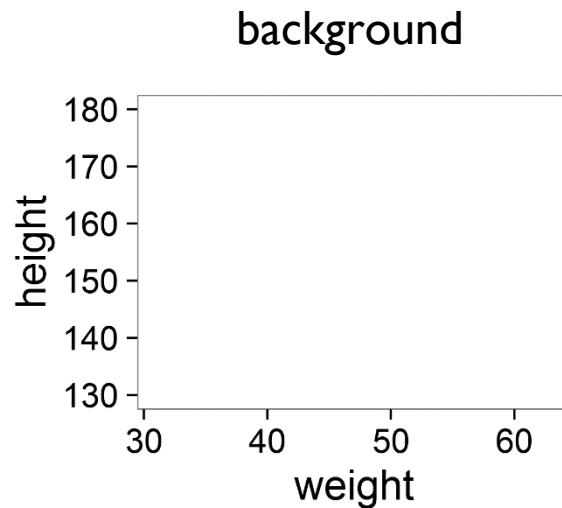


# Brief Intro to ggplot2

cognitive model  
statistics  
computing

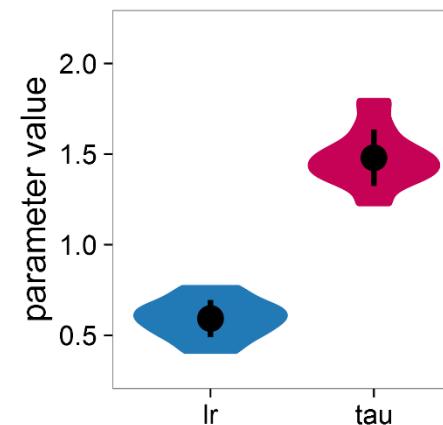
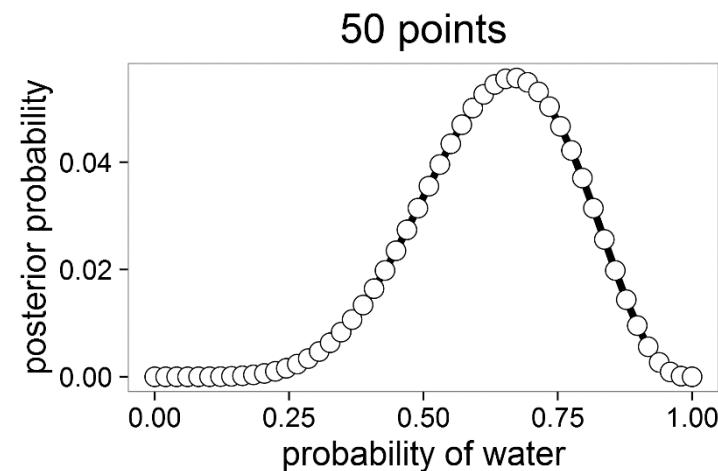
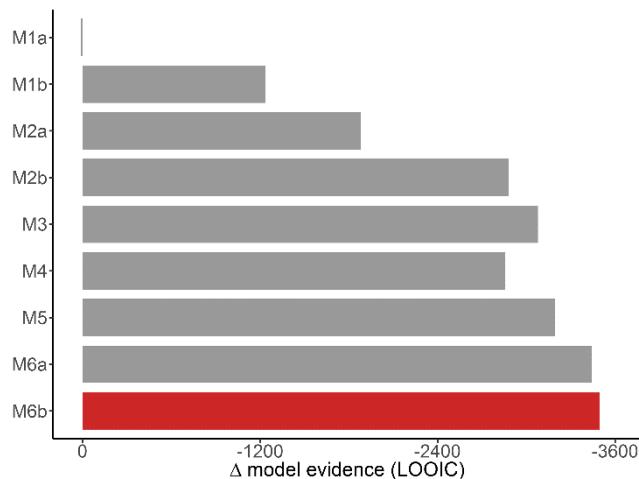
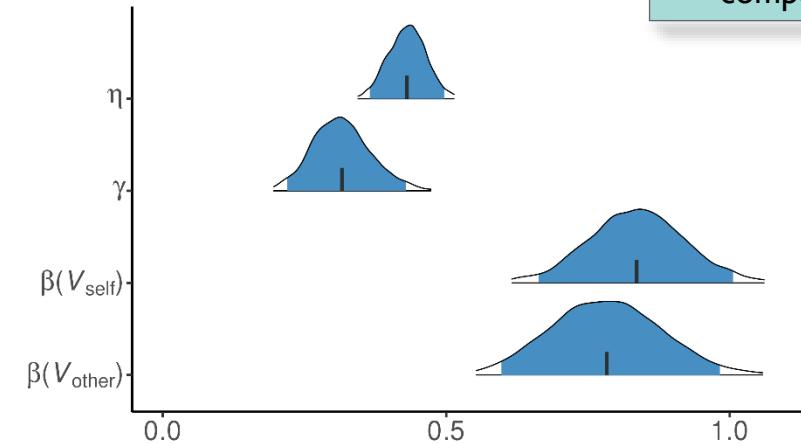
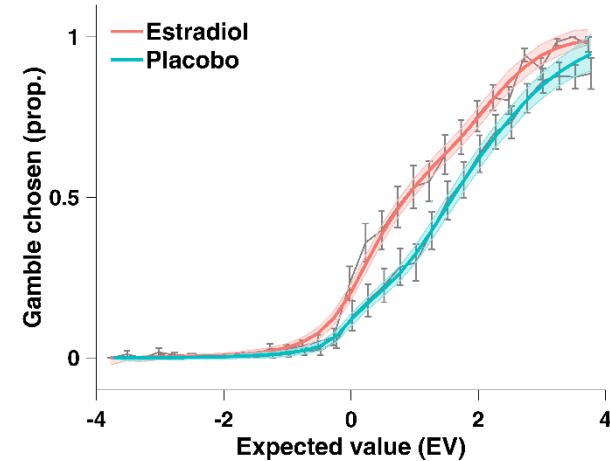
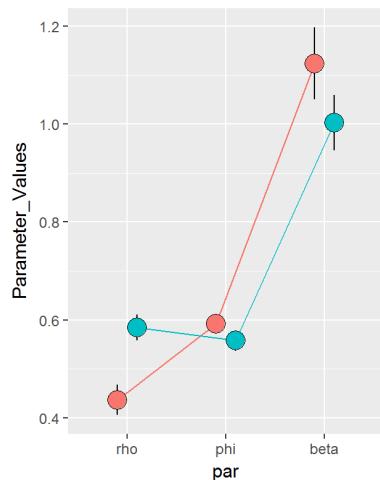
`plot = geometric (points, lines, bars) + aesthetic (color, shape, size)`

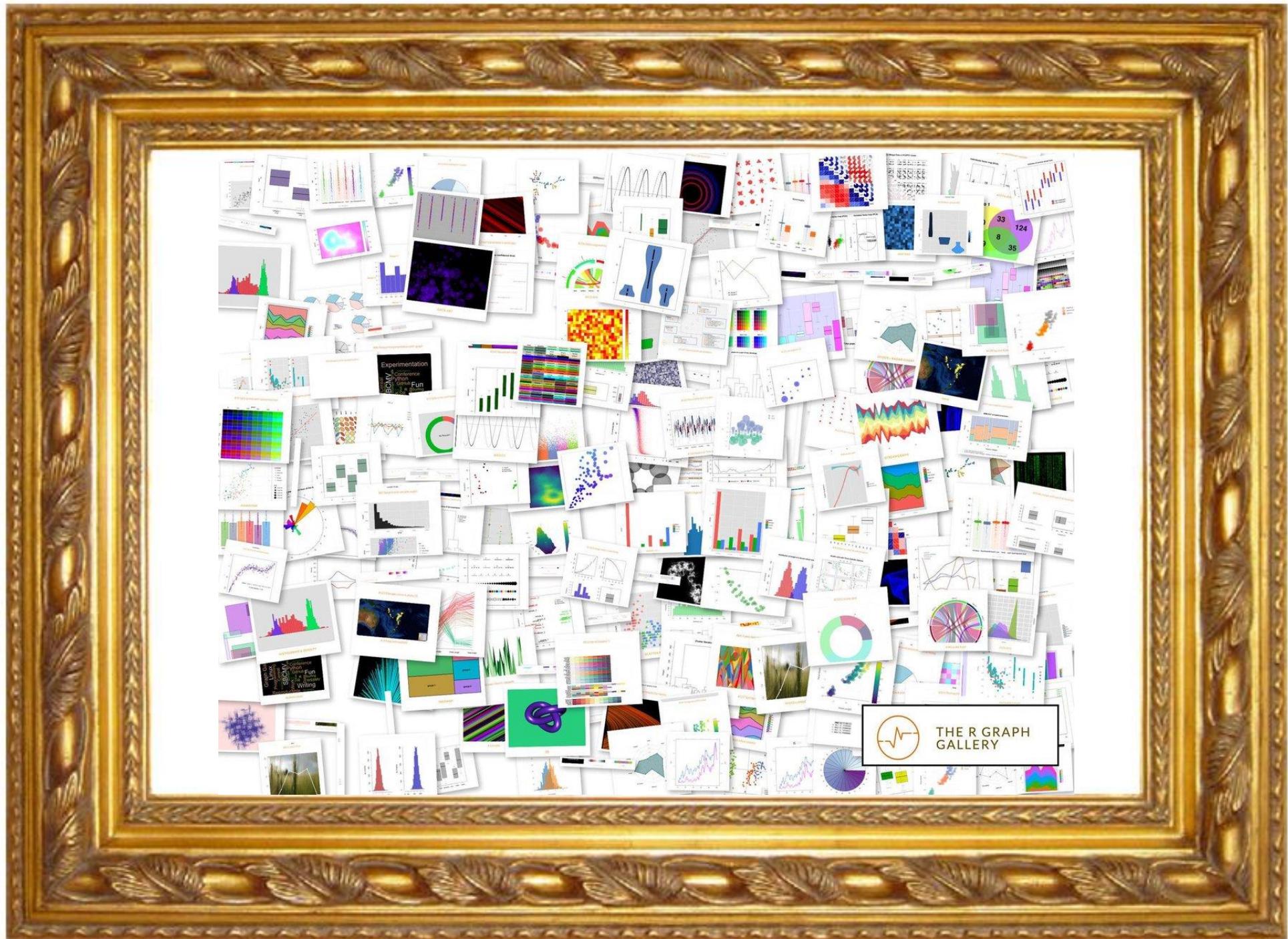
game of adding layers!



# A taste of ggplot2

cognitive model  
statistics  
computing

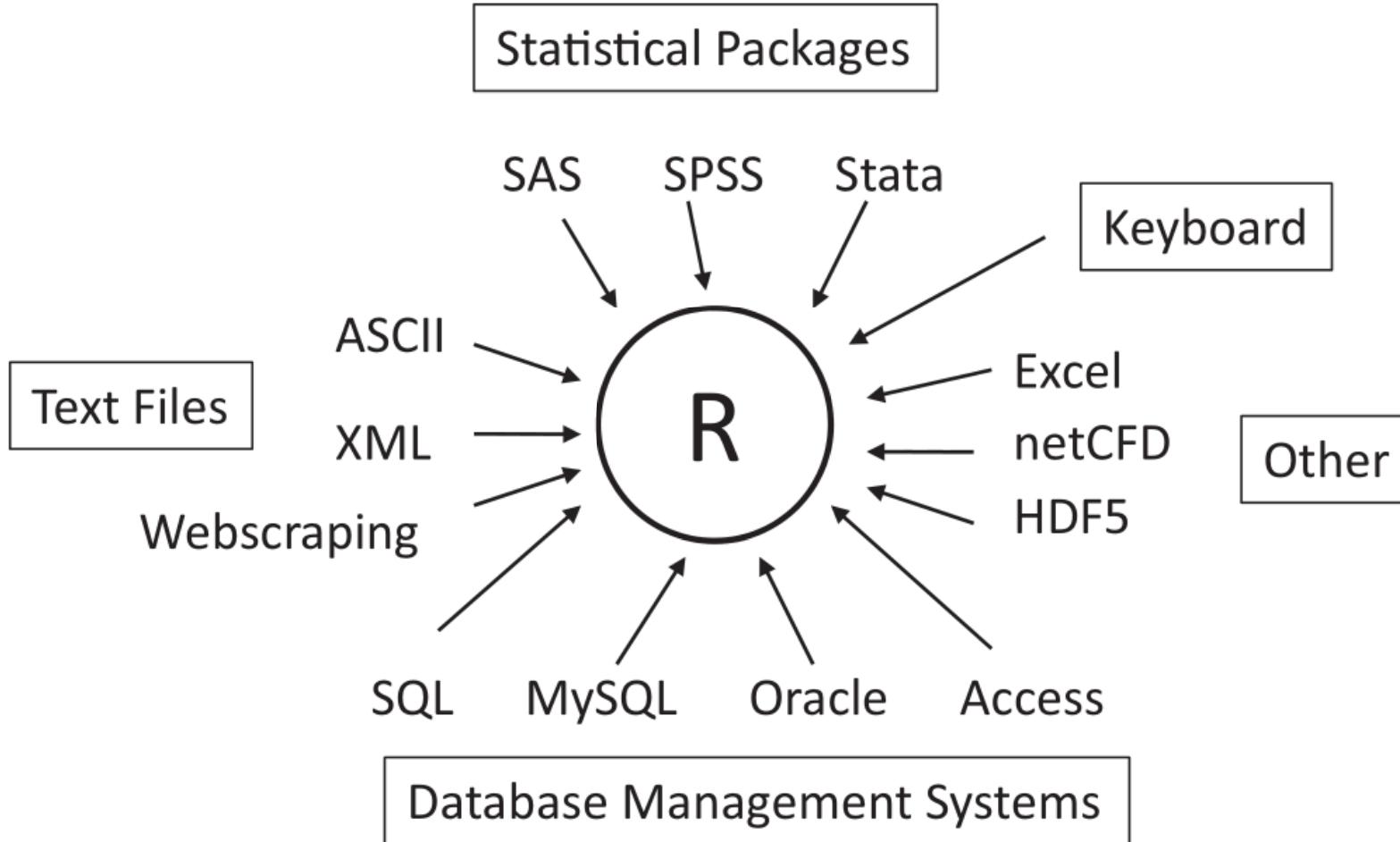




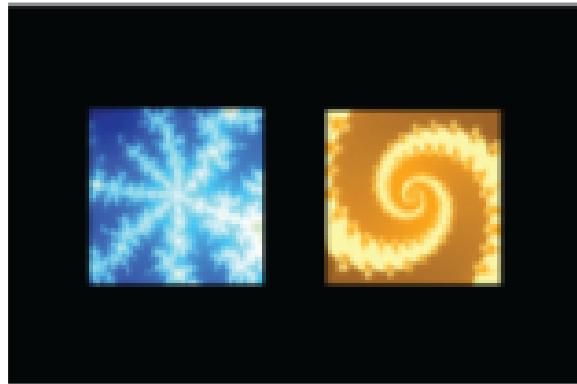
THE R GRAPH  
GALLERY

<https://www.r-graph-gallery.com/>

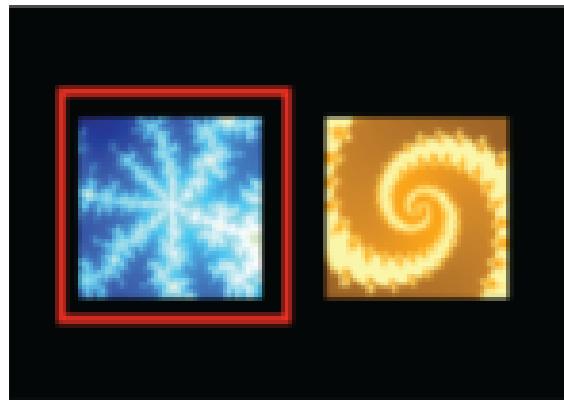
# Data management



# One simple experiment



choice  
presentation



action  
selection



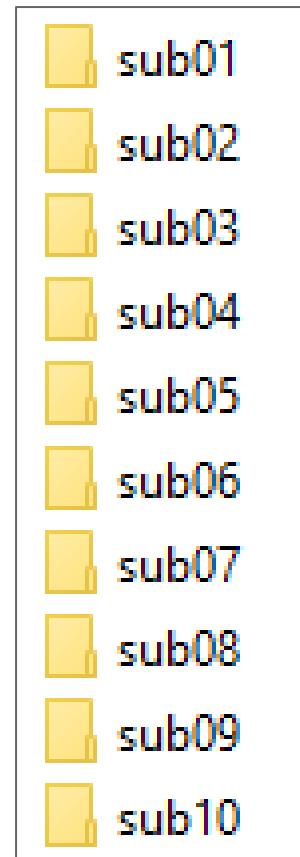
outcome

reward contingency – 80:20

# The data

- nSub = 10
- nTrial = 80

./\_data/\_raw\_data/sub01/raw  
\_data\_sub01.txt



subjID, trialID, choice, outcome, correct
1,1,2,-1,1
1,2,1,1,1
1,3,1,1,1
1,4,1,1,1
1,5,2,-1,1
1,6,1,1,1
1,7,1,1,1
1,8,1,1,1
1,9,1,-1,1
1,10,2,-1,1
1,11,1,1,1
1,12,1,1,1
1,13,1,-1,2

# Import some data!

```
data_dir = ('_data/RL_raw_data/sub01/raw_data_sub01.txt')
data = read.table(data_dir, header = T, sep = ",")
head(data)
```

	subjID	trialID	choice	outcome	correct
1	1	1	1	1	1
2	1	2	1	1	1
3	1	3	1	1	1
4	1	4	NA	1	1
5	1	5	1	-1	1
6	1	6	2	-1	1

# Indexing

```
data[1,1]
data[1,]
data[,1]
data[1:10,]
data[,1:2]
data[1:10, 1:2]
data[c(1,3,5,6), c(2,4)]  
  
data$choice
```

	subjID	trialID	choice	outcome	correct
1	1	1	1	1	1
2	1	2	1	1	1
3	1	3	1	1	1
5	1	5	1	-1	1
6	1	6	2	-1	1
7	1	7	1	1	1
8	1	8	1	1	1
9	1	9	1	1	1
10	1	10	1	1	1
11	1	11	1	1	1

# Import some data!

```
data_dir = ('_data/RL_raw_data/sub01/raw_data_sub01.txt')
data = read.table(data_dir, header = T, sep = ",")
head(data)
```

	subjID	trialID	choice	outcome	correct
1	1	1	1	1	1
2	1	2	1	1	1
3	1	3	1	1	1
4	1	4	NA	1	1
5	1	5	1	-1	1
6	1	6	2	-1	1

```
sum(complete.cases(data)) # number of valid trials
data = data[complete.cases(data),]
dim(data[complete.cases(data),])
```

# Exercise III

.../01.R\_basics/\_scripts/R\_basics.R

TASK:

write a for loop

... which reads in each participant's raw data

... and reshape it in the “long format” by subj

TIP: complete line 173; consider sprintf()

```
for ( j in 1:n ) {  
  read.table(file, header = T, sep = ",")  
}
```

subID	Choice
sub01	1
sub01	2
...	
sub02	2
sub02	2
...	
sub10	2
sub10	1

# Read all the data!

```
ns = 10
data_dir = '_data/RL_raw_data'

rawdata = c();
for (s in 1:ns) {
  sub_file = file.path(data_dir, sprintf('sub%02i/raw_data_sub%02i.txt',s,s))
  sub_data = read.table(sub_file, header = T, sep = ",")
  rawdata = rbind(rawdata, sub_data)
}
rawdata = rawdata[complete.cases(rawdata),]
rawdata$accuracy = (rawdata$choice == rawdata$correct) * 1.0

acc_mean = aggregate(rawdata$accuracy, by = list(rawdata$subjID), mean)[,2]
```

mean choice accuracy across trials, per participant.

# Basic stats

```
mean(acc_mean)  
sd(acc_mean)  
sem(acc_mean)
```

```
t.test(acc_mean, mu = 0.5) # one sample t-test
```

One Sample t-test

```
data: acc_mean
```

```
t = 13.788, df = 9, p-value = 2.34e-07
```

alternative hypothesis: true mean is not equal to 0.5

95 percent confidence interval:

0.6962988 0.7733565

sample estimates:

mean of x

0.7348277

```
> as.matrix(acc_mean, 10, 1)  
[1,] 0.8076923  
[2,] 0.7125000  
[3,] 0.6875000  
[4,] 0.6493506  
[5,] 0.7750000  
[6,] 0.7250000  
[7,] 0.7662338  
[8,] 0.8000000  
[9,] 0.7500000  
[10,] 0.6750000
```

# Basic correlation

```
load('_data/RL_descriptive.RData')
descriptive$acc = acc_mean
df = descriptive
```

```
cor.test(df$IQ, df$acc)
```

Pearson's product-moment correlation

data: df\$IQ and df\$acc

t = 4.8347, df = 8, p-value = 0.001297

alternative hypothesis: true correlation is not equal to 0

95 percent confidence interval:

0.5114810 0.9671586

sample estimates:

```
cor
0.8631401
```

	subjID	IQ	Age	acc
1	1	123.98691	31.07218	0.8125
2	2	87.63187	30.13800	0.7125
3	3	89.39930	23.44219	0.6875
4	4	84.34607	27.44848	0.6500
5	5	134.72208	23.30624	0.7750
6	6	84.60797	25.67858	0.7250
7	7	111.10238	24.36375	0.7750
8	8	117.89599	32.74026	0.8000
9	9	96.88233	22.80211	0.7500
10	10	76.01652	30.44258	0.6750

# Exercise IV

```
.../01.R_basics/_scripts/R_basics.R
```

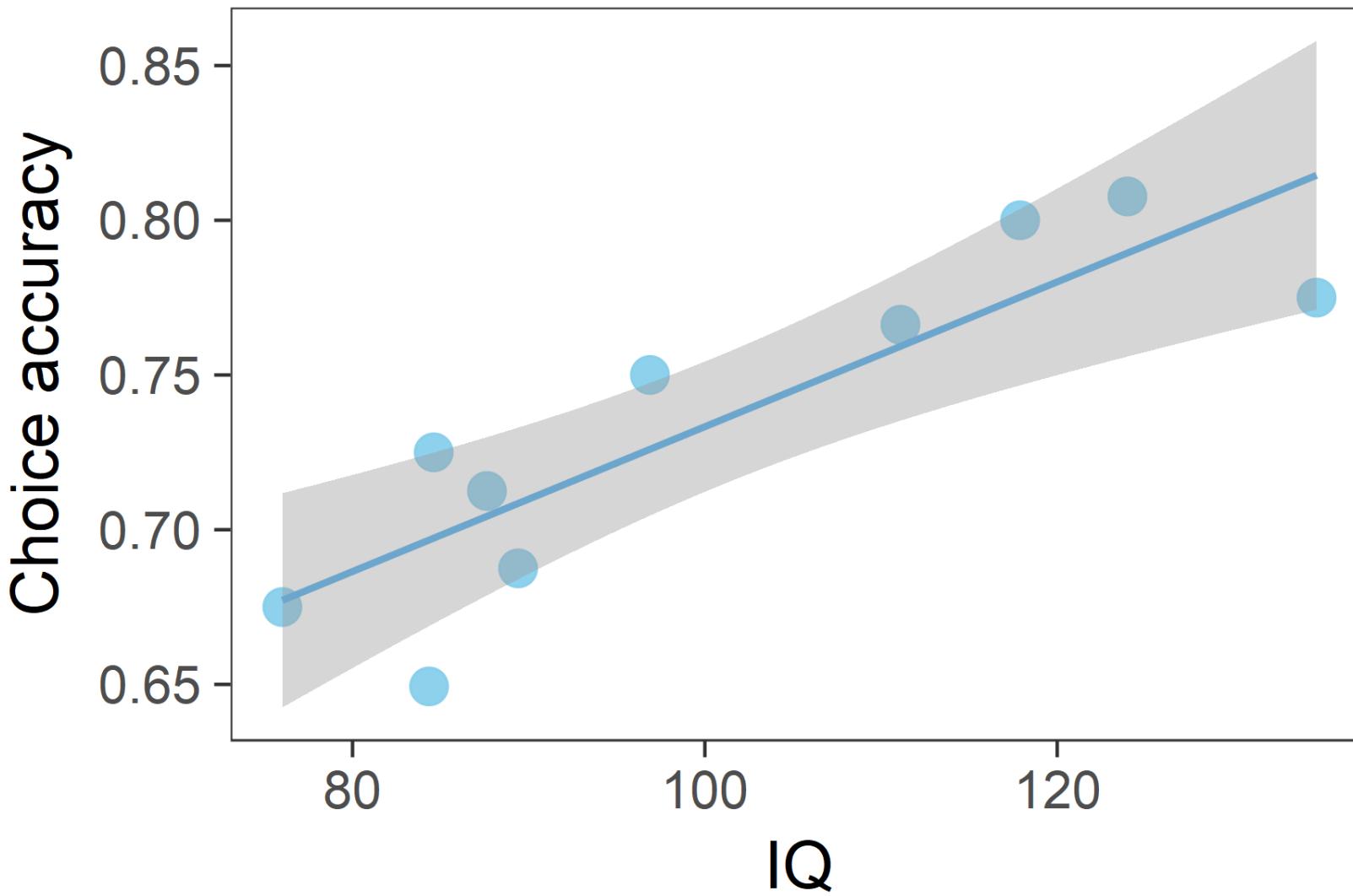
TASK:

Read in the descriptive data: \_data/descriptive.RData  
...include 'acc\_mean' as a new column, and  
...rename 'descriptive' as df.

Practice all the basic stats.

```
df$new_Col = new_Col
```

# A simple linear regression



# What is exactly the regression line in R?

```
fit1 = lm(acc ~ IQ, data = df)
summary(fit1)
```

Call:

```
lm(formula = acc ~ IQ, data = df)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.047305	-0.016277	0.007562	0.022577	0.027731

$$\mu_i = \alpha + \beta x_i$$

$$y_i = \mu_i + \varepsilon$$

Coefficients:

	Estimate	Std. Error	t value	Pr(> t )
(Intercept)	0.499292	0.049565	10.073	8.04e-06 ***
IQ	0.002340	0.000484	4.835	0.0013 **

---

Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.02885 on 8 degrees of freedom

Multiple R-squared: 0.745, Adjusted R-squared: 0.7131

F-statistic: 23.37 on 1 and 8 DF, p-value: 0.001297

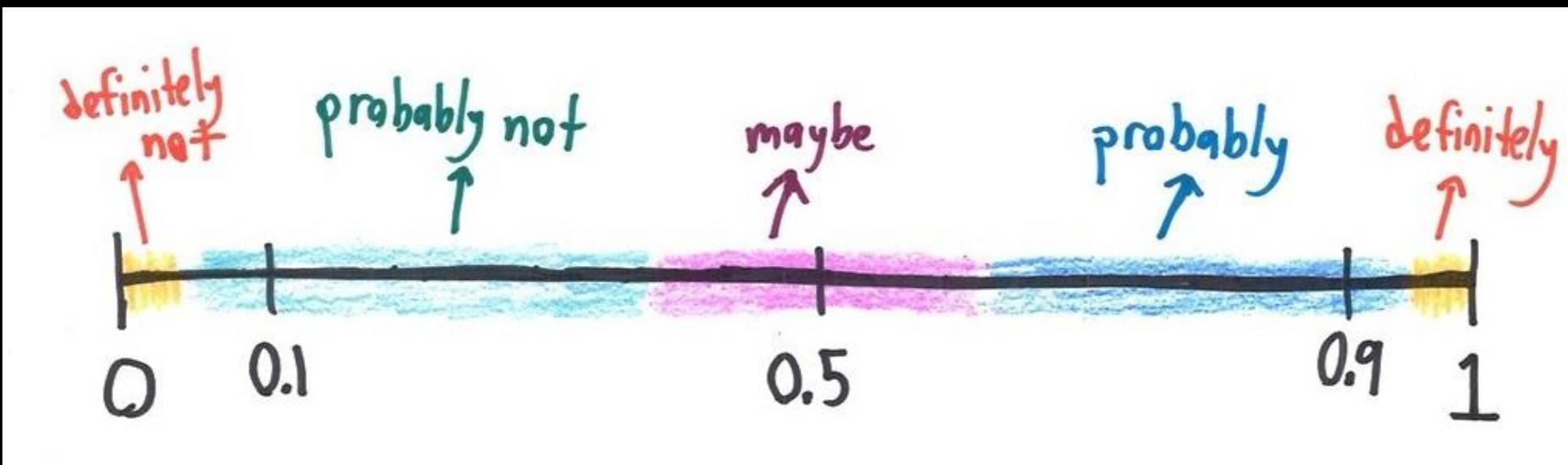
## Exercise V

.../01.R\_basics/\_scripts/R\_basics.R

### TASK:

Read and make sense of the ggplot functions,  
... experiment make some adjustments (color marker size etc. ), and  
... run the `lm(acc ~ IQ)`

# BASICS OF PROBABILITY



## to respondents' estimate of likelihood

### Word or phrase

Always

Certainly

Slam dunk

Almost certainly

Almost always

With high probability

Usually

Likely

Frequently

Probably

Often

Serious possibility

More often than not

Real possibility

With moderate probability

Maybe

Possibly

Might happen

Not often

Unlikely

With low probability

Rarely

Never

0% 50% 100%

# Probability

cognitive model  
statistics  
computing

...assigning numbers to a set of possibilities

Properties (Kolmogorov, 1956)

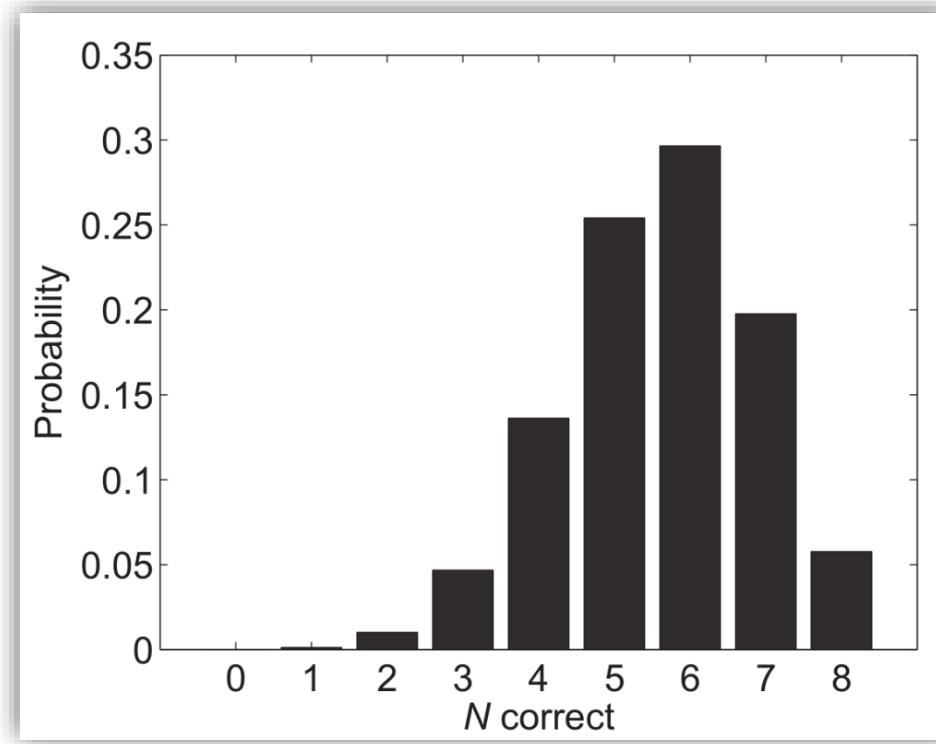
- $p \in [0,1]$
- $\sum p = 1$

Probabilities are used to express uncertainty.

# Probability Functions

discrete events – we talk about **mass**

Run a test and record each student's correct responses

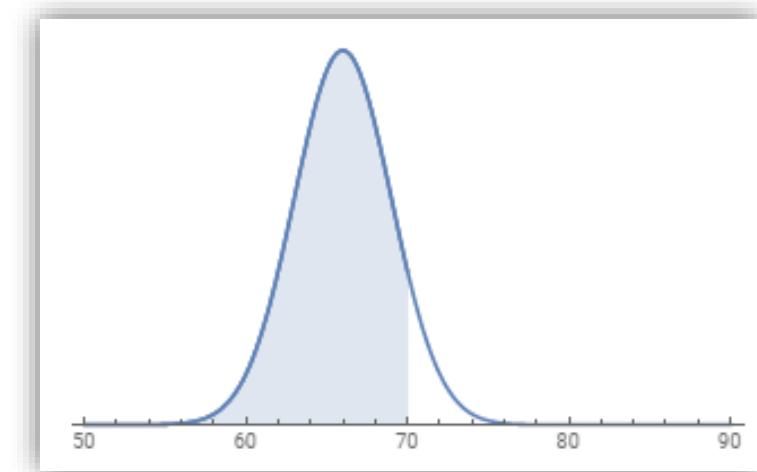
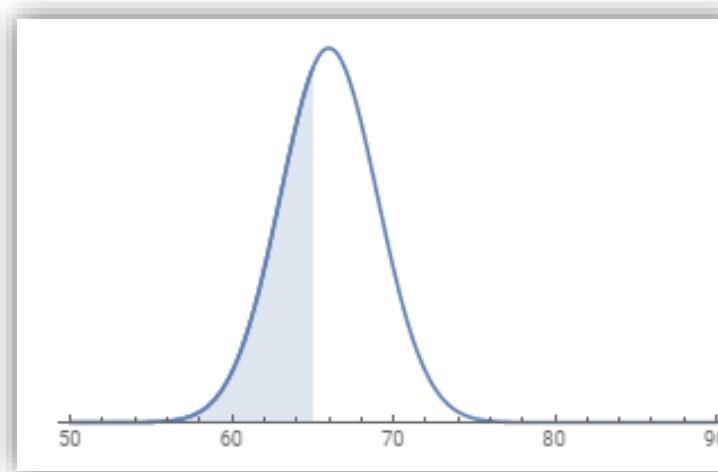


# Probability Functions

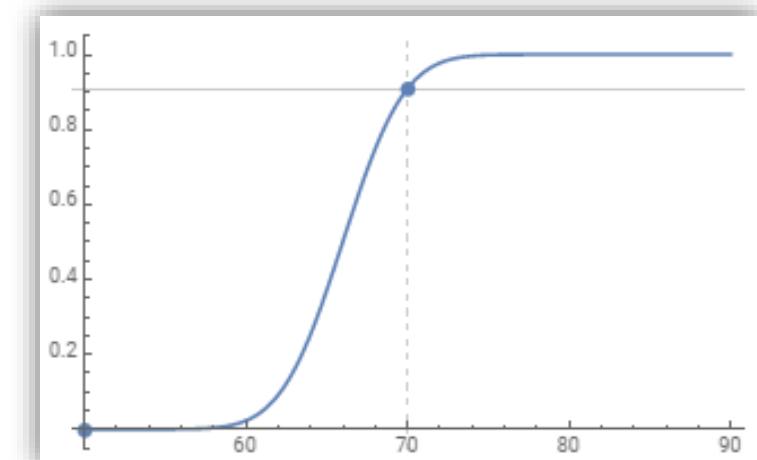
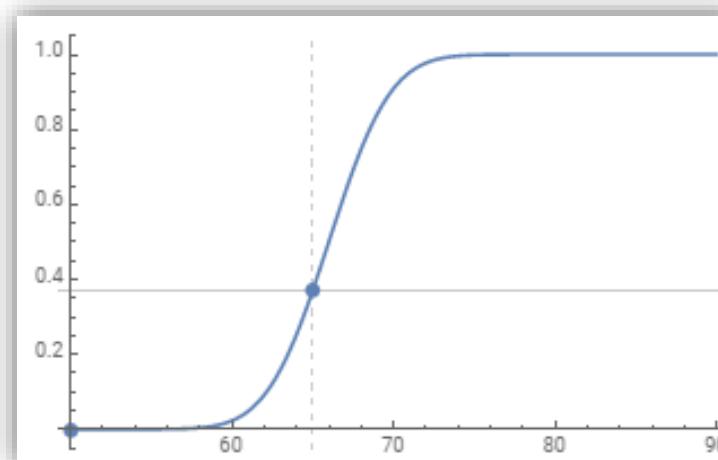
cognitive model  
statistics  
computing

continuous events – we talk about **density**

probability density function  
(PDF)

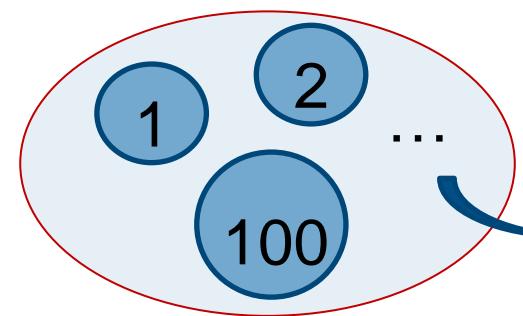


cumulative distribution function  
(CDF)



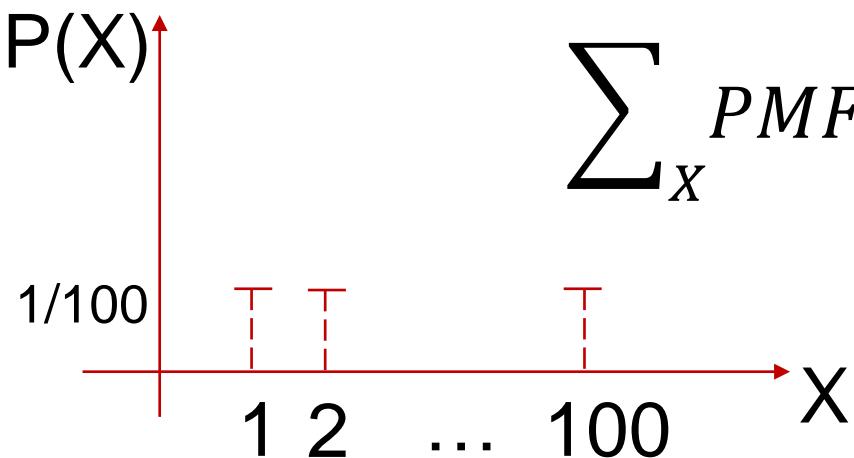
## Another example

Discrete



X	P(X)
1	1/100
2	1/100
...	...
100	1/100

$$\sum_X PMF(X) = 1$$

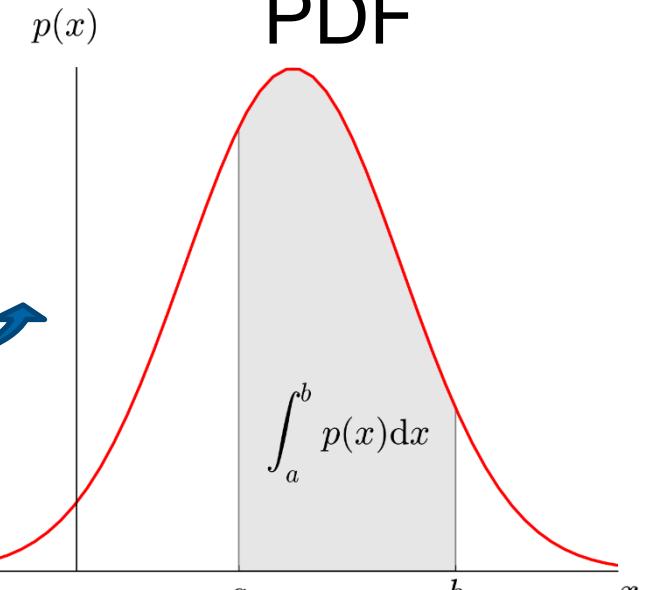


Continuous

Height

DE POPULATION

X	P(X)
1.8 m	0



P given by the area

$$1.75 \leq X \leq 1.85$$

# Playing with Probability Functions in R

cognitive model  
statistics  
computing

`dnorm()` – PDF

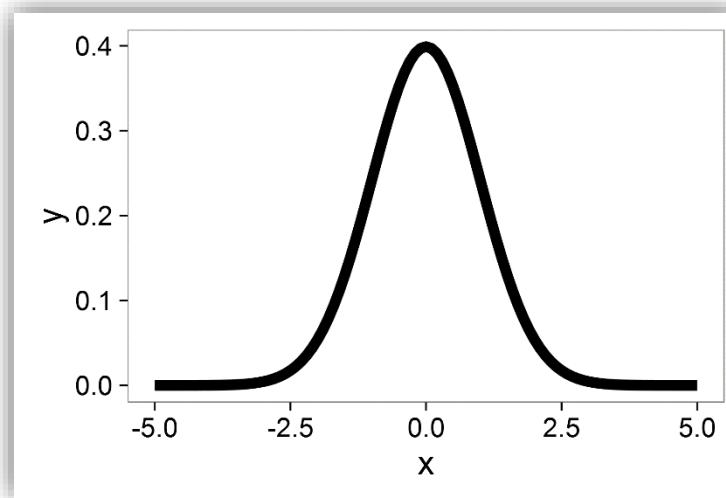
`pnorm()` – CDF

`qnorm()` – quantile, inverse cdf

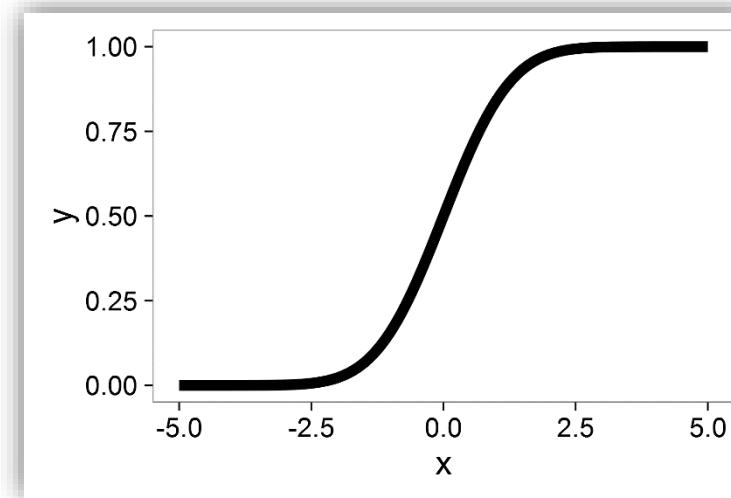
`rnorm()` – random number generator

# Example: Normal(0,1)

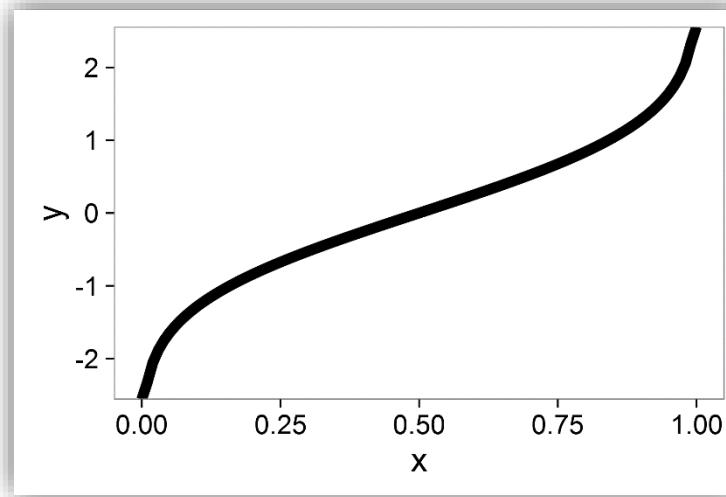
`dnorm()`



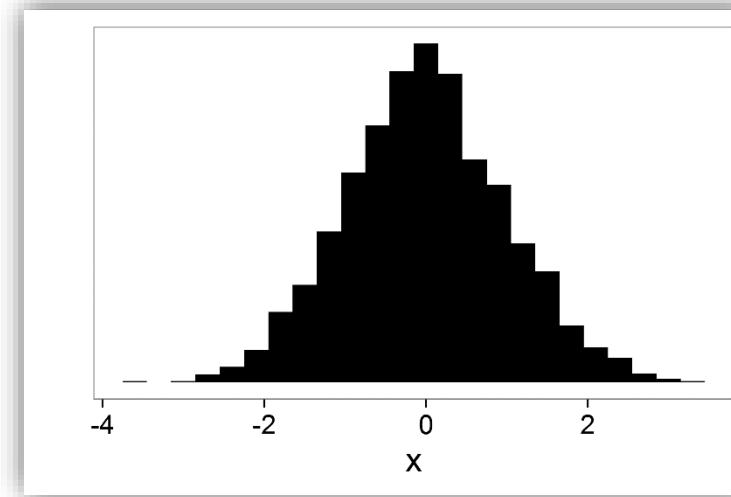
`pnorm()`



`qnorm()`



`rnorm()`



# Joint, Marginal and Conditional Probability

## Joint Probability

$$p(A, B) = p(B, A)$$

- e.g.,  $p(\text{rain, cold})$ :  $p(\text{rain})$  AND  $p(\text{cold})$

## Marginal Probability

$p(A)$  – ‘ $p$  of A irrespective of B’

- e.g.,  $p(\text{rain})$ :  $p(\text{rain, cold}) + p(\text{rain, not cold})$

## Conditional Probability

$p(A|B)$  – ‘ $p$  of A given B’ – event B is fixed, not uncertainty

$$p(A,B) = p(A|B)p(B)$$

- e.g.,  $p(\text{rain, cold}) = p(\text{rain|cold})p(\text{cold})$

# Example I: discrete

Joint probability :

$$P(X = 0, Y = 1) =$$

$$\sum_{x,y} P(X = x, Y = y) = 1$$

		rain	x
		1	0
		1	0.1
		0	0.3
Y		0.5	0.1

Marginal probability :

$$P(Y = 1) =$$

$$P(X = 0) =$$

Conditional probability :

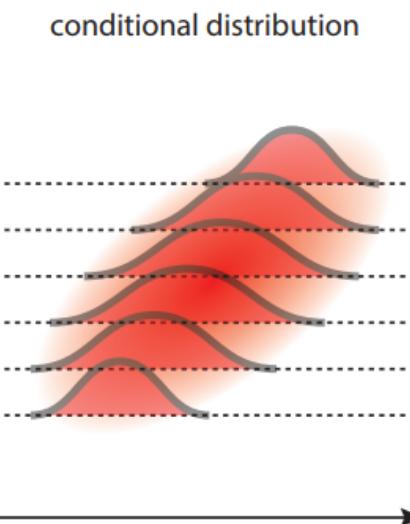
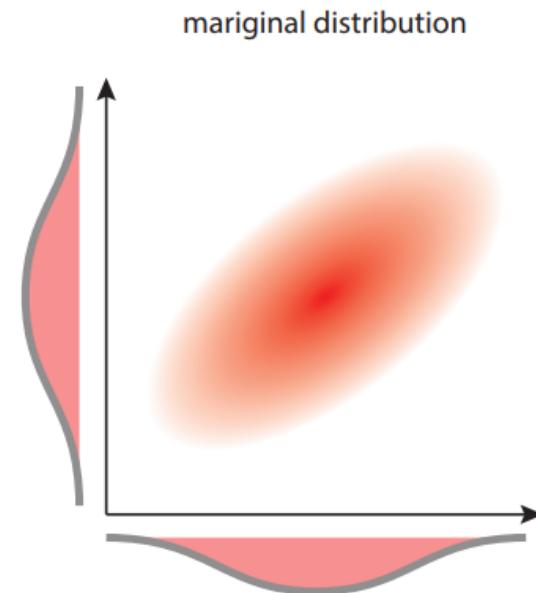
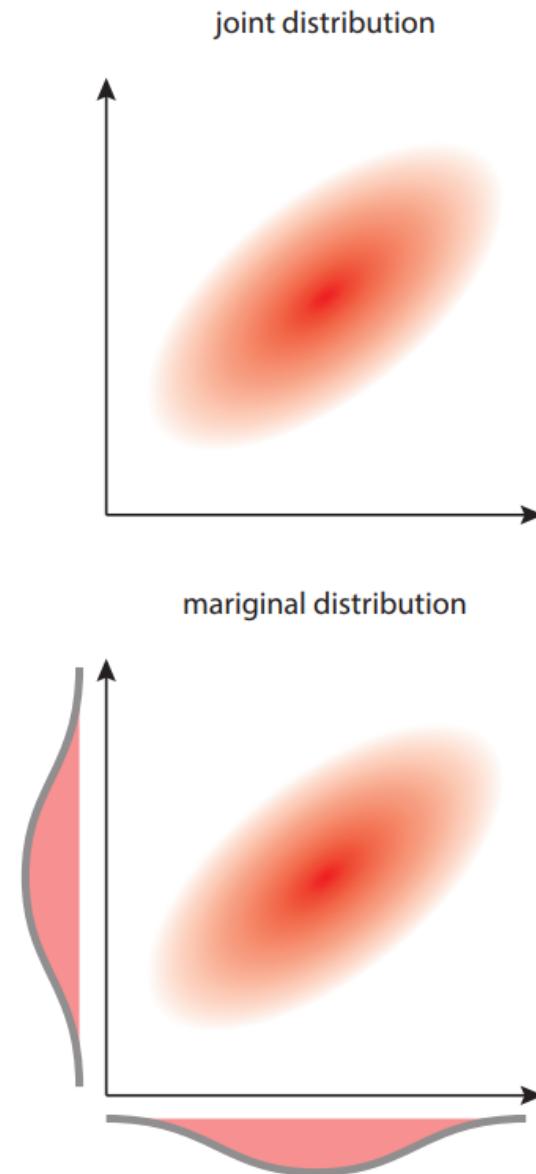
$$P(X = 1|Y = 1) =$$

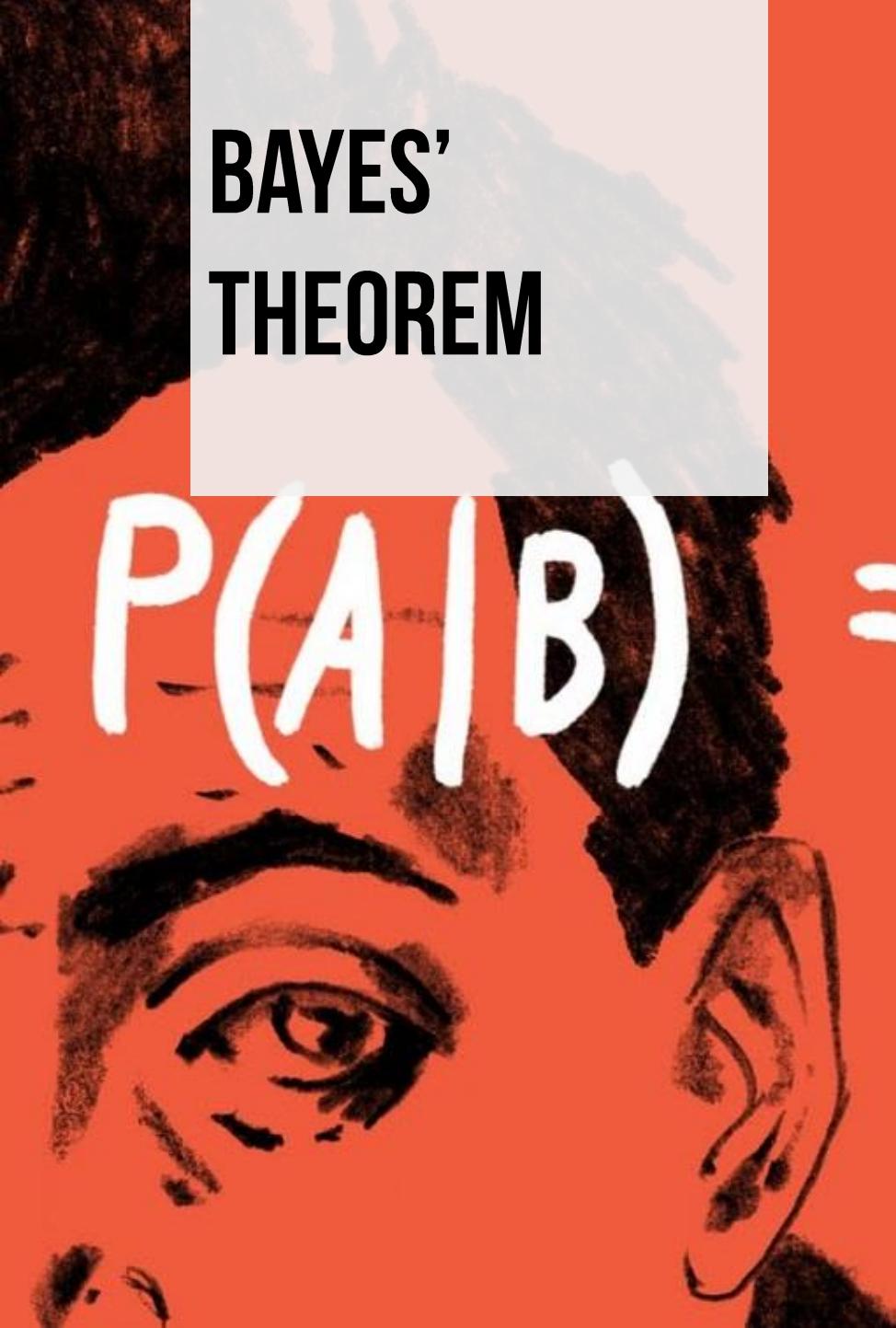
$$P(X = x) = \sum_y P(X = x, Y = y)$$

$$P(X = x|Y = y) = \frac{P(X = x, Y = y)}{P(Y = y)}$$

$$= \frac{P(X = x, Y = y)}{\sum_x P(X = x, Y = y)}$$

# Example I: continuous





# BAYES' THEOREM

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

# Bayes' theorem

$$p(A,B) = p(B,A)$$

$$p(A,B) = p(A|B)p(B)$$

$$p(B,A) = p(B|A)p(A)$$

$$p(A|B)p(B) = p(B|A)p(A)$$

$$p(A | B) = \frac{p(B | A)p(A)}{p(B)}$$

# Second Example

cognitive model  
statistics  
computing

		Column		Marginal
Row	...	$c$	...	
:			:	
$r$	...	$p(r, c) = p(r c) p(c)$	...	$p(r) = \sum_{c^*} p(r c^*) p(c^*)$
:			:	
Marginal		$p(c)$		

## Second Example

cognitive model  
statistics  
computing

Eye color	Hair color				Marginal (Eye color)
	Black	Brunette	Red	Blond	
Brown	0.11	0.20	0.04	0.01	0.37
Blue	0.03	0.14	0.03	0.16	0.36
Hazel	0.03	0.09	0.02	0.02	0.16
Green	0.01	0.05	0.02	0.03	0.11
Marginal (hair color)	0.18	0.48	0.12	0.21	1.0

$$p(A | B) = \frac{p(B | A)p(A)}{\sum_{A^*} p(B | A^*)p(A^*)}$$

# Exercise VI

cognitive model  
statistics  
computing

Suppose that in the general population, the probability of having a rare disease is 1/1000. We denote the true presence or absence of the disease as the value of a parameter,  $\vartheta$ , that can have the value  $\vartheta = \text{😊}$  if disease is present in a person, or the value  $\vartheta = \text{☺}$  if the disease is absent. The base rate of the disease is therefore denoted  $p(\vartheta = \text{😊}) = 0.001$ .

Suppose(1): a test for the disease that has a 99% hit rate:  $p(T = + | \vartheta = \text{😊}) = 0.99$

Suppose(2): the test has a false alarm rate of 5%:  $p(T = + | \vartheta = \text{☺}) = 0.05$

Q: Suppose we sample a person at random from the population, administer the test, and it comes up positive. What is the posterior probability that the person has the disease?

# Exercise VI

cognitive model  
statistics  
computing

Q: What is the posterior probability that the person has the disease?

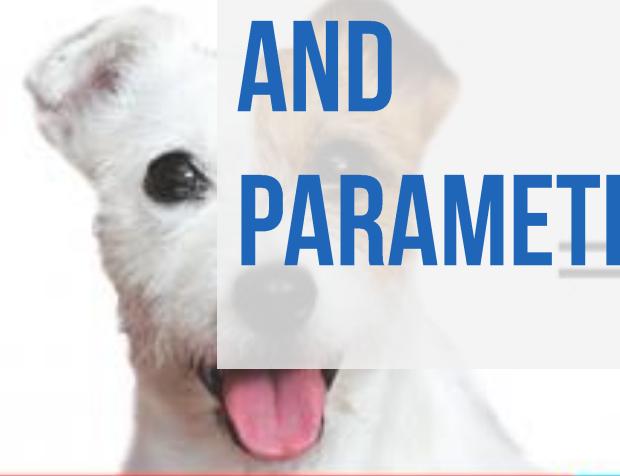
$$\rightarrow p(\vartheta = \text{患病} | T = +)$$

# Exercise VI

Test result	Disease		Marginal (test result)
	$\theta = \ddot{\circ}$ (present)	$\theta = \circ$ (absent)	
$T = +$	$p(+ \ddot{\circ}) p(\ddot{\circ})$ $= 0.99 \cdot 0.001$	$p(+ \circ) p(\circ)$ $= 0.05 \cdot (1 - 0.001)$	$\sum_{\theta} p(+ \theta) p(\theta)$
$T = -$	$p(- \ddot{\circ}) p(\ddot{\circ})$ $= (1 - 0.99) \cdot 0.001$	$p(- \circ) p(\circ)$ $= (1 - 0.05) \cdot (1 - 0.001)$	$\sum_{\theta} p(- \theta) p(\theta)$
Marginal (disease)	$p(\ddot{\circ}) = 0.001$	$p(\circ) = 1 - 0.001$	1.0

$$\begin{aligned}
 p(\theta = \ddot{\circ} | T = +) &= \frac{p(T = + | \theta = \ddot{\circ}) p(\theta = \ddot{\circ})}{\sum_{\theta} p(T = + | \theta) p(\theta)} \\
 &= \frac{0.99 \cdot 0.001}{0.99 \cdot 0.001 + 0.05 \cdot (1 - 0.001)} \\
 &= 0.019
 \end{aligned}$$

# LINKING DATA AND PARAMETER



$p(\theta | D)$

$p(D | \theta)$

$p(\theta)$

$p(D)$

# Linking Data and Parameter

cognitive model  
statistics  
computing

$$p(A|B) = \frac{p(B|A)p(A)}{p(B)}$$

A diagram illustrating the components of the Bayes' rule formula. On the left, there is a term  $p(A|B)$ . Two arrows point towards it: one from the parameter  $\theta$  above, and another from the data  $D$  above. This visualizes how both parameters and data contribute to the posterior probability.

# Linking Data and Parameter

cognitive model  
statistics  
computing

$$p(\theta|D) = \frac{p(D|\theta)p(\theta)}{p(D)}$$

# Linking Data and Parameter

cognitive model  
statistics  
computing

## Likelihood

How plausible is the data given our parameter is true?

## Prior

How plausible is our parameter before observing the data?

$$p(\theta|D) = \frac{p(D|\theta)p(\theta)}{p(D)}$$

## Posterior

How plausible is our parameter given the observed data?

## Evidence

How plausible is the data under all possible parameters?

# What is $p(\text{Data} | \vartheta)$

$L(\theta | \text{Data})$

- This is the “Model”
- Data is fixed,  $\vartheta$  varies
- Not a probability distribution
  - the sum is not “one”

$$Pr(X = 0 | \theta) = Pr(T, T | \theta) = Pr(T | \theta) \times Pr(T | \theta) = (1 - \theta)^2$$

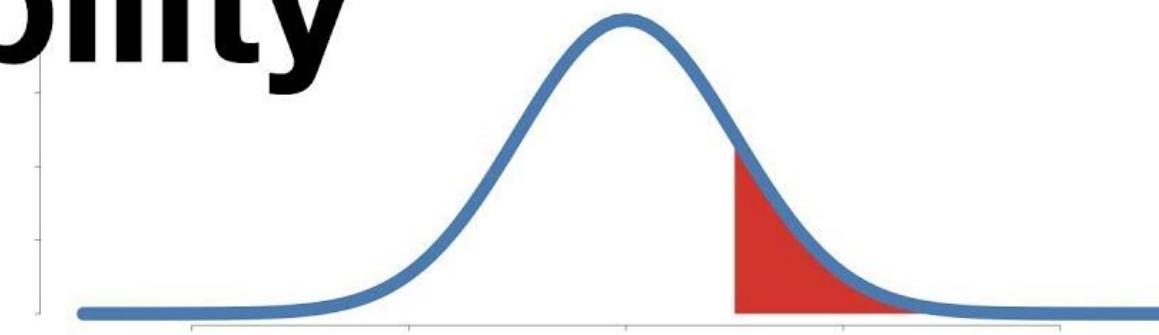
$$Pr(X = 1 | \theta) = Pr(H, T | \theta) + Pr(T, H | \theta) = 2 \times Pr(T | \theta) \times Pr(H | \theta) = 2\theta(1 - \theta)$$

$$Pr(X = 2 | \theta) = Pr(H, H | \theta) = Pr(H | \theta) \times Pr(H | \theta) = \theta^2.$$

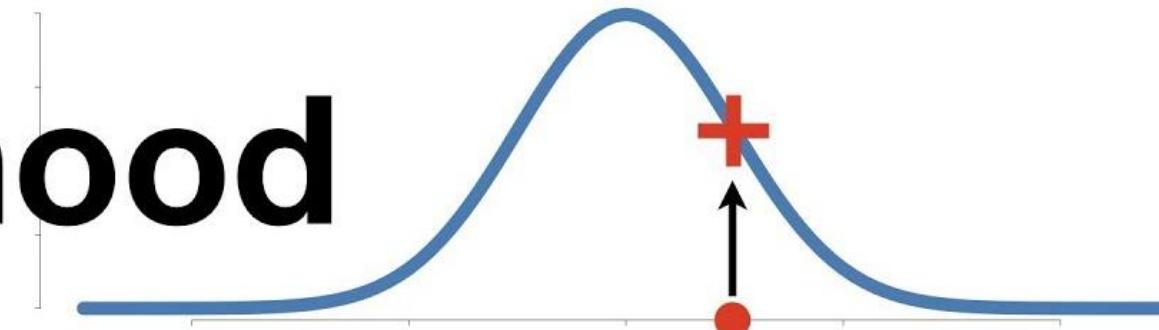
Probability of coin landing heads up, $\theta$	Number of heads, $X$				Total
	0	1	2		
0.0	1.00	0.00	0.00	1.00	
0.2	0.64	0.32	0.04	1.00	
0.4	0.36	0.48	0.16	1.00	
0.6	0.16	0.48	0.36	1.00	
0.8	0.04	0.32	0.64	1.00	
1.0	0.00	0.00	1.00	1.00	
Total	2.20	1.60	2.20		

**Watch this video!**

# Probability vs

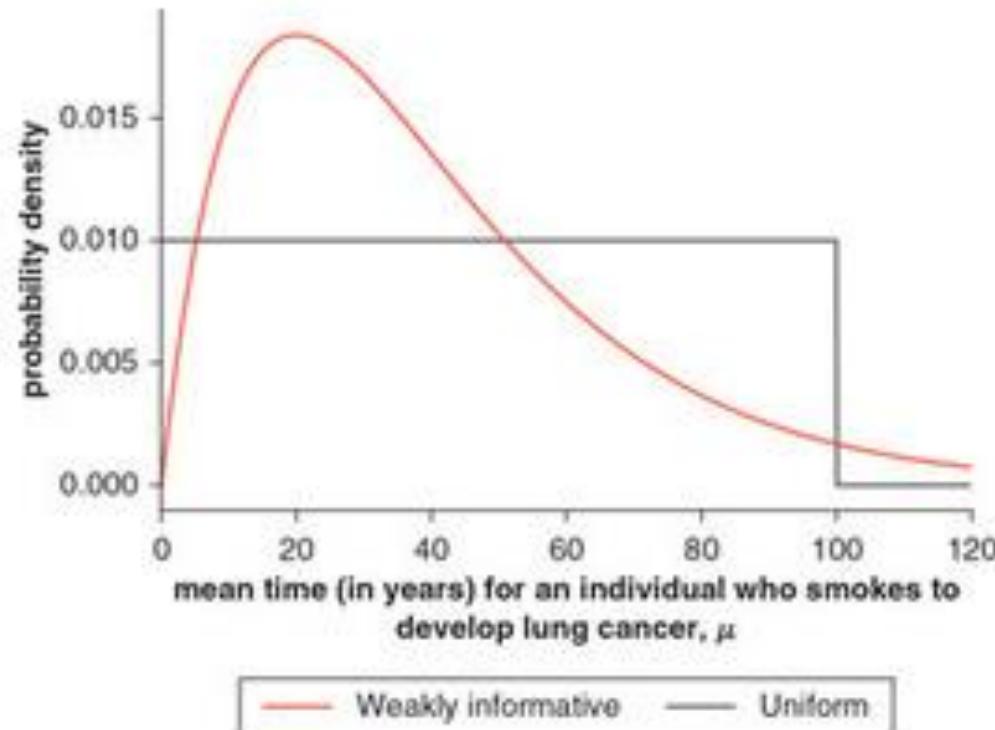


# Likelihood



StatQuest with Josh Starmer ✓  
250K subscribers

# What is $p(\vartheta)$ ?



# What is $p(\text{Data})$ ?

discrete parameters

$$p(\theta | D) = \frac{p(D | \theta)p(\theta)}{\sum_{\theta^*} p(D | \theta^*)p(\theta^*)}$$

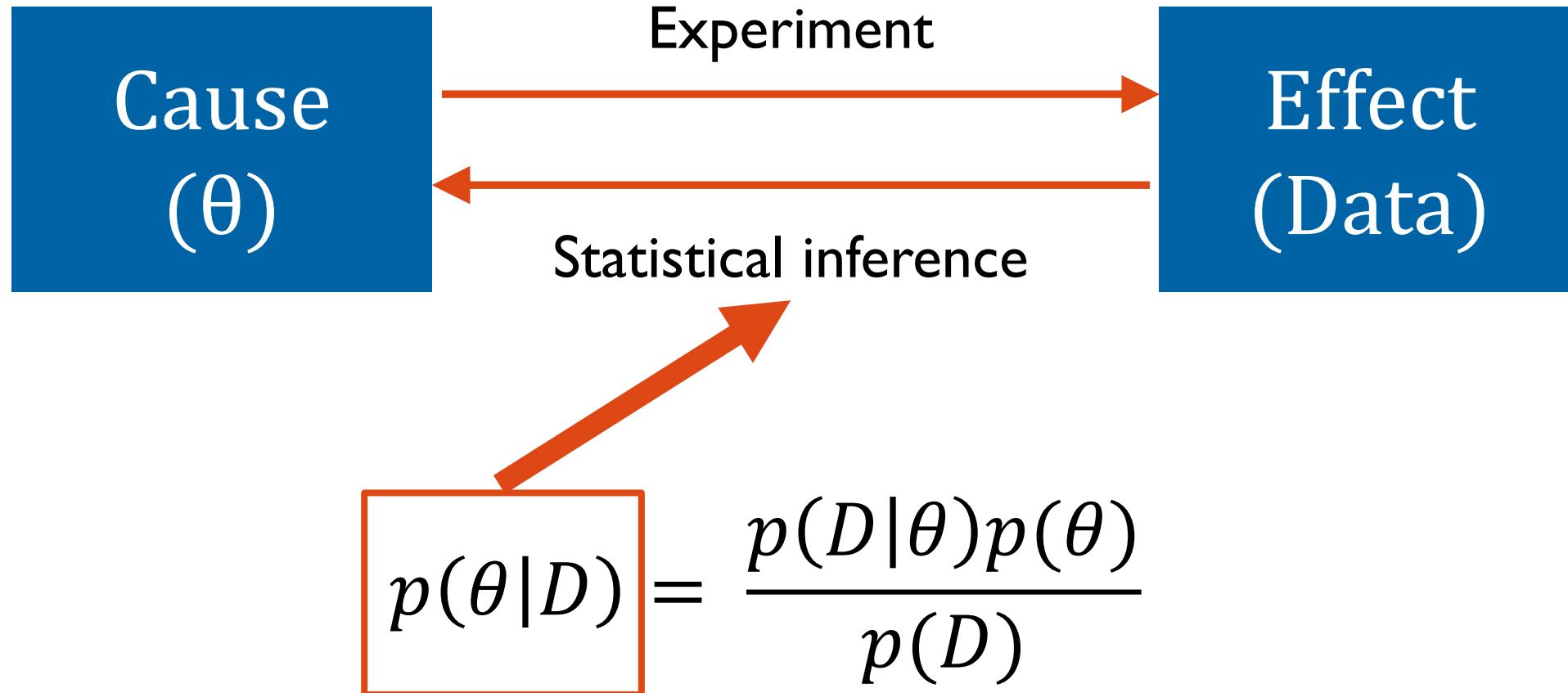
$$p(\theta | D) = \frac{p(D | \theta)p(\theta)}{p(D)}$$

continuous parameters

$$p(\theta | D) = \frac{p(D | \theta)p(\theta)}{\int p(D | \theta^*)p(\theta^*) d\theta^*}$$

# Why the Bayes' theorem is important?

cognitive model  
statistics  
computing



# **BINOMIAL MODEL**



# Binomial Model

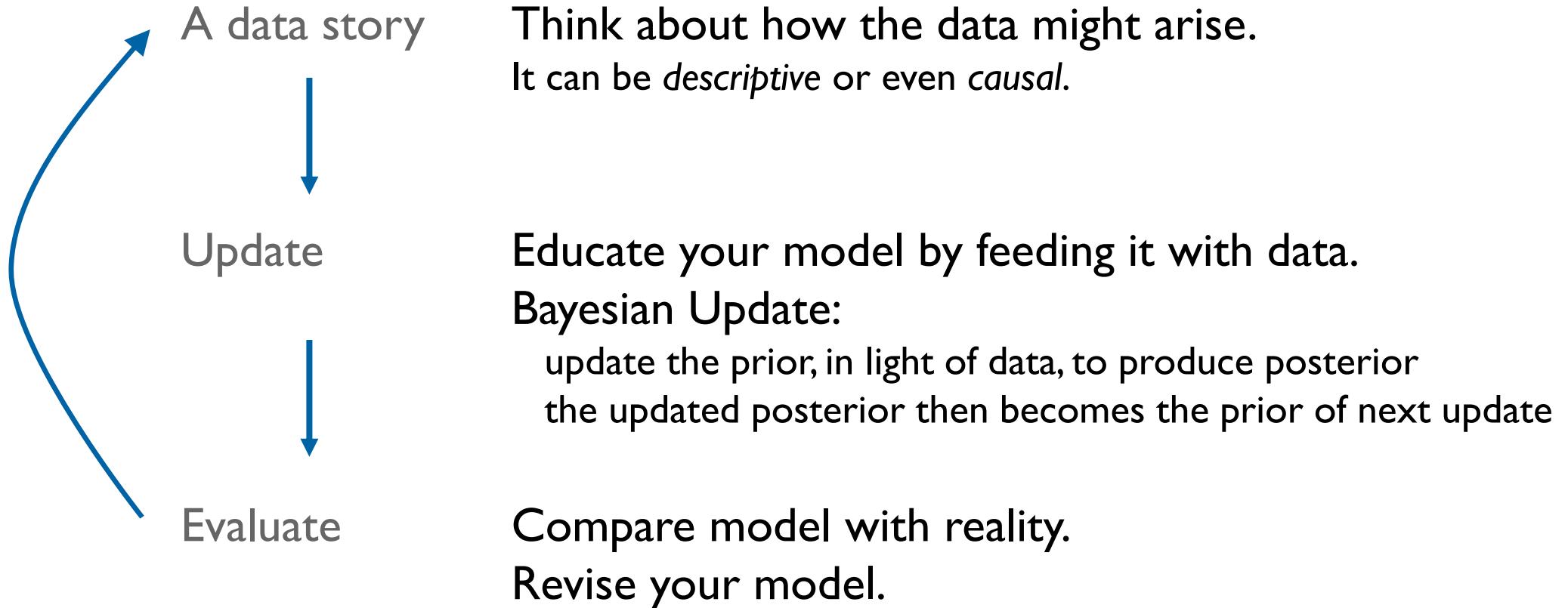
cognitive model  
statistics  
computing

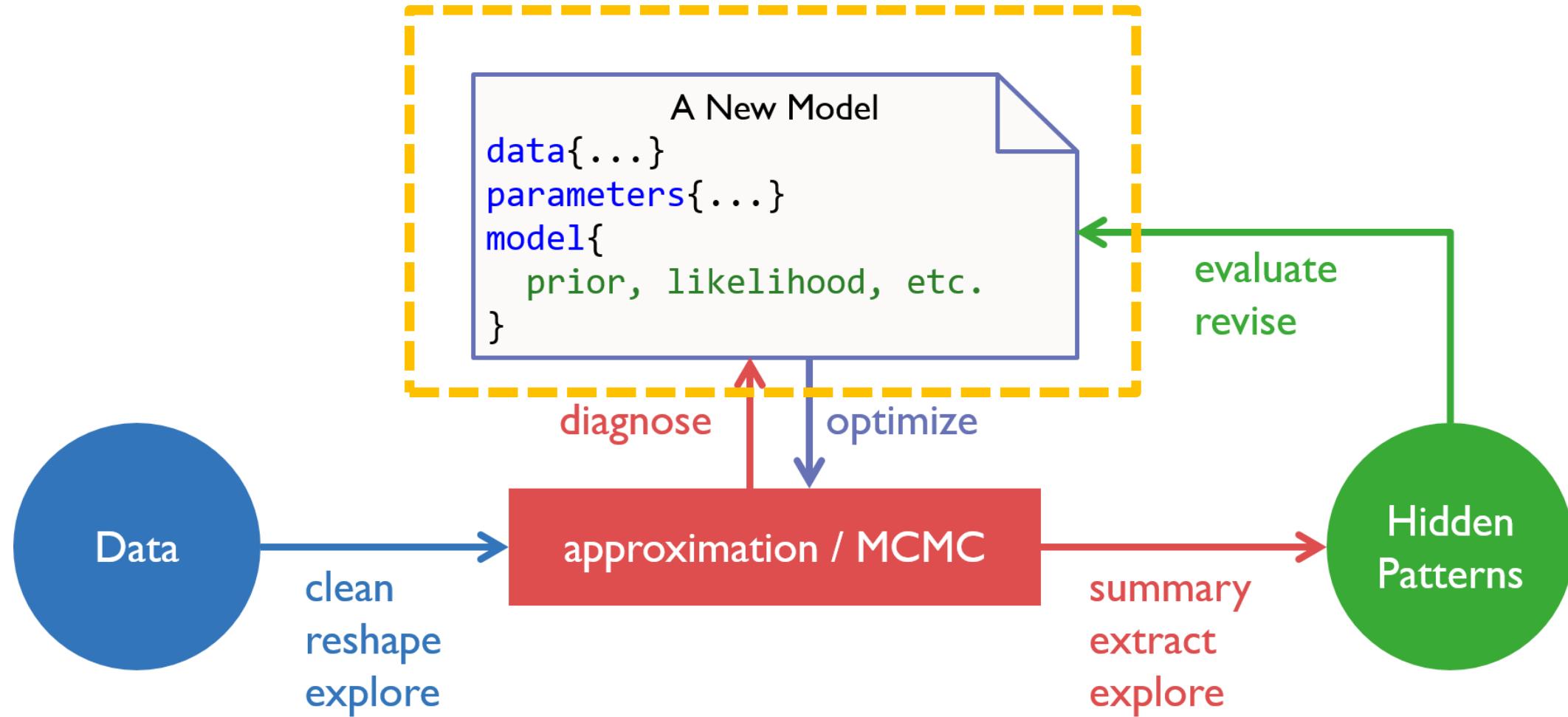
- You are curious how much of the surface is covered in water.
- You will toss the globe up in the air.
- You will record whether or not the surface under your right index finger is water (W) or land (L).
- You might observe: W L W W W L W L W
- $\rightarrow 6/9 = 0.666667?$
- Is it right? If not, what to do next?



# Steps of (Bayesian) Modeling?

cognitive model
statistics
computing





# A Data Story of the Globe

- The true proportion of water covering the globe is  $\vartheta$ .
- A single toss of the globe has a probability  $p$  of producing a water (W) observation.
- It has a probability  $(1 - \vartheta)$  of producing a land (L) observation.
- Each toss of the globe is independent of the others.



# Components of a Model

think about the likelihood function (of Binomial):

$$p(\theta | D) = \frac{p(D | \theta)p(\theta)}{\int p(D | \theta^*)p(\theta^*)d\theta^*}$$

$$p(w | N, \theta) = \binom{N}{w} \theta^w (1 - \theta)^{N-w}$$

$N$ : total number of observations

$w$ : number of water

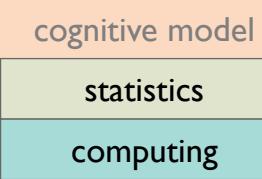
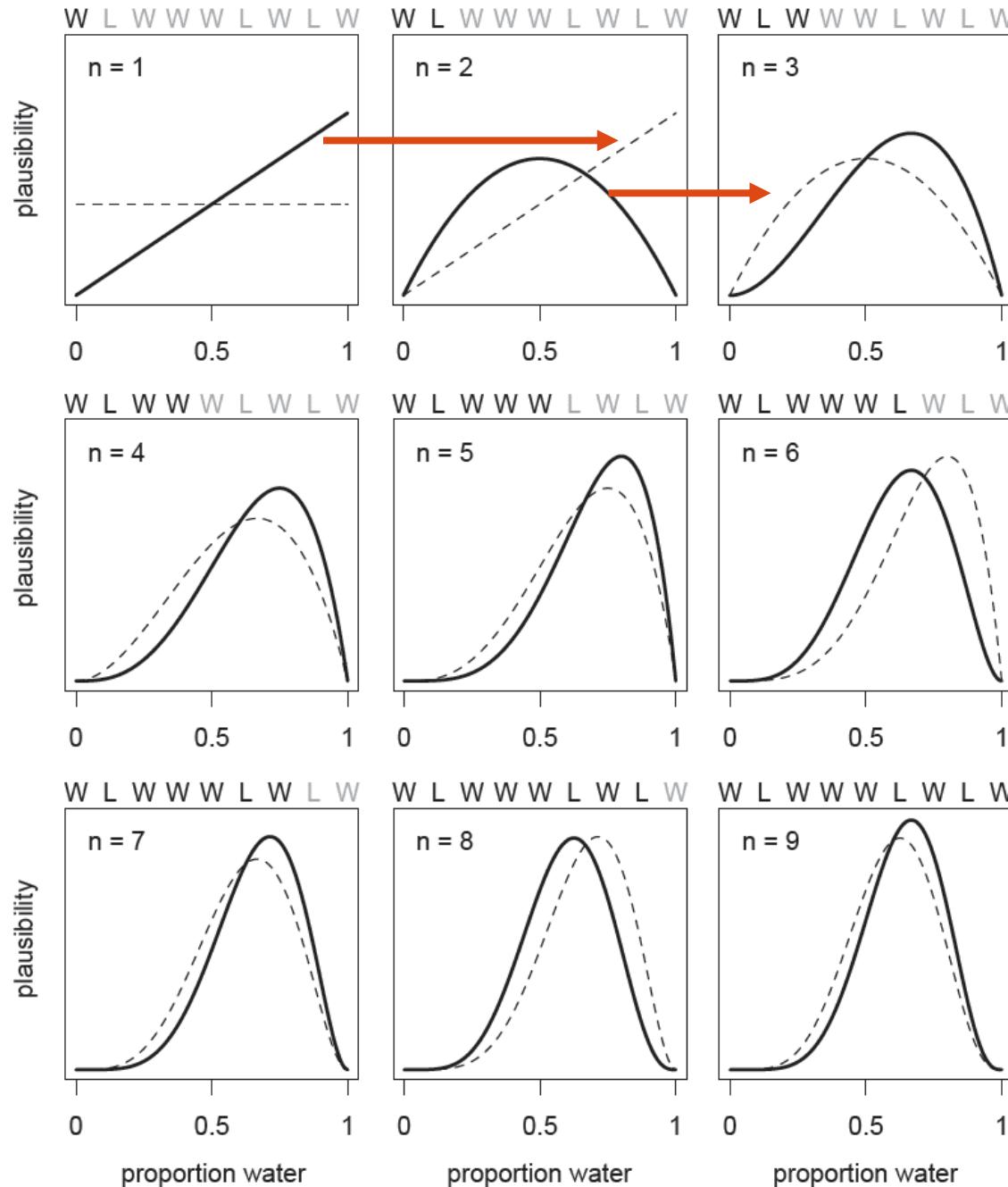
$\theta$ : proportion of water



known (data)

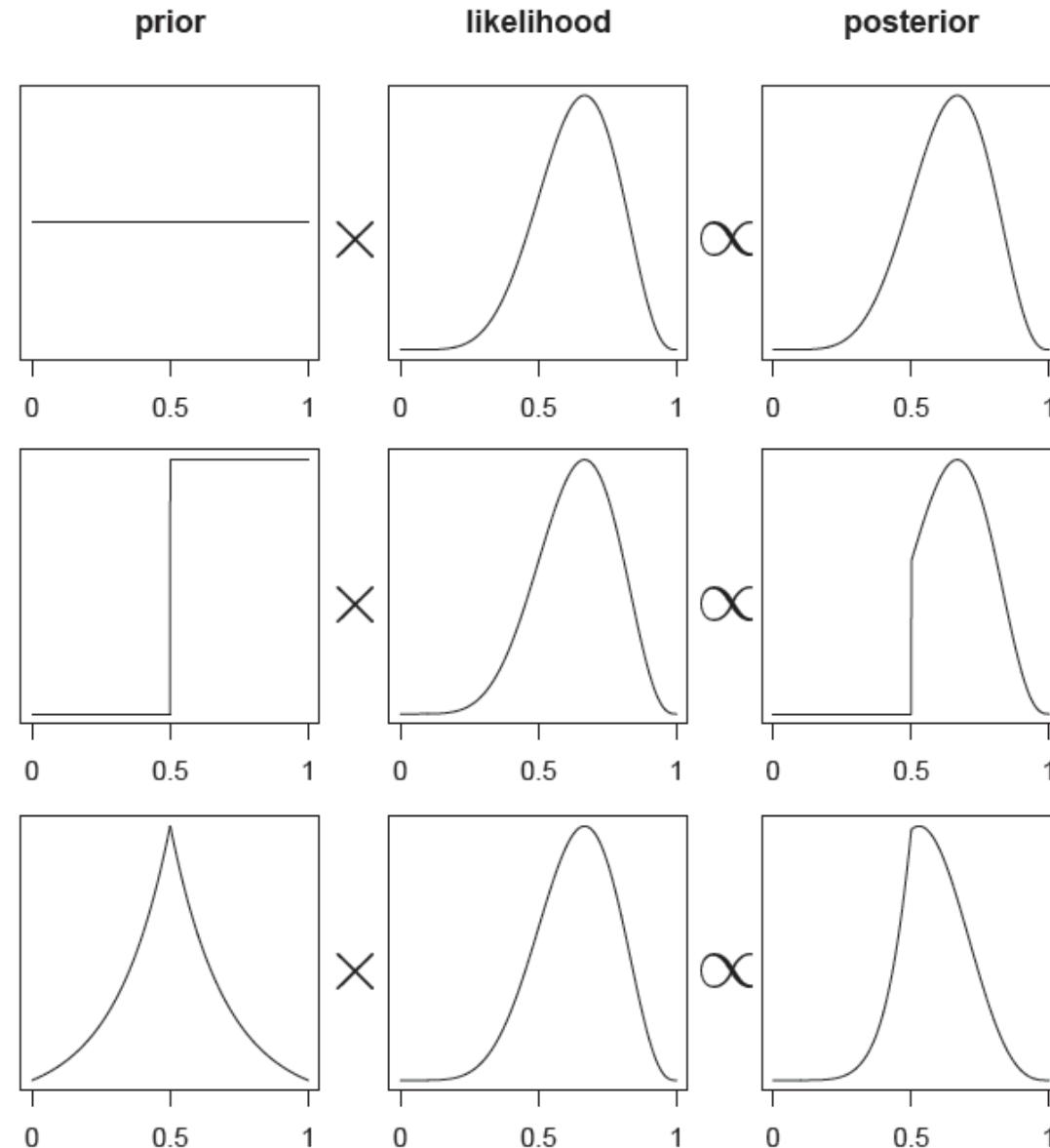
unknown (parameter)

# Update



# Impact of Prior

cognitive model
statistics
computing



# Solve it by Grid Approximation

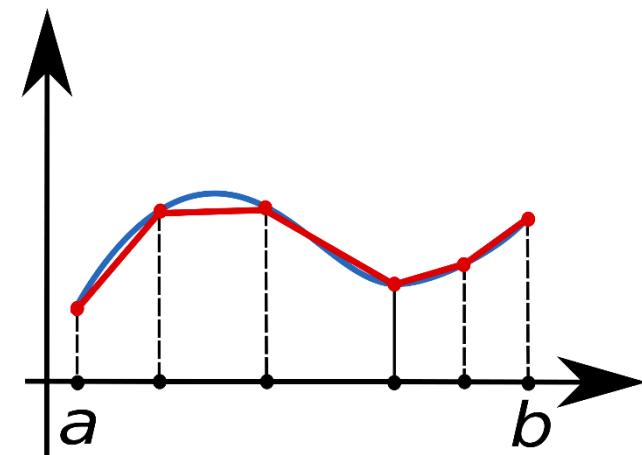
cognitive model  
statistics  
computing

discrete parameters

$$p(\theta | D) = \frac{p(D | \theta)p(\theta)}{\sum_{\theta^*} p(D | \theta^*)p(\theta^*)}$$

continuous parameters

$$p(\theta | D) = \frac{p(D | \theta)p(\theta)}{\int p(D | \theta^*)p(\theta^*)d\theta^*}$$



# Binomial Model – Grid Approximation

cognitive model
statistics
computing

```
theta_start <- 0; theta_end <- 1; n_grid <- 20  
w <- 6; N <- 9
```

```
# define grid  
theta_grid <- seq(from = theta_start, to = theta_end,  
length.out = n_grid)
```

```
# define prior  
prior <- rep(1 , n_grid)
```

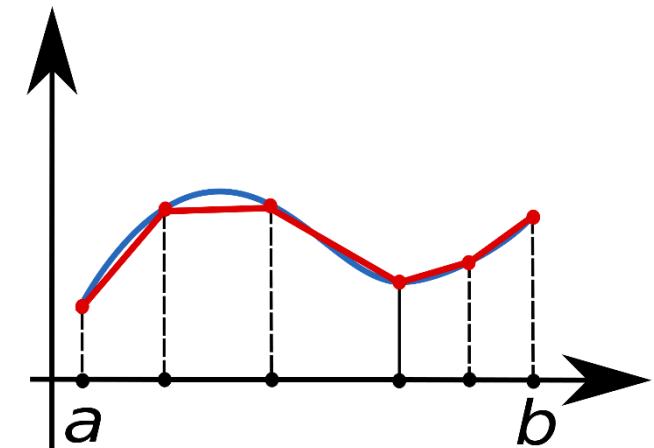
```
# compute likelihood at each value in grid  
likelihood <- dbinom(w, size = N, prob = theta_grid)
```

```
# compute product of likelihood and prior  
unstd.posterior <- likelihood * prior
```

```
# standardize the posterior, so it sums to 1  
posterior <- unstd.posterior / sum(unstd.posterior)
```

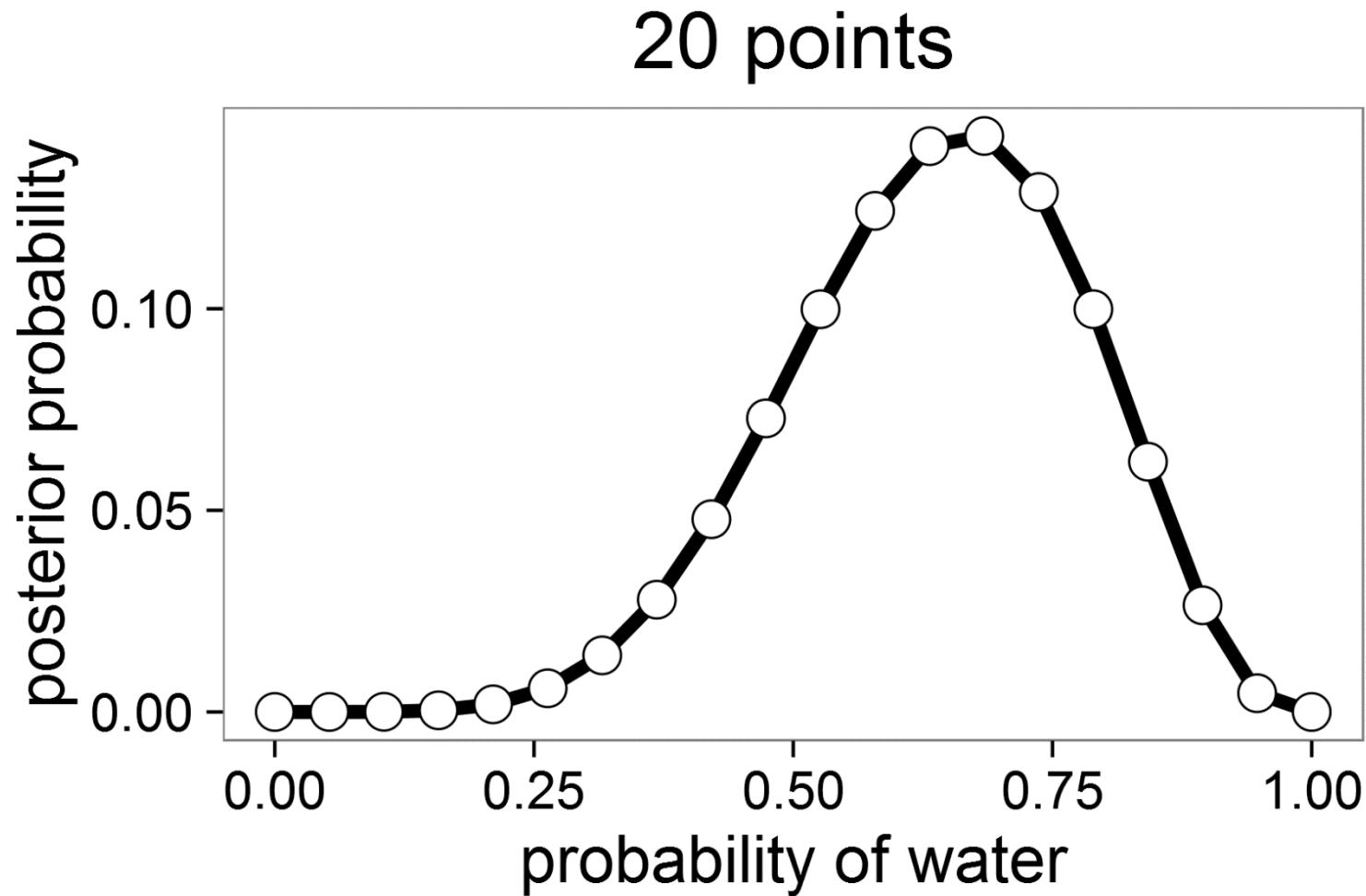
$$p(\theta | D) = \frac{p(D | \theta)p(\theta)}{\int p(D | \theta^*)p(\theta^*)d\theta^*}$$

$$p(w | N, \theta) = \binom{N}{w} \theta^w (1 - \theta)^{N-w}$$



# Binomial Model – Grid Approximation

cognitive model  
statistics  
computing



# Exercise VII

cognitive model
statistics
computing

```
.../BayesCog/02.binomial_globe/_scripts/binomial_globe_grid.R
```

TASK: run a grid approximation with `grid_size = 50`

# How do I know which likelihood to use?



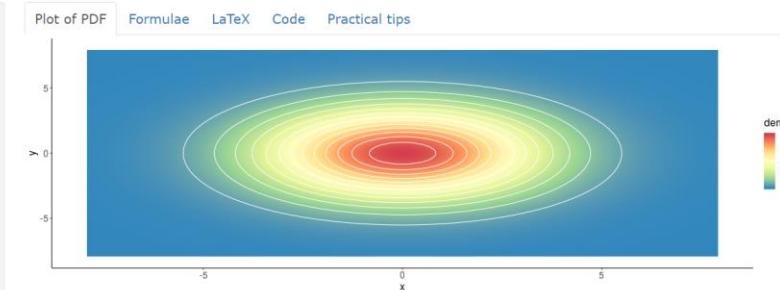
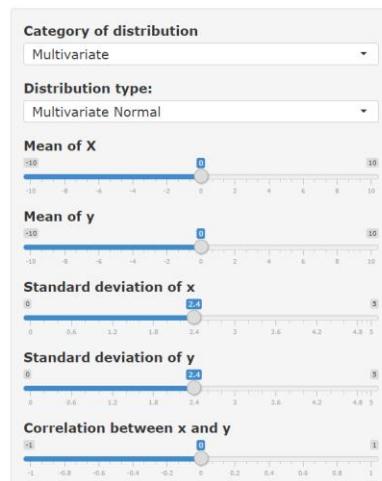
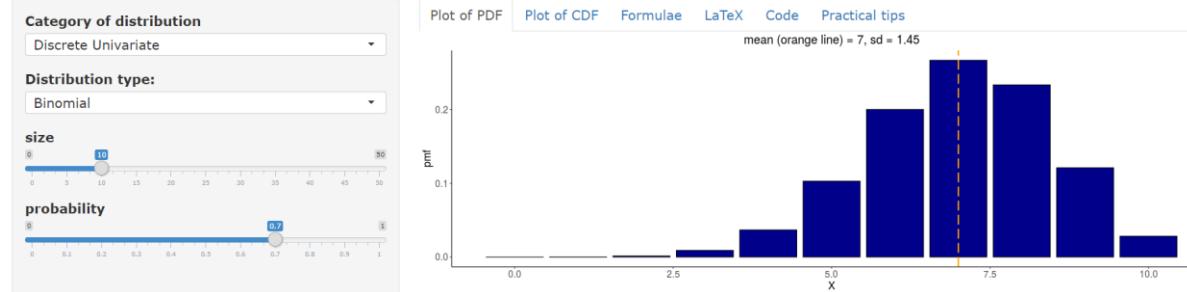
## The distribution zoo

by

Ben Lambert and Fergus Cooper

Last month: used by 285 people over 451 sessions in 41 countries

Since created: used by 4072 people over 6785 sessions in 107 countries



# What if I have multiple parameters?

grid approximation for  
2 parameters?  
5 parameters?  
10 parameters?

$$p(\theta | D) = \frac{p(D | \theta) p(\theta)}{\int p(D | \theta^*) p(\theta^*) d\theta^*}$$

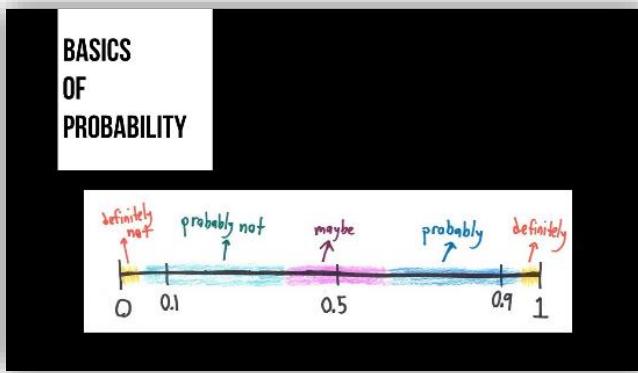
$$p(data) = \int_{\text{All } \theta_1} \int_{\text{All } \theta_2} p(data, \theta_1, \theta_2) d\theta_1 d\theta_2$$

$$p(data) = \int_{\mu_1} \int_{\sigma_1} \dots \int_{\mu_{100}} \int_{\sigma_{100}} \underbrace{p(data | \mu_1, \sigma_1, \dots, \mu_{100}, \sigma_{100})}_{\text{likelihood}} \times \underbrace{p(\mu_1, \sigma_1, \dots, \mu_{100}, \sigma_{100})}_{\text{prior}} \\ d\mu_1 d\sigma_1 \dots d\mu_{100} d\sigma_{100},$$

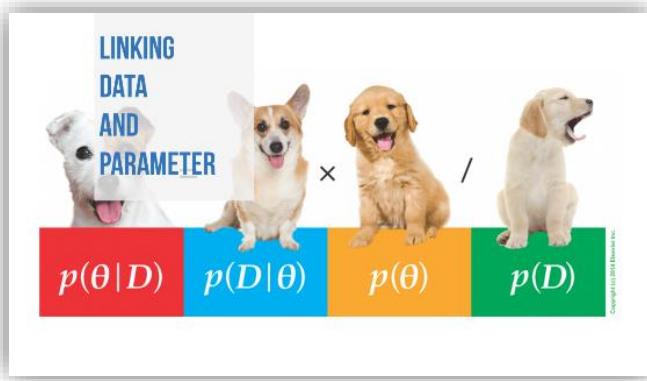
- Analytical solutions (often does not exist)
- Grid approximation (takes too long)
- Markov Chain Monte Carlo

$$p(\theta | D) \propto p(D | \theta) p(\theta)$$

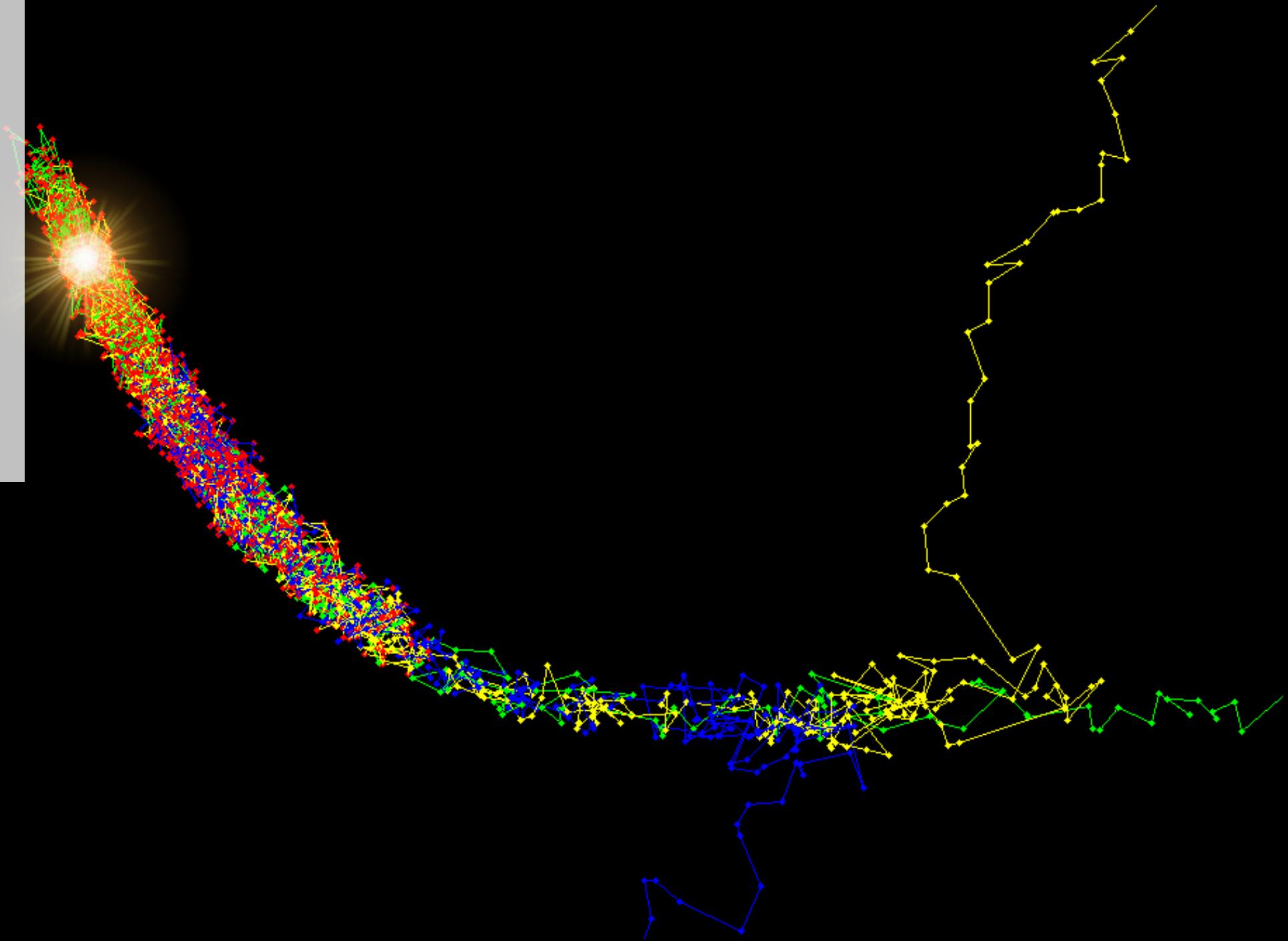
# Recap

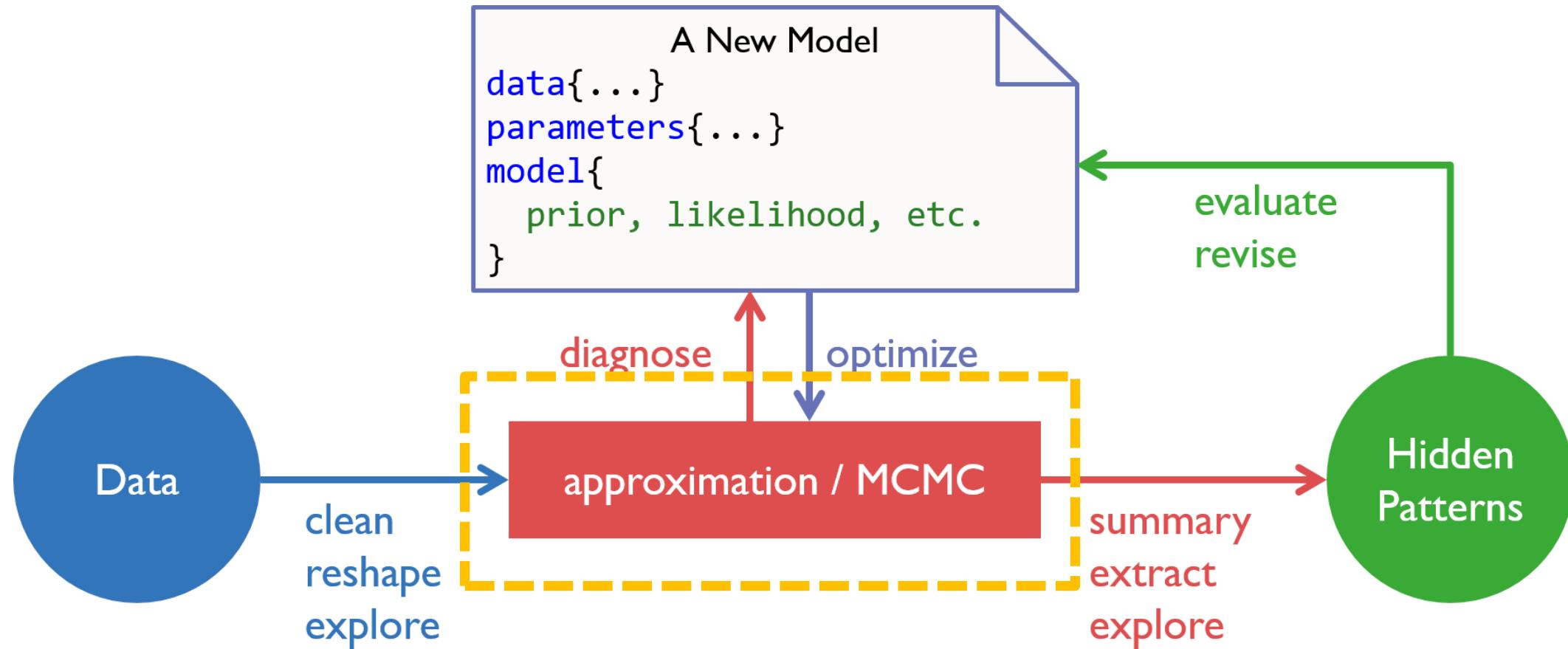


A slide titled "BAYES' THEOREM" displaying the formula for Bayes' Theorem:  $P(A|B) = \frac{P(B|A)P(A)}{P(B)}$ .



# MARKOV CHAIN MONTE CARLO





# Solving the Problem by Approximation

$$p(\theta | D) \propto p(D | \theta)p(\theta)$$

Deterministic  
Approximation

→ Variational Bayes

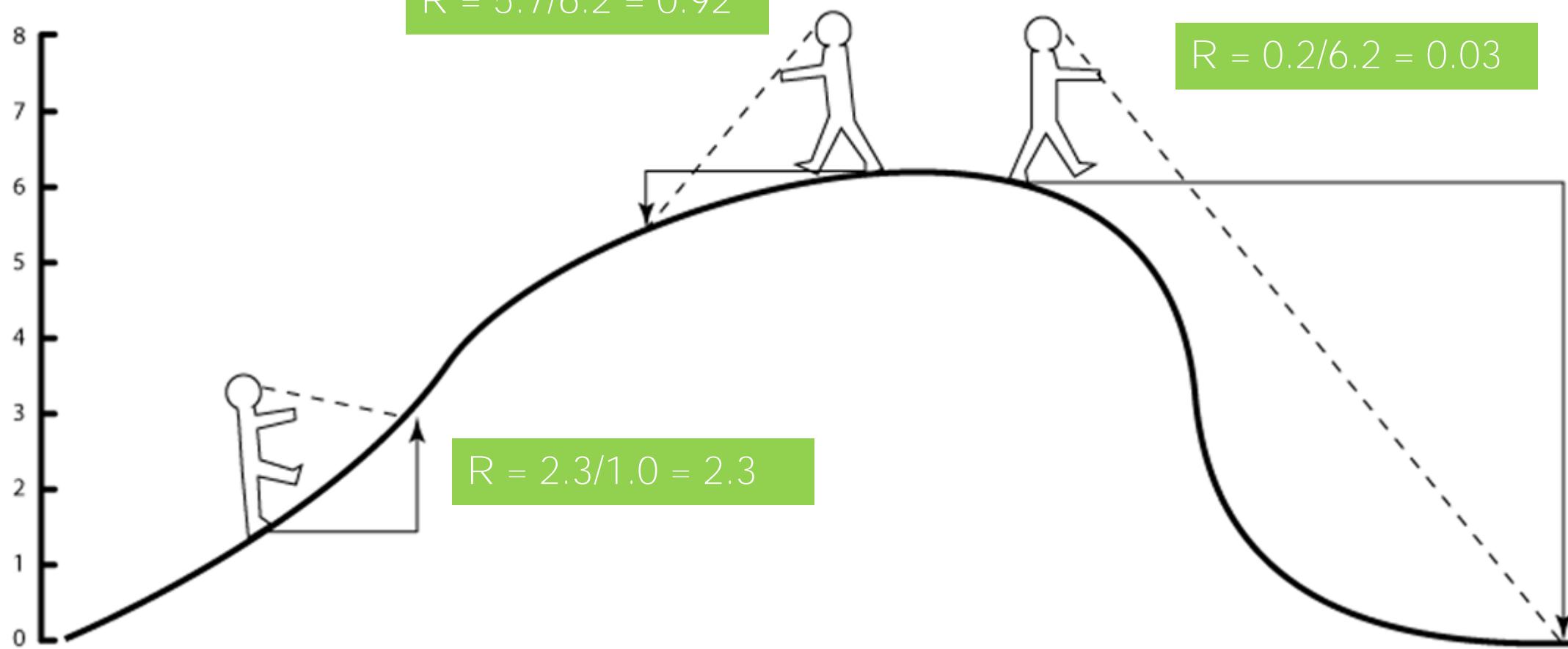
Stochastic  
Approximation

→ Sampling Methods

# An MCMC Robot

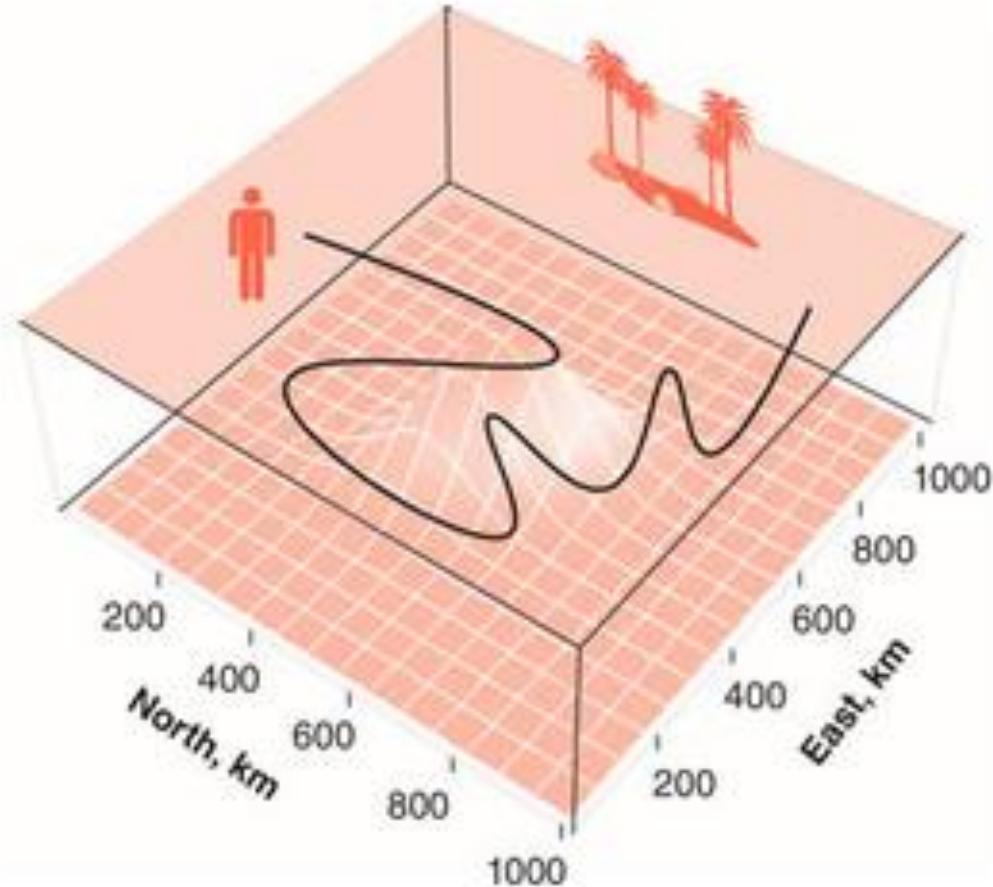
cognitive model  
statistics  
computing

$$p(\theta | D) \propto p(D | \theta)p(\theta)$$

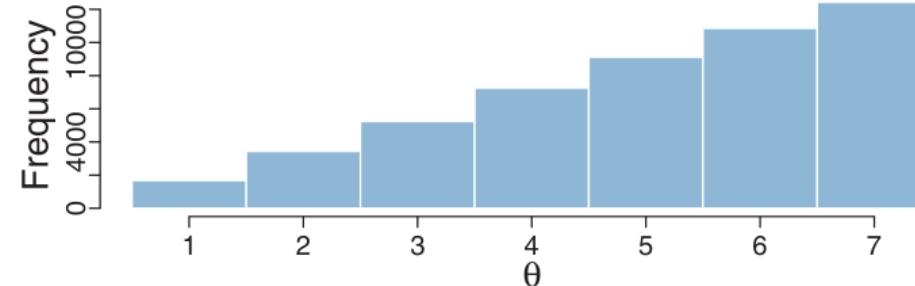


# An MCMC Robert in 3D

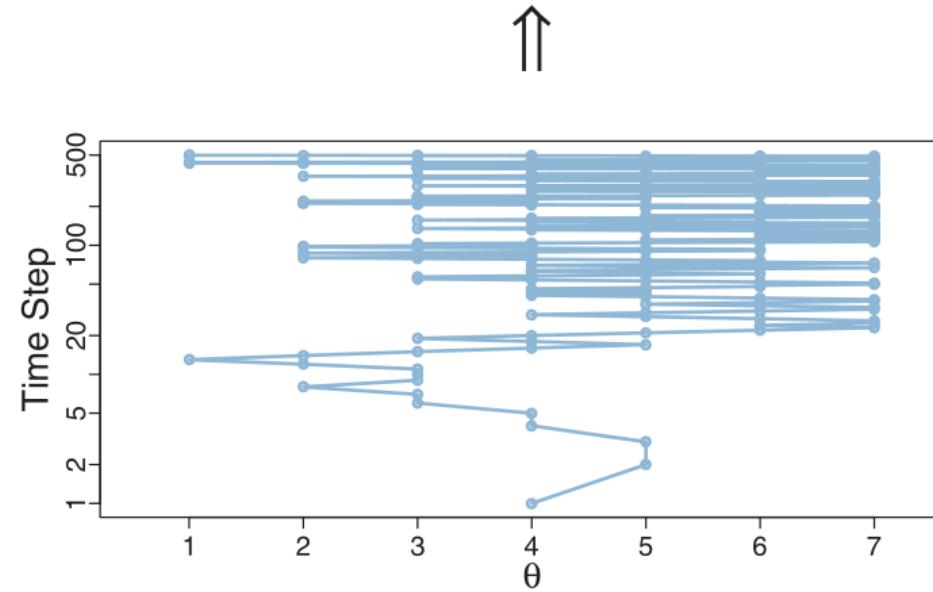
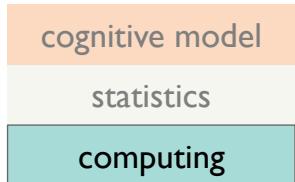
cognitive model  
statistics  
**computing**



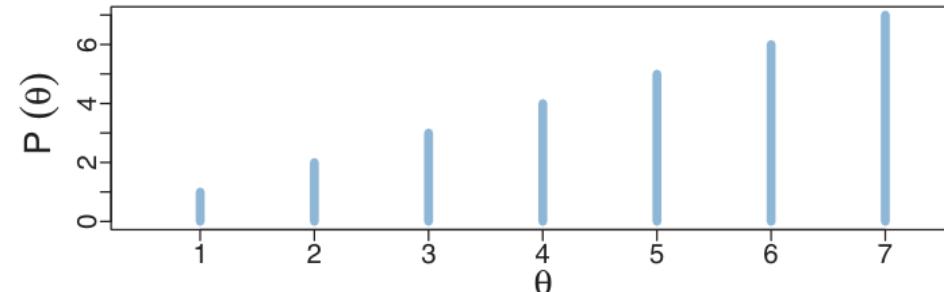
# Sampling Example: Discrete



MCMC summary

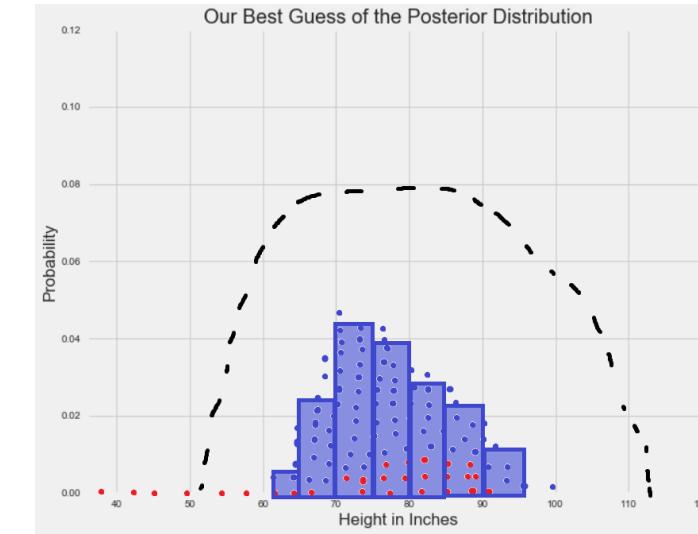
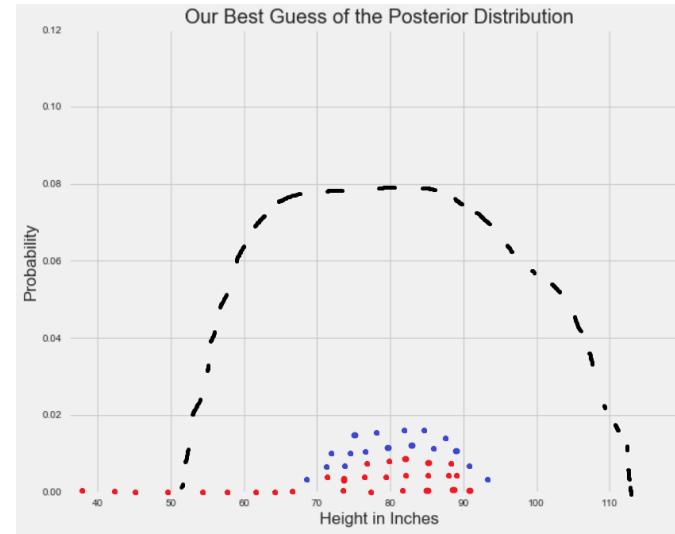
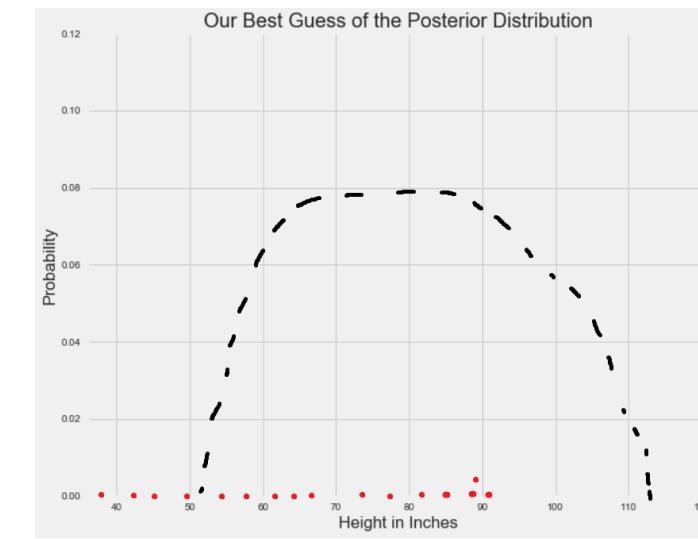
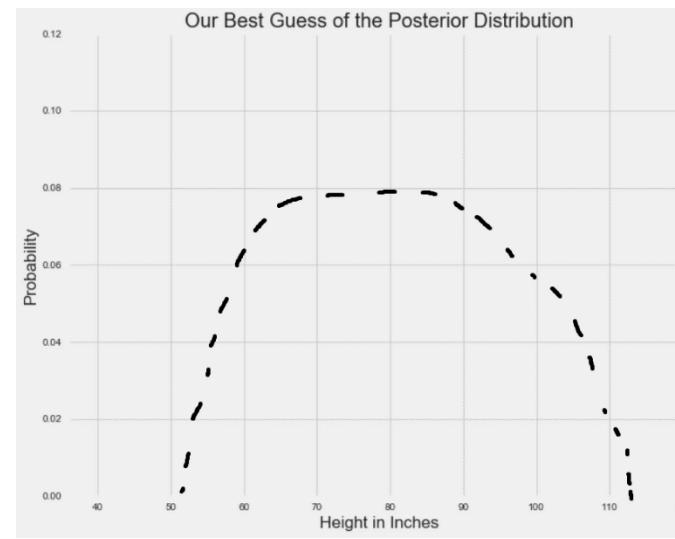


MCMC trace



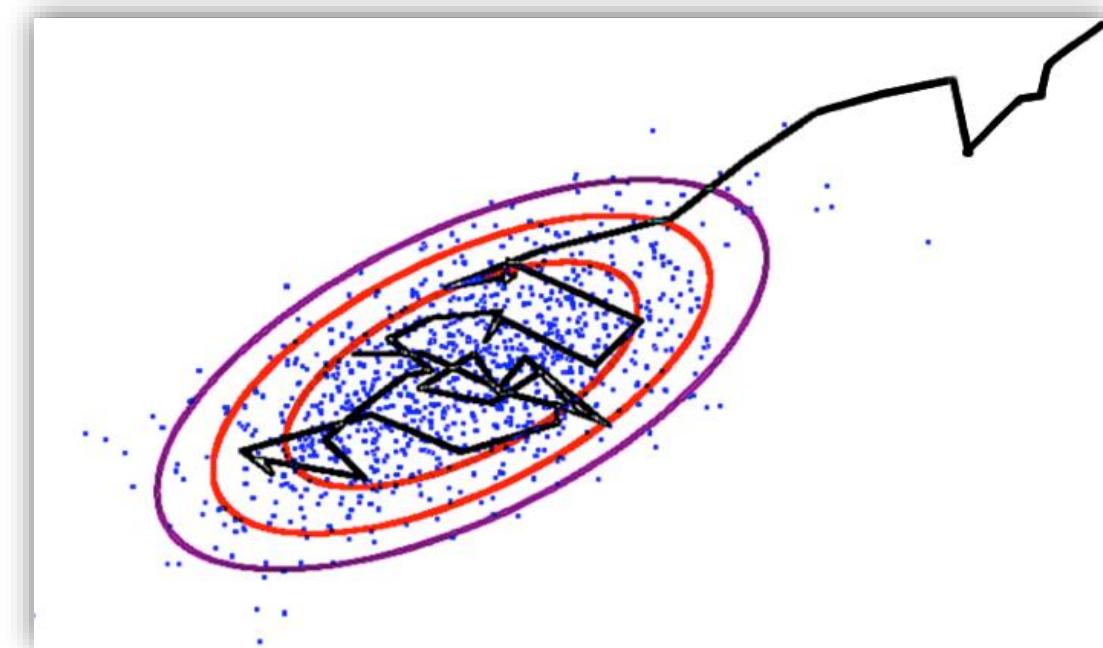
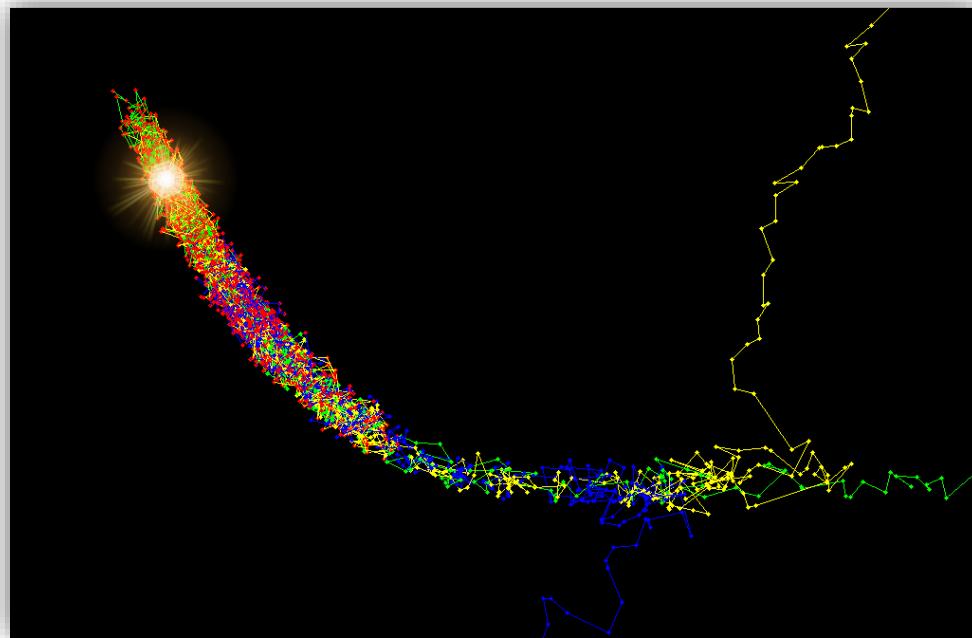
True distribution

# Sampling Example: Continuous



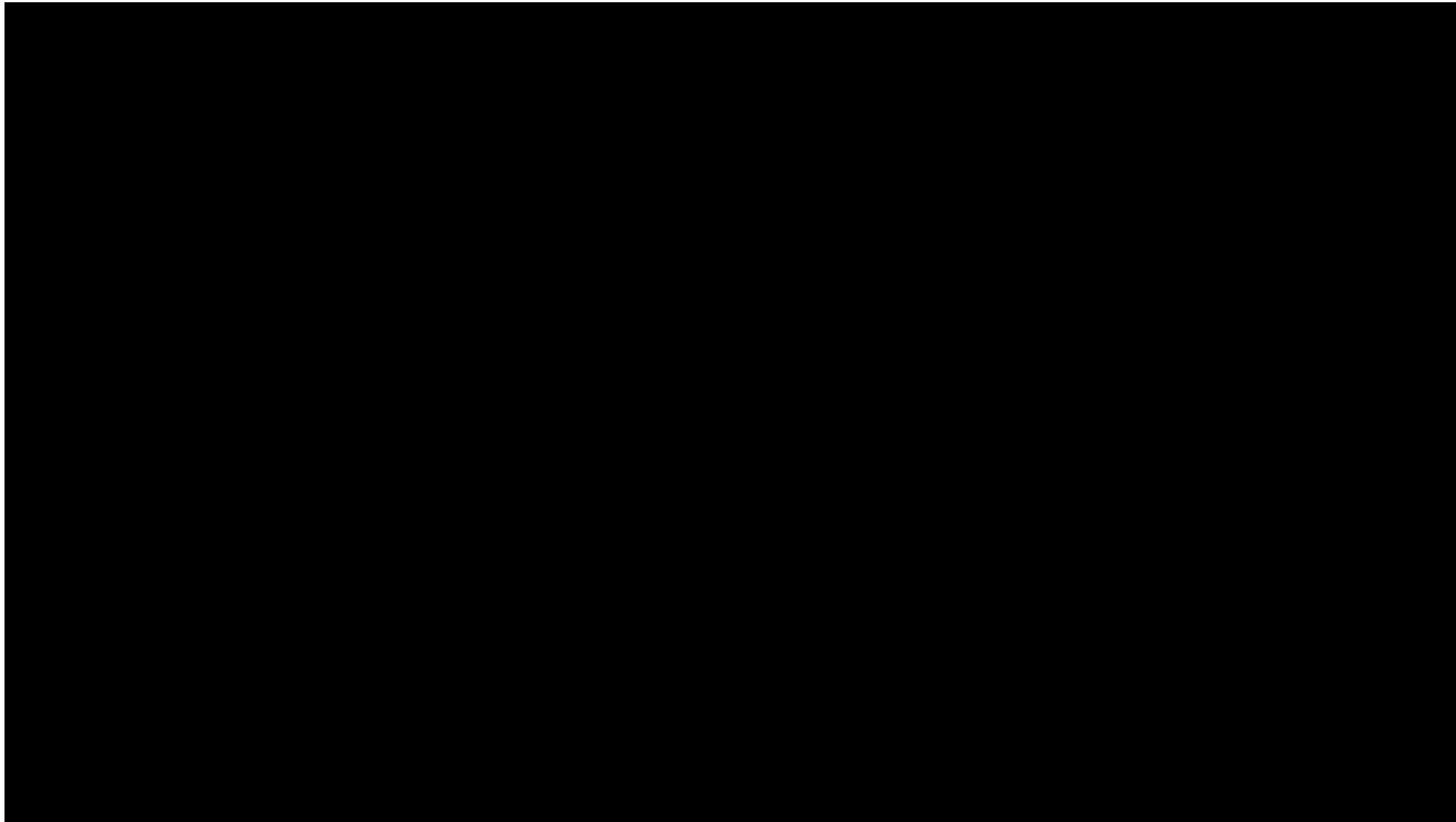
# Visual Example

cognitive model  
statistics  
computing



# Let's watch a video!

cognitive model  
statistics  
**computing**



# MCMC Sampling Algorithms

cognitive model  
statistics  
computing

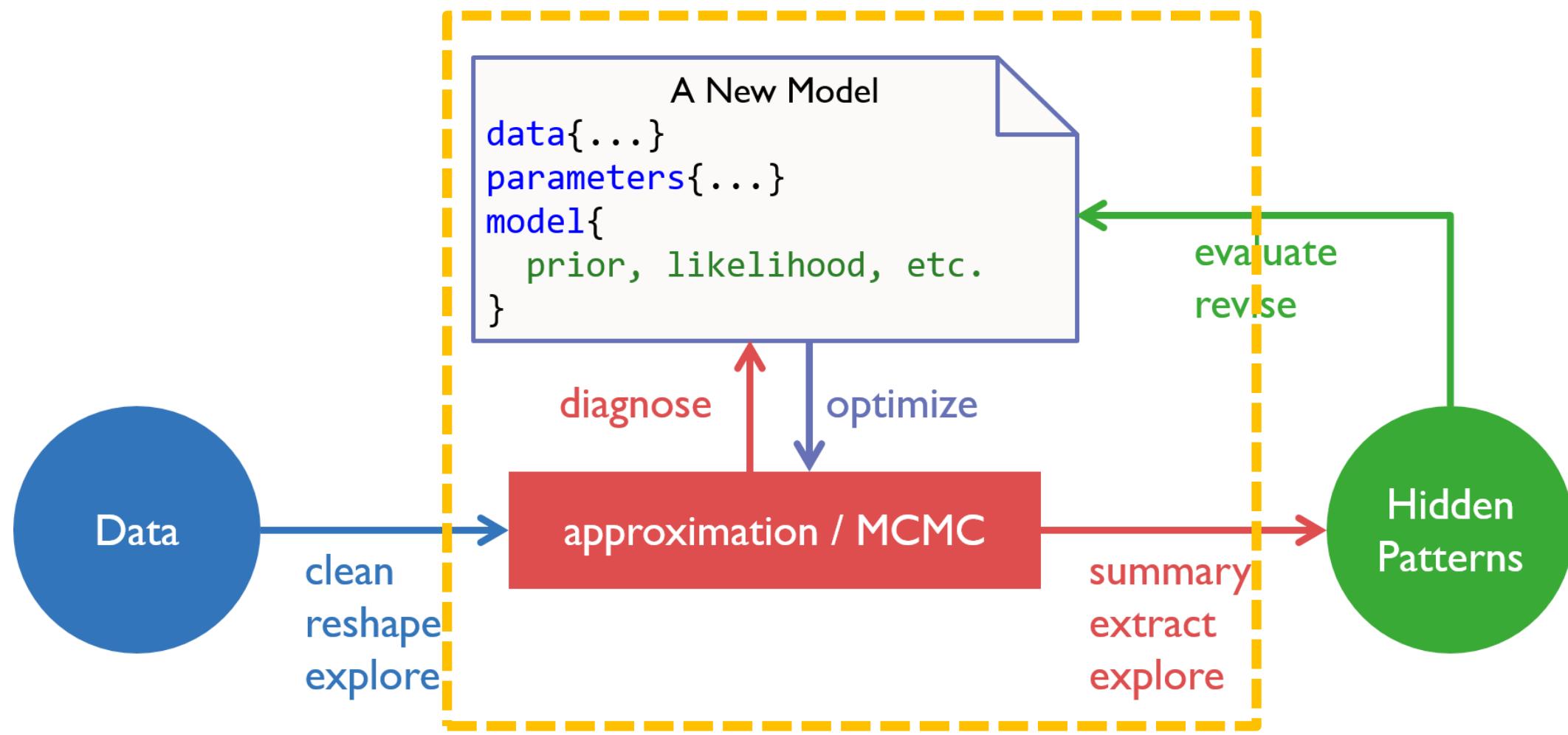
- Rejection sampling
- Importance sampling
- Metropolis algorithm
- Gibbs sampling → JAGS
- HMC sampling\*



Stan!

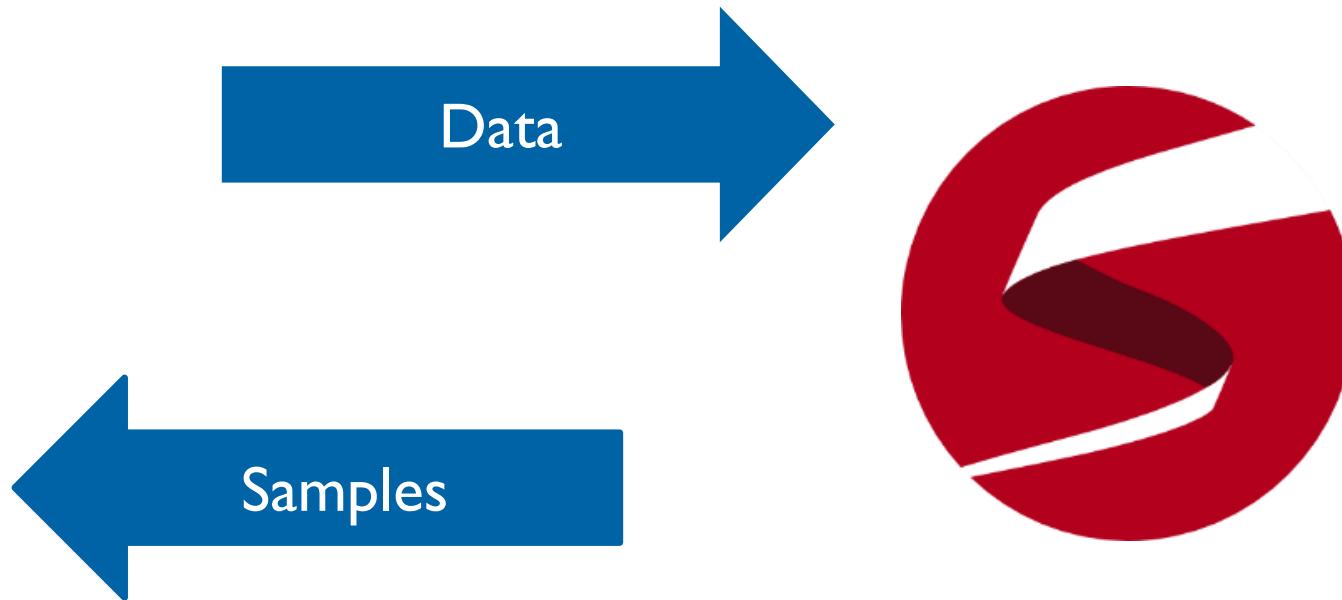
# **STAN PROGRAMMING LANGUAGE I**





# Stan and RStan

cognitive model  
statistics  
computing



# Steps of Bayesian Modeling, with Stan

A data story

Think about how the data might arise.  
It can be *descriptive* or even *causal*.  
**Write a Stan program (\*.stan).**

Update

Educate your model by feeding it the data.  
**Bayesian Update:**  
update the prior, in light of data, to produce posterior.  
**Run Stan using RStan (PyStan, MatlabStan etc. )**

Evaluate

Compare model with reality.  
Revise your model.  
**Evaluate in RStan and ShinyStan.**

# Steps of Using Stan

1. Stan program read into memory
2. Source-to-source transformation into C++
3. C++ compiled and linked (takes a while)
4. Run Stan program
5. Posterior analysis / interface



```
data {  
    int<lower=0> N;  
    int<lower=0,upper=1> y[N];  
}  
parameters {  
    real<lower=0,upper=1> theta;  
}  
model {  
    y ~ bernoulli(theta);  
}
```

```
// Stan generated by Stan version 3.0  
// include <stan/stan.hpp>  
// stan::model::model<stan::stan_rng>  
// stan::model::model<stan::stan_rng>
```

cognitive model  
statistics  
computing

# Stan Language

## model blocks

```
data {  
    //... read in external data...  
}  
  
transformed data {  
    //... pre-processing of data ...  
}  
  
parameters {  
    //... parameters to be sampled by HMC ...  
}  
  
transformed parameters {  
    //... pre-processing of parameters ...  
}  
  
model {  
    //... statistical/cognitive model ...  
}  
  
generated quantities {  
    //... post-processing of the model ...  
}
```

cognitive model  
statistics  
computing

# REVISIT BINOMIAL MODEL



# Binomial Model

cognitive model  
statistics  
computing

W L W W W L W L W

$$p(w | N, \theta) = \binom{N}{w} \theta^w (1 - \theta)^{N-w}$$

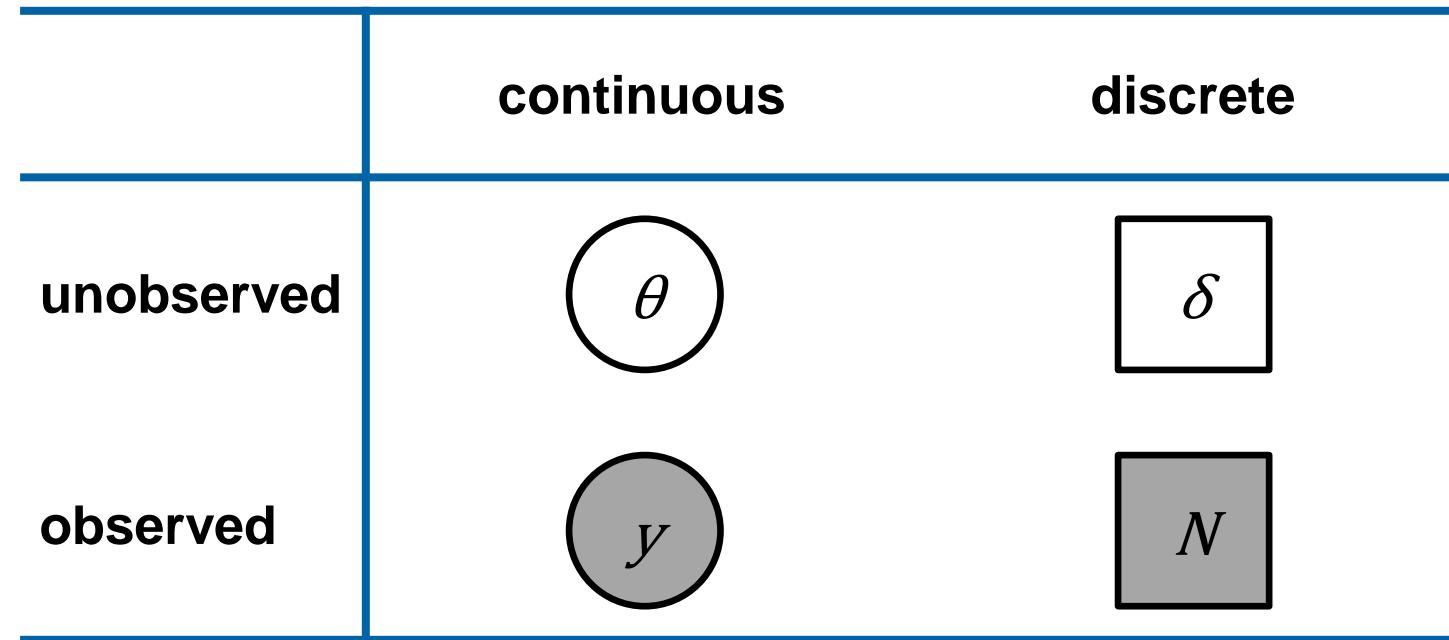
$$w \sim \text{Binomial}(N, \theta)$$

reads as:  
w is distributed as a binomial distribution, with number of trials N, and success rate  $\vartheta$ .



# Graphical Model Notations

cognitive model
statistics
computing

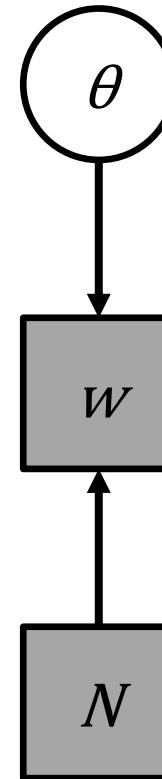


# Binomial Model

cognitive model  
statistics  
computing

W L W W W L W L W

$$p(w | N, \theta) = \binom{N}{w} \theta^w (1 - \theta)^{N-w}$$



$$\theta \sim \text{Uniform}(0, 1)$$

$$w \sim \text{Binomial}(N, \theta)$$

	continuous	discrete
unobserved	$\theta$	$\delta$
observed	$y$	$N$

# Binomial Model

cognitive model  
statistics  
computing

W L W W W L W L W

$$p(w | N, \theta) = \binom{N}{w} \theta^w (1 - \theta)^{N-w}$$



```
data {  
    int<lower=0> w;  
    int<lower=0> N;  
}  
  
parameters {  
    real<lower=0,upper=1> theta;  
}  
  
model {  
    w ~ binomial(N, theta);  
}
```

# Running Binomial Model with Stan

cognitive model
statistics
computing

```
.../BayesCog/02.binomial_globe/_scripts/binomial_globe_main.R
```

```
> R.version  
R version 3.5.1 (2018-07-02)
```

```
> stan_version()  
[1] "2.18.0"
```

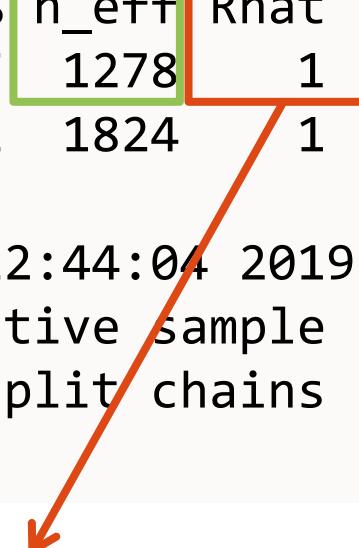
# Model Summary

cognitive model  
statistics  
computing

```
> print(fit_globe)
Inference for Stan model: binomial_globe_model.
4 chains, each with iter=2000; warmup=1000; thin=1;
post-warmup draws per chain=1000, total post-warmup draws=4000.
```

	mean	se_mean	sd	2.5%	25%	50%	75%	97.5%	n_eff	Rhat
theta	0.64	0.00	0.14	0.35	0.54	0.65	0.74	0.87	1278	1
lp__	-7.72	0.02	0.69	-9.77	-7.89	-7.46	-7.27	-7.21	1824	1

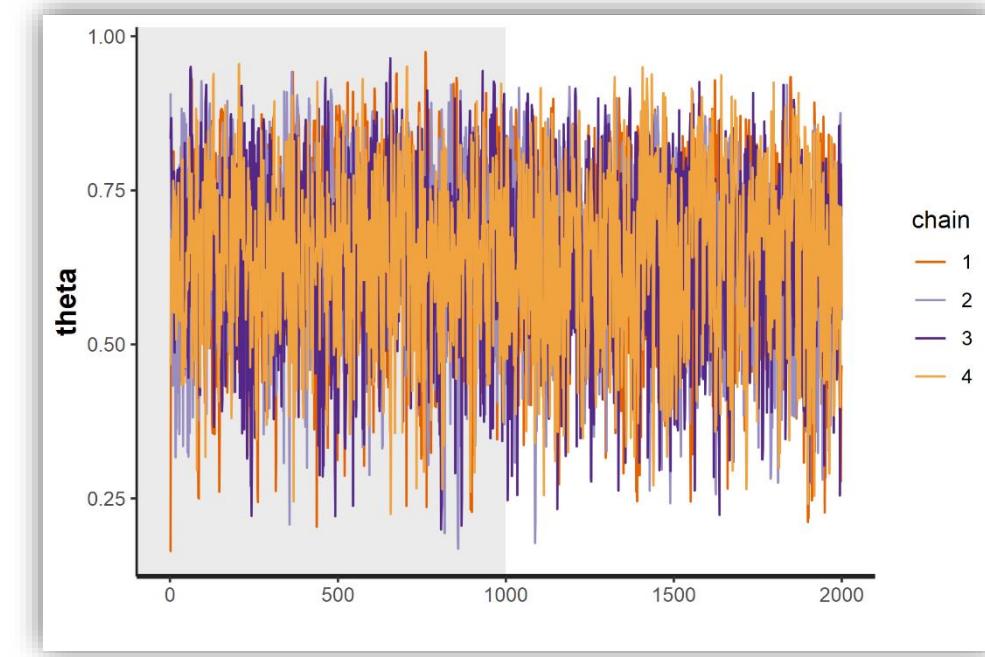
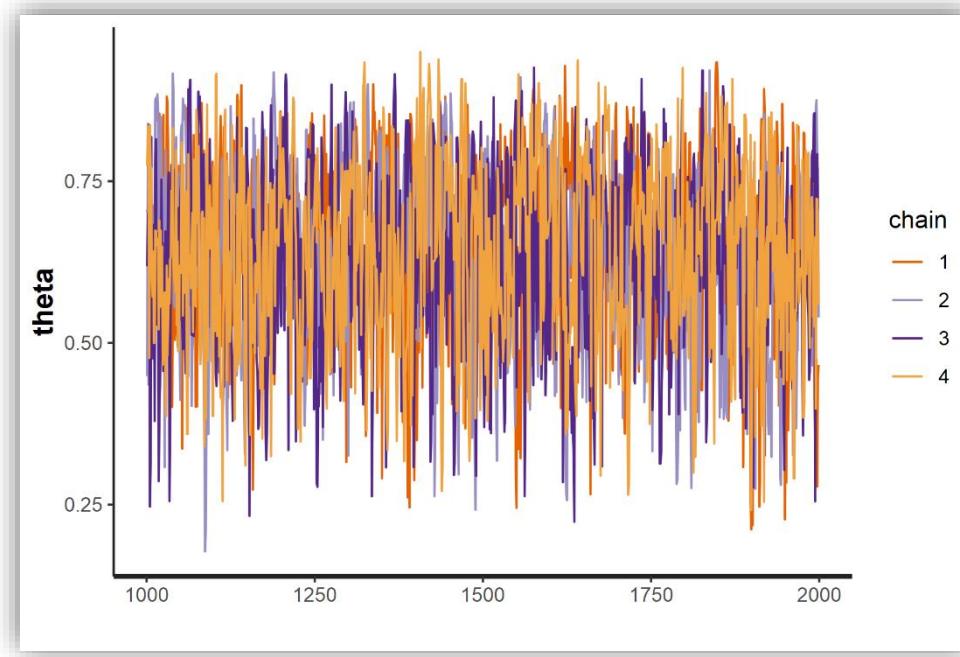
Samples were drawn using NUTS(diag\_e) at Tue Apr 09 12:44:04 2019.  
For each parameter, n\_eff is a crude measure of effective sample size,  
and Rhat is the potential scale reduction factor on split chains (at  
convergence, Rhat=1).



Gelman-Rubin convergence diagnostic  
(Gelman & Rubin, 1992)

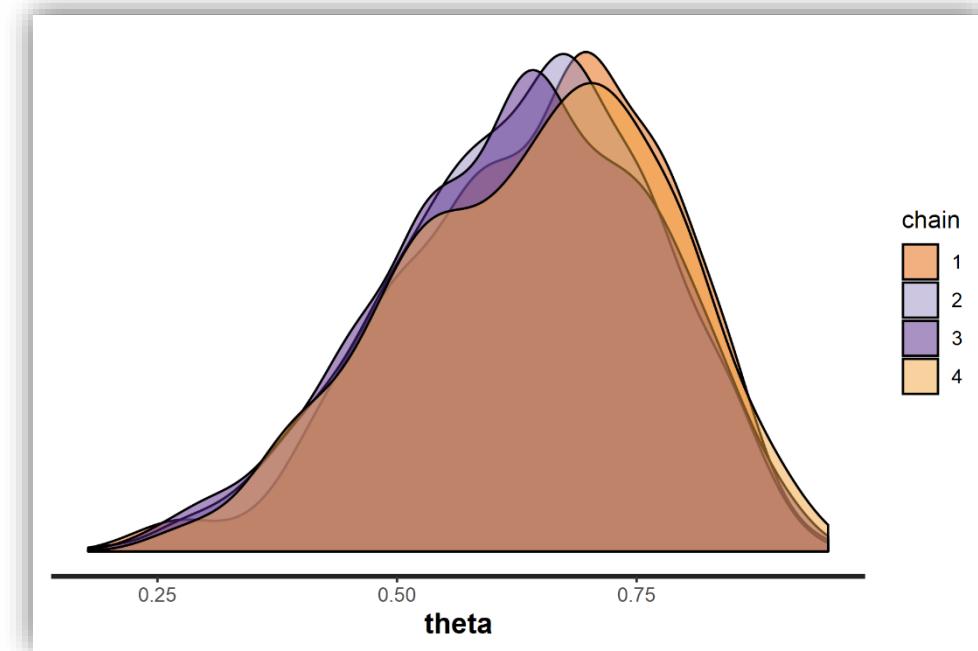
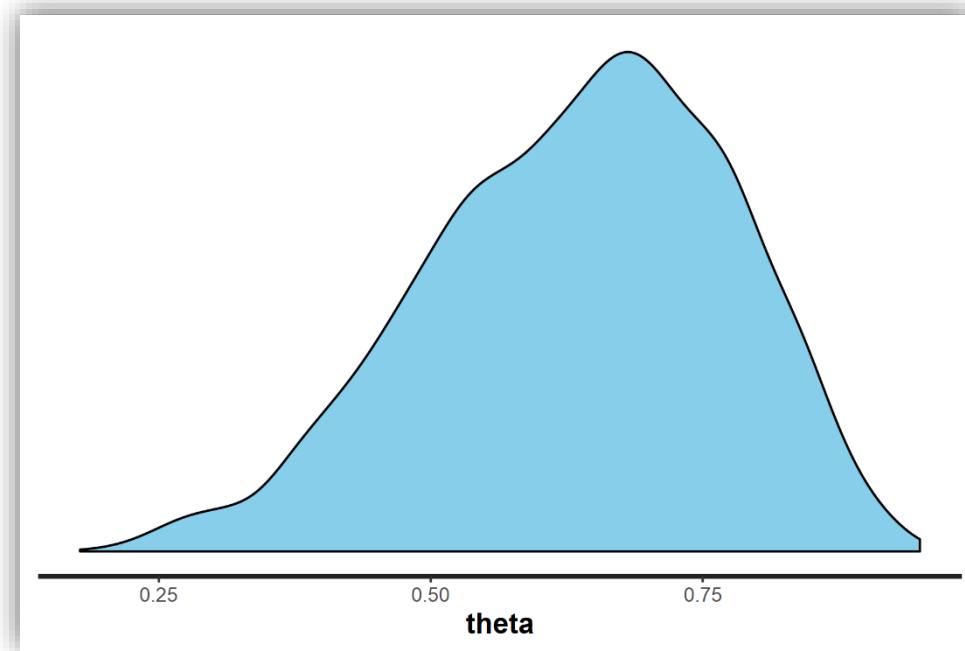
# Diagnostics - traceplot

cognitive model  
statistics  
computing



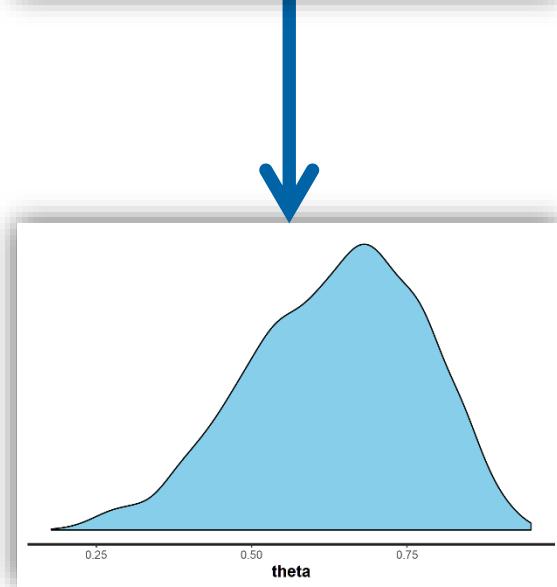
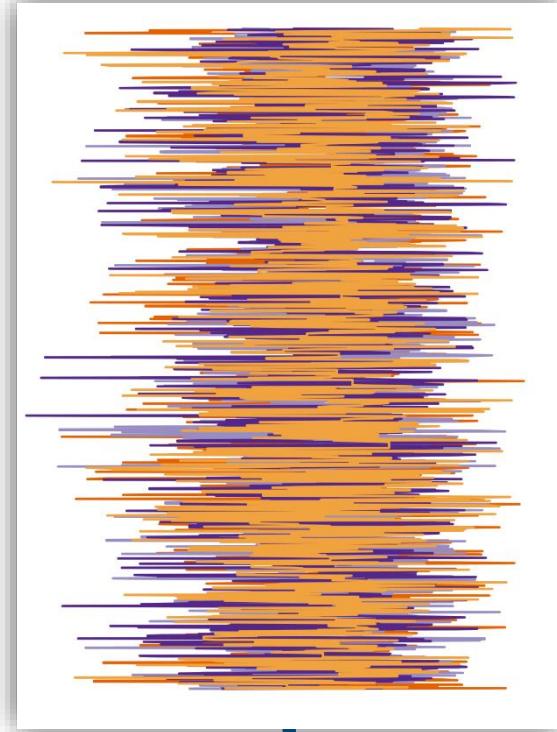
# Diagnostics - density

cognitive model  
statistics  
computing

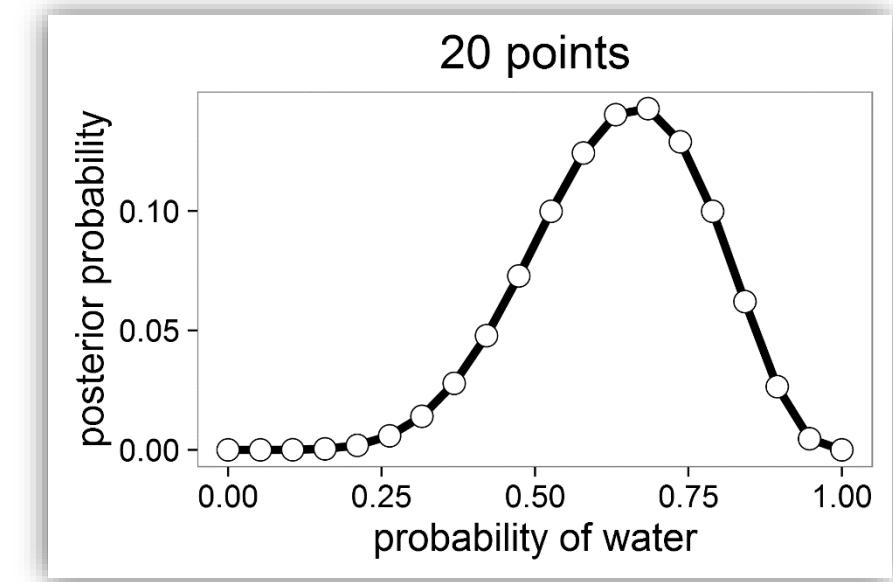


# Diagnostics

MCMC



Grid Approximation

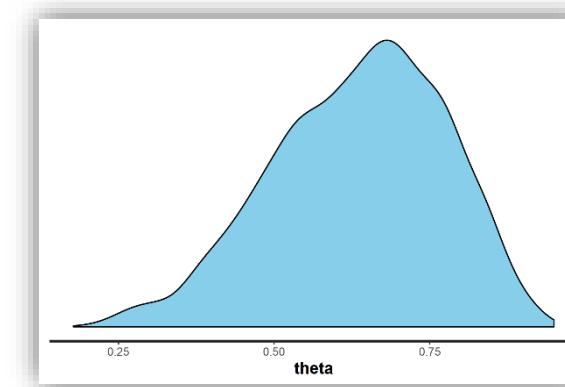
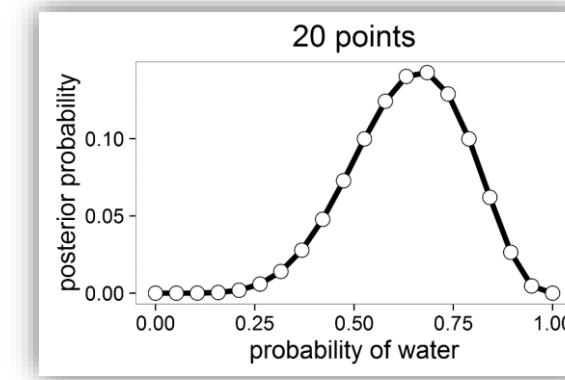


cognitive model
statistics
computing

# Draw a Conclusion?

cognitive model  
statistics  
computing

- $W = 6$  out of  $N = 9$
- uncertainty (relative plausibility) of all  $\vartheta$  values
- the relative plausibility of  $\vartheta = 0.64$  is the highest, but it never rules out the possibility of  $\vartheta$  being other values, e.g., 0.5, 0.75
- → when  $\vartheta = 0.5$ , you may still observe  $6W / 9$  trials



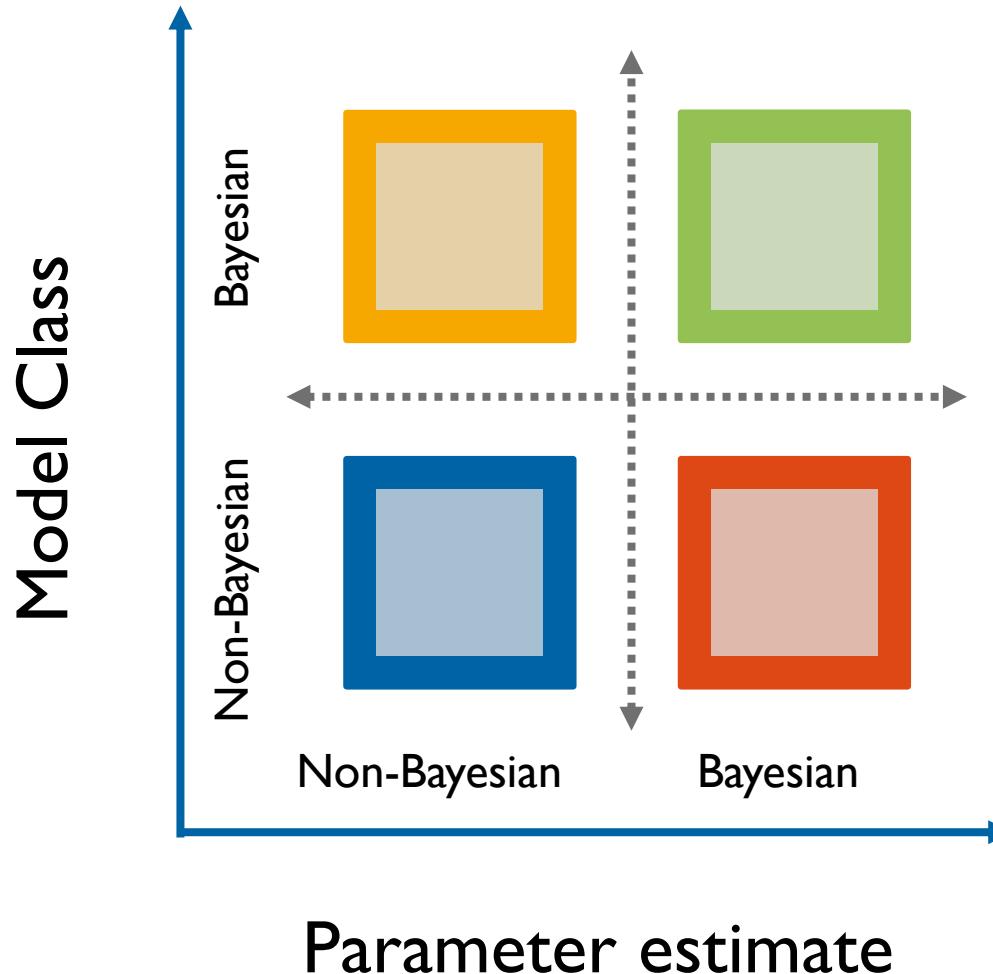
# Is Anything Missing? – NO

cognitive model
statistics
computing

```
data {  
    int<lower=0> w;  
    int<lower=0> N;  
}  
  
parameters {  
    real<lower=0,upper=1> theta;  
}  
  
model {  
    theta ~ uniform(0,1);  
    w ~ binomial(N, theta);  
}
```

```
data {  
    int<lower=0> w;  
    int<lower=0> N;  
}  
  
parameters {  
    real<lower=0,upper=1> theta;  
}  
  
model {  
    w ~ binomial(N, theta);  
}
```

# What We Talk About When We Talk About “Bayesian” Models



# **STAN PROGRAMMING LANGUAGE II**



# Why Use Stan?

cognitive model  
statistics  
computing

## vs. BUGS and JAGS

- Time to converge and per effective sample size:  
0.5 - ∞ times faster
- Memory usage: 1–10%
- Language features
  - variable overwrite: `a = 4`, then `a = 5`
  - formal control flow
  - full support of vectorizing

Krzysztof Sakrejda  
@sakrejda

I keep getting asked why people should use [@mcmc\\_stan](#) so I wrote an answer:

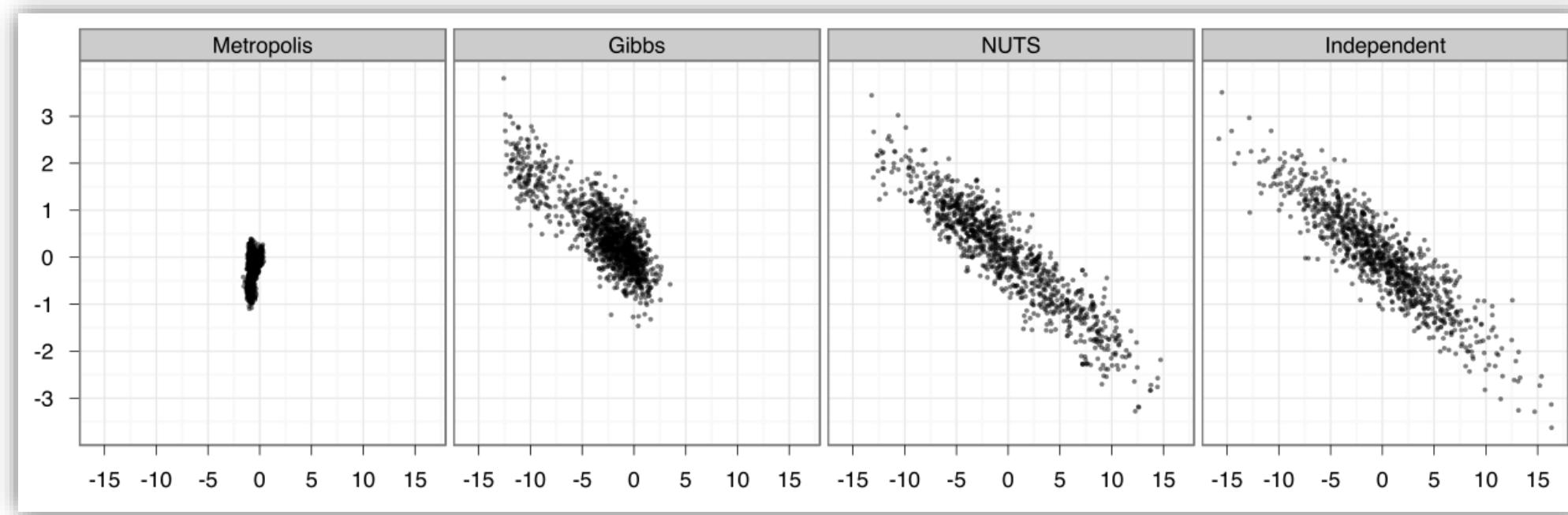
"Selling" Stan  
[discourse.mc-stan.org](https://discourse.mc-stan.org)

27.03.18, 16:01

# NUTS vs. Gibbs and Metropolis

cognitive model  
statistics  
computing

Hamilton MC (HMC) implements No-U-Turn Sampler (NUTS)



- Two dimensions of highly correlated 250-dim normal
- 1,000,000 draws from Metropolis and Gibbs (thin to 1000)
- 1,000 draws from NUTS; 1000 independent draws

# General Properties of Stan Language

cognitive model  
statistics  
computing

- Whitespace does not matter
- Comments
  - //
  - /\* ... \*/
- Must use semicolon ( ; )
- Variables are typed and scoped



# Variable Declaration

cognitive model  
statistics  
computing

- Each variable has a type (static type; scalar, vector, matrix etc.)
- Only values of that type can be assigned to the variable
  - e.g. cannot assign [1 2 3] to a (declared as a scalar)
- Declaration of variables happen at the top of a block (including local blocks)



# Variable's Scope

cognitive model  
statistics  
computing

	data	transformed data	parameters	transformed parameters	model	generated quantities
Variable Declarations	Yes	Yes	Yes	Yes	Yes	Yes
Variable Scope	Global	Global	Global	Global	Local	Local
Variables Saved?	No	No	Yes	Yes	No	Yes
Modify Posterior?	No	No	No	No	Yes	No
Random Variables	No	No	No	No	No	Yes

# Scalar Variables

cognitive model  
statistics  
computing

real

- scalar
- continuous

```
data {  
    real y;  
}
```

int

- scalar
- integer
- can't be used in **parameters** or **transformed parameters** blocks

```
data {  
    int n;  
}
```

# Constraining Scalar Variables

cognitive model  
statistics  
computing

```
data {  
    int<lower=1> m;  
    int<lower=0,upper=1> n;  
    real<lower=0> x;  
    real<upper=0> y;  
    real<lower=-1,upper=1> rho;  
}
```

# Vector & Matrix

cognitive model  
statistics  
computing

```
vector[3] a;  
// column vector  
  
row_vector[4] b;  
// row vector  
  
matrix[3,4] A;  
// A is a 3x4 matrix  
// A[1] returns a 4-element row vector  
  
vector<lower=0,upper=1>[5] rhos;  
row_vector<lower=0>[4] sigmas;  
matrix<lower=-1, upper=1>[3,4] Sigma;
```

# Control Flow

- if-else

```
if (cond) {  
    ..statement..  
}
```

```
if (cond) {  
    ..statement..  
} else {  
    ..statement..  
}
```

```
if (cond) {  
    ..statement..  
} else if (cond) {  
    ..statement..  
} else {  
    ..statement..  
}
```

- for-loop

```
for ( j in 1:J ) {  
    ..statement..  
}
```

```
for ( j in 1:J ) {  
    for ( k in 1:K ) {  
        ..statement..  
    }  
}
```

same as the R syntax, but  
terminate each line with ;

# BERNOULLI MODEL



# Bernoulli Model

cognitive model  
statistics  
computing

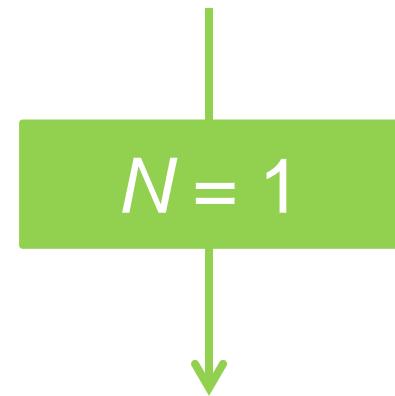
- You are interested in if a coin is biased.
- You will flip the coin.
- You will record whether it comes up a head (h) or a tail (t).
- You might observe 15 heads out of 20 flips.
- What is your degree of belief about the biased parameter  $\vartheta$ ?



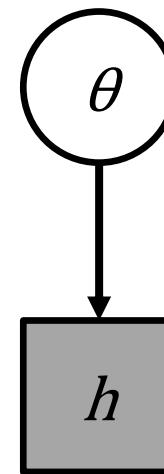
# Bernoulli Model

cognitive model  
statistics  
computing

$$p(w | N, p) = \binom{N}{w} p^w (1-p)^{N-w}$$



$$p(h | \theta) = \theta^h (1 - \theta)^{1-h}$$



$$\theta \sim \text{Uniform}(0, 1)$$

$$h \sim \text{Bernoulli}(\theta)$$

# Exercise VIII

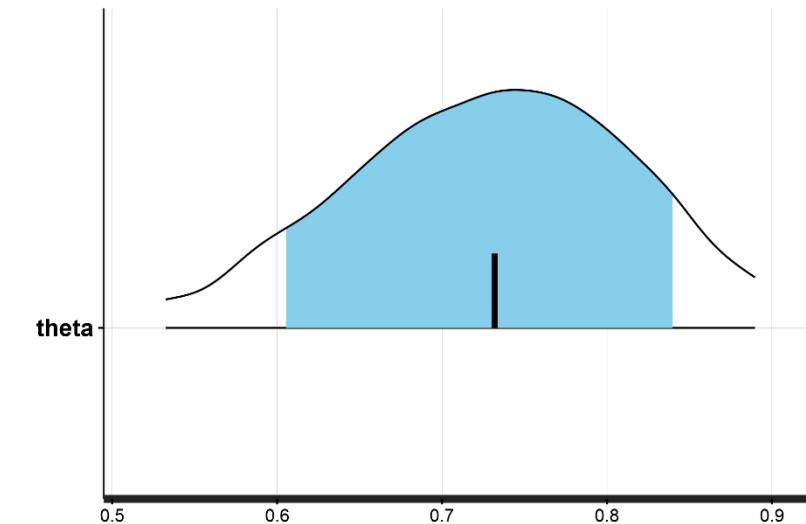
cognitive model  
statistics  
computing

.../BayesCog/03.bernoulli\_coin/\_scripts/bernoulli\_coin\_main.R

TASK: fit the Bernoulli model

```
> dataList
$`flip`
[1] 1 1 1 0 1 1 1 1 0 0 1 1 0 1 1 1 1 0 1

$N
[1] 20
```



# Possible Optimization?

cognitive model  
statistics  
computing

```
model {  
  for (n in 1:N) {  
    flip[n] ~ bernoulli(theta);  
  }  
}
```

61.59 secs\*

```
model {  
  flip ~ bernoulli(theta);  
}
```

53.25 secs\*

Thinking before looping!

# Recap

What we've learned...

- R Basics
- probability distributions
- Bayes' theorem,  $p(\theta|D)$
- Binomial model
- MCMC and Stan

# LINEAR REGRESSION

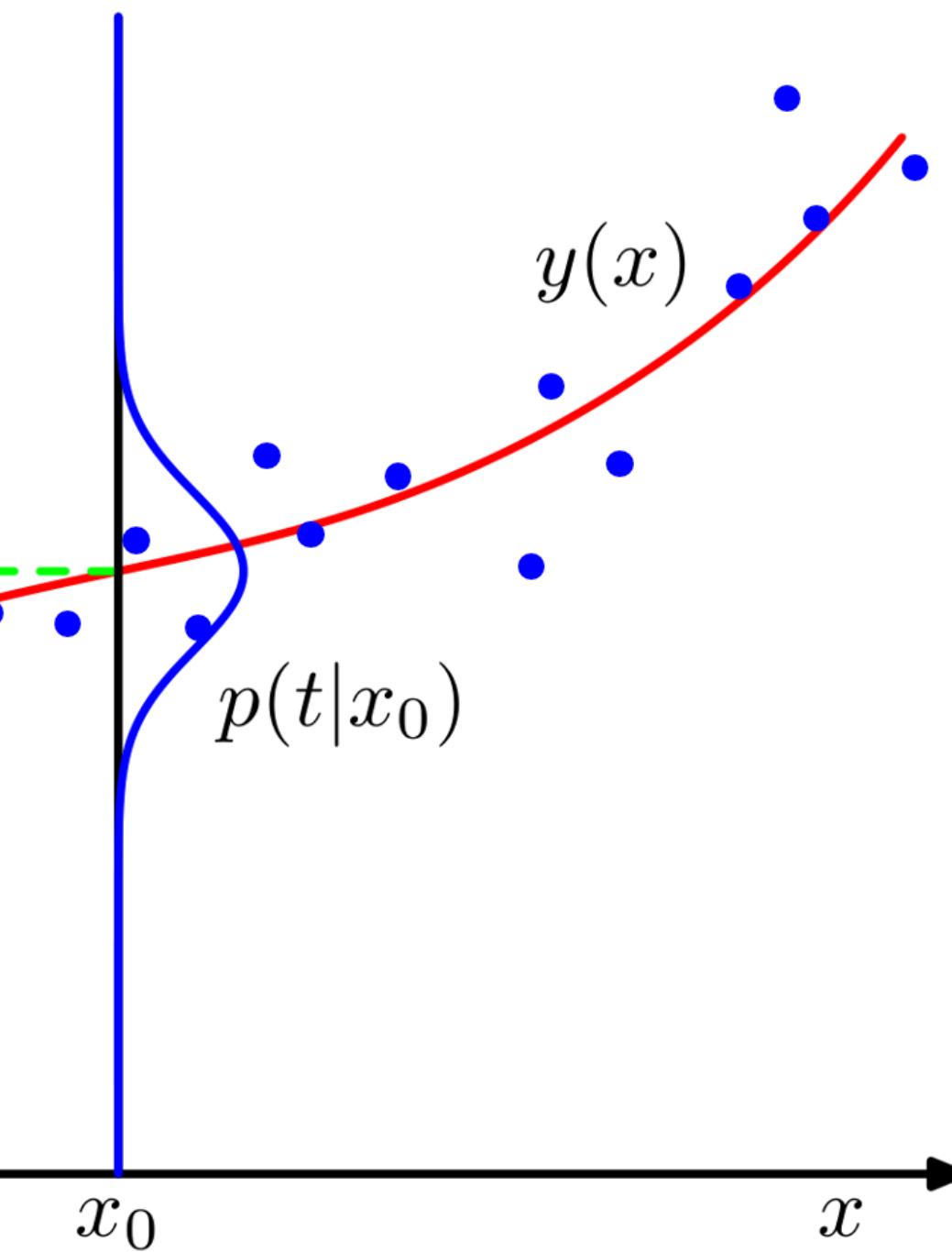
$$y(x_0)$$

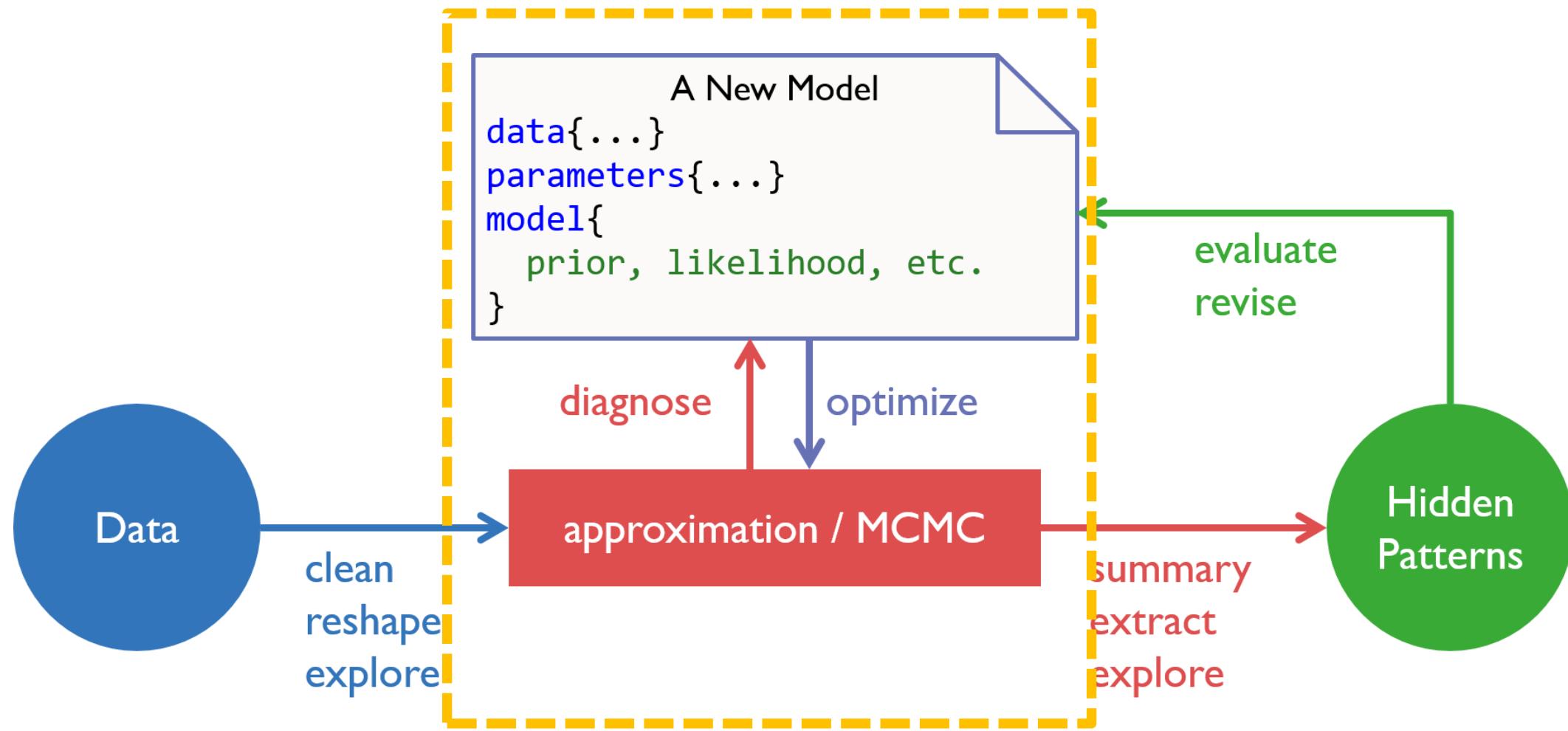
$$x_0$$

$$x$$

$$y(x)$$

$$p(t|x_0)$$





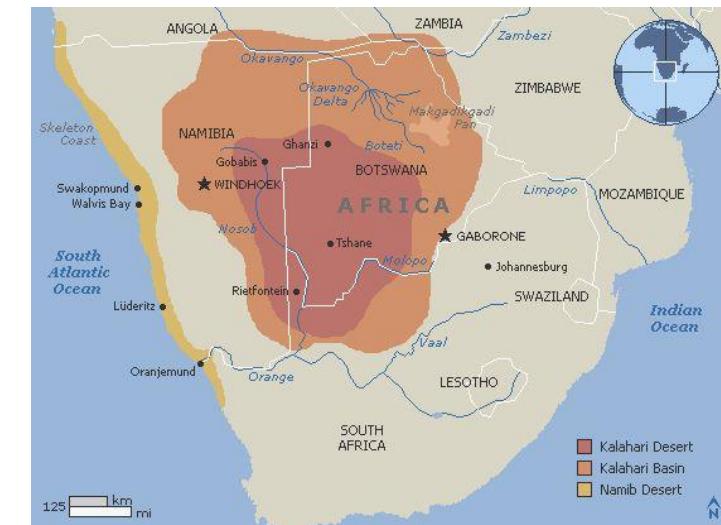
# Linear Regression: height ~ weight

cognitive model  
statistics  
computing

.../04.regression\_height/\_scripts/regression\_height\_main.R

make scatter plot and fit the model with lm()

```
>load('_data/height.RData')
>d <- Howell1
>d <- d[ d$age >= 18 , ]
>head(d)
height    weight age male
1 151.765 47.82561 63   1
2 139.700 36.48581 63   0
3 136.525 31.86484 65   0
4 156.845 53.04191 41   1
5 145.415 41.27687 51   0
6 163.830 62.99259 35   1
```



# Results with lm()

```
> L <- lm( height ~ weight, d) # estimate model by minimizing least squares errors  
> summary(L)
```

Call:

```
lm(formula = height ~ weight, data = d)
```

Residuals:

Min	1Q	Median	3Q	Max
-19.7464	-2.8835	0.0222	3.1424	14.7744

Coefficients:

	Estimate	Std. Error	t value	Pr(> t )
(Intercept)	113.87939	1.91107	59.59	<2e-16 ***
weight	0.90503	0.04205	21.52	<2e-16 ***

---

Signif. codes: 0 ‘\*\*\*’ 0.001 ‘\*\*’ 0.01 ‘\*’ 0.05 ‘.’ 0.1 ‘ ’ 1

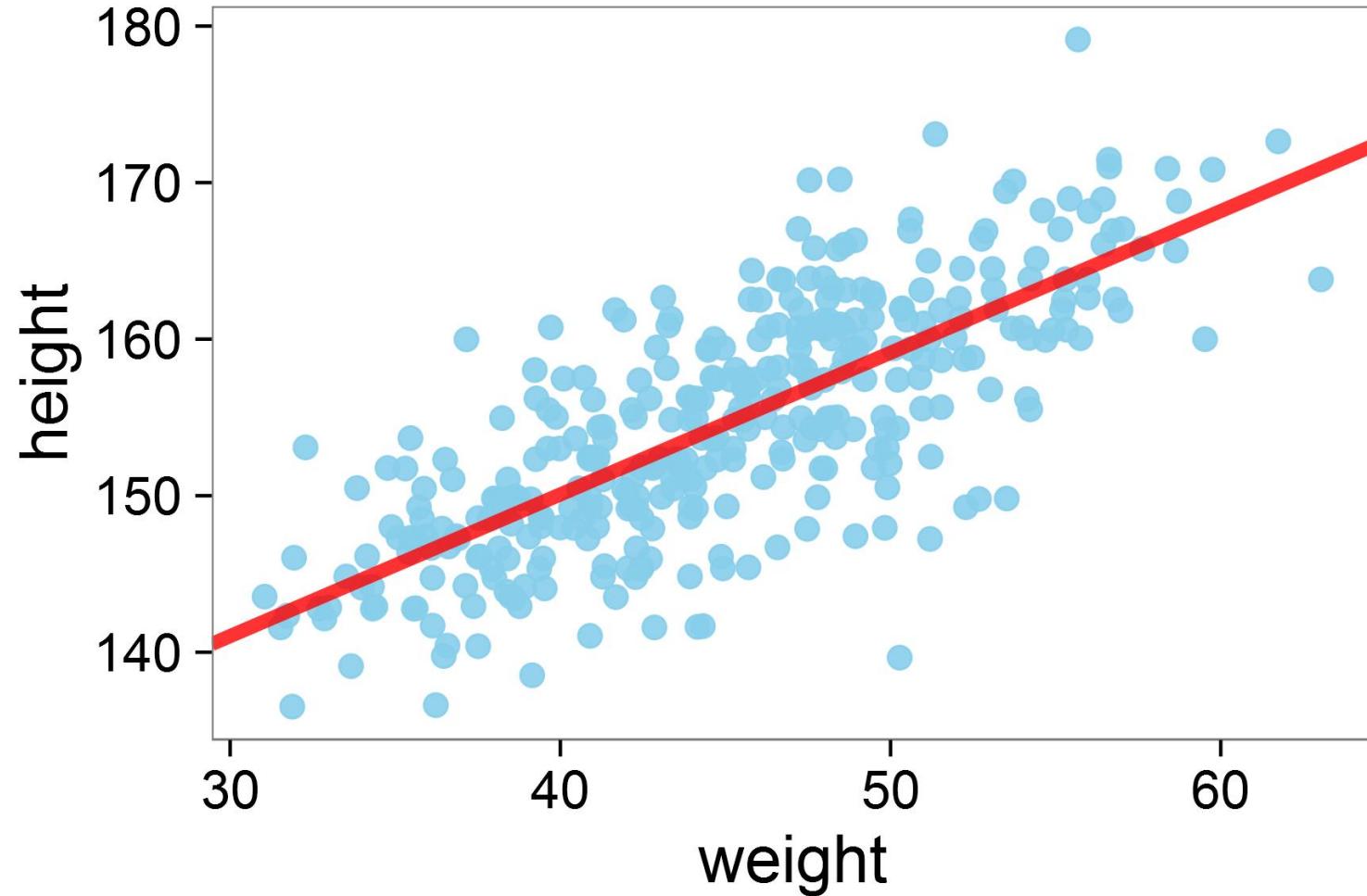
Residual standard error: 5.086 on 350 degrees of freedom

Multiple R-squared: 0.5696, Adjusted R-squared: 0.5684

F-statistic: 463.3 on 1 and 350 DF, p-value: < 2.2e-16

# height ~ weight

cognitive model  
statistics  
computing



# Rethinking Regression Model

cognitive model  
statistics  
computing

$$\mu_i = \alpha + \beta x_i$$

$$y_i = \mu_i + \varepsilon$$

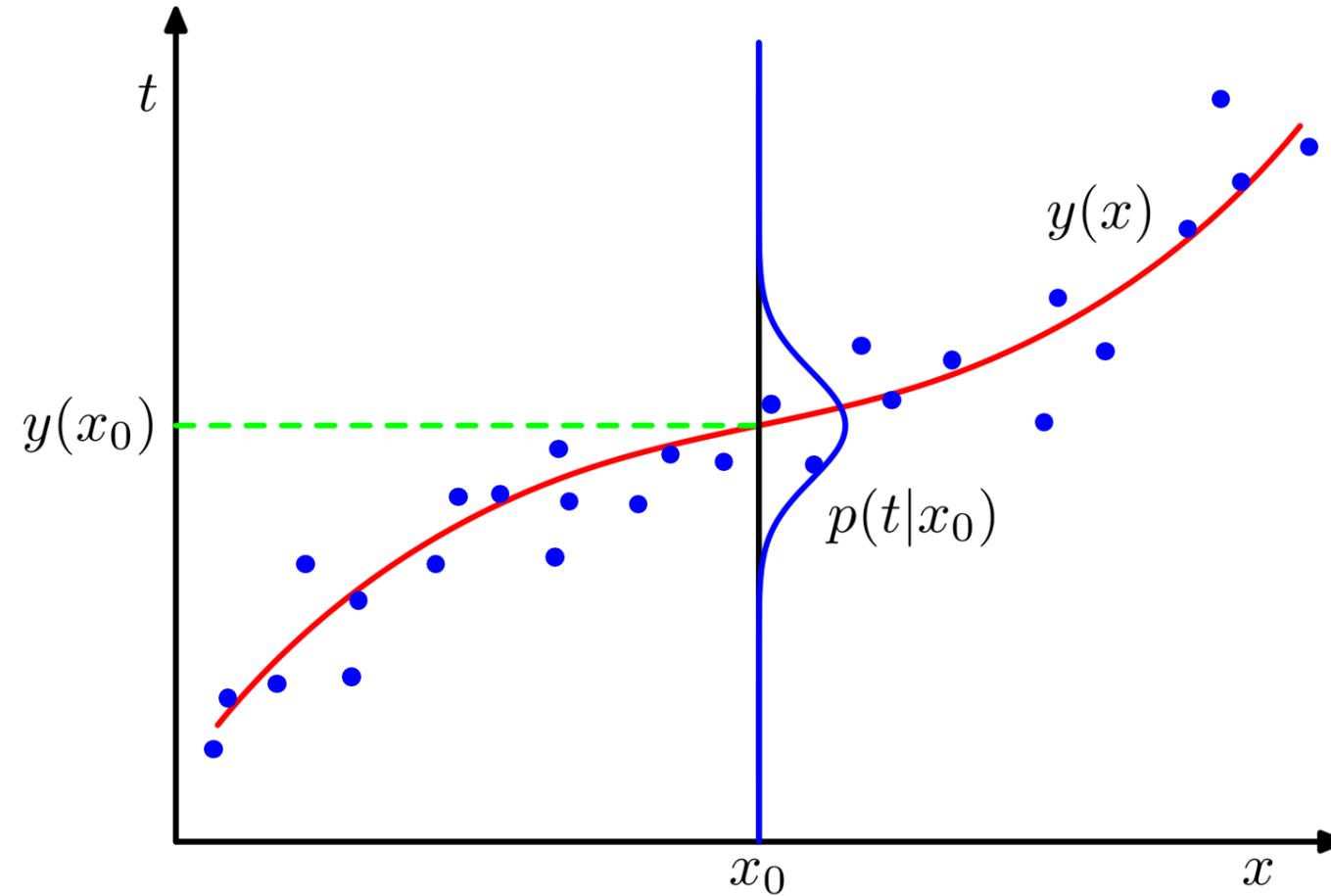
$$\varepsilon \sim Normal(0, \sigma)$$

$$y_i \sim Normal(\mu_i, \sigma)$$

# Rethinking Regression Model

cognitive model
statistics
computing

$$\mu_i = \alpha + \beta x_i$$
$$y_i \sim Normal(\mu_i, \sigma)$$





**Demetri**  
@PhDemetri

...

I wish linear regression was never taught as

$$y = a + bx + e$$

and was instead taught as

$$y \sim \text{Normal}(Xb, \sigma)$$

Because then explaining and learning GLM would be easier

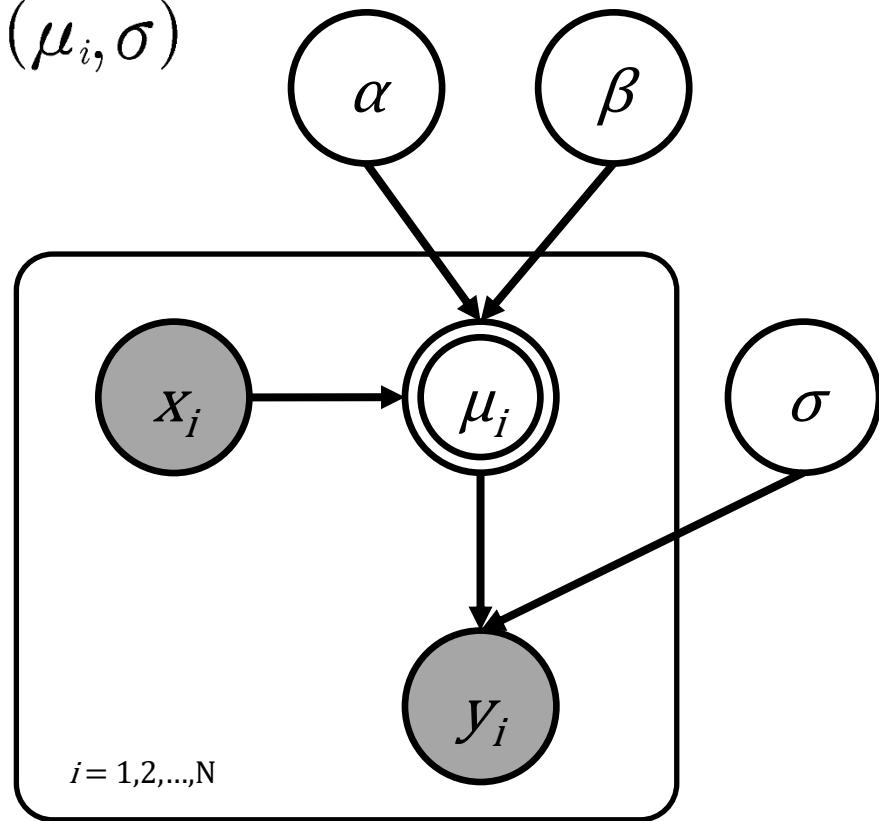
1:19 AM · Apr 12, 2021 · Twitter Web App

# from model to code

cognitive model  
statistics  
computing

$$\mu_i = \alpha + \beta x_i$$

$$y_i \sim Normal(\mu_i, \sigma)$$



```
model {  
  vector[N] mu;  
  for (i in 1:N) {  
    mu[i] = alpha + beta * weight[i];  
    height[i] ~ normal(mu[i], sigma);  
  }  
}
```

```
model {  
  vector[N] mu;  
  mu = alpha + beta * weight;  
  height ~ normal(mu, sigma);  
}
```

```
model {  
  height ~ normal(alpha + beta * weight, sigma);  
}
```



deterministic variable

# Thinking about Priors?

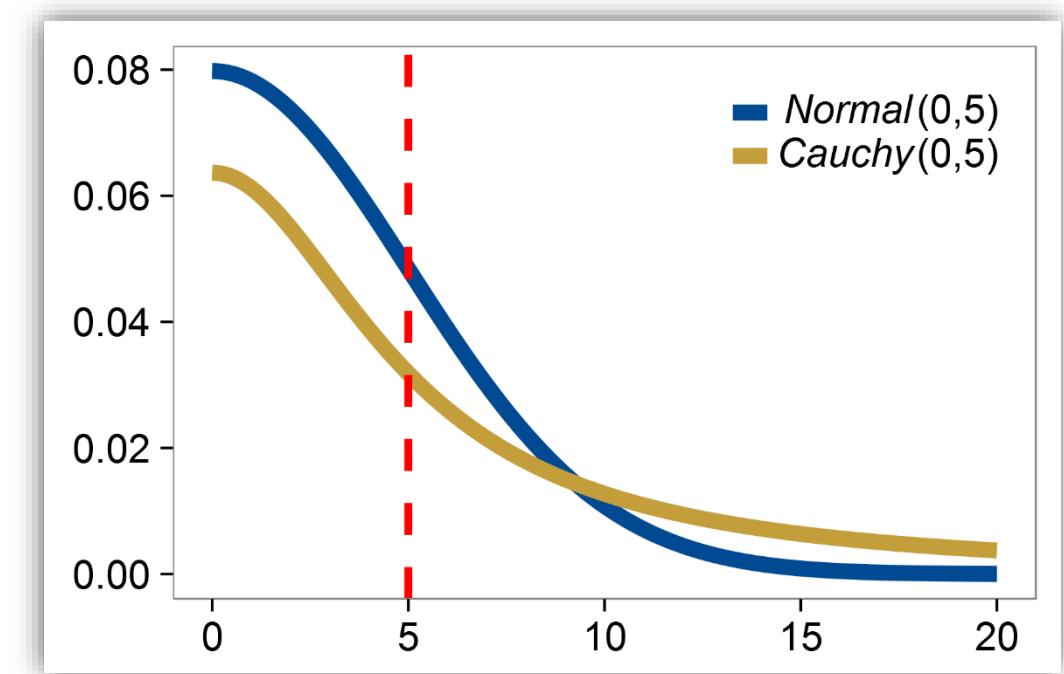
$\alpha \sim Normal(170, 100)$

$\beta \sim Normal(0, 20)$

$$\overline{\text{height}} = \alpha + \beta * \text{weight}$$

$\sigma \sim halfCauchy(0, 20)$

$\text{height} \sim Normal(\overline{\text{height}}, \sigma)$



# Exercise VIII

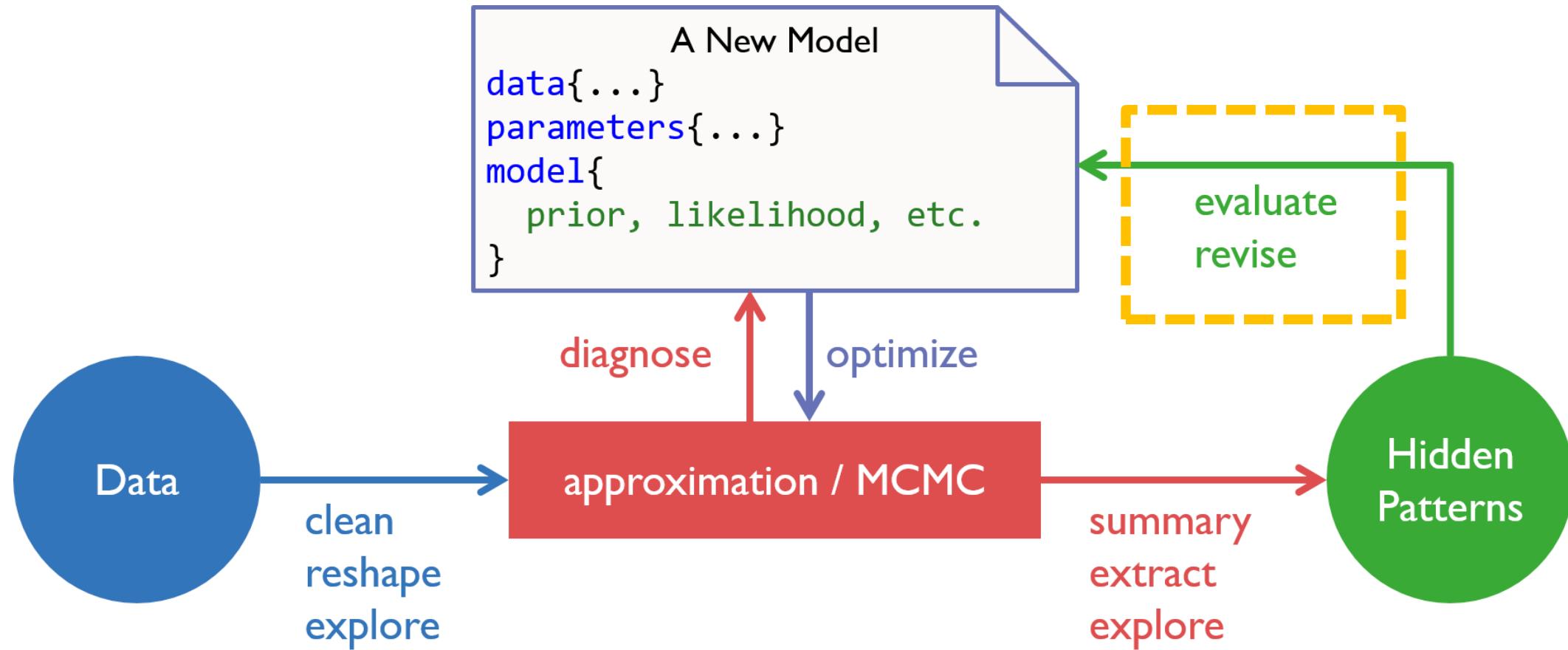
cognitive model  
statistics  
computing

.../04.regression\_height/\_scripts/regression\_height\_main.R

**TASK:** estimate the model and produce the results

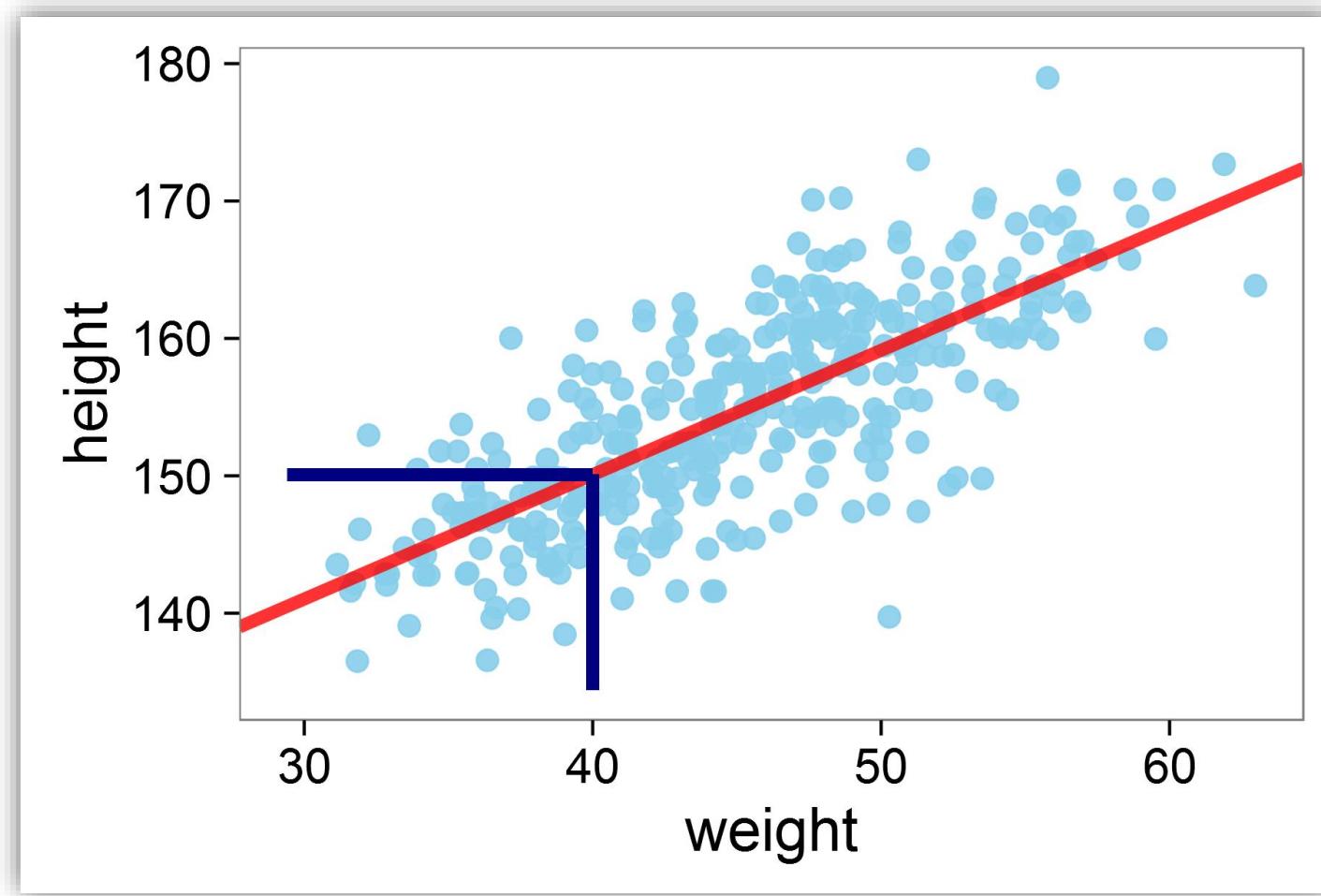
Inference for Stan model: regression\_height\_model.  
4 chains, each with iter=2000; warmup=1000; thin=1;  
post-warmup draws per chain=1000, total post-warmup draws=4000.

	mean	se_mean	sd	2.5%	25%	50%	75%	97.5%	n_eff	Rhat
alpha	113.97	0.06	1.86	110.27	112.76	113.93	115.20	117.66	934	1
beta	0.90	0.00	0.04	0.82	0.88	0.90	0.93	0.99	922	1
sigma	5.11	0.01	0.19	4.74	4.97	5.10	5.24	5.50	1437	1
lp__	-747.61	0.04	1.23	-750.80	-748.15	-747.28	-746.72	-746.24	993	1



# What does the Model Predict?

cognitive model  
statistics  
computing



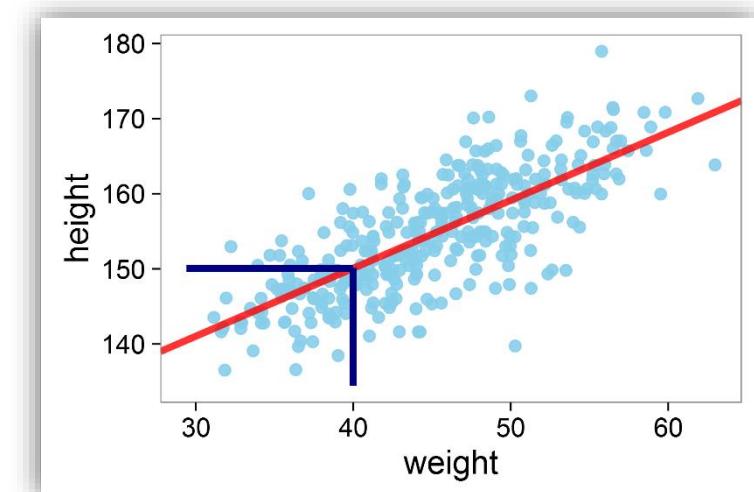
$$p(y_{rep} | y) = \int p(y_{rep} | \theta) p(\theta | y) d(\theta)$$

# Posterior Predictive Check (PPC)

cognitive model
statistics
computing

```
generated quantities {  
    vector[N] height_bar;  
    for (n in 1:N) {  
        height_bar[n] = normal_rng(alpha + beta * weight[n], sigma);  
    }  
}
```

the generated quantities  
block runs only AFTER the  
sampling, and the time it costs  
can be essentially ignored!



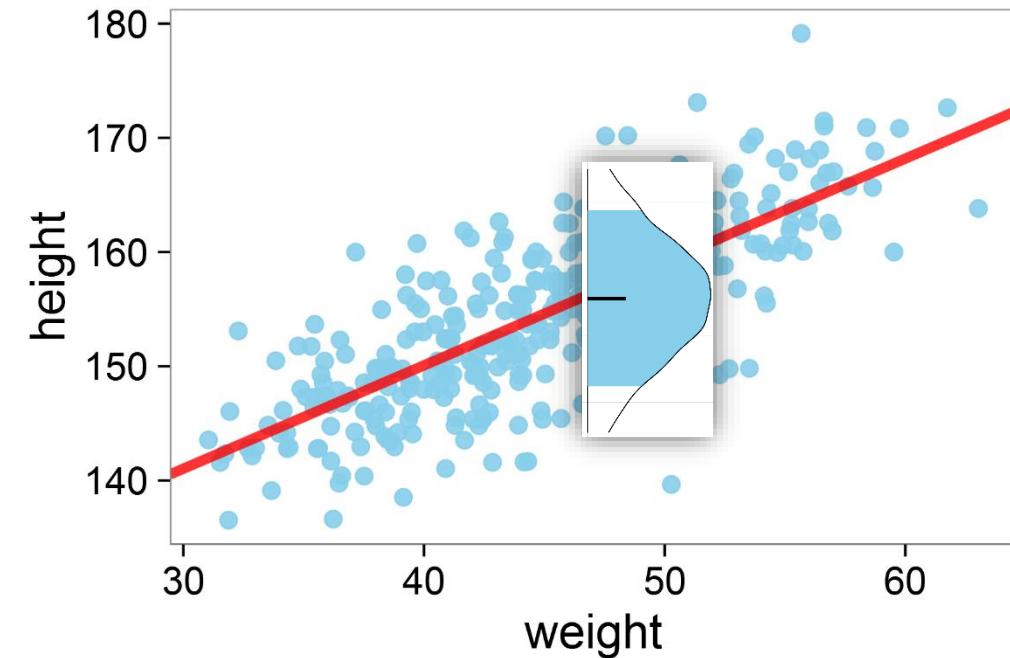
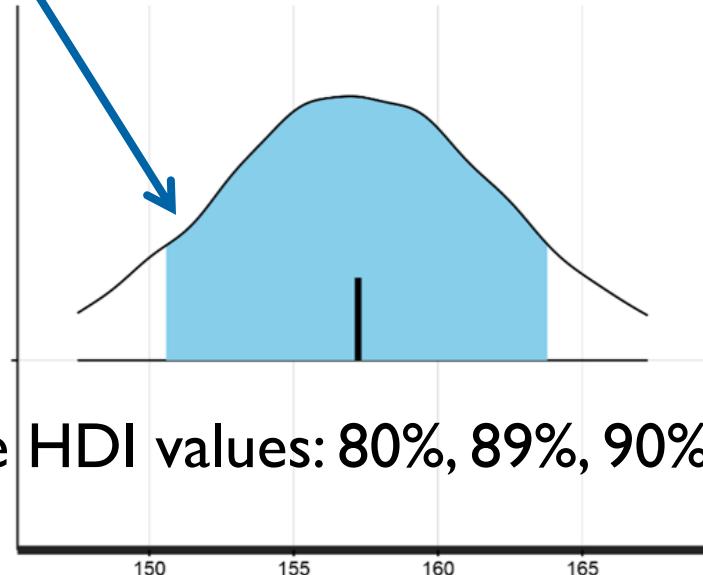
# Posterior Predictive Check (PPC)

cognitive model
statistics
computing

Highest density interval  
(HDI)

`dens(height_bar | x=47.8)`

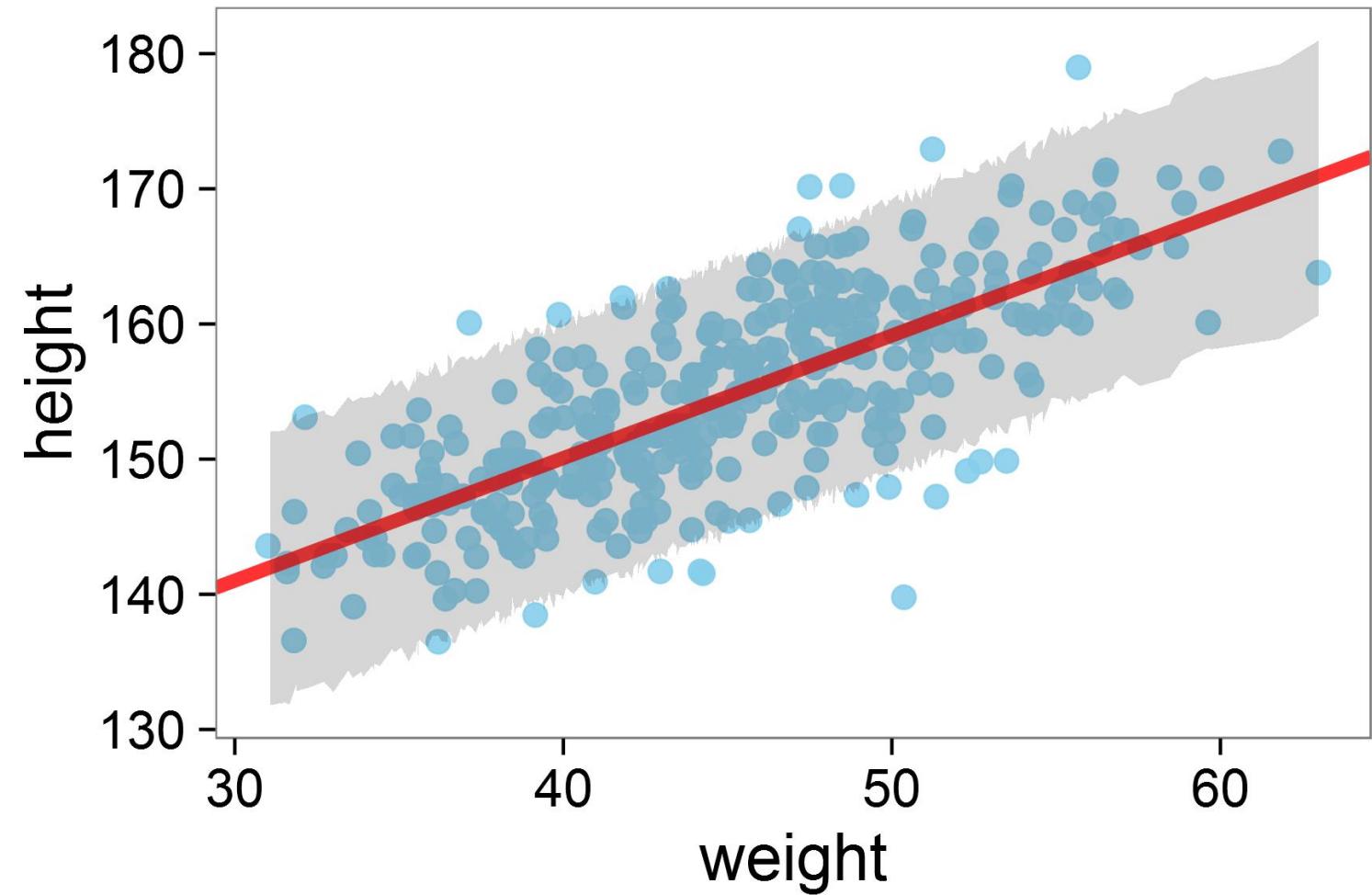
possible HDI values: 80%, 89%, 90%, 95%



```
height_bar <- extract(fit_reg_ppc, pars = 'height_bar',
                      permuted = FALSE)$height_bar
height_HDI <- apply(height_bar, 2, HDIofMCMC)
```

# Posterior Predictive Check (PPC)

cognitive model  
statistics  
computing

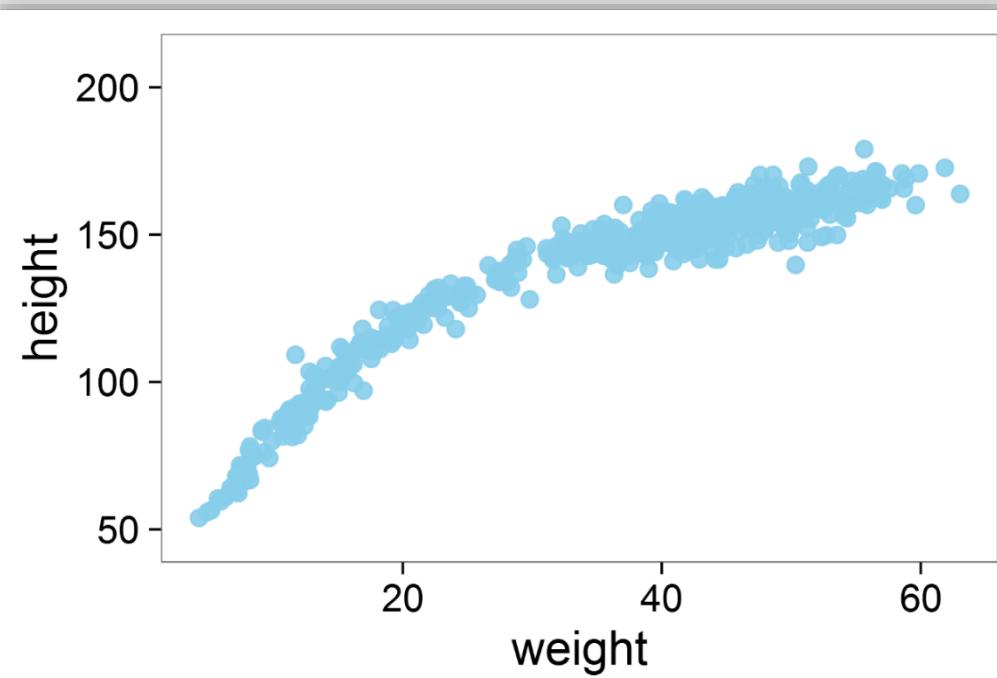


# Exercise IX

cognitive model
statistics
computing

```
.../05.regression_height_poly/_scripts  
/regression_height_poly_main.R
```

TASK: (1) Complete “regression\_height\_poly2\_model.stan”  
(2) produce PPC plot for both 1<sup>st</sup> order and 2<sup>nd</sup> order polynomial fit



# Exercise IX – Tips

cognitive model
statistics
computing

```
> source('_scripts/regression_height_poly_main.R')  
  
> out1 <- reg_poly(poly_order = 1)
```

$$\overline{\text{height}} = \alpha + \beta_1 * \text{weight} + \beta_2 * \text{weight}^2$$

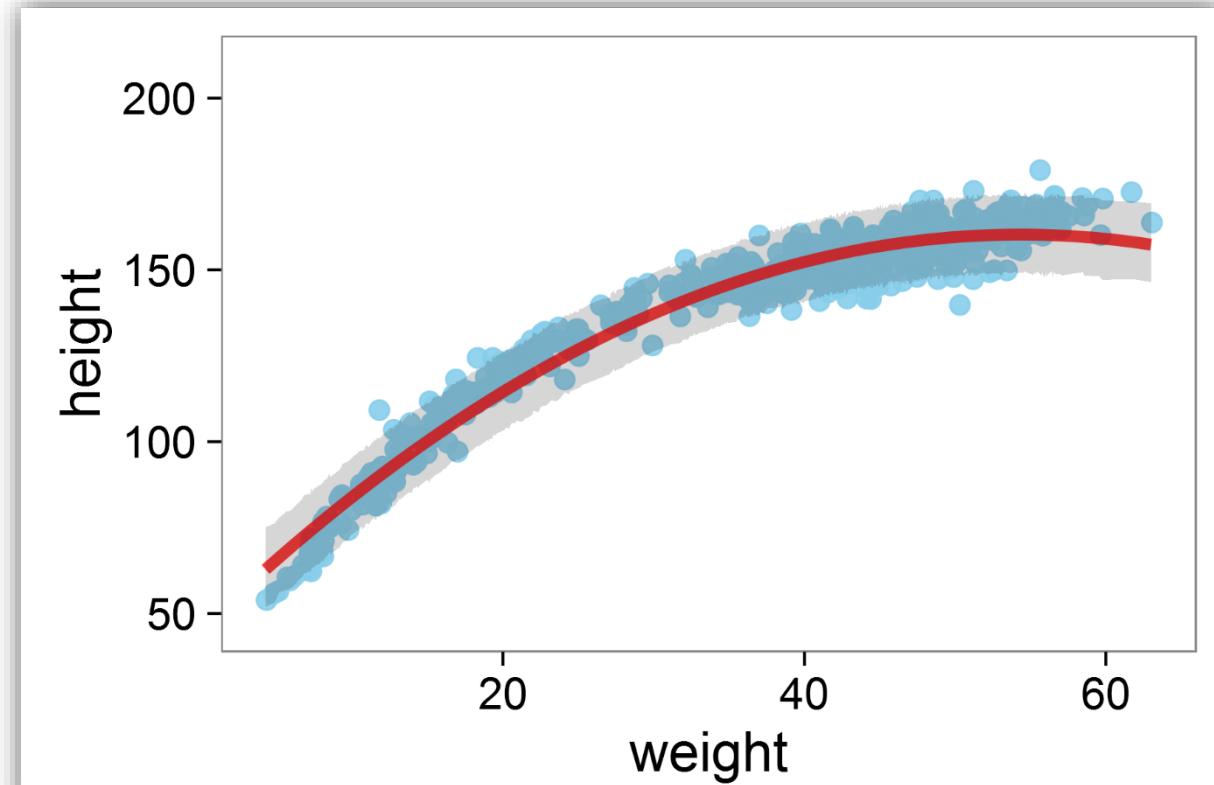
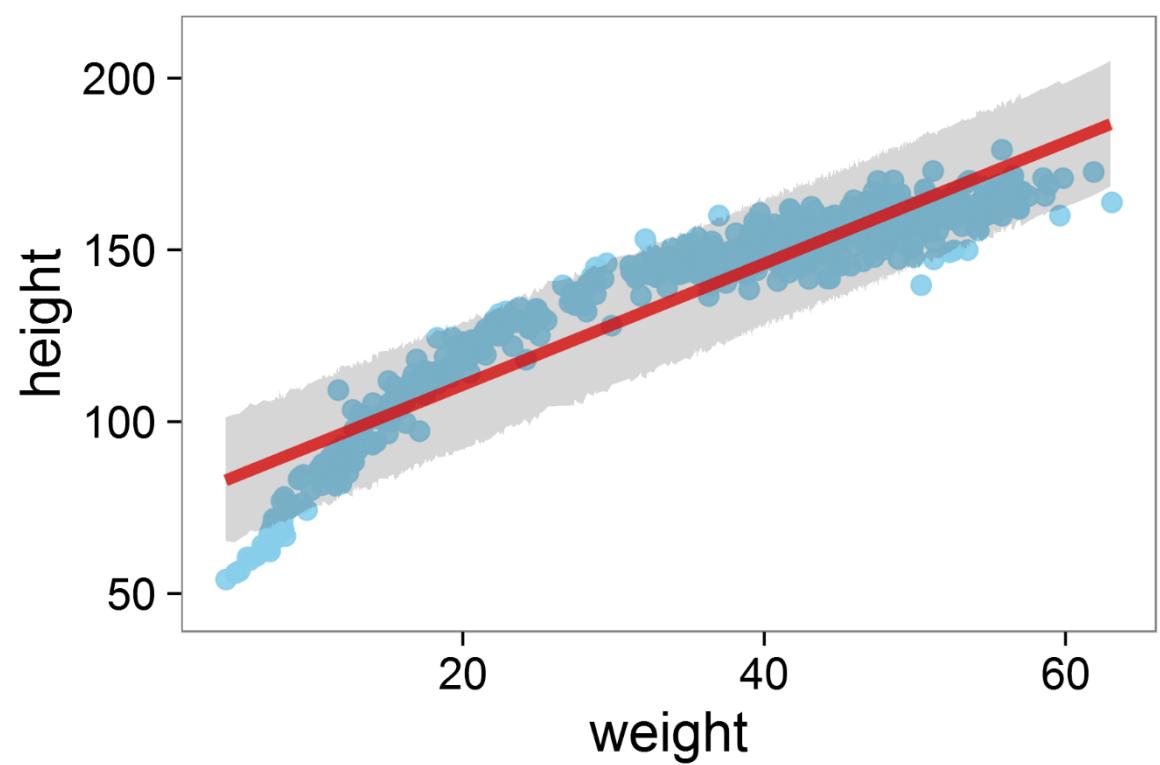
$$\text{height} \sim \text{Normal}(\overline{\text{height}}, \sigma)$$

```
data {  
  int<lower=0> N;  
  vector<lower=0>[N] height;  
  vector<lower=0>[N] weight;  
  vector<lower=0>[N] weight_sq;  
}
```

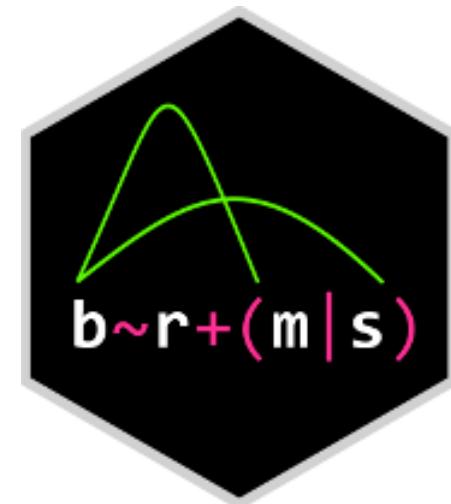
```
height ~ normal(alpha + beta1 * weight + beta2 * weight_sq, sigma);
```

# Exercise IX – output2

cognitive model
statistics
computing



# Complex GLMs in Stan?



# Want to learn more about Stan?

cognitive model
statistics
computing

# Workshops

- StanCon 2019 Hierarchical Models
- PyData NYC 2019
- StanCon 2018 Intro Stan
- StanCon 2018 Hierarchical Models

<https://mc-stan.org/workshops/>

# Stan forum

StanCon 2020, August 11-14 at Oregon State University

Announcements stancon

StanCon 2020 will be at Oregon State University! There will be two days of tutorials followed by two days of talks, open discussions, and statistical modeling. Up-to-date details at <https://mc-stan.org/events/stancon202...> [read more](#)



Welcome to the Stan Forums!

The Stan Forums provide a community for asking and answering questions about all aspects of Stan. Before creating a new topic please search the Forums to see if your question has already been answered, or check out the... [read more](#)



Unable to retrieve parameters from a dynamic model

Modeling fitting-issues specification



<https://discourse.mc-stan.org/>

# Twitter



**Richard McElreath**  
@rlmcelreath



**Quiche Lorraine,**  
@dan\_p\_simpson



**\mathfrak{mathfrak}{Michael}**  
@betanalpha



**EJ Wagenmakers**  
@EJWagenmakers

ANY  
QUESTIONS?  
?

Happy Computing!