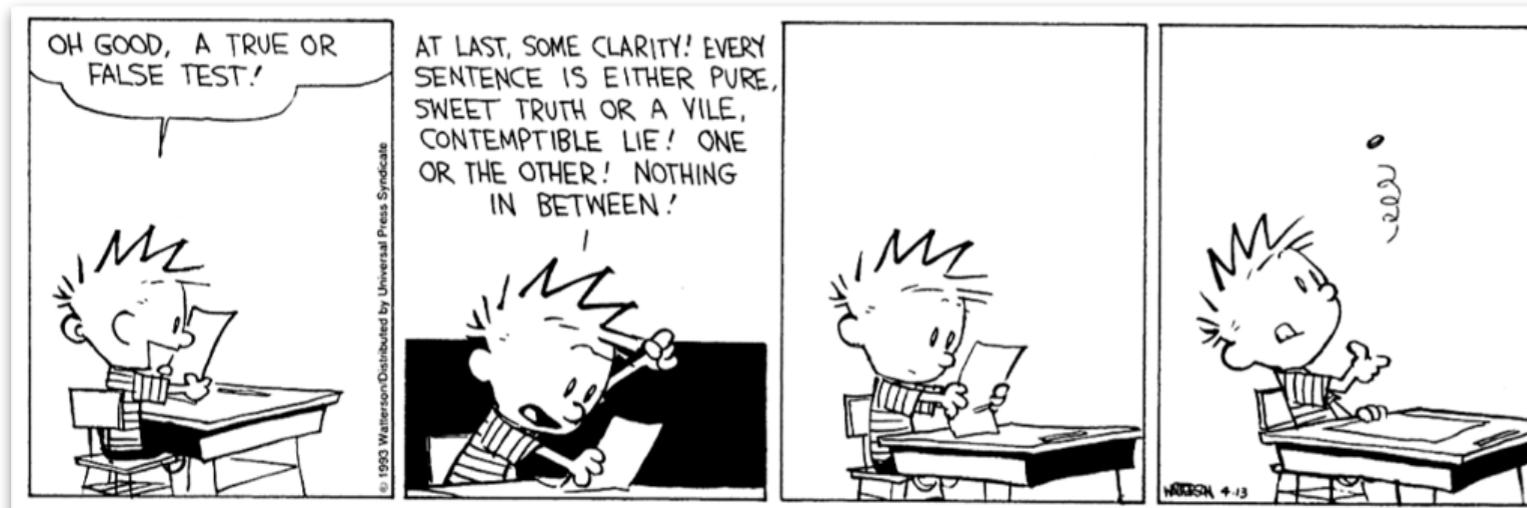


Model comparison



Chat

If you could be in the Guinness book of world records, what record-breaking feat would you attempt?

To: Everyone ▾ More ▾

Type message here...

COLLABORATIVE PLAYLIST

psych252

<https://tinyurl.com/psych252spotify22>

PLAY ...

We're listening to
"INDUSTRY BABY" by
"Lil Nas X, Jack Harlow"
submitted by Sarah Wu

02/07/2022

Plan for today

- Quick recap
- Simulating a power analysis
 - Demonstration in RStudio
- Model comparison
 - Cross-validation
 - AIC and BIC
- Linear mixed effects models

Things that came up

Midterm: Part 3



AI speculates on meaning and p-value



Andrew Perfors
@AndyPerfors

...

AI doing its best to start a war on statistics twitter...

Get inspiration for a story from an AI, just write two themes and see the first paragraph come alive.

Themes:

meaning and p-value

Story:

Many scientists across the globe have been searching for a meaning to life for years, but have been left empty-handed. Some have even gone as far as to propose that life has no meaning, and that all of the universe's complexity and beauty is just an illusion. One of these scientists is Professor Pritchard, who has been working on a new study that he hopes will provide some answers. His team is trying to create a computer program that can determine the meaning of life, and they believe that they have found the perfect candidate: the p-value. The p-value is a statistic that is used to measure the probability of obtaining a result by chance. Professor Pritchard and his team believe that the p-value is the key to unlocking the meaning of life. If they can find a way to calculate the p-value for any given set of data, they believe that they can determine the meaning of life for that data. The team is working hard to find the perfect p-value, but they are facing some obstacles. The p-value is a difficult statistic to calculate, and it is not always easy to find data that can be used to calculate it. However, the team

Feedback

🌐 When poll is active, respond at **pollev.com/psych252**



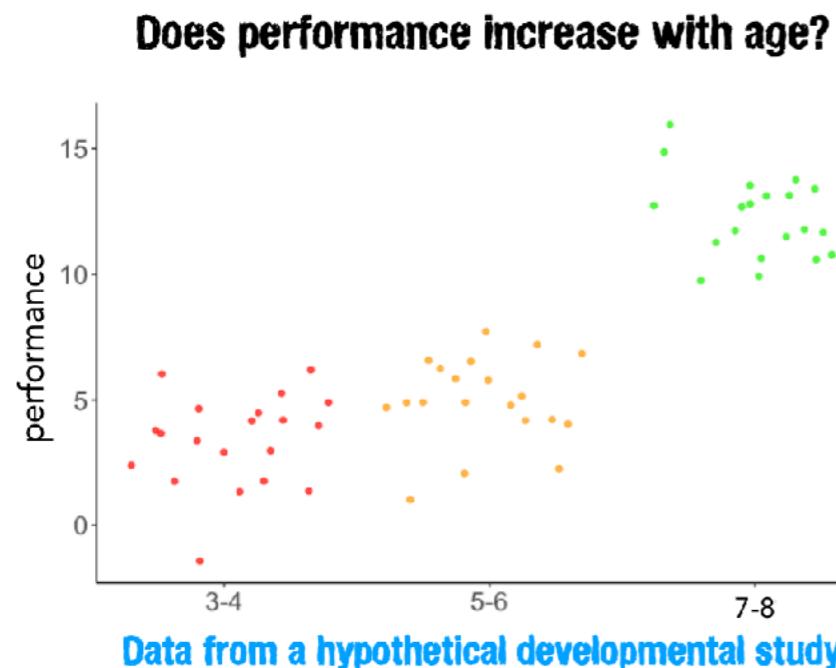
How many hours did it take you to complete Homework 4?



Quick recap

Quick recap: Linear contrasts

Contrasts



Does performance increase with age?

↓
ANOVA

Does performance differ between age groups?

3-4 vs. 5-6

post-hoc tests

5-6 vs. 7-8



Is there are more direct way of asking this question with a statistical model?

Linear contrasts in R

```
1 library("emmeans") # for calculating contrasts
2
3 # fit the linear model
4 fit = lm(formula = performance ~ group,
5           data = df.development)
6
7 # check factor levels
8 levels(df.development$group) [1] "3-4" "5-6" "7-8"
9
10 # define the contrasts of interest
11 contrasts = list(young_vs_old = c(-0.5, -0.5, 1),
12                   three_vs_five = c(-0.5, 0.5, 0))
13
14 # compute significance test on contrasts
15 fit %>%
16   emmeans("group",      compute the results
17           contr = contrasts,
18           adjust = "bonferroni") %>%
19   pluck("contrasts")
```

```
[1] "3-4" "5-6" "7-8"
contrast   estimate      SE df t.ratio p.value
young_vs_old 16.093541 0.4742322 57 33.936 <.0001
three_vs_five 1.606003 0.5475962 57  2.933  C.0097
P value adjustment: bonferroni method for 2 tests
```

16

Post hoc tests

```
1 fit = lm(formula = performance ~ group,
2           data = df.development)
3
4 # pairwise differences between all the groups
5 fit %>%
6   emmeans(pairwise ~ group) %>%
7   pluck("contrasts")
```

↑
all pairwise tests between groups

| contrast | estimate | SE | df | t.ratio | p.value |
|-----------|------------|-----------|----|---------|---------|
| 3-4 - 5-6 | -1.606009 | 0.5475962 | 57 | -2.933 | 0.0145 |
| 3-4 - 7-8 | -16.896546 | 0.5475962 | 57 | -30.856 | <.0001 |
| 5-6 - 7-8 | -15.290537 | 0.5475962 | 57 | -27.923 | <.0001 |

P value adjustment: bonferroni method for 3 tests

25

17

Quick recap: Unbalanced designs

Beware of unbalanced designs

```
1 lm(formula = balance ~ skill + hand, data = df.poker.unbalanced) %>%
2   anova()
```

```
Analysis of Variance Table

Response: balance
          Df Sum Sq Mean Sq F value Pr(>F)
skill      1    74.3   74.28  4.2904 0.03922 *
hand       2 2385.1 1192.57 68.8827 < 2e-16 ***
Residuals 286 4951.5   17.31
---
Signif. codes:  0 '****' 0.001 '***' 0.01 '**' 0.05 '.' 0.1 ' ' 1
```

flipped the order

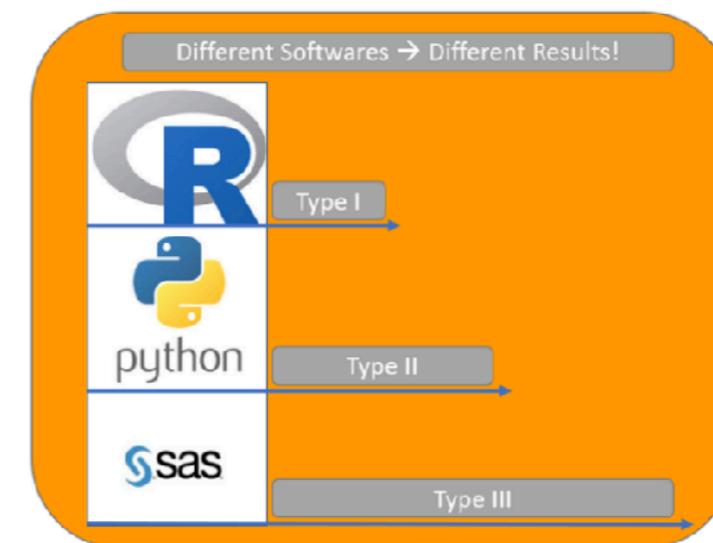
```
1 lm(formula = balance ~ hand + skill, data = df.poker.unbalanced) %>%
2   anova()
```

```
Analysis of Variance Table

Response: balance
          Df Sum Sq Mean Sq F value Pr(>F)
hand       2 2419.8 1209.92 69.8845 < 2e-16 ***
skill      1    39.6   39.59  2.2867 0.1316
Residuals 286 4951.5   17.31
---
Signif. codes:  0 '****' 0.001 '***' 0.01 '**' 0.05 '.' 0.1 ' ' 1
```

34

Default sums of squares ...



not great for reproducibility ...

36

Route I: Using "afex"

```
1 library("afex")
2
3 fit = aov_ez(id = "participant",
4                 dv = "balance",
5                 data = df.poker.unbalanced,
6                 between = c("hand", "skill"))
7 fit$anova
```

```
Contrasts set to contr.sum for the following variables: hand, skill
Anova Table (Type III tests)

Response: dv
          Sum Sq Df  F value    Pr(>F)
(Intercept) 27781.3  1 1676.9095 < 2.2e-16 ***
hand         2285.3  2   68.9729 < 2.2e-16 ***
skill        48.9   1    2.9540  0.0867525 .
hand:skill   246.5  2    7.4401  0.0007089 ***
Residuals    4705.0 284
---
Signif. codes:  0 '****' 0.001 '***' 0.01 '**' 0.05 '.' 0.1 ' ' 1
```

40

Route II: Using "emmeans"

```
1 library("emmeans")
2
3 lm(formula = balance ~ hand + skill,
4      data = df.poker.unbalanced) %>%
5   joint_tests()
```

| model term | df1 | df2 | F.ratio | p.value |
|------------|-----|-----|---------|---------|
| hand | 2 | 284 | 68.973 | <.0001 |
| skill | 1 | 284 | 2.954 | 0.0868 |
| hand:skill | 2 | 284 | 7.440 | 0.0007 |

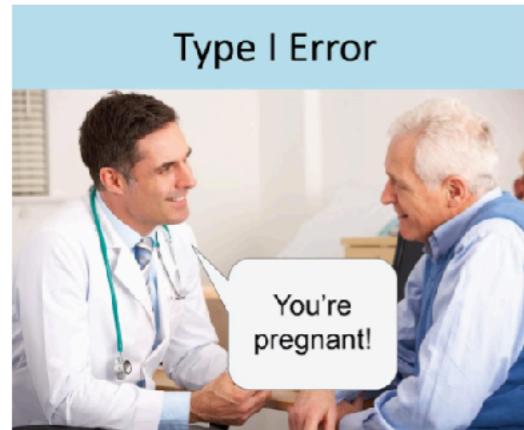
very handy function

preferred route!!

10

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Quick recap: Power analysis

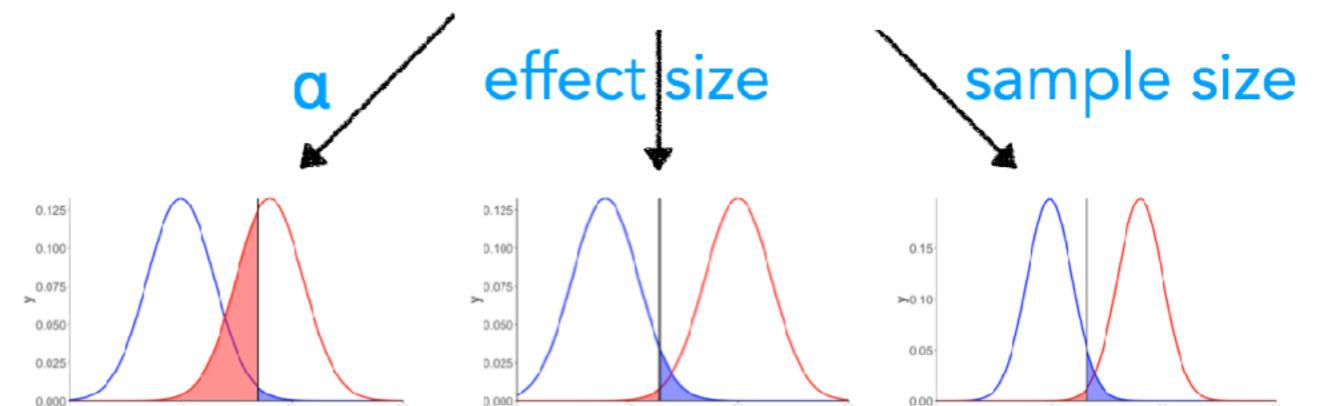
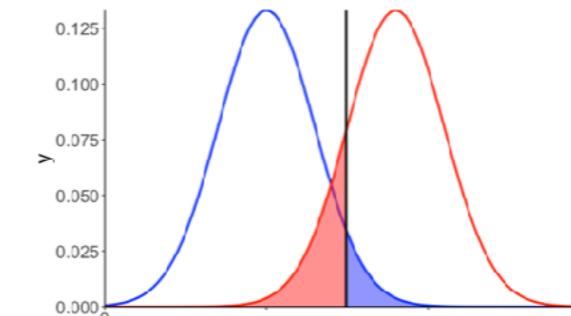


H_0 : Not pregnant. H_1 : Pregnant.

Type I Error: Falsely rejecting the null hypothesis (even though it is true).

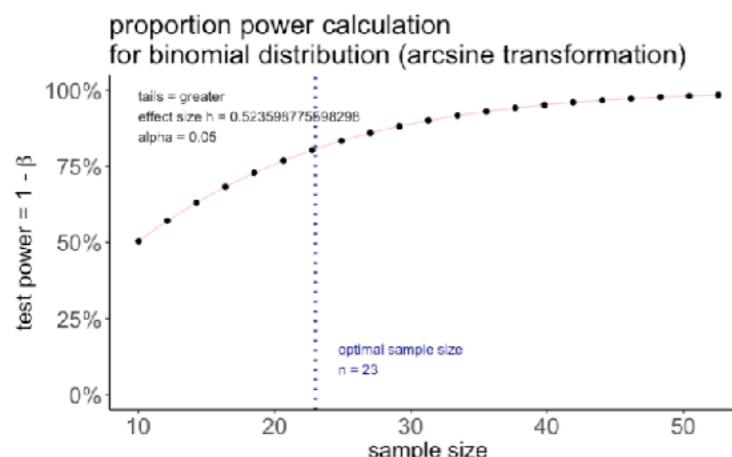
Type II Error: Failing to reject the null hypothesis (even though it is false).

The knobs we can turn to affect power



"pwr" package in R

```
1 library("pwr")
2 pwr.p.test(h = ES.h(p1 = 0.75, p2 = 0.50),
3             sig.level = 0.05,
4             power = 0.80,
5             alternative = "greater") %>%
6   plot()
```



Option 2

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Power simulation recipe

- assume:
 - α , n , effect size
- simulate a large number of data sets of size n with the specified effect size
- for each data set, run a statistical test to calculate the p-value
- determine the probability of rejecting the H_0 (given that H_1 is true)

Option 3

54

11

67

68

Simulating a power analysis

Power simulation recipe

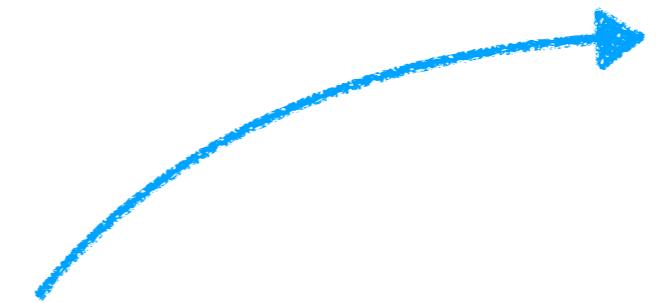
- assume:
 - α , n , effect size
- simulate a large number of data sets of size n with the specified effect size
- for each data set, run a statistical test to calculate the p-value
- determine the probability of rejecting the H_0 (given that H_1 is true)

Let's simulate ...

```
1 # make reproducible
2 set.seed(1)
3
4 # number of simulations
5 n_simulations = 5
6
7 # run simulation
8 expand_grid(n = seq(10, 40, 2),
9             simulation = 1:n_simulations,
10            p = 0.75) %>%
11 mutate(index = 1:n(),
12         .before = n) %>%
13 group_by(index, n, p, simulation) %>%
14 mutate(response = rbinom(n = 1,
15                         size = n,
16                         prob = p),
17         p.value = binom.test(x = response,
18                               n = n,
19                               p = 0.5,
20                               alternative = "two.sided")$p.value) %>%
21 group_by(n, p) %>%
22 summarize(power = sum(p.value < 0.05) / n())
```

Let's simulate ...

```
1 # make reproducible
2 set.seed(1)
3
4 # number of simulations
5 n_simulations = 5
6
7 # run simulation
8 expand_grid(n = seq(10, 40, 2),
9             simulation = 1:n_simulations,
10            p = 0.75) %>%
11 mutate(index = 1:n(),
12         .before = n) %>%
```



| index | n | simulation | p |
|-------|----|------------|------|
| 1 | 10 | 1 | 0.75 |
| 2 | 10 | 2 | 0.75 |
| 3 | 10 | 3 | 0.75 |
| 4 | 10 | 4 | 0.75 |
| 5 | 10 | 5 | 0.75 |
| 6 | 12 | 1 | 0.75 |
| 7 | 12 | 2 | 0.75 |
| 8 | 12 | 3 | 0.75 |
| 9 | 12 | 4 | 0.75 |
| 10 | 12 | 5 | 0.75 |

Let's simulate ...

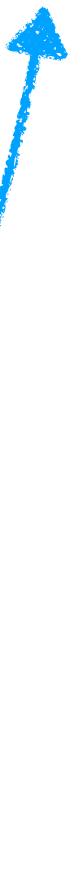
```
1 # make reproducible
2 set.seed(1)
3
4 # number of simulations
5 n_simulations = 5
6
7 # run simulation
8 expand_grid(n = seq(10, 40, 2),
9             simulation = 1:n_simulations,
10            p = 0.75) %>%
11 mutate(index = 1:n(),
12         .before = n) %>%
13 group_by(index, n, p, simulation) %>%
14 mutate(response = rbinom(n = 1,
15                           size = n,
16                           prob = p),
```

| index | n | simulation | p | response |
|-------|----|------------|------|----------|
| 1 | 10 | 1 | 0.75 | 8 |
| 2 | 10 | 2 | 0.75 | 7 |
| 3 | 10 | 3 | 0.75 | 8 |
| 4 | 10 | 4 | 0.75 | 8 |
| 5 | 10 | 5 | 0.75 | 7 |
| 6 | 12 | 1 | 0.75 | 10 |
| 7 | 12 | 2 | 0.75 | 8 |
| 8 | 12 | 3 | 0.75 | 11 |
| 9 | 12 | 4 | 0.75 | 10 |
| 10 | 12 | 5 | 0.75 | 11 |

Let's simulate ...

```
1 # make reproducible
2 set.seed(1)
3
4 # number of simulations
5 n_simulations = 5
6
7 # run simulation
8 expand_grid(n = seq(10, 40, 2),
9             simulation = 1:n_simulations,
10            p = 0.75) %>%
11 mutate(index = 1:n(),
12         .before = n) %>%
13 group_by(index, n, p, simulation) %>%
14 mutate(response = rbinom(n = 1,
15                           size = n,
16                           prob = p),
17         p.value = binom.test(x = response,
18                               n = n,
19                               p = 0.5,
20                               alternative = "two.sided")$p.value) %>%
```

| index | n | simulation | p | response | p.value |
|-------|----|------------|------|----------|---------|
| 1 | 10 | 1 | 0.75 | 8 | 0.11 |
| 2 | 10 | 2 | 0.75 | 7 | 0.34 |
| 3 | 10 | 3 | 0.75 | 8 | 0.11 |
| 4 | 10 | 4 | 0.75 | 8 | 0.11 |
| 5 | 10 | 5 | 0.75 | 7 | 0.34 |
| 6 | 12 | 1 | 0.75 | 10 | 0.04 |
| 7 | 12 | 2 | 0.75 | 8 | 0.39 |



Let's simulate ...

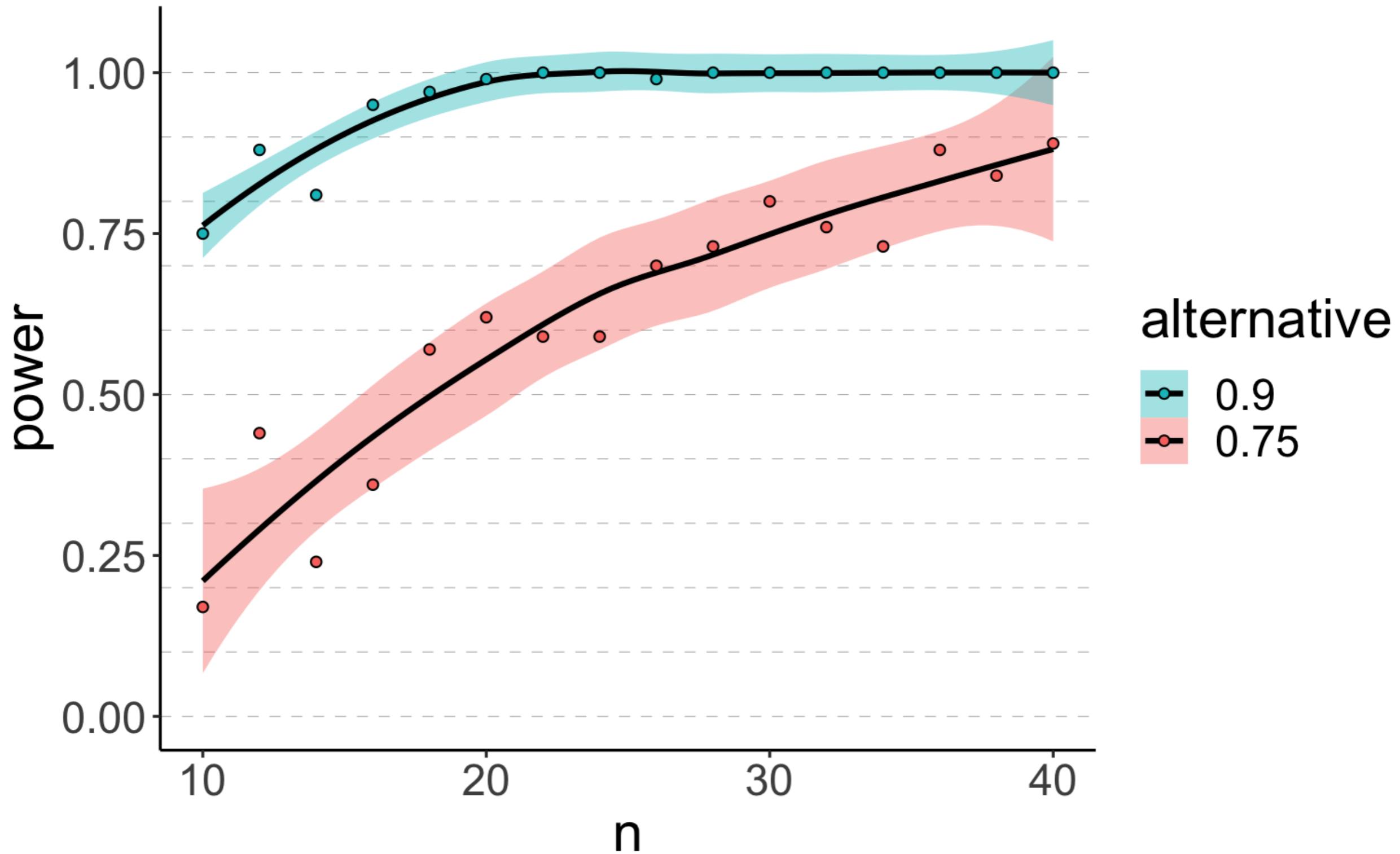
```
1 # make reproducible
2 set.seed(1)
3
4 # number of simulations
5 n_simulations = 5
6
7 # run simulation
8 expand_grid(n = seq(10, 40, 2),
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12         .before = n) %>%
13 group_by(index, n, p, simulation) %>%
14 mutate(response = rbinom(n = 1,
15                         size = n,
16                         prob = p),
17         p.value = binom.test(x = response,
18                               n = n,
19                               p = 0.5,
20                               alternative = "two.sided")$p.value) %>%
21 group_by(n, p) %>%
22 summarize(power = sum(p.value < 0.05) / n())
```

| n | p | power |
|----|------|-------|
| 10 | 0.75 | 0.2 |
| 12 | 0.75 | 0.2 |
| 14 | 0.75 | 0.4 |
| 16 | 0.75 | 0.2 |
| 18 | 0.75 | 0.6 |
| 20 | 0.75 | 0.8 |
| 22 | 0.75 | 0.6 |
| 24 | 0.75 | 0.4 |
| 26 | 0.75 | 0.6 |
| 28 | 0.75 | 0.8 |
| 30 | 0.75 | 0.8 |



Let's simulate ...

in this example, I looked at the power for two different alternative hypotheses



Let's simulate ...

- here, I've used a simple example (Binomial test)
- but: we can use the same recipe for any statistical test that we are planning on running

Power simulation recipe

- assume:
 - α , n , effect size
- simulate a large number of data sets of size n with the specified effect size
- for each data set, run a statistical test to calculate the p-value for a given α
- determine the probability of rejecting the H_0 (given that H_1 is true)



Model comparison

The general procedure

1. Define H_0 as Model C (compact) and H_1 as Model A (augmented)
2. Fit model parameters to the data
3. Calculate the proportional reduction of error (PRE) in our sample
4. Decide whether the augmented model is **worth it** by comparing the observed PRE in our sample to the sampling distribution of PRE (assuming that H_0 is true)

Any problems with our approach?

sometimes it doesn't work ...

Model C

$$\text{balance}_i = \beta_0 + \epsilon_i$$

$$\text{balance}_i = \beta_0 + \beta_1 \cdot \text{student}_i + \epsilon_i$$

$$\text{balance}_i = \beta_0 + \beta_1 \cdot \text{student}_i + \epsilon_i$$

$$\text{balance}_i = \beta_0 + \beta_1 \cdot \text{student}_i + \epsilon_i$$

Model A

$$\text{balance}_i = \beta_0 + \beta_1 \cdot \text{student}_i + \beta_2 \cdot \text{age}_i + \epsilon_i$$

$$\text{balance}_i = \beta_0 + \beta_1 \cdot \text{student}_i + \beta_2 \cdot \text{age}_i + \epsilon_i$$

$$\text{balance}_i = \beta_0 + \beta_1 \cdot \text{age}_i + \epsilon_i$$

$$\text{balance}_i = \beta_0 + \beta_1 \cdot \text{age}_i + \beta_2 \cdot \text{degree}_i + \epsilon_i$$

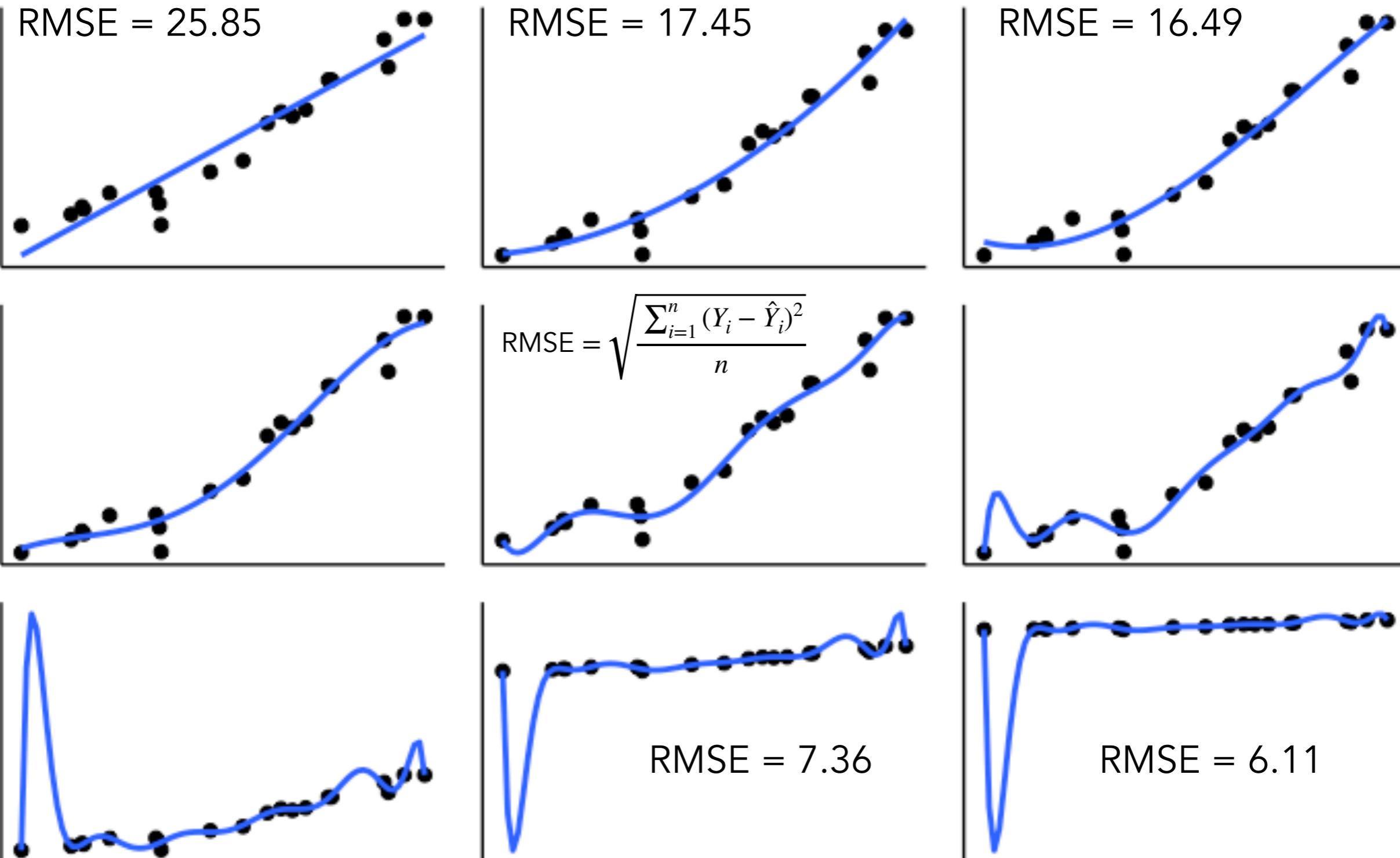


Tools for model comparison

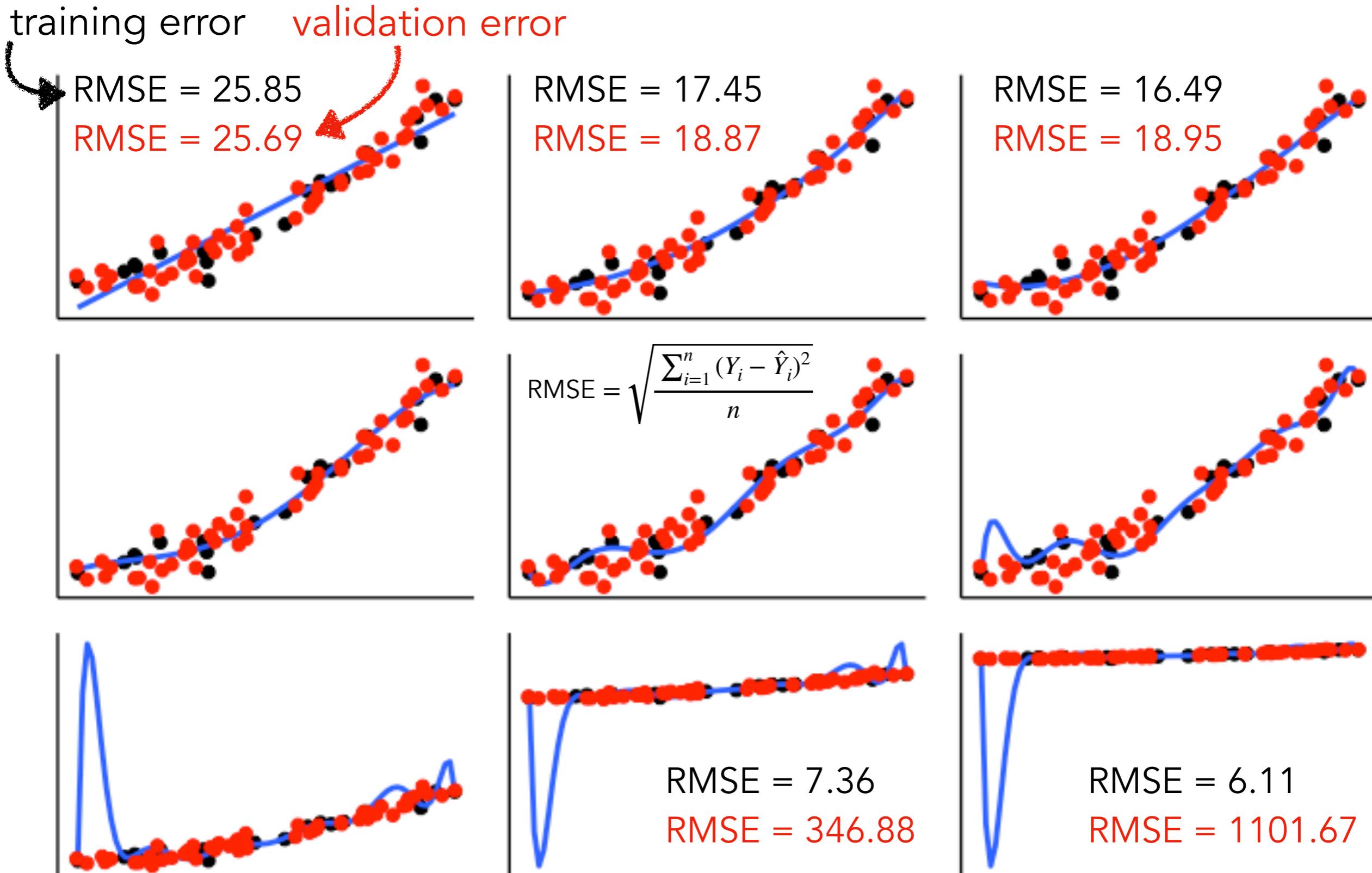
- **anova()** : compare a compact model with an augmented model via the F-test
 - problem: only works for nested models (where the augmented model contains all the predictors of the compact model and more)
- **What if we want to compare models that aren't nested?**
 - Cross-validation
 - AIC and BIC
 - Bayesian data analysis (we'll get there soon)

Cross-validation

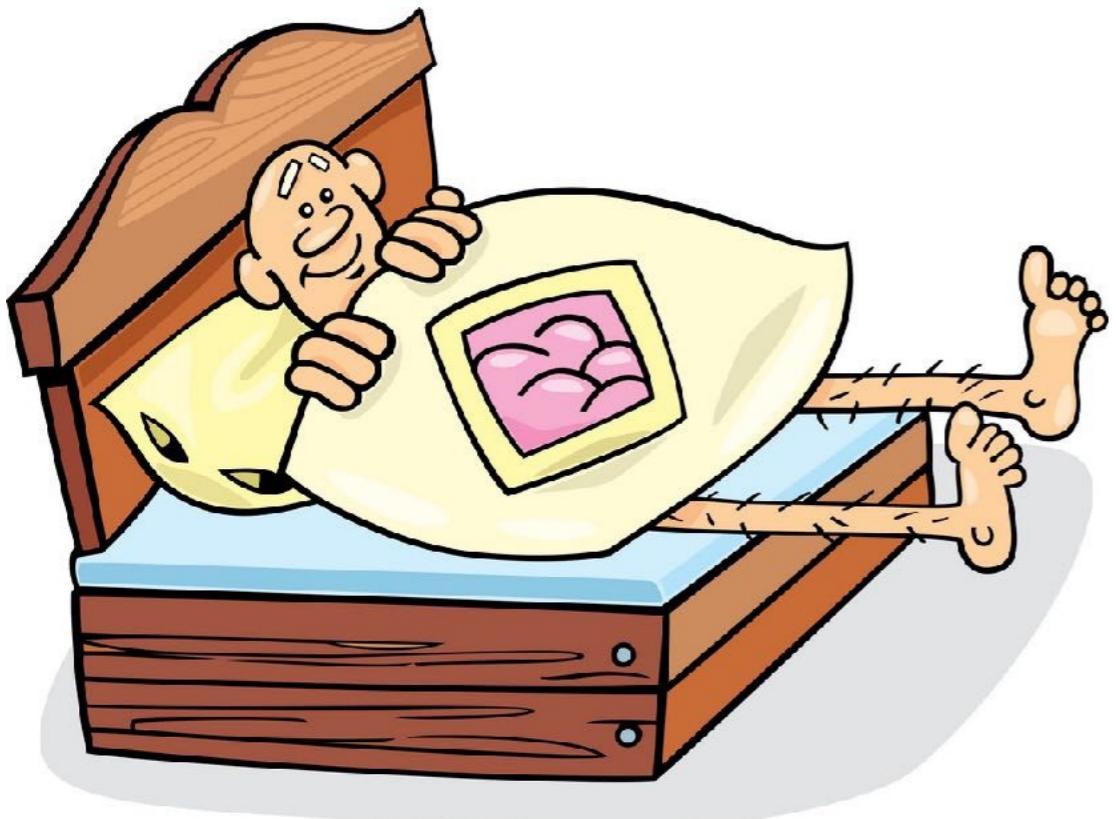
Which model describes the data best?



Which model describes the data best?



Underfitting vs. Overfitting



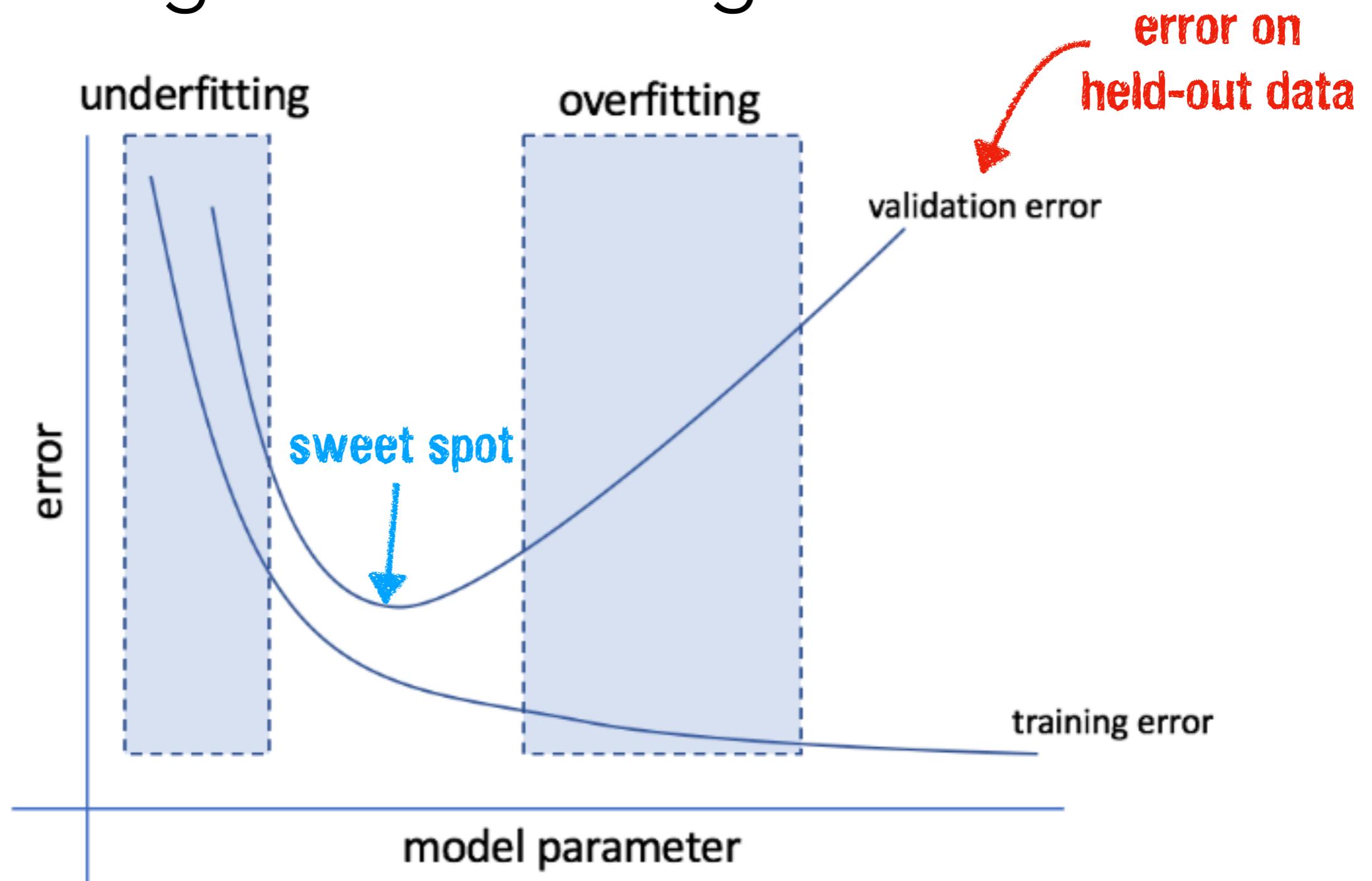
**ONE WAY TO EXPLAIN
UNDERFITTING**



Underfitting vs. Overfitting

- a good model should:
 - explain the actual data well
 - predict future data well
- bias-variance tradeoff:
 - **bias** = error from erroneous assumptions in the model, high bias can cause a model to miss the relevant relations between predictors and outcome underfitting
 - **variance** = error from sensitivity to small fluctuations in the data, high variance can cause a model to fit the random **noise** in the data overfitting

Underfitting vs. Overfitting



the goal is to find the **sweet spot** between underfitting and overfitting

Leave-one-out crossvalidation



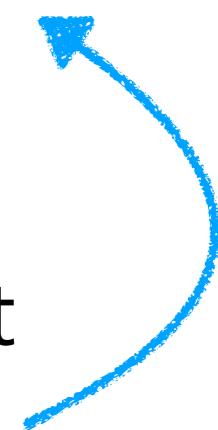
LOO

Leave One
Out

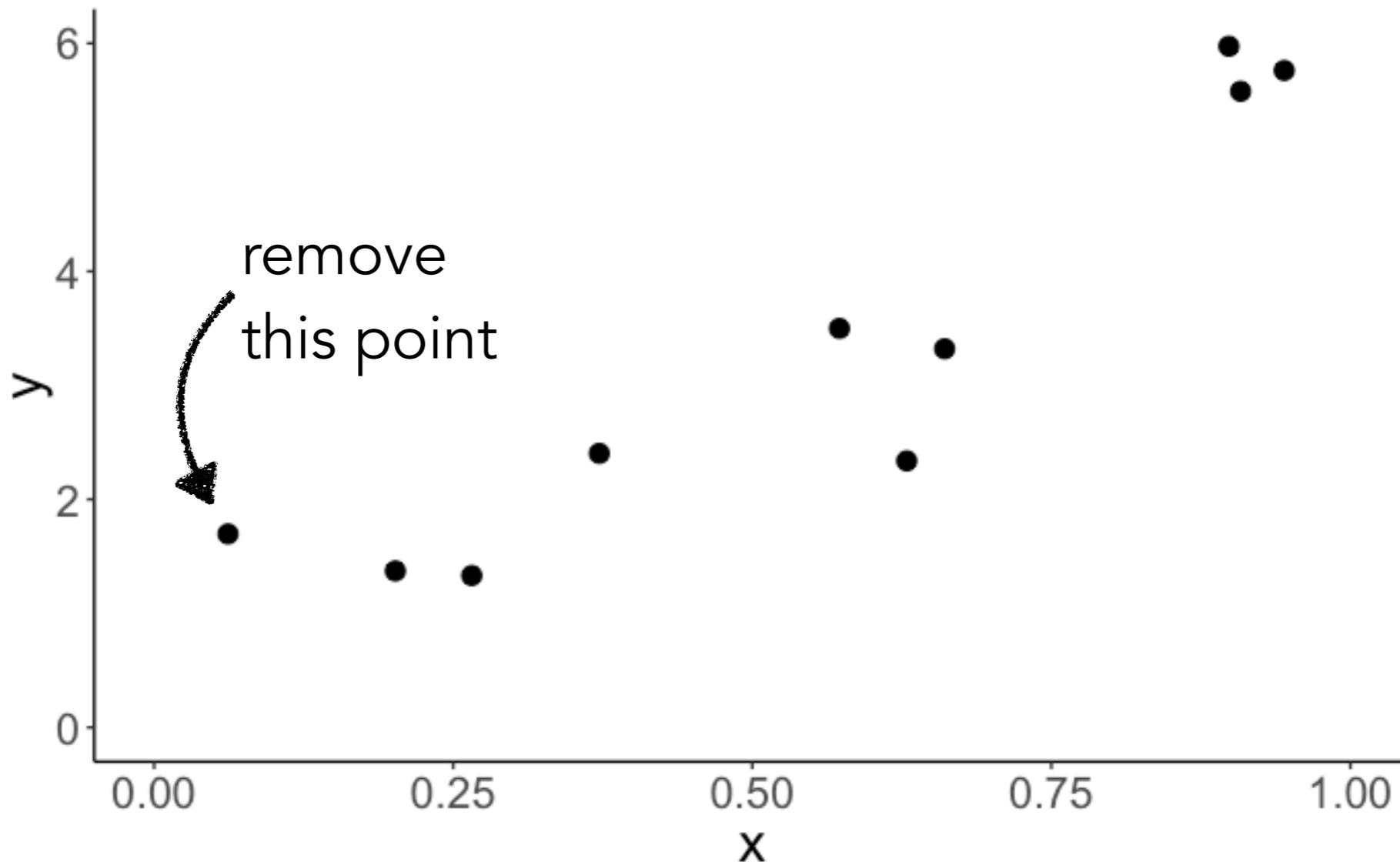
non-inspirational quote



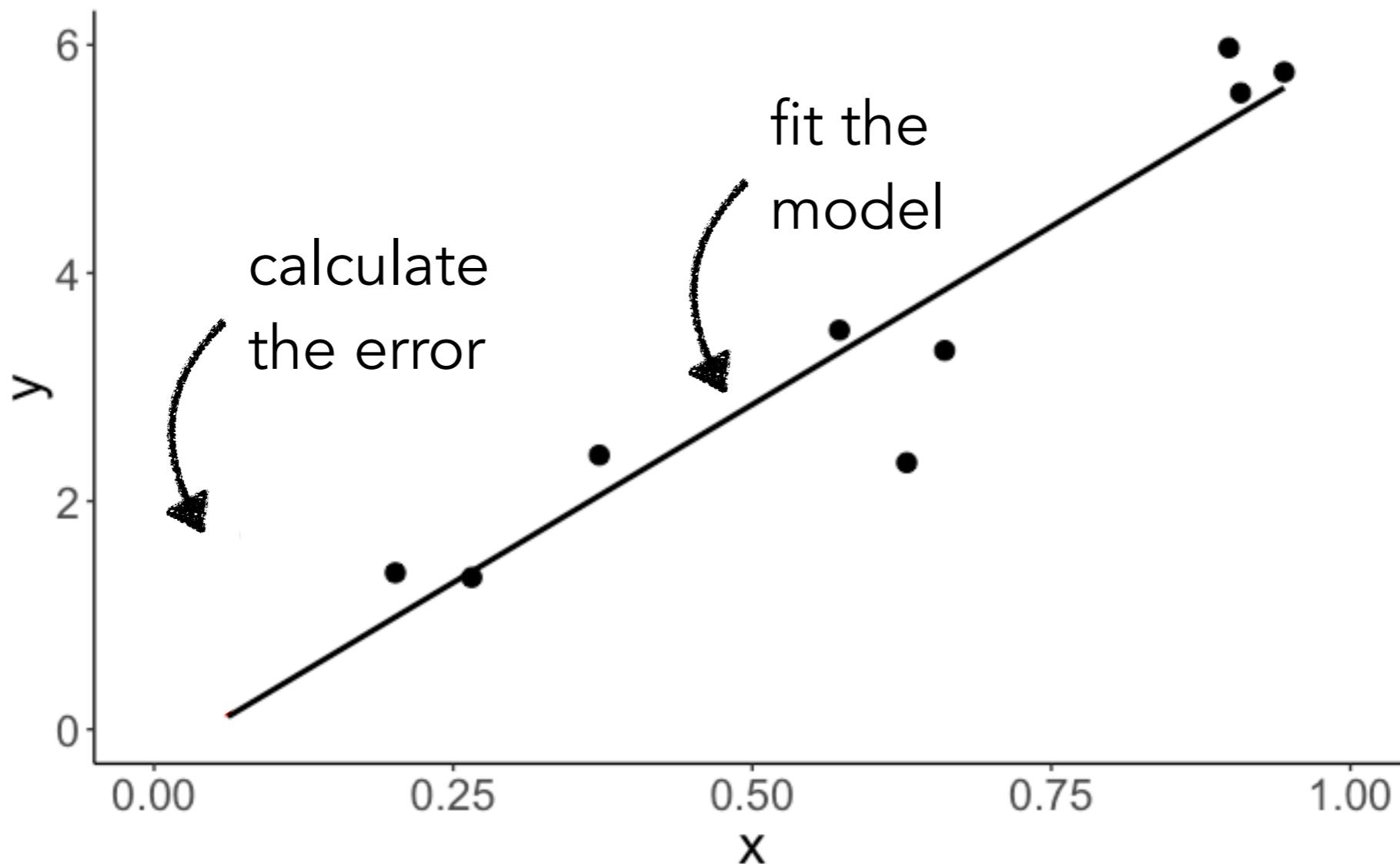
Leave one out cross-validation

- train the model on all the data points except for one
 - calculate the prediction error for the held-out data point
- repeat for all data points**
- 

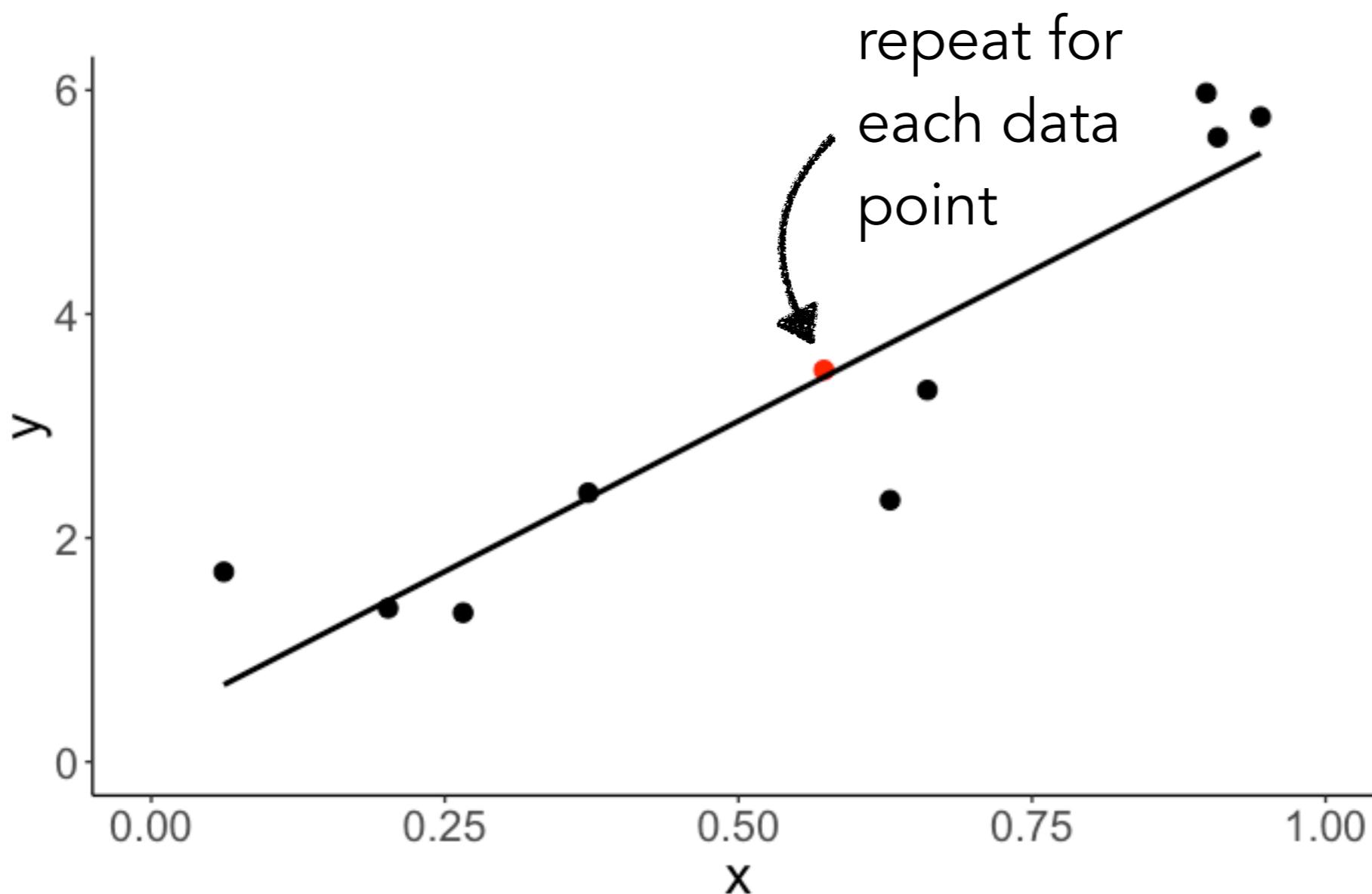
Leave one out cross-validation



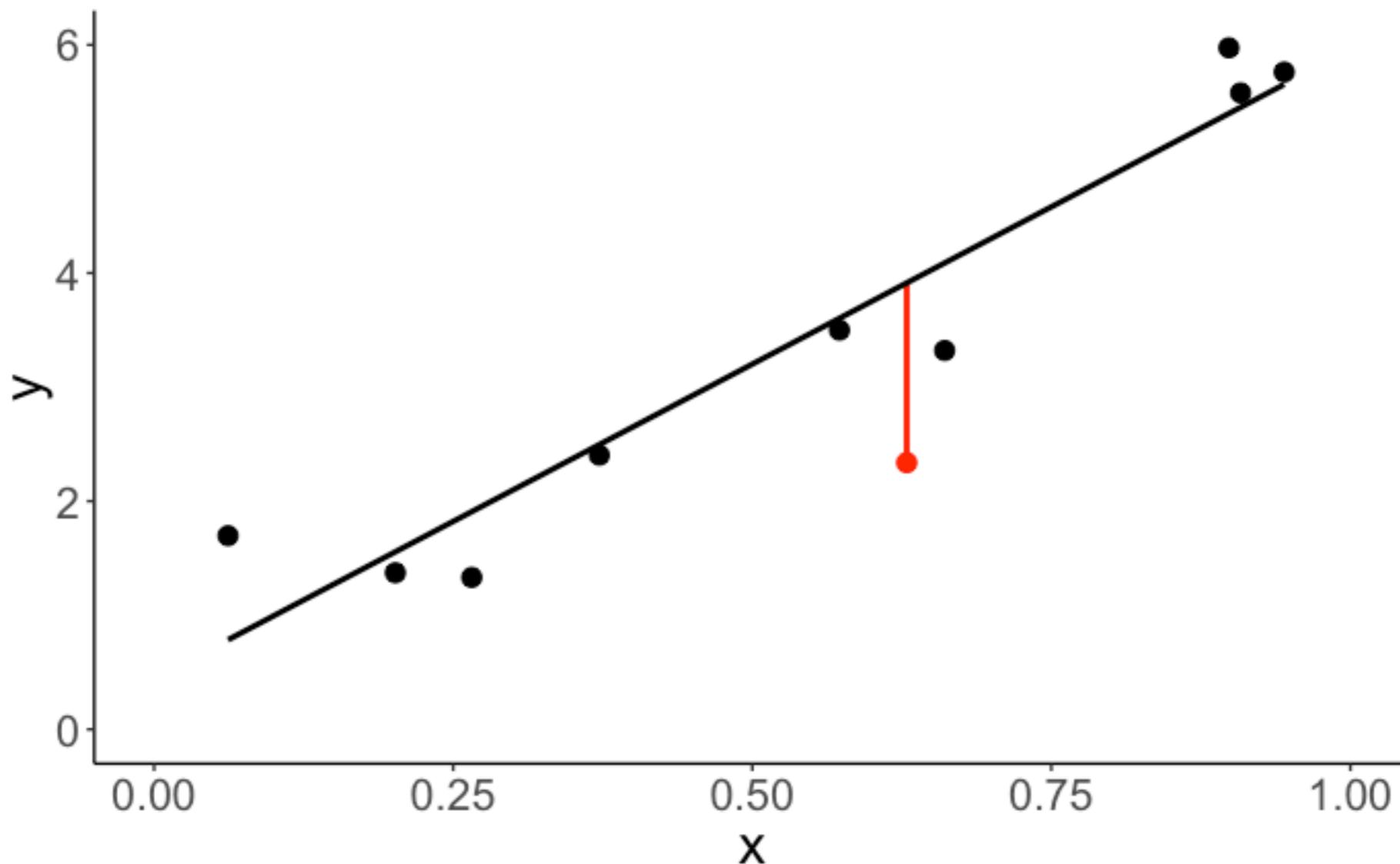
Leave one out cross-validation



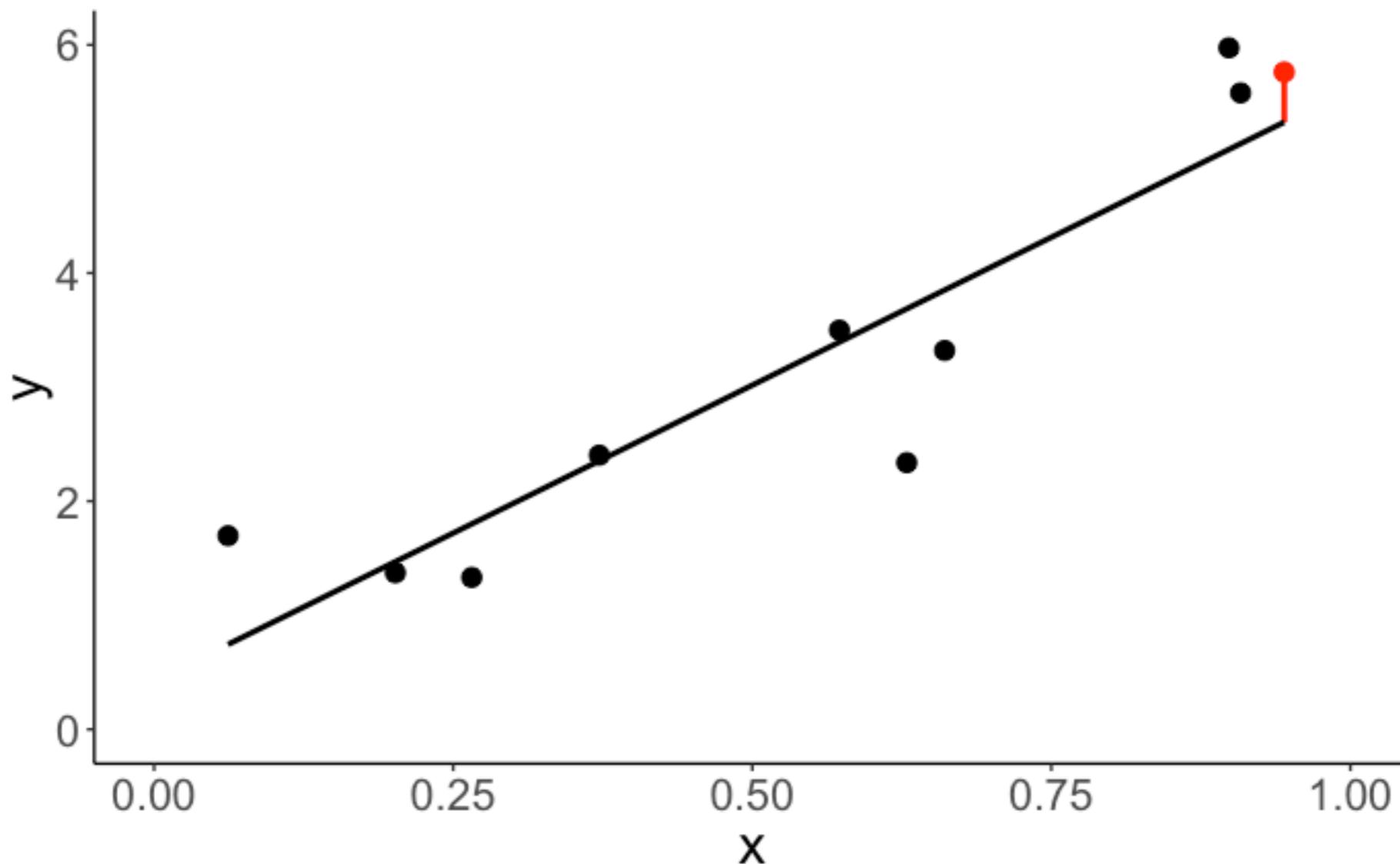
Leave one out cross-validation



Leave one out cross-validation

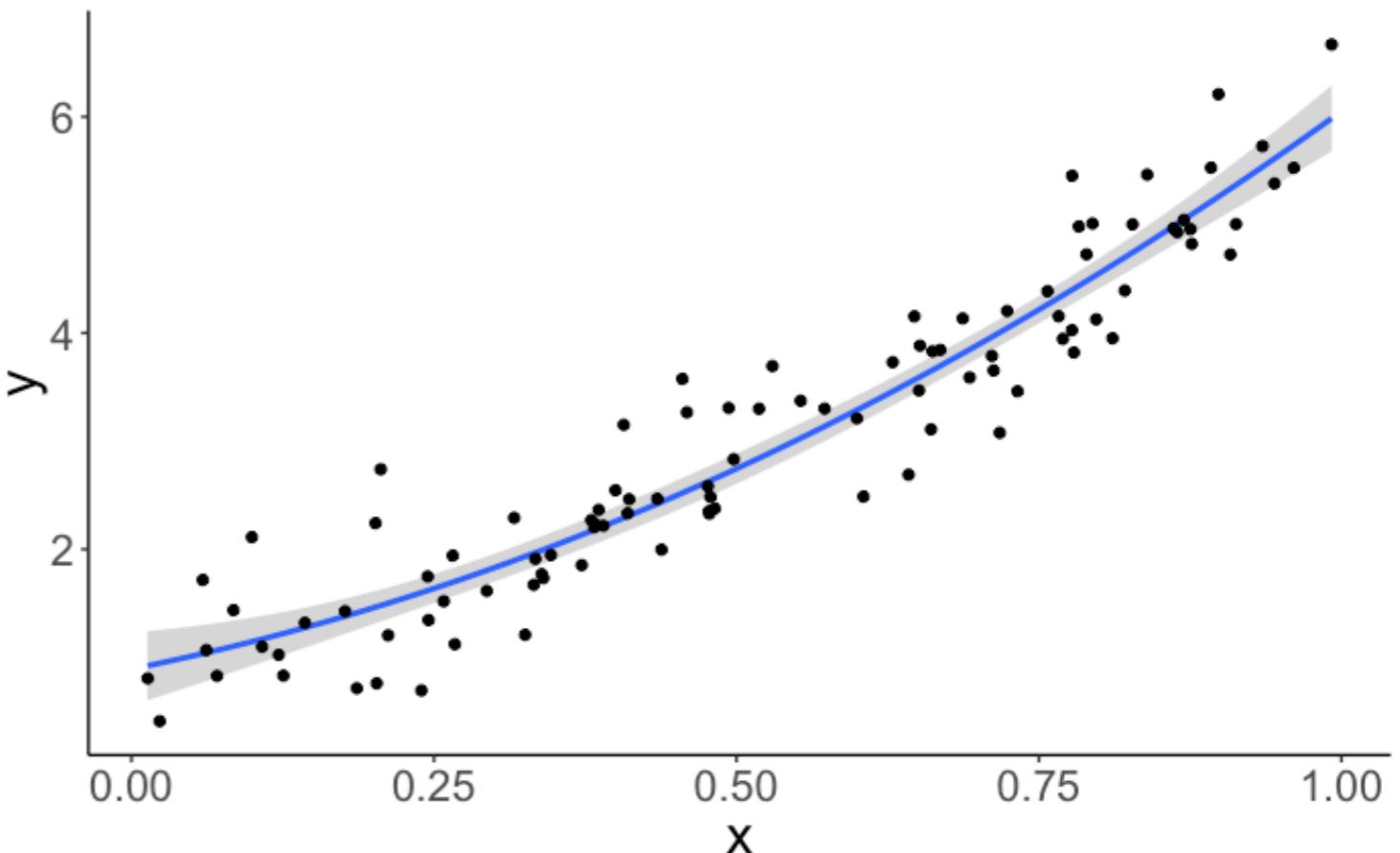


Leave one out cross-validation



Leave-one out crossvalidation

```
1 # make example reproducible
2 set.seed(1)
3
4 # parameters
5 sample_size = 100
6 b0 = 1
7 b1 = 2
8 b2 = 3
9 sd = 0.5
10
11 # sample
12 df.data = tibble(
13   participant = 1:sample_size,
14   x = runif(sample_size, min = 0, max = 1),
15   y = b0 + b1*x + b2*x^2 + rnorm(sample_size, sd = sd)
16 )
```



Leave-one out crossvalidation

ground truth

$$y_i = 1 + 2 \cdot x_i + 3 \cdot x_i^2 + e$$

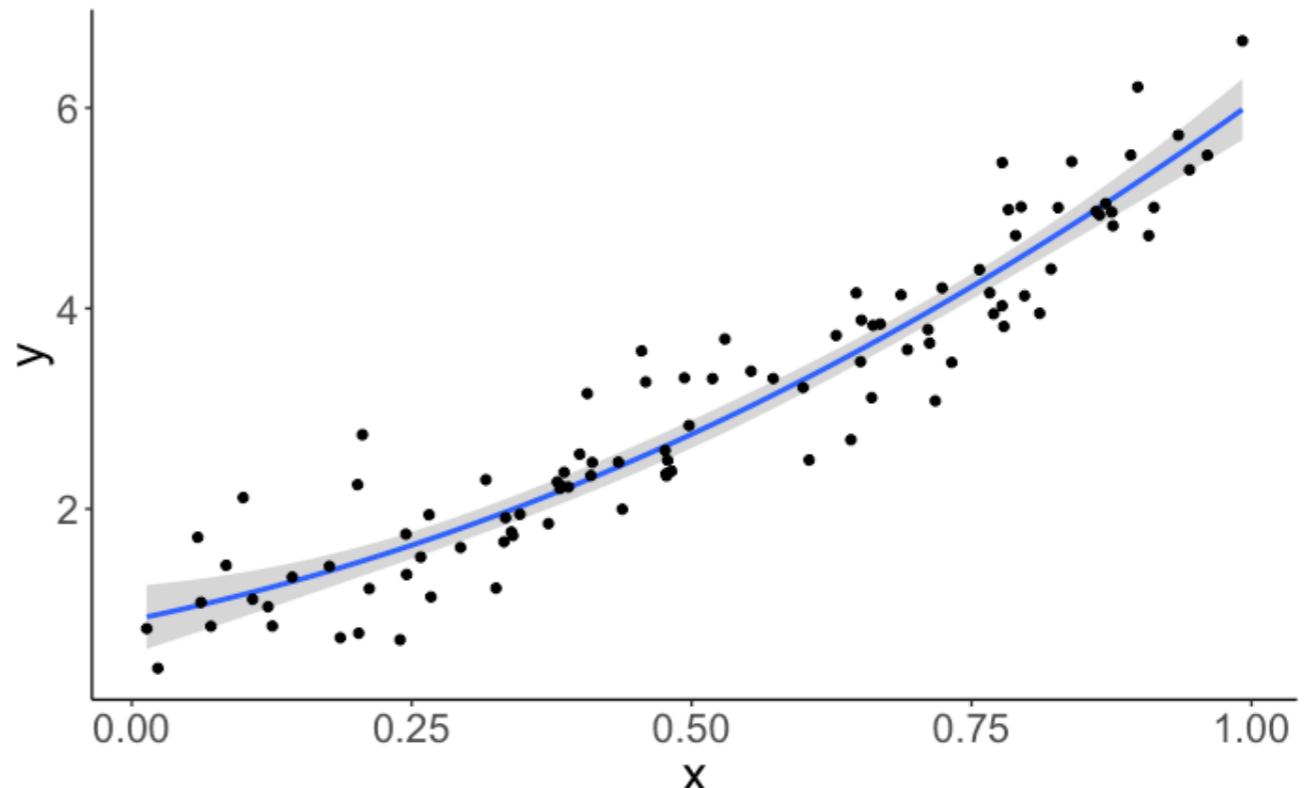
$$e \sim \mathcal{N}(\text{mean} = 0, \text{sd} = 0.5)$$

candidate models

simple $\hat{y}_i = b_0 + b_1 \cdot x_i$

correct $\hat{y}_i = b_0 + b_1 \cdot x_i + b_2 \cdot x_i^2$

complex $\hat{y}_i = b_0 + b_1 \cdot x_i + b_2 \cdot x_i^2 + b_3 \cdot x_i^3$



we could do an F-test
here since the models
are nested ...

Leave-one out crossvalidation

```
1 library("modelr") ← nice package for basic cross-validation
2
3 df.cross = df.data %>%
4   crossv_loo() %>% # function which generates training and test data sets
5   mutate(model_simple = map(train, ~ lm(y ~ 1 + x, data = .)),
6         model_correct = map(train, ~ lm(y ~ 1 + x + I(x^2), data = .)),
7         model_complex = map(train, ~ lm(y ~ 1 + x + I(x^2) + I(x^3), data = .))) %>%
8   pivot_longer(cols = contains("model"),
9                 names_to = "index",
10                values_to = "model") %>%
11   mutate(rmse = map2_dbl(.x = model, .y = test, .f = ~ rmse(.x, .y)))
```

| index | mean_rmse |
|---------|-----------|
| simple | 0.65 |
| correct | 0.42 |
| complex | 0.41 |

complex model has the lowest error on the training data

Leave-one out crossvalidation

```
1 library("modelr")
2
3 df.cross = df.data %>%
4   crossv_loo() %>%
```

splits the data set into training and test

| | train | test | .id |
|----|---|---|-----|
| 1 | list(data = list(participant = 1:10, x = c(0.265508663...)) | list(data = list(participant = 1:10, x = c(0.265508663...)) | 1 |
| 2 | list(data = list(participant = 1:10, x = c(0.265508663...)) | list(data = list(participant = 1:10, x = c(0.265508663...)) | 2 |
| 3 | list(data = list(participant = 1:10, x = c(0.265508663...)) | list(data = list(participant = 1:10, x = c(0.265508663...)) | 3 |
| 4 | list(data = list(participant = 1:10, x = c(0.265508663...)) | list(data = list(participant = 1:10, x = c(0.265508663...)) | 4 |
| 5 | list(data = list(participant = 1:10, x = c(0.265508663...)) | list(data = list(participant = 1:10, x = c(0.265508663...)) | 5 |
| 6 | list(data = list(participant = 1:10, x = c(0.265508663...)) | list(data = list(participant = 1:10, x = c(0.265508663...)) | 6 |
| 7 | list(data = list(participant = 1:10, x = c(0.265508663...)) | list(data = list(participant = 1:10, x = c(0.265508663...)) | 7 |
| 8 | list(data = list(participant = 1:10, x = c(0.265508663...)) | list(data = list(participant = 1:10, x = c(0.265508663...)) | 8 |
| 9 | list(data = list(participant = 1:10, x = c(0.265508663...)) | list(data = list(participant = 1:10, x = c(0.265508663...)) | 9 |
| 10 | list(data = list(participant = 1:10, x = c(0.265508663...)) | list(data = list(participant = 1:10, x = c(0.265508663...)) | 10 |

each entry is simply a pointer to the data set plus some indices .idx for the filtered data points

Leave-one out crossvalidation

```
1 library("modelr")
2
3 df.cross = df.data %>%
4   crossv_loo() %>%
5   mutate(model_simple = map(train, ~ lm(y ~ 1 + x, data = .)),
6         model_correct = map(train, ~ lm(y ~ 1 + x + I(x^2), data = .)),
7         model_complex = map(train, ~ lm(y ~ 1 + x + I(x^2) + I(x^3), data = .))) %>%
```

fit three different models to the training data set

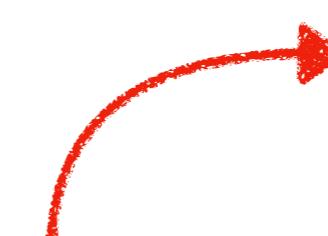
Leave-one out crossvalidation

```
1 library("modelr")
2
3 df.cross = df.data %>%
4   crossv_loo() %>%
5   mutate(model_simple = map(train, ~ lm(y ~ 1 + x, data = .)),
6         model_correct = map(train, ~ lm(y ~ 1 + x + I(x^2), data = .)),
7         model_complex = map(train, ~ lm(y ~ 1 + x + I(x^2) + I(x^3), data = .))) %>%
8   pivot_longer(cols = contains("model"),
9                 names_to = "index",
10                values_to = "model") %>%
11   mutate(rmse = map2_dbl(.x = model, .y = test, .f = ~ rmse(.x, .y)))
```

calculate the root mean squared error for each model on the test data set

```
1 df.cross %>%
2   group_by(index) %>%
3   summarize(mean_rmse = mean(rmse))
```

| index | mean_rmse |
|---------|-----------|
| simple | 0.65 |
| correct | 0.48 |
| complex | 0.70 |



the correct model has the lowest prediction error

Leave-one out crossvalidation

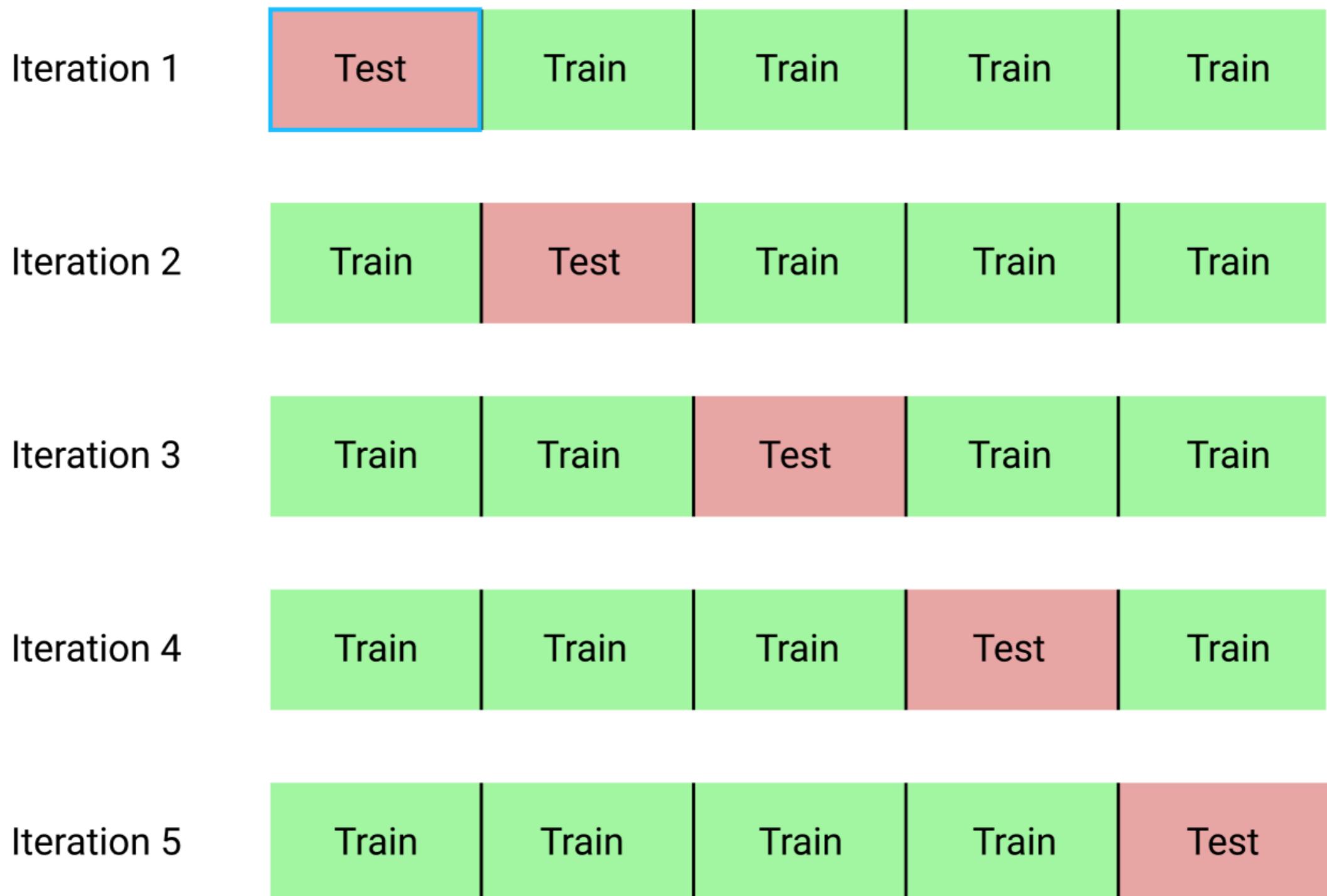
Any potential problems with LOO?

can be computationally expensive since it requires fitting the model n times (once for each data point) ...

k-fold cross validation

k-fold crossvalidation

Full data set



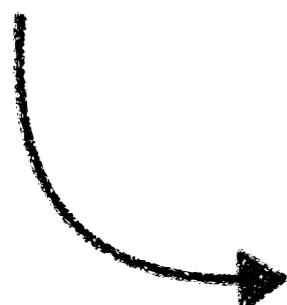
k-fold crossvalidation

k-fold crossvalidation

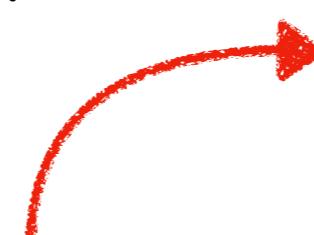
```
1 df.cross = df.data %>%
2   crossv_kfold(k = 10) %>%
3   mutate(model_simple = map(.x = train,
4                             .f = ~ lm(y ~ 1 + x, data = .)),
5         model_correct = map(.x = train,
6                             .f = ~ lm(y ~ 1 + x + I(x^2), data = .)),
7         model_complex = map(.x = train,
8                             .f = ~ lm(y ~ 1 + x + I(x^2) + I(x^3), data = .))) %>%
9   pivot_longer(cols = contains("model"),
10               names_to = "model",
11               values_to = "fit") %>%
12   mutate(rsquare = map2_dbl(.x = fit,
13                           .y = test,
14                           .f = ~ rsquare(.x, .y)))
```

using R² as a measure

why didn't we use R² for LOO?



this wouldn't work for LOO
since we only have one data
point in the test data...



| index | median_rsquare |
|---------|----------------|
| simple | 0.839 |
| correct | 0.865 |
| complex | 0.860 |

the correct model accounts for
the most variance in the test data

k-fold vs. leave-one-out crossvalidation

- LOO:
 - trained on **more** data
 - more variance
 - less bias
- k-fold:
 - trained on **less** data
 - less variance
 - more bias

Monte Carlo crossvalidation

Monte Carlo crossvalidation

`crossv_mc(n = 50, test = 0.5)`

random splits into training and test data

number of training-test splits

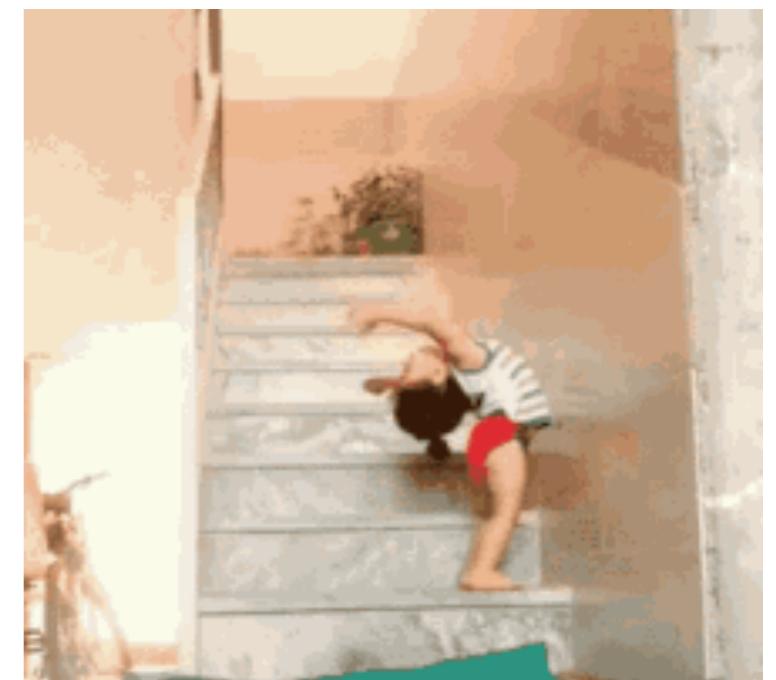
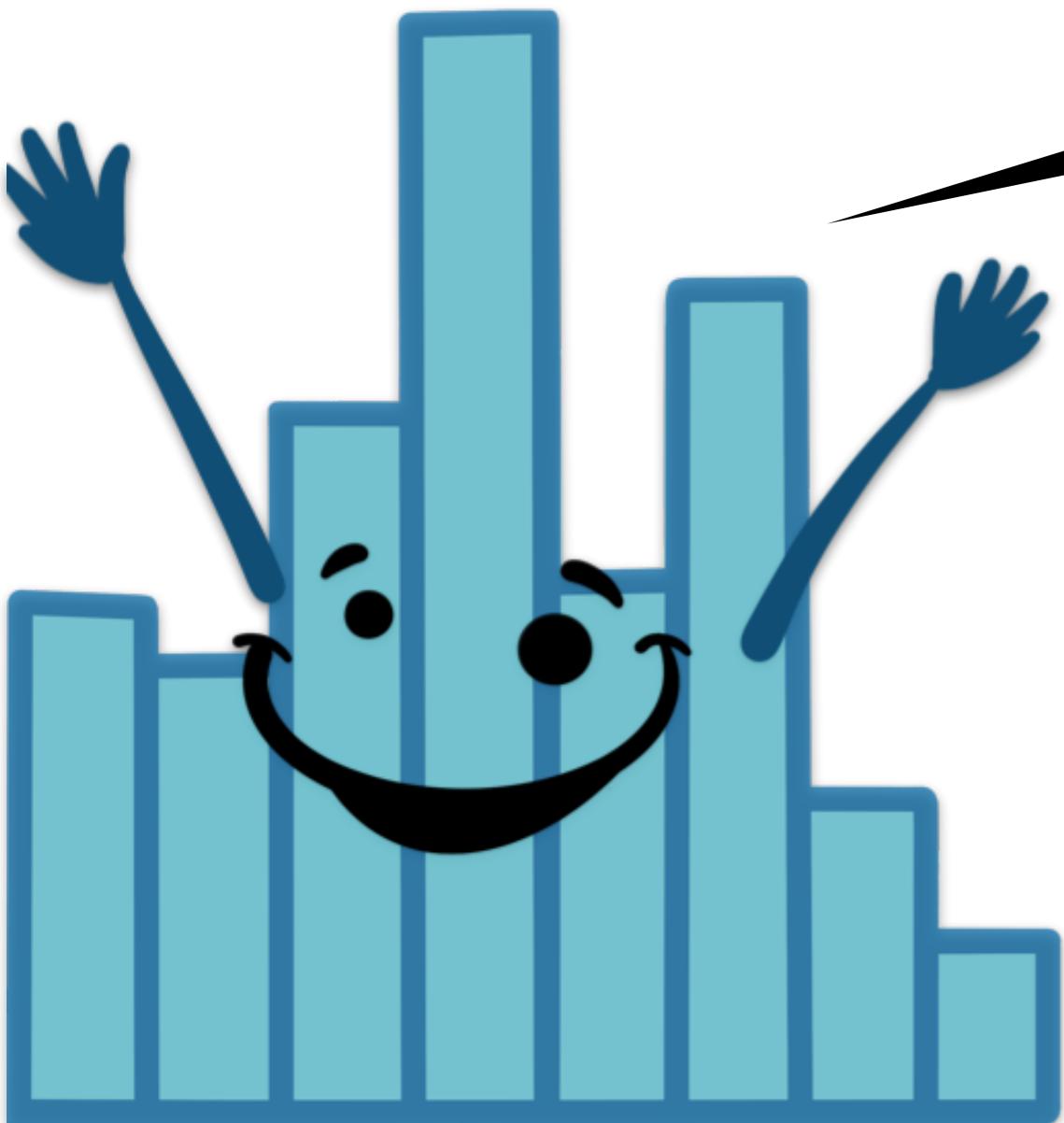
proportion of test data in each split

- splits can also be done in a **stratified** way (check out the `tidymodels` package)
- for example, generate training data that has the same percentage of cases from each group
- fit data from some participants, test on data from other participants, ...

We're listening to
"Liability" by "Tape
Machines, Astyn Turr"
submitted by Sarah Wu

02:00

stretch break!





Studio[®]

time

AIC and BIC

AIC and BIC

- AIC = Akaike Information Criterion
- BIC = Bayesian Information Criterion

not that much Bayesian about it ...

$$\text{AIC} = 2k - 2 \ln(\hat{L})$$



$$\text{BIC} = \ln(n)k - 2 \ln(\hat{L})$$

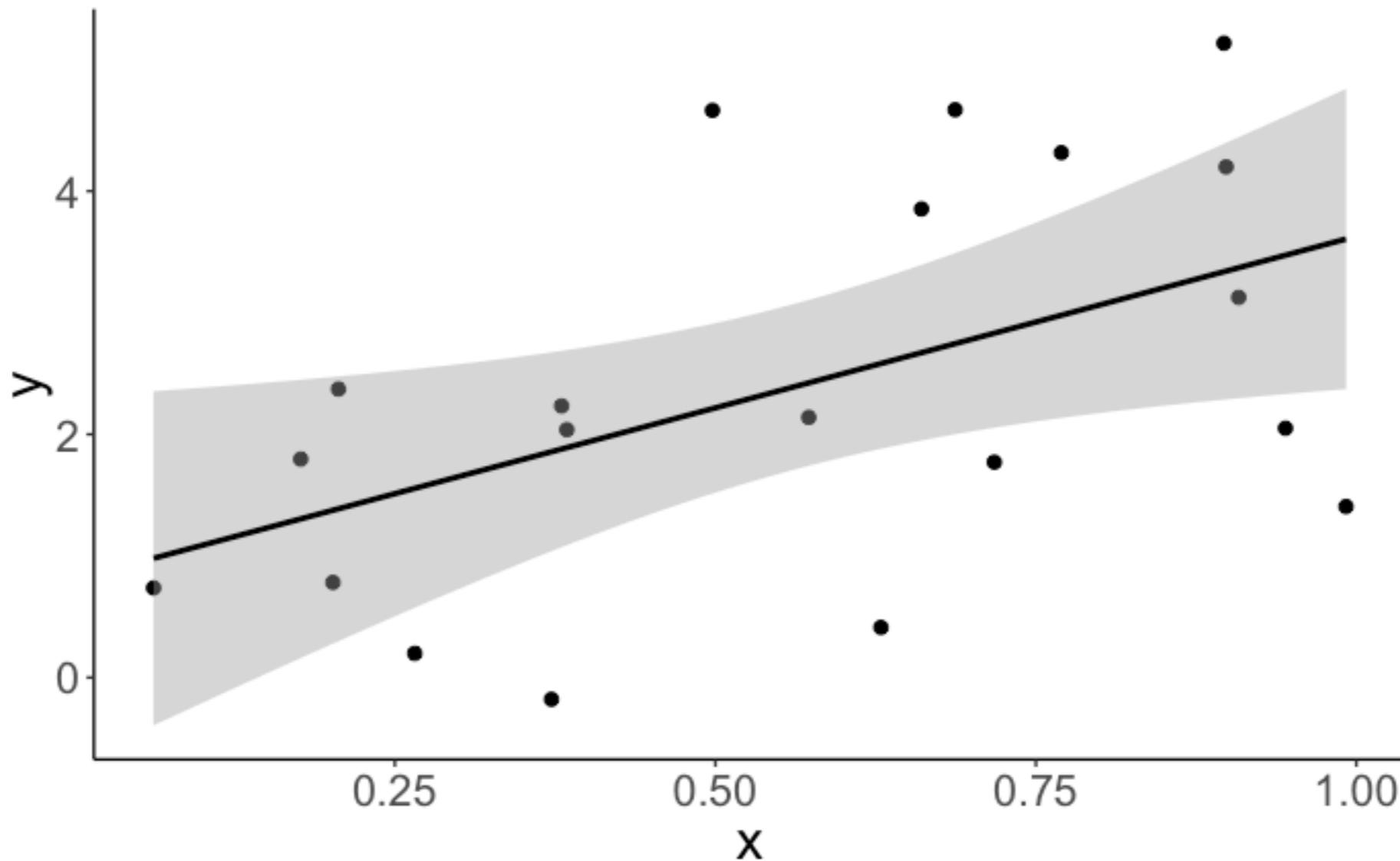
- \hat{L} = maximized value of the likelihood function of the model
 k = number of parameters in the model
 n = number of observations

AIC and BIC

- How do we get the likelihood of our model?
 - in a linear regression, minimizing least squares is equivalent to maximizing the likelihood of the data given the model
- Assumptions of the linear model:
 - residuals are normally distributed with:
 - mean = 0 and sd = sigma
 - calculate overall likelihood by computing the likelihood of each residual, and then multiplying

AIC and BIC

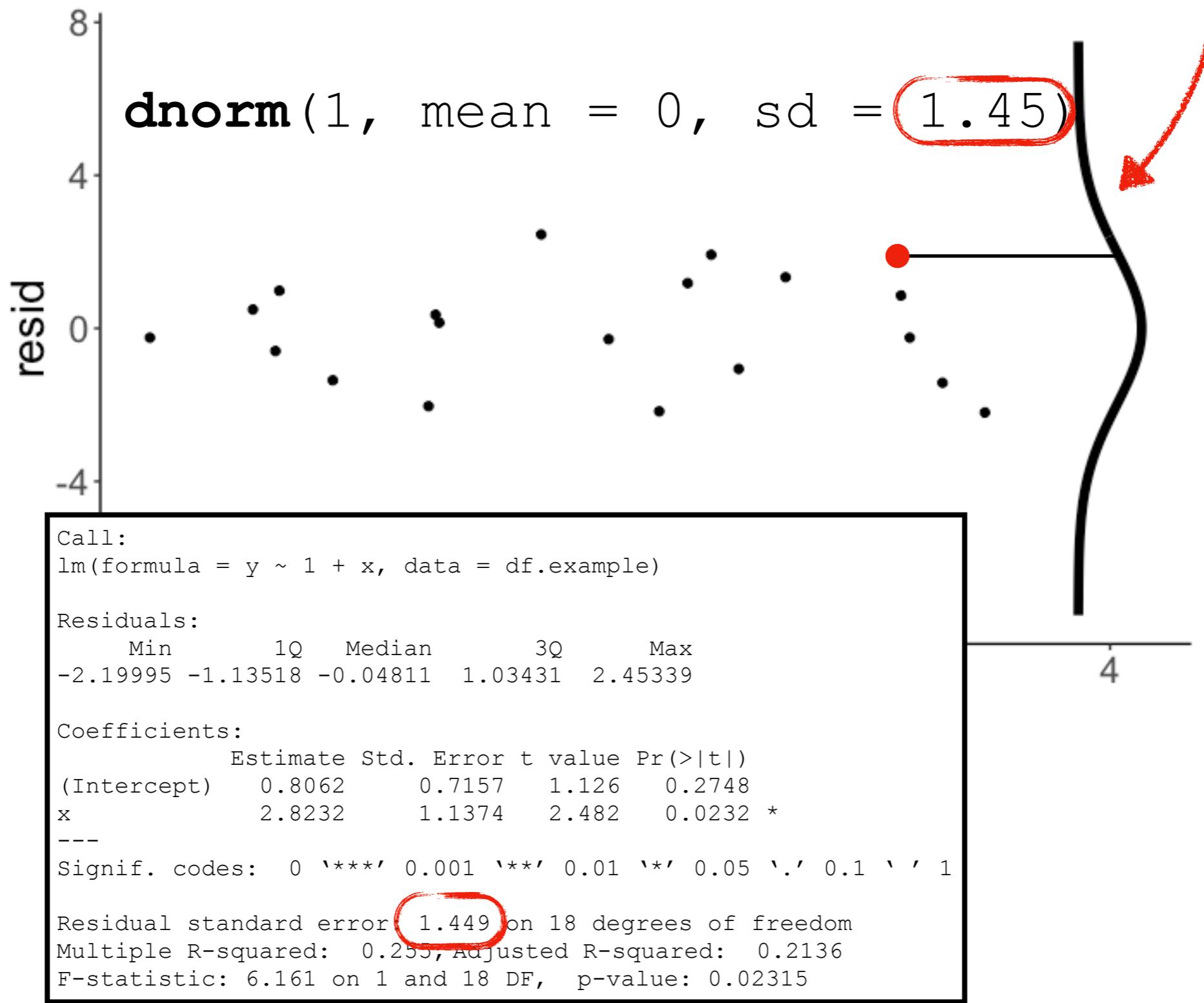
data with linear model fit



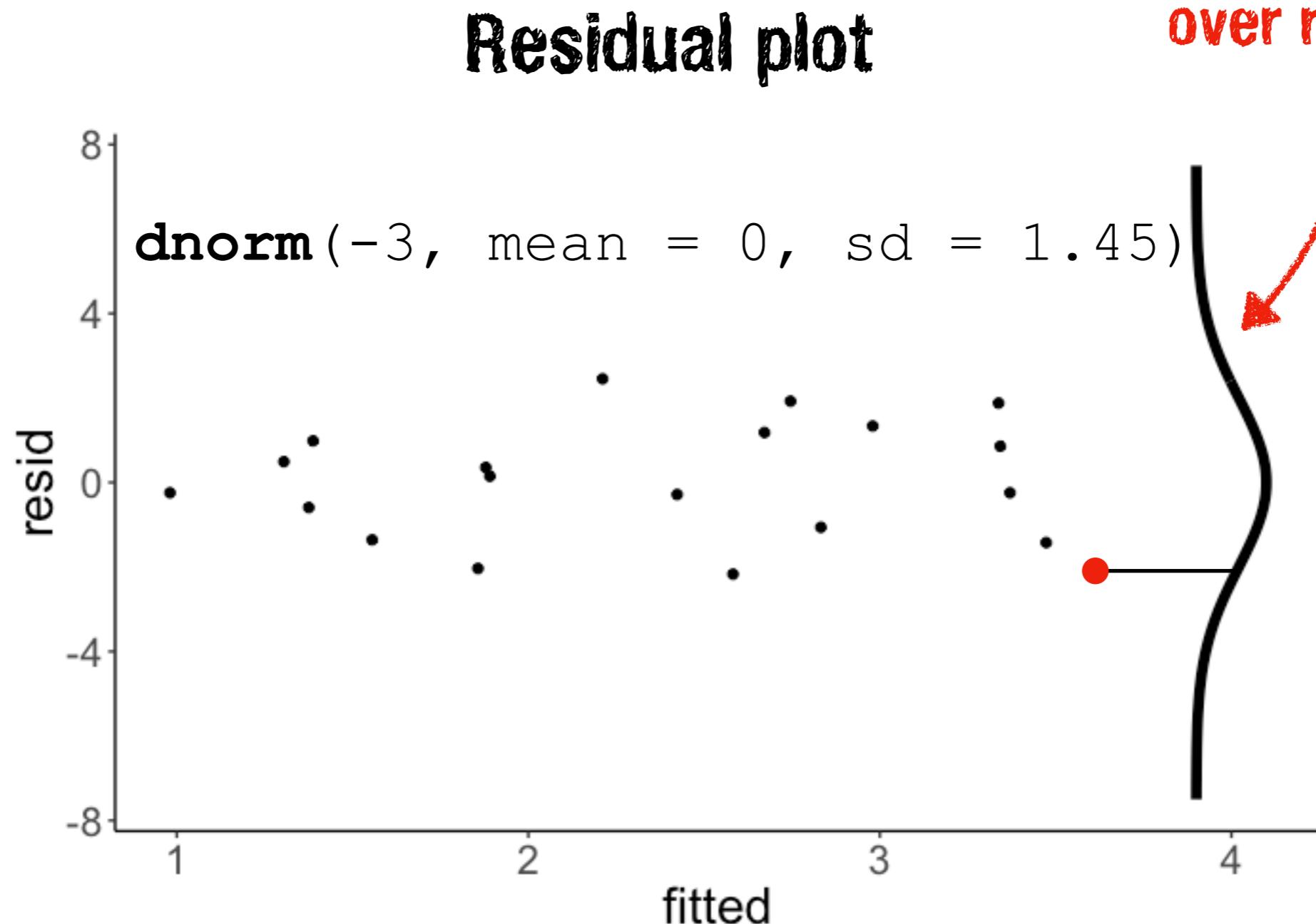
AIC and BIC

normal distribution
over residuals

Residual plot



AIC and BIC



normal distribution
over residuals

since the data points are independent, we can calculate the overall likelihood by multiplying the likelihood of each observation

AIC and BIC

```

1 # generate some data
2 df.like = tibble(
3   x = runif(20, min = 0, max = 1),
4   y = 1 + 3 * x + rnorm(20, sd = 2)
5 )
6
7 # fit the model
8 fit = lm(formula = y ~ x,
9           data = df.like)
10
11 # model summary
12 fit %>%
13   glance()

```

`dnorm(1.88, mean = 0, sd = 1.45) = 0.12`

| x | y | fitted | resid | likelihood |
|------|-------|--------|-------|------------|
| 0.90 | 5.22 | 3.34 | 1.88 | 0.12 |
| 0.27 | 0.20 | 1.56 | -1.36 | 0.18 |
| 0.37 | -0.18 | 1.86 | -2.04 | 0.10 |
| 0.57 | 2.14 | 2.42 | -0.28 | 0.27 |
| 0.91 | 3.13 | 3.37 | -0.24 | 0.27 |
| 0.20 | 0.78 | 1.38 | -0.59 | 0.25 |
| 0.90 | 4.20 | 3.34 | 0.86 | 0.23 |
| 0.94 | 2.05 | 3.47 | -1.42 | 0.17 |
| 0.66 | 3.85 | 2.67 | 1.18 | 0.20 |
| 0.63 | 0.41 | 2.58 | -2.17 | 0.09 |

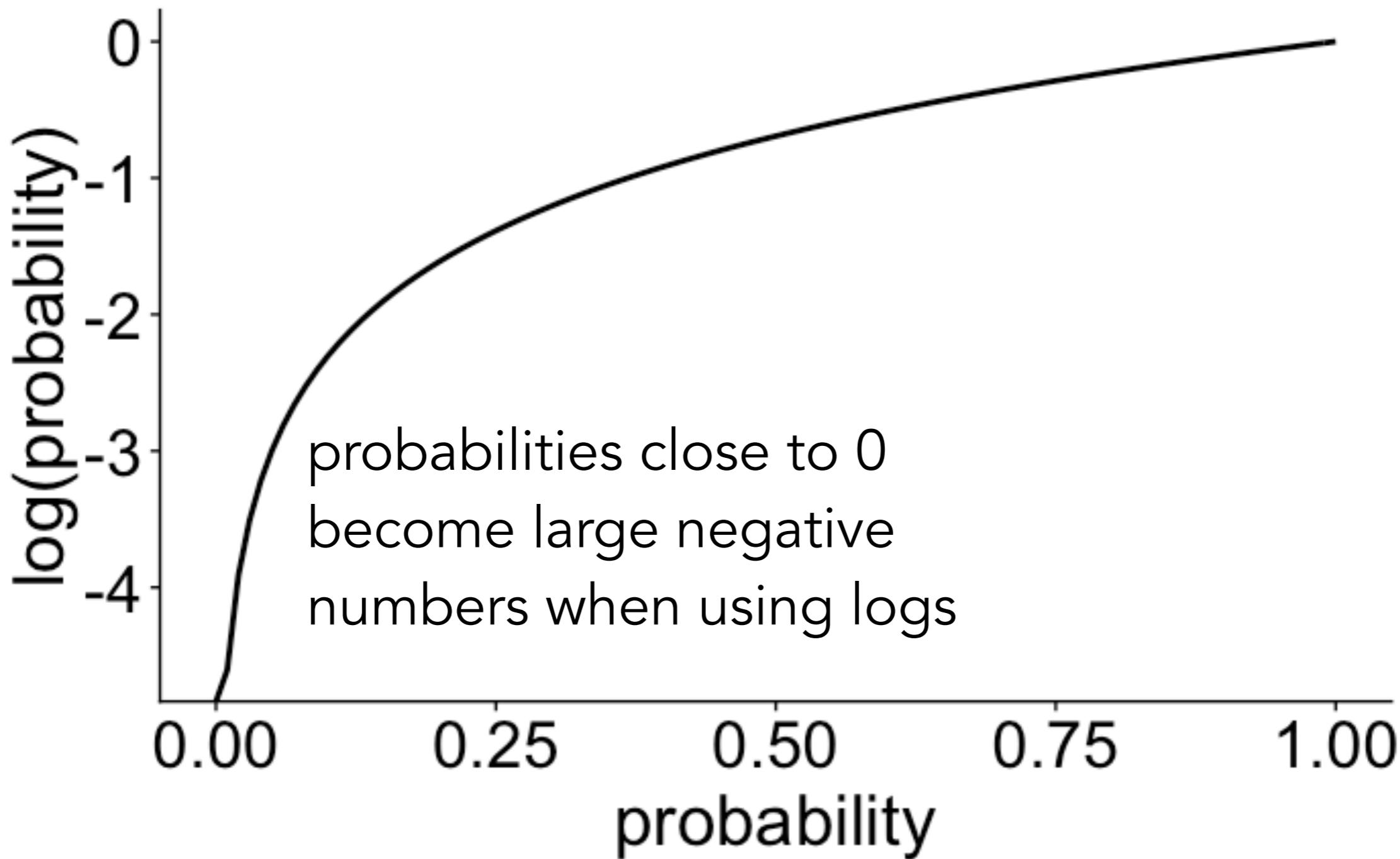
inferred standard
deviation of the error

$$\sum_{i=1}^n \ln(\text{likelihood})$$

| r.squared | adj.r.squared | sigma | statistic | p.value | df | logLik | AIC | BIC | deviance | df.residual |
|-----------|---------------|-------|-----------|---------|----|--------|-------|-------|----------|-------------|
| 0.25 | 0.21 | 1.45 | 6.16 | 0.02 | 2 | -34.74 | 75.47 | 78.46 | 37.77 | 18 |

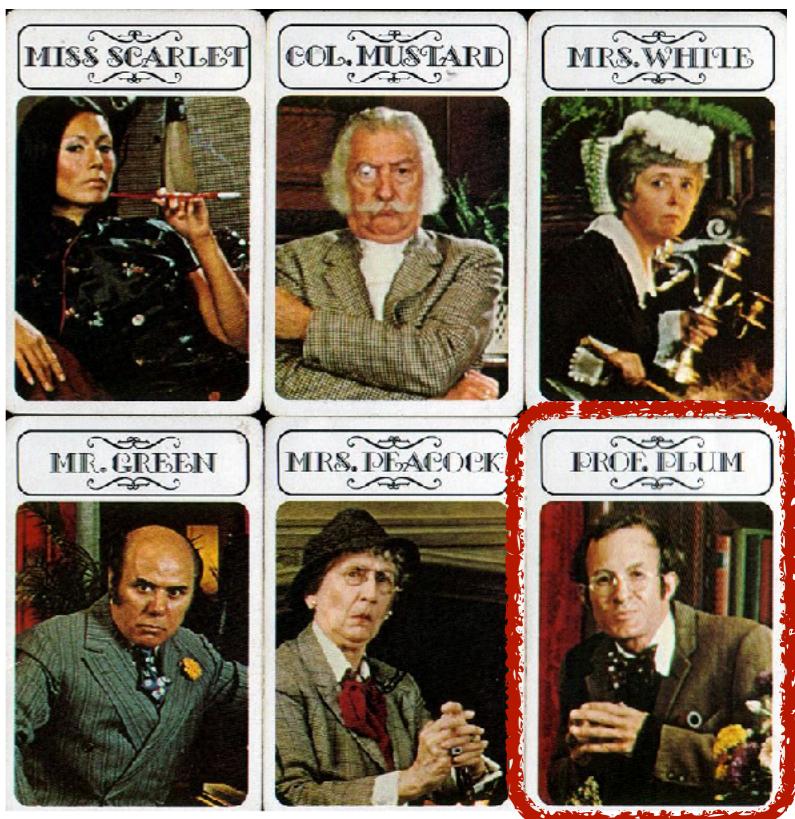
$e \sim \mathcal{N}(\text{mean} = 0, \text{sd} = 1.45)$

`log()` is your friend!



Clue guide to probability

Who?



- joint probability:

- if A and B are independent then

- Definition: $p(A, B) = p(A) \cdot p(B)$

- $p(\text{Prof Plum, candle stick}) =$

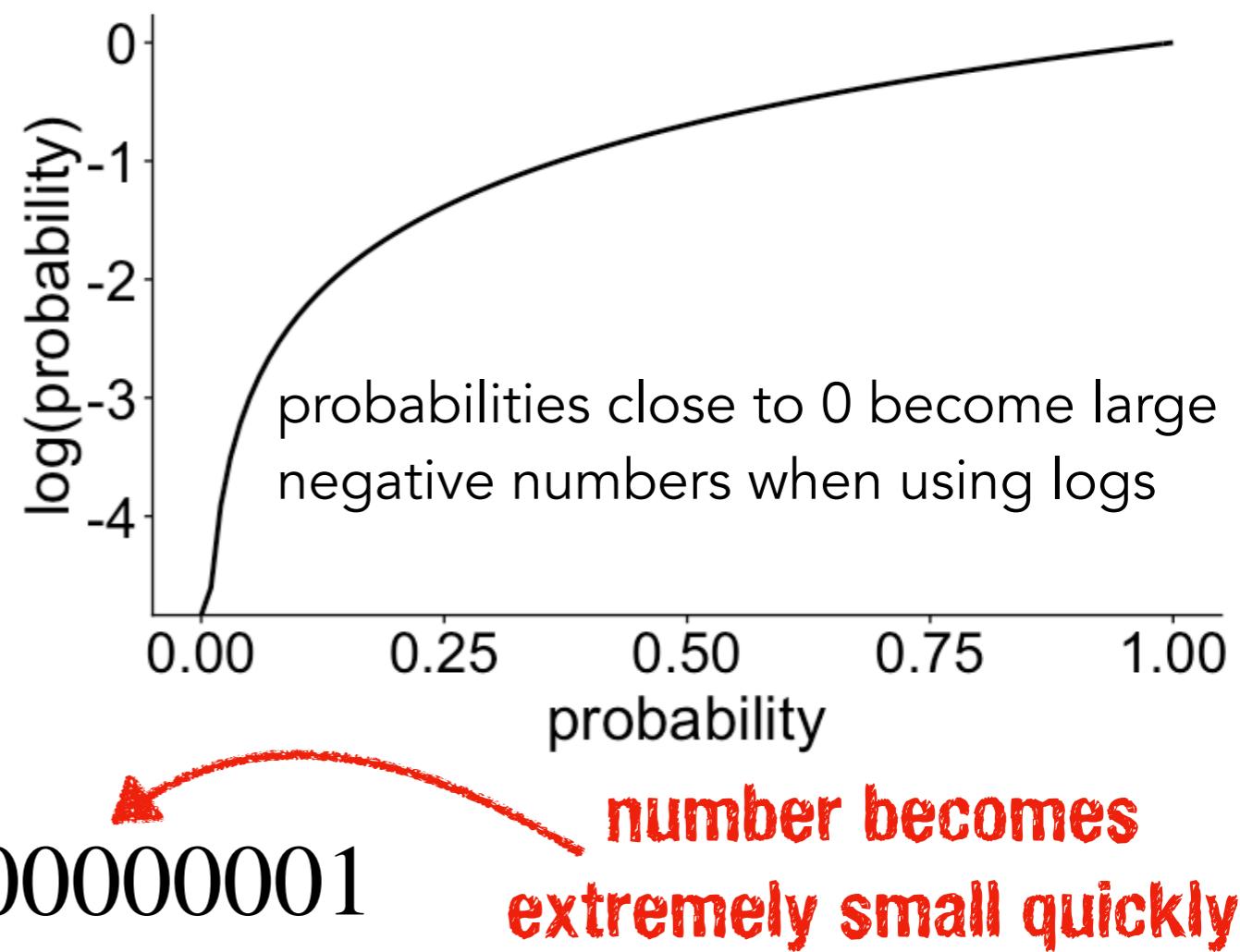
$$p(\text{Prof Plum}) \cdot p(\text{candle stick}) =$$

$$\frac{1}{6} \cdot \frac{1}{6} = \frac{1}{36}$$

What?



`log()` is your friend!



multiplying probabilities

$$0.01 \cdot 0.01 \cdot 0.01 \cdot 0.01 = 0.00000001$$

take `log()`

$$\log(0.01) = -4.60517$$

number becomes large
but that's ok

summing logs

$$(-4.60517) + (-4.60517) + (-4.60517) + (-4.60517) = -18.42068$$

transform back into probability

$$\exp(-18.42068) = 0.00000001$$

often not necessary since
we just use `logLikelihood`

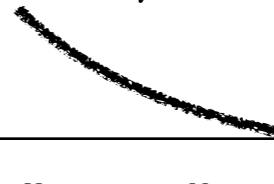
AIC and BIC

```

1 # generate some data
2 df.like = tibble(
3   x = runif(20, min = 0, max = 1),
4   y = 1 + 3 * x + rnorm(20, sd = 2)
5 )
6
7 # fit the model
8 fit = lm(formula = y ~ x,
9           data = df.like)
10
11 # model summary
12 fit %>%
13   glance()

```

`dnorm(1.88, mean = 0, sd = 1.45) = 0.12`



| x | y | fitted | resid | likelihood |
|------|-------|--------|-------|------------|
| 0.90 | 5.22 | 3.34 | 1.88 | 0.12 |
| 0.27 | 0.20 | 1.56 | -1.36 | 0.18 |
| 0.37 | -0.18 | 1.86 | -2.04 | 0.10 |
| 0.57 | 2.14 | 2.42 | -0.28 | 0.27 |
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| 0.66 | 3.85 | 2.67 | 1.18 | 0.20 |
| 0.63 | 0.41 | 2.58 | -2.17 | 0.09 |

inferred standard
deviation of the error




| r.squared | adj.r.squared | sigma | statistic | p.value | df | logLik | AIC | BIC | deviance | df.residual |
|-----------|---------------|-------|-----------|---------|----|--------|-------|-------|----------|-------------|
| 0.25 | 0.21 | 1.45 | 6.16 | 0.02 | 2 | -34.74 | 75.47 | 78.46 | 37.77 | 18 |

$e \sim \mathcal{N}(\text{mean} = 0, \text{sd} = 1.45)$

AIC and BIC

$$\text{AIC} = 2k - 2 \ln(\hat{L})$$

$$\text{BIC} = \ln(n)k - 2 \ln(\hat{L})$$

$\ln(\hat{L})$ = maximized value of the likelihood function of the model **-34.74**

k = number of parameters in the model **3**

n = number of observations **20**

the sd of the normal distribution modeling the residuals counts as a parameter

```
lm(formula = y ~ 1 + x, data = df.example)
```

| r.squared | adj.r.squared | sigma | statistic | p.value | df | logLik | AIC | BIC | deviance | df.residual |
|-----------|---------------|-------|-----------|---------|----|--------|-------|-------|----------|-------------|
| 0.25 | 0.21 | 1.45 | 6.16 | 0.02 | 2 | -34.74 | 75.47 | 78.46 | 37.77 | 18 |

AIC and BIC

$$\text{AIC} = 2k - 2 \ln(\hat{L}) = 2 \cdot 3 - 2 \cdot (-34.74) = 75.47$$

$$\text{BIC} = \ln(n)k - 2 \ln(\hat{L}) = \ln(20) \cdot 3 - 2 \cdot (-34.74) = 78.46$$

$\ln(\hat{L})$ = maximized value of the likelihood function of the model **-34.74**

k = number of parameters in the model **3**

n = number of observations **20**

the sd of the normal distribution modeling the residuals counts as a parameter

```
lm(formula = y ~ 1 + x, data = df.example)
```

| r.squared | adj.r.squared | sigma | statistic | p.value | df | logLik | AIC | BIC | deviance | df.residual |
|-----------|---------------|-------|-----------|---------|----|--------|-------|-------|----------|-------------|
| 0.25 | 0.21 | 1.45 | 6.16 | 0.02 | 2 | -34.74 | 75.47 | 78.46 | 37.77 | 18 |

AIC and BIC

$$\text{AIC} = 2k - 2 \ln(\hat{L})$$

$$\text{BIC} = \ln(n)k - 2 \ln(\hat{L})$$

- for both AIC and BIC, *lower* is better!
- neither provide a test of a model in the sense of testing a null hypothesis
 - AIC or BIC tell us nothing about the absolute quality of a model, only the quality relative to other models
- BIC generally penalizes free parameters more strongly than AIC (though it depends on the size of n)

| ΔBIC | Evidence against higher BIC |
|--------------------|------------------------------------|
| 0 to 2 | Not worth more than a bare mention |
| 2 to 6 | Positive |
| 6 to 10 | Strong |
| >10 | Very Strong |

What shall I use when?

- Use it all!
- ideally, the different measures provide converging evidence

Table 2

Summary of the model results. Values for r and RMSE indicate means (with 5% and 95% quantiles in parentheses) based on 100 split-half cross-validation runs. BIC scores are based on running the models on the full data set.

| Model | r | RMSE | BIC |
|-------------------------|----------------|----------------------|--------|
| Difference & pivotality | .86 (.66, .95) | 10.56 (6.17, 17.21) | 158.59 |
| Difference | .70 (.30, .90) | 26.92 (16.4, 40.6) | 209.74 |
| Pivotality | .63 (.41, .77) | 14.23 (11.39, 17.54) | 199.53 |
| Optimality | .66 (.42, .84) | 14.55 (10.54, 17.91) | 199.47 |

Note: BIC = Bayesian Information Criterion (lower values indicate better model performance).

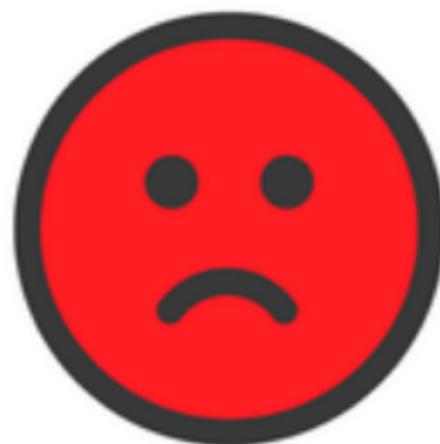
Plan for today

- Quick recap
- Simulating a power analysis
 - Demonstration in RStudio
- Model comparison
 - Cross-validation
 - AIC and BIC
- Linear mixed effects models

How was the pace of today's class?

much a little just a little much
too too right too too
slow slow fast fast

How happy were you with today's class overall?



What did you like about today's class? What could be improved next time?

Thank you!