

Simple linear regression



Overview

Simple linear regression

Inference for simple linear regression

- Errors and residuals
- Hypothesis tests for regression coefficients
- If there is time: confidence and prediction intervals

Announcements

Homework 6 is out

- Due Sunday October 27th at 11pm

Exam grades will be available by 2pm on Friday

- If you need to know your exam score earlier talk to me after class

Where we are: completed

- | | | |
|---|-----------|---|
| 1 | Aug 29 | Course overview, introduction to R, descriptive statistics |
| 2 | Sep 3-5 | Review of central statistical concepts and exploratory analysis using R |
| 3 | Sep 10-12 | Confidence Intervals and the bootstrap |
| 4 | Sep 17-19 | Review of hypothesis tests and permutation tests in R |
| 5 | Sep 24-26 | Parametric, non-parametric and theories of hypothesis testing |
| 6 | Oct 1-3 | Data manipulation and visualization |
| 7 | Oct 8-10 | Review and midterm exam |
| 8 | Oct 15-17 | Odds and ends, October break |

Analysis

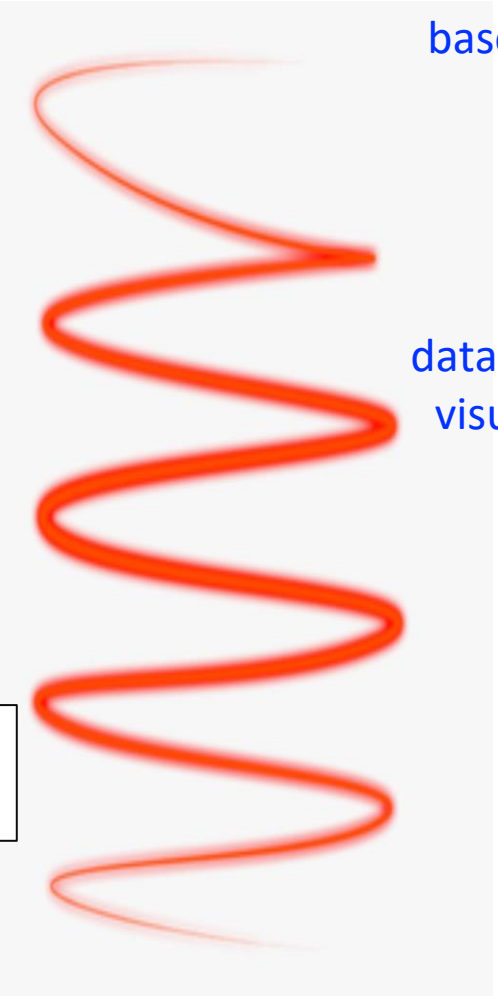
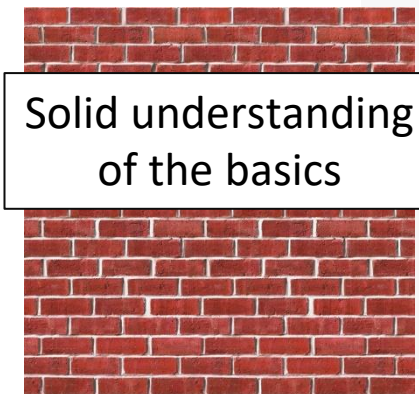
R

resampling
methods

base R

data wrangling
visualization

Solid understanding
of the basics



Where we are: up next

9	Oct 22-24	Simple linear regression
10	Oct 29-31	Multiple regression
11	Nov 5-7	Model selection and logistic regression

Next: building linear models

We will use these models to:

1. Make accurate predictions
2. Understand the relationship between explanatory variables x_i 's and a response variable y
 - (e.g., try to account for the variation in a response variable y)

Analysis

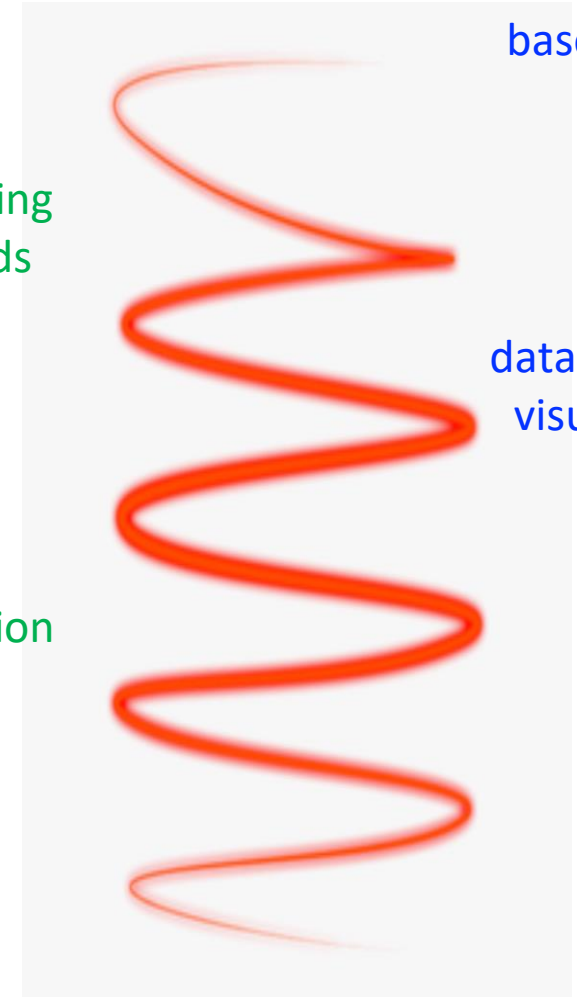
R

resampling
methods

regression

base R

data wrangling
visualization



Statistical modeling motivation

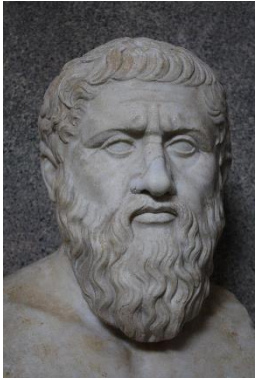
Quick Review of central concepts in Intro Statistics



THE TRUTH IS OUT THERE

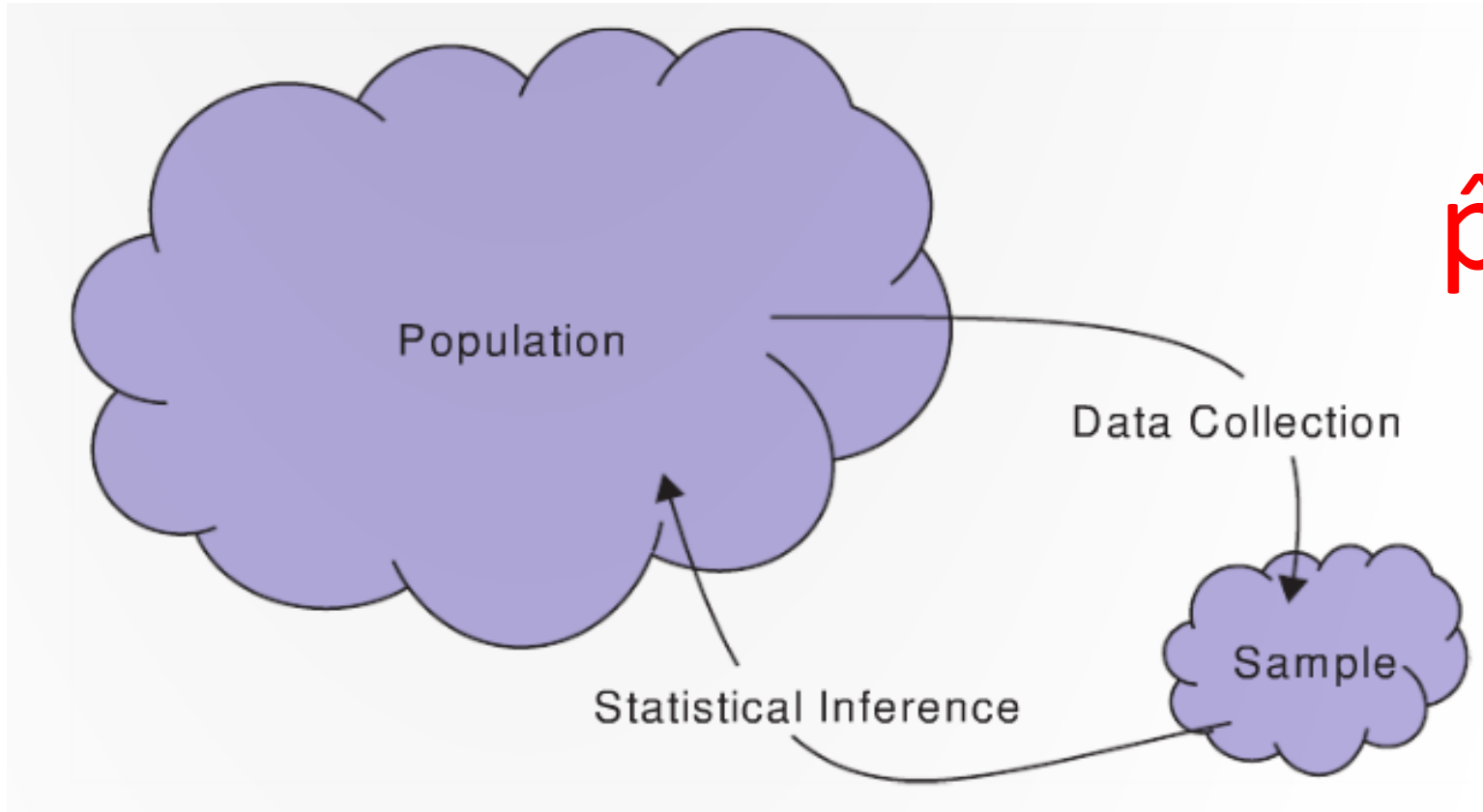
**We need to see through the random variation (noise)
to get to the underlying consistency (Truth)**



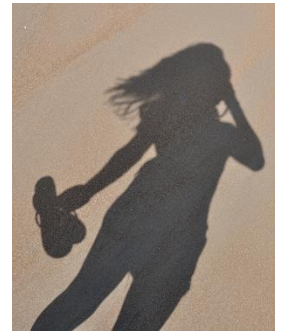


$\pi, \mu, \sigma, \rho, \beta$

Parameter: a number characterizing a property of a population



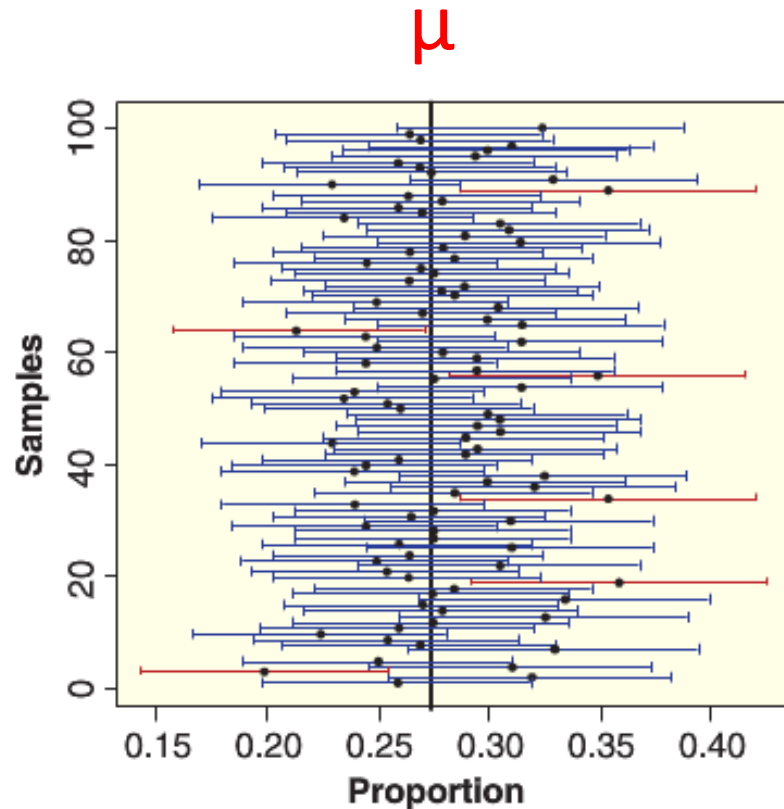
$\hat{p}, \bar{x}, s, r, b$



Statistic: A number computed from a sample

Inference on parameters

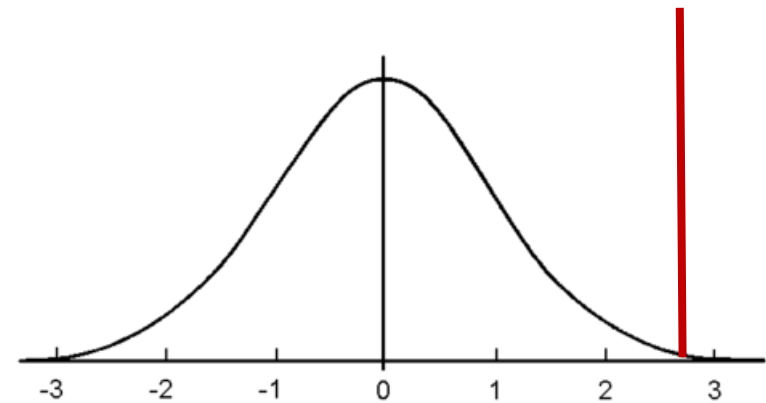
Confidence intervals



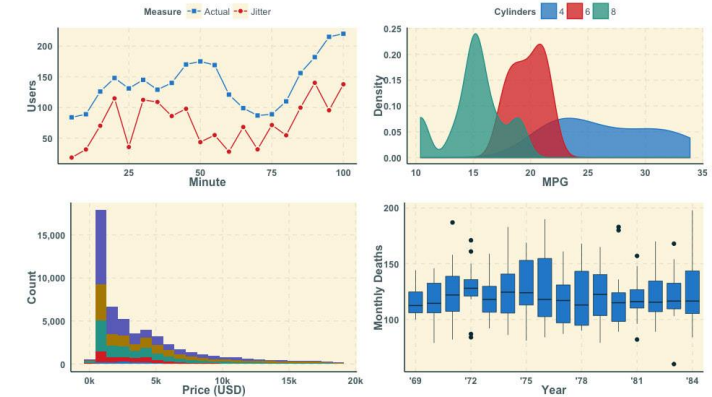
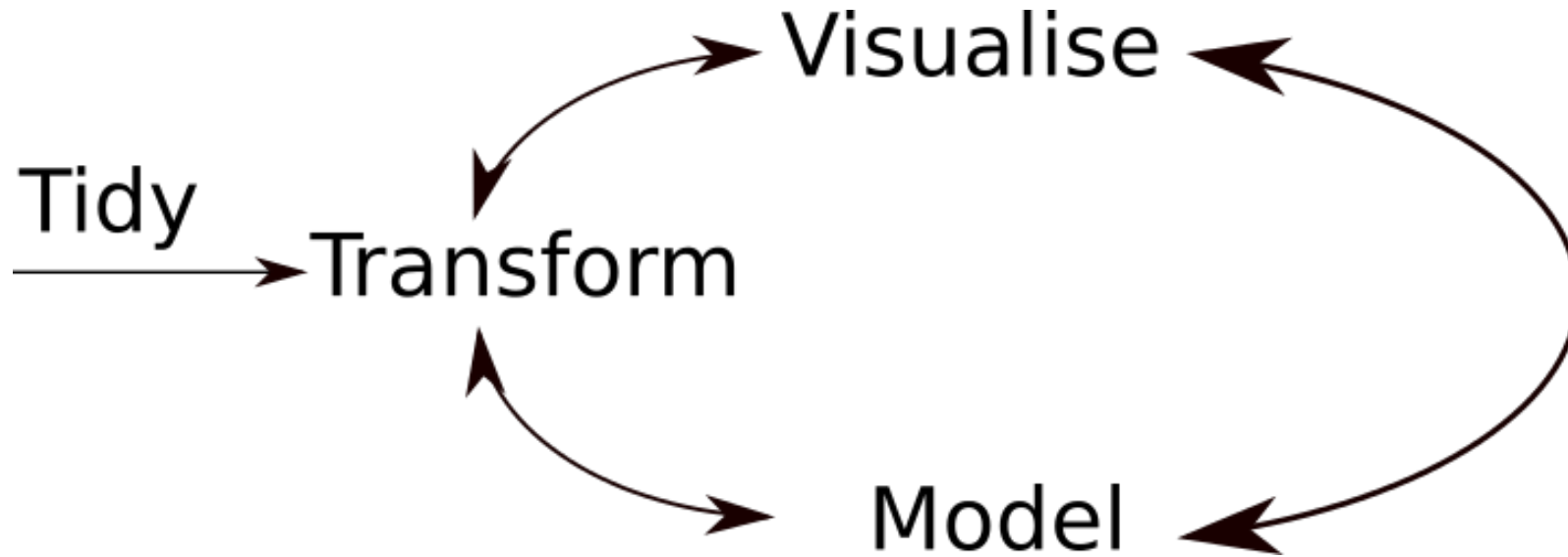
Hypothesis tests

$$H_0: \mu = 0$$

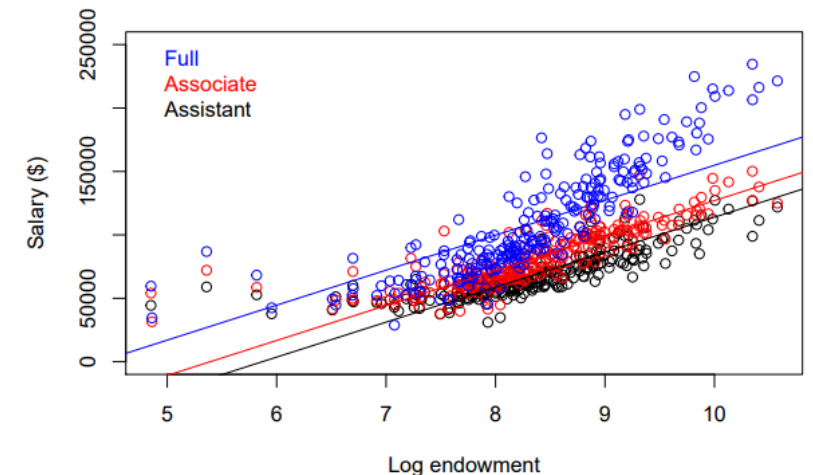
$$H_A: \mu > 0$$



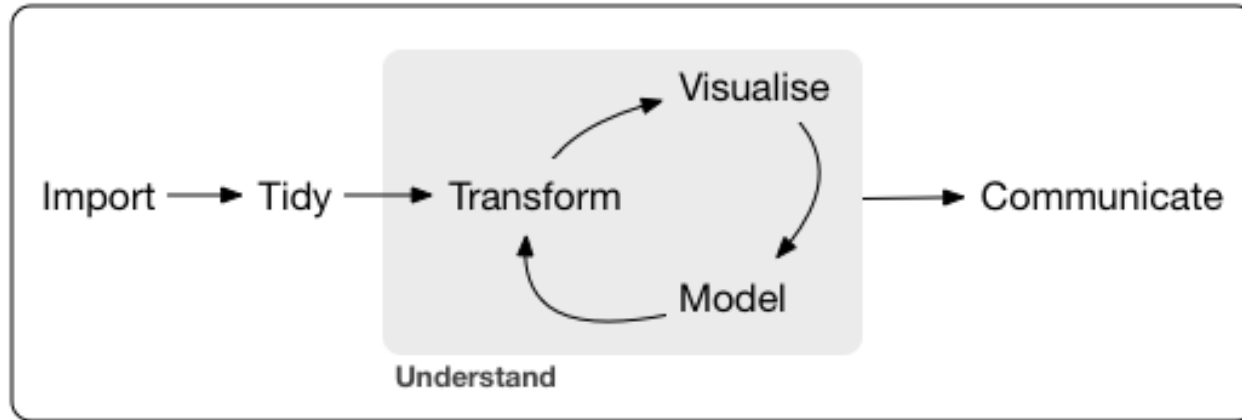
Sometimes the Truth is more complicated...



Curve information - Curve quality data											
Name	Formula	Slope at Intercept	ED-20	ED-50	ED-80	Correlation	Forced through origin				
Standard Calc 1: C	standard	standard	3792394	27752	0.2	0.5	0.8	1	No		
Plate information											
Plate	Repeat	Barcode	Measure	Chamber	Chamber	Humidity	Humidity	Ambient	Ambient	Formula	Measurement date
1	1		N/A	N/A	N/A	N/A	N/A	N/A	N/A	Calc 1: C	standard standard 10.12.2013 10:23:33
Background information											
Plate	Label	Result	Signal	Flashes/T	MeasTime	MeasInfo					
1	PicoGreen	0	110307	10	0	De=1st Ex=Top Em=Top Wdw=N/A					
Calculate: standard standards on each plate) where Label: PicoGreenFilterTop(1) channel 1											
	1	2	3	4	5	6	7	8	9	10	11
A	-0.0011	-0.0011	-0.001	-0.001	-0.0011	-0.0012	-0.0011	-0.0011	-0.0012	-0.0012	0.9973
B	0.0012	0.0014	0.0013	0.0012	0.0013	0.0012	0.0014	0.0003	-0.0011	-0.0011	0.0981
C	0.0016	0.0013	0.0013	0.0011	0.0012	0.0015	0.0016	-0.0004	-0.0011	-0.0011	0.0104
D	0.0019	0.0024	0.0018	0.0015	-0.001	-0.001	-0.001	-0.001	-0.0011	-0.0011	0.0008
E	-0.001	-0.0011	-0.0011	-0.0011	-0.001	-0.0012	-0.0011	-0.001	-0.0009	-0.0011	-0.0001
F	-0.001	-0.0011	-0.001	-0.001	-0.0012	-0.0011	-0.0011	-0.0009	-0.001	-0.001	-0.0003
G	-0.0011	-0.0011	-0.0011	-0.001	-0.001	-0.0012	-0.0011	-0.001	-0.001	-0.0011	-0.0002
H	-0.0011	-0.0012	-0.0011	-0.001	-0.0011	-0.0011	-0.0012	-0.0011	-0.0011	-0.001	-0.0003



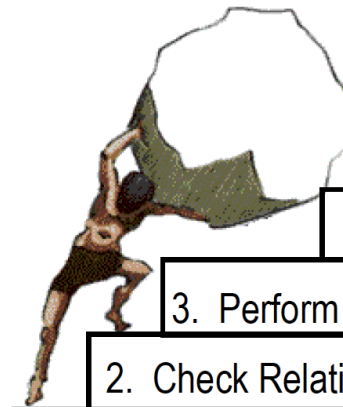
The process of building regression models



Hadley Wickham



Sisyphus' Five Steps for Simple Linear Regression



1. Identify Variables : response and predictor

2. Check Relationships (plots) : make transformations

3. Perform Regression

4. Identify Significant Predictors

5. Check Model Assumptions

Jonathan Reuning-Scherer

"All models are wrong, but some are useful"
- George Box

Simple linear regression

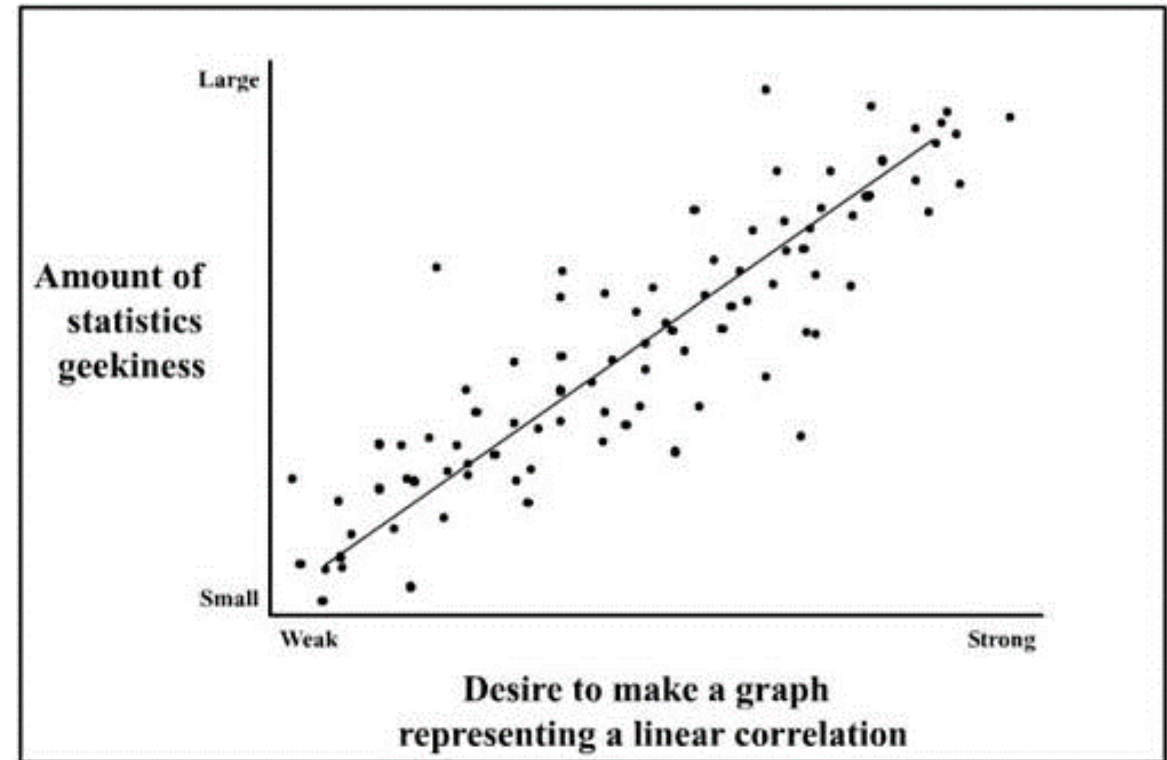
Simple linear regression

Regression is method of using one variable x to predict the value of a second variable y

$$\hat{y} = f(x)$$

In **linear regression** we fit a line to the data, called the **regression line**

- In *simple* linear regression, we use a single variable x , to predict y



Motivation: Predicting the 2020 election



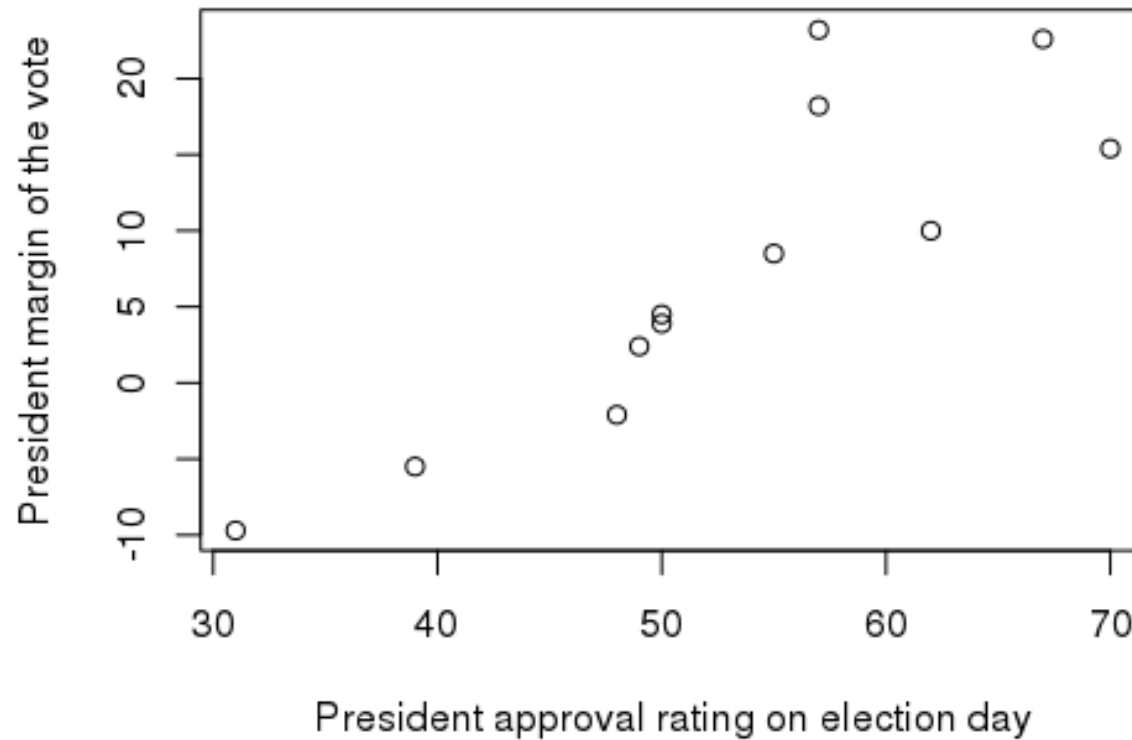
Predict the margin of the popular vote based on the president's approval rating

Data from an article on the 2012 election on the [Five Thirty Eight website](#)



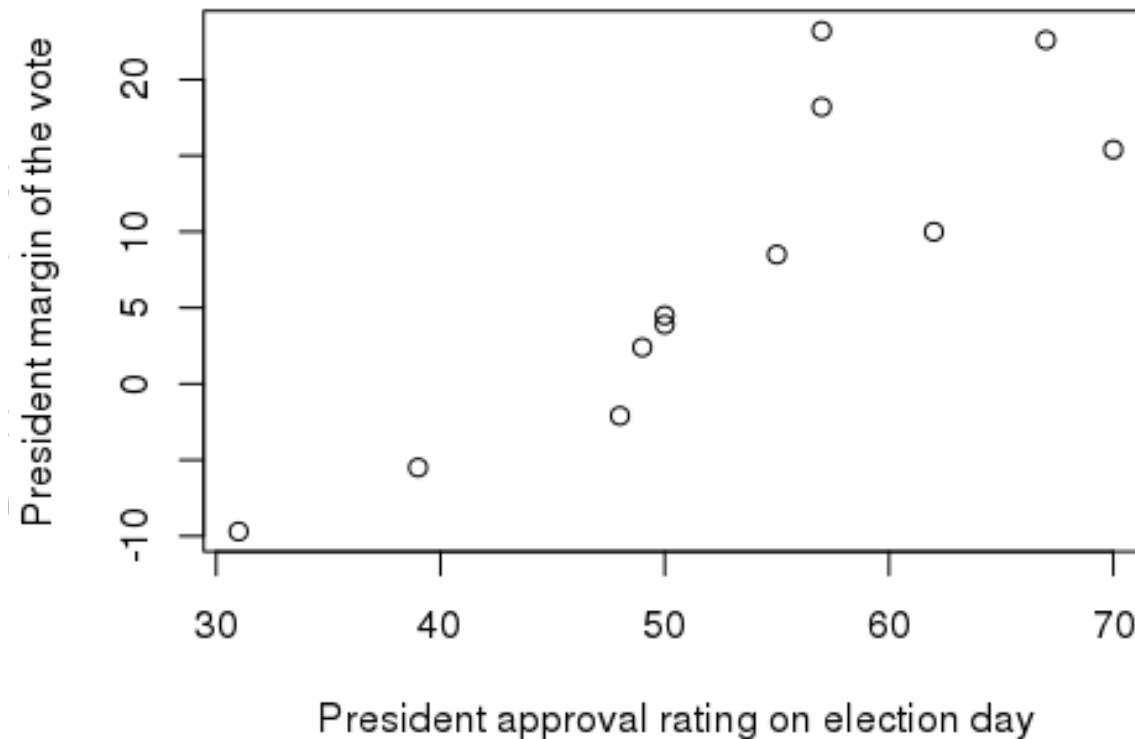
Approval rating vote margin regression line

From previous 12 US president's running for reelection



Approval rating vote margin regression line

From previous 12 US president's running for reelection



$$\hat{y} = b_0 + b_1 \cdot x$$

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x$$

$$R: \text{lm}(y \sim x)$$

$$\hat{\beta}_0 = -36.76$$

$$\hat{\beta}_1 = 0.84$$

$$\hat{y} = -36.76 + 0.84 \cdot x$$

Approval rating vote margin regression line

1. If a president had a 0% approval rating, what vote margin does this model predict the president would get?
2. If a president's approval rating increased by 1%, how much would the president's margin of the vote be predicted to increase by?
3. At what presidential approval level would there be an exactly even split of the vote?

$$\hat{y} = b_0 + b_1 \cdot x$$

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x$$

$$R: \text{lm}(y \sim x)$$

$$\hat{\beta}_0 = -36.76$$

$$\hat{\beta}_1 = 0.84$$

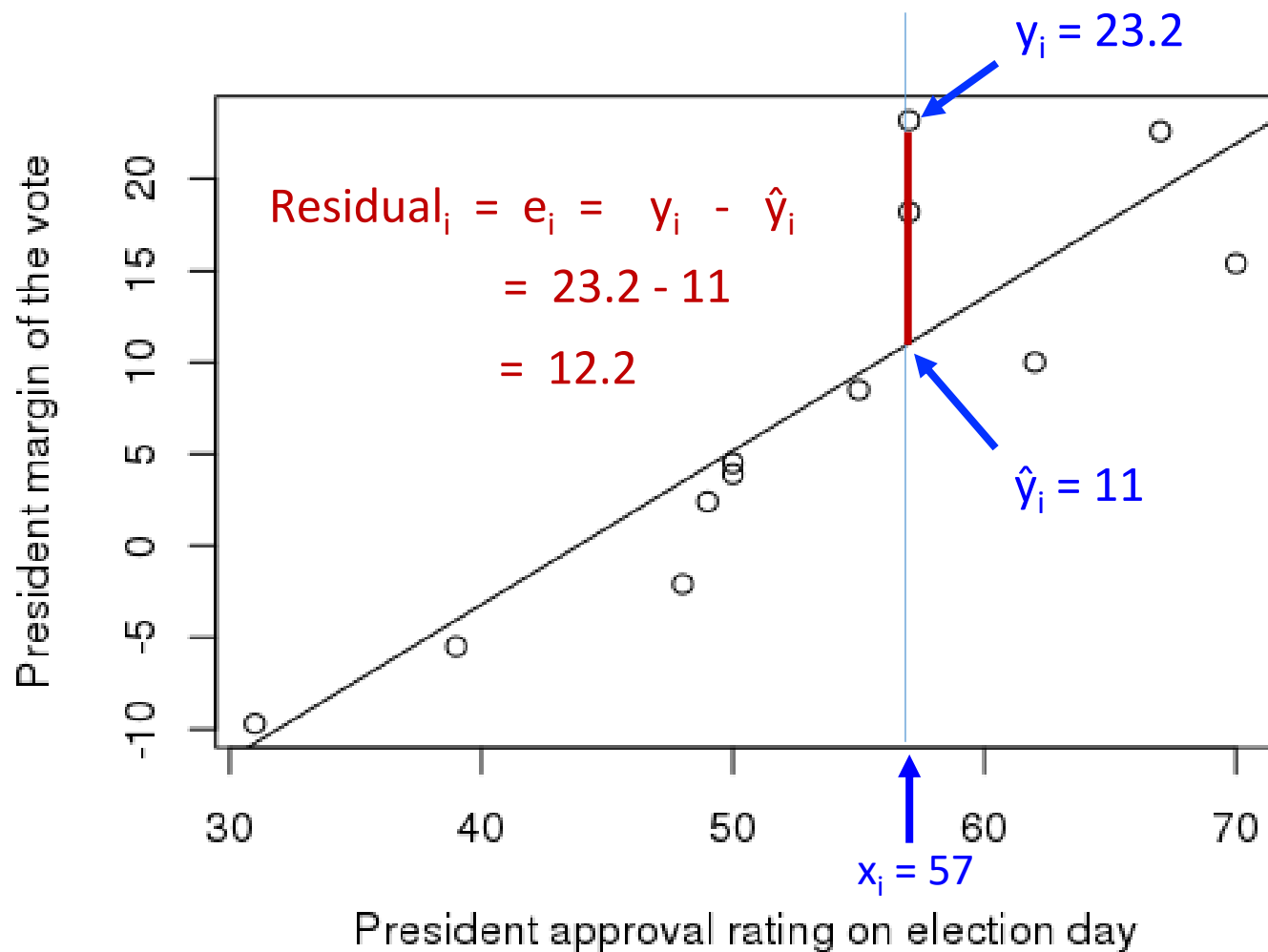
$$\hat{y} = -36.76 + 0.84 \cdot x$$

Residuals

The **residual** at a data value is the difference between the observed (y) and predicted value of the response variable

$$\begin{array}{ccccc} \textit{Residual}_i & = & \textit{Observed}_i & - & \textit{Predicted}_i \\ \swarrow \text{red arrow} & & \swarrow \text{red arrow} & & \swarrow \text{red arrow} \\ e_i & = & y_i & - & \hat{y}_i \end{array}$$

Approval rating vote margin regression line



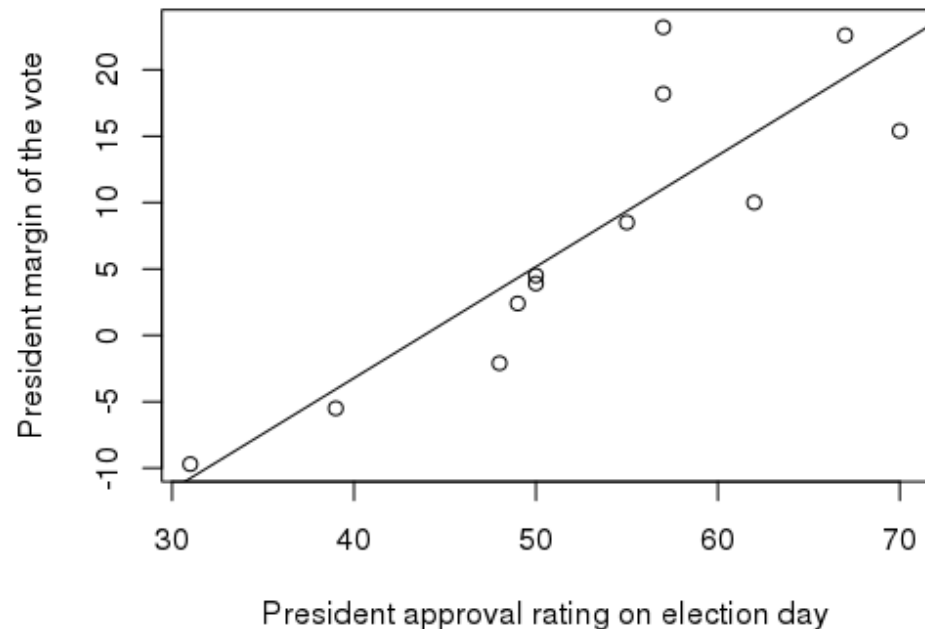
Approval rating vote margin regression line

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x$$

Approval x	Margin obs y	Margin pred \hat{y}	Residuals $e = y - \hat{y}$
62	10	15.23	-5.23
50	4.5	5.17	-0.67
70	15.4	21.94	-6.54
67	22.6	19.43	3.17
57	23.2	11.04	12.16
48	-2.1	3.49	-5.59
31	-9.7	-10.76	1.06
57	18.2	11.04	7.16

Least squares line

The **least squares line** is the line which minimizes the sum of squared residuals



Try to find the line of best fit

Approval rating vote margin regression line

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x$$

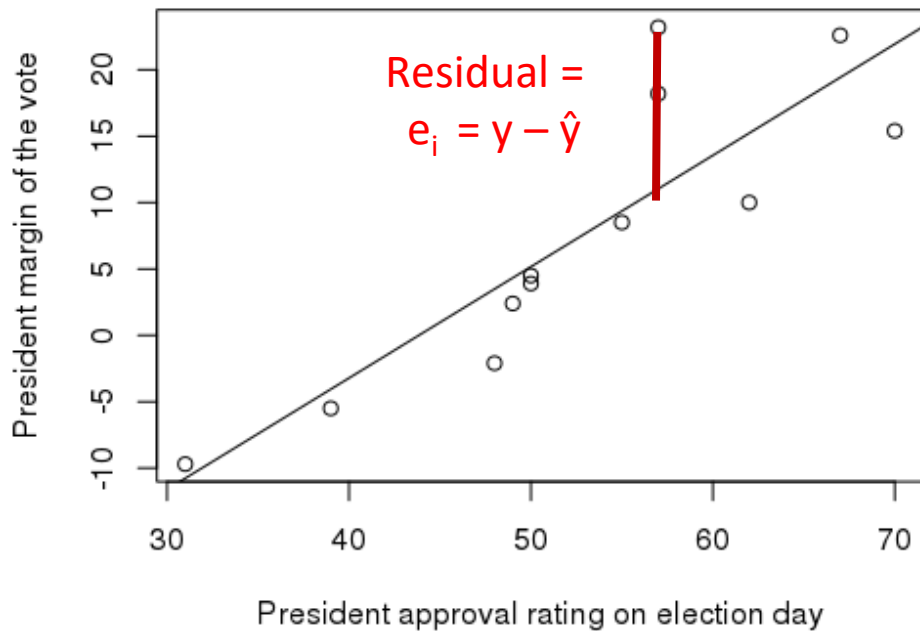
Approval x	Margin obs y	Margin pred \hat{y}	Residuals $e = y - \hat{y}$	Residuals ² $e^2 = (y - \hat{y})^2$
62	10	15.23	-5.23	27.40
50	4.5	5.17	-0.67	0.45
70	15.4	21.94	-6.54	42.81
67	22.6	19.43	3.17	10.07
57	23.2	11.04	12.16	147.84
48	-2.1	3.49	-5.59	31.29
31	-9.7	-10.76	1.06	1.13
57	18.2	11.04	7.16	51.25

Q: Why do we minimize the sum of **squared** residuals rather than just the sum of residuals?

Minimizing the sum of the squared residuals to find the regression coefficients

To find the regression coefficients $\hat{\beta}_0$ and $\hat{\beta}_1$ we minimize the **sum of squared residuals**

- We will use the notation **SSRes** to denote the sum of squared residuals
 - (The residual sum of squares is also called the "**error sum of squares**" (SSE))



$$\text{residual} = e_i$$

$$\begin{aligned} SSRes &= \sum_{i=1}^n e_i^2 = \sum_{i=1}^n (y_i - \hat{y}_i)^2 \\ &= \sum_{i=1}^n (y_i - \hat{f}(x_i))^2 = \sum_{i=1}^n (y_i - (\hat{\beta}_0 + \hat{\beta}_1 x_i))^2 \end{aligned}$$

$$R: \text{lm}(y \sim x)$$

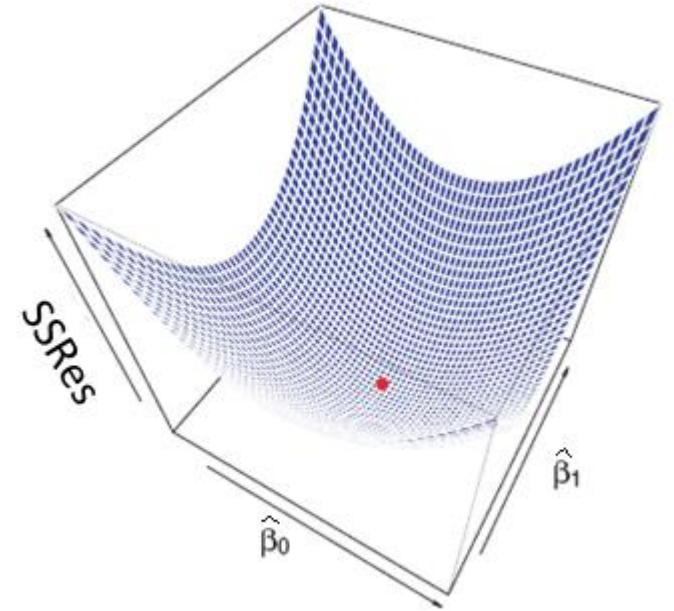
How do we minimize the SSE?

$$SSRes = \sum_{i=1}^n (y_i - (\hat{\beta}_0 + \hat{\beta}_1 x))^2$$

How do we find $\hat{\beta}_0, \hat{\beta}_1$?

Calculus and linear algebra:

- Take the derivative, set to 0 and solve
- This mathematical convenience is why the squared loss is so commonly used



$$\hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x} \qquad \hat{\beta}_1 = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^n (x_i - \bar{x})^2}$$

Basic regression caution # 1

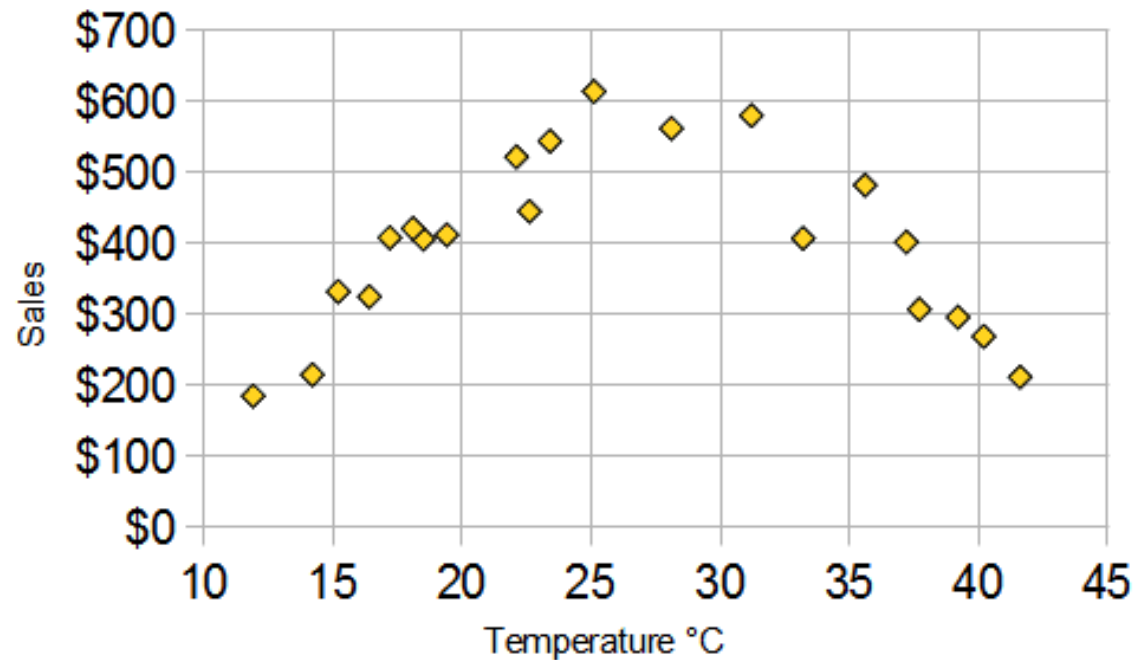
Avoid trying to apply the regression line to predict values far from those that were used to create the line.

- i.e., do not extrapolate too far

Basic regression caution # 2

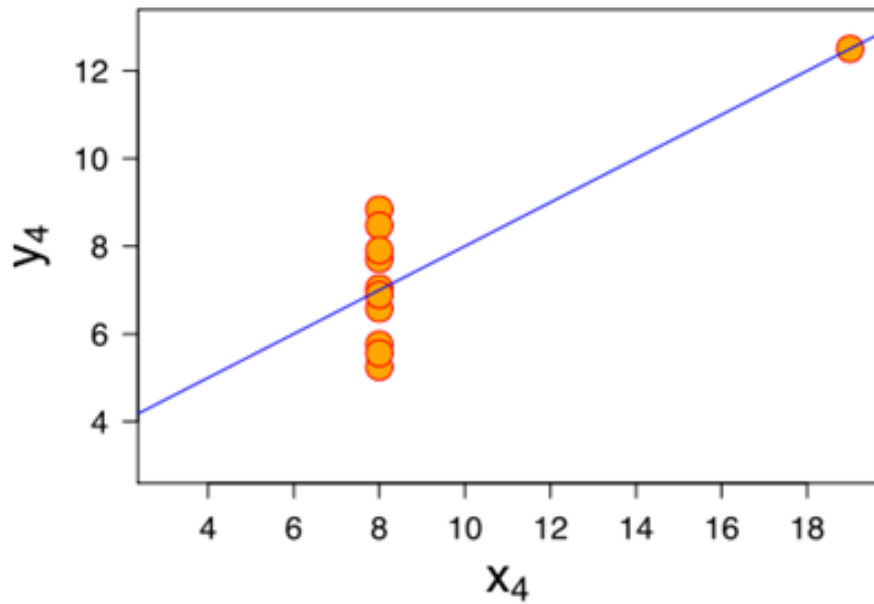
Plot the data! Linear regression is only appropriate when there is a linear trend in the data.

- We will discuss a set of checks on the appropriateness of using linear models soon



Basic regression caution #3

Be aware of outliers and high leverage points. They can have a large effect on the regression line.



Outlier: big $|y_i - \bar{y}|$

Leverage: big $|x_i - \bar{x}|$

Influential point: big outlier and leverage

There are statistics that quantify/describe influential points

- We will discuss these soon as well

Let's try simple linear regression in R...

Faculty salaries

- Predict faculty salaries based on the size of a university's endowment



Inference for simple linear regression

Inference for simple linear regression



Warning: there is a minefield of poor/misleading terminology out there

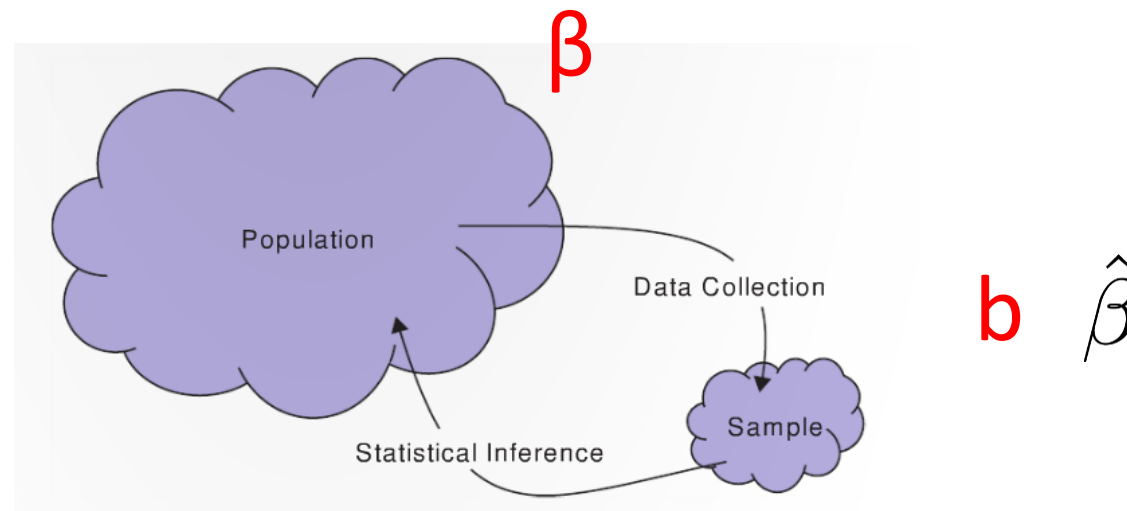
- So be careful when reading material related to inference on regression models

I will try to help you navigate this...

Inference for simple linear regression

The Greek letter β is used to denote the slope *of the population*

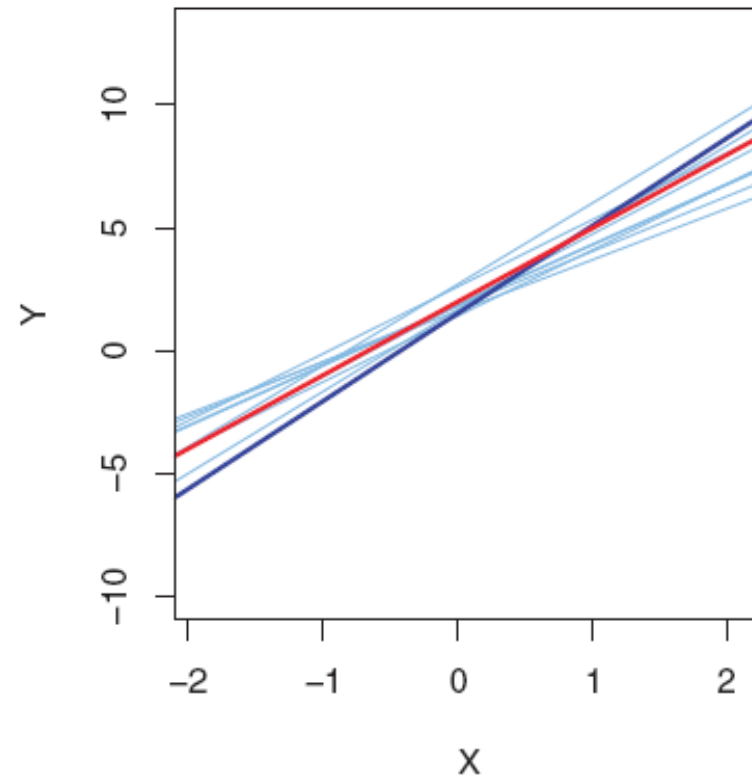
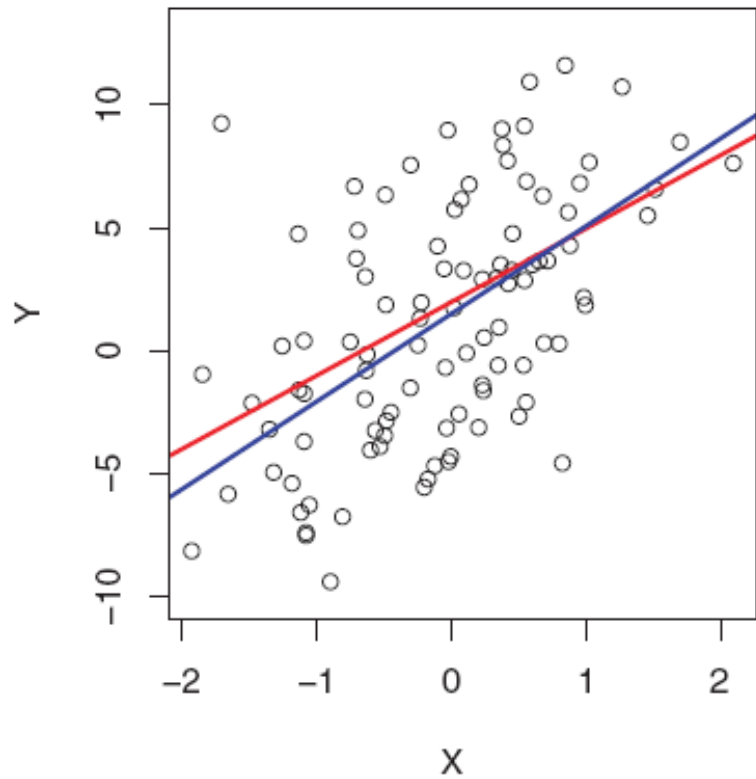
The letter b or $\hat{\beta}$ is typically used to denote the slope *of the sample*



Population: β_0 and β_1

Sample estimates: b_0 and b_1

$\hat{\beta}_0$ and $\hat{\beta}_1$



Linear regression underlying model

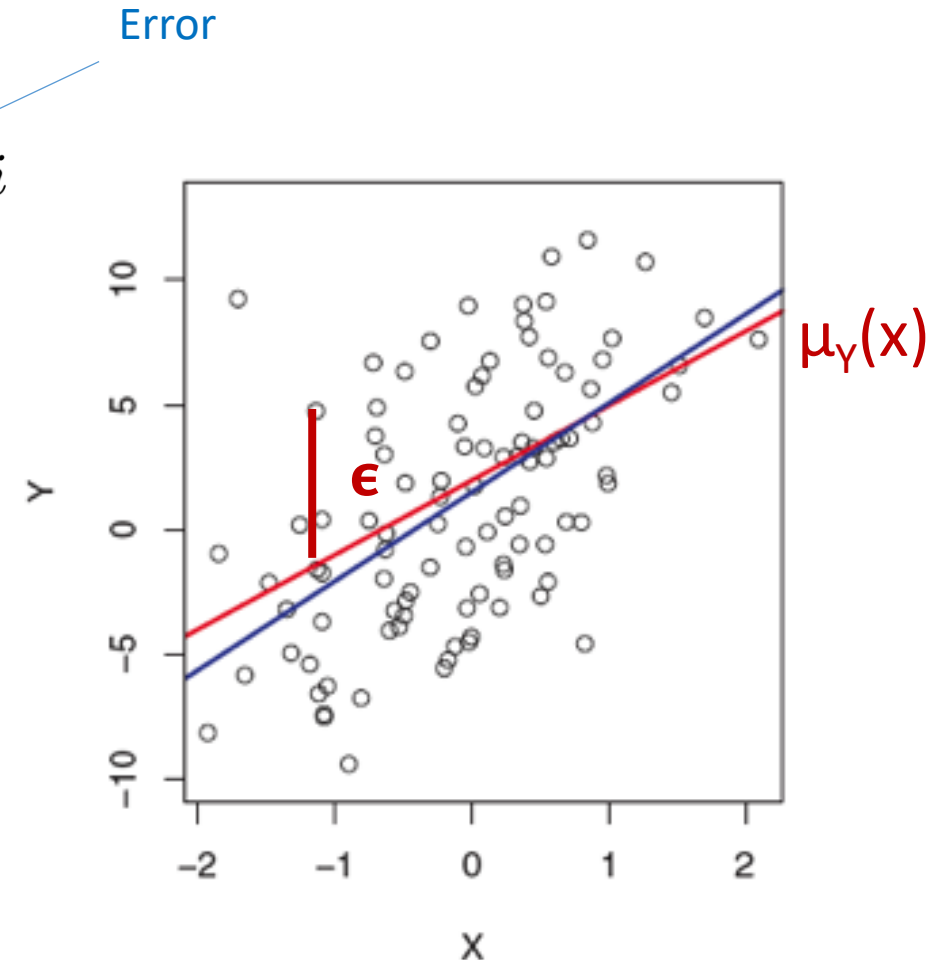
Intercept Slope } Parameters

True regression line: $\mu_Y(x) = \beta_0 + \beta_1 x$

Observed data point: $Y_i = \beta_0 + \beta_1 x_i + \epsilon_i$
 $= \mu_Y(x_i) + \epsilon_i$

Errors ϵ_i are the difference between an observed data points Y_i and the **true regression line** $\mu_Y(x_i)$

$$\epsilon_i = Y_i - \mu_Y(x_i) = Y_i - (\beta_0 + \beta_1 x_i)$$



Linear regression underlying model

Intercept Slope } Parameters

True regression line: $\mu_Y(x) = \beta_0 + \beta_1 x$

Observed data point: $Y_i = \beta_0 + \beta_1 x_i + \epsilon_i$

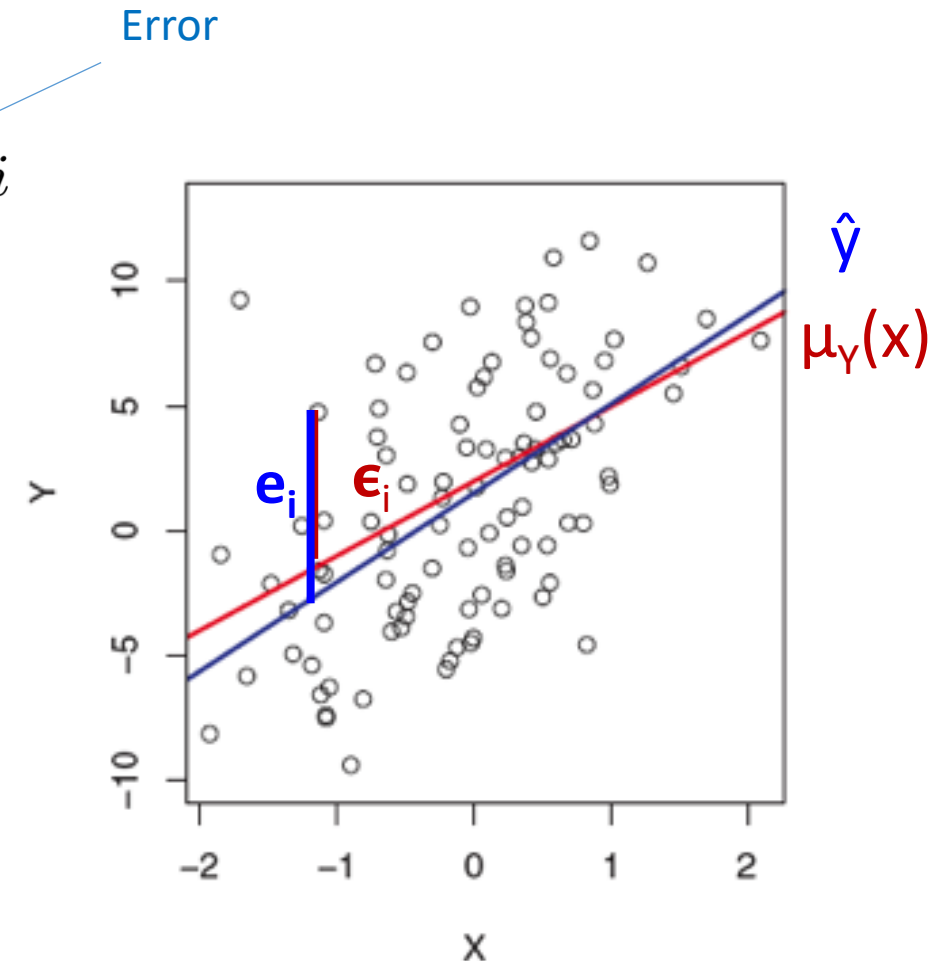
Estimated regression line: $\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x$

Errors ϵ_i are the difference between an observed data points Y_i and the **true regression line** $\mu_Y(x_i)$

$$\epsilon_i = Y_i - \mu_Y(x_i)$$

Residuals e_i are the difference between the **estimated regression line** \hat{y}_i and observed data points Y_i

$$e_i = Y_i - \hat{y}_i = Y_i - (\hat{\beta}_0 + \hat{\beta}_1 x_i)$$



Linear regression underlying model

Intercept Slope } Parameters

True regression line: $\mu_Y(x) = \beta_0 + \beta_1 x$

Observed data point: $Y_i = \beta_0 + \beta_1 x_i + \epsilon_i$ Error

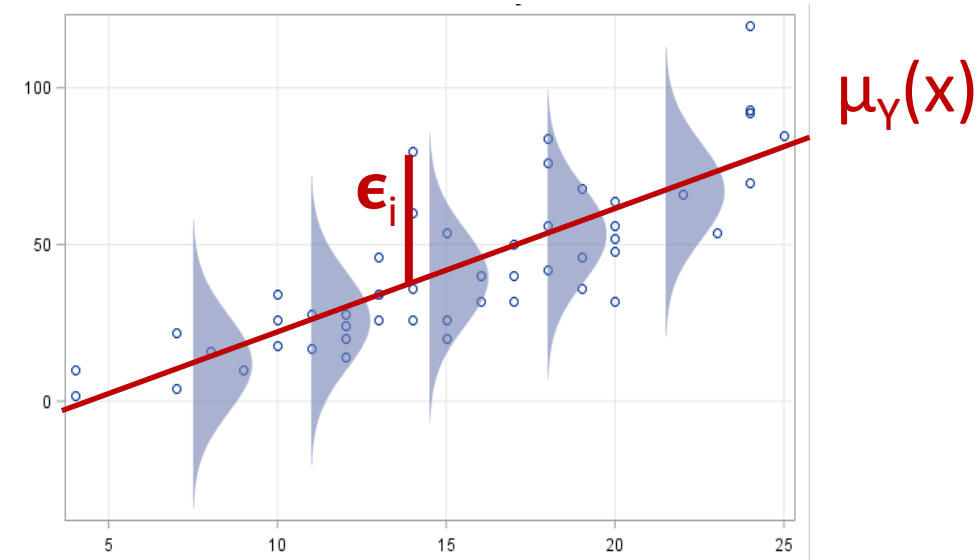
$\epsilon_i \sim N(0, \sigma_\epsilon)$

Errors ϵ_i are the difference between an observed data points Y_i and the **true regression line** $\mu_Y(x_i)$

$$\epsilon_i = Y_i - \mu_Y(x_i) = Y_i - (\beta_0 + \beta_1 x_i)$$

We will *assume* that the errors ϵ_i are **normally distributed**

- This is needed for inference using parametric methods
 - e.g., to use t-distributions and F-distributions



Recap: Errors vs. residuals

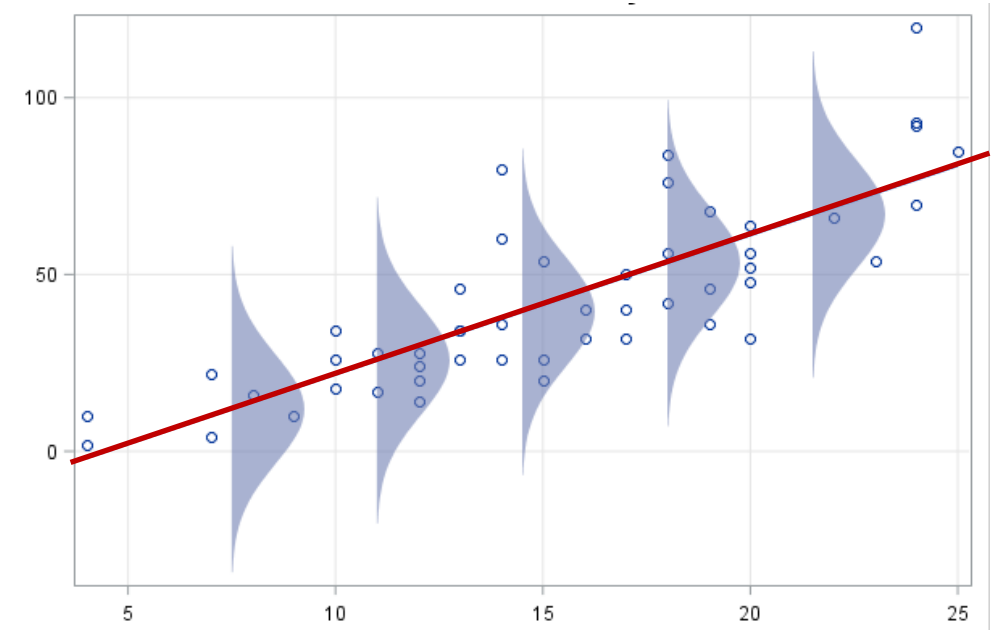
The data: $Y_i = \beta_0 + \beta_1 x_i + \epsilon_i$ $\epsilon_i \sim N(0, \sigma_\epsilon)$

"True" model: $\mu_Y(x_i) = \beta_0 + \beta_1 x_i$

- Errors: $\epsilon_i = Y_i - \mu_Y(x_i)$

Estimated model: $\hat{y}_i = \hat{\beta}_0 + \hat{\beta}_1 x_i$

- Residuals: $e_i = Y_i - \hat{y}_i$



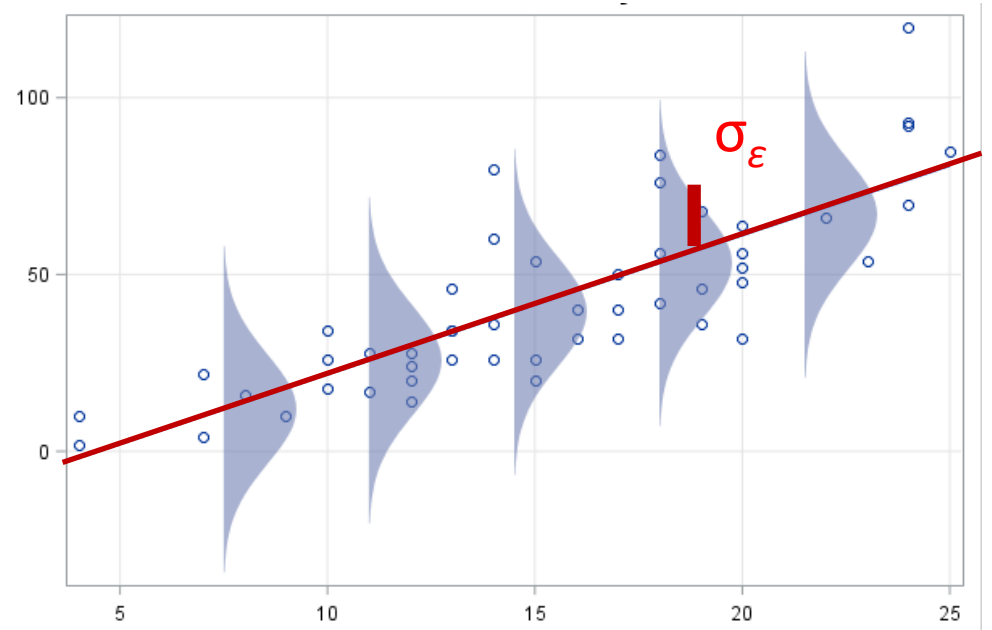
Standard deviation of the errors: σ_ε

The standard deviation of the errors is denoted σ_ε

We can use the **standard deviation of residuals** $\hat{\sigma}_e$ as an estimate standard deviation of the errors σ_ε

- $\hat{\sigma}_e$ often called the "~~residual standard error~~"
- $\hat{\sigma}_e$ we will call it the "residual standard deviation"

$$\begin{aligned}\hat{\sigma}_e &= \sqrt{\frac{1}{n-2} SSRes} \\ &= \sqrt{\frac{1}{n-2} \sum_{i=1}^n (y_i - \hat{y}_i)^2}\end{aligned}$$



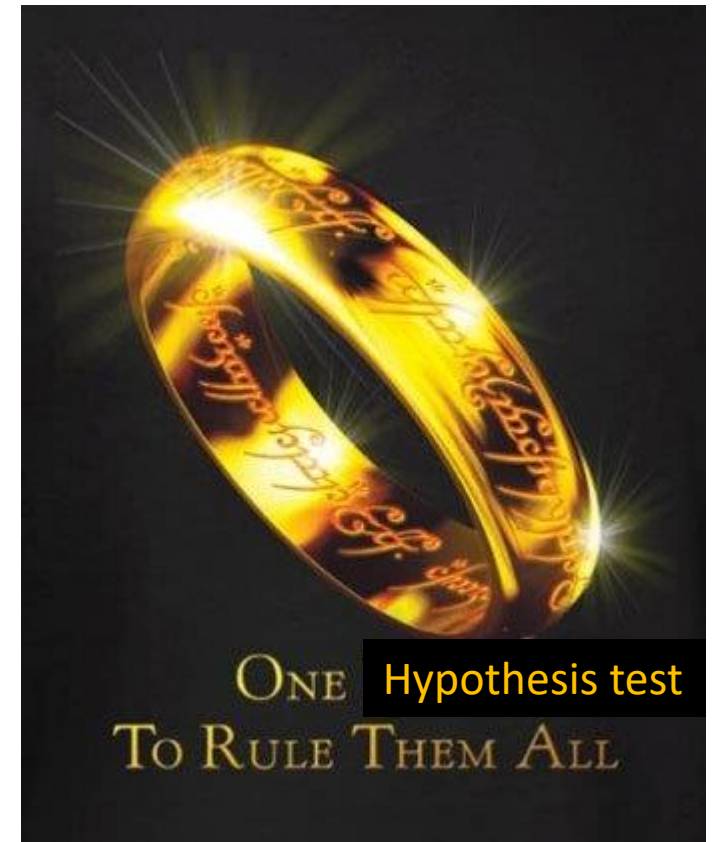
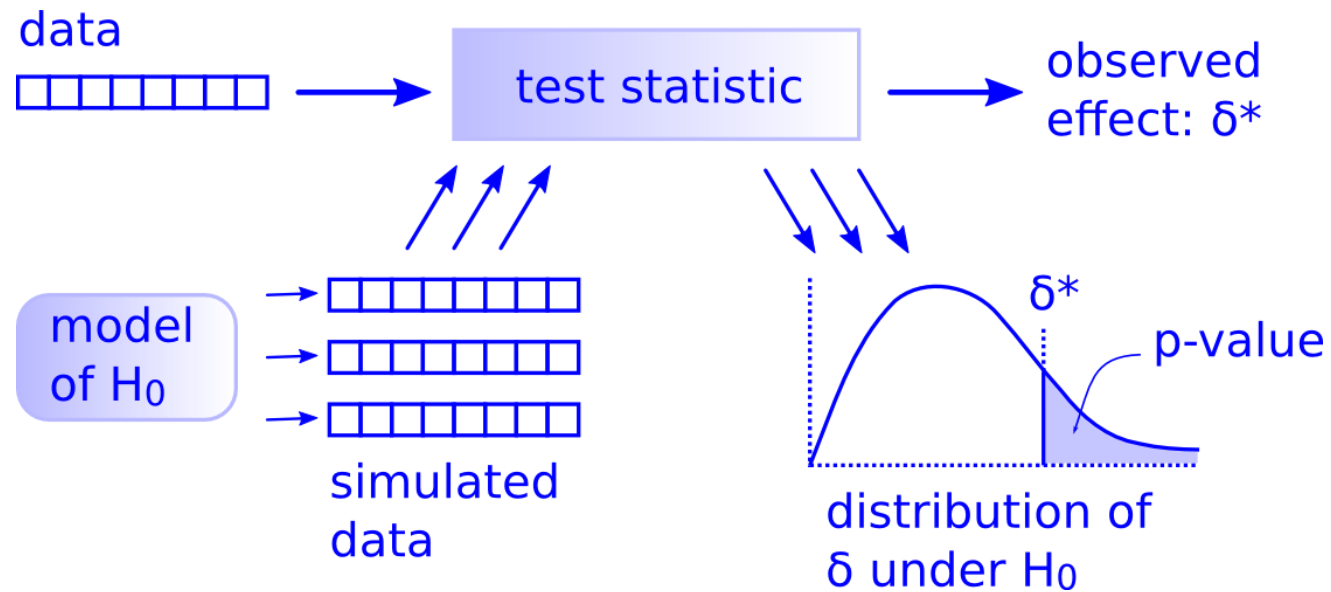
How are we feeling?

Let's quickly try this in R...

Inference for linear regression: hypothesis tests

Hypothesis test for regression coefficients

There is only one [hypothesis test](#)!



Hypothesis test for regression coefficients

We can run hypothesis tests to assess whether there is a relationship between y and x , and calculate p-values

- $H_0: \beta_1 = 0$ (slope is 0, so no relationship between x and y)
- $H_A: \beta_1 \neq 0$

One type of hypothesis test we can run is based on a t-statistic: $t = \frac{\hat{\beta}_1 - 0}{\hat{SE}_{\hat{\beta}_1}}$

- The t-statistic comes from a t-distribution with $n - 2$ degrees of freedom

$$\hat{SE}_{\hat{\beta}_1} = \frac{\hat{\sigma}_e}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2}}$$

$$\hat{SE}_{\hat{\beta}_0} = \hat{\sigma}_e \sqrt{\frac{1}{n} + \frac{\bar{x}^2}{\sum_{i=1}^n (x_i - \bar{x})^2}}$$

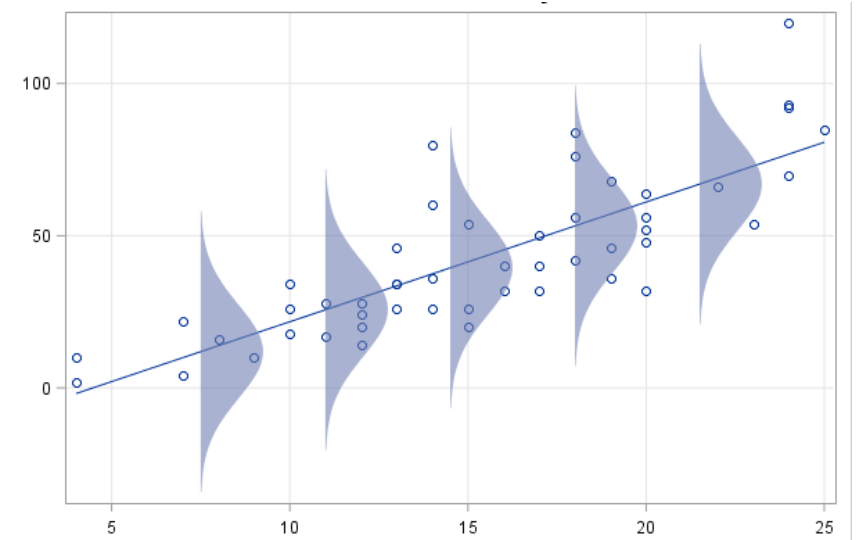
Inference using parametric methods

When using parametric methods, we make the following (LINE) assumptions:

- **Linearity**: A line can describe the relationship between x and y
- **Independence**: each data point is independent from the other points
- **Normality**: errors are normally distributed
- **Equal variance (homoscedasticity)**: constant variance of errors over the whole range of x values

$$Y_i = \beta_0 + \beta_1 x_i + \epsilon_i$$

$$\epsilon_i \sim N(0, \sigma_\epsilon)$$



These assumptions are usually checked after the models are fit using ‘regression diagnostic’ plots.

Let's look at inference for simple linear regression in R

Back to faculty salaries...



Inference for linear regression: confidence intervals

We can estimate three types of intervals for a regression:

1. Confidence intervals for the regression coefficients: β_0 and β_1
2. Confidence intervals for the full line $\mu_Y(x)$
3. Prediction intervals where most of the data is expected

Confidence intervals for regression coefficients

For the slope coefficient , the confidence interval is: $\hat{\beta}_1 \pm t^* \cdot \hat{SE}_{\hat{\beta}_1}$

Where: $\hat{SE}_{\hat{\beta}_1} = \hat{\sigma}_e \sqrt{\frac{1}{\sum_{i=1}^n (x_i - \bar{x})^2}}$

t^* is a quantile value from a t-distribution with $n-2$ degrees of freedom obtain to get a desired confidence level

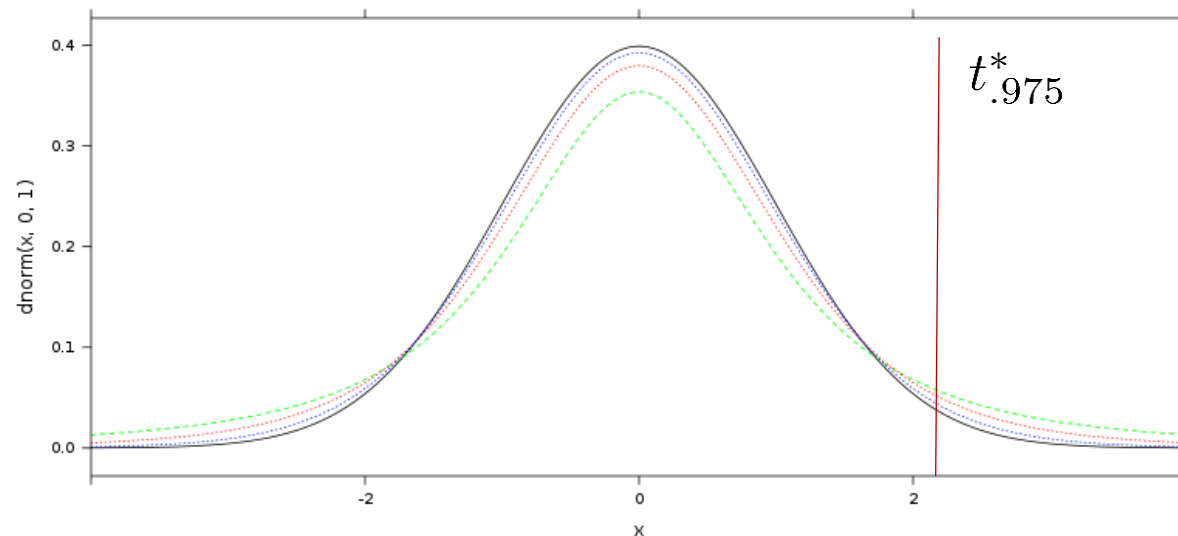
`qt(.975, df)`

$N(0, 1)$

$df = 2$

$df = 5$

$df = 15$



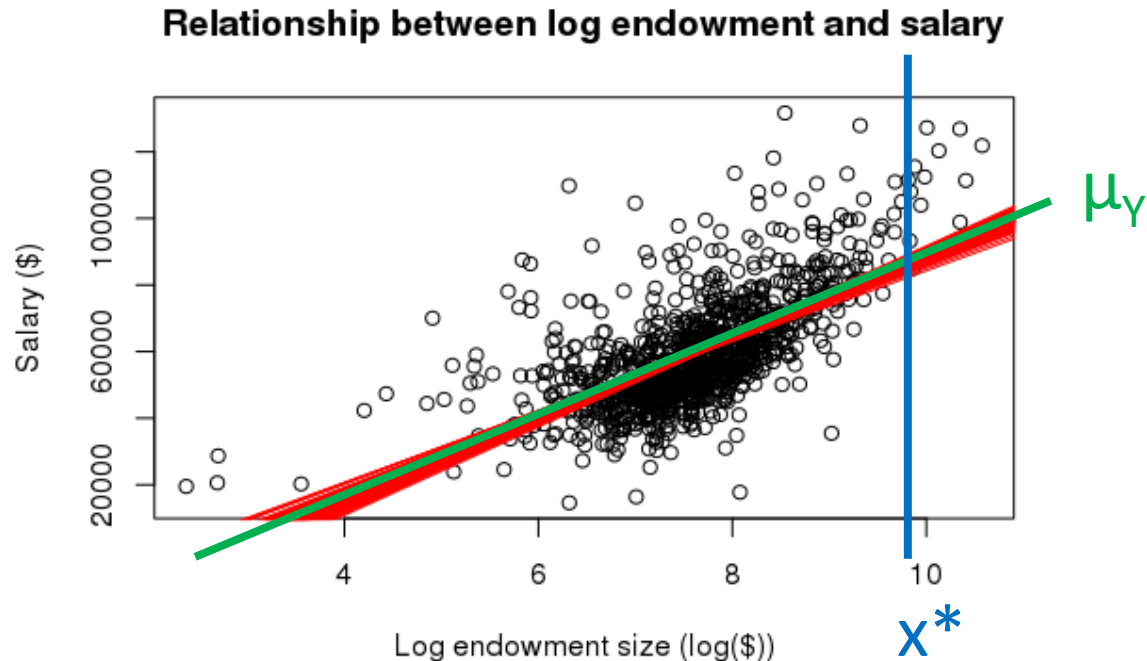
Confidence intervals for the regression line μ_Y

A confidence interval for the mean response for the **true regression line** μ_Y when $X = x^*$ is:

$$\hat{y} \pm t^* \cdot \hat{SE}_{\hat{\mu}}$$

where

$$\hat{SE}_{\hat{\mu}} = \hat{\sigma}_e \sqrt{\frac{1}{n} + \frac{(x^* - \bar{x})^2}{\sum_{i=1}^n (x_i - \bar{x})^2}}$$



Note:

- There is more uncertainty at the ends of the regression line
- The confidence interval for the regression line μ_Y is different than the confidence interval for slope β_1

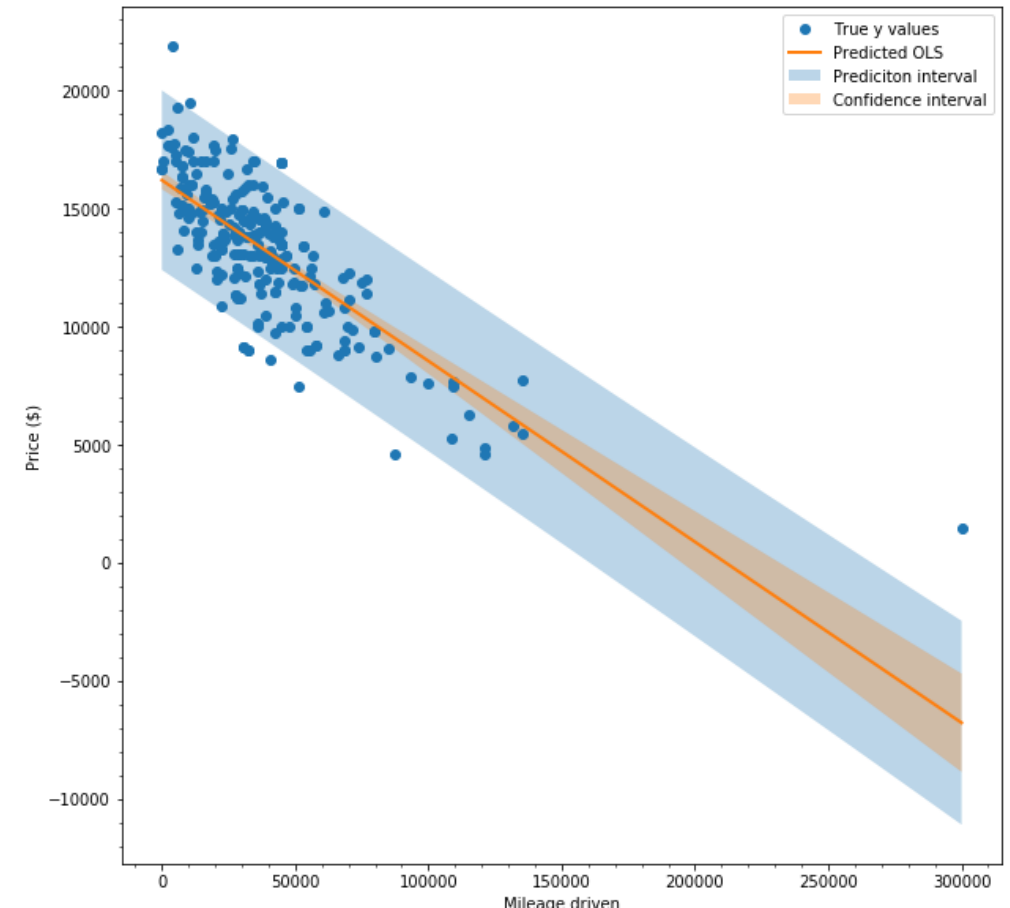
Prediction intervals

Confidence intervals give us a measure of uncertain about the true relationship between x and y for:

- The true regression slope β_1
- The true regression line μ_y

Prediction intervals give us a range of plausible values for y

- i.e., 95% of our y 's will be within this range



Prediction intervals

A **prediction intervals** for the y can be calculated using:

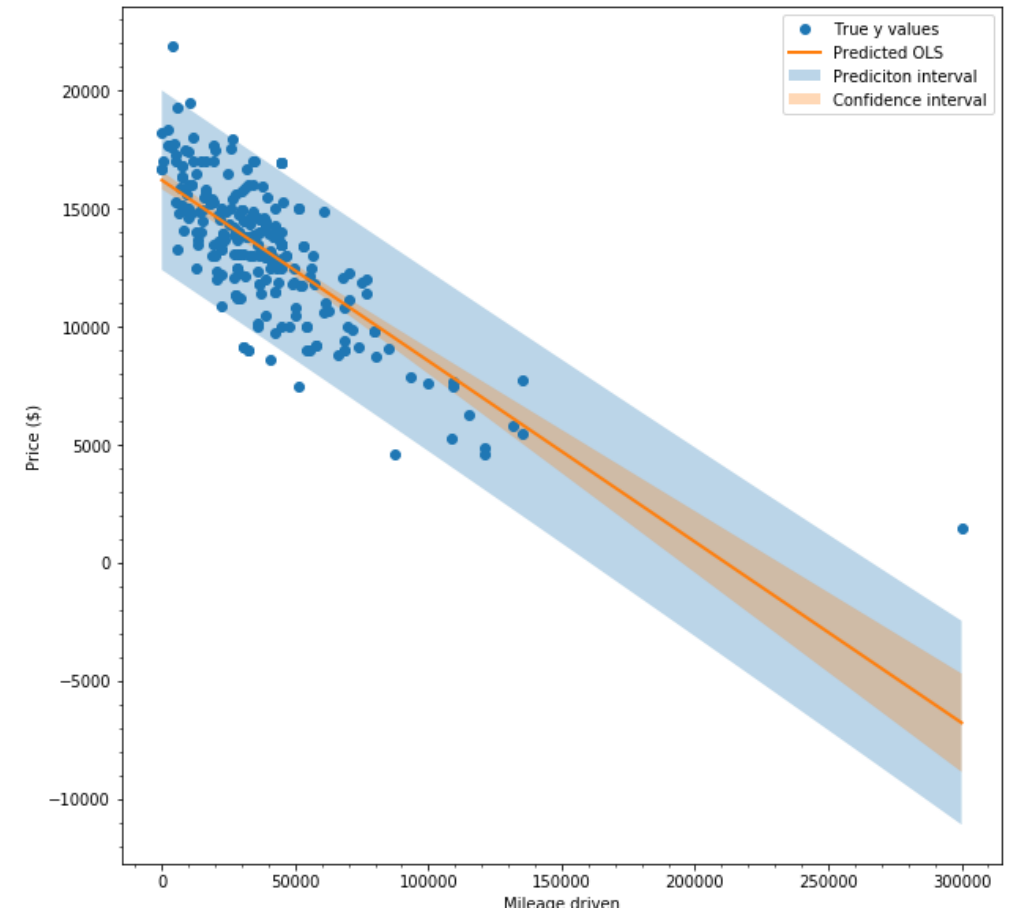
$$\hat{y} \pm t^* \cdot \hat{S}E_{\hat{y}}$$

where

$$\hat{S}E_{\hat{y}} = \hat{\sigma}_e \sqrt{1 + \frac{1}{n} + \frac{(x^* - \bar{x})^2}{\sum_{i=1}^n (x_i - \bar{x})^2}}$$

Due to y 's scattering
around the true
regression line

Due to uncertainty
in where the true
regression line is



Summary of confidence and prediction intervals

1. CI for Slope β

$$\hat{\beta}_1 \pm t^* \cdot \hat{SE}_{\hat{\beta}_1} \quad \hat{SE}_{\hat{\beta}_1} = \hat{\sigma}_e \sqrt{\frac{1}{\sum_{i=1}^n (x_i - \bar{x})^2}}$$

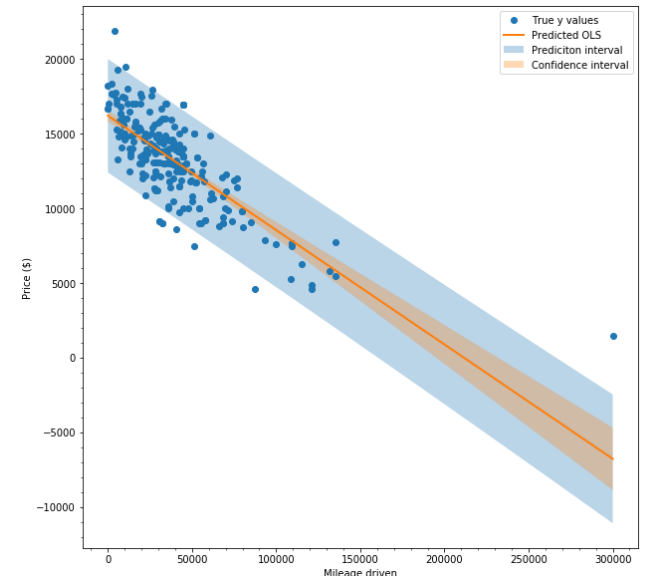


2. CI for regression line μ_y at point x^*

$$\hat{y} \pm t^* \cdot \hat{SE}_{\hat{\mu}} \quad \hat{SE}_{\hat{\mu}} = \hat{\sigma}_e \sqrt{\frac{1}{n} + \frac{(x^* - \bar{x})^2}{\sum_{i=1}^n (x_i - \bar{x})^2}}$$

3. Prediction interval y

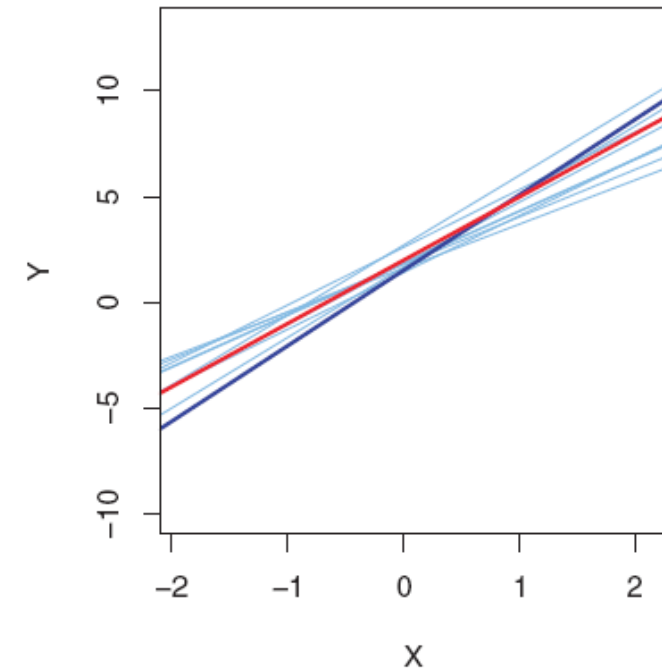
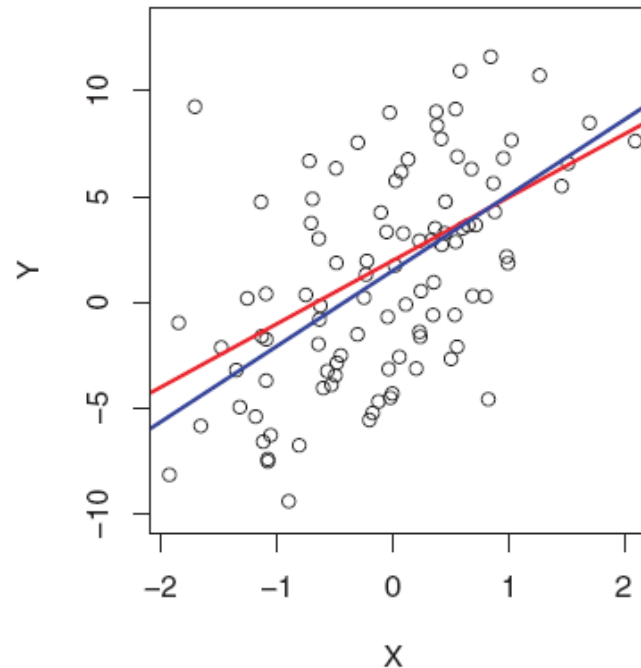
$$\hat{y} \pm t^* \cdot \hat{SE}_{\hat{y}} \quad \hat{SE}_{\hat{y}} = \hat{\sigma}_e \sqrt{1 + \frac{1}{n} + \frac{(x^* - \bar{x})^2}{\sum_{i=1}^n (x_i - \bar{x})^2}}$$



Resampling methods for inference in regression

We can also use resampling methods to estimate run hypothesis tests and create confidence intervals for the regression coefficients

- Bootstrap
- Permutation test



Let's look at inference for simple linear regression in R

More faculty salary data...