

1.4 Bootstrap CIs

We will look at five different ways to create confidence intervals using the bootstrap and discuss which to use when.

- 
- 1. Percentile Bootstrap CI
 - 2. Basic Bootstrap CI
 - 3. Standard Normal Bootstrap CI
 - 4. Bootstrap t (*studentized*)
 - 5. Accelerated Bias-Corrected (BCa)
"adjusted for skewness."

Key ideas:

- ① When you say "we used bootstrapping to estimate CI", you need to say which one.
- * ② Whatever you are bootstrapping needs to be independent.
- ③ Bootstrapping is an attempt to simulate replication.
(think about interpretation of a CI).

1.4.1 Percentile Bootstrap CI

Let $\hat{\theta}^{(1)}, \dots, \hat{\theta}^{(B)}$ be bootstrap replicates and let $\hat{\theta}_{\alpha/2}$ be the $\alpha/2$ quantile of $\hat{\theta}^{(1)}, \dots, \hat{\theta}^{(B)}$.

Then, the $100(1 - \alpha)\%$ Percentile Bootstrap CI for θ is

$$(\hat{\theta}_{\alpha/2}, \hat{\theta}_{1-\alpha/2})$$

In R, if `bootstrap.reps = c($\hat{\theta}^{(1)}, \dots, \hat{\theta}^{(B)}$)`, the percentile CI is
vector of Bootstrap replicates.

`quantile(bootstrap.reps, c(alpha/2, 1 - alpha/2))`

Assumptions/usage

- ① Widely used because simple to implement & explain.
- ② Use when little bias and skewness in bootstrap dsn.
- ③ Drawback: CI's usually too narrow! (coverage too low)
- ④ BCa intervals usually performs better (nominal coverage).

1.4.2 Basic Bootstrap CI (corrects for bias).

The $100(1 - \alpha)\%$ Basic Bootstrap CI for θ is

$$\left(\hat{\theta} - [\hat{\theta}_{1-\alpha/2} - \hat{\theta}], \hat{\theta} - [\hat{\theta}_{\alpha/2} - \hat{\theta}] \right)$$

↑ *estimate from original data set.*

1 - α/2 quantile of bootstrap dsn
recentering interval
based on $\hat{\theta}$.

$$\Rightarrow (\hat{2\theta} - \hat{\theta}_{1-\alpha/2}, \hat{2\theta} - \hat{\theta}_{\alpha/2}).$$

Assumptions/usage

- (1) Better than percentile bootstrap CI b/c corrects for bias
(does nothing for skewness).
- (2) Harder to explain.

1.4.3 Standard Normal Bootstrap CI

If our statistic is of the form that we have a CLT,

From the CLT,

$$\frac{\hat{\theta} - E(\hat{\theta})}{\text{se}(\hat{\theta})} \stackrel{\text{CLT}}{\sim} N(0, 1).$$

So, the $100(1 - \alpha)\%$ Standard Normal Bootstrap CI for θ is

$$\hat{\theta} \pm z_{1-\alpha/2} \underbrace{\text{se}(\hat{\theta})}_{\substack{\text{from bootstrap samples} \\ \text{sd(bootstrap samples)} = \text{sd}(\hat{\theta}^{(1)}, \dots, \hat{\theta}^{(B)})}}$$

Assumptions/usage

$$\textcircled{1} \quad \hat{\theta} \stackrel{\text{Normal}}{\sim} \left(E(\hat{\theta}), \text{se}(\hat{\theta})^2 \right) \leftarrow \begin{array}{l} \text{BIG assumption if} \\ \hat{\theta} \text{ is not a sample mean!} \end{array}$$

$$\textcircled{2} \quad \hat{\theta} \text{ is unbiased} \Rightarrow E\hat{\theta} = \theta \quad (\text{can use bias correction w/ this method too}) \rightarrow \text{see later code.}$$

$$\textcircled{3} \quad \text{typically requires large } n.$$

1.4.4 Bootstrap t CI (Studentized Bootstrap)

Even if the distribution of $\hat{\theta}$ is Normal and $\hat{\theta}$ is unbiased for θ , the Normal distribution is not exactly correct for z . (because we estimate $se(\hat{\theta})$).

$$t^* = \frac{\hat{\theta} - E(\hat{\theta})}{\hat{se}(\hat{\theta})} \sim t_{n-1}?$$

Additionally, the distribution of $\hat{se}(\hat{\theta})$ is unknown.

So we cannot claim $t^* \sim t_{n-1}$.

\Rightarrow The bootstrap t interval does not use a Student t distribution as the reference distribution, instead we estimate the distribution of a "t type" statistic by resampling.

studentized = centered and scaled.

The $100(1 - \alpha)\%$ Bootstrap t CI is

$$\left(\hat{\theta} - t_{1-\alpha/2}^* \cdot \hat{se}(\hat{\theta}), \hat{\theta} + t_{\alpha/2}^* \cdot \hat{se}(\hat{\theta}) \right).$$

from bootstrap, based on $\hat{\theta}^{(1)}, \dots, \hat{\theta}^{(B)}$

Overview

$$t\text{-type statistic: } t^{(1)} = \frac{\hat{\theta}^{(1)} - \hat{\theta}}{\hat{se}(\hat{\theta}^{(1)})}, \dots, t^{(B)} = \frac{\hat{\theta}^{(B)} - \hat{\theta}}{\hat{se}(\hat{\theta}^{(B)})}$$

To estimate the "t style distribution" for $\hat{\theta}$, bootstrap estimate of se of $\hat{\theta}$ based on 1st bootstrap sample.

1. Compute $\hat{\theta}$

2. for each replicate $b=1, \dots, B$

a) sample w/ replacement from \mathcal{X}

$$\mathcal{X}^{(b)} = (x_1^{(b)}, \dots, x_n^{(b)}).$$

b) Compute $\hat{\theta}^{(b)}$.

c) for each replicate $r=1, \dots, R$

i) sample w/ replacement from $\mathcal{X}^{(b)}$

$$\mathcal{X}^{(b)(r)} = (x_1^{(b)(r)}, \dots, x_n^{(b)(r)})$$

ii) $\hat{\theta}^{(b)(r)}$ based on $\mathcal{X}^{(b)(r)}$.

$$d) \text{ Compute } \hat{se}(\hat{\theta}^{(b)}) = \text{sd}(\hat{\theta}^{(b)(1)}, \dots, \hat{\theta}^{(b)(R)}).$$

DOUBLE BOOT STRAP! WAIT.

e) Compute "t-style" statistic

$$t^{(b)} = \frac{\hat{\theta}^{(b)} - \hat{\theta}}{\hat{se}(\hat{\theta}^{(b)})}.$$

3. get quantiles

$$t_{1-\alpha/2}^*, t_{\alpha/2}^*$$

4. compute CI.

Assumptions/usage

- * ① Requires small bias and skewness in bootstrap dsn.
- * ② Computationally intensive
- * ③ Need $\hat{\theta}$ independent $\hat{s.e}(\hat{\theta})$.

bias corrected accelerated

1.4.5 BCa CIs

Modified version of percentile intervals that adjusts for bias of estimator and skewness of the sampling distribution.

This method automatically selects a transformation so that the normality assumption holds.

Idea:

Assume there exists a monotonically increasing function g and constant a, b st.

$$U = \frac{g(\hat{\theta}) - g(\theta)}{1 + ag(\theta)} + b \sim N(0, 1).$$

where $1 + ag(\theta) > 0$.

The BCa method uses bootstrapping to estimate the bias and skewness then modifies which percentiles are chosen to get the appropriate confidence limits for a given data set.

In summary,

BCa is like the percentile bootstrap, but instead of $(\hat{\theta}_{\alpha/2}, \hat{\theta}_{1-\alpha/2})$.

BCa choose better quantiles ($\text{not } \alpha/2 \text{ & } 1-\alpha/2$) to account for both bias and skewness.

Assumptions / Usage :

- ① Better theoretical & practical performance than percentile method (better coverage).
- ② Harder to explain.

Your Turn

We will consider a telephone repair example from Hesterberg (2014). Verizon has repair times, with two groups, CLEC and ILEC, customers of the “Competitive” and “Incumbent” local exchange carrier.

Verizon is required by law to serve both at the same speed.

`library(resample) # package containing the data`

*↑
other
carriers
↑
Verizon
customers.*

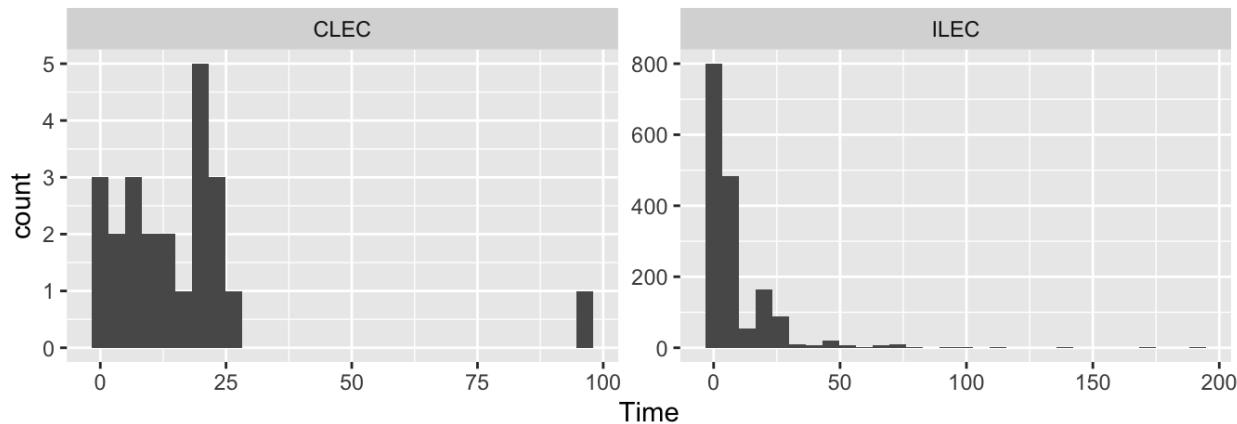
```
data(Verizon)
head(Verizon)
```

```
##      Time Group
## 1 17.50  ILEC
## 2  2.40  ILEC
## 3  0.00  ILEC
## 4  0.65  ILEC
## 5 22.23  ILEC
## 6  1.20  ILEC
```

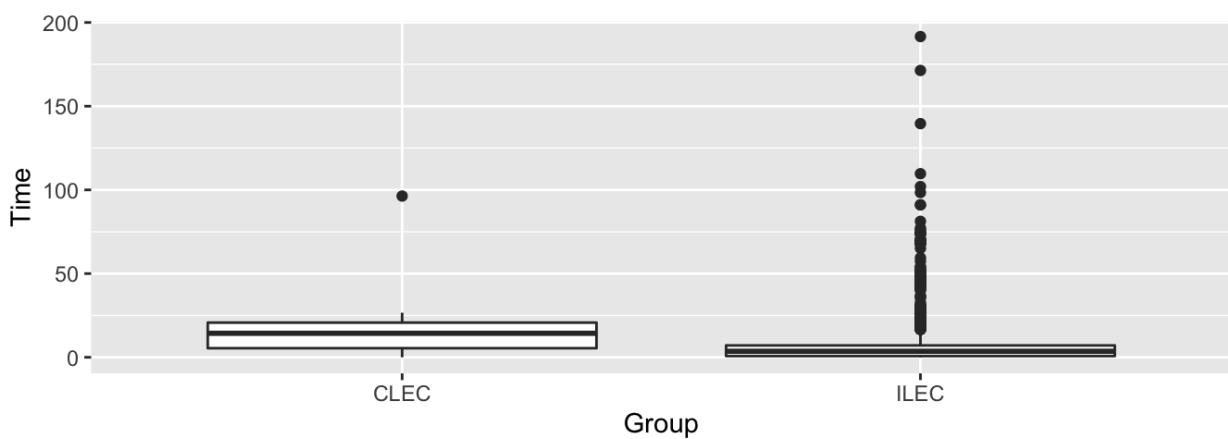
```
Verizon %>%
  group_by(Group) %>%
  summarize(mean = mean(Time), sd = sd(Time), min = min(Time), max =
max(Time)) %>%
  kable()
```

Group	mean	sd	min	max	n
CLEC	16.509130	19.50358	0	96.32	23
ILEC	8.411611	14.69004	0	191.60	164

```
ggplot(Verizon) +
  geom_histogram(aes(Time)) +
  facet_wrap(.~Group, scales = "free")
```



```
ggplot(Verizon) +
  geom_boxplot(aes(Group, Time))
```



1.5 Bootstrapping CIs

There are many bootstrapping packages in R, we will use the `boot` package. The function `boot` generates R resamples of the data and computes the desired statistic(s) for each sample. This function requires 3 arguments:

1. `data` = the data from the original sample (`data.frame` or `matrix`).
2. `statistic` = a function to compute the statistic from the data where the first argument is the `data` and the second argument is the indices of the observations in the bootstrap sample.
3. `R` = the number of bootstrap replicates.

*↑
our "B"*

```

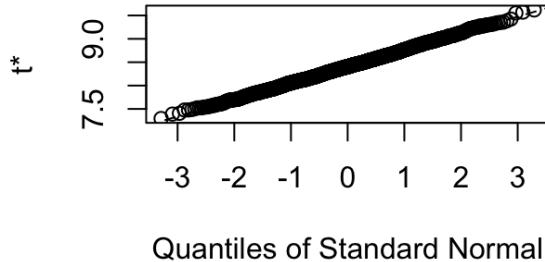
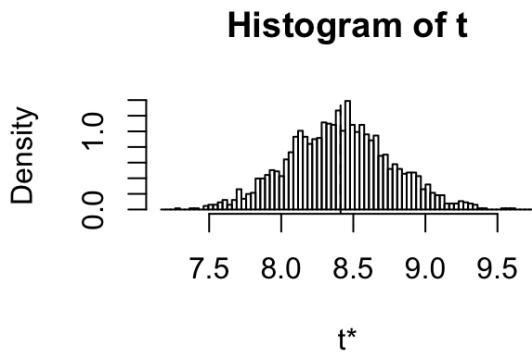
library(boot) # package containing the bootstrap function

mean_func <- function(x, idx) {
  mean(x[idx])
}

ilec_times <- Verizon[Verizon$Group == "ILEC", ]$Time
boot.ilec <- boot(ilec_times, mean_func, 2000)
plot(boot.ilec)

just Verizon customers.
bootstrap object.

```



If we want to get Bootstrap CIs, we can use the **boot.ci** function to generate the 5 different nonparametric bootstrap confidence intervals.

```

boot.ci(boot.ilec, conf = .95, type = c("perc", "basic", "norm",
  "bca"))

CI's

## BOOTSTRAP CONFIDENCE INTERVAL CALCULATIONS
## Based on 2000 bootstrap replicates
##
## CALL :
## boot.ci(boot.out = boot.ilec, conf = 0.95, type = c("perc", "basic",

```

```

##      "norm", "bca"))
##
## Intervals :
## Level      Normal          Basic
## 95%   ( 7.719,  9.114 )   ( 7.709,  9.119 )
##
## Level      Percentile      BCa
## 95%   ( 7.704,  9.114 )   ( 7.752,  9.164 )
## Calculations and Intervals on Original Scale

## we can do some of these on our own
## normal
mean(boot.ilec$t) + c(-1, 1)*qnorm(.975)*sd(boot.ilec$t)

$$\hat{\theta} = \text{mean}(\text{boot.ilec\$t}) + c(-1, 1) * qnorm(.975) * \text{sd}(\text{boot.ilec\$t})$$

## [1] 7.709670 9.104182

## in bart package, Normal bootstrap CI
## normal is bias corrected
2*mean(ilec_times) - (mean(boot.ilec$t) - c(-1,
1)*qnorm(.975)*sd(boot.ilec$t))

$$\hat{\theta} = 2 * \text{mean}(\text{ilec\_times}) - (\text{mean}(\text{boot.ilec\$t}) - c(-1, 1) * qnorm(.975) * \text{sd}(\text{boot.ilec\$t}))$$

## [1] 7.719039 9.113551

## percentile
quantile(boot.ilec$t, c(.025, .975))

##      2.5%    97.5%
## 7.707656 9.111150

## basic
2*mean(ilec_times) - quantile(boot.ilec$t, c(.975, .025))

$$\hat{\theta} = 2 * \text{mean}(\text{ilec\_times}) - \text{quantile}(\text{boot.ilec\$t}, c(.975, .025))$$

##      97.5%    2.5%
## 7.712071 9.115565

```

(not much bias).

very similar

To get the studentized bootstrap CI, we need our statistic function to also return the variance of $\hat{\theta}$.

```

mean_var_func <- function(x, idx) {
  c(mean(x[idx]), var(x[idx])/length(idx))
}
 $\hat{\theta} = \bar{X}$ 
 $\text{Var } \hat{\theta} = \text{Var } \bar{X} = \frac{\text{Var } X}{n}$ 
boot.ilec_2 <- boot(ilec_times, mean_var_func, 2000)
boot.ci(boot.ilec_2, conf = .95, type = "stud")

```

estimate w/
 bootstrap.
 ↙
 also look at
 simpleboot: one.boot

```

## BOOTSTRAP CONFIDENCE INTERVAL CALCULATIONS
## Based on 2000 bootstrap replicates
##
## CALL :
## boot.ci(boot.out = boot.ilec_2, conf = 0.95, type = "stud")
##
## Intervals :
## Level      Studentized
## 95%   ( 7.733,  9.231 )
## Calculations and Intervals on Original Scale
  
```

Which CI should we use?

All very similar, don't look very skewed or biased.

depends on what we are going to do w/ CI:

BCa default choice because shown to have good coverage.

If need to explain CI: may choose percentile or basic

$\hat{\theta} \sim \bar{X}^{\text{mean}}$
 n large \Rightarrow CLT \Rightarrow Normal CI not a bad choice either.

1.6 Bootstrapping for the difference of two means

Given iid draws of size n and m from two populations, to compare the means of the two groups using the bootstrap,

1. For replicates $b=1, \dots, B$

a) Draw a sample of size \underline{n} w/ replacement from sample 1 and separately of size \underline{m} from sample 2.

b) Compute a statistic that compares 2 groups (i.e. $\hat{\theta} = \bar{x}_1 - \bar{x}_2$)
 $\hookrightarrow \hat{\theta}^{(b)} = \bar{x}_1^{(b)} - \bar{x}_2^{(b)}$

2. Construct bootstrap distn of our statistic $\hat{\theta}^{(1)}, \dots, \hat{\theta}^{(B)}$ - inspect shape, bias, se.

3. Compute appropriate CI.

The function `two.boot` in the `simpleboot` package is used to bootstrap the difference between univariate statistics. Use the bootstrap to compute the shape, bias, and bootstrap sample error for the samples from the `Verizon` data set of CLEC and ILEC customers.

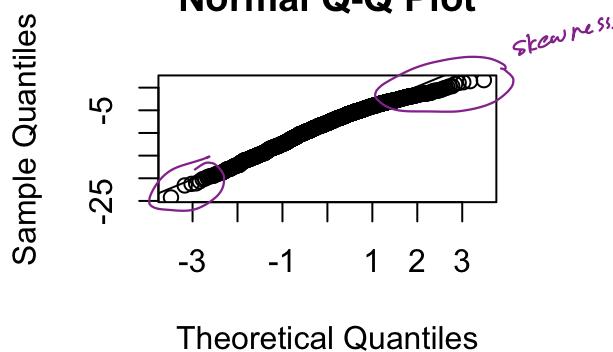
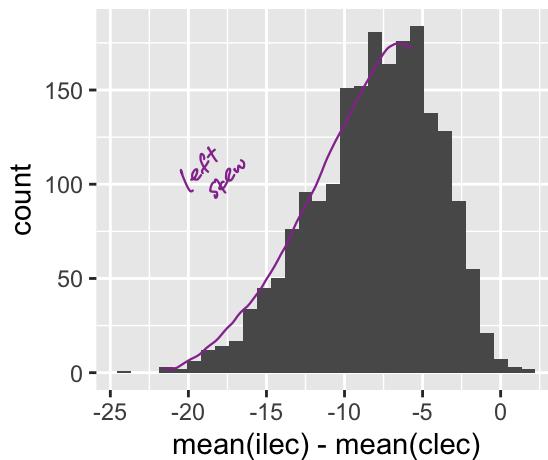
```
library(simpleboot)

clec_times <- Verizon[Verizon$Group == "CLEC", ]$Time

diff_means.boot <- two.boot(ilec_times, clec_times, "mean", R = 2000)
 $\curvearrowleft \hat{\theta}^{(1)}, \dots, \hat{\theta}^{(B)}$ 

ggplot() +
  geom_histogram(aes(diff_means.boot$t)) +
  xlab("mean(ilec) - mean(clec)")

qqnorm(diff_means.boot$t)
qqline(diff_means.boot$t)
```



Your turn: estimate the bias and se of the sampling distribution

Which confidence intervals should we use?

Your turn: get the chosen CI using boot.ci

Is there evidence that

$$\begin{aligned} H_0 &: \mu_1 - \mu_2 = 0 \\ H_a &: \mu_1 - \mu_2 < 0 \end{aligned}$$

is rejected?

Yes.

2 Parametric Bootstrap

In a **nonparametric bootstrap**, we resample the ^{observed} data.

Create a bootstrap sample y_1^*, \dots, y_n^* iid from the empirical distribution function \hat{F} .

This is equivalent to resampling the original data w/ replacement.

In a **parametric bootstrap**, we assume a parametric model (for the original data generation process).

Key idea: use a fitted parametric model $\hat{F}(y) = F(y|\hat{\psi})$ to estimate F where $\hat{\psi}$ estimated using MLE (or other method) from data.

Create a bootstrap sample y_1^*, \dots, y_n^* iid from $F(y|\hat{\psi})$, i.e. resample from a model w/ parameters estimated using original data.

For both methods,

① We compute the statistic $\hat{\theta}^{*(b)}$ for each bootstrap sample $y_1^{*(b)}, \dots, y_n^{*(b)}$

② Repeat the procedure B times to get

$$\hat{\theta}^{*(1)}, \dots, \hat{\theta}^{*(B)}$$

and make inferences using the results.

2.1 Bootstrapping for linear regression

Consider the regression model $Y_i = \mathbf{x}_i^T \boldsymbol{\beta} + \epsilon_i, i = 1, \dots, n$ with $\epsilon_i \stackrel{iid}{\sim} N(0, \sigma^2)$.

$Y_i \stackrel{ind}{\sim} N(\mathbf{x}_i^T \boldsymbol{\beta}, \sigma^2)$ NOT iid! They have different conditional means.

Resampling in the bootstrap must be done on iid quantities.

Two approaches for bootstrapping linear regression models –

1. Bootstrapping the residuals (model based resampling) – parametric
2. Paired bootstrapping (case resampling) – nonparametric

2.1.1 Bootstrapping the residuals

1. Fit the regression model using the original data

2. Compute the residuals from the regression model,

$$\hat{\epsilon}_i = y_i - \hat{y}_i = y_i - \mathbf{x}_i^T \hat{\boldsymbol{\beta}}, \quad i = 1, \dots, n$$

residuals $\hat{\epsilon}_i$ are assumed iid!

3. Sample $\hat{\epsilon}_1^*, \dots, \hat{\epsilon}_n^*$ with replacement from $\hat{\epsilon}_1, \dots, \hat{\epsilon}_n$.

4. Create the bootstrap sample

$$y_i^* = \underbrace{\mathbf{x}_i^T \hat{\boldsymbol{\beta}}}_{\text{fixed values based on the model/data.}} + \underbrace{\hat{\epsilon}_i^*}_{\text{bootstrapped residuals.}}, \quad i = 1, \dots, n$$

5. Estimate $\hat{\boldsymbol{\beta}}^*$ use $(\Xi_i, y_i^*)_{i=1, \dots, n}$ to fit new regression model (get $\hat{\boldsymbol{\beta}}^*$).

6. Repeat steps 2-4 B times to create B bootstrap estimates of $\hat{\boldsymbol{\beta}}$.

Assumptions:

$$\hat{\boldsymbol{\beta}}^{*(1)}, \dots, \hat{\boldsymbol{\beta}}^{*(B)}$$

The design matrix $X = (x_1, \dots, x_n)$ is fixed.

ϵ_i are iid

2.1.2 Paired bootstrapping (case resampling).

Resample $z_i^* = (y_i, \mathbf{x}_i)^*$ from the empirical distribution of the pairs (y_i, \mathbf{x}_i) .

fit regression model w/ n boot strapped $(y_i, \mathbf{x}_i)^*$ pairs.

$$y_i^* = (\mathbf{x}_i^*)^\top \beta + \varepsilon_i \quad i=1, \dots, n.$$

Assumptions:

- Assumes (y_i, \mathbf{x}_i) are iid from population

Can have varying design matrix \mathbf{X} .

2.1.3 Which to use?

1. Standard inferences - (i.e. from STAT 341).

Most of the time!

2. Bootstrapping the residuals -

- most appropriate for designed experiments where X_i are fixed in advance.
- model based (regression model must be valid for the data).
- often useful if complex sampling dsn for $\hat{\beta}$.

3. Paired bootstrapping -

- robust to model misspecification (if we have doubts about adequacy of regression model, e.g. heteroscedasticity).
- useful for observational studies where values of predictors aren't fixed in advance \Rightarrow bootstrap mirror data generating mechanism.

Your Turn

This data set is the Puromycin data in R. The goal is to create a regression model about the rate of an enzymatic reaction as a function of the substrate concentration.

```
head(Puromycin)
```

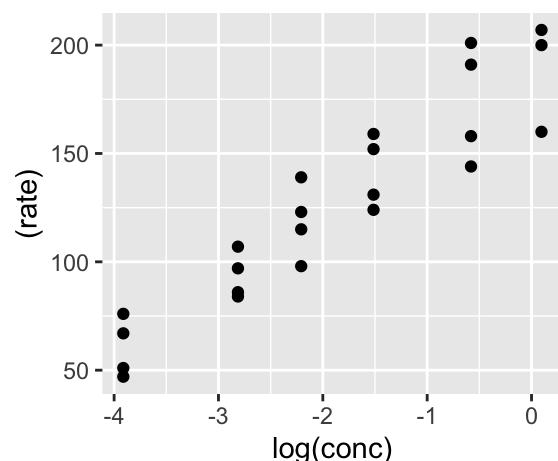
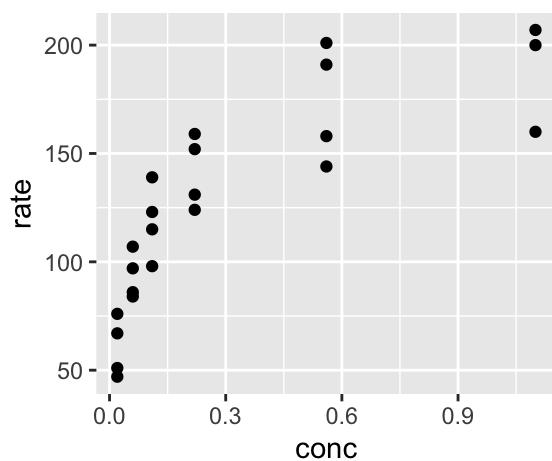
```
##   conc  rate state
## 1 0.02    76 treated
## 2 0.02    47 treated
## 3 0.06    97 treated
## 4 0.06   107 treated
## 5 0.11   123 treated
## 6 0.11   139 treated
```

```
dim(Puromycin)
```

```
## [1] 23  3
```

```
ggplot(Puromycin) +
  geom_point(aes(conc, rate))
```

```
ggplot(Puromycin) +
  geom_point(aes(log(conc), (rate)))
```



2.1.4 Standard regression

```
m0 <- lm(rate ~ conc, data = Puromycin)
plot(m0)
summary(m0)

##
## Call:
## lm(formula = rate ~ conc, data = Puromycin)
##
## Residuals:
##     Min      1Q  Median      3Q     Max 
## -49.861 -15.247  -2.861   15.686   48.054 
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)    
## (Intercept)  93.92      8.00   11.74 1.09e-10 ***
## conc        105.40     16.92    6.23 3.53e-06 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 28.82 on 21 degrees of freedom
## Multiple R-squared:  0.6489, Adjusted R-squared:  0.6322 
## F-statistic: 38.81 on 1 and 21 DF,  p-value: 3.526e-06

confint(m0)

##
##              2.5 %    97.5 %
## (Intercept) 77.28643 110.5607
## conc        70.21281 140.5832

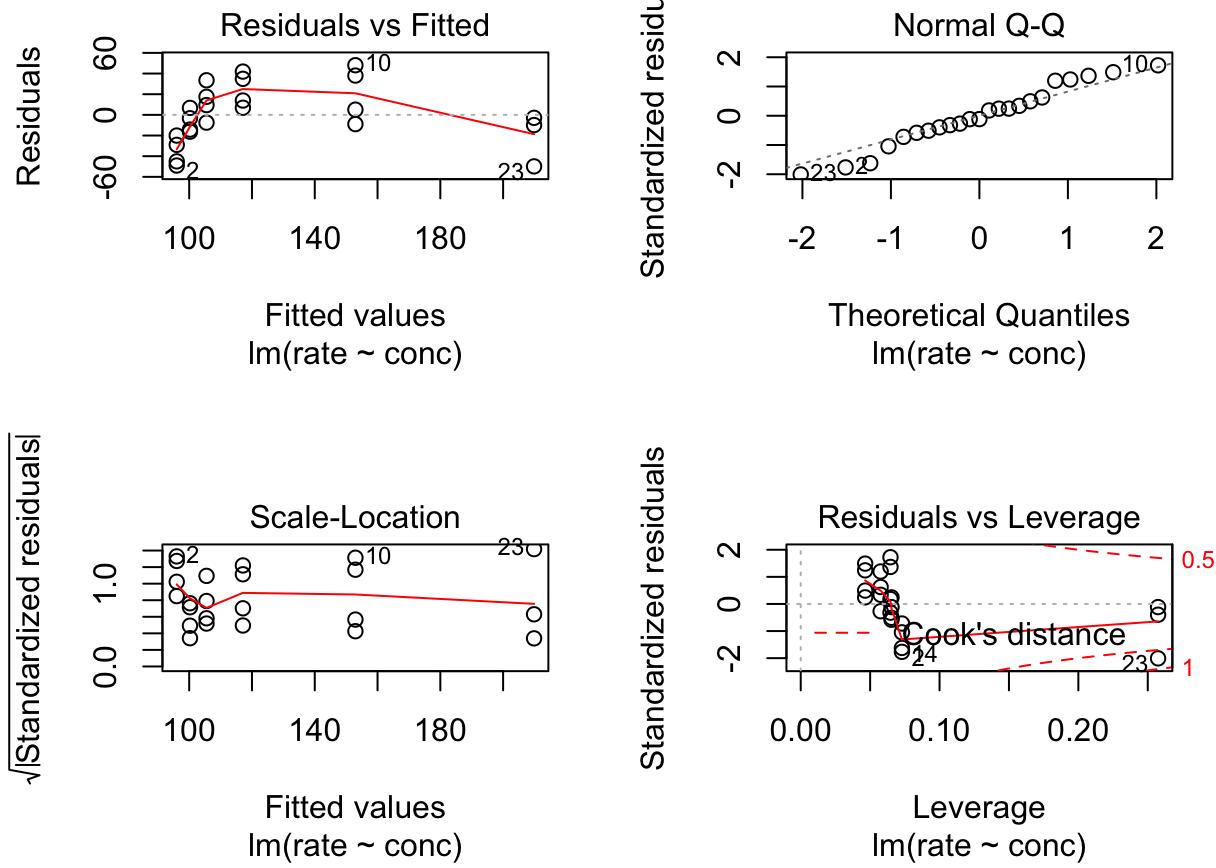
m1 <- lm(rate ~ log(conc), data = Puromycin)
plot(m1)
summary(m1)

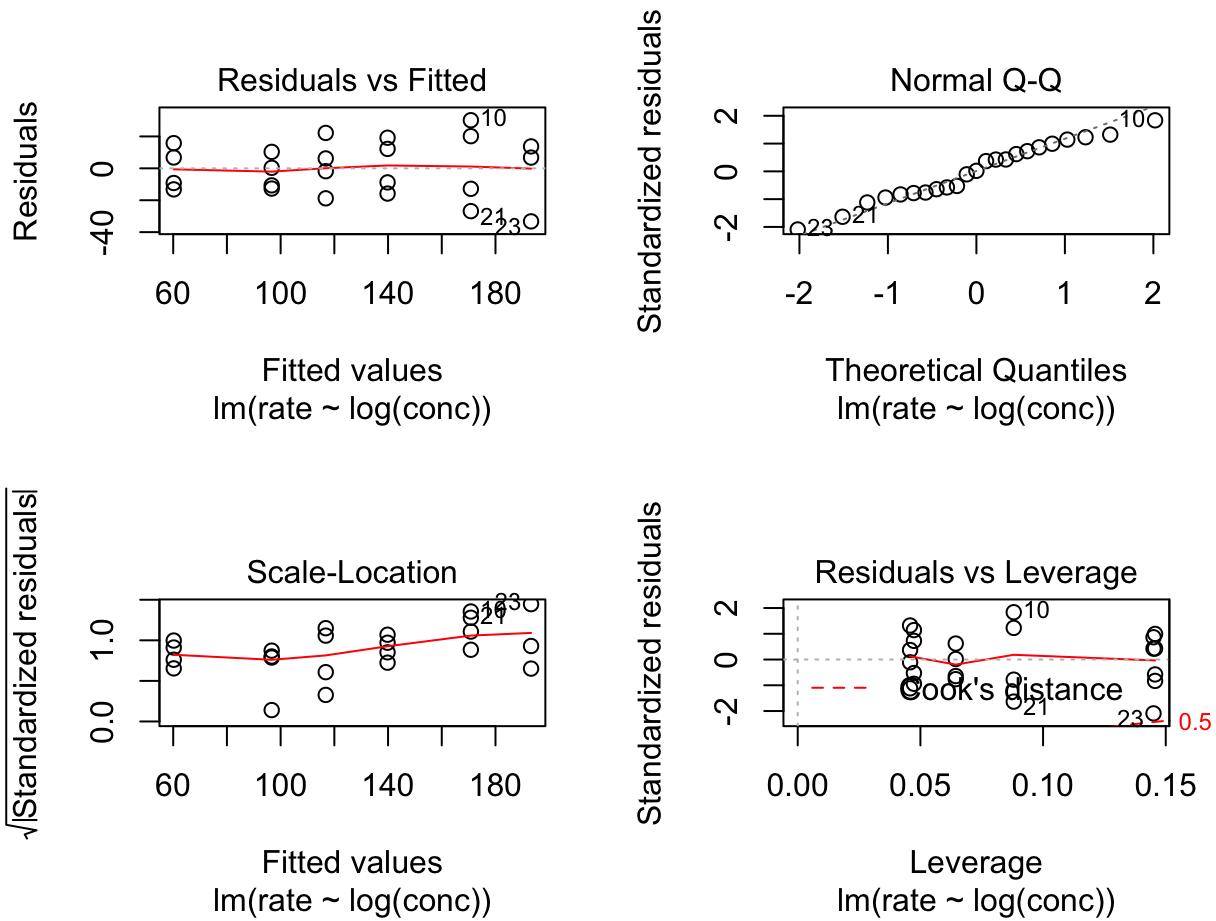
##
## Call:
## lm(formula = rate ~ log(conc), data = Puromycin)
##
```

```
## Residuals:  
##      Min     1Q Median     3Q    Max  
## -33.250 -12.753   0.327 12.969 30.166  
##  
## Coefficients:  
##             Estimate Std. Error t value Pr(>|t|)  
## (Intercept) 190.085     6.332   30.02 < 2e-16 ***  
## log(conc)    33.203     2.739   12.12 6.04e-11 ***  
## ---  
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1  
##  
## Residual standard error: 17.2 on 21 degrees of freedom  
## Multiple R-squared:  0.875, Adjusted R-squared:  0.869  
## F-statistic: 146.9 on 1 and 21 DF, p-value: 6.039e-11
```

```
confint(m1)
```

```
##                 2.5 %    97.5 %  
## (Intercept) 176.91810 203.2527  
## log(conc)    27.50665 38.8987
```





2.1.5 Paired bootstrap

```
# Your turn
library(boot)

reg_func <- function(dat, idx) {
  # write a regression function that returns fitted beta
}

# use the boot function to get the bootstrap samples

# examining the bootstrap sampling distribution, make histograms

# get confidence intervals for beta_0 and beta_1 using boot.ci
```

2.1.6 Bootstrapping the residuals

```
# Your turn
library(boot)

reg_func_2 <- function(dat, idx) {
  # write a regression function that returns fitted beta
  # from fitting a y that is created from the residuals

}

# use the boot function to get the bootstrap samples

# examing the bootstrap sampling distribution, make histograms

# get confidence intervals for beta_0 and beta_1 using boot.ci
```