# Resampling Magic

BERDC Special Topics Talk 18

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DAKOTA COMMUNITY COLLABORATIVE ON TRANSLATIONAL ACTIVITY

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**Biostatistics, Epidemiology, and Research Design Core**

# Introduction

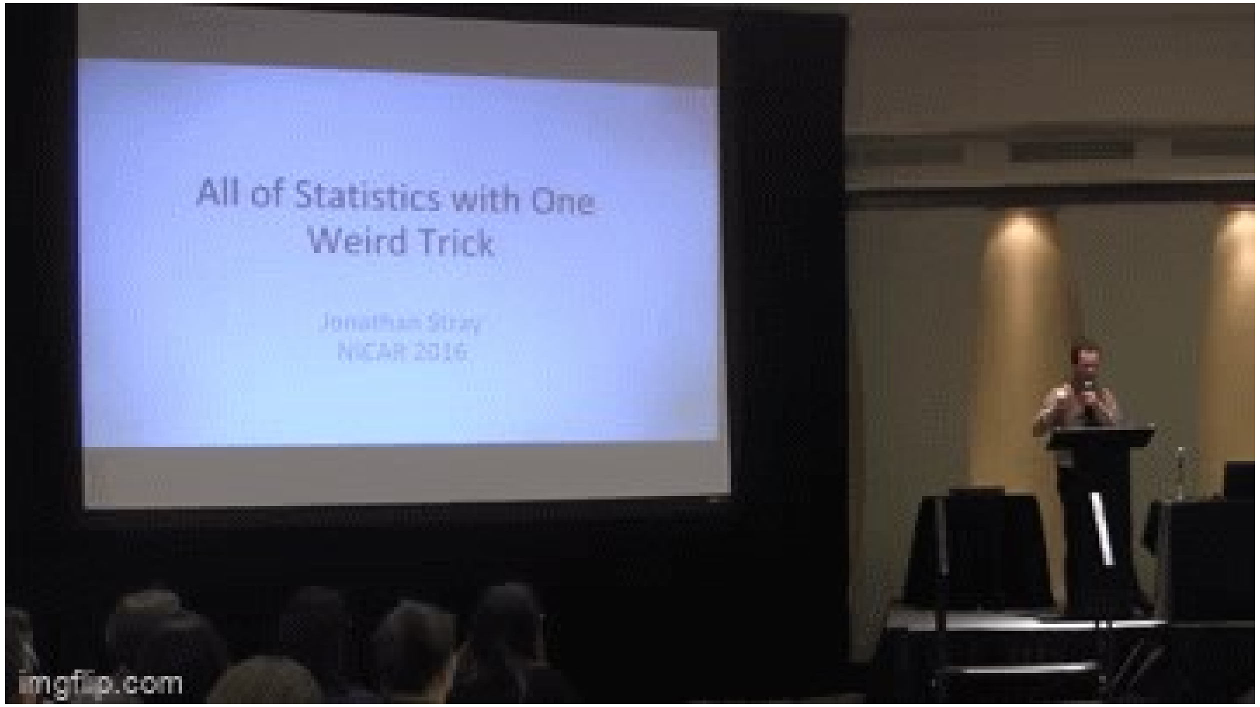
**Goal**: Spell out the benefits and methods of resampling

- What is resampling?
- What are the major types?
- What can resampling be used for?
- How does resampling work?
- Worked examples

# Interlude

**Solve Every Statistics Problem with One Weird Trick [1]**

- Resampling and Visualization
- Monte Carlo
- Confidence Intervals
- Significance Testing
- Error Detection
- And Beyond



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# The What

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- **Resample Definition:**

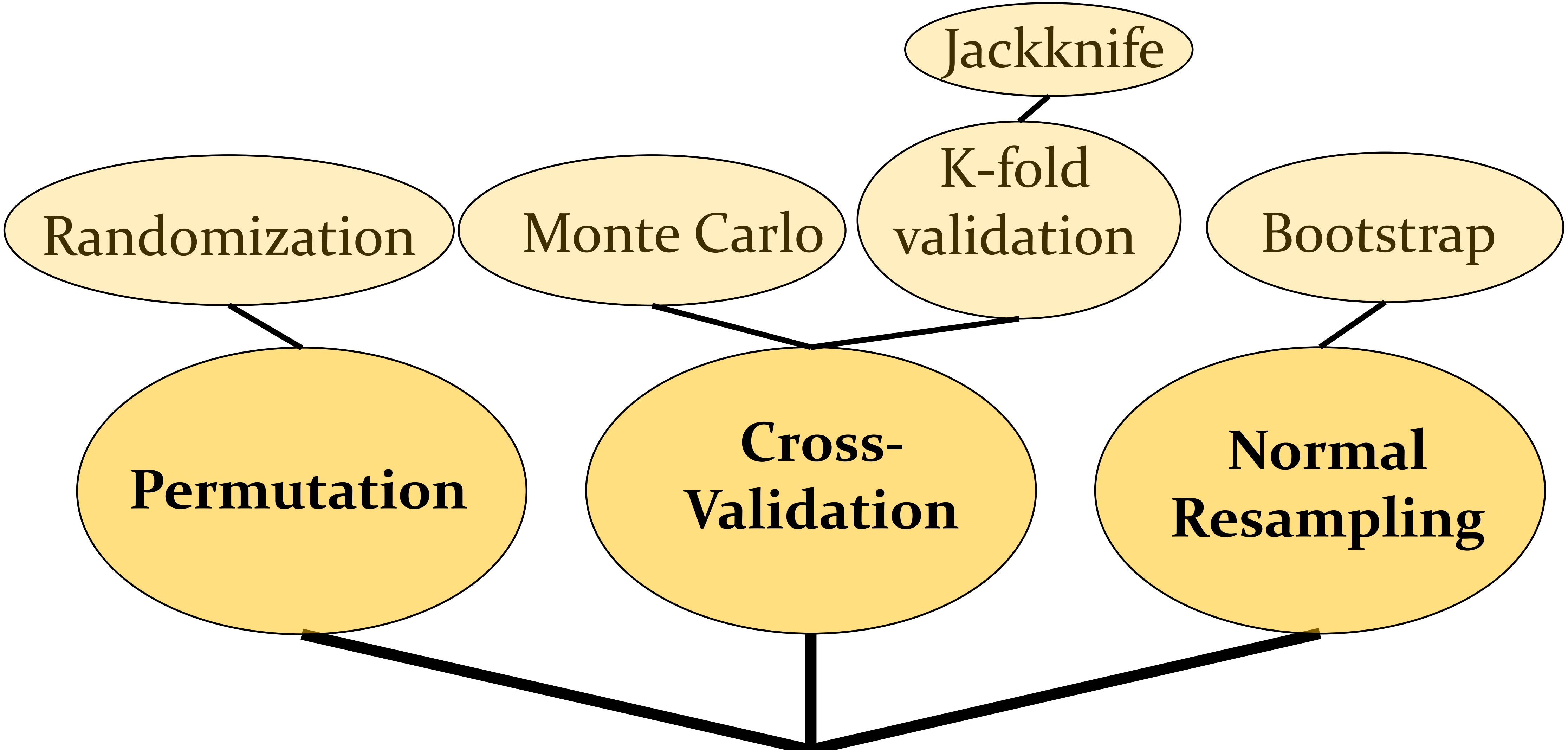
  *"Creation of new samples based on one observed sample."*

  -Wikipedia [2]

  *"Series of techniques used in statistics to gather more information about a sample. This can include retaking a sample or estimating its accuracy."*

  -Indeed [3]

# The Types [4-7]


Jackknife
Randomization
Monte Carlo
K-fold validation
Bootstrap
Permutation
Cross-Validation
Normal Resampling

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# The Uses

- Null Hypothesis significance testing (permutation)
- Accuracy, confidence intervals (bootstrap)
- Sampling distribution of test statistic (bootstrap)
- Validating a predictive model (jackknife, Monte Carlo, etc.)

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# The How

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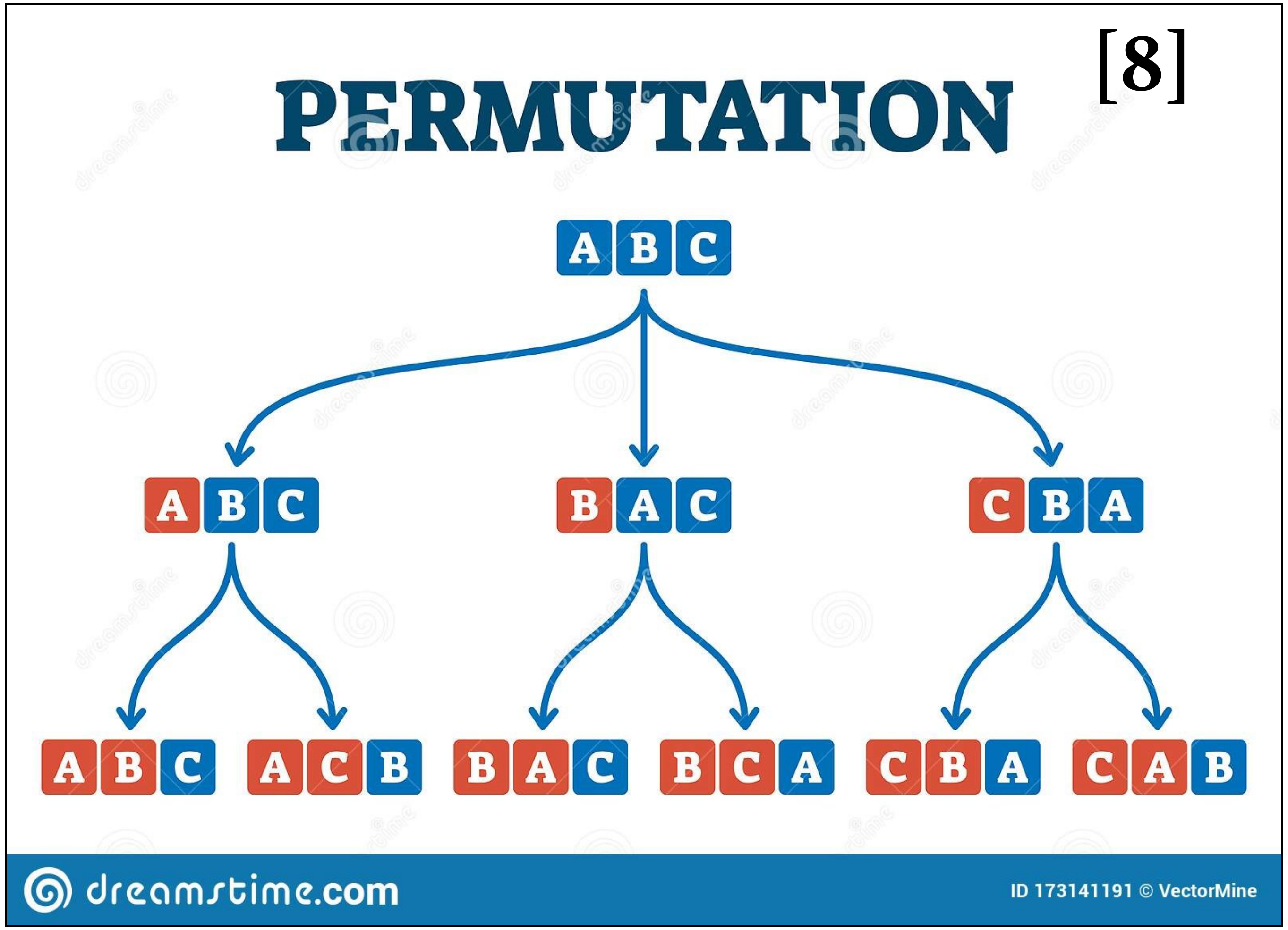
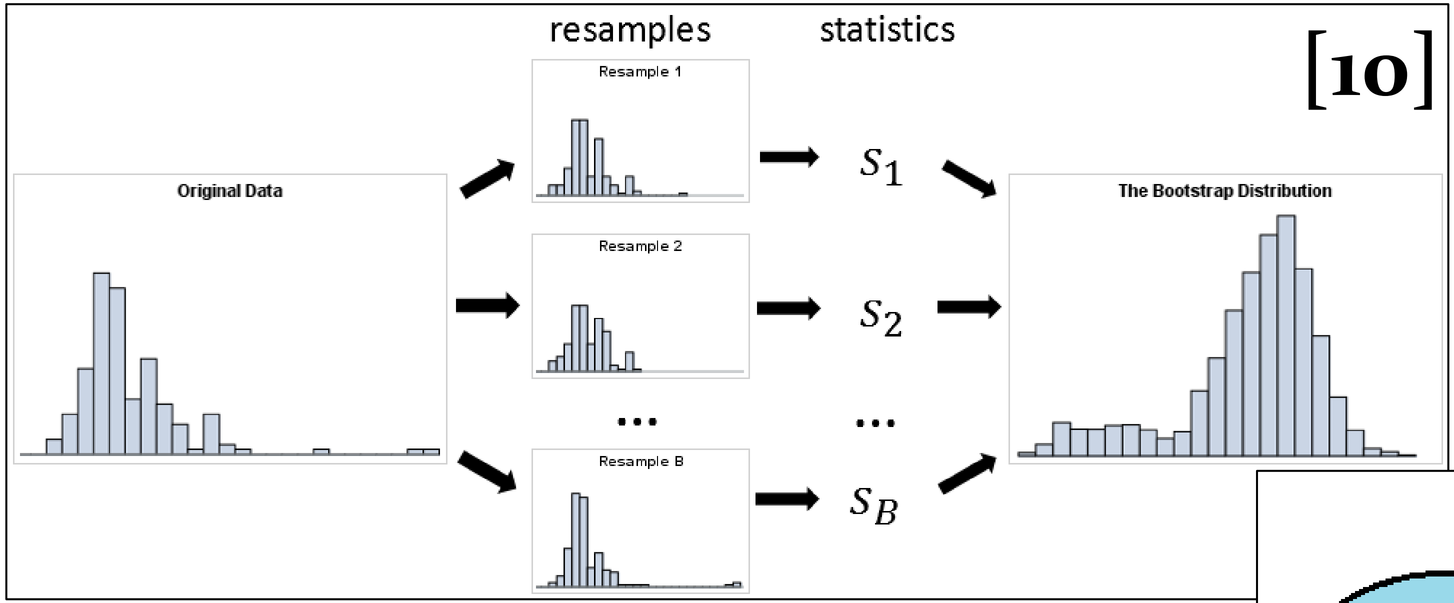
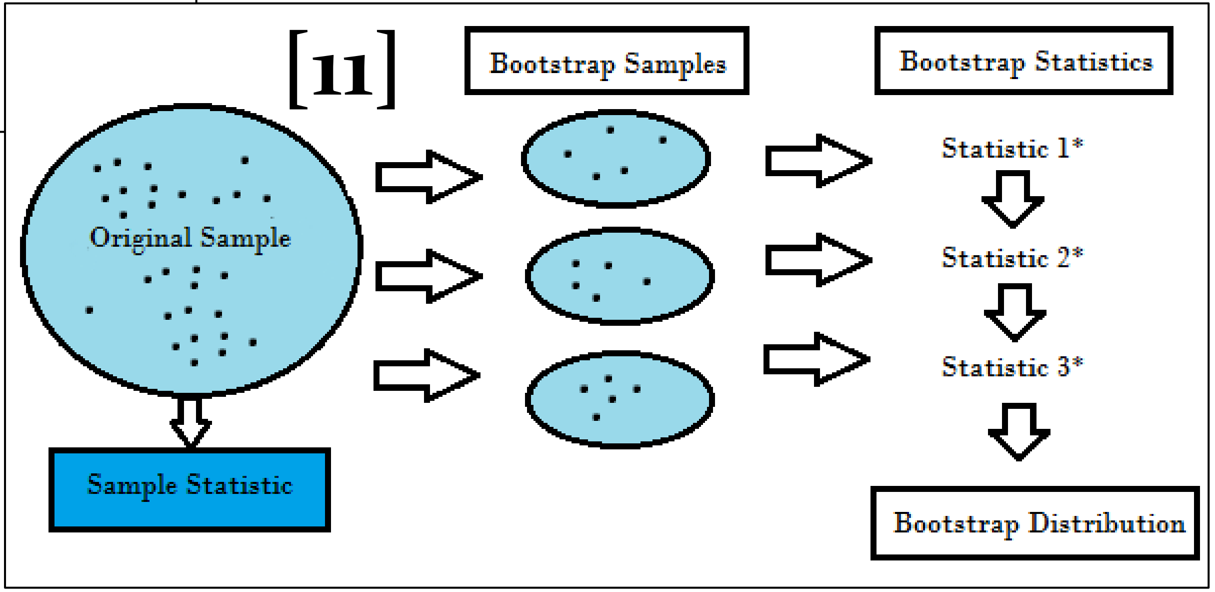
- Mostly done by computers
- R, SAS, Python, etc.
- Need dataset and objective



# The How [9]

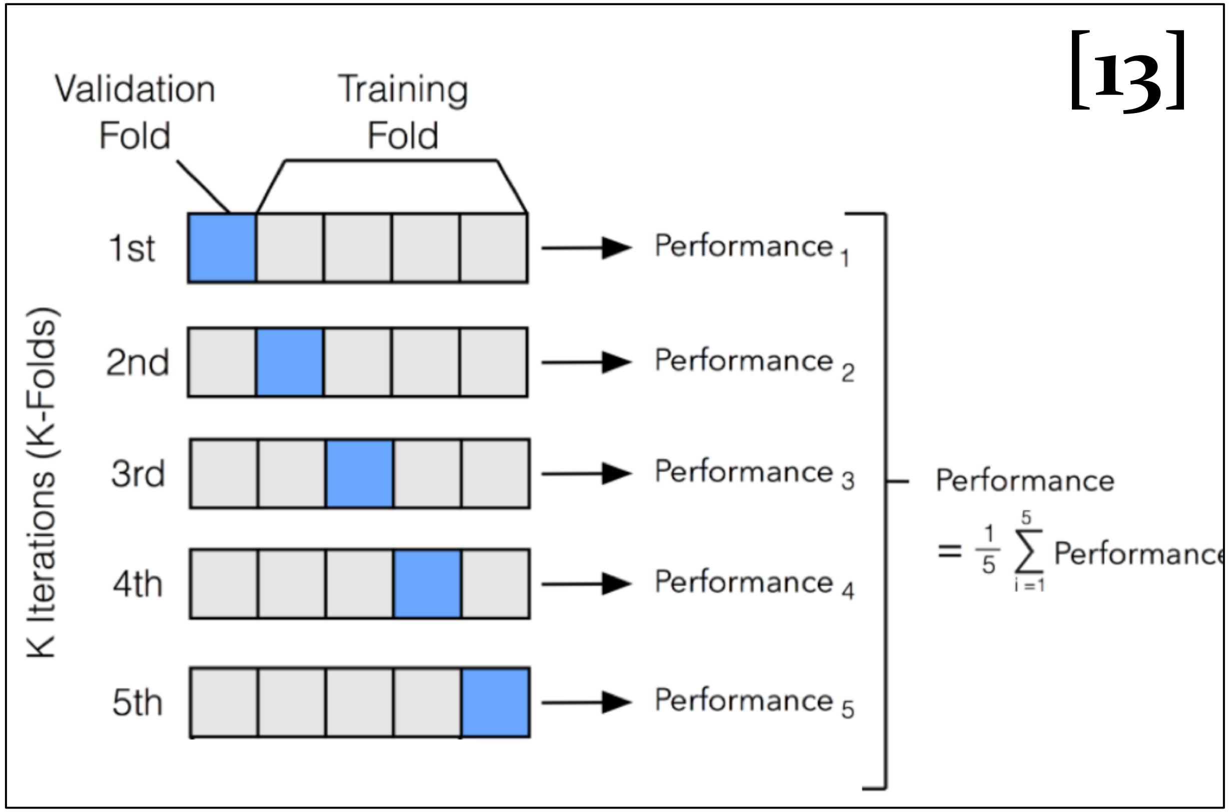


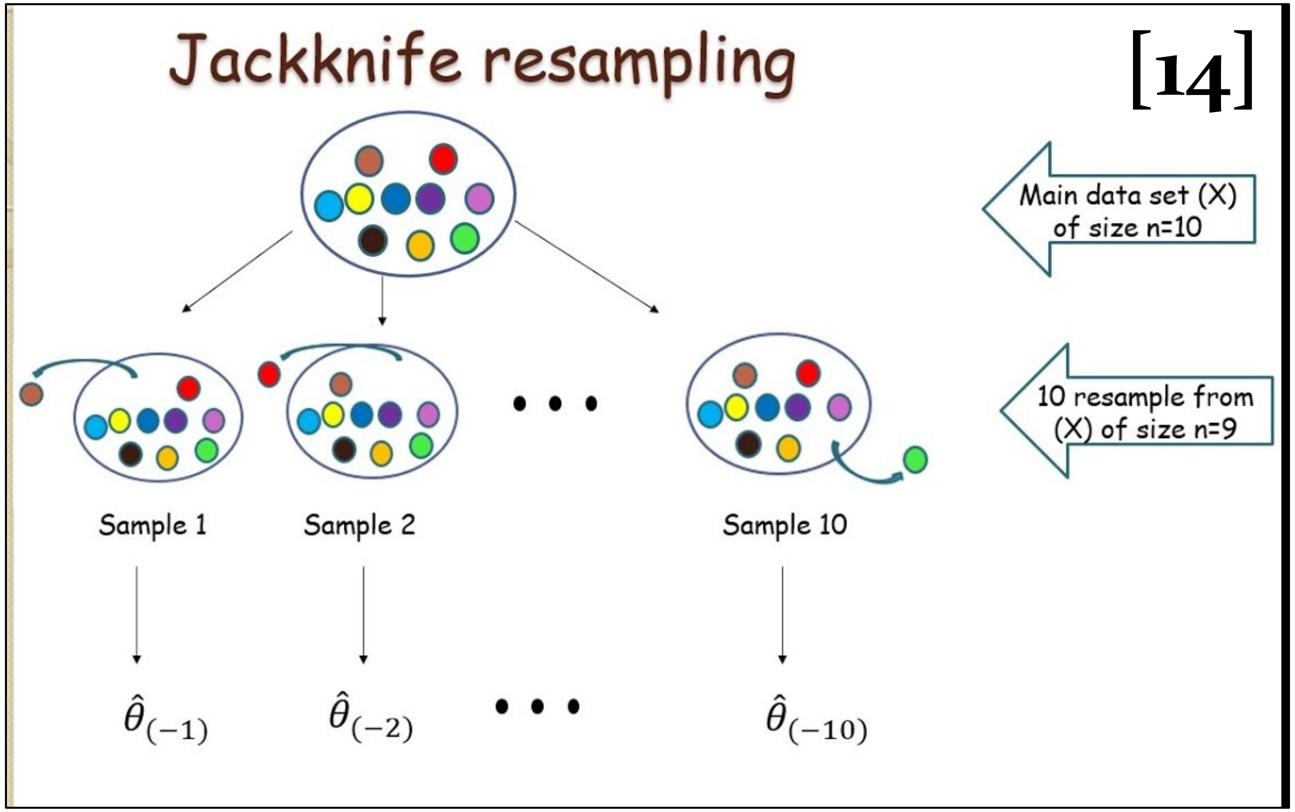
resamples
statistics
[10]
Resample 1
Original Data
Resample 2
The Bootstrap Distribution
Resample B
$s_1$
$s_2$
$s_B$

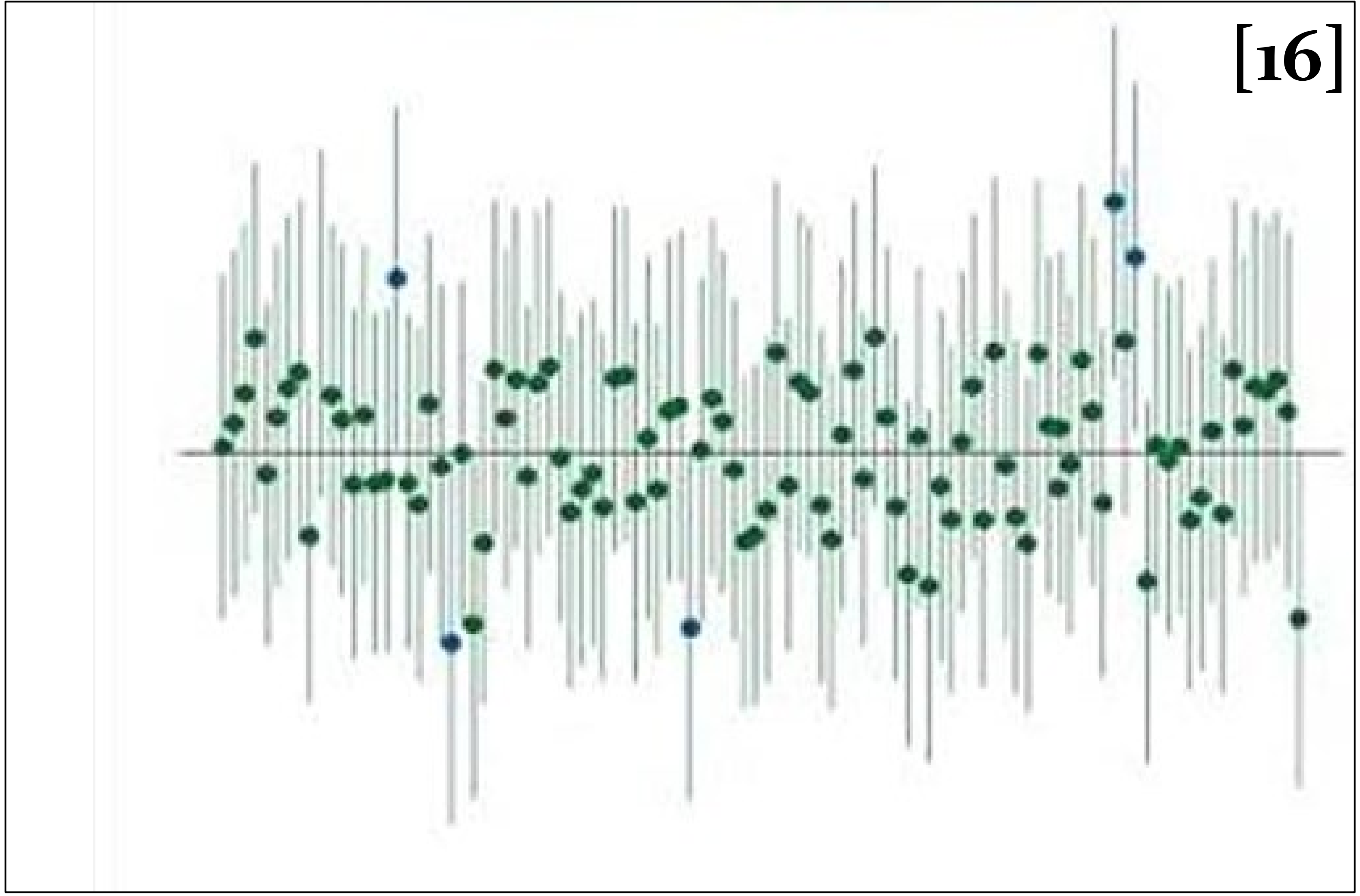
[11]
Bootstrap Samples
Bootstrap Statistics
Original Sample
Statistic 1*
Statistic 2*
Statistic 3*
Sample Statistic
Bootstrap Distribution

# The How [12]


[13]
Validation Fold
Training Fold
1st
2nd
3rd
4th
5th
K Iterations (K-Folds)
Performance 1
Performance 2
Performance 3
Performance 4
Performance 5
Performance
$= \frac{1}{5} \sum_{i=1}^{5}$ Performance


Jackknife resampling
[14]
Main data set (X) of size n=10
10 resample from (X) of size n=9
Sample 1
Sample 2
Sample 10
$\hat{\theta}_{(-1)}$
$\hat{\theta}_{(-2)}$
$\hat{\theta}_{(-10)}$

# The How [15]


[16]

# Examples

## Dataset

Magic the Gather Playing card data [17]

```
> head(magic)
```

| Name | Colors | Set Code | Mana Cost | Power | Toughness | Types |
|---|---|---|---|---|---|---|
| Ancestor's Chosen | W | 10 | 7 | 4 | 4 | Creature |
| Angel of Mercy | W | 10 | 5 | 3 | 3 | Creature |
| Angelic Blessing | W | 10 | 3 | NA | NA | Sorcery |
| Angelic Wall | W | 10 | 2 | 0 | 4 | Creature |
| Aven Cloudchaser | W | 10 | 4 | 2 | 2 | Creature |
| Benalish Knight | W | 10 | 3 | 2 | 2 | Creature |
| … | … | … | … | … | … | … |

```r
#Resampling Magic R-code:

#References:
  #   https://rcompanion.org/handbook/K_01.html
  #   https://www.statology.org/bootstrap-standard-error-in-r/
  #   https://stackoverflow.com/questions/58393608/bootstrapped-correlation-in-r
  #   https://www.statology.org/k-fold-cross-validation-in-r/
  #   #https://search.r-project.org/CRAN/refmans/pls/html/jack.test.html

#Get data and packages
library(lmPerm)
library(dplyr)
library(ggplot2)
library(boot)
library(caret)
library(pls)


  #magic cards:
setwd("C:/Users/Mark.Williamson.2/OneDrive - North Dakota University System/Desktop/Williamson Data/Magic")
magic<-read.csv("cards_condensed_10E_clean.csv")
head(magic)

boxplot(magic$convertedManaCost~magic$colors, col=c("grey", "green", "red", "blue", "white"))

boxplot(magic$convertedManaCost[magic$types=="Creature"]~magic$colors[magic$types=="Creature"],
        col=c("grey", "green", "red", "blue", "white"))

boxplot(magic$toughness[magic$types=="Creature"]~magic$colors[magic$types=="Creature"],
        col=c("grey", "green", "red", "blue", "white"))

boxplot(magic$power[magic$types=="Creature"]~magic$colors[magic$types=="Creature"],
        col=c("grey", "green", "red", "blue", "white"))

creatures <-magic[magic$types=="Creature",]
```

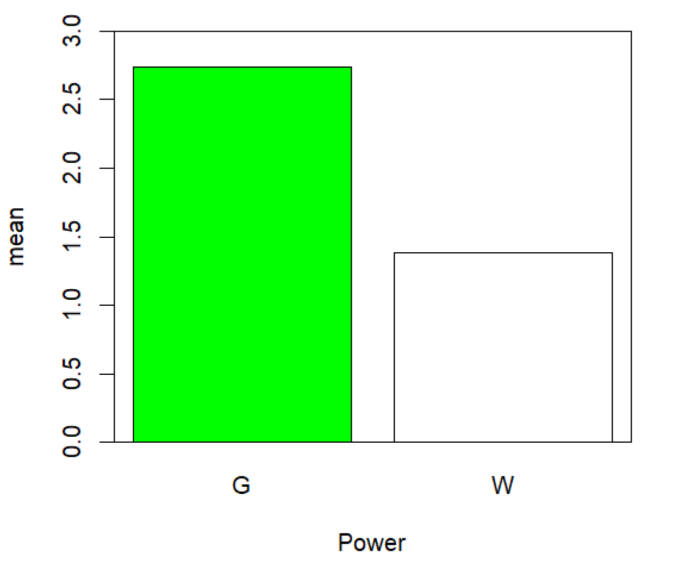
```
par(mfrow=c(2,3))
hist(creatures$convertedManaCost[creatures$colors=="R"], col="red", main="Mana Cost", xlab="Cost")
hist(creatures$convertedManaCost[creatures$colors=="U"], col="blue", main="", xlab="Cost")
hist(creatures$convertedManaCost[creatures$colors=="B"], col="grey", main="", xlab="Cost")
hist(creatures$convertedManaCost[creatures$colors=="W"], col="white", main="", xlab="Cost")
hist(creatures$convertedManaCost[creatures$colors=="G"], col="green", main="", xlab="Cost")
par(mfrow=c(1,1))

par(mfrow=c(2,3))
hist(creatures$power[creatures$colors=="R"], col="red", main="Power", xlab="Power")
hist(creatures$power[creatures$colors=="U"], col="blue", main="", xlab="Power")
hist(creatures$power[creatures$colors=="B"], col="grey", main="", xlab="Power")
hist(creatures$power[creatures$colors=="W"], col="white", main="", xlab="Power")
hist(creatures$power[creatures$colors=="G"], col="green", main="", xlab="Power")
par(mfrow=c(1,1))

par(mfrow=c(2,3))
hist(creatures$toughness[creatures$colors=="R"], col="red", main="Toughness", xlab="Toughness")
hist(creatures$toughness[creatures$colors=="U"], col="blue", main="", xlab="Toughness")
hist(creatures$toughness[creatures$colors=="B"], col="grey", main="", xlab="Toughness")
hist(creatures$toughness[creatures$colors=="W"], col="white", main="", xlab="Toughness")
hist(creatures$toughness[creatures$colors=="G"], col="green", main="", xlab="Toughness")
par(mfrow=c(1,1))

creatures %>%
  group_by(colors) %>%
  summarize(mean_Mana = mean(convertedManaCost),
            mean_power= mean(power),
            mean_toughness=mean(toughness))
```

# Examples

## Permutation Test

Is average power different between Green and White creatures?


```
#Example 1: Permutation test

  #Question: Is average power different between Green and White creatures?
creatures_GW <-subset(creatures, colors =="G" | colors == "W")
head(creatures_GW)

glm1 <- glm(power ~ colors, data=creatures_GW, family="poisson")
summary(glm1)

lm1 <-lm(power ~ colors, data=creatures_GW)
summary(lm1)
anova(lm1)

barplot(c(2.74,1.38)~c("G","W"), xlab="Power", ylab="mean", col=c("Green", "White"), ylim=c(0,3))
box()

lmp1 <-lmp(power ~ colors, data=creatures_GW, perm="Prob", seqs=FALSE)
summary(lmp1)
anova(lmp1)
```




```
> summary(glm1)

Call:
glm(formula = power ~ colors, family = "poisson", data = creatures_GW)

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-2.34247  -0.71120   0.08007   0.15248   2.57099

Coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)  1.00927    0.09667  10.440   <2e-16 ***
colorsW     -0.37328    0.15509  -2.407   0.0161 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 73.171  on 74  degrees of freedom
Residual deviance: 67.247  on 73  degrees of freedom
AIC: 262.53

Number of Fisher Scoring iterations: 5
```

```
> summary(lm1)

Call:
lm(formula = power ~ colors, data = creatures_GW)

Residuals:
    Min      1Q  Median      3Q     Max
-2.7436 -0.8889  0.1111  0.2564  5.2564

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   2.7436     0.2479  11.066   <2e-16 ***
colorsW      -0.8547     0.3578  -2.388   0.0195 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.548 on 73 degrees of freedom
Multiple R-squared:  0.07248,   Adjusted R-squared:  0.05978
F-statistic: 5.705 on 1 and 73 DF,  p-value: 0.01951

> anova(lm1)
Analysis of Variance Table

Response: power
          Df  Sum Sq Mean Sq F value  Pr(>F)
colors     1  13.675 13.6752  5.7048 0.01951 *
Residuals 73 174.991  2.3971
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

```
> summary(lmp1)

Call:
lmp(formula = power ~ colors, data = creatures_GW, perm = "Prob",
    seqs = FALSE)

Residuals:
    Min      1Q  Median      3Q     Max
-2.7436 -0.8889  0.1111  0.2564  5.2564

Coefficients:
        Estimate Iter Pr(Prob)
colors1   0.4274 2732   0.0355 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.548 on 73 degrees of freedom
Multiple R-Squared: 0.07248,    Adjusted R-squared: 0.05978
F-statistic: 5.705 on 1 and 73 DF,  p-value: 0.01951

> anova(lmp1)
Analysis of Variance Table

Response: power
          Df R Sum Sq R Mean Sq Iter Pr(Prob)
colors1    1   13.675   13.6752 2732  0.03551 *
Residuals 73  174.991    2.3971
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

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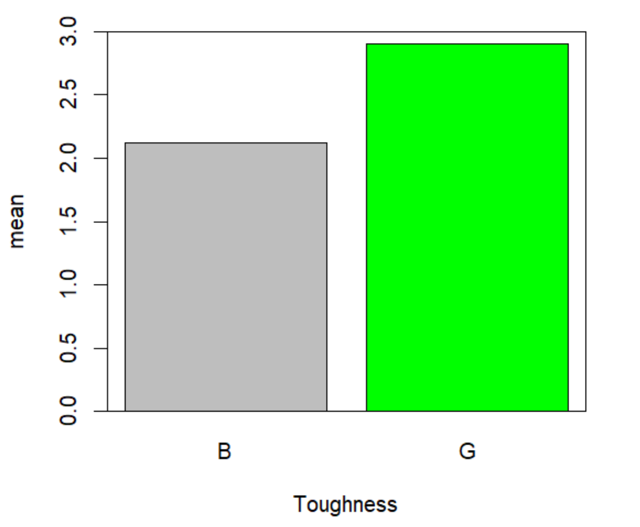
# Examples

## Permutation Test

Is average toughness different between Green and Black creatures?


```
#Question: Is average toughness different between Black and Green creatures?
creatures_BG <-subset(creatures, colors =="B" | colors == "G")
head(creatures_BG)

glm2 <- glm(toughness ~ colors, data=creatures_BG, family="poisson")
summary(glm2)

lm2 <-lm(toughness ~ colors, data=creatures_BG)
summary(lm2)
anova(lm2)

barplot(c(2.12,2.90)~c("B","G"), xlab="Toughness", ylab="mean", col=c("Grey", "Green"), ylim=c(0,3))
box()

lmp2 <-lmp(toughness ~ colors, data=creatures_BG, perm="Prob", seqs=FALSE)
summary(lmp2)
anova(lmp2)
```




```
> summary(glm2)

Call:
glm(formula = toughness ~ colors, family = "poisson", data = creatures_BG)

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-1.29121  -0.85933  -0.08404   0.56760   2.63768

Coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)   0.7520     0.1195   6.292 3.14e-10 ***
colorsG       0.3118     0.1521   2.050   0.0403 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 67.728  on 71  degrees of freedom
Residual deviance: 63.438  on 70  degrees of freedom
AIC: 260.04

Number of Fisher Scoring iterations: 5
```

```
> summary(lm2)

Call:
lm(formula = toughness ~ colors, data = creatures_BG)

Residuals:
    Min      1Q  Median      3Q     Max
-1.8974 -1.1212 -0.1212  0.8788  5.1026

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   2.1212     0.2815   7.534 1.31e-10 ***
colorsG       0.7762     0.3825   2.029   0.0462 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.617 on 70 degrees of freedom
Multiple R-squared:  0.05555,	Adjusted R-squared:  0.04206
F-statistic: 4.117 on 1 and 70 DF,  p-value: 0.04625

> anova(lm2)
Analysis of Variance Table

Response: toughness
          Df Sum Sq Mean Sq F value  Pr(>F)
colors     1  10.77 10.7701  4.1174 0.04625 *
Residuals 70 183.10  2.6158
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

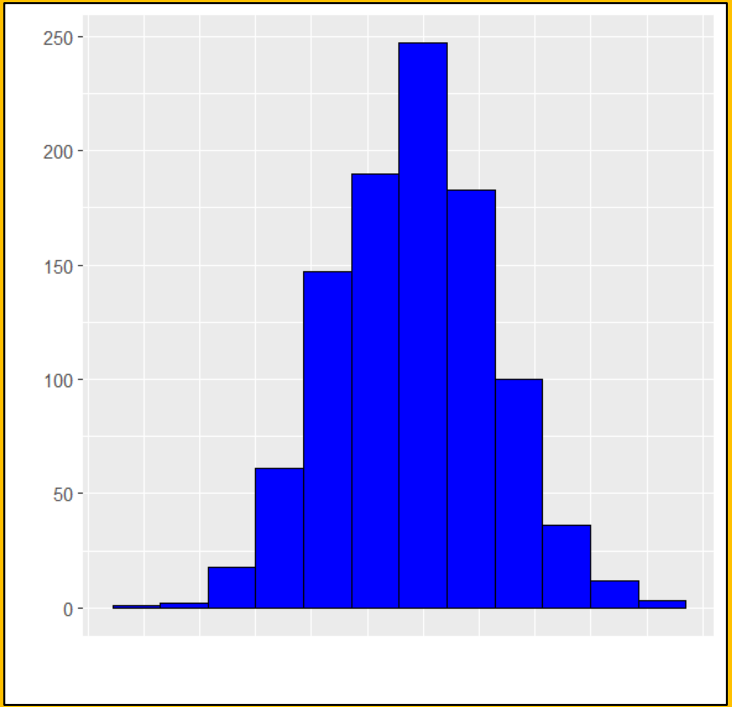
```
> summary(lmp2)

Call:
lmp(formula = toughness ~ colors, data = creatures_BG, perm = "Prob",
    seqs = FALSE)

Residuals:
    Min      1Q  Median      3Q     Max
-1.8974 -1.1212 -0.1212  0.8788  5.1026

Coefficients:
        Estimate Iter Pr(Prob)
colors1  -0.3881 3148   0.0308 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.617 on 70 degrees of freedom
Multiple R-Squared: 0.05555,	Adjusted R-squared: 0.04206
F-statistic: 4.117 on 1 and 70 DF,  p-value: 0.04625

> anova(lmp2)
Analysis of Variance Table

Response: toughness
          Df R Sum Sq R Mean Sq Iter Pr(Prob)
colors1    1    10.77    10.7701 3148  0.03081 *
Residuals 70   183.10     2.6158
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

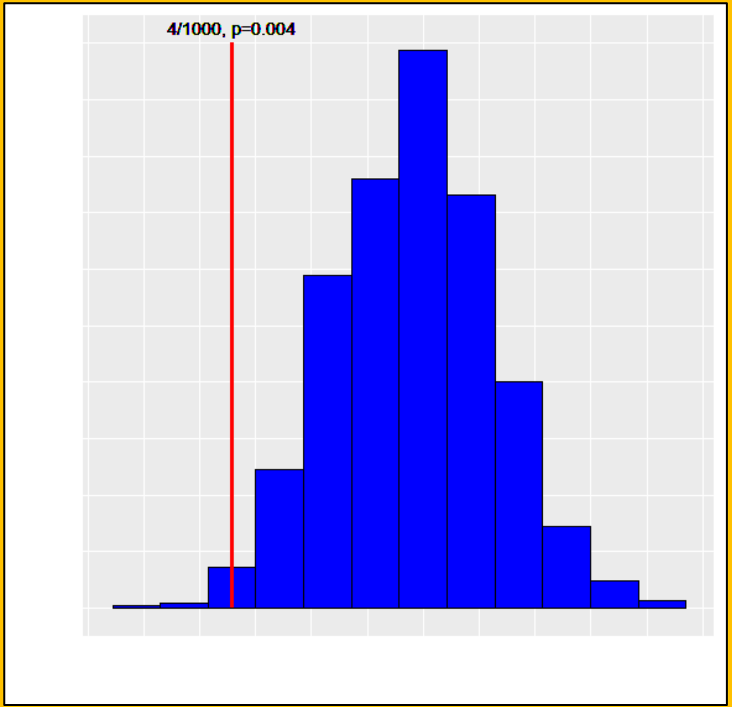
# Examples

## Permutation Test

Visualization

```
  #visualization:
t_coeff<-unname(lm1$coefficients[2]) #estimate of difference between Green and White creature power

set.seed(10)
coeff_list <-c()
for (i in seq(1:1000)) {
  perm_colors<-sample(creatures_GW$colors,replace=FALSE)
  perm_power <-creatures_GW$power
  perm_df <-data.frame(colors=perm_colors, power=perm_power)
  plm <-lm(power ~ colors, data=perm_df)
  perm_coeff <-unname(plm$coefficients[2])
  coeff_list <<-c(coeff_list, perm_coeff)
}
coeff_df <-data.frame(coeff=coeff_list)

plot1 <-ggplot(data=coeff_df, aes(x=coeff))+
  geom_histogram(, bins=12, fill="blue", col="black")
plot1

t_coeff #actual coefficient we got
1000-sum(coeff_list>t_coeff)

plot1+
  geom_segment(aes(x=t_coeff, y=0, xend=t_coeff, yend=250), colour="red", linewidth=1)+
  geom_text(aes(label=c("4/1000, p=0.004")), x=t_coeff, y=257, size=3)
#---------------------------------------------------------------------------------;
```



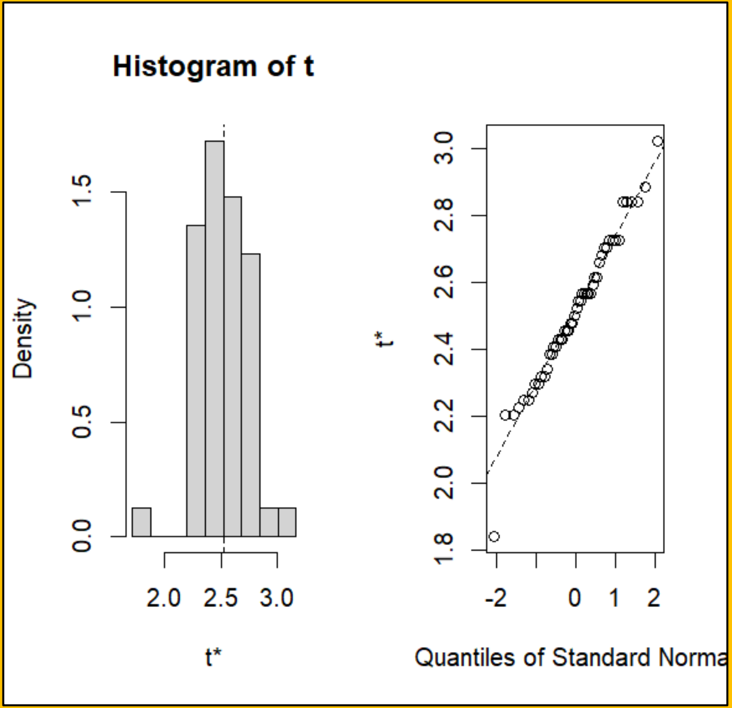
# Examples

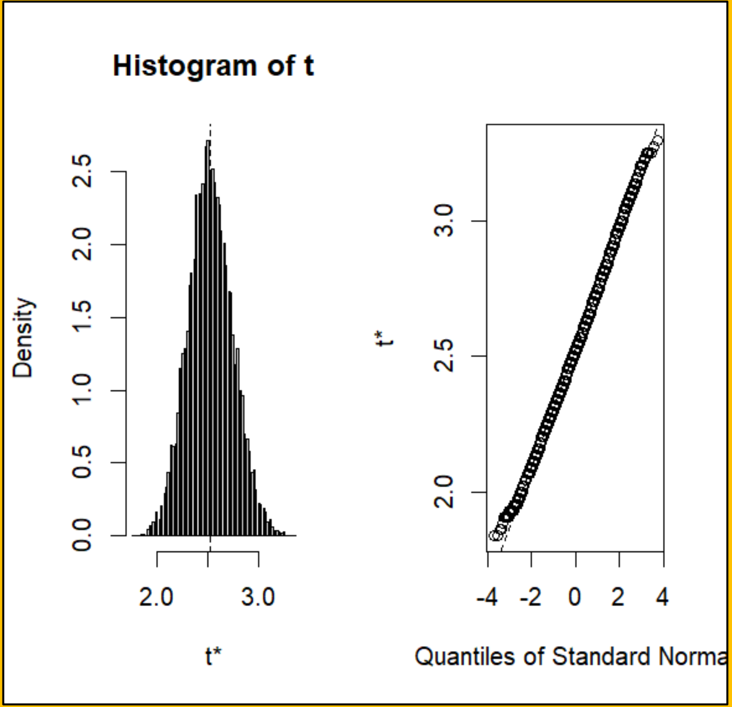
## Bootstrapping

What is the bootstrap confidence in mean cost for Instants?

```
#Example 2: Bootstrapping

  #Question: What is the bootstrap confidence in mean cost for Instants?
head(magic[magic$types=="Instant",])

Instant_Cost <-magic$convertedManaCost[magic$types=="Instant"]
mean(Instant_Cost)

    #Bootstrap standard error
set.seed(10)
meanFunc <- function(x,i){mean(x[i])}
reps1 <-boot(Instant_Cost, meanFunc, 50)
reps2 <-boot(Instant_Cost, meanFunc, 10000)

    #Plot Bootstrap distribution
plot(reps1)
plot(reps2)

    #Calculate confidence intervals
boot.ci(reps1, type="bca")
boot.ci(reps2, type="bca")
```

```
> boot.ci(reps1, type="bca")
BOOTSTRAP CONFIDENCE INTERVAL CALCULATIONS
Based on 50 bootstrap replicates

CALL :
boot.ci(boot.out = reps1, type = "bca")

Intervals :
Level       BCa
95%   ( 2.071,  3.021 )
Calculations and Intervals on Original Scale
Some BCa intervals may be unstable
> boot.ci(reps2, type="bca")
BOOTSTRAP CONFIDENCE INTERVAL CALCULATIONS
Based on 10000 bootstrap replicates

CALL :
boot.ci(boot.out = reps2, type = "bca")

Intervals :
Level       BCa
95%   ( 2.114,  2.977 )
Calculations and Intervals on Original Scale
```



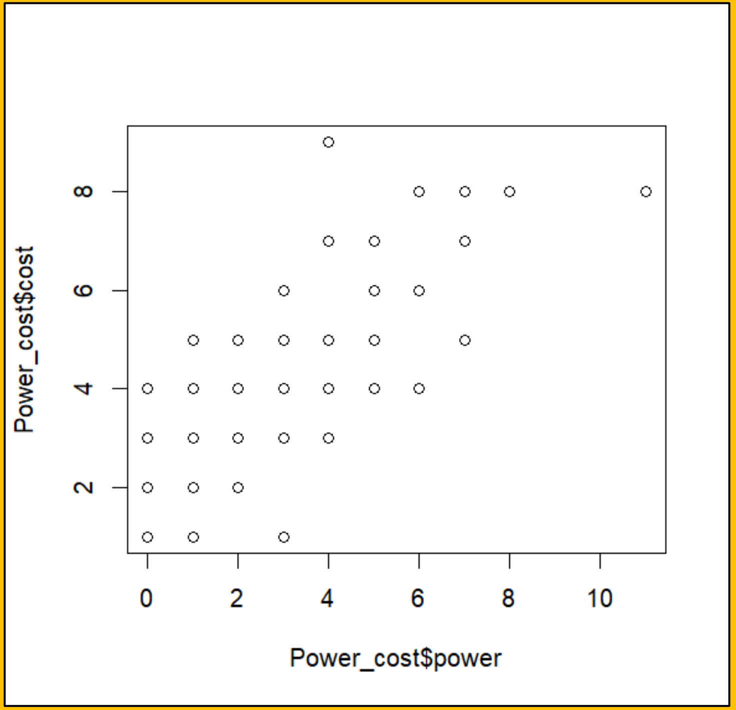



# Examples

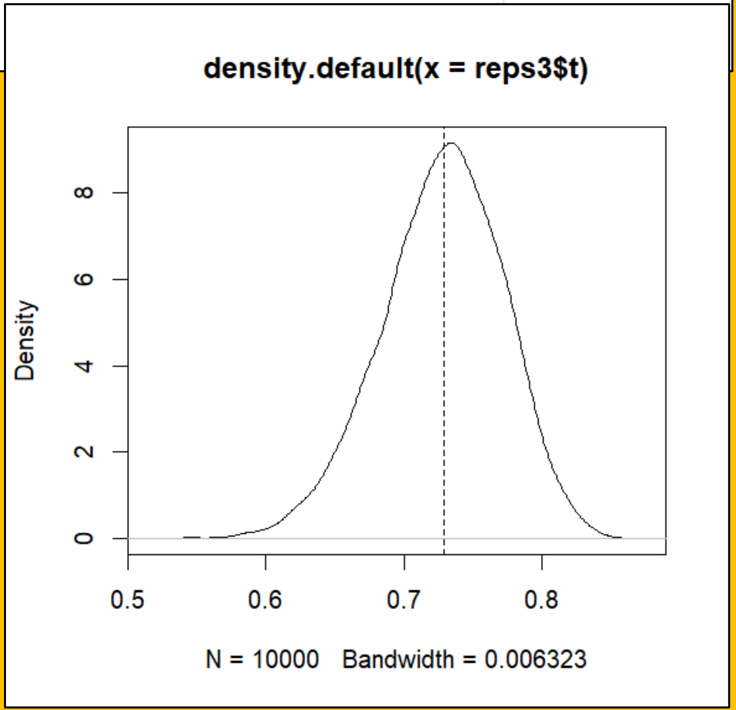
## Bootstrapping

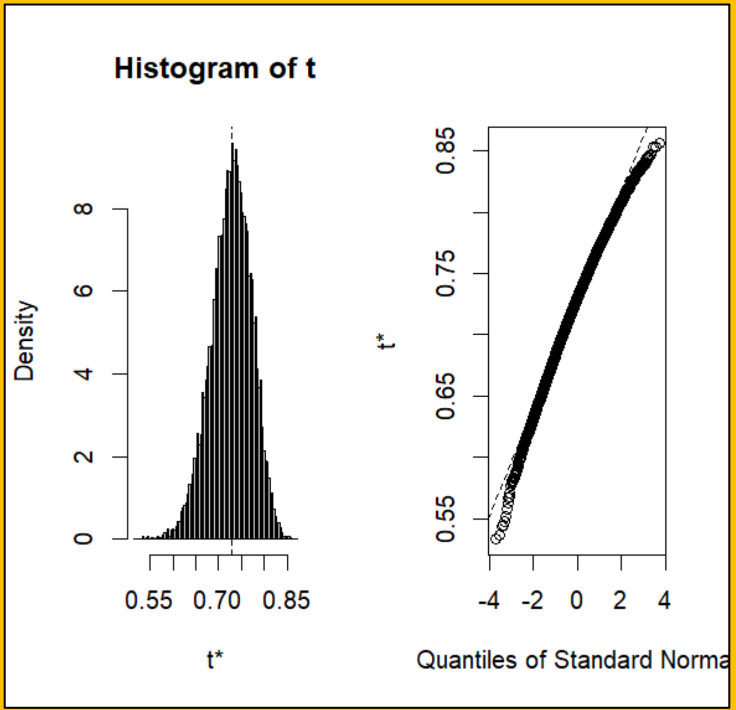
How confident can we be in a correlation between Mana cost and Creature power?

```r
#Question: How confident can we be in a correlation between Mana cost and Creature power?
Power_cost <-data.frame(power=creatures$power, cost=creatures$convertedManaCost)
head(Power_cost)

cor1<-cor(Power_cost$power, Power_cost$cost, method="spearman")
cor1

plot(Power_cost$power, Power_cost$cost)

corFunc <- function(data,i){cor(data[i,"power"], data[i,"cost"], method="spearman")}

reps3 <-boot(Power_cost, corFunc, 10000)
reps3

plot(reps3)

boot.ci(reps3, type="bca")

#density plot
plot(density(reps3$t))
abline(v=cor1, lty="dashed")
```




```
> boot.ci(reps3, type="bca")
BOOTSTRAP CONFIDENCE INTERVAL CALCULATIONS
Based on 10000 bootstrap replicates

CALL :
boot.ci(boot.out = reps3, type = "bca")

Intervals :
Level       BCa
95%   ( 0.6252,  0.8024 )
Calculations and Intervals on Original Scale
```



# Examples

## K-fold validation

How accurate is using power and toughness to predict Mana cost for creatures, using K-fold validation?

```
#Example 3: K-fold validation/ Jackknife

  #Question: How accurate is using power and toughness to predict Mana cost for creatures, using K-fold?
lm3 <-lm(convertedManaCost ~ power * toughness, data=creatures)
summary(lm3)

ctrl <- trainControl(method="cv", number =5)
modelA <-train(convertedManaCost ~ power, data=creatures, method="lm", trControl=ctrl)
modelB <-train(convertedManaCost ~ toughness, data=creatures, method="lm", trControl=ctrl)
modelC <-train(convertedManaCost ~ power + toughness, data=creatures, method="lm", trControl=ctrl)
modelD <-train(convertedManaCost ~ power * toughness, data=creatures, method="lm", trControl=ctrl)

    #RSME=root mean squared error: lower the better;
    #Rsquared=correlation: the higher the better;
    #MAE=mean absolute error: lower the better;

modelA$results; modelB$results; modelC$results; modelD$results
  #Model 4 had lowest RSME, highest Rsquared, and lowest MAE
modelD$finalModel
```

```
> summary(lm3)

Call:
lm(formula = convertedManaCost ~ power * toughness, data = creatures)

Residuals:
    Min      1Q  Median      3Q     Max 
-3.1036 -0.5313 -0.0468  0.4688  3.4379 

Coefficients:
                Estimate Std. Error t value Pr(>|t|)    
(Intercept)      0.56212    0.21331   2.635   0.0092 ** 
power            0.72678    0.09178   7.918 3.12e-13 ***
toughness        0.63933    0.08303   7.700 1.11e-12 ***
power:toughness -0.06187    0.01446  -4.279 3.14e-05 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.9487 on 168 degrees of freedom
Multiple R-squared:  0.6911,	Adjusted R-squared:  0.6856 
F-statistic: 125.3 on 3 and 168 DF,  p-value: < 2.2e-16
```

```
> modelA$results; modelB$results; modelC$results; modelD$results
  intercept     RMSE  Rsquared       MAE    RMSESD RsquaredSD      MAESD
1      TRUE 1.100968 0.6108597 0.8388541 0.1124086 0.05188265 0.09605917
  intercept     RMSE  Rsquared       MAE    RMSESD RsquaredSD      MAESD
1      TRUE 1.112877 0.5833777 0.8348641 0.0970927 0.04482937 0.06114345
  intercept     RMSE  Rsquared       MAE     RMSESD RsquaredSD      MAESD
1      TRUE 1.005161 0.6442761 0.7370279 0.07047771 0.09868055 0.04877122
  intercept      RMSE  Rsquared       MAE     RMSESD RsquaredSD      MAESD
1      TRUE 0.9545428 0.6822408 0.6921889 0.09801078 0.08017481 0.09421169
>   #Model 4 had lowest RSME, highest Rsquared, and lowest MAE
> modelD$finalModel

Call:
lm(formula = .outcome ~ ., data = dat)

Coefficients:
      (Intercept)              power          toughness  `power:toughness`  
          0.56212            0.72678            0.63933           -0.06187  
```

# Examples

## K-fold validation

How accurate is using power and toughness to predict Mana cost for creatures, using jackknife validation?


```
#Question: what about jackknife?
jlm <-pcr(convertedManaCost ~ power * toughness, data=creatures, validation="LOO", jackknife=TRUE)

jack.test(jlm)
```

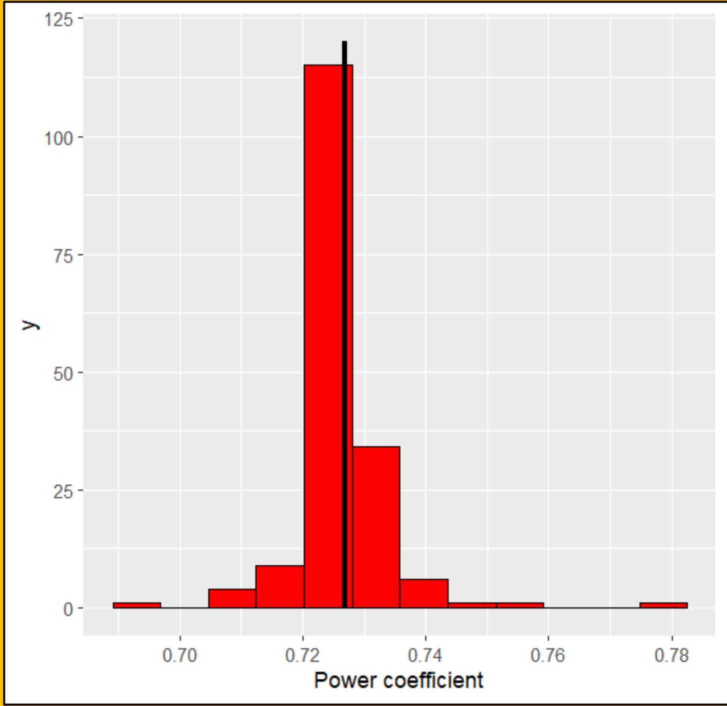
```
> jack.test(jlm)
Response convertedManaCost (3 comps):
                 Estimate Std. Error  Df t value  Pr(>|t|)    
power            0.726778   0.096417 171  7.5379 2.668e-12 ***
toughness        0.639332   0.099895 171  6.4000 1.440e-09 ***
power:toughness -0.061874   0.014454 171 -4.2808 3.097e-05 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

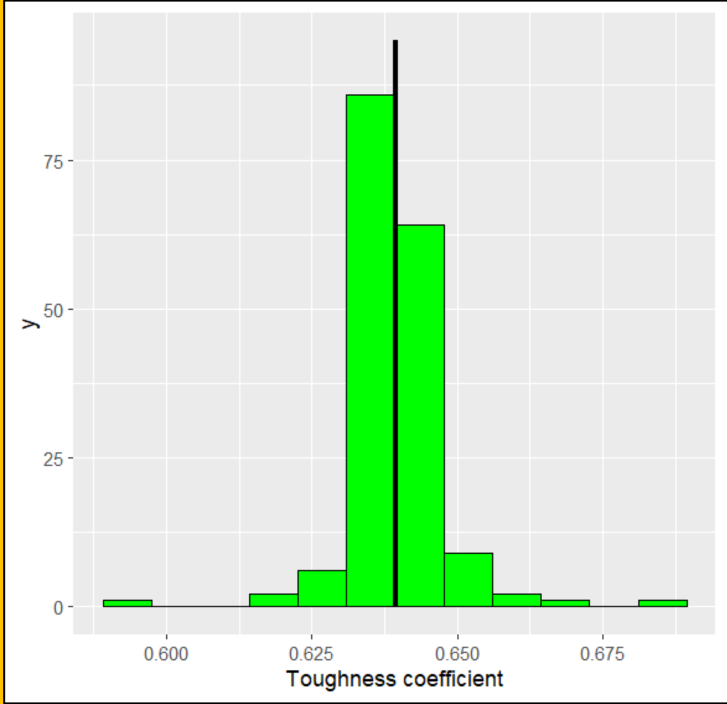
# Examples

## K-fold validation

Visualization (jackknife)

```
#visualization example:
lm3$coefficients

power_c <-unname(lm3$coefficients[2])
tough_c <-unname(lm3$coefficients[3])

lc<-length(creatures$convertedManaCost)
power_coeff_list <-c()
tough_coeff_list <-c()
for (i in seq(1:lc)){
  new_df <-creatures[-c(i), ]
  lm_loo <-lm(convertedManaCost ~ power * toughness, data=new_df)
  power_coeff <-unname(lm_loo$coefficients[2])
  tough_coeff <-unname(lm_loo$coefficients[3])
  power_coeff_list <<-c(power_coeff_list, power_coeff)
  tough_coeff_list <<-c(tough_coeff_list, tough_coeff)
}
power_jack_df <-data.frame(coeff=power_coeff_list)
tough_jack_df <-data.frame(coeff=tough_coeff_list)


plot2 <-ggplot(data=power_jack_df, aes(x=coeff))+
  geom_histogram(bins=12, fill="red", col="black")+
  geom_segment(aes(x=power_c, y=0, xend=power_c, yend=120), colour="black", linewidth=1.2)+
  labs(x="Power coefficient")
plot2

plot3 <-ggplot(data=tough_jack_df, aes(x=coeff))+
  geom_histogram(bins=12, fill="green", col="black")+
  geom_segment(aes(x=tough_c, y=0, xend=tough_c, yend=95), colour="black", linewidth=1.2)+
labs(x="Toughness coefficient")
plot3
```



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