



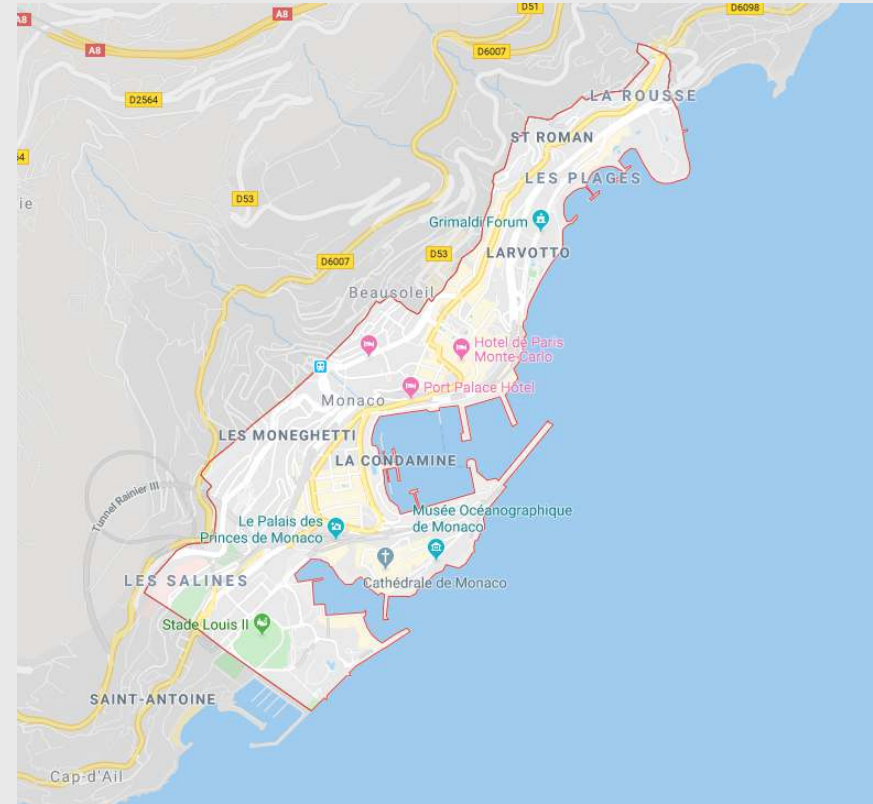
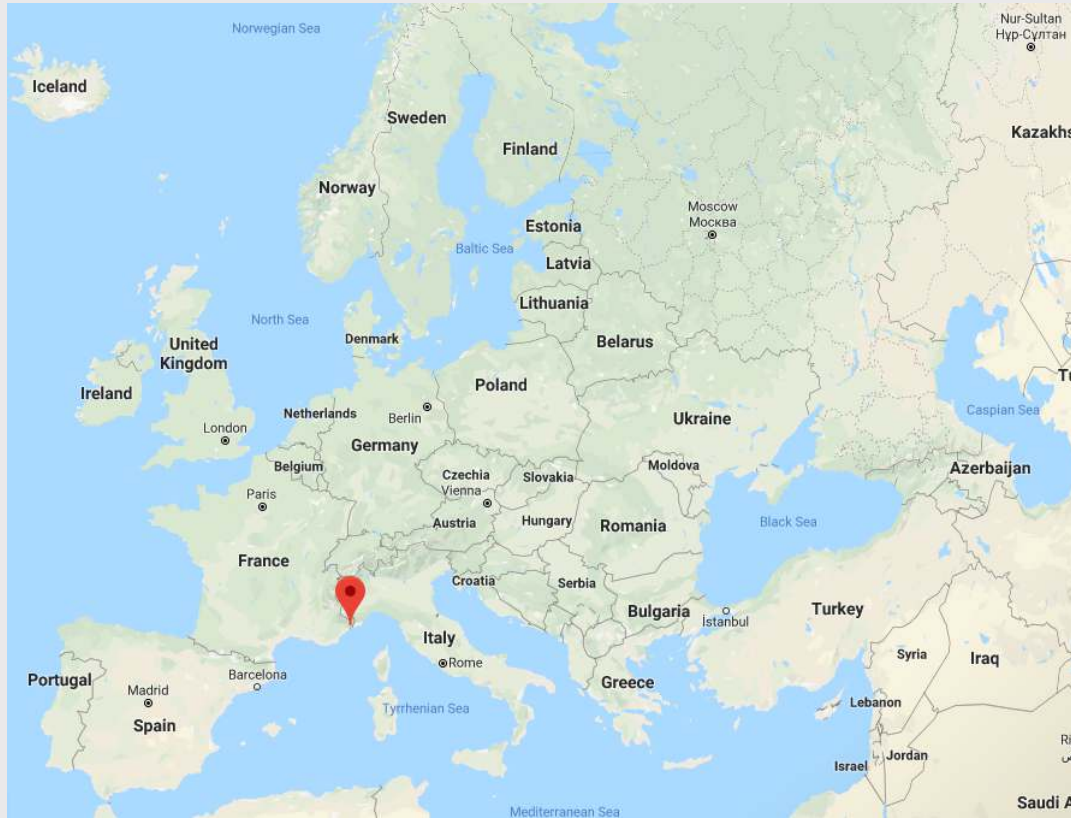
Week 13: *Monte Carlo Methods*

🏛️ EMSE 4571 / 6571: Intro to Programming for Analytics

👤 John Paul Helveston

📅 April 23, 2026

Monte Carlo, Monaco



"Monte Carlo" is associated with 3 things

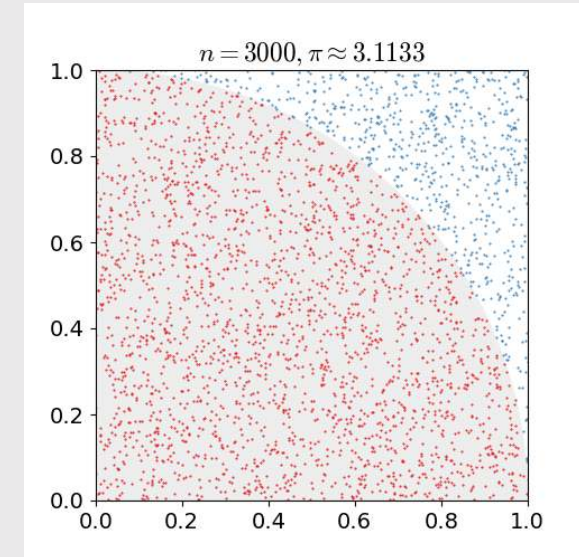
Gambling



Racing



Simulation



Week 13: *Monte Carlo Methods*

1. Monte Carlo Simulation

BREAK

2. Monte Carlo Integration

Week 13: *Monte Carlo Methods*

1. Monte Carlo Simulation

BREAK

2. Monte Carlo Integration

Monte Carlo Simulation: *Computing Probability*

General process:

- Run a series of trials.
- In each trial, simulate an event (e.g. a coin toss, a dice roll, etc.).
- Count the number of "successful" trials

$$\frac{\# \text{ Successful Trials}}{\# \text{ Total Trials}} = \text{Observed Odds} \simeq \text{Expected Odds}$$

Law of large numbers:

As N increases, Observed Odds $\gg$ Expected Odds

How would you measure if a coin is "fair"?

Run a series of trials and record outcome: "heads" or "tails"

```
coin <- c("heads", "tails")  
N <- 10000  
tosses <- sample(x = coin, size = N, replace = TRUE)  
head(tosses) # Preview first few tosses
```

```
#> [1] "tails" "tails" "tails" "heads" "heads" "heads"
```

Probability of getting "heads":

```
sum(tosses == "heads") / N
```

```
#> [1] 0.4928
```

Tossing an unfair coin

Set the `prob` argument to a 40-60 coin

```
coin <- c("heads", "tails")  
N <- 10000  
tosses <- sample(x = coin, size = N, replace = TRUE, prob = c(0.4, 0.6))  
head(tosses) # Preview first few tosses
```

```
#> [1] "heads" "tails" "heads" "heads" "tails" "tails"
```

Probability of getting "heads":

```
sum(tosses == "heads") / N
```

```
#> [1] 0.3959
```


A more complex simulation: *dice rolling*

What is the probability of rolling a 6-sided dice 3 times and getting the sequence 1, 3, 5?

```
library(tidyverse)
dice <- c(1, 2, 3, 4, 5, 6)
N <- 10000
rolls <- tibble(
  roll1 = sample(x = dice, size = N, replace = T),
  roll2 = sample(x = dice, size = N, replace = T),
  roll3 = sample(x = dice, size = N, replace = T)
)
```

```
head(rolls)
```

```
#> # A tibble: 6 × 3
#>   roll1 roll2 roll3
#>   <dbl> <dbl> <dbl>
#> 1     1     2     1
#> 2     3     6     2
#> 3     5     6     6
#> 4     6     5     5
#> 5     2     3     4
#> 6     4     2     1
```

A more complex simulation: *dice rolling*

Simulated probability of getting sequence 1, 3, 5:

```
successes <- rolls %>%  
  filter(roll1 == 1 & roll2 == 3 & roll3 == 5)  
  
nrow(successes) / N
```

```
#> [1] 0.0042
```

Actual probability of getting sequence 1, 3, 5:

```
(1/6)^3
```

```
#> [1] 0.00462963
```

Your Turn: Coins & Dice

Using the `sample()` function, conduct a monte carlo simulation to estimate the answers to these questions:

- If you flipped a coin 3 times in a row, what is the probability that you'll get three "tails" in a row?
- If you rolled 2 dice, what is the probability that you'll get "snake-eyes" (two 1's)?
- If you rolled 2 dice, what is the probability that you'll get an outcome that sums to 8?

When `replace = FALSE`

Sometimes events cannot be independently simulated

What are the odds that 3 cards drawn from a 52-card deck will sum to 13?

- Aces = 1
- Jack = 10
- Queen = 10
- King = 10

When `replace = FALSE`

Sometimes events cannot be independently simulated

```
cards <- c(seq(1, 10), 10, 10, 10)
deck <- rep(cards, 4) # Rep because there are 4 suits
length(deck)
```

```
#> [1] 52
```

Draw 3 cards from the deck *without replacement*:

```
draw <- sample(x = deck, size = 3, replace = FALSE)
draw
```

```
#> [1] 3 6 10
```

When `replace = FALSE`

Note: You can't draw more than 52 cards *without replacement*.

```
draw <- sample(x = deck, size = 53, replace = FALSE)
```

```
#> Error in sample.int(length(x), size, replace, prob): cannot take a sample larger than  
the population when 'replace = FALSE'
```

Using `map` to take draws *without* replacement

What are the odds that 3 cards drawn from a 52-card deck will sum to 13?

Make a function that returns 3 cards in a data frame:

```
three_card_sum <- function(deck) {  
  cards <- sample(  
    x = deck,  
    size = 3,  
    replace = FALSE  
  )  
  return(sum(cards))  
}
```

```
three_card_sum(deck)
```

```
#> [1] 18
```

Repeat the 3-card draw N times:

```
N <- 10000  
  
three_card_sums <- map_int(  
  1:N,  
  function(x) three_card_sum(deck)  
)  
  
count <- sum(three_card_sums == 13)  
count / N # Compute the probability
```

```
#> [1] 0.0367
```

Using `for` loop to take draws *without* replacement

What are the odds that 3 cards drawn from a 52-card deck will sum to 13?

Repeat the 3-card draw N times:

```
N <- 10000
count <- 0

for (i in 1:N) {
  draw <- sample(x = deck, size = 3, replace = FALSE)
  if (sum(draw) == 13) {
    count <- count + 1
  }
}

count / N # Compute the probability
```

```
#> [1] 0.0391
```


Your Turn: Cards

15:00

Use the `sample()` function and a monte carlo simulation to estimate the answers to these questions:

- What are the odds that four cards drawn from a 52-card deck will have the same suit?
- What are the odds that five cards drawn from a 52-card deck will sum to a prime number?

For face cards, assign numbers like this:

- Aces = 1
- Jack = 10
- Queen = 10
- King = 10

Hint: use `isPrime()` to help:

```
isPrime <- function(n) {  
  if (n == 2) { return(TRUE) }  
  for (i in seq(2, n-1)) {  
    if (n %% i == 0) {  
      return(FALSE)  
    }  
  }  
  return(TRUE)  
}
```

Intermission

05 : 00

Week 13: *Monte Carlo Methods*

1. Monte Carlo Simulation

BREAK

2. Monte Carlo Integration

Discrete vs. continuous random numbers

Discrete

`sample()`

Takes random samples from vector `x`

```
sample_discrete <- sample(  
  x      = c("heads", "tails"),  
  size   = 5,  
  replace = TRUE  
)  
  
sample_discrete
```

```
#> [1] "heads" "tails" "tails" "heads"  
"tails"
```

Continuous

`runif()`

Takes random samples between bounds

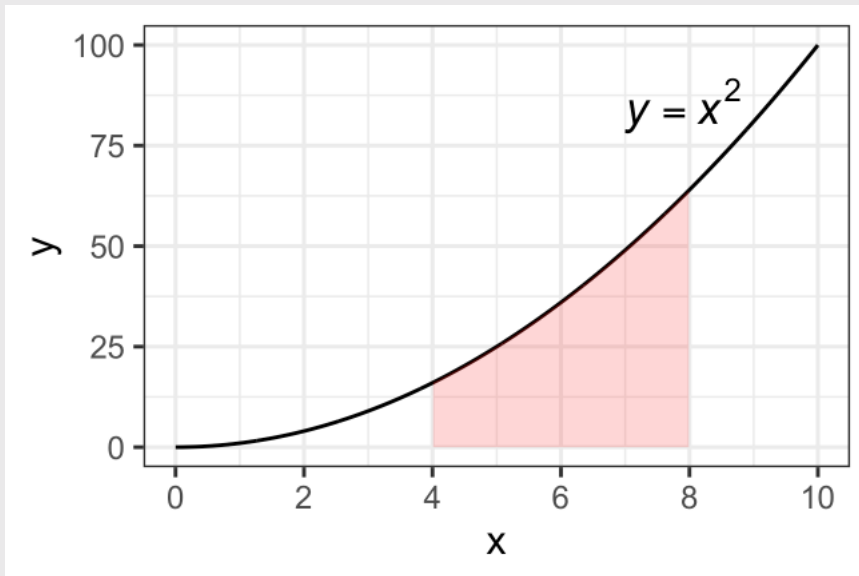
```
sample_continuous <- runif(  
  n      = 5,  
  min    = 0,  
  max    = 1  
)  
  
sample_continuous
```

```
#> [1] 0.26053556 0.77522196 0.02003059  
0.79451214 0.50433068
```

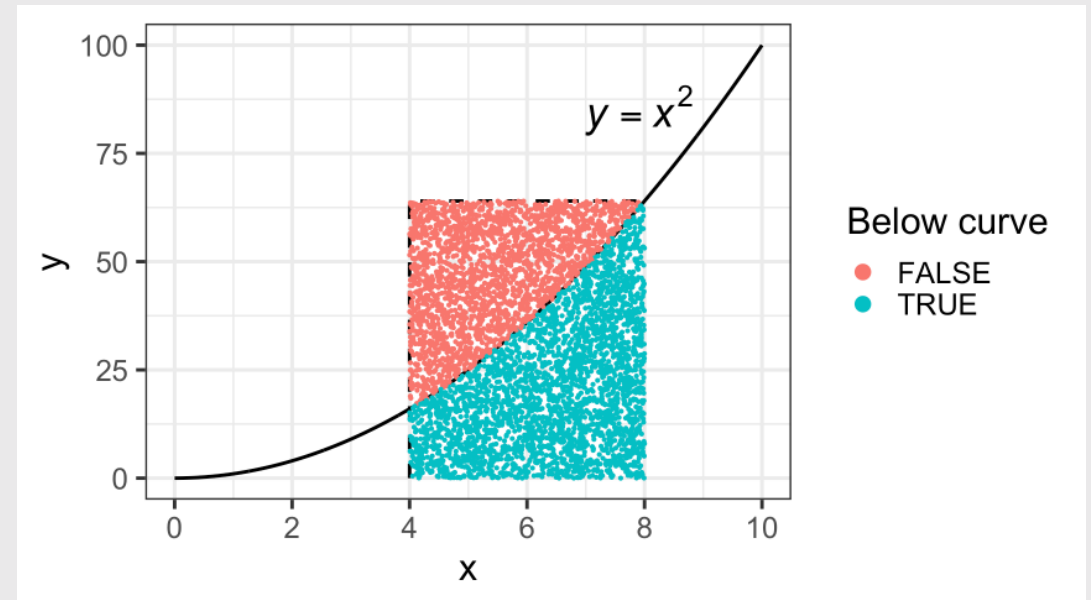
Monte Carlo Integration

Integration = compute the area "under the curve"

Find the area of $y = x^2$ between
 $4 < x < 8$

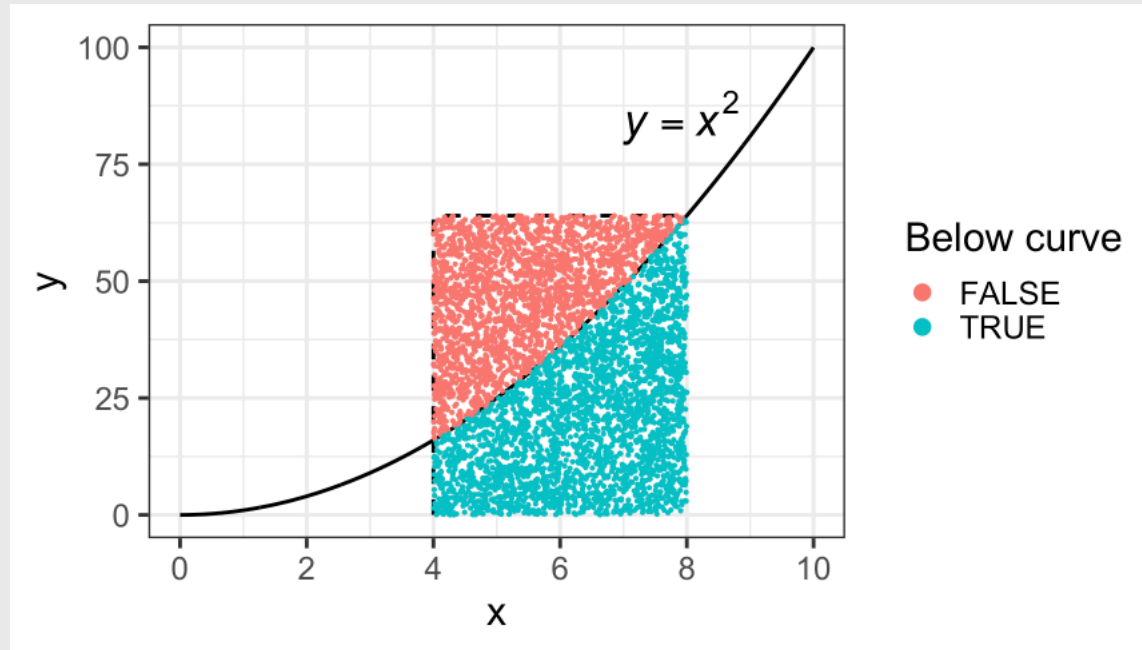


$$\frac{\text{Area Under Curve}}{\text{Area of Rectangle}} = \frac{\# \text{ Points Under Curve}}{\# \text{ Total Points}}$$



Monte Carlo Integration

$$\frac{\text{Area Under Curve}}{\text{Area of Rectangle}} = \frac{\# \text{ Points Under Curve}}{\# \text{ Total Points}}$$



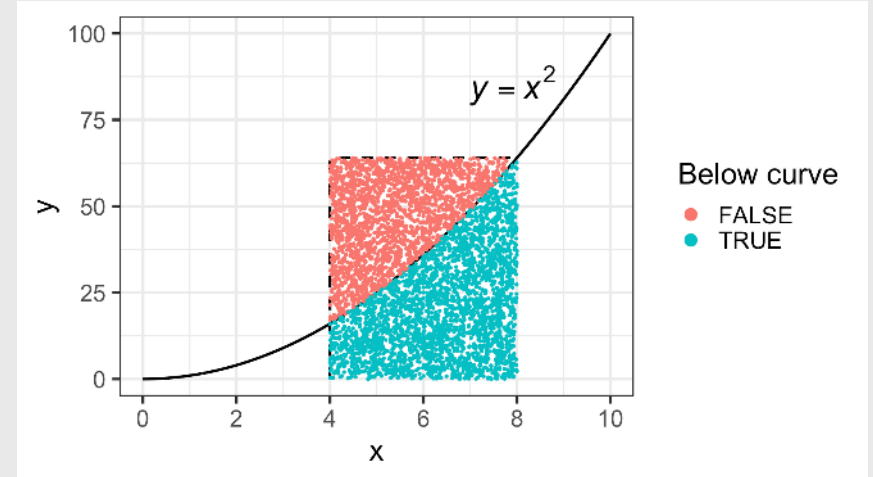
$$\text{Area Under Curve} = \text{Area of Rectangle} \left(\frac{\# \text{ Points Under Curve}}{\# \text{ Total Points}} \right)$$

Monte Carlo Integration

Step 1: Compute area of rectangle

```
area_rectangle <- (8 - 4) * (8^2 - 0)
area_rectangle
```

```
#> [1] 256
```



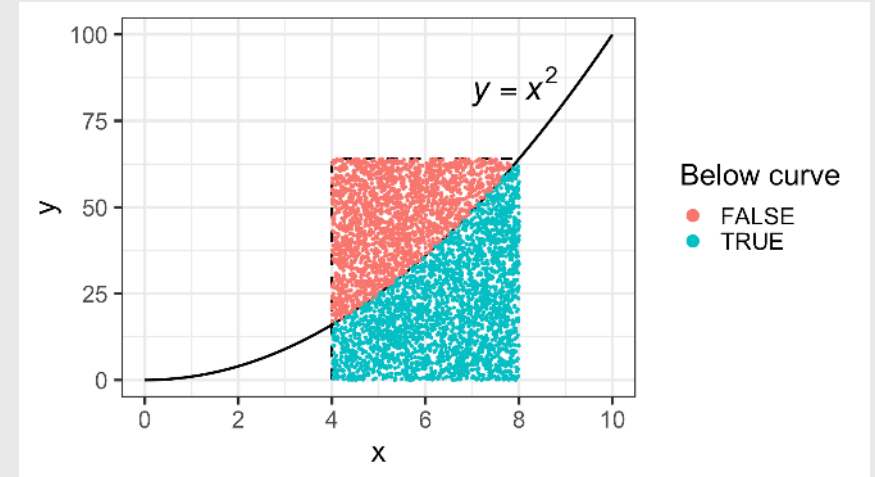
Monte Carlo Integration

Step 2: Simulate points

```
N <- 100000
points <- tibble(
  x = runif(N, min = 4, max = 8),
  y = runif(N, min = 0, max = 8^2)) %>%
  mutate(belowCurve = y < x^2)

head(points)
```

```
#> # A tibble: 6 × 3
#>       x     y belowCurve
#>   <dbl> <dbl> <lgl>
#> 1  5.18  6.03 TRUE
#> 2  7.61 62.2 FALSE
#> 3  4.34 56.1 FALSE
#> 4  5.35  3.65 TRUE
#> 5  7.58 42.3 TRUE
#> 6  4.13 44.2 FALSE
```



Monte Carlo Integration

Step 3: Compute area under curve

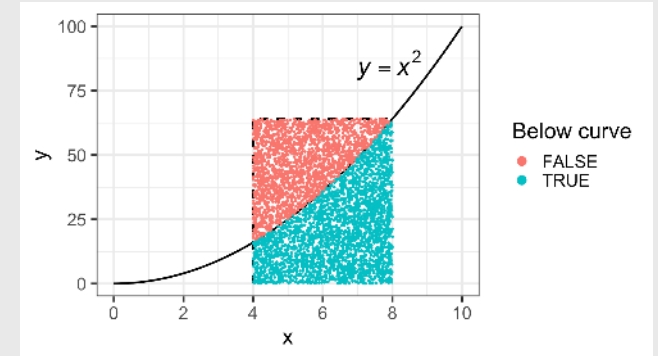
```
N <- 100000
points <- tibble(
  x = runif(N, min = 4, max = 8),
  y = runif(N, min = 0, max = 8^2)) %>%
  mutate(belowCurve = y < x^2)

points_ratio <- sum(points$belowCurve) / N
points_ratio
```

```
#> [1] 0.58226
```

```
area_under_curve <- area_rectangle * points_ratio
area_under_curve
```

```
#> [1] 149.0586
```



How did we do?

Simulated area under curve:

```
area_under_curve
```

```
#> [1] 149.0586
```

Actual area under curve:

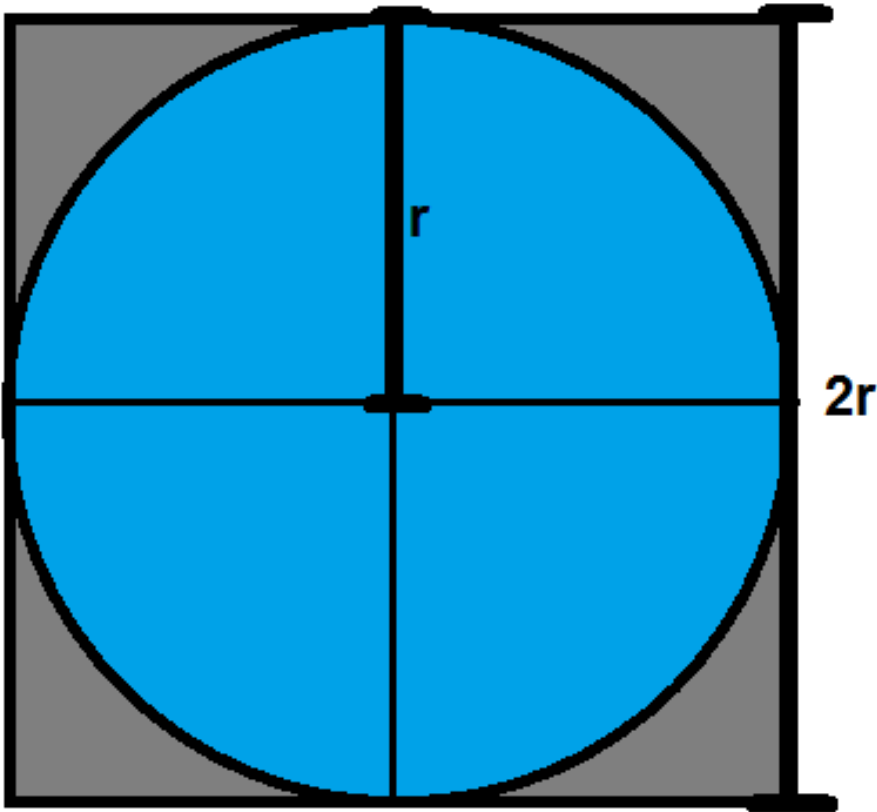
$$\int_4^8 x^2 dx = \left(\frac{x^3}{3} \right) \Big|_4^8 = \frac{8^3}{3} - \frac{4^3}{3} = 149.33\bar{3}$$

% Error:

```
true_area <- ((8^3 / 3) - (4^3 / 3))  
100*((area_under_curve - true_area) / true_area)
```

```
#> [1] -0.184
```

Monte Carlo π



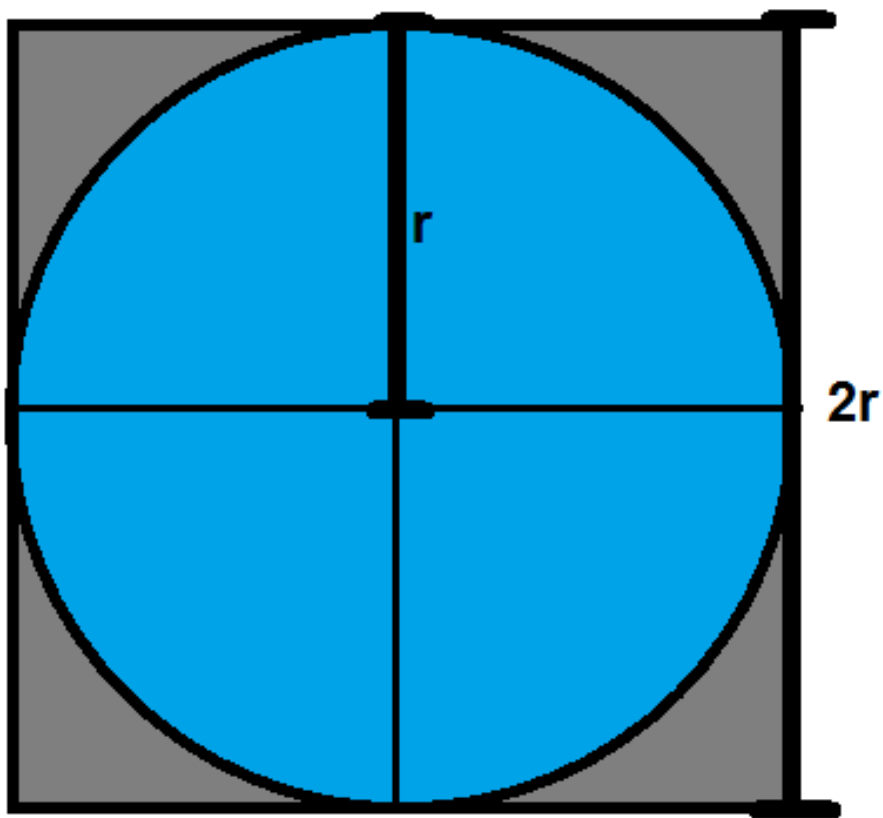
Area of a circle:

$$A_{circle} = \pi r^2$$

Area of square containing circle:

$$A_{square} = 4r^2$$

Monte Carlo π



Area of a circle:

$$A_{circle} = \pi r^2$$

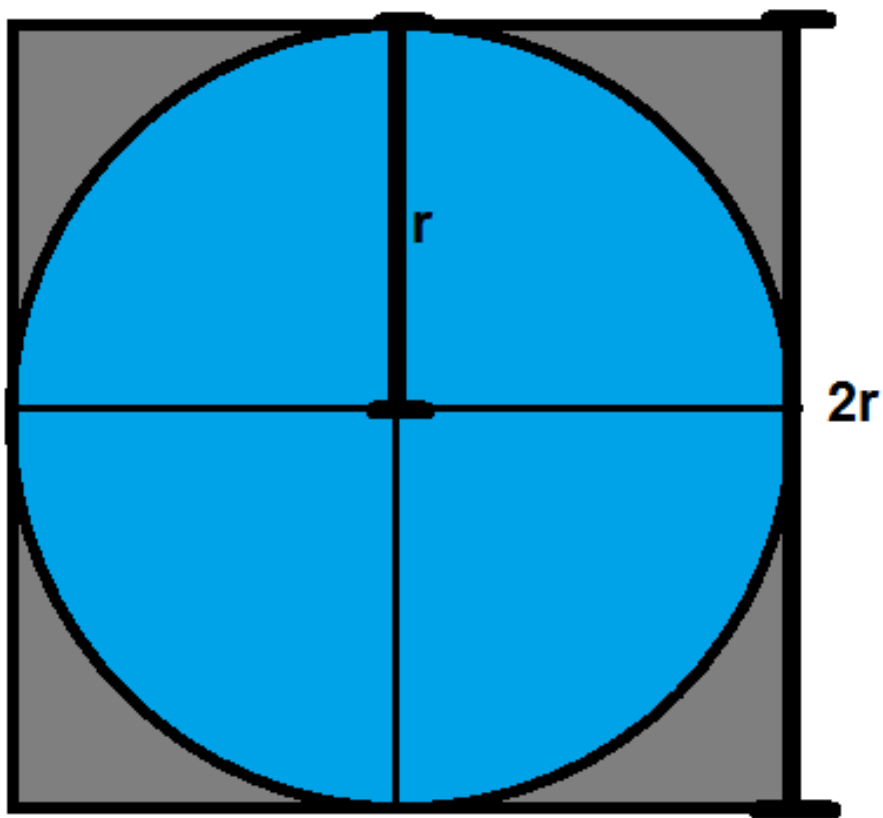
Area of square containing circle:

$$A_{square} = 4r^2$$

Ratio of areas = $\pi/4$:

$$\frac{A_{circle}}{A_{square}} = \frac{\pi r^2}{4r^2} = \frac{\pi}{4}$$

Monte Carlo π



Area of a circle:

$$A_{circle} = \pi r^2$$

Area of square containing circle:

$$A_{square} = 4r^2$$

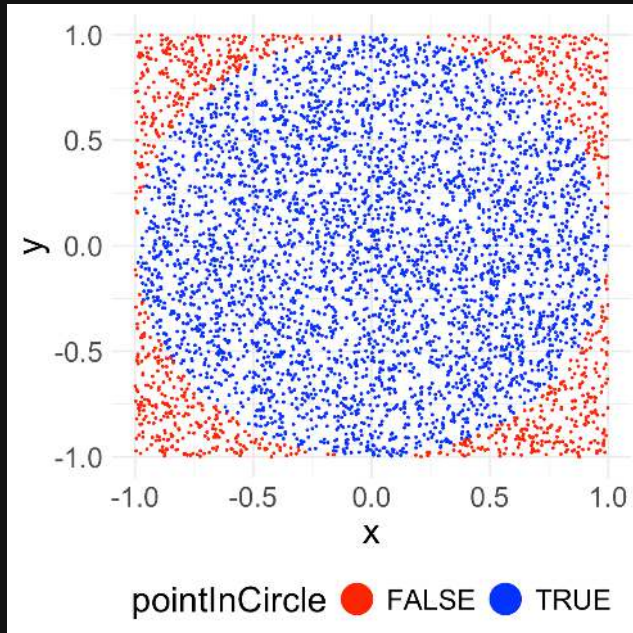
Ratio of areas = $\pi/4$:

$$\frac{A_{circle}}{A_{square}} = \frac{\pi r^2}{4r^2} = \frac{\pi}{4}$$

$$\pi = 4 \left(\frac{A_{circle}}{A_{square}} \right)$$

Your Turn: Estimate π

15:00



$$\pi = 4 \left(\frac{A_{circle}}{A_{square}} \right)$$

1. Create a tibble with variables `x` and `y` that each contain 10,000 random points between -1 and 1, representing the (x, y) coordinates to a random point inside a square of side length 2 centered at `(x, y) = (0, 0)`. **Hint:** use `runif()`
2. Create a new column, `radius`, that is equal to the distance to each `(x, y)` point from the center of the square.
3. Create a new column, `pointInCircle`, that is **TRUE** if the point lies *within* the circle inscribed in the square, and **FALSE** otherwise.
4. Create the scatterplot on the left (don't worry about the precise colors, dimensions, etc.).
5. Estimate π by multiplying 4 times the ratio of points inside the circle to the total number of points

The Monty Hall Problem



Your Turn: Monte Hall Problem

15:00

The Monty Hall Problem



1. You choose door 1, 2, or 3
2. One door is removed
3. Should you swap doors?

In this simulation, the prize is always behind door #1:

- If you choose door #1, you must KEEP it to win.
- If you choose door #2 or #3, you must SWAP to win.

1) Create the tibble, `choices`, with two variables:

- `door` contains the first door chosen (1, 2, or 3)
- `swap` contains a logical (TRUE or FALSE) for whether the contestant swaps doors. **Hint:** use `sample()`

2) Create a new tibble, `wins`, which contains only the rows from `choices` that resulted in a win.

3) Compute the percentage of times the contestant won after swapping doors.

Reminders

- 1) Please fill the [GW course feedback](#) (see slack announcement)
- 2) Final is [Thursday, May 07, 3:00pm-5:00pm, same room](#)