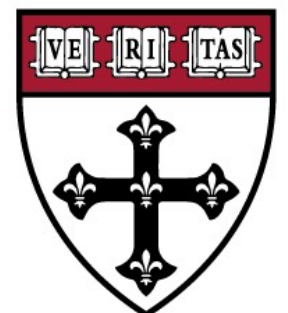


Visualizing Data Distributions

Summer Institute in Data Science

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HARVARD
SCHOOL OF PUBLIC HEALTH

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What to expect today

- Often vectors of data are summarized by two numbers: the average and the standard deviation
- Ex 1: The average test score in the midterm was 86% with 11%
- Today we will learn effective data visualization techniques:
 - Properties of distributions
 - How to visualize distributions

Variable types

- We will be working with two types of variables: **categorical** and **numeric**
- **categorical:**
 1. **nominal:** values fall into unordered categories or classes
 2. **ordinal:** values fall into ordered categories or classes
- **numeric:**
 1. **discrete:** quantities that take on only specified values (e.g, integers or counts)
 2. **continuous:** quantities that can take on any value

Variable types: Examples

- We will be working with two types of variables: **categorical** and **numeric**
- **categorical:**
 1. **nominal (Ex):** cardinal points, blood type
 2. **ordinal (Ex):** categories of a hurricane and difficulty of a video game
- **numeric:**
 1. **discrete (Ex):** population size of municipios in Puerto Rico
 2. **continuous (Ex):** a person's height and birth weight

Distribution function

- The most basic, and perhaps most important, summary of data is its distribution
- For categorical data, the distribution corresponds to the proportion of each class
- Example with heights data:

```
library(tidyverse)
library(dslabs)
data("heights")
ds_theme_set()

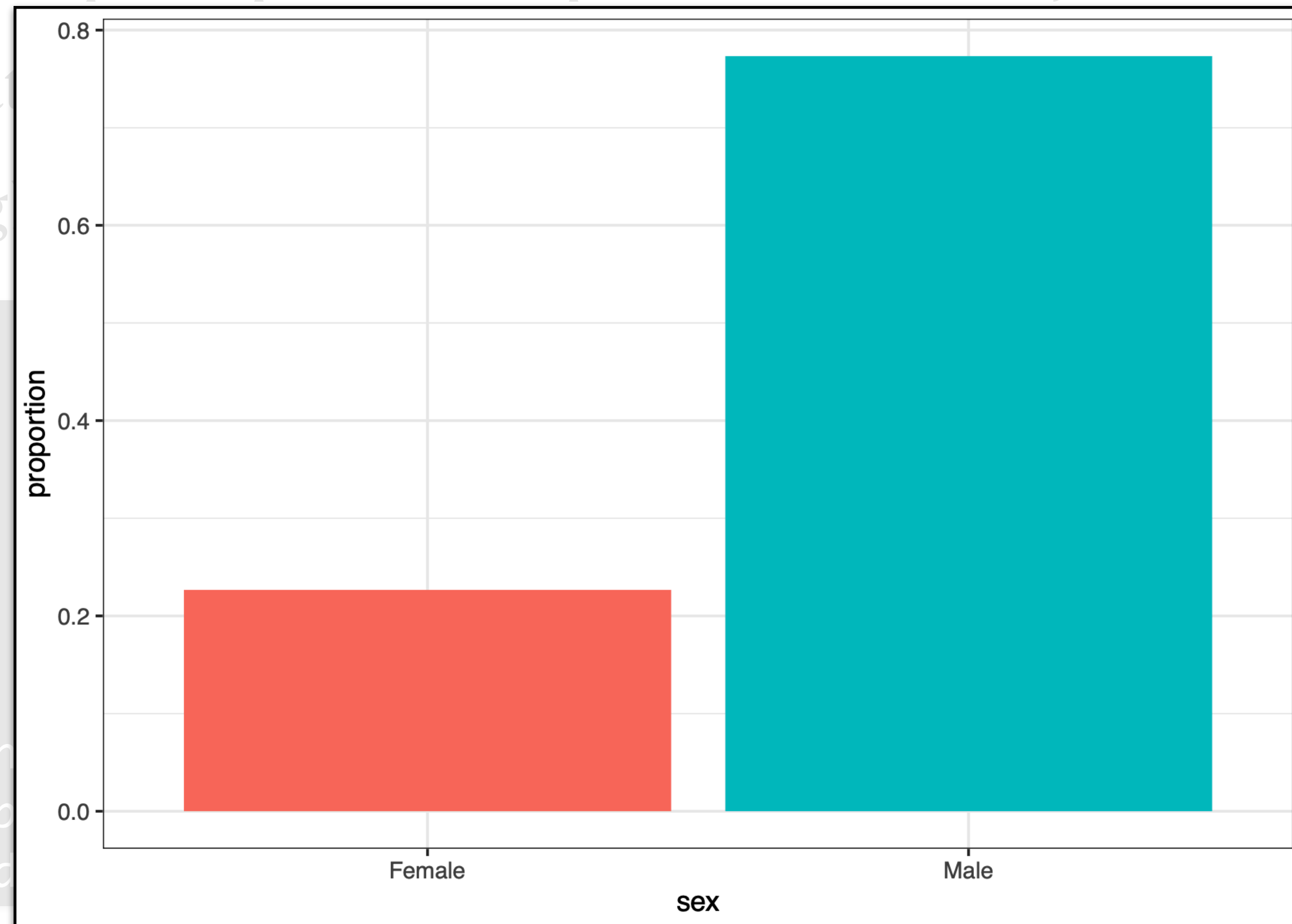
heights %>%
  group_by(sex) %>%
  summarize(proportion = n()/nrow()) %>%
  ggplot(aes(sex, proportion, fill=sex)) +
  geom_col(show.legend = FALSE)
```

Distribution function

- The most basic, and perhaps most important, summary of data is its distribution
- For categorical data, the distribution is the proportion of each class
- Example with heights

```
library(tidyverse)
library(dslabs)
data("heights")
ds_theme_set()

heights %>%
  group_by(sex) %>%
  summarize(proportion = sum(height < 170))
ggplot(aes(sex, proportion)) +
  geom_col(show.legend = FALSE)
```

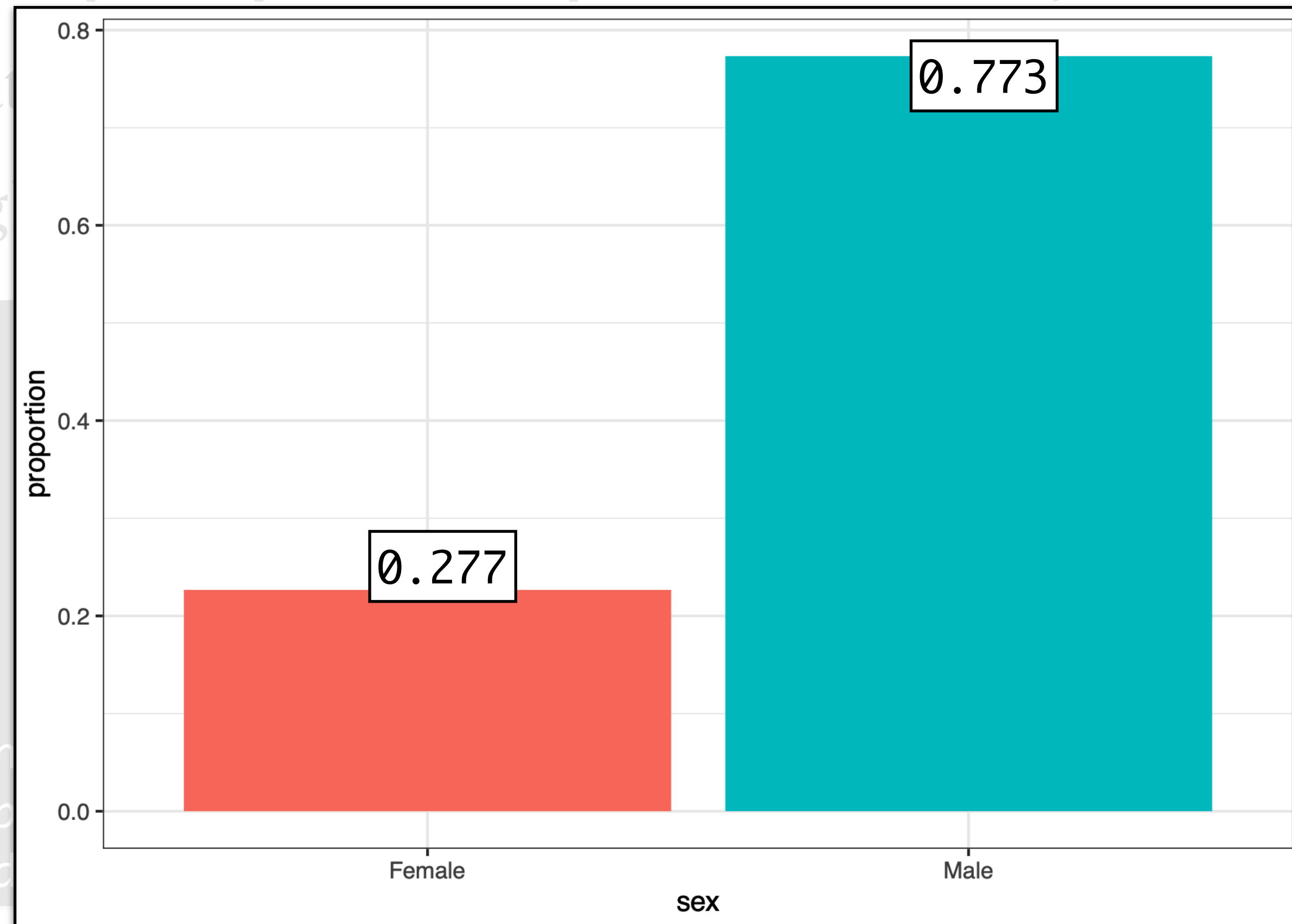


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library(tidyverse)
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ds_theme_set()

heights %>%
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  summarize(proportion = sum(height < 170))
ggplot(aes(sex, proportion)) +
  geom_col(show.legend = FALSE)
```



Distribution function

- Another example with the murders dataset:

```
library(tidyverse)
library(dslabs)
data("murders")
ds_theme_set()

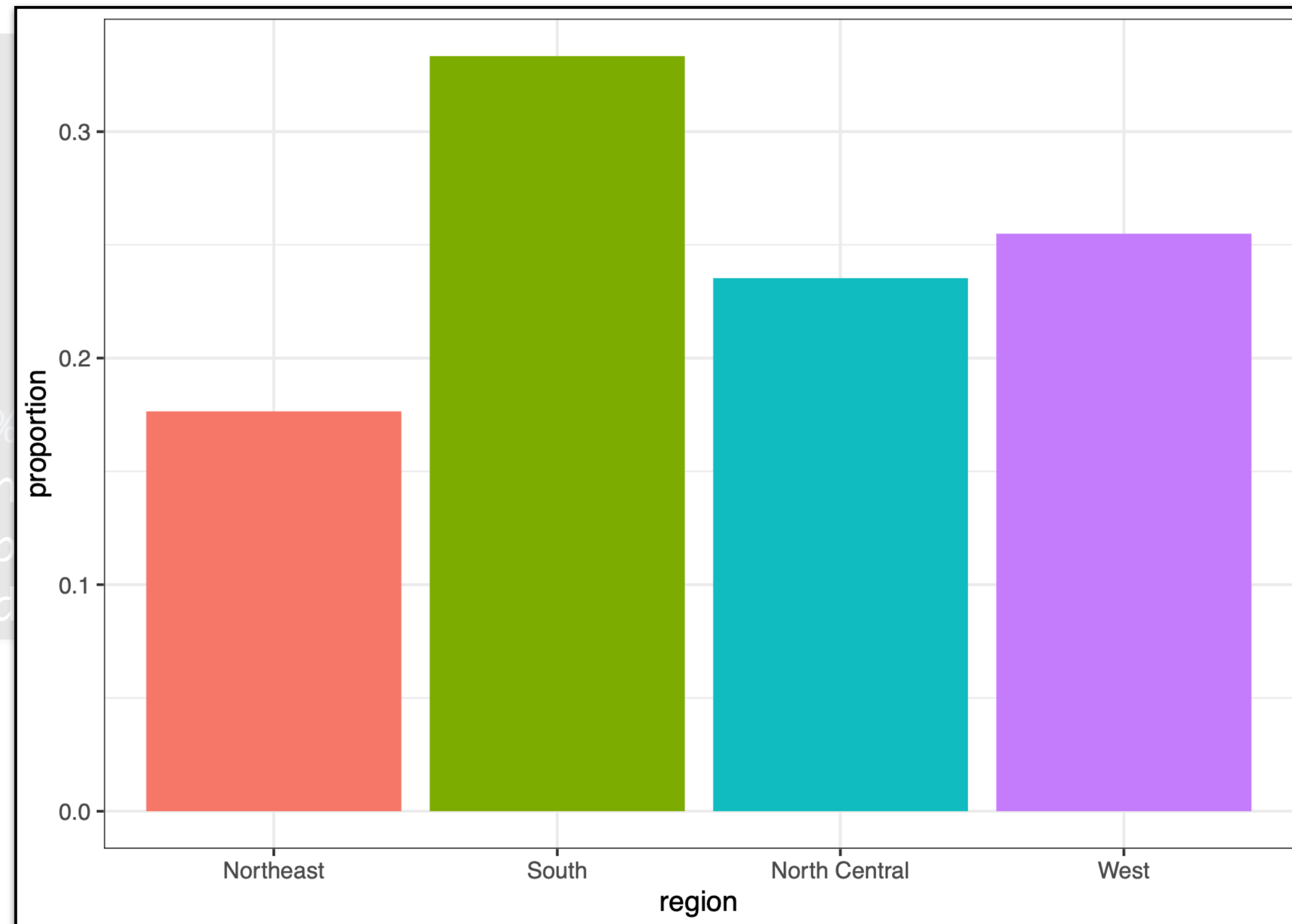
murders %>%
  group_by(region) %>%
  summarize(proportion = n()/nrow(.)) %>%
  ggplot(aes(region, proportion, fill=region)) +
  geom_col(show.legend = FALSE)
```


Distribution function

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```
library(tidyverse)
library(dslabs)
data("murders")
ds_theme_set()

murders %>%
  group_by(region) %>%
  summarize(proportion = sum(murders) / n())
ggplot(aes(region, proportion)) +
  geom_col(show.legend = FALSE)
```



Distribution function

- Let's add a small tweak

```
library(tidyverse)
library(dslabs)
data("murders")
ds_theme_set()

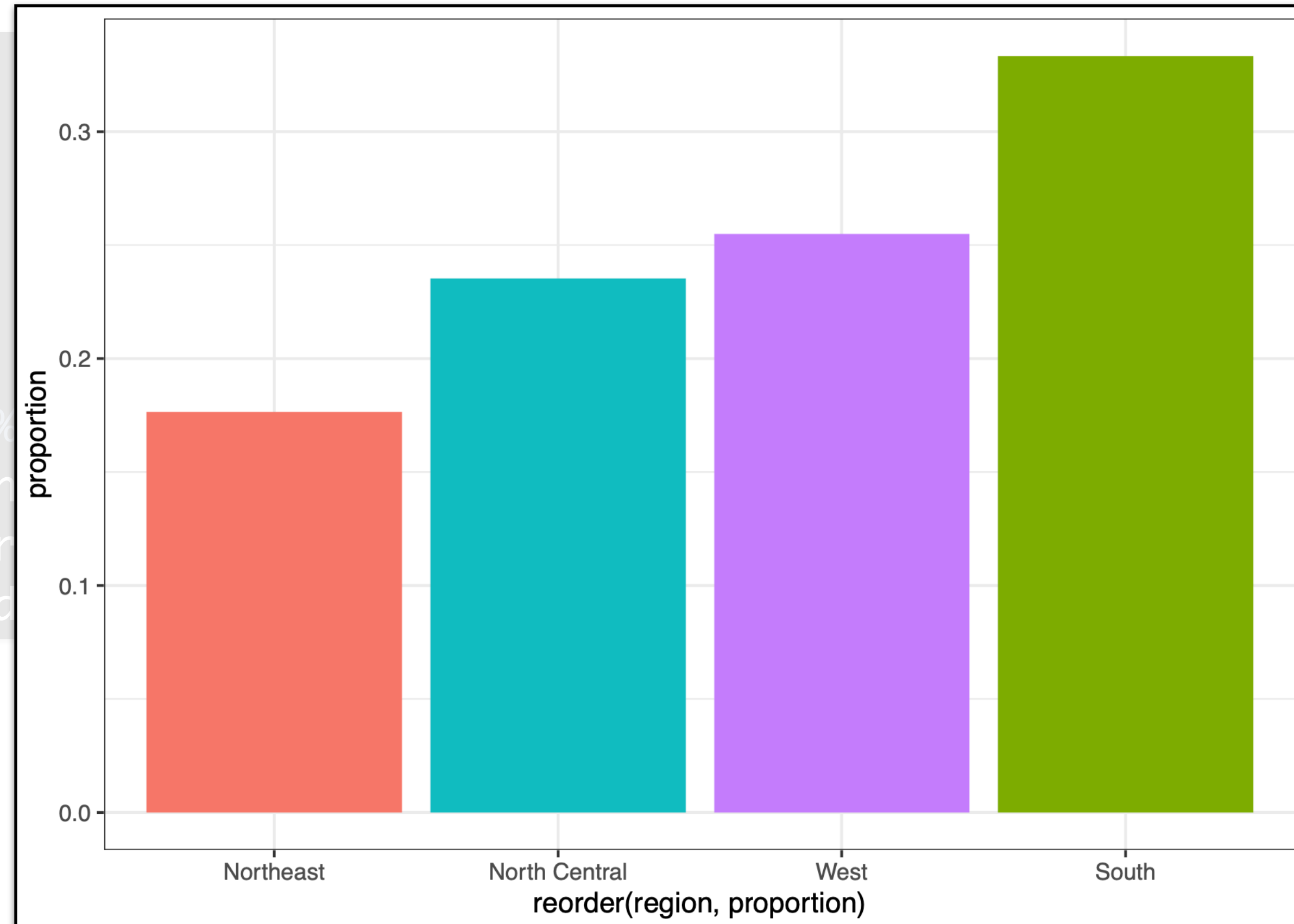
murders %>%
  group_by(region) %>%
  summarize(proportion = n()/nrow(.)) %>%
  ggplot(aes(reorder(region, proportion), proportion, fill=region)) +
  geom_col(show.legend = FALSE)
```

Distribution function

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```
library(tidyverse)
library(dslabs)
data("murders")
ds_theme_set()

murders %>%
  group_by(region) %>%
  summarize(proportion = sum(murders) / n())
ggplot(aes(reorder(region, proportion)))
geom_col(show.legend = FALSE)
```

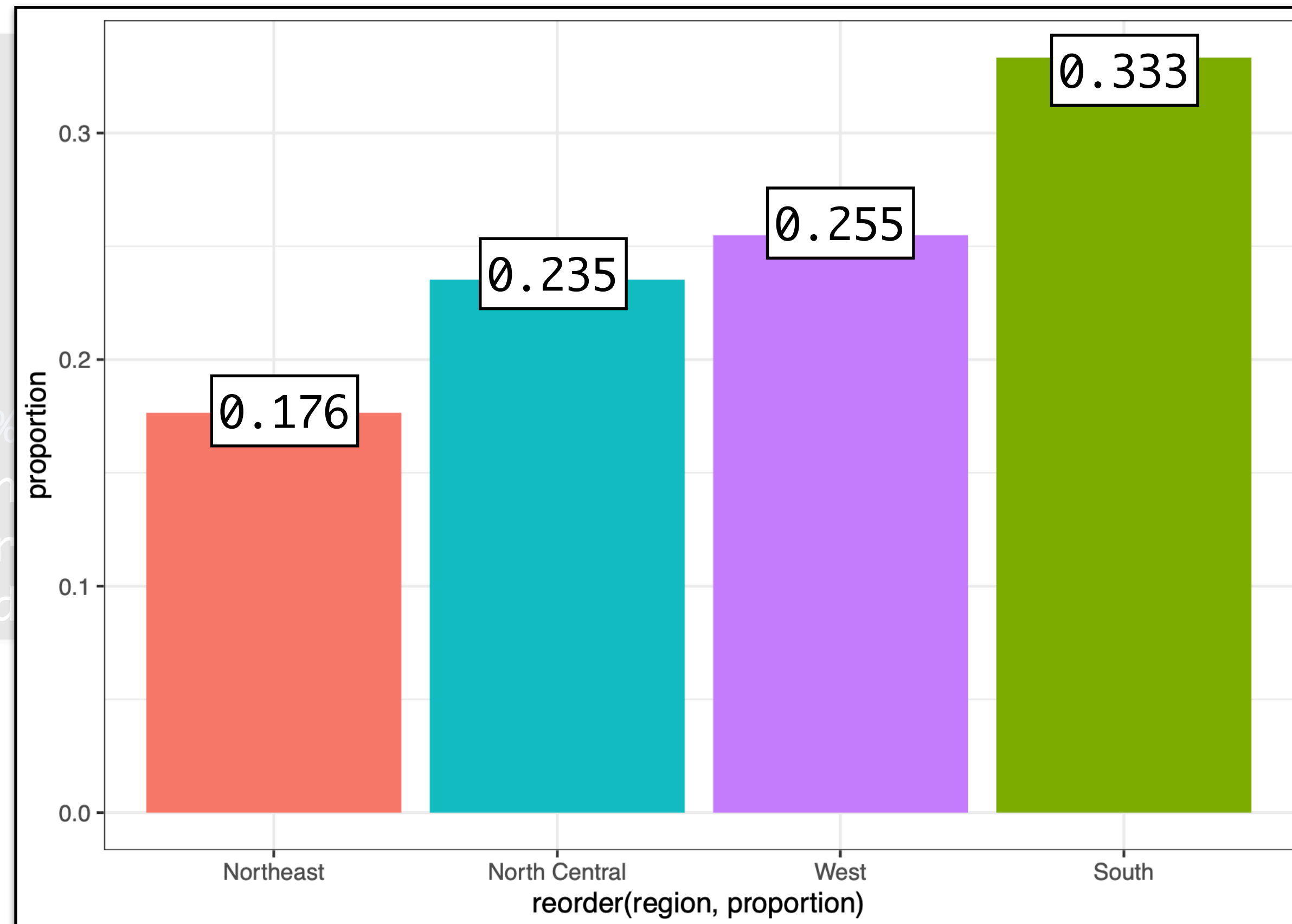


Distribution function

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murders %>%
  group_by(region) %>%
  summarize(proportion = sum(murders) / n())
ggplot(aes(reorder(region, proportion)))
geom_col(show.legend = FALSE)
```



- Note that this figure only show us four numbers
- A frequency table may be better

Cumulative distribution function

- The cumulative distribution function (CDF) is applicable only to ordered data and its define as the proportion of data below some value a :

$$F(a) = P(x \leq a)$$

- Example: CDF of male heights

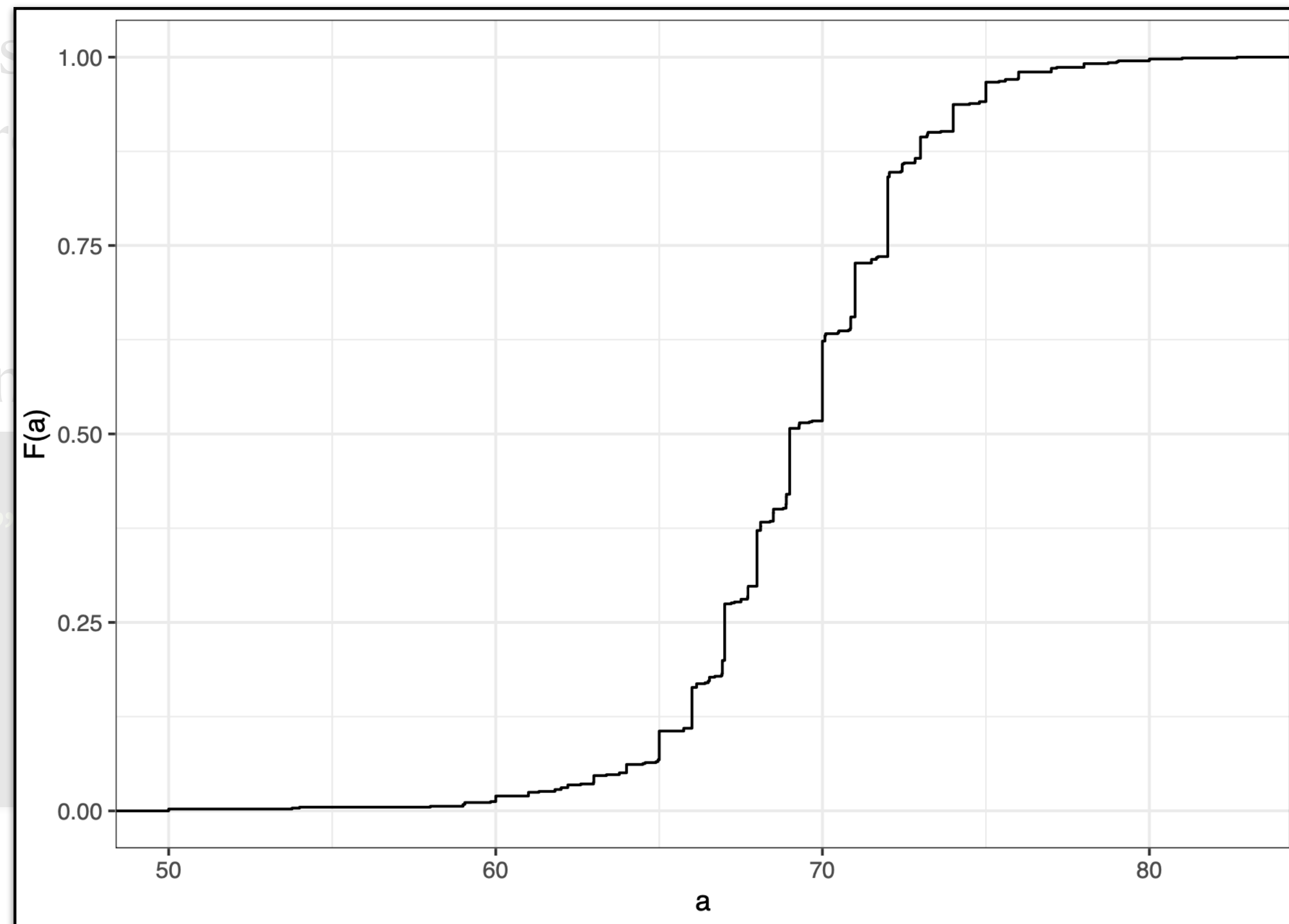
```
heights %>%  
  filter(sex == "Male") %>%  
  ggplot(aes(height)) +  
  stat_ecdf() +  
  xlab("a") +  
  ylab("F(a)")
```

Cumulative distribution function

- The cumulative distribution function (CDF) is defined as the probability that a random variable X is less than or equal to a given value a . It is calculated by ordering the data and then finding the proportion of data points that are less than or equal to a .

- Example: CDF of male heights

```
heights %>%  
  filter(sex == "Male") %>%  
  ggplot(aes(height)) +  
  stat_ecdf() +  
  xlab("a") +  
  ylab("F(a)")
```

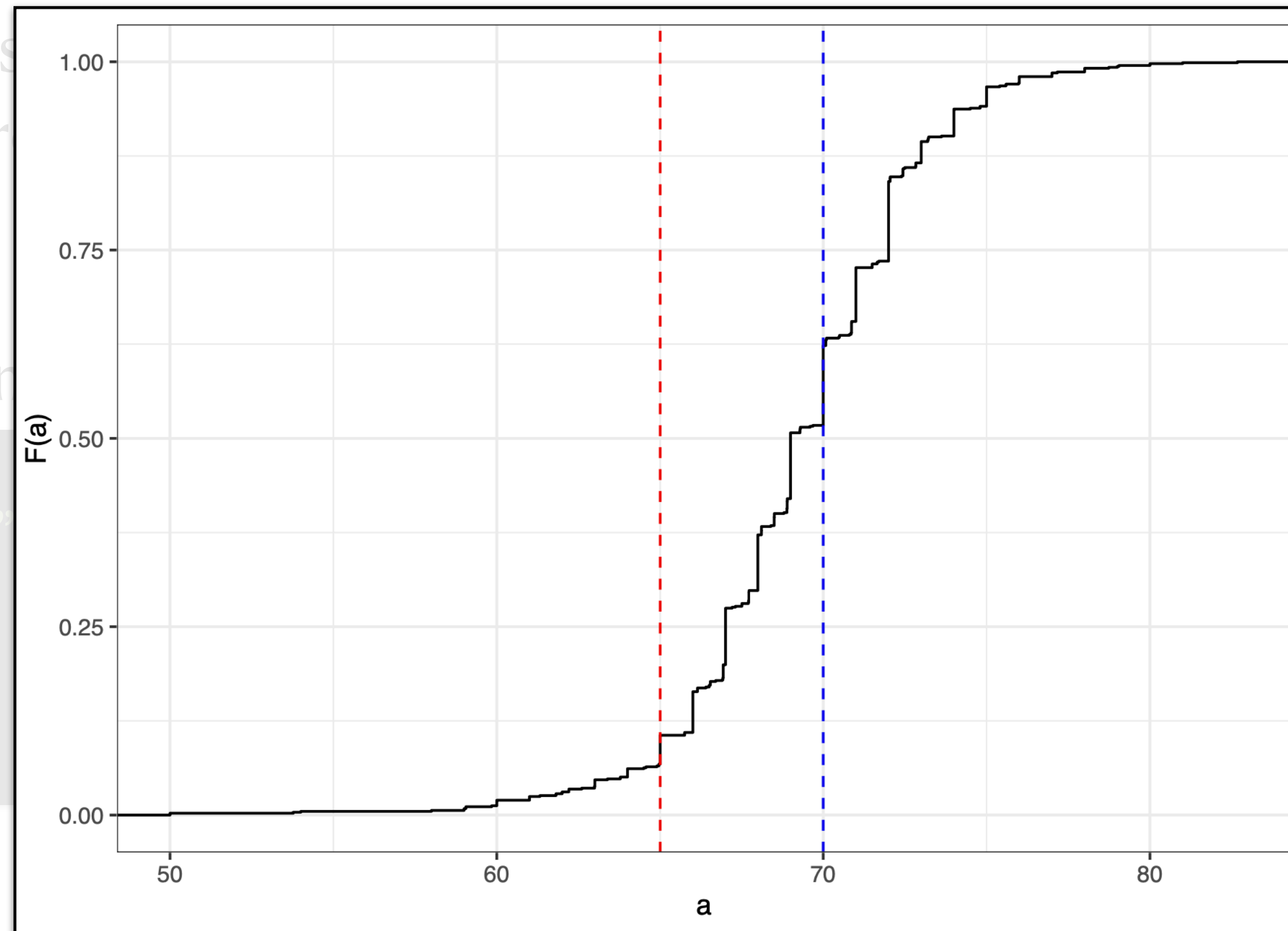


Cumulative distribution function

- The cumulative distribution function (CDF) is defined as the probability that a random variable is less than or equal to a given value. It is calculated by ordering the data and then summing the probabilities of the values less than or equal to the given value.

- Example: CDF of male student heights

```
heights %>%  
  filter(sex == "Male") %>%  
  ggplot(aes(height)) +  
  stat_ecdf() +  
  xlab("a") +  
  ylab("F(a)")
```



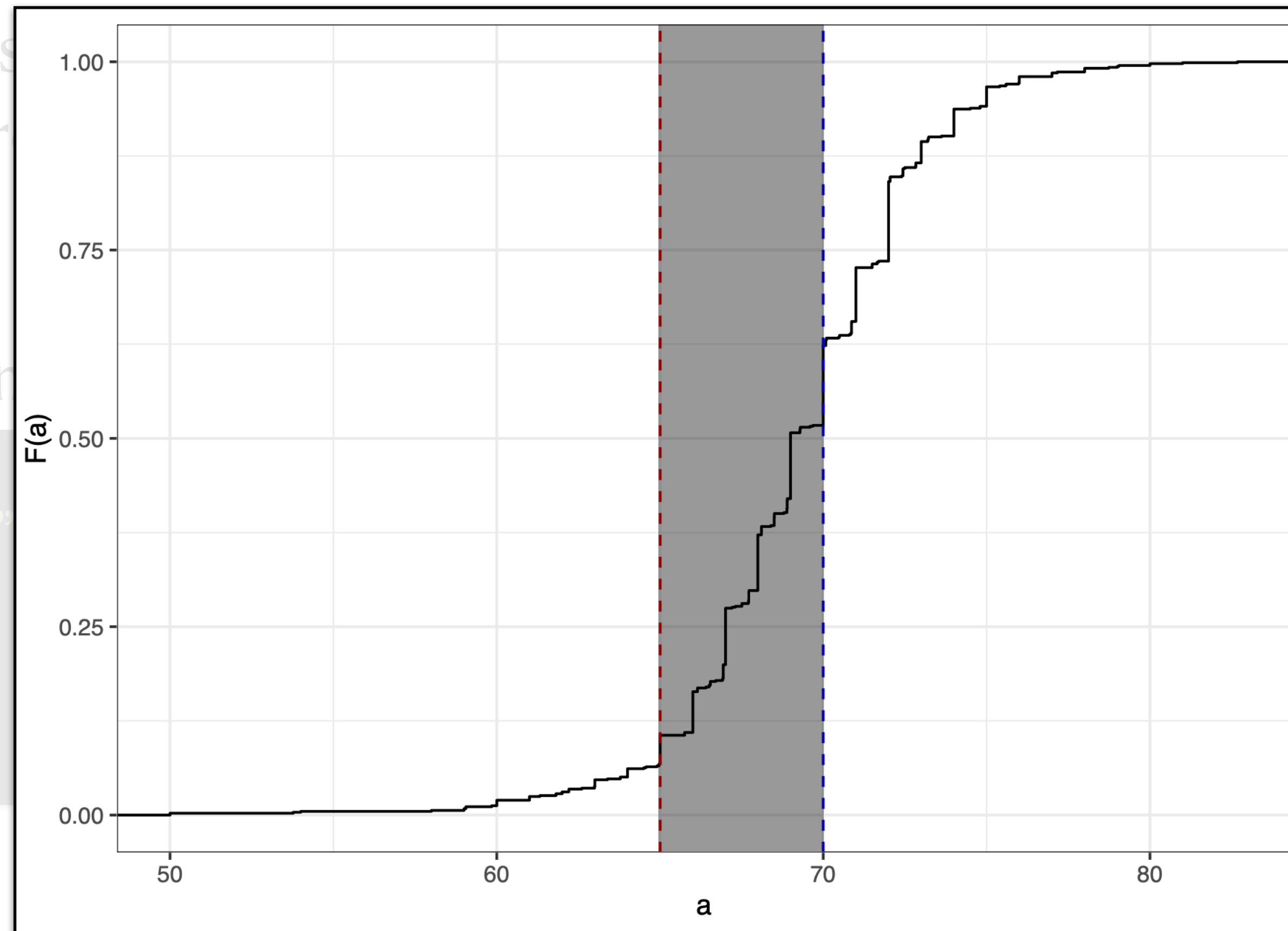
- $F(65) = 0.106$: This implies that 10.6% of male student's height is less than 65in
- $F(70) = 0.623$: This implies that 62.3% of male student's height is less than 70in

Cumulative distribution function

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- Example: CDF of male student heights

```
heights %>%  
  filter(sex == "Male") %>%  
  ggplot(aes(height)) +  
  stat_ecdf() +  
  xlab("a") +  
  ylab("F(a)")
```



- $F(70) - F(65) = 0.517$: This implies that 51.7% of male student's height is between 65 and 70 inches

Histograms

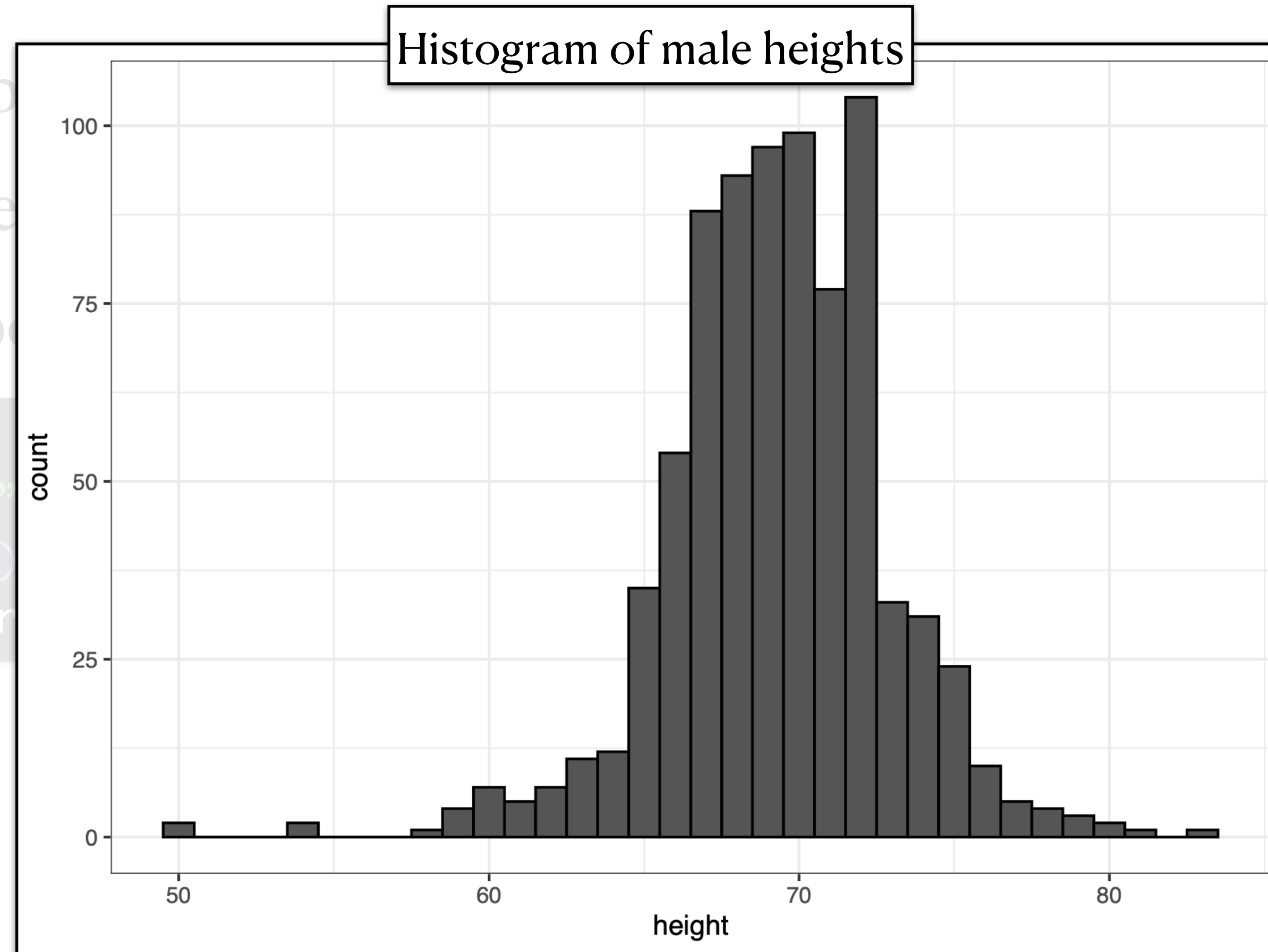
- A histogram depicts a frequency distribution of numeric data
- The *x-axis* is divided into non-overlapping bins of the same size
- The *y-axis* corresponds to the number of values that fall within each bin

```
heights %>%  
  filter(sex == "Male") %>%  
  ggplot(aes(x=height)) +  
  geom_histogram(color="black", binwidth = 1)
```

Histograms

- A histogram is depicted as a series of vertical bars
- The *x-axis* is divided into bins
- The *y-axis* corresponds to the count of observations in each bin

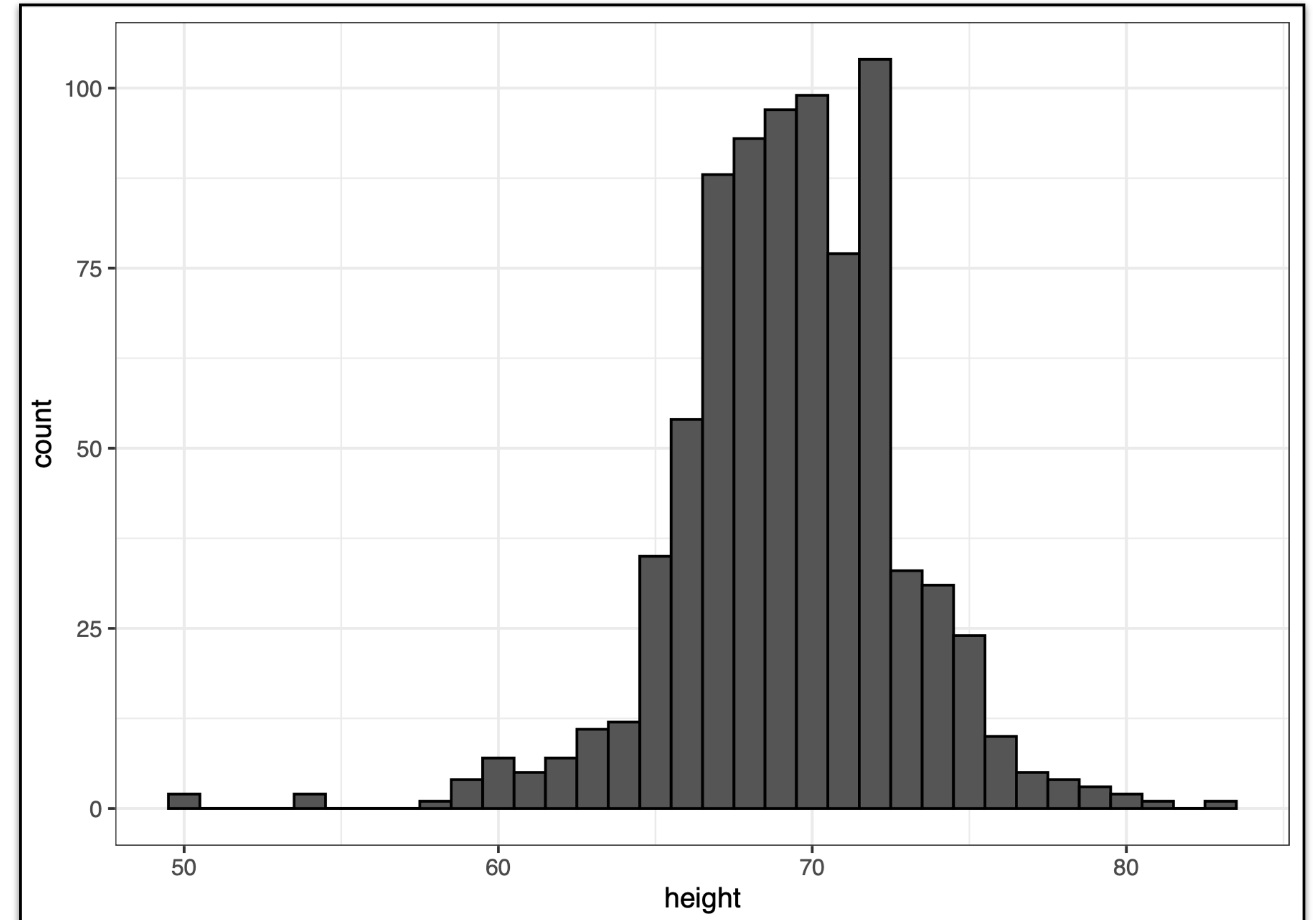
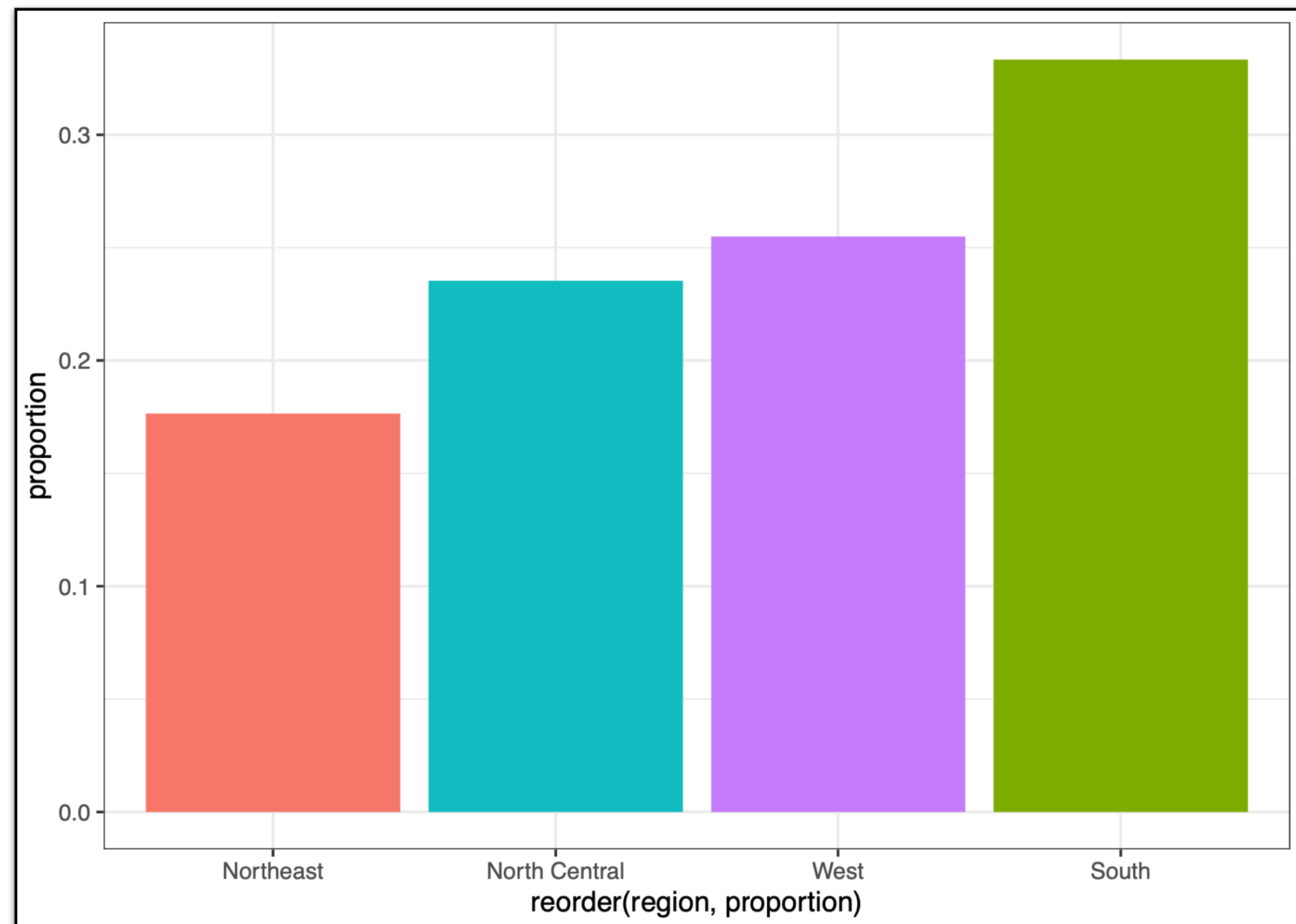
```
heights %>%  
  filter(sex == "Male") %>%  
  ggplot(aes(x=height)) +  
  geom_histogram(color="black", fill="darkgray")
```



- The *x-axis* is split into 1 inch bins
- $(49.5, 50.5]$, $(50.5, 51.5]$, ..., $(82.5, 83.5]$

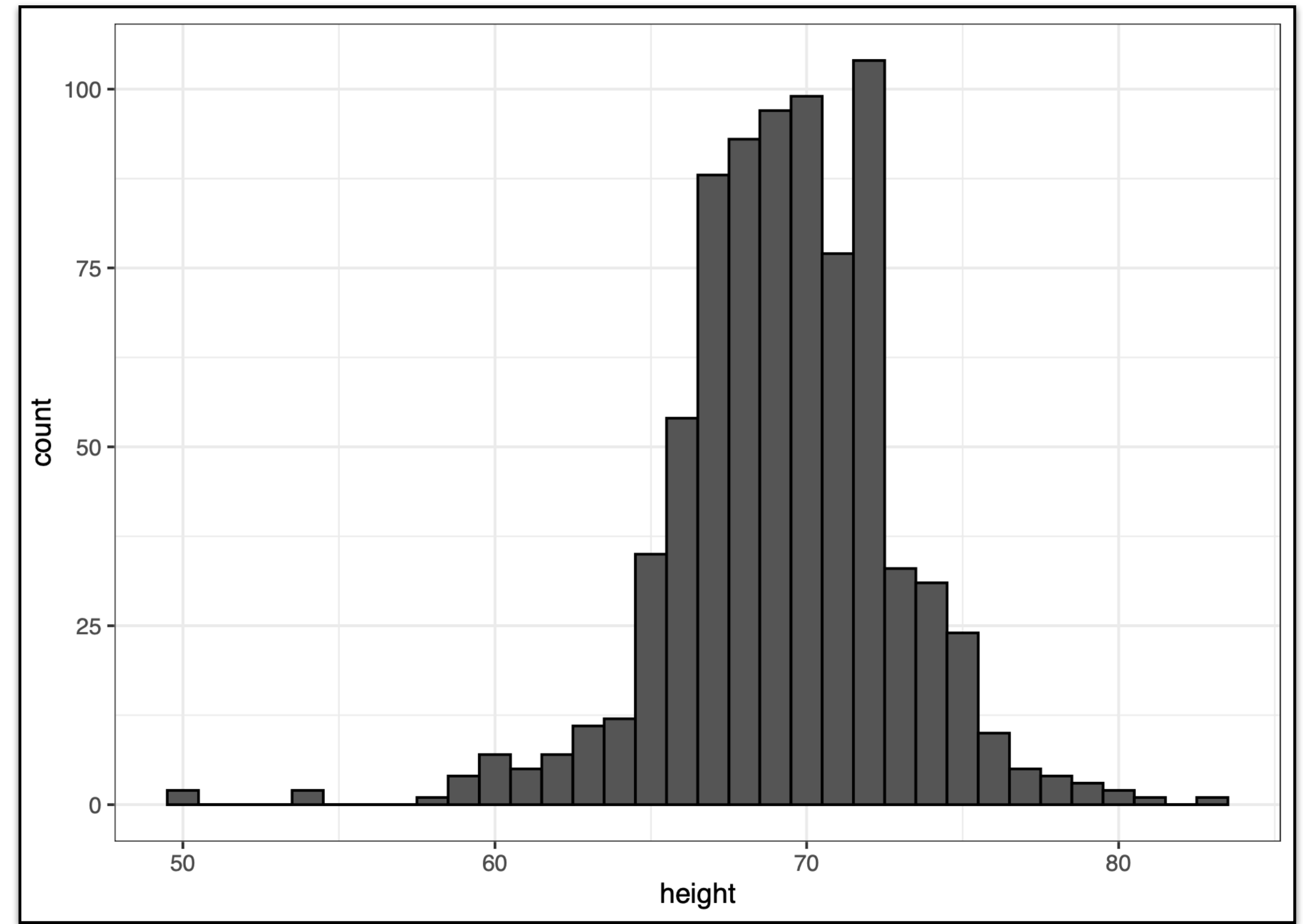
Histograms

- Note that a histogram is similar to a barplot but the *x-axis* is numerical



Histograms

- From this we see:
 - Range: [50in, 84in]
 - Most of the data is between 63in and 75in
 - The distribution is more or less symmetric around 69in



Smoothed density

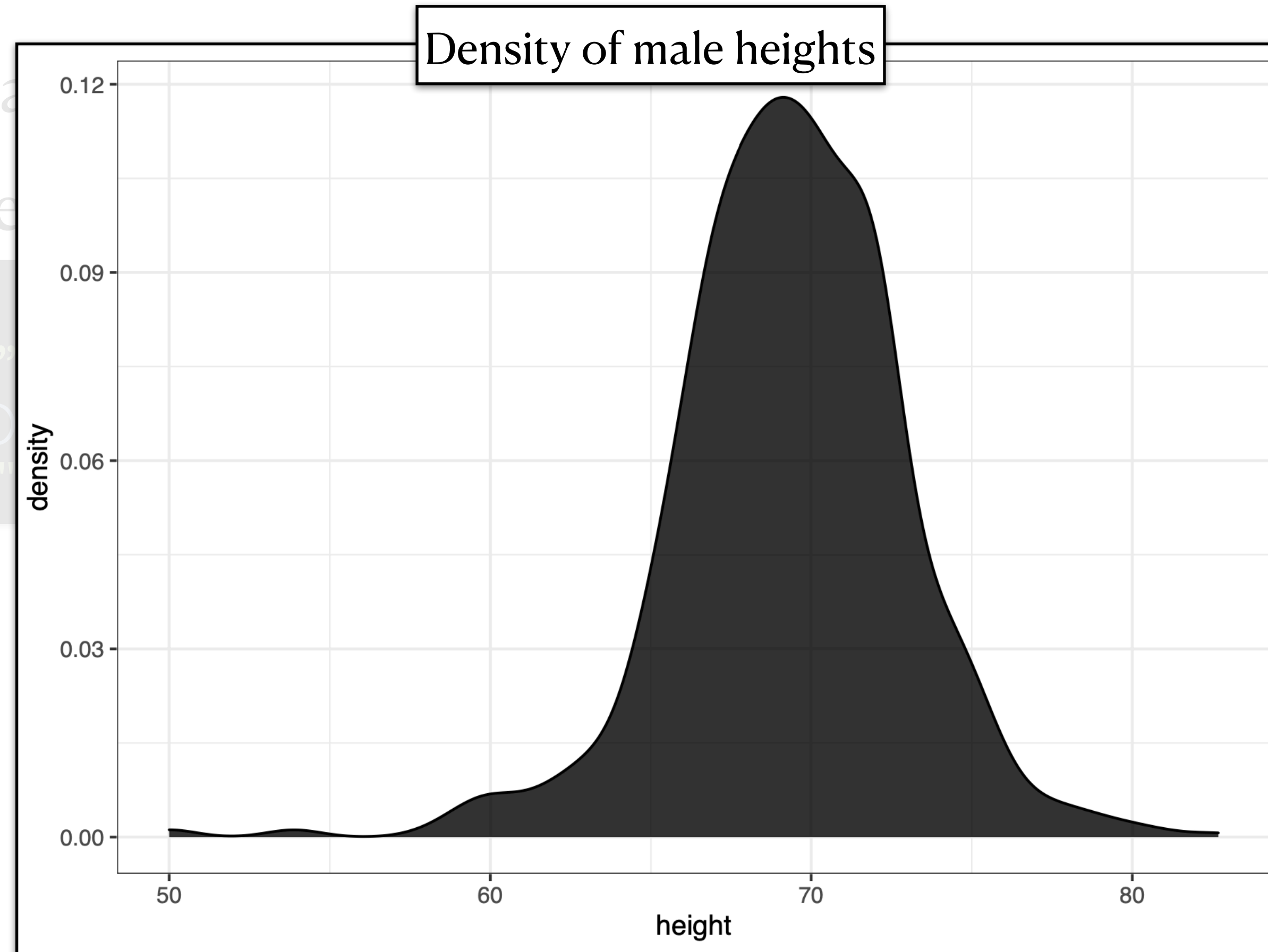
- Smooth densities are more aesthetically pleasing than histograms
- Here is an example:

```
heights %>%  
  filter(sex == "Male") %>%  
  ggplot(aes(x=height)) +  
  geom_density(fill="black", alpha = 0.80)
```

Smoothed density

- Smooth densities are
- Here is an example

```
heights %>%  
  filter(sex == "Male")  
  ggplot(aes(x=height))  
  geom_density(alpha=0.5)
```



Smoothed density

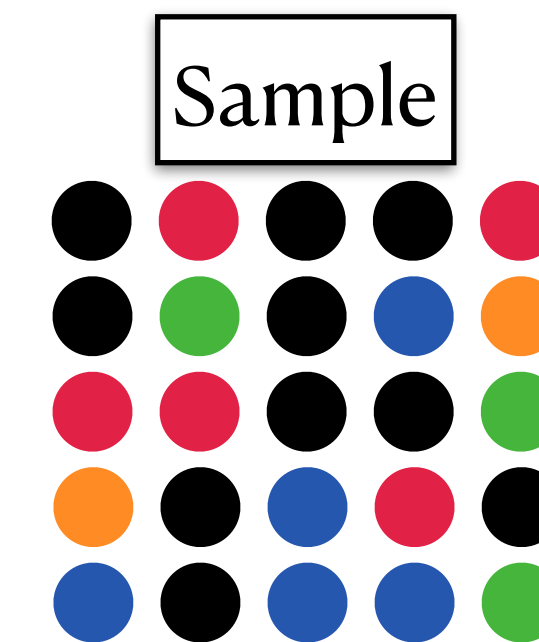
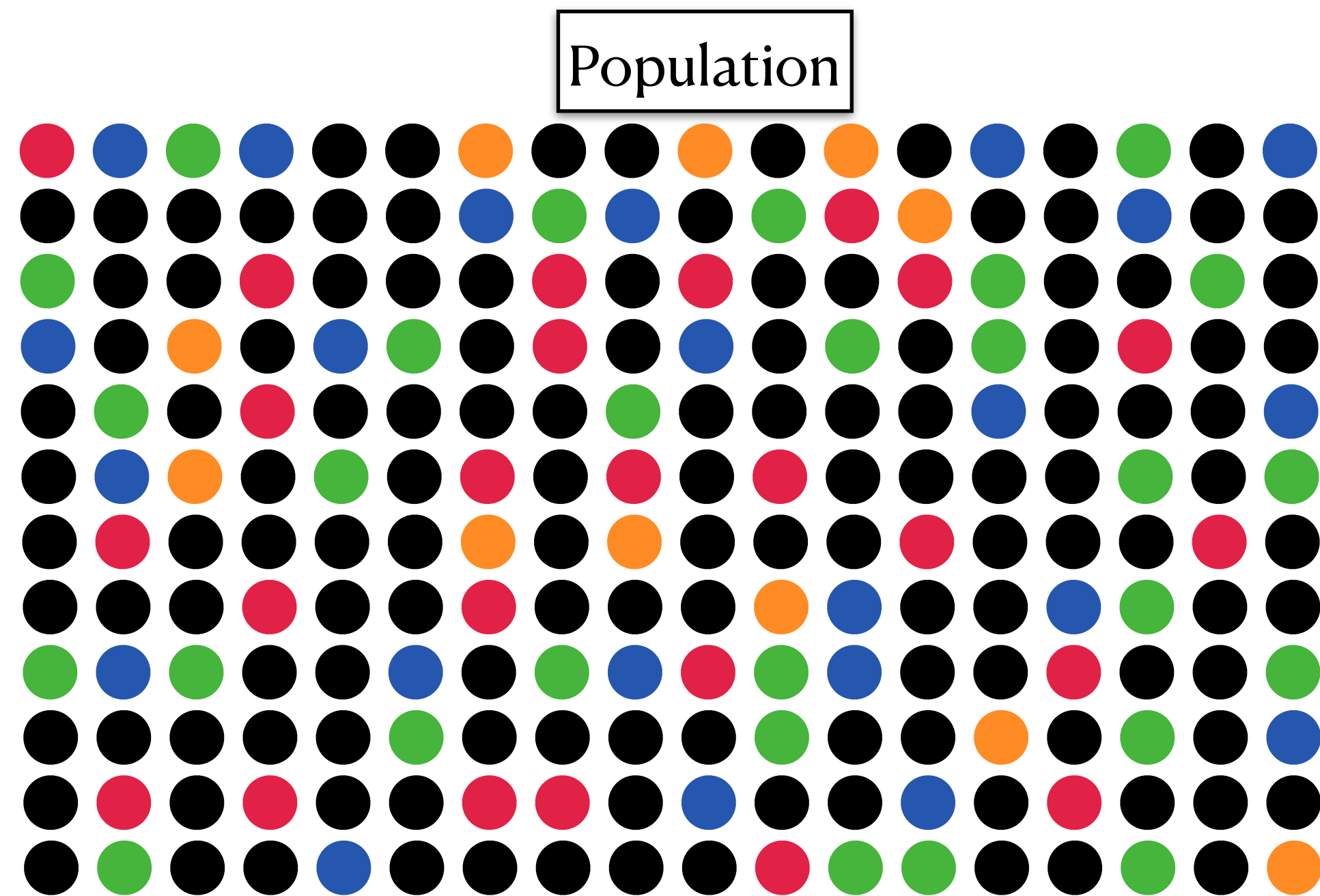
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```

- Note that the sharp edges at the interval boundaries are gone
- The local peaks are no more
- The *y-axis* changed from counts to density

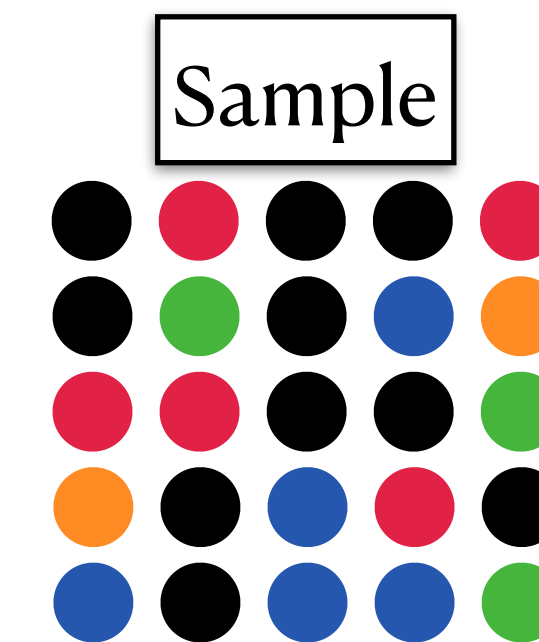
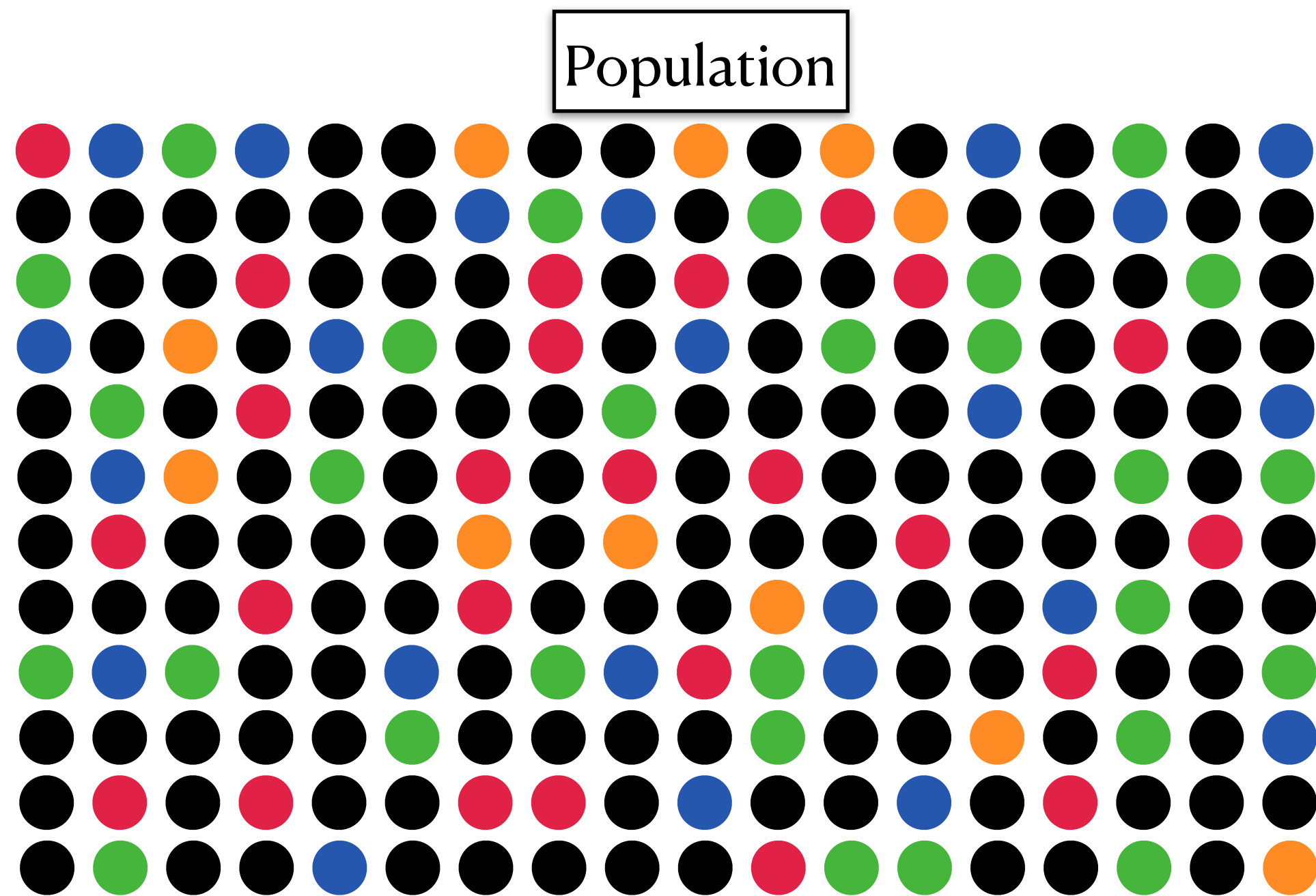
Understanding smooth densities

- We assume that our list of observed values is a subset of much larger list of unobserved values



Understanding smooth densities

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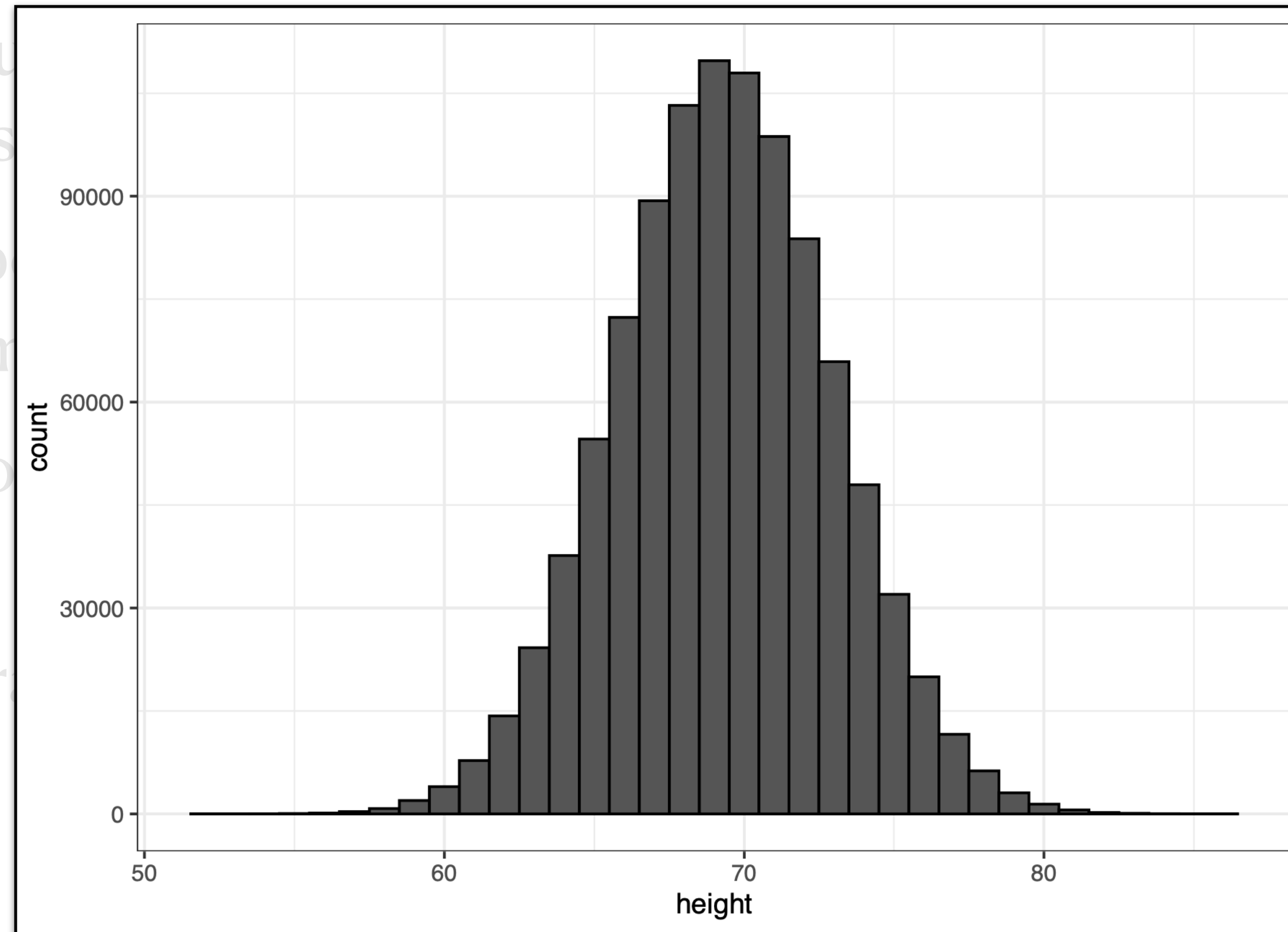
- For example, suppose that our list of 812 male students comes from a hypothetical population of all male students in the world

Understanding smooth densities

- We assume that our list of observed values is a subset of much larger list of unobserved values
- For example, suppose that our list of 812 male students comes from a hypothetical population of all male students in the world
- Specifically, suppose that the size of the population is 1,000,000 and that we have access to it
- Here is the histogram

Understanding smooth densities

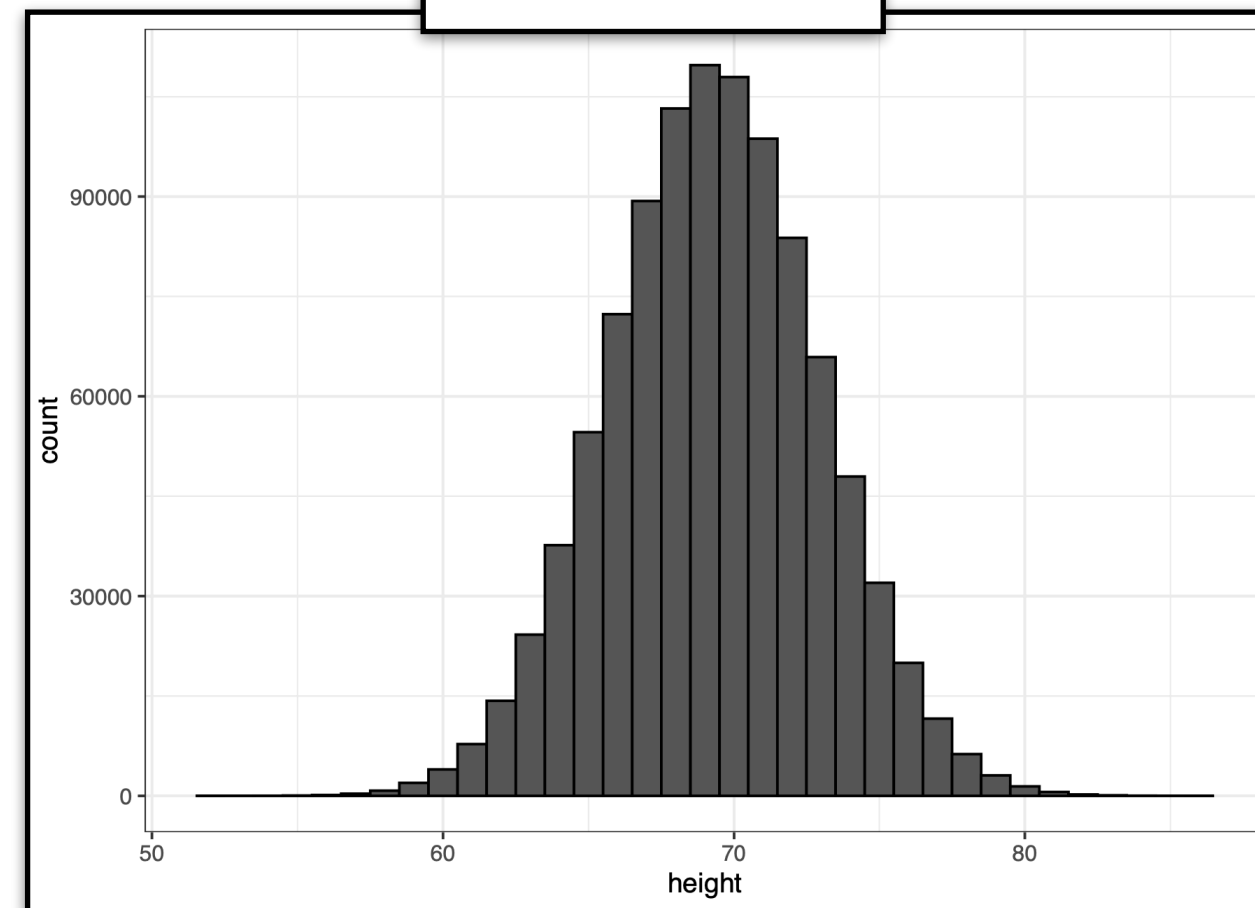
- We assume that our data is a random sample from a larger list of unobserved values
- For example, suppose we have a population of all men in the United States
- Specifically, suppose we have access to it
- Here is the histogram



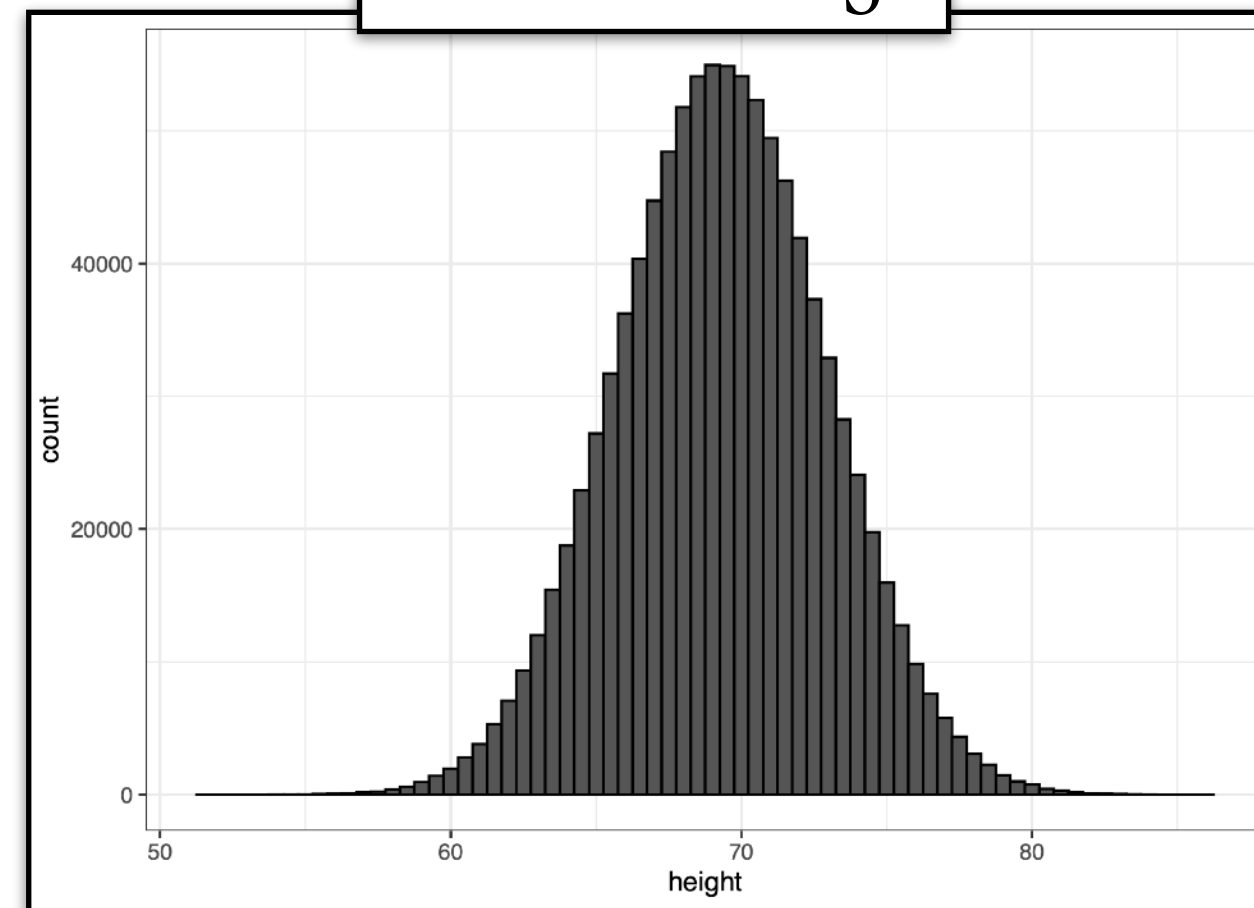
- Bins of 1 inch

Understanding smooth densities

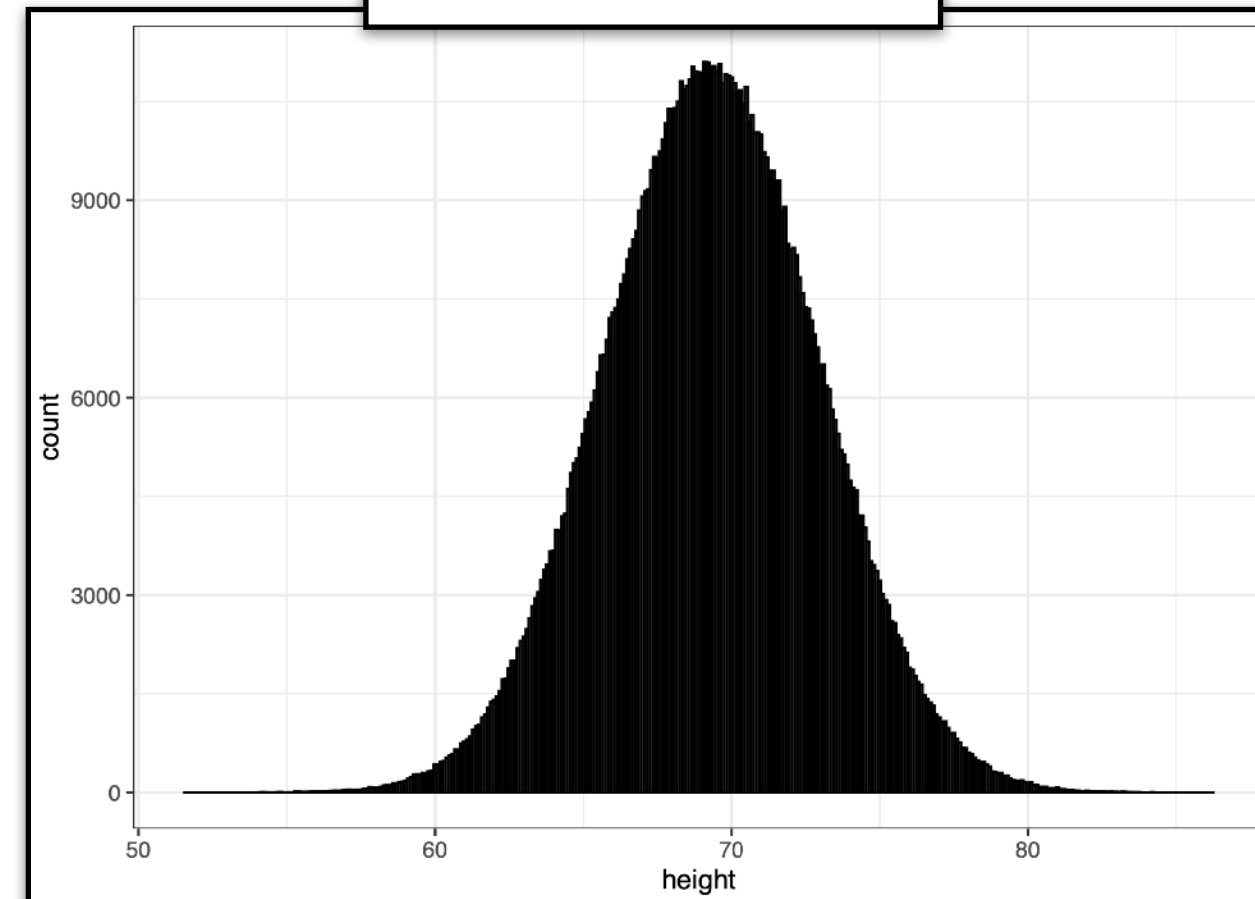
bandwidth = 1



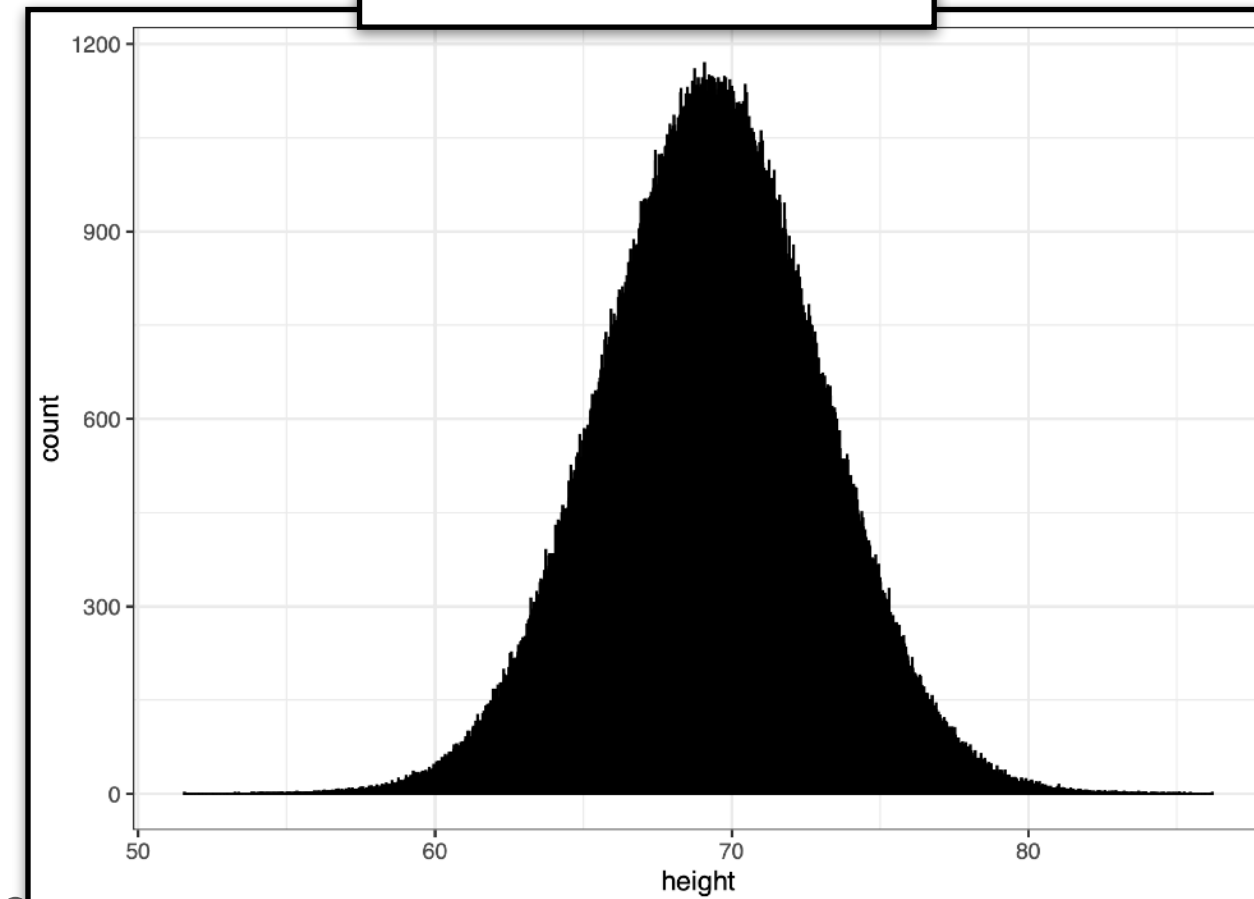
bandwidth = 0.50



bandwidth = 0.10

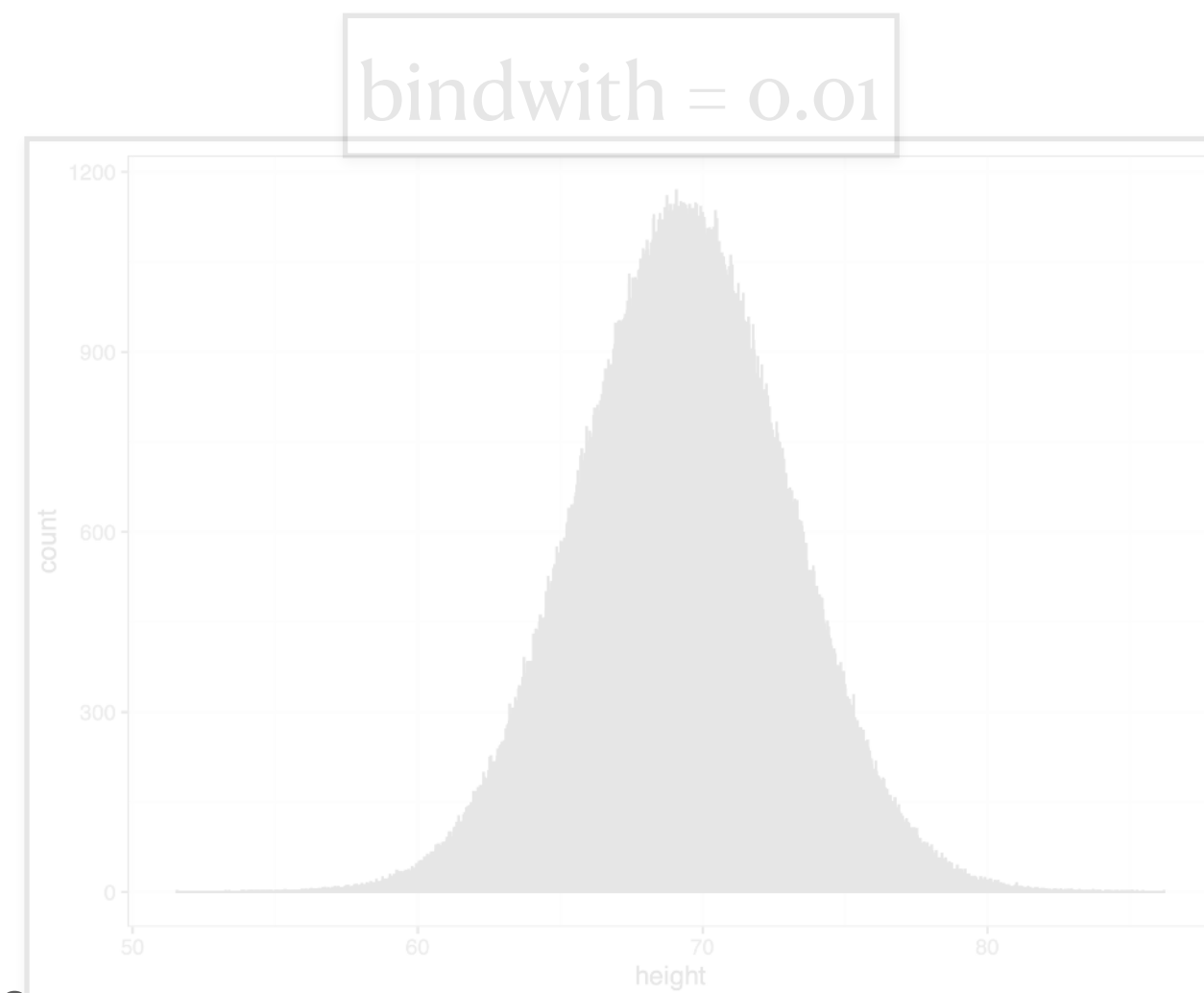
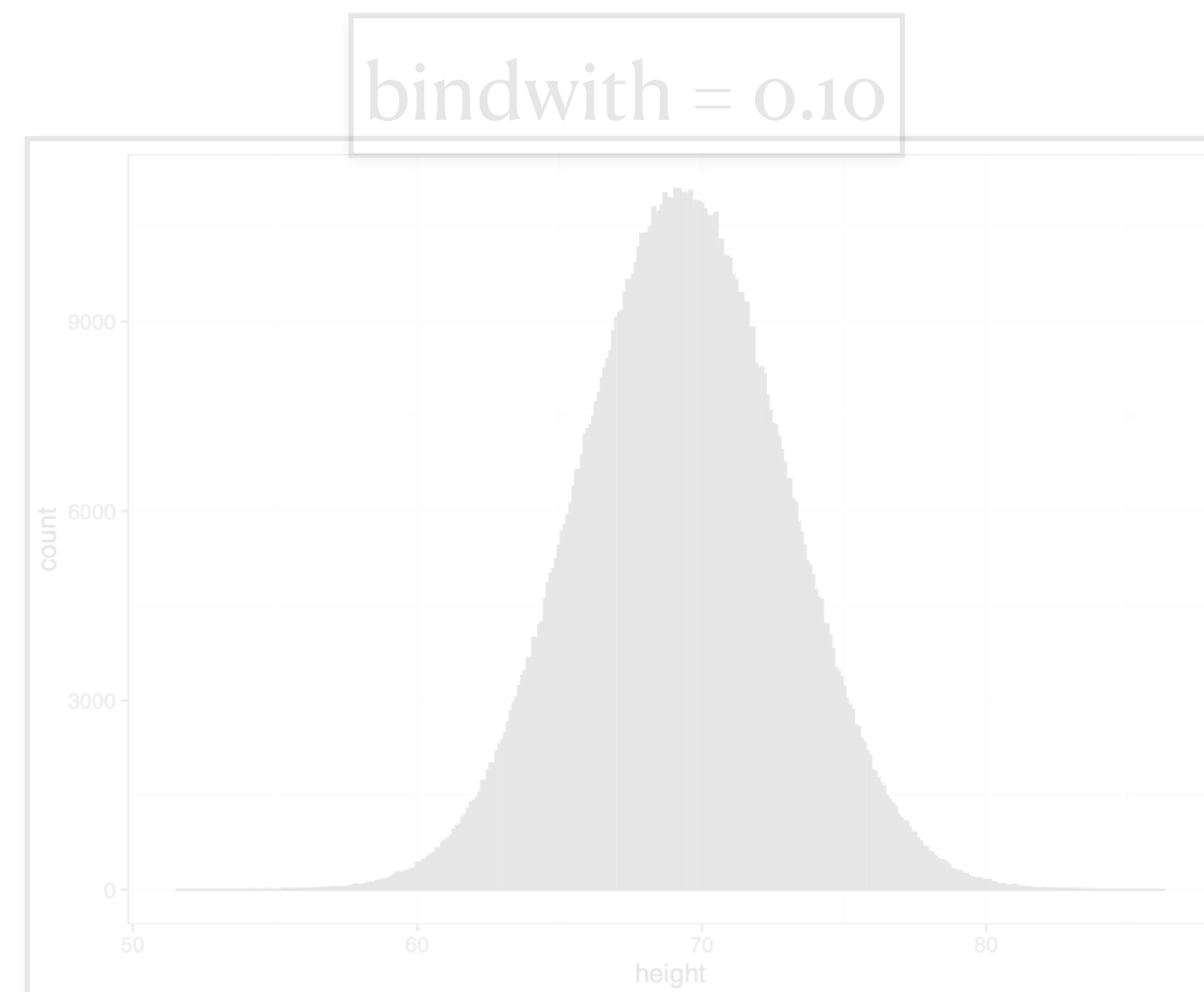
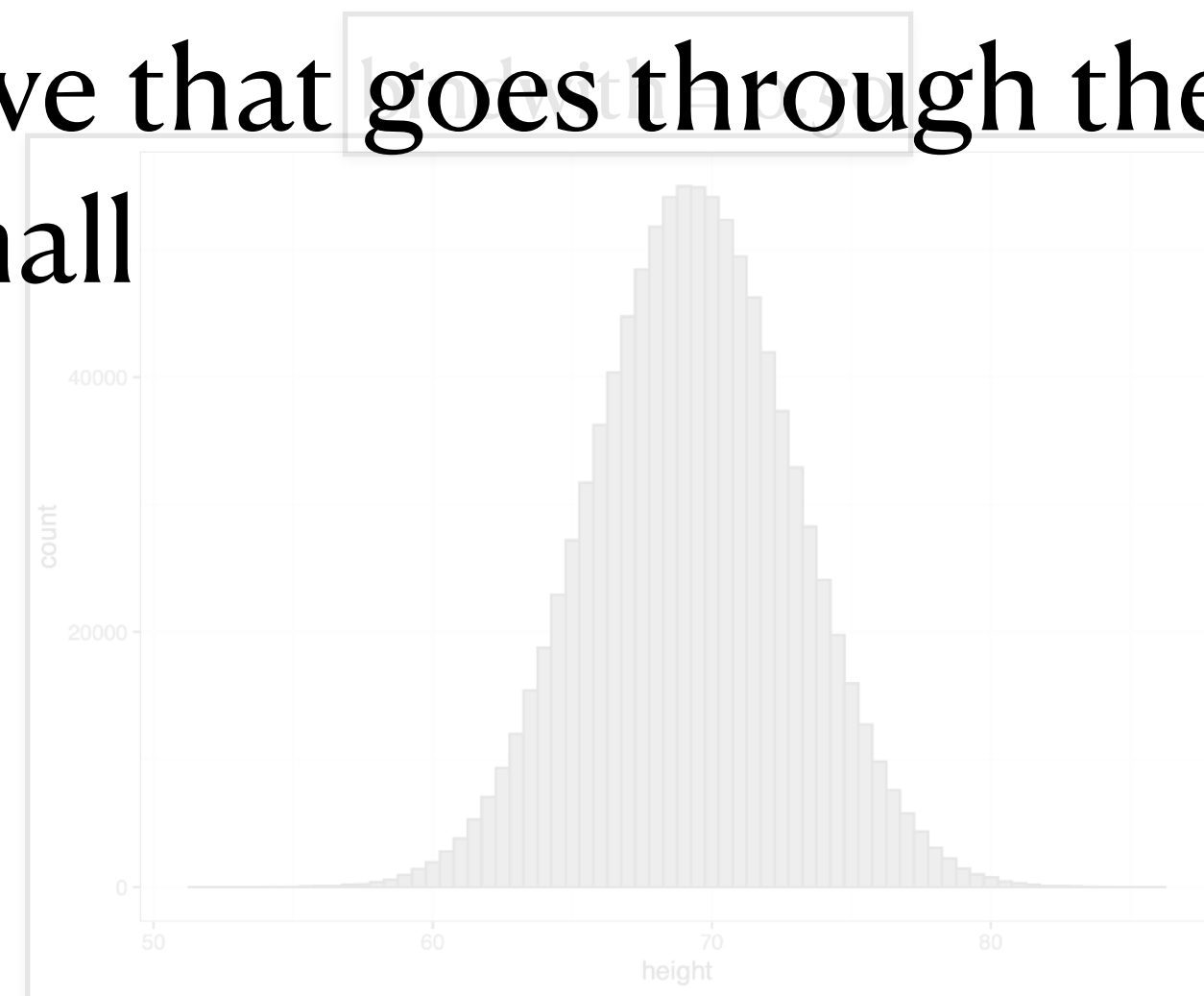
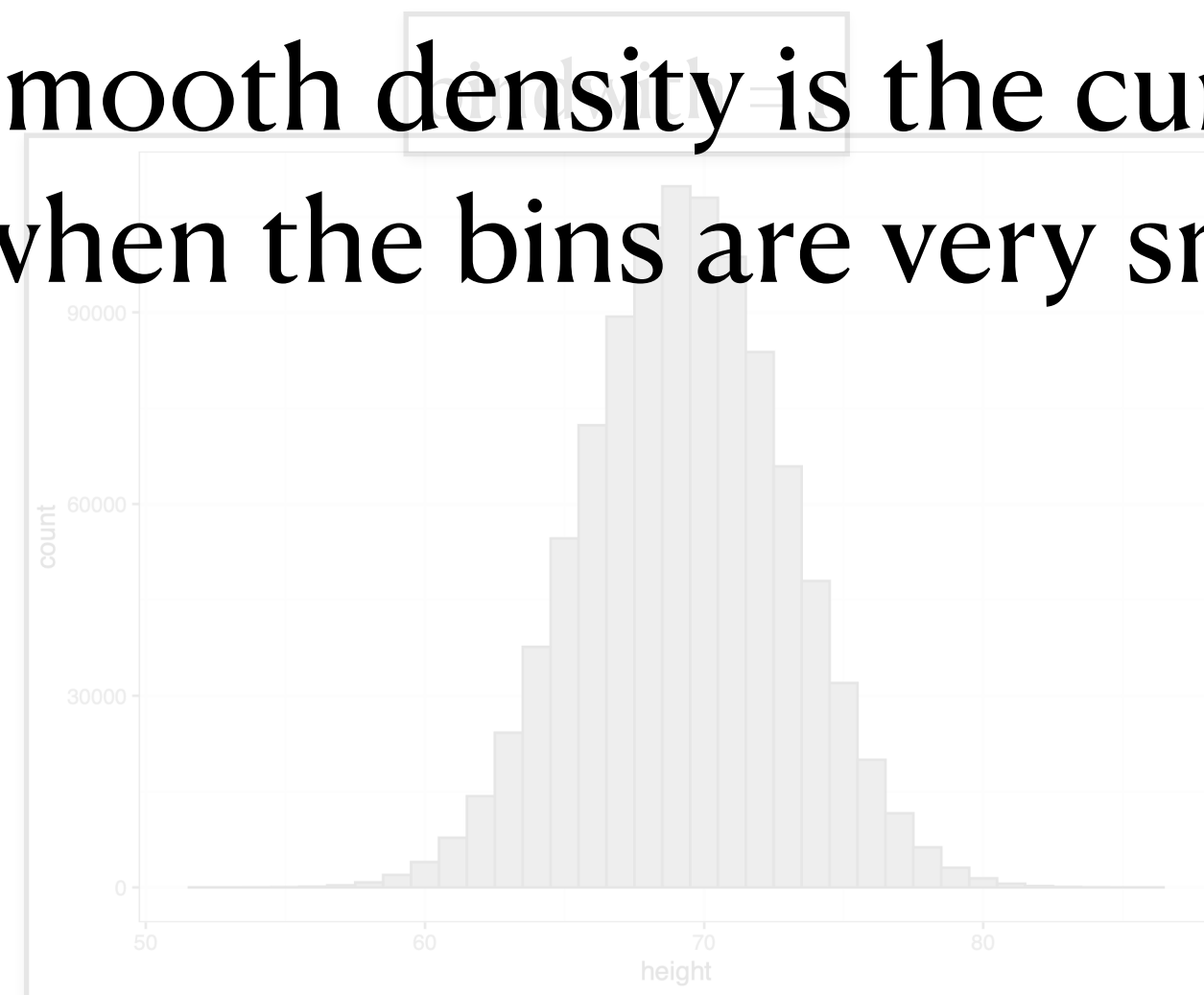


bandwidth = 0.01



Understanding smooth densities

- Essentially, the smooth density is the curve that goes through the top of the histogram bars when the bins are very small



Understanding smooth densities

- Now back to reality, all we have access to is the list of 812 male students

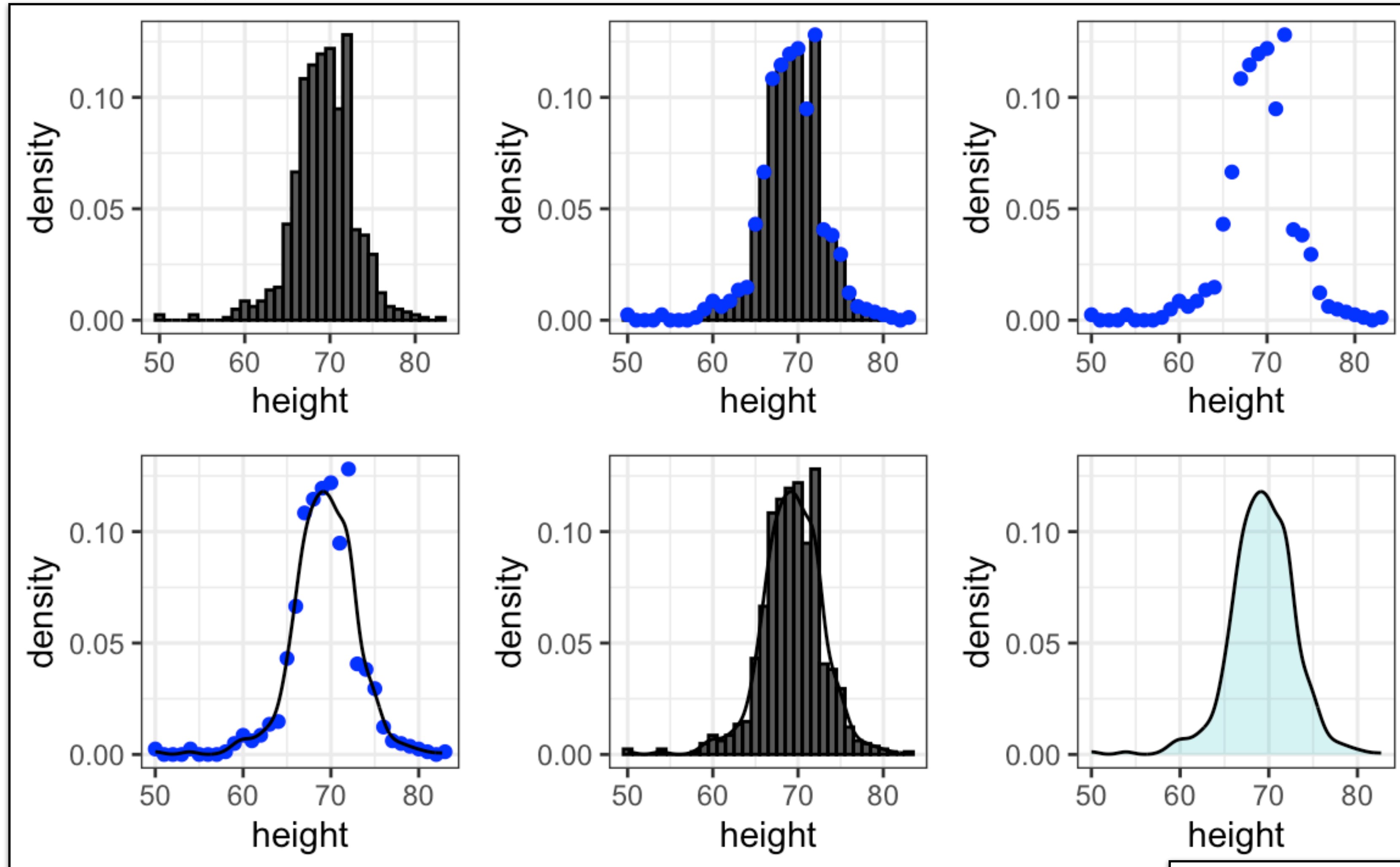
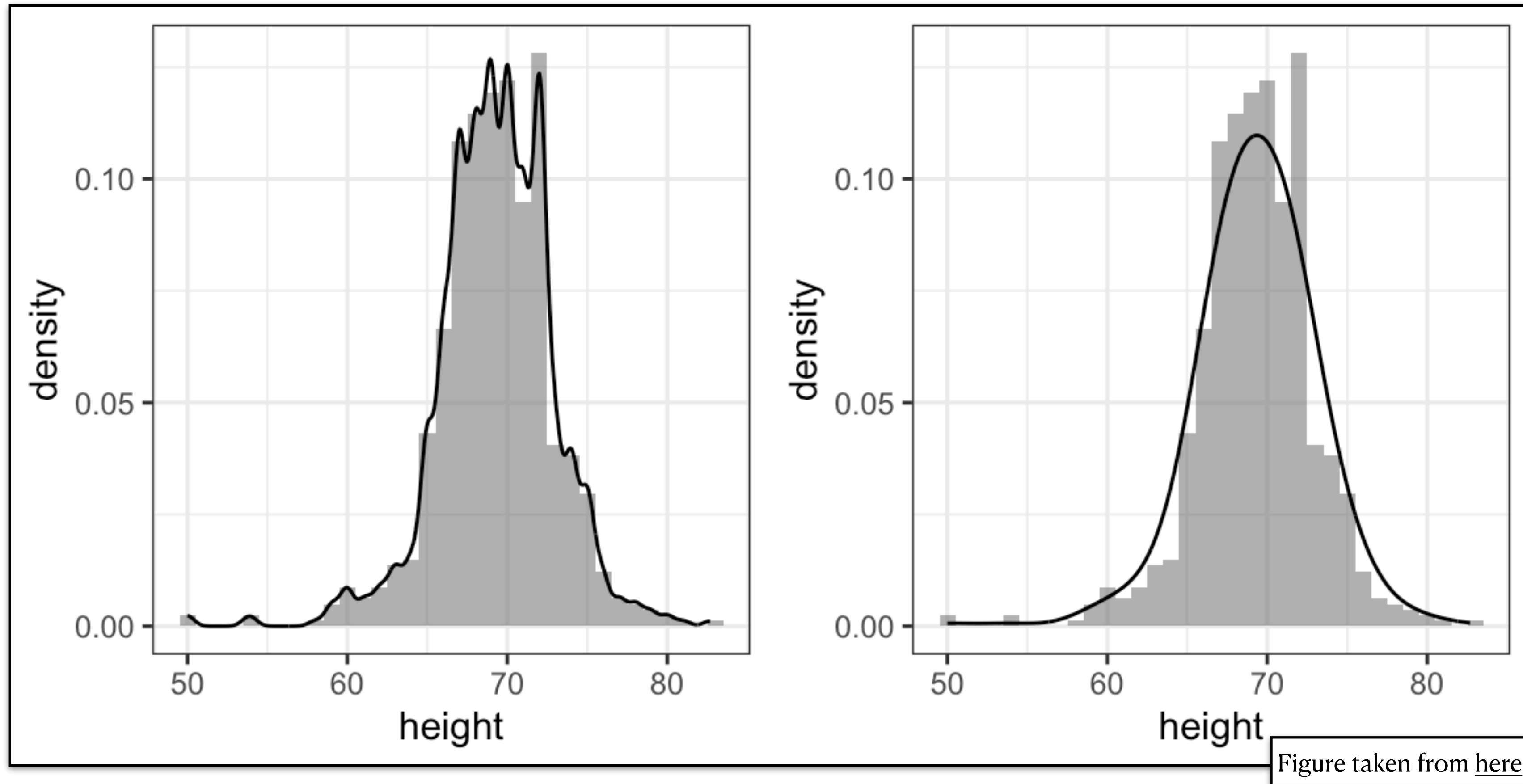


Figure taken from [here](#)

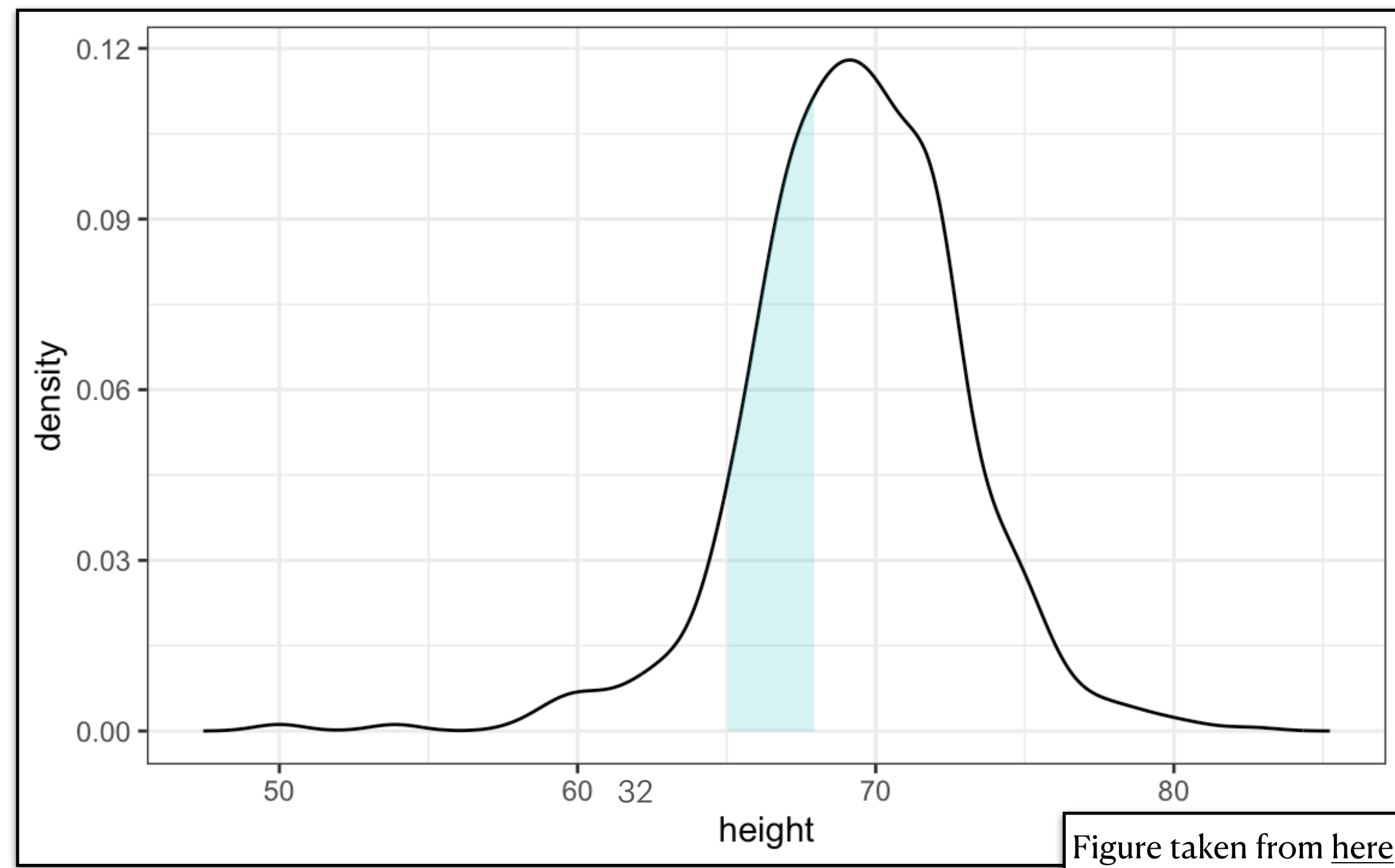
Understanding smooth densities

- However, *smooth* is relative term. We can control the smoothness of the curve



Smooth densities: The *y*-axis

- Densities are scaled so that the area under the curve is equal to 1
- To know the proportion of data in some interval $[a, b]$ we have to compute the proportion of the total area that's inside the interval
- For example: the proportion between 65 and 68 is around 0.30



Smooth densities: Stratification

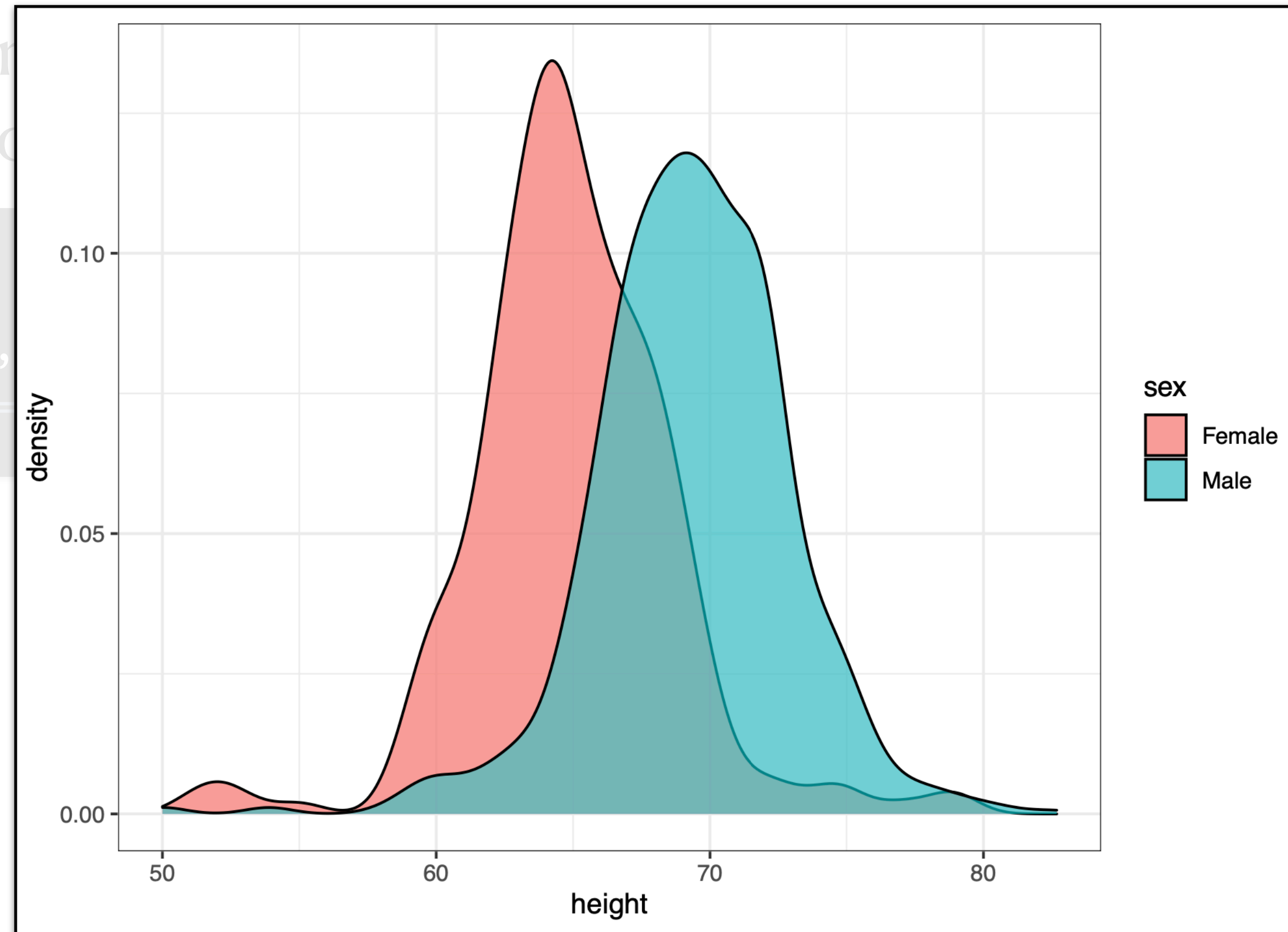
- One more appealing aspect of densities over histograms is that its easier to visualize multiple distributions

```
heights %>%  
  ggplot(aes(x=height, fill=sex)) +  
  geom_density(alpha = 0.80)
```

Smooth densities: Stratification

- One more appealing way to visualize multiple distributions

```
heights %>%  
  ggplot(aes(x=height,  
             geom_density(alpha =
```



The Normal distribution

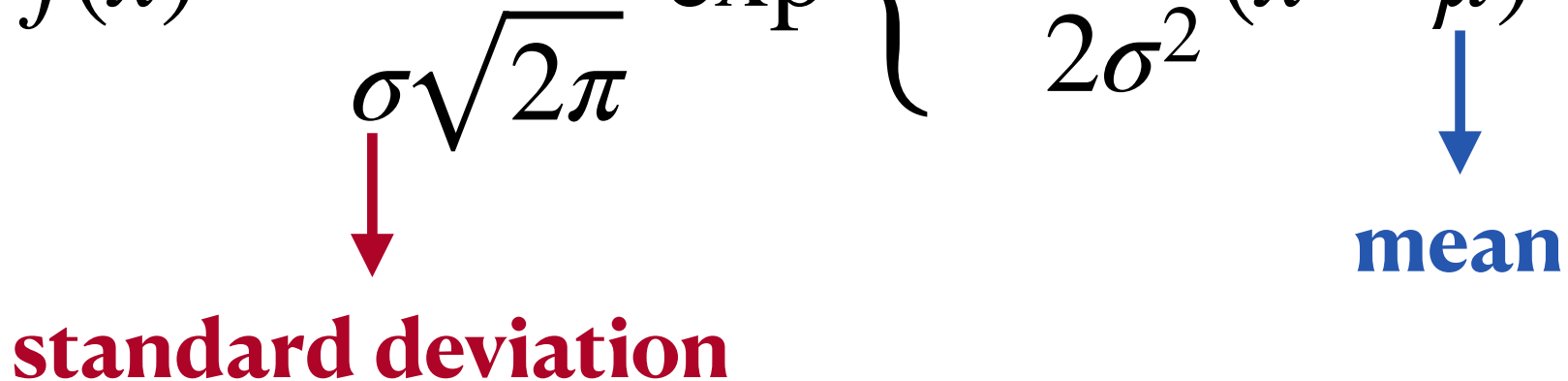
- Histograms and densities provide excellent ways of summarizing data
- Can we further summarize our data? A two-number summary?
- The Normal distribution, also known as the bell curve or the Gaussian distribution, has the following density function:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp \left\{ -\frac{1}{2\sigma^2}(x - \mu)^2 \right\}$$

The Normal distribution

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standard deviation **mean**

- No need to memorize this, just note that this distribution is completely defined by two numbers

The Normal distribution

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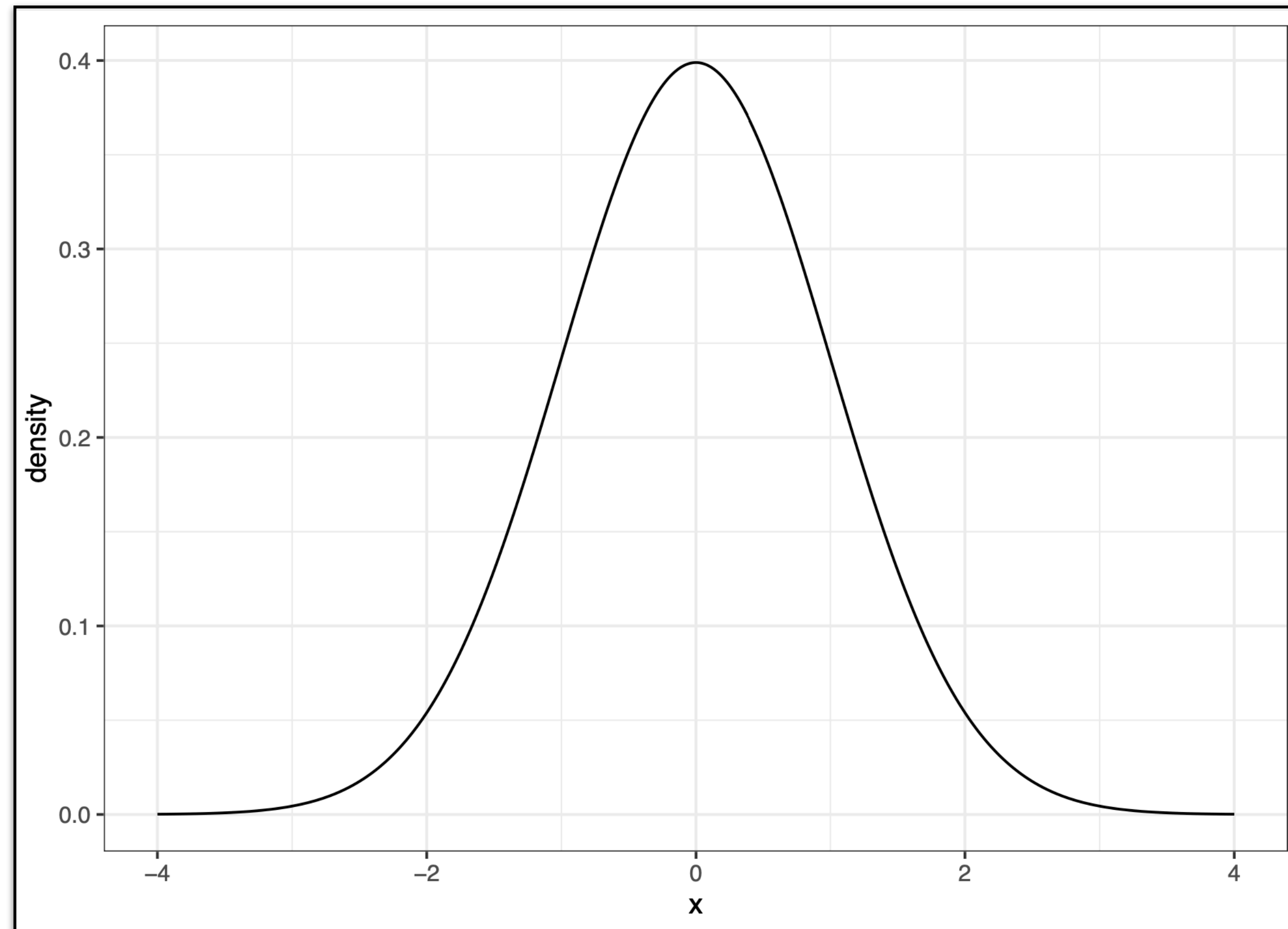

standard deviation mean

- We find the proportion between two numbers (a, b) with:

$$P(a < x < b) = \int_a^b \frac{1}{\sigma\sqrt{2\pi}} \exp \left\{ -\frac{1}{2\sigma^2}(x - \mu)^2 \right\}$$

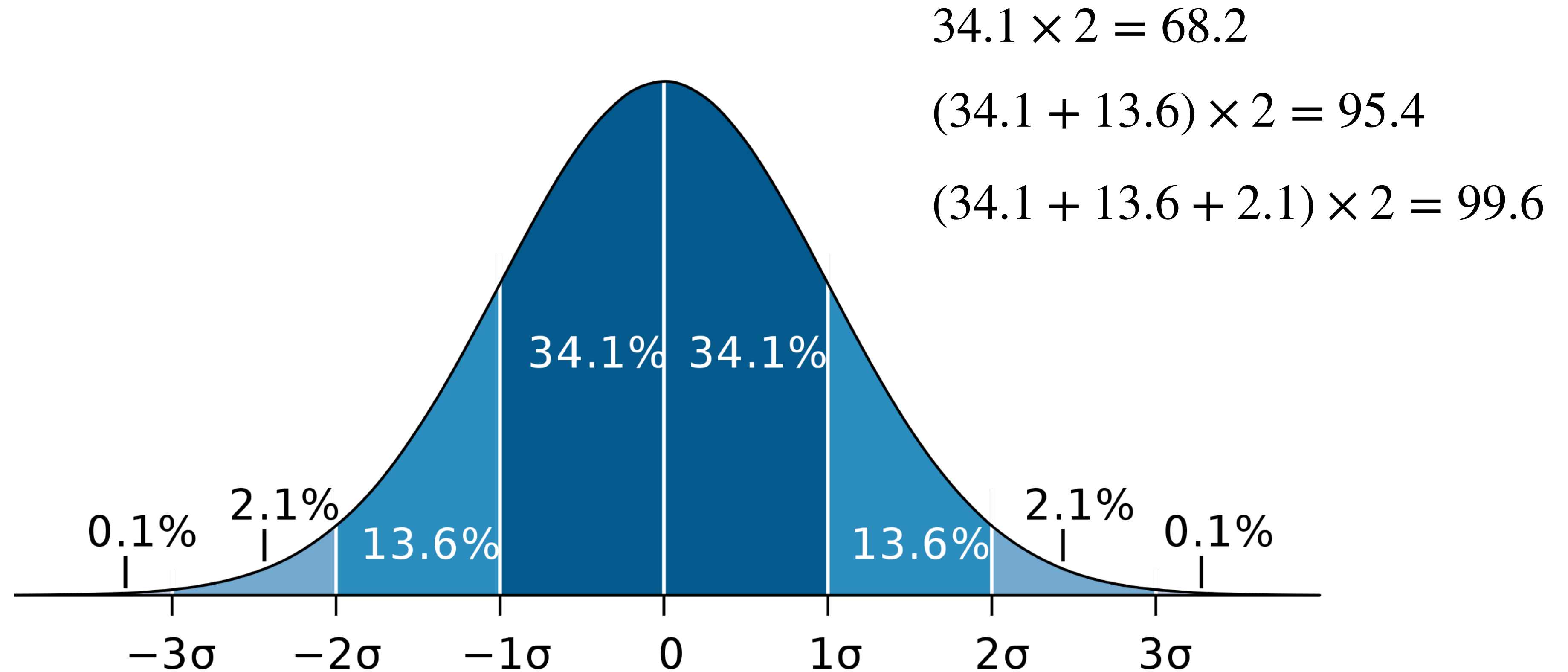
The Normal distribution

- Here is the density of a normal distribution with mean 0 and standard deviation 1



The Normal distribution

- Here is the density of a normal distribution with mean 0 and standard deviation 1



The Normal distribution

- Suppose that we have a list of data: $\{x_1, \dots, x_n\}$
- Then we can compute the average with:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$

- and we can compute the standard deviation with:

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}$$

- In R we can compute these quantities with:

```
mean(x)  
sd(x)
```


The Normal distribution

- Let's see how the normal distribution approximates the empirical distribution of male heights

```
index <- heights$sex == "Male"
x      <- heights$height[index]
m      <- mean(x)
s      <- sd(x)
```

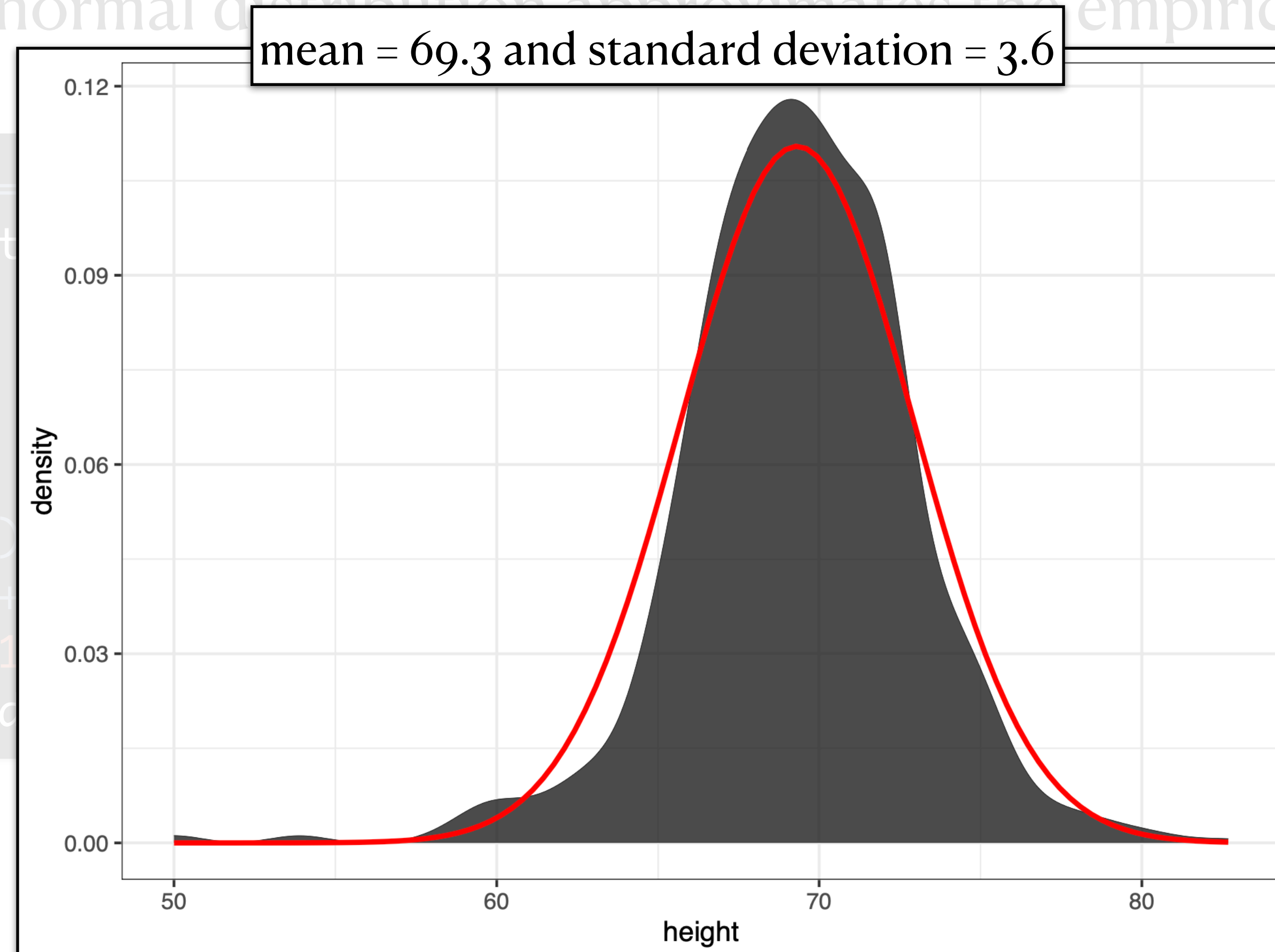
```
heights %>%
  filter(sex == "Male") %>%
  ggplot(aes(height)) +
  geom_density(size=0.10, fill="black", alpha=0.70) +
  stat_function(fun = dnorm, size=1, args = list(mean = m, sd = s), color="red")
```

The Normal distribution

- Let's see how the normal distribution approximates the empirical distribution of male heights

```
index <- heights$sex ==  
x      <- heights$height  
m      <- mean(x)  
s      <- sd(x)
```

```
heights %>%  
  filter(sex == "Male")  
  ggplot(aes(height)) +  
    geom_density(size=0.1,  
    stat_function(fun = d
```



- The normal distribution seems to be a good approximation for male heights

Standard units

- We can talk in terms of *standard units* for data that is approximately normally distributed.
- The standard unit of a value tell us how many standard deviations away from the average it is.
- For a value x from a list of values $\{x_1, \dots, x_n\}$ we define the value of x in standard units as:

$$z = \frac{x - \mu \rightarrow \text{mean}}{\sigma \rightarrow \text{standard deviation}}$$

Standard units

- Recall the density function of a normal distribution:

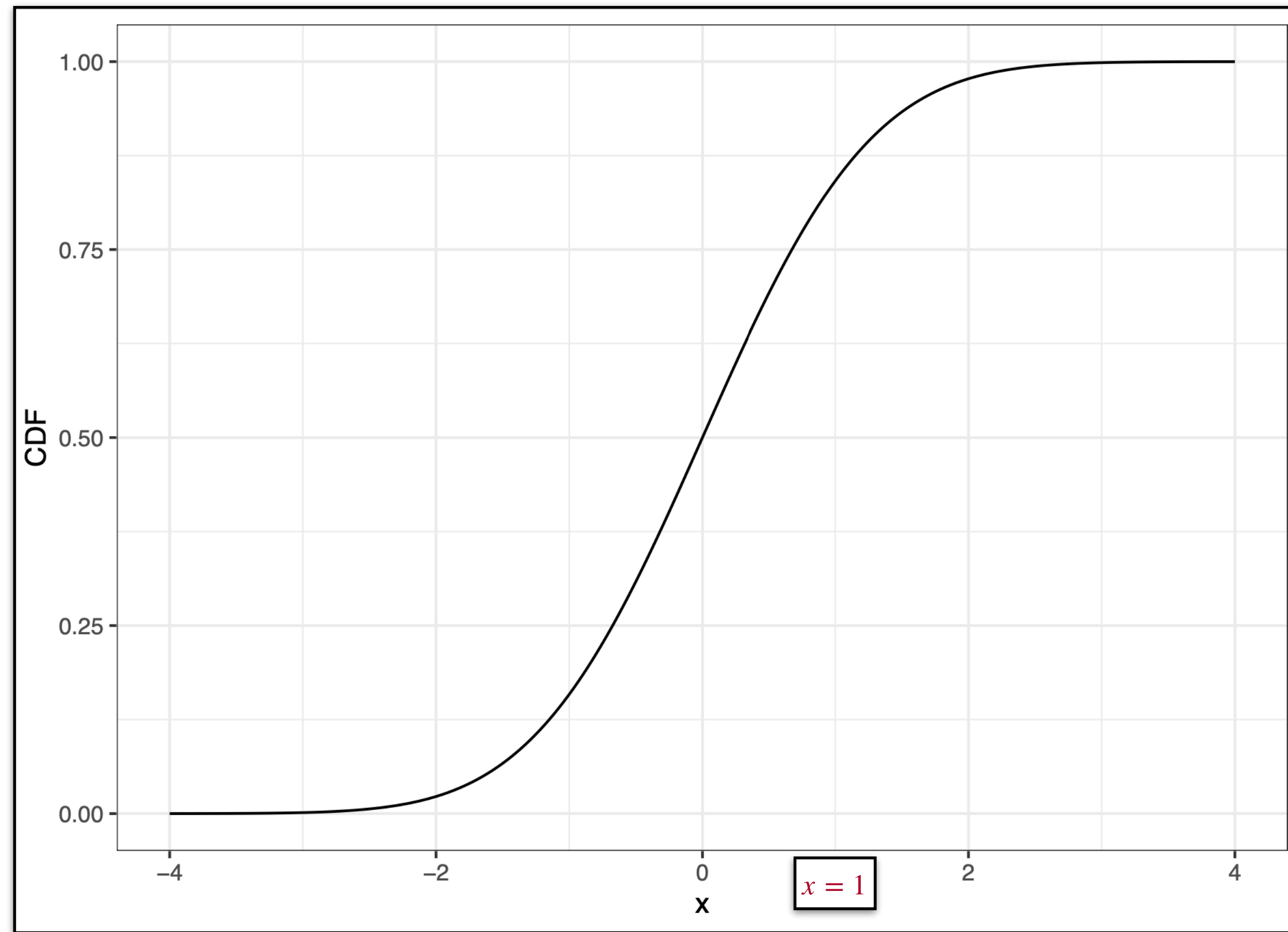
$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp \left\{ -\frac{1}{2\sigma^2}(x - \mu)^2 \right\} = \frac{1}{\sigma\sqrt{2\pi}} \exp \left\{ -\frac{1}{2}z^2 \right\}$$

- The maximum of $f(x)$ is when $z = 0$ or $x = \mu$
 - The maximum occurs at the average
- Further, note that $-z^2/2$ is symmetric around 0
- Finally, standard units allow us to assess if an observation is about average ($z \approx 0$), very large or very small ($|z| \approx 2$), or an extremely rare occurrence ($|z| > 3$)
- Note that this is true regardless of the original distribution of the data, as long as it is approximately normal.

Quantile-quantile plot

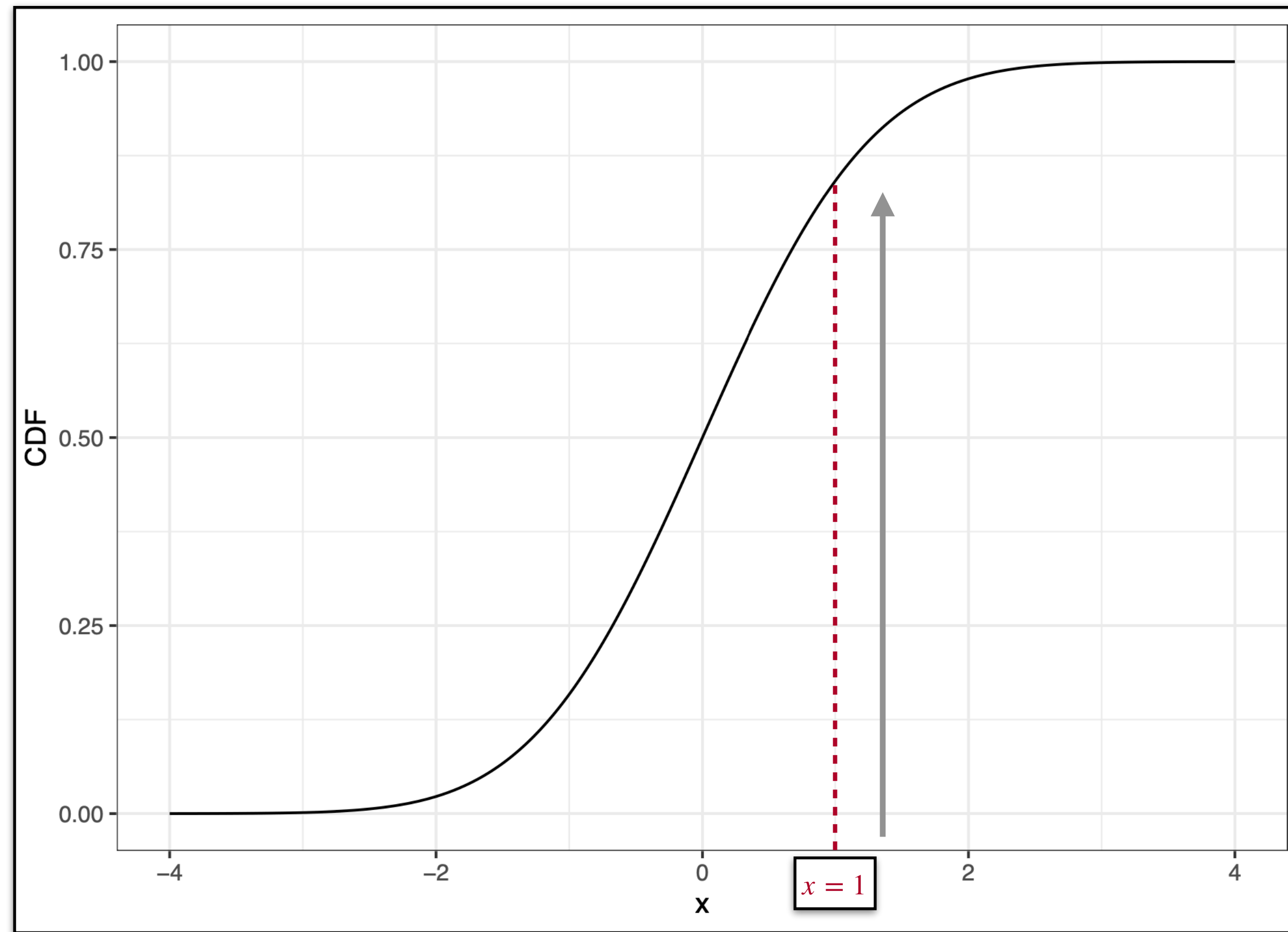
- A systematic way to assess the normal approximation is to see if the observed and theoretical proportions match.
- These proportions are known as quantiles, hence the name
- Denote $\Phi(x)$ as the function that gives us the probability of a standard normal variables being smaller than x . We've seen this before, any ideas?
- Then, the inverse function $\Phi^{-1}(x)$ yields the theoretical quantiles of a normal distribution
- Let me provide some intuition

Quantile-quantile plot



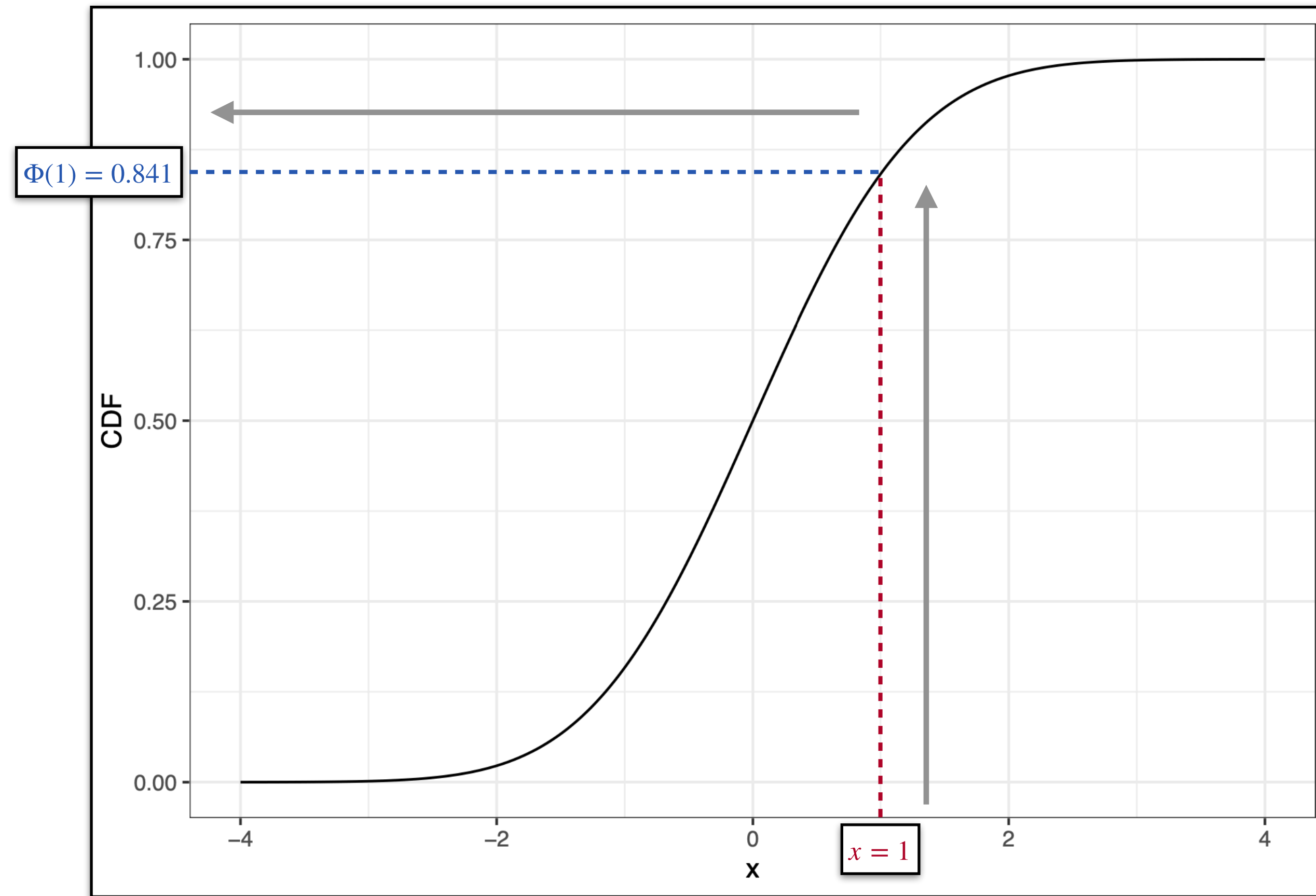
- $\Phi(1) = 0.841$: Again, this tells us the proportion of values that is less than 1

Quantile-quantile plot



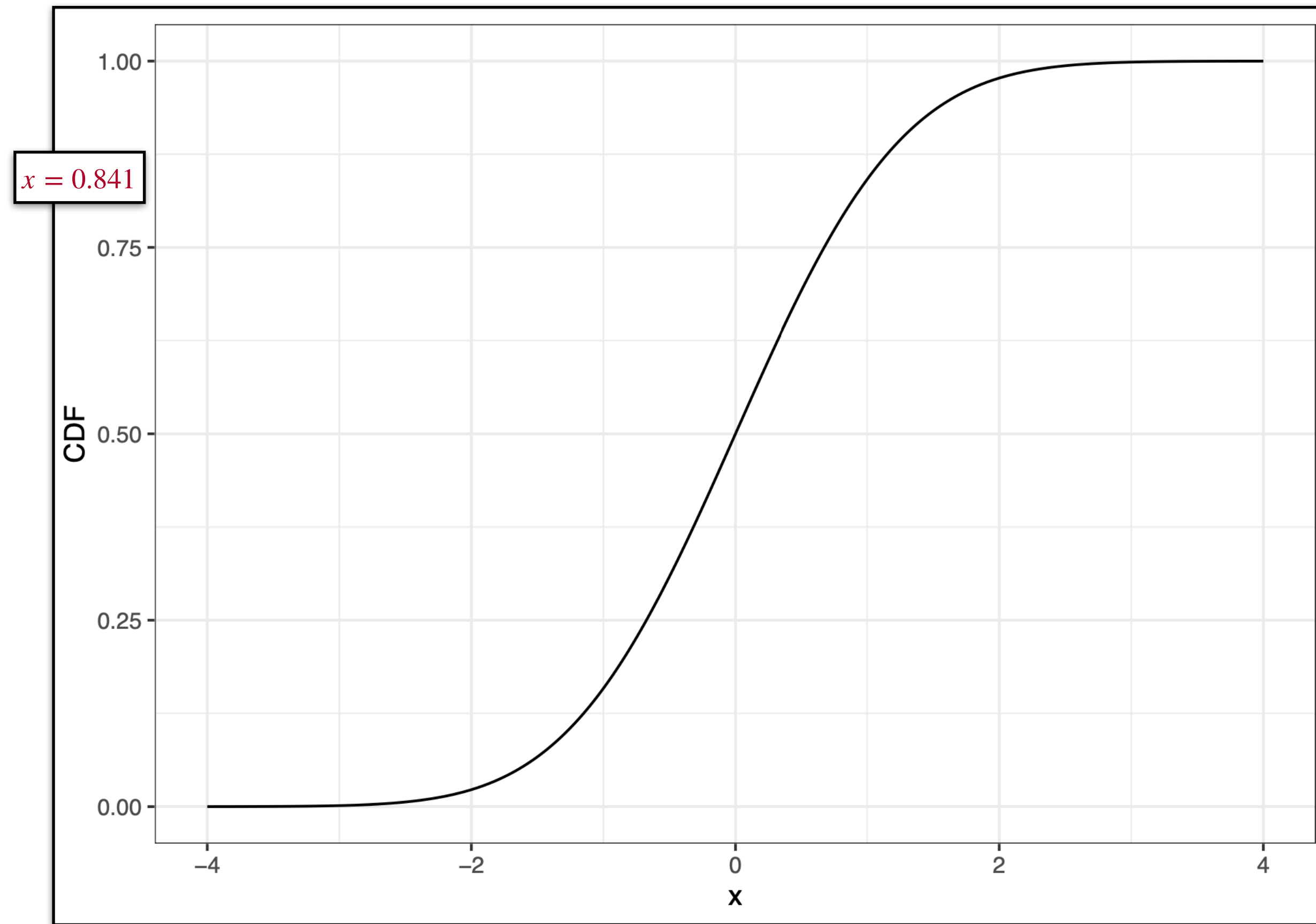
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Quantile-quantile plot



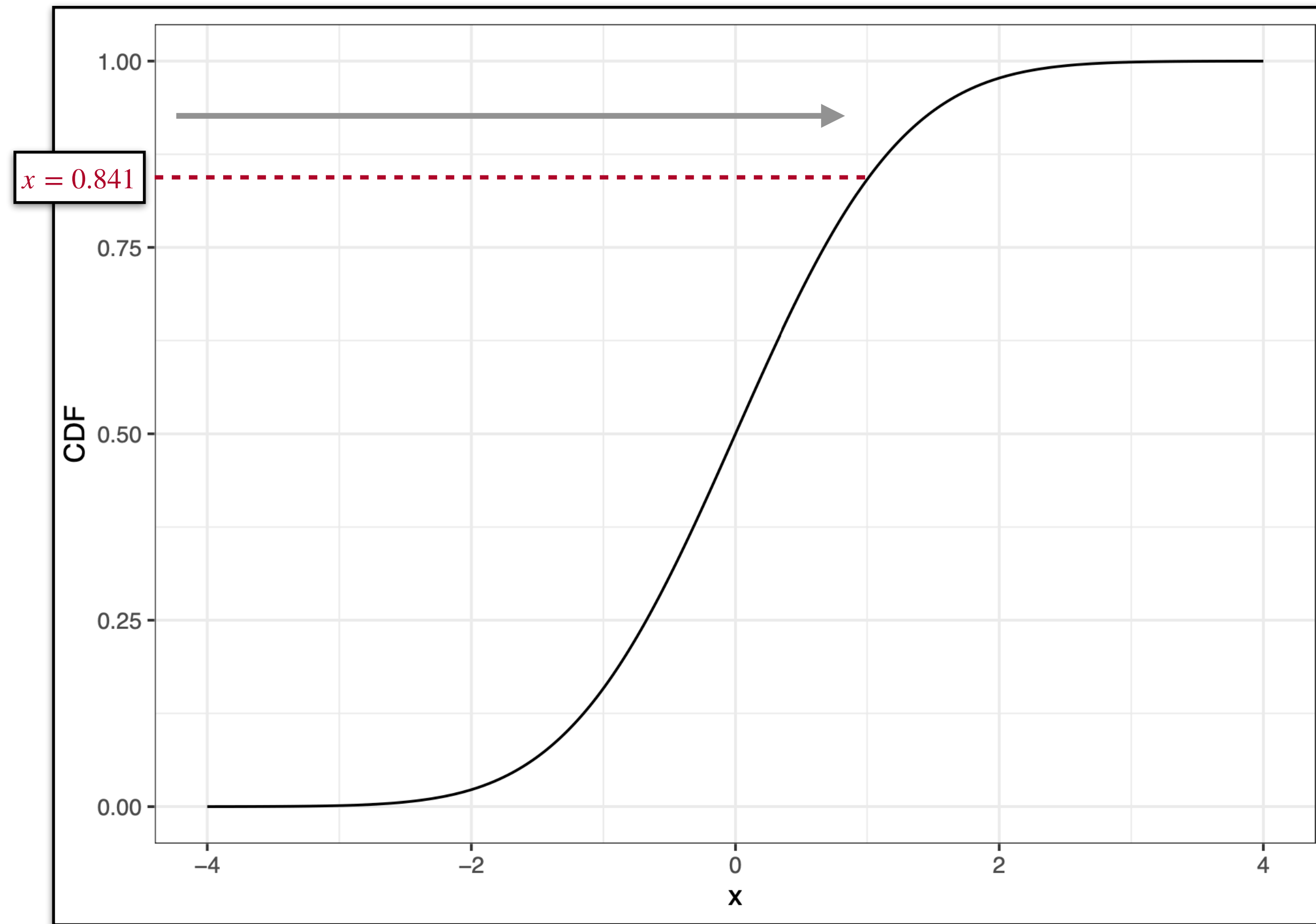
- $\Phi(1) = 0.841$: Again, this tell us the proportion of values that is less than 1

Quantile-quantile plot



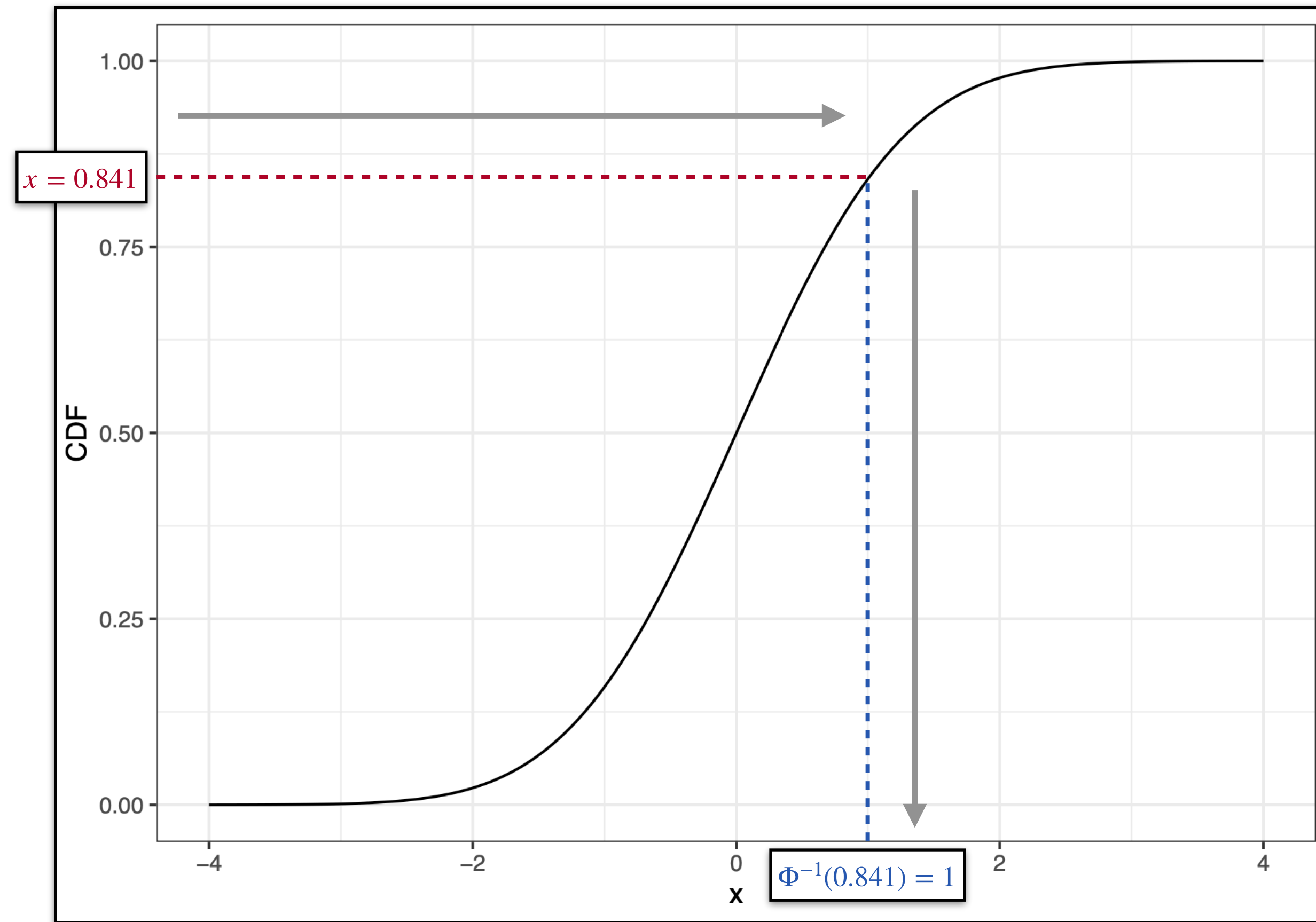
- $\Phi^{-1}(0.841) = 1$: This tells us, what is the value that is bigger than 84.1% of all values

Quantile-quantile plot



- $\Phi^{-1}(0.841) = 1$: This tells us, what is the value that is bigger than 84.1% of all values

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Quantile-quantile plot

- In R we can evaluate $\Phi(x)$ using the following code:

```
> pnorm(1, mean=0, sd=1)
[1] 0.8413447
```

- and we can evaluate $\Phi^{-1}(x)$ with:

```
> qnorm(0.8413447, mean=0, sd=1)
[1] 0.9999998
```

- Quantiles can be defined for any distribution, including an empirical one
- If we have data $\{x_1, \dots, x_n\}$, we can define the quantile associated with any proportion p as the q for which the proportion of values below q is p
- The idea of a QQ-plot is that if your data is well approximated by a normal distribution, then the quantiles of your data should be similar to the quantiles of a normal distribution

Quantile-quantile plot

- How to construct a QQ-plot:
 1. Define a vector of m proportions p_1, \dots, p_m
 2. Define a vector of quantiles q_1, \dots, q_m for your data for the proportions above
 - These are known as *Sample quantiles*
 3. Define a vector of quantiles for the proportions above from a normal distribution with the same mean and standard deviation as your data
 - These are known as the *Theoretical quantiles*
 4. Plot the *Sample quantiles* versus the *Theoretical quantiles*

Quantile-quantile plot

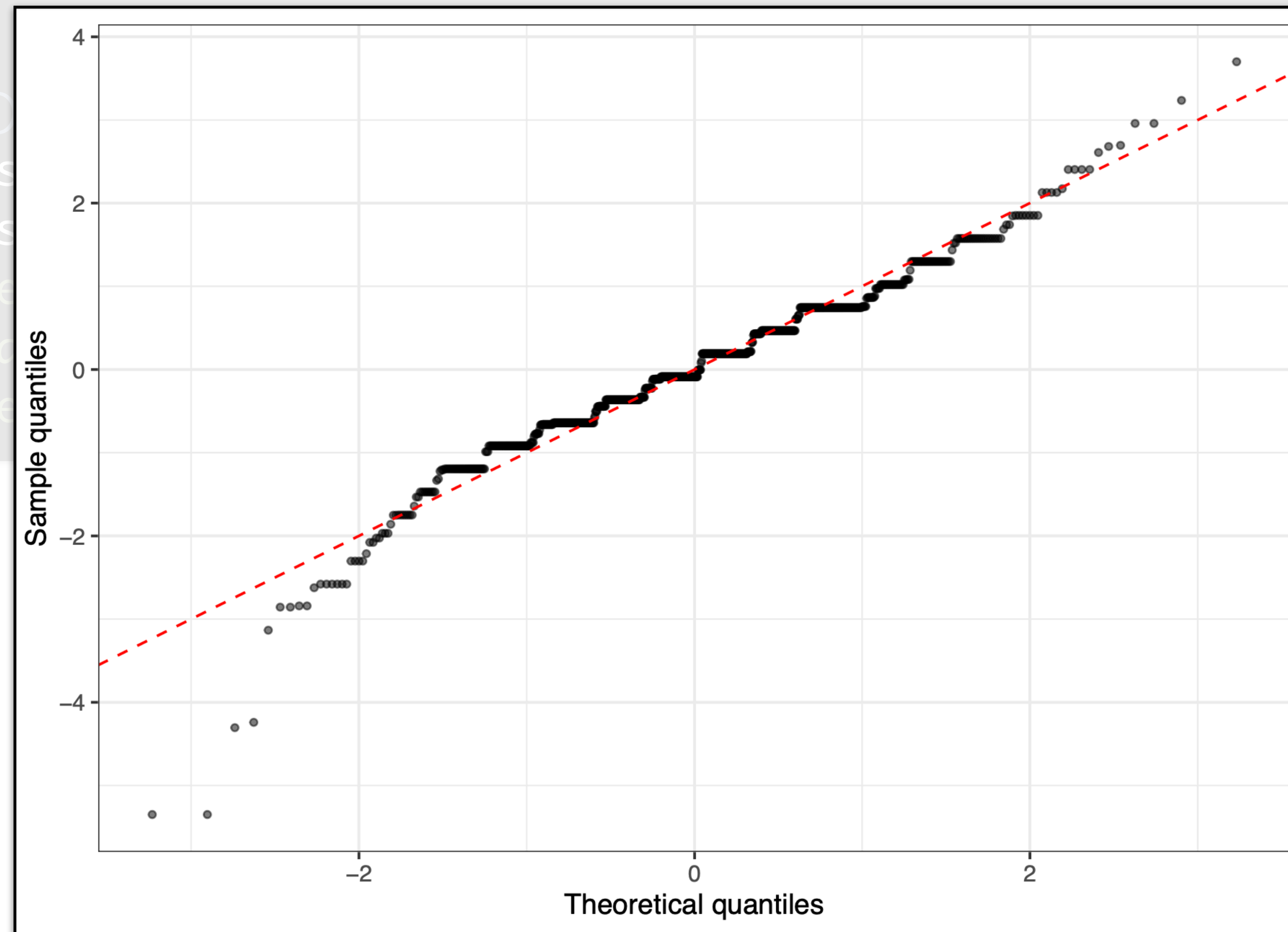
- QQ-plots in R:

```
heights %>%  
  filter(sex == "Male") %>%  
  ggplot(aes(sample = scale(height))) +  
  geom_qq(alpha=0.50, size=1) +  
  ylab("Sample quantiles") +  
  xlab("Theoretical quantiles") +  
  geom_abline(color="red", lty=2)
```

Quantile-quantile plot

- QQ-plots in R:

```
heights %>%  
  filter(sex == "Male")  
  ggplot(aes(sample = sample_n(1000)))  
  geom_qq(alpha=0.50, size=1)  
  ylab("Sample quantiles")  
  xlab("Theoretical quantiles")  
  geom_abline(color="red", lty=2)
```



Boxplots

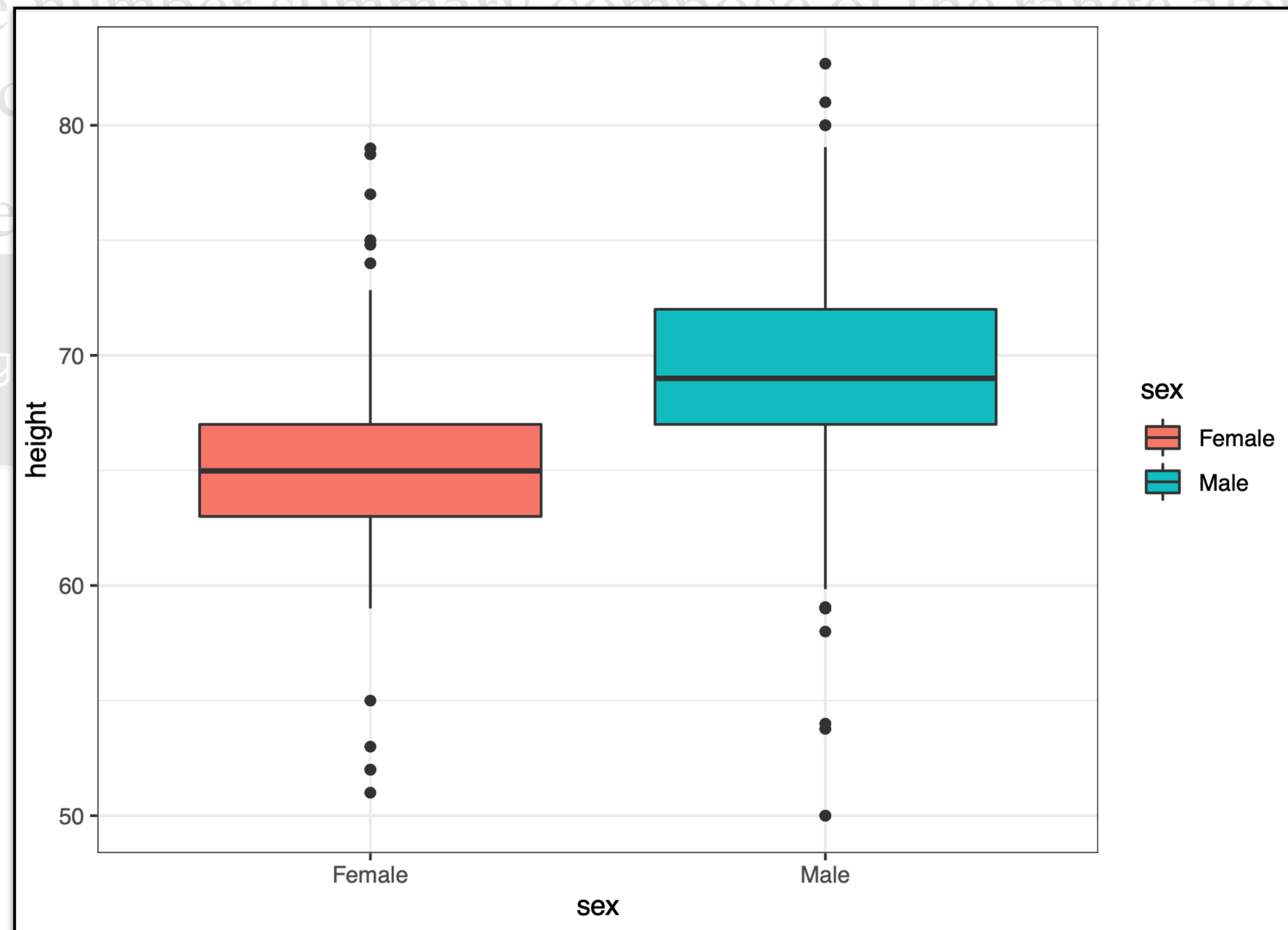
- Boxplots are a five-number summary composed of the range along with the 25th, 50th, and 75th percentiles.
- Here is an example

```
heights %>%  
  ggplot(aes(sex, height, fill = sex)) +  
  geom_boxplot()
```

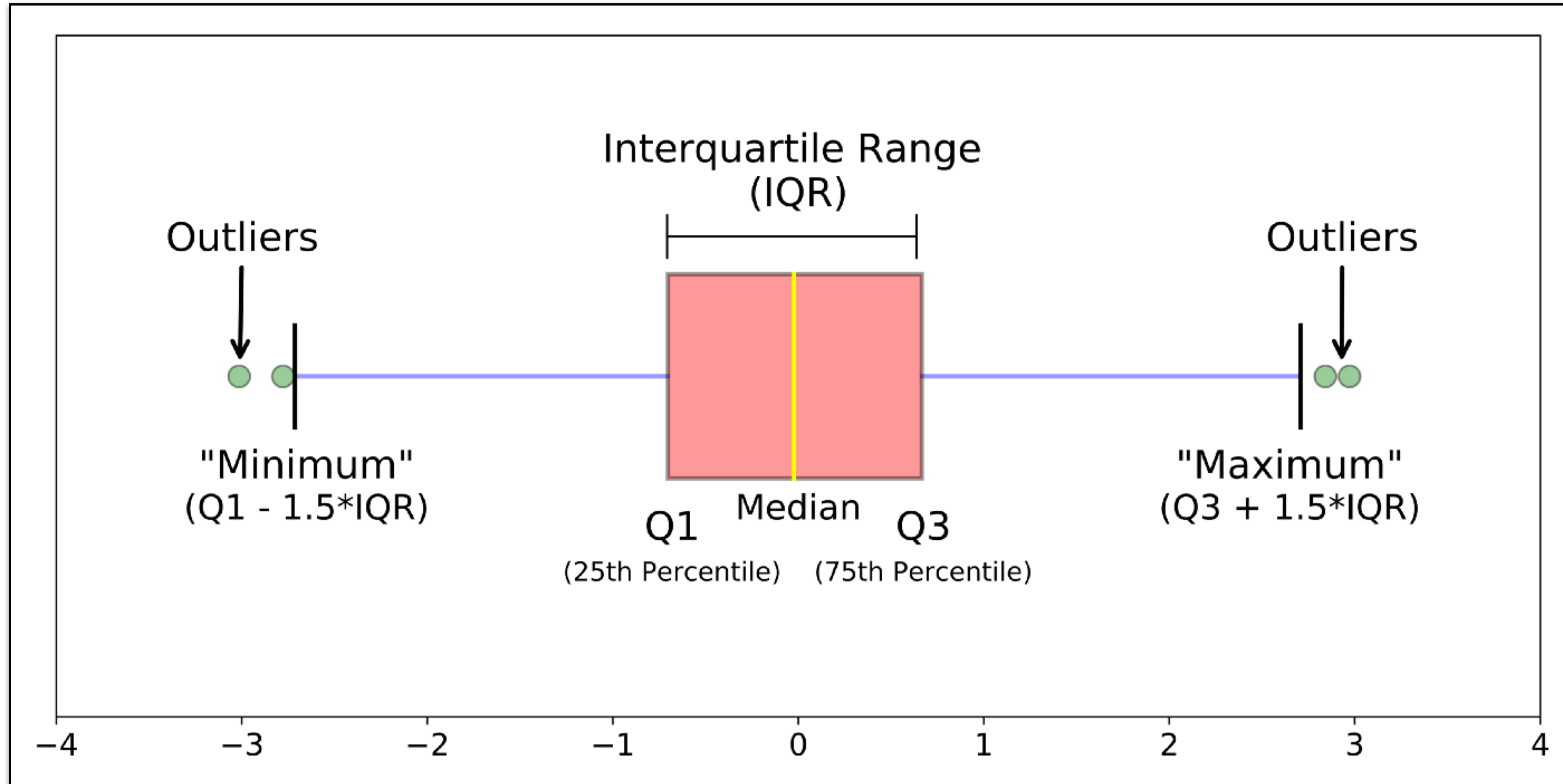

Boxplots

- Boxplots are a five number summary composed of the range along with the, 25th, 50th, and 75th percentiles
- Here is an example

```
heights %>%  
  ggplot(aes(sex, height)) +  
  geom_boxplot()
```

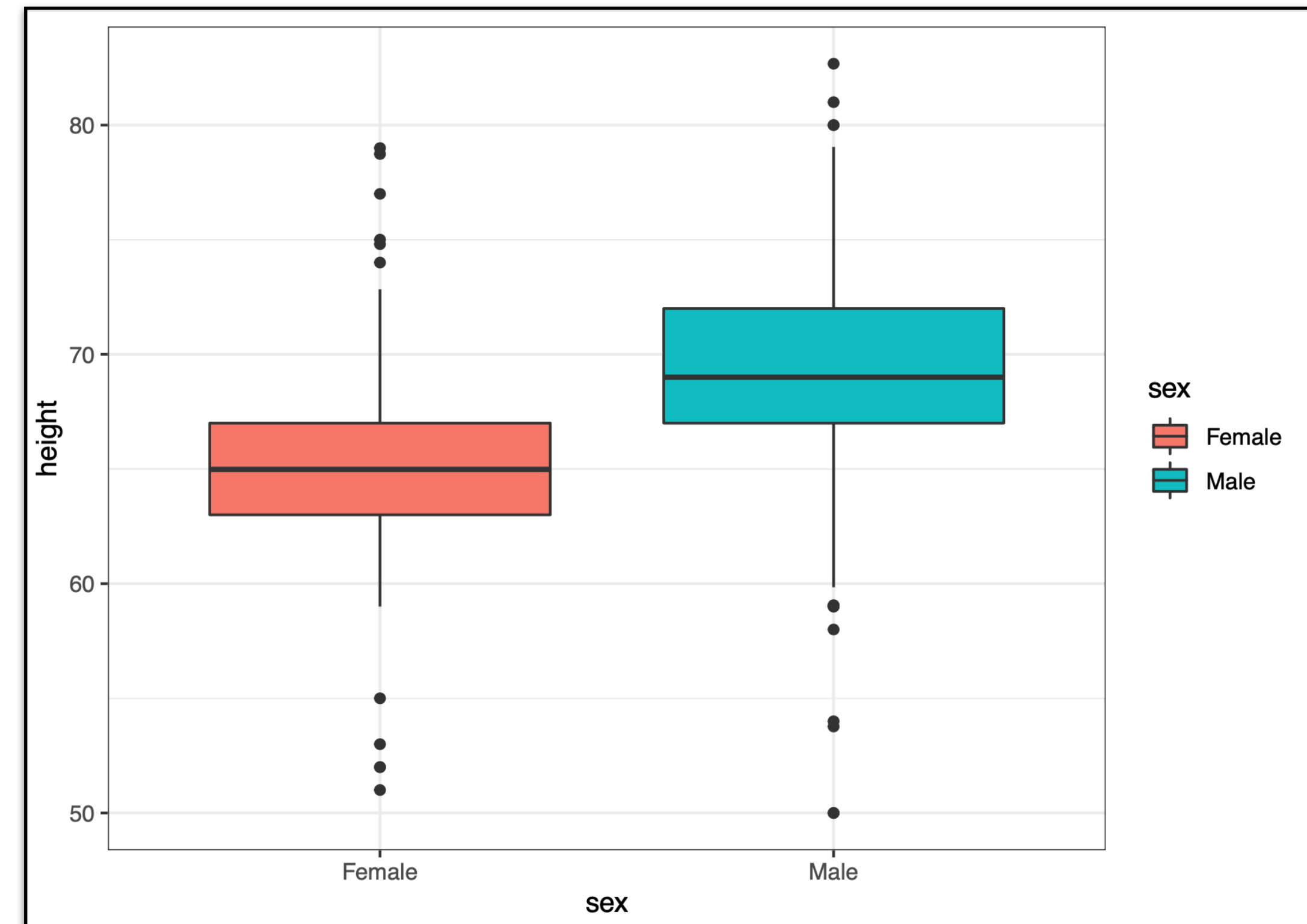


Boxplots



Boxplots

- We see that males are, on average, higher than females
- The standard deviation seems to be similar between the two groups
- More analysis needed to assess if the normal approximation is appropriate for female data



Why is all of this important?

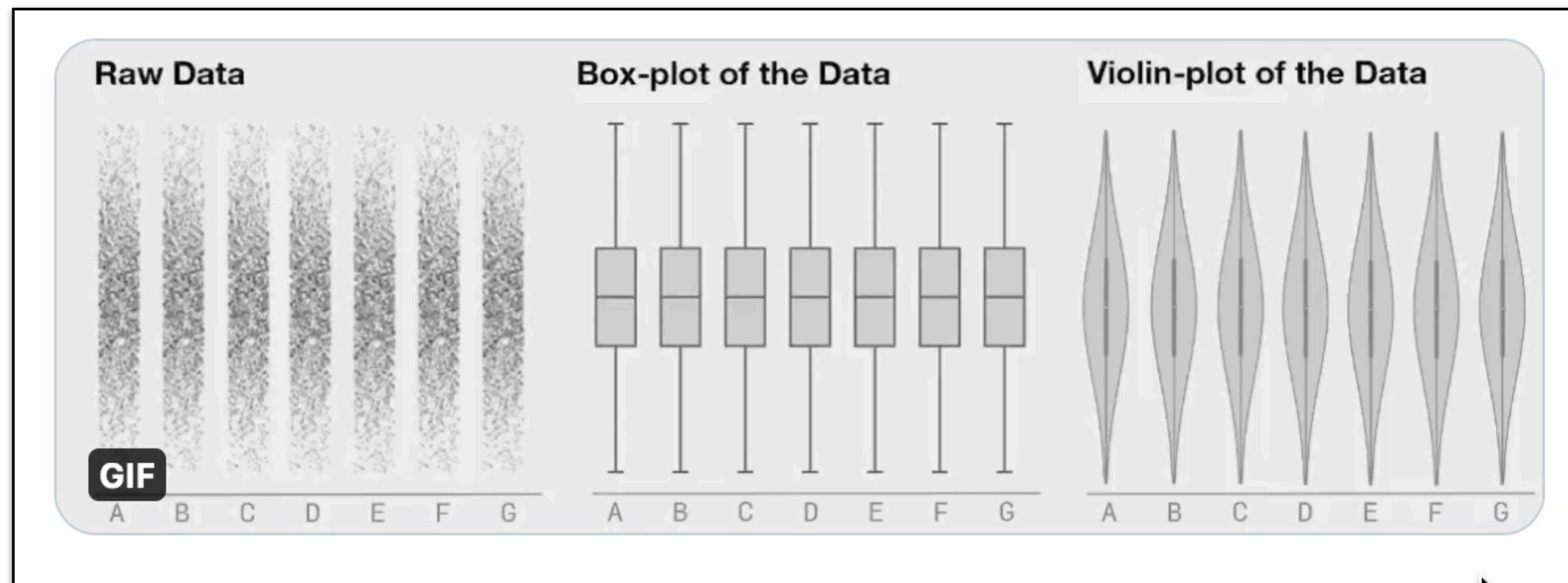


Indrajeet Patil
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I am often asked why I insist on complicating a plot by overlaying a violin plot on top of a box plot when the latter already gives a good visual summary of the distribution.

This gif provides a reason.

For a more nuanced argument, see:
[autodesk.com/research/publi...](https://www.autodesk.com/research/publications/same-stats-different-graphs)



References

1. Introduction to Data Science: Data analysis and prediction algorithms with R by Rafael A. Irizarry, Chapter 8. <https://rafalab.github.io/dsbook/>
2. R for Data Science by Grolemund & Wickham, Chapter 3. <https://r4ds.had.co.nz/index.html>
3. ggplot2: Elegant graphics for data analysis: Wickham. <https://ggplot2-book.org>

Referencias en español:

1. Introducción a la Ciencia de Datos: Análisis de datos y algoritmos de predicción con R por Rafael A. Irizarry, Capítulo 8. <https://rafalab.github.io/dslibro/>
2. R para Ciencia de Datos por Grolemund & Wickham, Capítulo 3. <https://es.r4ds.hadley.nz>

Your turn!

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