Lecture 6: Graphs and graphing relationships

LSC 563: Data Visualization – Spring 2022

1

Journal Club

Franconeri, S. L., Padilla, L. M., Shah, P., Zacks, J. M., & Hullman, J. (2021). The Science of Visual Data Communication: What Works. Psychological Science in the Public Interest.

2

Learning Objectives

- By the end of this section, students should be able to:
  - Discuss the connection between data, aesthetics, & the grammar of graphics
  - Outline the grammatical layers in ggplot
  - Label the basic elements of a graph
  - List the three primary marks used in data visualization
  - List the 5 channels discussed during lesson 4
  - Distinguish between “viewing” and graph in R and saving a graph in R.

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Coordinate systems and axes

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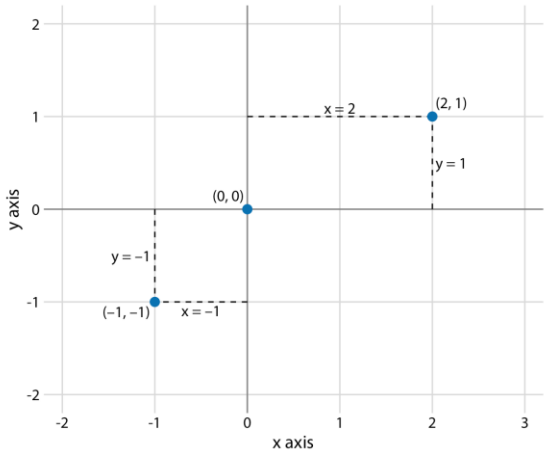
Coordinate systems and axes

- Data visualizations need position scales, which determine where different data values are located
- 2D vizs require:
  - Two numbers which define the two positions
  - Usually the x and y axes of the plot
  - Specify the relative geometric arrangement of these scales



Wilke, 2019

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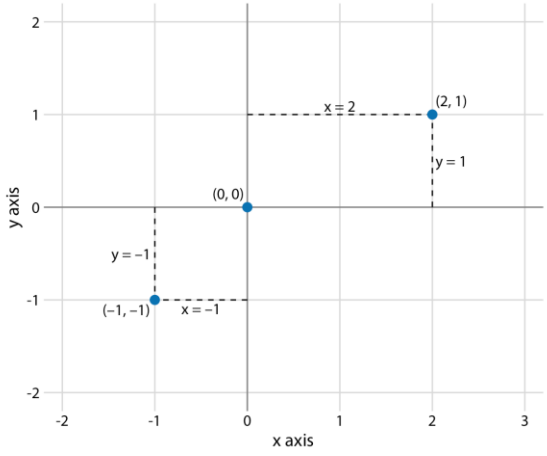
Coordinate systems: Cartesian

- Data values are placed in an even spacing along both axes
- Two axes are continuous position scales
- Can represent both positive and negative real numbers
- X-axis runs from -2.2 to 3.2 and the y-axis runs from -2.2 to 2.2
- Data values between these axis limits are placed at the respective location in the plot



Wilke, 2019

6

Nonlinear Axes and Log Transformations

- Cartesian coordinates are linear
- Scenarios exist where nonlinear scales are preferred
- Most used nonlinear scale is the logarithmic scale, or log scale for short
- Log scales are linear in multiplication, a unit step on the scale corresponds to multiplication with a fixed value
- Log scales are frequently used when the dataset contains numbers of very different magnitudes

Wilke, 2019

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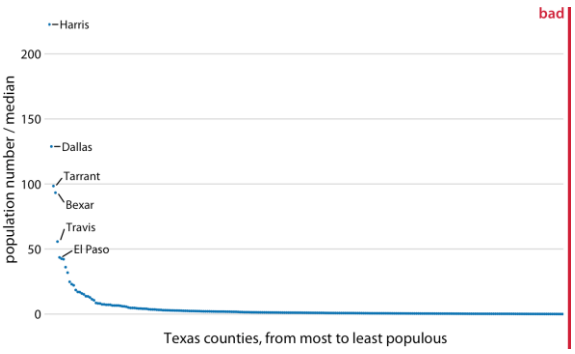
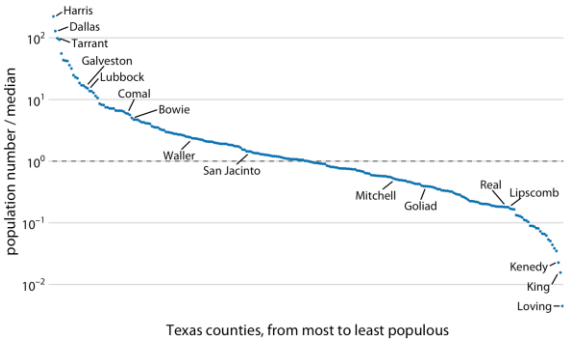
Log Transformations: Example



Data when graph using a linear scale

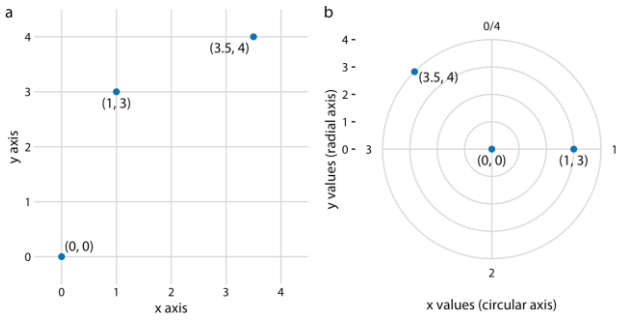


Data when graph using a log scale

Wilke, 2019

8

Coordinate Systems with Curved Axes



3 data points shown in Cartesian coordinate system, compared to the same three data points shown in a polar coordinate system

Wilke, 2019

- There are other coordinate systems, where the axes are curved
- Polar coordinate system, position is specified via an angle and a radial distance from the origin

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Introduction to Graphs

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Elements of Graphs

- A graph is a visual display of quantitative information, with the following characteristics:
  - Values are displayed within an area delineated by one or more axes
  - Values are encoded as visual objects positioned in relation to the axes
  - Axes provide scales (quantitative and categorical) that are used to label and assign values to the visual objects

Few, 2012a

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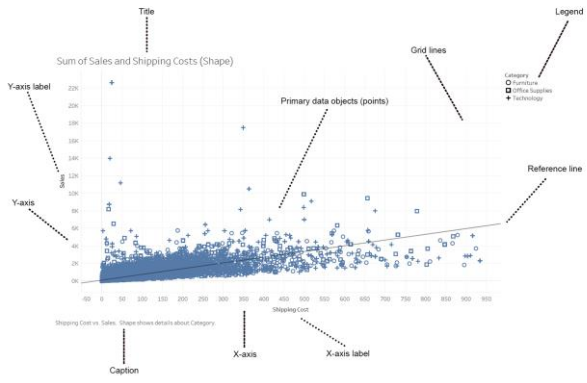
Elements of Graphs: Example



- Two axes: horizontal, called the X axis, and vertical, called the Y axis
- Quantitative scale, labels the costs associated with shipping a product, resides along the X axis
- Quantitative scale, which represents the sum of sales resides along the Y axis
- Shape is used to divide these values by the category of the product

Few, 2012a

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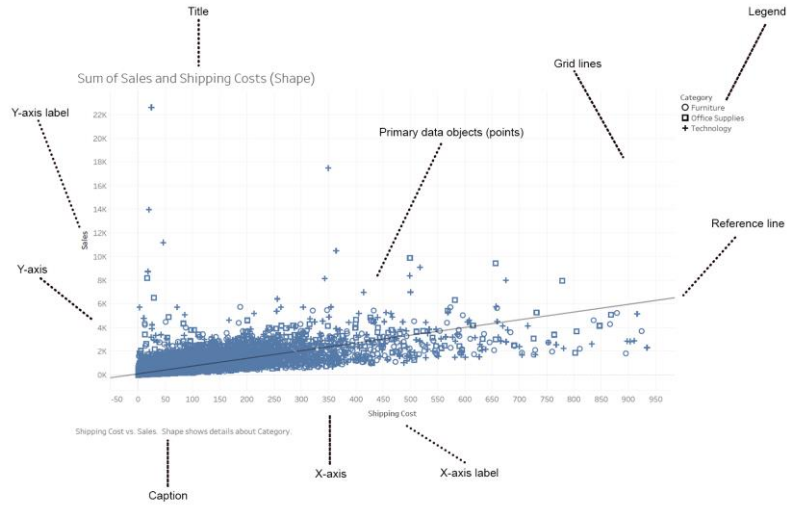
Anatomy of a Chart



Few, 2012

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Marks and Channels

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Why Marks and Channels?

- Learning to reason about marks and channels gives you the building blocks for analyzing visual encodings
- Core of data visualization can be broken down into two fundamental groups:
  - Marks
  - Visual channels

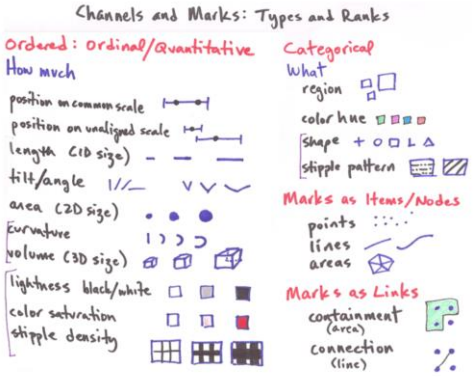

Image source: © Munzner/Möller

Munzner, T. (2015).

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Marks

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Marks: Data Without Marks

Sales by Sub-Category and Year

Sub-Category	Order Date 2011	2012	2013	2014
Accessories	113,456	172,398	209,895	253,488
Appliances	173,383	222,943	254,951	359,787
Art	64,139	82,358	98,007	127,588
Binders	86,999	93,418	121,075	160,420
Bookcases	259,396	317,953	376,026	513,197
Chairs	285,731	295,058	427,514	493,378
Copiers	216,368	327,169	415,515	550,385
Envelopes	27,987	38,014	50,805	54,099
Fasteners	13,609	19,478	21,597	28,559
Furnishings	63,934	81,804	111,820	128,020
Labels	13,616	15,518	18,381	25,889
Machines	160,546	159,859	198,376	260,279
Paper	42,666	51,512	70,513	79,601
Phones	337,282	364,016	453,519	552,006
Storage	205,627	228,556	309,476	383,427
Supplies	47,581	43,297	65,913	86,283
Tables	147,131	164,086	202,364	243,460

Sales by Sub-Category and Quarter

Sub-Category	Order Date Q1	Q2	Q3	Q4
Accessories	103,268	169,360	221,154	255,455
Appliances	154,173	243,949	274,620	338,321
Art	57,593	88,214	111,390	114,896
Binders	70,050	98,262	138,437	155,163
Bookcases	232,430	303,435	439,693	491,015
Chairs	240,942	327,760	400,595	532,385
Copiers	238,260	346,126	398,852	526,199
Envelopes	26,691	40,732	48,483	54,998
Fasteners	12,051	21,241	21,742	28,207
Furnishings	62,269	87,252	104,558	131,499
Labels	10,388	17,576	21,396	24,044
Machines	143,705	176,739	189,517	269,099
Paper	35,910	58,645	66,172	83,565
Phones	231,883	396,700	491,681	586,560
Storage	191,502	257,438	310,444	367,702
Supplies	45,081	54,144	71,709	72,140
Tables	133,177	184,718	170,153	268,994

Munzner, T. (2015).

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Marks

- A mark is a basic graphical element in a graph:
  - Point: A zero-dimensional (OD) mark
  - Line: a one-dimensional (1D) mark
  - Area: A two-dimensional (2D) mark. Areas can also be a three-dimensional (3D) volume mark, but they are not frequently used in data visualization.

Points

Lines

Areas

Munzner, T. (2015).

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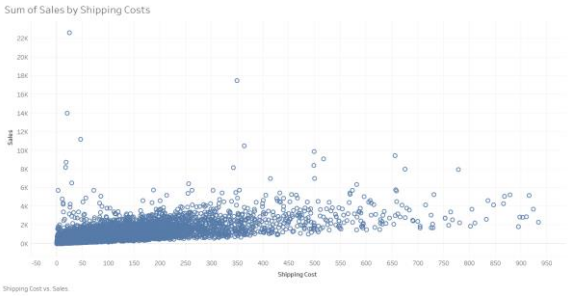
Mark Types: Points Example

- Simple geometric shape that is used to mark a specific location on a graph, often a dot
- Scatterplot is used to encodes each quantitative value
  - Every mark represents a data item, and typically its position represents two values
- Also used in maps, as a proportional symbol map
  - If you see the points clustering on a symbol map, it might mean something is going on in that region



Munzner, T. (2015).

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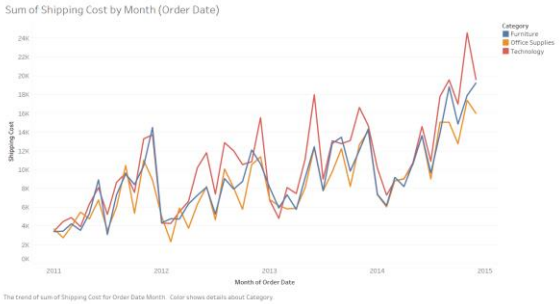
Mark Types: Lines Example

- Common example is a line chart
- Typically show how values change over time
- Also used in network diagrams:
  - Role of the lines is to show the relationship between different nodes
- Can also have trend lines which we will learn about later in the semester



Munzner, T. (2015).

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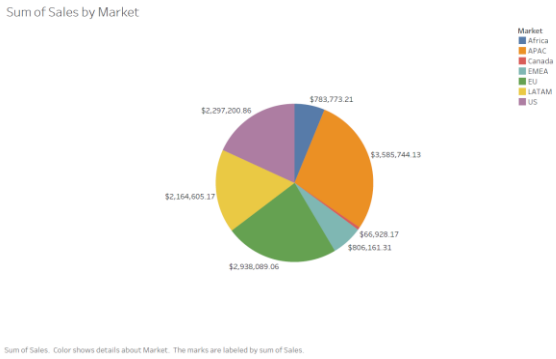
Mark Types: Area

- Number of different ways that area marks can be used
- Pie chart encodes quantitative values as the sizes of 2-D areas
  - Pie charts use segments of a circle (i.e., slices of a pie)
  - Size of each piece of the pie is equal to its value compared to the total value of all the slices
- Perimeter of the circle serves as a circular axis



Munzner, T., 2015.

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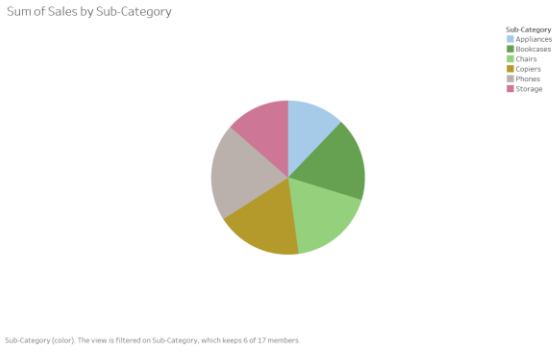
Area: The Problems with Pie Charts

- Visual perception is not designed to accurately assign quantitative values to 2-D areas, and we have an even harder time when a third dimension of depth is added
- If the slices of a pie chart are close in size, it's difficult to tell which slice is bigger
- Take a minute and rank each slice from largest to smallest.



Few, 2012.

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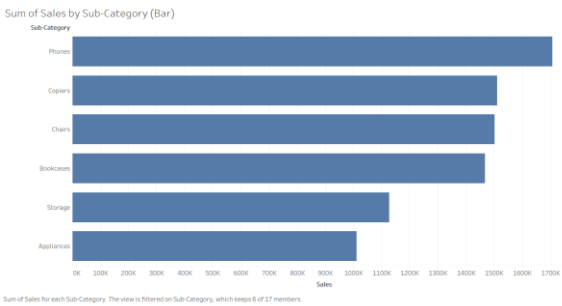
Area: The Problems with Pie Charts

- Much easier with a bar chart
- We can determine that one is bigger than the other, but not by how much
- Easier in the bar graph because visual perception is highly tuned for seeing differences among the lengths of objects that share a common baseline

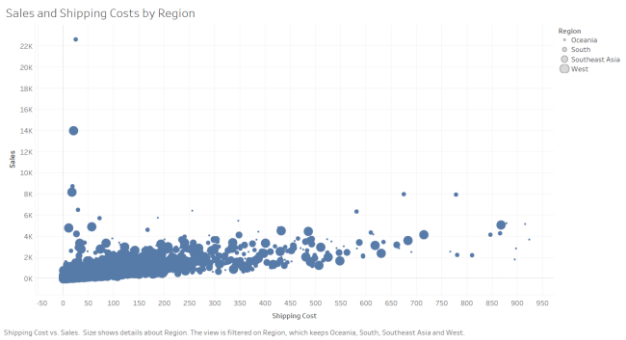


Few, 2012.

23

Area: Bubble Charts

- Like a scatter plot that uses the vertical and horizontal positions of objects to encode two variables (sales and shipping costs), and the size to encode a third variable (region)



Few, 2012.

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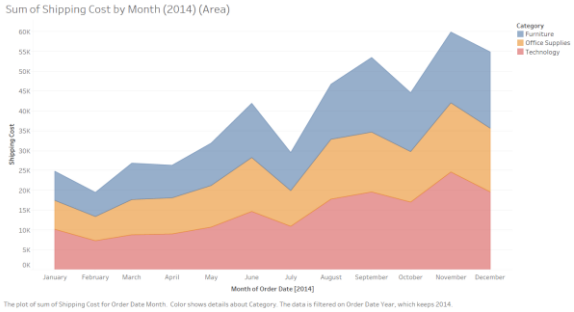
Area: Area Charts

- Same data as lines chart, but using area
- Makes it easier to compare contributions per time period (month)
- Total shipping costs for October 2014 were 44,622
  - Biggest “slice” is Technology which contributed 16,989 to the total shipping costs.



Few, 2012.

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Channels

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Channels

- Visual channel is a way to control the appearance of marks, which is independent of the dimensionality of the mark
- Human perceptual system has two different kinds of sensory modalities:
  - An identity channel
  - Magnitude channel

Munzner, T., 2015.

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Channel Types: Identity

- Categorical classification
- Tells us information about what something is:
  - What shape do I see?
  - What color (hue) do I see?

Munzner, T., 2015.

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Channel Types: Magnitude

- Ordered classification
- Tells us how much of something there is:
  - How much longer is line segment A versus line segment B?
  - How much area is contained in this square?
  - What is the volume of this cube?

Munzner, T., 2015.

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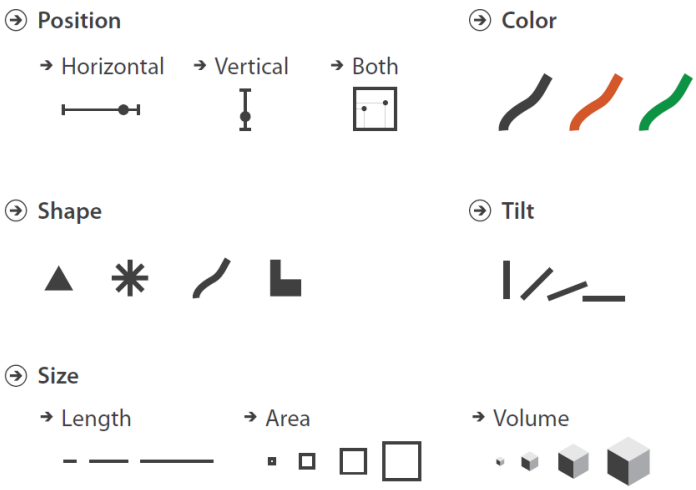
Defining Channels: Examples



Munzner, T., 2015.

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Preattentive Processing and Encoding: Ranking

- Thankfully, there has been a lot of research on how these differences are perceived.

Type	Attribute	Quantitatively Perceived?
Form	**Length**	**Yes**
	Width	**Yes, but limited**
	Orientation	No
	Size	**Yes, but limited**
	Shape	No
	Enclosure	No
Color	Hue	No
	Lightness (Intensity)	**Yes, but limited**
Spatial Position	**2-D Position**	**Yes**

Ware, 2013.

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Exercise in Data Abstract

- Learning goals:
  - Learn how to recognize dataset and attribute types.
  - Learn how to generate data analysis questions and transform data in ways that enable you to answer them.
- Dataset: Dataset: aid_data_example.xlsx
- Specific instructions are in the Google Doc

Break Out Rooms
15 minutes to discuss
Pick someone to report out

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Using Marks and Channels

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Marks and Channels and Visual Encoding

- Visualizations encode numbers in lines, shapes, and colors
  - Interpretation of these encodings is partly conditional on how we perceive geometric shapes and relationships
- Also, not all channels are equal
  - If same data is encoded with two different channels, might result in the information being processed in different ways
  - We learned about this in the Preattentive Processing section
- The use of marks and channels in a visualization design should be guided by the principles of expressiveness and effectiveness
  - We will focus on effectiveness

Healy, K. 2018

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Effectiveness

- Principle dictates that the importance of the attribute should match the salience of the channel
- So, what do we mean by the effectiveness of a channel?
  - Presentation is effective if the perceptual judgements it requires are easy to make and noticeable
- Let us look at this principle using an example

Wehrend & Lewis, 1990
Munzner, T., 2015

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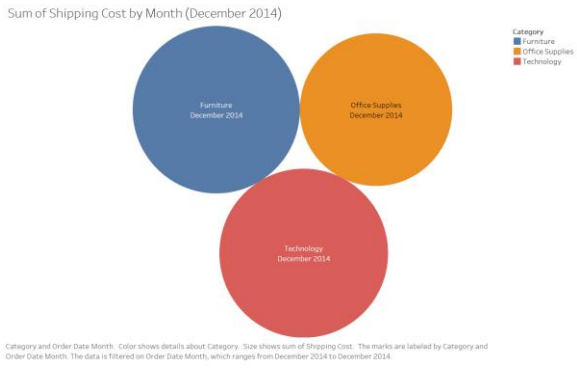
Effectiveness: Example

- We want to estimate how much bigger is the value of these three circles
- We could try to estimate this, but it is kind of hard



Wehrend & Lewis, 1990
Munzner, T., 2015

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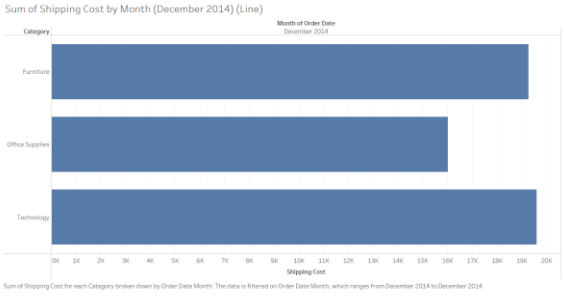
Effectiveness: Example

- This task is a little easier when bars are used
- This is showing the same data as a line chart, which using a common scale.



Wehrend & Lewis, 1990
Munzner, T., 2015

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Effectiveness: Evaluating

- The primary questions of channel effectiveness:
  - Accuracy: How accurate is the visual encoding
  - Discriminability: encode data using a particular visual channel, are the differences between items perceptible to the human as intended
  - Separability: cannot treat all visual channels as completely independent from each other, because some have dependencies and interactions with others
- Journal Club 3: Group 2 (Week 10) explores the work of Cleveland and McGill, so we will wait and discus this later in the semester.

Munzner, T., 2015

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Relative and Absolute Judgements

- Weber's Law is that the human perceptual system is fundamentally based on relative judgements, not absolute ones
  - The amount of length difference we can detect is a percentage of the object's length
- When considering questions such as the accuracy and discriminability of our perceptions, we must distinguish between relative and absolute judgements
- Let us look at a classic example

Munzner, T., 2015

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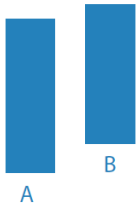
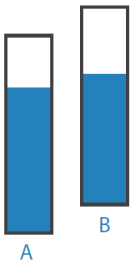
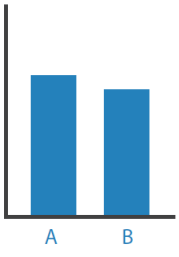
Relative and Absolute Judgements: Example



Unframed
Unaligned



Framed
Unaligned



Unframed
Aligned

Munzner, T., 2015

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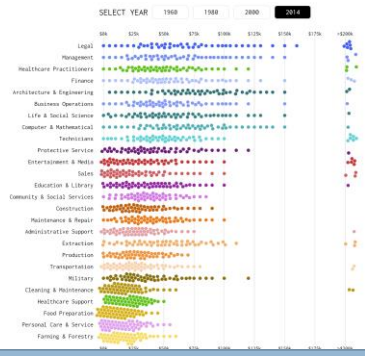
Marks and Channels Exercise

- Learning Goals
  - Develop the ability to decode charts in an effort to better understand how graphs can be described using the language and rules of visual encoding
  - Develop the skills need to breakdown visual encoding into low-level graphical components.



Break Out Rooms
10 minutes to discuss
Pick someone to report out

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Preview of lab 4

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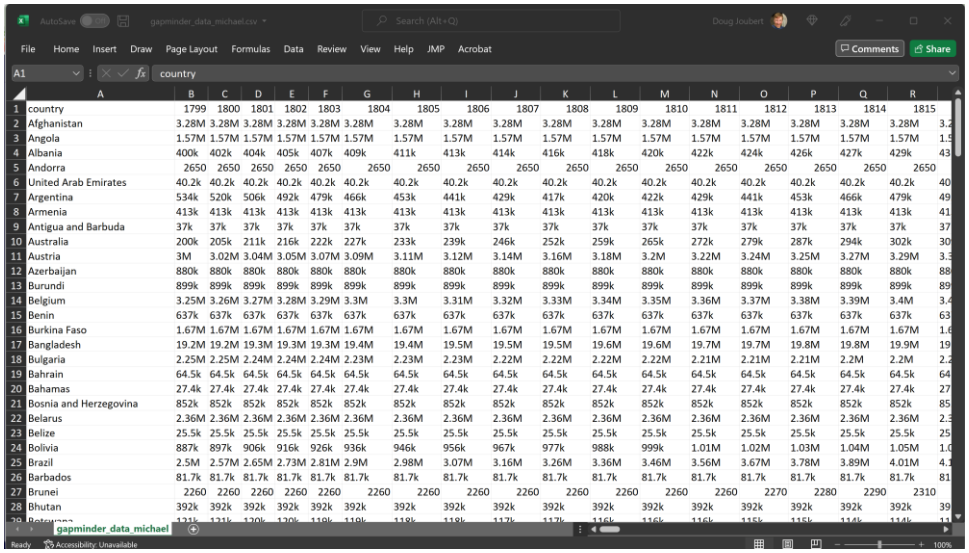
Pivoting Data in R (tidyverse)



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	country	1799	1800	1801	1802	1803	1804	1805	1806	1807	1808	1809	1810	1811	1812	1813	1814	1815
2	Afghanistan	3.28M	3.28M	3.28M	3.28M	3.28M	3.28M	3.28M	3.28M	3.28M	3.28M	3.28M	3.28M	3.28M	3.28M	3.28M	3.28M	3.28M
3	Angola	1.57M	1.57M	1.57M	1.57M	1.57M	1.57M	1.57M	1.57M	1.57M	1.57M	1.57M	1.57M	1.57M	1.57M	1.57M	1.57M	1.57M
4	Albania	400k	402k	404k	405k	407k	409k	411k	413k	414k	416k	418k	420k	422k	424k	426k	427k	429k
5	Andorra	2650	2650	2650	2650	2650	2650	2650	2650	2650	2650	2650	2650	2650	2650	2650	2650	2650
6	United Arab Emirates	40.2k	40.2k	40.2k	40.2k	40.2k	40.2k	40.2k	40.2k	40.2k	40.2k	40.2k	40.2k	40.2k	40.2k	40.2k	40.2k	40.2k
7	Argentina	534k	520k	506k	492k	479k	466k	453k	441k	429k	417k	420k	422k	429k	441k	453k	466k	479k
8	Armenia	413k	413k	413k	413k	413k	413k	413k	413k	413k	413k	413k	413k	413k	413k	413k	413k	413k
9	Antigua and Barbuda	37k	37k	37k	37k	37k	37k	37k	37k	37k	37k	37k	37k	37k	37k	37k	37k	37k
10	Australia	200k	205k	211k	216k	222k	227k	233k	239k	246k	252k	259k	265k	272k	279k	287k	294k	302k
11	Austria	3M	3.02M	3.04M	3.05M	3.07M	3.09M	3.11M	3.12M	3.14M	3.16M	3.18M	3.2M	3.22M	3.24M	3.25M	3.27M	3.29M
12	Azerbaijan	880k	880k	880k	880k	880k	880k	880k	880k	880k	880k	880k	880k	880k	880k	880k	880k	880k
13	Burundi	899k	899k	899k	899k	899k	899k	899k	899k	899k	899k	899k	899k	899k	899k	899k	899k	899k
14	Belgium	3.25M	3.26M	3.27M	3.28M	3.29M	3.3M	3.3M	3.31M	3.32M	3.33M	3.34M	3.35M	3.36M	3.37M	3.38M	3.39M	3.4M
15	Benin	637k	637k	637k	637k	637k	637k	637k	637k	637k	637k	637k	637k	637k	637k	637k	637k	637k
16	Burkina Faso	1.67M	1.67M	1.67M	1.67M	1.67M	1.67M	1.67M	1.67M	1.67M	1.67M	1.67M	1.67M	1.67M	1.67M	1.67M	1.67M	1.67M
17	Bangladesh	19.2M	19.2M	19.3M	19.3M	19.3M	19.4M	19.4M	19.5M	19.5M	19.5M	19.6M	19.6M	19.7M	19.7M	19.8M	19.8M	19.9M
18	Bulgaria	2.25M	2.25M	2.24M	2.24M	2.24M	2.23M	2.23M	2.23M	2.22M	2.22M	2.22M	2.22M	2.21M	2.21M	2.21M	2.2M	2.2M
19	Bahrain	64.5k	64.5k	64.5k	64.5k	64.5k	64.5k	64.5k	64.5k	64.5k	64.5k	64.5k	64.5k	64.5k	64.5k	64.5k	64.5k	64.5k
20	Bahamas	27.4k	27.4k	27.4k	27.4k	27.4k	27.4k	27.4k	27.4k	27.4k	27.4k	27.4k	27.4k	27.4k	27.4k	27.4k	27.4k	27.4k
21	Bosnia and Herzegovina	852k	852k	852k	852k	852k	852k	852k	852k	852k	852k	852k	852k	852k	852k	852k	852k	852k
22	Belarus	2.36M	2.36M	2.36M	2.36M	2.36M	2.36M	2.36M	2.36M	2.36M	2.36M	2.36M	2.36M	2.36M	2.36M	2.36M	2.36M	2.36M
23	Belize	25.5k	25.5k	25.5k	25.5k	25.5k	25.5k	25.5k	25.5k	25.5k	25.5k	25.5k	25.5k	25.5k	25.5k	25.5k	25.5k	25.5k
24	Bolivia	887k	897k	906k	916k	926k	936k	946k	956k	967k	977k	988k	999k	1.01M	1.02M	1.03M	1.04M	1.05M
25	Brazil	2.5M	2.57M	2.65M	2.73M	2.81M	2.9M	2.98M	3.07M	3.16M	3.26M	3.36M	3.46M	3.56M	3.67M	3.78M	3.89M	4.01M
26	Barbados	81.7k	81.7k	81.7k	81.7k	81.7k	81.7k	81.7k	81.7k	81.7k	81.7k	81.7k	81.7k	81.7k	81.7k	81.7k	81.7k	81.7k
27	Brunei	2260	2260	2260	2260	2260	2260	2260	2260	2260	2260	2260	2260	2260	2270	2280	2290	2310
28	Bhutan	392k	392k	392k	392k	392k	392k	392k	392k	392k	392k	392k	392k	392k	392k	392k	392k	392k

Pivoting Data in R (tidyverse)

- pivot_longer() "lengthens" data, increasing the number of rows and decreasing the number of columns. The inverse transformation is pivot_wider()
- pivot_long Arguments:
  - data: A data frame to pivot
  - names_to: A string specifying the name of the column to create from the data stored in the column names of data.
  - values_to: A string specifying the name of the column to create from the data stored in cell values
  - col: Columns to pivot into longer format. Add a "-" to not include a column.

Pivoting Data in R (tidyverse)

- We now need to map out of the elements we need for pivot_long to work.
- Now we can plug in our elements.

```
gapminder_long <-pivot_longer(gapminder, names_to = “year”,
values_to = “DollarsMillon”)
```

```
gapminder_long <- gapminder %>%
  pivot_longer(!country, names_to = "year",
values_to = "DollarsMillon")
gapminder_long
```

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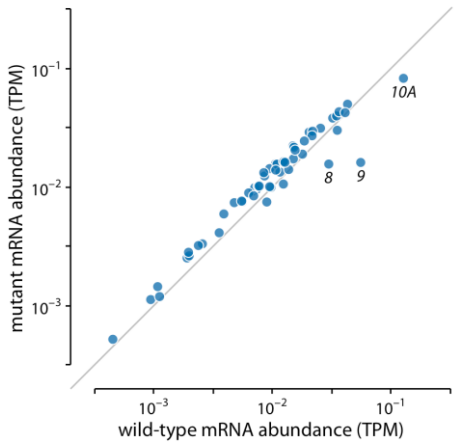
Lab Learning Objectives

- By the end of the lab, learners should be able to:
  - Understand the basics of plotting in ggplot.
  - Demonstrate how to add a layer to a plot using ggplot
  - Define ggplot aesthetics
  - Add a geometric function to a plot



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Reading in the Data

- Use ***read_csv()*** to load into memory the content of the CSV file as an object of class data.frame.
- We then need to import some data to work with, and save it to an object named: **surveys_complete**
- Function is: **read_csv**
- Dataset is: **surveys_complete.csv (RStudio Cloud users will need to upload first)**

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Reading in the Data

- Use ***read_csv()*** to load into memory the content of the CSV file as an object of class data.frame.
- We then need to import some data to work with, and save it to an object named: **surveys**
- Function is: **read_csv**

```
surveys_complete <- read_csv("../raw_data/surveys_complete.csv")
```

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Introduction to ggplot

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Plotting in R

- Plotting our data is one of the best ways to quickly explore it and the various relationships between variables.
- There are three main plotting systems in R, the base plotting system, the lattice package, and the ggplot2 package.

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Introduction to ggplot

- Plotting package that makes it simple to create complex plots from data in a data frame.
- Provides a more programmatic interface for specifying what variables to plot, how they are displayed, and general visual properties.
- Only need minimal changes if the underlying data change or if we decide to change from a bar plot to a scatterplot.

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Introduction to ggplot: Data and Layers

- ggplot2 functions like data in the 'long' format, i.e., a column for every dimension, and a row for every observation.
- Well-structured data will saves time when making figures with ggplot2
- ggplot graphics are built systematically by adding new elements.

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Basics of Plotting with ggplot

- Built on the grammar of graphics: any plot can be expressed from the same set of components:
  - a data set, a coordinate system, and a set of geoms–the visual representation of data points.
- Helps to think about a figure in layers
  - This idea may be familiar to you if you have used image-editing programs like Photoshop, Illustrator, or Inkscape

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Basics of Plotting with ggplot: Framework

- Start by defining the dataset, lay out the axes, and choose a geom.
- Use the following basic template that can be used for different types of plots:

```
ggplot(data = x, mapping = aes()) +
  geom_xx()
```

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Correct Method for Adding a Layer

- The + sign used to add new layers **must be placed at the end of the line containing the previous layer.**
- If the + sign is added at the beginning of the line containing the new layer, ggplot2 will not add the new layer and will return an error message.

```
ggplot(data = x, mapping = aes()) +
  Layer 2 +
  Layer 3
```

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Notes about ggplot () Function

- Anything you put in the ggplot() function is “seen” by any geom layers that you add.
- Means that aesthetics supplied to ggplot() are used as defaults for every layer
  - This includes the x and y axis mapping you set up in aes().
- You can also specify mappings for a given geom independently of the mappings defined globally in the ggplot() function.

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Defining Plot Aesthetics

- **aes()** allows us to select the variables to be plotted and specify how to present them in the graph.
  - For example, x and y positions, or characteristics such as size, shape, or color.
- Let us add **aes()** to our plot. We are going to plot the following variables, which we will place inside the (x = **weight**, y = **hindfoot_length**)

```
ggplot(data = surveys_complete, mapping = aes(x = weight,
y = hindfoot_length))
```

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Aesthetics of Plot Characteristics

- Once you map an aesthetic, ggplot2 takes care of the rest:
  - Selects a reasonable scale to use with the aesthetic
  - Constructs a legend that explains the mapping between levels and values.

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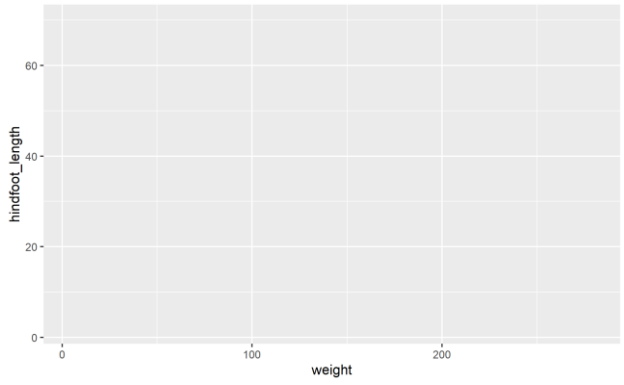
Aesthetics of Plot Characteristics

- As we have seen, for x and y aesthetics, ggplot2 does not create a legend. However, it does create…?



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Adding Geometric Functions

- **geom_xx** is the graphical representations of the data in the plot (points, lines, bars).
- ggplot2 offers many different geoms; we will be using:
  - **geom_point()** for scatter plots, dot plots, etc.
  - **geom_boxplot()** for boxplots
  - **geom_line()** for trend lines, time series, etc.

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Adding Geometric Function: Example

- Since we are using two continuous variables, we are going to start with a scatter plot **geom_point()**.
- Do not forget the + sign at the end of line 1!!

```
ggplot(data = surveys_complete, mapping = aes(x = weight,
y = hindfoot_length)) +
  geom_point()
```

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Assigning a Plot to an Object

- The + in the ggplot2 package is particularly useful because it allows you to modify existing ggplot objects.
- This means you can easily set up plot templates and conveniently explore different types of plots, so the above plot can also be generated by calling the newly created object.

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Assigning a Plot to an Object

```
# Assign plot to an Object
survey_plot <- ggplot(data = surveys_complete,
mapping = aes(x = weight, y = hindfoot_length))
```

- Once this object is created, the plot can also be generated with code like this:

```
# Generate a new plot based on survey_plot object
survey_plot +
  geom_point()
```

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Adding Multiple Colors in ggplot

- *ggplot2* will automatically assign a unique level of the aesthetic (here a unique color) to each unique value of the variable, a process known as scaling.
- *ggplot2* will provide a different color corresponding to different values in the vector. *ggplot2* will also add a legend that explains which levels correspond to which values.
- Before we do this, let us look at how many different types of species that we have using table()

```
table(surveys_complete$species_id)
```

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Adding Multiple Colors in ggplot

- OK, now let us construct our plot

```
survey_plot +
  geom_point(mapping = aes(color = species_id))
## Warning: Removed 4048 rows containing missing values (geom_
point).
```

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Challenge 1

- Use what you just learned to create a scatter plot of *weight (y)* over *species_id (x)* with the *plot types* showing in different colors.
- Is this a good way to visualize the data?

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Challenge 1: Answer

```
ggplot(data = surveys_complete, mapping = aes(x = species_id,
y = weight)) +
  geom_point(mapping = aes(color = plot_type))
```

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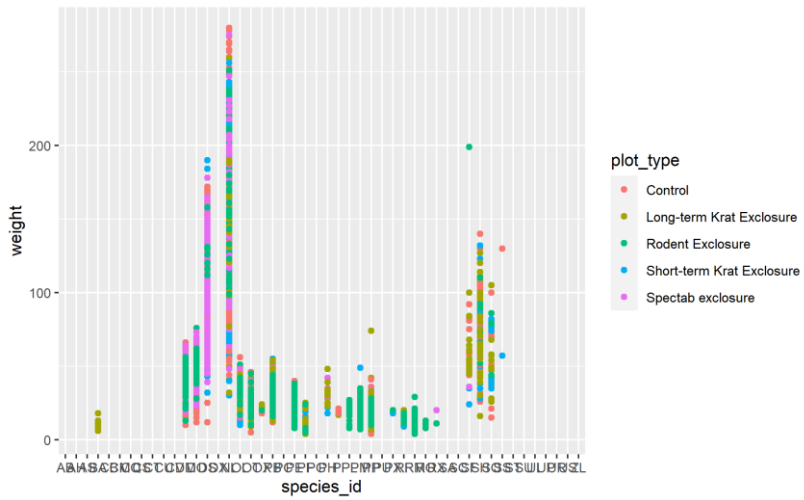
Challenge 1: Answer



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Bibliography

- Few, S. (2012a). Differing roles of tables and graphs [Book Section]. In Show me the numbers : Designing tables and graphs to enlighten (2nd ed., pp. 39–52). Analytics Press.
- Few, S. (2012b). Fundamental variations in graphs [Book Section]. In Show me the numbers : Designing tables and graphs to enlighten (2nd ed., pp. 87–136). Analytics Press.
- Friendly, M. (2008). A brief history of data visualization [Book Section]. In C. Chen, W. Härdle, & A. Unwin (Eds.), Handbook of data visualization (pp. 15–56). https://doi.org/https://doi.org/10.1007/978-3-540-33037-0_2
- Healy, K. (2018). Make a plot [Book Section]. In Data visualization: A practical introduction (pp. 54–72). Princeton University Press.

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69

Bibliography

- Munzner, T. (2014). Marks and channels [Book Section]. In Visualization analysis and design (pp. 95–115). CRC Press, Taylor & Francis Group.
- Ware, C. (2019a). Foundations for an applied science of data visualization [Book Section]. In Information visualization: Perception for design (4th ed., pp. 1–30). Morgan Kaufmann (Elsevier). https://doi.org/10.1016/B978-0-12-812875-6.00001-3
- Ware, C. (2019b). Visual salience: Finding and reading data glyphs [Book Section]. In Information visualization: Perception for design (pp. 143–182). Morgan Kaufmann (Elsevier). https://doi.org/https://doi.org/10.1016/B978-0-12-812875-6.00005-0
- Wilke, C. (2019). Coordinate systems and axes [Book Section]. In Fundamentals of data visualization: A primer on making informative and compelling figures (First edition., pp. 13–26). O'Reilly Media.

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