MTH 3270 Notes 2

3 Data Visualization (Graphics) (2)

3.1 Introduction

- Two important R graphics packages:
  - The `"graphics"` package in base R (discussed in Class Notes 1).
  - The `"ggplot2"` package (discussed below).
- A set of variables can be displayed many ways. The goal of visualization is to **convey information clearly** (E. Tufte).

Data Set: `diamonds`

The `diamonds` data set (in `"ggplot2"`) contains the prices and other attributes of almost 54,000 round cut diamonds. The ten variables are:

`price`	price in US dollars ($326–$18,823).
`carat`	weight of the diamond (0.2–5.01)
`cut`	quality of the cut (Fair, Good, Very Good, Premium, Ideal).
`color`	diamond color, from J (worst) to D (best).
`clarity`	a measurement of how clear the diamond is (I1 (worst), SI2, SI1, VS2, VS1, VVS2, VVS1, IF (best)).
`x`	length in mm (0–10.74).
`y`	width in mm (0–58.9).
`z`	depth in mm (0–31.8).
`depth`	total depth percentage = z / mean(x, y) = 2 * z / (x + y) (43–79).
`table`	width of top of diamond relative to widest point (43–95).

- **Example**: In the `diamonds` data set, how prevalent are the different `cut` classes? Here are three ways of visualizing that information:

```
## Bar plot
ggplot(data = diamonds) +
  geom_bar(mapping = aes(x = cut, fill = cut)) +
  ggtitle("Cuts of Diamonds")
```

```
## Stacked bar plot
ggplot(data = diamonds)  +
  geom_bar(mapping = aes(x = "", fill = cut))  +
  xlab(label = NULL) +
  ggtitle("Cuts of Diamonds")
```

```
## Pie chart
ggplot(data = diamonds)  +
  geom_bar(mapping = aes(x = "", fill = cut))  +
  xlab(label = NULL) +
  coord_polar(theta = "y") +
  ggtitle("Cuts of Diamonds")
```

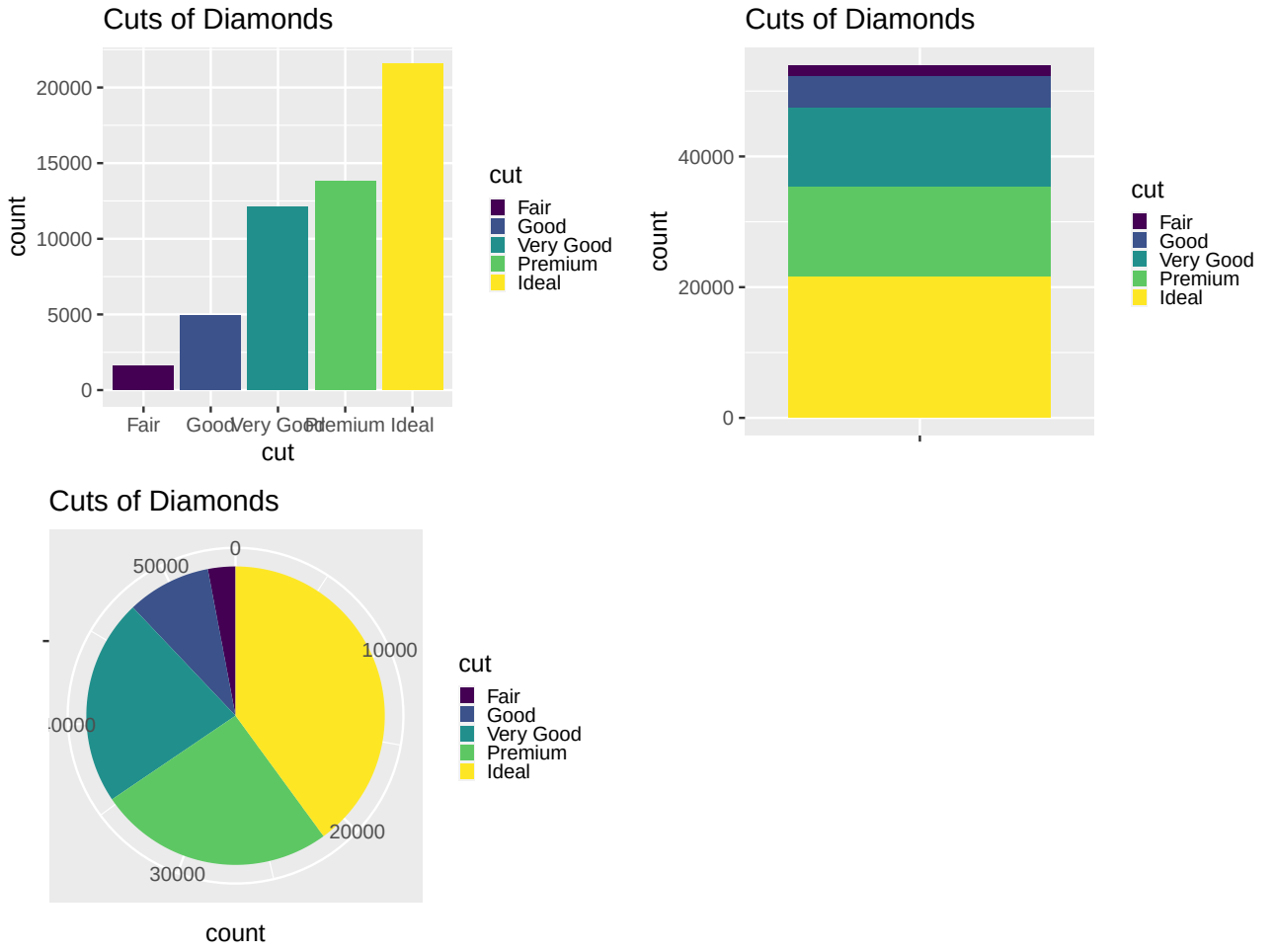


Figure 1

We can see from the graphs in Fig. 1 that `Ideal` is most prevalent class and `Fair` the least.

- A challenge is displaying **multiple** variables at the same time. One way to do it is to map values of variables to **aesthetic properties** such as color, shape, and size.

Data Set: `mpg`

The `mpg` data set (bundled with `"ggplot2"`) includes information about the fuel economy of popular car models from 1999 to 2008.

`manufacturer`	Categorical variable (`"audi"`, `"chevrolet"`, `"dodge"`, etc.).
`model`	Categorical variable indicating the model of car. The 38 models had a new edition every year between 1999 and 2008.
`displ`	is the engine displacement in liters.
`year`	The year of manufacture.
`cyl`	The number of cylinders.
`trans`	The type of transmission.
`drv`	The drivetrain: front wheel (`"f"`), rear wheel (`"r"`), or four wheel (`"4"`).
`cty`	Miles per gallon (mpg) for city driving.
`hwy`	Miles per gallon (mpg) for highway driving.
`fl`	The fuel type.
`class`	Categorical variable describing the ”type” of car: `two-seater`, `SUV`, `compact`, etc.

- **Example**: Using the `mpg` data set, Fig. 2 shows three ways of displaying **three** variables, `displ`, `hwy`, and `drv`:

```
## scatterplot with drv as different colors
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy, color = drv)) +
  ggtitle("Hwy Mpg vs Displacement")
```

```
## scatterplot with drv as different shapes
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy, shape = drv)) +
  ggtitle("Hwy Mpg vs Displacement")
```

```
## smooth lines with drv as different colors
ggplot(data = mpg) +
  geom_smooth(mapping = aes(x = displ, y = hwy, color = drv), se = FALSE) +
  ggtitle("Hwy Mpg vs Displacement")
```

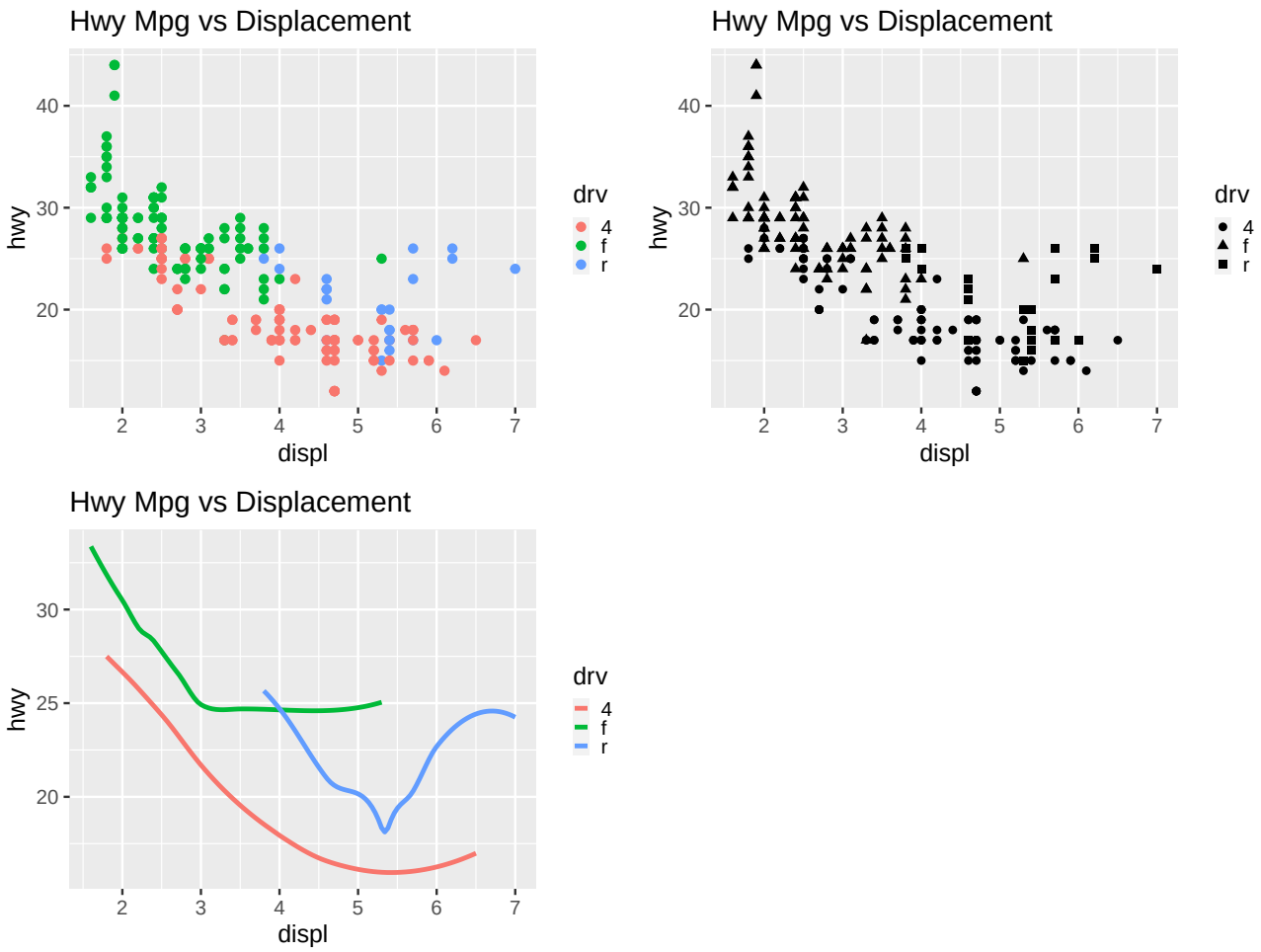


Figure 2

- Another way to display three variables (when one of them is categorical) is via **faceting**.
- **Example**: In Fig. 3, the **three** variables, `displ`, `hwy`, and `drv`, are displayed using **faceting**:

```
## Scatterplots with faceting
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy)) +
  facet_wrap(facets = ~ drv, nrow = 1, ncol = 3)
```

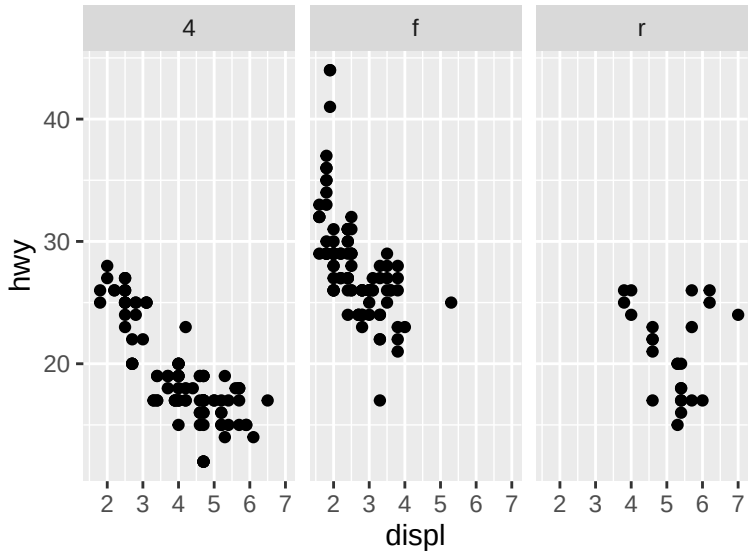


Figure 3

3.2 A Taxonomy for Data Graphics

- Here's a **taxonomy** for characterizing statistical graphs (N. Yau). Graphs are characterized by:
  - ***Visual cues***: For portraying **values** of variables (both numerical and categorical).

Human Ability to **Discern Differences**	**Visual Cue (and Type of Variable)**
Easiest to Discern	Position (numerical)
↓	Length (numerical)
	Angle (numerical)
	Direction (numerical)
↓	Shape (categorical)
	Area (numerical)
	Volume (numerical)
↓	Shade (either)
Hardest to Discern	Color (either)

  - ***Coordinate system***: For determining the positions of points or other geometric elements in the graph.
    - Cartesian (x and y axes)
    - Polar (angle θ and radius r)
    - Geographic (latitude and longitude)
  - ***Scale***: For determining how distances in the graph translate to differences in the value of the variable.
    - Numerical (linear or logarithmic)
    - Categorical (nominal or ordinal)
    - Time (linear or cyclical)
  - ***Context***: Title, axis labels, legend, etc. which make the graph *meaningful*.
- **Example**:
  - In Fig. 1, upper left (bar plot):
    - **Visual cues**: *position* (along the y axis) and *color*.
    - **Coordinate system**: *Cartesian* (but the x coordinate is meaningless).
    - **Scale**: *numerical* (on the y-axis) and *categorical* (on the x-axis and as colors).
    - **Context**: *legend*, *axis labels*, and *title*.
  - In Fig. 1, upper right (stacked bar plot):

    - **Visual cues**: *length* (along the y axis) and *color*.
    - **Coordinate system**: *Cartesian* (but the x coordinate is meaningless).
    - **Scale**: *numerical* (along the y axis) and *categorical* (as colors).
    - **Context**: *legend*, *y-axis label*, and *title*.
  - Fig. 1, bottom left (pie chart):
    - **Visual cues**: arc *length* (or *angle*) and *color*.
    - **Coordinate system**: *polar* (but the r coordinate is meaningless).
    - **Scale**: *numerical* (for the arc *length* or *angle* θ) and *categorical* (as colors).
    - **Context**: *legend*, *label below horizontal axis*, and *title*.

- **Example**:
  - In Fig. 2, upper left (scatterplot):
    - **Visual cues**: *position* (along the x and y axes) and *color*.
    - **Coordinate system**: *Cartesian*.
    - **Scale**: *numerical* (on the two axes) and *categorical* (as colors).
    - **Context**: *legend*, *axis labels*, and *title*.
  - In Fig. 2, upper right (scatterplot):
    - **Visual cues**: *position* (along the x and y axes) and *shape*.
    - **Coordinate system**: *Cartesian*.
    - **Scale**: *numerical* (on the two axes) and *categorical* (as shapes).
    - **Context**: *legend*, *axis labels*, and *title*.
  - In Fig. 2, bottom left (smooth line plot):
    - **Visual cues**: *position* (along the x and y axes), *direction* (of the lines), and *color*.
    - **Coordinate system**: *Cartesian*.
    - **Scale**: *numerical* (on the two axes) and *categorical* (as colors).
    - **Context**: *legend*, *axis labels*, and *title*.

Section 3.2 Exercises

Exercise 1 Load the `"ggplot2"` package (which contains the `diamonds` data set):

```
library(ggplot2)
```

Run each code chunk below, and for each graph indicate:

- The **visual cues** that are used.
- The **coordinate system** that's used.
- The **scales** that are used.
- How **context** is provided.

a)
```
ggplot(data = diamonds) +
  geom_point(mapping = aes(x = carat, y = price, color = cut)) +
  ggtitle("Diamond Price vs Weight")
```

b)
```
ggplot(data = diamonds) +
  geom_point(mapping = aes(x = carat, y = price)) +
  geom_smooth(mapping = aes(x = carat, y = price), se = FALSE) +
  ggtitle("Diamond Price vs Weight")
```

c)
```
ggplot(data = diamonds) +
  geom_histogram(mapping = aes(x = price)) +
  ggtitle("Histogram of Diamond Prices")
```

Exercise 2 This exercise uses the `mpg` data set. Run each code chunk below, and for each graph indicate:

- The **visual cues** that are used.
- The **coordinate system** that's used.
- The **scales** that are used.
- How **context** is provided.

a)
```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy, size = cyl)) +
  ggtitle("Highway MPG vs Displacement")
```

b)
```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = cty, size = hwy,
             color = cyl, shape = drv)) +
  ggtitle("City MPG vs Displacement")
```

4 A Grammar for Graphics with "ggplot2" (3)

4.1 Introduction

- We'll see now how to make graphs using the "ggplot2" package. Typing:

```
help(package = "ggplot2")
```

  shows a list of the functions (and data sets) in "ggplot2".

- "ggplot2" (H. Wickham) is based on the so-called ***grammar of graphics*** (L. Wilkinson).

  The **grammar of graphics** is slightly different from the **taxonomy** described above. It uses the following components shared by all statistical graphs:

  - A ***data set*** containing the *variables* to be plotted.
  - ***Aesthetic mappings*** that associate *variables* with *aesthetic properties* (aka **visual cues**) such as position, color, size, and shape.
  - At least one ***layer*** of ***geometric objects*** such as points, bars, or lines.
  - A ***coordinate system*** and, for each aesthetic mapping, a ***scale*** that associates *values of the variable* to *values of the aesthetic property*. The scale is conveyed in legends, x and y axis annotations, etc.
  - Optionally, a ***statistical transformation*** to be displayed (instead of the raw data), for example category *counts* for a bar plot, bin *counts* for a histogram, etc.
  - Optionally, a ***facet*** specification (usually no faceting).

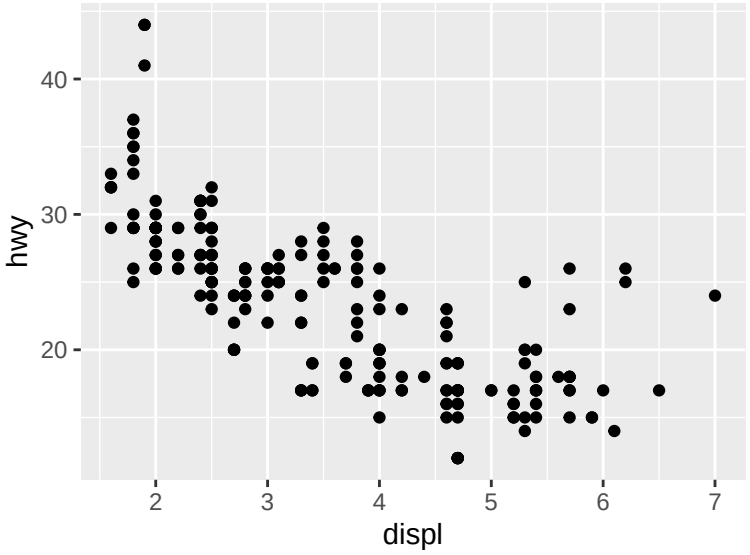
- **Every "ggplot2" plot command requires**:

  1. A **data set**, usually specified in `ggplot()`, containing the variables to be plotted.
  2. One or more **aesthetic mappings** associating variables with aesthetic properties (visual cues), specified in `aes()`.
  3. At least one **layer** of **geometric objects**, added via a `geom_*()` function.

```
ggplot()      Specify a data set and initialize a plot.
aes()         Specify aesthetic mappings.  Used within ggplot() or a
              geom_*() function.
geom_*()      Add a layer of geometric objects (e.g. geom_bar(),
              geom_point(), etc.).
```

- The graph is initiated using `ggplot()`, and **layers** of **geometric objects** are added using one ore more of the `geom_*()` functions.
- **Example**:

```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy))
```

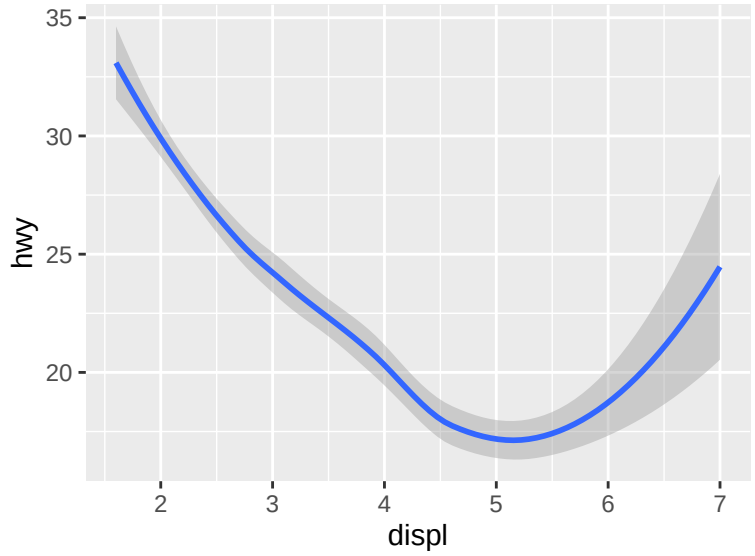


In the command above:

  - The **data set** is `mpg`.
  - The two **aesthetic mappings** map `displ` to the x-axis and `hwy` to the y-axis.
  - The **layer** consists of points added via `geom_point()`.

- **Example**:

```
ggplot(data = mpg) +
  geom_smooth(mapping = aes(x = displ, y = hwy))
```

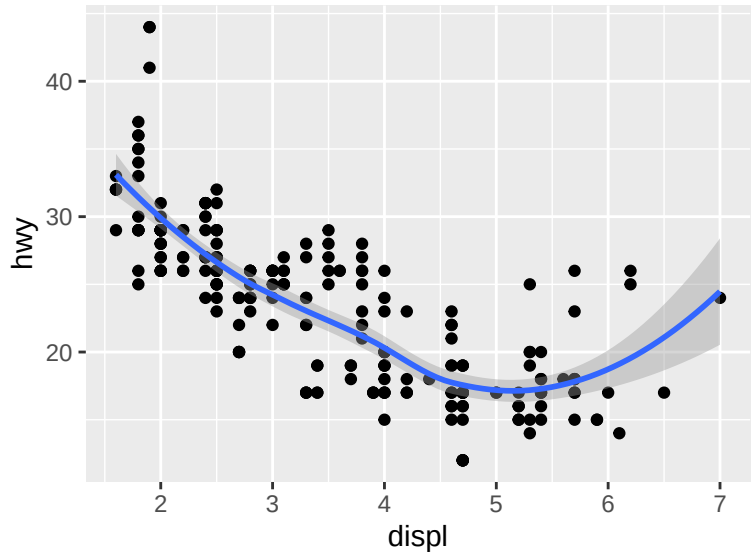


In the command above:

- The **data set** is `mpg`.
- The two **aesthetic mappings** map `displ` to the x-axis and `hwy` to the y-axis.
- The **layer** consists of a smooth line added via `geom_smooth()`.

- We can add *more than one* **layer** to a single graph using different `geom_*()` functions.
- **Example**:

```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy)) +
  geom_smooth(mapping = aes(x = displ, y = hwy))
```



- Here's a basic **graphing template**:

```
ggplot(data = <DATA>) +
  <GEOM_FUNCTION>(mapping = aes(<MAPPINGS>))
```

Replace the bracketed sections with a **data set**, `geom_*()` **function**, and **aesthetic mappings**. Add layers using additional `geom_*()` functions.

- Three comments:
  1. `ggplot()` merely initializes the graph by setting up a **coordinate system**.
  2. The **data set** is usually specified in `ggplot()`, but it could also be specified in the `geom_*()` function.
     - If it's specified in `ggplot()`, it's used as the default for *all* **layers**.
     - If it's specified in the `geom_*()` function, it only applies to that *particular* **layer**.
  3. The **aesthetic mapping** is usually specified in the `geom_*()` function, but it could also be specified in `ggplot()`.
     - If it's specified in `ggplot()`, it's used as the default for *all* **layers**.
     - If it's specified in the `geom_*()` function, it only applies to that *particular* **layer**.
- Other components of the *grammar* (**coordinate system** and **scale**, **statistical transformation**, and **faceting**) aren't required in the `"ggplot2"` plot command – they have reasonable default settings. But they can be altered with the following functions.

```
coord_*()     Set the coordinate system (e.g. coord_polar()
              for polar coordinates, i.e. pie charts, and coord_flip()
              to flip the horizontal and vertical axes).
scale_*()     Define the scale (e.g. scale_y_log10() for a log
              scale on the y-axis), and control its features.
stat_*()      Specify a statistic to be plotted (e.g. stat_count() for
              a bar plot and stat_function() to graph a function).
facet_*()     Specify faceting configuration.
```

- **Titles** and **axis labels** can be added to provide context using these functions.

```
ggtitle()         Add a main title.
xlab(), ylab()    Add an x-axis or y-axis label.
labs()            Add a title to the legend.
```

Section 4.1 Exercises

Exercise 3 `ggplot()` merely sets up a coordinate system. Type the following command, involving the `mpg` data set, and describe what you see:

```
ggplot(data = mpg)
```

Exercise 4 The *data set* is usually specified in `ggplot()`, but it could also be specified in the `geom_*()` function. If it's specified in `ggplot()`, it's used for all layers. If it's specified in `geom_*()`, it only applies to that layer.

Guess whether the following commands both make the same scatterplot, then check your answer:

```
## Specify data in ggplot():
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy))
```

```
## Specify data in geom_*() function:
ggplot() +
  geom_point(data = mpg, mapping = aes(x = displ, y = hwy))
```

Exercise 5 The *aesthetic mapping* is usually specified in the `geom_*()` function, but it could also be specified in `ggplot()`. If it's specified in `geom_*()`, it only applies to that layer. If it's specified in

`ggplot()`, it's used for all layers.

Guess whether the following commands both make the same scatterplot, then check your answer:

```
## Specify aesthetics in geom_*() function:
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy))
```

```
## Specify aesthetics in ggplot():
ggplot(data = mpg, mapping = aes(x = displ, y = hwy)) +
  geom_point()
```

Exercise 6 This exercise uses the `mpg` data set again.

a) Guess what the `ggtitle()`, `xlab()`, and `ylab()` commands do to the scatterplot below. Then check your answers.

```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy)) +
  ggtitle(label = "Highway MPG vs Displacement") +
  xlab(label = "Displacement") +
  ylab(label = "Highway MPG")
```

b) Guess what the `labs()` command does to the scatterplot below. Then check your answer.

```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy, color = drv)) +
  labs(color = "Drivetrain")
```

Exercise 7 This exercise uses the `mpg` data set again.

a) Make a scatterplot of `hwy` (on the y-axis) versus `cyl` (x-axis). Report your R command(s).

b) Reproduce the scatterplot of Part *a*, but now add a second *layer* to the plot using `geom_smooth()`. Report your R command(s).

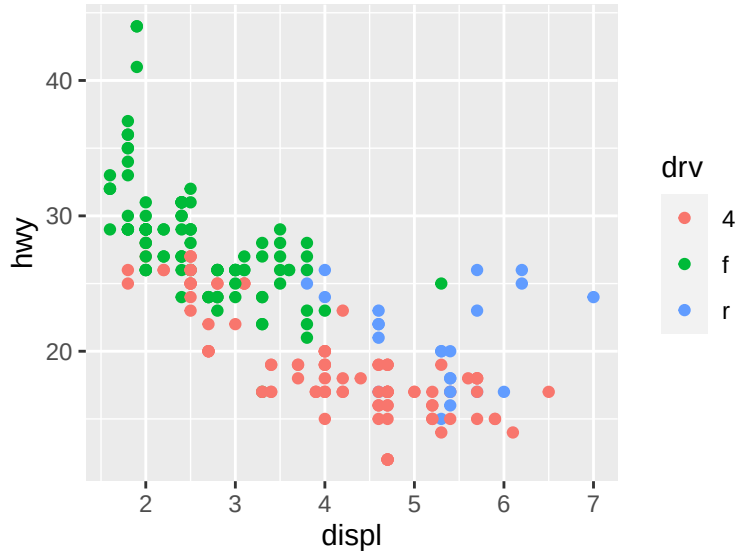
(You'll see some warning messages. The so-called *loess* smooth curve involves fitting a *regression line* locally in a moving window of `cyl` (x-axis) values, similar to a *moving average*. The warning messages stem from the discreteness of the `cyl` values.)

c) Make a scatterplot of `class` (y-axis) versus `drv` (x-axis)? What happens? Why is the plot not useful?

4.2 More on Aesthetic Mappings

- Here's a graph with *three* **aesthetic properties** (`x` position, `y` position, and `color`) associated with the *variables* `displ`, `hwy`, and `drv` (from the `mpg` data set):

```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy, color = drv))
```



The **scale** associating a specific color to each `drv` class is created automatically (as is the legend conveying that **scale**).

- The set of **aesthetic mappings** that are available will depend on what type of **geometric object** is being plotted. For example, the `linetype` aesthetic would be available for a variable in `geom_line()` but not in `geom_point()`.

  To see which **aesthetic mappings** are available for a given **geometric object**, look at the help page for the `geom_*()` function, e.g.

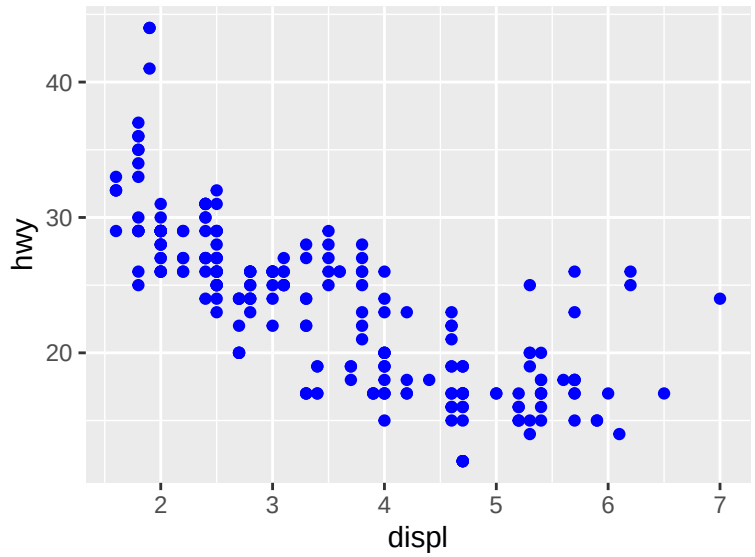
```
? geom_point
```

  From the help page for `geom_point()`, we can see that the `x`, `y`, `color`, `shape`, and `size` **aesthetics** (among others) are available.

- Instead of mapping **aesthetic properties** to values of a *variable*, we can set them *manually* by passing a value for the **aesthetic** via a named argument in the `geom_*()` function, *outside* `aes()`.

  For example, to make *all* of the points in the plot blue, we pass the value `"blue"` for the color **aesthetic** via the `color` argument in `geom_point()`, *outside* `aes()`:

```
## Specify color = "blue" outside aes():
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy), color = "blue")
```



We could also *manually* set points to a specific `size` (in mm) or a `shape` (as numeric identifier from 0 to 24).

For more information, look at the so-called **vignette** for "ggplot2"s aesthetic specifications by typing:

```
vignette("ggplot2-specs")
```

Section 4.2 Exercises

Exercise 8 This exercise concerns changing the **aesthetic mappings** in a plot. First, produce the following plot:

```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy, color = cyl))
```

a) Reproduce the plot, but with `cyl` mapped to the `size` aesthetic (instead of `color`). How does the plot differ from the one above?

b) What happens when you try to map `cyl` to the `shape` aesthetic? Try it, and report what happens.

c) What happens when you map the `"logical"` values in `displ < 5` to an aesthetic property? Try it by running the following command, and describe the plot in a sentence or two.

```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy, color = displ < 5))
```

d) What happens when you map the same variable to multiple aesthetics? Try the both of the following.

- Alter the code below so that `hwy` gets mapped to *both* `y` *and* `color`. Describe the plot in a sentence or two.

```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy))
```

- Now alter the code so that `hwy` gets mapped to `y`, `color`, *and* `size`. Describe the plot in a sentence or two.

Exercise 9 To make *all* of the points in a plot blue, we can set the `color` aesthetic of the points *manually* in the `geom_*()` function, *outside* `aes()`, by typing:

```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy), color = "blue")
```

A common mistake is doing it *inside* `aes()`. What happens when you type the following?

```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ, y = hwy, color = "blue"))
```

4.3 More on Layers

- Here are some of the most important `geom_*()` functions for adding **layers** of **geometric objects** to a plot:

```
geom_point()      Add scatterplot points
geom_smooth()     Add smoothed scatterplot line
geom_histogram()  Add a histogram
geom_density()    Add a density curve
```

```
geom_bar()        Add bars, with heights corresponding to the number
                  of cases in each group.
geom_col()        Add bars, with heights corresponding to values in
                  the data.
geom_boxplot()    Add boxplot
geom_line()       Add line through points in the order of the variable
                  on the x-axis.
geom_path()       Add line through points in the order in which they
                  appear in the data set.
geom_text()       Add text directly to the plot.  The position and label
                  of the text are specified via aes(x, y,  label).
geom_label()      Add text with a rectangle behind it, making it easier
                  to read.  The position and label of the text are
                  specified via aes(x, y, label).
```

For a full list, type:

```
help(package = "ggplot2")
```

- Recall that typing:

```
ggplot(data = mpg)
```

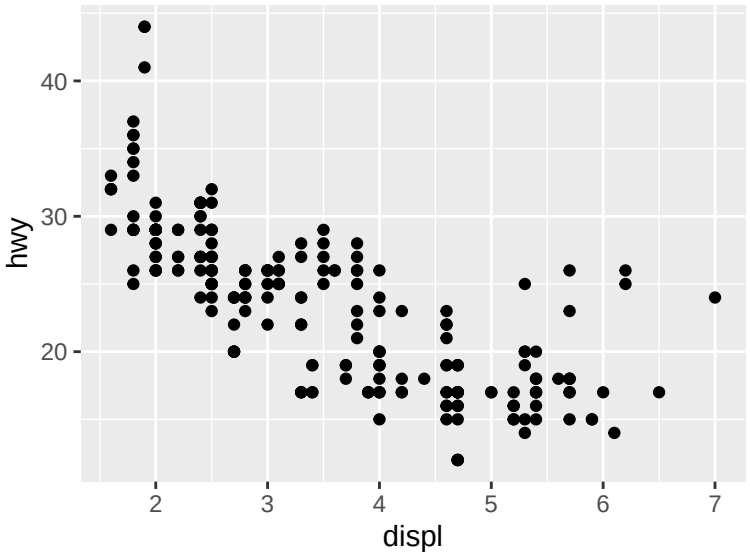
just creates a blank graph, and **layers** of **geometric objects** are added using one or more `geom_*()` functions.

- We can *change* the type of **layer** by using a different `geom_*()` function. For example, below, we first save the graph (without *any* **layers**) as an object `g`:

```
g <- ggplot(data = mpg)
```

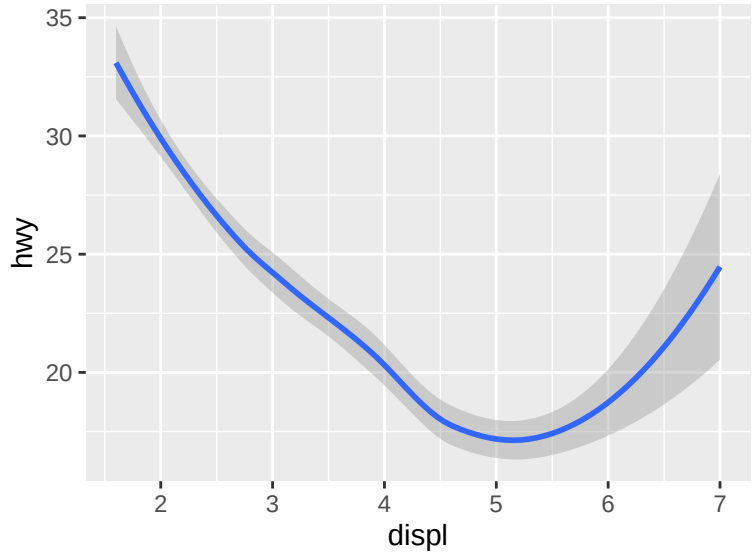
Now we *add* a **layer** of *points*:

```
g + geom_point(mapping = aes(x = displ, y = hwy))
```



Here we use a *different* `geom_*()` function to *change* the **layer** to *a smooth line*:

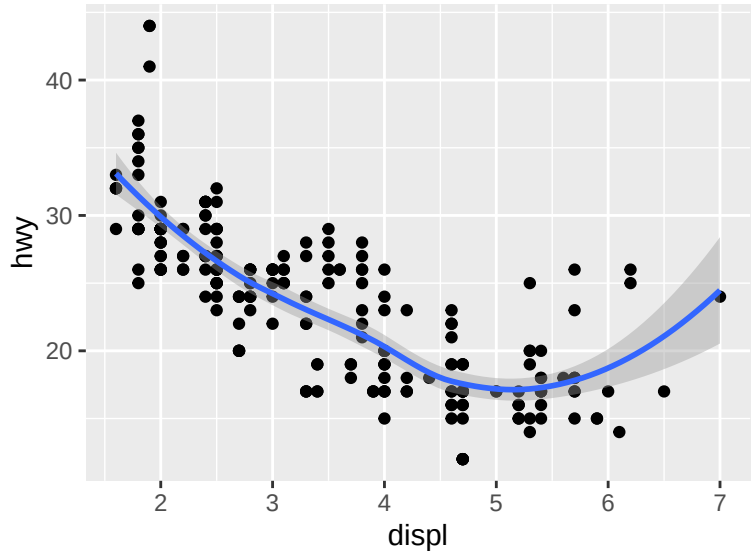
```
g + geom_smooth(mapping = aes(x = displ, y = hwy))
```



- Below we add *more than one* **layer** to a single graph.

  Notice we set the **aesthetic mapping** in `ggplot()` (instead of in the `geom_*()` functions) so that it applies to *both* **layers**:

```
g <- ggplot(data = mpg, mapping = aes(x = displ, y = hwy))
g + geom_point() +
    geom_smooth()
```

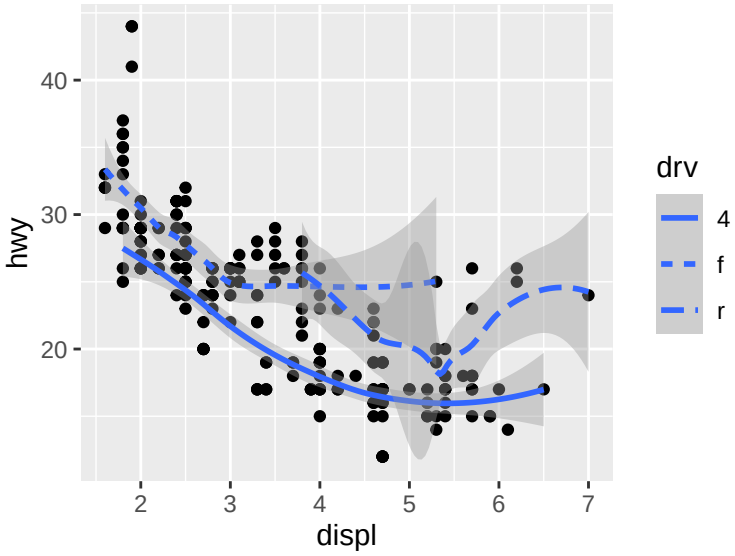


- Recall that the set of **aesthetic mappings** available depends on the type of **geometric object** being plotted.

  For example, `linetype` is available for `geom_smooth()` but not for `geom_point()`.

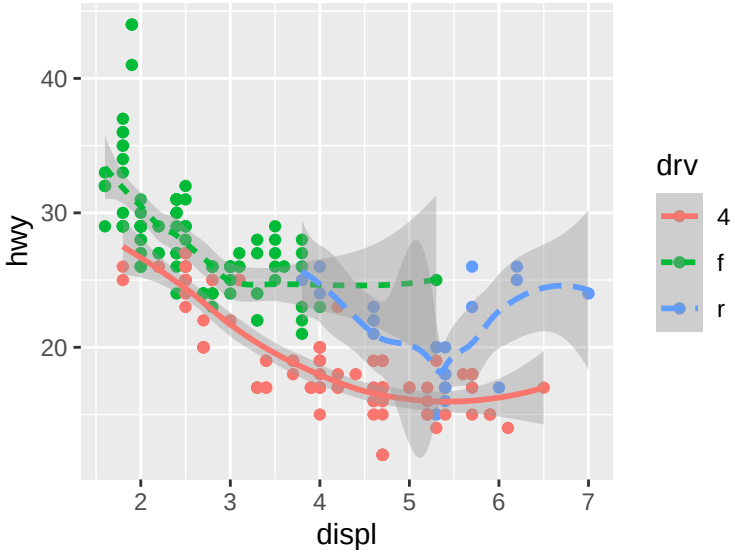
  Below, we display a third variable, `drv`, via the `linetype` **aesthetic**. This plots a separate line for each `drv` class of cars:

```
ggplot(data = mpg, mapping = aes(x = displ, y = hwy)) +
  geom_point() +
  geom_smooth(mapping = aes(linetype = drv))
```



- To see the different `drv` groups better, we can use the `color` **aesthetic** to distinguish them:

```
ggplot(data = mpg, mapping = aes(x = displ, y = hwy, color = drv)) +
  geom_point() +
  geom_smooth(mapping = aes(linetype = drv))
```

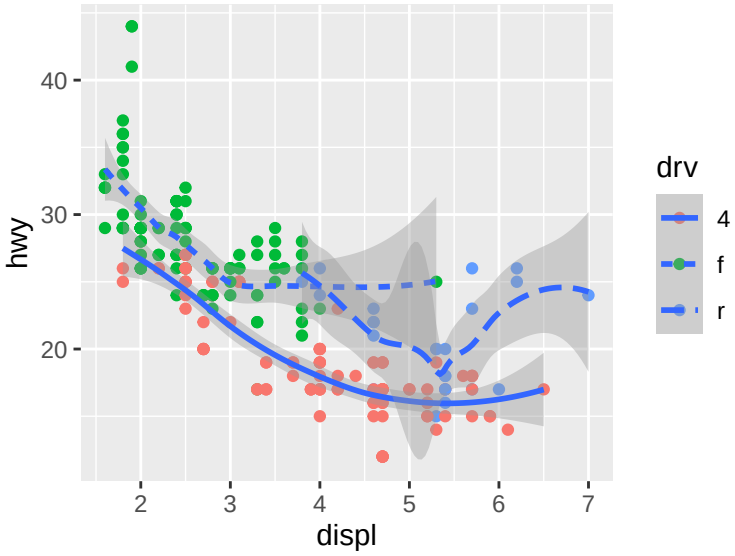


Above, the `color` **aesthetic** applied to *both* **layers** (points and smooth lines) because `color = drv` was specified in `ggplot()`.

- **Aesthetic mappings** specified in a `geom_*()` function apply to *only that layer*.

Below, the `color` **aesthetic** applies to the *points* but *not* the smooth *lines*:

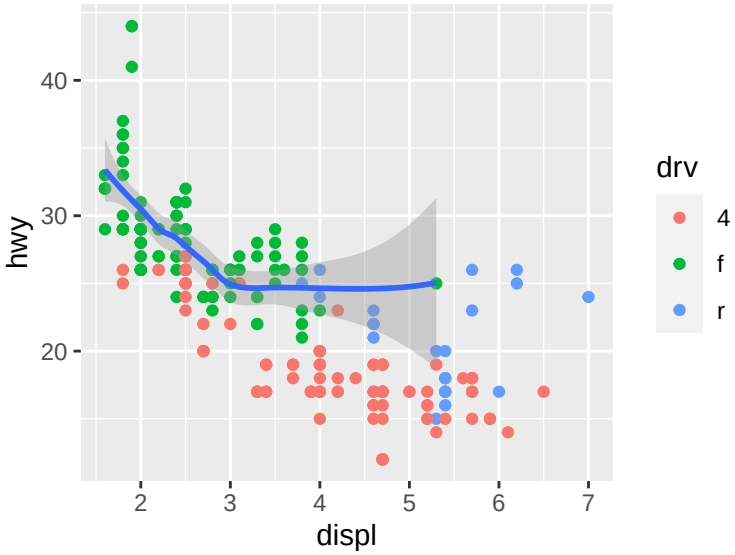
```
ggplot(data = mpg, mapping = aes(x = displ, y = hwy)) +
  geom_point(mapping = aes(color = drv)) +
  geom_smooth(mapping = aes(linetype = drv))
```



- We can even use a *different* **data set** for each **layer** of **geometric objects**. To do so, specify the **data sets** via the `geom_*()` functions (instead of in `ggplot()`).

  Below, we use only a subset of the `mpg` data set for the smooth line. (The `filter()` function from the `"dplyr"` package extracts just the `"f"` `drv` class of cars from `mpg`):

```
library(dplyr)
ggplot() +
  geom_point(data = mpg, mapping = aes(x = displ, y = hwy, color = drv)) +
  geom_smooth(data = filter(mpg, drv == "f"), mapping = aes(x = displ, y = hwy))
```



Section 4.3 Exercises

Exercise 10 Recall that if an aesthetic mapping is specified in `ggplot()`, it's used for all layers, but if it's specified in `geom_*()`, it only applies to that layer.

Look at the graph the following commands produce.

```
ggplot(data = mpg, mapping = aes(x = displ, y = hwy, color = drv)) +
  geom_point() +
  geom_smooth()
```

Note that above, `drv` is mapped to `color` for *both* the points *and* the lines because the mapping is specified in `ggplot()`.

a) Try to predict what the following graph will look like, then check your answer. Report your findings.

```
ggplot(data = mpg, mapping = aes(x = displ, y = hwy)) +
  geom_point(mapping = aes(color = drv)) +
  geom_smooth()
```

b) Now try to predict what the following graph will look like, then check your answer. Report your findings.

```
ggplot(data = mpg, mapping = aes(x = displ, y = hwy)) +
  geom_point() +
  geom_smooth(mapping = aes(color = drv))
```

Exercise 11 This exercise concerns adding and altering **layers** of a plot. Recall that `ggplot()` merely sets up a coordinate system:

```
ggplot(data = mpg)
```

a) Modify the command above so that the following **layer** is added to the plot. Report what you see.

```
geom_boxplot(mapping = aes(x = drv, y = displ))
```

b) What happens if you use `geom_col()` in place of `geom_boxplot()` in Part *b*? Try it and report what you see.

(Note that `geom_col()` makes a bar plot of the *sums* of the `displ` values for each `drv` group. To plot the *means*, see the examples on the help page for `geom_col()`.)

Exercise 12 *Univariate* (one-variable) numerical data are often graphed in a histogram or density plot. In either case, the variable is mapped to `x` via `aes()`, and there's no `y` variable.

a) Use `ggplot()` and `geom_histogram()` to make a histogram of `hwy` (from the `mpg` data set). Report your R command(s).

b) Replace `geom_histogram()` in your command from Part *a* by `geom_density()` to make a density plot `hwy`. Report your R command(s).

c) To make a plot with *two* **layers**, the histogram from Part *a* and the density plot from Part *b*, we need rescale that histogram so that the y-axis scale is the same as the density curve. Make the following graph and describe the result:

```
ggplot(mpg, mapping = aes(x = hwy)) +
  geom_histogram(mapping = aes(y = stat(density))) +
  geom_density()
```

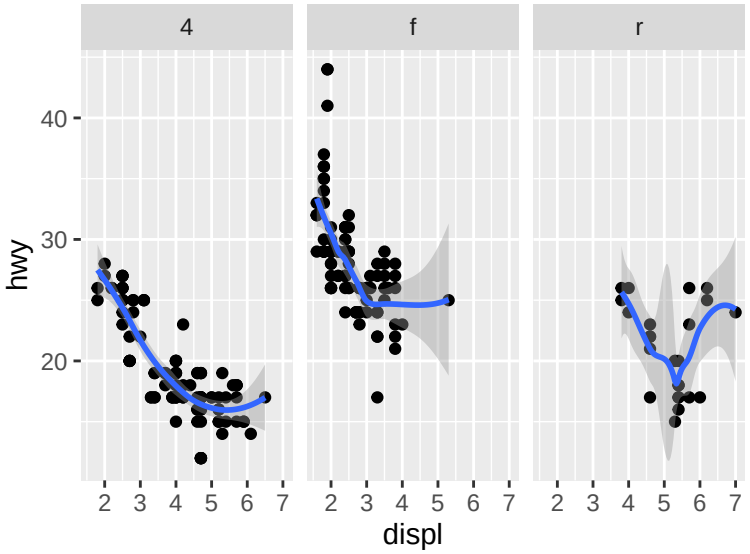
Specifying `mapping = aes(y = stat(density))` in `geom_histogram()` produces a histogram whose y-axis scale is such that the areas of the bars sum to one, to match the area under the density curve.

4.4 More on Faceting

- Another way to display a third *categorical* variable (such as `drv`), instead of mapping it to an aesthetic property, is to use **faceting**. Faceting results in a separate plot for each subset of the data (e.g. for each `drv`

class). It's done using `facet_wrap()` or one of the other `facet_*()` functions:

```
ggplot(data = mpg, mapping = aes(x = displ, y = hwy)) +
  geom_point() +
  geom_smooth() +
  facet_wrap(facets = ~ drv, nrow = 1, ncol = 3)
```

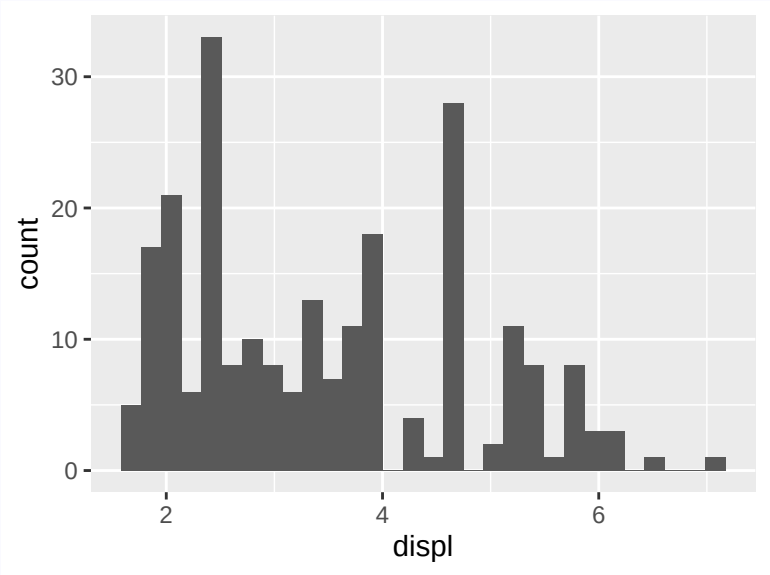


Above, we pass a so-called *formula*, `~ drv`, to `facet_wrap()` via the `facets` argument.

Section 4.4 Exercises

Exercise 13 This exercise concerns *faceting* for displaying a *categorical* variable. Here's a histogram of the `displ` variable from the `mpg` data set:

```
ggplot(data = mpg) +
  geom_histogram(mapping = aes(x = displ))
```



a) One way to display the *categorical* variable `drv` is via either the `color` or `fill` *aesthetic*. Look at the following two graphs.

```
ggplot(data = mpg) +
  geom_histogram(mapping = aes(x = displ, color = drv))
```

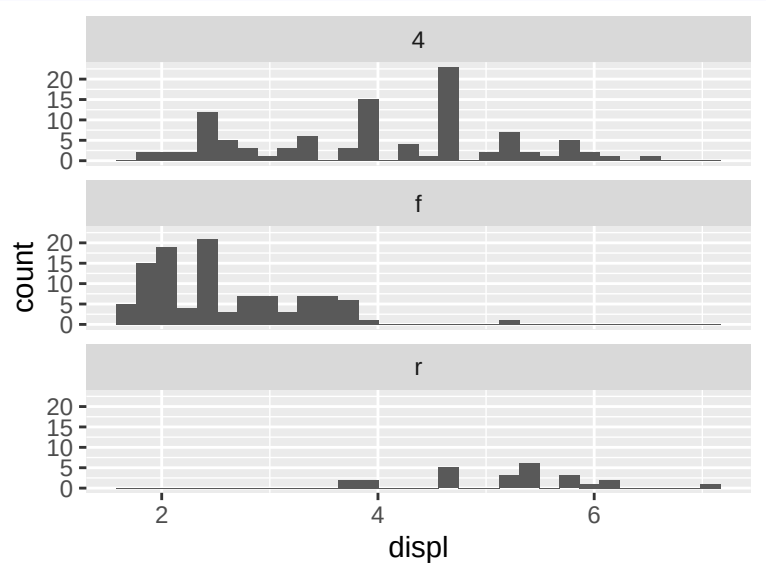
```
ggplot(data = mpg) +
  geom_histogram(mapping = aes(x = displ, fill = drv))
```

Which graph do you prefer?

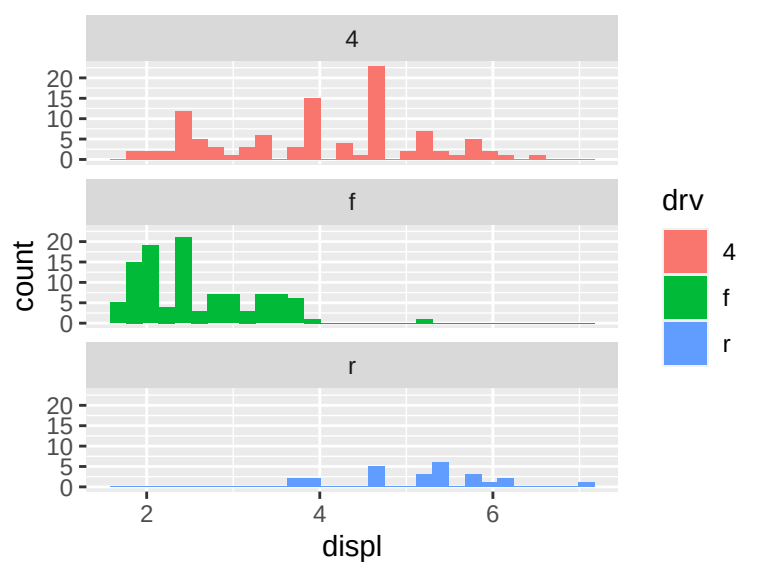
b) Alter the following code chunk,

```
ggplot(data = mpg) +
  geom_histogram(mapping = aes(x = displ))
```

using `facet_wrap()`, with `facets = ~ drv`, to duplicate the following graph. Report your R command(s):



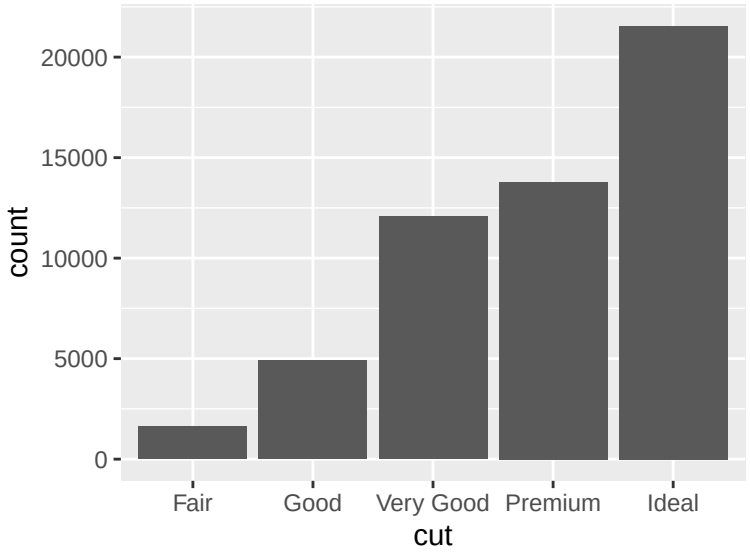
c) Now alter the code chunk you wrote for Part *b* by adding another aesthetic mapping, `fill = drv`, to duplicate the following graph:



4.5 Statistical Transformations

- Consider the bar plot below:

```
ggplot(data = diamonds) +
  geom_bar(mapping = aes(x = cut))
```



On the x-axis is `cut`, a (categorical) variable in the `diamonds` data set. On the y-axis is `count`, which is *not* a variable in the data set.

- Many graphs (e.g. scatterplots) plot the raw data. Others plot ***statistics*** computed from the data:
  - *Bar plots* plot **counts** for each category.
  - *Histograms* plot **counts** for each bin (class interval).
  - *Scatterplot smoothers* plot predicted y values based on fitting a model to the data.
  - *Boxplots* plot a set of five summary statistics of the data.
- Each `geom_*()` function has a default ***statistical transformation*** of the data that it plots.

  (For some `geom_*()` functions, such as `geom_point()`, the **statistical transformation** is the `"identity"` transformation, meaning the raw, untransformed data are plotted.)

  You can see the default **statistical transformation** by looking at the `geom_*()` function's help page. For example, typing:

```
? geom_bar
```

  shows that the default **statistic** for `geom_bar()` is "count".
- Each `stat_*()` function has a default set of **geometric objects** that it plots.

  We can usually use a `stat_*()` function in place of its `geom_*()` function. For example, the following do the same thing:

```
ggplot(data = diamonds) +
  geom_bar(mapping = aes(x = cut))
```

```
ggplot(data = diamonds) +
  stat_count(mapping = aes(x = cut))
```

- Occasionally, we need to override the default **statistical transformation** of a `geom_*()` function. We can do this using the `stat` argument in the `geom_*()` function.

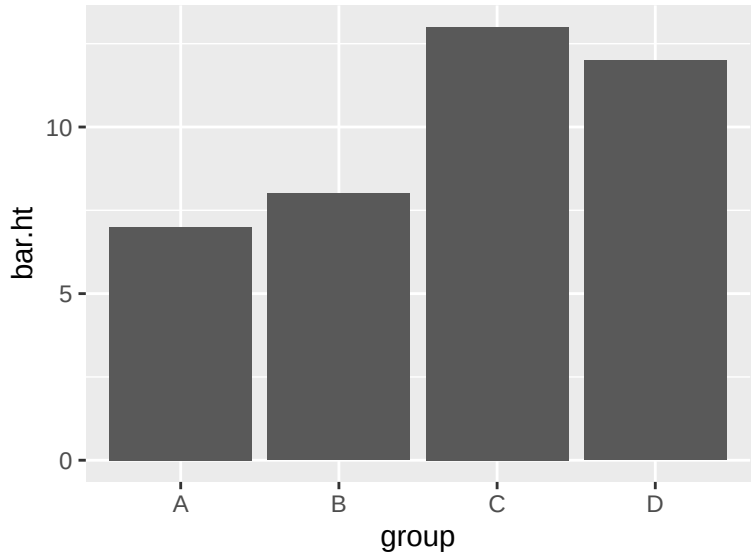
  For example, the following makes a bar plot whose bar heights are *values* in a data set, *not* category *counts*:

```
my.data <- data.frame(group = c("A", "B", "C", "D"), bar.ht = c(7, 8, 13, 12))

my.data

##   group bar.ht
## 1     A      7
## 2     B      8
## 3     C     13
## 4     D     12
```

```
ggplot(data = my.data) +
  geom_bar(mapping = aes(x = group, y = bar.ht), stat = "identity")
```



- Sometimes it's desirable to use a `stat_*()` function directly (instead of a `geom_*()` function), for example to make your code more readable:

```
ggplot(data = diamonds) +
  stat_summary(mapping = aes(x = cut, y = depth),
               fun.min = min,
               fun.max = max,
               fun = median)
```

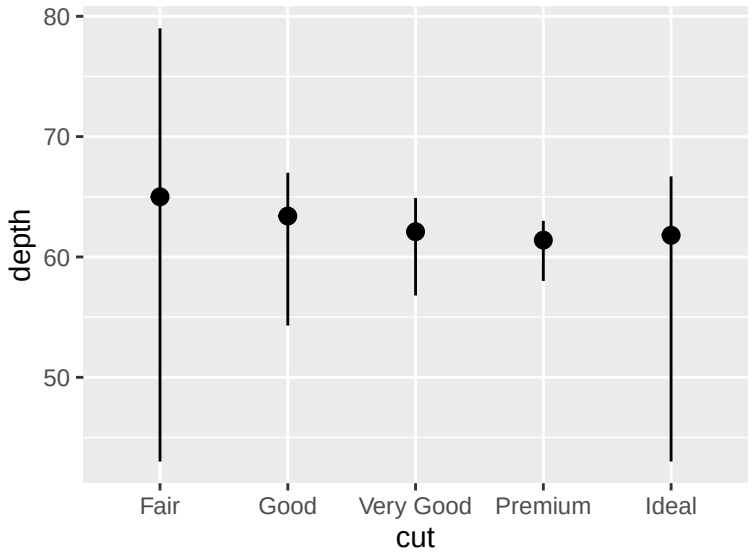


Figure 4

- There are more than 20 `stat_*()` functions, each of which has its own help page. For a list, see the "ggplot2" help page:

```
help(package = ggplot2)
```

Section 4.5 Exercises

Exercise 14 Here's the code for Fig. 4 again.

```
ggplot(data = diamonds) +
  stat_summary(mapping = aes(x = cut, y = depth),
               fun.ymin = min,
               fun.ymax = max,
               fun.y = median)
```

a) Each `stat_*()` function has a default type of **geometric object** that it plots. Look at the help page for `stat_summary()`:

```
? stat_summary
```

What's its default type of **geometric object** (i.e. its default for the `geom` argument)?

b) Verify that `geom_pointrange()` (the default **geometric object** for `stat_summary()`) can be used to duplicate Fig. 4 by running the following commands:

```
grouped_by_cut <- data.frame(
                      cut = c("Fair",  "Good", "Very Good",
                              "Premium", "Ideal"),
                      lower = c(43.0, 54.3, 56.8, 58.0, 43.0),
                      upper = c(79.0, 67.0, 64.9, 63.0, 66.7),
                      median = c(65.0, 63.4, 62.1, 61.4, 61.8))
```

```
ggplot(data = grouped_by_cut) +
  geom_pointrange(mapping = aes(x = cut,
                                y = median,
                                ymin = lower,
                                ymax = upper))
```

Exercise 15 Look under "Computed Variables" in the help page for `stat_smooth()`:

```
? stat_smooth
```

What statistical values does it compute?

Exercise 16 Look at the help page for `geom_col()`:

```
? geom_col
```

What does `geom_col()` do? How does it differ from `geom_bar()`?

4.6 Position Adjustments

- There are two **aesthetics** for coloring bars of a bar plot, `fill` and `color`.

  Look at the difference between the following graphs.

```
## Color the bars using the color aesthetic
ggplot(data = diamonds) +
  geom_bar(mapping = aes(x = cut, color = cut))
```

```
## Color the bars using the fill aesthetic
ggplot(data = diamonds) +
  geom_bar(mapping = aes(x = cut, fill = cut))
```

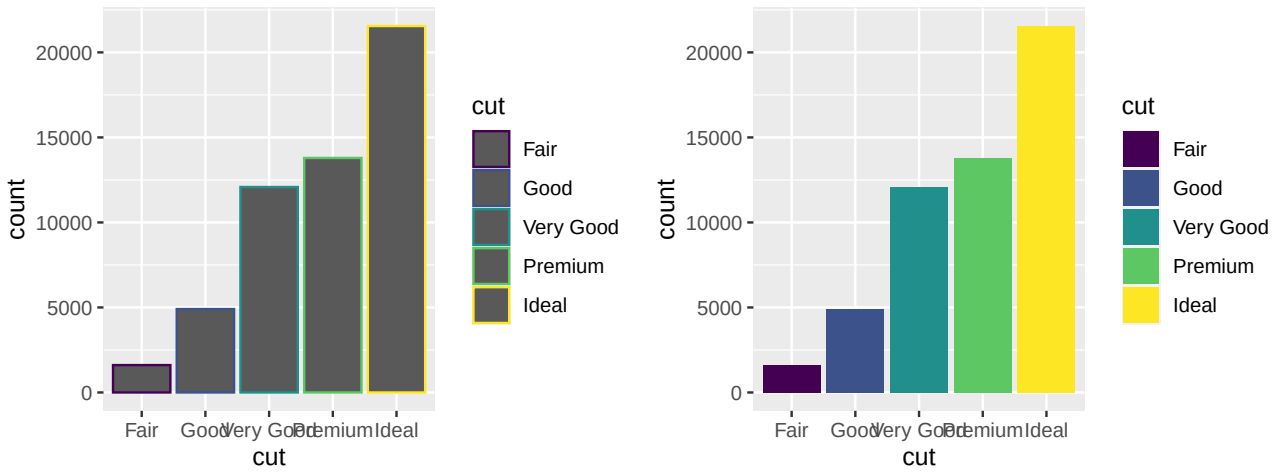
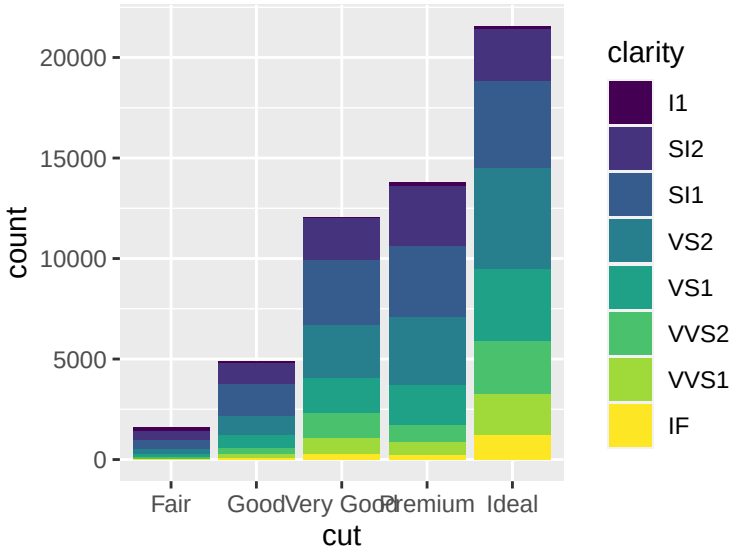


Figure 5

- Now watch what happens when we map `fill` to *another* (categorical) variable, like `clarity`:

```
ggplot(data = diamonds) +
  geom_bar(mapping = aes(x = cut, fill = clarity))
```



The bars are automatically "stacked" – each colored rectangle is a combination of a `cut` class and a `clarity` class.

The stacking is done automatically by the **position adjustment** default of `"stacked"` for the `position` argument to `geom_bar()`.

- If we don't want the bars "stacked", we can specify one of the other three options for `position`: `"identity"`, `"fill"`, and `"dodge"`.
  - `position = "identity"` will place the object exactly where it falls in the graph, which is not very useful for bar plots because the bars will overlap. To see the bars, we'd need to ether set the **alpha transparency** value (e.g. `alpha = 1/5`) or make the bars completely transparent (`fill = NA`). For example, try the following:

```
ggplot(data = diamonds,
       mapping = aes(x = cut, fill = clarity)) +
  geom_bar(alpha = 1/5,
       position = "identity")
```

```
ggplot(data = diamonds,
       mapping = aes(x = cut, color = clarity)) +
  geom_bar(fill = NA, position = "identity")
```

  - `position = "fill"` stacks the bars but makes them all the same height. This makes it easier to compare *proportions* across the groups that are represented on the x-axis.

```
ggplot(data = diamonds) +
  geom_bar(mapping = aes(x = cut, fill = clarity), position = "fill")
```

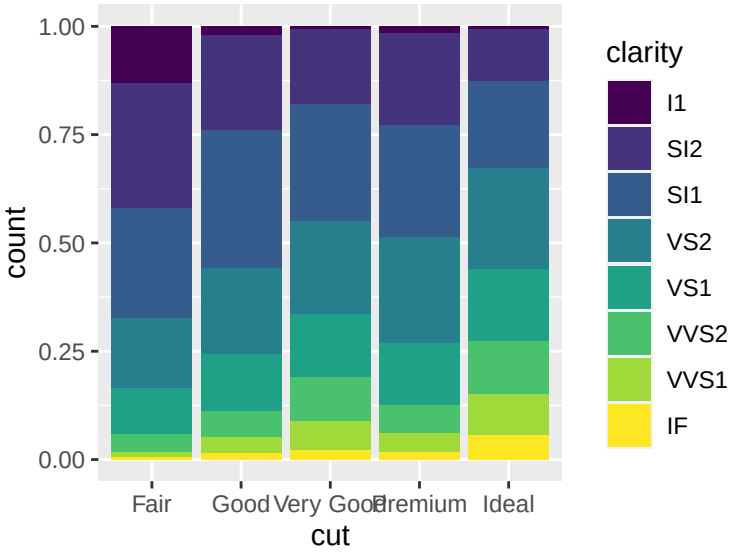
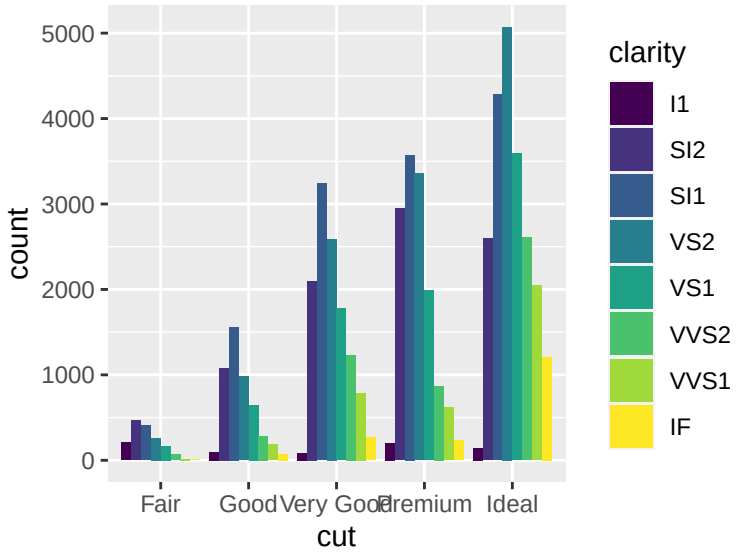


Figure 6

– `position = "dodge"` places overlapping objects directly *beside* each other. This makes it easier to compare the *counts*.

```
ggplot(data = diamonds) +
  geom_bar(mapping = aes(x = cut, fill = clarity), position = "dodge")
```



- There's one other `position` adjustment that's useful for *scatterplots* when x is a *discrete* variable.

  In the `mpg` data set, there are 236 observations. With *no* **position adjustment** (i.e. using the `"identity"` default for `position` in `geom_point()`), only 126 points are visible (Fig. 7, left).

  The problem is that many points overlap each other, which is called ***overplotting***.

  A solution is to specify `position = "jitter"`, which adds a small amount of random noise (in the x direction) to each observation before plotting (Fig. 7, right).

```
## No position adjustment -- leads to overplotting
g1 <- ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ , y = hwy))
```

```
## Add jitter to the positions -- eliminates overplotting
ggplot(data = mpg) +
  geom_point(mapping = aes(x = displ , y = hwy), position = "jitter")
```

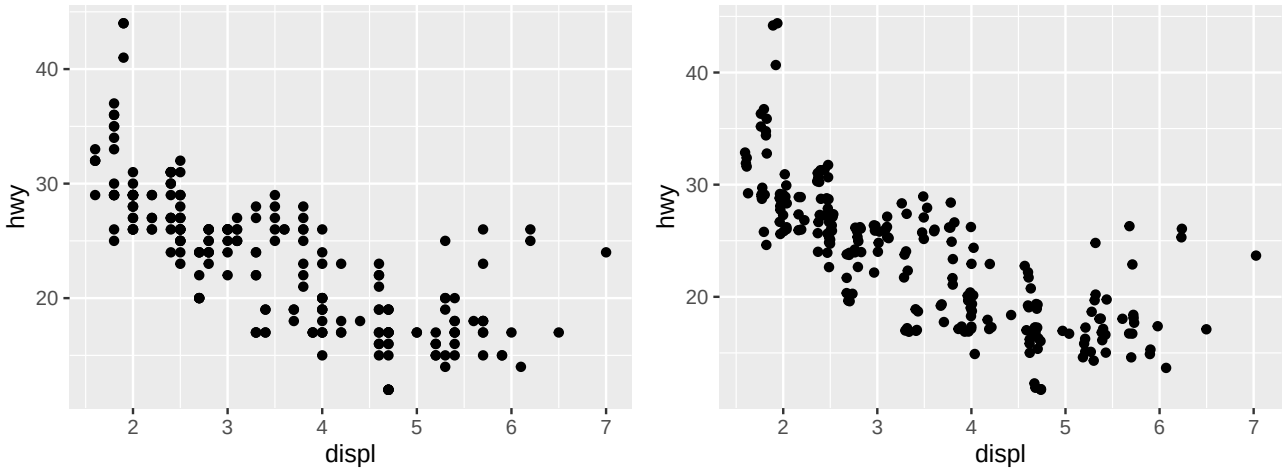


Figure 7

- Because "jittering" points is so useful, `"ggplot2"` has a shorthand for `geom_point(position = "jitter")`: `geom_jitter()`.

  For example, the following would also produce the right plot in Fig. 7.

```
## Another way to add jitter to the positions
ggplot(data = mpg) +
  geom_jitter(mapping = aes(x = displ , y = hwy))
```

- To learn more about **position adjustments**, look at the help pages:

```
? position_dodge
? position_fill
? position_identity
? position_jitter
? position_stack
```

Section 4.6 Exercises

Exercise 17 Look at the help page for the `geom_bar()` function:

```
? geom_bar
```

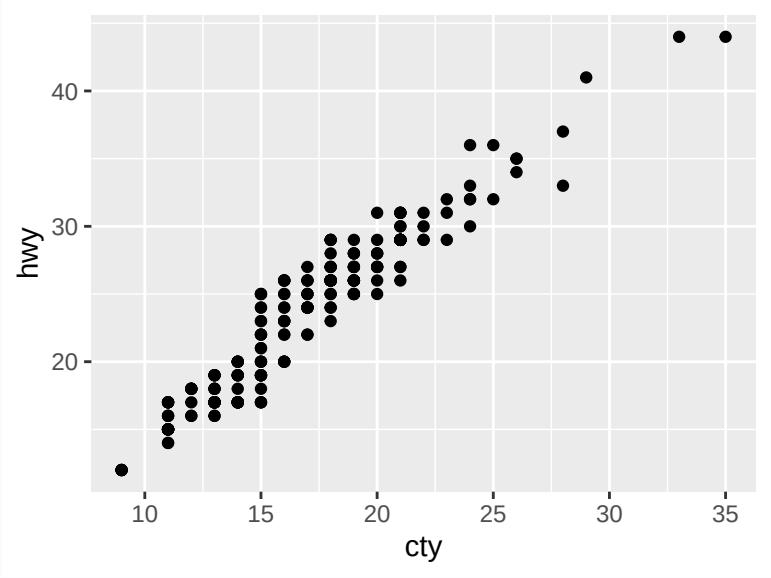
What's its default **position adjustment** (i.e. its default for the `position` argument)?

What's the default **position adjustment** for `geom_point()`?

Exercise 18 This problem concerns **position adjustments**.

a) **Overplotting** is when points in a scatterplot overlap. What's the problem with the following plot? **Hint**: The `mpg` data set contains 234 observations.

```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = cty, y = hwy))
```



b) Re-run the command above using `position = "jitter"` in `geom_point()`, and describe the improvement in the plot.

c) Because "jittering" points is so useful, `"ggplot2"` has a shorthand for `geom_point(position = "jitter")`: `geom_jitter()`.

Verify that the following command reproduces the "jittered" plot of Part *b*:

```
ggplot(data = mpg) +
  geom_jitter(mapping = aes(x = displ, y = hwy))
```

d) Another remedy for **overplotting** is setting the **transparency level** via the argument `alpha` in `geom_point()`. The `alpha` argument takes values between 0 (fully transparent) and 1 (fully opaque).

Run the following command, and describe the improvement compared to the plot in Part *a*.

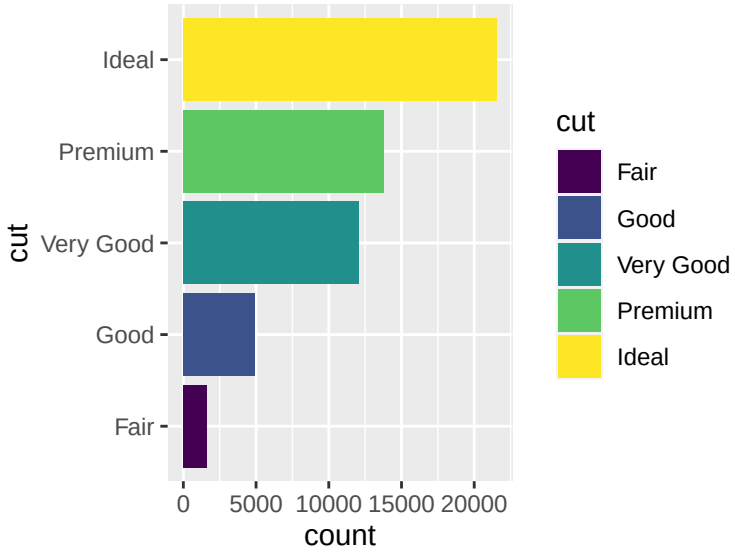
```
ggplot(data = mpg) +
  geom_point(mapping = aes(x = cty, y = hwy), alpha = 0.2)
```

4.7 Coordinate Systems

- The default **coordinate system** in `ggplot()` is *Cartesian*. Occasionally, other coordinate systems are useful. They can be specified via one of the `coord_*()` functions.

In particular, the `coord_flip()` function is useful for switching the x and y axes. Here's and example:

```
ggplot(data = diamonds) +
  geom_bar(mapping = aes(x = cut, fill = cut)) +
  coord_flip()
```

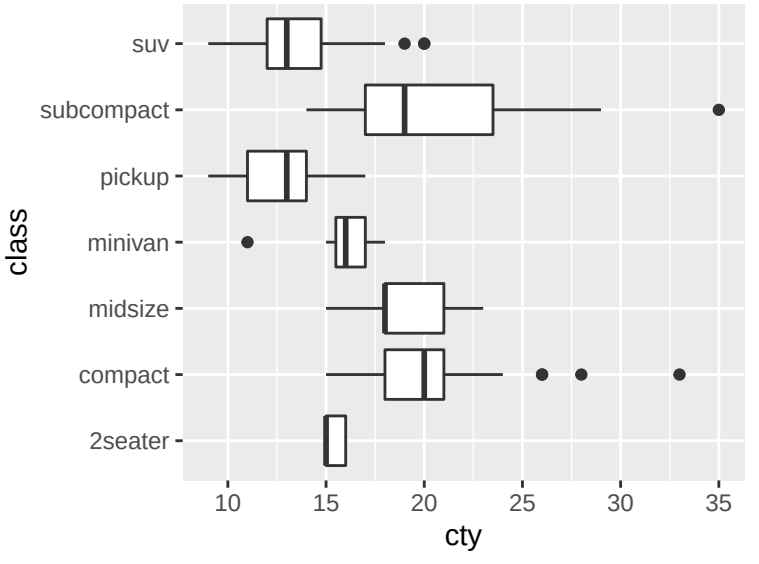


Section 4.7 Exercises

Exercise 19 Consider the following plot:

```
ggplot(data = mpg) +
  geom_boxplot(mapping = aes(x = class, y = cty))
```

Alter the code given above using `coord_flip()` to produce the following plot. Report your R command(s).



Exercise 20 Run the following commands. What does the plot tell you about city and highway mpg? Why is `coord_fixed()` important? What does `geom_abline()` do? **Hint**: Look at the help pages for `coord_fixed()` and `geom_abline()`.

```
ggplot(data = mpg, mapping = aes(x = cty, y = hwy)) +
  geom_point() +
  coord_fixed() +
  geom_abline()
```

4.8 The Layered Grammar of Graphics

- You now have the foundation to make *any* type of graph using the "ggplot2" package.
- Here's a **general template** that incorporates **statistical transformation**, **position adjustment**, **coordinate system**, and **faceting** into the **basic template** given earlier:

```
ggplot(data = <DATA>) +
  <GEOM_FUNCTION>(mapping = aes(<MAPPINGS>),
    stat = <STAT>,
    position = <POSITION>)  +
  <COORDINATE_FUNCTION> +
  <FACET_FUNCTION>
```

4.9 Acknowledgment

- The above notes (and several examples) on the "ggplot2" package borrow heavily from the book:

  R for Data Science, by Wickham, H., Grolemund, G., O'Reilly, 2017.

4.10 Mosaic Plots

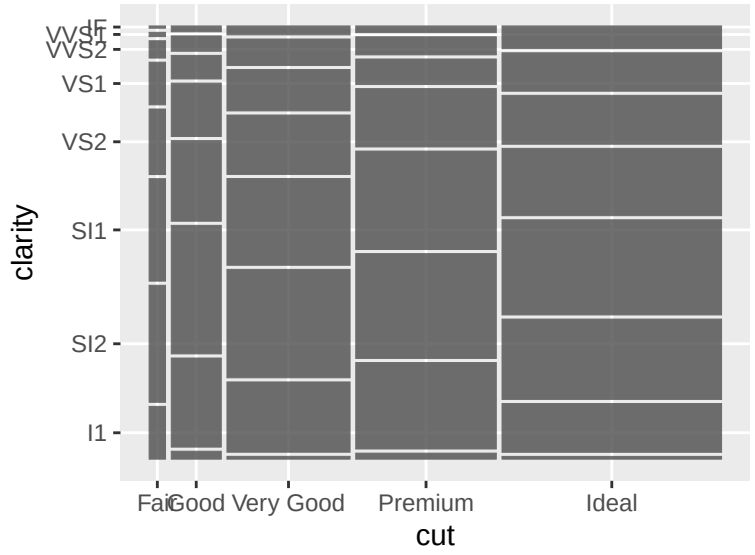
- We saw one way to plot *two* categorical variables (cut and clarity) using bar plots (in Section 4.6).
- Another way is using a ***mosaic plot***, which can be created using the geom_mosaic() function (from the "ggmosaic" package).

```
geom_mosaic()      Make a mosaic plot of two categorical variables.
```

- The main argument passed to geom_mosaic() is the **aesthetic mapping** indicating the two categorical variables to be plotted.
- For example, here's how to make a *mosaic plot* of the cut and clarity variables from the diamonds data set:

```
# Load the ggmosaic package:
library(ggmosaic)
```

```
ggplot(data = diamonds) +
  geom_mosaic(mapping = aes(x = product(clarity, cut)))
```



The *area* of each box in the *mosaic plot* is proportional to the percentage of `diamonds` in that combination of `cut` and `clarity`.

The *width* of each box is proportional to the percentage of `diamonds` with the given `cut`.

The height of each box is proportional to the percentage of `diamonds`, within the associated `cut` class, that have the given `clarity`.

Compare this *mosaic plot* with the *bar plot* in Fig. 6.

Section 4.10 Exercises

Exercise 21 This exercise uses the `diamonds` data set.

Load the `"ggmosaic"` package (which contains the `geom_mosaic()` function):

```
library(ggmosaic)
```

a) Make a *mosaic plot* of the `cut` and `color` variables. Report your R command(s).

b) Based on the plot, which combination of `cut` and `color` do you think is most prevalent? Which is least prevalent?

c) Type the following command:

```
table(diamonds$color, diamonds$cut)
```

Is your answer to Part *b* consistent with the values in the *contingency table*?