

Introduction to ggplot2



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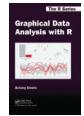
Resources: Books



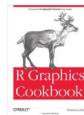
Hadley Wickham, *ggplot2: Elegant graphics for data analysis*, 2nd Ed.
1st Ed: Online, <http://ggplot2.org/book/>
ggplot2 Quick Reference: <http://r-statistics.co/ggplot2-cheatsheet.html>
Complete ggplot2 documentation: <http://docs.ggplot2.org/current/>



Kieran Healy, *Data Visualization, a Practical Introduction*
A hands-on introduction to data visualization using ggplot2, with a wide range of topics.
The online version: <https://socviz.co/> is a great example of R bookdown publishing.



Antony Unwin, *Graphical Data Analysis with R*
A gentle introduction to doing visual data analysis, mainly with ggplot2.
R code: <http://www.gradaanwr.net/>

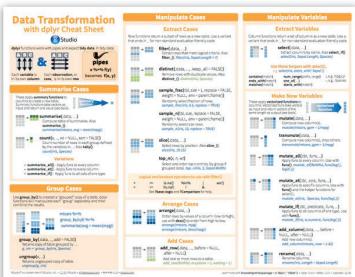
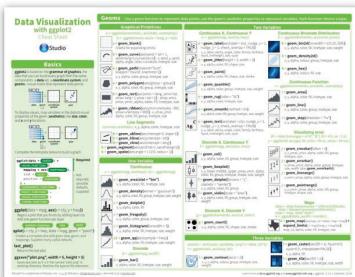


Winston Chang, *R Graphics Cookbook: Practical Recipes for Visualizing Data*
Cookbook format, covering common graphing tasks; the main focus is on ggplot2
R code from book: <http://www.cookbook-r.com/Graphs/>
Download from: <http://ase.tufts.edu/bugs/guide/assets/R%20Graphics%20Cookbook.pdf>

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Resources: Cheat sheets

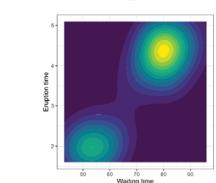
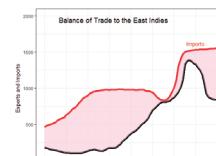
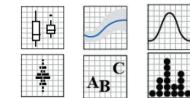
- R Studio maintains a large number of cheat sheets, <https://www.rstudio.com/resources/cheatsheets/>
- Topics:
 - [R Studio IDE](#), [Data import](#), [Data transformation \(dplyr\)](#), [Data visualization \(ggplot2\)](#), [R Markdown](#), ...
 - My collection: [R Studio Cheat Sheets](#)



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Topics

- **ggplot overview**
 - components: geoms, stats, scales, ...
 - getting stylish: themes
 - Using **NICE fonts**
- Some examples
 - Playfair, balance of trade
 - Arbuthnot's birth ratios
 - Guerry's enhanced scatterplots
- Beyond 2D
- Animation



What is ggplot2?

- ggplot2 is Hadley Wickham's R package for producing “elegant graphics for data analysis”
 - An implementation of the ideas for graphics introduced in Lee Wilkinson's *Grammar of Graphics*
 - Ideas and the syntax of ggplot2 help to think of graphs in a new and more general way
 - → pleasing plots, taking care of many fiddly details (legends, axes, colors, ...)
 - Built on the “grid” graphics system: consistency
 - Open software, with a large number of gg_ extensions.
See: <https://exts.ggplot2.tidyverse.org/gallery/>

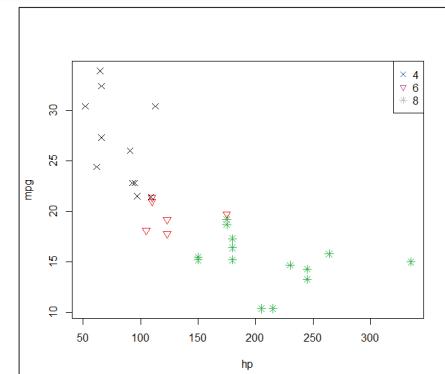
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ggplot vs base graphics

Some things that should be simple are harder than you'd like in base graphics

Here, I'm plotting gas mileage (mpg) vs. horsepower and want to use color and shape for different # of cylinders.

But I don't quite get it right!



```
mtcars$cyl <- as.factor(mtcars$cyl)
plot(mpg ~ hp , data=mtcars,
     col=cyl, pch=c(4,6,8)[mtcars$cyl], cex=1.2)
legend("topright", legend=levels(mtcars$cyl),
       pch = c(4,6,8),
       col=levels(mtcars$cyl))
```

colors and point symbols work differently in plot() and legend()

goal of ggplot2: this should “just work”

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ggplot vs base graphics

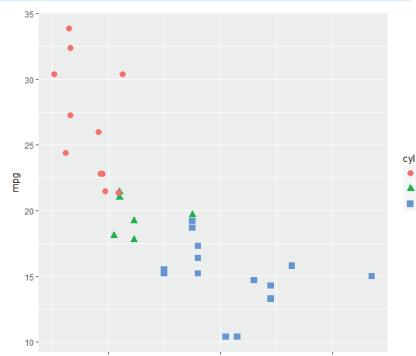
In ggplot2, just map the data variables to aesthetic attributes

`aes(x, y, shape, color, size, ...)`

ggplot() takes care of the rest

aes() mappings set in the call to ggplot() are passed to geom_point()
here

```
library(ggplot2)
ggplot(mtcars, aes(x=hp, y=mpg, color=cyl, shape=cyl)) +
  geom_point(size=3)
```

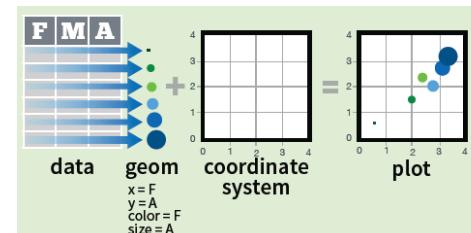


Follow along: the R script for this example is at: <https://friendly.github.io/6135/R/gg-cars.R>

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ggplot components

- Every graph can be described as a combination of independent building blocks:
 - **data**: a data frame: quantitative, categorical; local or data base query
 - **aesthetic mapping** of variables into visual properties: size, color, x, y
 - **geometric objects (“geom”)**: points, lines, areas, arrows, ...
 - **coordinate system (“coord”)**: Cartesian, log, polar, map,

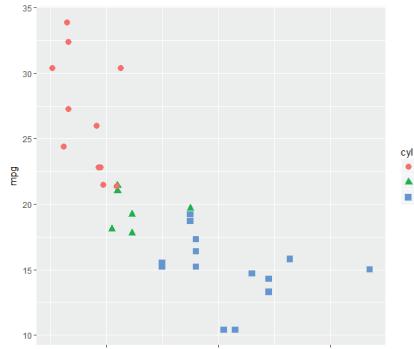


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ggplot: data + geom -> graph

```
ggplot(data=mtcars,
       aes(x=hp, y=mpg,
           color=cyl, shape=cyl)) +
  geom_point(size=3)
```

1
2
3
4



In this call,

1. data=mtcars: data frame
2. aes(x=hp, y=mpg): plot variables
3. aes(color, shape): attributes
4. geom_point(): what to plot
- the coordinate system is taken to be the standard Cartesian (x,y)

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ggplot geoms: basic

Graphical Primitives

```
a <- ggplot(economics, aes(date, unemploy))
b <- ggplot(seals, aes(x=long, y=lat))
a + geom_blank()
  (Useful for expanding limits)
b + geom_curve(aes(yend = lat + 1,
                    xend=long+1, curvature=z)) - x, yend, y, end,
  alpha, angle, color, curvature, linetype, size
a + geom_path(lineend="butt",
              linejoin="round", linemetre=1)
  x, y, alpha, color, group, linetype, size
a + geom_polygon(aes(group = group))
  x, y, alpha, color, fill, group, linetype, size
b + geom_rect(aes(xmin = long, ymin = lat,
                    xmax = long + 1, ymax = lat + 1)) - xmax, xmin,
  ymax, ymin, alpha, color, fill, linetype, size
a + geom_ribbon(aes(ymin=unemploy - 900,
                    ymax=unemploy + 900)) - x, ymax, ymin
  alpha, color, fill, group, linetype, size
```

Line Segments

```
common aesthetics: x, y, alpha, color, linetype, size
b + geom_abline(aes(intercept=0, slope=1))
b + geom_hline(aes(intercept = lat))
b + geom_vline(aes(xintercept = long))
b + geom_segment(aes(yend=lat+1, xend=long+1))
b + geom_spoke(aes(angle = 1:1155, radius = 1))
```

One Variable

Continuous

```
c <- ggplot(mpg, aes(hwy)); c2 <- ggplot(mpg)
c + geom_area(stat = "bin")
  x, y, alpha, color, fill, linetype, size
c + geom_density(kernel = "gaussian")
  x, y, alpha, color, fill, group, linetype, size, weight
c + geom_dotplot()
  x, y, alpha, color, fill
c + geom_freqpoly()
  x, y, alpha, color, group, linetype, size
c + geom_histogram(binwidth = 5)
  x, y, alpha, color, fill, linetype, size, weight
c2 + geom_qq(aes(sample = hwy))
  x, y, alpha, color, fill, group, linetype, size, weight
```

Discrete

```
d <- ggplot(mpg, aes(fl))
d + geom_bar()
  x, alpha, color, fill, linetype, size, weight
```

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ggplot geoms: two variables

Continuous X, Continuous Y

```
e + geom_label(aes(label = cty), nudge_x = 1,
               nudge_y = 1, check_overlap = TRUE)
  x, y, label, alpha, angle, color, family, fontface,
  hjust, lineheight, size, vjust
e + geom_jitter(height = 2, width = 2)
  x, y, alpha, color, fill, shape, size
e + geom_point()
  x, y, alpha, color, fill, shape, size, stroke
e + geom_quantile()
  x, y, alpha, color, group, linetype, size, weight
e + geom_rug(sides = "bl")
  x, y, alpha, color, linetype, size
e + geom_smooth(method = lm)
  x, y, alpha, color, fill, group, linetype, size, weight
```

AB e + geom_text(aes(label = cty), nudge_x = 1,
 nudge_y = 1, check_overlap = TRUE)
 x, y, label, alpha, angle, color, family, fontface,
 hjust, lineheight, size, vjust

Discrete X, Continuous Y

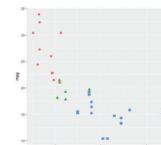
```
f <- ggplot(mpg, aes(class, hwy))
f + geom_col()
  x, y, alpha, color, fill, group, linetype, size
f + geom_boxplot()
  x, y, lower, middle, upper, ymax, ymin, alpha,
  color, fill, group, linetype, shape, size, weight
f + geom_dotplot(binaxis = "y",
                  stackdir = "center")
  x, y, alpha, color, fill, group
f + geom_violin(scale = "area")
  x, y, alpha, color, fill, group, linetype, size,
  weight
```

Continuous Bivariate Distribution

```
h <- ggplot(diamonds, aes(carat, price))
h + geom_bin2d(binwidth = c(0.25, 500))
  x, y, alpha, color, fill, linetype, size, weight
h + geom_density2d()
  x, y, alpha, colour, group, linetype, size
h + geom_hex()
  x, y, alpha, colour, fill, size
```

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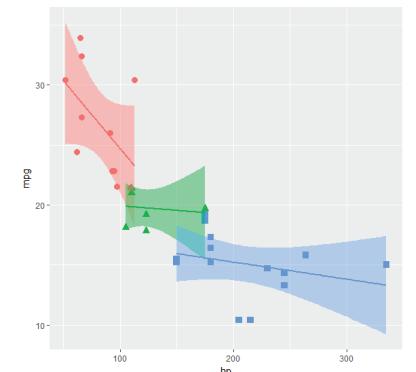
ggplot: geoms



How can I enhance this visualization?

Easy: add a geom_smooth() to fit linear regressions for each level of cyl

It is clear that horsepower and # of cylinders are highly related (Duh!)



```
ggplot(mtcars, aes(x=hp, y=mpg, color=cyl, shape=cyl)) +
  geom_point(size=3) +
  geom_smooth(method="lm", aes(fill=cyl))
```

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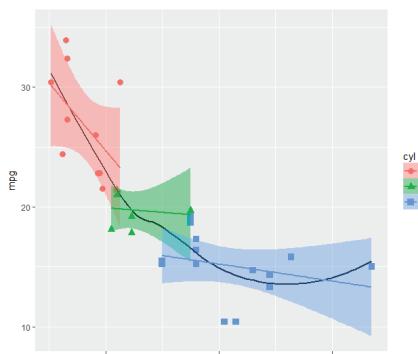
ggplot: layers & aes()

Aesthetic attributes in the ggplot() call are **inherited** in geom_() layers

Other attributes can be passed as **constants** (size=3, color="black") or with aes(color=, ...) in different layers

This plot adds an overall loess smooth to the previous plot.

color="black" overrides the aes(color=cyl)



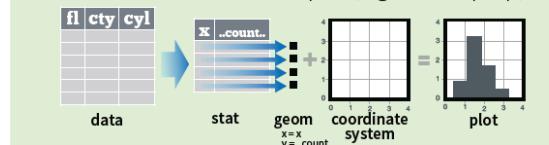
```
ggplot(mtcars, aes(x=hp, y=mpg)) +  
  geom_point(size=3, aes(color=cyl, shape=cyl)) +  
  geom_smooth(method="lm", aes(color=cyl, fill=cyl)) +  
  geom_smooth(method="loess", color="black", se=FALSE)
```

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ggplot: stats

- **statistical calculations ("stat")** -- data summaries: mean, sd, binning & counting, ...
- stats have a default geom and geoms have a default stat
 - geom_bar(stat = "count") ← → stat_count(geom = "bar")
- computed variables (eg, ..count.., ..level..) can be mapped to aesthetics
 - ggplot(aes(x=, y=)) + stat_density_2d(aes(fill = ..level..), geom="polygon")

A stat builds new variables to plot (e.g., count, prop).



some stats:

- stat_count()
- stat_bin()
- stat_density()
- stat_boxplot()
- stat_density_2d()
- stat_ellipse()

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scales

Scales map **data** values to the **visual** values of an aesthetic.

- axis labels, legends, colors
- formatting of values

General Purpose scales

Use with most aesthetics

scale_*_continuous() - map cont' values to visual ones
scale_*_discrete() - map discrete values to visual ones
scale_*_identity() - use data values as visual ones
scale_*_manual(values = c()) - map discrete values to manually chosen visual ones
scale_*_date(date_labels = "%m/%d"), date_breaks = "2 weeks" - treat data values as dates.
scale_*_datetime() - treat data x values as date times.
Use same arguments as scale_x_date().
See ?strptime for label formats.

X and Y location scales

Use with x or y aesthetics (x shown here)

scale_x_log10() - Plot x on log10 scale
scale_x_reverse() - Reverse direction of x axis
scale_x_sqrt() - Plot x on square root scale

Color and fill scales (Discrete)

```
n <- d + geom_bar(aes(fill = fl))  
n + scale_fill_brewer(palette = "Blues")  
For palette choices: RColorBrewer::display.brewer.all  
n + scale_fill_grey(start = 0.2, end = 0.8, na.value = "red")
```

Color and fill scales (Continuous)

```
o <- c + geom_dotplot(aes(fill = ..x..))  
o + scale_fill_distiller(palette = "Blues")  
o + scale_fill_gradient(low="red", high="yellow")  
o + scale_fill_gradient2(low="red", high="blue", mid = "white", midpoint = 25)  
o + scale_fill_gradientn(colours=topo.colors(6))  
Also: rainbow(), heat.colors(), terrain.colors(), cm.colors(), RColorBrewer::brewer.pal()
```

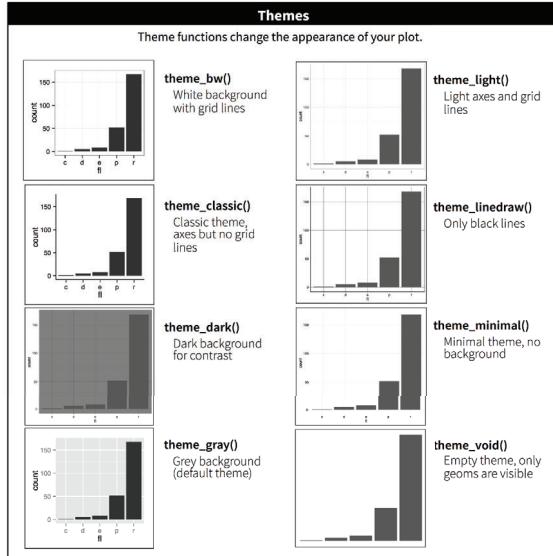
ggplot themes

ggplot themes set the general style for **all** graphic elements

Designed to provide a pleasing **coherent** design – simply!

Yet, all the details can be customized

One theme can rule them all!

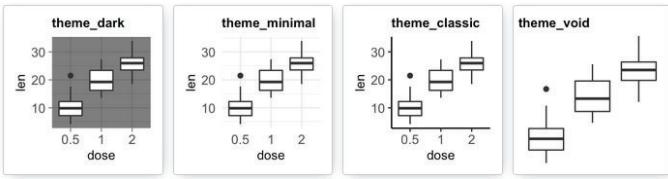


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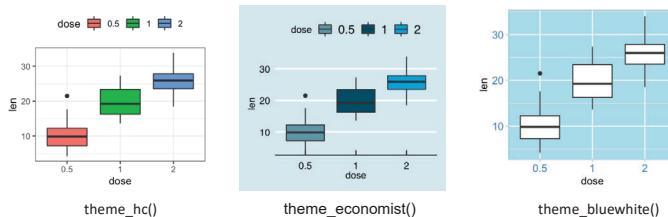
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ggplot2: themes

Built-in ggplot themes provide a wide variety of basic graph styles



Other packages provide custom themes, or you can easily define your own



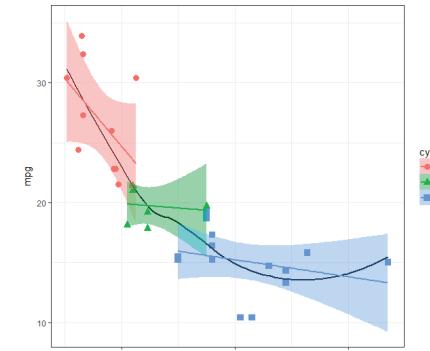
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ggplot2: themes

All the graphical attributes of ggplot2 are governed by themes – settings for all aspects of a plot

A given plot can be rendered quite differently just by changing the theme

If you haven't saved the ggplot object, last_plot() gives you something to work with further



last_plot() + theme_bw()

Tip: set base_size = here to control all text size

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Other ggplot features

Coordinate Systems

r + coord_cartesian(xlim = c(0, 5))

xlim, ylim
The default cartesian coordinate system

r + coord_fixed(ratio = 1/2)

ratio, xlim, ylim

Cartesian coordinates with fixed aspect ratio between x and y units

r + coord_flip()

xlim, ylim

Flipped Cartesian coordinates

r + coord_polar(theta = "x", direction = 1)

theta, start, direction

Polar coordinates

r + coord_trans(xtrans = "sqrt")

xtrans, ytrans, xlim, ylim

Transformed cartesian coordinates. Set xtrans and ytrans to the name of a window function.

Zoom / clip : use xlim, ylim = c(lo,hi)

Faceting

Facets divide a plot into subplots based on the values of one or more discrete variables.

t <- ggplot(mpg, aes(cty, hwy)) + geom_point()

t + facet_grid(. ~ fl)

facet into columns based on fl

t + facet_grid(year ~ .)

facet into rows based on year

t + facet_grid(year ~ fl)

facet into both rows and columns

t + facet_wrap(~ fl)

wrap facets into a rectangular layout

Set scales to let axis limits vary across facets

t + facet_grid(drv ~ fl, scales = "free")

x and y axis limits adjust to individual facets

- "free_x" - x axis limits adjust

- "free_y" - y axis limits adjust

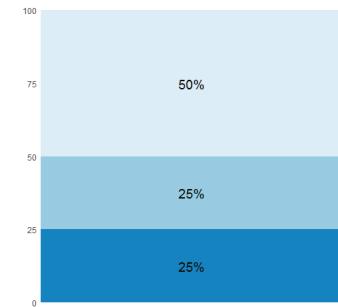
ggplot2: coords

Coordinate systems, coord_*() functions, handle conversion from geometric objects to what you see on a 2D plot.

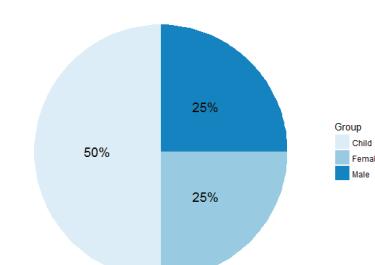
- A simple bar chart, standard coordinates

- A pie chart is just a bar chart in polar coordinates!

p <- ggplot(df, aes(x = "", y = value, fill = group)) +
geom_bar(stat = "identity")



p + coord_polar("y", start = 0)



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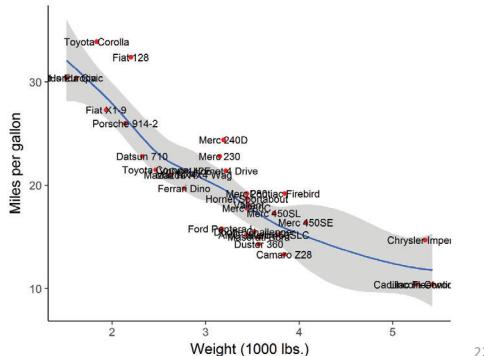
labeling points: geom_text()

```
plt2 <- ggplot(mtcars, aes(x=wt, y=mpg)) +  
  geom_point(color = 'red', size=2) +  
  geom_smooth(method="loess") +  
  labs(y="Miles per gallon", x="Weight (1000 lbs.)") +  
  theme_classic(base_size = 16)  
  
plt2 + geom_text(aes(label = rownames(mtcars)))
```

Note the use of theme_classic(), better axis labels and increased font size.

But this is still messy: wouldn't want to publish this.

Sometimes it is useful to label points to show their identities.
geom_text() usually gives messy, overlapping text



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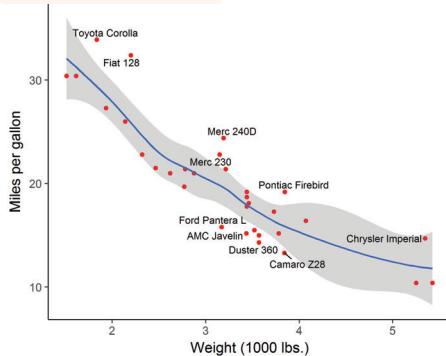
labeling points: selection

It is easy to label points **selectively**, using some criterion to assign labels to points

```
mod <- loess( mpg ~ wt, data=mtcars)  
resids <- residuals(mod)  
mtcars$label <- ifelse(abs(resids) > 2.5,  
  rownames(mtcars), "")  
  
plt2 + geom_text_repel(aes(label = mtcars$label))
```

- Here, I:
1. fit the smoothed loess curve,
 2. extract residuals, r_i ,
 3. assign labels where $|r_i| > 2.5$
 4. add the text layer

- 1
- 2
- 3
- 4



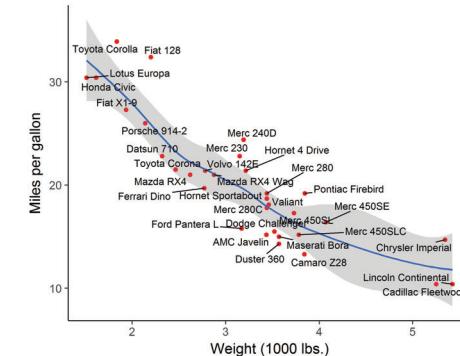
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labeling points: geom_text_repel()

```
library(ggrepel)  
plt2 +  
  geom_text_repel(aes(label = rownames(mtcars)))
```

geom_text_repel() assigns repulsive forces among points and labels to assure no overlap

Some lines are drawn to make the assignment clearer



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ggplot objects

Traditional R graphics just produce graphical output on a device
However, ggplot() produces a "ggplot" object, a list of elements

```
> names(plt)  
[1] "data"      "layers"     "scales"     "mapping"    "theme"      "coordinates"  
[7] "facet"     "plot_env"   "labels"  
> class(plt)  
[1] "gg"        "ggplot"
```

What methods are available?

```
> methods(class="gg")  
[1] +  
  
> methods(class="ggplot")  
[1] grid.draw  plot  print  summary
```

The "gg" class provides the "+" method

The "ggplot" class provides other, standard methods

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Saving plots: ggsave()

- If the plot is on the screen:

```
ggsave("path/filename.png") # height=, width=, dpi=
```

- If you have a plot object:

```
ggsave(myplot, file="path/filename.png")
```

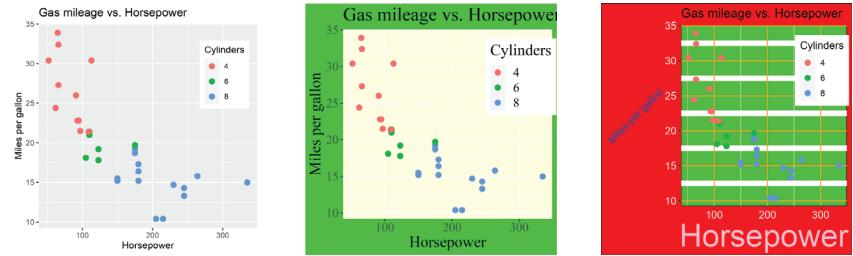
- Specify size:

```
ggsave(myplot, "path/filename.png", width=6, height=4)
```

- any plot format (pdf, png, eps, svg, jpg, ...)

```
ggsave(myplot, file="path/filename.jpg")
```

```
ggsave(myplot, file="path/filename.pdf")
```



STYLING WITH THEMES

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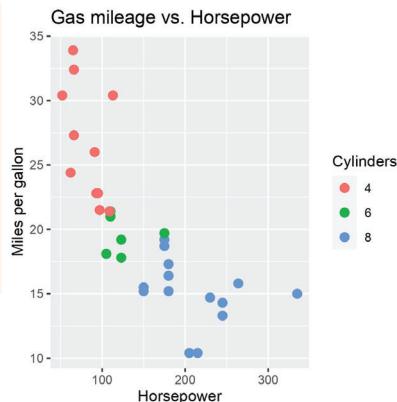
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Options vs. themes

```
p1 <-  
  ggplot(mtcars, aes(x = hp, y=mpg)) +  
  geom_point(aes(color=factor(cyl)),  
             size=3, pch=16) +  
  labs(color = "Cylinders",  
       x = "Horsepower",  
       y = "Miles per gallon") +  
  ggtitle("Gas mileage vs. Horsepower")
```

Some graphic attributes (size, symbol)
are controlled as options of geoms

Others must be controlled by theme
elements



ggplot default: theme_gray()

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Moving the legend

Move the legend inside the plot region

```
p1 + theme(  
  legend.position = c(0.85, 0.75))
```

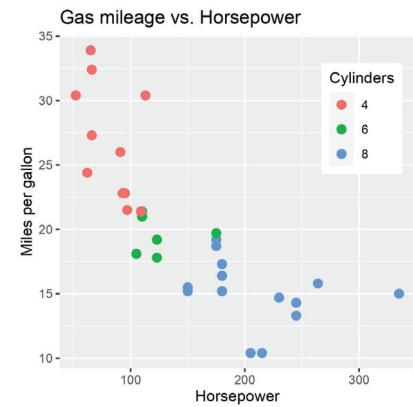
This gives more room for the data

Legend position is a theme attribute

Might also want to control:

- legend title: font, size, label...
- legend background, margin, ...

Need to know their names &
properties



NB: This just changed in ggplot2 3.5.0
Now: legend.position = "inside",
 legend.position.inside=c(0.85, 0.75)

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ggplot2 Theme Elements

```
theme(element_name = element_function())
- element_text()
- element_line()
- element_rect()
- element_blank()
```

Plot elements:

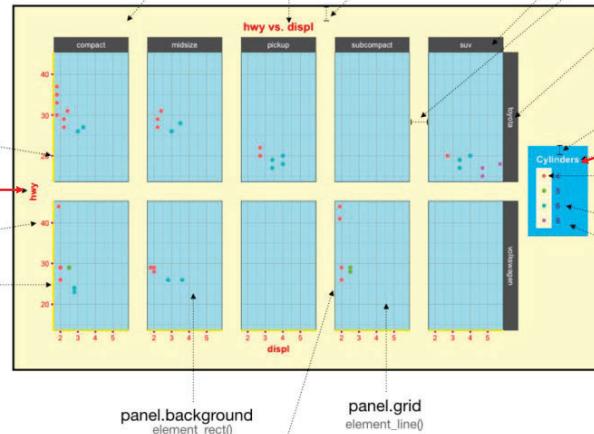
plot.background
element_rect()
plot.title
element_text()
plot.margin
margin()

Facetting elements:

strip.background
element_rect()
panel.spacing
unit()
strip.text
element_text()

Axis elements:

axis.ticks
element_line()
axis.title
element_text()
axis.text
element_text()
axis.line
element_line()



Legend elements:
legend.margin
margin()
legend.title
element_text()
legend.key
element_rect()
legend.text
element_text()
legend.background
element_rect()

Panel elements:

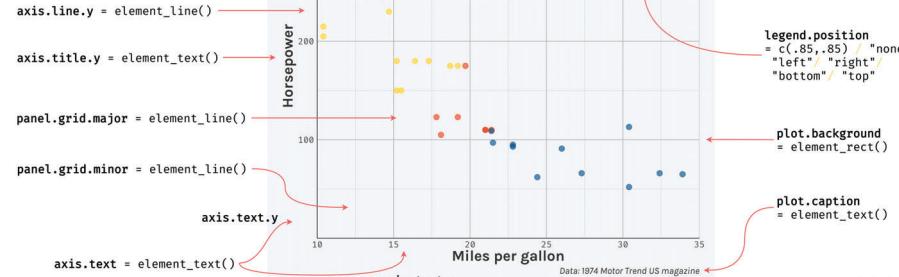
henrywang.nl
Derived from "ggplot2: Elegant Graphics for Data Analysis"

ggplot2 theme elements reference

Set minimal as the baseline theme:
theme_minimal() +
theme(theme.element = element_type())

Use element_blank() to remove an element

Axis titles, text, ticks, and lines can be specified per axis using theme inheritance by putting .x/.y at the end of the theme element.



text = element_text() ← modifications will be applied to all text elements

Full list of elements at ggplot2.tidyverse.org/reference/theme.html

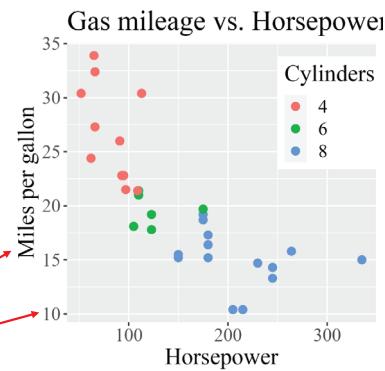
31

Styling with themes: text

```
p1 + theme(
  legend.position = c(0.85, 0.75),
  text = element_text(size=18, family = "serif"))
```

Change the font family & size for all text.

- axis.title = element_text()
- axis.text = element_text()
- legend.title =
- legend.text =
- ...



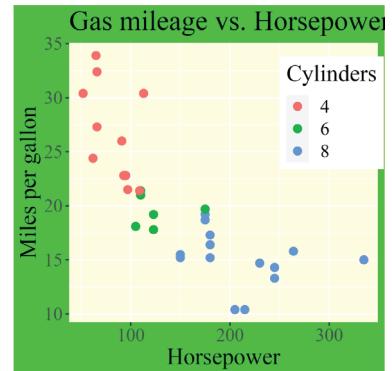
NB: could also use
theme_gray(base_size=, base_family=, ...)

32

Styling with themes: backgrounds

Change the backgrounds

```
p1 + theme(
  legend.position = c(0.85, 0.75),
  text = element_text(size=18, family = "serif"),
  plot.background = element_rect(fill="green"),
  panel.background =
    element_rect(fill="lightyellow"))
)
```



33

Custom themes

You can define & save your own theme and then use to style all plots consistently

```
theme_ugly <- function (base_size = 12, base_family = "") {  
  theme_gray(base_size = base_size, base_family = base_family) ← base theme  
  %+replace%  
  theme(  
    axis.text = element_text(colour = "white"),  
    axis.title.x = element_text(colour = "pink", size=rel(3)),  
    axis.title.y = element_text(colour = "blue", angle=45),  
    panel.background = element_rect(fill="green"),  
    panel.grid.minor.y = element_line(size=3),  
    panel.grid.major = element_line(colour = "orange"),  
    plot.background = element_rect(fill="red")  
)  
}
```

override these properties

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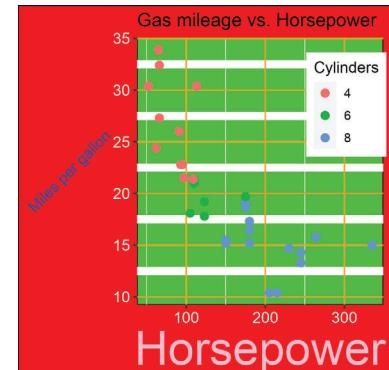
Styling with themes

Use your theme:

```
p1 + theme_ugly() +  
  theme(legend.position = c(0.85, 0.75))
```

To set a theme as the default for all subsequent graphics:

- `theme_set(theme_bw())`
- `theme_set(theme_ugly())`



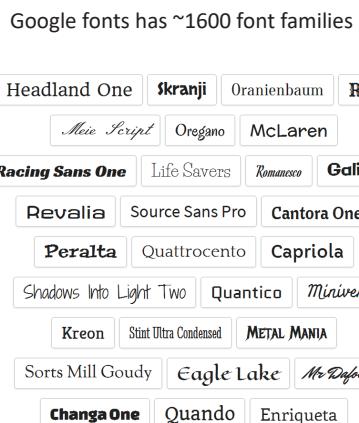
35

Gimme *nicer* FONTS, please

Base R has access to a limited number of font families

R family	Font (Win)
sans	Arial
serif	Times New Roman
mono	Courier
symbol	Σψμβθλ

These can be rendered in plain face, **bold**, *italic*, or **bold italic**



The `showtext` package is among the easiest for using custom fonts
<https://cran.rstudio.com/web/packages/showtext/vignettes/introduction.html>

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Basic font manipulations

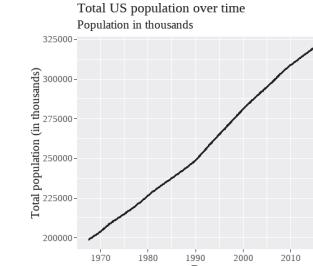
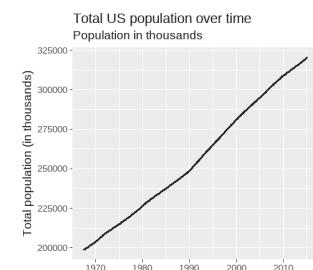
A simple plot

```
library(ggplot2)  
theme_set(theme_gray(base_size = 14))  
base_fig <- ggplot(data = economics, aes(date, pop)) +  
  geom_line(linewidth = 1.3) +  
  labs(title = "Total US population over time",  
       subtitle = "Population in thousands",  
       x = "Date",  
       y = "Total population (in thousands)")  
  
base_fig
```

To change **all** text in the figure to **serif**, update the `text` option of the theme

```
base_fig +  
  theme(text = element_text(family = "serif"))
```

You can also change fonts for any component, e.g., `plot.title`, `axis.title`, ...



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showtext package

Setup:

```
library(showtext)
## Load some Google fonts (https://fonts.google.com/)
# args: Google name, R name
font_add_google("Gochi Hand", "gochi")
font_add_google("Schoolbell", "bell")

## Automatically use showtext to render text
showtext_auto()
```

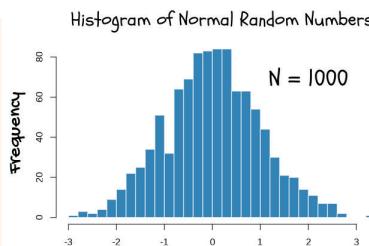
Use in a histogram (base R):

```
set.seed(123)
hist(rnorm(1000), breaks = 30,
  col = "steelblue", border = "white",
  main = "", xlab = "", ylab = "")
title("Histogram of Normal Random Numbers",
  family = "bell", cex.main = 2)
title(ylab = "Frequency",
  family = "gochi", cex.lab = 2)
text(2, 70, "N = 1000", family = "bell", cex = 2.5)
```

Fonts are actually registered with the **sysfonts** package

Any local font can be registered with **font_add()**

```
font_add("Times New Roman")
```



showtext demo

```
library(showtext); library(glue)
font_add_google('Lora', 'lora')
font_add_google('Lobster', 'lobster')
font_add_google('Anton', 'anton')
font_add_google('Fira Sans', 'firasans')
font_add_google('Synk Mono', 'synk')
# Enable showtext font rendering!
showtext_auto()
```

```
tib <- tibble(
  family = c('firasans', 'lora', 'lobster', 'anton', 'synk'),
  x = 0,
  y = seq(.9, .1, length.out = 5),
  label = glue('Showtext {family}. What a font!'))
```

```
tib |>
  ggplot(aes(x, y, label = label)) +
  geom_text(family = tib$family,
            size = 12, hjust = 0, col = 'dodgerblue4') +
  coord_cartesian(xlim = c(0, 1), ylim = c(0, 1)) +
  theme_void() +
  theme(plot.background = element_rect(fill = grey(.90)))
```

Add a bunch of fonts

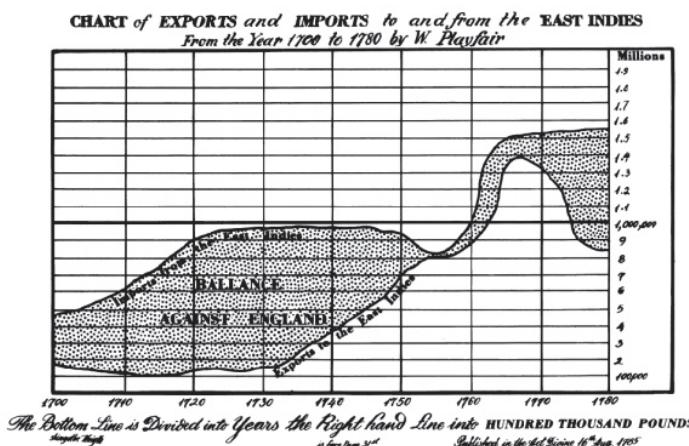
Showtext firasans. What a font!
Showtext lora. What a font!
Showtext lobster. What a font!
Showtext anton. What a font!
Showtext synk. What a font!

Example from: https://albert-rapp.de/posts/ggplot2-tips/08_fonts_and_icons/08_fonts_and_icons.html

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Re-visioning old masters in ggplot2

In the *Commercial and Political Atlas*, William Playfair used charts of imports and exports from England to its trading partners to ask “How are we doing”?



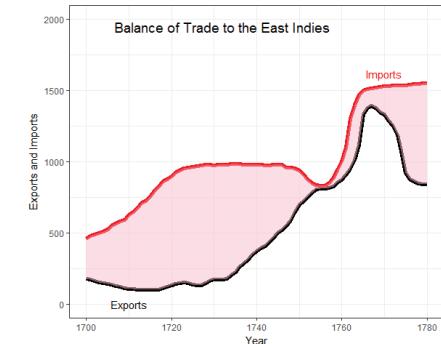
40

Playfair: Balance of trade charts

In the *Commercial and Political Atlas*, William Playfair used charts of imports and exports from England to its trading partners to ask “How are we doing”?

Here is a re-creation of one example, using ggplot2. How was it done?

```
> data(EastIndiesTrade, package="GDAdat")
> head(EastIndiesTrade)
  Year Exports Imports
1 1700    180    460
2 1701    170    480
3 1702    160    490
4 1703    150    500
5 1704    145    510
6 1705    140    525
...   ...   ...
```



Code for this example: <https://friendly.github.io/6135/R/playfair-east-indies.R>

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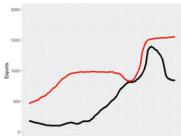
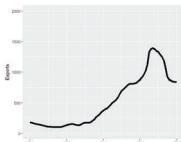
ggplot thinking

I want to plot two time series, & fill the area between them

Start with a line plot of Exports vs. Year: `geom_line()`

Add a layer for the line plot of Imports vs. Year

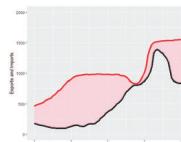
```
c1 <-  
  ggplot(EastIndiesTrade, aes(x=Year, y=Exports)) +  
    ylim(0,2000) +  
    geom_line(colour="black", size=2) +  
    geom_line(aes(x=Year, y=Imports), colour="red", size=2)
```



Fill the area between the curves: `geom_ribbon()`

change the Y label

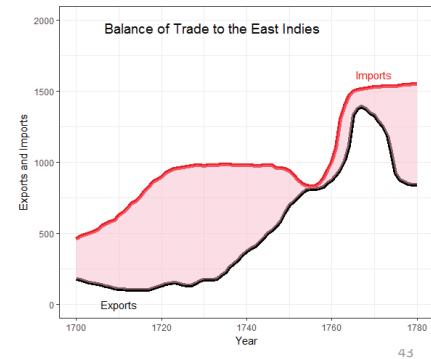
```
c1 <- c1 +  
  geom_ribbon(aes(ymin=Exports, ymax=Imports), fill="pink") +  
  ylab("Exports and Imports")
```



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That looks pretty good. Add some text labels using `annotate()`

```
c1 <- c1 +  
  annotate("text", x = 1710, y = 0, label = "Exports", size=4) +  
  annotate("text", x = 1770, y = 1620, label = "Imports", color="red", size=4) +  
  annotate("text", x = 1732, y = 1950, label = "Balance of Trade to the East Indies", color="black", size=5)
```



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Plot what you want to show

Playfair's goal was to show the balance of trade with different countries.

Why not plot Exports – Imports directly?

```
c2 <-  
  ggplot(EastIndiesTrade, aes(x = Year, y = Exports - Imports)) +  
  geom_line(colour="red", size=2) +  
  ylab("Balance = Exports - Imports") +  
  geom_ribbon(aes(ymin=Exports-Imports, ymax=0), fill="pink", alpha=0.5) +  
  annotate("text", x = 1710, y = -30, label = "Our Deficit", color="black", size=5) +  
  theme_bw()
```

`aes(x=, y=)` can use expressions calculated from data variables



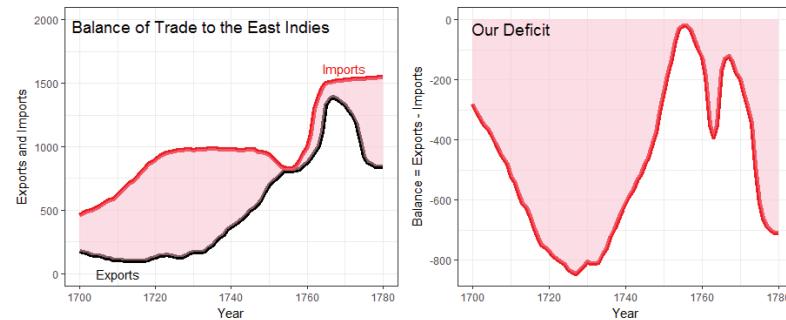
44

Composing several plots

ggplot objects use grid graphics for rendering

The `gridExtra` package has functions for combining or manipulating grid-based graphs

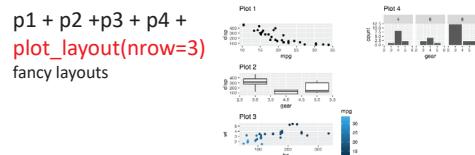
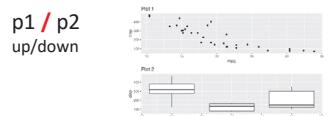
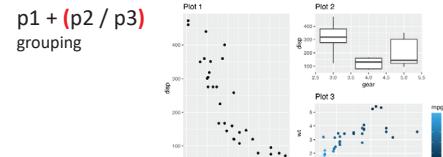
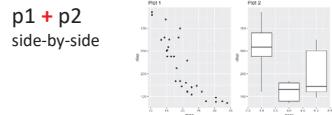
```
library(gridExtra)  
grid.arrange(c1, c2, nrow=1)
```



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General composing: patchwork

The **patchwork** package provides a new, complete syntax for plot compositions



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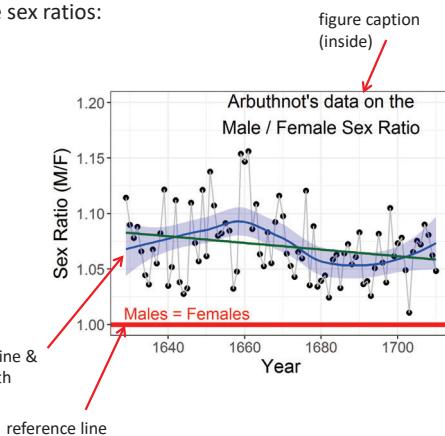
Arbuthnot's data on birth ratios

Custom graphs can be constructed by adding graphical elements (points, lines, text, arrows, etc.) to a basic ggplot()

John Arbuthnot: data on male/female sex ratios:

```
> data(Arbuthnot, package="HistData")
> head(Arbuthnot[,c(1:3,6,7)])
  Year Males Females Ratio Total
1 1629 5218 4683 1.114 9.901
2 1630 4858 4457 1.090 9.315
3 1631 4422 4102 1.078 8.524
4 1632 4994 4590 1.088 9.584
5 1633 5158 4839 1.066 9.997
6 1634 5035 4820 1.045 9.855
... ... ... ... ...
```

Arbuthnot didn't make a graph. He simply calculated the probability that in 81 years from 1629–1710, the sex ratio would always be > 1
The first significance test!

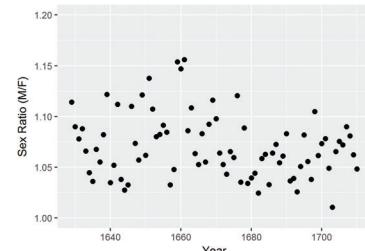


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Building a custom graph

```
ggplot(Arbuthnot, aes(x=Year, y=Ratio)) +
  ylim(1, 1.20) +
  ylab("Sex Ratio (M/F)") +
  geom_point(pch=16, size=2)
```

Start with a basic scatterplot,
Ratio vs. Year



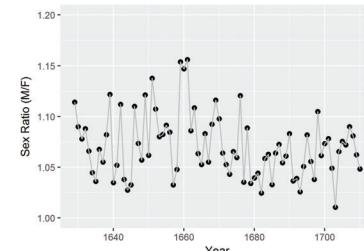
R script for this example:
<https://friendly.github.io/6135/R/arbuthnot-gg.R>

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Building a custom graph

```
ggplot(Arbuthnot, aes(x=Year, y=Ratio)) +
  ylim(1, 1.20) +
  ylab("Sex Ratio (M/F)") +
  geom_point(pch=16, size=2) +
  geom_line(color="gray")
```

Connect points with a line



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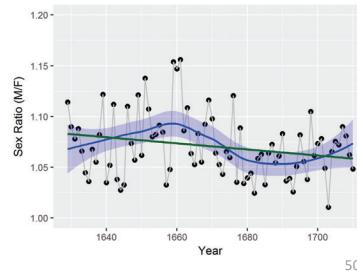
Building a custom graph

```
ggplot(Arbuthnot, aes(x=Year, y=Ratio)) +  
  ylim(1, 1.20) +  
  ylab("Sex Ratio (M/F)") +  
  geom_point(pch=16, size=2) +  
  geom_line(color="gray") +  
  geom_smooth(method="loess", color="blue",  
    fill="blue", alpha=0.2) +  
  geom_smooth(method="lm", color="darkgreen",  
    se=FALSE)
```

```
# save what we have so far  
arbuth <- last_plot()
```

Add smooths:

- loess curve
- linear regression line

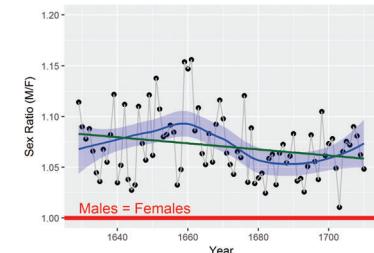


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Building a custom graph

```
arbuth +  
  geom_hline(yintercept=1, color="red", size=2) +  
  annotate("text", x=1645, y=1.01, label="Males = Females", color="red", size=5)
```

Add horizontal reference line & text label

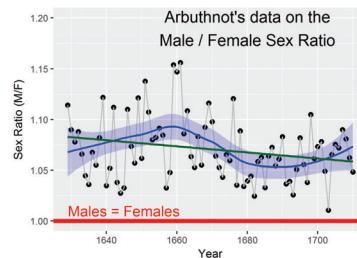


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Building a custom graph

```
arbuth +  
  geom_hline(yintercept=1, color="red", size=2) +  
  annotate("text", x=1645, y=1.01, label="Males = Females", color="red", size=5) +  
  annotate("text", x=1680, y=1.19,  
    label="Arbuthnot's data on the Male / Female Sex Ratio", size=5.5)
```

Add figure title (but inside!)

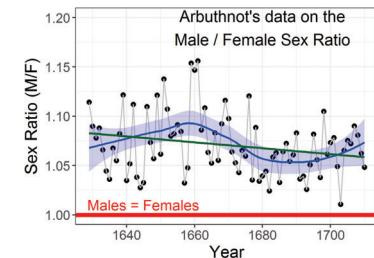


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Building a custom graph

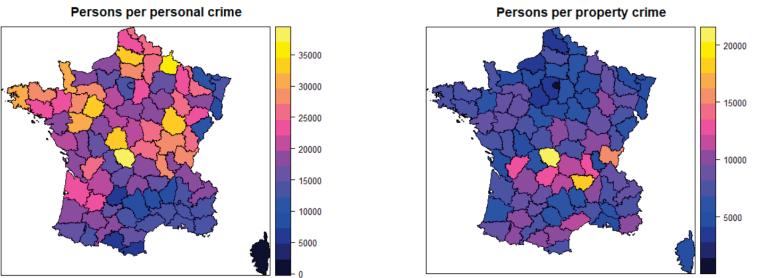
```
arbuth +  
  geom_hline(yintercept=1, color="red", size=2) +  
  annotate("text", x=1645, y=1.01, label="Males = Females", color="red", size=5) +  
  annotate("text", x=1680, y=1.19,  
    label="Arbuthnot's data on the Male / Female Sex Ratio", size=5.5) +  
  theme_bw() + theme(text = element_text(size = 16))
```

Change the theme and font size



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Guerry: Moral statistics of France



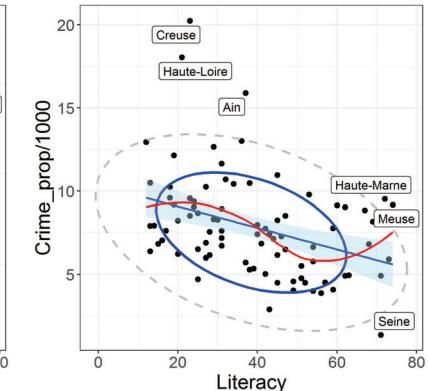
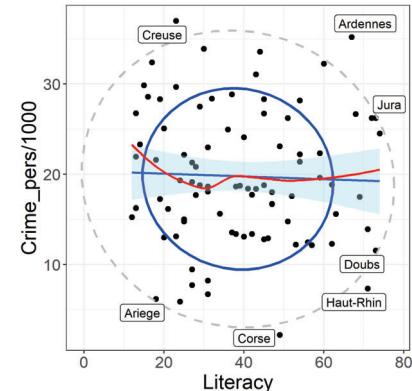
Guerry (1833) made shaded maps of France to determine if crime was related to literacy & other factors

```
library(Guerry)
library(sp)
spplot(gfrance, "Crime_pers")
spplot(gfrance, "Crime_prop")
spplot(gfrance, "Literacy")
```

Consulting for Guerry

Guerry: Mes cartes sont très jolies, non? But how can I go further?

MF: Make scatterplots! Add smooths & data ellipses. See you next week at Café Lillas
Guerry: Les boissons sont sur moi, mon ami!

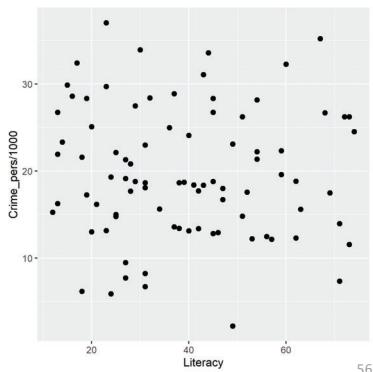


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Building Guerry's plots

```
ggplot(aes(x=Literacy, y=Crime_pers/1000), data=Guerry) +
  geom_point(size=2)
```

Start with a basic scatterplot

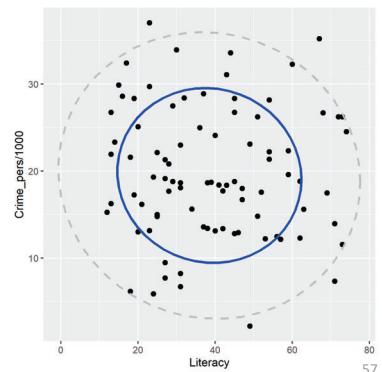


Building Guerry's plots

```
ggplot(aes(x=Literacy, y=Crime_pers/1000), data=Guerry) +
  geom_point(size=2) +
  stat_ellipse(level=0.68, color="blue", size=1.2) +
  stat_ellipse(level=0.95, color="gray", size=1, linetype=2)
```

Add data ellipses to show correlation

- 68% ~ mean \pm 1 sd
- 95% ~ mean \pm 2 sd



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Guerry's plots: Add smooths

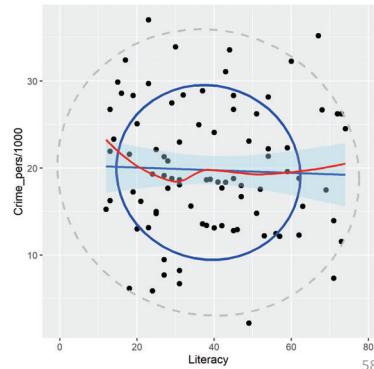
```
ggplot(aes(x=Literacy, y=Crime_pers/1000), data=Guerry) +
  geom_point(size=2) +
  stat_ellipse(level=0.68, color="blue", size=1.2) +
  stat_ellipse(level=0.95, color="gray", size=1, linetype=2) +
  geom_smooth(method="lm", formula=y~x, fill="lightblue") +
  geom_smooth(method="loess", formula=y~x, color="red", se=FALSE)
```

Add lm() and loess() smooths

- lm shows regression slope
- loess diagnoses possible non-linearity

Coffee break: save the current plot object

```
gplot <- last.plot()
```



Guerry's plots: Labeling

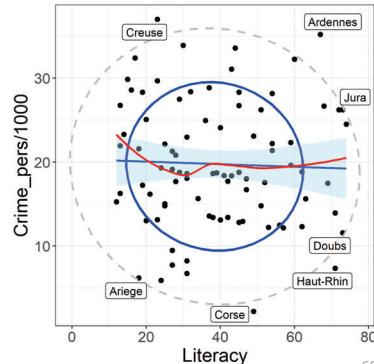
Guerry: OK, but I see some unusual points. What are they?

MF: Need to calculate "unusualness" – Mahalanobis D² squared distance from centroid

```
gdf <- Guerry[, c("Literacy", "Crime_pers", "Department")]
gdf$dsq <- mahalanobis(gdf[,1:2], colMeans(gdf[,1:2]), cov(gdf[,1:2]))
```

$$D^2 = (x - \bar{x})' S^{-1} (x - \bar{x})'$$

```
library(ggrepel)
gplot +
  theme_bw() +
  theme(text = element_text(size=18)) +
  geom_label_repel(aes(label=Department),
    data = gdf[gdf$dsq > 4.6,])
```



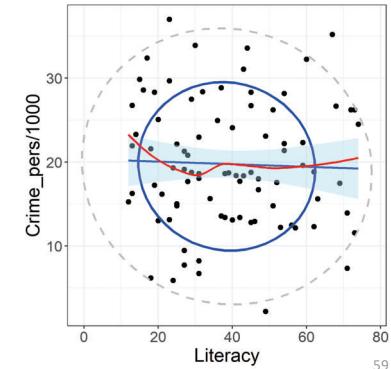
Guerry's plots: Styling

Guerry: I want to publish this! But need to make axis labels larger

```
gplot <- last_plot()
gplot + theme_bw() +
  theme(text = element_text(size=18))
```

MF:

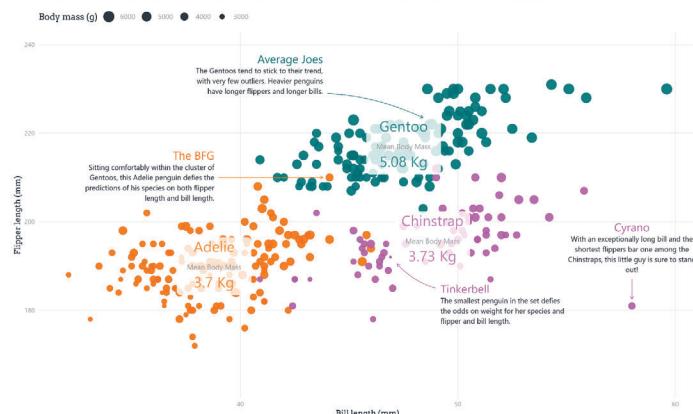
- Change the basic theme to theme_bw()
- Increase the font size for all text
- You can change the style of anything you want
- Create a theme_Guerry() to do many of these



Penguin tour-de-force

Perfectly proportional penguins - with a few exceptions!

Typically, the heavier the penguin, the longer its flippers and bill. The proportions within each species are also very consistent. **Adelie** penguins tend to be the smallest penguins, with the shortest bills and flippers. **Chinstraps** have longer bills, but not much longer flippers. The largest birds in this dataset, with the longest flippers, are the **Gentoo**.



Thompson, Cara. 2022. "Level Up Your Labels: Tips and Tricks for Annotating Plots." <https://www.carathompson.com/talks/user2022>.

Beyond 2D: Contour plots

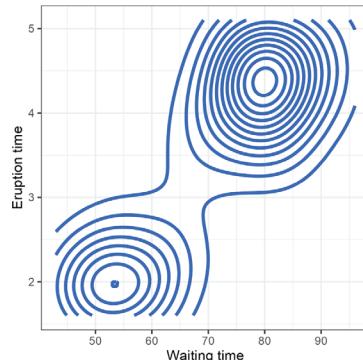
Data on eruptions of geysers at Old Faithful (Yellowstone Natl Park)

```
p <- ggplot(faithful, aes(waiting, eruptions))  
p + geom_density_2d(size=1.2) +  
  labs(x = "Waiting time",  
       y = "Eruption time")
```

`geom_density_2d()` calculates relative frequency (density) over a grid of X, Y values

It plots contours of equal density

```
> str(faithful)  
'data.frame': 272 obs. of 2 variables:  
 $ eruptions: num 3.6 1.8 3.33 2.28 4.53 ...  
 $ waiting : num 79 54 74 62 85 55 88 85 51 85 ...
```

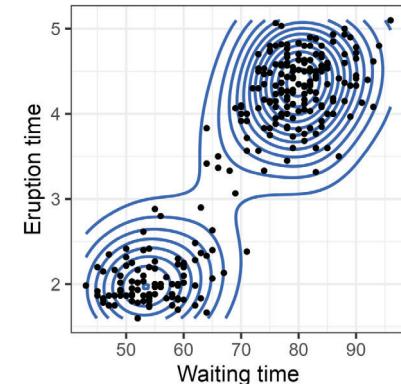


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Contours: add another layer

We also want to see the data: add points

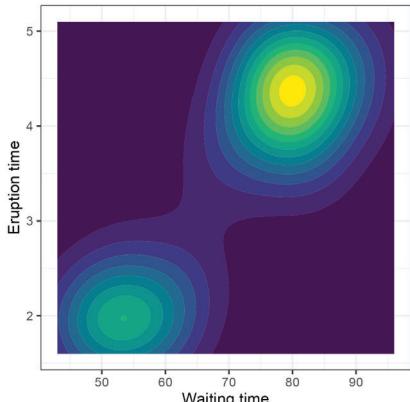
```
p + geom_density_2d() +  
  geom_point() +  
  labs(x = "Waiting time",  
       y = "Eruption time") +  
  theme_bw(base_size = 16)
```



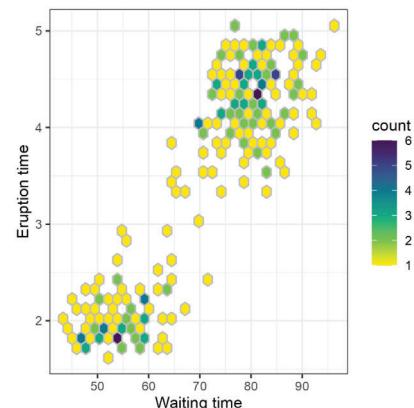
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Other forms: Filled contours, hex bins

```
p +  
  geom_density_2d_filled(show.legend = FALSE)
```



```
p +  
  geom_hex(bins=30, color="gray") +  
  scale_fill_viridis_c(direction = -1) +
```



The rayshader package produces stunning 3D visualizations of X, Y, Z data Z ("elevation") data above an X, Y plane

Allows:

- photo-realistic lighting & shading
- animation
- camera motion
- cinematic depth of field



⚠ computationally intensive

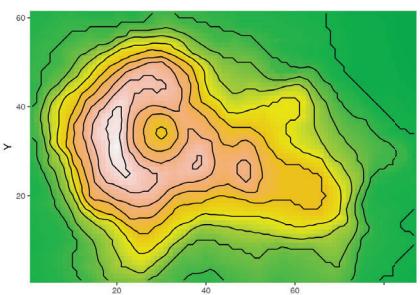


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rayshader::plot_gg()

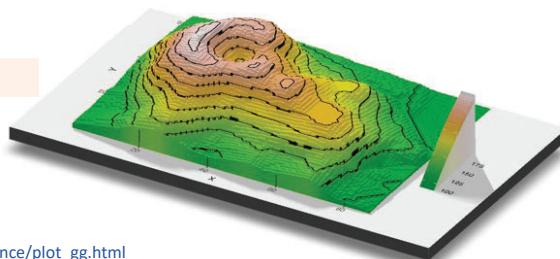


A volcano:



plot_gg(): Plots a ggplot2 object in 3D by mapping the `color` or `fill` aesthetic to elevation.

```
ggvolcano <-  
  volcano %>%  
  ggplot() + geom_contour(...)
```

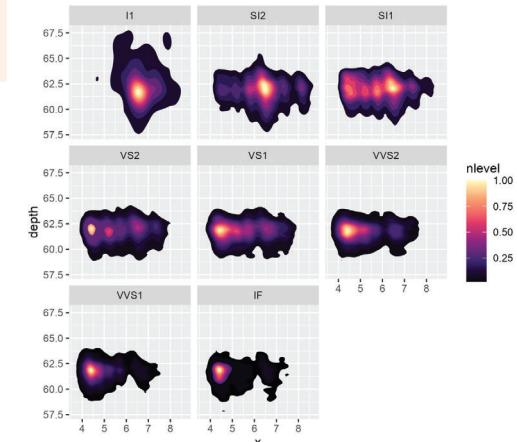


```
plot_gg(ggvolcano, ...)
```

From: https://www.rayshader.com/reference/plot_gg.html

Give your data the full 3D treatment (if you dare)

```
ggdiamonds <-  
  ggplot(diamonds, aes(x, depth)) +  
  stat_2d_density(...) +  
  facet_wrap(clarity ~ .)
```

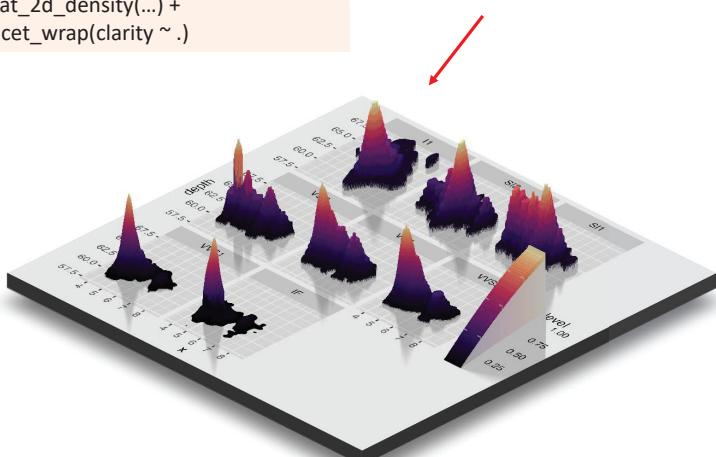


"Please Ma, can I have it in 3D?"

Give your data the full 3D treatment (if you dare)

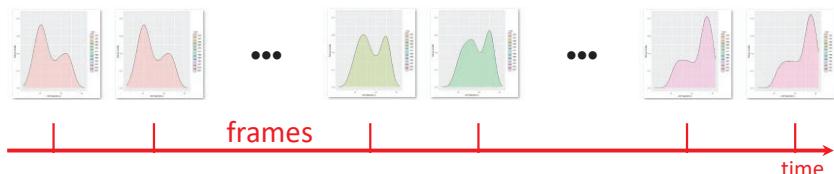
```
ggdiamonds <-  
  ggplot(diamonds, aes(x, depth)) +  
  stat_2d_density(...) +  
  facet_wrap(clarity ~ .)
```

```
plot_gg(ggdiamonds, zoom = 0.55,  
        phi = 30, ...)
```



Animation

An animation is a sequence of frames showing a series of related images



Frames can be based on:

- data subsets (year)
- plot attributes (color, shape)
- plot elements or layers
- ...

Enter / exit types:

- fade
- grow / shrink
- fly / drift



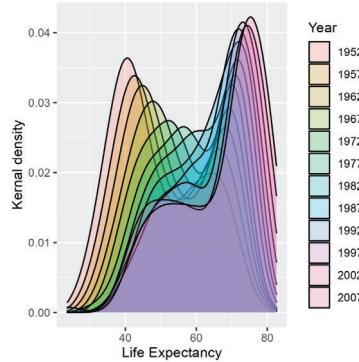
Transition effects:

Animation with ganimate

Draw density curves for life expectancy over years
-- separate curve for each year

```
data(gapminder, package="gapminder")
p <- gapminder %>%
  ggplot(aes(lifeExp, fill = factor(year))) +
  geom_density(alpha=.2) +
  xlab("Life Expectancy") +
  ylab("Kernel density") +
  guides(fill = guide_legend(title = "Year"))
plot(p)
```

This is pretty, but there is too much going on
-> Animate to show changes over years



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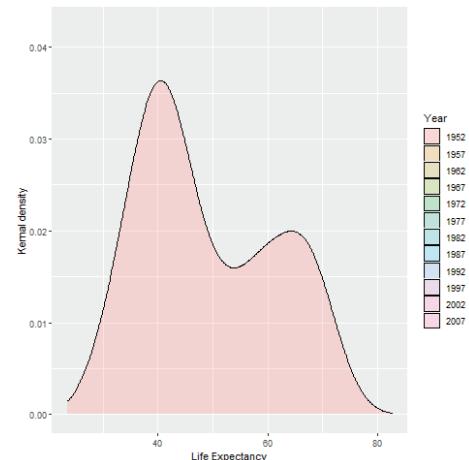
Make it an animation

Frames are defined by `transition_*` functions

`enter_*`, `exit_*`, `ease_*` functions define the change between transition states

```
p +
  transition_time(year) +
  ease_aes('linear')
```

```
anim_save("gap-anim.gif",
          nframes=20)
```



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Frames: `transition_*`()

`transition_*`()

`transition_states()`
a + transition_states(color, transition_length = 3, state_length = 1)
... and spending 3 times as long going to the next cut as we do pausing there.

`transition_time()`
b + transition_time(year, range = c(2002L, 2006L))
...from 2002 to 2006 (range is optional; default is the whole time frame). Unlike `transition_states()`, `transition_time()` treats the data as continuous and so the transition length is based on the actual values. Using 2002L instead of 2002 because the underlying data is an integer.

`transition_reveal()`
c + transition_reveal(date)
We're adding each date of the data on top of 'old' data

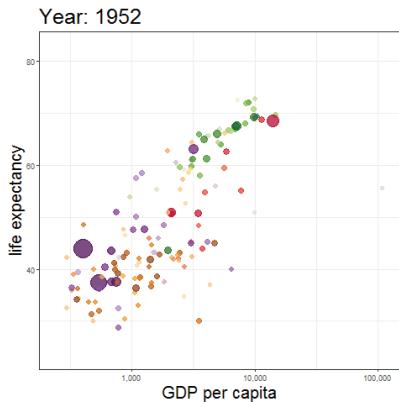
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`transition_time()`

The classic Rosling moving bubble plot

```
plt <-
  ggplot(gapminder,
         aes(x = gdpPercap, y = lifeExp,
              size = pop, colour = country)) +
  geom_point(alpha = 0.7) +
  scale_colour(values=country_colors) +
  scale_size(range = c(2, 15)) +
  scale_x_log10(labels = scales::comma) +
  theme_bw() +
  theme(legend.position = "none",
        plot.title = element_text(size = 25),
        axis.title = element_text(size = 20 ))
```

```
plt +
  labs(title = 'Year: {frame_time}') +
  transition_time(year) +
  ease_aes('linear')
```



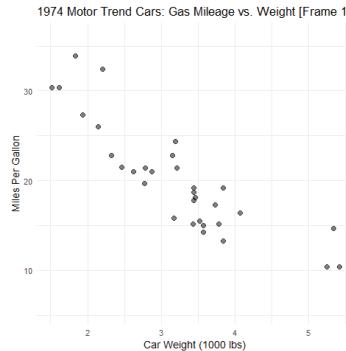
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transition_layers()

transition_layers(): Add layers or geoms one at a time

```
ggplot(mtcars, aes(y=mpg, x=wt)) +  
  geom_point(size=3, alpha=0.5) +  
  labs(x="Car Weight (1000 lbs)",  
       y="Miles Per Gallon") +  
  ggtitle("1974 Motor Trend Cars: Gas Mileage  
          vs. Weight [Frame {frame}]") +  
  theme_minimal(base_size = 14) +  
  geom_smooth(method = "lm", color="red") +  
  geom_smooth(method = "loess", color="blue") +  
  
  # do the animation, by layers  
  transition_layers() +  
  enter_fade() +  
  enter_grow()
```

element grows as it enters



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Summary

- Understand ggplot components
 - geoms, stats, scales, ...
- think in terms of layers:
 - + geom_point(), + geom_line(), + geom_smooth()
- themes
 - basic themes, extension packages
 - theme components
 - Fonts: use showtext
- Going beyond 2D
- Animation

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