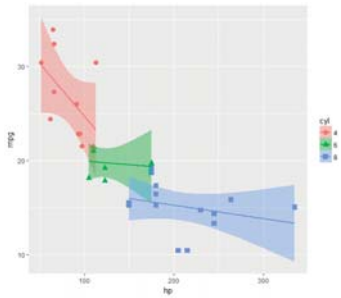
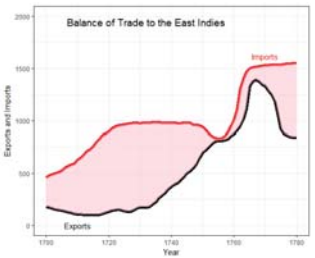
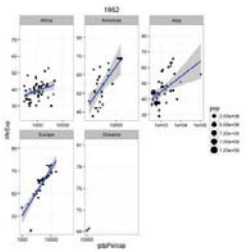





An introduction to R Graphics

4. ggplot2

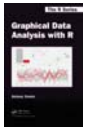
Michael Friendly
SCS Short Course
March, 2017

http://www.datavis.ca/courses/RGraphics/

Resources: Books

Hadley Wickham, *ggplot2: Elegant graphics for data analysis*, 2nd Ed.
1st Ed: Online, http://ggplot2.org/book/
ggplot2 Quick Reference: http://sape.inf.usi.ch/quick-reference/ggplot2/
Complete ggplot2 documentation: http://docs.ggplot2.org/current/

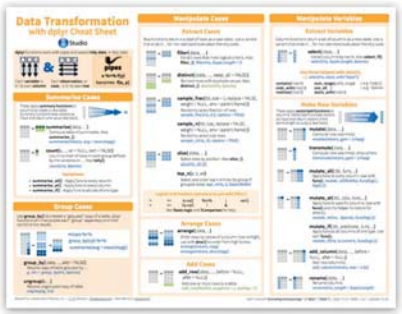
Winston Chang, *R Graphics Cookbook: Practical Recipes for Visualizing Data*
Cookbook format, covering common graphing tasks; the main focus is on ggplot2
R code from book: http://www.cookbook-r.com/Graphs/
Download from: http://ase.tufts.edu/bugs/guide/assets/R%20Graphics%20Cookbook.pdf



Antony Unwin, Graphical Data Analysis with R
R code: http://www.gradaanwr.net/

Resources: Cheat sheets

- Data visualization with ggplot2:
  https://www.rstudio.com/wp-content/uploads/2016/11/ggplot2-cheatsheet-2.1.pdf
- Data transformation with dplyr:
  https://github.com/rstudio/cheatsheets/raw/master/source/pdfs/data-transformation-cheatsheet.pdf



What is ggplot2?

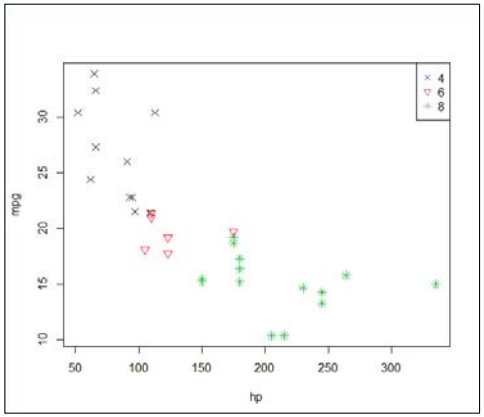
- ggplot2 is Hadley Wickham's R package for producing "elegant graphics for data analysis"
  - It is an implementation of many of the ideas for graphics introduced in Lee Wilkinson's *Grammar of Graphics*
  - These ideas and the syntax of ggplot2 help to think of graphs in a new and more general way
  - Produces pleasing plots, taking care of many of the fiddly details (legends, axes, colors, …)
  - It is built upon the "grid" graphics system
  - It is open software, with a large number of gg_ extensions. See: http://www.ggplot2-exts.org/gallery/

ggplot2 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))
```

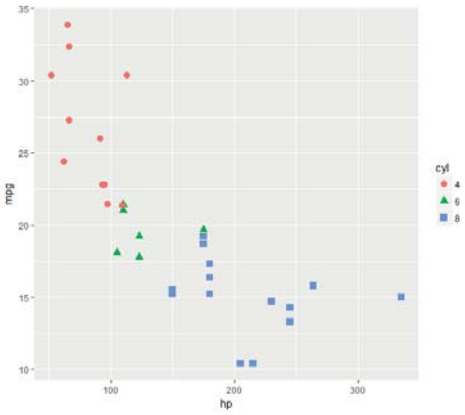
colors and point symbols work differently in plot() and legend()

ggplot2 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

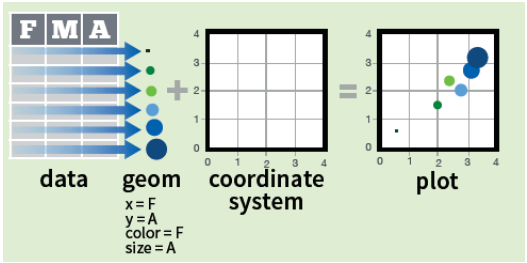
aes() mappings set in the call to ggplot() are passed to geom_point() here




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

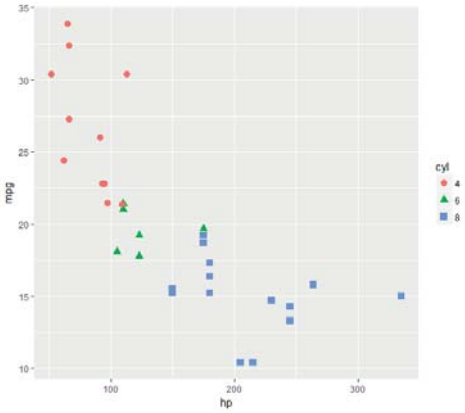

Grammar of Graphics

- 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,



ggplot2: data + geom -> graph

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



In this call,

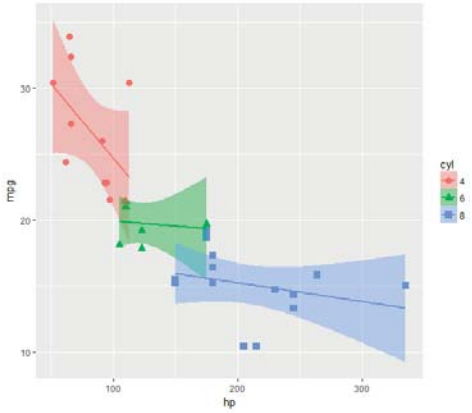
- data=mtcars: data frame
- aes(x=hp, y=mpg): plot variables
- aes(color, shape): attributes
- geom_point(): what to plot
- the coordinate system is taken to be the standard Cartesian (x,y)

ggplot2: geoms

Wow! I can really see something there.

How can I enhance this visualization?

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

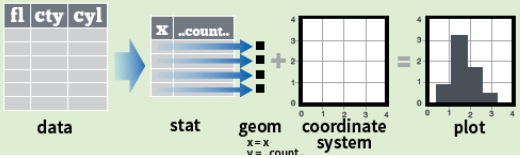



```
ggplot(mtcars, aes(x=hp, y=mpg, color=cyl, shape=cyl)) +
   geom_point(size=3) +
   geom_smooth(method="lm", aes(fill=cyl))
```


Grammar of Graphics

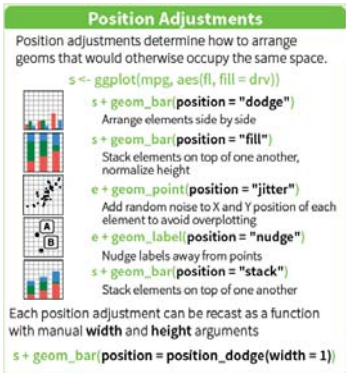
- Other GoG building blocks:
  - statistical transformations ("stat") -- data summaries: mean, sd, binning & counting, …
  - scales: legends, axes to allow reading data from a plot

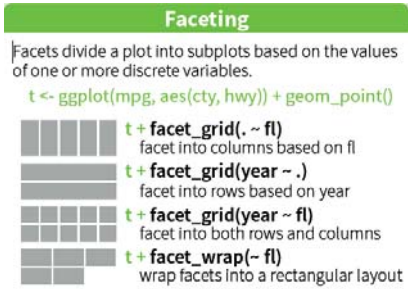
A stat builds new variables to plot (e.g., count, prop).



Grammar of Graphics

- Other GoG building blocks:
  - position adjustments: jitter, dodge, stack, …
  - faceting: small multiples or conditioning to break a plot into subsets.



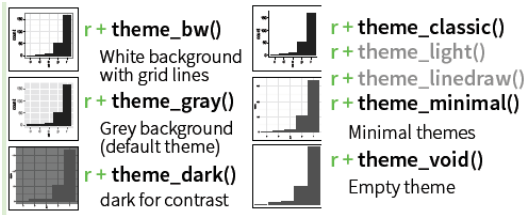


ggplot2: GoG -> graphic language

- The implementation of GoG ideas in ggplot2 for R created a more expressive language for data graphs
  - layers: graph elements combined with "+" (read: "and")

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

  - themes: change graphic elements consistently

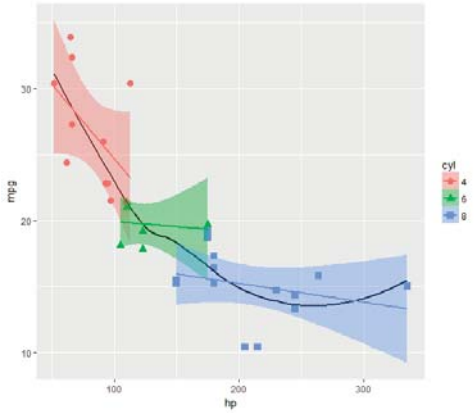


ggplot2: layers & aes()

Aesthetic attributes in the ggplot() call are passed to 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



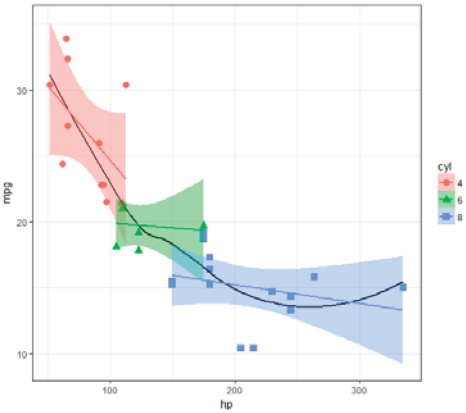

```
ggplot(mtcars, aes(x=hp, y=mpg)) +
   geom_point(size=3, aes(color=cyl, shape=cyl)) +
   geom_smooth(method="loess", color="black", se=FALSE) +
   geom_smooth(method="lm", aes(color=cyl, fill=cyl))
```


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

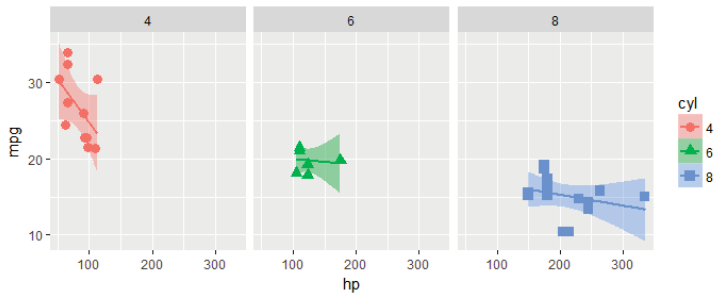



```
last_plot() + theme_bw()
```


ggplot2: facets

Facets divide a plot into separate subplots based on one or more discrete variables

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

plt + facet_wrap(~gear)
```

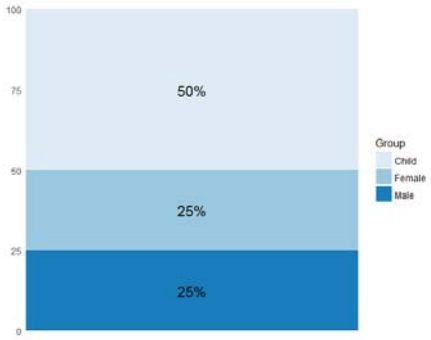


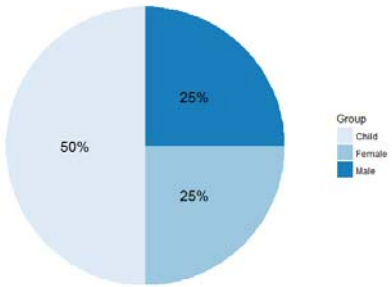
ggplot2: coords

Coordinate systems, coord_*() functions, handle conversion from geometric objects to what you see on a 2D plot.
A pie chart is just a bar chart in polar coordinates!

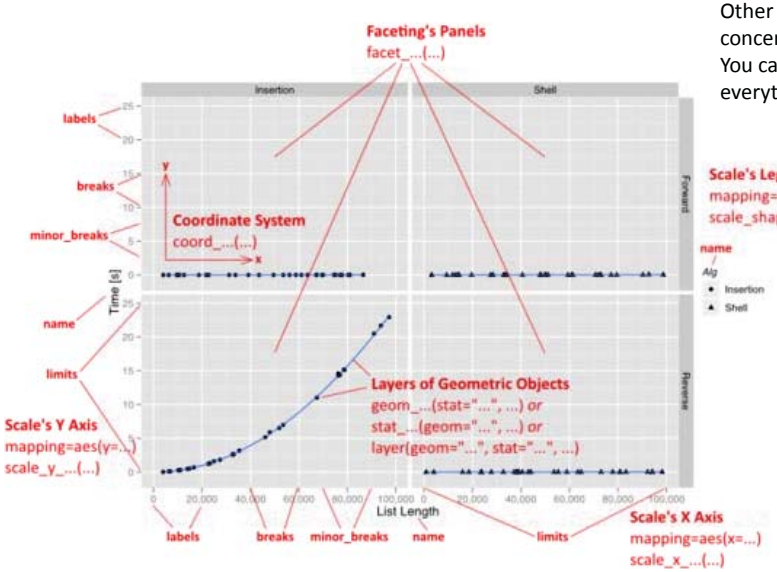
```
p <- ggplot(df, aes(x = "", y = value, fill = group)) +
        geom_bar( stat = "identity")
```

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





Anatomy of a ggplot



Other details of ggplot concern scales
You can control everything

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?

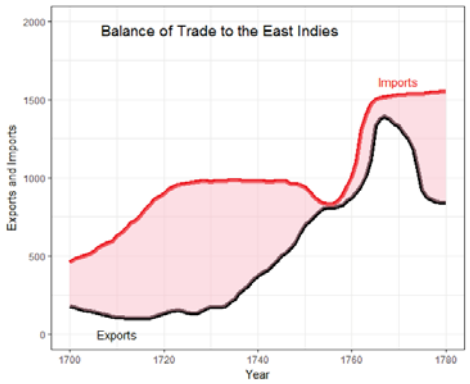
```
> methods(class="gg")
[1] +

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


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"?

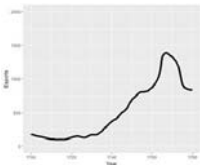
Here is a re-creation of one example, using ggplot2. How was it done?

```
> data(EastIndiesTrade,package="GDAdata")
> 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
  ...      ...     ...
```



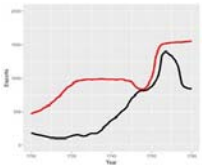
ggplot thinking

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



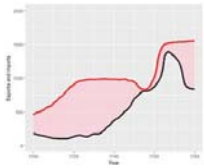
Start with a line plot of Exports vs. Year: geom_line()
Add a layer for the line plot of Imports vs. Year

```
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")
```

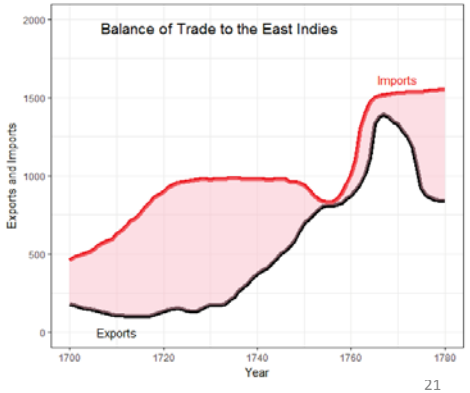


That looks pretty good. Add some text labels using annotate()

```
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)
```

Finally, change the theme to b/w

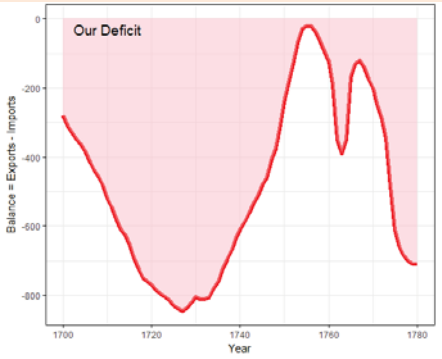
```
c1 <- c1 + theme_bw()
```



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?

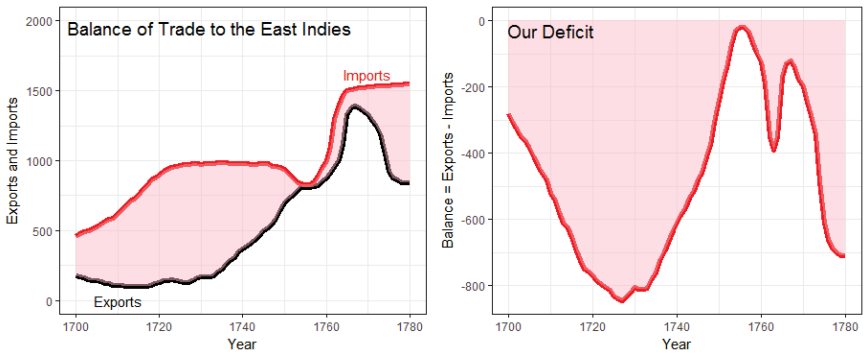
```
c2 <-
ggplot(EastIndiesTrade, aes(x=Year, y=Exports-Imports)) +
    geom_line(colour="red", size=2) +
     ylab("Balance = Exports - Imports") +
     geom_ribbon(aes(ymin=Exports-Imports, ymax=0), fill="pink",alpha=0.5) +
     annotate("text", x = 1710, y = -30, label = "Our Deficit", color="black",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



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)
```



Saving plots: ggsave()

- If the plot is on the screen

  ggsave("path/filename.png")

- If you have a plot object

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

- Specify size:

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

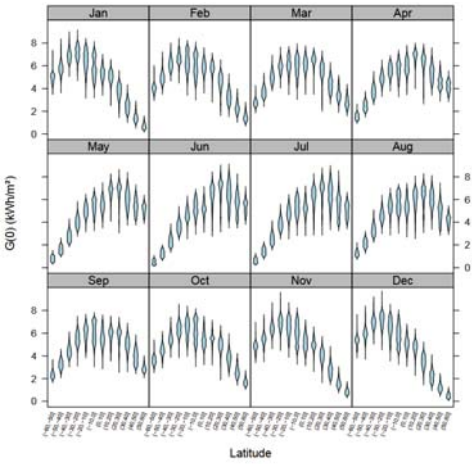
- any plot format (pdf, png, eps, svg, jpg, …)

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

Faceting & tidy data

Recall the lattice example plotting solar radiation vs. latitude over months of the year.

This was complicated, because the data structure was **untidy**--- months were in separate variables (wide format)




```
> str(nasa)
'data.frame':   64800 obs. of  15 variables:
 $ Lat: int  -90 -90 -90 -90 -90 -90 -90 -90 -90 -90 ...
 $ Lon: int  -180 -179 -178 -177 -176 -175 -174 -173 -172 -171 ...
 $ Jan: num  9.63 9.63 9.63 9.63 9.63 9.63 9.63 9.63 9.63 9.63 ...
 $ Feb: num  5.28 5.28 5.28 5.28 5.28 5.28 5.28 5.28 5.28 5.28 ...
 $ Mar: num  0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 0.75 ...
 $ Apr: num  0 0 0 0 0 0 0 0 0 0 ...
 $ May: num  0 0 0 0 0 0 0 0 0 0 ...
 $ Jun: num  0 0 0 0 0 0 0 0 0 0 ...
 $ Jul: num  0 0 0 0 0 0 0 0 0 0 ...
 $ Aug: num  0 0 0 0 0 0 0 0 0 0 ...
 $ Sep: num  0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 ...
 $ Oct: num  3.24 3.24 3.24 3.24 3.24 3.24 3.24 3.24 3.24 3.24 ...
 $ Nov: num  8.28 8.28 8.28 8.28 8.28 8.28 8.28 8.28 8.28 8.28 ...
 $ Dec: num  11 11 11 11 11 ...
 $ Ann: num  3.19 3.19 3.19 3.19 3.19 3.19 3.19 3.19 3.19 3.19 ...
```


tidying the data

In wide format, I had to construct a plot formula to plot those columns

```
> x <- paste(names(nasa)[3:14], collapse='+')
> (formula <- as.formula(paste(x, '~cut(Lat, pretty(Lat, 20))', sep='')))
Jan + Feb + Mar + Apr + May + Jun + Jul + Aug + Sep + Oct + Nov +
    Dec ~ cut(Lat, pretty(Lat, 20))
```

It is much easier to reshape the data to long format, so solar is all in one column

```
library(tidyr)
library(dplyr)
library(ggplot2)

nasa_long <- nasa %>%
   select(-Ann) %>%
   gather(month, solar, Jan:Dec, factor_key=TRUE) %>%
   filter( abs(Lat) < 60 ) %>%
   mutate( Lat_f = cut(Lat, pretty(Lat, 12)))
```

%>% "pipes" data to the next stage

select() extracts or drops columns

gather() collapses columns into key-value pairs

filter() subsets observations

mutate() creates new variables

tidying the data

```
> str(nasa_long)
'data.frame':   514080 obs. of  5 variables:
 $ Lat  : int  -59 -59 -59 -59 -59 -59 -59 -59 -59 -59 ...
 $ Lon  : int  -180 -179 -178 -177 -176 -175 -174 -173 -172 -171 ...
 $ month: Factor w/ 12 levels "Jan","Feb","Mar",..: 1 1 1 1 1 1 1 1 1 1 ...
 $ solar: num  5.19 5.19 5.25 5.25 5.17 5.17 5.15 5.15 5.15 5.15 ...
 $ Lat_f: Factor w/ 12 levels "(-60,-50]","(-50,-40]",..: 1 1 1 1 1 1 1 1 1 1 ...

> head(nasa_long)
  Lat  Lon month solar     Lat_f
1 -59 -180   Jan  5.19 (-60,-50]
2 -59 -179   Jan  5.19 (-60,-50]
3 -59 -178   Jan  5.25 (-60,-50]
4 -59 -177   Jan  5.25 (-60,-50]
5 -59 -176   Jan  5.17 (-60,-50]
6 -59 -175   Jan  5.17 (-60,-50]
```

For ease of plotting, I created a factor version of Lat with 12 levels

The data are now in a form where I can plot solar against Lat or Lat_f and facet by month

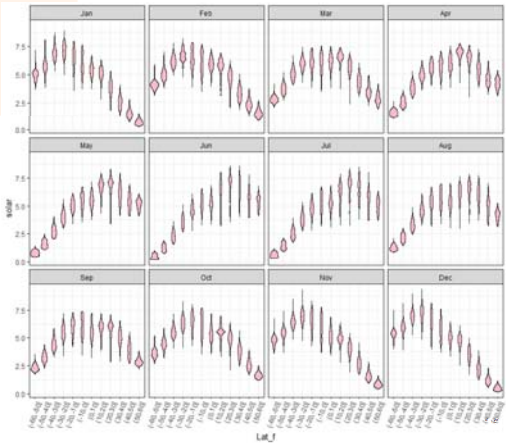
plotting the tidy data

Using geom_violin() shows the shapes of the distributions for levels of Lat_f

```
ggplot(nasa_long, aes(x=Lat_f, y=solar)) +
   geom_violin(fill="pink") +
   facet_wrap(~ month) +
   theme_bw() +
   theme(axis.text.x =
         element_text(angle = 70,
                      hjust = 1))
```

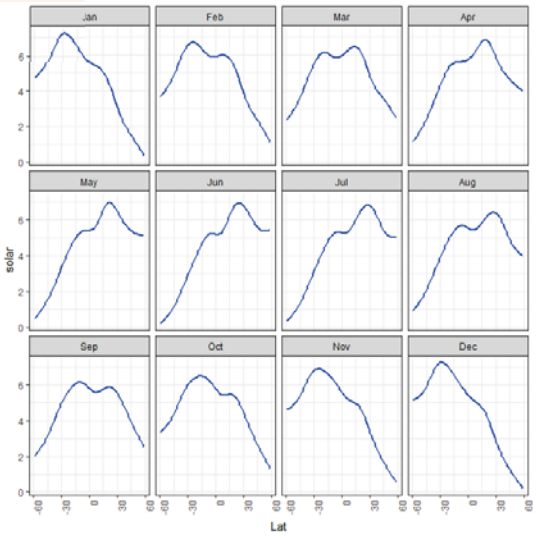
facet_wrap(~month) does the right thing

I had to adjust the x-axis labels for Lat_f to avoid overplotting



plotting the tidy data: smoothing

```
ggplot(nasa_long, aes(x=Lat, y=solar)) +
  geom_smooth(color="blue" ) +
  facet_wrap(~ month) +
  theme_bw()
```



Here we treat Lat as quantitative geom_smooth() uses method = "gam" here because of large *n*

The variation in the smoothed trends over the year suggest quite lawful behavior

build a model

What we saw in the plot suggests a generalized additive model, with a smooth, s(Lat)

```
library(mgcv)
nasa.gam <- gam(solar ~ Lon + month + s(Lat), data=nasa_long)
summary(nasa.gam)
```

```
Family: gaussian
Link function: identity

Formula:
solar ~ Lon + month + s(Lat)

Parametric coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  4.691e+00  6.833e-03 686.409  < 2e-16 ***
Lon         -1.713e-04  1.898e-05  -9.022  < 2e-16 ***
monthFeb     1.195e-01  9.664e-03  12.364  < 2e-16 ***
  ...            ...
monthDec    -8.046e-02  9.664e-03  -8.326  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
       edf Ref.df     F p-value
s(Lat) 8.997      9 37285  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.398   Deviance explained = 39.8%
GCV = 2.0006  Scale est. = 2.0005    n = 514080
```

The violin plots suggest that variance is not constant. I'm ignoring this here by using the default gaussian model.

Model terms:

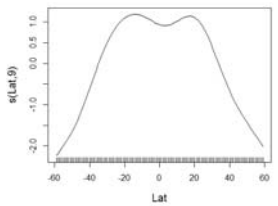
- Lon wasn't included before
- month is a factor, for the plots
- s(Lat) fits a smoothed term in latitude, averaged over other factors

There are other model choices, but it is useful to visualize what we have done so far

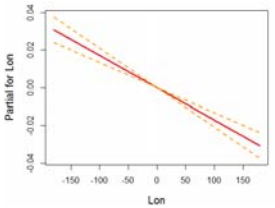
visualize the model

Effect plots show the fitted relationship between the response and model terms, averaged over other predictors.
The mgcv package has its own versions of these.

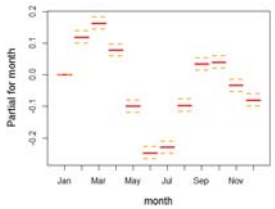
```
plot(nasa.gam, cex.lab=1.25)
termplot(nasa.gam, terms="month", se=TRUE, lwd.term=3, lwd.se=2, cex.lab=1.25)
termplot(nasa.gam, terms="Lon", se=TRUE, lwd.term=3, lwd.se=2, cex.lab=1.25)
```



why the dip at the equator?



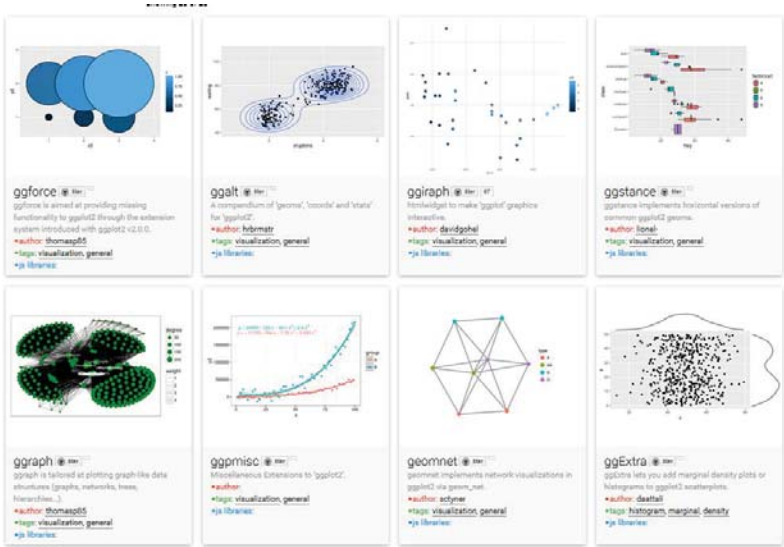
effect of longitude is very small, but maybe interpretable



month should be modeled as a time variable

ggplot extensions

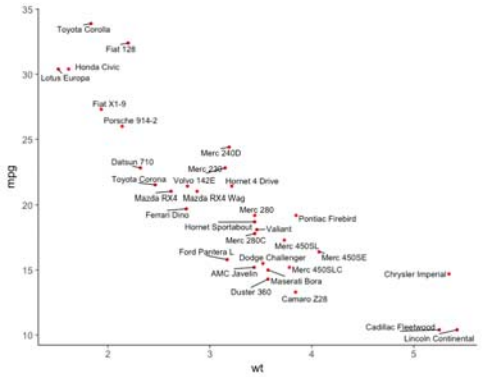
There are a large number of ggplot extensions. See: http://www.ggplot2-exts.org/



ggplot extensions: ggrepel

```
devtools::install_github("slowkow/ggrepel")
library(ggplot2)
library(ggrepel)
ggplot(mtcars, aes(wt, mpg)) +
  geom_point(color = 'red') +
  geom_text_repel(aes(label = rownames(mtcars))) +
  theme_classic(base_size = 16)
```

Plotting text labels is often difficult
ggrepel provides geoms for ggplot2 to repel overlapping text labels.

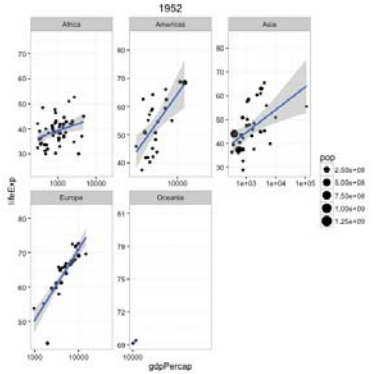


ggplot extensions: gganimate

gganimate is a wrapper for the animation package with ggplot2.

It adds a frame= aesthetic, and animates the image as the frame variable changes

Install from github:
devtools::install_github("dgrtwo/gganimate")



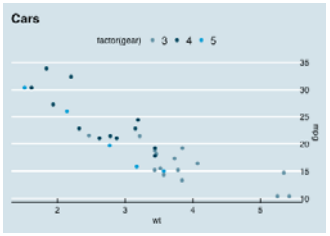

```
p5 <- ggplot(gapminder, aes(gdpPercap, lifeExp, size = pop, frame = year)) +
  geom_point() +
  geom_smooth(aes(group = year), method = "lm", show.legend = FALSE) +
  facet_wrap(~continent, scales = "free") +
  scale_x_log10()

gganimate(p5)
```


ggthemes

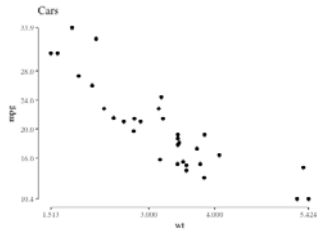
ggthemes provides a large number of extra geoms, scales, and themes for ggplot

```
install.packages('ggthemes', dependencies = TRUE)
```

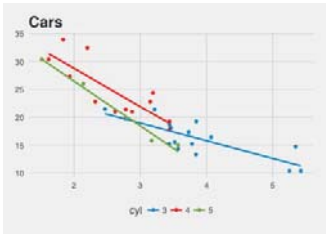
+ theme_economist()



+ theme_tufte()



+ theme_fivethirtyeight()



Tables in R

- Not a ggplot topic, but it is useful to know that you can also produce beautiful tables in R
- There are many packages for this: See the CRAN Task View on Reproducible Research, https://cran.r-project.org/web/views/ReproducibleResearch.html
  - xtable: Exports tables to LaTeX or HTML, with lots of control
  - stargazer: Well-formatted model summary tables, side-by-side
  - apaStyle: Generate APA Tables for MS Word

Tables in R: xtable

Just a few examples, stolen from xtable: vignette("xtableGallery.pdf")

```
fm1 <- aov(tlimth ~ sex + ethnicty + grade + disadvg, data = tli)
xtable(fm1)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
sex	1	75.37	75.37	0.38	0.5417
ethnicty	3	2572.15	857.38	4.27	0.0072
grade	1	36.31	36.31	0.18	0.6717
disadvg	1	59.30	59.30	0.30	0.5882
Residuals	93	18682.87	200.89		

```
fm3 <- glm(disadvg ~ ethnicty*grade, data = tli, family = binomial)
xtable(fm3)
```

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	3.1888	1.5966	2.00	0.0458
ethnictyHISPANIC	-0.2848	2.4808	-0.11	0.9086
ethnictyOTHER	212.1701	22122.7093	0.01	0.9923
ethnictyWHITE	-8.8150	3.3355	-2.64	0.0082
grade	-0.5308	0.2892	-1.84	0.0665
ethnictyHISPANIC:grade	0.2448	0.4357	0.56	0.5742
ethnictyOTHER:grade	-32.6014	3393.4687	-0.01	0.9923
ethnictyWHITE:grade	1.0171	0.5185	1.96	0.0498

Too many decimals are used here, but you can control all that