

## Visualizing Linear Models: An R Bag of Tricks Session 1: Getting Started

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SCS Short Course  
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<https://friendly.github.io/VisMLM-course/>

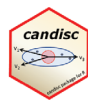
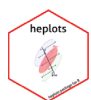
## Today's topics

- What you need for this course
- Why plot your data?
- Data plots
- Model (effect) plots
- Diagnostic plots

2

## What you need

- R, version  $\geq 3.6$ 
  - Download from <https://cran.r-project.org/>
- RStudio IDE, highly recommended
  - <https://www.rstudio.com/products/rstudio/>
- R packages: see course web page
  - car
  - effects
  - heplots
  - candisc
  - visreg



## Why plot your data?

*Getting information from a table is like extracting sunlight from a cucumber. --- Farquhar & Farquhar, 1891*

*Information that is imperfectly acquired, is generally as imperfectly retained; and a man who has carefully investigated a printed table, finds, when done, that he has only a very faint and partial idea of what he has read; and that like a figure imprinted on sand, is soon totally erased and defaced.*

--- William Playfair, *The Commercial and Political Atlas* (p. 3), 1786

3

4



## Cucumbers

Table 7  
Stevens et al. 2006, table 2: Determinants  
of authoritarian aggression

| Variable  | Coefficient<br>(Standard Error) |
|---|---------------------------------|
| Constant  | .41 (.93)                       |
| Countries   |                                 |
| Argentina   | 1.31 (.33)**B,M                 |
| Chile   | .93 (.32)**B,M                  |
| Colombia  | 1.46 (.32)**B,M                 |
| Mexico  | .07 (.32) <sup>A,CH,CO,V</sup>  |
| Venezuela   | .96 (.37)**B,M                  |
| Threat  |                                 |
| Retrospective egocentric<br>economic perceptions  | .20 (.13)                       |
| Prospective egocentric<br>economic perceptions    | .22 (.12) <sup>a</sup>          |
| Retrospective sociotropic<br>economic perceptions | -.21 (.12) <sup>a</sup>         |
| Prospective sociotropic<br>economic perceptions   | -.32 (.12) <sup>a</sup>         |
| Ideological distance from<br>president            | -.27 (.07)**                    |
| Ideology  |                                 |
| Ideology  | .23 (.07)**                     |
| Individual Differences                            |                                 |
| Age   | .00 (.01)                       |
| Female  | -.03 (.21)                      |
| Education   | .13 (.14)                       |
| Academic Sector                                   | .15 (.29)                       |
| Business Sector                                   | .31 (.25)                       |
| Government Sector                                 | -.10 (.27)                      |
| R <sup>2</sup>                                    | .15                             |
| Adjusted R <sup>2</sup>                           | .12                             |
| N   | 500                             |

Results of a one model for authoritarian  
aggression

The information is overwhelmed by  
footnotes & significance \*\*stars\*\*

\*\*p < .01, \*p < .05, <sup>a</sup>p < .10 (twotailed)

<sup>A</sup>Coefficient is significantly different from Argentina's at  
p < .05;

<sup>B</sup>Coefficient is significantly different from Brazil's at p < .05;

<sup>CH</sup>Coefficient is significantly different from Chile's at p < .05;

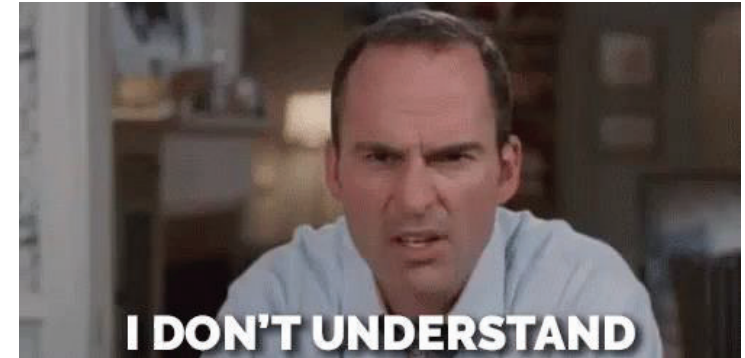
<sup>CO</sup>Coefficient is significantly different from Colombia's at  
p < .05;

<sup>M</sup>Coefficient is significantly different from Mexico's at p < .05;

<sup>V</sup>Coefficient is significantly different from Venezuela's at  
p < .05.

5

## What's wrong with this picture?

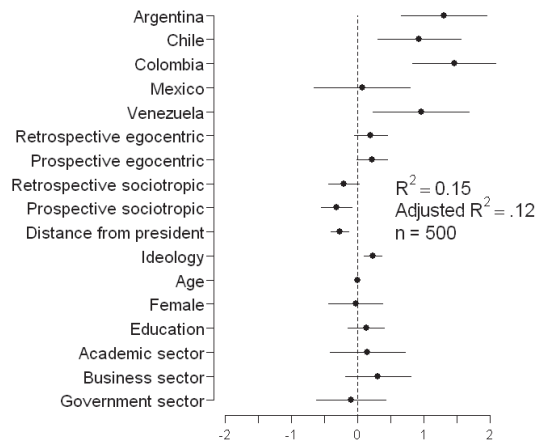


6



## Sunlight

coefplot(model)



Why didn't they say  
this in the first place?

NB: This is a  
presentation graph  
equivalent of the  
table

Shows coefficient  
with 95% CI

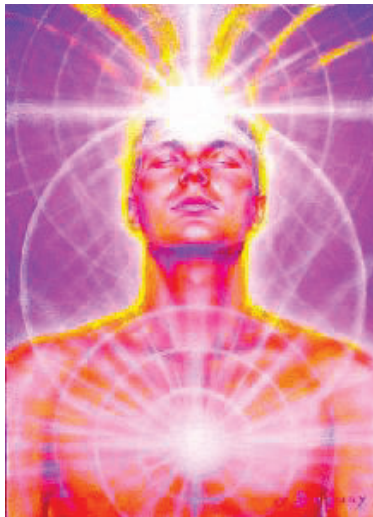
7

## Run, don't walk toward the sunlight



8

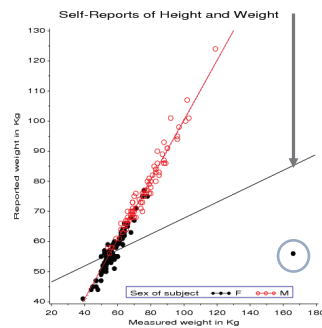
## Graphs can give enlightenment



*The greatest value of a picture is when it forces us to notice what we never expected to see.*

-- John W. Tukey

Effect of one rotten point on regression



9

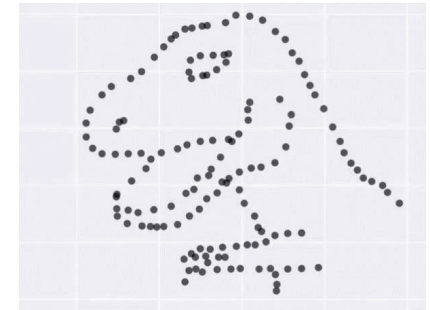
## Dangers of numbers-only output

*Student:* You said to run descriptives and compute the correlation. What next?

*Consultant:* Did you plot your data?

```
X Mean: 54.26
Y Mean: 47.83
X SD : 16.76
Y SD : 26.93
Corr. : -0.06
```

With **exactly** the same stats, the data could be *any* of these plots



See how this is done in R: <https://cran.r-project.org/web/packages/datasauRus/>

10

## Sometimes, don't need numbers at all

COVID transmission risk ~ Occupancy \* Ventilation \* Activity \* Mask? \* Contact.time

A complex 5-way table, whose message is clearly shown w/o numbers

There are 1+ unusual cells here. Can you see them?

| Type and level of group activity                          | Low occupancy                |                             |                   | High occupancy               |                             |                   |
|---|------------------------------|-----------------------------|-------------------|------------------------------|-----------------------------|-------------------|
|   | Outdoors and well ventilated | Indoors and well ventilated | Poorly ventilated | Outdoors and well ventilated | Indoors and well ventilated | Poorly ventilated |
| <b>Wearing face coverings, contact for short time</b>     |                              |                             |                   |                              |                             |                   |
| Silent  | Low                          | Low                         | Low               | Low                          | Low                         | Low               |
| Speaking  | Low                          | Low                         | Low               | Low                          | Low                         | Low               |
| Shouting, singing   | Low                          | Low                         | Low               | Low                          | Low                         | Low               |
| <b>Wearing face coverings, contact for prolonged time</b> |                              |                             |                   |                              |                             |                   |
| Silent  | Low                          | Low                         | Low               | Low                          | Low                         | Low               |
| Speaking  | Low                          | Low                         | Low               | Low                          | Low                         | Low               |
| Shouting, singing   | Low                          | Low                         | Low               | Low                          | Low                         | Low               |
| <b>No face coverings, contact for short time</b>          |                              |                             |                   |                              |                             |                   |
| Silent  | Low                          | Low                         | Low               | Low                          | Low                         | Low               |
| Speaking  | Low                          | Low                         | Low               | Low                          | Low                         | Low               |
| Shouting, singing   | Low                          | Low                         | Low               | Low                          | Low                         | Low               |
| <b>No face coverings, contact for prolonged time</b>      |                              |                             |                   |                              |                             |                   |
| Silent  | Low                          | Low                         | Low               | Low                          | Low                         | Low               |
| Speaking  | Low                          | Low                         | Low               | Low                          | Low                         | Low               |
| Shouting, singing   | Low                          | Low                         | Low               | Low                          | Low                         | Low               |

Risk of transmission

Low Medium High

\* Borderline case that is highly dependent on quantitative definitions of distancing, number of individuals, and time of exposure

From: N.R. Jones et al (2020). Two metres or one: what is the evidence for physical distancing in covid-19? *BMJ* 2020;370:m3223, doi: <https://doi.org/10.1136/bmj.m3223>

11

## If you do need tables– make them pretty

Several R packages make it easier to construct informative & pretty semi-graphic tables

Presentation graph

Perhaps too cute!

Distribution of variables shown

Flipper lengths (mm) of the famous penguins of Palmer Station, Antarctica.

| Species   | Distribution | Female |           | Male |           |
|-----------|--------------|--------|-----------|------|-----------|
|           |              | Avg.   | Std. Dev. | Avg. | Std. Dev. |
| Adelie    |              | 188    | 5.6       | 192  | 6.6       |
| Chinstrap |              | 192    | 5.8       | 200  | 6.0       |
| Gentoo    |              | 213    | 3.9       | 222  | 5.7       |

Artwork by @allison\_horst

12

## Visual table ideas: Heatmap shading

**Heatmap shading:** Shade the background of each cell according to some criterion

The trends in the US and Canada are made obvious

NB: Table rows are sorted by Jan. value, lending coherence

### Unemployment rate in selected countries

January-August 2020, sorted by the unemployment rate in January.

| country       | Jan         | Feb         | Mar         | Apr          | May          | Jun          | Jul          | Aug          |
|---------------|-------------|-------------|-------------|--------------|--------------|--------------|--------------|--------------|
| Japan         | 2.4%        | 2.4%        | 2.5%        | 2.6%         | 2.9%         | 2.8%         | 2.9%         | 3.0%         |
| Netherlands   | 3.0%        | 2.9%        | 2.9%        | 3.4%         | 3.6%         | 4.3%         | 4.5%         | 4.6%         |
| Germany       | 3.4%        | 3.6%        | 3.8%        | 4.0%         | 4.2%         | 4.3%         | 4.4%         | 4.4%         |
| Mexico        | 3.6%        | 3.6%        | 3.2%        | 4.8%         | 4.3%         | 5.4%         | 5.2%         | 5.0%         |
| <b>US</b>     | <b>3.6%</b> | <b>3.5%</b> | <b>4.4%</b> | <b>14.7%</b> | <b>13.3%</b> | <b>11.1%</b> | <b>10.2%</b> | <b>8.4%</b>  |
| South Korea   | 4.0%        | 3.3%        | 3.8%        | 3.8%         | 4.5%         | 4.3%         | 4.2%         | 3.2%         |
| Denmark       | 4.9%        | 4.9%        | 4.8%        | 4.9%         | 5.5%         | 6.0%         | 6.3%         | 6.1%         |
| Belgium       | 5.1%        | 5.0%        | 5.0%        | 5.1%         | 5.0%         | 5.0%         | 5.0%         | 5.1%         |
| Australia     | 5.3%        | 5.1%        | 5.2%        | 6.4%         | 7.1%         | 7.4%         | 7.5%         | 6.8%         |
| <b>Canada</b> | <b>5.5%</b> | <b>5.6%</b> | <b>7.8%</b> | <b>13.0%</b> | <b>13.7%</b> | <b>12.3%</b> | <b>10.9%</b> | <b>10.2%</b> |
| Finland       | 6.8%        | 6.9%        | 7.0%        | 7.3%         | 7.5%         | 7.8%         | 8.0%         | 8.1%         |

Source: OECD • Get the data • Created with Datarapper

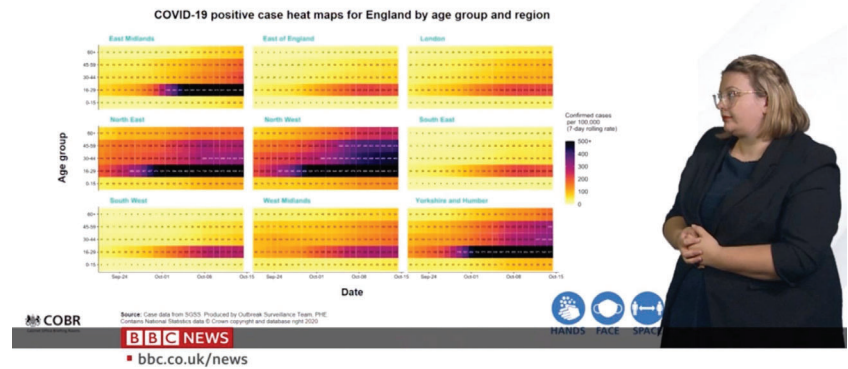
13

## Visual table ideas: Heatmap shading

As seen on TV ...

Covid rate ~ Age x Date x UK region

Better: incorporate geography, not just arrange regions alphabetically



14

## Visual table ideas: Sparklines

**Sparklines:** Mini graphics inserted into table cells or text



From: <https://www.pluralsight.com/guides/tableau-playbook-sparklines>

15

## Linear models

• Model:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \dots + \beta_p x_{ip} + \varepsilon_i$$

• Xs: quantitative predictors, factors, interactions, ...

• Assumptions:

- **Linearity:** Predictors (possibly transformed) are linearly related to the outcome,  $y$ . [This just means linear in the **parameters**.]
- **Specification:** No important predictors have been omitted; only important ones included. [This is often key & overlooked.]
- The “holy trinity”:
  - **Independence:** the errors are uncorrelated
  - **Homogeneity of variance:**  $\text{Var}(\varepsilon_i) = \sigma^2 = \text{constant}$
  - **Normality:**  $\varepsilon_i$  have a normal distribution

$$\varepsilon_i \sim_{iid} \mathcal{N}(0, \sigma^2)$$

16

## The General Linear Model

- “linear” models can include:
  - transformed predictors:  $\sqrt{age}$ ,  $\log(income)$
  - polynomial terms:  $age^2$ ,  $age^3$ ,  $poly(age, n)$
  - categorical “factors”, coded as dummy (0/1) variables
    - treated (Yes/No), Gender (M/F/non-binary)
  - interactions: effects of  $x_1$  vary over levels of  $x_2$ 
    - treated  $\times$  age, treated  $\times$  sex, (2 way)
    - treated  $\times$  age  $\times$  sex (3 way)
- Linear model means **linear** in the parameters ( $\beta_i$ ),  

$$y = \beta_0 + \beta_1 age + \beta_2 age^2 + \beta_3 \log(income) + \beta_4 (sex = "F") + \beta_5 age \times (sex = "F") + \epsilon$$
- In R, all handled by `lm(y ~ ...)`

17

## Fitting linear models in R: lm()

- In R, `lm()` for everything
  - Regression models ( $X_1, \dots$  **quantitative**)

```
lm(y ~ X1, data=dat)           # simple linear regression
lm(y ~ X1+X2+X3, data=dat)     # multiple linear regression
lm(y ~ (X1+X2+X3)^2, data=dat) # all two-way interactions
lm(log(y) ~ poly(X,3), data=dat) # arbitrary transformations
```

- ANOVA/ANCOVA models ( $A, B, \dots$  **factors**)

```
lm(y ~ A)                       # one way ANOVA
lm(y ~ A*B)                     # two way: A + B + A:B
lm(y ~ X + A)                   # one way ANCOVA
lm(y ~ (A+B+C)^2)               # 3-way ANOVA: A, B, C, A:B, A:C, B:C
```

18

## Fitting linear models in R: lm()

- Multivariate models: `lm()` with 2+ y vars

- Multivariate regression

```
lm(cbind(y1, y2) ~ X1 + X2 + X3) # std MMreg: all linear
lm(cbind(y1, y2) ~ poly(X1,2) + poly(X2,2)) # response surface
```

- MANOVA/MANCOVA models

```
lm(cbind(y1, y2, y3) ~ A * B) # 2-way MANOVA: A + B + A:B
lm(cbind(y1, y2, y3) ~ X + A) # MANCOVA (equal slopes)
lm(cbind(y1, y2) ~ X + A + X:A) # heterogeneous slopes
```

19

## Generalized Linear Models: glm()

Transformations of  $y$  & other error distributions

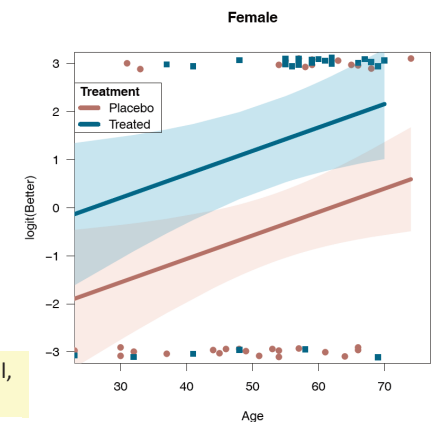
- $y \in (0/1)$ : lived/died; success/fail; ...

- logit (log odds) model:

- $\text{logit}(y) = \log \frac{\Pr(y=1)}{\Pr(y=0)}$
- linear logit model:  

$$\text{logit}(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots$$

```
glm(better ~ age + treat, family=binomial, data=Arthritis)
```



20

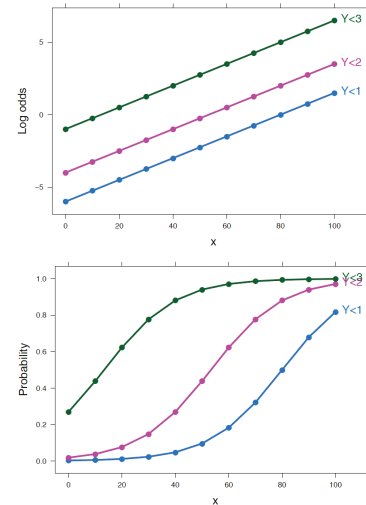
## Generalized Linear Models

### Ordinal responses

- Improved  $\in$  ("None" < "Some" < "Marked")
- Models: Proportional odds, generalized logits, ...

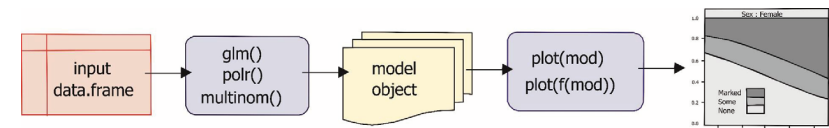
```
library(MASS)
polr(Improved ~ Sex + Treat + Age,
     data=Arthritis)

library(nnet)
multinom(Improved ~ Sex + Treat + Age,
         data=Arthritis)
```



21

## Model-based methods: Overview



- models in R are specified by a symbolic model formula, applied to a data.frame
  - `mod<-lm(prestige ~ income + educ, data=Prestige)`
  - `mod<-glm(better ~ age + sex + treat, data=Arthritis, family=binomial)`
  - `mod<-MASS:polr(improved ~ age + sex + treat, data=Arthritis)`
- result (`mod`) is a "model object", of class "`lm`", "`glm`", ...
- method functions:
  - `plot(mod)`, `plot(f(mod))`, ...
  - `summary(mod)`, `coef(mod)`, `predict(mod)`, ...

22

## Plots for linear models

- Data plots:
  - plot response ( $y$ ) vs. predictors, with smooth summaries
  - scatterplot matrix --- all pairs
- Model (effect) plots
  - plot predicted response ( $\hat{y}$ ) vs. predictors, **controlling** for variables not shown.
- Diagnostic plots
  - Influence plots: leverage & outliers
  - Spread-level plots (non-constant variance?)

23

## R packages

- car**
  - Enhanced scatterplots
  - Diagnostic plots
- effects**
  - Plot fitted effects of one predictor, controlling all others
- visreg**
  - similar to effect plots, simpler syntax
- Both **effects** & **visreg** handle nearly all formula-based models
  - `lm()`, `glm()`, `gam()`, `rlm`, `nlme()`, ...

24



## Occupational Prestige data

- Data on prestige of 102 occupations and
  - average education (years)
  - average income (\$)
  - % women
  - type (Blue Collar, Professional, White Collar)

```
> car::some(Prestige, 6)
```

|                    | education | income | women | prestige | census | type |
|--------------------|-----------|--------|-------|----------|--------|------|
| architects         | 15.44     | 14163  | 2.69  | 78.1     | 2141   | prof |
| physicians         | 15.96     | 25308  | 10.56 | 87.2     | 3111   | prof |
| commercial.artists | 11.09     | 6197   | 21.03 | 57.2     | 3314   | prof |
| tellers.cashiers   | 10.64     | 2448   | 91.76 | 42.3     | 4133   | wc   |
| bakers             | 7.54      | 4199   | 33.30 | 38.9     | 8213   | bc   |
| aircraft.workers   | 8.78      | 6573   | 5.78  | 43.7     | 8515   | bc   |

25

## Informative scatterplots

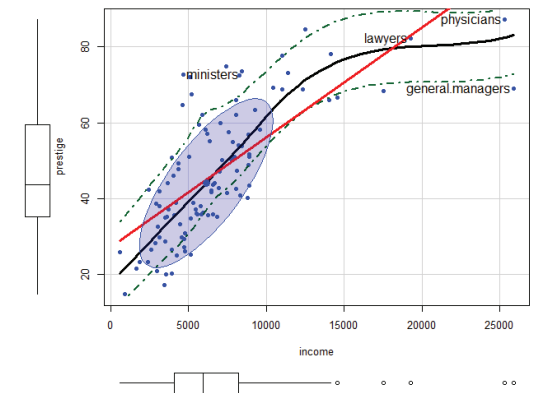
Scatterplots are most useful when enhanced with annotations & statistical summaries

Data ellipse and regression line show the linear model,  $\text{prestige} \sim \text{income}$

Point labels show possible outliers

Smoothed (loess) curve and CI show the trend

Boxplots show marginal distributions



26

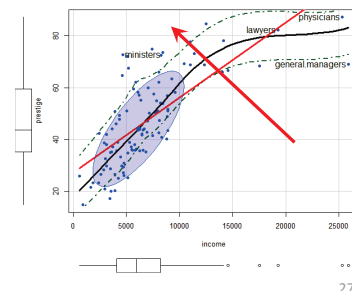
## Informative scatterplots

`car::scatterplot()` provides all these enhancements

```
scatterplot(prestige ~ income, data=Prestige,
  pch = 16,
  regLine = list(col = "red", lwd=3),
  smooth = list(smoother=loessLine,
    lty.smooth = 1, col.smooth = "black",
    lwd.smooth=3, col.var = "darkgreen"),
  ellipse = list(levels = 0.68),
  id = list(n=4, col="black", cex=1.2))
```

Skewed distribution of income & non-linear relation suggest need for a transformation

**Arrow rule:** move on the scale of powers in direction of the bulge  
e.g.:  $x \rightarrow \sqrt{x}$  or  $\log(x)$



27

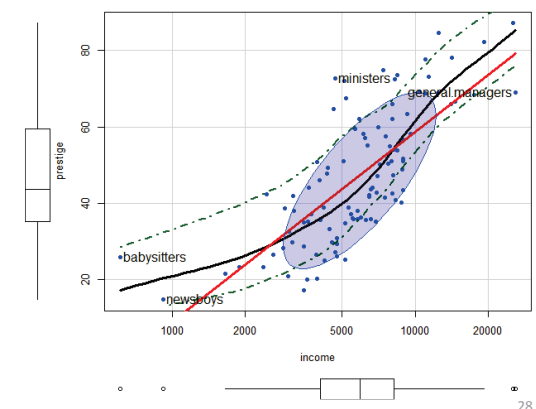
## Try log(income)

```
scatterplot(prestige ~ income, data=Prestige,
  log = "x",
  pch = 16,
  regLine = list(col = "red", lwd=3),
  ...)
```

Income now ~ symmetric

Relation closer to linear

$\log(\text{income})$ : interpret as effect of a multiple



28

## Stratify by type?

```
scatterplot

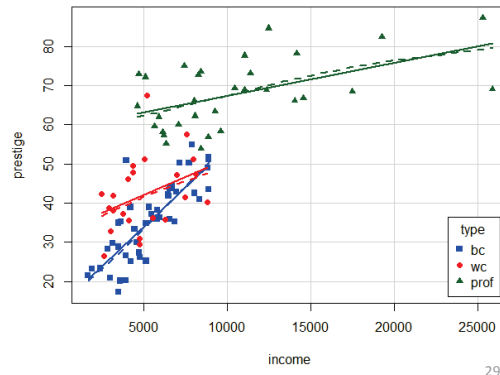
```

Formula: | **type** → "given type"

Different slopes: **interaction** of income \* type

Provides another explanation of the non-linear relation

This may be a new finding!



## Scatterplot matrix

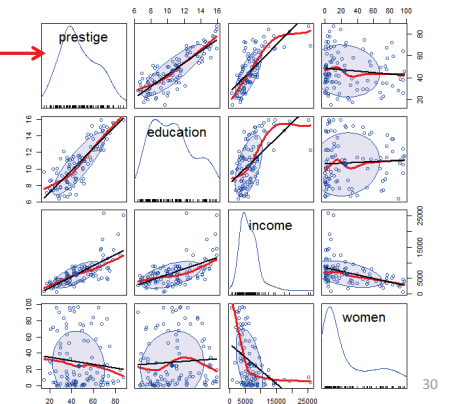
```
scatterplotMatrix(~ prestige + education + income + women ,
  data=Prestige,
  regLine = list(method=lm, lty=1, lwd=2, col="black"),
  smooth=list(smoother=loessLine, spread=FALSE,
    lty.smooth=1, lwd.smooth=3, col.smooth="red"),
  ellipse=list(levels=0.68, fill.alpha=0.1))
```

prestige vs. all predictors

diagonal: univariate distributions

- income: + skewed
- %women: bimodal

off-diagonal: relations among predictors



## Fit a model

```
> mod1 <- lm

• allow women2 term



• interaction of log(income) and type


```

```
> summary(mod1)
```

Coefficients:

|                      | Estimate | Std. Error | t value | Pr(> t )    |
|----------------------|----------|------------|---------|-------------|
| (Intercept)          | -137.500 | 23.522     | -5.85   | 8.2e-08 *** |
| education            | 2.959    | 0.582      | 5.09    | 2.0e-06 *** |
| poly(women, 2)1      | 28.339   | 10.190     | 2.78    | 0.0066 **   |
| poly(women, 2)2      | 12.566   | 7.095      | 1.77    | 0.0800 .    |
| log(income)          | 17.514   | 2.916      | 6.01    | 4.1e-08 *** |
| typeprof             | 74.276   | 30.736     | 2.42    | 0.0177 **   |
| typewc               | 0.969    | 39.495     | 0.02    | 0.9805      |
| log(income):typeprof | -7.698   | 3.451      | -2.23   | 0.0282 *    |
| log(income):typewc   | -0.466   | 4.620      | -0.10   | 0.9199      |

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

Multiple R-squared: **0.879** Adjusted R-squared: 0.868

F-statistic: 81.1 on 8 and 89 DF, p-value: <2e-16

• Fits very well!

But how to understand?

## Model (effect) plots

- We'd like to see plots of the predicted value ( $\hat{y}$ ) of the response against predictors ( $x_j$ )
  - Ordinary plot of  $y$  vs.  $x_j$  doesn't allow for other correlations
  - → Must **control** (adjust) for other predictors ( $x_{-j}$ ) not shown in a given plot
- Effect plots
  - Variables not shown ( $x_{-j}$ ) are averaged over.
  - Slopes of lines reflect the **partial** coefficient in the model
  - Partial residuals can be shown also

For details, see `vignette("predictor-effects-gallery", package="effects")`

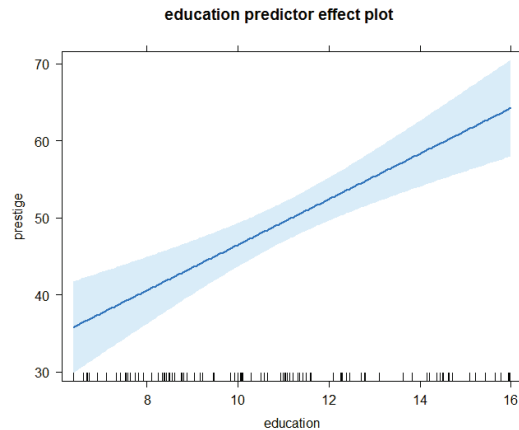


## Model (effect) plots: education

```
library("effects")
mod1.e1 <- predictorEffect("education", mod1)
plot(mod1.e1)
```

This graph shows the **partial** slope for education

For each  $\uparrow$  year in education, fitted prestige  $\uparrow$ 2.96 points, (other predictors held fixed)

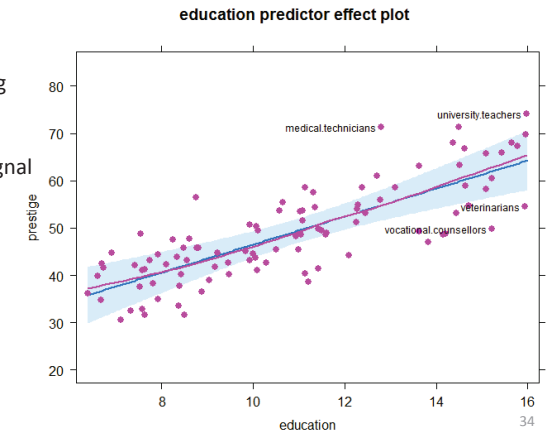


## Model (effect) plots

```
mod1.e1a <- predictorEffect("education", mod1, residuals=TRUE)
plot(mod1.e1a,
     residuals.pch=16, id=list(n=4, col="black"))
```

Partial residuals show the residual of prestige controlling for other predictors

Unusual points here would signal undue influence



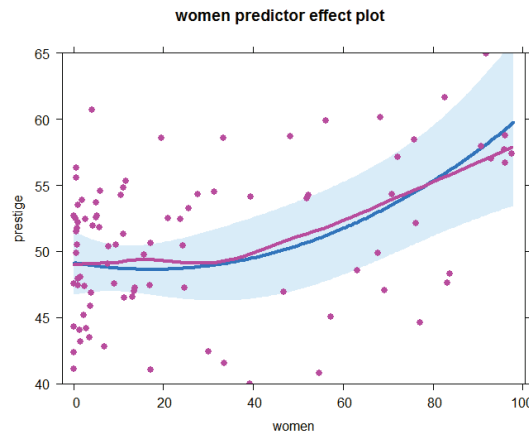
## Model (effect) plots: women

```
mod1.e2 <- predictorEffect("women", mod1, residuals=TRUE)
plot(mod1.e2, ylim=c(40, 65), lwd=4,
     residuals.pch=16)
```

Surprise!

Prestige of occupations  $\uparrow$  with % women (controlling for other variables)

I allowed a quadratic term in % women.  
Does this make sense?

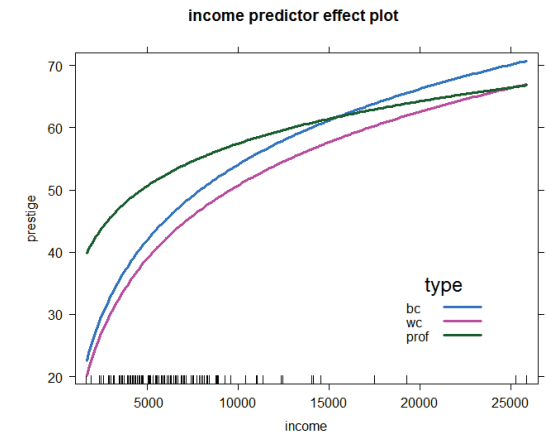


## Model (effect) plots: income

```
plot(predictorEffect("income", mod1),
     lines=list(multiline=TRUE, lwd=3),
     key.args = list(x=.7, y=.35))
```

Income interacts with type in the model

The plot is curved because  $\log(\text{income})$  is in the model



## visreg plots: Air quality data

Daily air quality measurements in New York, May - Sep 1973

How does Ozone concentration vary with solar radiation, wind speed & temperature?

```
> head(airquality)
  Ozone Solar.R Wind Temp Month Day
1    41    190   7.4   67     5    1
2    36    118   8.0   72     5    2
3    12    149  12.6   74     5    3
4    18    313  11.5   62     5    4
5     NA     NA  14.3   56     5    5
6    28     NA  14.9   66     5    6
```

see: <https://pbreheny.github.io/visreg/> for examples & details

37

## Air quality: main effects model

```
> fit1 <- lm(Ozone ~ Solar.R + Wind + Temp, data=airquality)
> summary(fit1)
```

Coefficients:

|                | Estimate | Std. Error | t value  | Pr(> t ) |           |
|----------------|----------|------------|----------|----------|-----------|
| (Intercept)    | -64.3421 | 23.0547    | -2.79    | 0.0062   | **        |
| Solar.R        | 0.0598   | 0.0232     | 2.58     | 0.0112   | *         |
| Wind           | -3.3336  | 0.6544     | -5.09    | 1.5e-06  | ***       |
| Temp           | 1.6521   | 0.2535     | 6.52     | 2.4e-09  | ***       |
| ---            |          |            |          |          |           |
| Signif. codes: | 0 '***'  | 0.001 '**' | 0.01 '*' | 0.05 '.' | 0.1 ' ' 1 |

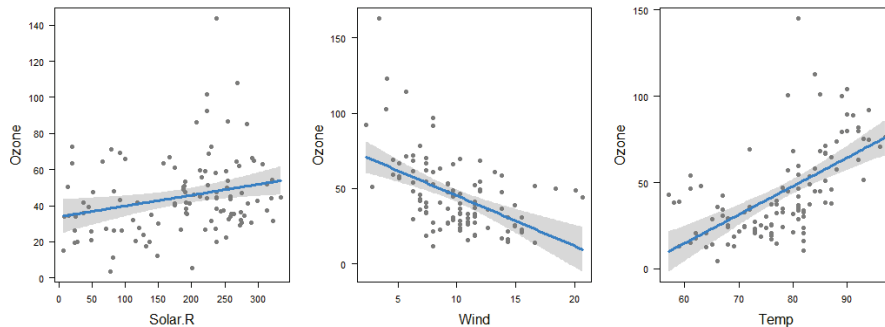
Residual standard error: 21.18 on 107 degrees of freedom  
(42 observations deleted due to missingness)  
Multiple R-squared: 0.6059, Adjusted R-squared: 0.5948  
F-statistic: 54.83 on 3 and 107 DF, p-value: < 2.2e-16

38

## visreg conditional plots

```
visreg(fit1, "Solar.R")
visreg(fit1, "Wind")
visreg(fit1, "Temp")
```

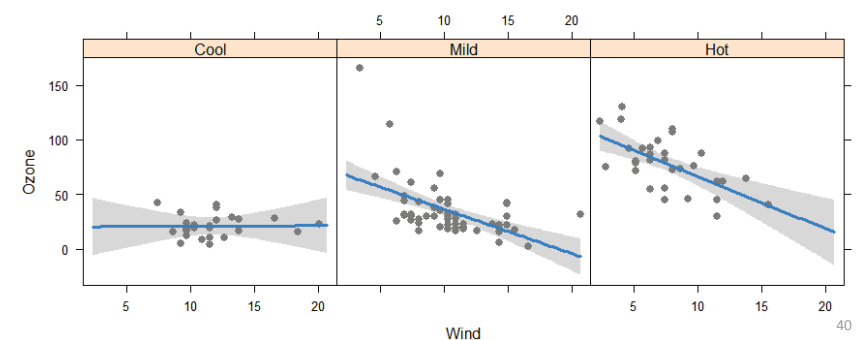
model summary =  
predicted values (line) +  
confidence band (uncertainty) +  
partial residuals (objections)



## Factor variables & interactions

```
# cut Temp into three ordered levels of equal range
airquality$Heat <- cut(airquality$Temp, 3,
  labels=c("Cool", "Mild", "Hot"))
```

```
# fit model with interaction of Wind * Heat
fit2 <- lm(Ozone ~ Solar.R + Wind*Heat, data=airquality)
visreg(fit2, "Wind", by="Heat", layout=c(3,1), points=list(cex=1))
```



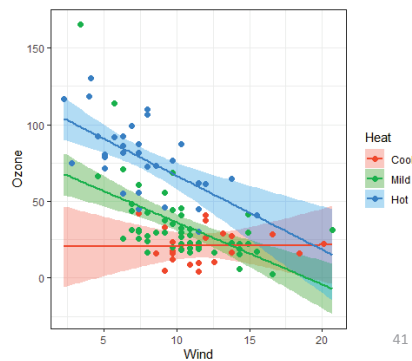
## Factor variables & interactions

```
visreg(fit2, "wind", by="Heat",
      overlay=TRUE,
      gg=TRUE,
      points=list(size=2)) +
  theme_bw()
```

`overlay=TRUE` → superpose panels  
`gg=TRUE` → uses ggplot

This allow slope for Wind to vary with Heat e.g., Wind has no effect when Cool

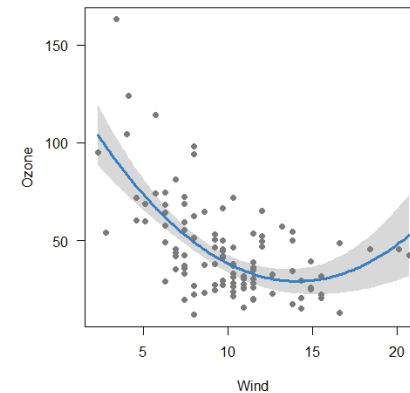
This model still assumes **linear** effects of Heat & Wind



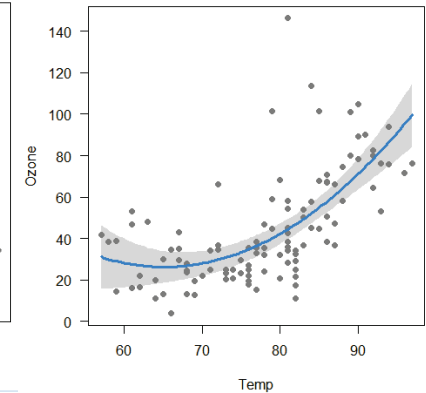
41

## Non-linear effects

```
fit <- lm(Ozone ~ Solar.R + poly(Wind,2) +
  Temp, data=airquality)
visreg(fit, "Wind")
```



```
fit <- lm(Ozone ~ Solar.R + Wind +
  poly(Temp,2), data=airquality)
visreg(fit, "Temp")
```

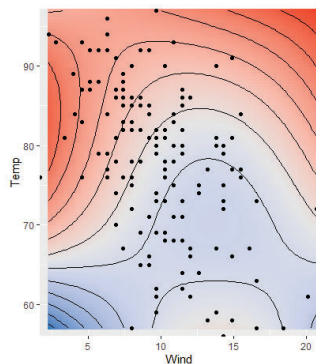


42

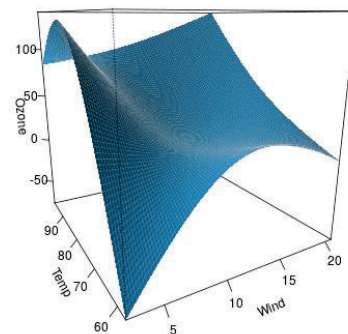
## Response surface models (visreg2d)

```
# Fit quadratics in both Wind & Temp and interaction Wind * Temp
fitp <- lm(Ozone ~ Solar.R + poly(Wind,2) * poly(Temp,2), data=airquality)
```

```
visreg2d(fitp, "Wind", "Temp", plot.type="gg") +
  geom_contour(aes(z=z), color="black")
```



```
visreg2d(fitp, "Wind", "Temp", plot.type="persp")
```

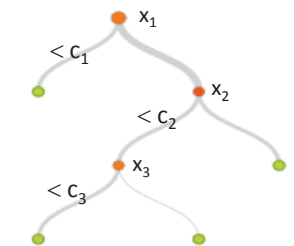


43

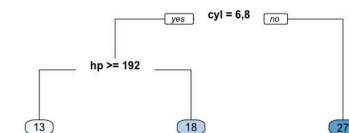
## Regression trees

Regression trees are a non-parametric alternative to linear models

- Essential ideas:
  - Find predictor and split value which minimizes SSE
  - fitted value in each subgroup = mean
  - repeat, recursively, splitting by next best predictor
- Large literature
  - cost, complexity tradeoff
  - pruning methods
  - boosting, cross-validation
  - tree averaging



e.g.:  $\text{mpg} \sim \text{cyl} + \text{hp}$



44

## Prestige data: rpart tree

```
> library(rpart)      # calculating regression trees
> library(rpart.plot)  # plotting regression trees

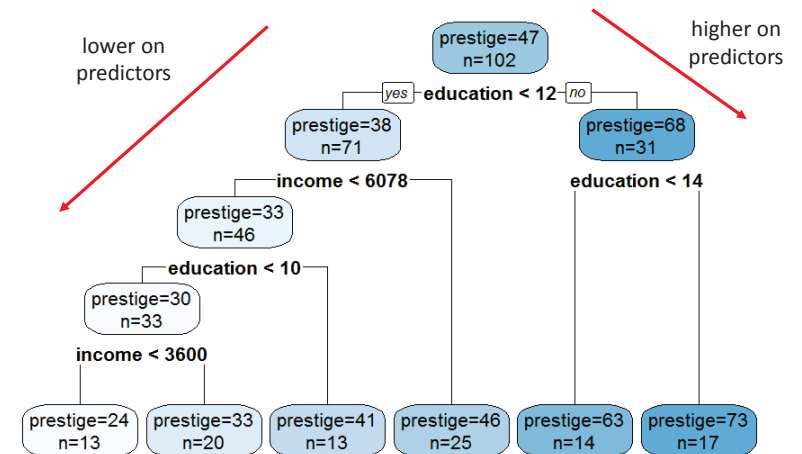
> rmod <- rpart(prestige ~ education + income + women + type,
  data=Prestige,
  method = "anova")

> rpart.rules(rmod)    # print prediction rules
prestige
24 when education < 10      & income < 3600
33 when education < 10      & income is 3600 to 6078
41 when education is 10 to 12 & income < 6078
46 when education < 12      & income >= 6078
63 when education is 12 to 14
73 when education >= 14
```

45

## Prestige data: rpart tree

```
rpart.plot(rmod, prefix="prestige=")
```



46

## Diagnostic plots

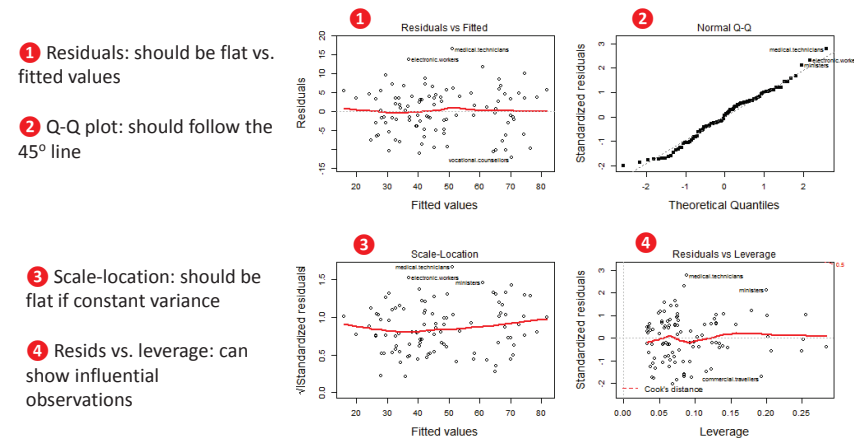
- The linear model,  $y = X\beta + \epsilon$  assumes:
  - Residuals,  $\epsilon_i$  are normally distributed,  $\epsilon_i \sim N(0, \sigma^2)$
  - (Normality not required for  $X$ s)
  - Constant variance,  $\text{Var}(\epsilon_i) = \sigma^2$
  - Observations  $y_i$  are statistically independent
- Violations  $\rightarrow$  inferences may not be valid
- A variety of plots can diagnose all these problems
- Other methods (boxCox, boxTidwell) diagnose the need for transformations of  $y$  or  $X$ s.

47

## The “regression quartet”

In R, plotting a `lm` model object  $\rightarrow$  the “regression quartet” of plots

```
plot(mod1, lwd=2, cex.lab=1.4)
```

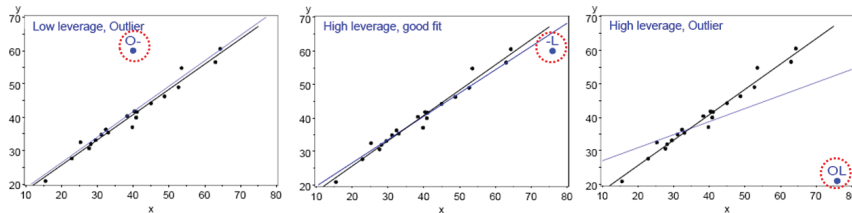


48

## Unusual data: Leverage & Influence

- “Unusual” observations can have dramatic effects on least-squares estimates in linear models
- Three archetypal cases:
  - Typical X (low leverage), bad fit -- Not much harm
  - Unusual X (high leverage), good fit -- Not much harm
  - Unusual X (high leverage), bad fit -- **BAD, BAD, BAD**
- Influential observations: unusual in *both* X & Y
- Heuristic formula:

$$\text{Influence} = \text{X leverage} \times \text{Y residual}$$



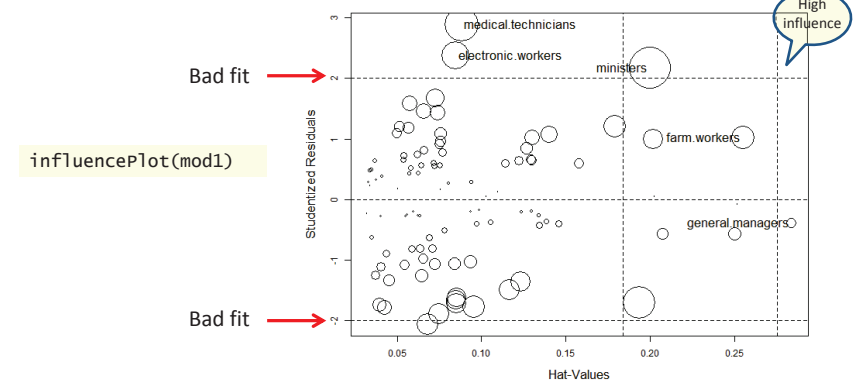
49

## Influence plots

Influence (Cook's D) measures impact of individual obs. on coefficients, fitted values

$$\text{Influence} \sim \text{Residual } (y - \hat{y}) \times \text{Hat-value } (\mathbf{X} - \bar{\mathbf{X}})^2$$

Bubble size  $\sim$  influence



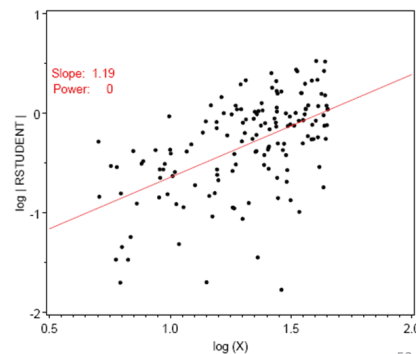
50

## Spread-level plots

- To diagnose non-constant variance, plot:
  - $\log |\text{Std. residual}|$  vs.  $\log(x)$
  - $\log(\text{IQR})$  vs  $\log(\text{median})$  [for grouped data]
- If  $\approx$  linear w/ slope  $b$ , transform  $y \rightarrow y^{(1-b)}$

Artificial data, generated so  $\sigma \sim x$

- $b \approx 1 \rightarrow \text{power} = 0$
- $\rightarrow \text{analyze } \log(y)$



52

## Spread-level plot: baseball data

Data on salary and batter performance from 1987 season

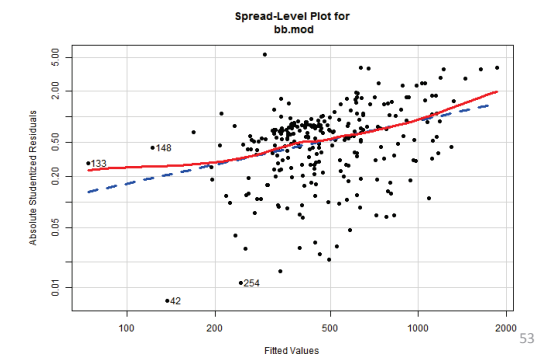
```
data("Baseball", package="vcd")
bb.mod <- lm(sal187 ~ years + hits + runs + homeruns, data=Baseball)
spreadLevelPlot(bb.mod, pch=16, lwd=3,
                id=list(n=2))
```

## Suggested power transformation: 0.2609

slope = .74  $\rightarrow$   $p = .26$

i.e.,  $y \rightarrow \log(y)$  or  $y^{1/4}$

NB: both axes plotted on log scale



53

## Box Cox transformation

- Box & Cox proposed to transform  $y$  to a power,  $y \rightarrow y^{(\lambda)}$  to minimize the residual SS (or maximize the likelihood)
  - Makes  $y^{(\lambda)}$  more nearly normal
  - Makes  $y^{(\lambda)}$  more nearly linear in with  $X$

Formula for  $y^{(\lambda)}$

- $y^{(0)} : \log_e(y)$
- $\lambda < 0$ : flip sign to keep same order

$$y_i^{(\lambda)} = \begin{cases} \frac{y_i^\lambda - 1}{\lambda} & \text{if } \lambda \neq 0, \\ \ln(y_i) & \text{if } \lambda = 0, \end{cases}$$

| Power(p)       | Transformation             | Name              |
|----------------|----------------------------|-------------------|
| 2              | $Y^2$                      | Square            |
| 1              | $Y$ (No transformation)    | Original Data     |
| $\frac{1}{2}$  | $\sqrt{Y}$                 | Square root       |
| $0^+$          | $\log Y$ or $\log_{10}(Y)$ | Logarithm         |
| $-\frac{1}{2}$ | $-1/\sqrt{Y}$              | Reciprocal Root   |
| -1             | $-1/Y$                     | Reciprocal        |
| -2             | $-1/Y^2$                   | Reciprocal Square |

54

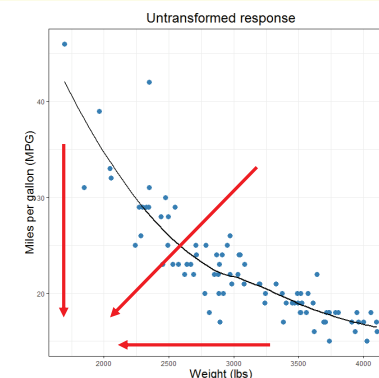
## Example: Cars93 data

How does gas mileage (MPG.city) depend on vehicle weight?

```
> cars.mod <- lm(MPG.city ~ weight, Cars93)
> coef(cars.mod)
(Intercept)      weight 
  47.04835      -0.00803
```

Relationship clearly non-linear

**Tukey arrow rule:** transform  $Y$  (or  $X$ )  
as arrow thru the curve bulges  
 $y \rightarrow \sqrt{y}, \log(y), 1/y$   
 $x \rightarrow \sqrt{x}, \log(x), 1/x$

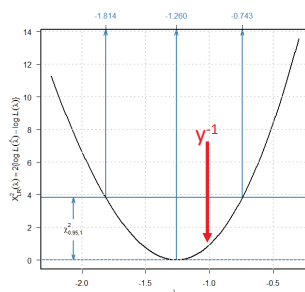


55

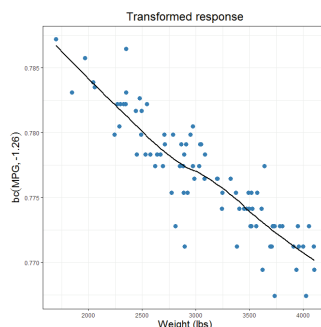
## MASSextra package

```
> library(MASSextra)
> box_cox(cars.mod) # plot log likelihood vs. lambda
> lambda(cars.mod)
[1] -1.26
```

The plot of  $-\log(L) \sim \text{RSS}$  shows the minimum & CI



plot(bc(MPG.city, lambda(cars.mod)))



56

## Summary

- Tables are for look-up; graphs can give insight
- “Linear” models include so much more than ANOVA & regression
- Data plots are more effective when enhanced
  - data ellipses  $\rightarrow$  strength & precision of correlation
  - regression lines and smoothed curves
  - point identification  $\rightarrow$  noteworthy observations
- Effect plots show informative views of models
  - Visualize conditional effects, holding others constant
- Diagnostic plots can reveal influential observations and need for transformations.

57