

Regression: modelling

ENVX2001 Applied Statistical Methods

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Welcome to regression modelling!

About me

- Research topics: spatial modelling and mapping, precision agriculture, winter grains
- Timeline at USYD
 - BSc (Hons) in Agricultural Science
 - PhD in Digital Agriculture
 - Postdoc in Spatial Modelling
 - Associate Lecturer in Agricultural Data Science



Figure 1: Faba beans at Trangie

Learning Outcomes

LO1. demonstrate proficiency in designing sample schemes and analysing data from them using using R

LO2. describe and identify the basic features of an experimental design; replicate, treatment structure and blocking structure

LO3. demonstrate proficiency in the use or the statistical programming language R to an ANOVA and fit regression models to experimental data

LO4. demonstrate proficiency in the use or the statistical programming language R to use multivariate methods to find patterns in data

LO5. interpret the output and understand conceptually how its derived of a regression, ANOVA and multivariate analysis that have been calculated by R

LO6. write statistical and modelling results as part of a scientific report

LO7. appraise the validity of statistical analyses used publications.

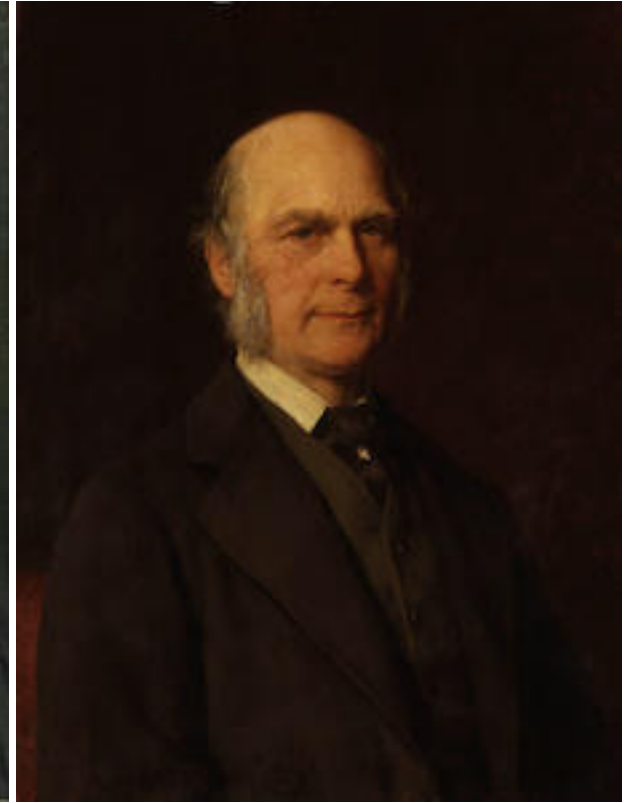
Refresher from ENVX1002

- Regression modelling is for one *continuous numerical* response (y) and one or more *numerical* predictors (x_1, x_2, x_n)
- Can be for linear or nonlinear relationships – focus on linear in ENVX2001
- To help us:
 - Understand the relationship between variables
 - Predict new values of y based on x
 - Test hypotheses about the relationship between variables
- Fit a ‘line of best fit’ that minimises the sum of the squared residuals (least-squares)

Workflow

1. Model development
 - Explore: visualise, summarise
 - Model: fit, check assumptions, interpret – (transform, repeat).
 - Transform predictors
2. Variable selection
 - VIF: remove predictors with high variance inflation factor
 - Model selection: stepwise selection, AIC, principle of parsimony, assumption checks
3. Predictive modelling
 - Predict: Use the model to predict new data
 - Validate: Evaluate the model's performance

Brief history



Adrien-Marie Legendre, Carl Friedrich Gauss, Francis Galton

i Note

Many other people contributed to the development of regression analysis, but these three are the most well-known.

Brief history

- **Method of least squares** first theorised by Adrien-Marie Legendre in 1805
- **Technique of least squares** first used by Carl Friedrich Gauss in 1809 (to fit a parabola to the orbit of the asteroid Ceres)
- **Model fitting** first published by Francis Galton in 1886 (predicting the height of a child from the height of the parents)

Simple linear regression

■ An example with Galton's data: parent and child heights.

Example: child vs parent height

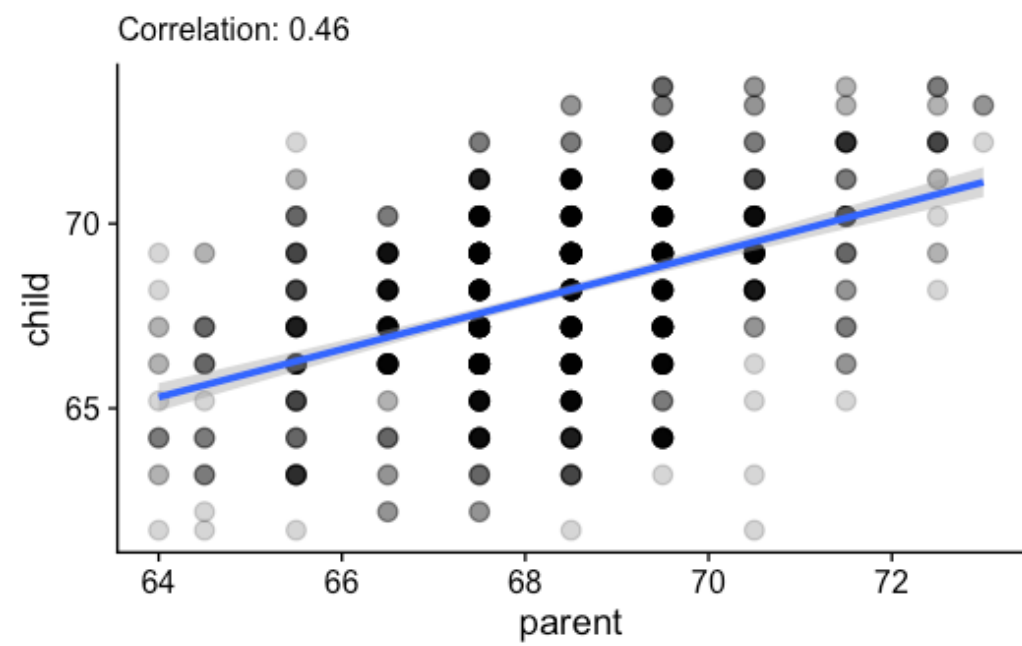
Galton, F. (1886). *Regression Towards Mediocrity in Hereditary Stature* *Journal of the Anthropological Institute*, 15, 246-263

```
library(HistData)
data(Galton)
str(Galton)
```

```
'data.frame':  928 obs. of  2 variables:
 $ parent: num  70.5 68.5 65.5 64.5 64 67.5 67.5
67.5 66.5 66.5 ...
 $ child : num  61.7 61.7 61.7 61.7 61.7 62.2
62.2 62.2 62.2 62.2 ...
```

```
ggplot(Galton, aes(x = parent, y = child)) +
  geom_point(alpha = .2, size = 3) +
  geom_smooth(method = "lm") +
  labs(subtitle = paste("Correlation:",
round(cor(Galton$parent, Galton$child), 2)))
```

- 928 children of 205 pairs of parents
- Average height of both parents and their child's height measured in inches
- Size classes were binned (hence data looks discrete)



Defining a linear relationship

- Pearson correlation coefficient (r) measures the linear correlation between two variables (ranges from -1 to 1)
- Useful for distinguishing *strength* (weak/moderate/strong) and *direction* (positive/negative) of the association
- Does not distinguish different *patterns* – i.e. is the relationship actually linear?

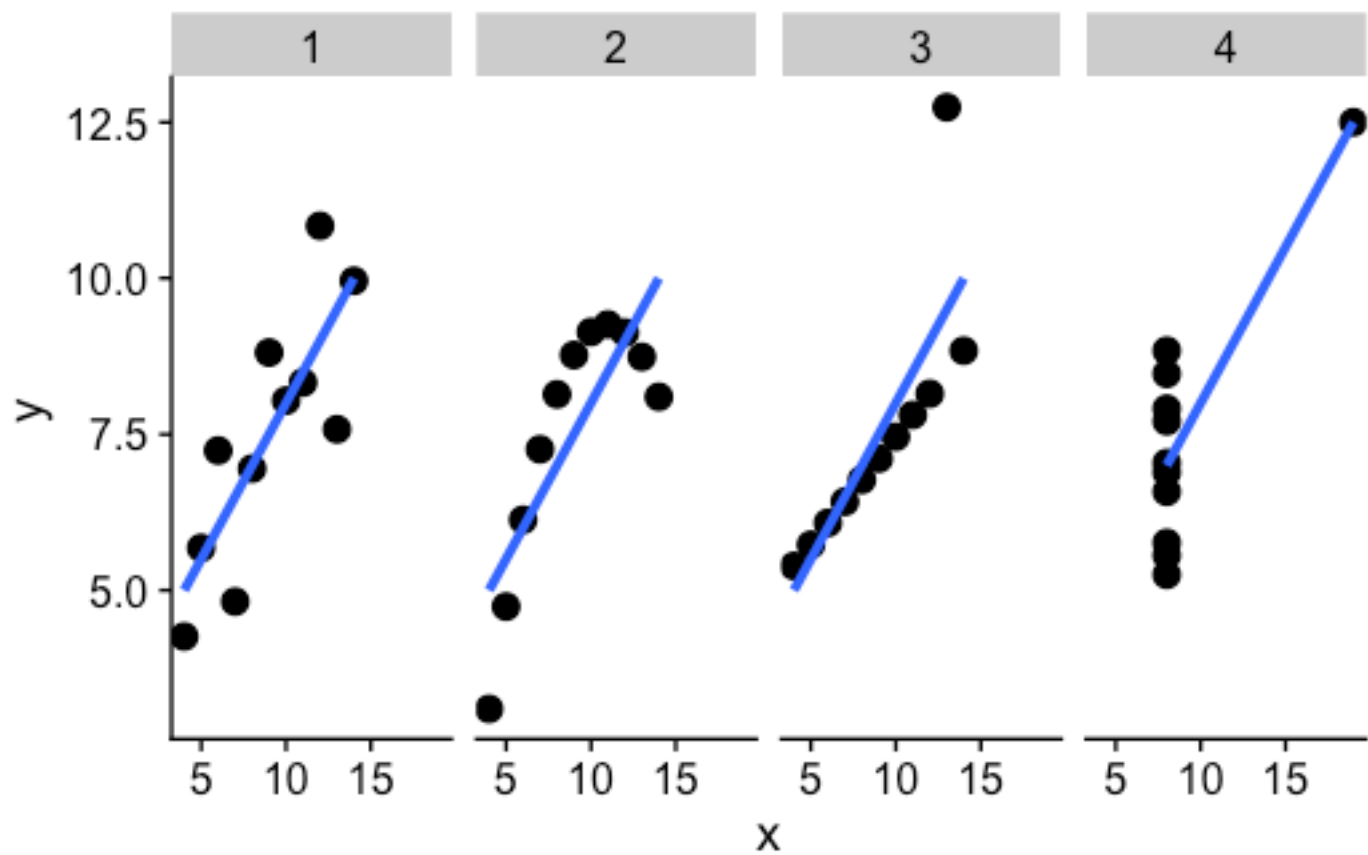
$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}}$$

```
cor(Galton$parent, Galton$child) |> round(2)
```

```
[1] 0.46
```

Anscombe's quartet

```
library(tidyverse)
anscombe %>%
  pivot_longer(everything(), cols_vary = "slowest",
    names_to = c(".value", "set"), names_pattern = "(.)(.)") %>%
  ggplot(aes(x = x, y = y)) +
    geom_point(size = 3) +
    geom_smooth(method = "lm", se = FALSE) +
    facet_wrap(~set, ncol = 4)
```



All of these data have a correlation coefficient of about 0.8 – always visualise your data.

Simple linear regression model

We want to predict a response Y based on a predictor x for i number of observations:

$$Y_i = \beta_0 + \beta_1 x_i + \epsilon_i$$

where

$$\epsilon_i \sim N(0, \sigma^2)$$

- Y_i , the *response*, is an observed value of the dependent variable.
- β_0 , the *constant*, is the population intercept and is **fixed**.
- β_1 is the population *slope* parameter, and like β_0 , is also **fixed**.
- ϵ_i is the error associated with predictions of y_i , and unlike β_0 or β_1 , it is *not fixed*.

Because ϵ_i is the only part of the equation that is not fixed, we associate it with the **residual error** (*observed — predicted*). It would also cover other aspects of error (e.g. sampling error, parallax error) but these are hard to discern.

Fitting the model

- \hat{y}_i is the predicted value of y_i :

$$\hat{y}_i = \beta_0 + \beta_1 x_i$$

- The *residual* is the difference between the observed value of the response and the predicted value:

$$\hat{\epsilon}_i = y_i - \hat{y}_i$$

- Therefore:

$$\hat{\epsilon}_i = y_i - (\beta_0 + \beta_1 x_i)$$

- We use the **method of least squares** and minimise the sum of the squared residuals (SS):

$$\sum_{i=1}^n \hat{\epsilon}_i^2 = \sum_{i=1}^n (y_i - (\beta_0 + \beta_1 x_i))^2$$

Finding the minimum SS requires solving the following problem:

$$\operatorname{argmin}_{\beta_0, \beta_1} \sum_{i=1}^n (y_i - (\beta_0 + \beta_1 x_i))^2$$

We can find β_0 and β_1 **analytically**. We first find β_1 :

$$\beta_1 = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^n (x_i - \bar{x})^2} = \frac{\operatorname{Cov}(x, y)}{\operatorname{Var}(x)} = \frac{SS_{xy}}{SS_{xx}}$$

And then substitute β_1 into the equation for β_0 :

$$\beta_0 = \bar{y} - \beta_1 \bar{x}$$

Numerical fitting

Computers use “random guesses” to find set of parameters that minimises objective function (SS) – more computationally efficient and applies beyond linear regression.

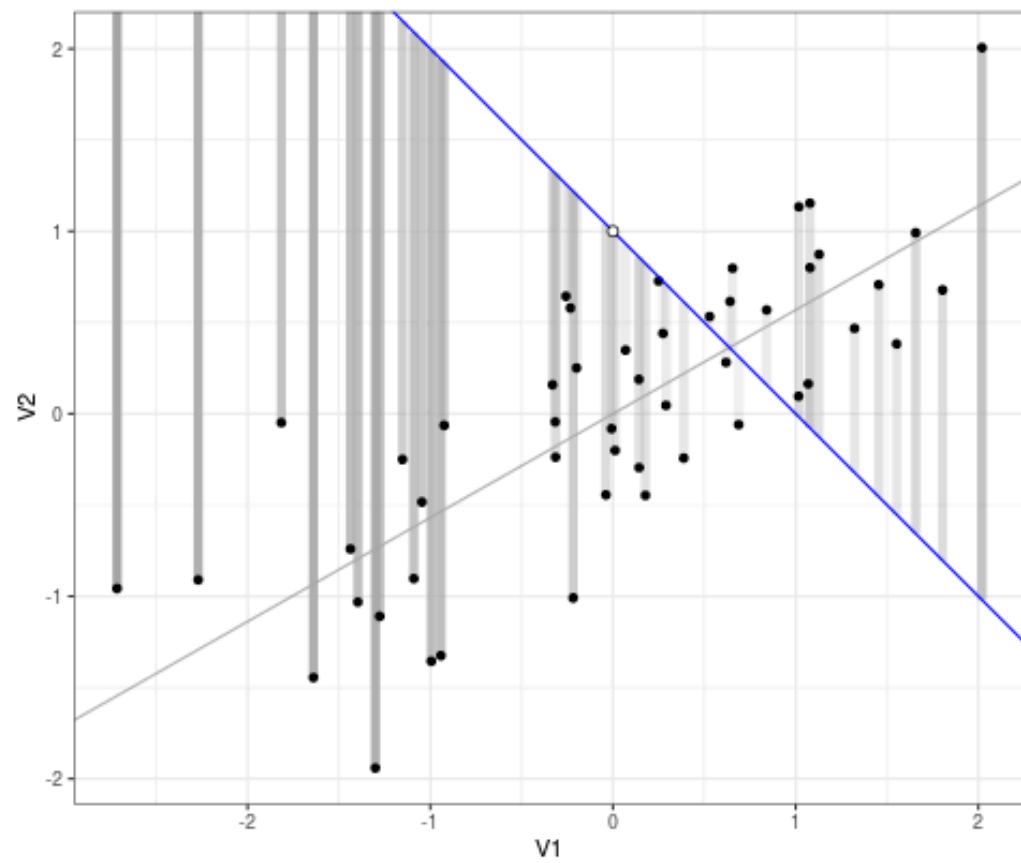


Figure 1: [source](#)

Fitting a model in R is easy with `lm()`

```
fit ← lm(child ~ parent, data = Galton)
```

That's it – the model has been fitted.

But there is a process similar to HATPC (hypothesis, assumptions, test, p-value, conclusions).

Define the hypothesis

$$H_0 : \beta_1 = 0$$

$$H_1 : \beta_1 \neq 0$$

The null model is a line with no slope (i.e. flat or horizontal) at the mean of the child height ($\bar{y} = 68$ inches).

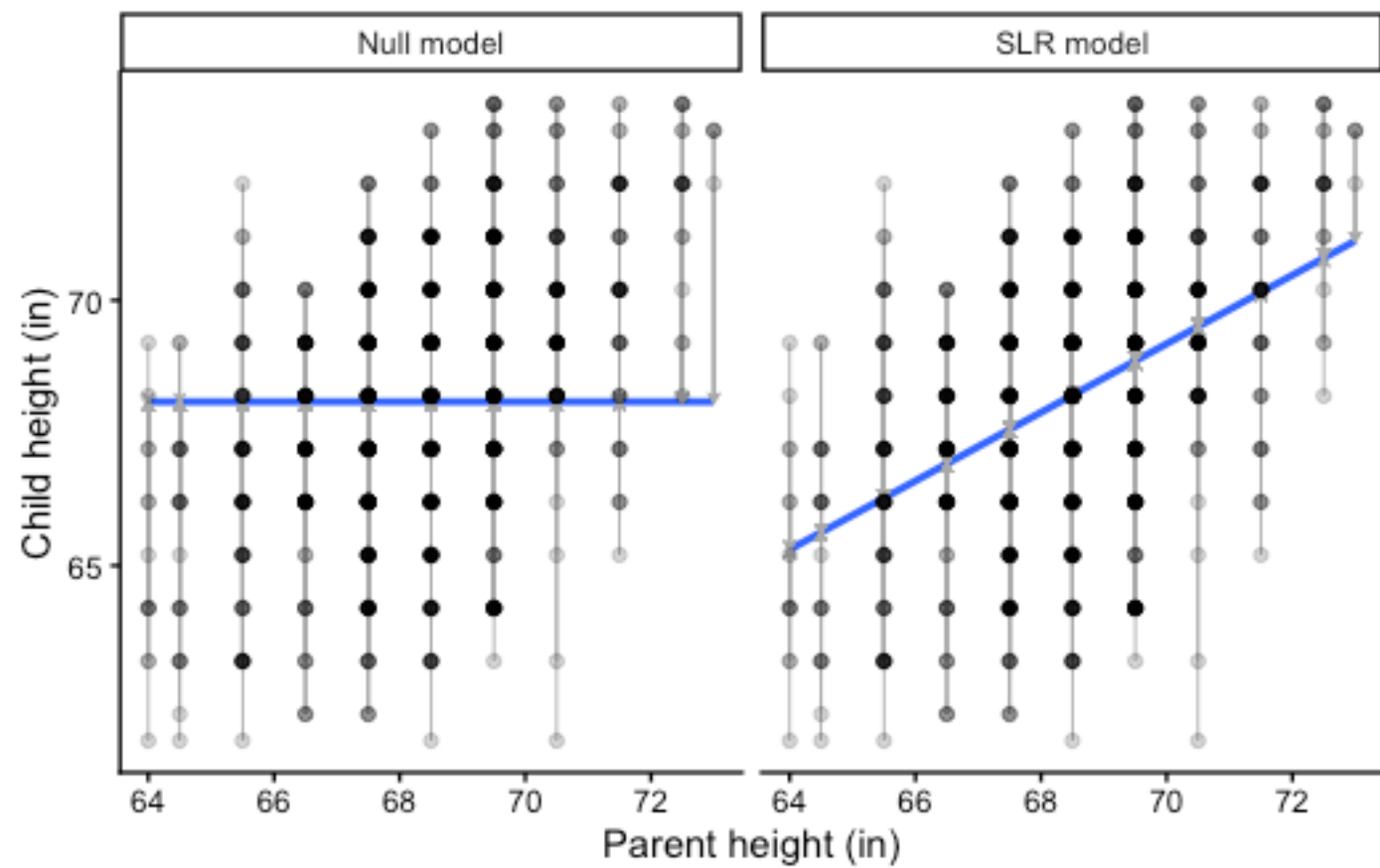
```
library(dplyr)
null_model <- Galton %>%
  lm(child ~ 1, data = .) %>%
  broom::augment(Galton)
lin_model <- Galton %>%
  lm(child ~ parent, data = .) %>%
  broom::augment(Galton)
models <- bind_rows(null_model, lin_model) %>%
  mutate(model = rep(c("Null model", "SLR model"), each = nrow(Galton)))

ggplot(data = models, aes(x = parent, y = child)) +
  geom_smooth(
    data = filter(models, model == "Null model"),
```

```

    method = "lm", se = FALSE, formula = y ~ 1, size = 1
) +
geom_smooth(
  data = filter(models, model == "SLR model"),
  method = "lm", se = FALSE, formula = y ~ x, size = 1
) +
geom_segment(
  aes(xend = parent, yend = .fitted),
  arrow = arrow(length = unit(0.1, "cm")),
  size = 0.3, color = "darkgray"
) +
geom_point(alpha = .2) +
facet_wrap(~model) +
xlab("Parent height (in)") +
ylab("Child height (in)") +
theme_classic()

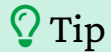
```



Assumptions

The data **must** meet certain criteria, which we often call *assumptions*. They can be remembered using **LINE**:

- **L**inearity. The relationship between y and x is linear.
- **I**ndependence. The errors ϵ are independent.
- **N**ormal. The errors ϵ are normally distributed.
- **E**qual Variance. At each value of x , the variance of y is the same i.e. homoskedasticity, or constant variance.



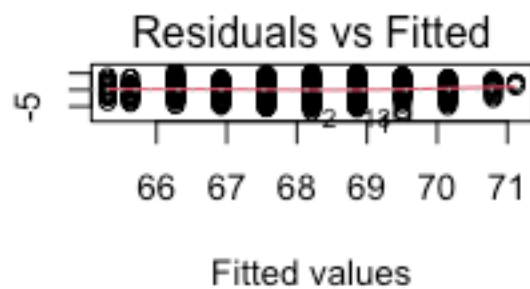
Tip

All but the independence assumption can be assessed using diagnostic plots.

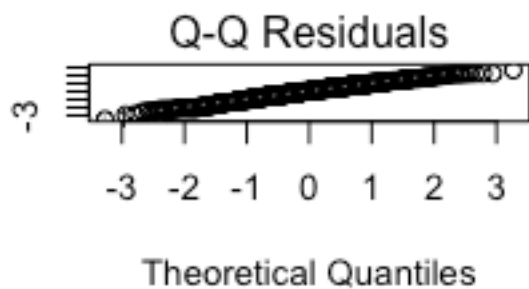
Assumptions with base R `plot()`

```
par(mfrow= c(2, 2)) # plots combined into 2x2 grid  
plot(fit)
```

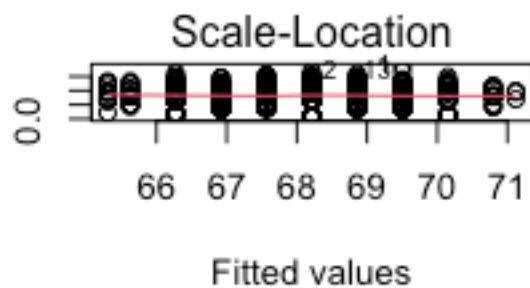
Residuals



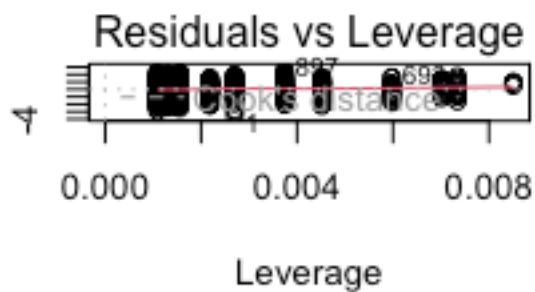
Standardized residuals



$\sqrt{|\text{Standardized residuals}|}$

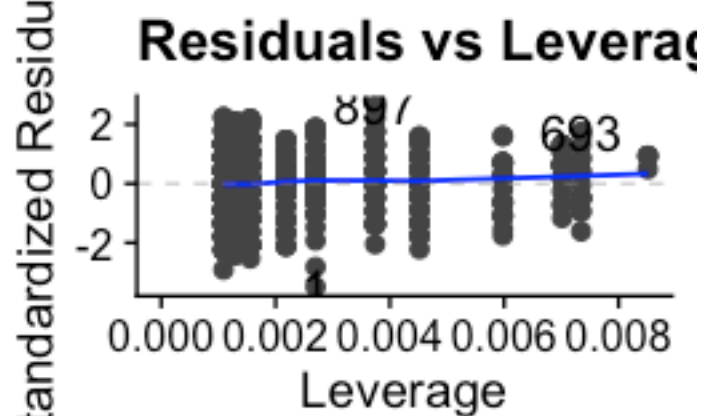
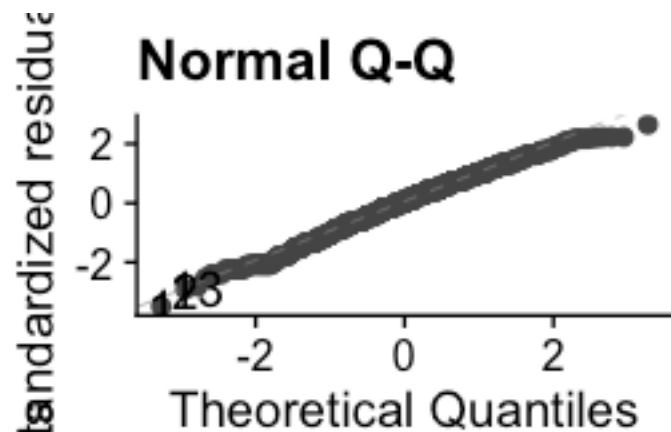
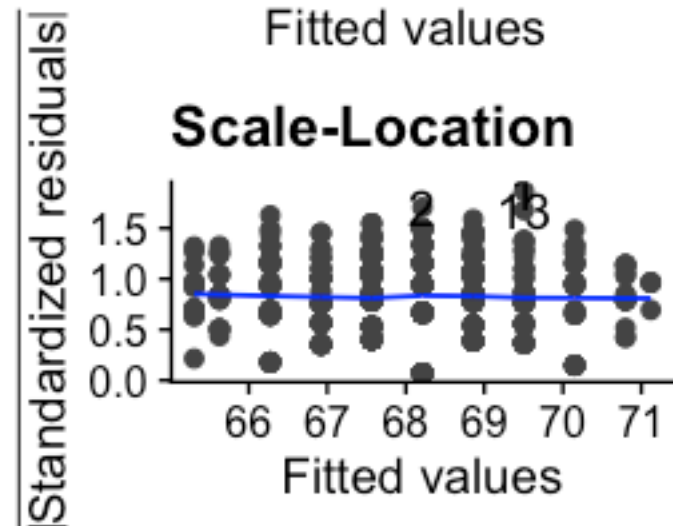
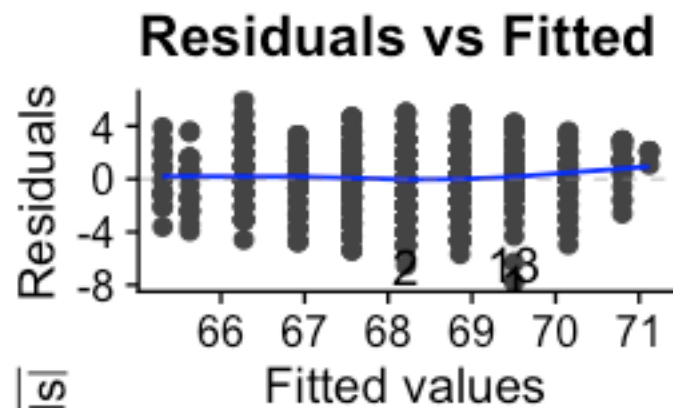


Standardized residuals



Assumptions with `ggfortify` package and `autoplot()`

```
library(ggfortify)  
autoplot(fit)
```



Assumptions using performance

(Also provides a guide on what to check for in the assumption plot)

```
library(performance)
performance::check_model(fit) # check all assumptions
performance::check_model(fit, check = c("linearity", "qq", "homogeneity", "outliers")) # check
specific assumptions
```

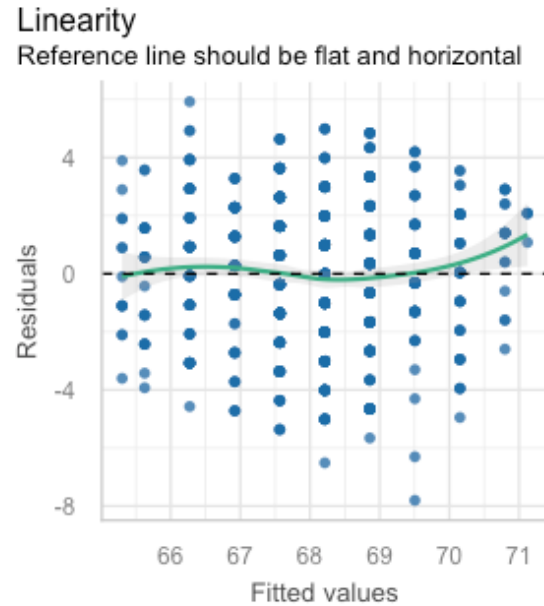
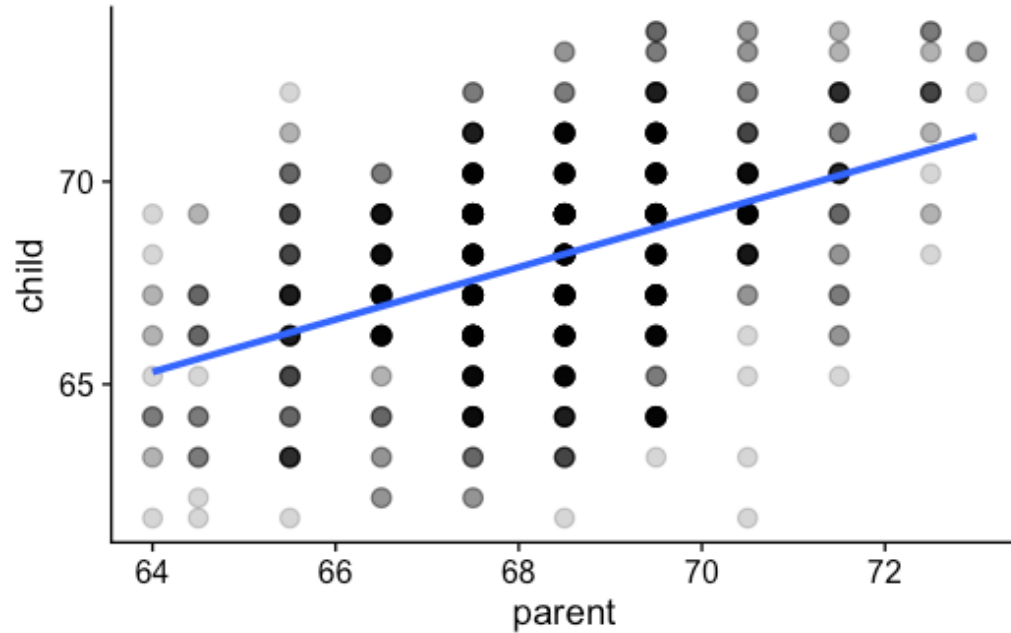
Assumption: Linearity

Prior knowledge and visual inspection comes into play. Does the relationship look approximately linear?

```
ggplot(Galton, aes(x = parent, y = child)) +  
  geom_point(alpha = .2, size = 3) +  
  geom_smooth(method = "lm", se = FALSE)
```

The linearity assumption can be checked again by looking at a plot of the residuals against x (i.e. `parent` height).

```
performance::check_model(fit, check =  
  "linearity")
```



- Where the green reference line is > 0 , the model *underestimates*, and where it is < 0 , it *overestimates*.
- If the linearity assumption is **violated**, we should not be fitting a linear model – transform or use a nonlinear model.

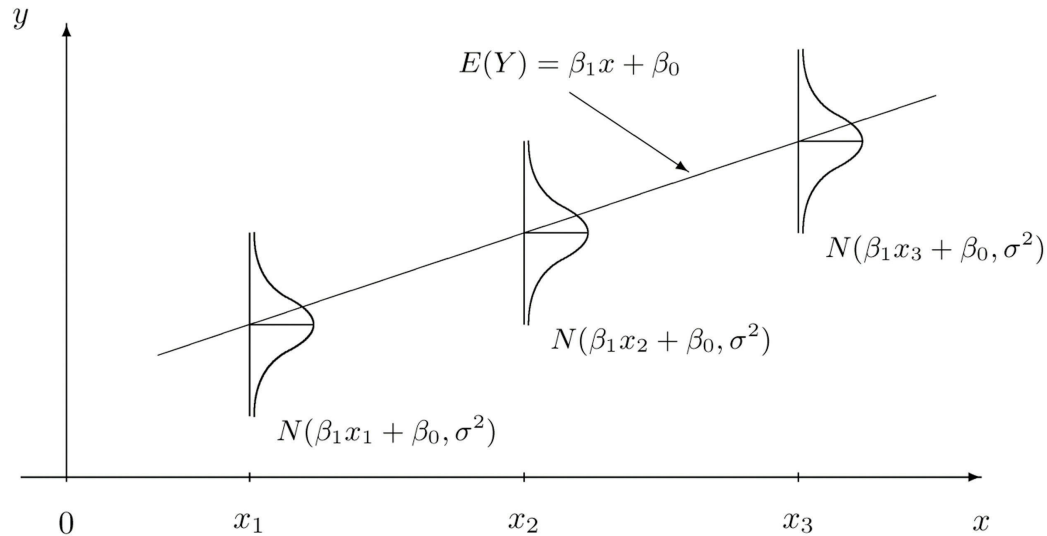
Assumption: Independence

This assumption is addressed during experimental design, but issues like correlation between errors and patterns occurring due to time are possible if:

- Observations of the same subject are related i.e. **multicollinearity**
- Time-series data, if the same subjects are sampled i.e. **autocorrelation**

Assumption: Normality

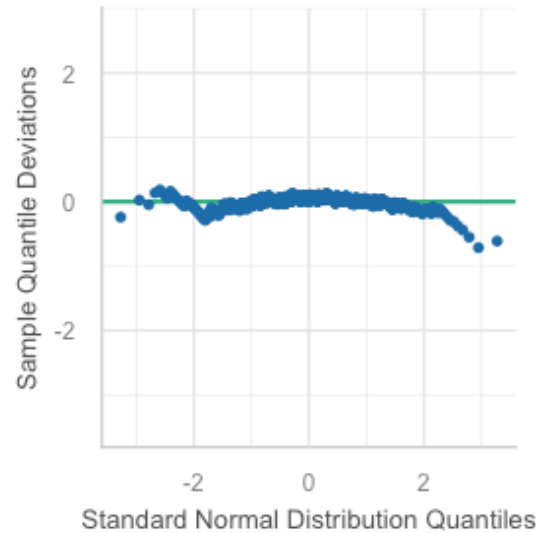
For a given value of x , the residuals should be normally distributed. In a scatterplot of x and y , the points would appear evenly distributed (linear and no fanning).



```
performance::check_model(fit, check =  
c("normality", "qq"))
```

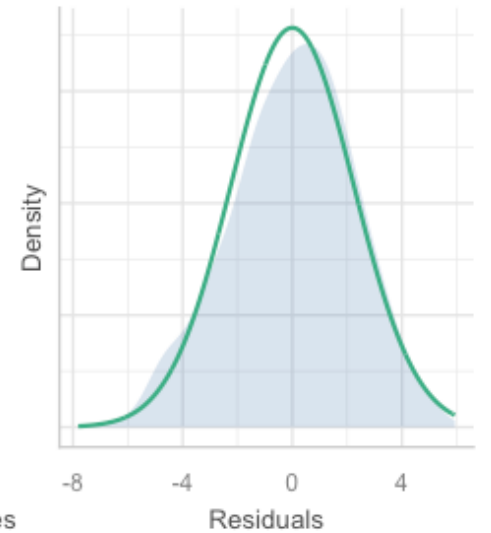
Normality of Residuals

Dots should fall along the line



Normality of Residuals

Distribution should be close to the normal



- How to interpret a QQ plot

- QQ plot interpretation

Assessing normality using residuals

- **Light-tailed**: small variance in residuals, resulting in a narrow distribution
- **Heavy-tailed**: many extreme positive and negative residuals, resulting in a wide distribution
- **Left-skewed** (n shape): more data falls to the left of the mean
- **Right-skewed** (u shape): more data falls to the right of the mean

Heavy-tailed, left-skewed.

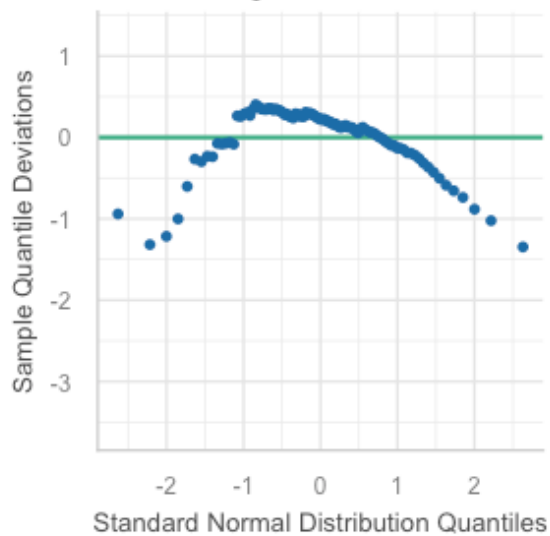
```
set.seed(1028)
x ← rnorm(100)
y ← 2 + 5 * x + rchisq(100, df = 3) * -1
df ← data.frame(x, y)
performance::check_model(lm(y ~ x, data = df),
  check = c(c("qq")))
```

Light-tailed, right-skewed.

```
set.seed(1028)
x ← rnorm(100)
y ← 2 + 5 * x + rbinom(100, 10, .5)
df ← data.frame(x, y)
performance::check_model(lm(y ~ x, data = df),
  check = c(c("qq")))
```

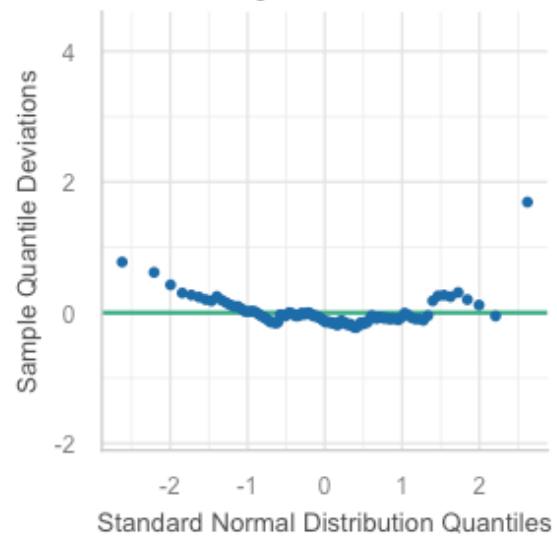
Normality of Residuals

Dots should fall along the line



Normality of Residuals

Dots should fall along the line

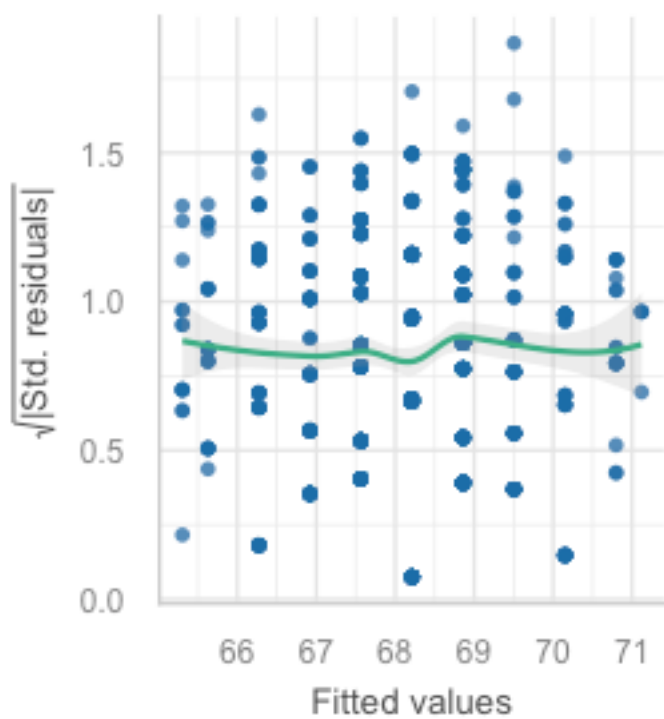


Asumption: Equal variances

```
performance::check_model(fit, check = c("homogeneity", "outliers"))
```

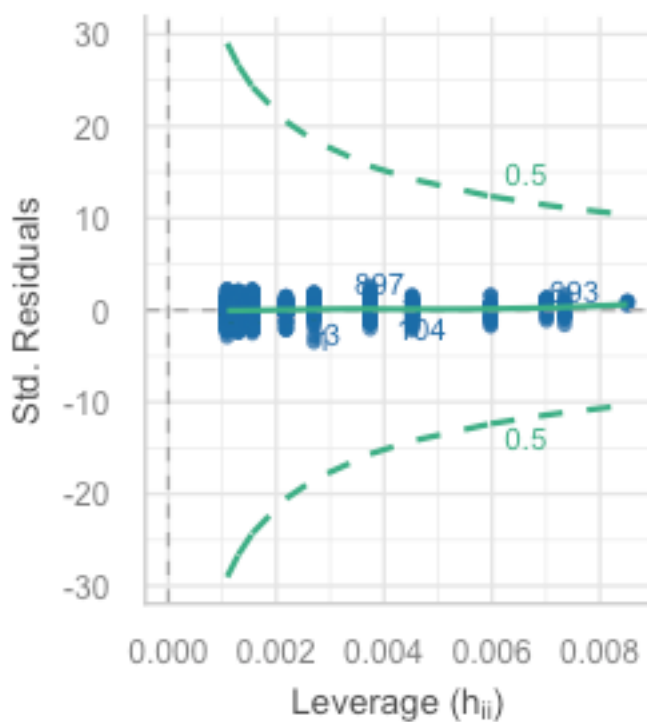
Homogeneity of Variance

Reference line should be flat and horizontal



Influential Observations

Points should be inside the contour lines



Outliers are not a strict assumption, but they will affect the model fit.

What is a standardised residual?

- The standardised residual is the residual divided by the standard error of the residual (normalised).

$$\text{Standardised residual} = \frac{\text{Residual}}{\text{Standard error of the residual}}$$

- The *mean* of the residuals is 0 in linear regression
- A standardised residual of 2 or above suggests the point is an outlier (far from the regression line)
- Spread should be random i.e. no pattern (fanning, W), which indicates **equal variances**

Model Fit

How well does our fitted model represent the relationship between the variables?

ANOVA and linear regression

ANOVA is a variation of linear regression – both partition variance into sum of squares for residuals (variance explained) and sum of squares for error (variance not explained) aka **the components of the F-statistic**.

ANOVA Output

```
fit ← lm(child ~ parent, data = Galton)
anova(fit)
```

Analysis of Variance Table

Response: child

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
parent	1	1236.9	1236.93	246.84	< 2.2e-16
Residuals	926	4640.3	5.01		

- **parent Sum Sq**: the variation that **parent** explains in the **child** variable
- **Residuals Mean Sq**: variation (per degree of freedom) that the model does not explain
- The **F-value** is the ratio, i.e. does **parent** explain enough variation in **child** to be considered significant?

$$\text{F-value} = \frac{\text{parent Sum Sq}}{\text{Residuals Mean Sq}} = \frac{1236.9}{5.01} = 246.84$$

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

Regression Output

```
fit ← lm(child ~ parent, data = Galton)  
summary(fit)  
  
# F-statistic: 246.8 on 1 and 926 DF,  p-value: < 2.2e-16
```

ANOVA and linear regression

ANOVA is a variation of linear regression – both partition variance into sum of squares for residuals (variance explained) and sum of squares for error (variance not explained) aka **the components of the F-statistic**.

ANOVA Output

The ANOVA suggests that the main effect of parent is statistically significant and large ($F(1, 926) = 246.84, p < .001$)

Regression Output

We fitted a linear model (estimated using OLS) to predict child with parent (formula: `child ~ parent`). The model explains a statistically significant and moderate proportion of variance ($R^2 = 0.21, F(1, 926) = 246.84, p < .001$). Within this model, the effect of parent is statistically significant and positive ($\beta_1 = 0.65, 95\% \text{ CI } [0.57, 0.73], t(926) = 15.71, p < .001$).

i Note

For simple linear regression, the significance of the predictor (i.e. `child`) is the same as the model significance.

Interpret output

■ Model fit and predictions

Model fit

```
summary(fit)
```

```
Call:
lm(formula = child ~ parent, data = Galton)

Residuals:
    Min       1Q   Median       3Q      Max
-7.8050 -1.3661  0.0487  1.6339  5.9264

Coefficients:
              Estimate Std. Error t value Pr(>|
t|)
(Intercept) 23.94153     2.81088   8.517  <2e-16
***
parent       0.64629     0.04114  15.711  <2e-16
***
---
```

$$\widehat{child} = 23.9 + 0.65 \cdot parent$$

For every unit change in parent (i.e. *1 inch*), we expect a 0.65 unit change in child.

How much variation is explained? $R^2 = 0.21 = 21\%$

- **Multiple R^2** : proportion of variance in the response variable explained by the model.
- **Adjusted R^2** : as above but adjusted for the number of predictors in the model.
 - For multiple linear regression
 - It only increases if the new term improves the model more than would be expected by chance
 - *Always lower than multiple R^2*

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

Residual standard error: 2.239 on 926 degrees of
freedom

Multiple R-squared: 0.2105, Adjusted R-
squared: 0.2096

F-statistic: 246.8 on 1 and 926 DF, p-value: <
2.2e-16

Making predictions

What is the predicted child height for a parent height of 70 inches?

```
child ← 23.9 + 0.65 * 70  
child
```

```
[1] 69.4
```

We use `predict()` to make predictions – it takes in the `lm()` model, recreates the equation and applies it to new data.

```
predict(fit, data.frame(parent = 70)) # using 70 as this is the value we want to sub in and predict
```

```
1  
69.18187
```

i Note

How good is our prediction actually? What if we had more parents and children, would the equation still hold up? We cover this in Week 9.

Transformations

What if assumptions are not met, or we want to improve the model?

What if assumptions are not met?

Violations of...

- **Linearity** can cause systematically wrong predictions
- **Homoskedasticity** makes it difficult to estimate “true” standard deviation of errors (i.e. noisy estimates)
- **Normality** can compromise inferences and hypothesis testing

How do we solve these problems?

- Use less restrictive (but more complicated) models, e.g. generalised linear models, non-parametric techniques (ENVX3002)
- Perform variance corrections (complicated)
- **Transform the response variable (y)** to stabilise variance and correct normality
- **Transform the predictor variable (x)** if issues still exist in the diagnostics

i Note

We can also perform transformations to improve the model fit, but **beware of overfitting** – we want to make reasonable predictions, not fit the data!

Example: air quality

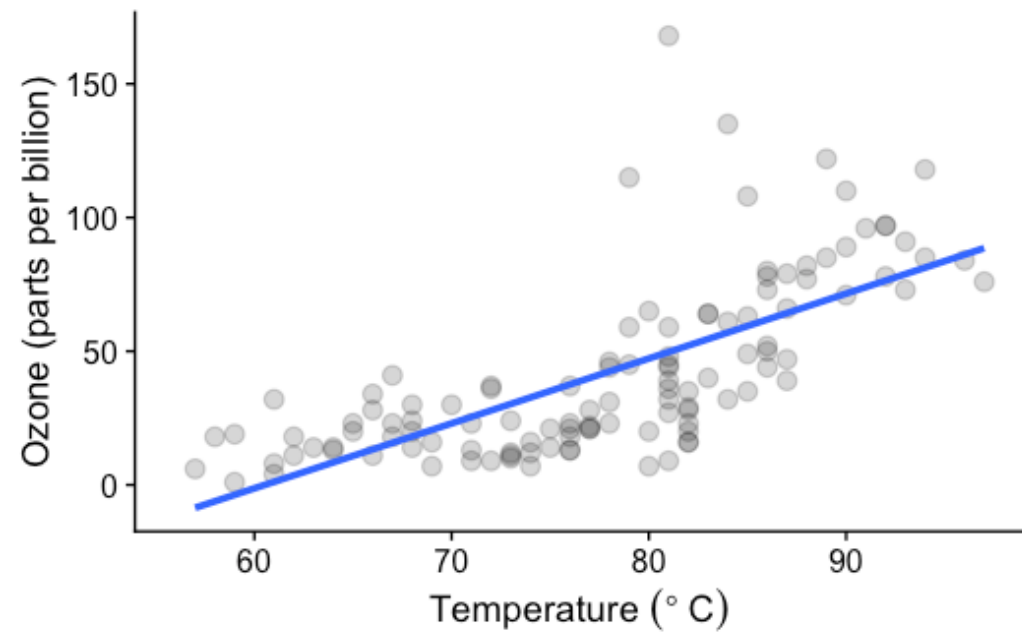
Daily air quality measurements in New York, May to September 1973.

```
str(airquality)
```

```
'data.frame':  153 obs. of  6 variables:
 $ Ozone   : int  41 36 12 18 NA 28 23 19 8
NA ...
 $ Solar.R: int  190 118 149 313 NA NA 299 99 19
194 ...
 $ Wind    : num  7.4 8 12.6 11.5 14.3 14.9 8.6
13.8 20.1 8.6 ...
 $ Temp    : int  67 72 74 62 56 66 65 59 61
69 ...
 $ Month   : int  5 5 5 5 5 5 5 5 5 ...
 $ Day     : int  1 2 3 4 5 6 7 8 9 10 ...
```

We start with one variable: is ozone concentration influenced by temperature?

```
ggplot(airquality, aes(x = Temp, y = Ozone)) +
  geom_point(alpha = .2, size = 3) +
  labs(
    x = expression("Temperature " ( degree~C)),
    y = "Ozone (parts per billion)" +
  geom_smooth(method = "lm", se = FALSE)
```

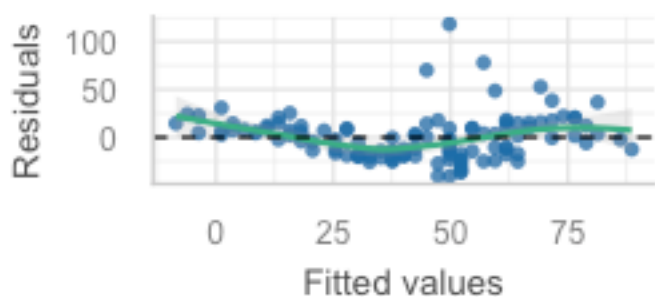


Assumption checks

```
fit ← lm(Ozone ~ Temp, data = airquality)
performance::check_model(fit, check = c("linearity", "qq", "homogeneity", "outliers")) # check
specific assumptions
```

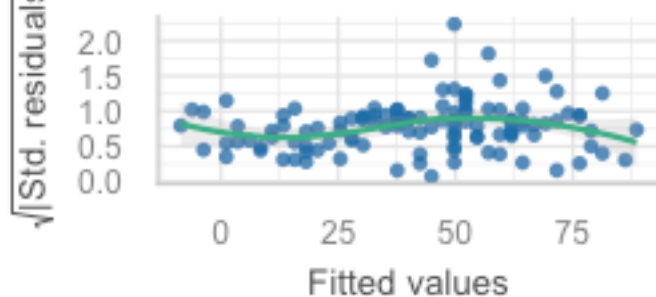
Linearity

Reference line should be flat and horizontal



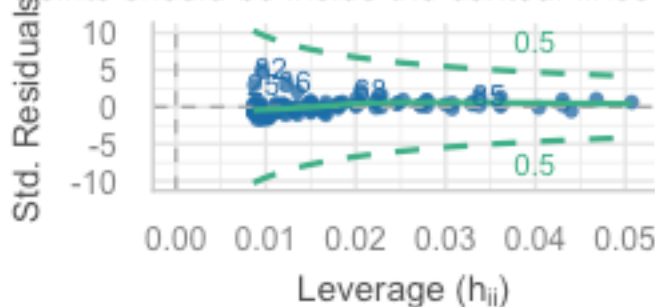
Homogeneity of Variance

Reference line should be flat and horizontal



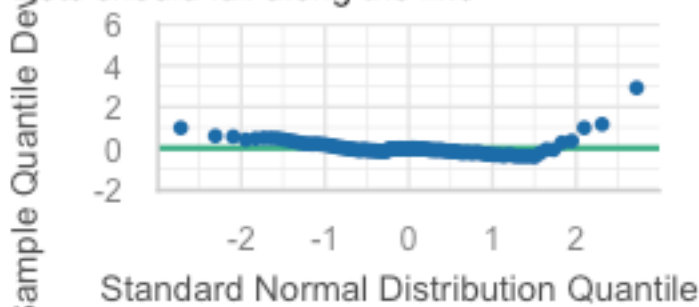
Influential Observations

Points should be inside the contour lines



Normality of Residuals

Points should fall along the line



Is a simple linear model appropriate? *Depends on your threshold for what is acceptable.*

Backtransforming – FYI

A log transformation (natural or a base) is relatively easy to back-transform.

$$\log(\widehat{Ozone}) = -1.8380 + 0.0675 \times Temp$$

$$\widehat{Ozone} = e^{-1.8380 + 0.0675 \times Temp} = e^{-1.8380} \times e^{0.0675 \times Temp}$$

But given we are focused on a 1-unit change of `Temp`, \widehat{Ozone} changes by $e^{0.0675} = 1.07$ **times**.

If this had been a `sqrt()` transformation...

$$\sqrt{\widehat{Ozone}} = -1.8380 + 0.0675 \times Temp$$

$$\widehat{Ozone} = (-1.8380 + 0.0675 \times Temp)^2 = 3.3782 - (0.2481 \times Temp) + (0.0675 \times Temp)^2$$

Interpreting log transformations – FYI

- Log-linear: $\text{Log}(Y) = \beta_0 + \beta_1 x$
 - An increase of x by 1 unit corresponds to a β_1 unit increase in $\log(Y)$
 - An increase of x by 1 unit corresponds to approximately a $\beta_1 \times 100\%$ increase in Y
- Linear-log: $Y = \beta_0 + \beta_1 \log(x)$
 - An increase of 1% in x corresponds to a $\frac{\beta_1}{100}$ increase in Y
- Log-log: $\text{Log}(Y) = \beta_0 + \beta_1 \log(x)$
 - An increase of 1% in x corresponds to a $\beta_1\%$ increase in Y

Percent change with \ln transformation – FYI

Interpreting as a percent change can be more meaningful - it can be done with any log transformation (substitute e below for 10 or any other base), but the **quick approximation only works with natural log transformations**.

If y has been transformed with a natural log ($\log(y)$), for a one-unit increase in x the **percent change in y** (not $\log(y)$) is calculated with:

$$\Delta y\% = 100 \cdot (e^{\beta_1} - 1)$$

If β_1 is small (i.e. $-0.25 < \beta_1 < 0.25$), then: $e^{\beta_1} \approx 1 + \beta_1$. So $\Delta y\% \approx 100 \cdot \beta_1$.

β	Exact $(e^{\beta} - 1)\%$	Approximate $100 \cdot \beta$
-0.25	-22.13	-25
-0.1	-9.52	-10
0.01	1.01	1
0.1	10.52	10
0.25	28.41	25
0.5	64.87	50
2	638.91	200

- **y transformed**: a one-unit increase in x is *approximately* a $\beta_1\%$ change in y .
- **x transformed**: a 1% increase in x is *approximately* a $0.01 \cdot \beta_1$ change in y .
- **Both x and y transformed**: a 1% increase in x is *approximately* a $\beta_1\%$ change in y .

Transforming Ozone

Let's transform Ozone using the natural log (`log()`).

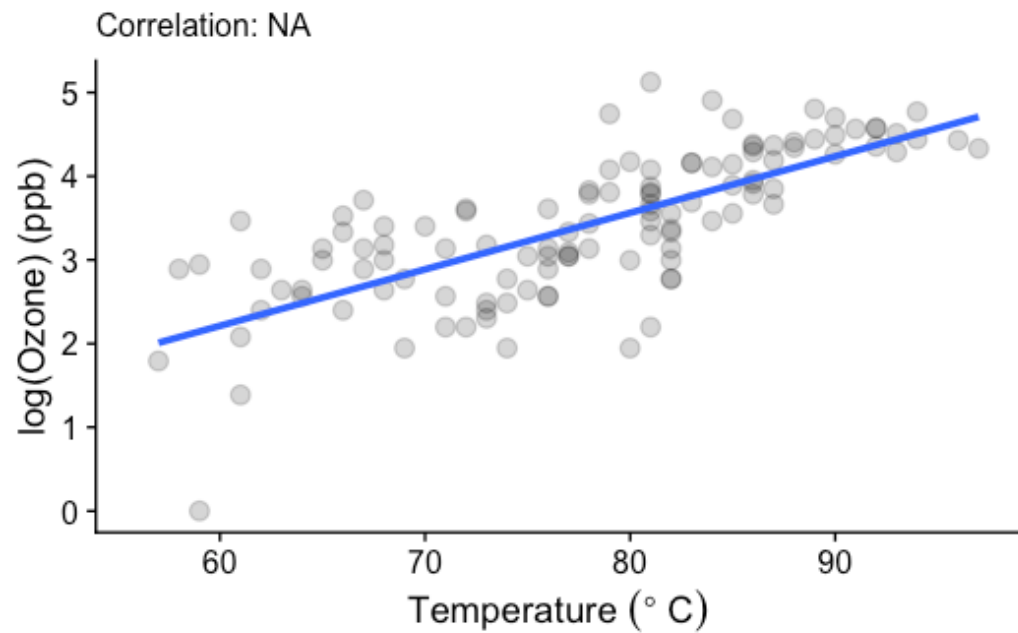
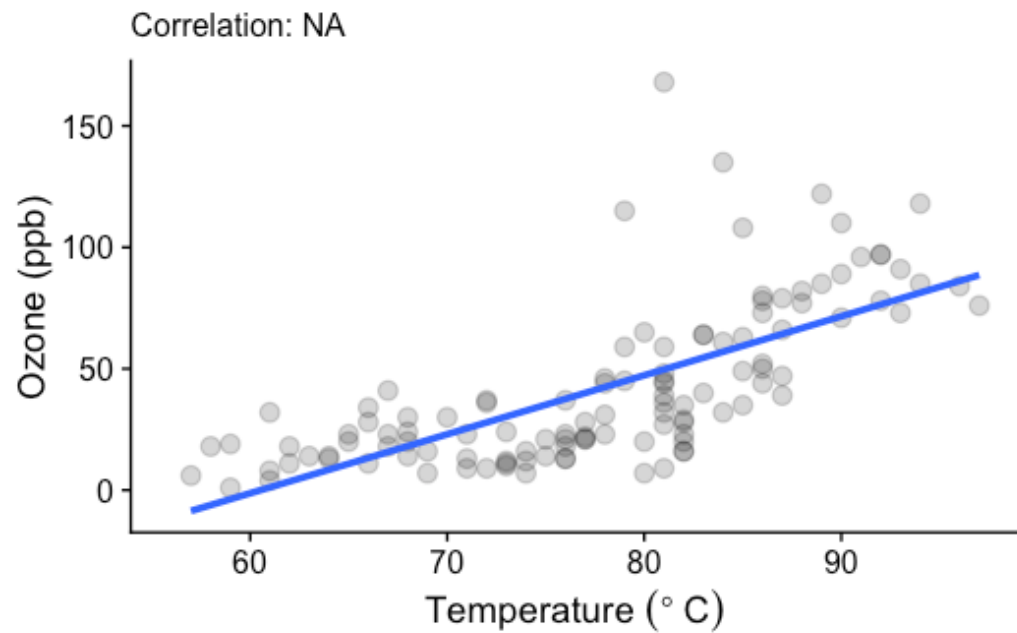
```
fit_log ← lm(log(Ozone) ~ Temp, data = airquality)
```

Before

```
ggplot(airquality, aes(x = Temp, y = Ozone)) +  
  geom_point(alpha = .2, size = 3) +  
  labs(  
    x = expression("Temperature " ( degree~C)),  
    y = "Ozone (ppb)") +  
  geom_smooth(method = "lm", se = FALSE) +  
  labs(subtitle = paste("Correlation:",  
    round(cor(airquality$Temp, airquality$Ozone),  
    2)))
```

After

```
ggplot(airquality, aes(x = Temp, y =  
  log(Ozone))) +  
  geom_point(alpha = .2, size = 3) +  
  labs(  
    x = expression("Temperature " ( degree~C)),  
    y = "log(Ozone) (ppb)") +  
  geom_smooth(method = "lm", se = FALSE) +  
  labs(subtitle = paste("Correlation:",  
    round(cor(airquality$Temp,  
    log(airquality$Ozone)), 2)))
```



Assumption: Linearity

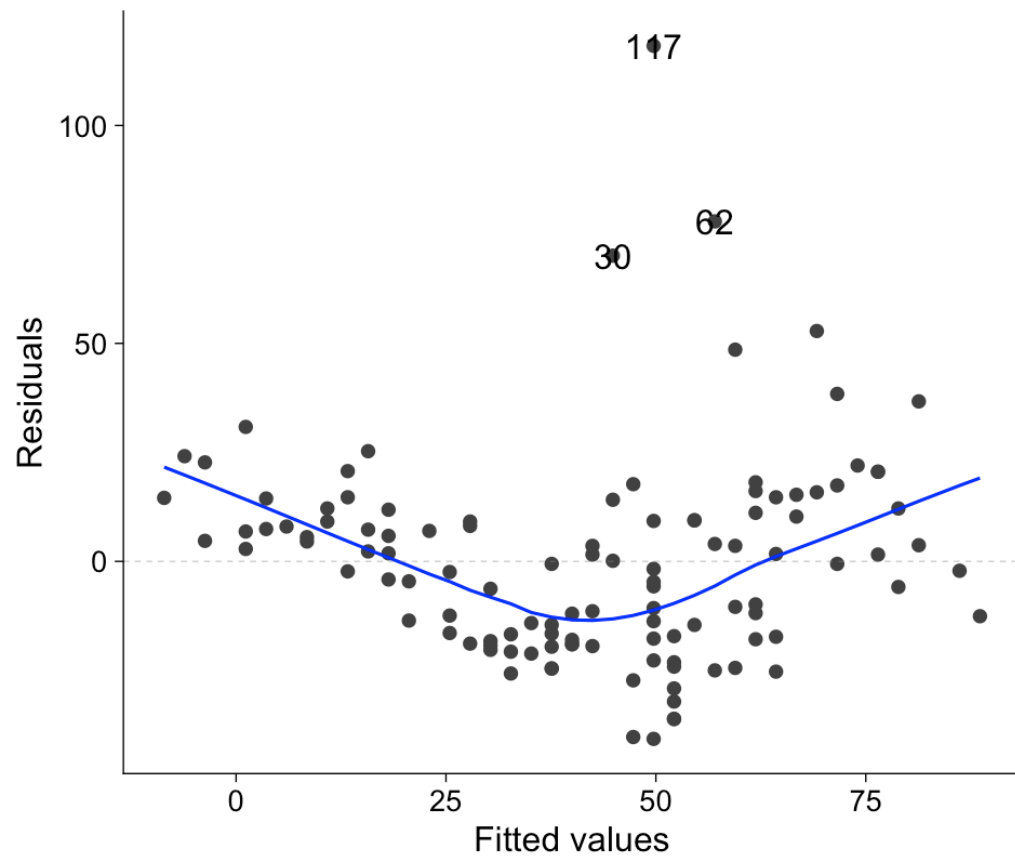
Before

```
autoplot(fit, 1, ncol = 1) +  
  cowplot::theme_cowplot(font_size = 24)
```

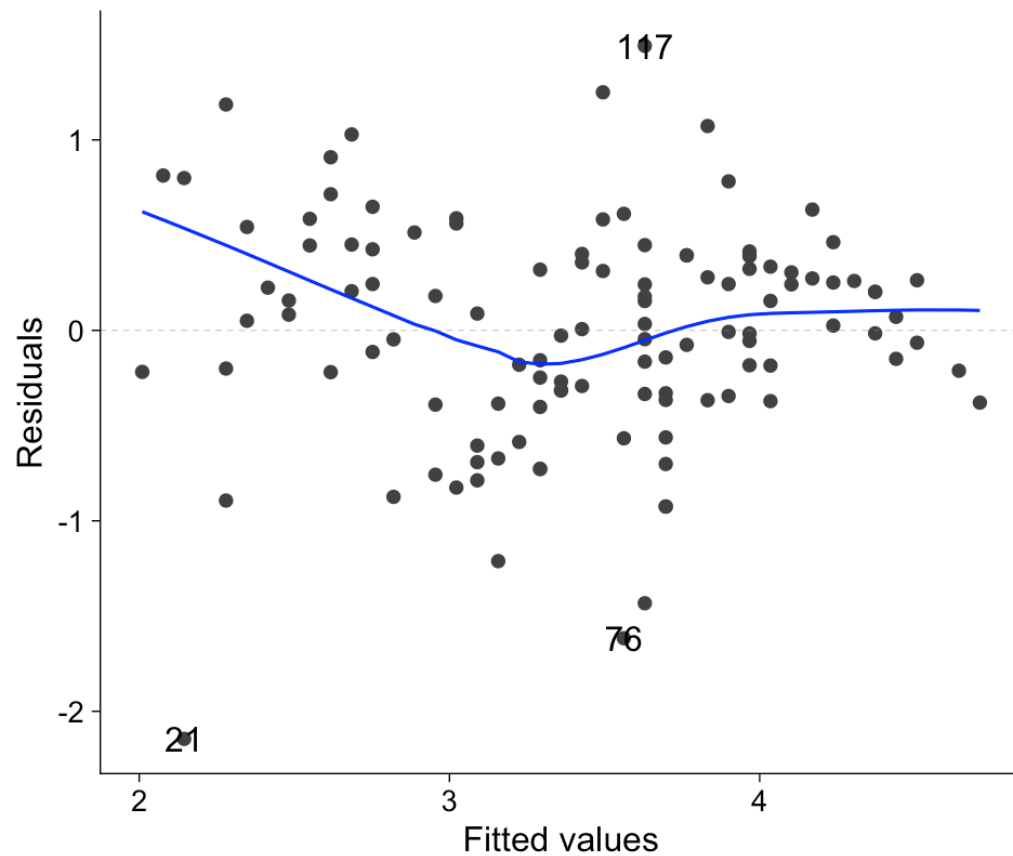
After

```
autoplot(fit_log, 1, ncol = 1) +  
  cowplot::theme_cowplot(font_size = 24)
```

Residuals vs Fitted



Residuals vs Fitted



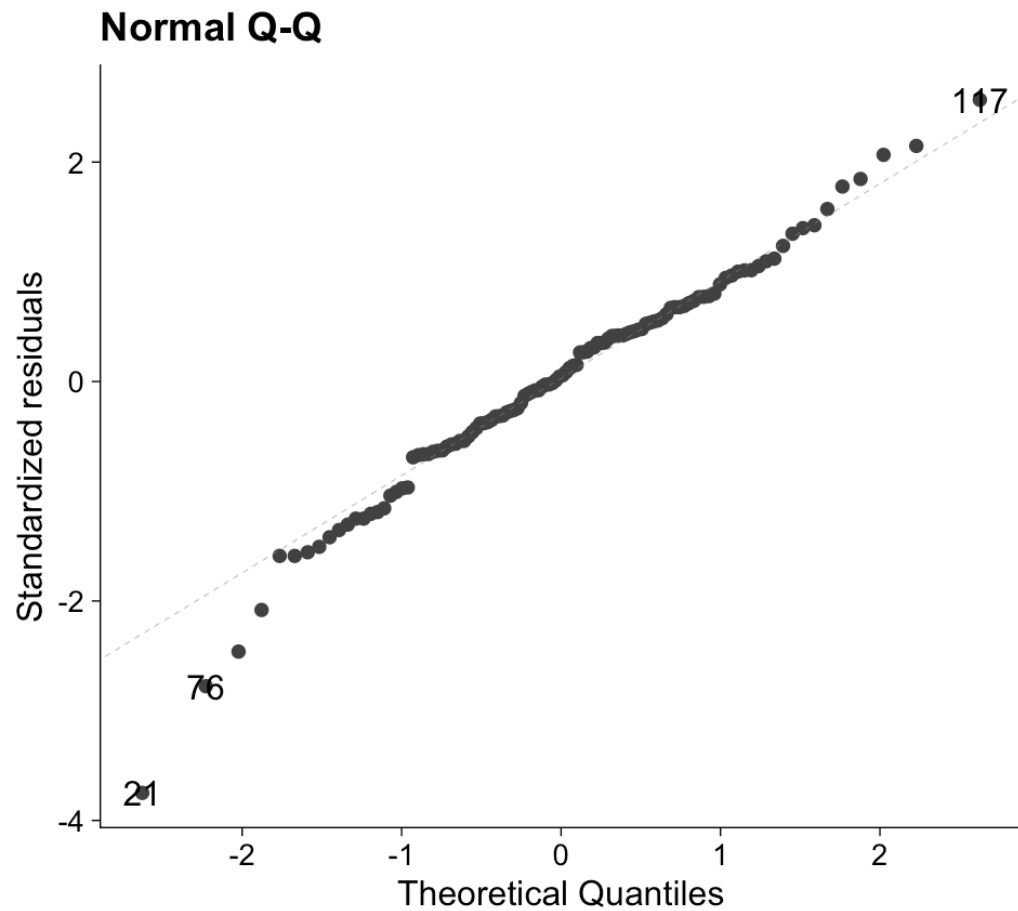
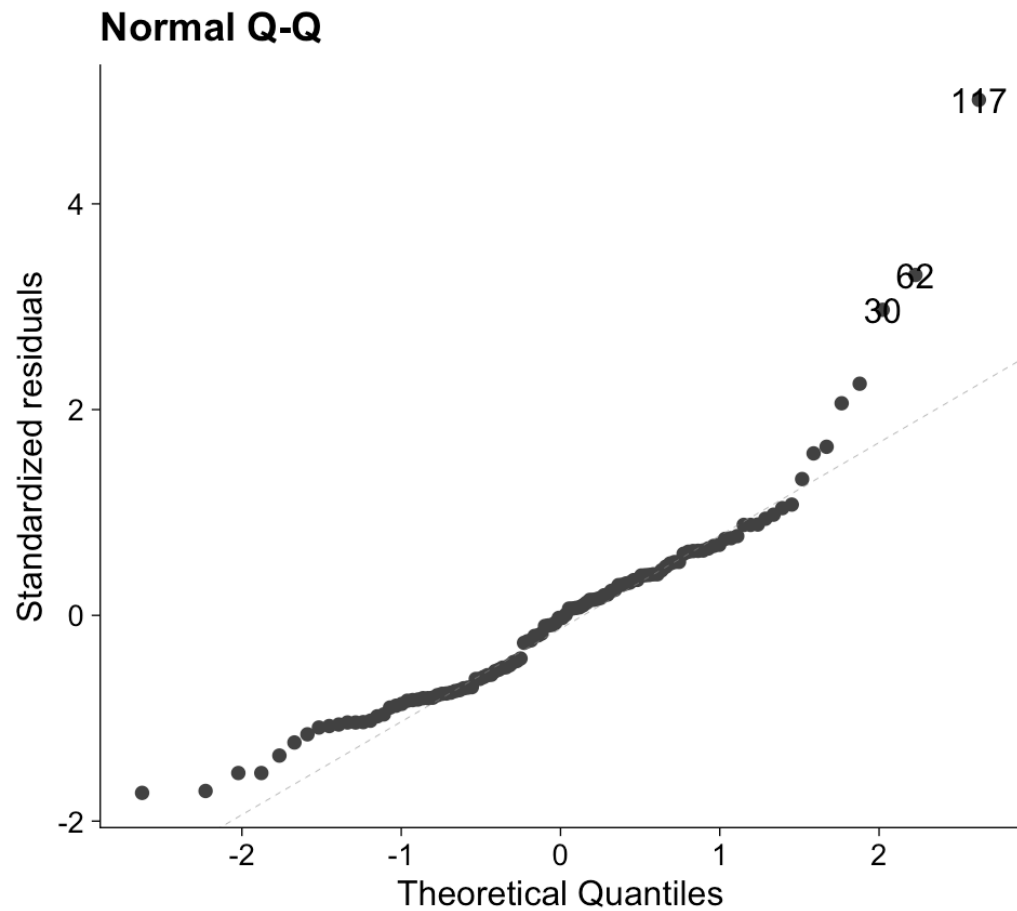
Assumption: Normality

Before

```
autoplot(fit, 2, ncol = 1) +  
  cowplot::theme_cowplot(font_size = 24)
```

After

```
autoplot(fit_log, 2, ncol = 1) +  
  cowplot::theme_cowplot(font_size = 24)
```



Assumption: Equal variances

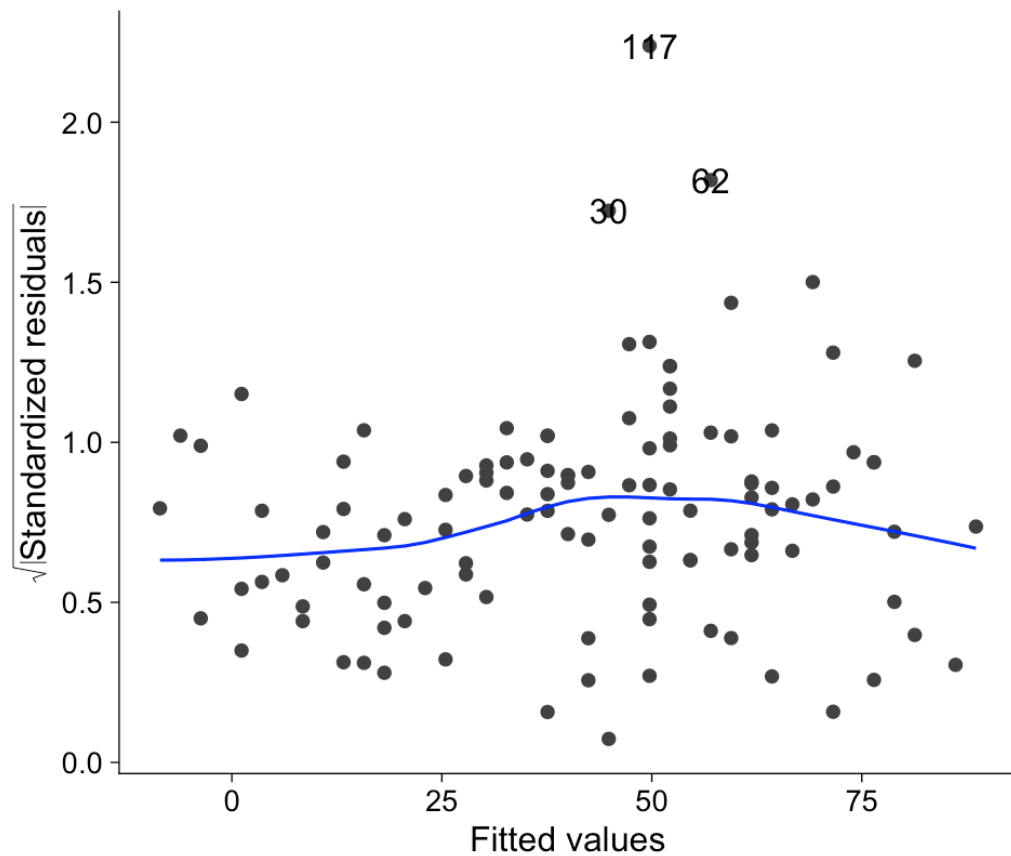
Before

```
autoplot(fit, 3, ncol = 1) +  
  cowplot::theme_cowplot(font_size = 24)
```

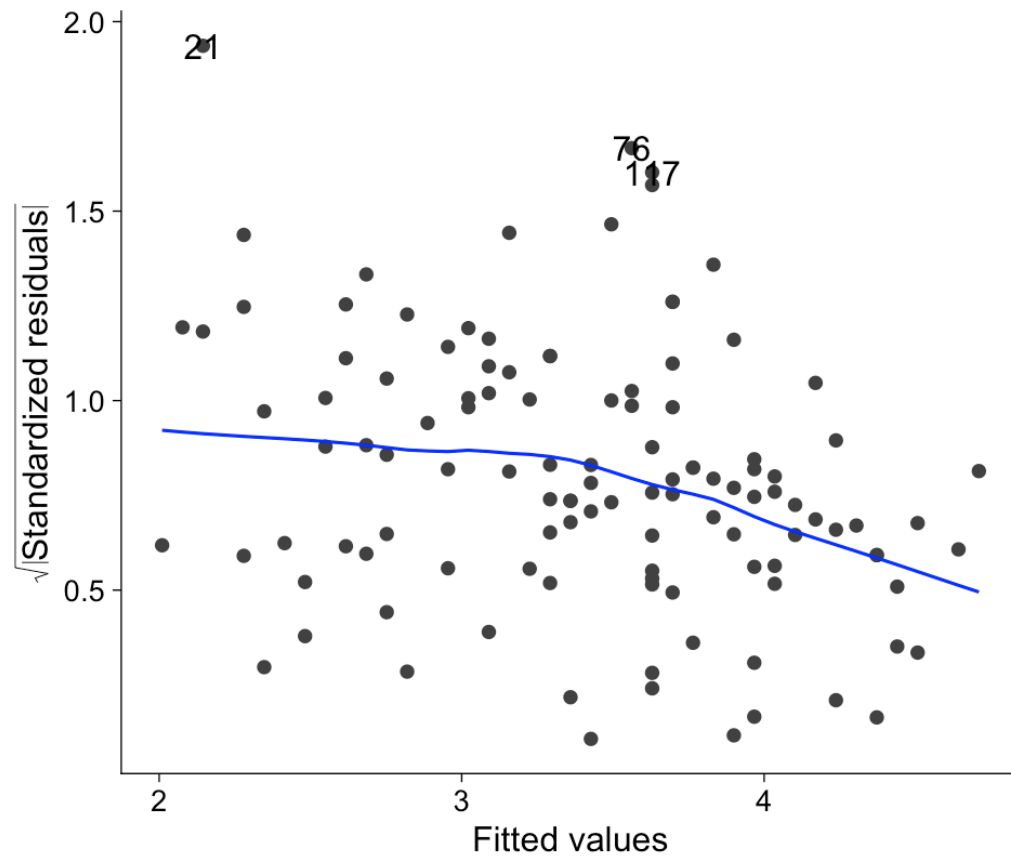
After

```
autoplot(fit_log, 3, ncol = 1) +  
  cowplot::theme_cowplot(font_size = 24)
```

Scale-Location



Scale-Location



Is transforming better?

Before

```
summary(fit)
```

```
Call:
lm(formula = Ozone ~ Temp, data = airquality)

Residuals:
    Min       1Q   Median       3Q      Max
-40.729 -17.409  -0.587  11.306  118.271

Coefficients:
            Estimate Std. Error t value Pr(>|
t|)
(Intercept) -146.9955    18.2872  -8.038  9.37e-13 ***
Temp         2.4287     0.2331  10.418  2e-16 ***
```

After

```
summary(fit_log)
```

```
Call:
lm(formula = log(Ozone) ~ Temp, data =
airquality)

Residuals:
    Min       1Q   Median       3Q      Max
-2.14469 -0.33095  0.02961  0.36507  1.49421

Coefficients:
            Estimate Std. Error t value Pr(>|
t|)
(Intercept) -1.83797    0.45100  -4.075  8.53e-05 ***
Temp         0.06750    0.00575  11.741  < 2e-16
```

```

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

Residual standard error: 23.71 on 114 degrees of
freedom
(37 observations deleted due to missingness)
Multiple R-squared:  0.4877,    Adjusted R-
squared:  0.4832
F-statistic: 108.5 on 1 and 114 DF,  p-value: <
2.2e-16

```

```

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

Residual standard error: 0.5848 on 114 degrees
of freedom
(37 observations deleted due to missingness)
Multiple R-squared:  0.5473,    Adjusted R-
squared:  0.5434
F-statistic: 137.8 on 1 and 114 DF,  p-value: <
2.2e-16

```

The transformed model equation is:

$$\log(\widehat{Ozone}) = -1.8380 + 0.0675 \times Temp$$

A 1 degree (°F) increase in temperature is associated with a:

- 0.0675 increase in `log(Ozone)` concentration
- $e^{0.0675} = 1.07$ times increase in `Ozone` concentration

- Approximately a 6.75% increase in **Ozone** concentration

Multiple linear regression

The MLR model

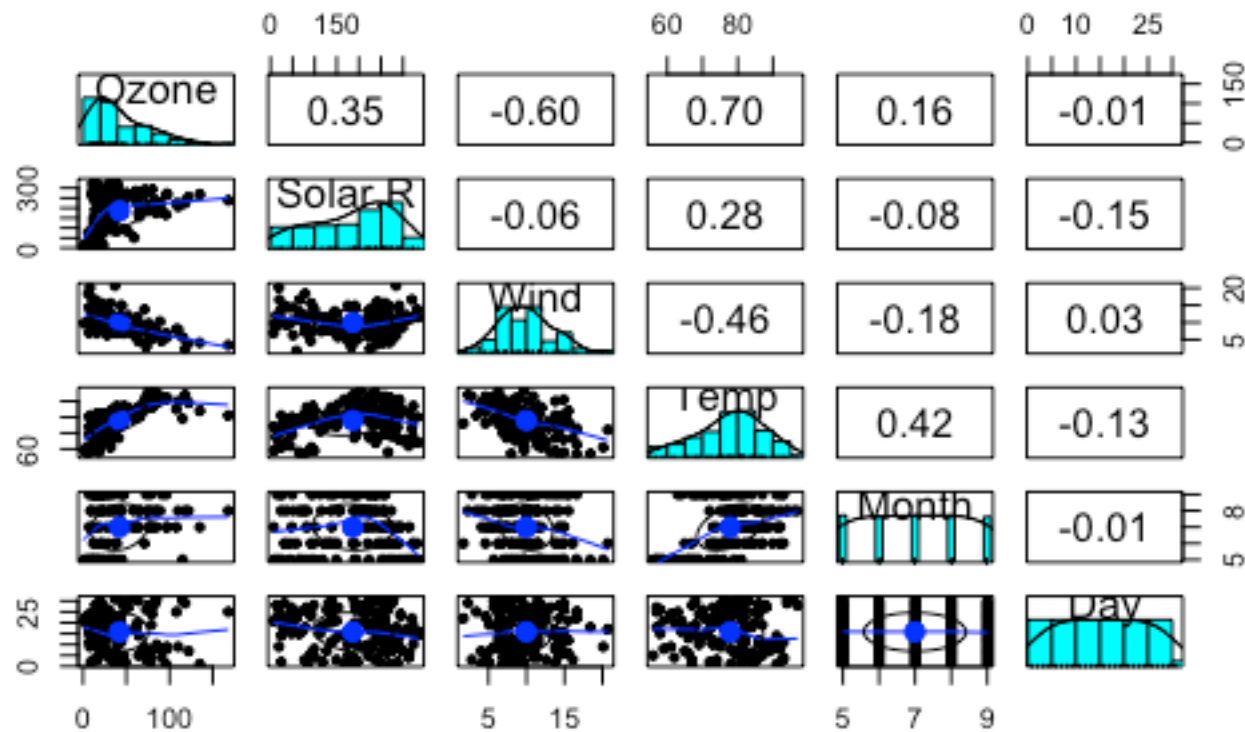
$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k + \epsilon$$

where

- a response variable (Y) which we wish to predict using predictor variables (x_k)
- β_0 is the y-intercept
- β_k is the partial regression coefficient associated with the k^{th} predictor variable
- ϵ is error and $\epsilon \sim N(0, \sigma^2)$

Can we use more predictors?

```
psych::pairs.panels(airquality)
```



Can we improve the current model by adding *wind* and *solar radiation* as additional predictors?

Can we use more predictors?

From:

$$\log(size)_i = \beta_0 + \beta_1 Temp_i + \epsilon_i$$

To:

$$\log(size)_i = \beta_0 + \beta_1 Temp_i + \beta_2 Solar.R_i + \beta_3 Wind_i + \epsilon_i$$

Can we use more predictors?

$$\log(size)_i = \beta_0 + \beta_1 Temp_i + \beta_2 Solar.R_i + \beta_3 Wind_i + \epsilon_i$$

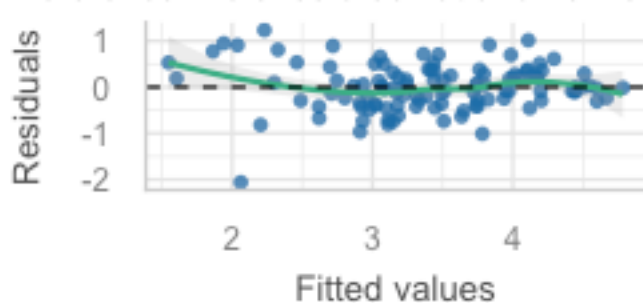
```
multi_fit ← lm(log(Ozone) ~ Temp + Solar.R + Wind, data = airquality)
```

Assumptions

```
performance::check_model(multi_fit, check = c("linearity", "qq", "homogeneity", "outliers")) #  
check specific assumptions
```

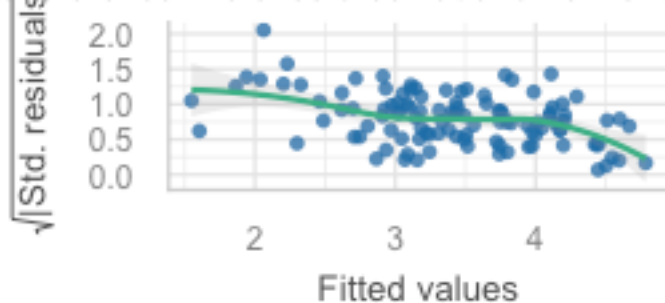
Linearity

Reference line should be flat and horizontal



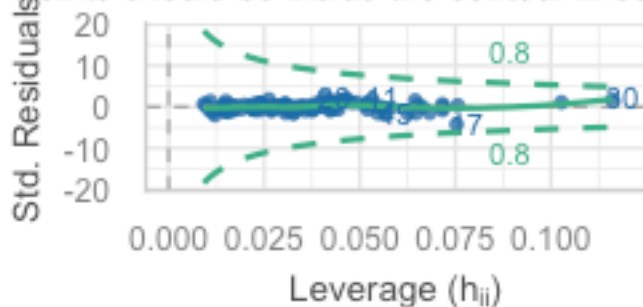
Homogeneity of Variance

Reference line should be flat and horizontal



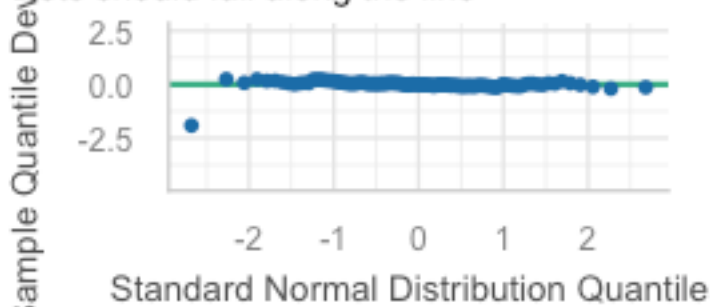
Influential Observations

Points should be inside the contour lines



Normality of Residuals

Points should fall along the line



There is one additional assumption for multiple linear regression. **Collinearity** is when two or more predictors are very highly correlated. If the predictors are basically identical, the model cannot distinguish how much variability each explains. (Correlations in previous slides look fine).

Hypothesis

For multiple linear regression, there are two hypothesis tests:

- Individual predictors, where the significance of each predictor is tested via t-tests

$$H_0 : \beta_k = 0$$

$$H_1 : \beta_k \neq 0$$

- The overall model, which is tested with an F-test (to get F-stat). H_0 is an intercept-only model (i.e. the mean), so if at least one predictor is useful, the model is better than the intercept-only model.

$$H_0 : \beta_1 = \beta_2 = \dots = \beta_k = 0$$

$$H_1 : \text{At least one } \beta_k \neq 0$$

Model Fit

```
summary(multi_fit)
```

Call:

```
lm(formula = log(Ozone) ~ Temp + Solar.R + Wind, data = airquality)
```

Residuals:

Min	1Q	Median	3Q	Max
-2.06193	-0.29970	-0.00231	0.30756	1.23578

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-0.2621323	0.5535669	-0.474	0.636798
Temp	0.0491711	0.0060875	8.077	1.07e-12 ***
Solar.R	0.0025152	0.0005567	4.518	1.62e-05 ***
Wind	-0.0615625	0.0157130	-3.918	0.000158 ***

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

Residual standard error: 0.5086 on 107 degrees of freedom
(42 observations deleted due to missingness)
Multiple R-squared: 0.6644, Adjusted R-squared: 0.655
F-statistic: 70.62 on 3 and 107 DF, p-value: < 2.2e-16

Model equation:

$$\log(\widehat{Ozone}) = -0.262 + 0.0492 \cdot Temp + 0.00252 \cdot Solar.R - 0.0616 \cdot Wind$$

Interpretation

$$\log(\widehat{Ozone}) = -0.262 + 0.0492 \cdot Temp + 0.00252 \cdot Solar.R - 0.0616 \cdot Wind$$

Holding all other variables constant:

- A one degree (°F) increase in `Temp` is associated with a 4.9% increase in `Ozone` concentration.
- A one unit increase in `Solar.R` is associated with a 0.25% increase in `Ozone` concentration.
- A one unit increase in `Wind` is associated with a 6.2% decrease in `Ozone` concentration.

Automating extracting the model equation into latex using `extract_eq()` from the package `equatiomatic`:

```
equatiomatic::extract_eq(multi_fit, use_coefs = TRUE, coef_digits = 3) |> print()
```

```
$$  
\operatorname{\widehat{\log(Ozone)}} = -0.262 + 0.049(\operatorname{Temp}) +  
0.003(\operatorname{Solar.R}) - 0.062(\operatorname{Wind})  
$$
```

Is MLR model better?

```
sjPlot::tab_model(fit_log, multi_fit, digits = 4, show.ci = FALSE)
```

<i>Predictors</i>	log(Ozone)		log(Ozone)	
	<i>Estimates</i>	<i>p</i>	<i>Estimates</i>	<i>p</i>
(Intercept)	-1.8380	<0.001	-0.2621	0.637
Temp	0.0675	<0.001	0.0492	<0.001
Solar R			0.0025	<0.001
Wind			-0.0616	<0.001
Observations	116		111	
R ² / R ² adjusted	0.547 / 0.543		0.664 / 0.655	

- The adjusted R^2 is higher for the MLR model...
- Interpretation of R^2 is the same as for simple linear regression: how much of the variation in the response variable is explained by the model
- **Are all the variables/predictors needed?** (next week)

Summing up

- We fit a simple linear model to represent a linear relationship between two variables
 - used method of least squares to find the best fitting line
 - model equation; $Y_i = \beta_0 + \beta_1 x_i + \epsilon_i$
- Multiple linear regression
 - Do more predictors improve model fit?
 - $Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k + \epsilon$
- Hypothesis testing with linear models + Is our model the best representation of the relationship?
- Check assumptions to understand the validity of the model
 - collinearity, linearity, independence, normality, equal variance (CLINE)
- Transformations to meet assumptions and improve model fit
- Interpreting model output + F-test via ANOVA and summary(), R^2

Next lecture: Variable selection

We will discuss how to select the best subset of predictors for a model.

Thanks!

Questions? Comments?

Slides made with **Quarto**