Lecture 01b – Reproducible Science

ENVX1002 Statistics in Life and Environmental Sciences

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Importance of statistics

> Never leave a number all by itself. Never believe that one number on its own can be meaningful. If you are offered one number, always ask for at least one more. Something to compare it with.
>
> – Hans Rosling (1948-2017)

Why learn statistics?

All of science (and industry) are increasingly data-driven and computational:

- **Research** papers are filled with statistical analyses
- **Business** and **policy** decisions are based on data analytics
- Environmental **policies** are guided by statistical models
- **Medical** treatments are evaluated using statistical methods

Most of you are majoring in a field that will require you to understand and use statistics in some form.

Benefits

Even if you don’t become a data scientist, statistics will help you to:

1. **Evaluate claims critically**
   - Understand and analyse data in your field
   - Make informed decisions based on evidence
2. **Communicate effectively**
   - Create compelling data visualisations and reports
   - Present findings clearly to different audiences
3. **Solve real-world problems**
   - Design and analyse experiments properly
   - Make evidence-based predictions and identify trends

The joy of stats

200 countries, 200 years, 4 minutes

In your own time: The best stats you've ever seen

Lionel Messi is impossible

> It's not possible to shoot more efficiently from outside the penalty area than many players shoot inside it. It's not possible to lead the world in weak-kick goals and long-range goals. It's not possible to score on unassisted plays as well as the best players in the world score on assisted ones. It's not possible to lead the world's forwards both in taking on defenders and in dishing the ball to others. And it's certainly not possible to do most of these things by insanely wide margins.
>
> **But Messi does all of this and more.**

Figure 1: Messi playing for Argentina

Image credit: Кирилл Венедиктов, CC BY-SA 3.0 GFDL, via Wikimedia Commons

Lionel Messi is impossible

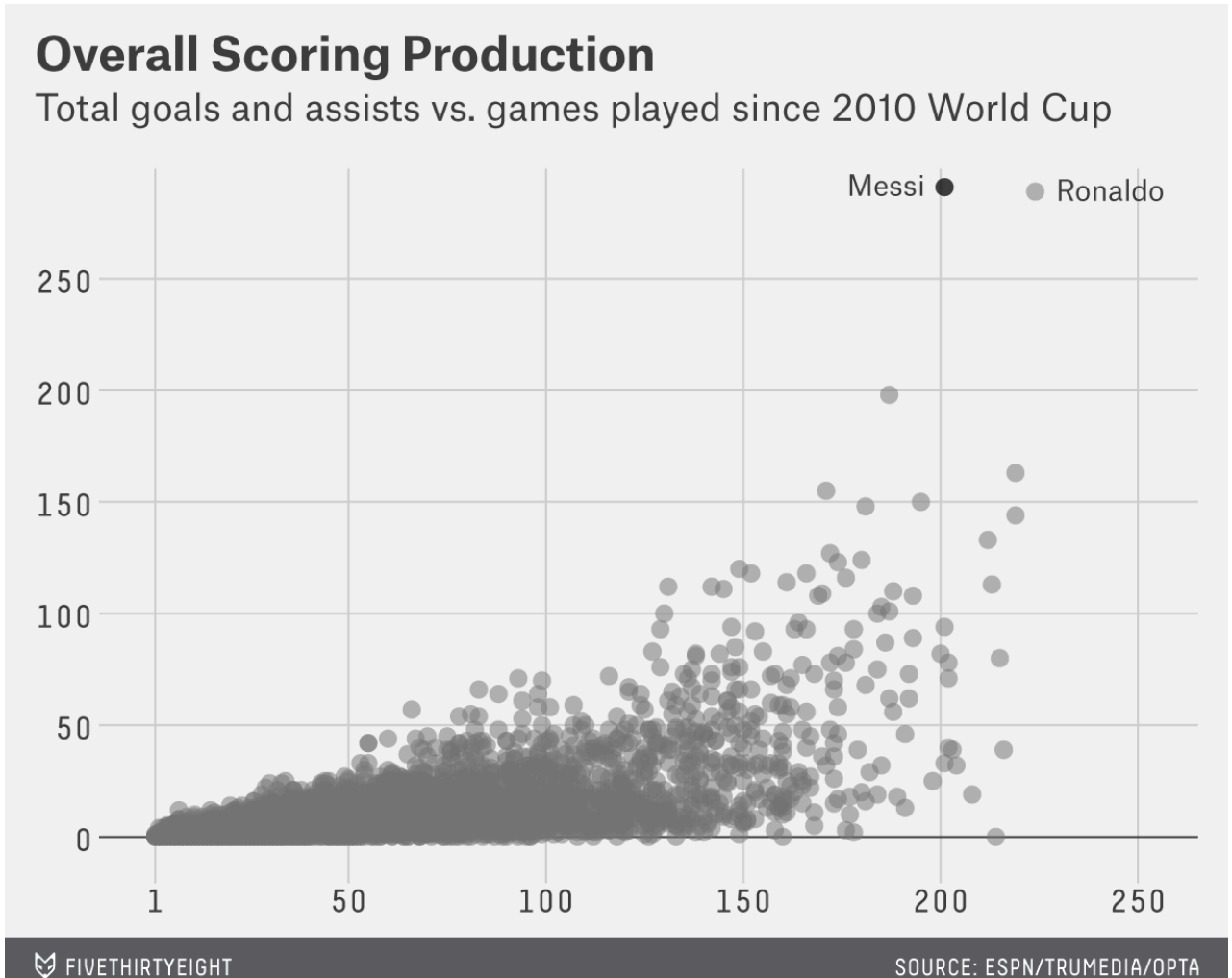


Figure 2: Source: fivethirtyeight

Lionel Messi is impossible

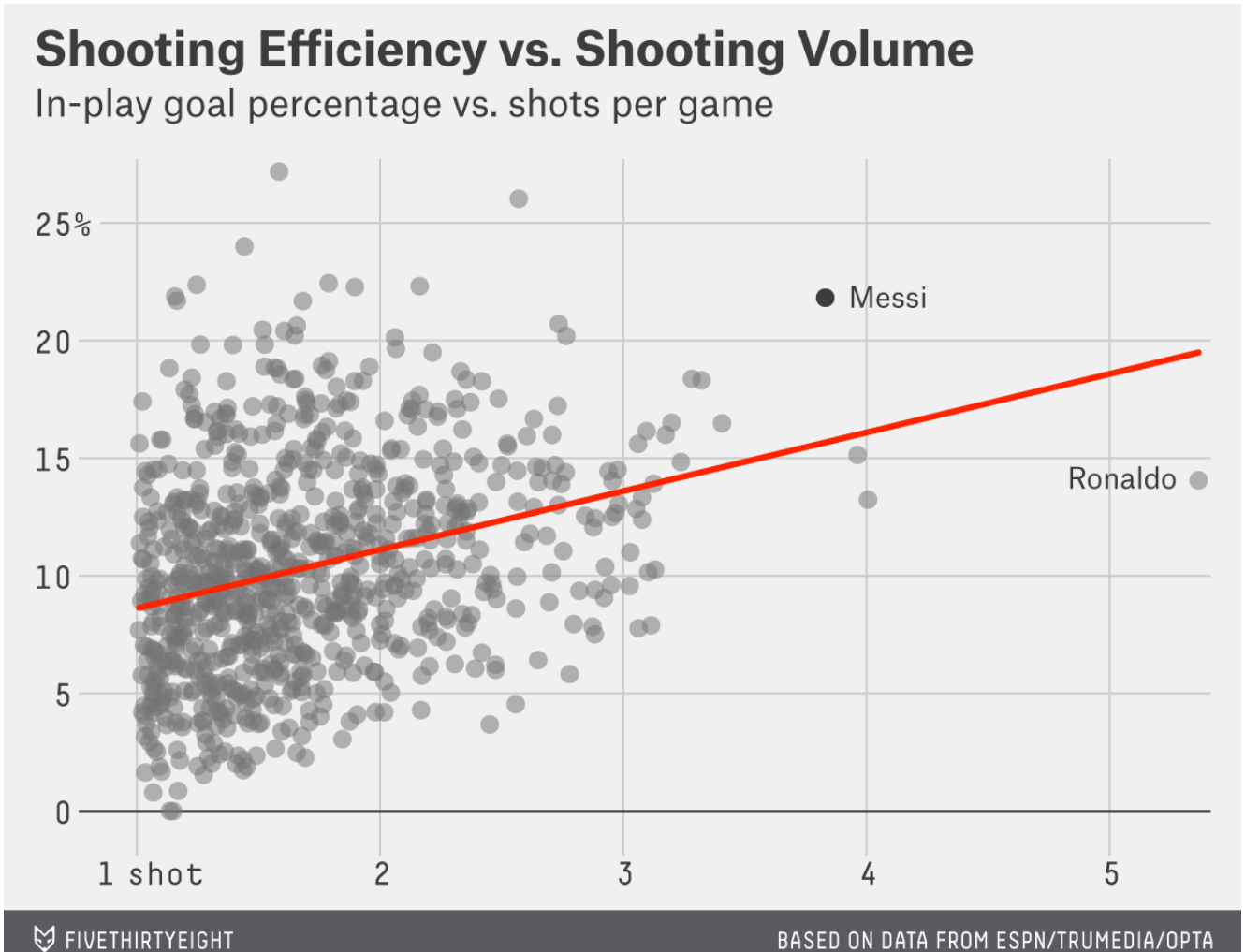


Figure 3: Source: fivethirtyeight

Serious stats

Which sepal length is longer?

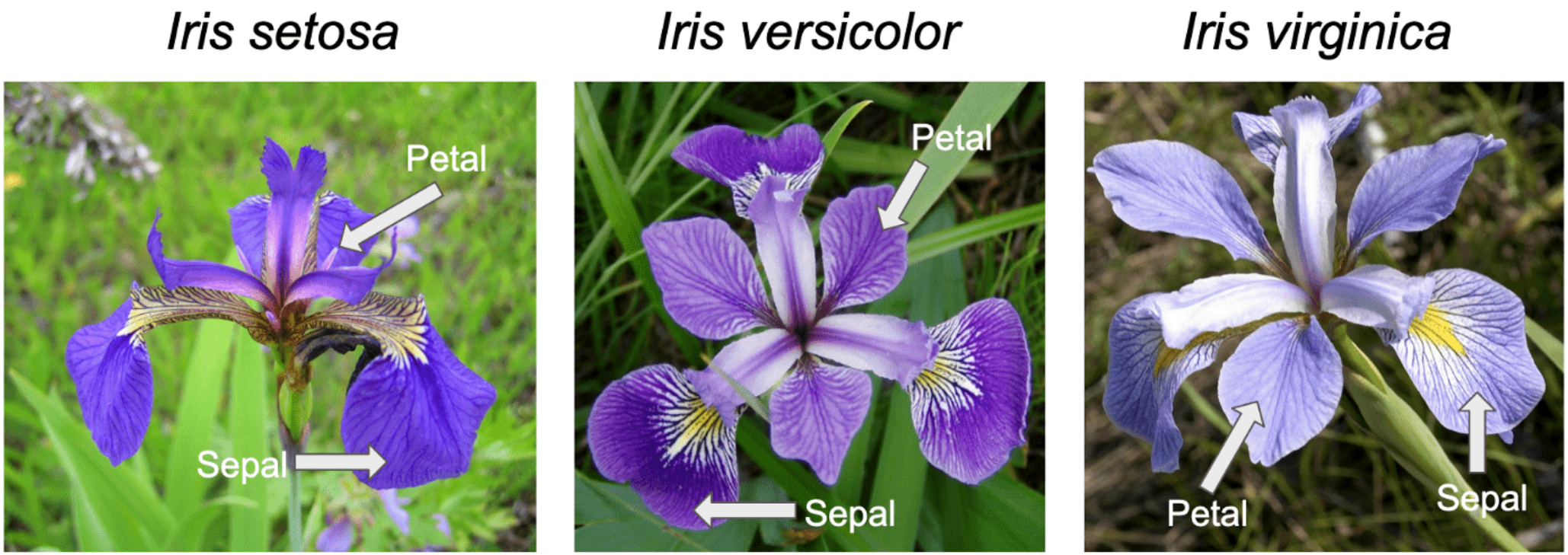


Figure 4: Source: Embedded Robotics

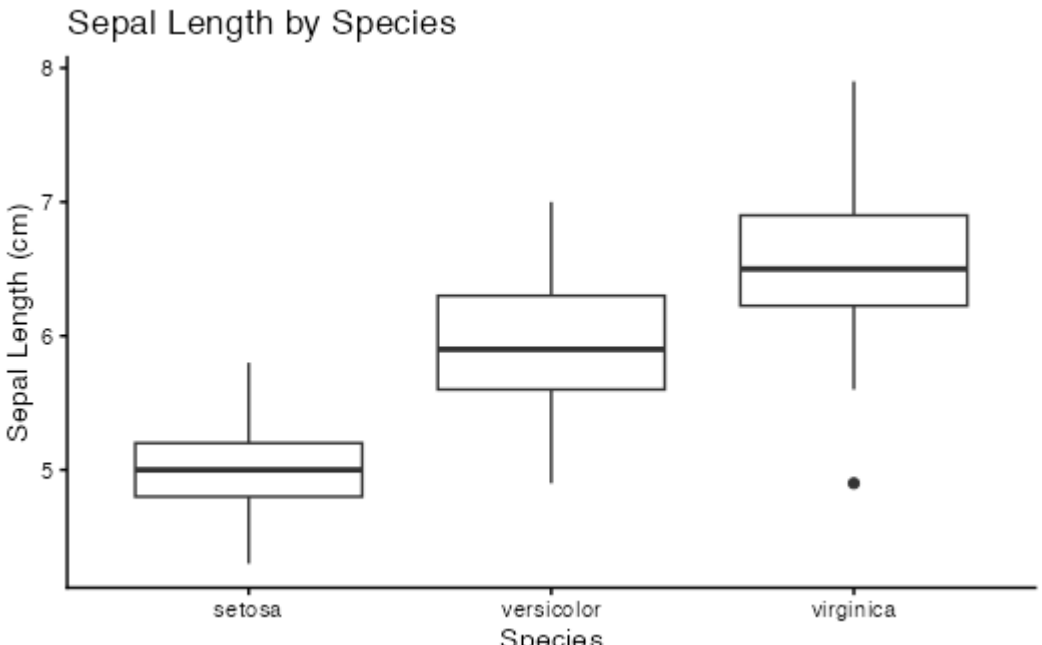
Note: common dataset used in statistics and machine learning.

Serious stats

Visualise

```
# load libraries
pacman::p_load(ggplot2, rstatix, gt)

# create boxplot
ggplot(iris, aes(x = Species, y = Sepal.Length)) +
  geom_boxplot() +
  theme_classic() +
  labs(y = "Sepal Length (cm)", title = "Sepal Length by Species")
```


Sepal Length by Species
Sepal Length (cm)
8
7
6
5
setosa
versicolor
virginica
Species

Serious stats

Infer

We use formal statistical tests to determine if differences are **statistically significant** so that we can make **inferences** about the population based on the sample data – part of the **scientific method**.

```
# run ANOVA
model ← aov(Sepal.Length ~ Species, data = iris)
f_stat ← summary(model)[[1]]$`F value`[1]
p_val ← summary(model)[[1]]$`Pr(>F)`[1]
rstatix::anova_summary(model) |>
  gt() |>
  opt_table_font(font = "Crimson Pro", add = FALSE) |>
  tab_caption(
    caption = "Table 1: One-way ANOVA results comparing sepal length between iris species"
  )
```

Effect	DFn	DFd	F	p	p<.05	ges
Species	2	147	119.265	1.67e-31	*	0.619

Scientific reporting

> A one-way ANOVA revealed significant differences in sepal length between species (ANOVA, $F(2, 147) = 119.26$, $p < .001$).

Not *always* formal

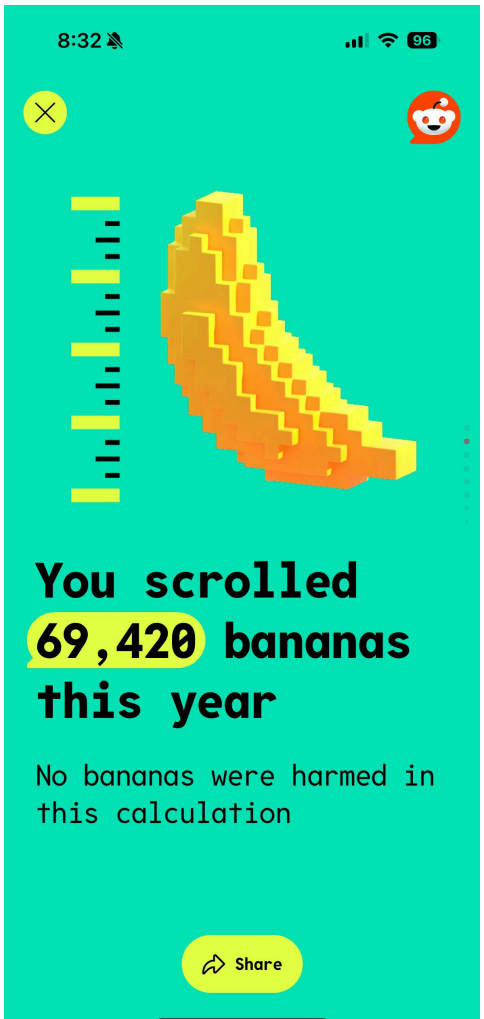


Figure 5: Source: You scrolled

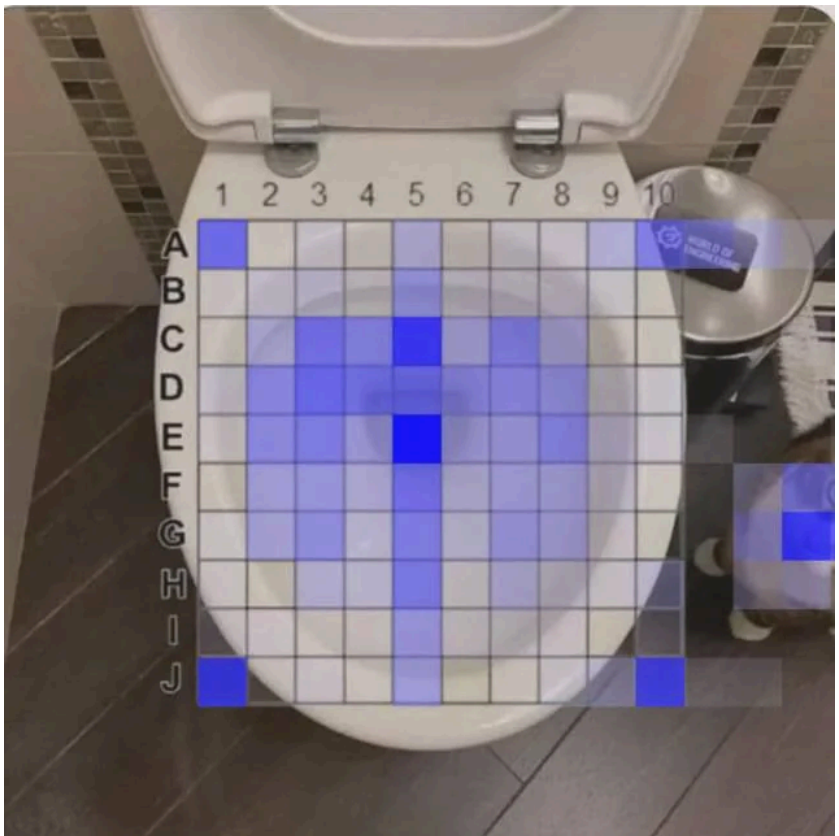


Figure 6: Source: "Guys where do you pee?"

The *beauty* of statistics – formal hypothesis testing is not always required to make a point!

The scientific method

> *The man of science has learned to believe in justification, not by faith, but by verification.*
>
> – Thomas Huxley (1825-1895)

Science as an enterprise

- The scientific method – fundamental to centuries of scientific progress
- If you discover something (**or not**), it should be possible for others to verify your findings independently
- Your findings should be **reproducible** and **replicable**

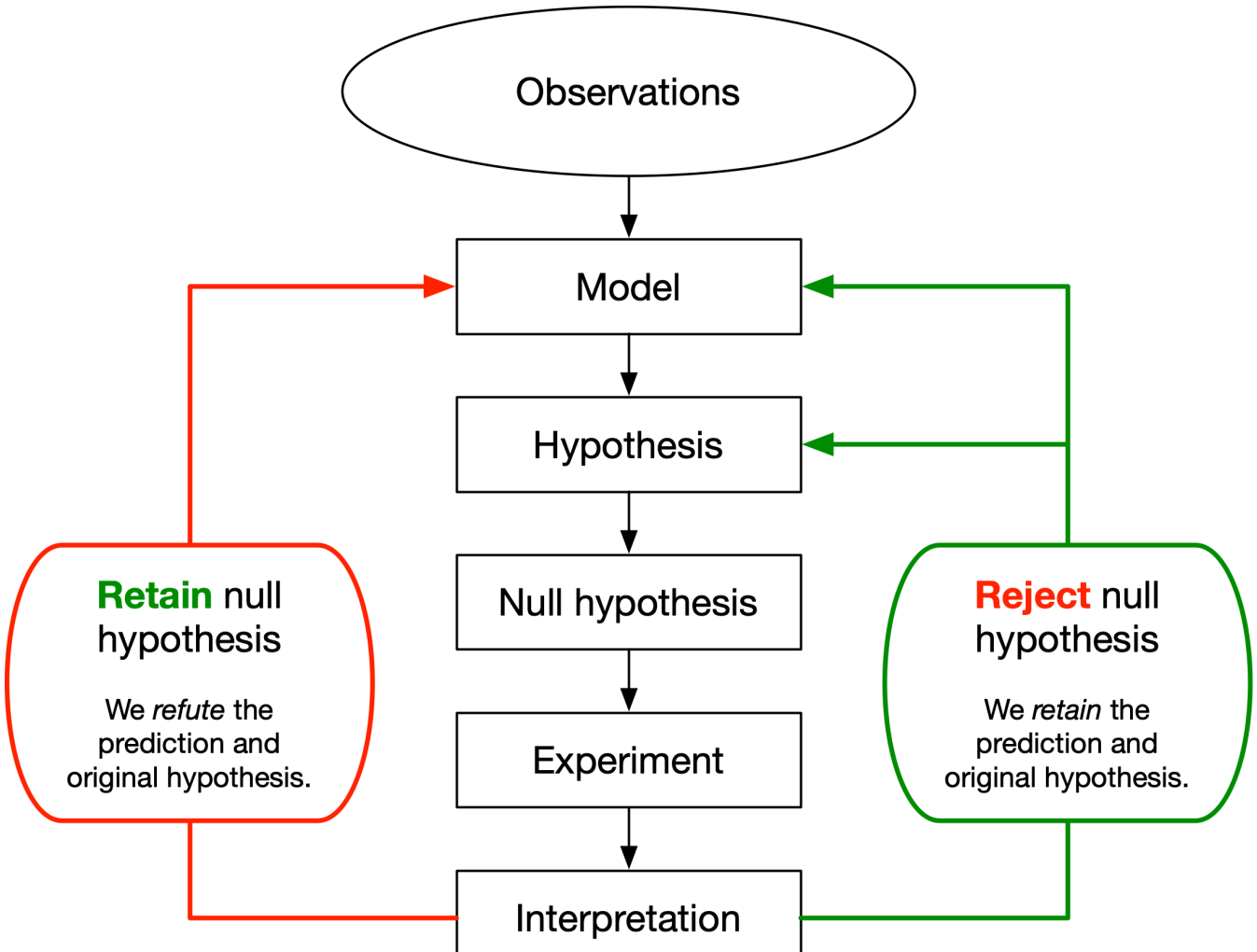
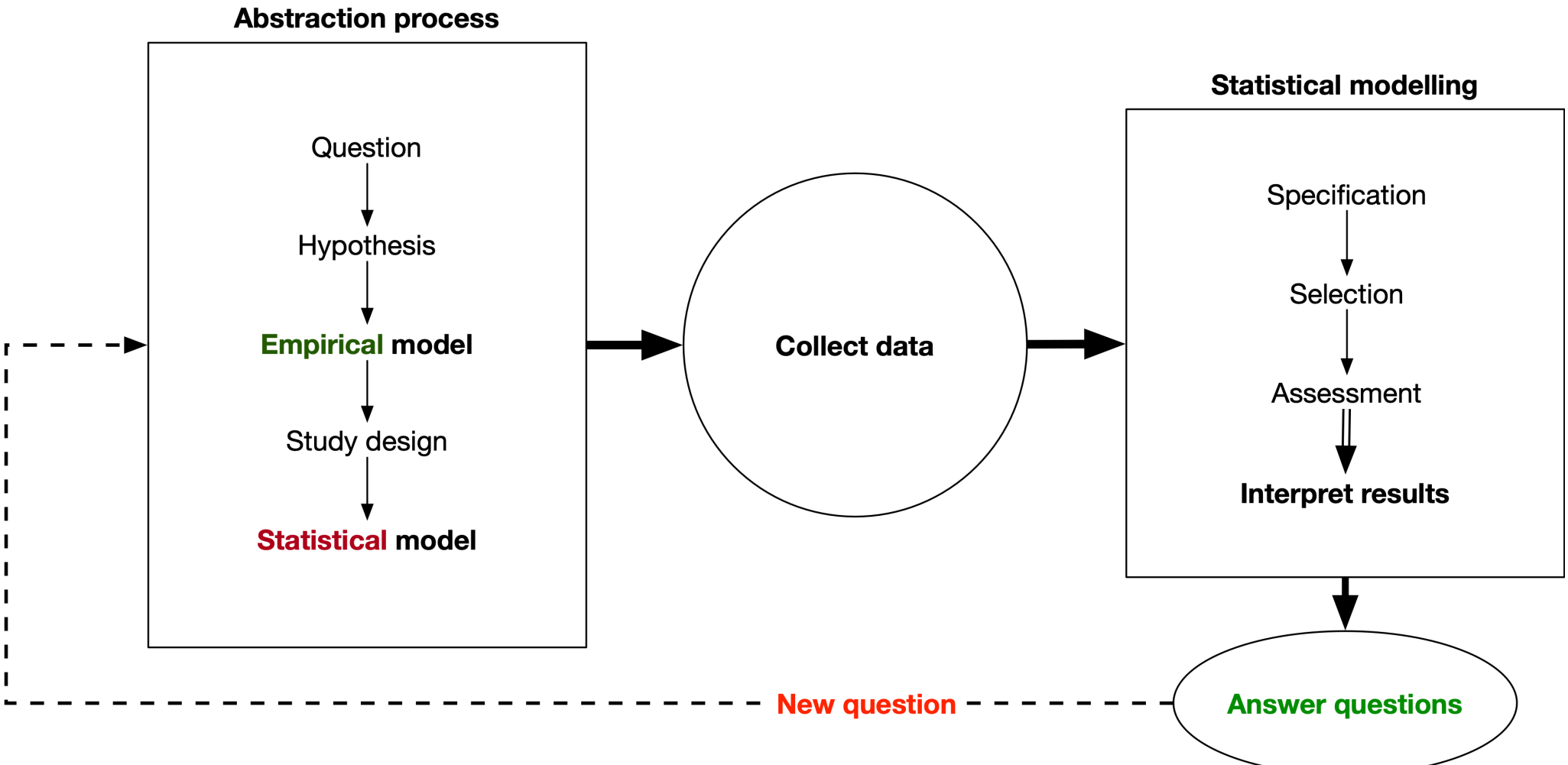


Figure 7: The logical framework by Underwood (1997)

No single method

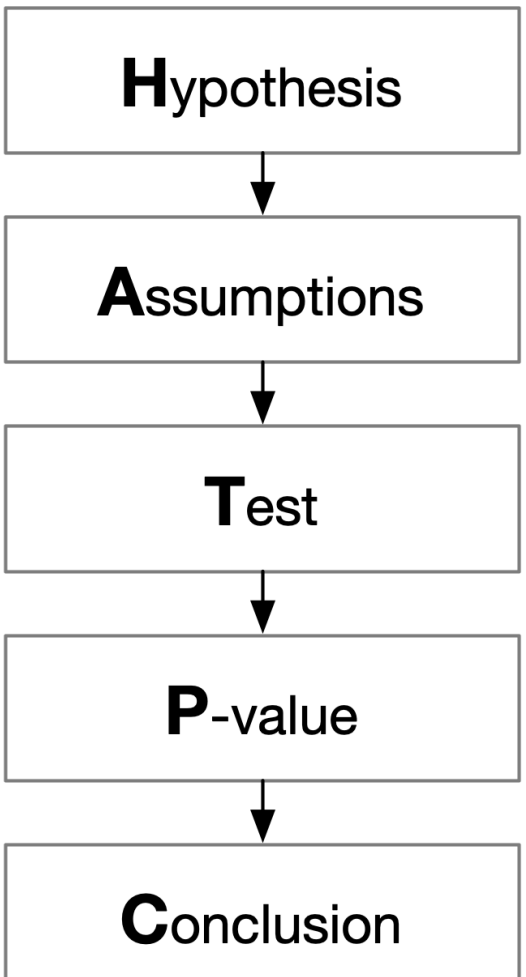
Variations of the scientific method exist – it is a **framework** that guides the process of scientific inquiry


Abstraction process
Question
Hypothesis
Empirical model
Study design
Statistical model
Collect data
Statistical modelling
Specification
Selection
Assessment
Interpret results
Answer questions
New question

No single method

HATPC

Hypothesis – **A**ssumptions – **T**est statistic – **P**-value – **C**onclusion



You will see some variation of the HATPC in your first-year units – a common framework for **report writing**

Key principles (1/2)

1. **Observation**: Identify a phenomenon of interest that can be measured
2. **Question**: Formulate a question that can be answered by collecting data
3. **Research**: Review the literature to understand what is already known – your question may already have been asked by someone else. This step helps in understanding what is already known and what gaps in knowledge may exist.
4. **Hypothesis**: Formulate a **testable** hypothesis – something that can be assessed using data collection and analysis

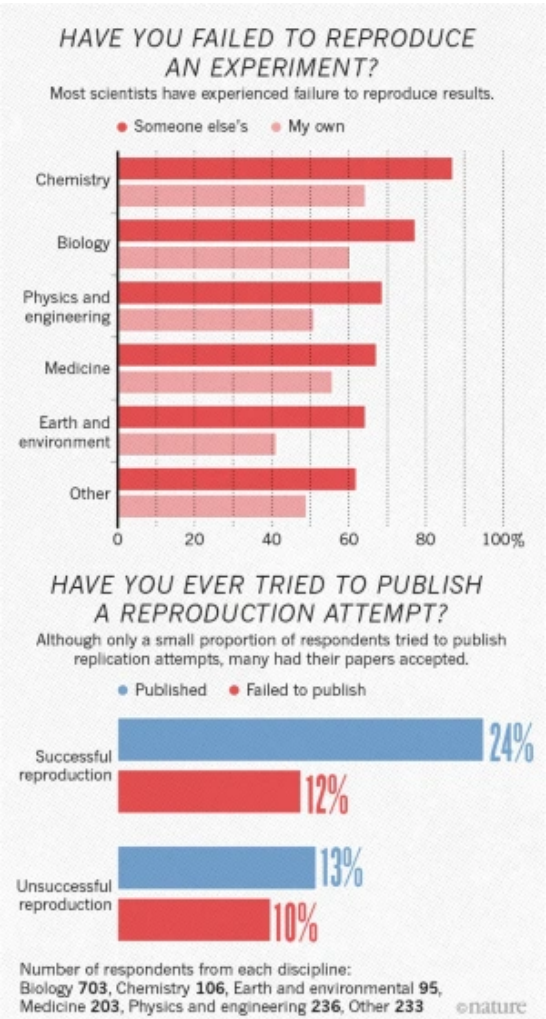
Key principles (2/2)

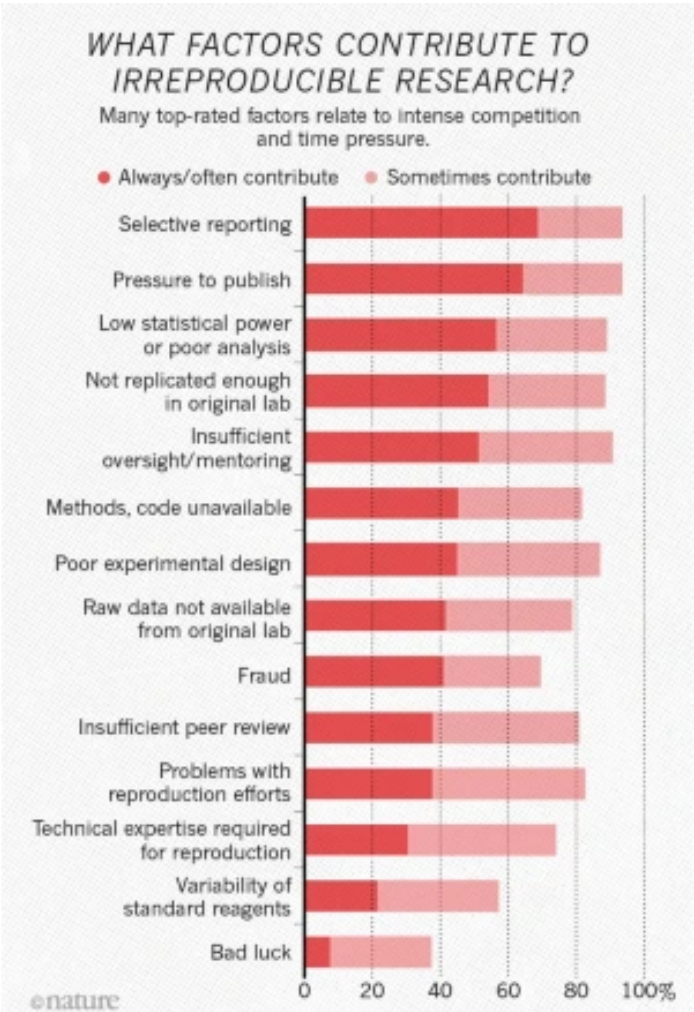
5. **Experiment**: Design an experiment to test the hypothesis
6. **Data collection**: Collect data
7. **Analysis**: use statistical methods to analyse the data and determine if results are statistically significant or demonstrate a pattern
8. **Conclusion**: Interpret the results and draw conclusions. If the results are not significant, this is still a valid conclusion!

Reproducibility crisis despite the scientific method

From Nature (including image sources):

> More than 70% of researchers have tried and failed to reproduce another scientist's experiments, and more than half have failed to reproduce their own experiments.


HAVE YOU FAILED TO REPRODUCE AN EXPERIMENT?
Most scientists have experienced failure to reproduce results.
Someone else's
My own
Chemistry
Biology
Physics and engineering
Medicine
Earth and environment
Other
0
20
40
60
80
100%
HAVE YOU EVER TRIED TO PUBLISH A REPRODUCTION ATTEMPT?
Although only a small proportion of respondents tried to publish replication attempts, many had their papers accepted.
Published
Failed to publish
Successful reproduction
24%
12%
Unsuccessful reproduction
13%
10%
Number of respondents from each discipline:
Biology 703, Chemistry 106, Earth and environmental 95, Medicine 203, Physics and engineering 236, Other 233
©nature


WHAT FACTORS CONTRIBUTE TO IRREPRODUCIBLE RESEARCH?
Many top-rated factors relate to intense competition and time pressure.
Always/often contribute
Sometimes contribute
Selective reporting
Pressure to publish
Low statistical power or poor analysis
Not replicated enough in original lab
Insufficient oversight/mentoring
Methods, code unavailable
Poor experimental design
Raw data not available from original lab
Fraud
Insufficient peer review
Problems with reproduction efforts
Technical expertise required for reproduction
Variability of standard reagents
Bad luck
0
20
40
60
80
100%
©nature

Statistical analysis, experimental design and data issues are the main factors affecting research reproducibility.

Reproducibility and replicability

Key definitions

- **Reproducibility**: the ability to re-run an analysis and obtain the same results
- **Replicability**: the ability to obtain the same conclusions using a *different* dataset or study population

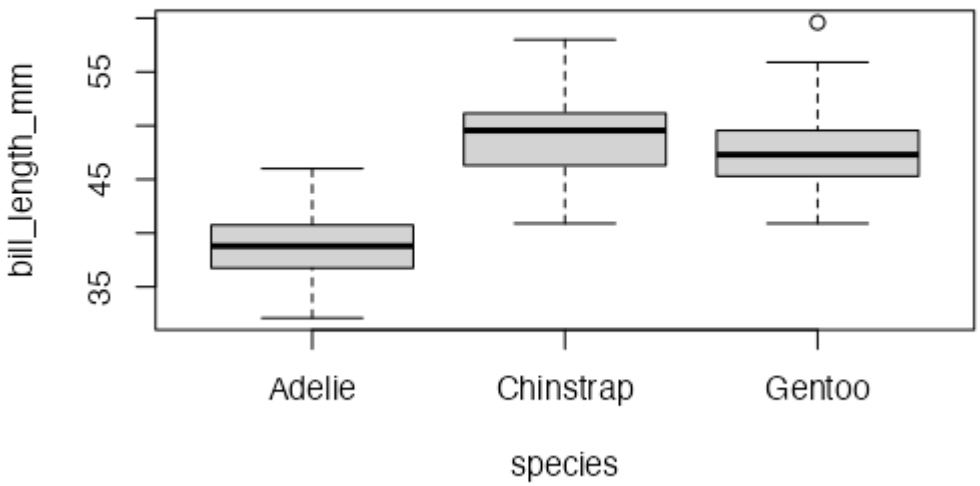
Scientific findings should be **both** reproducible and replicable – the tools that we use *should* facilitate this in the most efficient way possible.

Reproducibility

How would you explain to someone how to reproduce this plot...

- in Excel? Check the guide
- In SPSS? Check the guide
- In R?

```
library(palmerpenguins)
boxplot(bill_length_mm ~ species, data = penguins)
```


bill_length_mm
35
45
55
Adelie
Chinstrap
Gentoo
species

An over-simplification

Those without programming knowledge will *still* struggle to understand and use the two lines of R code shown above.

What you'll learn

- How to read and write basic R code for data analysis
- How to debug by reading error messages and experimenting with code
- Transferable programming skills – all programming languages follow similar principles and you will find others easier to learn, even if not for statistics...

Demonstration

Live demo: walk through a short reproducible analysis in RStudio using Quarto — load data, create a plot, and render the document to show the full workflow from code to output.

References

- Quinn & Keough (2002). Sections 1.1-1.2, pages 1-7.
- Underwood AJ (1997) Experiments in Ecology: Their Logical Design and Interpretation using Analysis of Variance. Cambridge University Press, Cambridge.

Thanks!