Lecture 8

Introduction to Design of Experiments

Reading: Oehlert 2010 Chapters 1, 2; DAE 2017 Chapters 1, 2

STAT 8020 Statistical Methods II

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Agenda

1. **Background and Definitions**
2. **Fundamental Principles of Experimental Design**
3. **History of Experimental Design**

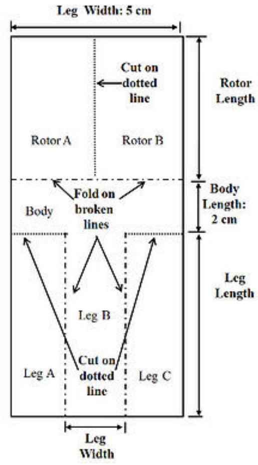
Learning Objectives

By the end of this module, you should be able to:

- Explain the purpose of **design of experiments** (DOE)
- Identify **factors**, **treatments**, and **responses**
- Identify **experimental units and measurement units** in a study
- Explain **randomization**, **replication**, and **blocking**
- Distinguish **observational** vs **experimental** studies

Example: Paper Helicopter Experiment

Research Question: What affects helicopter flight time?



Source: https://blog.minitab.com/en/learning-design-of-experiments-with-paper-helicopters-and-minitab

Response Variable: Flight time

Factors:

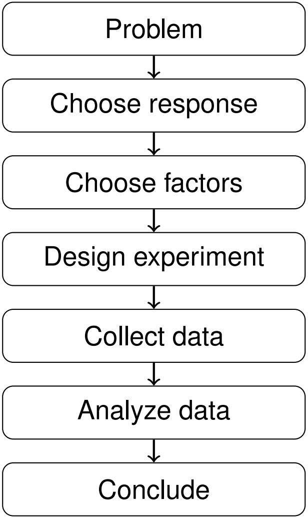
- Paper type
- Rotor length
- Leg length
- Leg width

Levels: Example: Rotor length: 7.5 cm vs 8.5 cm

Experimental Unit: One helicopter

Factor → setting → response

Steps for Planning, Conducting and Analyzing an Experiment



Poor planning at the beginning can invalidate the entire experiment

Battery Experiment [DAE 2017 p. 24]

Research Question: How do battery types vary with respect to life-per-unit cost?

DOE Concept	Example
Response	Battery life per cost
Factor	Battery type (4 types total)
Experimental unit	One battery
Replication	Four batteries per type
Control	All batteries tested using the same device

Basic DOE Terminology

Core DOE Vocabulary

Term	Plain English
Factor	Input variable
Level	Setting of a factor
Response	Outcome measured
Treatment	Combination of factor levels

Additional DOE Concepts

Term	Meaning
Experimental unit	Receives treatment
Randomization	Random treatment assignment
Experimental error	Random variability

Treatments, Experimental Units, and Responses

Treatments
Four battery types: A, B, C, D

↓ assigned to

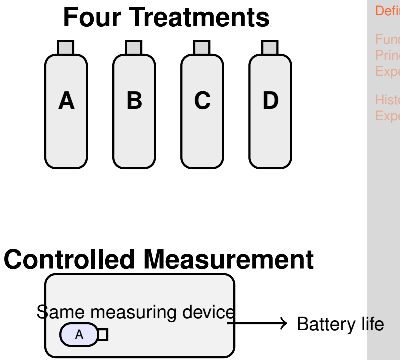
Experimental Units
Individual batteries

↓ tested using

Measurement
Same device measures battery life

↓ produces

Responses
Battery life data



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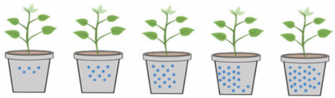
- **The experimental unit determines the true sample size**
- Replication means repeating the treatment on multiple **experimental units**, not just taking multiple measurements on the same unit

Experimental Unit = What Gets Randomized

If a group of "units" must receive the same treatment, they are likely **measurement units** rather than **experimental units**

Scenario	Experimental Unit	Measurement Unit
Fertilizer applied to pots	Pot	Plant
Food placed in fish tanks	Tank	Fish



Fertilizer is assigned to **pots**

Food is assigned to **tanks**

The experimental unit determines the true sample size

More measurements ≠ more replication

Example

1 tank with 100 fish

⇒ still only **ONE experimental unit**

Replication requires multiple experimental units,
not multiple measurements on the same unit.

This is one of the most important ideas in DOE

Observational vs. Experimental Studies

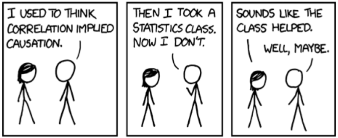
Study Type	Researcher Controls Treatment?	Can Support Causation?
Observational	No	Usually no
Experimental	Yes	Often yes

Examples

- **Observational study:** Smoking and health studies
- **Experimental study:** Clinical trials with randomized treatments

Key Idea

Experimental studies can often support **cause-and-effect conclusions** because treatments are controlled and randomized



Source: `http://users.stat.umn.edu/~gary/classes/5303/lectures/Introduction.pdf`

Why Designed Experiments?

- Design for direct comparison of treatments
- Design to reduce bias in comparisons (avoid systematic errors)
- Design to reduce variability (be precise)
- Experiments support causual inference

Why Designed Experiments?

Why not change one thing at a time?

- **Randomization** helps protect against **hidden variables** and confounding effects that may otherwise bias comparisons
- Factors may **interact** with each other, so changing only one factor at a time can miss important relationships
- DOE studies multiple factors simultaneously, allowing us to learn more information from fewer experimental runs
- Good experimental design helps reduce both **variability** and **bias**, leading to more precise comparisons
- Proper experimental design provides stronger support for **cause-and-effect conclusions**

DOE helps us learn MORE with FEWER experiments

Fundamental Principles: Replication, Randomization, and Blocking

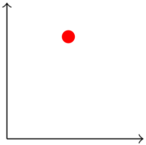
These three principles form the foundation of experimental design

Replication

Why do we replicate experiments?

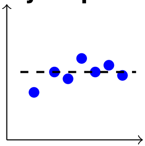
- Replication helps us **estimate variability** in the response
- Replication reduces **uncertainty** in estimated treatment effects
- Replication improves the **reliability** and stability of conclusions

One Observation



Very noisy estimate

Many Replications



Averaging reduces noise

Randomization = Protection Against Confounding

Randomization uses a chance mechanism (such as a random number generator) to assign treatments to experimental units

- Protects against **lurking** or hidden variables
- Reduces the influence of **subjective bias** in treatment assignment
- Supports the validity of **statistical inference**

What can go wrong without randomization?

Treatment Assignment	Problem
Morning runs → Treatment A Afternoon runs → Treatment B	Temperature changes throughout the day → treatment becomes **confounded** with temperature

Randomization helps balance unknown sources of variability

Blocking

Blocking removes known nuisance variation

A **block** is a group of similar experimental units

Treatments are compared within blocks to reduce variability

Source of Variation	How to Block
Day	Compare treatments within the same day
Batch	Compare treatments within the same batch

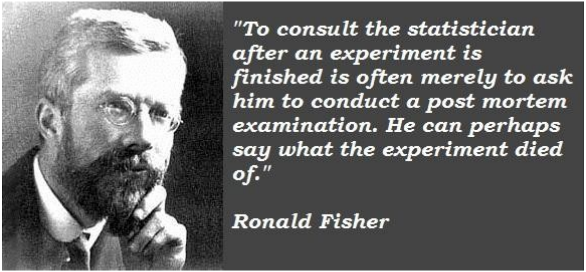
- Blocking reduces **variability** in treatment comparisons
- Compare treatments within homogeneous groups
- Effective blocking creates:

  large between-block variation > small within-block variation

Block what you can and randomize what you cannot

A Brief History of Experimental Design: Agricultural Era

- R. A. Fisher and his co-workers, Rothamsted Agricultural Experimental Station (1930, England)
- Introduced statistical experimental design and data analysis. Summarized the fundamental principles: **replication**, **randomization**, and **blocking**
- Factorial designs, ANOVA



A Brief History of Experimental Design: Industrial Eras

- The first industrial era, 1951 - late 1970s
  - Process modeling and optimization
  - G. E. P. Box & K. B. Wilson and coworkers in chemical industries and other processing industries
  - Empirical modeling, response surface methodologies, central composite design
- The second industrial era, late 1970s - 1990
  - Quality improvement and variation reduction
  - G. Taguchi and robust parameter design

Modern Experimental Design and Emerging Applications

- Experimental design is now widely used beyond statistics and has become an indispensable tool in many scientific and engineering applications.
- New challenges include:
  - Large and complex experiments, such as screening designs in the pharmaceutical industry and experimental design in biotechnology.
  - **Computer experiments:** efficient methods for modeling complex systems using computer simulations.
- Modern application areas include:
  - pharmaceutical screening
  - A/B testing
  - autonomous vehicles
  - and climate simulation

Summary

These slides cover:

- Basic concepts of design of experiments (DOE):
- A brief history of DOE
- Fundamental principles: randomization, blocking, replication

Summary

- DOE supports stronger **cause-and-effect conclusions**
- **Randomization** protects against bias and confounding
- **Replication** reduces uncertainty and improves reliability
- **Blocking** reduces variability from nuisance factors
- **Experimental units** determine the true sample size

Good experimental design leads to better decisions

Upcoming Topics in Design of Experiments

- Completely Randomized Designs
- Randomized Complete Block Designs, Factorial Designs, and Split-Plot Designs
- Random and Mixed Effects Models
- Computer Experiments