

Design and Analysis of Experiments

02 - The Role of Experimentation

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“Science makes people reach selflessly for truth and objectivity; it teaches people to accept reality, with wonder and admiration, not to mention the deep awe and joy that the natural order of things brings to the true scientist.”

Lise Meitner (1878 - 1968)
Austrian-Swedish physicist



Image: <https://www.surlatoile.com/WomenInScience/lise-meitner/>

Art by Fran6co: <http://fran6co.blog2b.net/>

Experiments

Definition of experiment

An experiment can be characterized as a test (or a series of tests) wherein changes are introduced in the state of a system or process, enabling the observation and characterization of effects that can occur as a result of these changes.

Usually performed with an objective in mind:

- Uncovering influential variables in a given system or process;
- Determining desired values for certain parameters
- Characterize behavior of the system or process under study.

Experiments

Data gathering

- Retrospective study;
- Observational study;
- Designed experiment;

Characteristics

- Use of historical data;
- Investigating correlations;

Problems

- Data representativeness;
- Availability of data;

Experiments

Data gathering

- Retrospective study;
- **Observational study**;
- Designed experiment;

Characteristics

- Observation of the system with minimal disturbance;
- Investigation of usual behaviors;

Problems

- Low representativeness of extreme cases;
- Low variability can affect observation of interesting effects;

Experiments

Data gathering

- Retrospective study;
- Observational study;
- **Designed experiment;**

Characteristics

- Introduction of deliberate changes in the system;
- Inference on the *causality* of the effects;

Problems

- Requires rigorous experimental design and data analysis;
- Usually more expensive.

Experimentation strategies

Educated guessing

- Select arbitrary combination of levels for the factors;
 - Test and observe behavior;
 - Change one or two factors at a time, then re-test;
-
- Widely used in industry;
 - Can achieve good results, but has a lot of limitations;

Experimentation strategies

Educated guessing

- Select arbitrary combination;
- Test and observe;
- Change and re-test;

Educated Guess

(NAPA VALLEY + 2007)

CABERNET SAUVIGNON

Why "Educated Guess?" Have you ever found yourself in a wine shop or restaurant perusing the wines and wondering... how do I choose the best wine for the money? You may admire a label, recognize a name, or recall a great review... in essence you're making an "Educated Guess." This is exactly what goes on in the vineyards and wineries around the world. When should we pick the grapes? Should we barrel age in French Oak? Will our customers like the package? Our experts use their knowledge, intuition, and years of experience to make the best possible decisions; however, at the end of the day, it still remains an "Educated Guess." At Roots Run Deep we have done the Guesswork for you. This Napa Valley Cabernet Sauvignon is the richest, ripest, and most complex Cabernet you can buy for the money. So don't settle for less, buy "Educated Guess!"



Experimentation strategies

Educated guessing

- Select arbitrary combination;
- Test and observe;
- Change and re-test;

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When should we pick the grapes? Should we barrel age in French Oak?

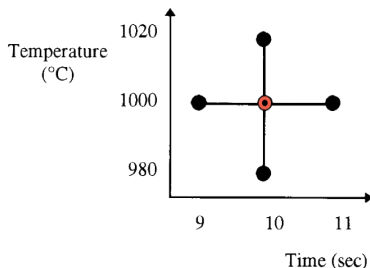
When should we pick the grapes? Should we barrel age in French Oak? Will our customers like the package? Our experts use their knowledge, intuition, and years of experience to make the best possible decisions; however, at the end of the day, it still remains an "Educated Guess." At



Experimentation strategies

COST: Change One Separate factor at a Time

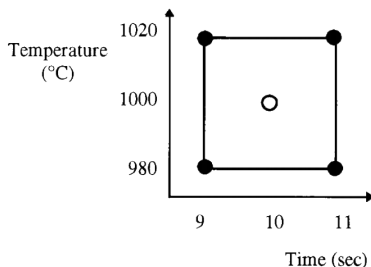
- Select a reference point;
- Change each factor individually, keeping all others constant;
- Also widely used;
- Can achieve good results as long as there are no interaction effects;



Experimentation strategies

Factorial designs

- Select **levels** for each factor;
- Vary the factors simultaneously, in a systematic way;
- Estimation of main effects and interactions;
- Greater precision in the effect estimates;
- More efficient use of resources (information/observation);



Fundamental principles

Design of experiments (DoE)

Process of designing data gathering protocols to enable accurate analyses by statistical tools, capable of supporting sound and objective conclusions.

- Applicable to systems and processes subject to noise, experimental errors, uncertainties, etc.
- Necessary for the conclusions to have a quantifiable meaning;
- Helpful in avoiding errors due to personal biases or other artifacts of experimentation and analysis.

Fundamental principles

Design of experiments (DoE)

Design of the experiment

- Scientific/technical question of interest;
- Selection of variables and values;
- Definition of the desired confidence level;
- Sample size calculations;
- Determination of protocols for data gathering;

Statistical analyses of the data

- Calculation of a test statistic;
- Validation of the assumptions of the statistical model;
- Calculation of the magnitude of effects;
- Drawing of conclusions and recommendations;

Fundamental principles

Design of experiments (DoE)

- Repetition and replication;
 - Randomization;
 - Blocking.
-
- Repeated measurements - estimation of within-group variability;
 - Replication - estimative of the experimental error;
 - Greater precision in estimating the model parameters;

Fundamental principles

Design of experiments (DoE)

- Repetition and replication;
 - **Randomization**;
 - Blocking;
-
- Avoids contamination of the data by order-dependent effects such as:
 - Heating effects;
 - Wear and tear effects;
 - External interferences;

Fundamental principles

Design of experiments (DoE)

- Repetition and replication;
 - Randomization;
 - **Blocking**;
-
- Isolation of nuisance variables (those that influence the response, but are not interesting for the analyses) that can be controlled;
 - Improvement in the estimation of effects for the factors of interest;
 - Reduction or eliminations of inconvenient factor effects;

Fundamental principles

The role of experimental design

Experimental design is useful for avoiding the influence of spurious factors and personal biases on the results, by performing experiments in a impartial and objective way.

“Never have too much love for your hypotheses.”

“The great tragedy of Science - the slaying of a beautiful hypothesis by an ugly fact.”
– Thomas H. Huxley



Structure of Experimental Design

Main points

To enable the use of a scientific approach in the design of an experiment, it is important to have on a solid understanding of:

- The field where the experiment is to be conducted;
- The strategy for data collection;
- The way the data should be analyzed (at least qualitatively).

Structure of Experimental Design

Guidelines for a good design

- Pre-experimental design:
 - Identification and definition of the problem;
 - Selection of experimental and response variables of interest;
 - Choice of experimental protocols;
- Choice of the experimental design;
- Collection of the data;
- Statistical data analyses;
- Conclusions and recommendations;

Pre-experimental design

Before we start

- Is the investigation relevant?
- Would the results be interesting for the research community?
- Practical relevance?
 - Employ exploratory experiments;
- Placement within the literature;
 - Avoid repetition and irrelevance.

"Sometimes one should do a completely wild experiment, like blowing the trumpet to the tulips every morning for a month. Probably nothing would happen, but what if it did?"

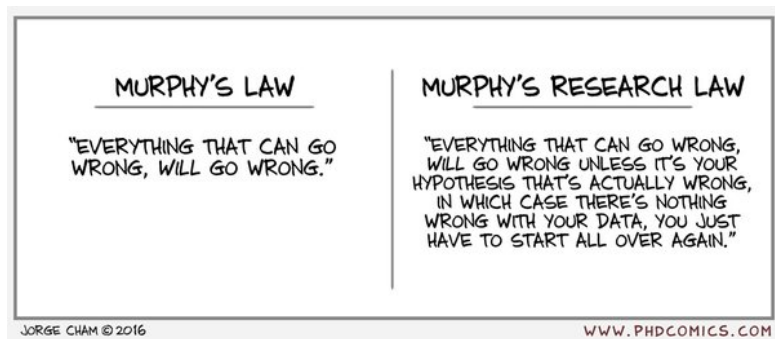
– Sir George Howard Darwin



Pre-experimental design

Definition of hypotheses

- The translation *scientific question* → *test hypothesis* requires special attention, and a solid knowledge of the technical area in which the experiment is being performed;



Choice of Experimental Design

Experimental design

- (Relatively) simple, as long as the pre-experimental part is well done;
- Dependent on what is being tested (statistical question);
- A sound design tends to determine the analyses technique to be used, at least qualitatively;
- Involves considerations about:
 - Sample size;
 - Ordering of observations;
 - Determination of restrictions to the randomization and the use of blocks, etc.
- Available in several statistical/mathematical packages;

Choice of Experimental Design

Problem-dependent

- Depending on the experimental question, different experimental designs are required
- A solid, statistically sound design tends to determine which statistical tests must be employed in the analysis step, at least qualitatively.
- Quantification of the proportion between intra-groups and inter-groups variability;

Actual Experiment

Data gathering

- Must be consistent with design, otherwise the validity of the results may be compromised - data collection must always follow the plan:
 - No premature stops;
 - *No-peeking rule*^a;
- Use of pilot experiments:
 - Gathering of preliminary information;
 - Practice with the experimental conditions;

^aExcept when planned, of course.

Analysis of the experimental data

A consequence of design

- Analysis techniques are generally relatively simple, but *the devil is in the details*;
- Use of existing statistical tools and frameworks, such as



- Free, versatile, good graphical capabilities, relatively simple (but with one hell of a learning curve);

Analysis of the experimental data

Statistical modeling

- General procedure for testing the experimental hypotheses:
 - Definition of a *null-model* (absence of effects) and of a desired level of significance;
 - Determination of $P(\text{data}|\text{null-model})$;
 - Decision by rejection (or not) of the null hypothesis;
 - Validation of model assumptions;
 - Estimation of the *magnitude* of differences - **practical significance**;

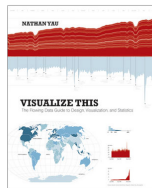
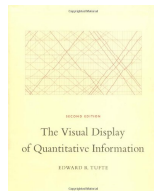
*Statistical methods do not **prove** anything, but they allow an objective definition of margins of plausibility for certain statements.*

Reporting of results

Presentation

Combine textual, numeric and graphical elements to tell a story with your data. It simplifies the understanding and analysis of the results.

- Strive to achieve graphical excellence;
- Coherence of notation - special attention to figures and tables;
- Display simultaneous confidence intervals and other graphical indicators of effect size.



Other great resources on graphical excellence:

Flowing Data (<http://flowingdata.com/>)

Information is Beautiful (<http://www.informationisbeautiful.net>)

Conclusions

Drawing and reporting conclusions

- Conclusions should be based on solid evidence from the data;
- Be conservative - it is common to exaggerate the generality of the results;
- Report significance levels and the assumptions under which the results are valid;
- *Suggest explanations* to the observed results;
- Careful with *anomaly hunting*;

Always let the science drive the statistics. If you get a statistically significant result, go back and describe what it means in the scientific context.

– Aaron Rendahl

Discussion

Some more relevant points

- Use of previous knowledge, theoretical or empirical;
- Iterative experimentation;
- Statistical \times practical significance;
- Use of additional experiments to validate conclusions.

Bibliography

Required reading

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Recommended reading

- 1 A. Rendahl, *Experimental design and statistical analysis: questions to consider as you write your grant*. - <http://goo.gl/yT0TK7>
- 2 V. Czitron, *One-Factor-at-a-Time Versus Designed Experiments*. The American Statistician, 53(2) 126-131, 1999.
- 3 S.C. Stearns, *Some Modest Advice for Graduate Students* - <http://goo.gl/jtT4hA>

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