Spring 2023

ME 794 Statistical Design of Experiments

Chapter 0

Introduction

Prof. Soham Mujumdar

Email: sohammujumdar@iitb.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Bombay

NOTE: Some of the course material is adopted from 'Design and Analysis of Experiments' by D. C. Montgomery, and similar courses taught by Prof. S. G. Kapoor at the University of Illinois at Urbana-Champaign and Prof. S. S. Joshi at IIT Bombay. You do NOT have permission to share this file or any of its contents with anyone else, and/or upload it on the internet or any of the platforms where it can be accessed by others.

ME 794 Schedule

Spring 2023, IIT Bombay

Time: Tuesdays and Fridays, 5.30 pm – 6.55 pm

CL 111 ESE

Instructor:

Prof. Soham Mujumdar

S23, Mechanical Engineering,

sohammujumdar@iitb.ac.in

Office hours: Wednesdays, 4:15 pm to 5:00 pm by appointment

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Grading Policy

Lecture Notes:

- Take your own notes
- Lecture notes/slides and reference material will be provided as and when required via MS Teams

Grading:

Quiz	40%	(Best 4/5, preannounced, typically after every 4-5 lectures, **NO MAKE-UP**)
Assignments	20%	(All assignments are mandatory, typically coding-based, submission via Teams)
Project	15%	(Team project, actual experiments are expected)
Final Exam	25%	(Comprehensive)

Any student/group found to have committed or aided and abetted the offence of plagiarism will receive ZERO marks for the relevant assignment/quiz without any exceptions

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What is the NEED for experiments?

- Why do we perform experiments? (scientific or otherwise)

- Share what experiments you have performed or are currently planning

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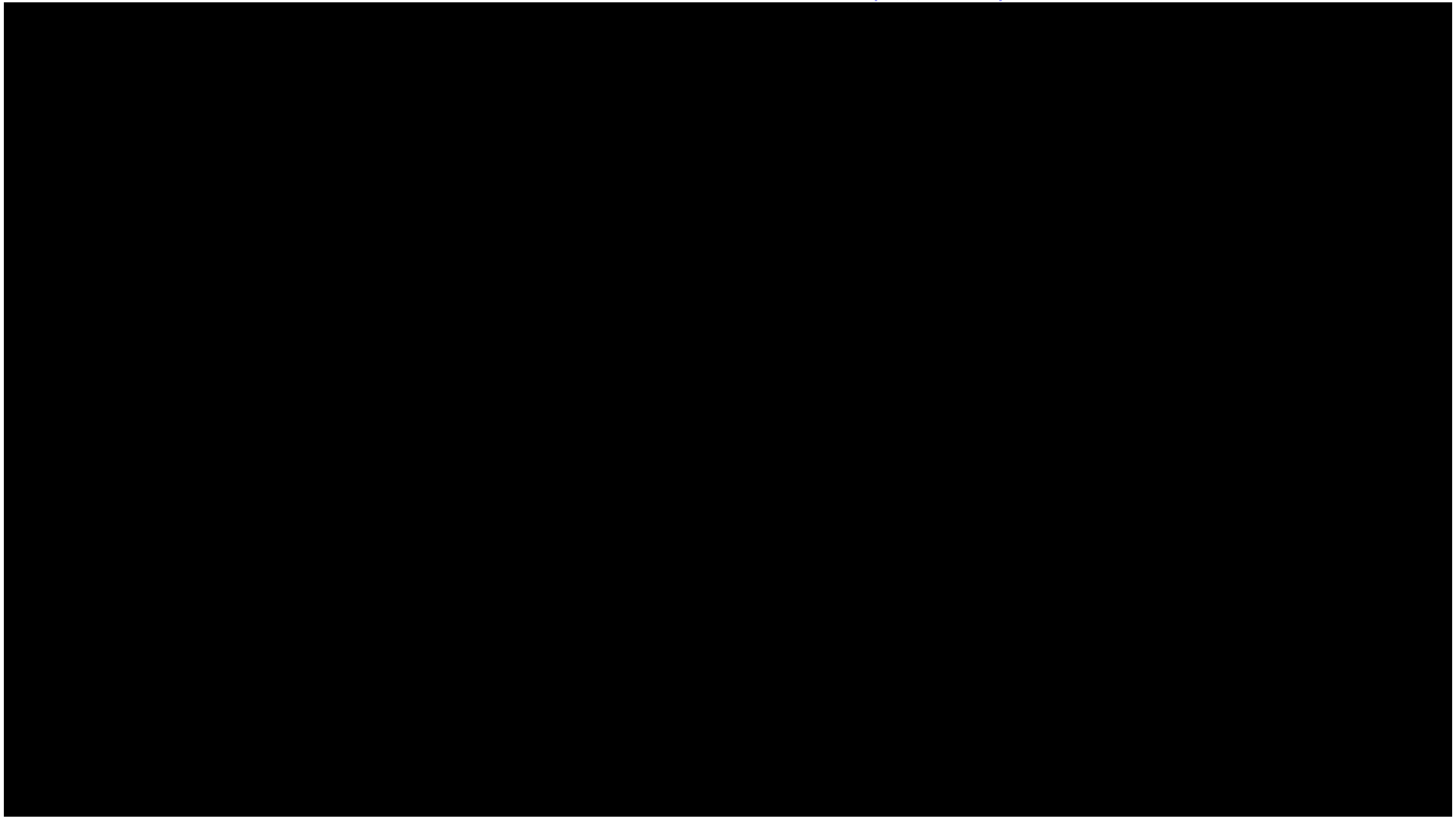
Example Experiment

Ref: https://www.youtube.com/watch?v=hJsZe6anWPo



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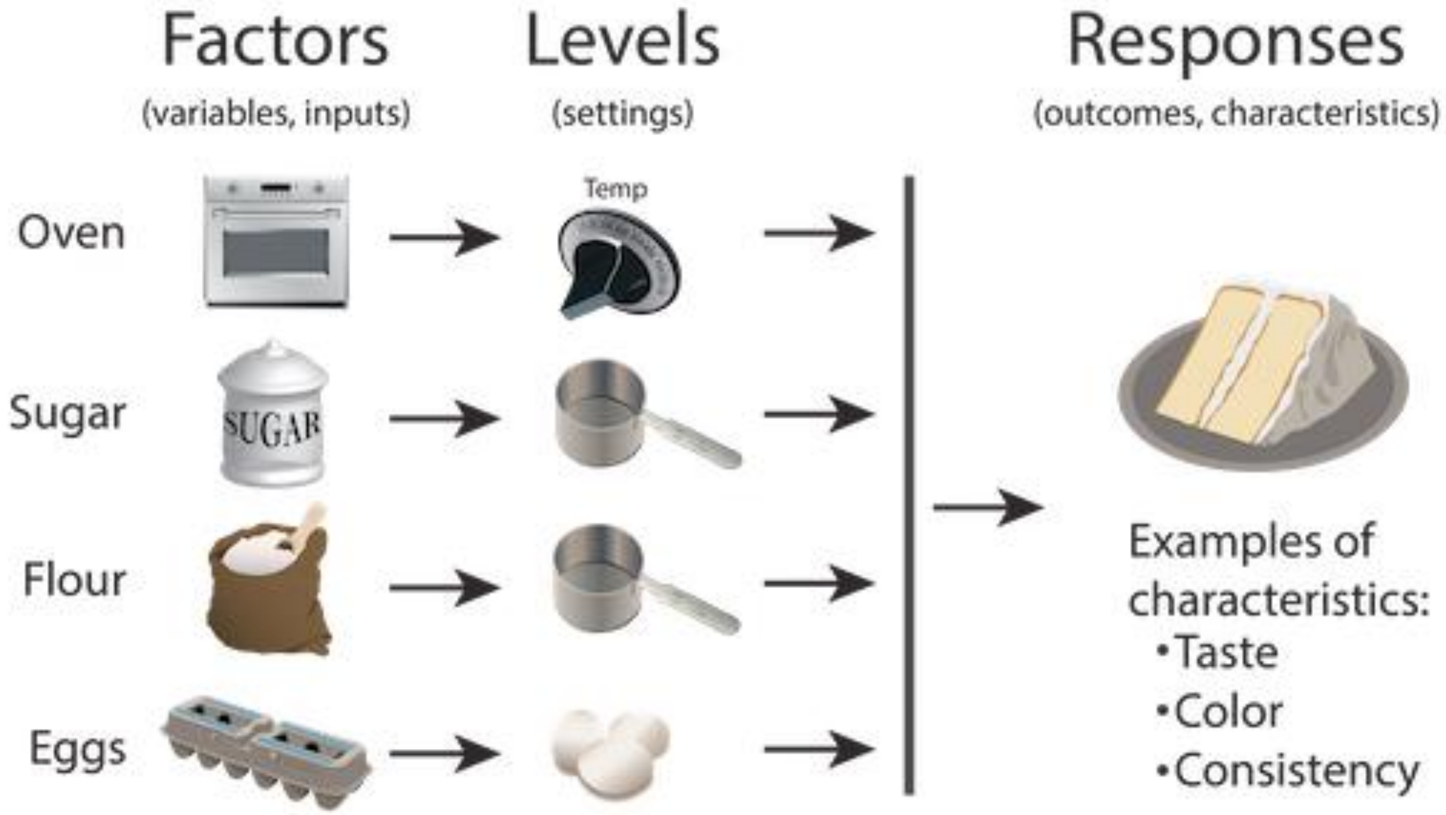
Example Experiment



Ref: www.morestream.com

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Need for Experiments

- To understand how a product functions or a process behaves
- To discover the direction of changes that may lead to improvements in both quality and productivity.

A fundamental task in designing a (scientific) experiment is to select an appropriate arrangement of test points within the space defined by the independent variables and develop a mathematical model

- For example, if a quadratic relationship between two variables is suspected, an experiment that studies the process at only two levels of these variables will be inadequate.
- Similarly, an experiment using four levels would be unnecessary and inefficient if the true relationship were linear.

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Why Statistical Methods?

- **The world around us is not deterministic!** – **Variability** is part of the natural order of things
- Variation in data is neither totally chaotic nor small enough to be ignored
- It is real, identifiable, and predictable statistically

What is variability?

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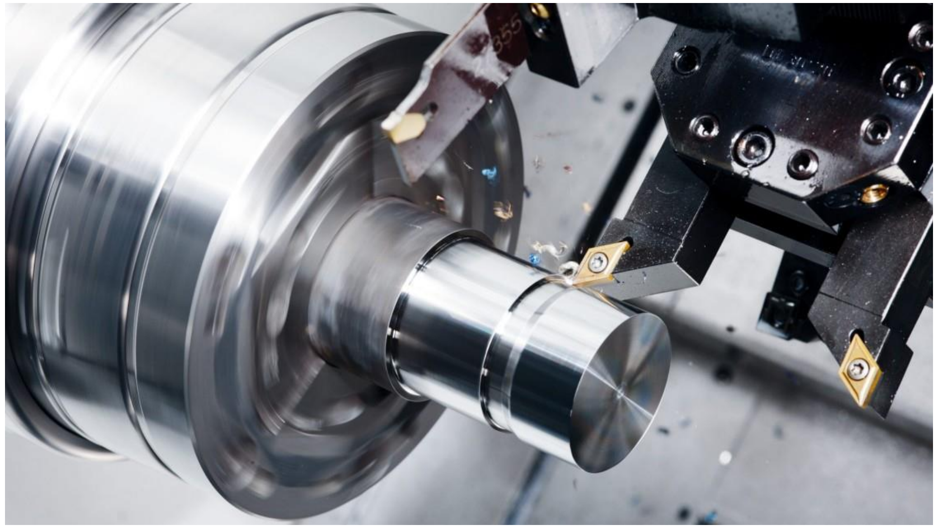
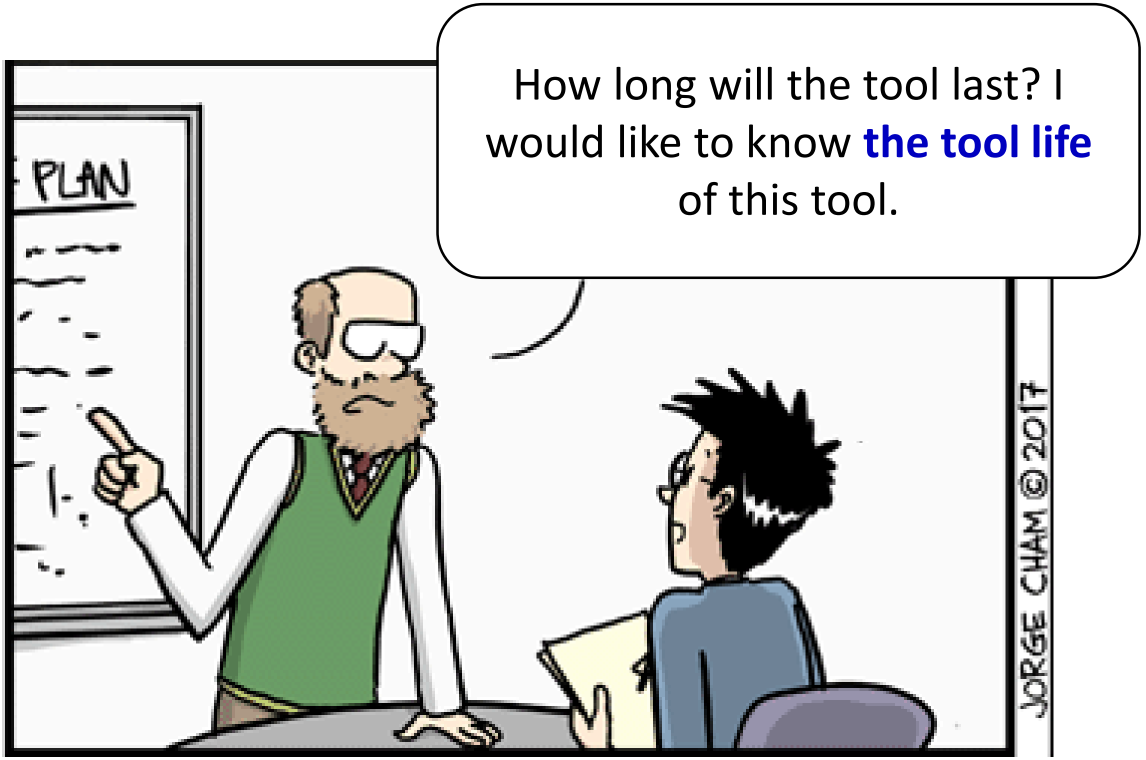
Example





Turning operation under following conditions

Speed:	170 FPM
Feed:	0.017 IPR
Depth of Cut:	0.07 IN
Workpiece:	1018 Steel of 6 IN Dia, 24 IN Length

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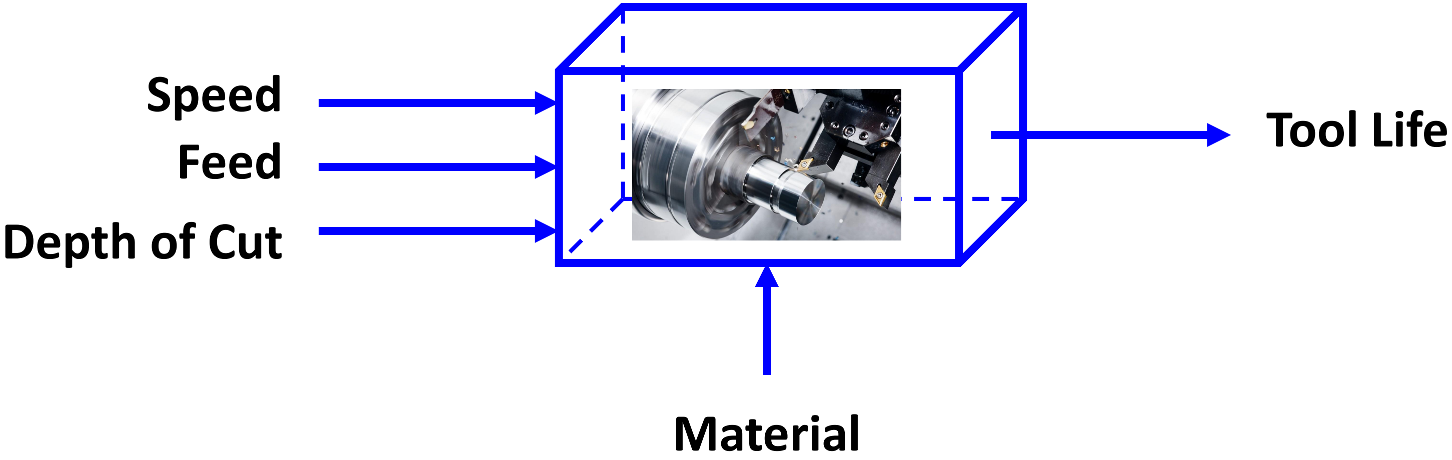

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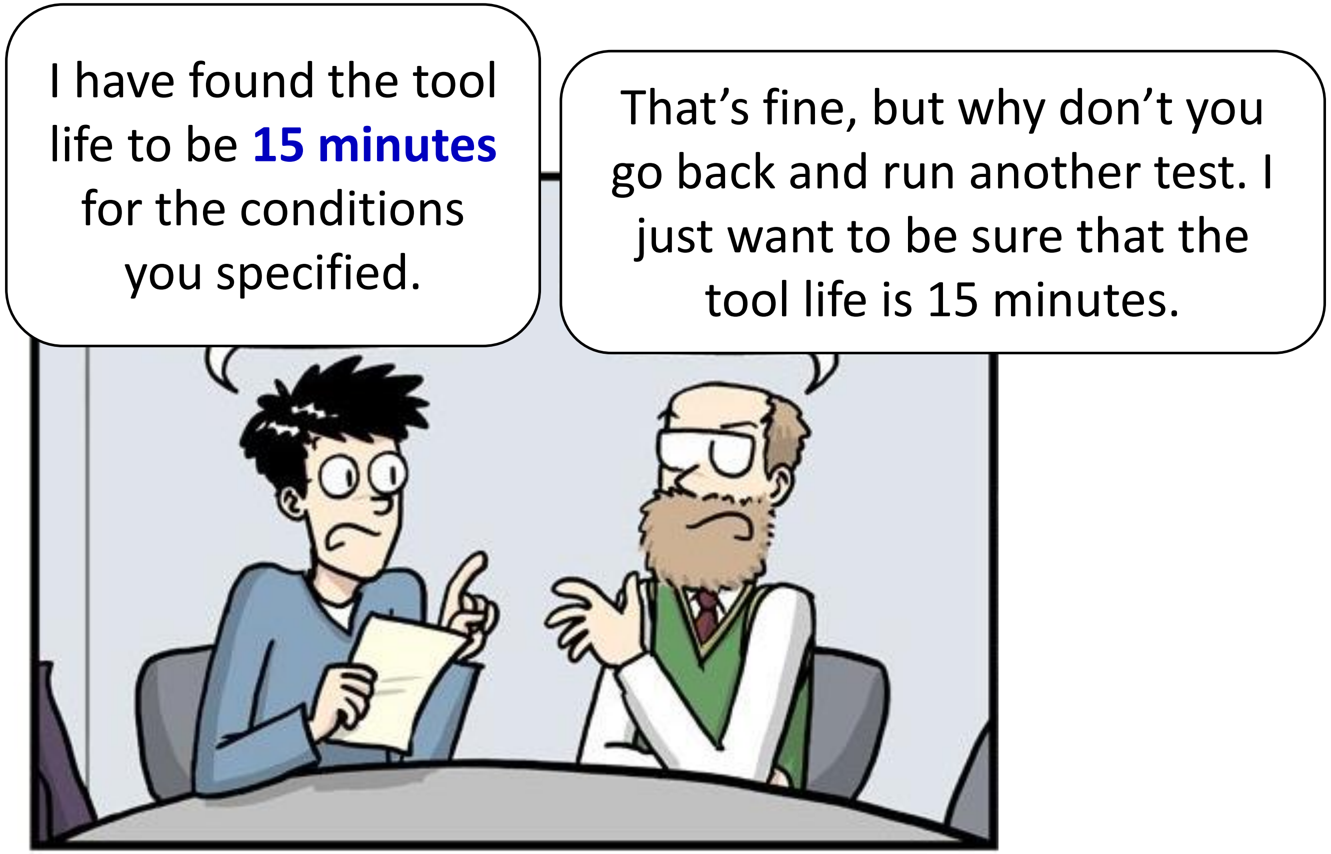

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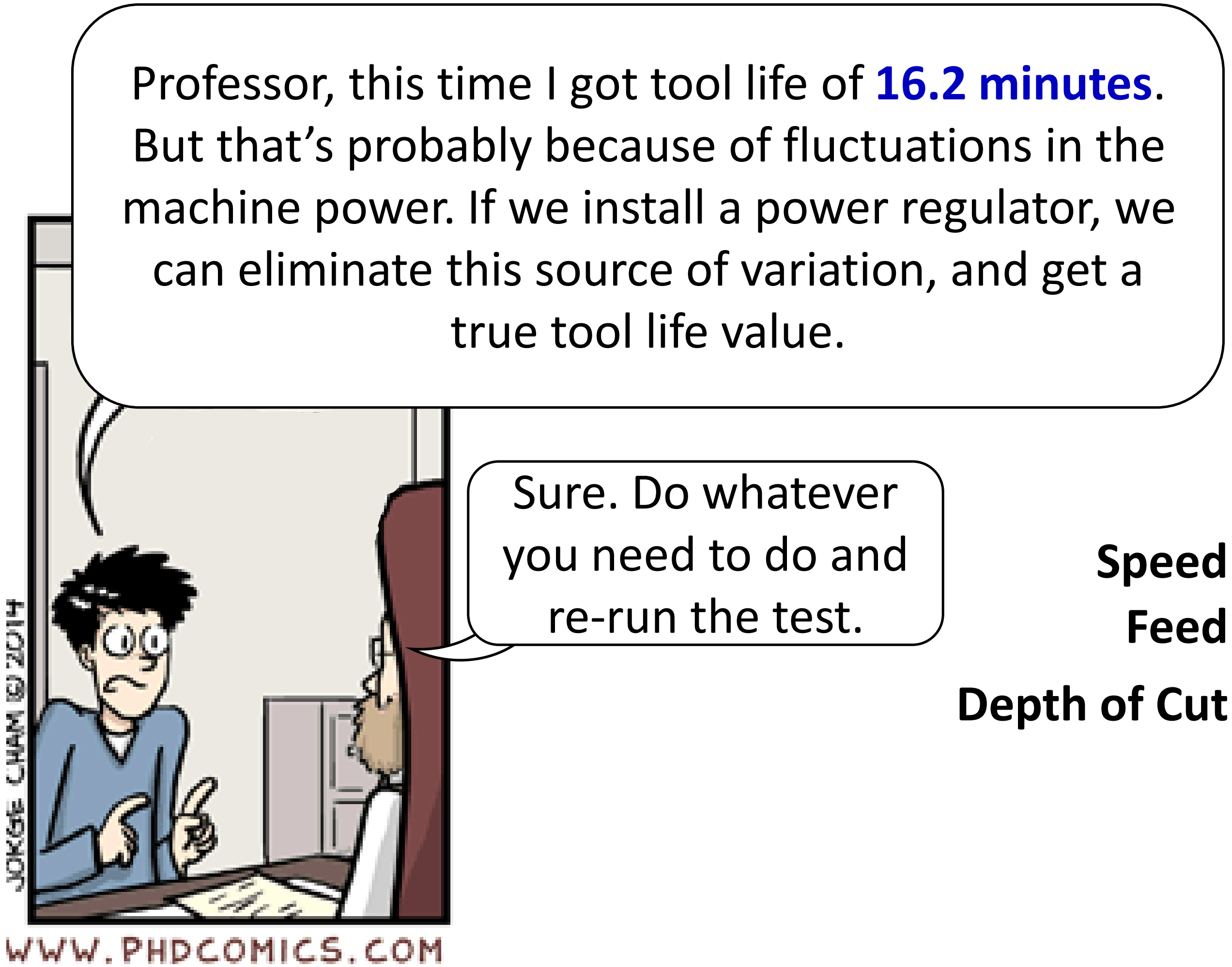
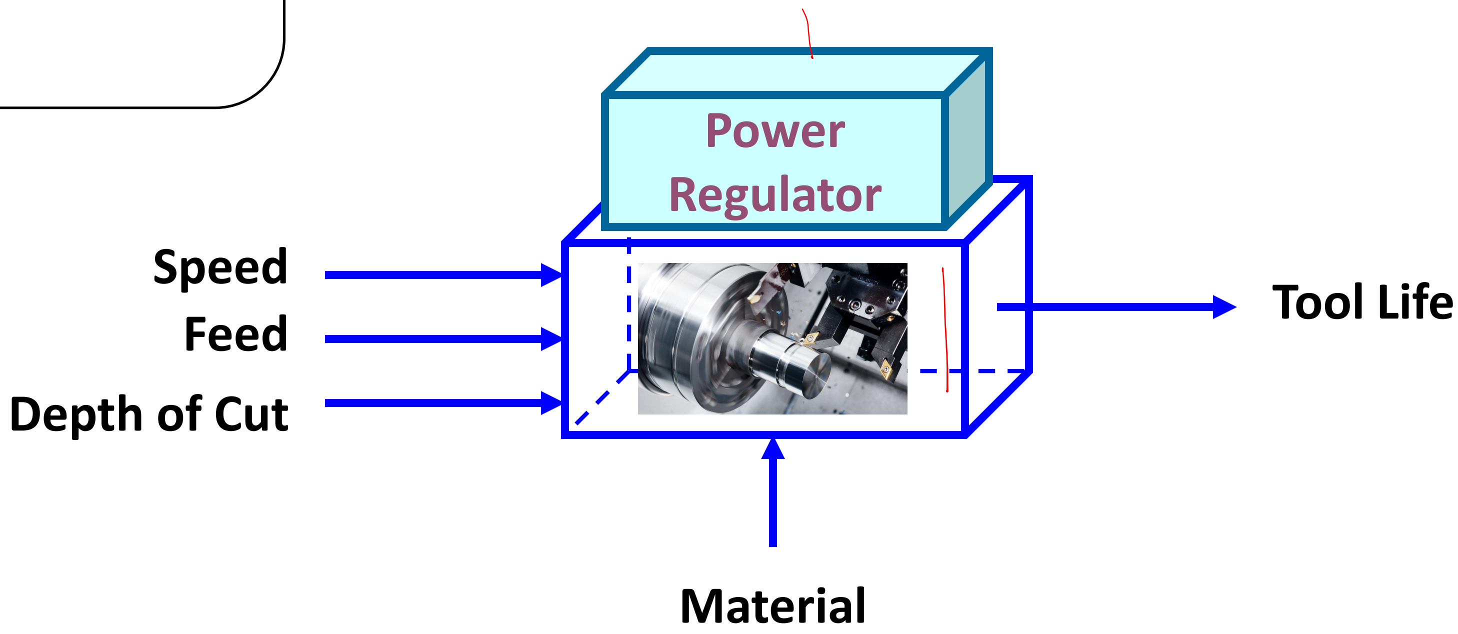
After running another test …





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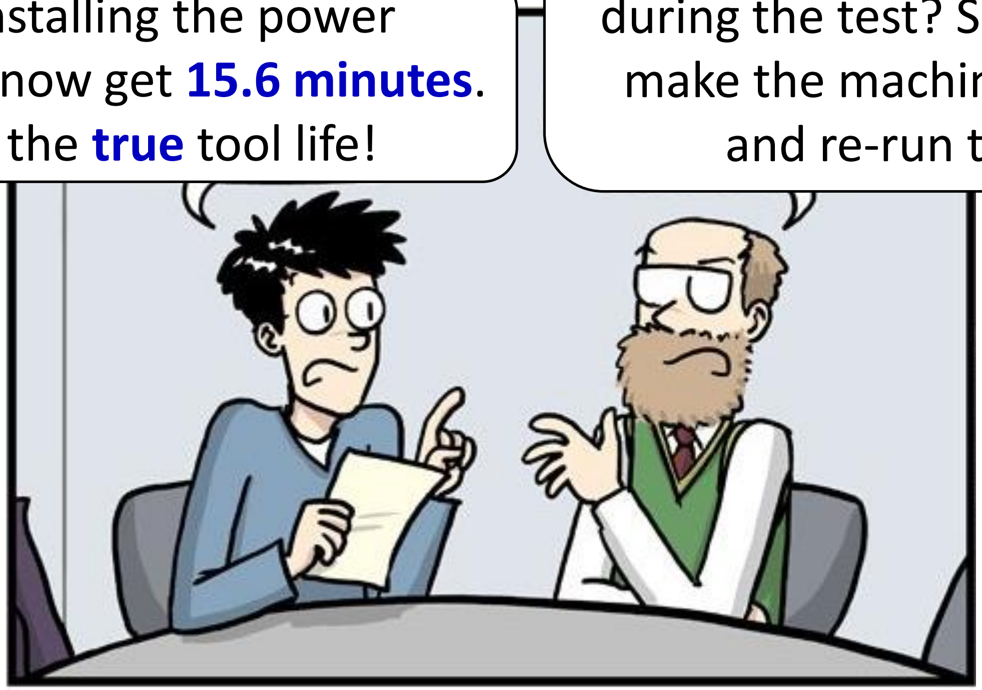
After installing the power regulator, I now get **15.6 minutes**. This is the **true** tool life!

But what about machine vibrations? Was it vibrating during the test? Should you not make the machine more rigid and re-run the test?



Oh yes! You are right. I better make the machine more rigid.

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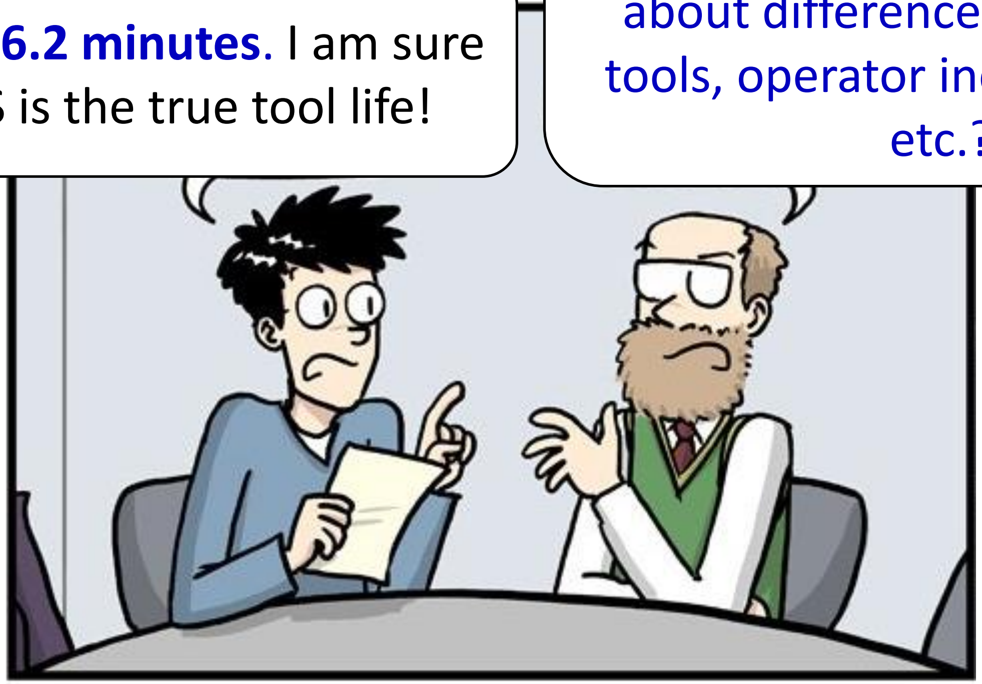
Now I get **16.2 minutes**. I am sure that THIS is the true tool life!

How can you be sure you have eliminated ALL variation? What about difference in materials, tools, operator inconsistencies, etc.?



Hmm. I suppose they could cause some variation,

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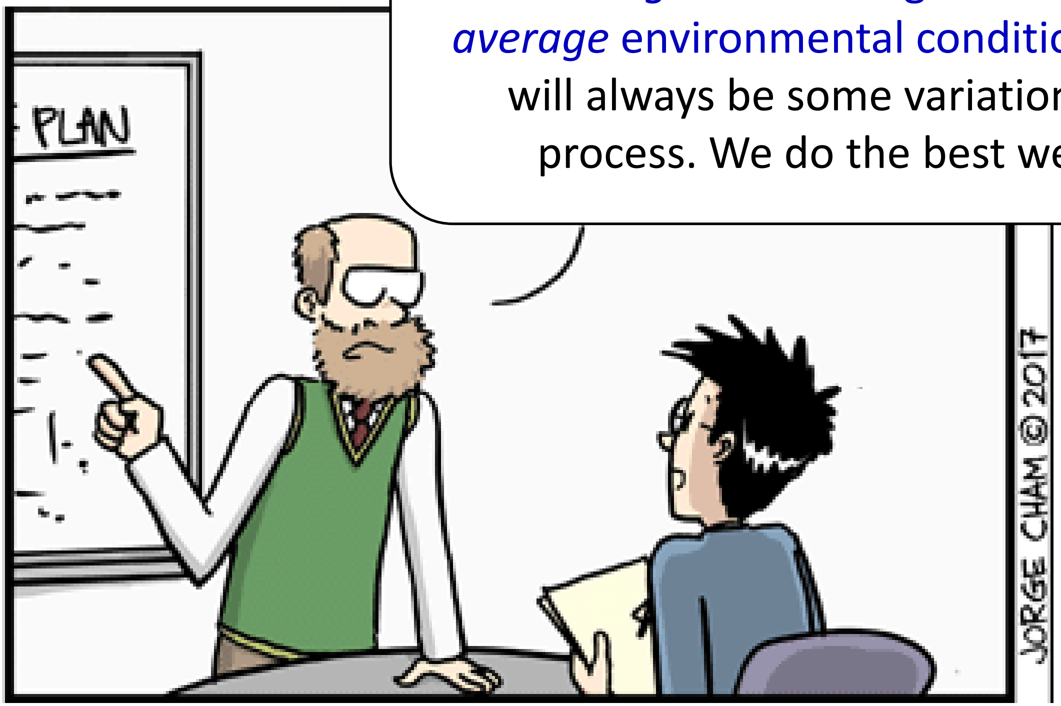
What I really want is an *average* tool life for an *average* tool cutting a material over *average* environmental conditions. There will always be some variation in the process. We do the best we can!



Okay, I will run more tests using several tools, material pieces, etc. and find out what the average tool life is.

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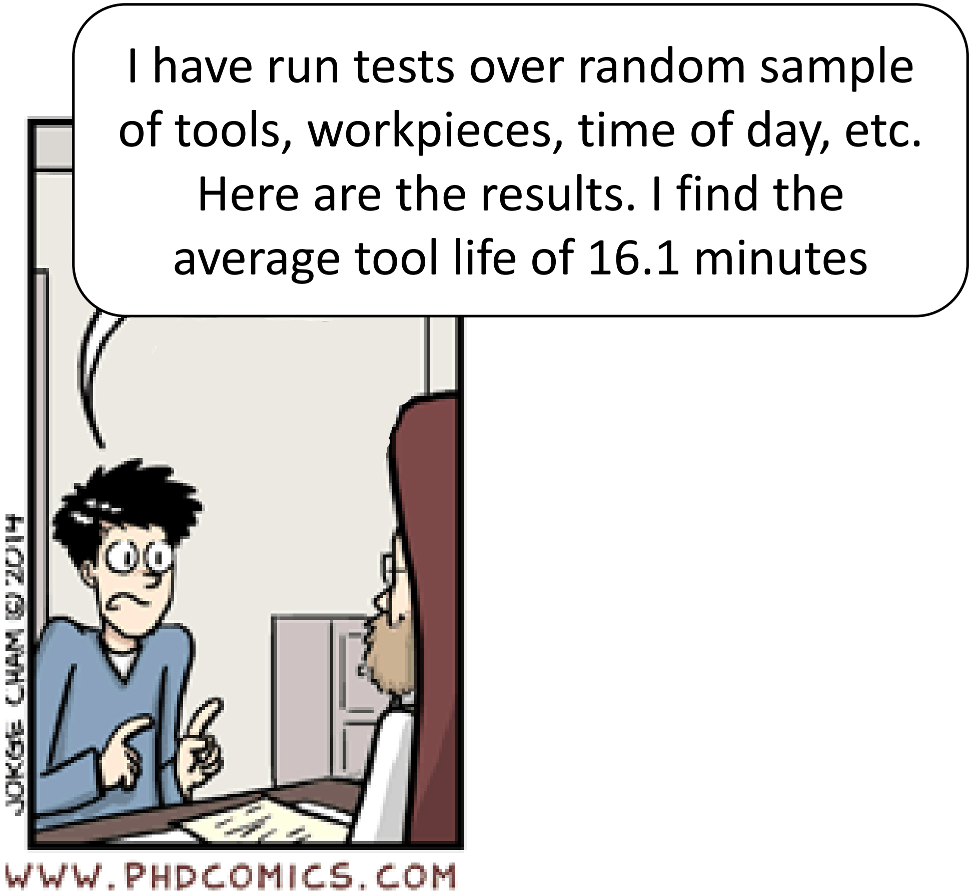

Test #	Tool Life	Test #	Tool Life
1	15	7	15
2	15.6	8	16.7
3	16.2	9	16
4	16.5	10	16
5	16.2	11	16.7
6	16.5	12	16.8

Average of 12 tests = 16.1 minutes

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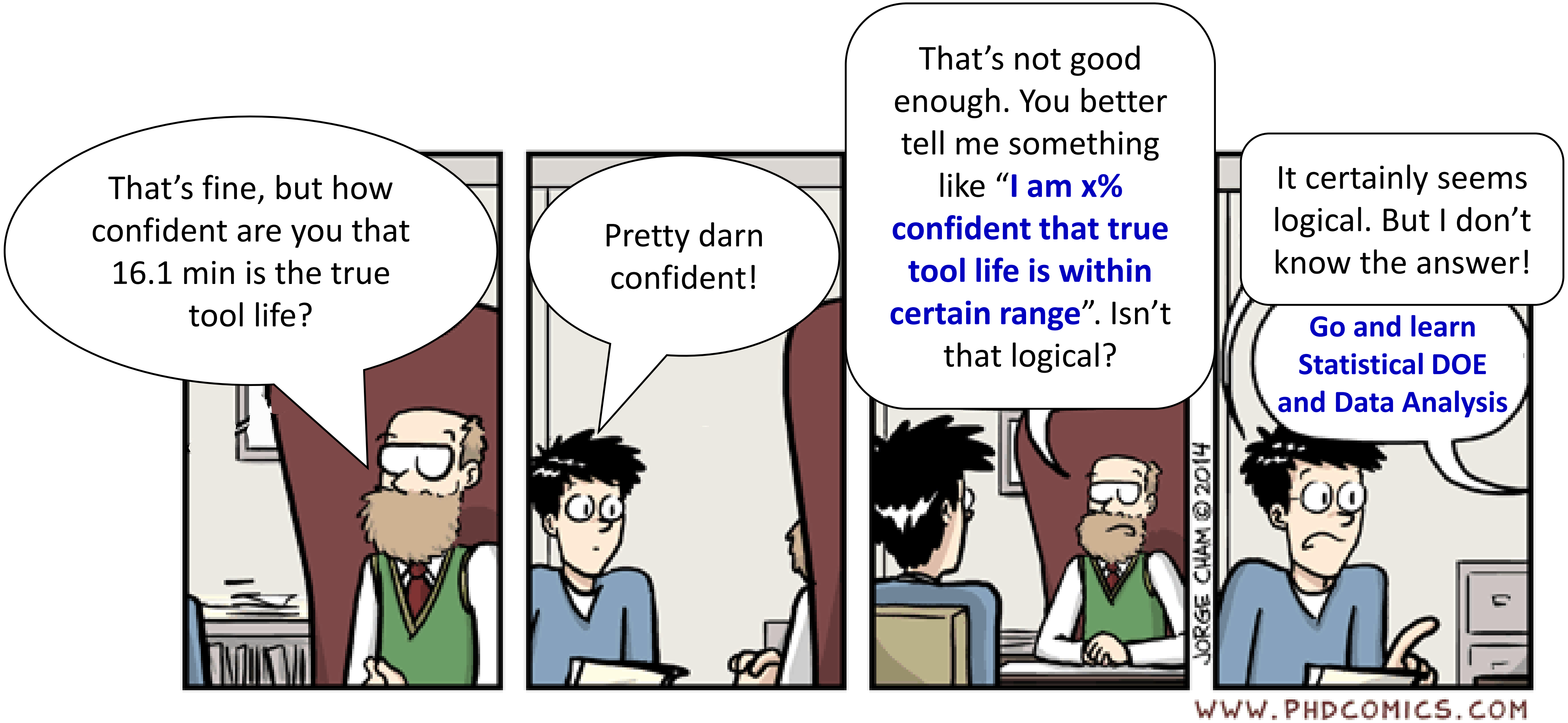

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Why Statistical Methods?

- **The world around us is not deterministic!** – **Variability** is part of the natural order of things
- It is real, identifiable, and predictable statistically
- We can easily define many factors of potential significance but only a few accounts for the vast majority of the structure/variation in the data.
- But, the problem is to screen from a large group of potentially important factors those few, which are worthy of continuing study.
- All processes are subject to identifiable and unidentifiable disturbances which can totally invalidate results.
- The world around us is non-linear.

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Experimental Difficulties

Experimental Error

- Composed of many minute disturbances which individually have little effect on the outcome of the experiment.
- Collectively these small chance occurrences may increase the dispersion or spread of the results to the point where real variable effects are masked
- Composed of more than errors of measurement – not all instrumentation oriented. A good measurement system accounts for no more than 10-15% of the total error.
- Can be a function of both unknown and known sources.

Here, statistical methods can help. They will tell us,

- Can the results be explained solely by chance causes?
- How much data is required to reveal the existence of true effects in light of chance error?

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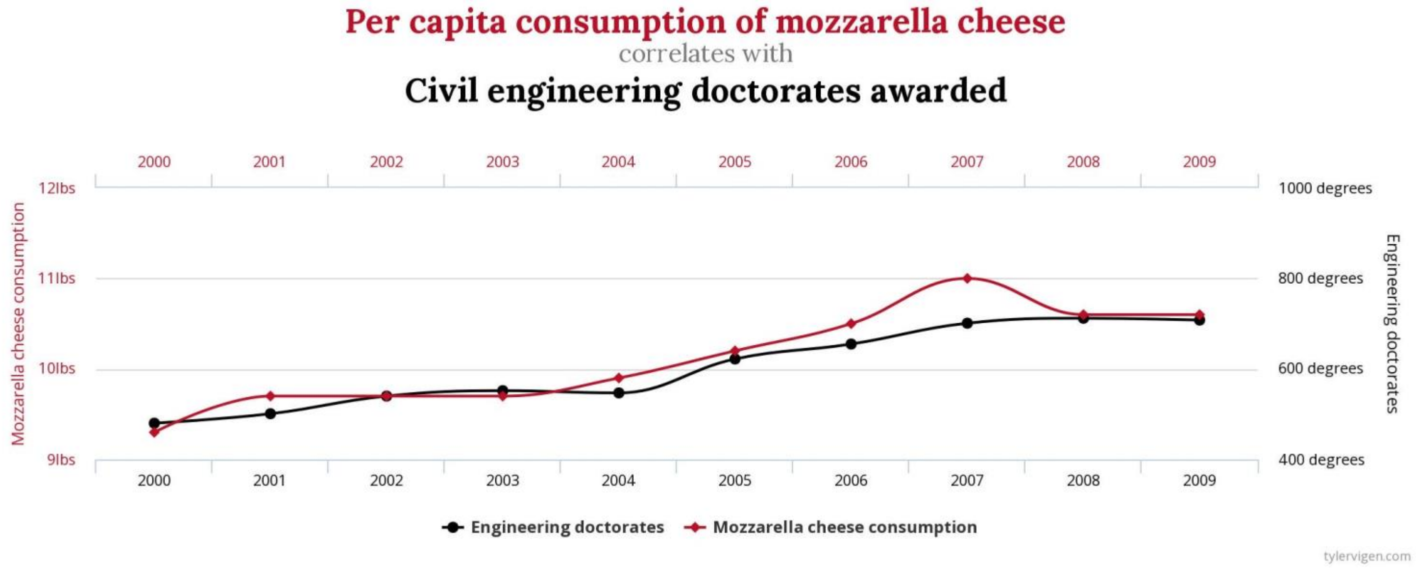
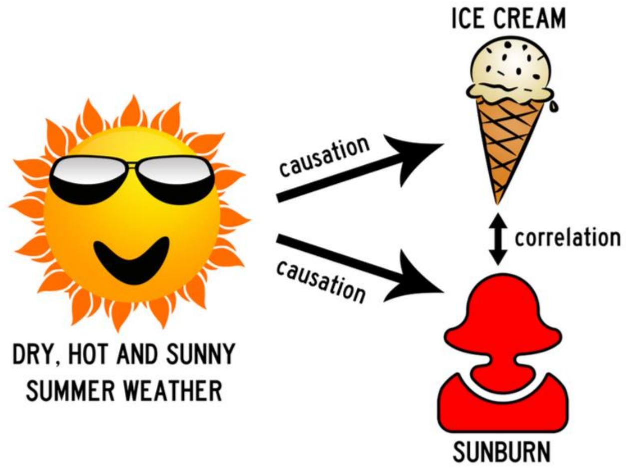
Experimental Difficulties

Correlation vs. Causation

- Two factors are highly related only because they are related to a third common (often unidentified) factor. Deliberate change in one may not lead to a change in the other- The concept of planned versus passively observed
- To really find out how changes in some factor affect the output, you have to change that factor deliberately and observe the change.





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Experimental Difficulties

Complexity of Variable Effects

- Ideal scenario: variable effects are linear and additive! Generally not the case!
  - Example: Effects of aspirin and coffee on driving reaction time: aspirin – increase Δ, coffee – reduce 2Δ.
  - Will one aspirin and one cup of coffee reduce reaction time by 1Δ? Additive: Will 10 aspirins and 5 cups of coffee keep reaction time constant? Linear?
- Need to plan experiments to reveal variable interactions and nonlinear variable effects

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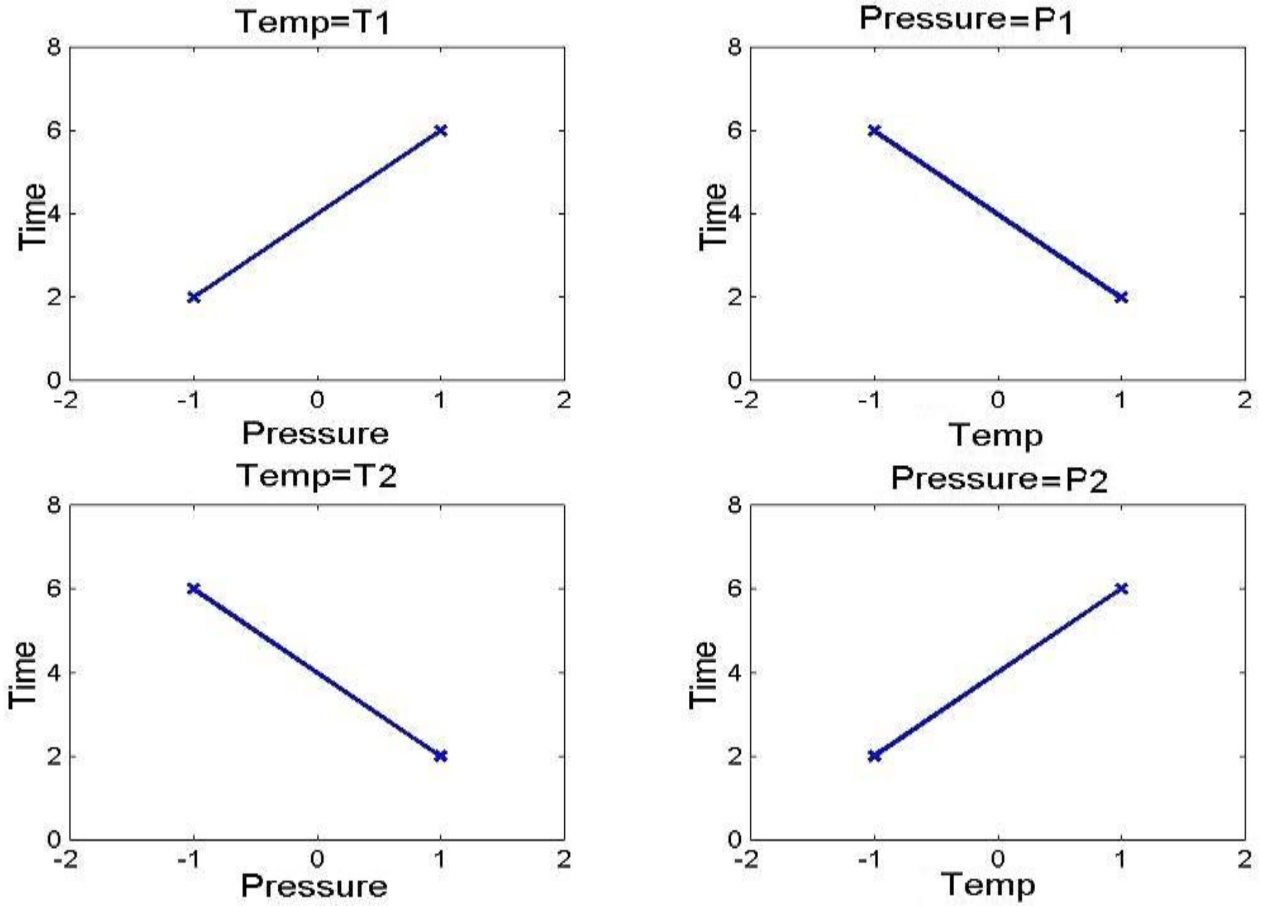
Experimental Difficulties

Example of Variable Interactions:

Temperature and Pressure are thought to affect the chemical reaction rate/time

Mr. X's Experiment

Mr. Y's Experiment



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Why Statistical Methods?

- We know much less about what makes things work than we think.
- Experimentation is a costly and time-consuming business. We better do it right.

Statistical tools can help us navigate through experimental problems

A myth: "Everything he is saying sounds logical and probably works fantastically for some people – but my specific problem simply doesn't lend itself to this approach and/or simply doesn't need it anymore."

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Course Objectives

- To learn DOE techniques based on probability theory and statistical tools
- Understand proper methods for data collection, defining quality parameters, diagnostic tools, quality analysis, and interpretation for process/product improvement.
- Statistical DOE enables understanding of the relationship between multiple input variables/factors and the key responses, or product/process performance.

In-depth knowledge of these tools is quintessential while conducting scientific experiments

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List of Topics*

Fundamental Concepts and Methods

- Quality philosophy and conceptual framework
- Statistical Methods and Probability Concepts for Data Characterization

Classical Design of Experiments

- Nature of variability, probability distributions
- Empirical models (regression, hypothesis testing, confidence intervals, applications)
- Two-level factorial designs (factor effects, ANOVA, residual analysis, interactions)
- General 2^k factorial designs
- Two-level fractional factorial designs

Response Surface Methodology

- First and second-order models and surfaces
- Central composite designs
- Multiple response analysis, Design rotatability, Box-Behnken design

Robust Design Method

- Quality loss function, signal, noise and control factors, product life cycle
- Matrix experiments using orthogonal arrays, analysis of means and variance, error prediction
- Steps in robust design: noise factors and testing, signal to noise ratio, degrees of freedom, selection of orthogonal arrays
- Conducting matrix experiments: randomization, confounding, result interpretation, verification
- Factor interactions, dynamic problems

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Spring 2023

ME 794 Statistical Design of Experiments

Chapter 1

Fundamental Concepts

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Nature of Data

Question: Is Sachin Tendulkar a 'good' batsman?

How would you answer that?

- You need some data to decide ..
- In general, when we collect data, we are interested in,
  - How the process/product is behaving in terms of an output quality characteristic(s)
  - Perhaps, in terms of (a) average value of the characteristic, (b) the variation in individual measurements of the characteristic

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Nature of Data

How would you collect the data?

In general, when we collect data, we have three choices,

- Observe the process ONCE, and use that observation as the absolute reflection of the process behavior

'Fatal Error!'

- Observe ALL of the output of the process to get a true reflection of its behavior

Observing **entire population/universe**, i.e. all possible realizations of the process – a very large number. **Neither practical nor necessary**

- Observe PART OF the output of the process and use it to infer something about the process behavior

More 'practical'! We are **'sampling'** the process (population)

Sachin Tendulkar stats
Batsman

Career Batting Stats
Right-Handed Batsman

Format	M	Inn	NO	Runs	HS	Avg	BF	BF	SR	100s	50s
Test 1989–13	200	329	33	15921	248*	53.8	29437	379	-	51	68
ODI 1989–12	463	452	41	18426	200*	44.8	21367	147	86.2	49	96
T20I 2006	1	1	0	10	10	10.0	12	12	83.3	0	0
IPL 2008–13	78	78	11	2334	100*	34.8	1948	66	119.8	1	13

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Nature of Data

We need an efficient and adequate method to collect and analyze the data

Critical Issues in Sampling

- How much do we sample?
- How do we sample?
- When do we sample?
- How/what can we say something about the process from the information contained in the sample?

We will keep exploring these answers throughout the course…

For now, it is important to understand the difference between a Sample vs. the Population

Sachin Tendulkar stats
Batsman

Career Batting Stats
Right-Handed Batsman

Format	M	Inn	NO	Runs	HS	Avg	BF	BF	SR	100s	50s
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T20I 2006	1	1	0	10	10	10.0	12	12	83.3	0	0
IPL 2008–13	78	78	11	2334	100*	34.8	1948	66	119.8	1	13

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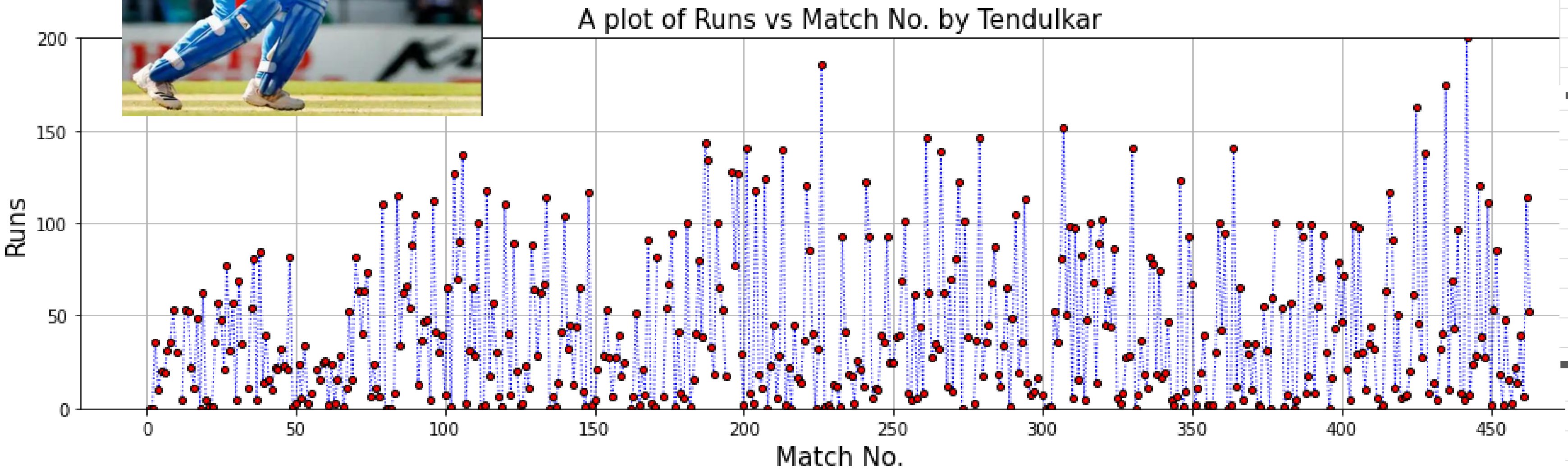
Nature of Data

CEP2022_Notebook (1.1)

What do you notice?

Variability!



Match No.	Runs	Balls	Mins	4s	6s
463	52	48	93	5	1
462	114	147	205	12	1
461	6	19	25	1	-
460	39	30	48	5	-
459	14	15	34	2	-
458	22	23	33	3	-
457	3	12	21	-	-
456	15	24	25	2	-
455	48	63	87	5	-
454	2	6	9	-	-
453	18	14	21	2	-
285	18	16	20	3	-
284	87	67	120	13	1
283	68	79	110	10	-
282	45	60	101	6	-
281	36	43	71	6	-
280	17	42	49	3	-
279	146	132	186	17	-
278	37	35	68	5	-
10	30	29	-	1	2
9	53	41	-	7	1
8	36	22	-	3	2
7	31	26	31	3	-
6	19	35	38	1	1
5	20	25	-	1	-
4	10	12	-	-	-
3	36	39	51	5	-
2	0	2	2	-	-
1	0	2	-	-	-

ODI BATTING

Ref: http://www.cricketweb.net

Mat	Inns	NO	Runs	Avg	HS	BF	SR	50s	100s	0s	G 0s	4s	6s	ct	st
463	452	41	18426	44.83	200*	21367	86.23	96	49	19	1	2016	192	140	0

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Sources of Variability

Taguchi suggests that variation in product and process function arises from three basic sources:

- **Outer Noise:** Sources of noise which influence performance as measured during field use under actual operating conditions, e.g., temp, humidity, supply voltage, vibration

- **Inner Noise:** Internal change in product characteristics such as drift from the nominal over time due to deterioration, e.g., mechanical wear, aging

- **Variational Noise:** Variation in the product parameters from one unit to another as a result of the manufacturing process, e.g., manufacturing imperfection

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Example 1: Refrigerator

- **Outer Noise** **[Operating Conditions]**
  - The number of times the door is opened and closed
  - The amount of food kept and the initial temperature of the food
  - Variation in the ambient temperature
  - Supply voltage variation
- **Inner Noise** **[Deterioration]**
  - The leakage of Refrigerant
  - Mechanical Wear of Compressor parts
- **Variational Noise** **[Mfg/Use Imperfection]**
  - The tightness of door closure
  - The amount of refrigerant used

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Example 2: Braking Distance of a Car

- **Outer Noise** **[Operating Conditions]**
  - Wet or dry road
  - Concrete or Asphalt pavement
  - Number of passengers in the car
- **Inner Noise** **[Deterioration]**
  - The leakage of brake fluid
  - Wear of brake drums and brake pads
- **Variational Noise** **[Mfg/Use Imperfection]**
  - Variation in friction coefficient of pads and drums
  - The amount of brake fluid

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