Creative Convergence

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Beyond Engineering Mathematics: Teaching Mathematics and Statistics to Engineers in the 21st Century
Loughborough University, July 13, 2017

What is engineering?

ABET (Accreditation Board of Engineering and Technology):

Deduction

"Engineering is the profession in which a knowledge of the mathematical and natural sciences, gained by study, experience, and practice, is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the benefit of mankind."

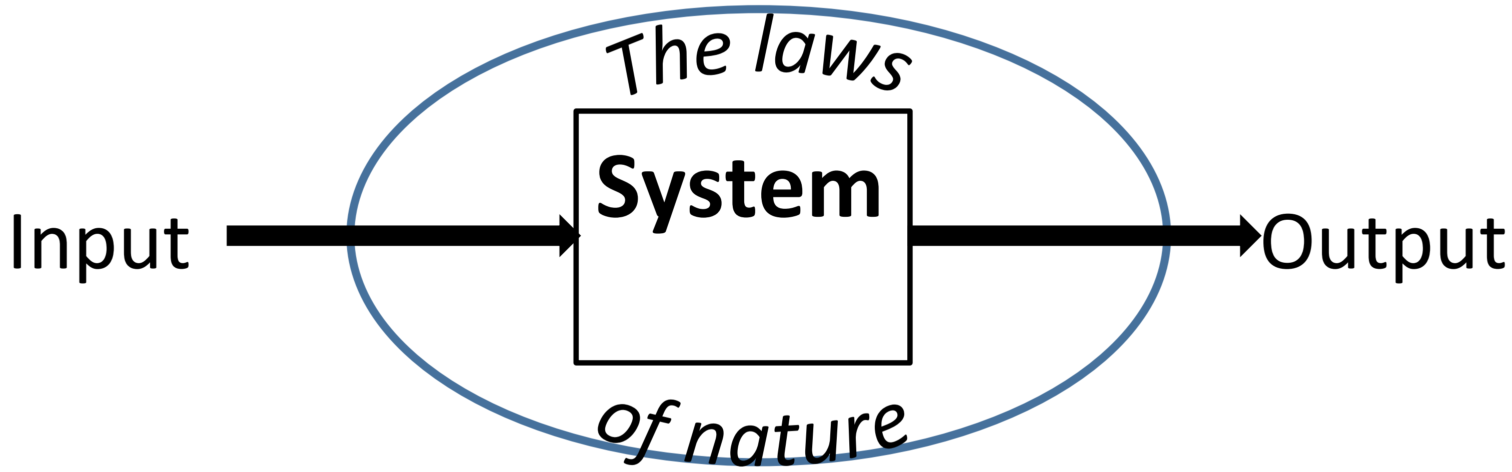
Induction

ABET is a (US) non-governmental organization that accredits post-secondary education programs in "applied science, computing, engineering, and engineering technology".

I would like to make the case today that statistical science should be considered as an engineering technology

A more formal model

[from *Mathematical Model Building – an introduction to engineering* - CR Mischke, (1980)]



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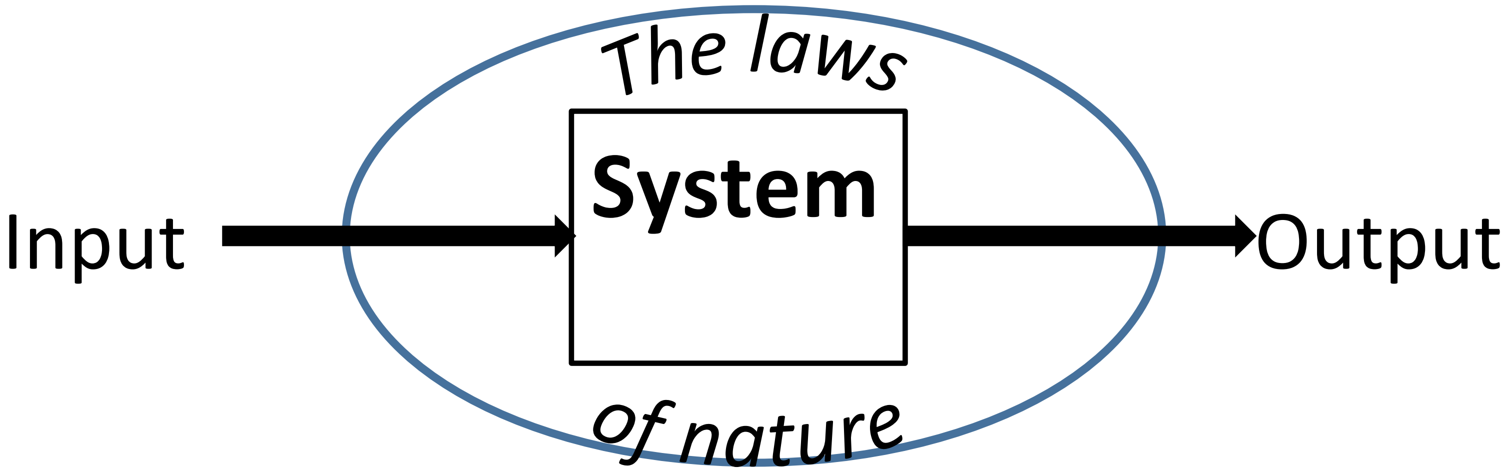

Given...	To find...	Skill needed	Name of the Game
System, Input, Laws	Output	Deduction	Analysis
System, Output, Laws	Input	Deduction	Reverse Analysis

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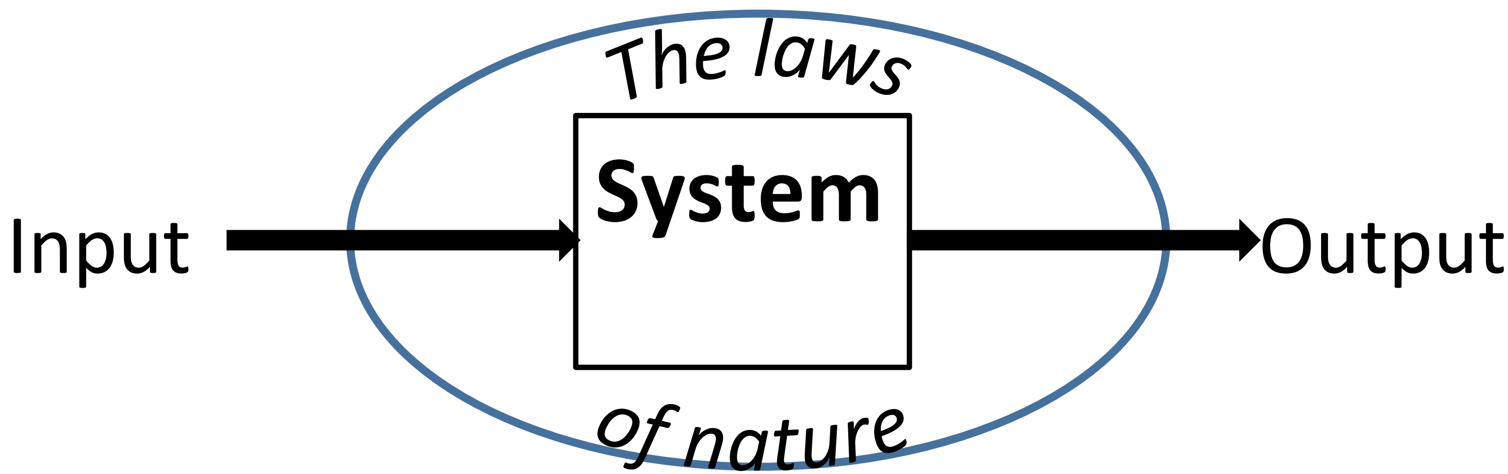

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System, Output, Laws	Input	Deduction	Reverse Analysis
Input, System, Output	Laws	Induction	Science

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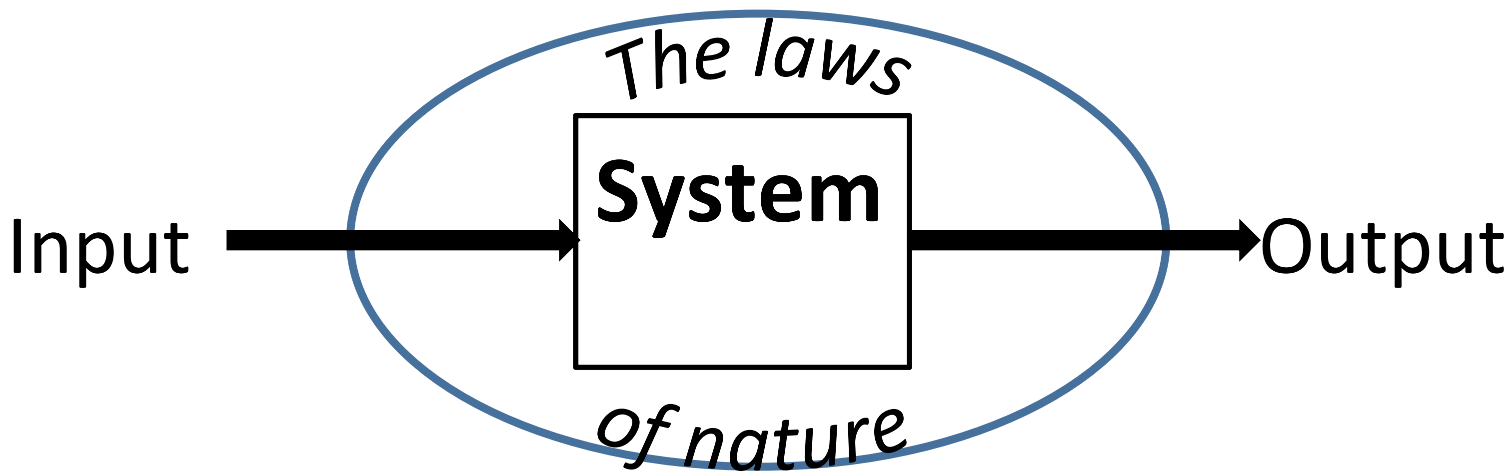

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Input, Output, Laws	**System**	**Synthesis**	**Engineering**

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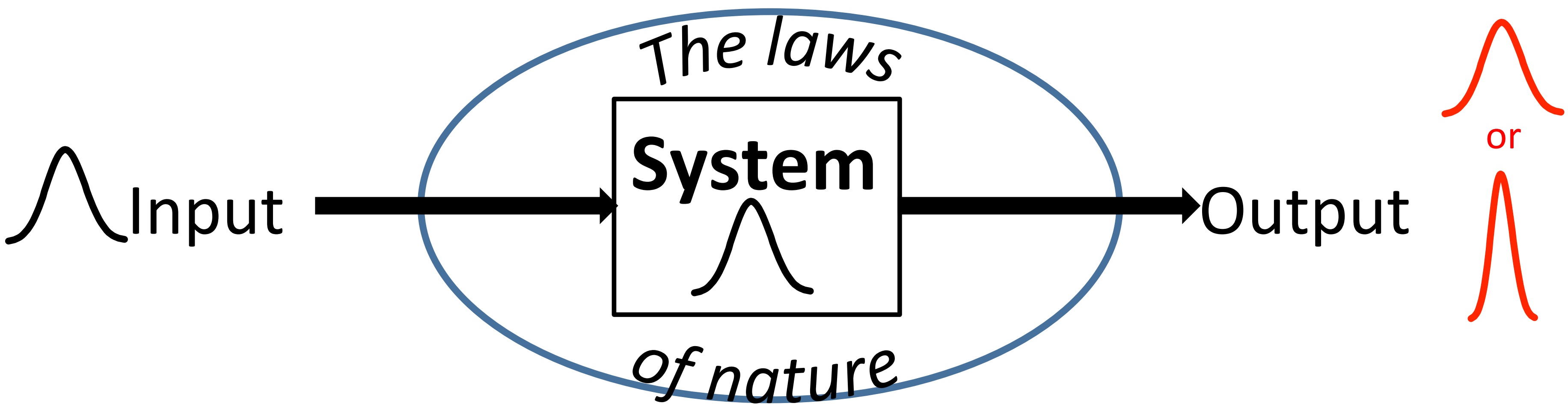

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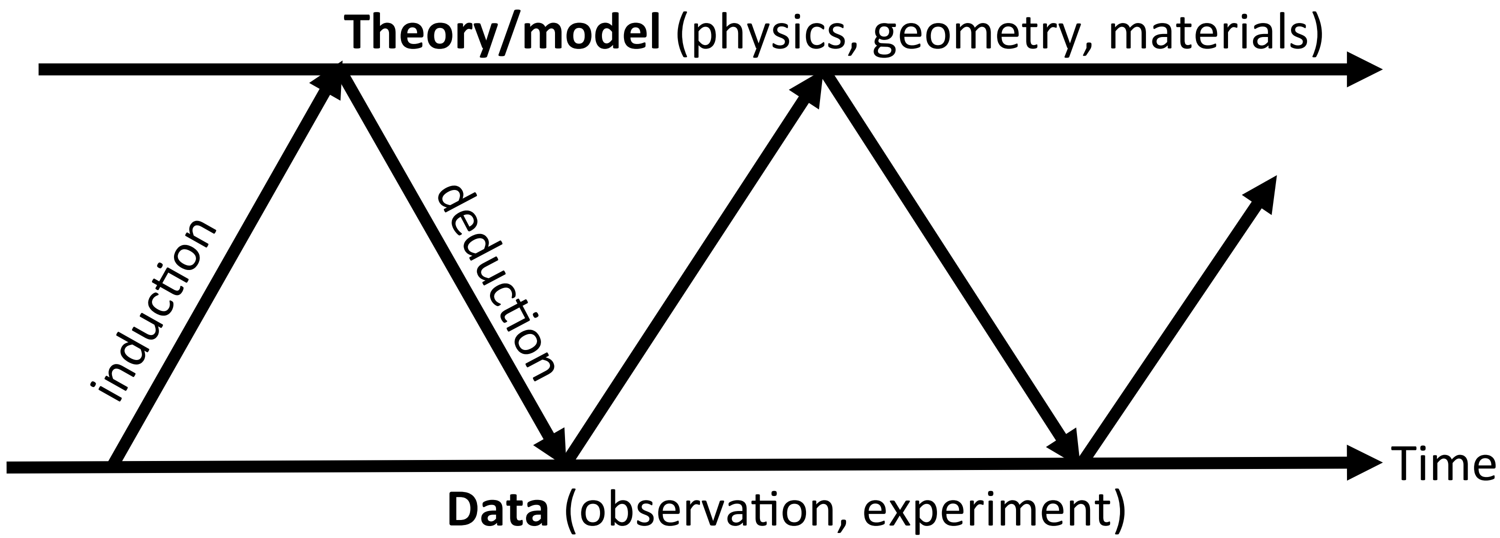
Input, Output, Laws	**System**	**Synthesis**	***Statistical* Engineering**

The iterative learning process

[GEP Box, *Science & Statistics* (1976)]

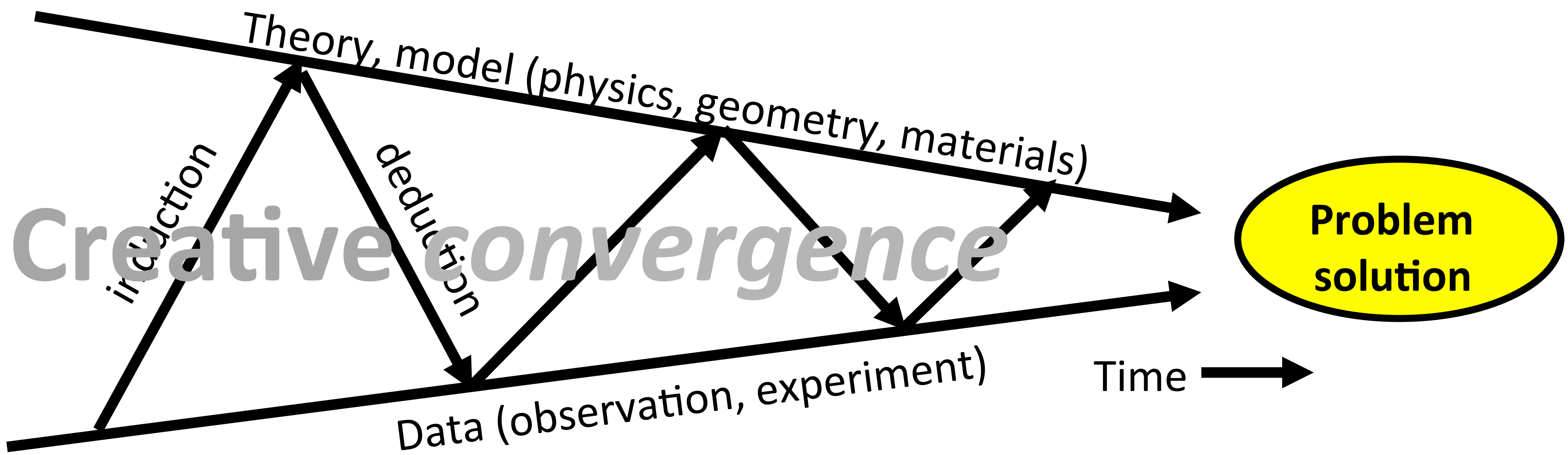


- Statistical Science is unique – it provides the catalyst for the "creative reaction" between deduction and induction.

- Context is crucial.

The iterative learning process

[TP Davis, *Science, Engineering, & Statistics* (2006)]



- **Stuart Pugh** *Total Design* – "controlled convergence, with a Product Design Specification in mind, thus avoiding "freedom without responsibility".
- **Richard Feynman** *The Character of Physical Law* – "what we need is imagination, but imagination in a… straightjacket"

Deduction & Induction

- **Deduction:** argues from a given theory's general principles to a specific case of expected data.

- **Induction:** argues in the opposite direction to deduction, from actual observed data, to an inferred model, from the specific to the general.

In addition, If we let **H=hypothesis** & **D=data**, then

- Deduction can be thought of **Pr(D|H)**; this probability has a ***frequency*** interpretation due to randomness. Also called *aleotory* uncertainty.

- Induction can be thought of as **Pr(H|D)**; this probability has a ***degree of belief*** interpretation, due to a lack of complete knowledge of the underlying system. Also called *epistemic* uncertainty.

Deduction & Induction

e.g. H=the coin is fair; D=40 heads in 100 tosses

Pr(D|H)

→ is deductive (the conclusion is contained in the premise)
→ no enquiry necessary
→ **probability theory**
→ hypothesis testing

Pr(H|D)

→ is inductive
→ enquiry necessary
→ **statistical science**
→ hypothesis *generation*

Statistics is the science of making inferences through inductive logic and reasoning in the face of uncertainty.

Context

There are three main areas of human endeavour through which, by interfering with the natural order of things, we attempt to make life better for mankind – these are

Medicine | Agriculture | Engineering

The important role that statistical science has played in the development of medicine and agriculture has long been recognised.

e.g. in medicine, the development of clinical trials to evaluate drug treatments, and uncovering cause-and-effect relationships such as smoking and lung cancer;

in agriculture, the development of the theory of design of experiments to discover ways to increase the yield of crops to feed ever-larger populations.

Context

- How fundamentally different is the context of engineering compared to either medicine or agriculture?
- For example, in medical and agricultural trials and experiments, the calculated sample size from classical probability theory is an *output* of the design of the trial, whereas in engineering, the sample size available is usually an *input*.
- It is no use probability theory saying that a sample size of 22 test pieces are needed for a trial, when there are only 6 available!
- The question has to be asked the other way round – i.e. what is the maximum amount of information that can be obtained from these 6 test pieces? This is a statistical question.

Context

- Additionally, medical trials are constrained, quite rightly, with heavy ethical considerations as to what kind of experiment or trial can be done. Agricultural experiments, by virtue of the motion of our planet around the sun, take a long time to complete.
- On the other hand, in engineering, we can often plan quick, small scale experiments, which *if carefully executed* can be completed, and conclusions quickly confirmed, without some of the ethical, safety, and time constraints of medical and agricultural trials.
- Additionally, engineering is often about *selection* rather than *estimation*. Therefore, we argue, engineering should be a more exciting field to work in than either medicine or agriculture!

A few exciting (!) examples of statistical engineering from my career

- Designing test protocols for pneumatic tires to induce particular failure modes (This work led to my PhD)
- Improving the reliability of an automatic transmission
- Improving the ability of an ICE to start under various conditions related to weather and fuel quality.
- Formulating the Engineering Quality plan of the Mk I Ford Focus (the first non-Japanese car to win the TÜV reliability award for ~20 years)
- Reducing the size of Engine mapping experiments
- Figuring out the root cause of the Firestone tire crisis that caused 300 fatalities
- Determining the optimal geometry and tensions in the OLE for the electrification of the GWML
- Tender submission for HS2 with Statistical Engineering positioned as a key enabler

How does engineering work?

An engineer has to be able to

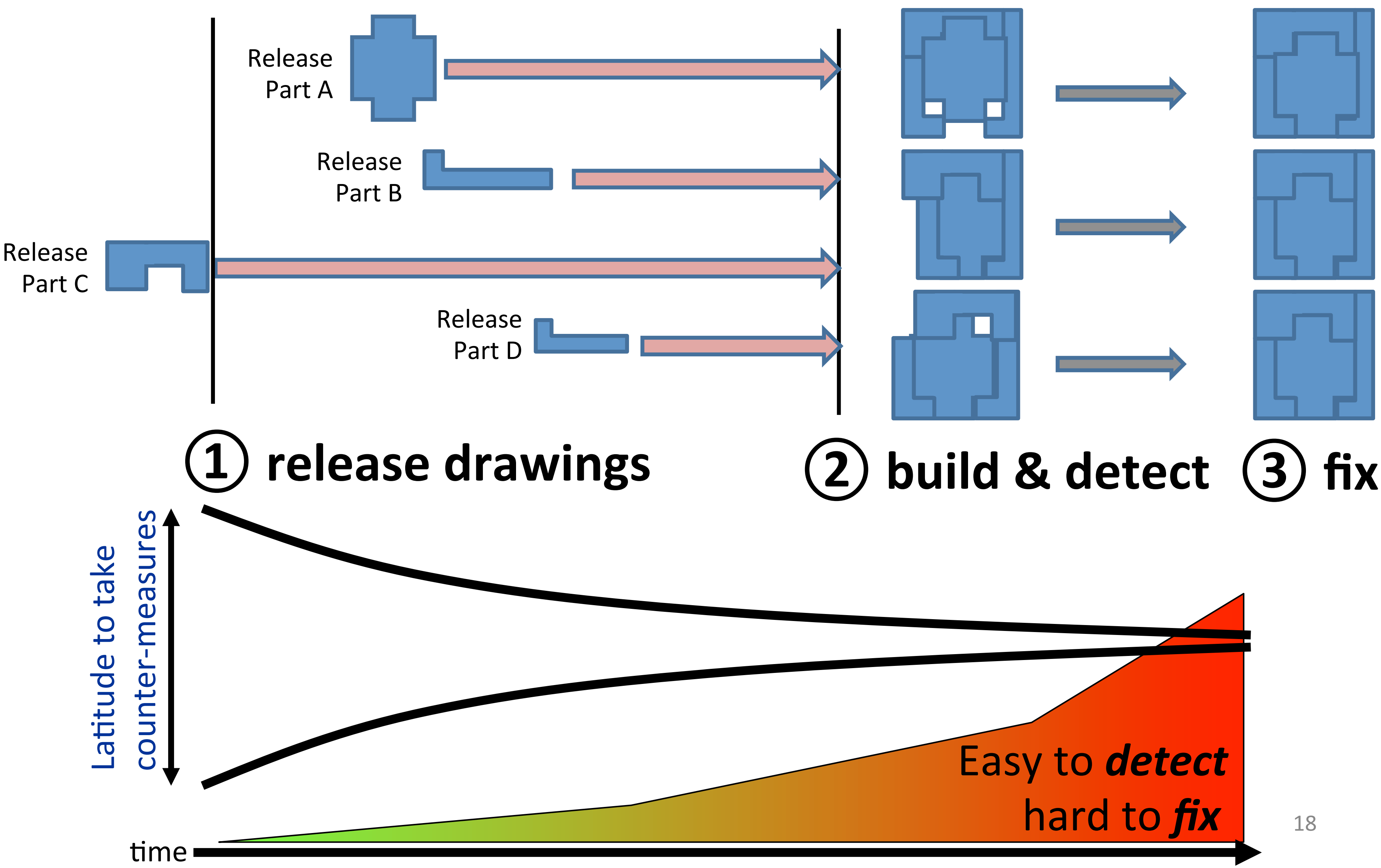
- Recognise need
- Define problems
- Conceive alternatives
- Predict consequences
- Design experiments and draw inferences
- Test and evaluate
- Delineate solutions
- Understand production and distribution
- Be intellectually honest

This list is from the classic text by Mischke. It should also apply to statisticians working in industry!

The Engineering Process

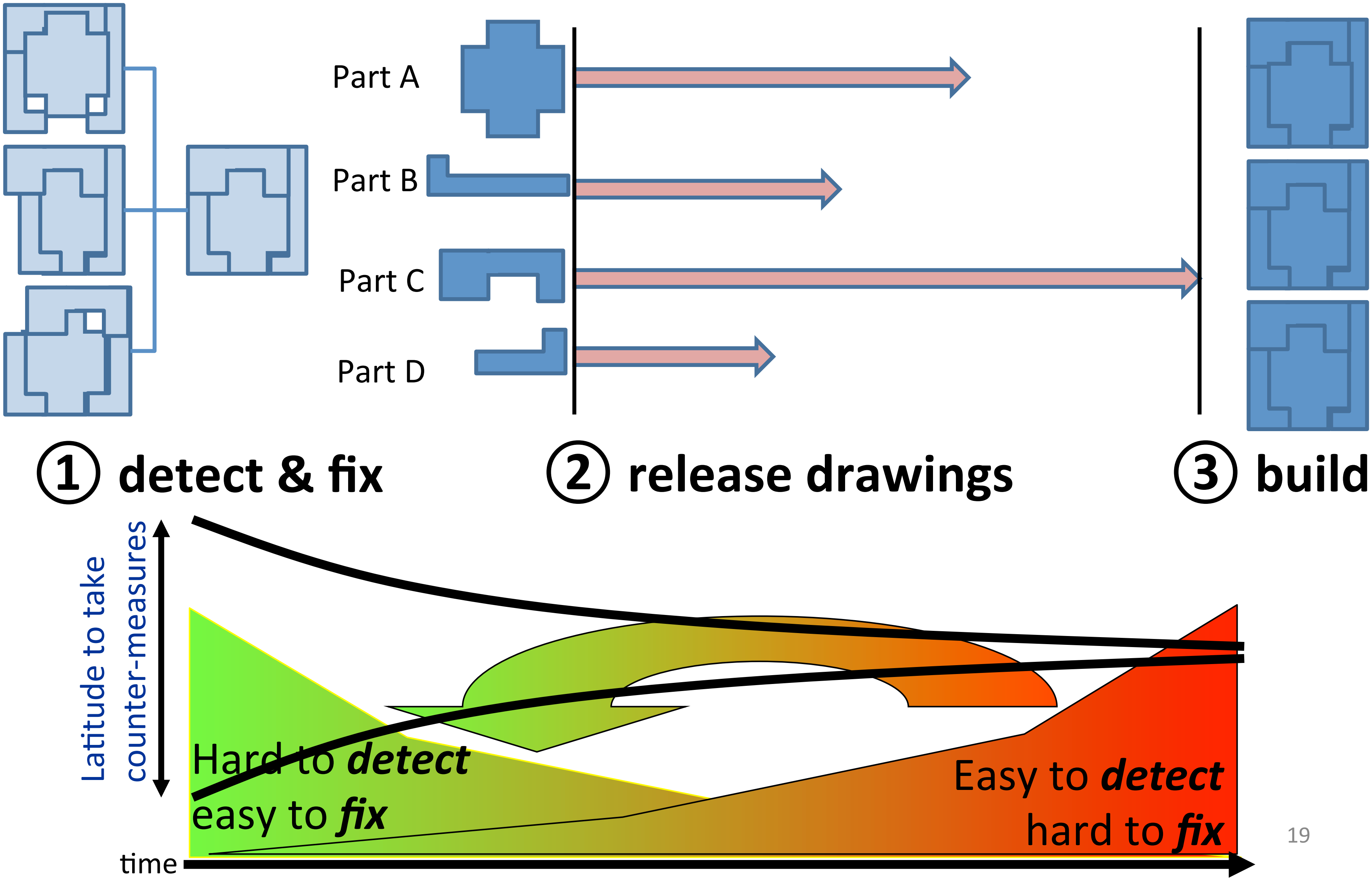
Engineering Phase of Product & Technology Development	Potential Failure Modes caused by • Variation • Poor data analysis • Wrong conclusions
Design Definition	• Mis-understood customer requirements • Poorly defined customer requirements
Design Characterization	• Over-complicated designs • Unnecessary changes to designs that work
Design Optimization	• Lack of robustness to noise factors • Making mistakes
Validation	• Unrepresentative testing and design evaluation
Production Preparation & Production	• Lack of process control (common & special causes of variation) • process tampering
Sales	• Shipping units just to keep the factory going
Service & field experience	• Poor root cause analysis

Product & Technology development
Asynchronous material and information flow



Product & Technology development

Synchronous material and information flow



Product & Technology Development

- Engineering (New Product Development) is about, at its most fundamental level, disturbing the current state of nature to create something tomorrow that does not exist today.
- We are therefore taking on Mother Nature at her own game; but she made up the rules, they are very strict, and because of scale & interaction, we don't always know exactly how they will turn out in every case.
- The creation of ***potential failure modes*** while we do engineering is, therefore, inevitable (Pahl & Beitz, *Engineering Design − a Systematic Approach* p52). This slows down development time and causes divergence.
- This is particularly true in many applications where there are
  - Rapid production rates e.g. 1 or more unit per minute
  - uncontrolled demand space of the product in the field together with incomplete field records
  - product complexities (wide "operating windows", many interfaces, and interactions, between components)

  all combine to make the task of engineering technically difficult.

Failure Modes – Root Causes

There are two primary (high-level) root causes for failure modes in engineering design (Clausing)

1. Lack of Robustness

- Lack of robustness is sensitivity of function to noise factors

Capacity Noises
1) Production variations
2) Wear-out and drift over time

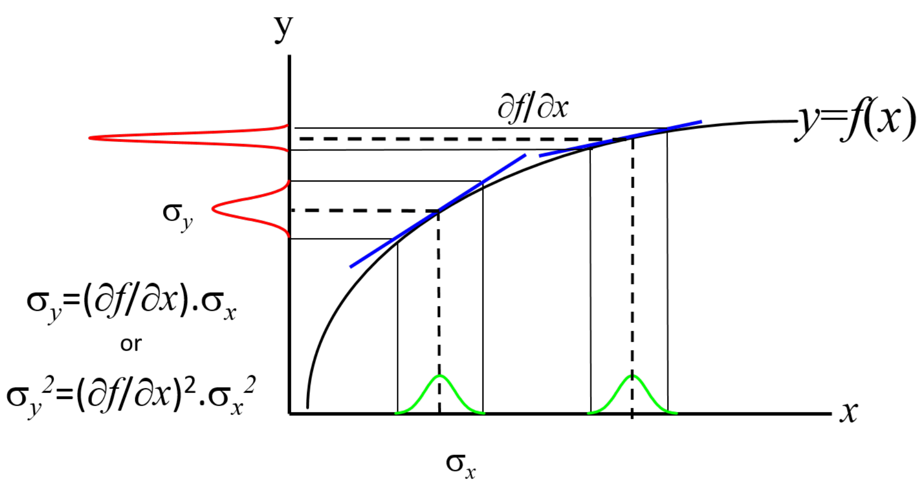
Demand Noises
3) Customer duty cycles
4) Environment
5) Component interactions

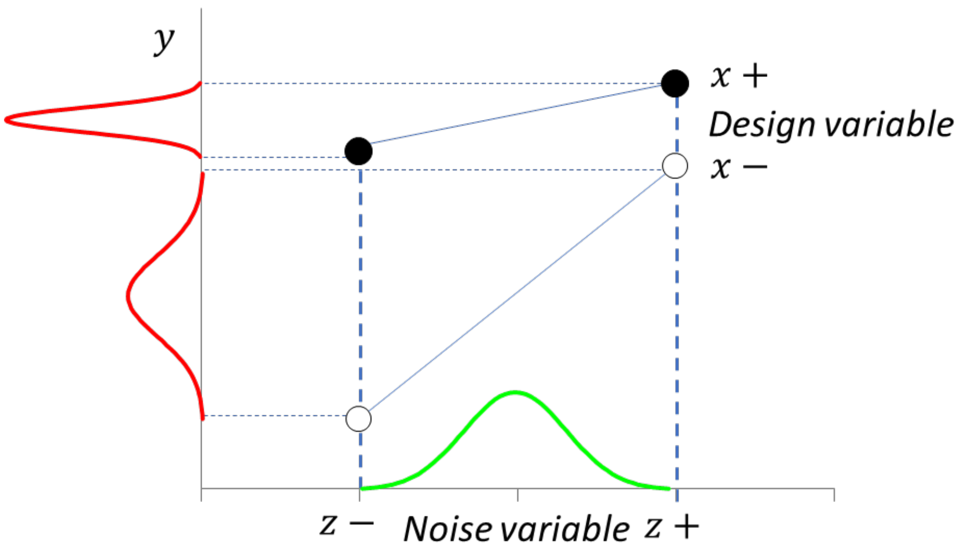
2. Mistakes

- The occurrence of mistakes, particularly in large organizations, is the entropic state (i.e. If something *can* go wrong it *will* go wrong - "when Murphy speaks, listen").
- A mistake is either not adopting a *known* counter-measure for a known failure mode, or mis-interpreting information during the NPDS process, and engineering the wrong thing.
- The counter-measure for mistakes (i.e. avoiding mistakes) is primarily a matter of vigilance.

Principles of Robustness

Exploit low gradients in transfer functions (via curvature [left] or interactions [right]) to reduce variability in the system output

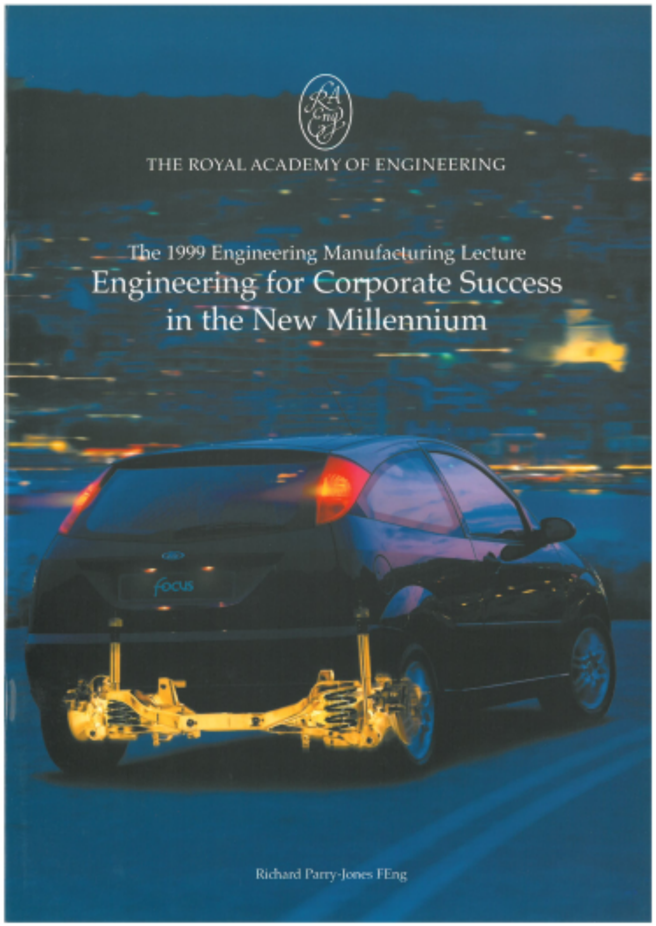




Note: reduce variability first – then adjust to target.

Like many profound ideas this is the reverse of the "obvious" order

1999 RAEng Engineering Manufacturing Lecture



"The combination of engineering science (the study of physics, [geometry] and materials) and statistical science (the empirical modelling of variability) is necessary to achieve what is demanded from us by our customers - a consistent level of superlative performance."

RAEng/RSS collaboration

Previous initiatives at integrating statistics into engineering curricula include a June 2013 collaboration between the Royal Academy of Engineering and the Royal Statistical Society

- Reduction of design complexity through better use of transfer functions
- Computer-based experiments
- Robustness and the problem of transmitted variation
- Dimensional Analysis as an aid to efficient experimentation
- Risk assessment of fielded product
- Production stability in mass production (with emphasis on i4.0)
- Managing large data sets generated by sensors and recording systems (so-called Big Data)

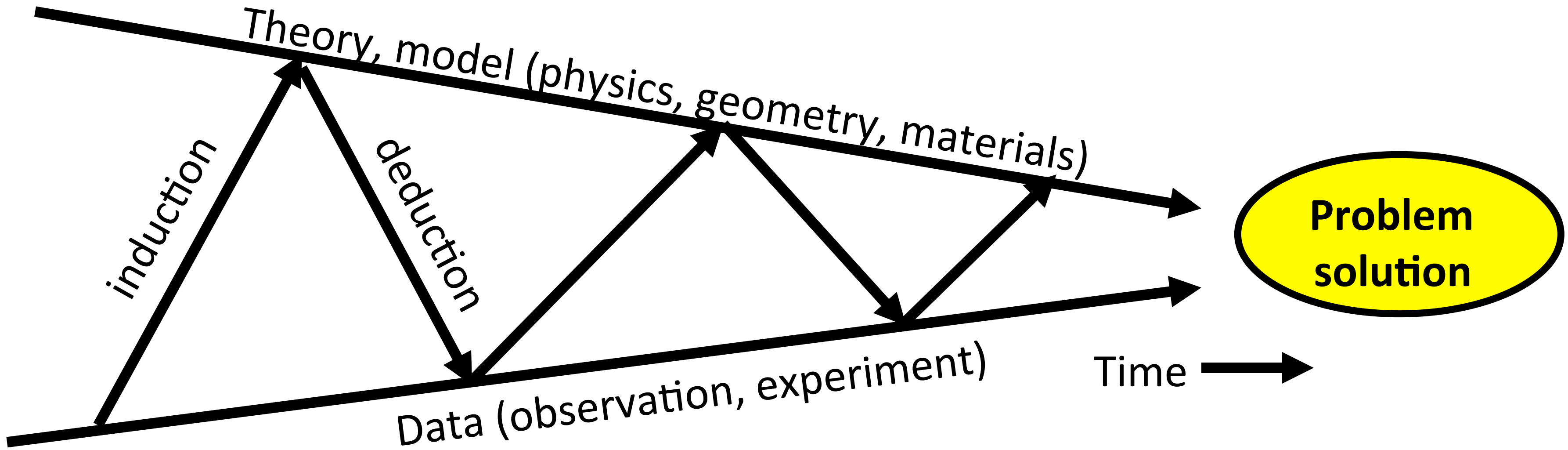
RAEng/RSS interim Conclusions

- Engineers need to understand the basis of any statistical analysis and any software used to implement such an analysis. It is important that teaching of the fundamental principles is not squeezed out.
- Graphical techniques should be presented, taught and used alongside analytical and numerical methods.
- Pre-requisite knowledge for the application of statistics should be recognised (principally, but not entirely mathematical).
- The list of statistical topics needs to reflect the wide diversity of context in engineering applications, and the teaching of statistics should avoid artificial constructs such as shuffling cards and rolling dice.
- Type III errors

A possible (high level) curriculum

Engineering Phase of Product & Technology Development	Intention	Potential Failure Modes* to avoid	Useful Statistical Methods & Ideas that help to avoid the failure modes**	Pre-requisite knowledge
GENERAL			Inductive & Deductive logic Population vs. Process Exploratory Data Analysis Emphasis on graphical methods Probability distributions	The scientific method Mathematical underpinnings Basic computer literacy Exploratory Data Analysis
Design Definition	Understand customer requirements & translate into engineering data measured with SI units	- Mis-understood requirements; - Poorly defined requirements; - Unmeasurable requirements.	Survey design Customer clinic design/Choice experiments	Probability distributions Appreciation of fitting empirical Matrix algebra Regression analysis
Design Characterization	To choose and configure hardware and software to deliver the requirements as specified	- Over-complicated designs (e.g. too many moving parts); - Unnecessary changes to designs that already work	Response surface methods Dimensional analysis Variability propagation Measurement uncertainty Design & Analysis of computer experiments (DACE)	Matrix Algebra Integral Calculus Regression analysis
Design Optimization	To minimize errors in technical execution	- Mistakes - Lack of robustness	FMEA*** Designed experiments with noise factors Simulation with e.g. Monte Carlo methods	Regression Analysis Matrix Algebra Basic Computer programming
Validation	A final check on all the above phases prior to committing the design to production		Reliability methods Accelerated testing Robustness metrics	Basic information theory Regression analysis
Production	Mistake free operation	Lack of process control	Shewhart Control Charts Cusum methods Automatic Process Control methods (incl. auto-correlation)	Basic computer literacy Exploratory data analysis
Sales	To only make what is sold	Over stocked unsold units	Queueing theory Inventory Control	Probability distributions
Service & Field experience	Monitor field experience to check and learn for next project		Regression analysis Residual Analysis Time series analysis Failure rate analysis (hazard plotting)	Probability distributions Basic computer literacy Exploratory data analysis

Creative Convergence



The role (actually, ***responsibility***) of statistical collaborators in engineering investigations, technology development, and process optimization, is to

a) encourage creativity,

and

b) to ensure convergence.

Things that stand in the way of convergence

- Getting stuck in deductive mode when an empirical approach requiring induction with statistical science is required and vice versa.
- Too much data collection/analysis devoted to eliminating "root cause theories" that, through deduction, can be shown not to be true, which slows down progress in problem solving.
- Initiatives such as Six Sigma have not helped; they have failed to teach the distinction between induction and deduction.
- Data thrown into computer packages and groping around in the output looking for significant "p-values".
- Complicated theories put forward to fit the facts "There are multiple root causes for this problem" – the engineering equivalent of a conspiracy theory. Apply Occam's Razor.

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