I MECH E
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Robustness Thinking & Robust Engineering Design

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Robust Engineering Design (RED)

IS ABOUT ...	IS NOT ABOUT ...
❍ engineering in ideal function	❍ measuring & predicting symptoms of poor quality
❍ anticipating the effects of noise factors upfront in the design process	❍ ignoring the effects of noise factors until it is too late
❍ developing a "noise factor management" strategy	❍ just running orthogonal array experiments ("let's do a Taguchi").
❍ lowest possible cost solutions	❍ adding to design cost

Terminology and Concepts:

Ideal Function: is the primary intended function of the design (often energy related, because mechanical engineering is about making or stopping things moving).

Signal Factor: is the energy which is put into the engineering system to make it work.

Error state: is an undesirable output of the engineering system (including too much variation in ideal function).

Control Factors: are features of the design that can be changed by the engineer (e.g. dimensions, shapes, materials, positions, locations etc).

Noise Factors: are sources of disturbing influences that can disrupt ideal function , causing error states.

Robustness: is low variation of ideal function around the target value *IN SPITE OF* the effects of Noise Factors.

There are several ways to measure robustness

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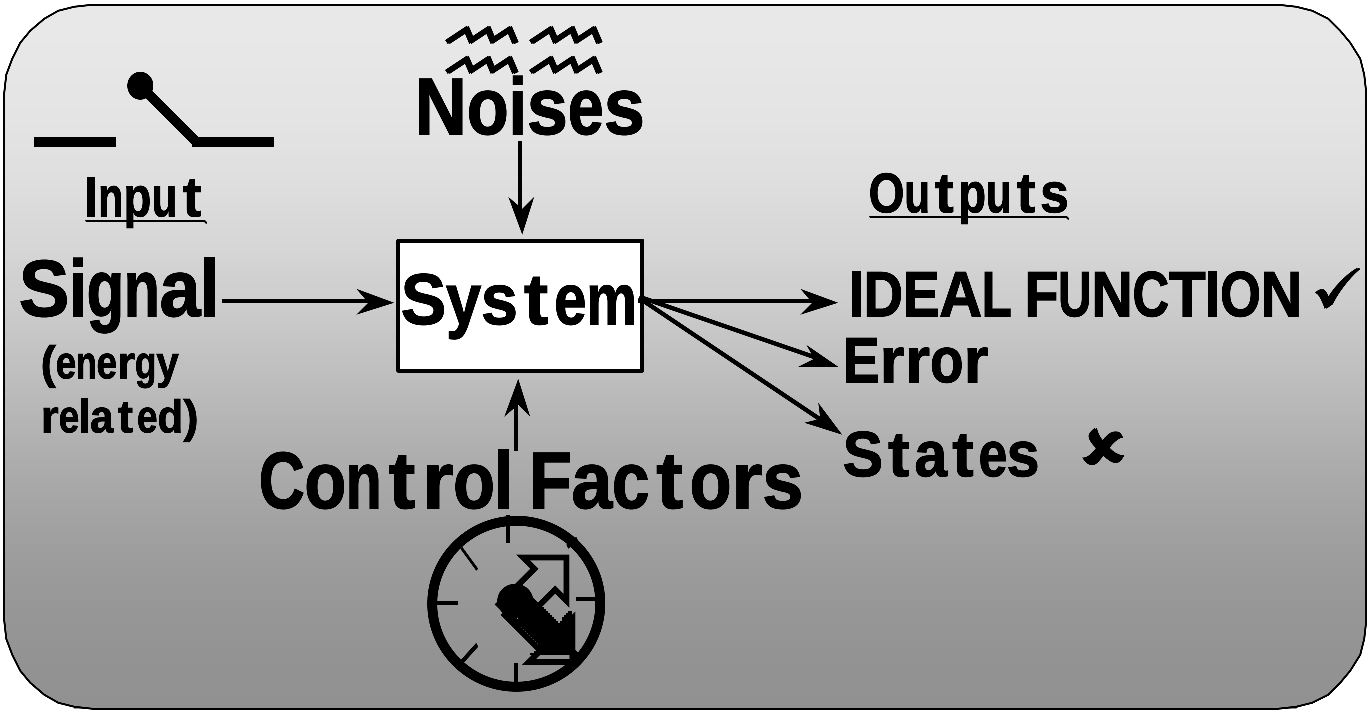
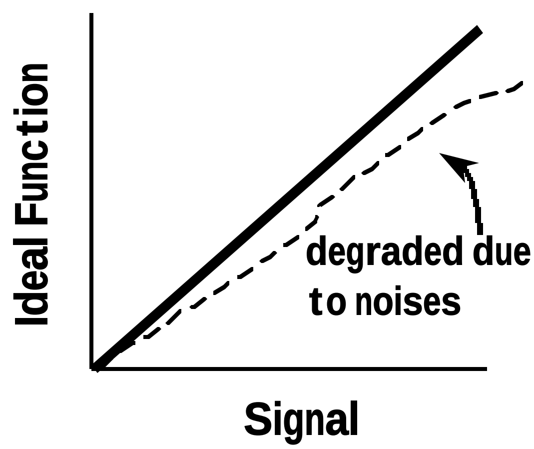
There are several ways to achieve robustness

Model for thinking (due to Taguchi)



IDEALLY 100% of input energy (the signal) should convert into 100% ideal function.



[We may have to think hard to understand the system in this paradigm, but it is not a pre-requisite to apply RED principles]

Parameter Design: Adjusting the control factors to discover improvements to Robustness (Nelder: QI experiments).

NOTE: THIS IS NOT CONCEPT DESIGN

Types of Noise Factor that disrupt ideal function

- Inner Noises
  - 1) Piece-to-piece variation of part dimensions
  - 2) Changes in dimension or strength over time/mileage (i.e. wear out and fatigue)
- Outer
  - Conditions of use
    - 3) Customer usage and duty cycle
  - Operating Environment
    - 4) External (climatic and road conditions)
    - 5) Internal, due to error states being transmitted from neighbouring sub-systems

NOTE: It is the EFFECTS of the noises which are important, rather than the noises themselves

Strategies for Improving Robustness

A: **choose the technology to be robust**

(e.g should we choose a mechanical or electronic speedometer).

B: **make current design assumptions insensitive to the noises.**

(i) - thru' parameter design; adjusting control factors to discover improvements to robustness

(ii) - by beefing up design (upgrading design specification)

C: **reduce or remove the noise factor**

e.g. tighter tolerances (seminal paper: Morrison, J (1957) "The study of variability in engineering design" JRSS C)

D: **insert a compensation device**

e.g. heat shield

Most likely use of statistically designed experiments for strategies B&C

Noise Factor Management

... is about choosing the appropriate strategy to deal with the identified noises. Running a parameter design experiment ("doing a DoE") may not always be the best choice.

Noise source	Strategy A Techn-ology	B (i)Parameter Design.	 (ii)Beef-up	C Remove Noise	D Compen-sate
Piece-to-piece	✓	✓		✓†	
Wear out		✓*		✓‡	
Cust. Use	✓	✓	✓	✗	
Climate	✓	✓	✓	✗	
System int.		✓*		✓§	✓#

†SPC ‡Reliability Engineering

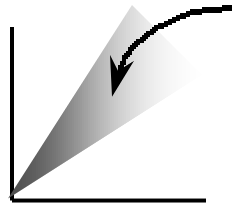
§Systems Engineering # FMEA

* Often forgotten

Measuring & Interpreting Robustness

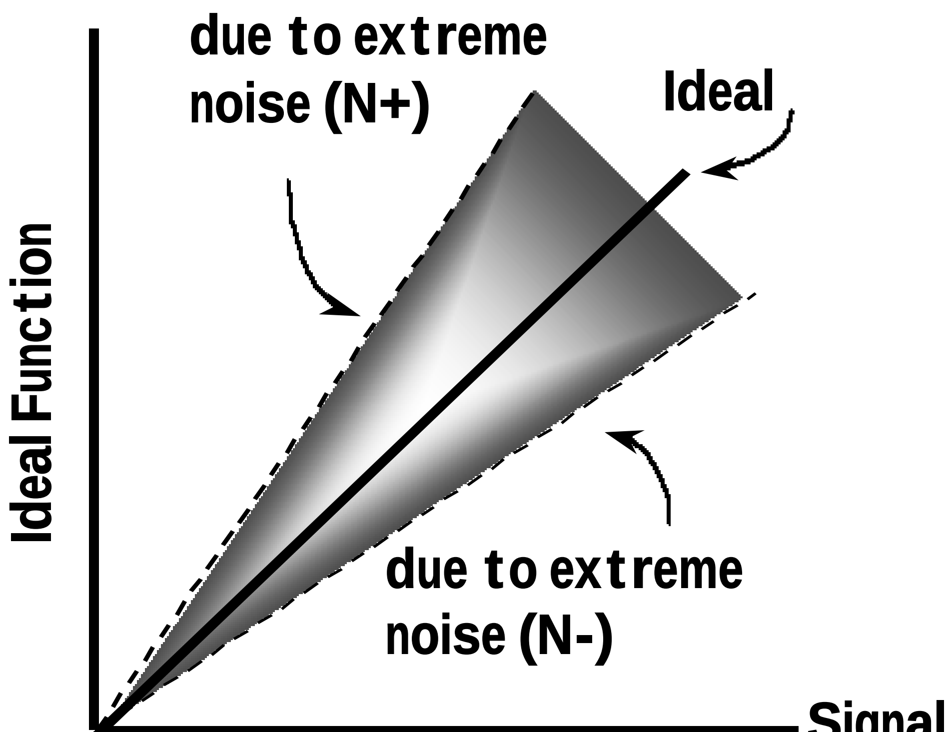
- establish an ideal measure of function (location).
- work out how to expose the system to noises.
- measure the effects of noises on the ideal function (dispersion).
- formulate a robustness measure (Taguchi always combines his location and dispersion measures into an S/N ratio).
- if a parameter design study is needed, model location and dispersion separately (more on this from John Nelder).
- formulate S/N ratio's (if required) after modelling location and dispersion.

"Classical" Robustness Measure

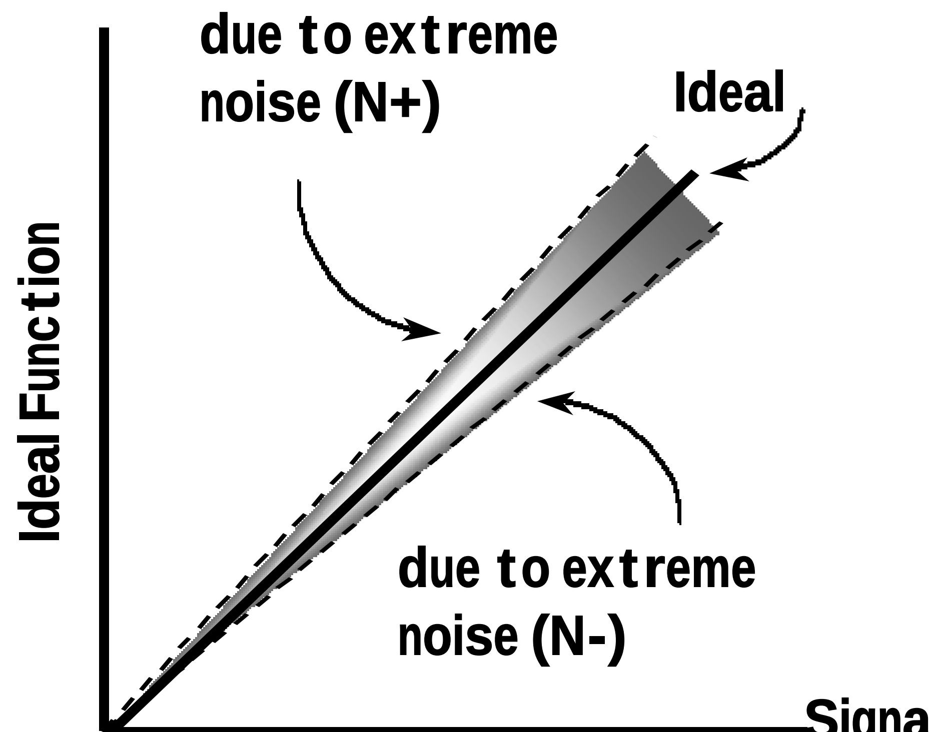


Robustness measure. Taguchi's signal- to-noise ratio measures this: $-20\log_{10}(\hat{b}/s)$

For a single value of the signal factor, Taguchi uses $-10\log_{10}(\bar{y}/s)$



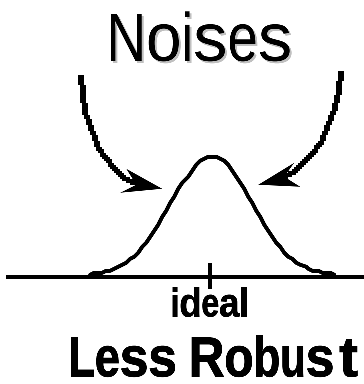
Less Robust

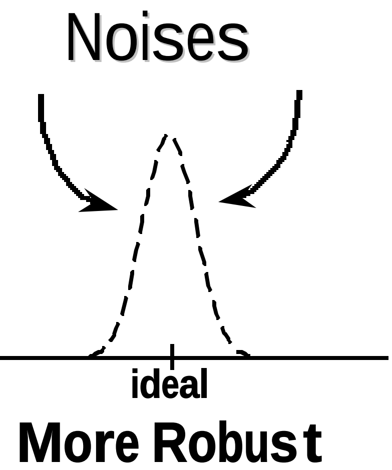


More Robust

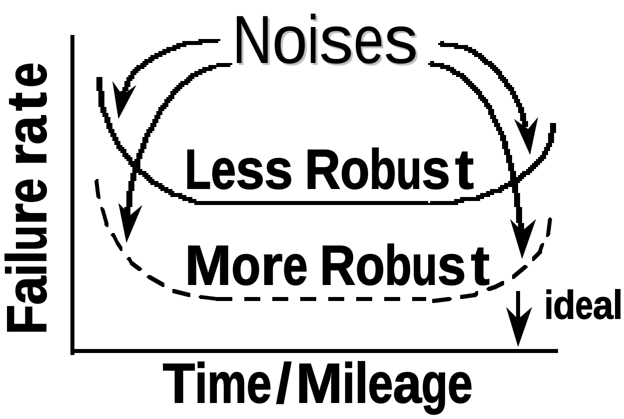
Other Robustness Measures

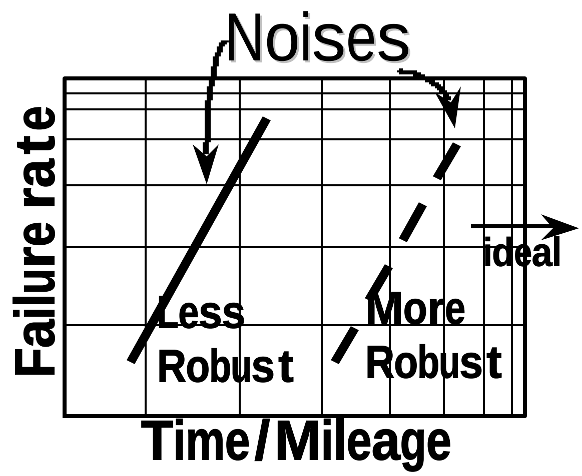
Variation in Output



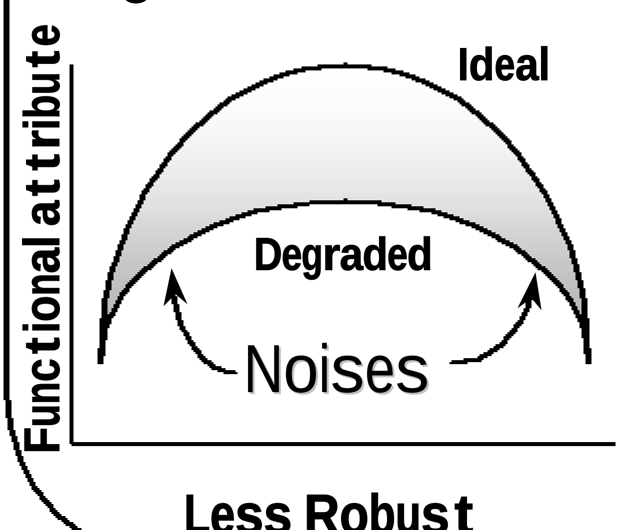


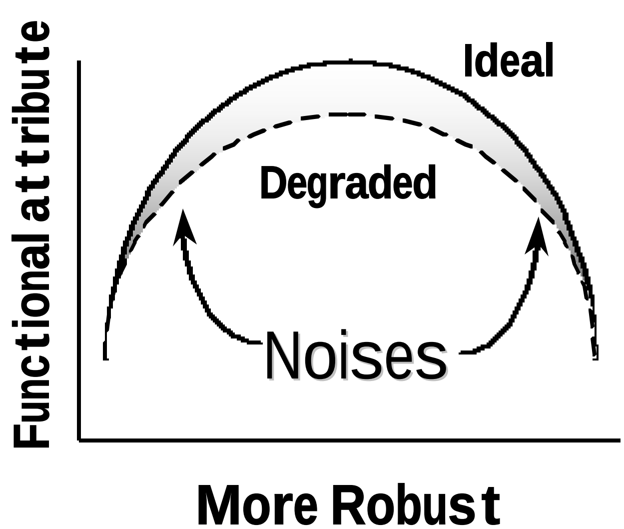
Time to Failure





Degradation

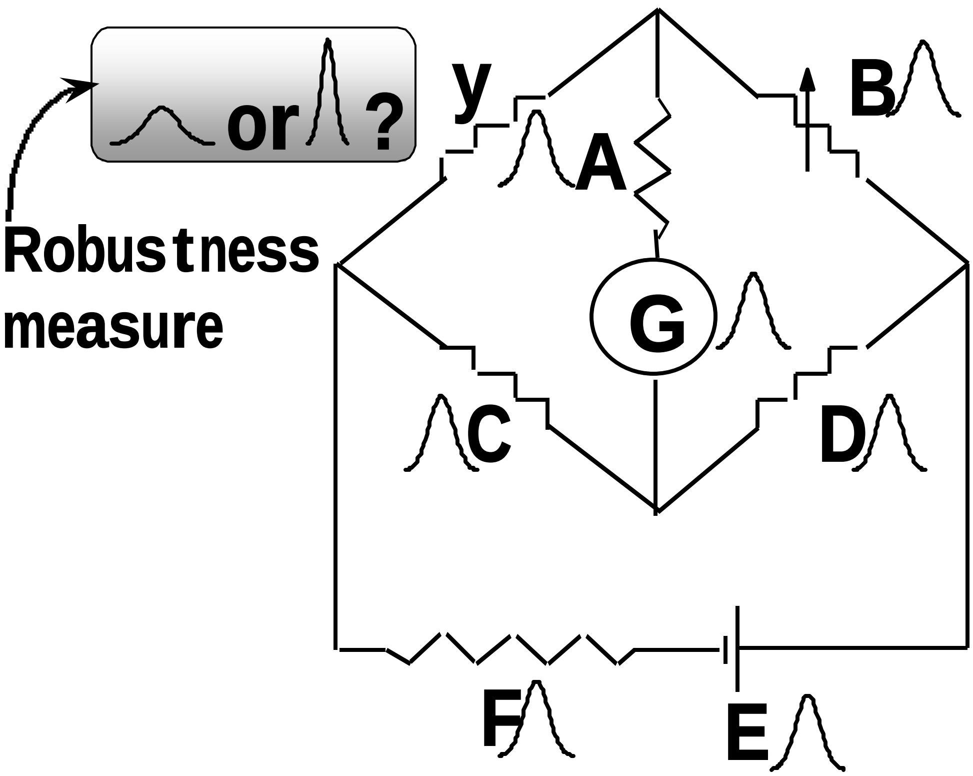




Making a design insensitive to noises

Simple example: Wheatstone Bridge

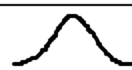
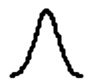
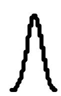
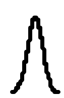
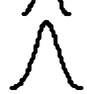
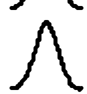
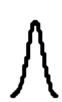
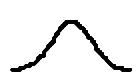
$$y = f(A,B,C,D,E,F,G)=f(\underline{X})$$



Robustness Problem: How to discover nominal values of A,C,D,E,&F to minimize variability transmitted to y. (Obvious Noise Factor Management strategy is C: tighten tolerances on circuit components).

Try strategy B: parameter design

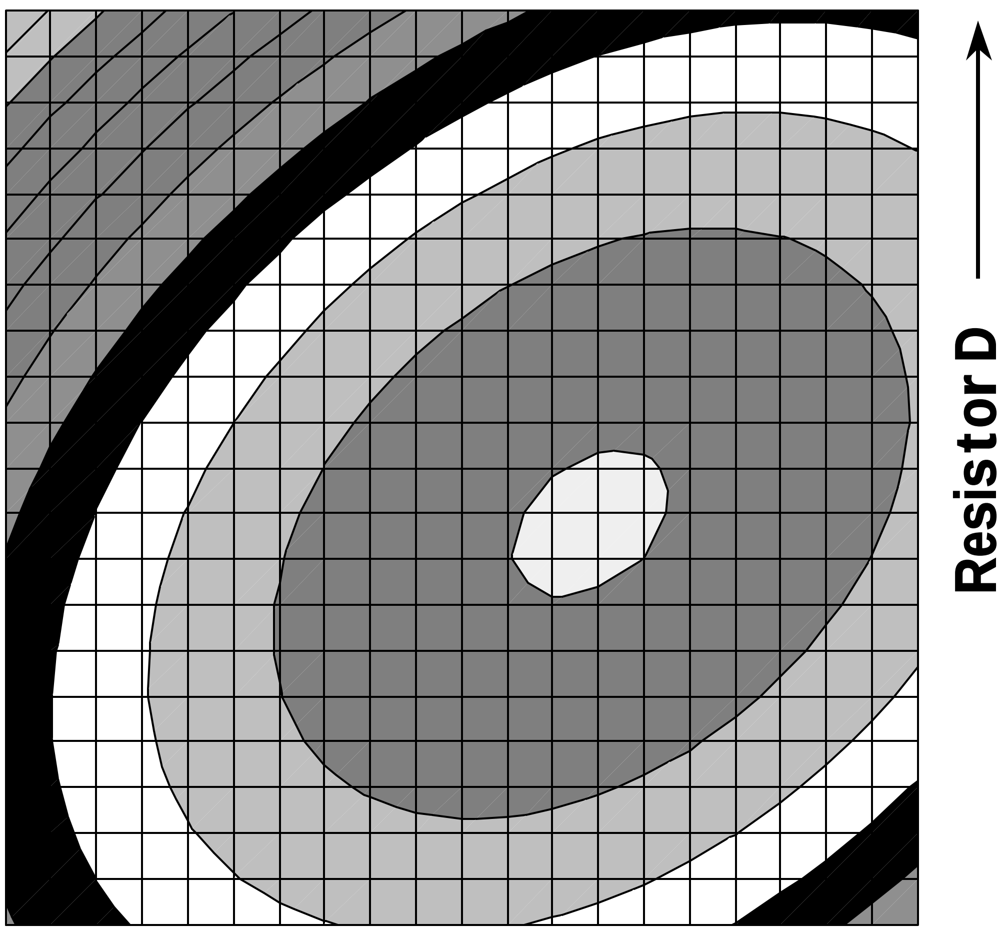
EXPERIMENT with control factor settings (A, C, D, E, & F) to DISCOVER a robust design of the circuit.

A	C	D	E	F	Variability transmitted to y	A	C	D	E	F
10	2	2	1.2	50		-	-	-	-	+
10	2	2	30	2		-	-	-	+	-
10	2	50	1.2	2		-	-	+	-	-
10	2	50	30	50		-	-	+	+	+
10	50	2	1.2	2		-	+	-	-	-
10	50	2	30	50		-	+	-	+	+
10	50	50	1.2	50		-	+	+	-	+
10	50	50	30	2		-	+	+	+	-
50	2	2	1.2	2		+	-	-	-	-
50	2	2	30	50		+	-	-	+	+
50	2	50	1.2	50		+	-	+	-	+
50	2	50	30	2		+	-	+	+	-
50	50	2	1.2	50		+	+	-	-	+
50	50	2	30	2		+	+	-	+	-
50	50	50	1.2	2		+	+	+	-	-
50	50	50	30	50		+	+	+	+	+

Note: All control factors changed together. This is counter intuitive to most engineers.

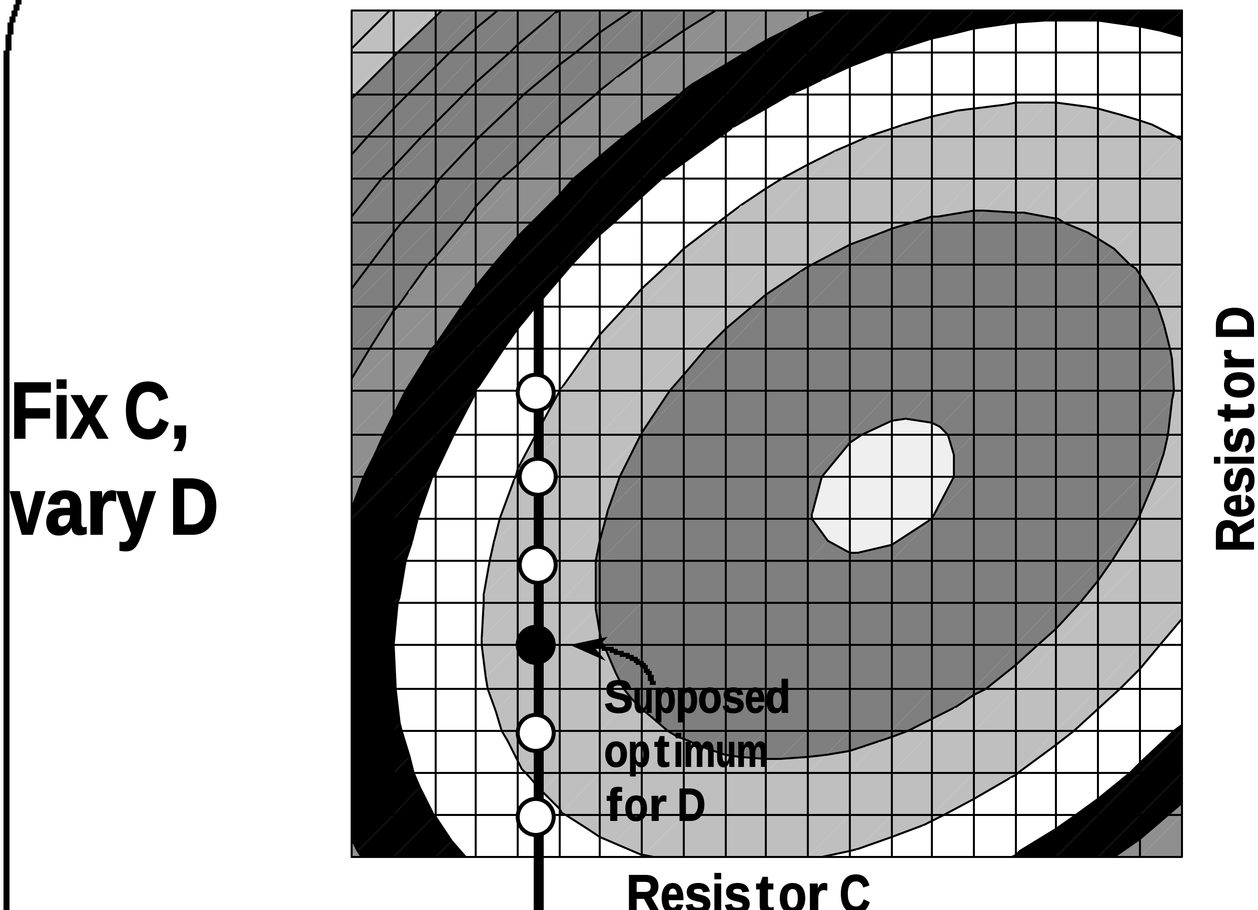
Solution: **Analysis of experimental data shows variability transmitted to y can be approximated by a 2ND order equation in the nominal values of resistors C&D** (1ST order in A, E, & F).

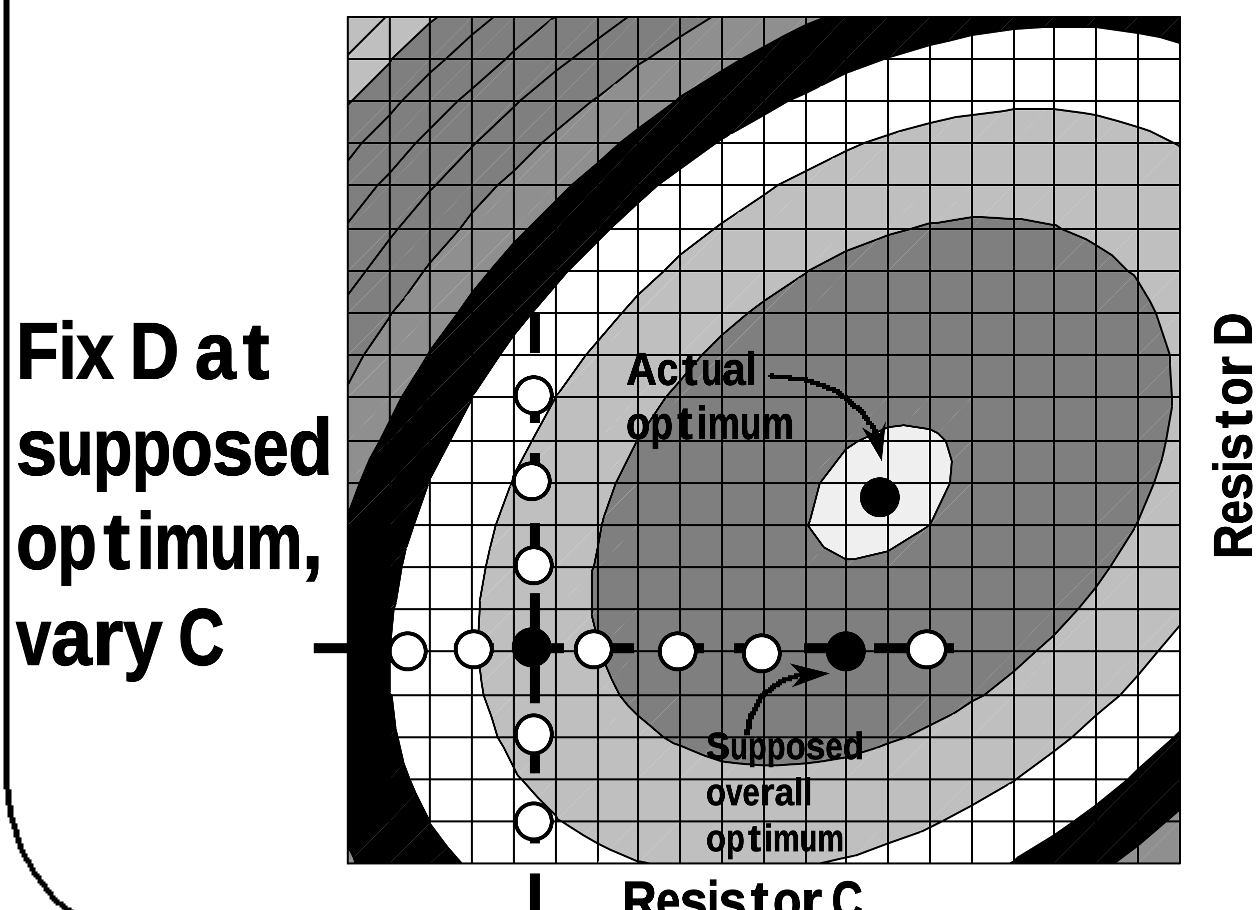
Contour Plot of variability transmitted to y



This solution cannot be found with a "vary-one-factor-at-a- time" experiment.

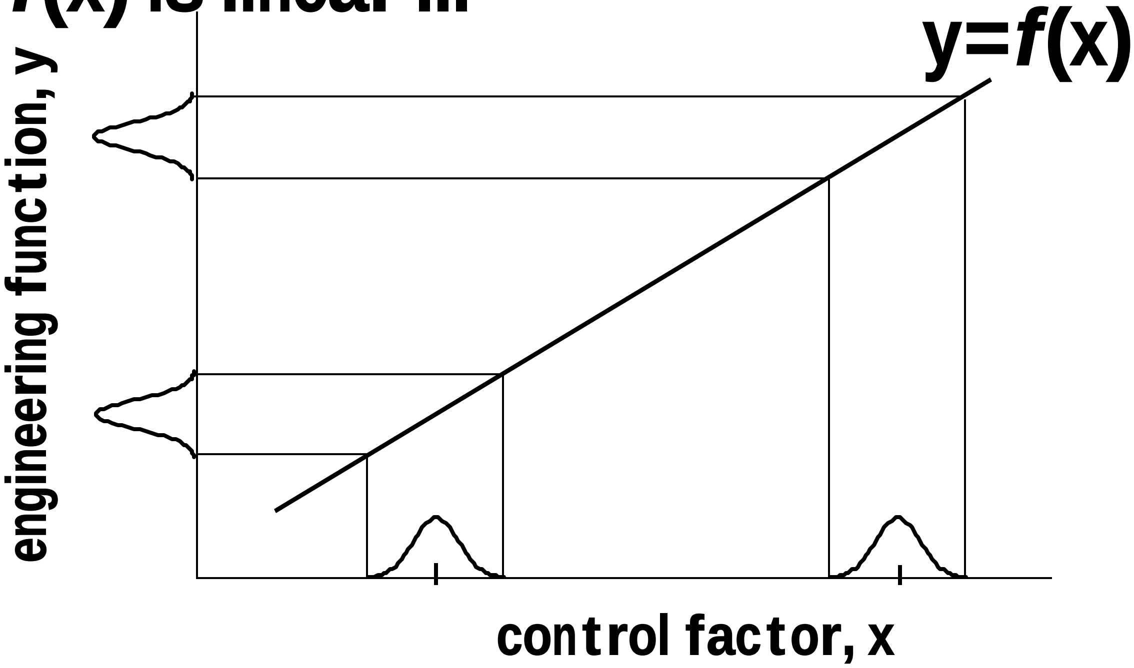
Why One Factor at a time experiments can fail





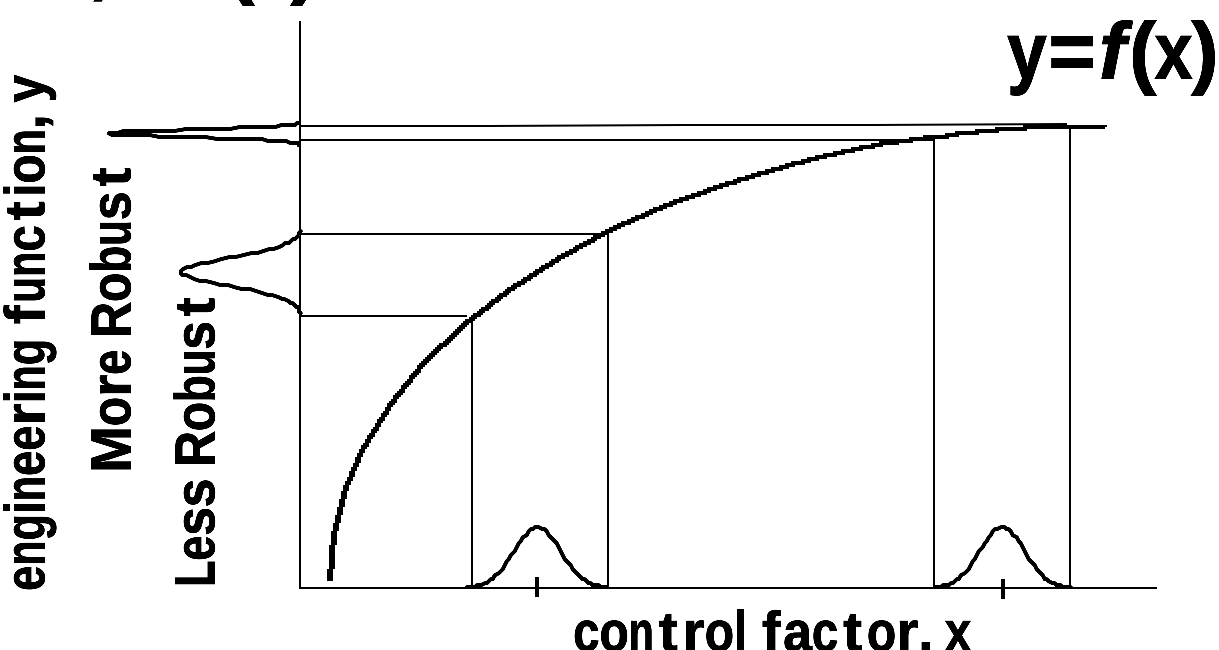
Principles at work (for inner noises)

If *f*(x) is linear ...



then changing the nominal of x has no effect on the variability of y.

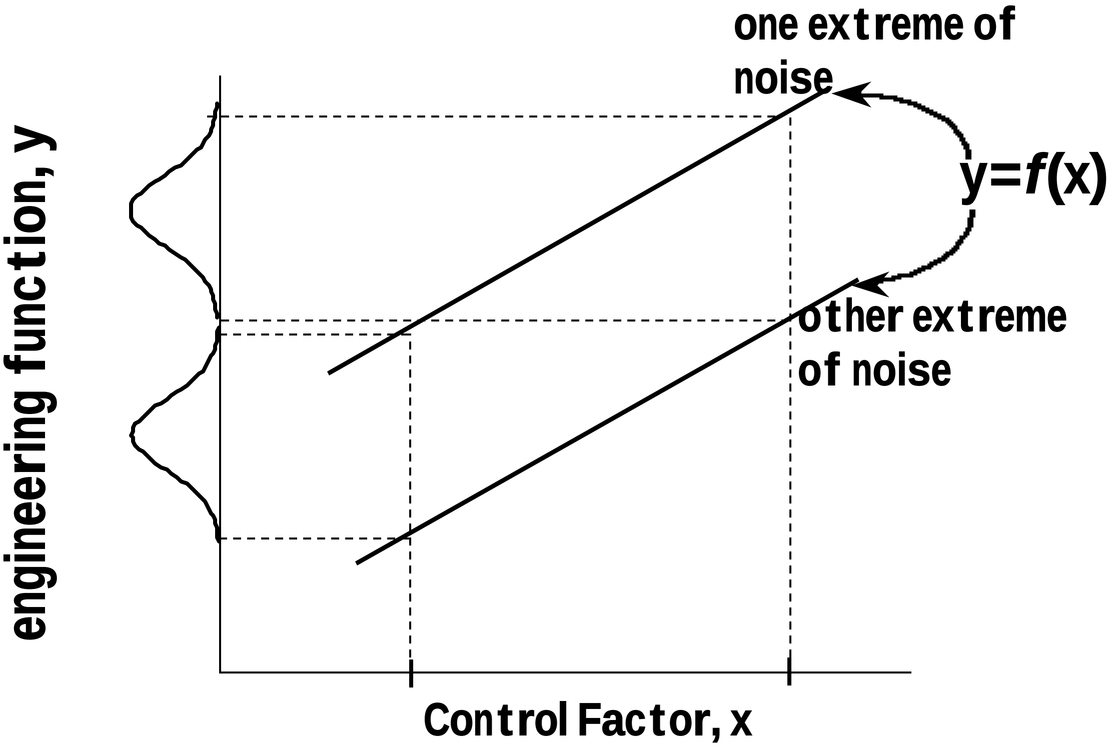
BUT, if *f*(x) is non-linear ...



changing the nominal of x can have a major effect on the variability of y.

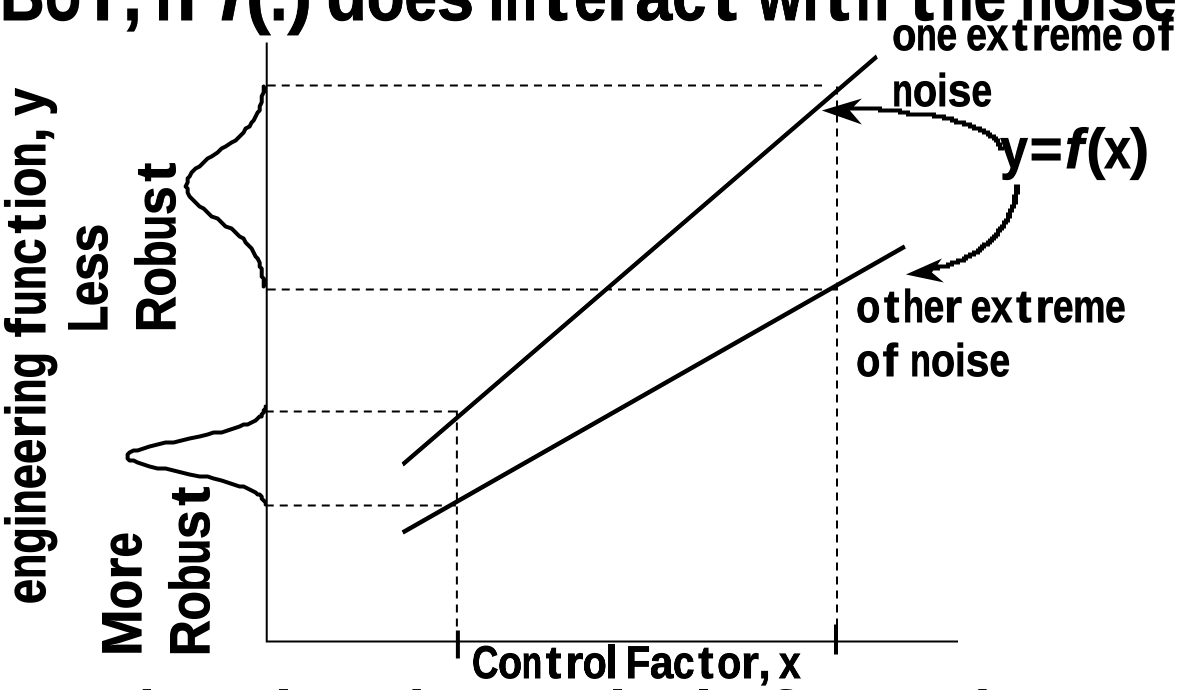
Principles at work (for outer noises)

If *f*(.) does not interact with the noise...



... then changing the nominal of x has no effect on the variability of y.

BUT, if *f*(.) does interact with the noise ...



... changing the nominal of x can have a major effect on the variability of y.

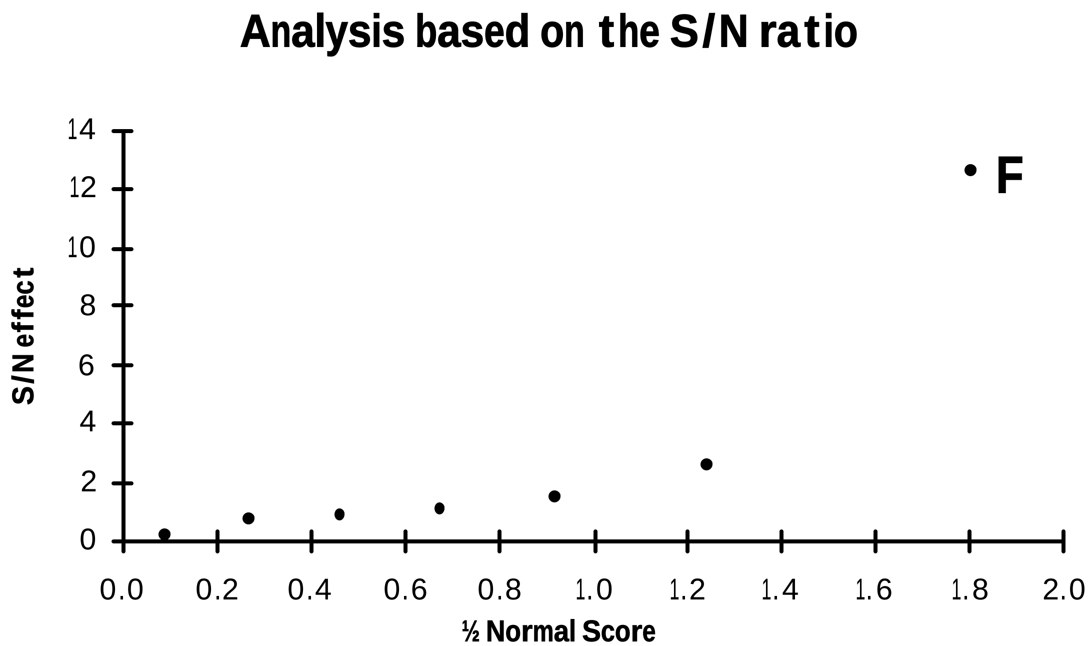
Looking for curvature in the response surface and interactions between control & noise factors requires the use of Statistical Experimental Design.

- be aware of possible interactions between control factors on the robustness measure (don't use linear graphs).
- "inner" arrays for control factors & "outer" arrays for noise factors can be inefficient for looking at control x noise interactions.
- looking at control x noise interaction plots is usually more informative than the S/N ratio (e.g. see Engel's 1992 experiment).
- response surface designs are generally preferable than 3-level OA's.
- analyse separately measures of location and dispersion
- Simple graphical methods are preferable than techniques such as ANOVA (e.g. ½ normal plot).

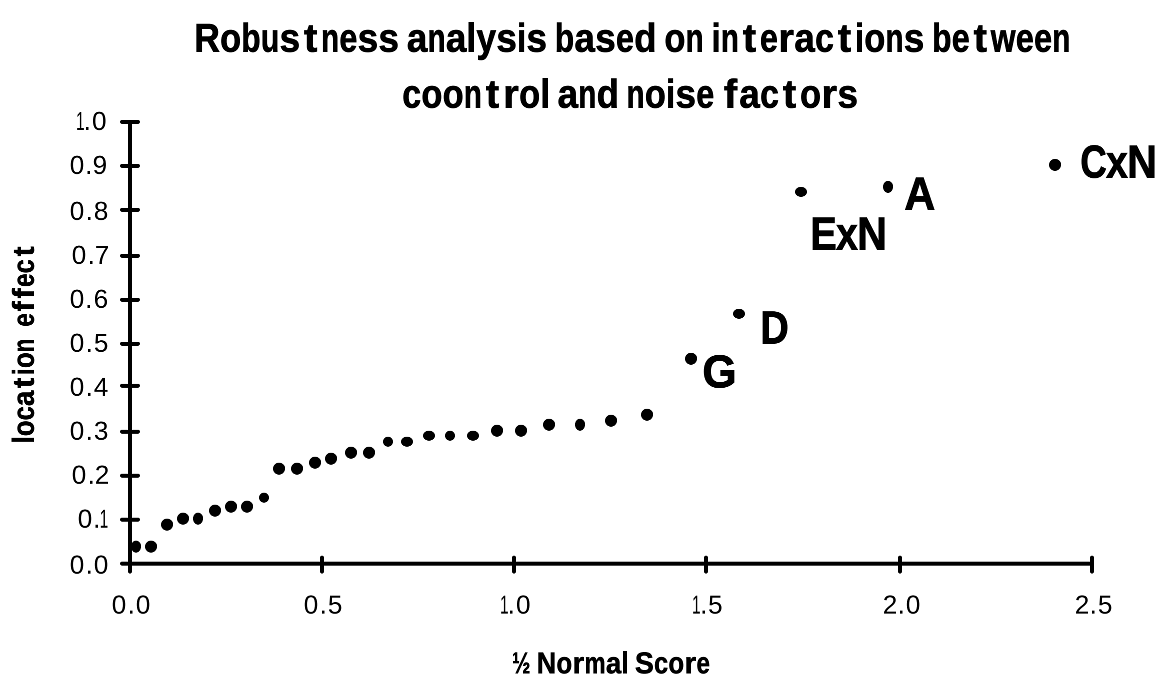
Engels Injection Moulding Experiment

7 control factors in a 2^{7-4} (L_8), 3 noise factors in a 2^{3-1} (L_4);

(1) Analysis of S/N ratio

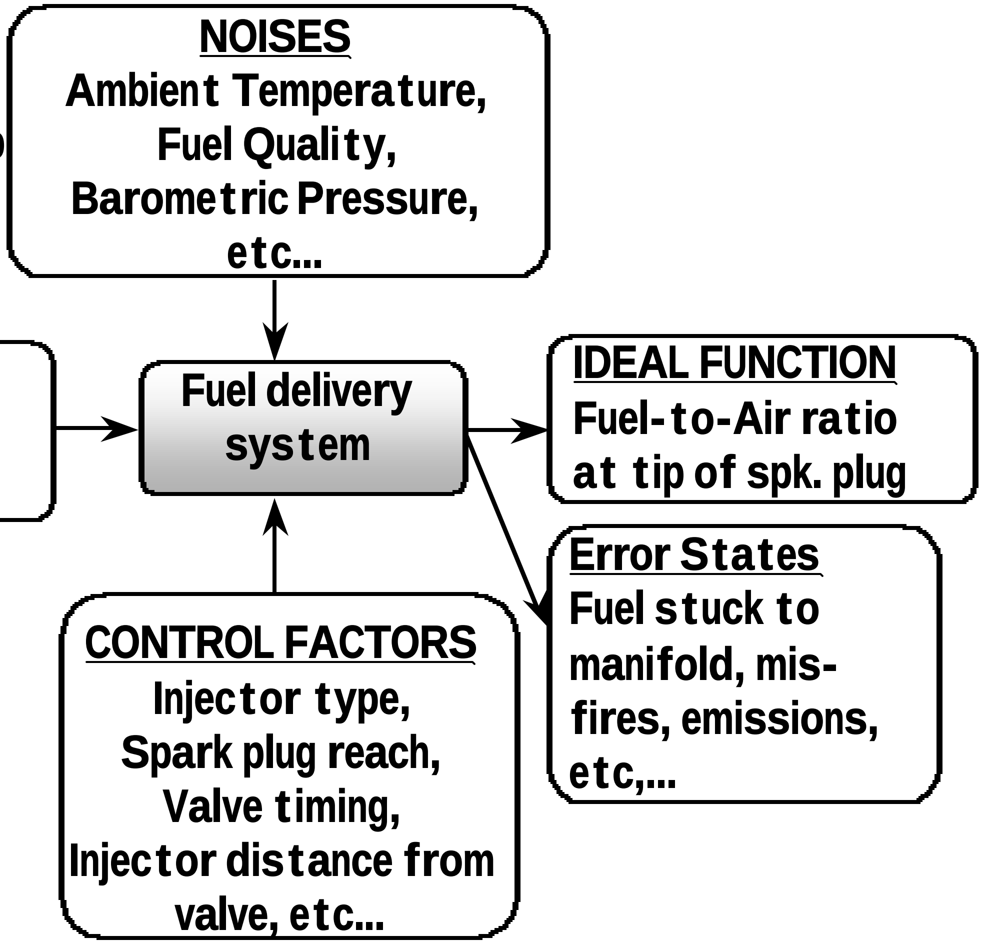


(2) Analysis of interaction effects

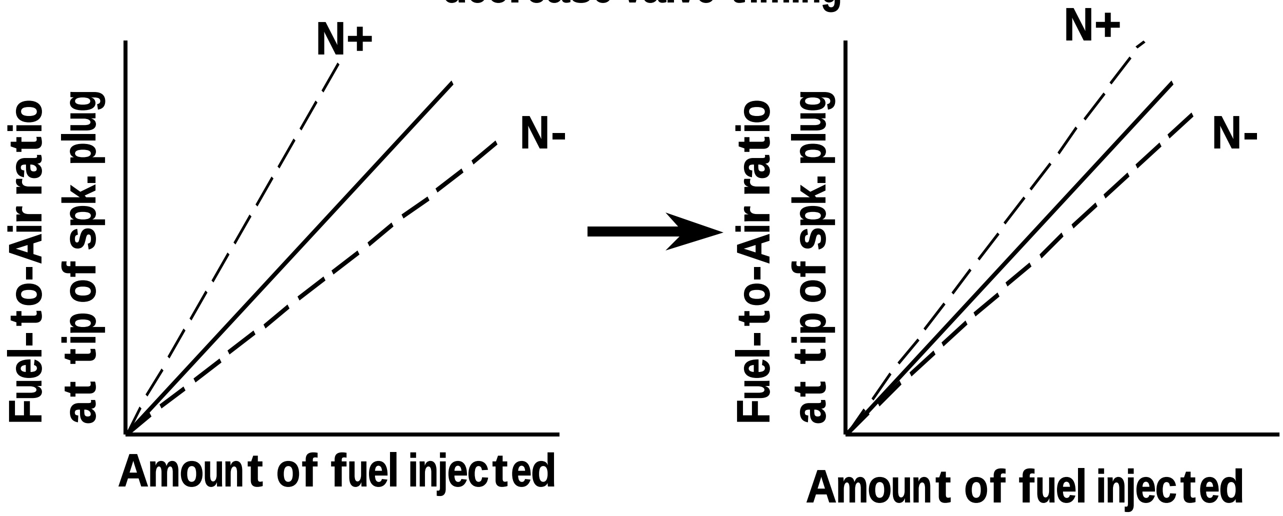


Another Example: Engine Starting

Control array: L_{18}
Noise Array: comp

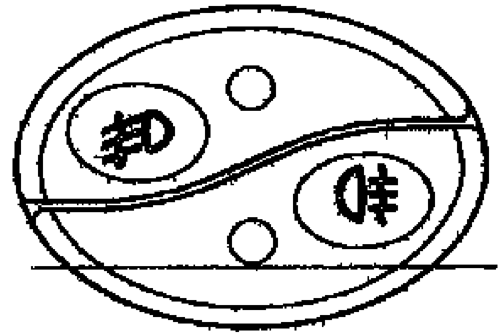


Change of injector (no heater needed)
Increased injector distance
decrease valve timing



For more details, see Grove & Davis (1992)

Large parameter design experiments are not always necessary

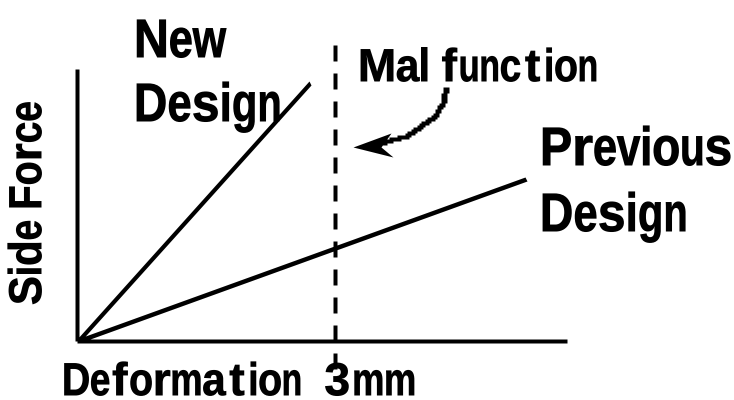


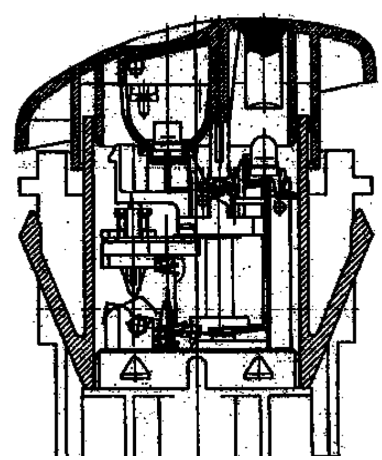
Example:
Sticking Switches

Concern: Push-Push switch sticking in cold weather.

Noises: Piece-to-piece variation in bezel aperture - caused by flash (#1), cold weather -causing shrinkage (#4).

Robustness measure.





Solution: Increase stiffness of housing, reduce flash, a combination of strategy B & C

Robustness "Rules of Engagement"

1. Concentrate on Ideal Function, and establish a way to measure it; do not use symptoms of poor quality.
2. Identify sources of the five types of noises and expected magnitudes. (Remember Noise 5).
3. Concentrate on the *effects* of the noises, rather than the noises themselves.
4. Understand how error states and noise factors cross system interfaces and boundaries.
5. Develop a noise factor management strategy. Removing the noise might be easier than becoming robust to it.
6. Work out how to include remaining Noise Factors in tests.
7. Plan a robustness assessment of current design to compare against ideal performance.
8. Where robustness improvement strategy is obvious from knowledge of physics, DO IT!
9. Where robustness improvement is not obvious from current knowledge of the physics, plan parameter design studies (using DoE if necessary) to discover the improvement.