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# ICT Innovation – Spring 2016

MSc in Computer Science and MEng Telecom. Engineering
EIT Masters ITA, S&P,SDE

## Lecture 07 – Robust Design

Prof. Fabio Massacci

## Robust Design and Quality in the Product

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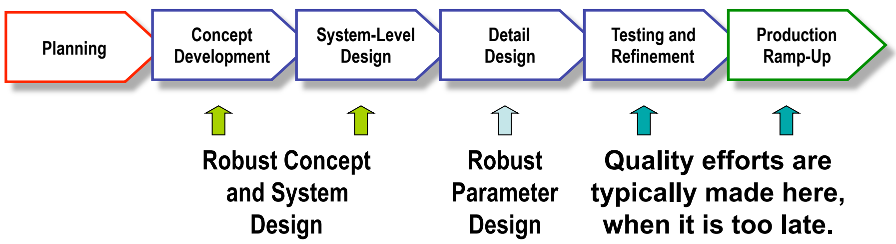

## Goals for Designed Experiments

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- **Modeling**
  - Understanding relationships between design parameters and product performance
  - Understanding effects of noise factors
- **Optimizing**
  - Reducing product or process variations
  - Optimizing nominal performance

## Esercise: the gun shooter

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- **Testing a laser-guided rifle**
  - Thunder
  - Storm
- **Experiment**
  - Ask 6 soldiers to take aim and shoot
  - Identify best gun
- **Decide what to do in response**

## Who is the better target shooter?

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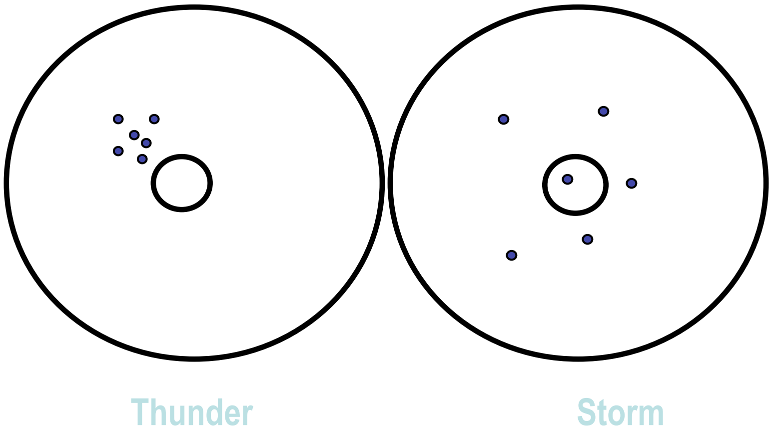


## Who is better? Mean vs Variance

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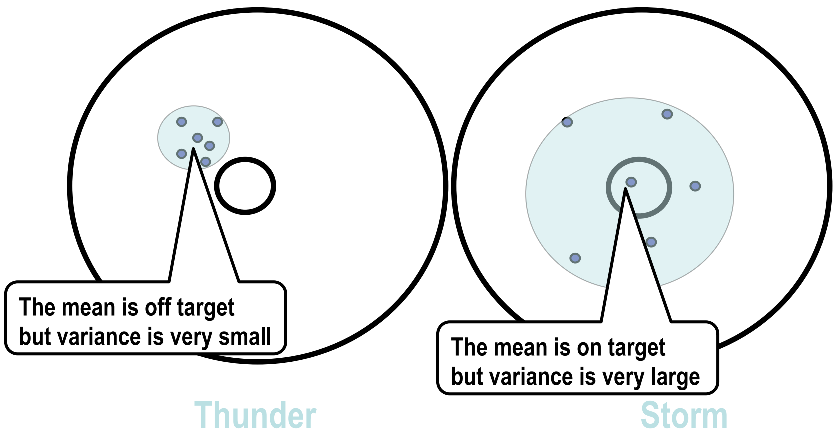

## Who is better? Mean vs Variance

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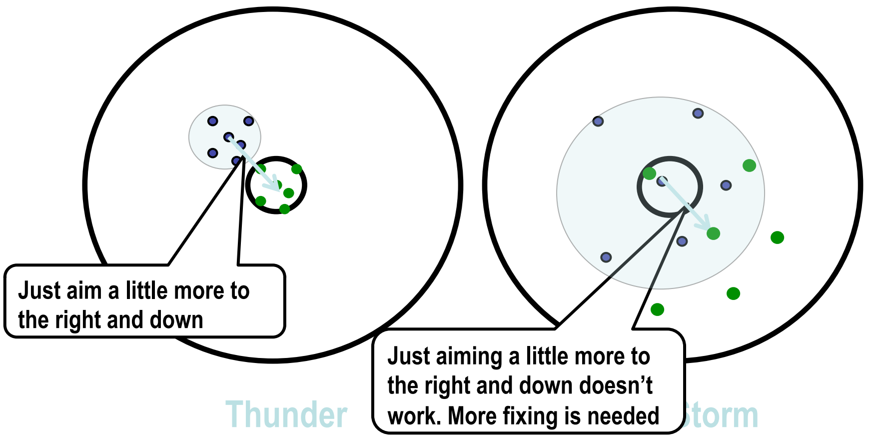


## Robust Designs

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- A robust product or process performs correctly, even in the presence of noise factors
- e.g. shooters (aka users)
- Noise factors may include:
  - parameter variations
  - environmental changes
  - operating conditions
  - manufacturing variations

## Response to Factors: linear

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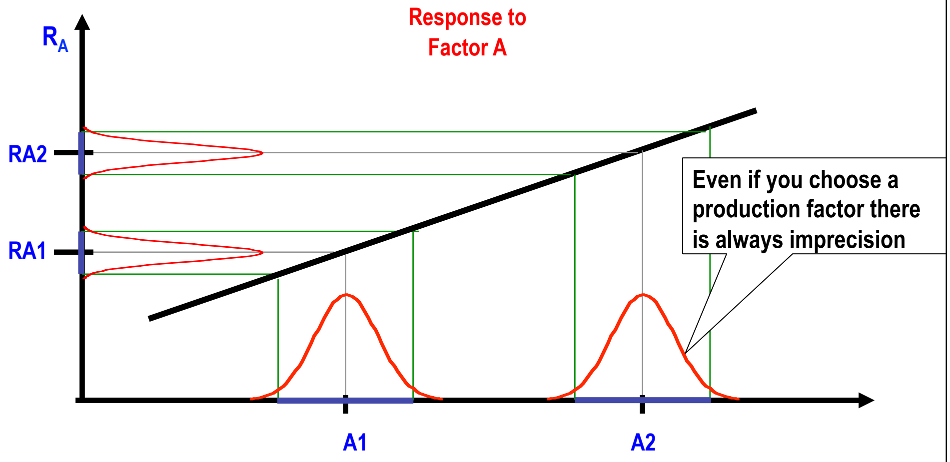


**Can chose Factor A between A1 and A2**

- **No difference in Variance**
- **Difference in Mean (R2 > R1)**

## Response to Factor: Exponential/Power Law

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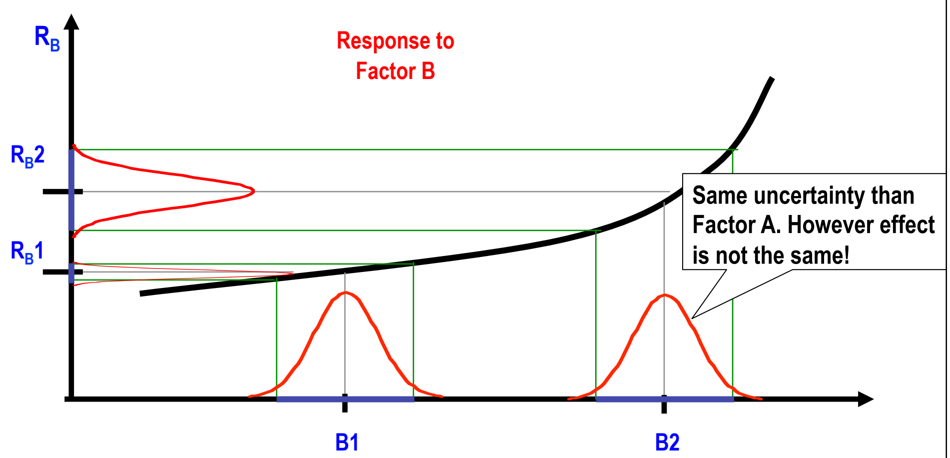


**Can chose Factor B between B1 and B2**

- **Difference in Variance**
- **Difference in Mean (RB2 > RB1)**

## Exploiting Non-Linearity to Achieve Robust Performance

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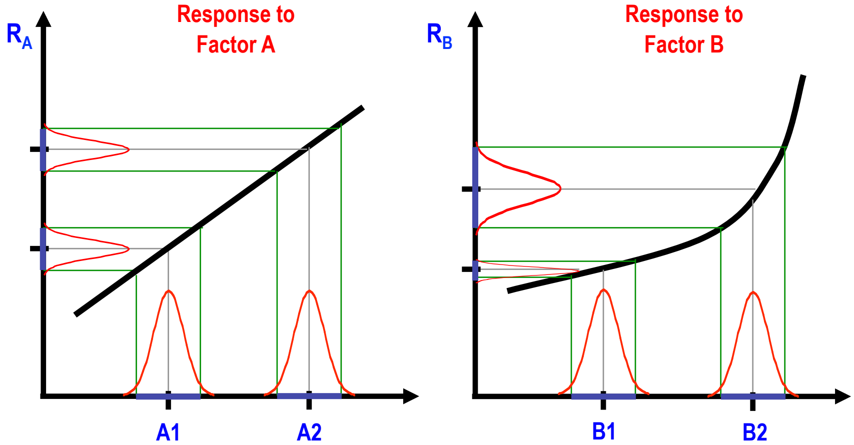


**Response = $R_A(A) + R_B(B)$**
**What level of factor B gives the robust response?**
**How do we use factor A?**

## Robust Designs

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- A robust product or process performs correctly, even in the presence of noise factors
- e.g. shooters (aka users)
- Noise factors may include:
  - parameter variations
  - environmental changes
  - operating conditions
  - manufacturing variations
- How do we find the robust design?

## Robust Design Procedure
## Step 1: Parameter Diagram

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- Step 1: Select appropriate controls, response, and noise factors to explore experimentally.
- Control factors (input parameters)
- Noise factors (uncontrollable)
- Performance metrics (response)

## Robust Design Example:
## Seat Belt Experiment

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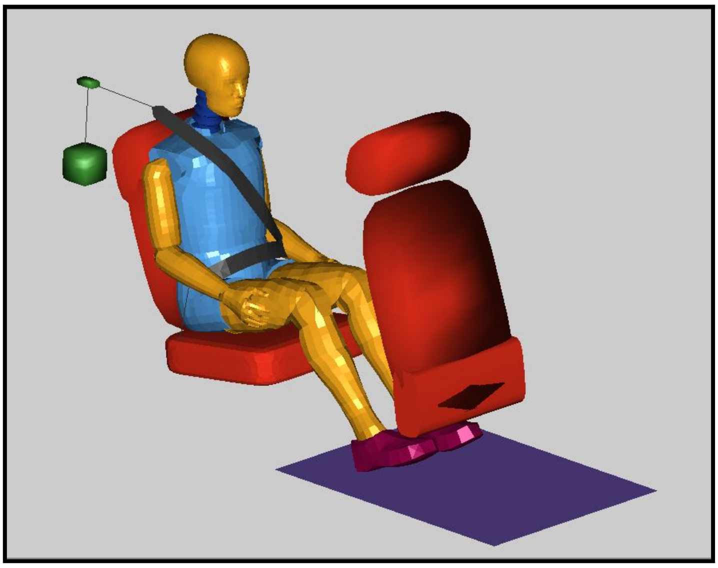

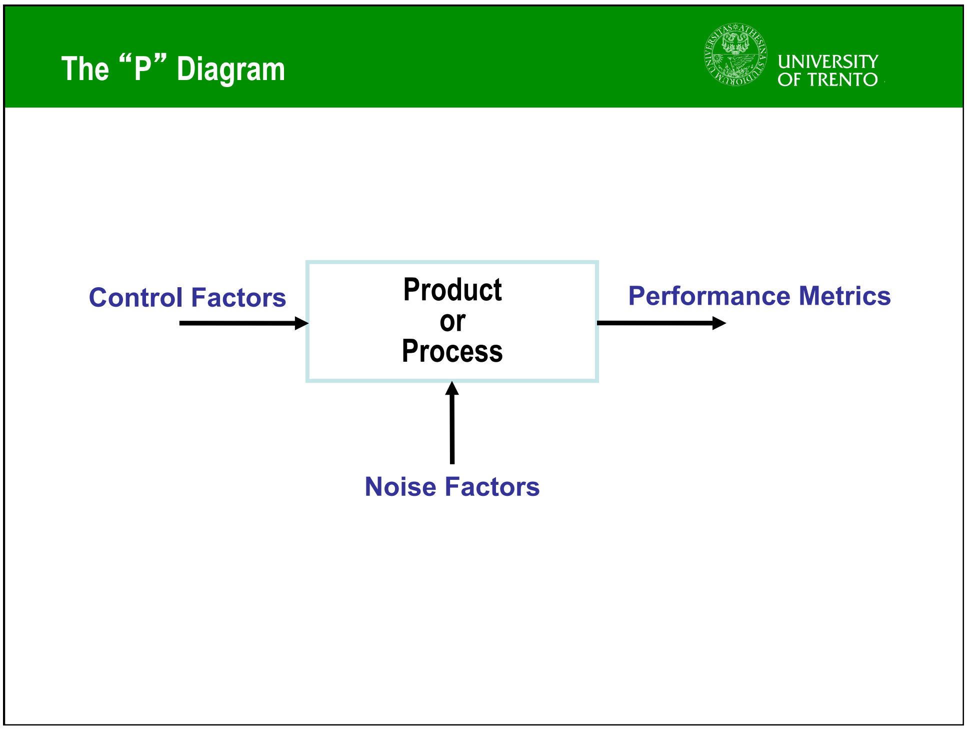
The “P” Diagram
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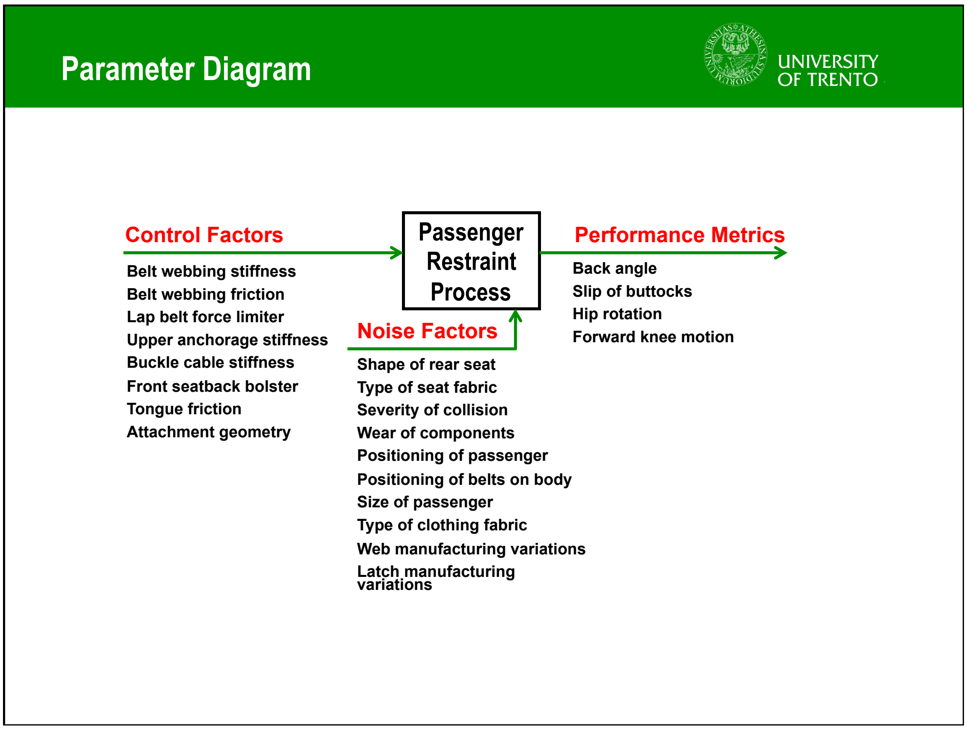
Control Factors
Product or Process
Performance Metrics
Noise Factors


Parameter Diagram
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Control Factors
Belt webbing stiffness
Belt webbing friction
Lap belt force limiter
Upper anchorage stiffness
Buckle cable stiffness
Front seatback bolster
Tongue friction
Attachment geometry
Passenger Restraint Process
Noise Factors
Shape of rear seat
Type of seat fabric
Severity of collision
Wear of components
Positioning of passenger
Positioning of belts on body
Size of passenger
Type of clothing fabric
Web manufacturing variations
Latch manufacturing variations
Performance Metrics
Back angle
Slip of buttocks
Hip rotation
Forward knee motion

## Example: Brownie Mix

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- **Control Factors**
  - Recipe Ingredients (quantity of eggs, flour, chocolate)
  - Recipe Directions (mixing, baking, cooling)
  - Equipment (bowls, pans, oven)
- **Noise Factors**
  - Quality of Ingredients (size of eggs, type of oil)
  - Following Directions (stirring time, measuring)
  - Equipment Variations (pan shape, oven temp)
- **Performance Metrics**
  - Taste Testing by Customers
  - Sweetness, Moisture, Density

## Robust Design Procedure

### Step 2: Objective Function

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**Step 2: Define an objective function (of the response) to optimize.**

- **maximize desired performance**
- **minimize variations**
- **target value**
- **signal-to-noise ratio**

## Types of Objective Functions

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**Larger-the-Better**
e.g. performance
$\eta = \mu^2$

**Smaller-the-Better**
e.g. variance
$\eta = 1/\sigma^2$

**Nominal-the-Best**
e.g. target
$\eta = 1/(\mu - t)^2$

**Signal-to-Noise**
e.g. trade-off
$\eta = 10\log[\mu^2/\sigma^2]$

## Robust Design Procedure
## Step 3: Plan the Experiment

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- **Step 3: Plan experimental runs to elicit desired effects.**
  - Use full or fractional factorial designs to identify interactions.
  - Use an orthogonal array to identify main effects with minimum of trials.
  - Use inner and outer arrays to see the effects of noise factors.

## Experiment Design: Full Factorial

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- Consider k factors, n levels each.
- Test all combinations of the factors.
- The number of experiments is $n^k$ .
- Generally this is too many experiments, but we are able to reveal all interactions.

| Expt # | Param A | Param B |
|---|---|---|
| 1 | A1 | B1 |
| 2 | A1 | B2 |
| 3 | A1 | B3 |
| 4 | A2 | B1 |
| 5 | A2 | B2 |
| 6 | A2 | B3 |
| 7 | A3 | B1 |
| 8 | A3 | B2 |
| 9 | A3 | B3 |

2 factors, 3 levels each:

$n^k = 3^2 = 9$ trials

4 factors, 3 levels each:

$n^k = 3^4 = 81$ trials

## Experiment Design: One Factor at a Time

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- Consider k factors, n levels each.
- Test all levels of each factor while freezing the others at nominal level.
- The number of experiments is 1+k(n-1).
- BUT this is an unbalanced experiment design.

| Expt # | Param A | Param B | Param C | Param D |
|---|---|---|---|---|
| 1 | A2 | B2 | C2 | D2 |
| 2 | A1 | B2 | C2 | D2 |
| 3 | A3 | B2 | C2 | D2 |
| 4 | A2 | B1 | C2 | D2 |
| 5 | A2 | B3 | C2 | D2 |
| 6 | A2 | B2 | C1 | D2 |
| 7 | A2 | B2 | C3 | D2 |
| 8 | A2 | B2 | C2 | D1 |
| 9 | A2 | B2 | C2 | D3 |

4 factors, 3 levels each

$1+k(n-1) =$

$1+4 \times 2 = 9$ trials

## Experiment Design: Orthogonal Array

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- Consider k factors, n levels each.
- For every pair of factors each level of one factor is paired with all levels of the other factors
- The number of experiments is order of (k-1)n.
- This is the smallest balanced experiment design.
- Trade-off effects and interactions are confounded.

| Expt # | Param A | Param B | Param C | Param D |
|---|---|---|---|---|
| 1 | A1 | B1 | C1 | D1 |
| 2 | A1 | B2 | C2 | D2 |
| 3 | A1 | B3 | C3 | D3 |
| 4 | A2 | B1 | C2 | D3 |
| 5 | A2 | B2 | C3 | D1 |
| 6 | A2 | B3 | C1 | D2 |
| 7 | A3 | B1 | C3 | D2 |
| 8 | A3 | B2 | C1 | D3 |
| 9 | A3 | B3 | C2 | D1 |

**4 factors, 3 levels each:**

(k-1)n =

(4-1)3 = 9 trials

## Using Inner and Outer Arrays

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- Induce the same noise factor levels for each combination of controls in a balanced manner

**3 factors, 2 levels each:** L4 outer array for noise

**4 factors, 3 levels each:** L9 inner array for controls

| | | | | E1 | E1 | E2 | E2 |
|---|---|---|---|---|---|---|---|
| | | | | F1 | F2 | F1 | F2 |
| | | | | G2 | G1 | G2 | G1 |
| A1 | B1 | C1 | D1 | | | | |
| A1 | B2 | C2 | D2 | | | | |
| A1 | B3 | C3 | D3 | | | | |
| A2 | B1 | C2 | D3 | | | | |
| A2 | B2 | C3 | D1 | | | | |
| A2 | B3 | C1 | D2 | | | | |
| A3 | B1 | C3 | D2 | | | | |
| A3 | B2 | C1 | D3 | | | | |
| A3 | B3 | C2 | D1 | | | | |

inner x outer = L9 x L4 = 36 trials

## Using Inner and Outer Arrays

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- Induce the same noise factor levels for each combination of controls in a balanced manner

**This design is not balanced**
**F1 never tested with G1**

**This design is balanced**
**Check it out**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | E1 | E1 | E2 | E2 |
| | | | | F1 | F2 | F1 | F2 |
| | | | | G2 | G1 | G2 | G1 |
| A1 | B1 | C1 | D1 | | | | |
| A1 | B2 | C2 | D2 | | | | |
| A1 | B3 | C3 | D3 | | | | |
| A2 | B1 | C2 | D3 | | | | |
| A2 | B2 | C3 | D1 | | | | |
| A2 | B3 | C1 | D2 | | | | |
| A3 | B1 | C3 | D2 | | | | |
| A3 | B2 | C1 | D3 | | | | |
| A3 | B3 | C2 | D1 | | | | |

## Robust Design Procedure
## Step 4: Run the Experiment

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- Step 4: Conduct the experiment.
- Vary the control and noise factors
- Record the performance metrics
- Compute the objective function
- Possibly more than one single run for each trial!
  - So total is (k-1) factors * n levels * m runs

## Why More Than a Single Trial?

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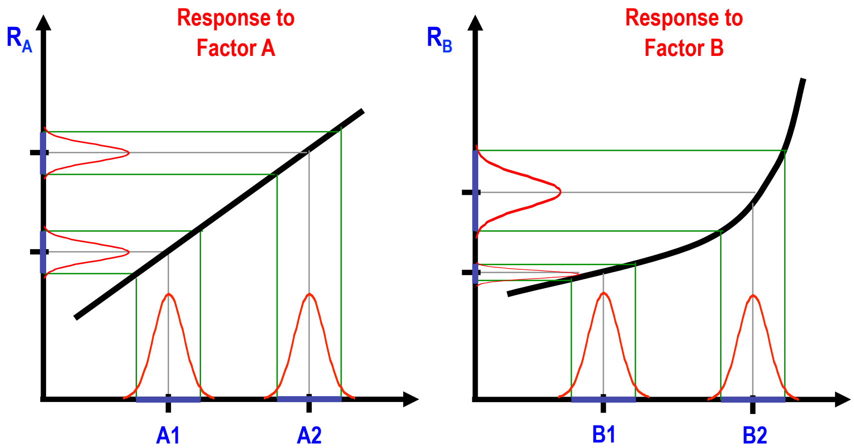


**Seems obvious that there is a difference between linear and exponential effects**

**BUT we don't know if B is linear or exponential before running the experiment!**

## Why More Than a Single Run?

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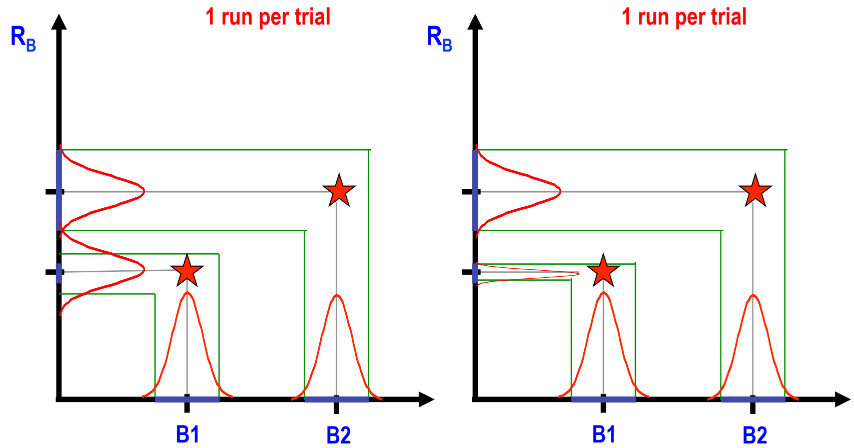


**How can we tell which of the two effects is the real one?**

## Why More Than a Single Run?

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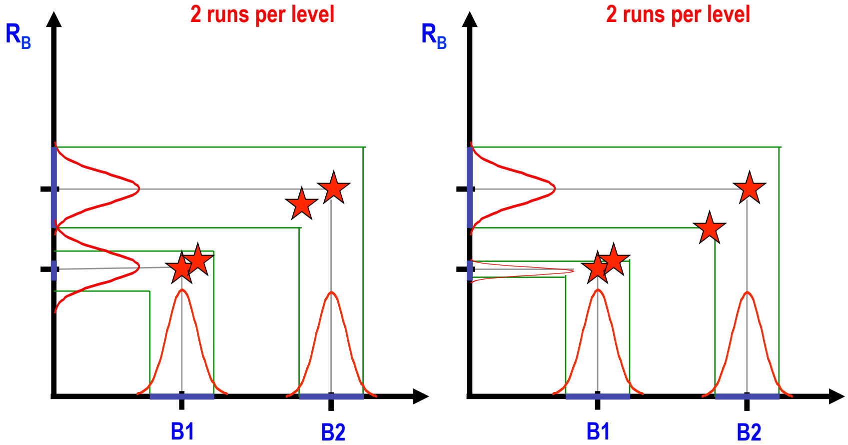


**How can we tell which of the two effects is the real one?**

## Why More Than a Single Run?

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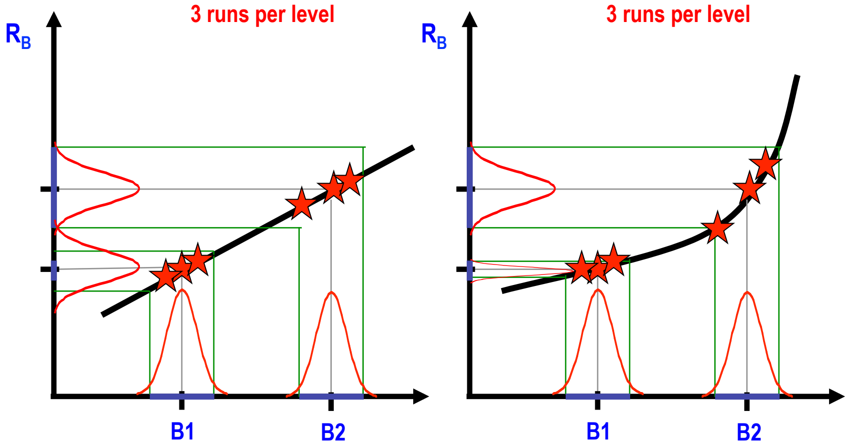


**How can we tell which of the two effects is the real one?**

## Robust Design Procedure
## Step 5: Conduct Analysis

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- **Step 5: Perform analysis of means and variance.**
  - Compute the mean value of the objective function for each factor setting.
  - Identify which control factors reduce the effects of noise and which ones can be used to scale the response. (2-Step Optimization)

## DOE Plan and Data

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| | A | B | C | D | E | F | G | N- | N+ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | |
| 2 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | | |
| 3 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | | |
| 4 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | | |
| 5 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | | |
| 6 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | | |
| 7 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | | |
| 8 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | | |

| | A | B | C | D | E | F | G | N- | N+ | Avg | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0.3403 | 0.2915 | 0.3159 | 0.0488 |
| 2 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 0.4608 | 0.3984 | 0.4296 | 0.0624 |
| 3 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 0.3682 | 0.3627 | 0.3655 | 0.0055 |
| 4 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 0.2961 | 0.2647 | 0.2804 | 0.0314 |
| 5 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 0.4450 | 0.4398 | 0.4424 | 0.0052 |
| 6 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 0.3517 | 0.3538 | 0.3528 | 0.0021 |
| 7 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 0.3758 | 0.3580 | 0.3669 | 0.0178 |
| 8 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 0.4504 | 0.4076 | 0.4290 | 0.0428 |

## Factor Effects Charts

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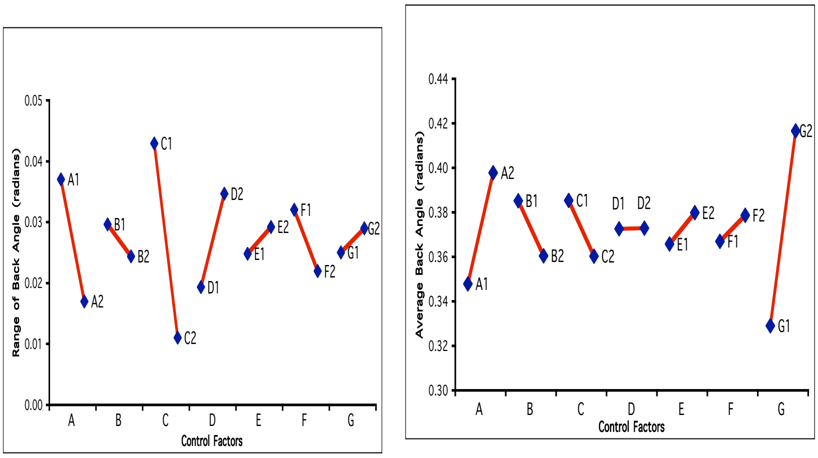


## Robust Design Procedure
## Step 6: Select Setpoints

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- **Step 6: Select control factor setpoints.**
  - Choose settings to maximize or minimize objective function.
  - Consider variations carefully. (Use means or variance to understand variation explicitly.)
- **Advanced use:**
  - Conduct confirming experiments.
  - Set scaling factors to tune response.
  - Iterate to find optimal point.
  - Use higher fractions to find interaction effects.
- **Test additional control and noise factors.**

## Confounding Interactions

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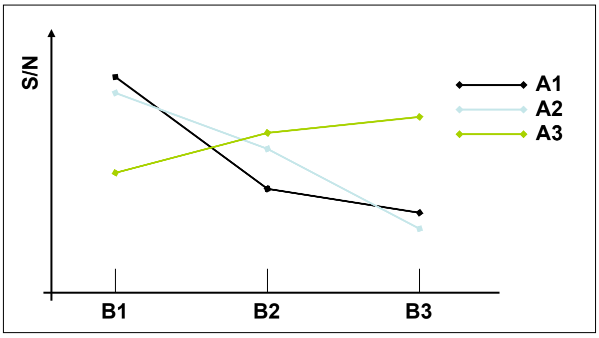
- **Generally the main effects dominate the response. BUT sometimes <u>interactions</u> are important. This is generally the case when the confirming trial fails.**
- **To explore interactions, use a fractional factorial experiment design.**




## Adaptive Factor: Hill Climbing

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- Consider k factors, n levels each.
- Start at nominal levels.
- Test each level of each factor one at a time, while freezing the previous ones at best level so far.
- The number of experiments is nk+1.
- Since this is an unbalanced experiment design, you can stop anytime (you have no info anyway).
- Helpful to sequence factors for strongest effects first.
- In some cases it work well when interactions are present.

| Expt # | Param A | Param B | Param C | Param D | Response | |
|---|---|---|---|---|---|---|
| 1 | A2 | B2 | C2 | D2 | 5.95 | |
| 2 | A1 | B2 | C2 | D2 | 5.63 | |
| 3 | A3 | B2 | C2 | D2 | 6.22 | A3 |
| 4 | A3 | B1 | C2 | D2 | 6.70 | B1 |
| 5 | A3 | B3 | C2 | D2 | 6.58 | |
| 6 | A3 | B1 | C1 | D2 | 4.85 | |
| 7 | A3 | B1 | C3 | D2 | 5.69 | C2 |
| 8 | A3 | B1 | C2 | D1 | 6.60 | |
| 9 | A3 | B1 | C2 | D3 | 6.98 | D3 |

**4 factors, 2 levels each:**

**nk+1 =**

**2x4+1 = 9 trials**

## Key Concepts of Robust Design

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- Variation causes quality loss
- Two-step optimization
- Matrix experiments (orthogonal arrays)
- Inducing noise (outer array or repetition)
- Data analysis and prediction
- Interactions and confirmation

## References

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## Paper Airplane Experiment

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| Expt # | Weight | Winglet | Nose | Wing | Trials | Mean | Std Dev | S/N |
|---|---|---|---|---|---|---|---|---|
| 1 | A1 | B1 | C1 | D1 | | | | |
| 2 | A1 | B2 | C2 | D2 | | | | |
| 3 | A1 | B3 | C3 | D3 | | | | |
| 4 | A2 | B1 | C2 | D3 | | | | |
| 5 | A2 | B2 | C3 | D1 | | | | |
| 6 | A2 | B3 | C1 | D2 | | | | |
| 7 | A3 | B1 | C3 | D2 | | | | |
| 8 | A3 | B2 | C1 | D3 | | | | |
| 9 | A3 | B3 | C2 | D1 | | | | |

## Textbook

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**Product Design and Development**
**Karl T. Ulrich and Steven D. Eppinger**
**5th edition, Irwin McGraw-Hill, 2012**

1. Introduction
2. Development Processes and Organizations
3. Opportunity Identification
4. Product Planning
5. Identifying Customer Needs
6. Product Specifications
7. Concept Generation
8. Concept Selection
9. Concept Testing
10. Product Architecture
11. Industrial Design
12. Design for Environment
13. Design for Manufacturing
14. Prototyping
15. **Robust Design**
16. Patents and Intellectual Property
17. Product Development Economics
18. Managing Projects