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ICT Innovation – Spring 20178MSc in Computer Science and MEng Telecom. Engineering EIT Masters ITA, S&P,SDE, DMT Management of Innovation

Lecture 11 – Robust Design

Prof. Fabio Massacci

Robust Design and Quality in the Product Dev process

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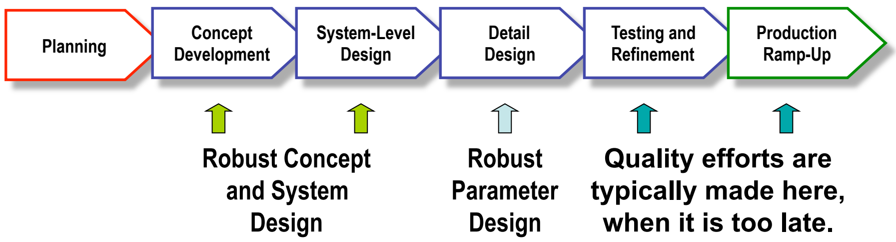

Goals for Designed Experiments

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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

Why is this needed?

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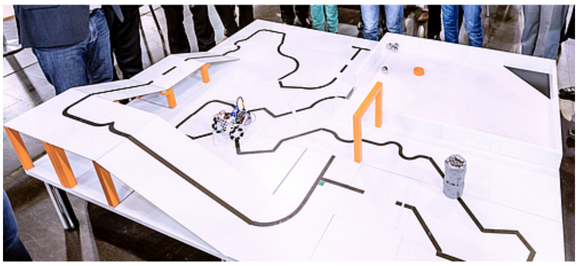
- **RobocupJr Rules**
  - Teenagers 12-18yrs old try to build a fully functional autonomous robot to achieve a goal
- **RescueMaze**
  - Follow a black line on a white surface until you reach a room where you have balls of predefined size you have to collect.



Why is this needed?

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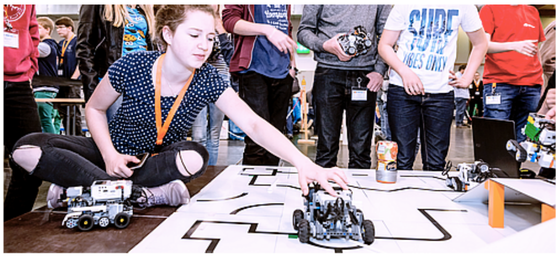
- **Robocup Jr Process**
  - Group first try locally at one's school, then regional selections, national finals and finally best group is selected for world finals
  - Map is almost the same, the only truly randomly placed things are the obstacle and the victims to be collected but they are in a confined area.
  - Some green spots are marked on the line to mark sharp corners
- **What can possibly go wrong if you have done a spotless program that work in your lab?**



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Lack of Robustness…

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- **The world competion is done in a big Fair Hall with a slightly different lighting**
  - Green looks therefore of a different hue from the innumerable test that you tried during the regional and national finals
- **Your cheap Lego sensor has only a binary recognition of green, white and black**
  - The "green spots" are no longer recognized as "green" by your sensors.
- **Outcome?**
  - First at national final, 13°/16 in World final.

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What if they were selling a product

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- **You tested the product in the lab…**
- **You run the software, simulations etc.**
- **Customers return it back because it is crappy and they can't use**
  - Missed sales
  - Lost reputation
- **Example**
  - server load → you didn't expect to have that many queries…
  - Washing Powder vs Washing Machine and Water →…

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How do we make sure this doesn't happen?

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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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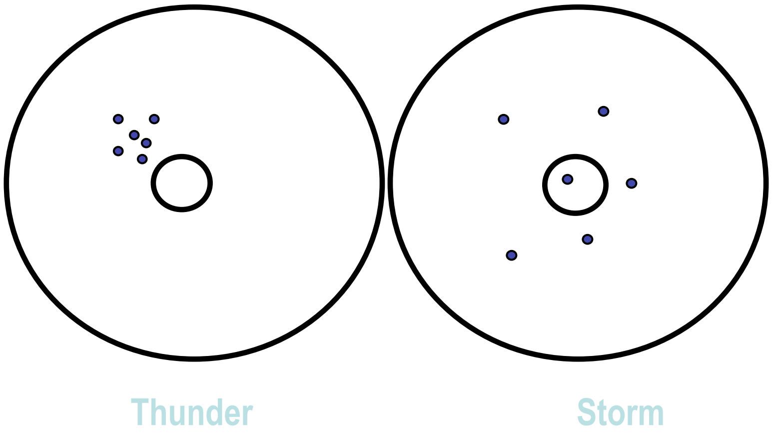

Who is better? Mean vs Variance

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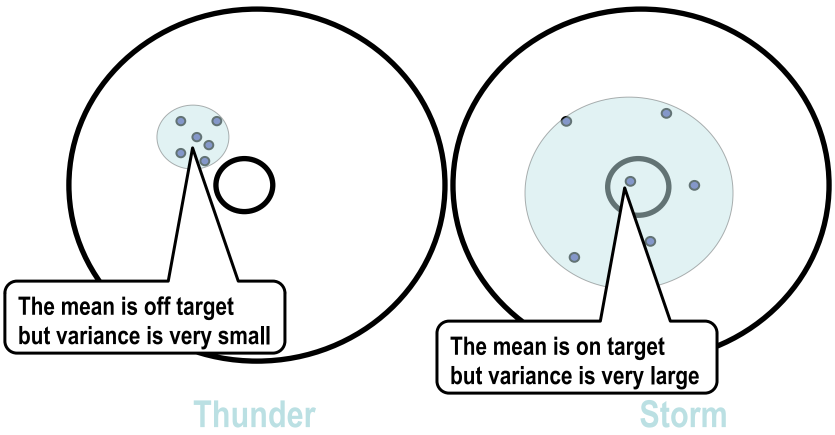

Who is better? Mean vs Variance

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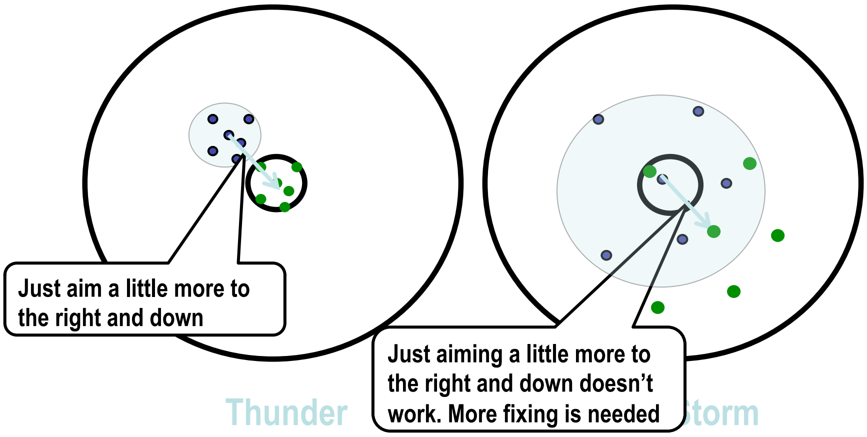

Robust Designs

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- **Up to know: select product parameters based on best performance metric**
  - Cost is included.
  - No point of buying an expensive 10-level green sensor if binary one works just fine.
- **Next: select "robustly best" performance factor in presence of noise**
  - A robust product or process performs correctly, even in the presence of noise factors
  - The notion of "best" might need to be adjusted
- **Noise factors may include:**
  - parameter variations
  - environmental changes
  - operating conditions
  - manufacturing variations
- **Performance factor**
  - Decide what it is based on your project
  - E.g. Bike → resistance to lateral torsion

Understanding Response

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- **Typical design**
  - Output: response factor
  - Input: different configuration parameter
- **Key idea (mistaken) of software developers**
  - Output is always the same give the input
  - No it is not because
    - the configuration is never completely specified
    - Only for trivial programs and trivial inputs you can verify it → as soon as you had concurrency this is theoretically impossible
    - You only specifies part of the output response
  - So we need to empircally test what happens and seen how a system **actually** respond to a input

Response to Factors: linear

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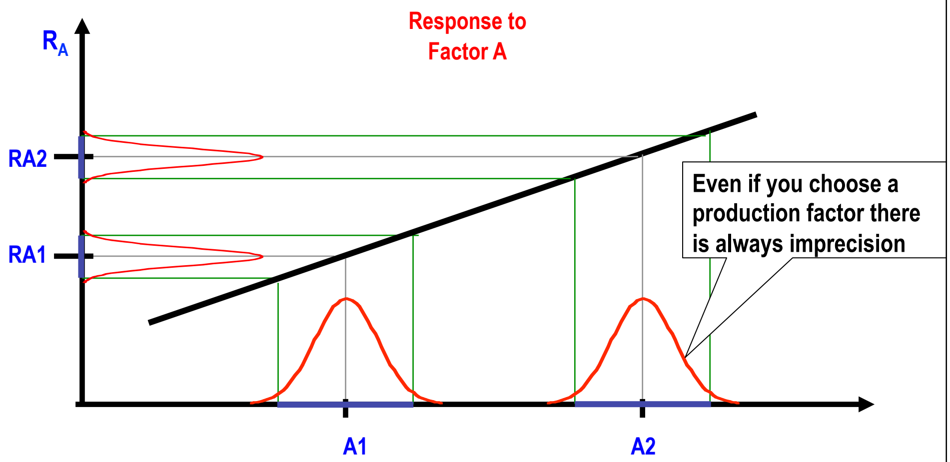

Can chose Factor A between A1 and A2
- **No difference in Variance**
- **Difference in Mean (R2 > R1)**

Response to Factor: Exponential/Power Law

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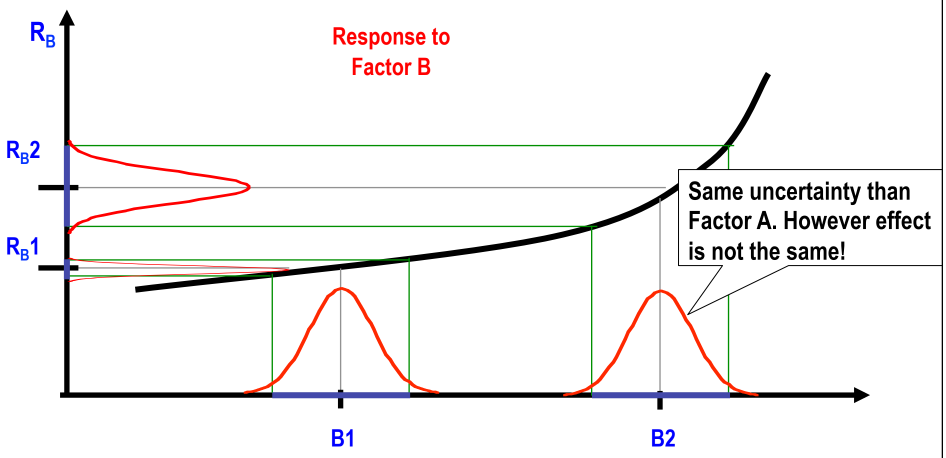

Can chose Factor B between B1 and B2

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

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?

Exploiting Non-Linearity to Achieve Robust Performance

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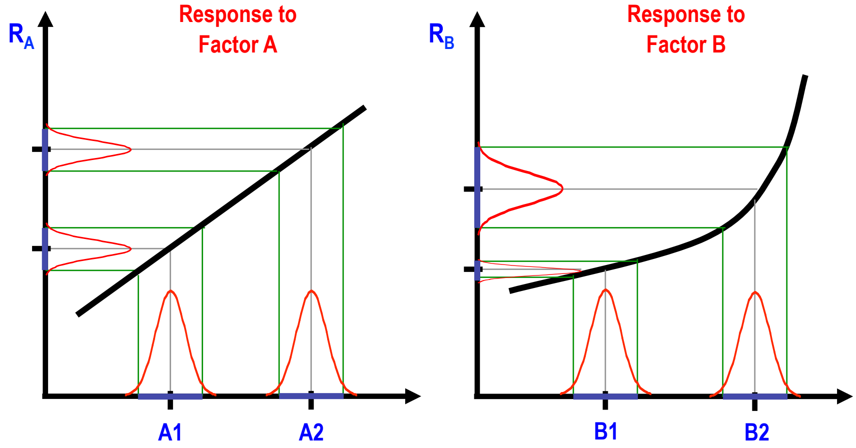

Response = $R_A(A) + R_B(B)$
What level of factor B gives the robust response?
How do we use factor A?

Robust 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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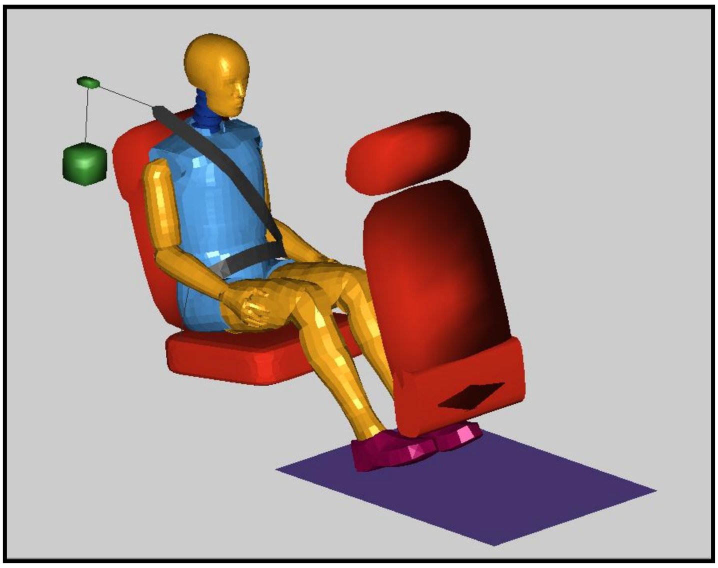

The "P" Diagram

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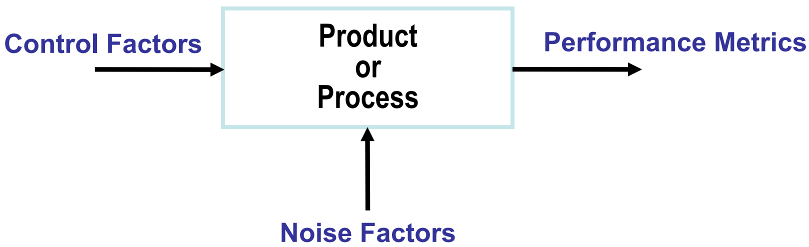

Parameter Diagram

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Passenger Restraint Process

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

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
$\eta = 10\log[\mu^2/\sigma^2]$

Example: Brownie Mix

- **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

- **Experiment 1 (a and b)**
  - 2 eggs, 200g of flour
  - Stir 5min – 10 minutes –manually
  - Bake 30min at 180C and test
- **Experiment 2 (a and b)**
  - 2 eggs, 200g of flour
  - Stir 5min – 10 minutes – use a mixer
  - Bake 30min at 180C and test
- **Out of 4 5min mixer is best**
- **Experiment 3**
  - 2 eggs, 200g of flour
  - Stir 5min with mixer
  - Bake at 30 at 200C
  - Bake at 25 att 180C

Example: Brownie Mix

- **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

- **Nominal**
  - 2 eggs, 200g of flour
  - Stir 10min
  - Bake 30min at 180C and test
- **Experiment 2**
  - 1 eggs, 200g of flour
  - Stir 10min
  - Bake 30min at 180C and test
- **Experiment 3**
  - 3 eggs, 200g of flour
  - Stir 10min
  - Bake 30min at 180C and test
- **Experiment 4**
  - 2 eggs, 100g of flour
  - Stir 10min
  - Bake 30min at 180C and test
- **Experiment …**
  - 2 eggs, 300g of flour
  - Stir 10min
  - Bake 30min at 180C and test

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+4x2 = 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 F1 G2	E1 F2 G1	E2 F1 G2	E2 F2 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

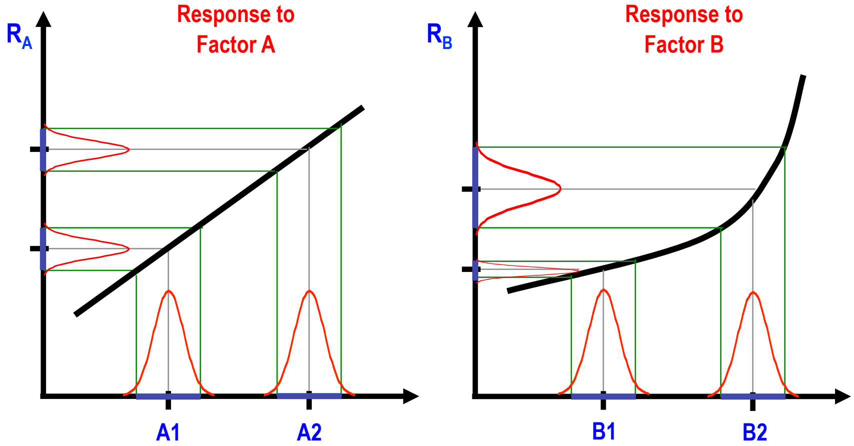
This design is balanced
Check it out

				E1 F1 G2	E1 F2 G1	E2 F1 G2	E2 F2 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

- 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?



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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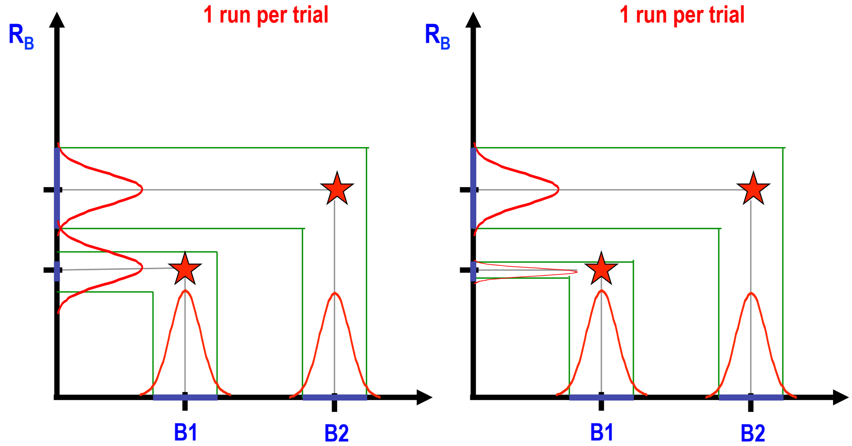

How can we tell which of the two effects is the real one?

Why More Than a Single Run?

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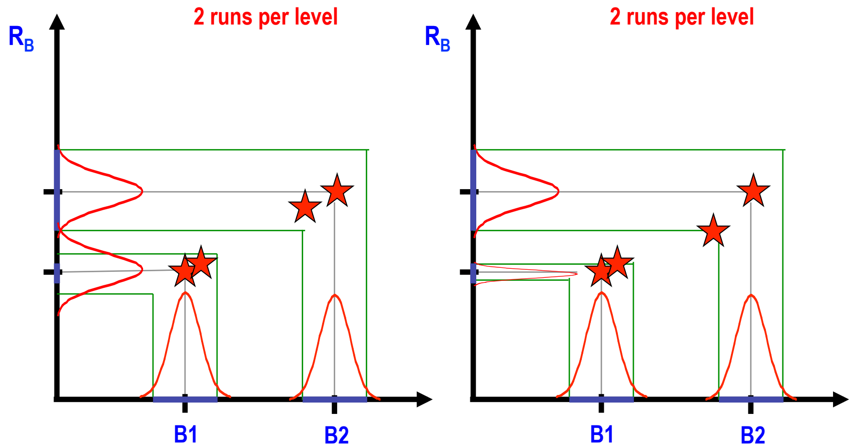

How can we tell which of the two effects is the real one?

Why More Than a Single Run?

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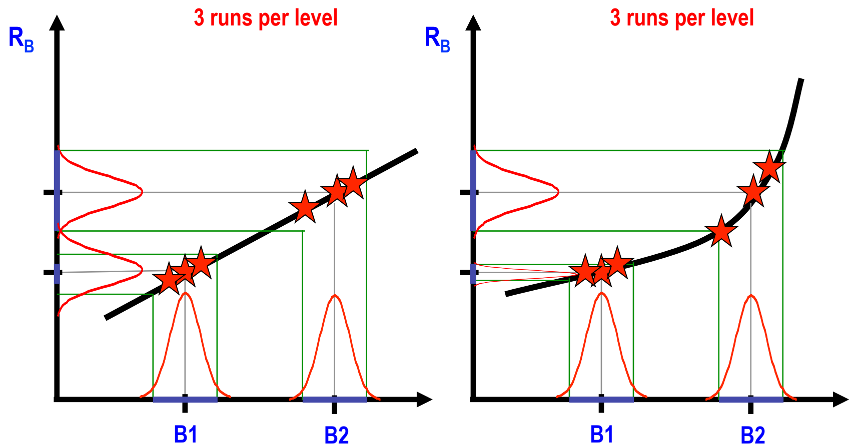

How can we tell which of the two effects is the real one?

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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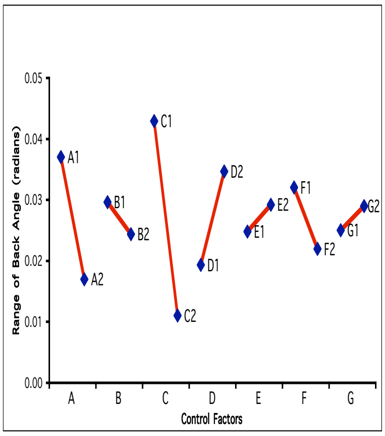

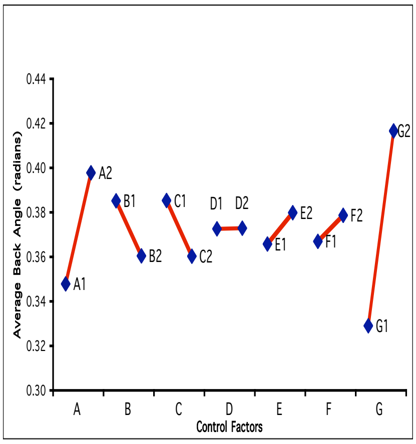

Robust Design Procedure
Step 6: Select Setpoints

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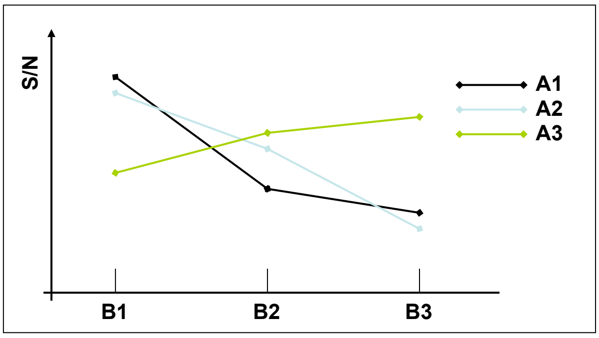
- **Generally the main effects dominate the response. BUT sometimes <u>interactions</u> are important. This is generally the case when the confirming trial fails.**
- **To explore interactions, use a fractional factorial experiment design.**



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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- Taguchi, Genichi and Clausing, Don
  "Robust Quality"
  Harvard Business Review, Jan-Feb 1990.
- Byrne, Diane M. and Taguchi, Shin
  "The Taguchi Approach to Parameter Design"
  Quality Progress, Dec 1987.
- Phadke, Madhav S.
  Quality Engineering Using Robust Design
  Prentice Hall, Englewood Cliffs, 1989.
- Ross, Phillip J.
  Taguchi Techniques for Quality Engineering
  McGraw-Hill, New York, 1988.

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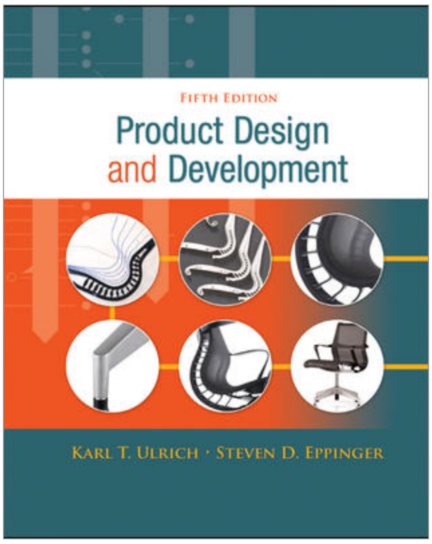
Product Design and Development
Karl T. Ulrich and Steven D. Eppinger
5th edition, Irwin McGraw-Hill, 2012



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