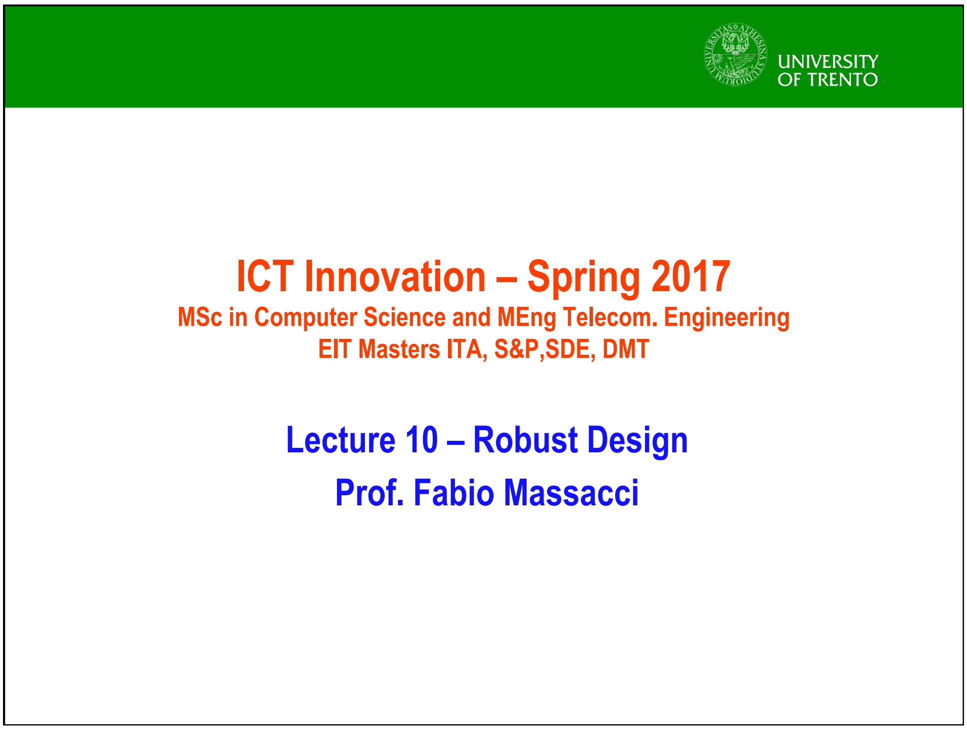

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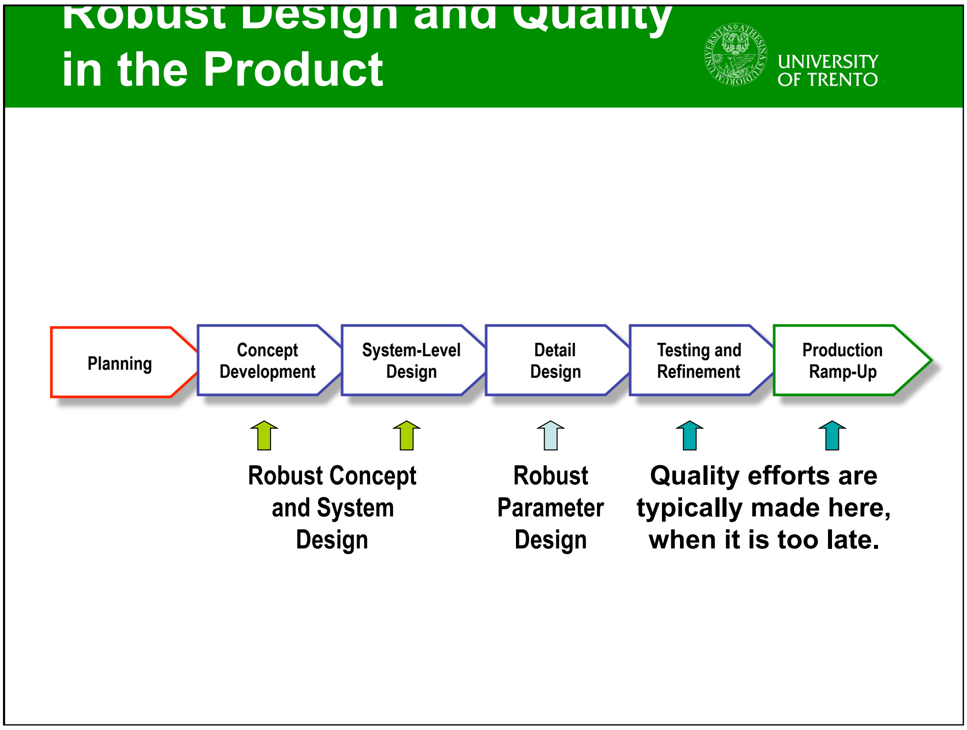
ICT Innovation – Spring 2017

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

Lecture 10 – Robust Design

Prof. Fabio Massacci



Robust Design and Quality in the Product

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Robust Concept and System Design

Robust Parameter Design

Quality efforts are typically made here, when it is too late.

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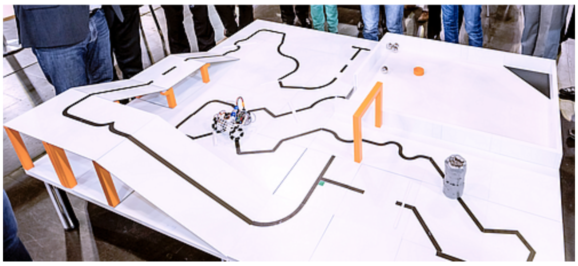
- **RobocupJr Rules**
  - Teenagers 12-18yrs old try to build a fully functional autonomous robot to achieve a goal
- **RescueMaze**
  - Follow a black line on a white surface until you reach a room where you have balls of predefined size you have to collect.



Why is this needed?

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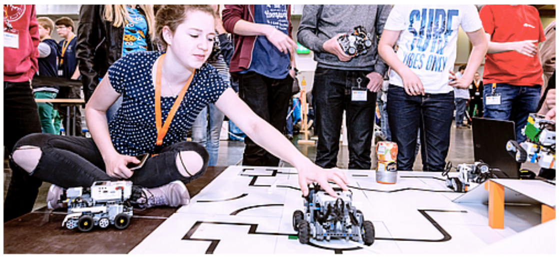
- **Robocup Jr Process**
  - Group first try locally at one’s school, then regional selections, national finals and finally best group is selected for world finals
  - Map is almost the same, the only truly randomly placed things are the obstacle and the victims to be collected but they are in a confined 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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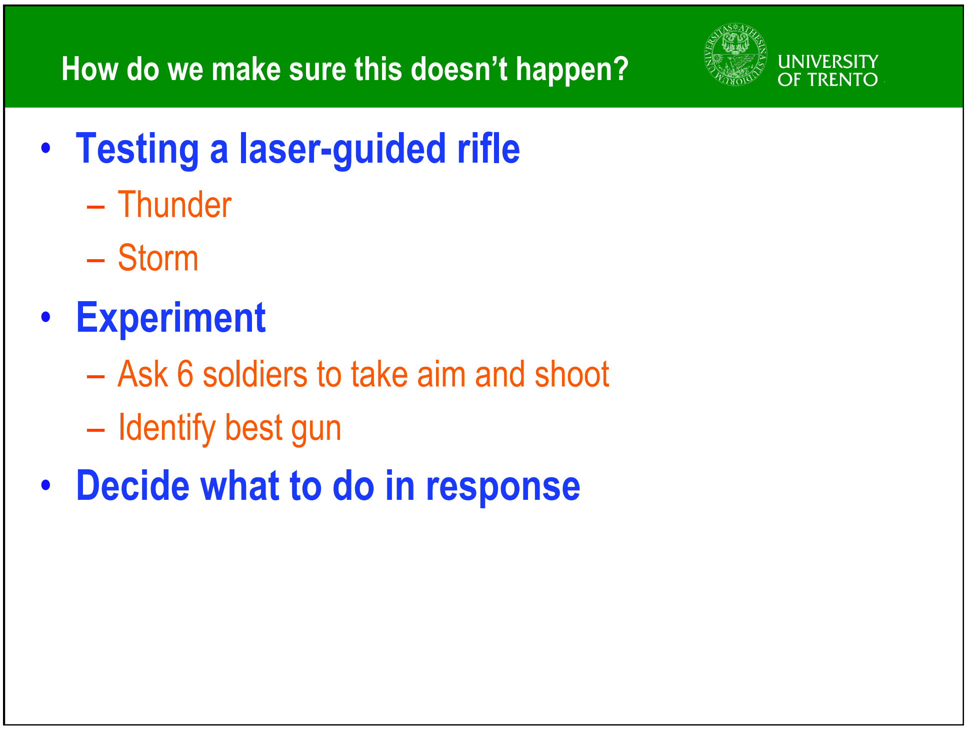

How do we make sure this doesn't happen?

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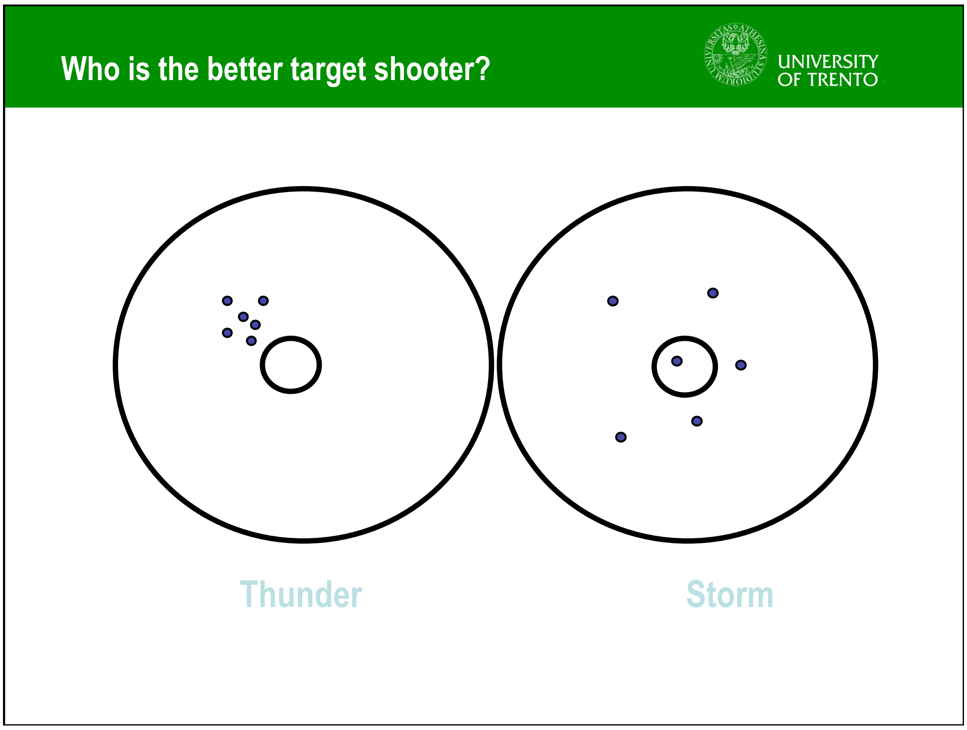
- Testing a laser-guided rifle
  - Thunder
  - Storm
- Experiment
  - Ask 6 soldiers to take aim and shoot
  - Identify best gun
- Decide what to do in response



Who is the better target shooter?

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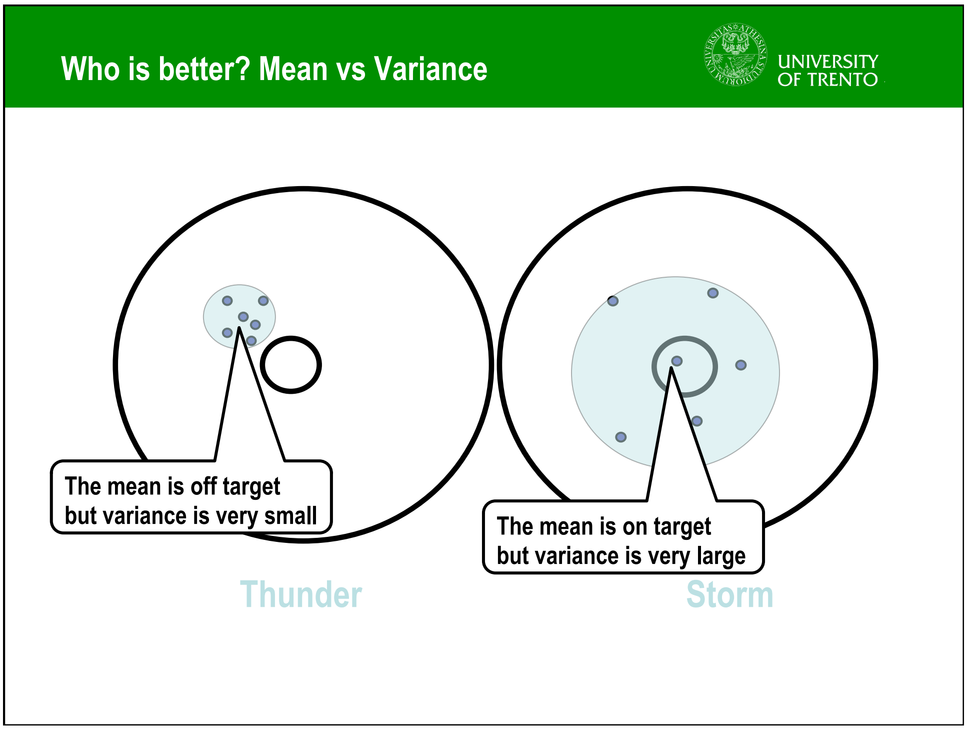
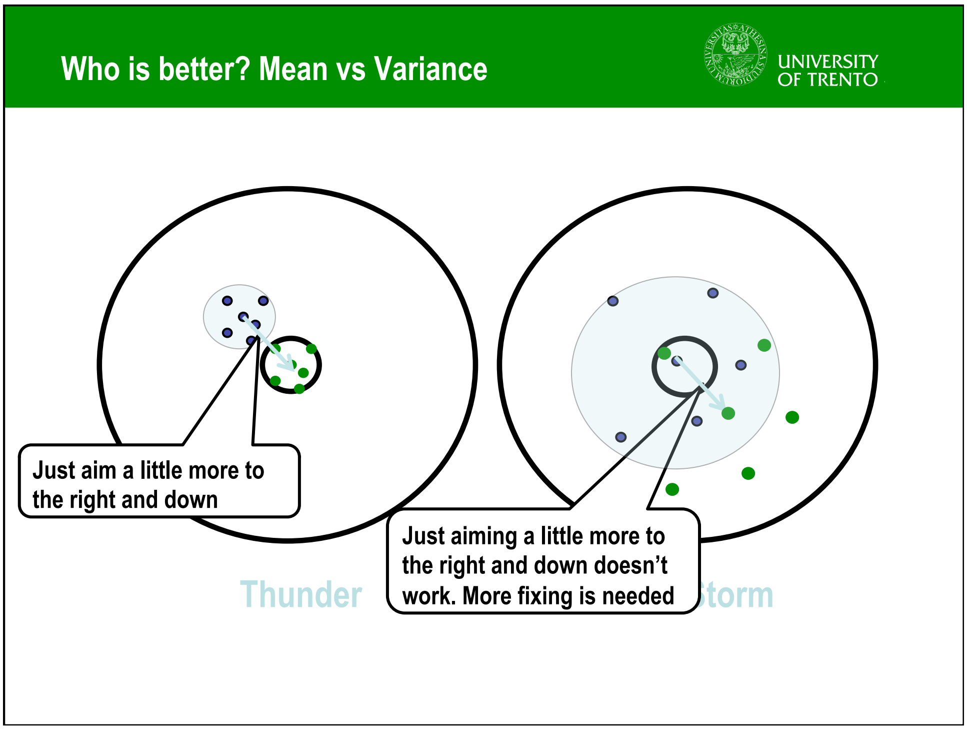


Who is better? Mean vs Variance

The mean is off target but variance is very small

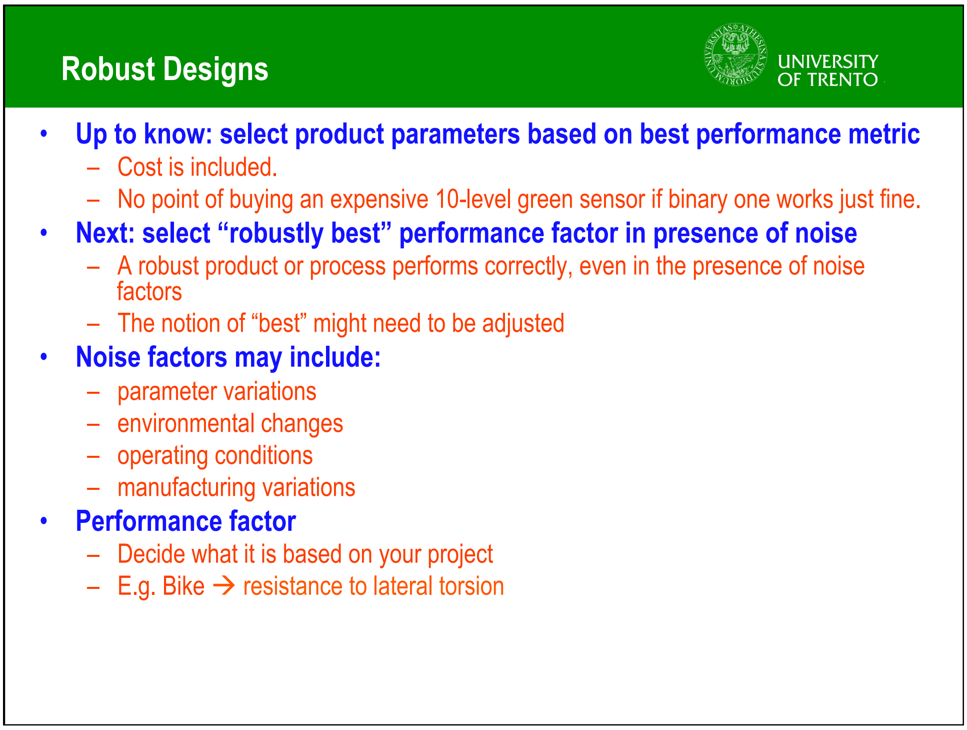
The mean is on target but variance is very large



Who is better? Mean vs Variance

Just aim a little more to the right and down

Just aiming a little more to the right and down doesn't work. More fixing is needed



Robust Designs

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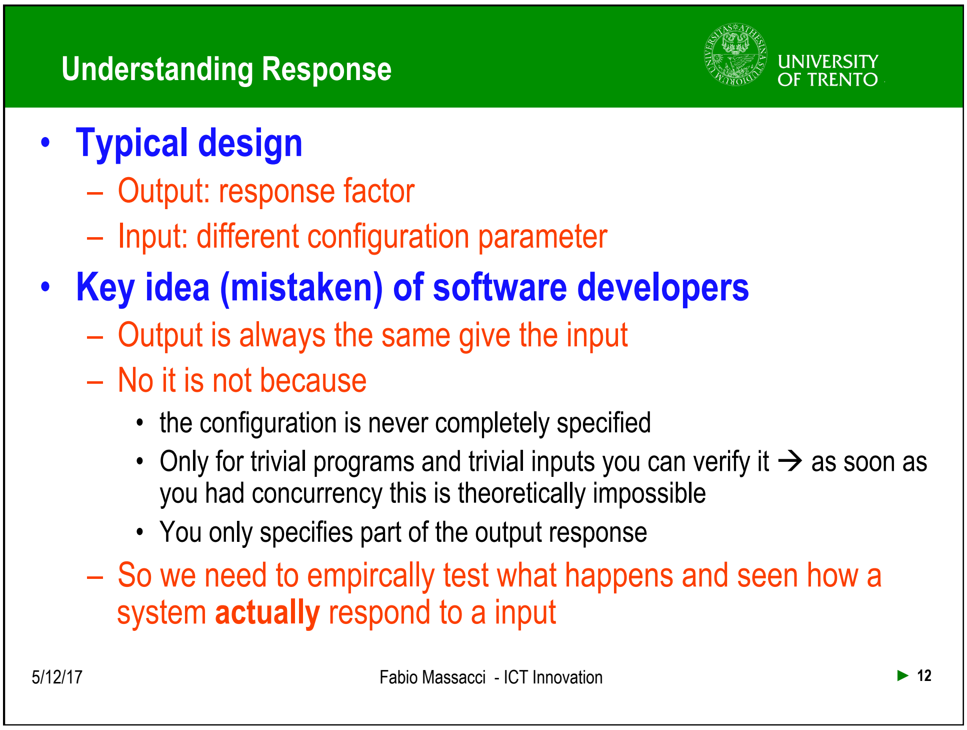
- **Up to know: select product parameters based on best performance metric**
  - Cost is included.
  - No point of buying an expensive 10-level green sensor if binary one works just fine.
- **Next: select "robustly best" performance factor in presence of noise**
  - A robust product or process performs 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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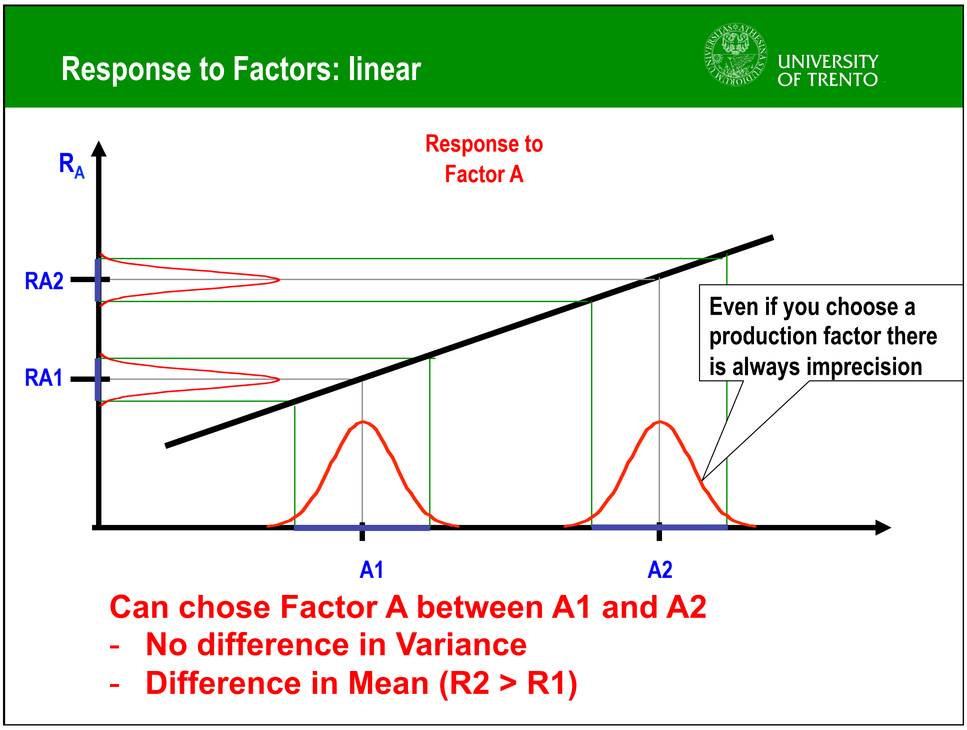
- **Typical design**
  - Output: response factor
  - Input: different configuration parameter
- **Key idea (mistaken) of software developers**
  - Output is always the same give the input
  - No it is not because
    - the configuration is never completely specified
    - Only for trivial programs and 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

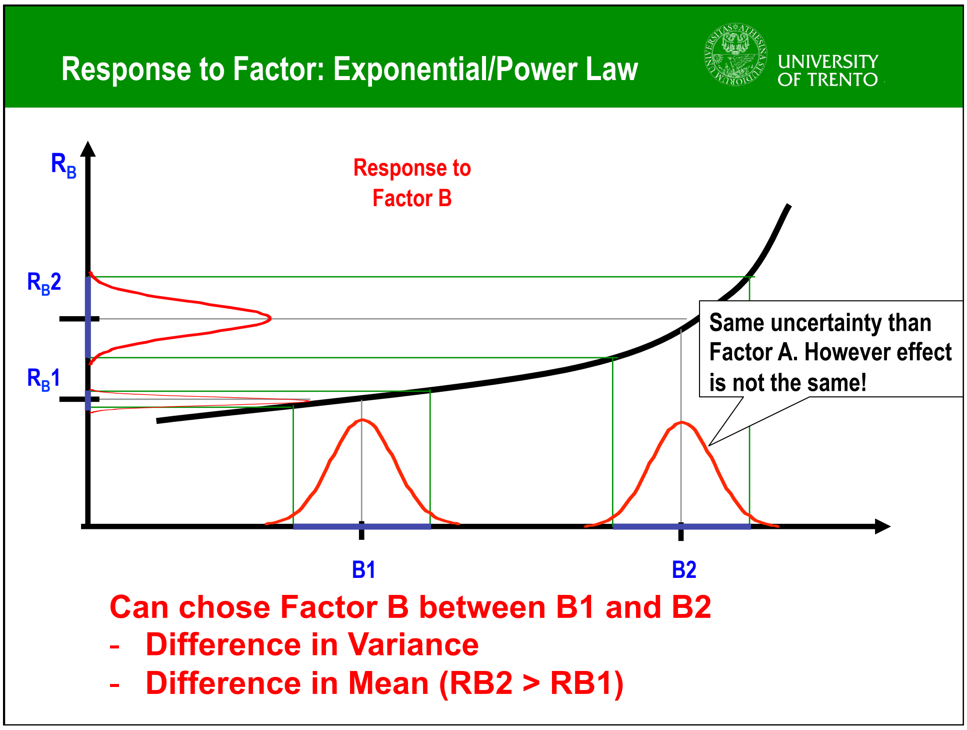


Response to Factors: linear

Even if you choose a production factor there is always imprecision

Can chose Factor A between A1 and A2

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

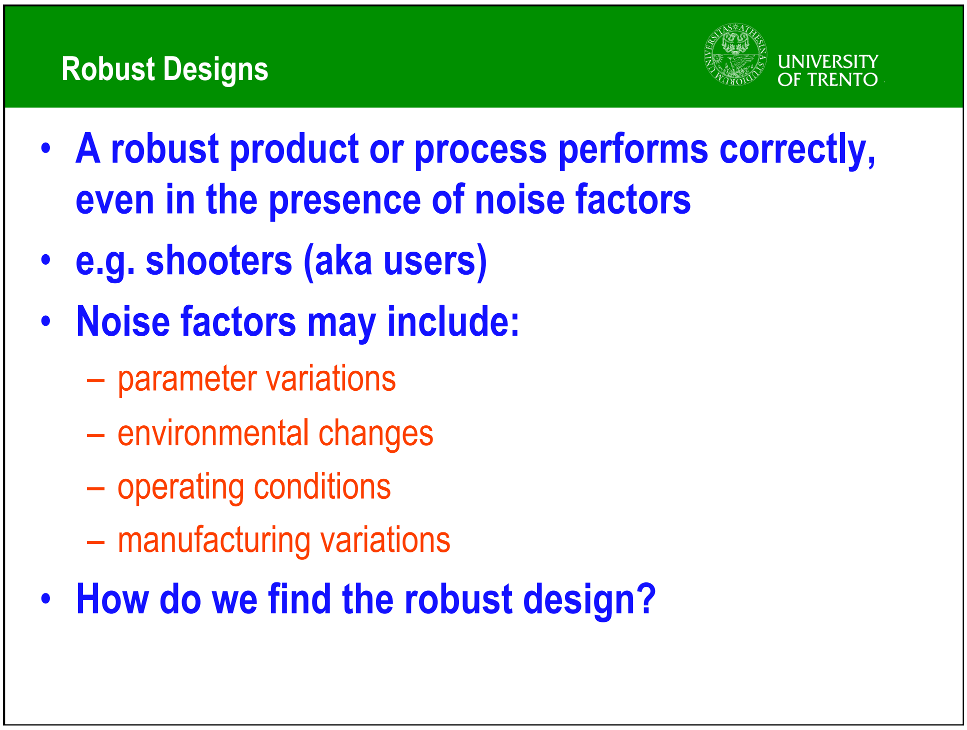


Response to Factor: Exponential/Power Law

Same uncertainty than Factor A. However effect is not the same!

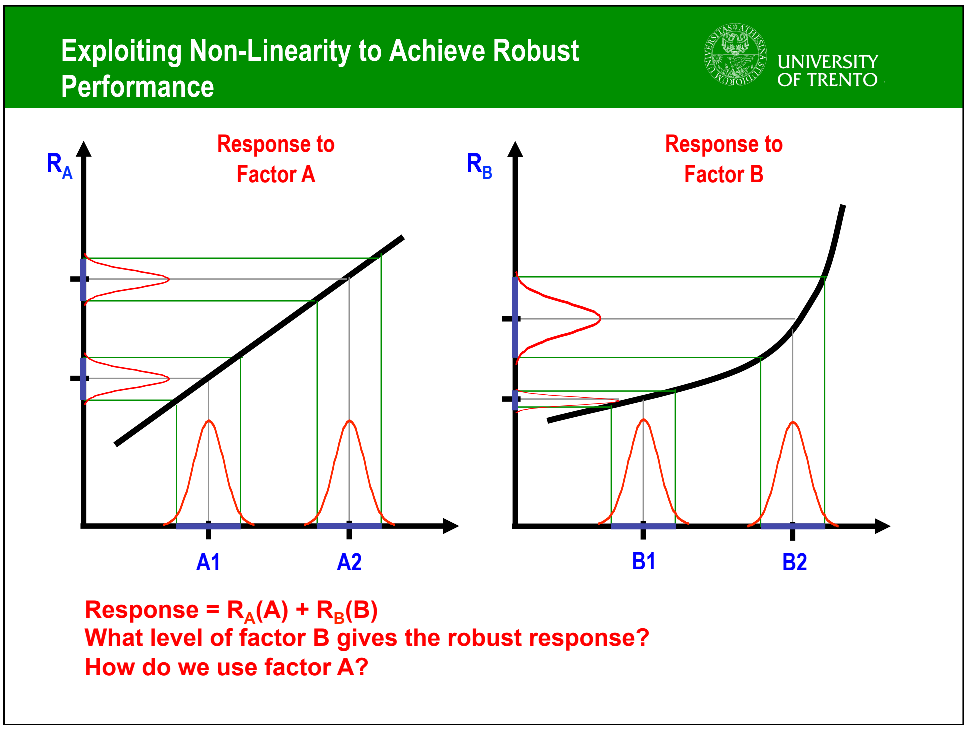
Can chose Factor B between B1 and B2

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



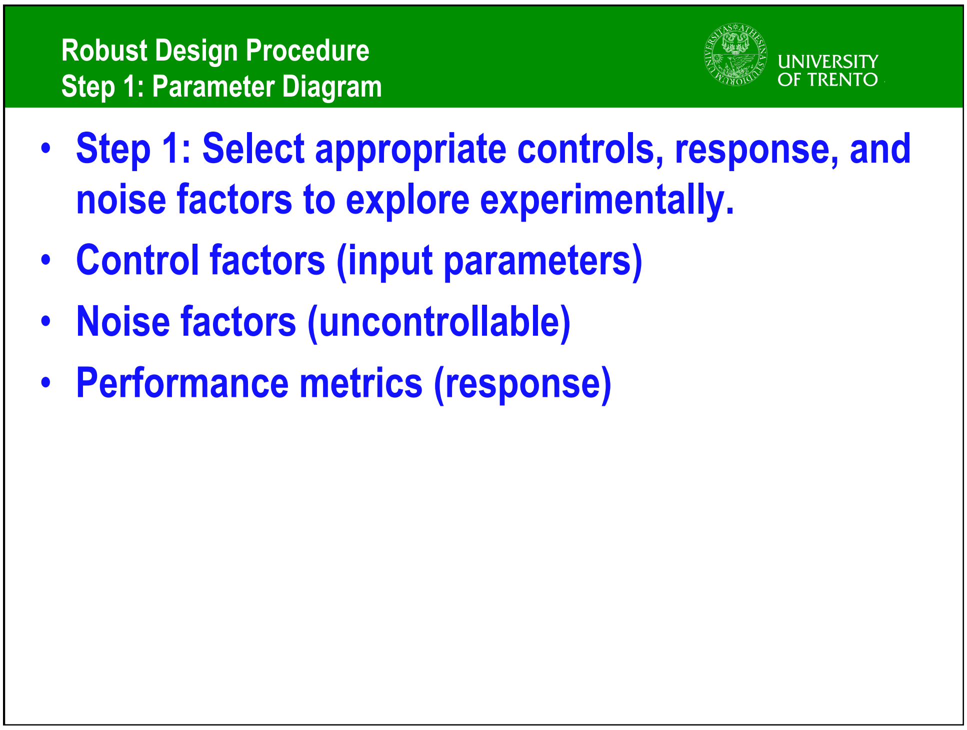
Robust Designs

- 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

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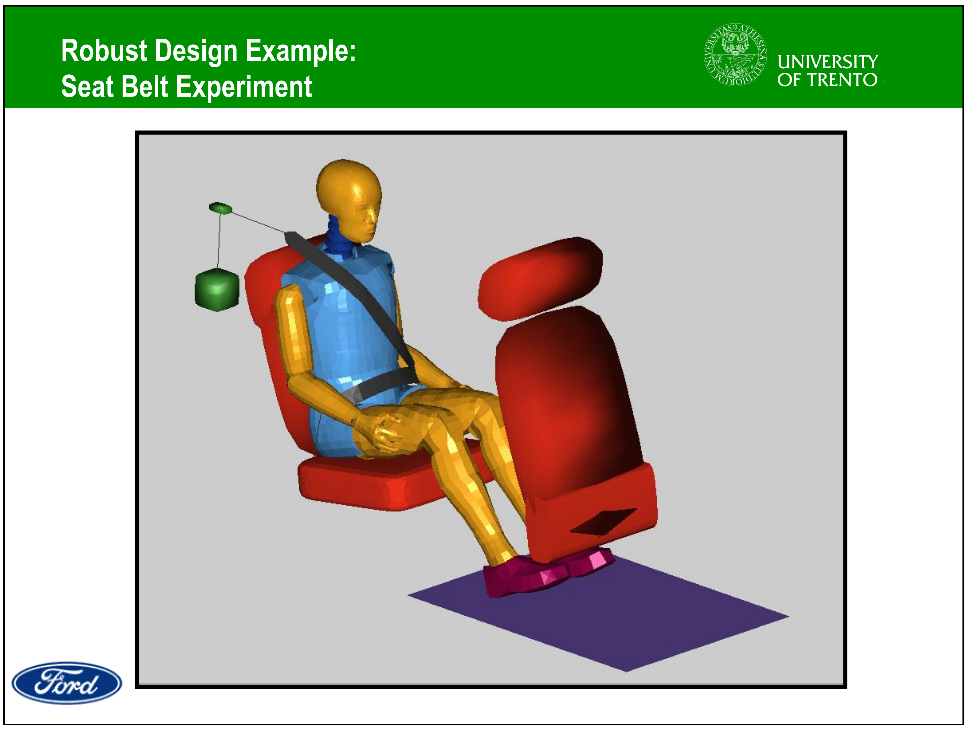
- Step 1: Select appropriate controls, response, and noise factors to explore experimentally.
- Control factors (input parameters)
- Noise factors (uncontrollable)
- Performance metrics (response)



Robust Design Example:
Seat Belt Experiment

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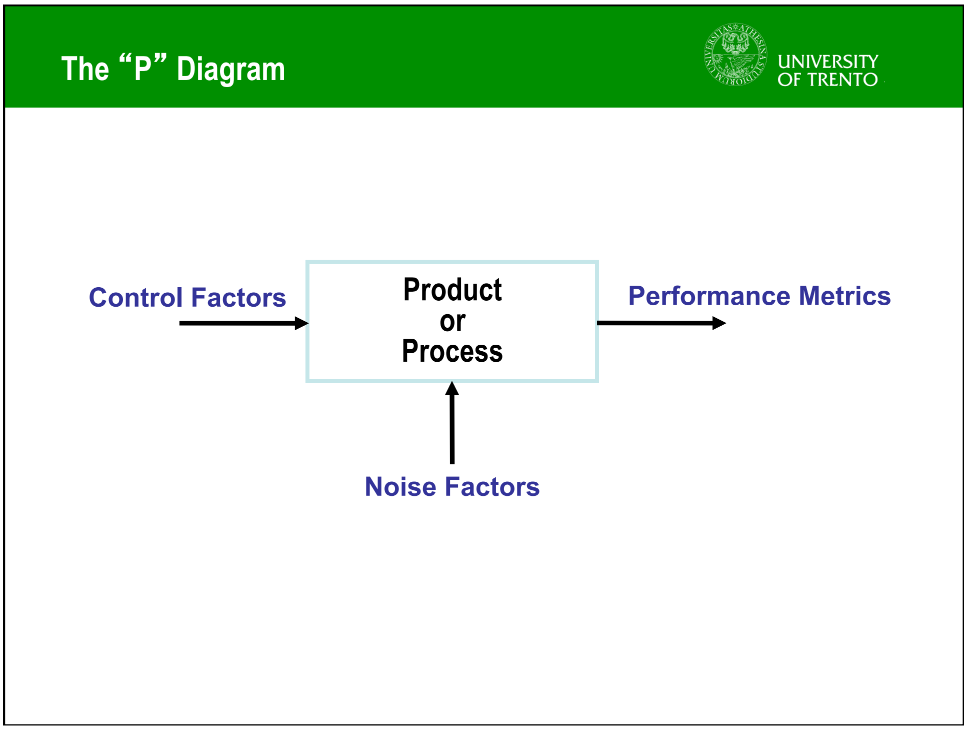

The “P” Diagram

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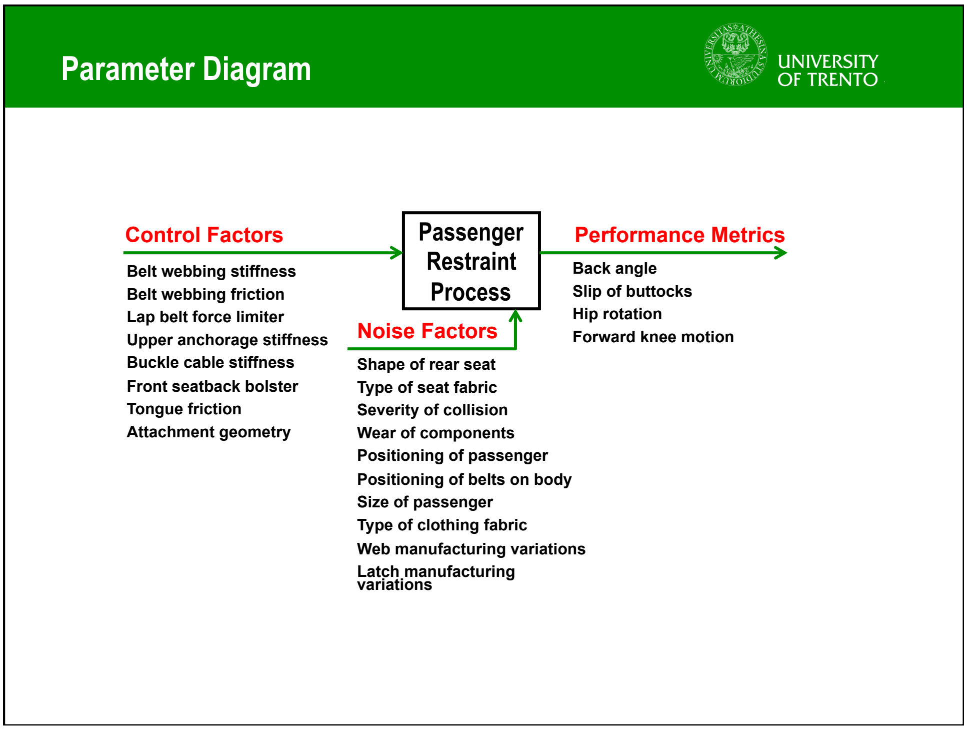
Control Factors

Product or Process

Performance Metrics

Noise Factors



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

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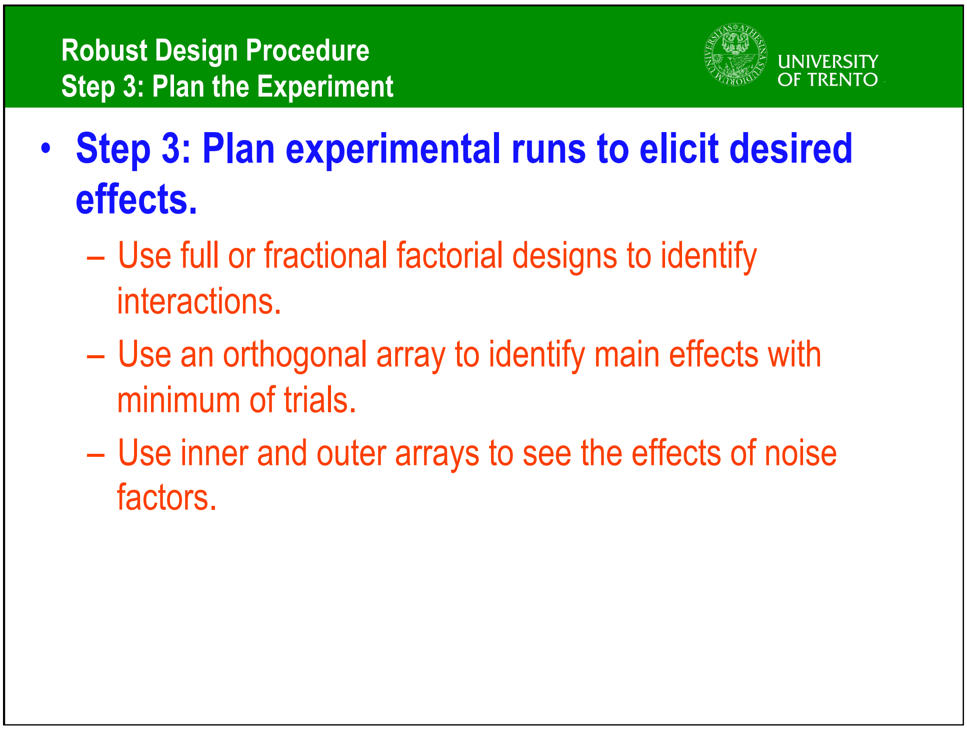
- **Control Factors**
  - Recipe Ingredients (quantity of eggs, flour, chocolate)
  - Recipe Directions (mixing, baking, cooling)
  - Equipment (bowls, pans, oven)
- **Noise Factors**
  - Quality of Ingredients (size of eggs, type of oil)
  - Following Directions (stirring time, measuring)
  - Equipment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

- Let’s write an experiment here



Robust Design Procedure
Step 3: Plan the Experiment

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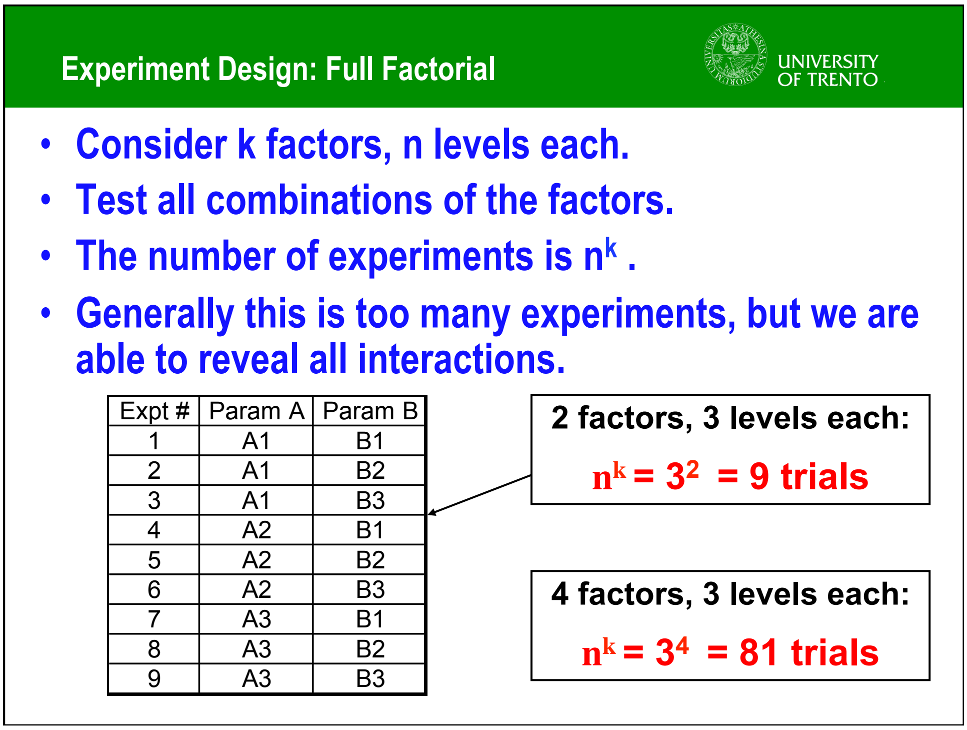
- **Step 3: Plan experimental runs to elicit desired effects.**
  - Use full or fractional factorial designs to identify interactions.
  - Use an orthogonal array to identify main effects with minimum of trials.
  - Use inner and outer arrays to see the effects of noise factors.



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.**

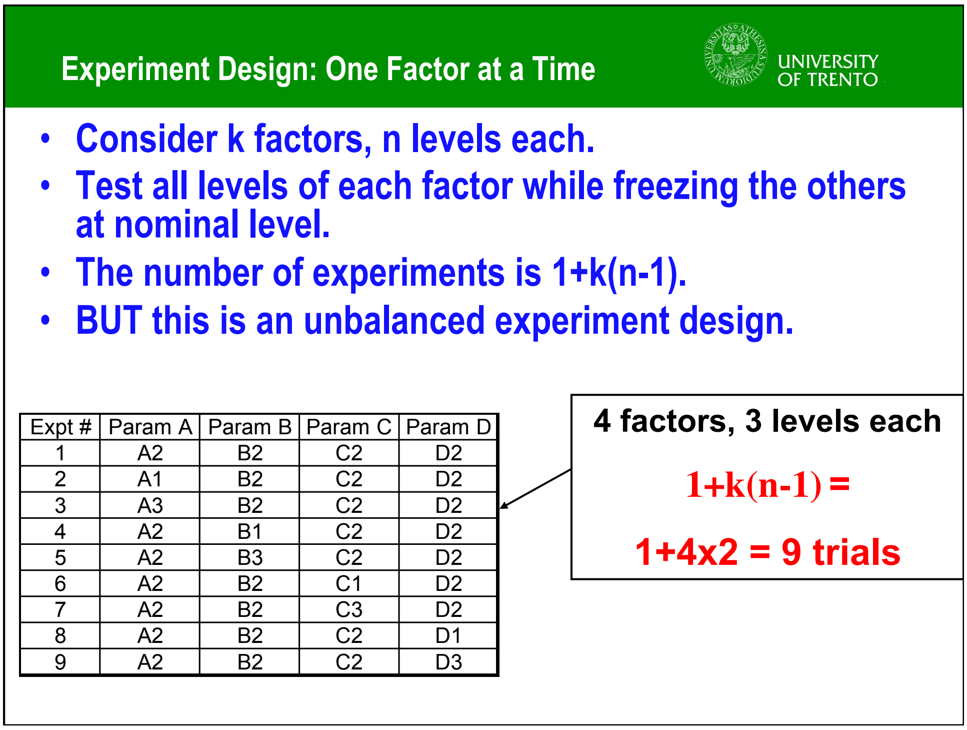
Expt #	Param A	Param B
1	A1	B1
2	A1	B2
3	A1	B3
4	A2	B1
5	A2	B2
6	A2	B3
7	A3	B1
8	A3	B2
9	A3	B3

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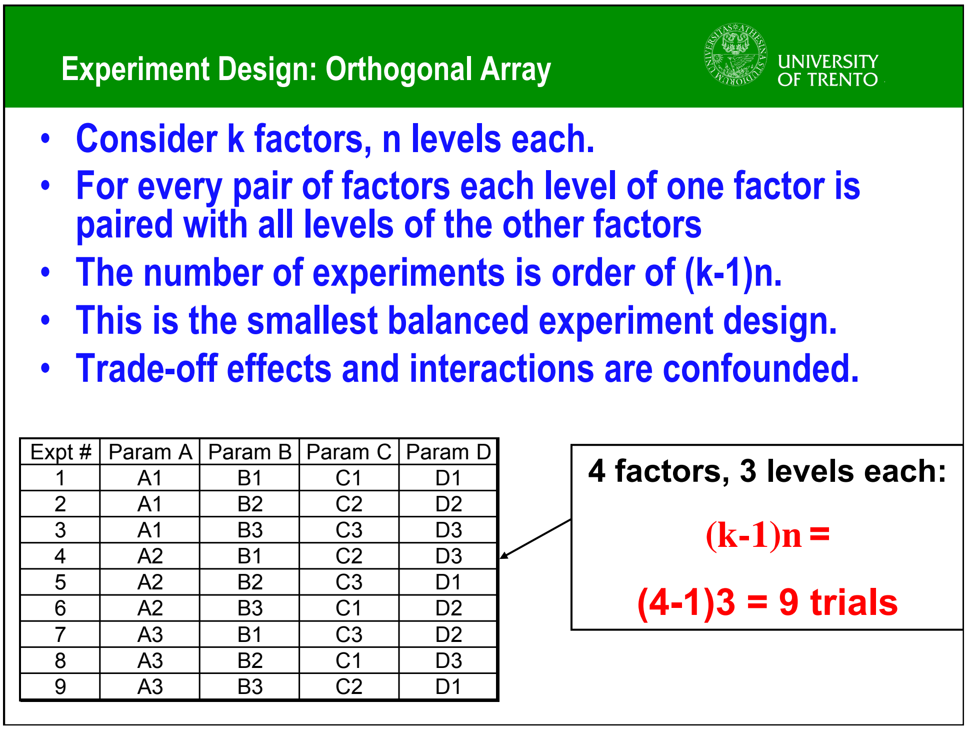
- Consider k factors, n levels each.
- Test all levels of each factor while freezing the others at nominal level.
- The number of experiments is 1+k(n-1).
- BUT this is an unbalanced experiment design.

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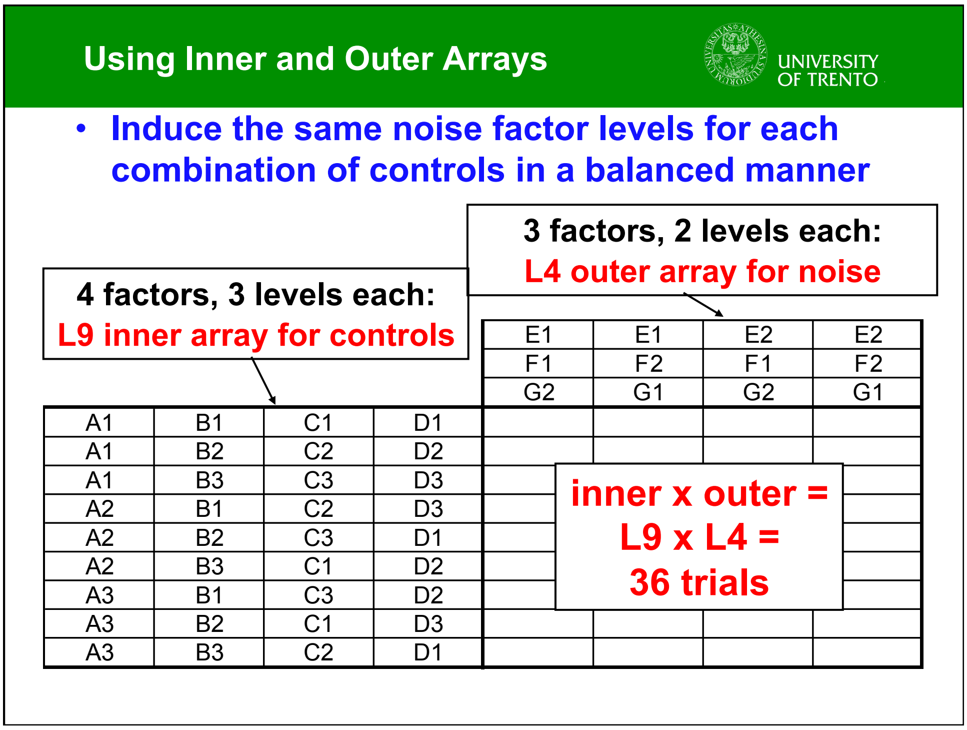
- Consider k factors, n levels each.
- For every pair of factors each level of one factor is paired with all levels of the other factors
- The number of experiments is order of (k-1)n.
- This is the smallest balanced experiment design.
- Trade-off effects and interactions are confounded.

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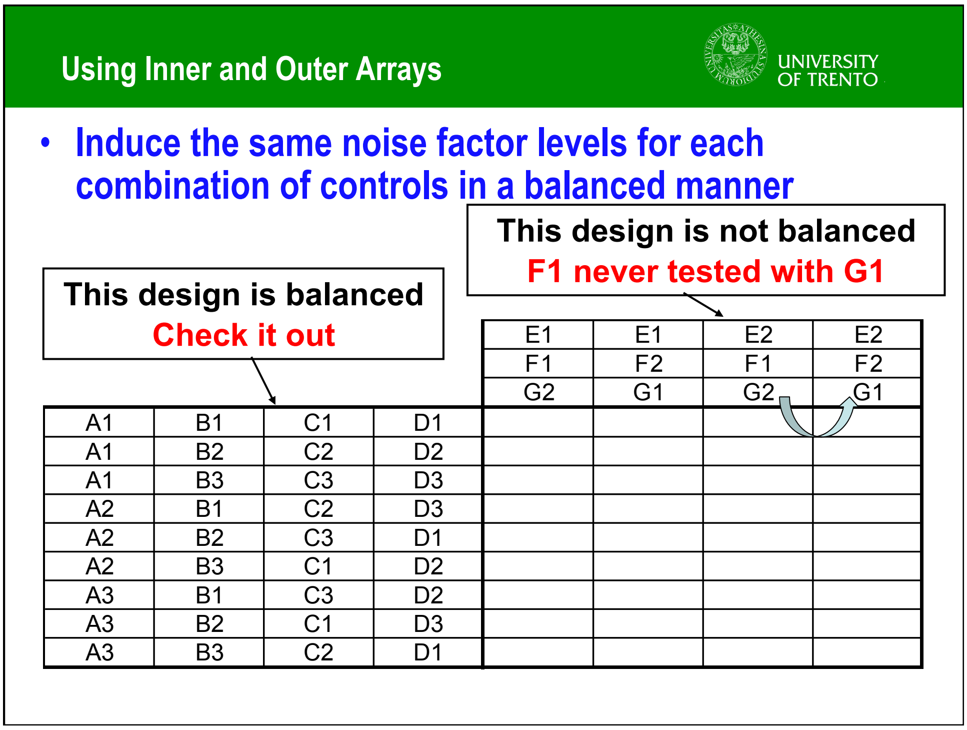
- Induce the same noise factor levels for each combination of controls in a balanced manner

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

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

				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 balanced
Check it out

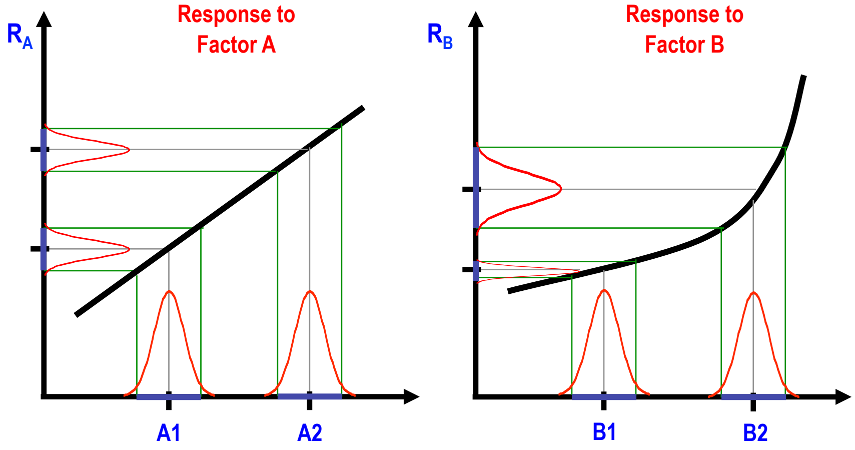
This design is not balanced
F1 never tested with G1

				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				

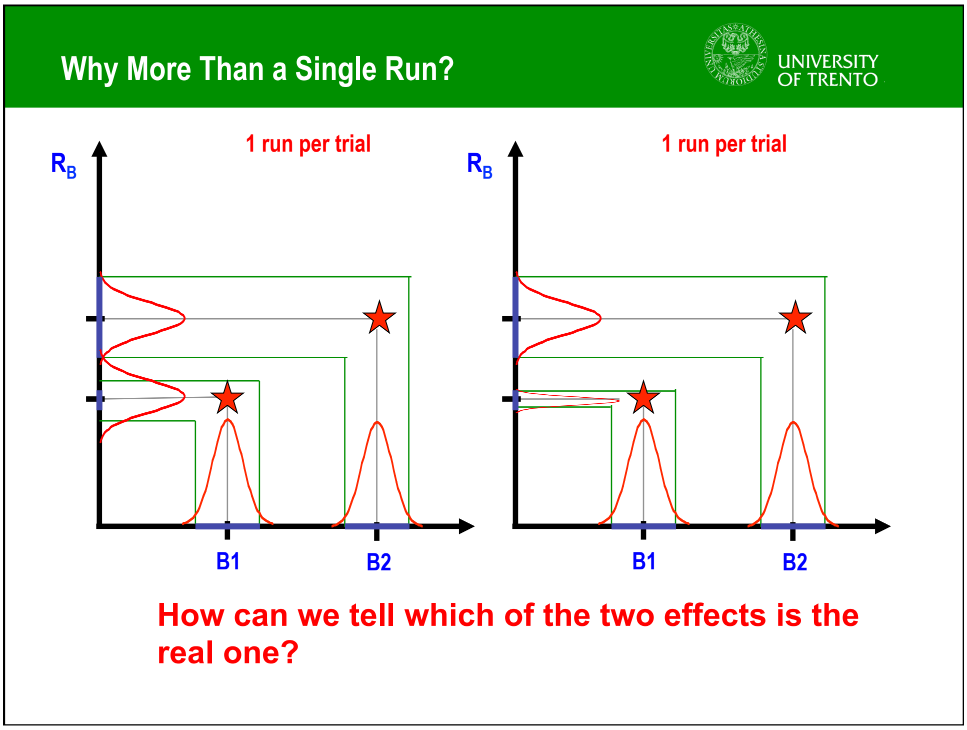
Robust Design Procedure
Step 4: Run the Experiment

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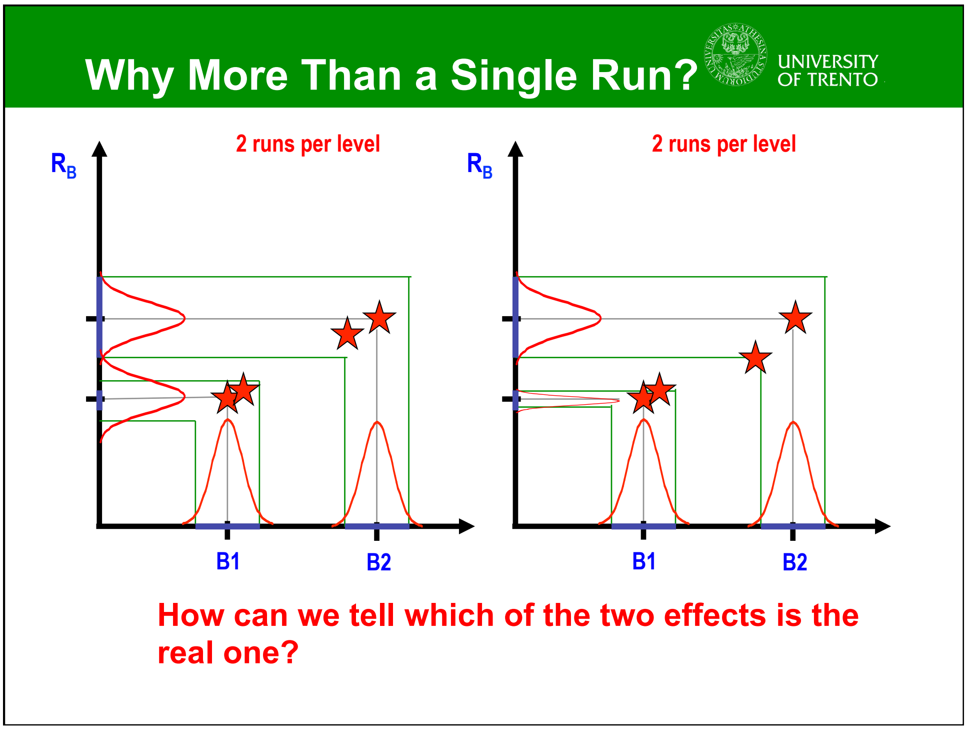
How can we tell which of the two effects is the real one?



Why More Than a Single Run?

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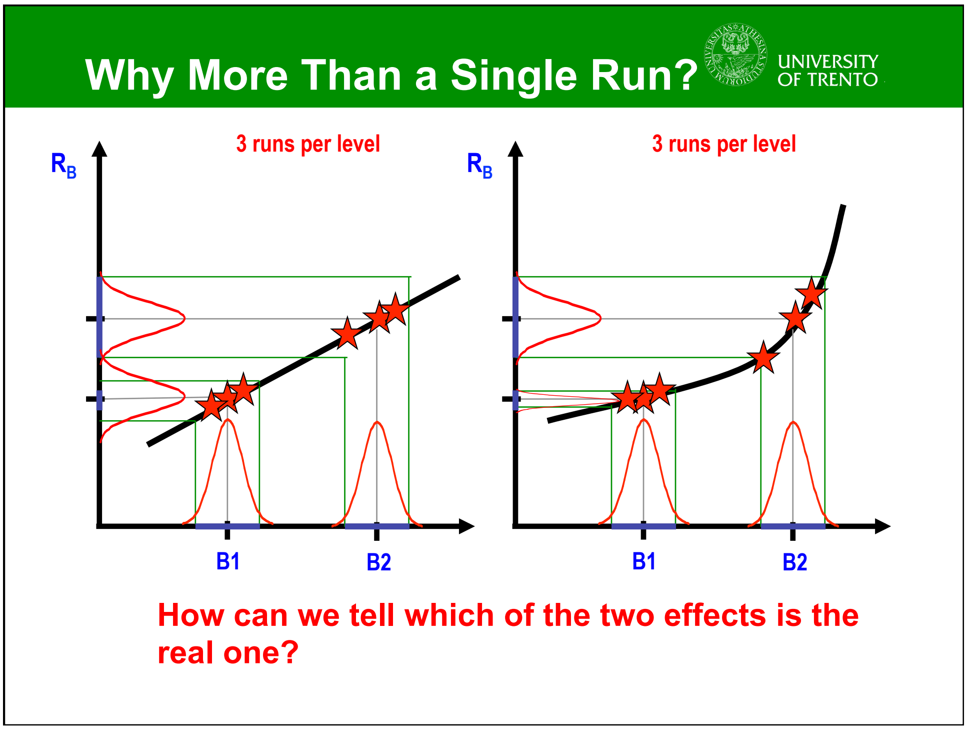
How can we tell which of the two effects is the real one?



Why More Than a Single Run?

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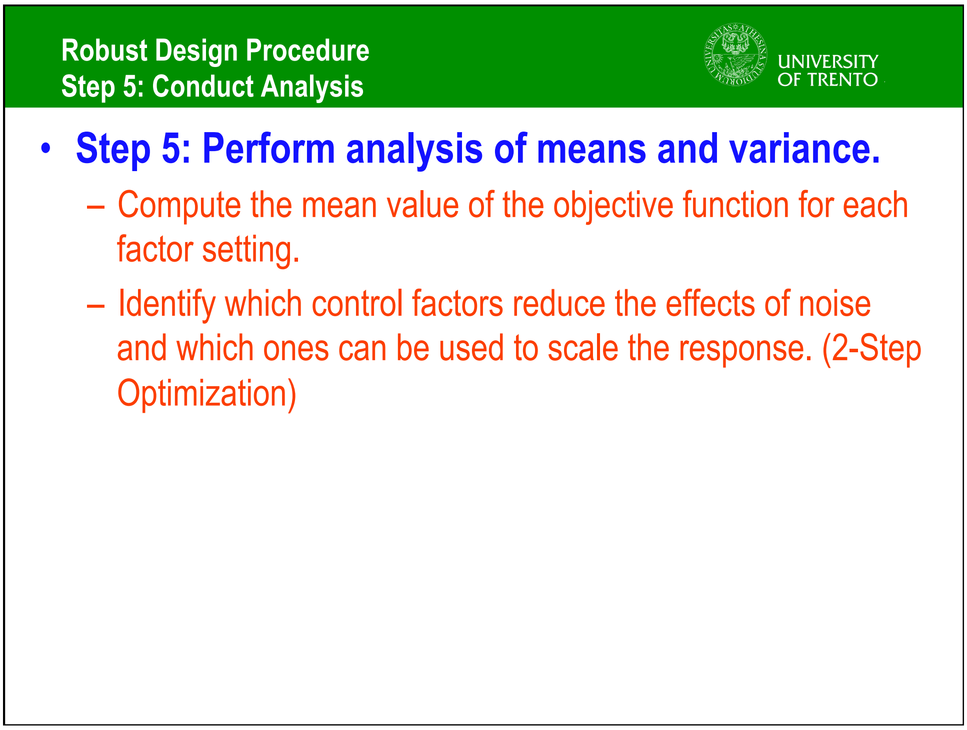
How can we tell which of the two effects is the real one?



Robust Design Procedure
Step 5: Conduct Analysis

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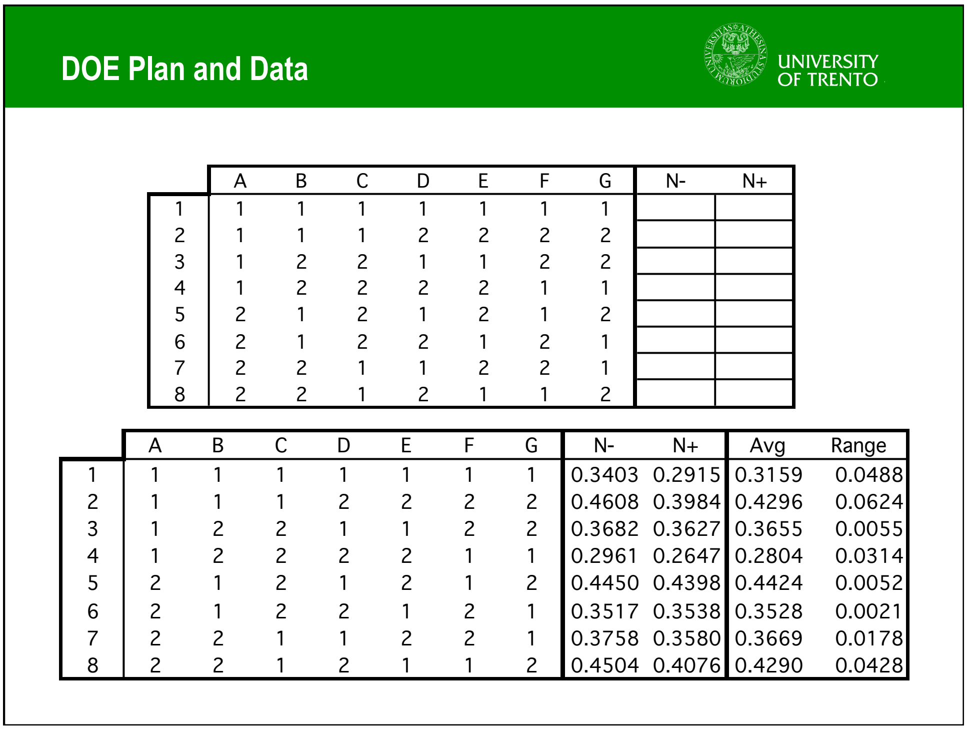
- **Step 5: Perform analysis of means and variance.**
  - Compute the mean value of the objective function for each factor setting.
  - Identify which control factors reduce the effects of noise and which ones can be used to scale the response. (2-Step Optimization)



DOE Plan and Data

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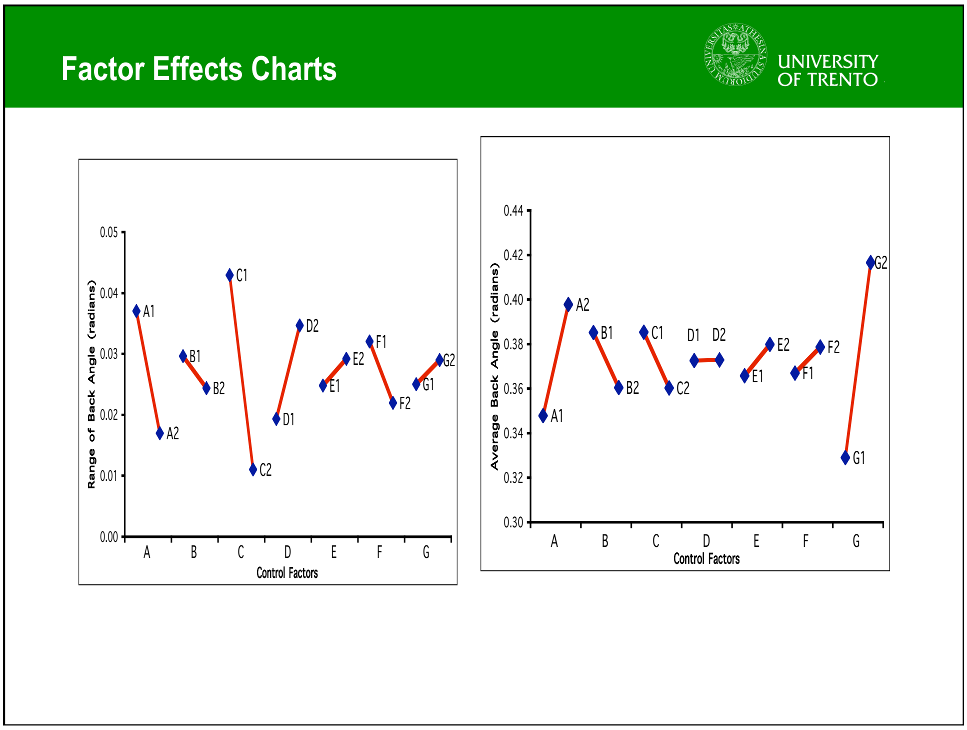
	A	B	C	D	E	F	G	N-	N+
1	1	1	1	1	1	1	1		
2	1	1	1	2	2	2	2		
3	1	2	2	1	1	2	2		
4	1	2	2	2	2	1	1		
5	2	1	2	1	2	1	2		
6	2	1	2	2	1	2	1		
7	2	2	1	1	2	2	1		
8	2	2	1	2	1	1	2		

	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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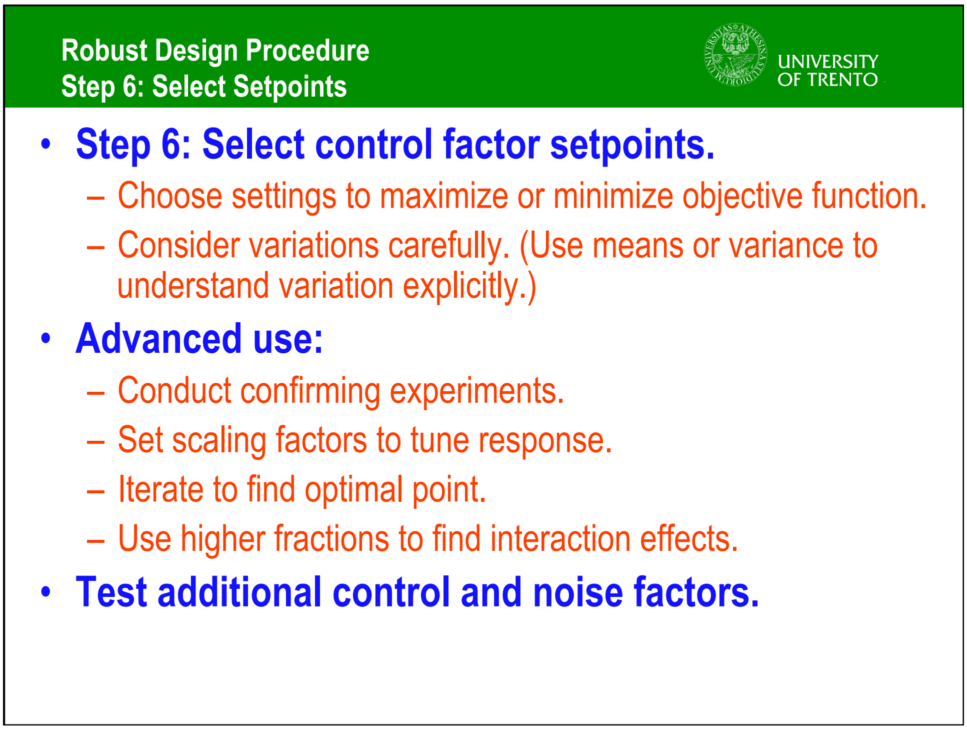
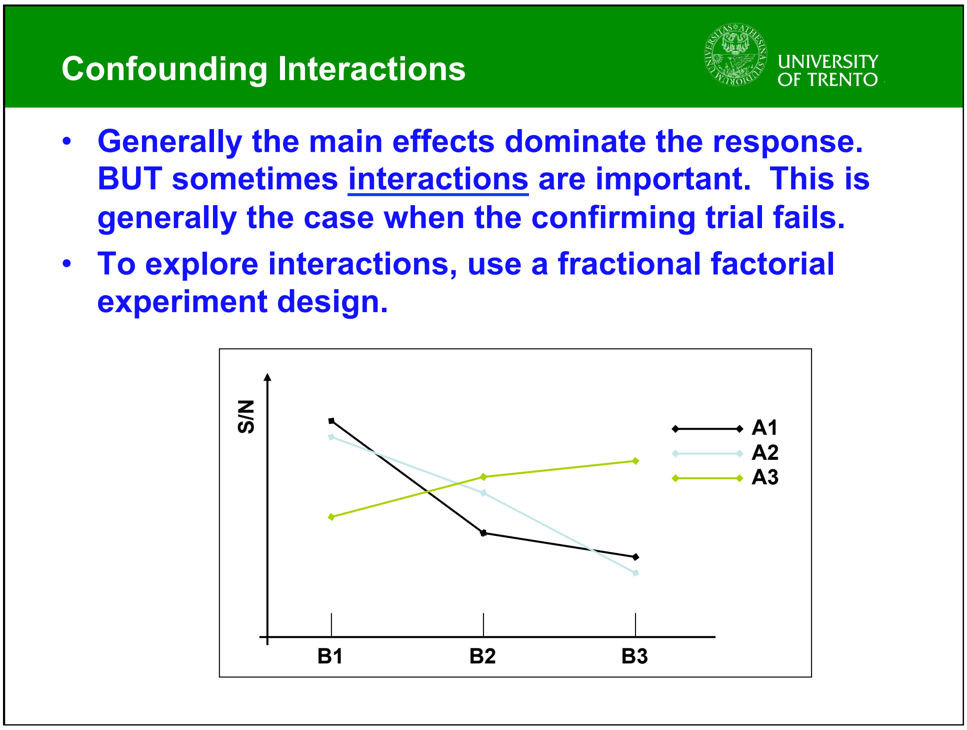


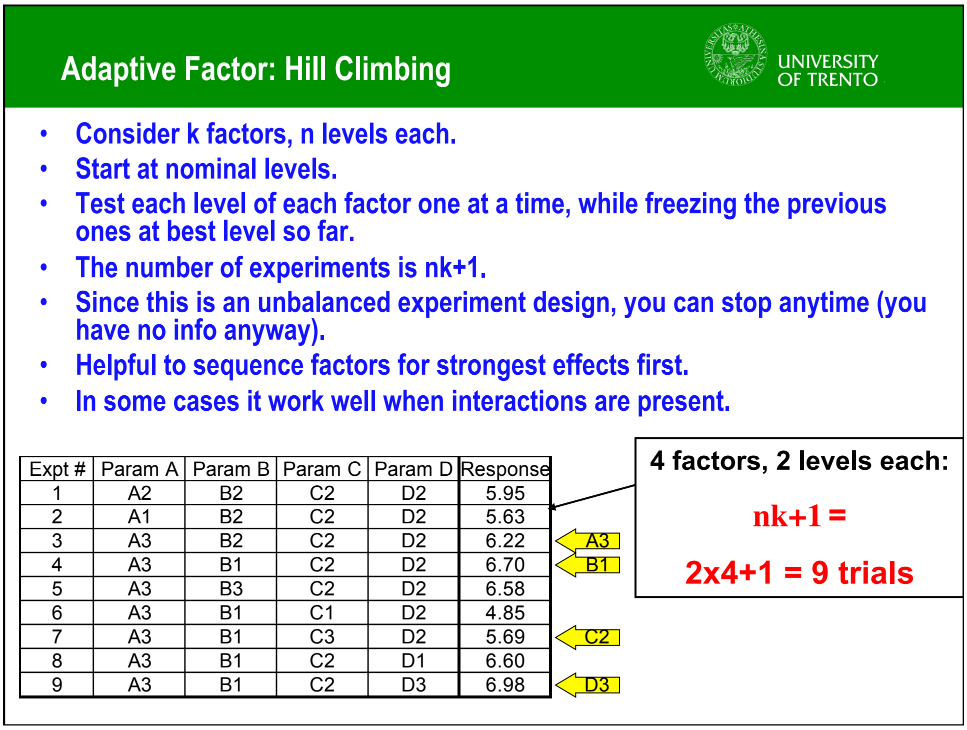
Robust Design Procedure
Step 6: Select Setpoints

- **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

- **Generally the main effects dominate the response. BUT sometimes interactions 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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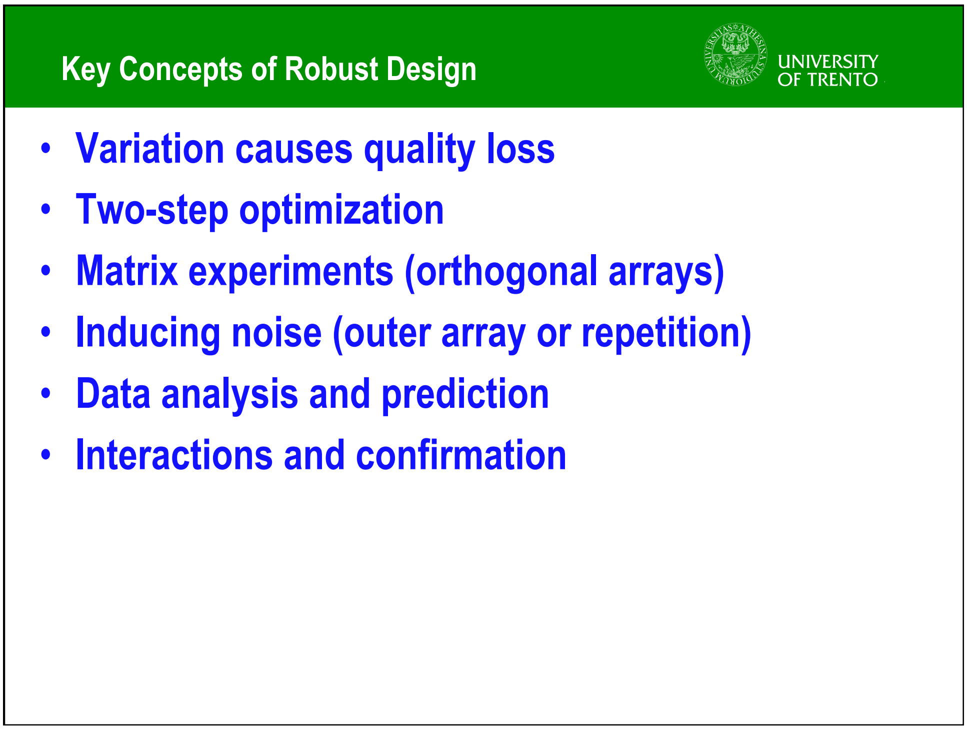
- Consider k factors, n levels each.
- Start at nominal levels.
- Test each level of each factor one at a time, while freezing the previous ones at best level so far.
- The number of experiments is nk+1.
- Since this is an unbalanced experiment design, you can stop anytime (you have no info anyway).
- 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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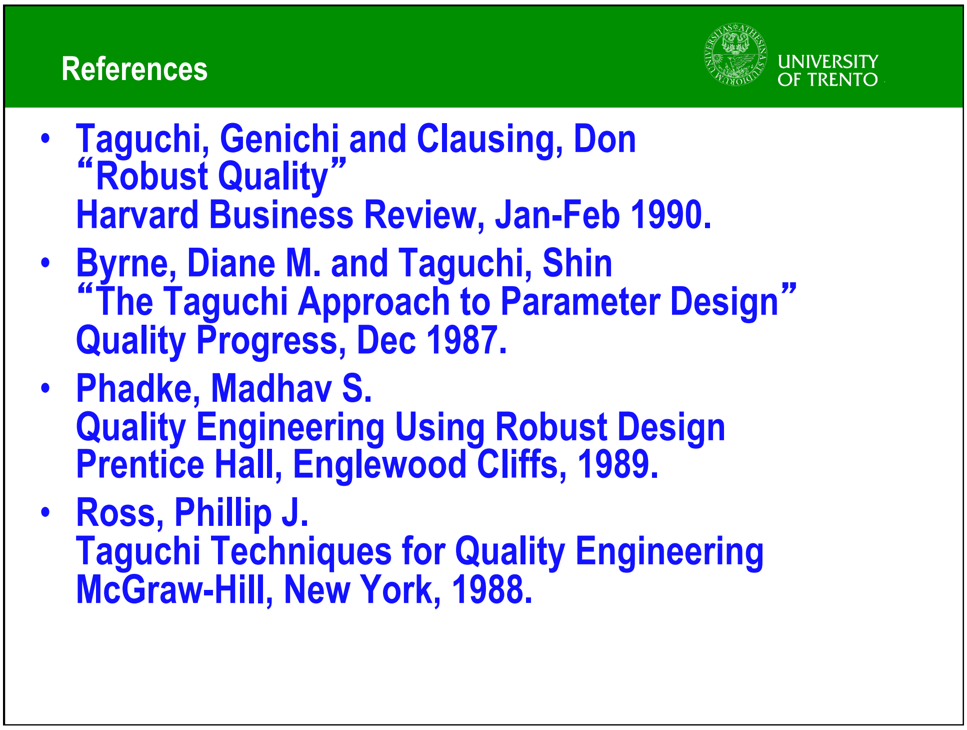
- Variation causes quality loss
- Two-step optimization
- Matrix experiments (orthogonal arrays)
- Inducing noise (outer array or repetition)
- Data analysis and prediction
- Interactions and confirmation



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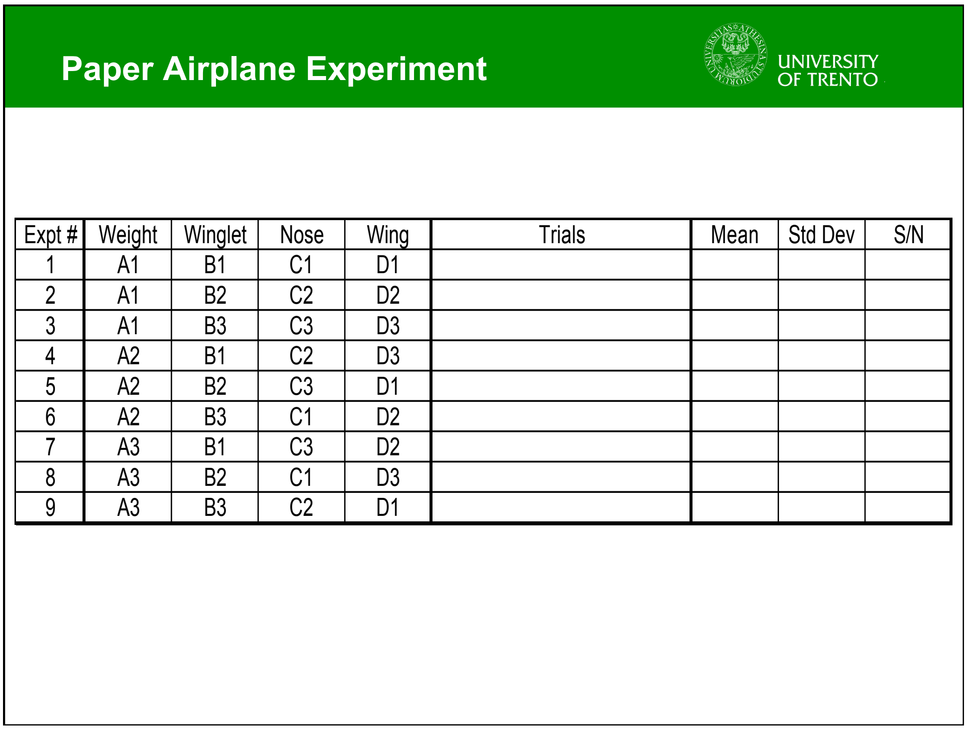

Paper Airplane Experiment

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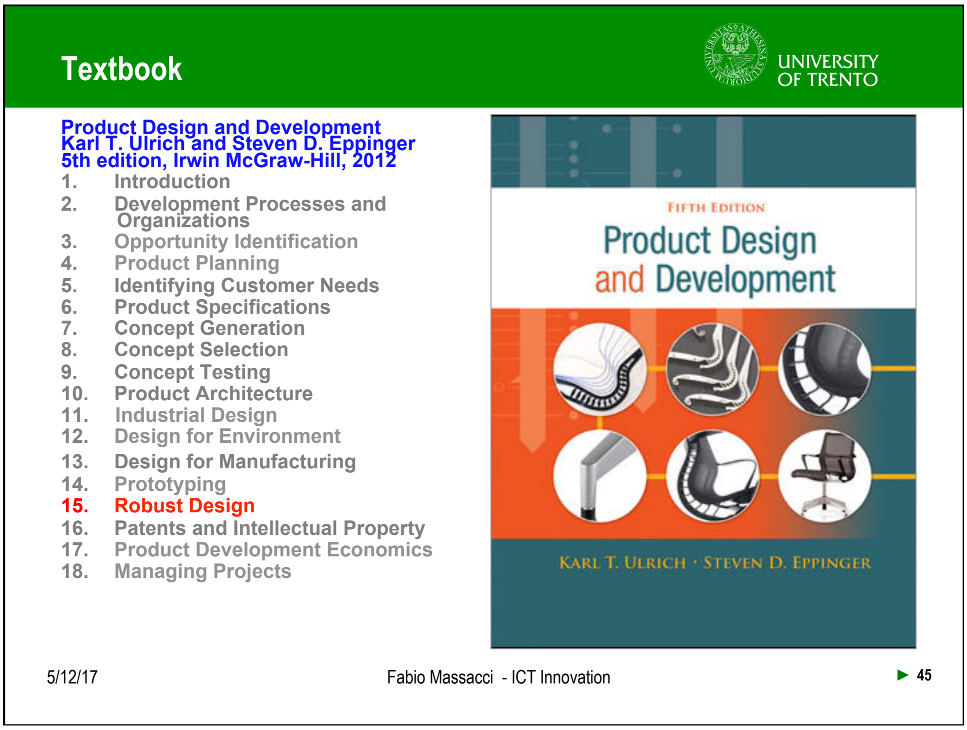
Expt #	Weight	Winglet	Nose	Wing	Trials	Mean	Std Dev	S/N
1	A1	B1	C1	D1				
2	A1	B2	C2	D2				
3	A1	B3	C3	D3				
4	A2	B1	C2	D3				
5	A2	B2	C3	D1				
6	A2	B3	C1	D2				
7	A3	B1	C3	D2				
8	A3	B2	C1	D3				
9	A3	B3	C2	D1				



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

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Product Design and Development
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