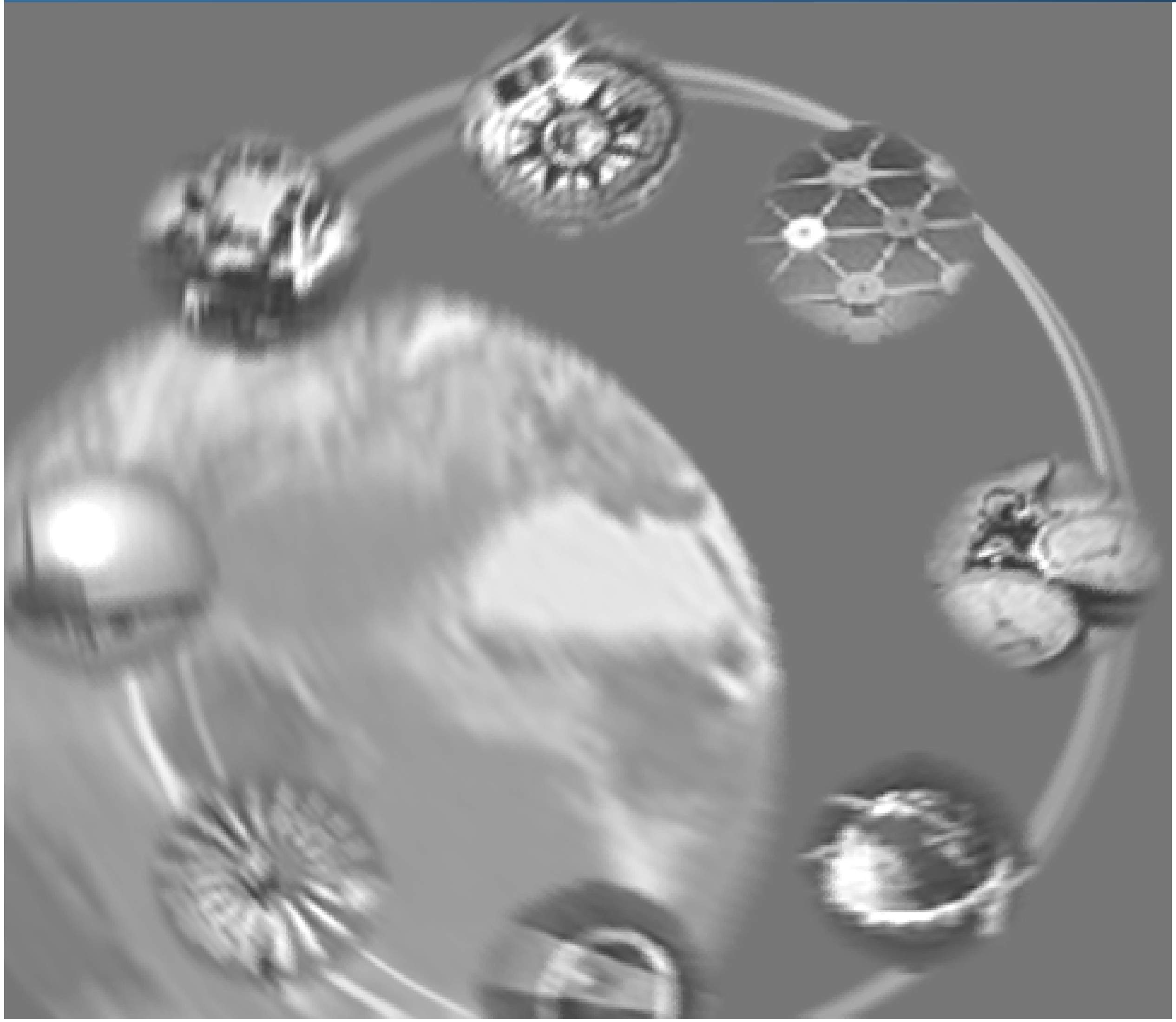
Robust Design

4013.315 Architectural Engineering System Design

June 3rd, 2009



Moonseo Park

Associate Professor, PhD

39동 433
Phone 880-5848, Fax 871-5518
E-mail: mspark@snu.ac.kr

Department of Architecture
College of Engineering
Seoul National University

Robust Design: Experiments for Better Products

Teaching materials to accompany:

Product Design and Development
Chapter 13

Karl T. Ulrich and Steven D. Eppinger
3rd Edition, Irwin McGraw-Hill, 2004.

Product Design and Development

Karl T. Ulrich and Steven D. Eppinger

3rd edition, Irwin McGraw-Hill, 2000.

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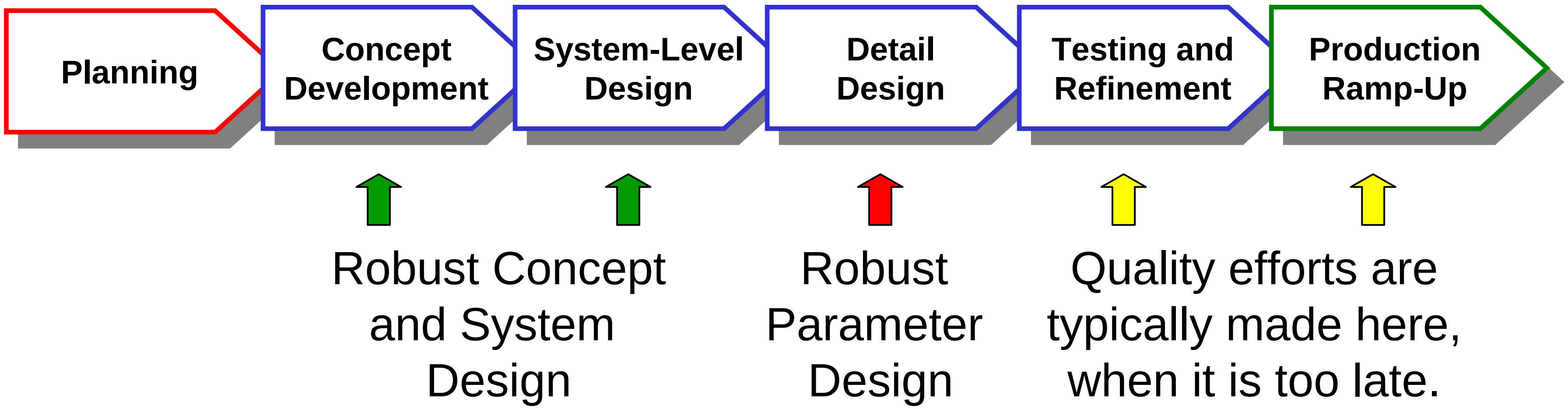
Robust Design and Quality in the Product Development Process



Goals for Designed Experiments

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

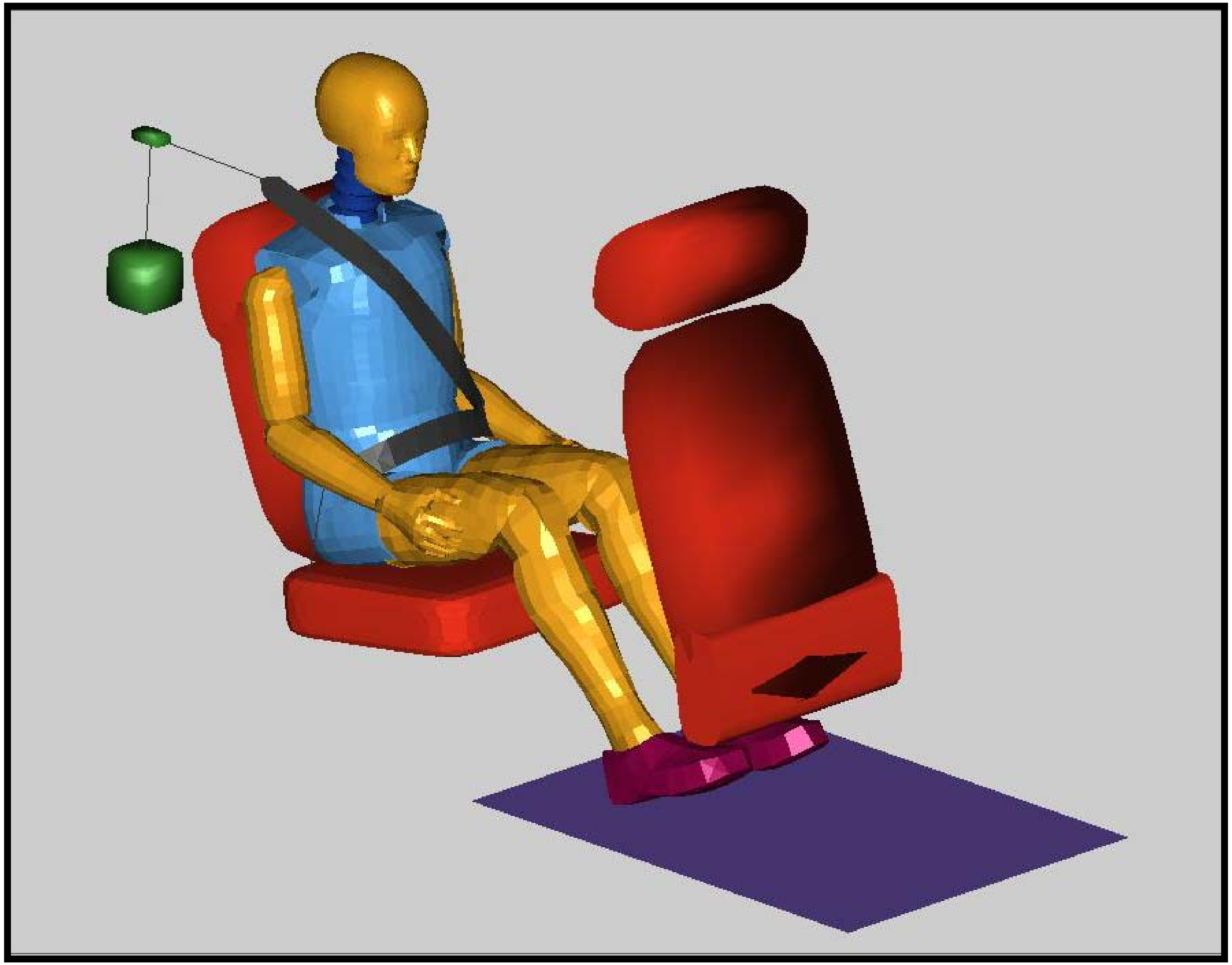
Robust Designs

A robust product or process performs correctly, even in the presence of noise factors.

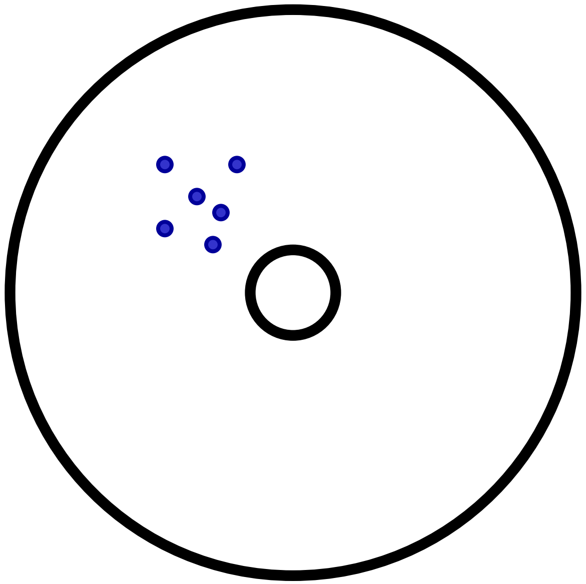
Noise factors may include:

- parameter variations
- environmental changes
- operating conditions
- manufacturing variations

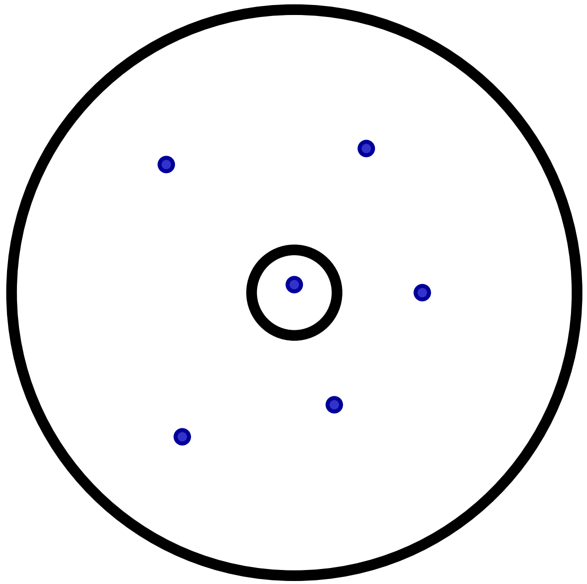
Robust Design Example: Seat Belt Experiment



Who is the better target shooter?

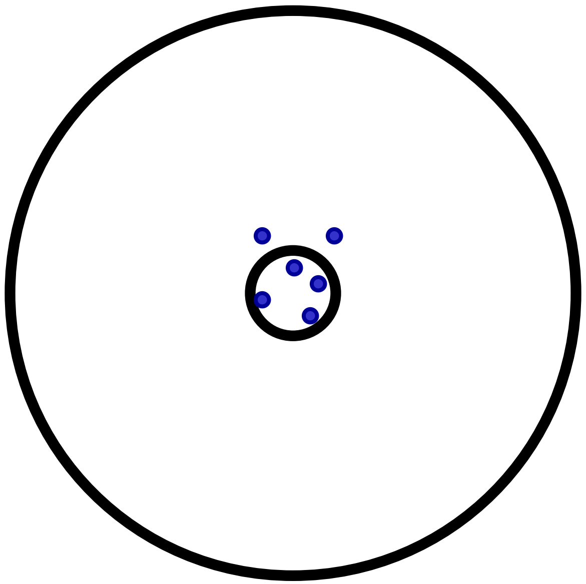


Sam



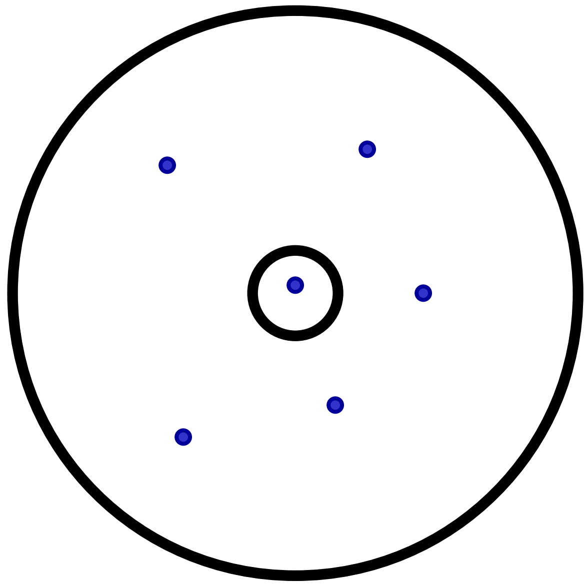
John

Who is the better target shooter?



Sam

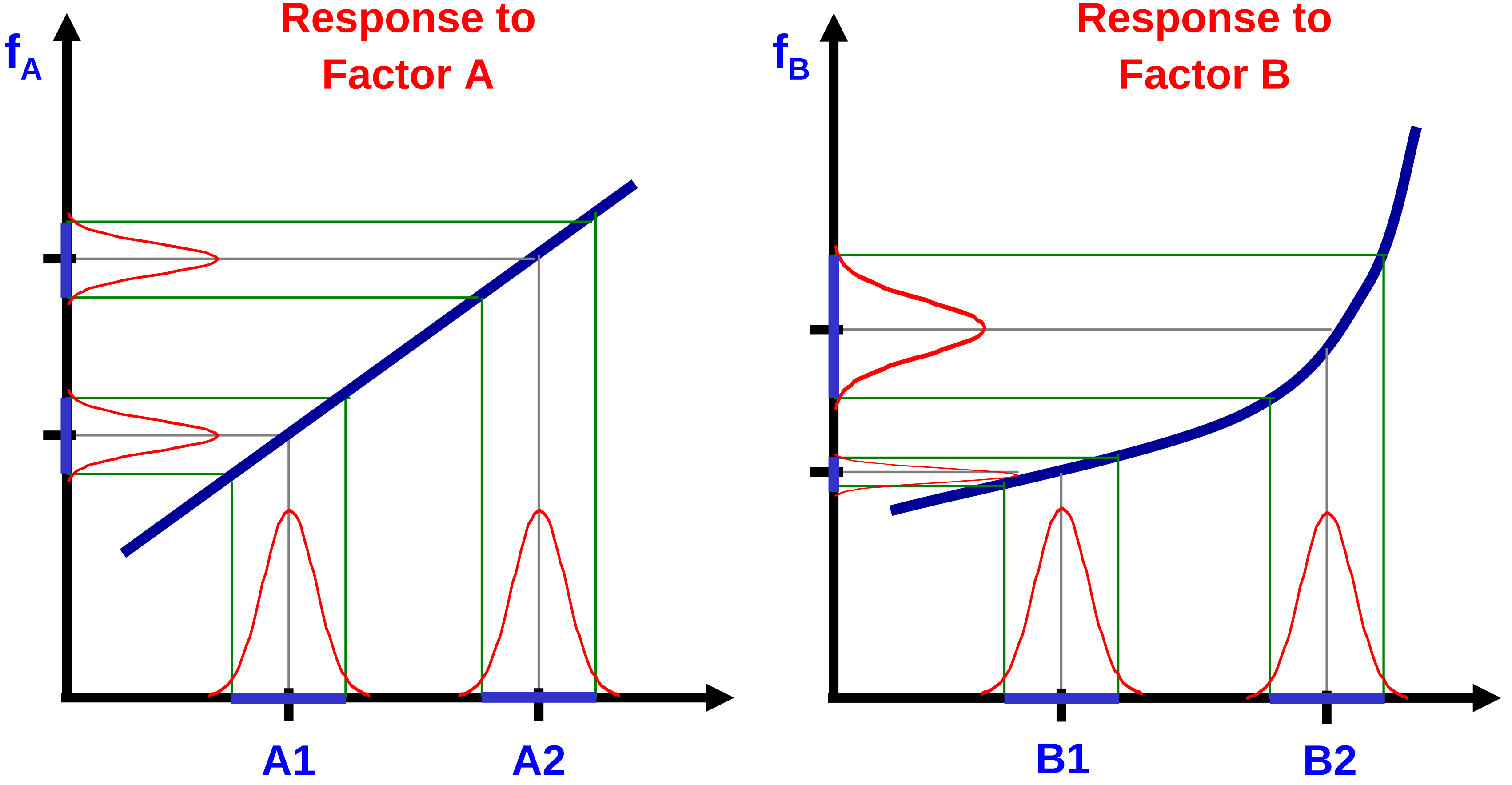
Sam can simply
adjust his sights.



John

John requires
lengthy training.

Exploiting Non-Linearity to Achieve Robust Performance



Response = $f_A(A) + f_B(B)$

What level of factor B gives the robust response?

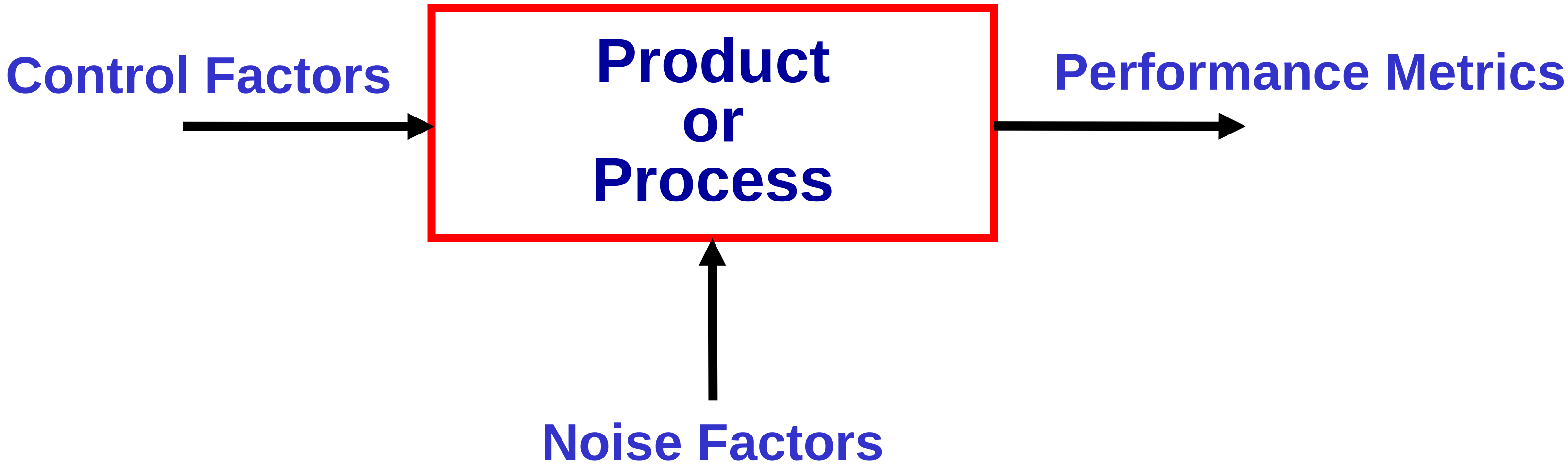
How do we use factor A?

Robust Design Procedure
Step 1: Parameter Diagram

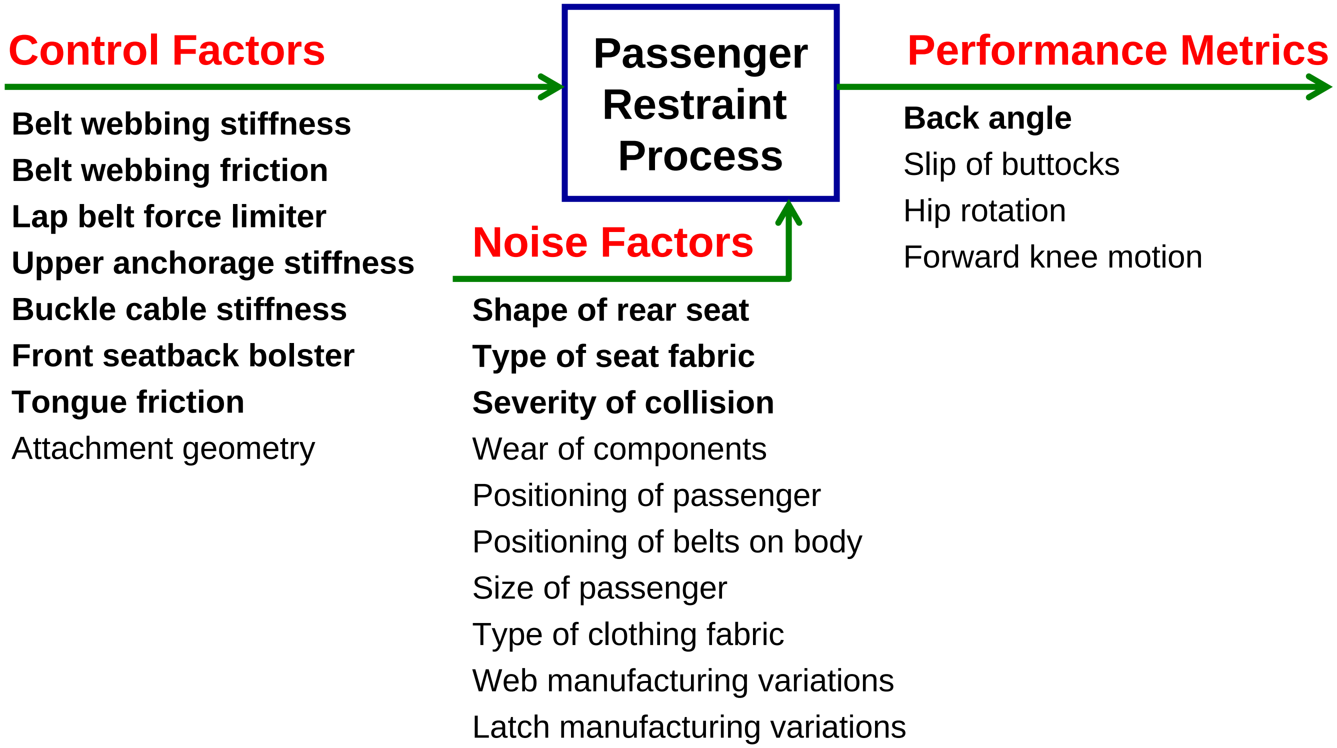
Step 1: Select appropriate controls, response, and noise factors to explore experimentally.

- Control factors (input parameters)
- Noise factors (uncontrollable)
- Performance metrics (response)

The “P” Diagram



Parameter Diagram



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

Robust Design Procedure
Step 2: Objective Function

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

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

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

- 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 of the 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

- Consider k factors, n levels each.
- Test all levels of each factor while freezing the others at nominal level.
- The number of experiments is nk+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, 2 levels each:

nk+1 =

2x4+1 = 9 trials

Experiment Design: Orthogonal Array

- Consider k factors, n levels each.
- Test all levels of each factor in a balanced way.
- The number of experiments is order of $1+k(n-1)$.
- This is the smallest balanced experiment design.
- BUT main 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:

$1+k(n-1) =$

$1+4(3-1) = 9$ trials

Using Inner and Outer Arrays

- 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

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

Paper Airplane Experiment

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				

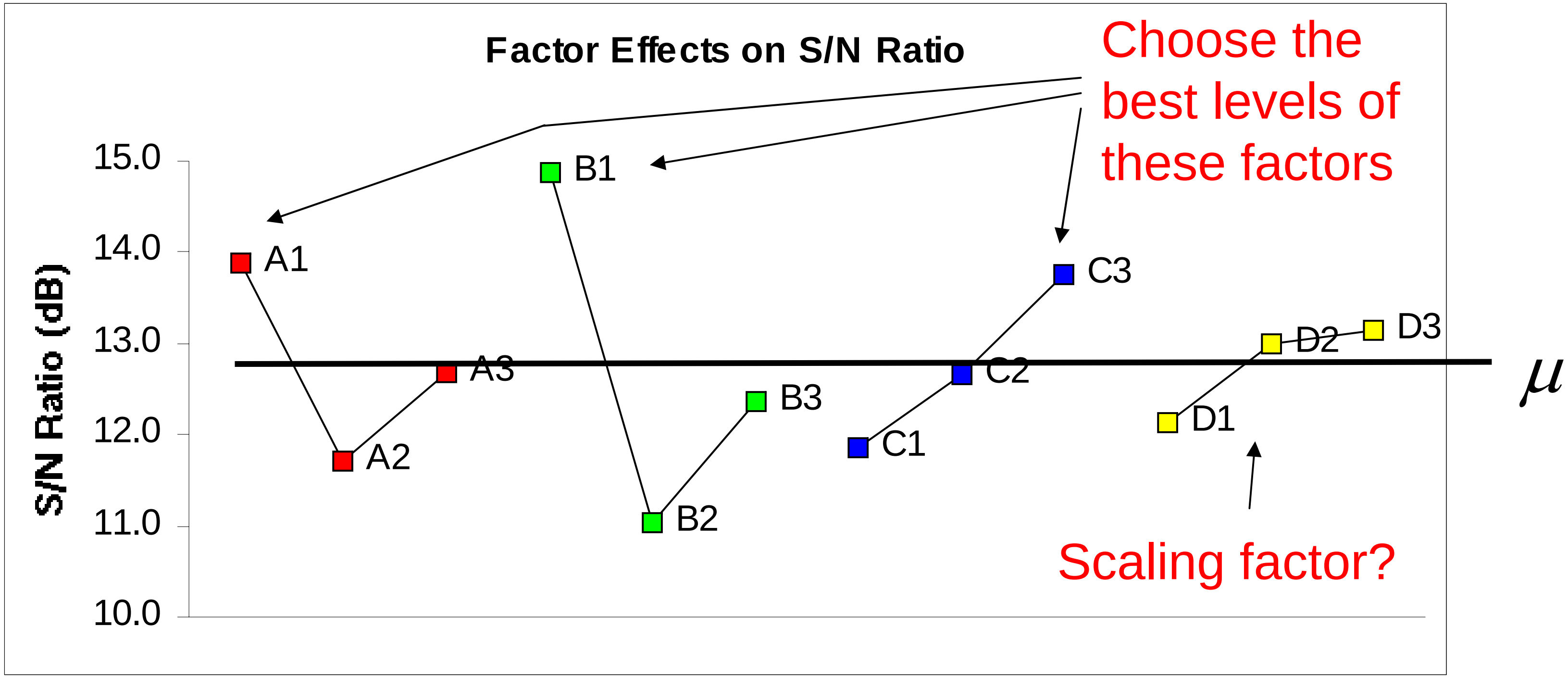
Robust Design Procedure
Step 5: Conduct Analysis

Step 5: Perform analysis of means.

- 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)

Analysis of Means (ANOM)

- Plot the average effect of each factor level.



Prediction of response:

$$E[\eta(Ai, Bj, Ck, Dl)] = \mu + a_i + b_j + c_k + d_l$$

Robust Design Procedure
Step 6: Select Setpoints

Step 6: Select control factor setpoints.

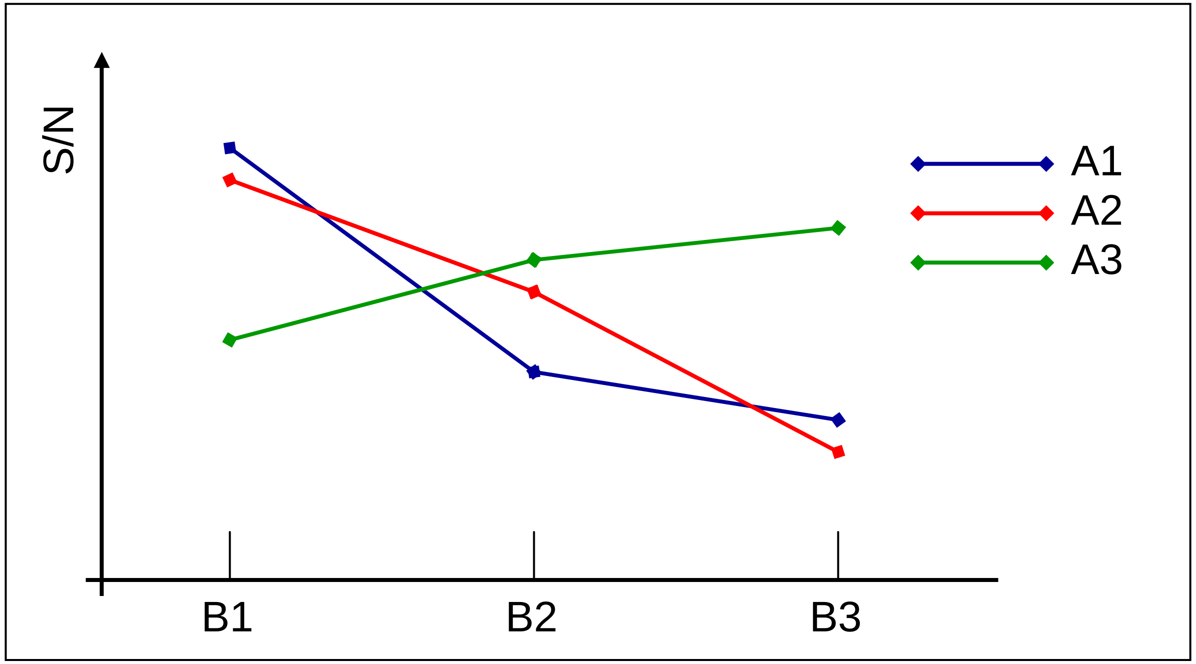
- Choose settings to maximize or minimize objective function.
- Consider variations carefully. (Use ANOM on variance to understand variation explicitly.)

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.



Alternative Experiment Design Approach: Adaptive Factor One at a Time

- 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, it is generally OK to stop early.
- Helpful to sequence factors for strongest effects first.
- Generally found to 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

Ref: Forthcoming paper by Dan Frey

Key Concepts of Robust Design

- 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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DOE Plan and Data

	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