

ROBUST
DESIGN PRINCIPLES

**GAIN CONTROL OF YOUR
PRODUCT PERFORMANCE**

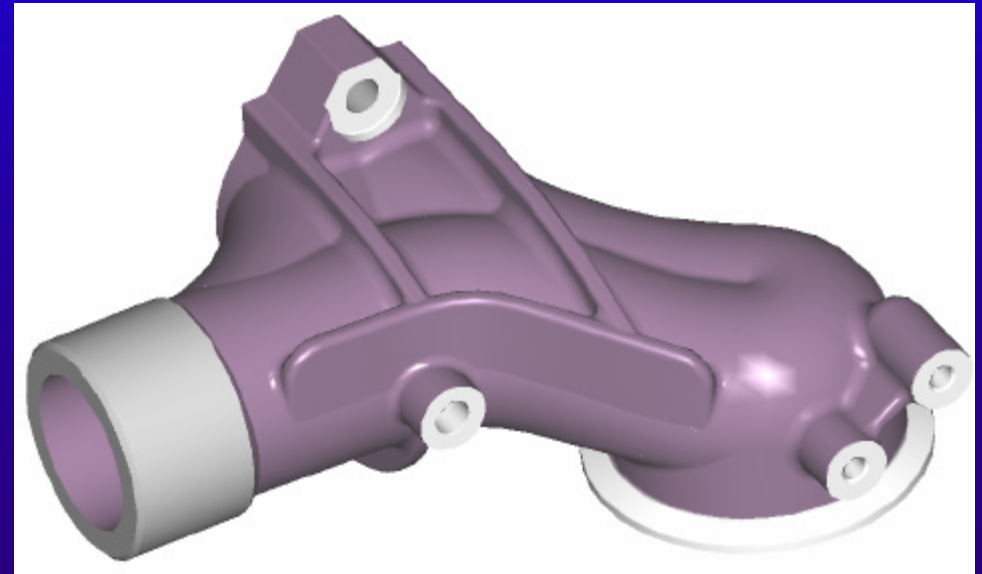
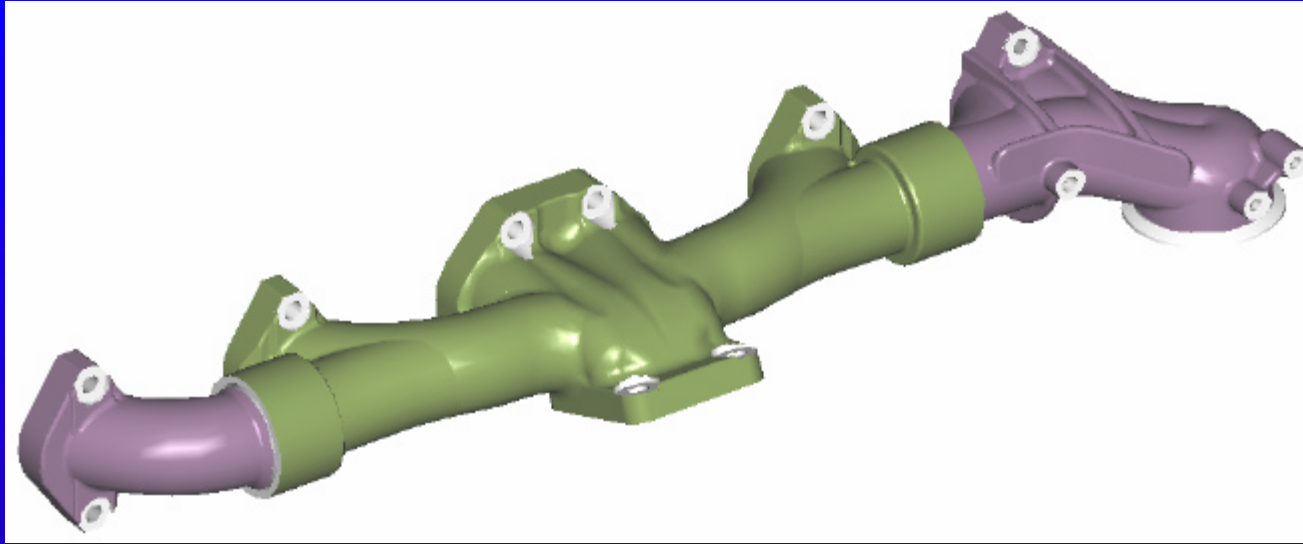
VARIATION IS THE ENEMY!

John Toksoy
Cummins Inc.

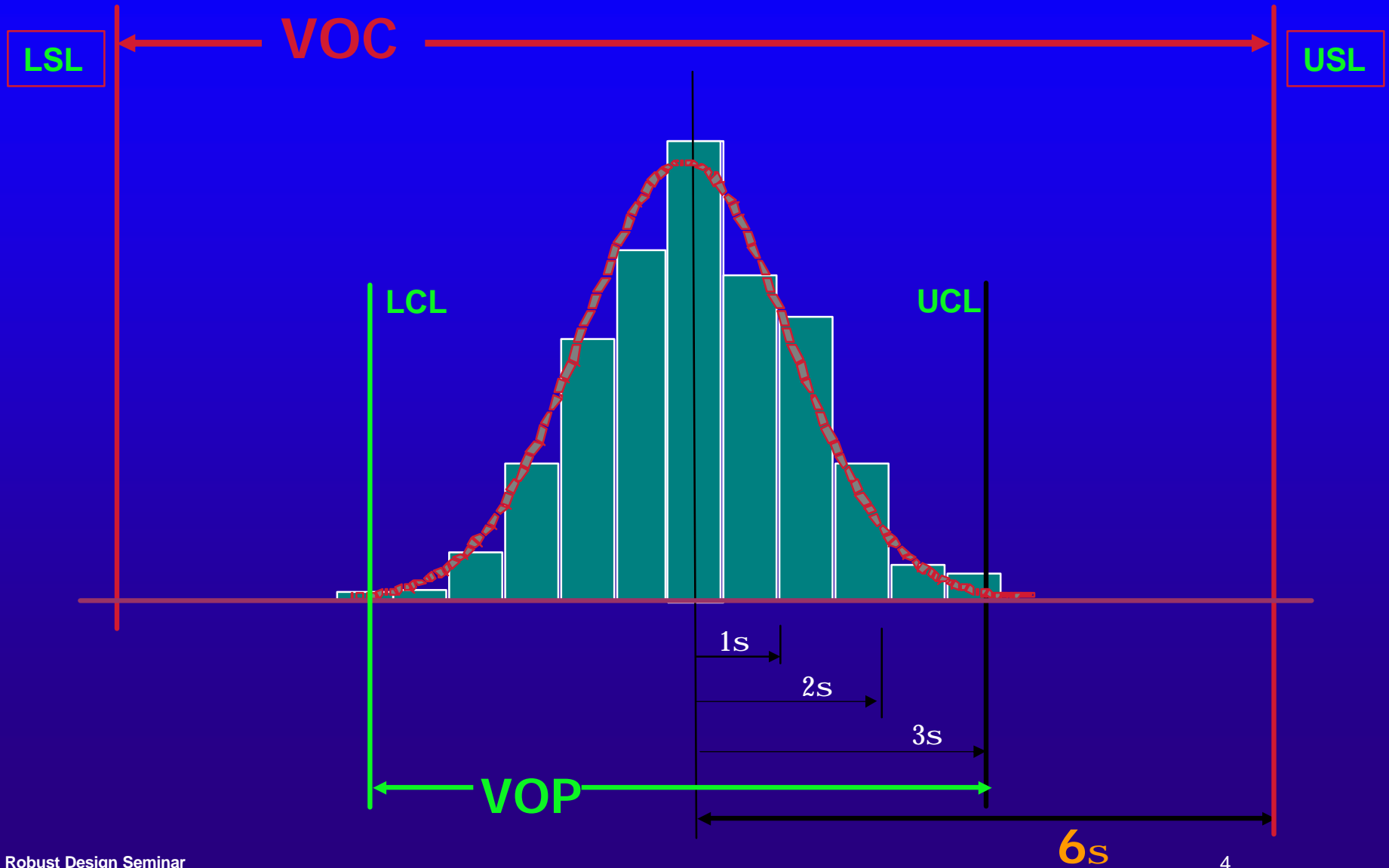
Objective

- Create awareness of Robust Design Principles
- Focus on robust design principles rather than the mathematics behind it
 - *Trust me ! it works...*

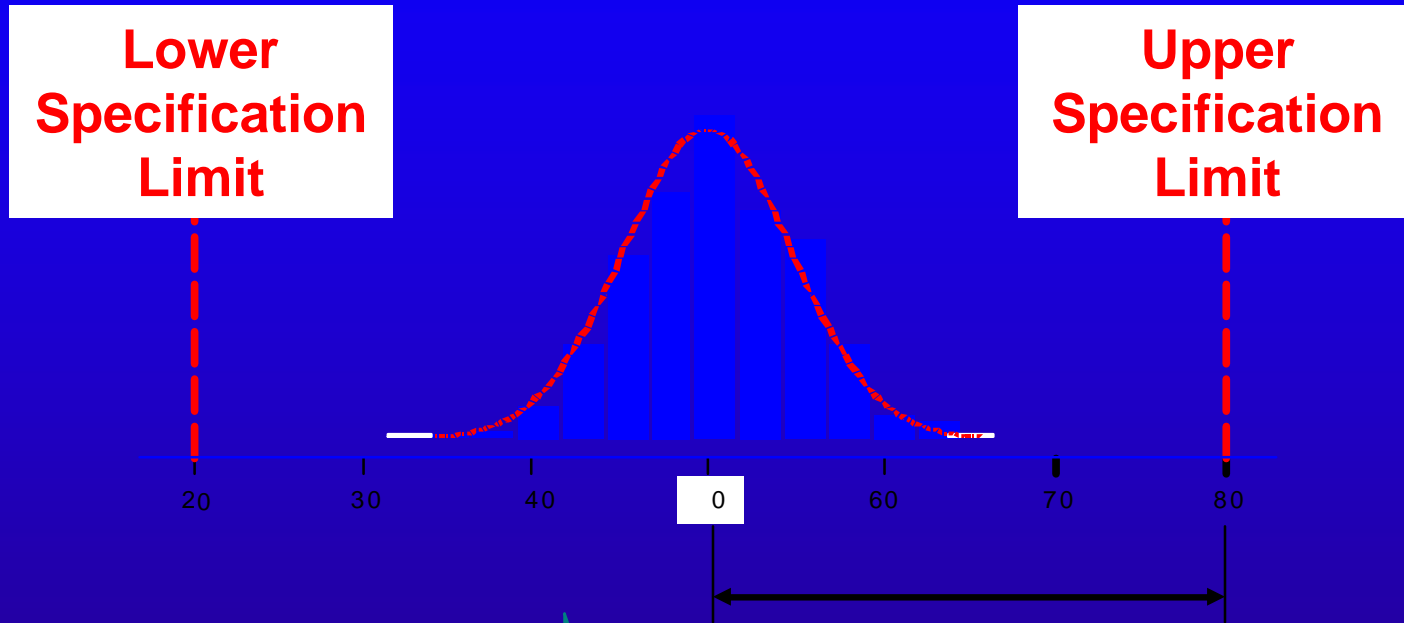
Exhaust Manifold Slip Joint



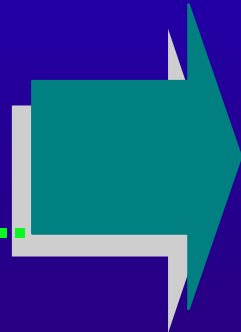
Capability Definition



Robust Design Definition



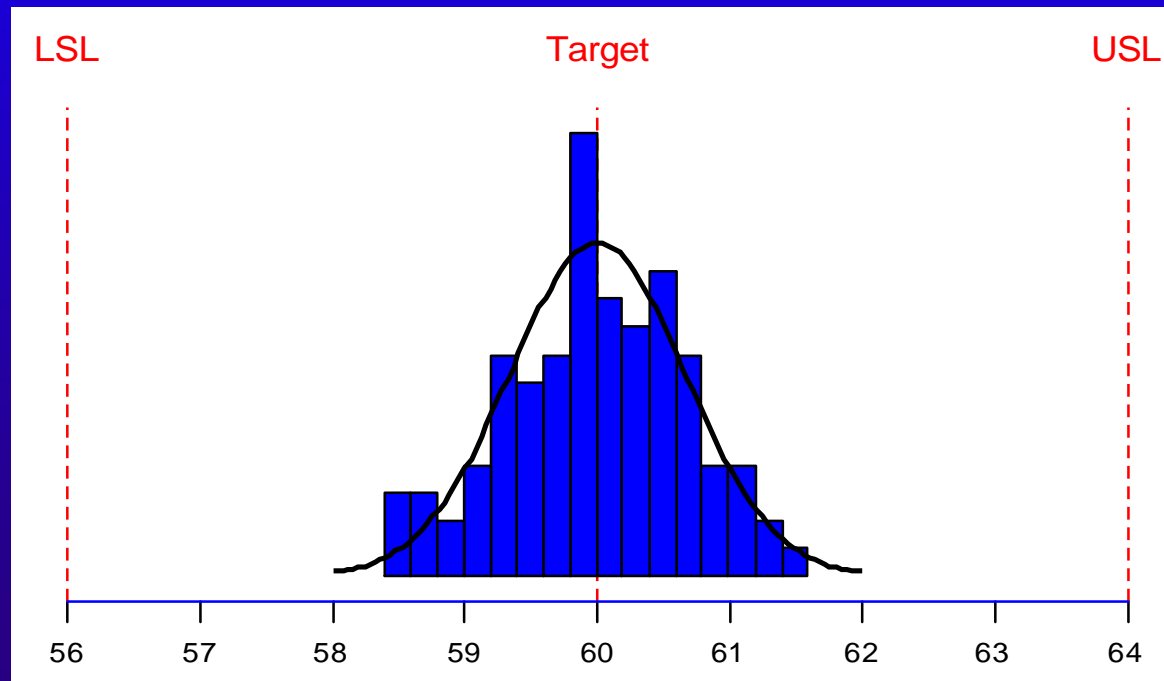
DFSS
Simply Means...



The mean of the data is six standard deviations away from the specification

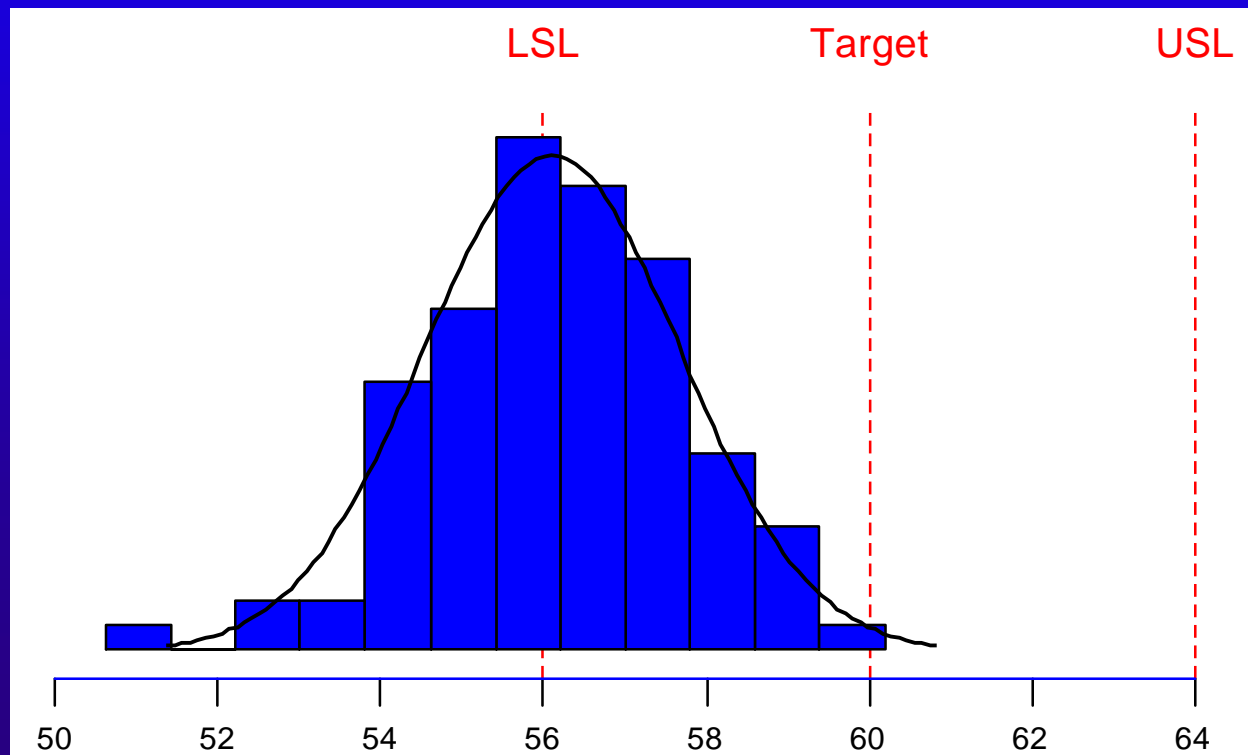
Do You Need to Apply Robust Design?

If your predicted design capability looks like this, you do not have a functional performance need to apply Robust Design tools. Cost, however, may still be an issue if the input (materials or process) requirements are tight!



Need to Apply Robust Design...

If your predicted capability looks like this, you have a need to both reduce the variation and shift the mean of this characteristic - a prime candidate for the application of robust design methods.



Summary

- Gain control of your product performance. Variation is the enemy.
- Apply Robust design principles at early stages of the project to “forecast” problems and take preventive action.
- Cost of a product extends well beyond development & manufacturing cost. Warranty, life cycle and cost to others can be major contributors due to varying product performance.

Outline

- **Product Robustness**
- **Design Phases**
- **Design & Development Process**
- **Product Cost**
- **Robust Design Methodology**
- **Case Study**

What is Robustness?

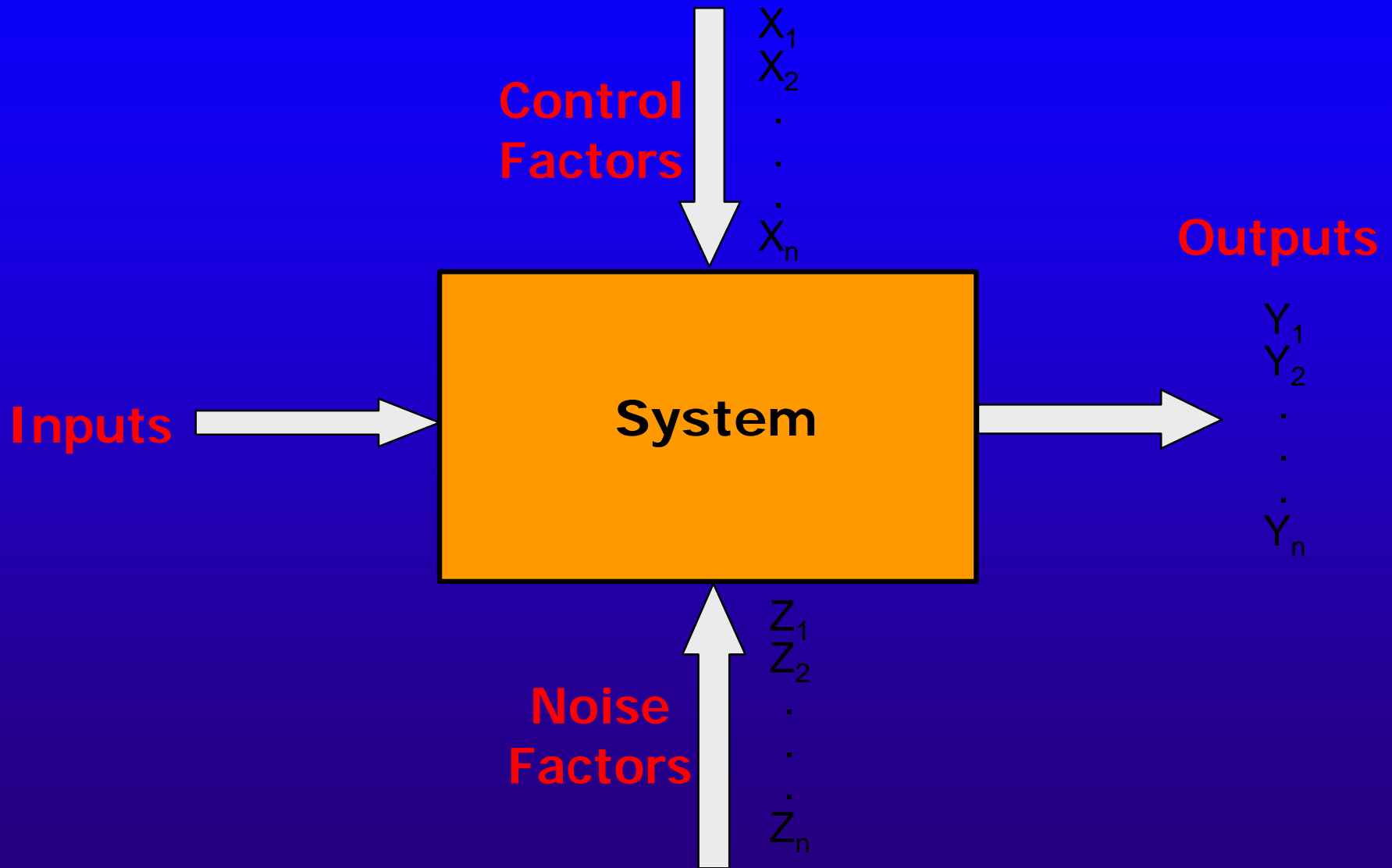
- **Robustness is defined as a condition in which the product or process will be minimally effected by outside sources of variation.**
 - **A product can be robust:**
 - **Against variation in raw materials**
 - **Against variation in manufacturing conditions**
 - **Against variation in manufacturing personnel**
 - **Against variation in the end use environment**
 - **Against variation in end-users**
 - **Against wear-out or deterioration**

A Product Is Said to Be Robust...

- Performs consistently as intended
- Throughout its life cycle
- Under a wide range of user conditions
- Under a wide range of outside influences

When it is insensitive to the effects of sources of variability

Engineering System



Overview of P Diagram Elements

CONTROL FACTORS

System design parameters that affect system performance, and are specified by nominal values

- material (chemical makeup, hardness)
- mechanical (pressures, flow rates)
- dimensional (length, width, roundness, coating thickness)
- surface finish (smoothness)

Input (Signal):

A measurable input of what the "customer" wants in engineering terms

System

Desired Output Response:

Meaningful, measurable performance data of what the "customer" gets in engineering terms

Undesired Output:

Symptoms of variability of the desired output response. These symptoms are what cause quality problems

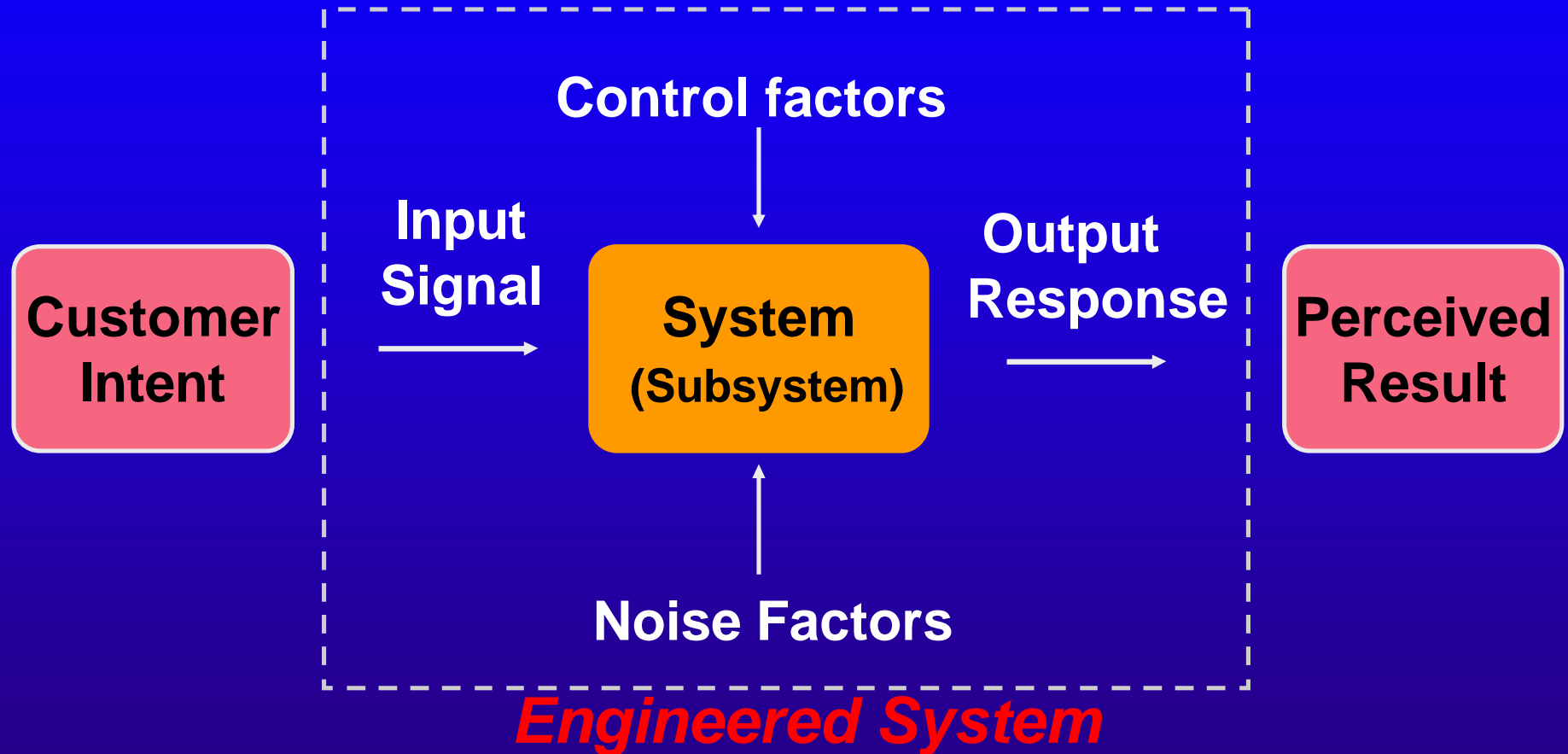
- Vibration, leaks, wear, etc.

NOISE FACTORS

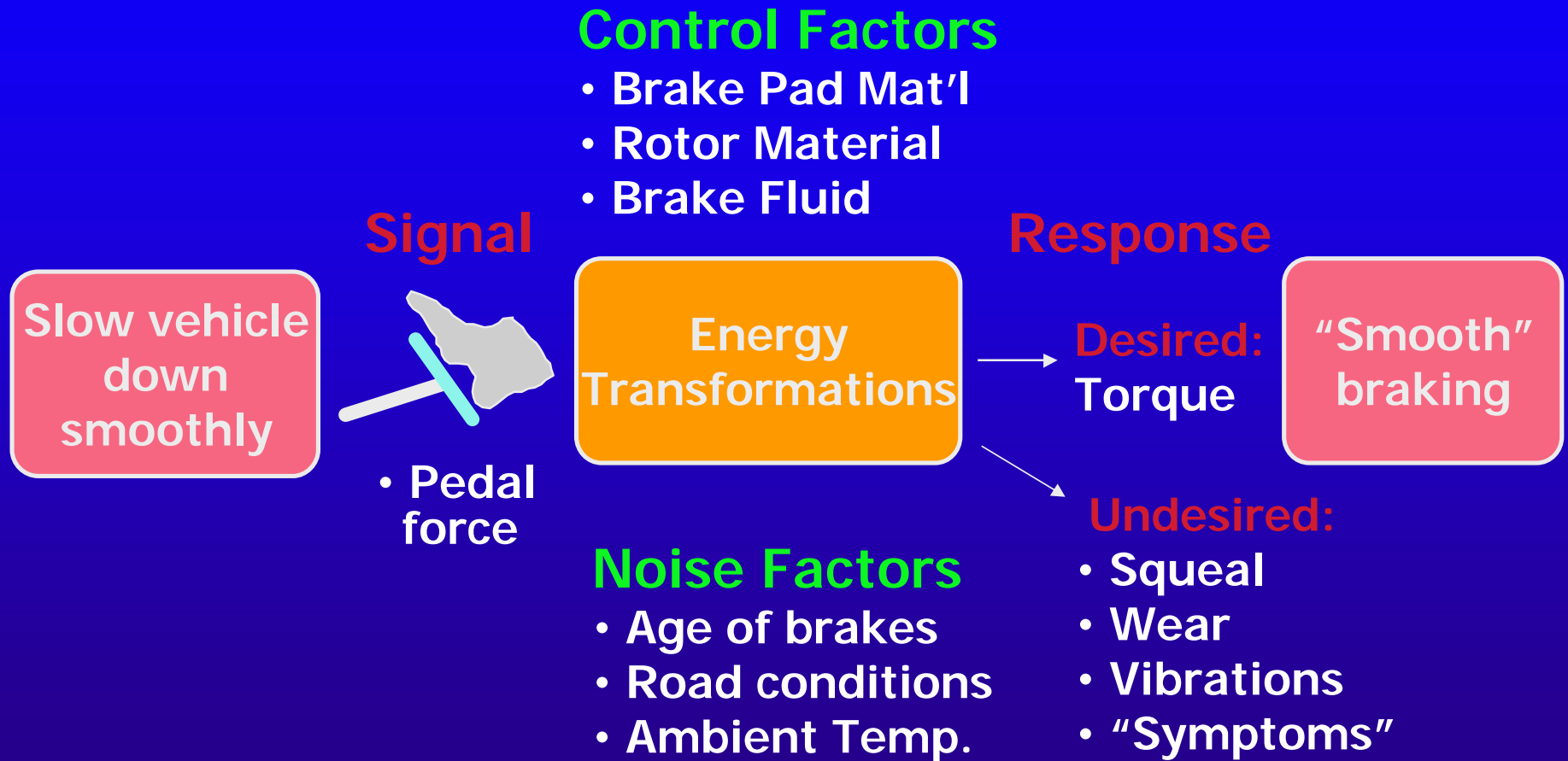
Variables that affect system performance, and are either uncontrollable or impractical to control

- Customer usage (maintenance, location, duty cycle)
- Mfg. (processes, equipment, tolerances)
- Aging (wear, corrosion, calibration drift)

Where does the customer fit in?



EXAMPLE - Auto Brake System



Three Types Of Noise Factors

- **Unit-to-Unit Noise Factors**
- **External Noise Factors**
- **Deterioration Noise Factors**

Three Types Of Noise Factors

UNIT-TO-UNIT NOISE FACTORS

Never being able to make any two items alike

- **Manufacturing processes**
 - Dimensions from any metal forming and removal process
- **Process non-uniformity and drift**
 - Torque applied to a bolt on the assembly line
- **Batch-to-Batch variation in material properties**

Three Types Of Noise Factors

UNIT-TO-UNIT NOISE FACTORS

EXTERNAL NOISE FACTORS

- Temperature and relative humidity
- The load to which a product is subjected
- Fuel type and octane level
- Human error including misuse & abuse
- Any unintended input of energy (heat, vibration, radiation) into design to which the system is sensitive

Three Types Of Noise Factors

UNIT-TO-UNIT NOISE FACTORS

EXTERNAL NOISE FACTORS

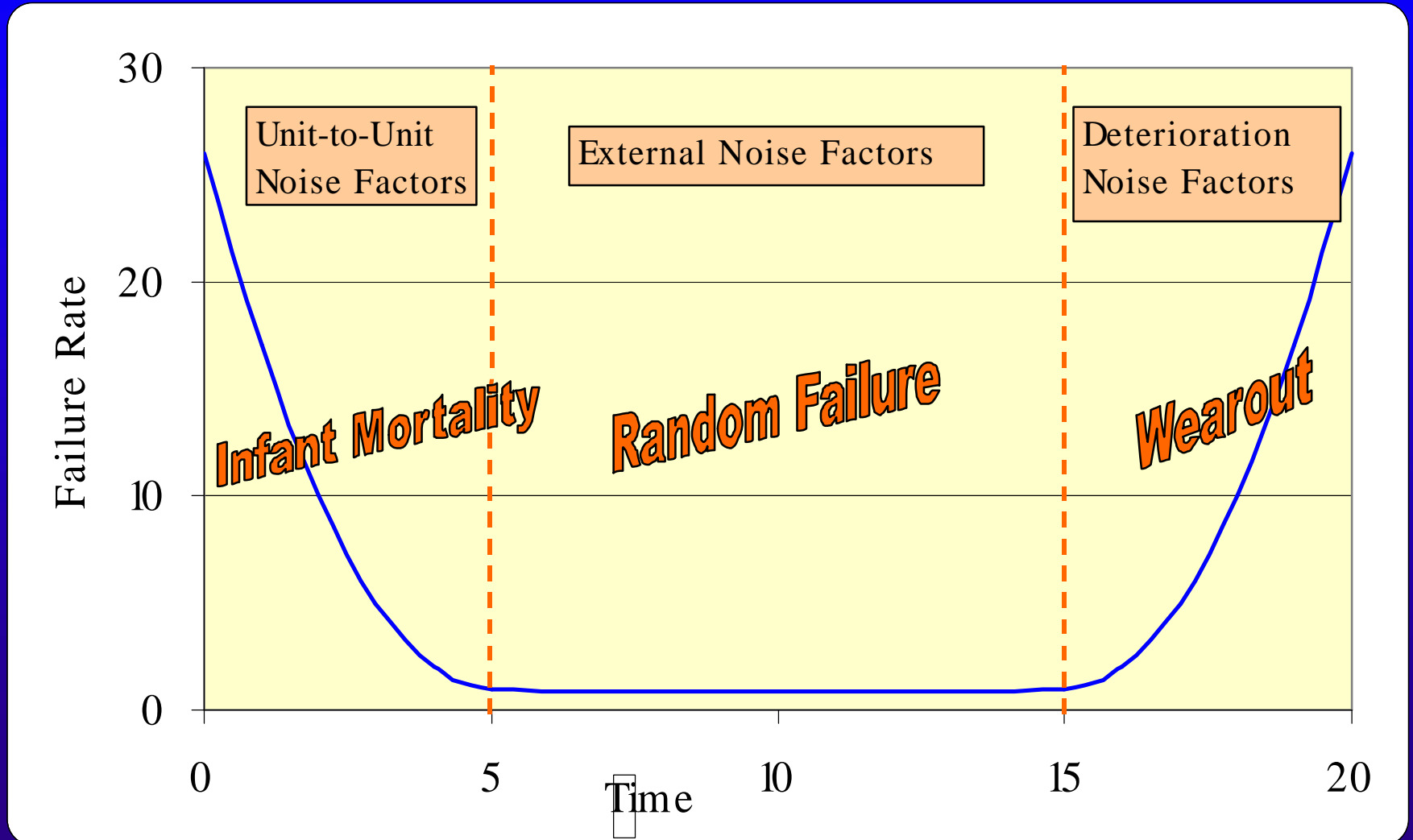
DETERIORATION NOISE FACTORS

(Internal Noise Factors)

**Something changes internally
within the product over time**

- **Change in material properties over time - AGING**
 - Compression set or plastic creep of a seal in a faucet
- **Loss of material over time**
 - Wear of material - Wear in brake pads
 - Loss of mass - Light-bulb filament

Reliability & Noise Factors



Lets Eliminate All Noise Factors !

- Huge **impact on cost**
 - There are materials used on “space-shuttle” that will retain their properties over time
- In some cases it will be a “godly” move!
 - Ambient pressure, temperature & humidity
- Assure Robustness at the lowest cost
- Learn to live with the noise factors
- Design a “Robust” system **in-sensitive to noise factors**

Robust Design – 2 STEP OPTIMIZATION



Step 1:
Reduce Variation

Minimize the effect
of Noise Factors

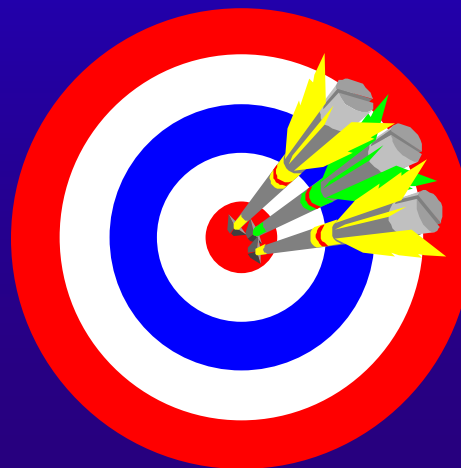
VARIATION

In Product Performance

Is the Enemy !

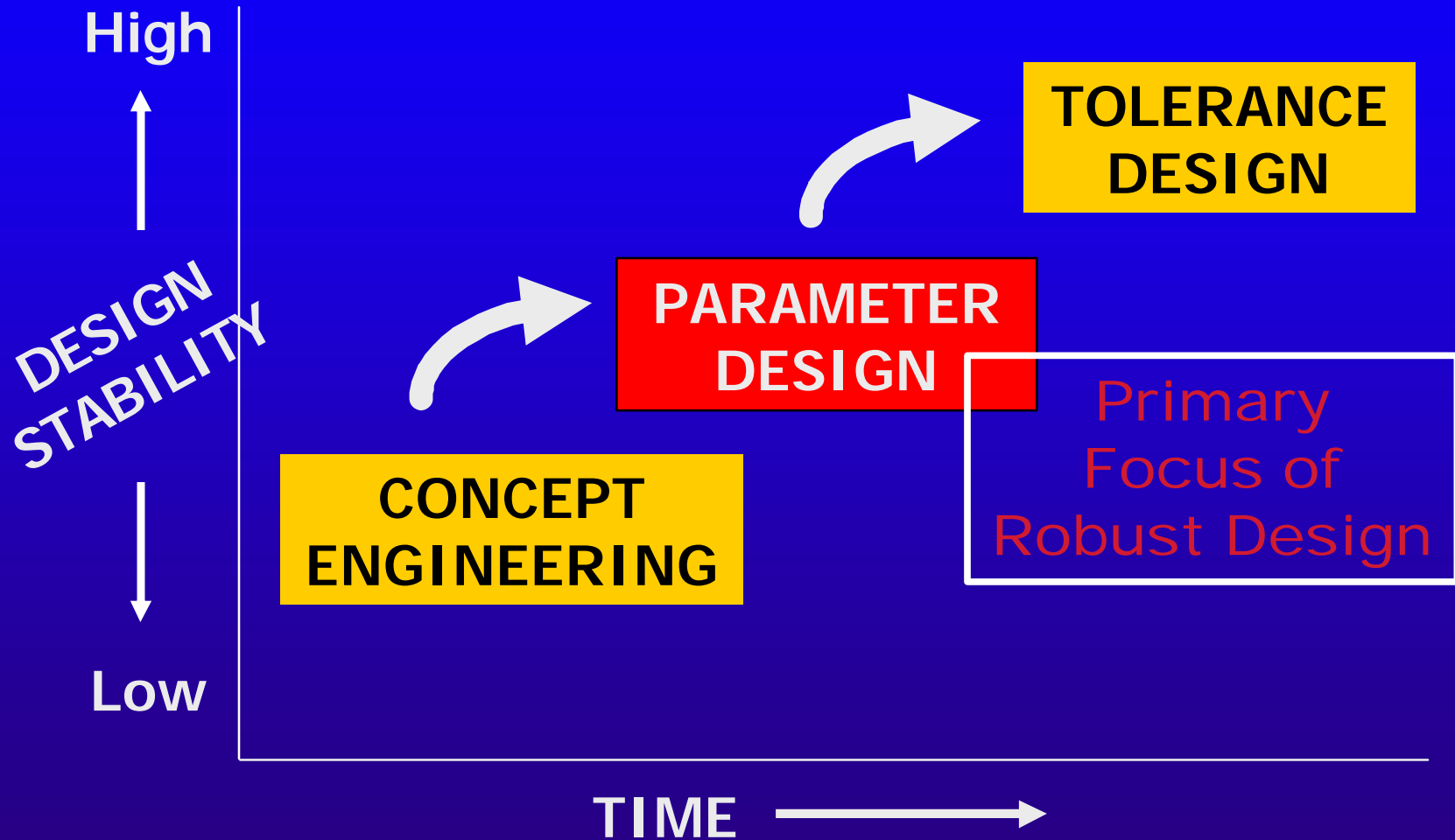


Step 2:
Put System
On Target

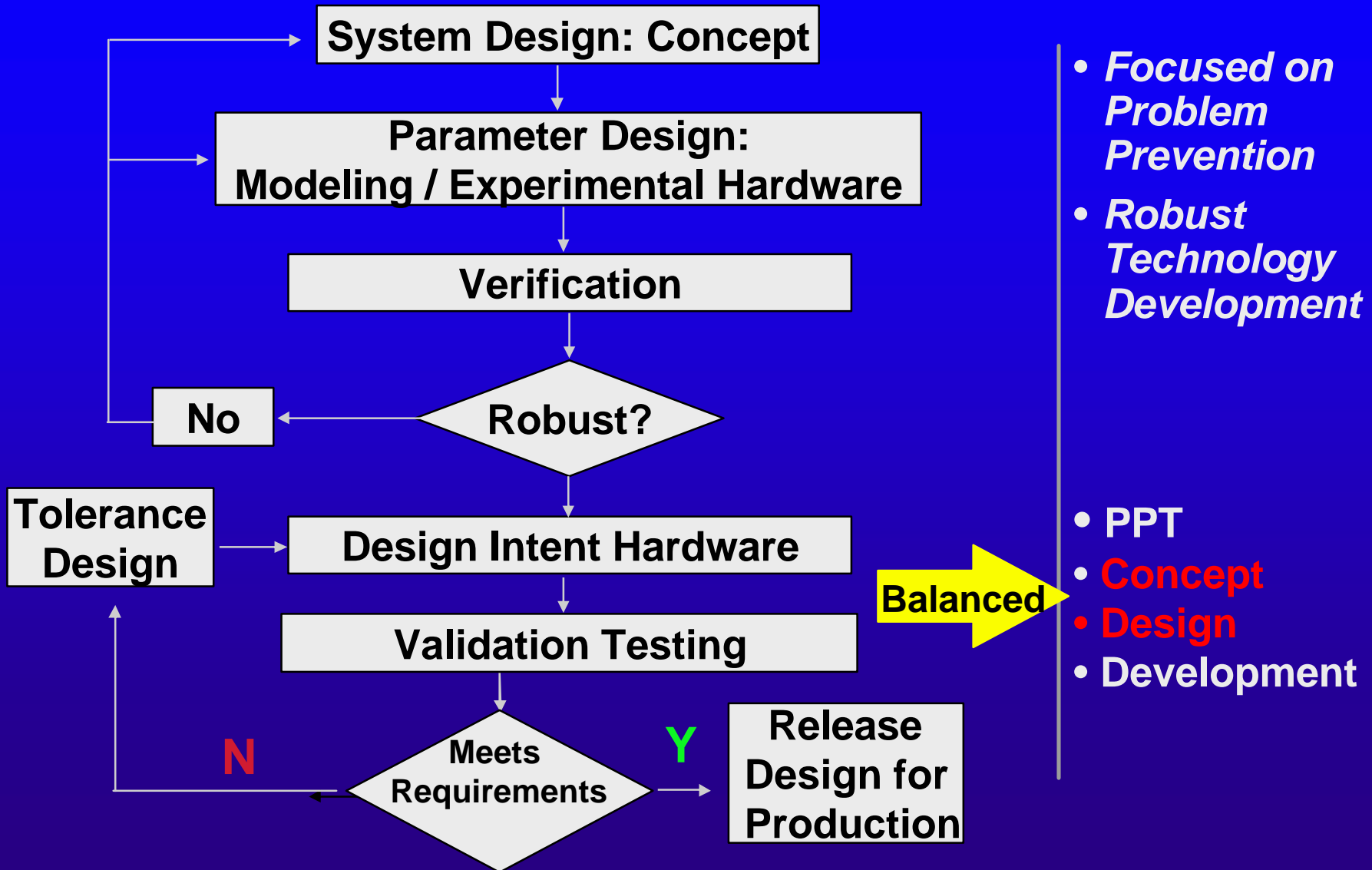


Two Step
Optimization

When to Apply Robust Design...



Design Process... Taguchi Method

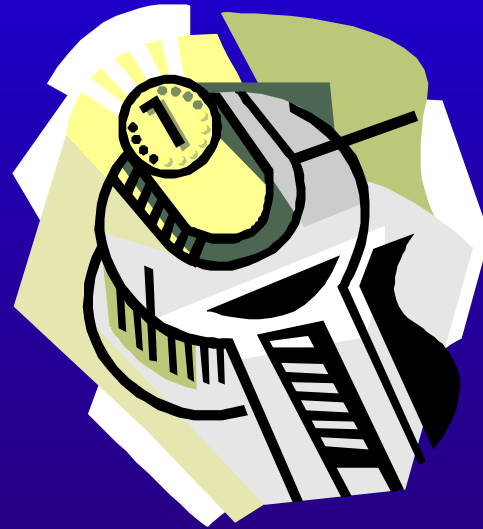


- *Focused on Problem Prevention*
- *Robust Technology Development*

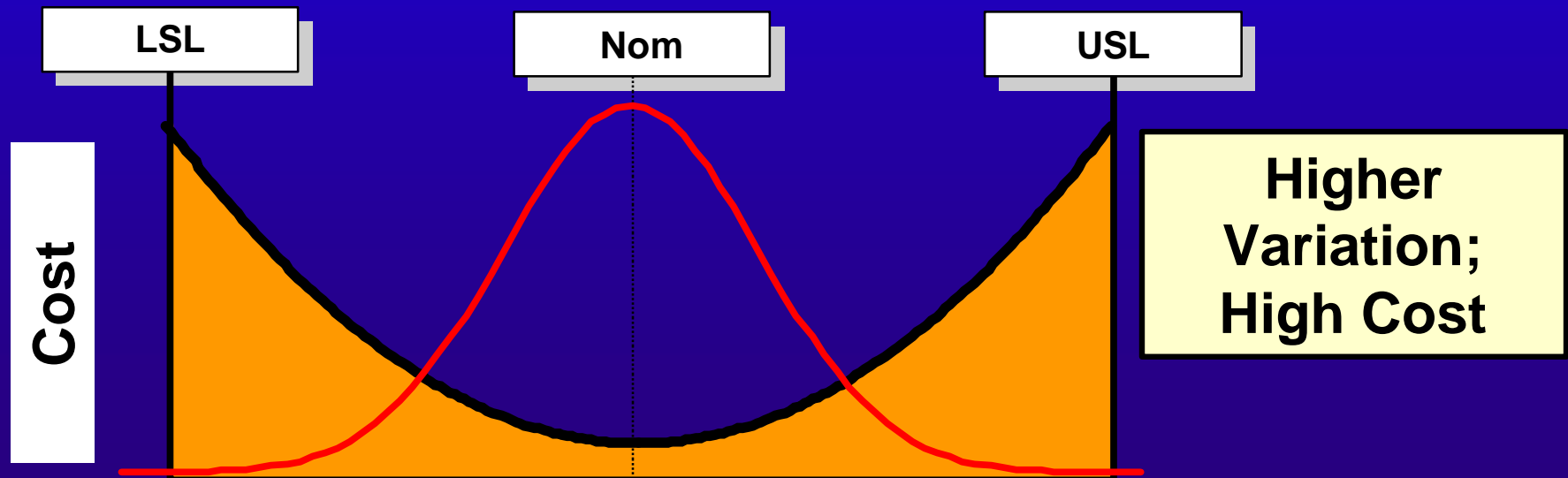
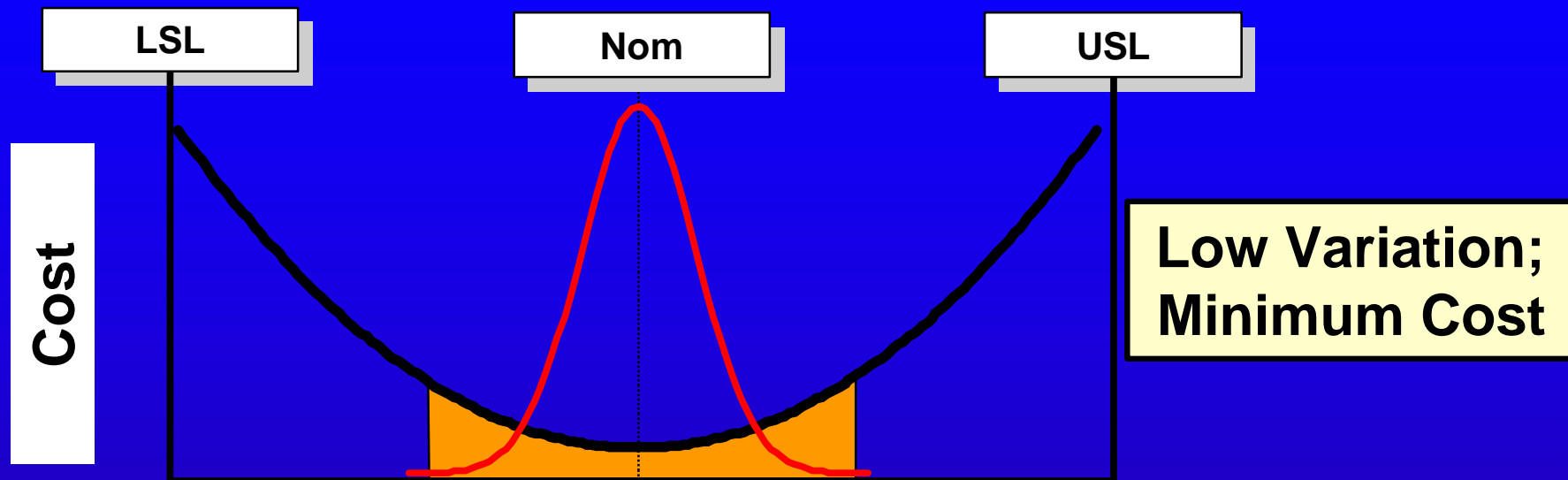
- PPT
- **Concept Design**
- **Development**

Why Robust Design ?

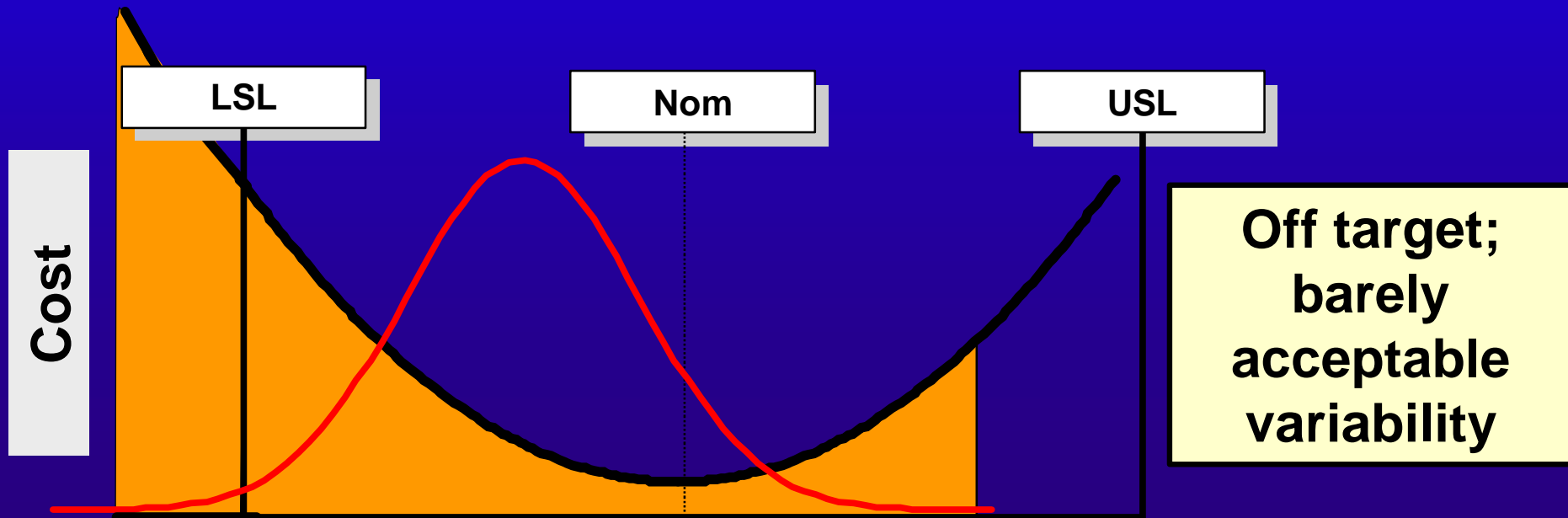
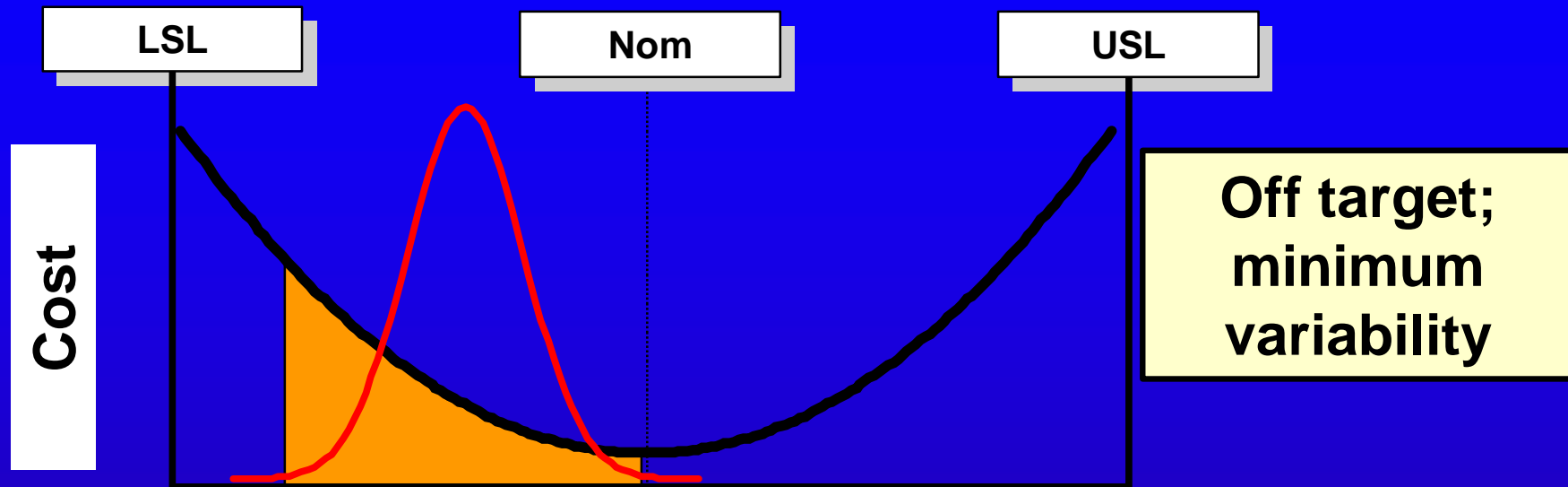
REDUCE COST !



Why We Need to Reduce Variation?



Why We Need to Shift Means



Cost Of A Product...

- Design & Development
- Manufacturing
- Distribution & Sales
- Warranty & Service
- Life cycle cost
- Cost to others – Loss to society
- Cost of lost sales & customers

Cost of a Product....

Design & Development

Manufacturing

Distribution & Sales

Warranty & Service

■ Life cycle cost

Cost to run & maintain the product

- Cost of scheduled maintenance, fuel, operator
(Think about a fleet with 1500 Trucks)
 - Oil & Coolant Change interval
 - Filter Cost

Cost of a Product....

Design & Development
Manufacturing
Distribution & Sales

Warranty & Service
Life cycle cost

- **Cost to others - Loss to society.**
 - Cost to others by any deficiencies of the product
 - **Pollution** - Engine Nox & hydrocarbon emissions
 - Personal **injury** and loss of life – Case of Ford Explorer and Firestone tires
 - **Disruption of function** – Refrigerated truck carrying ice cream

Cost of a Product....

Design Development

Manufacturing

Distribution & Sales

Warranty & service

Life Cycle Cost

Cost to Others

■ Cost of lost sales & customers

- "GM Europe (Opel) will loose \$600M this year after loosing \$676M last year"
- "Rebuilding the brand takes seven years..." concedes Alain Uyttenhoven, Opel's (GM Europe) Director of Brand Management
- "Commending a premium is a reward for building good product" Opel CEO Carl-Peter Forster

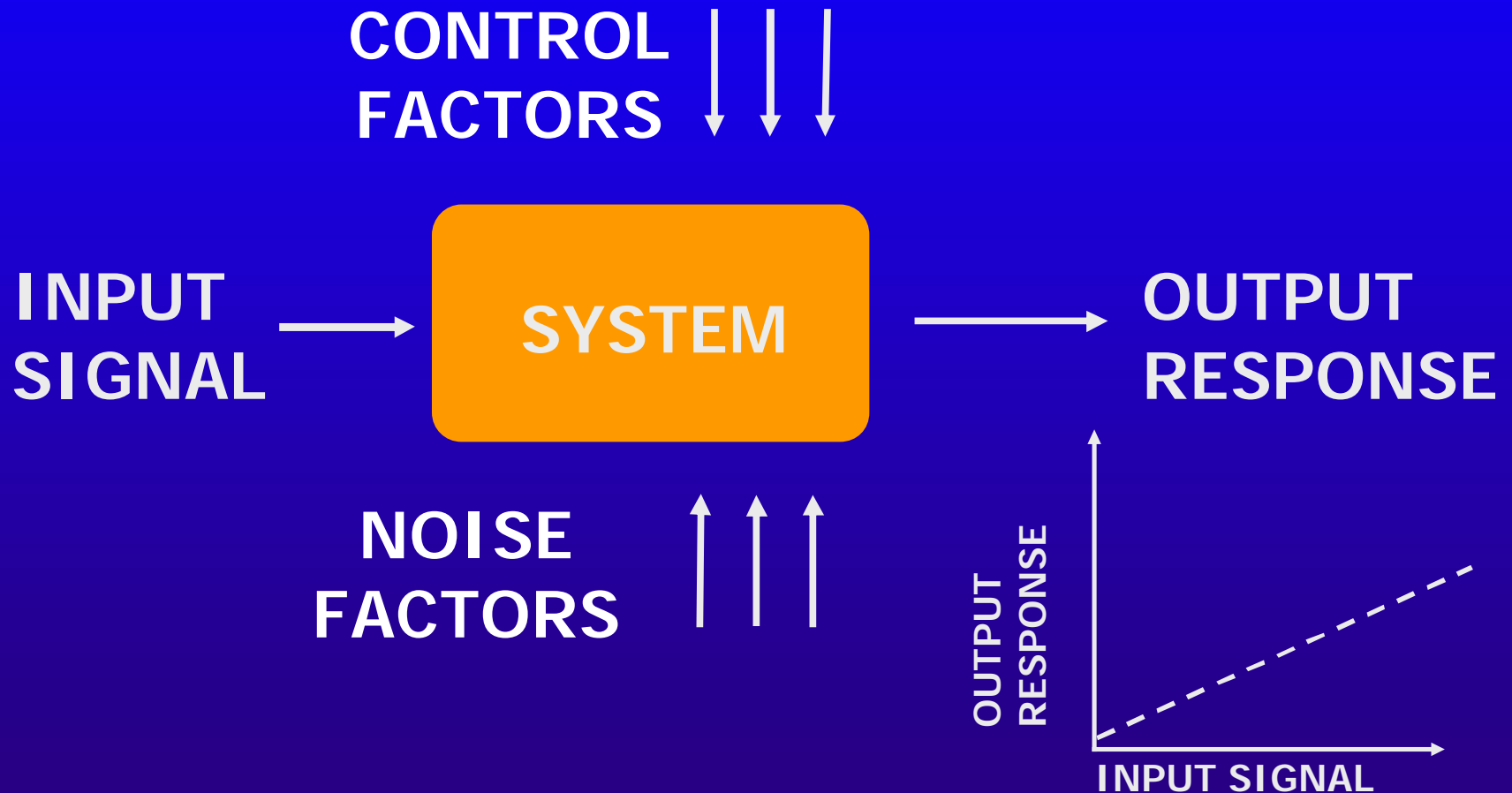
(A few excerpts from the Business Week Magazine dated October 1, 2001)

Outline

- Product Robustness
- Design Phases
- Design & Development Process
- Product Cost
- **Robust Design Methodology**
 - Parameter Diagram
 - Ideal Function
 - Control Parameters
 - Noise Factors
 - Robustness Metric
 - 2 Step Optimization
- Case Study

Parameter Diagram

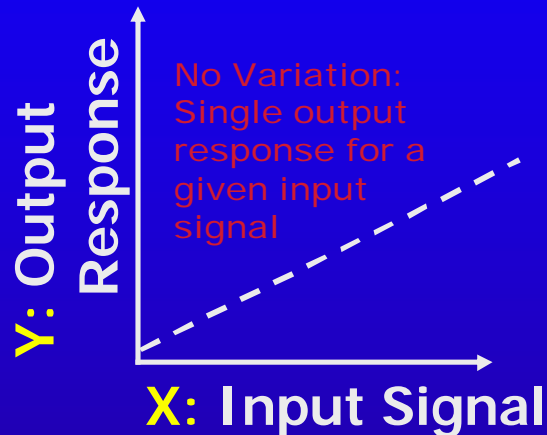
A Framework for Describing an Engineered System



Ideal Function

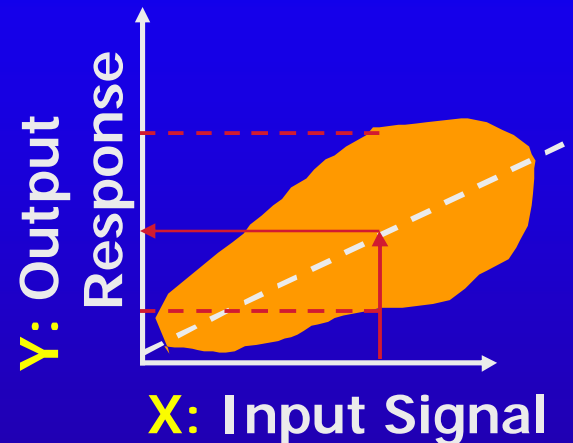
Ideal

Linear Relationship
Between Input & Output



Reality

Variation in Response
For A Given Input Signal



System

- Brake pad
- Motor
- Coating

Input Signal

- Force
- Wattage
- Time

Output Response

- Torque
- Torque * Rpm
- Thickness

(S/N) Ratio - Measure of Robustness

- Signal-to-Noise Ratio is defined as the ratio of transformed energy to intended and un-intended outputs

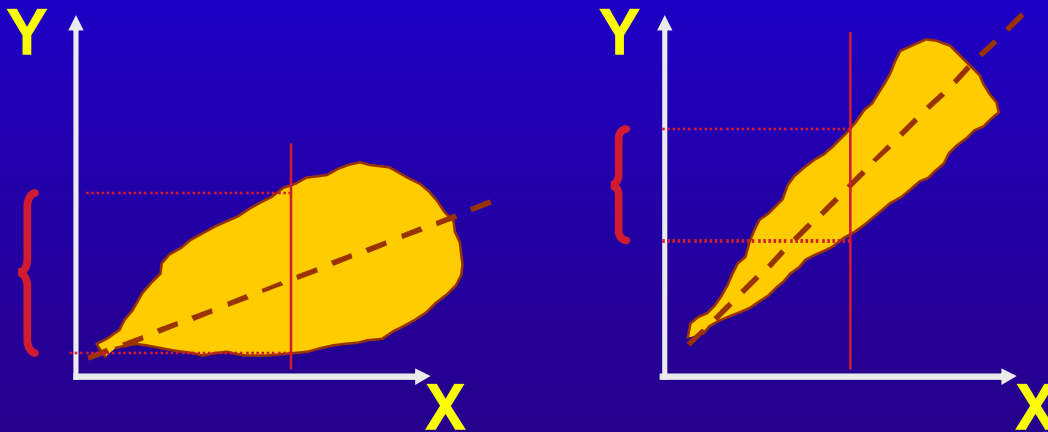
$$\text{S/N Ratio} = \frac{\text{Energy Transformed into Intended Output}}{\text{Energy Transformed into Un-Intended Output}}$$

- Measures the effects of noise factors on product performance
- **The higher the ratio**
 - More efficient the system is
 - Lower the systems response to noise factors
 - The system is more robust against noise factors

Robustness Metric - S/N Ratio

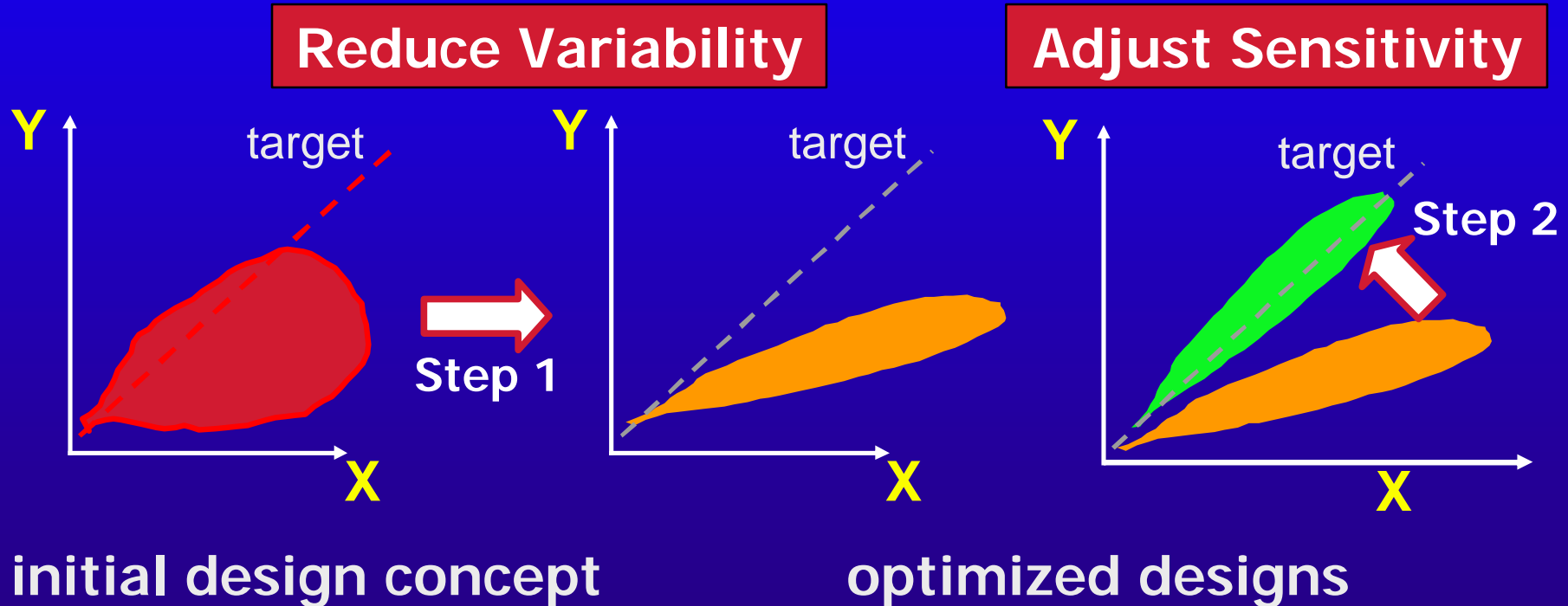
$$\text{S/N Ratio} = \frac{\text{Energy Transformed into Intended Output}}{\text{Energy Transformed into Un-Intended Output}}$$

Goal: **High S/N** \rightarrow **Reduced variation in output response for a given input signal**

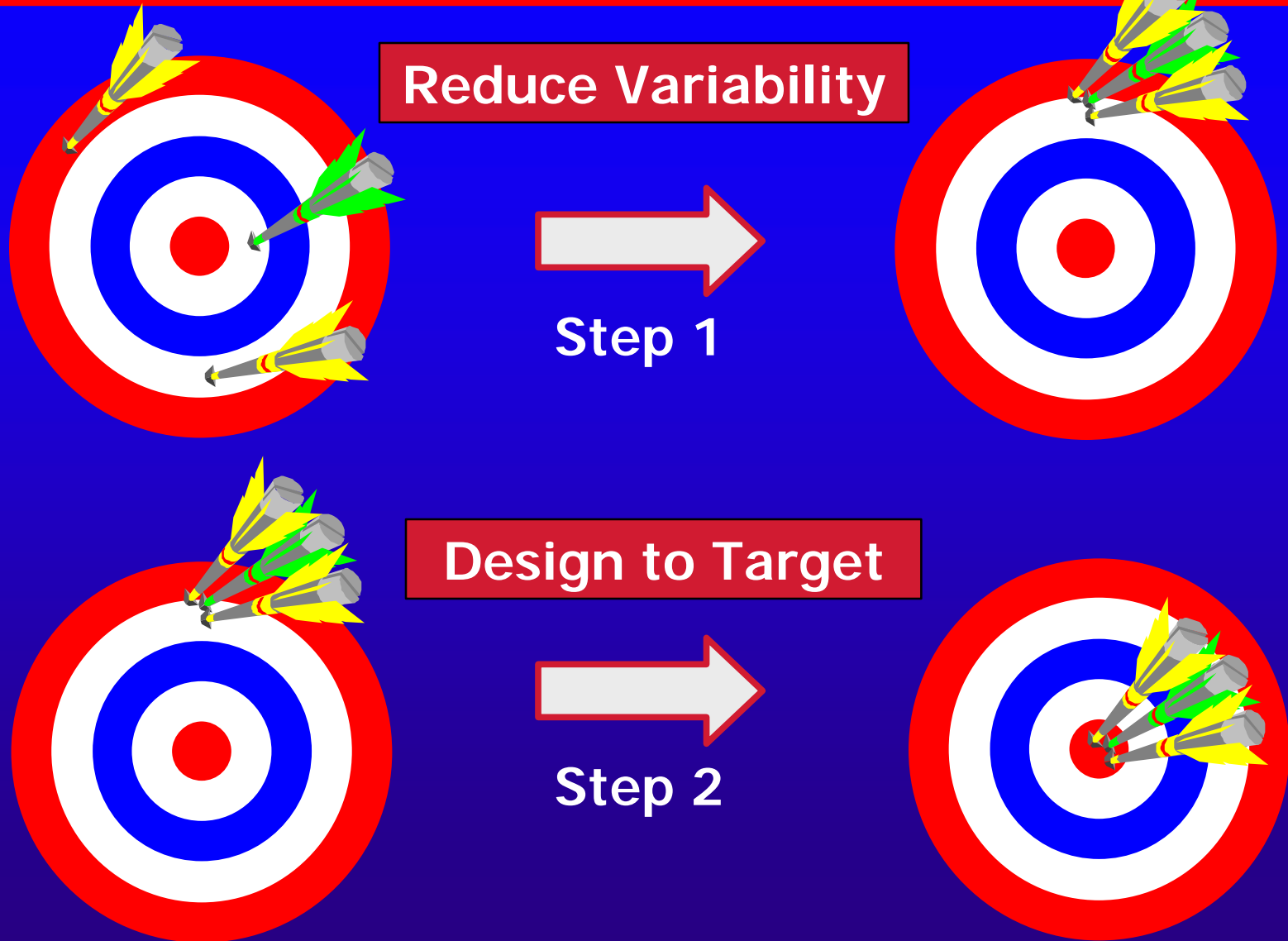


Robust Approach - 2 Step Opt

- Reduce Variability
- Adjust Sensitivity - Design to target



Robust Approach - 2 Step Opt



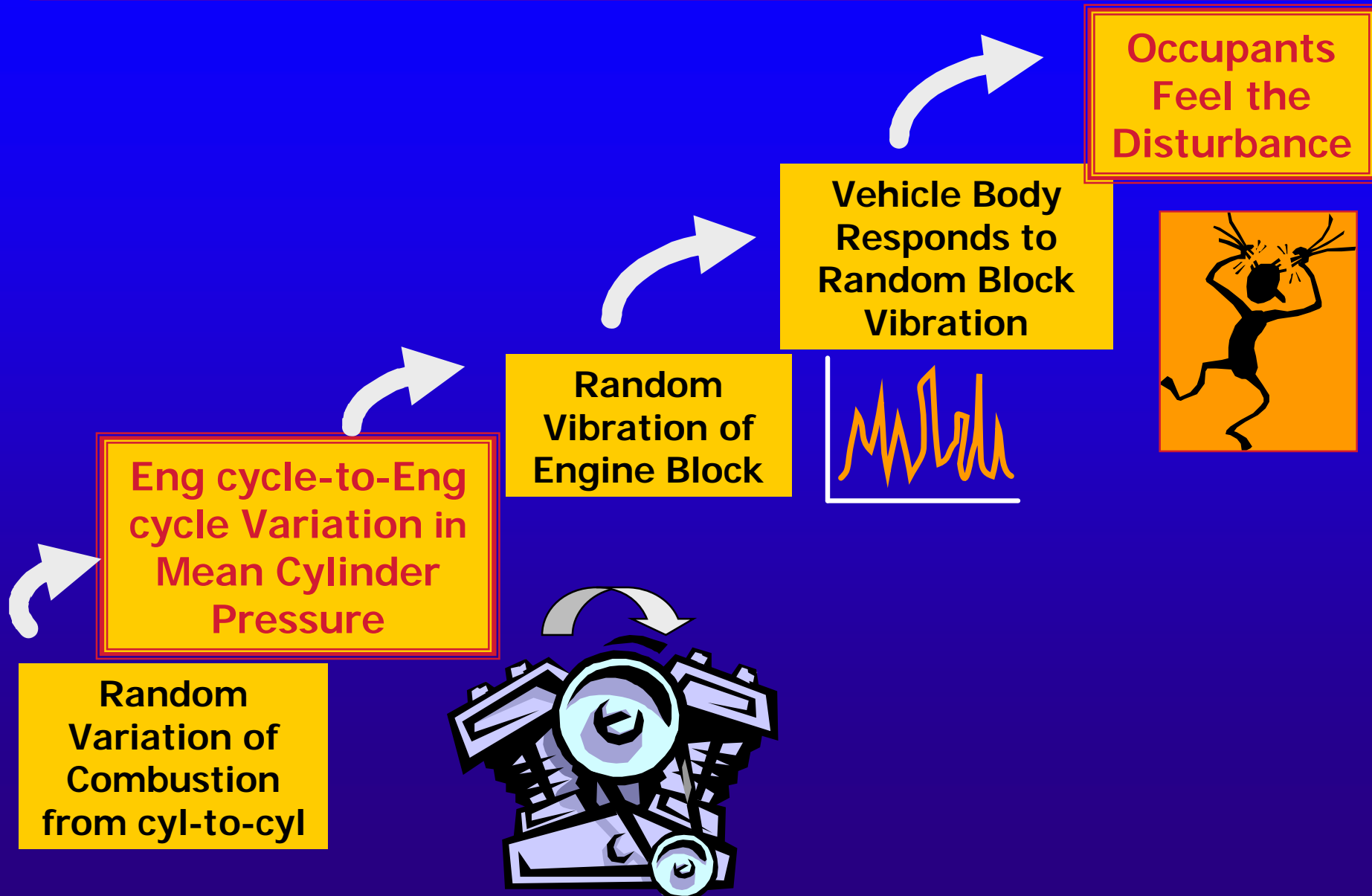
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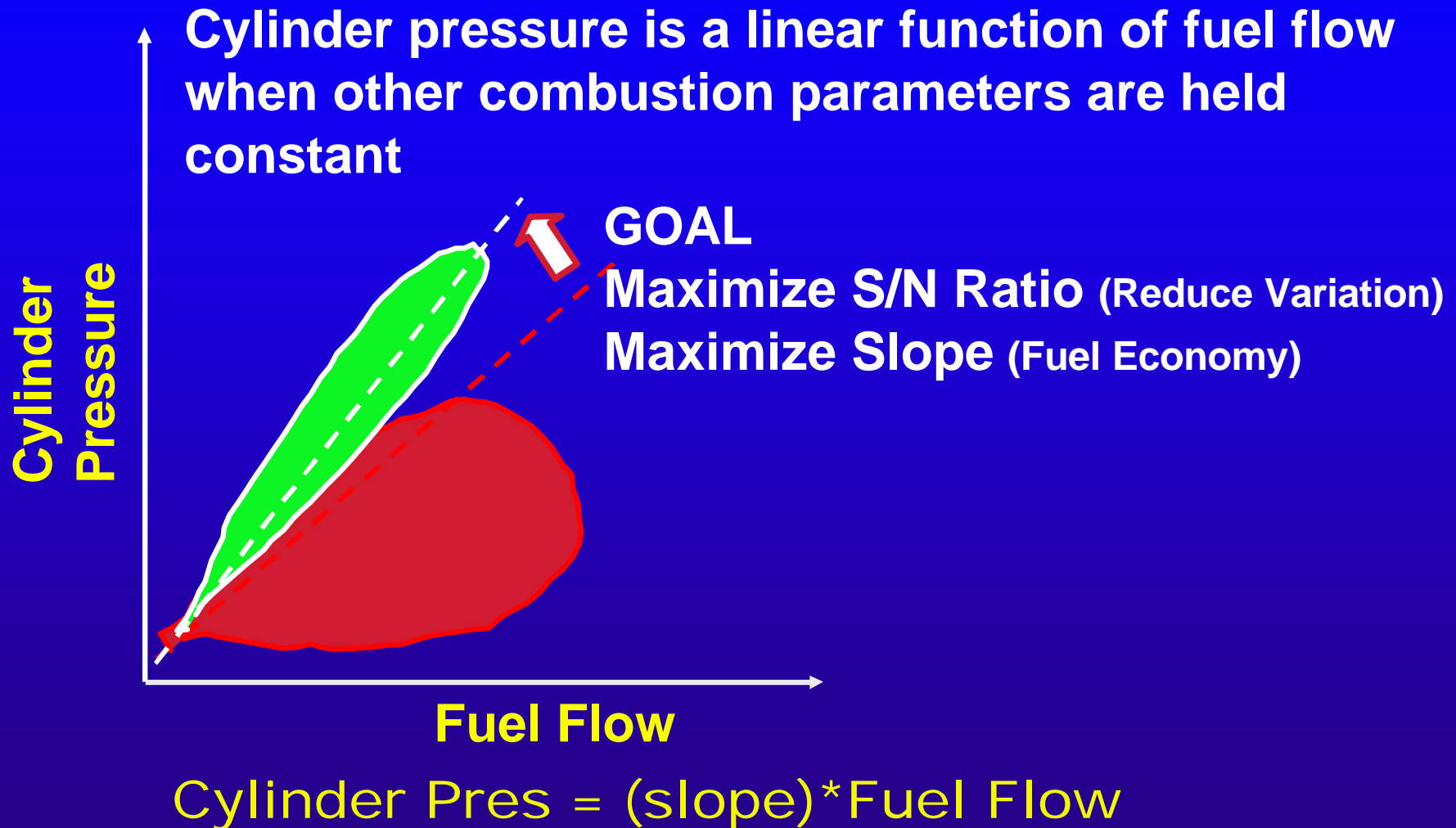
Parameter Design

- **Problem Definition**
- **Identify Ideal Function**
- **Identify Control Parameters**
- **Identify Noise Parameters**
- **Conduct Experiments & Analyze Data**
- **Select Best/Optimum Parameter Values**
- **Confirm Results**

Problem Definition - Engine Idle Quality



Ideal Function



Parameter Diagram

Engine Idle Quality

Noise Factors

- Reduced Friction
- Soot & Carbon Deposits
- Worn Parts

Engine
Mileage

Signal



Fuel
Flow

Energy
Transformations

Response



IMEP
Variation
(EC-2-EC)

Vibration Felt
By Occupants

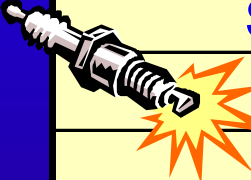
Smooth
Idle Quality

Control Factors

- Cylinder Head
- Fuel Injectors
- Spark Plug
- Ign & Inj Timing
- Air-to-Fuel Ratio
- Engine RPM

Control Factors & Levels

Engine Idle Quality

CONTROL FACTORS		CONTROL LEVELS			
		# OF	LEVEL 1	LEVEL 2	LEVEL 3
Cylinder Head	CH	2	Base	HISW	-
Fuel Injector	FINJ	3	Type 1	Type 2	Type 3
Spark Plug Gap	SPG	3	Narrow	Base	Wide
 Ignition Timing	IGT	3	Retarded	Base	Advanced
Air Fuel Ratio	AFR	3	Rich	Stoich	Lean
Spark Plug Penetration	SPP	2	Base	Long	-
Engine Speed	RPM	3	Low	Medium	High
Injection Timing	IJT	3	Advanced	Base	Retarded

Selection of a Test Matrix

- **Shot-Gun Approach:** Try until it works.
- **One Factor at a Time:** Parameters are varied one-at-a-time while holding others constant. No information for interactions!
- **Full Factorial:** Test every possible combination of control factors. Expensive!
- **Fractional Factorial:** Test a fraction a full factorial for selected interactions.
- **Taguchi Method (Orthogonal Arrays):** Average effect of all factors are balanced & separable.

Test Matrix - $L_{18}(2^2 \times 3^6)$ Engine Idle Quality

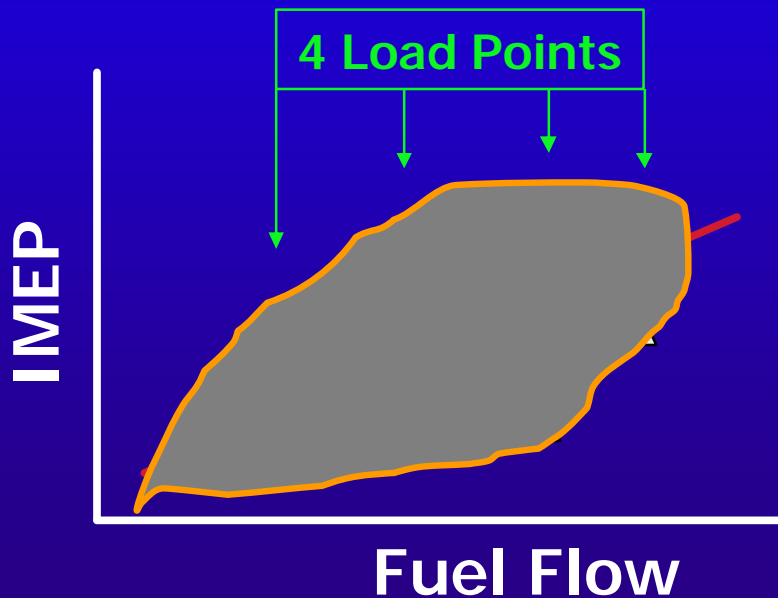
Test #	CONTROL FACTORS							
	CH	INJ	SPG	IGT	AFR	SPP	ES	IJT
1	Base	Type I	Narrow	Ret'd	Rich	Base	Low	Adv
2	Base	Type I		Base		Long	Med	Base
3	Base	Type I	Wide	Adv	Lean	Base	High	Ret'd
4	Base	Type II	Narrow	Ret'd		Long	High	Ret'd
5	Base	Type II		Base	Lean	Base	Low	Adv
6	Base	Type II	Wide	Adv	Rich	Base	Med	Base
7	Base	Type III	Narrow	Base	Rich	Base	Med	Ret'd
8	Base	Type III		Adv		Base	High	Adv
9	Base	Type III	Wide	Ret'd	Lean	Long	Low	Base
10	HISW	Type I	Narrow	Adv	Lean	Long	Med	Adv
11	HISW	Type I	Base	Ret'd	Rich	Base	High	Base
12	HISW	Type I	Wide	Base	Stoic	Base	Low	Ret'd
13	HISW	Type II	Narrow	Base	Lean	Base	High	Base
14	HISW	Type II	Base	Adv	Rich	Long	Low	Ret'd
15	HISW	Type II	Wide	Ret'd	Stoic	Base	Med	Adv
16	HISW	Type III	Narrow	Adv	Stoic	Base	Low	Base
17	HISW	Type III	Base	Ret'd	Lean	Base	Med	Ret'd
18	HISW	Type III	Wide	Adv	Rich	Long	High	Adv

Test Runs

	Test #	CONTROL FACTORS							
		CH	INJ	SPG	IGT	AFR	SPP	ES	IJT
LOW MILEAGE	1	Base	Type I	Narrow	Ret'd	Rich	Base	Low	Adv
	2	Base	Type I	Base	Base	Stoic	Long	Med	Base
	3	Base	Type I	Wide	Adv	Lean	Base	High	Ret'd
	4	Base	Type II	Narrow	Ret'd	Stoic	Long	High	Ret'd
	5	Base	Type II	Base	Base	Lean	Base	Low	Adv
	6	Base	Type II	Wide	Adv	Rich	Base	Med	Base
	7	Base	Type III	Narrow	Base	Rich	Base	Med	Ret'd
	8	Base	Type III	Base	Adv	Stoic	Base	High	Adv
	9	Base	Type III	Wide	Ret'd	Lean	Long	Low	Base
	10	HISW	Type I	Narrow	Adv	Lean	Long	Med	Adv
	11	HISW	Type I	Base	Ret'd	Rich	Base	High	Base
	12	HISW	Type I	Wide	Base	Stoic	Base	Low	Ret'd
	13	HISW	Type II	Narrow	Base	Lean	Base	High	Base
	14	HISW	Type II	Base	Adv	Rich	Long	Low	Ret'd
	15	HISW	Type II	Wide	Ret'd	Stoic	Base	Med	Adv
	16	HISW	Type III	Narrow	Adv	Stoic	Base	Low	Base
	17	HISW	Type III	Base	Ret'd	Lean	Base	Med	Ret'd
	18	HISW	Type III	Wide	Adv	Rich	Long	High	Adv
HIGH MILEAGE	1	Base	Type I	Narrow	Ret'd	Rich	Base	Low	Adv
	2	Base	Type I	Base	Base	Stoic	Long	Med	Base
	3	Base	Type I	Wide	Adv	Lean	Base	High	Ret'd
	4	Base	Type II	Narrow	Ret'd	Stoic	Long	High	Ret'd
	5	Base	Type II	Base	Base	Lean	Base	Low	Adv
	6	Base	Type II	Wide	Adv	Rich	Base	Med	Base
	7	Base	Type III	Narrow	Base	Rich	Base	Med	Ret'd
	8	Base	Type III	Base	Adv	Stoic	Base	High	Adv
	9	Base	Type III	Wide	Ret'd	Lean	Long	Low	Base
	10	HISW	Type I	Narrow	Adv	Lean	Long	Med	Adv
	11	HISW	Type I	Base	Ret'd	Rich	Base	High	Base
	12	HISW	Type I	Wide	Base	Stoic	Base	Low	Ret'd
	13	HISW	Type II	Narrow	Base	Lean	Base	High	Base
	14	HISW	Type II	Base	Adv	Rich	Long	Low	Ret'd
	15	HISW	Type II	Wide	Ret'd	Stoic	Base	Med	Adv
	16	HISW	Type III	Narrow	Adv	Stoic	Base	Low	Base
	17	HISW	Type III	Base	Ret'd	Lean	Base	Med	Ret'd
	18	HISW	Type III	Wide	Adv	Rich	Long	High	Adv

Test Runs

- Total of 36 cases
 - 18 with low mileage & 18 with high mileage
- For each the 36 cases
 - 4 engine idle load points (4 different fuel flows)
 - Each load point repeated 3 times



$$\text{IMEP} = (\text{slope}) * \text{Fuel Flow}$$

Slope = Best Fit Line
to 12 Points

S/N Ratio = Deviation
From the
Best Fit Line

Summary of Test Results

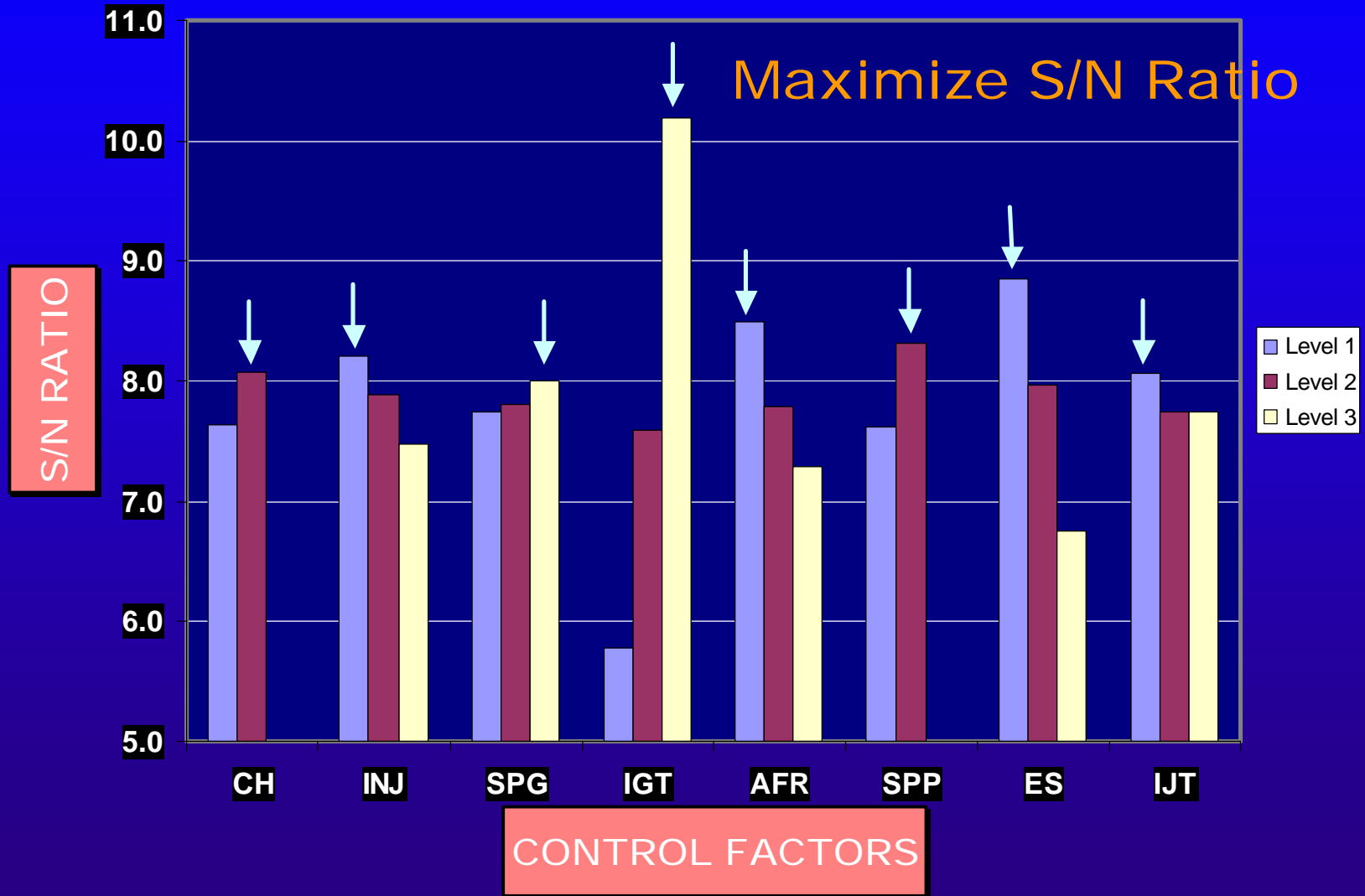
Engine Idle Quality

Test #	CONTROL FACTORS									RESPONSE	
	CH	INJ	SPG	IGT	AFR	SPP	ES	IJT	S/N	SLOPE	
1	Base	Type I	Narrow	Ret'd	Rich	Base	Low	Adv	8.39	9.67	
2	Base	Type I	Base	Base	Stoic	Long	Med	Base	8.91	10.18	
3	Base	Type I	Wide	Adv	Lean	Base	High	Ret'd	9.20	10.45	
4	Base	Type II	Narrow	Ret'd	Stoic	Long	High	Ret'd	5.67	8.04	
5	Base	Type II	Base	Base	Lean	Base	Low	Adv	8.65	10.87	
6	Base	Type II	Wide	Adv	Rich	Base	Med	Base	11.67	10.95	
7	Base	Type III	Narrow	Base	Rich	Base	Med	Ret'd	8.24	9.52	
8	Base	Type III	Base	Adv	Stoic	Base	High	Adv	9.53	10.19	
9	Base	Type III	Wide	Ret'd	Lean	Long	Low	Base	7.18	9.71	
10	HISW	Type I	Narrow	Adv	Lean	Long	Med	Adv	11.96	11.66	
11	HISW	Type I	Base	Ret'd	Rich	Base	High	Base	6.47	7.94	
12	HISW	Type I	Wide	Base	Stoic	Base	Low	Ret'd	10.10	11.19	
13	HISW	Type II	Narrow	Base	Lean	Base	High	Base	6.77	9.00	
14	HISW	Type II	Base	Adv	Rich	Long	Low	Ret'd	13.33	12.51	
15	HISW	Type II	Wide	Ret'd	Stoic	Base	Med	Adv	6.99	8.82	
16	HISW	Type III	Narrow	Adv	Stoic	Base	Low	Base	11.27	12.15	
17	HISW	Type III	Base	Ret'd	Lean	Base	Med	Ret'd	5.81	8.64	
18	HISW	Type III	Wide	Adv	Rich	Long	High	Adv	8.68	8.96	

Each of the 18 test cases includes the average of high & low mileage engines

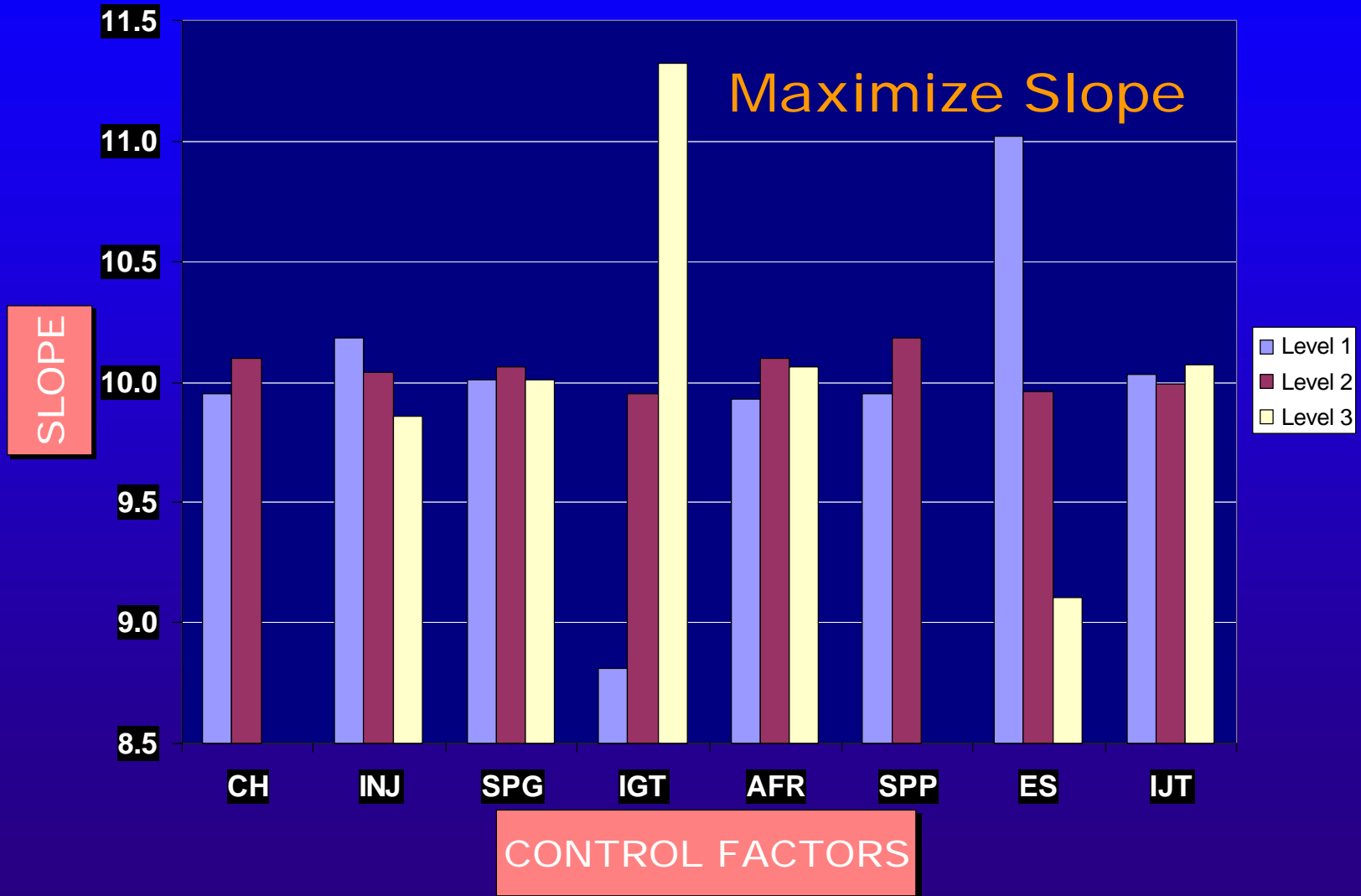
Control Factor Effects – S/N Ratio

Engine Idle Quality



Control Factor Effects - Slope

Engine Idle Quality



Control Factor Effects

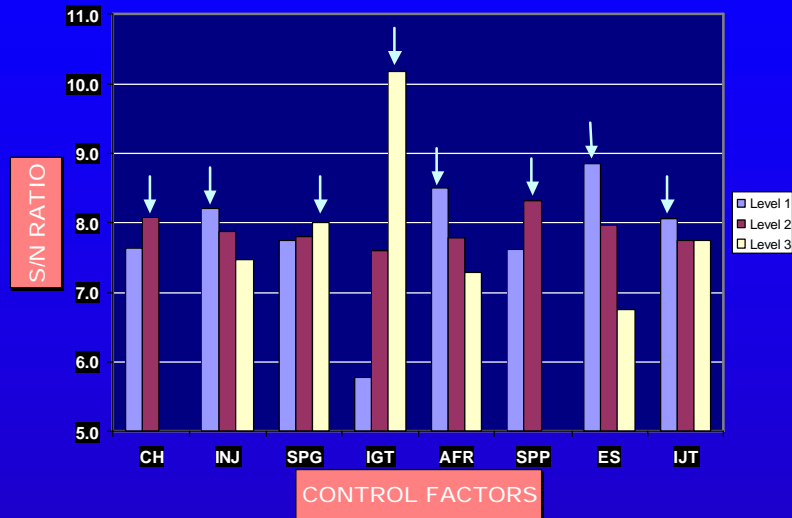
Engine Idle Quality

	SIGNAL TO NOISE RATIO							
Control Factors	CH	INJ	SPG	IGT	AFR	SPP	ES	IJT
Level 1	7.63		7.75	5.78		7.62		
Level 2		7.88	7.81	7.59	7.78		7.96	7.74
Level 3		7.48			7.29		6.75	7.75
Delta	0.44	0.72	0.25	4.41	1.20	0.70	2.10	0.32
Starting	Base	Type II	Base	Base	Stoic	Base	Low	Base
Optimum	H. Swirl	Type I	Wide	Adv	Rich	Long	Low	Adv

	SLOPE							
Control Factors	CH	INJ	SPG	IGT	AFR	SPP	ES	IJT
Level 1	9.95	10.18	10.01	8.81	9.93	9.95	11.02	10.03
Level 2	10.10	10.04	10.06	9.95	10.10	10.18	9.96	9.99
Level 3		9.86	10.01	11.32	10.06		9.10	10.07
Delta	0.15	0.32	0.05	2.51	0.17	0.23	1.92	0.08

Select Levels to Maximize S/N Ratio

Engine Idle Quality



- Optimum configuration which will reduce variability consists of factor levels that maximize the over-all Signal-to-Noise Ratio

SIGNAL TO NOISE RATIO								
Control Factors	CH	INJ	SPG	IGT	AFR	SPP	ES	IJT
Level 1	7.63		7.75	5.78		7.62		
Level 2		7.88	7.81	7.59	7.78		7.96	7.74
Level 3		7.48			7.29		6.75	7.75
Delta	0.44	0.72	0.25	4.41	1.20	0.70	2.10	0.32
Starting	Base	Type II	Base	Base	Stoic	Base	Low	Base
Optimum	H. Swirl	Type I	Wide	Adv	Rich	Long	Low	Adv

Confirmation Run

Control Factors	CONFIRMATION RUN							
	CH	INJ	SPG	IGT	AFR	SPP	ES	IJT
Starting	Base	Type II	Base	Base	Stoic	Base	Low	Base
Optimum	H. Swirl	Type I	Wide	Adv	Rich	Long	Low	Adv

	S/N RATIO		Slope	
	Predicted	Actual	Predicted	Actual
Starting	7.93	9.65	10.85	11.12
Optimum	12.77	12.58	12.41	12.67
GAIN	4.84 dB	2.93 dB	14.40%	13.90%

- Run two additional cases with **starting** and **optimum** control factor levels
- Compare the predicted and actual results

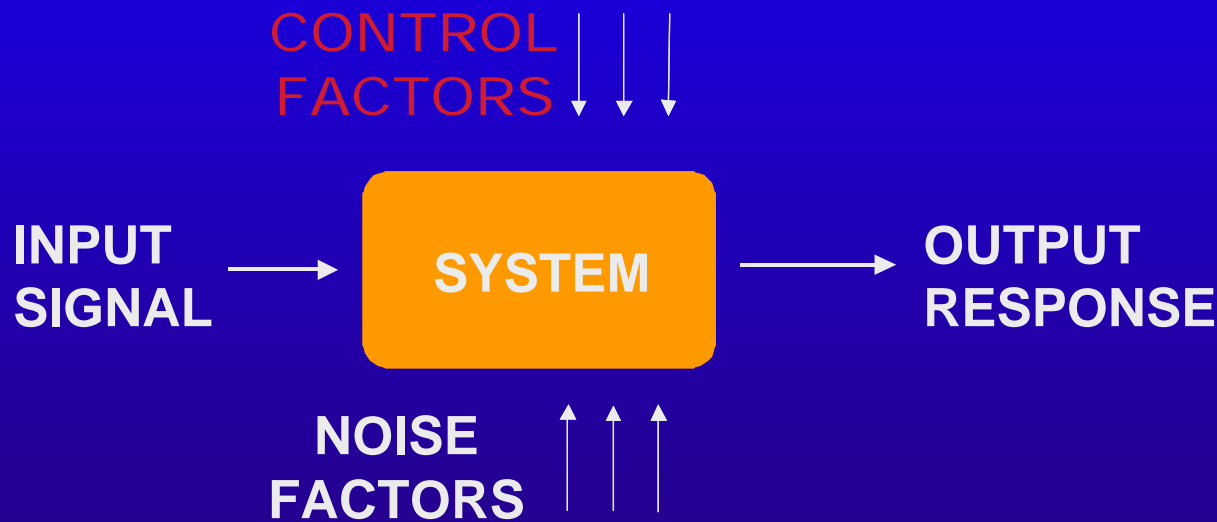
Summary

- Gain control of your product performance. Variation is the enemy.
- Apply Robust design principles at early stages of the project to “forecast” problems and take preventive action.
- Cost of a product extends well beyond development & manufacturing cost. Warranty, life cycle and cost to others can be major contributors due to varying product performance.

Supporting Slides

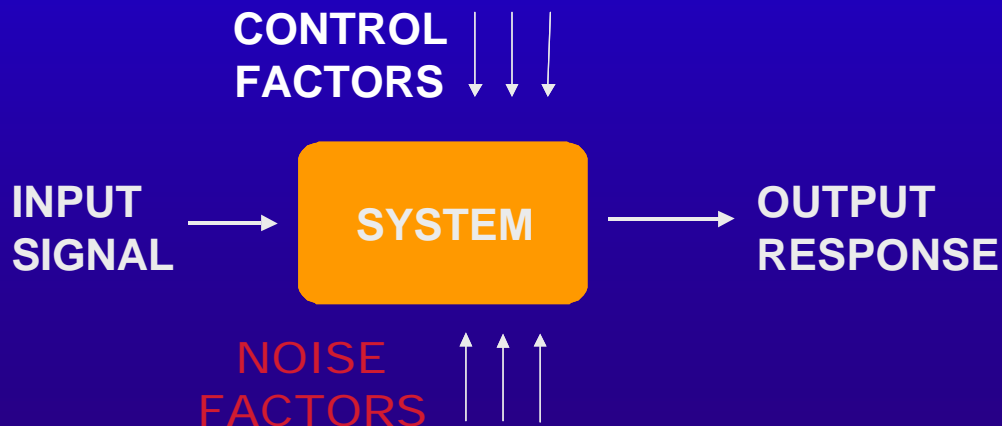
Control Factors

- Any **design parameters** of a system that engineers can **specify by nominal values** and maintain cost effectively



Noise Factors

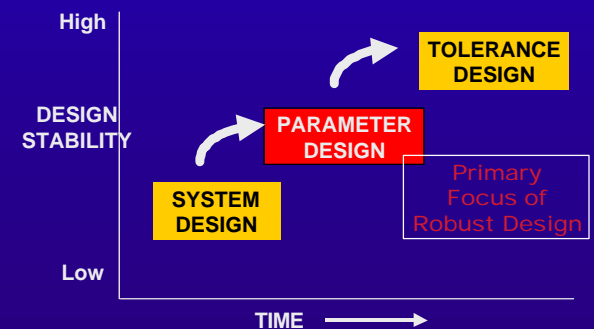
- **Any cause of variability** to product performance is a noise factor
 - Wear of a punch-press die – part dimensions will gradually reach to their tolerance limits
 - Ambient temperature in a manufacturing plant
 - Temperature distribution inside a heat treatment furnace



Design Phases

CONCEPT ENGINEERING (System Design)

- Gathering customer requirements (VOC)
 - Service, Manufacturing, Assembly
 - Voice of business
- Interpreting & prioritizing those requirements
- **Generate** many concepts
- Decision matrix to compare concepts
- **Select** the winning **concept**

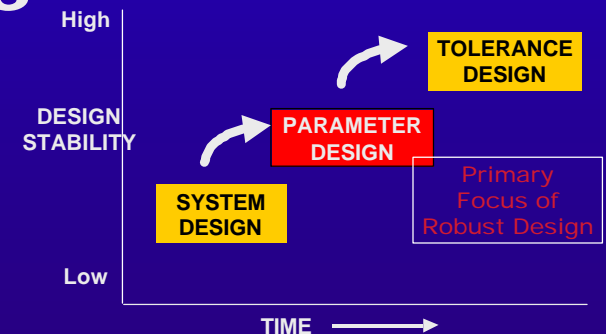


Design Phases

PARAMETER DESIGN

Selecting values for
design parameters (control factors)

which cause
system performance to be
insensitive to variations
(or noise factors)



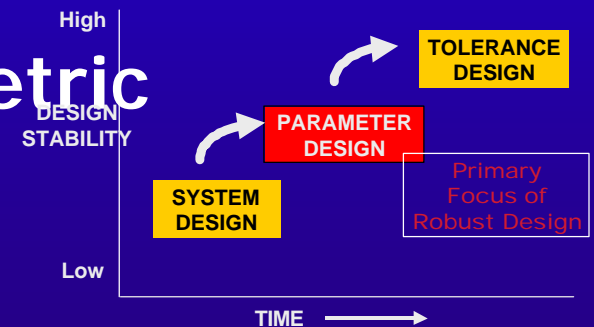
Taguchi Method

- A disciplined engineering approach for making a system insensitive to outside influences
- *A disciplined engineering approach (Parameter Design)* to find the best combination of design parameters (**control factors**) for *making a system insensitive to outside influences (noise factors)*
- **2 Step Optimization**
 - Reduce effect of variability on design function
 - Put the system on target

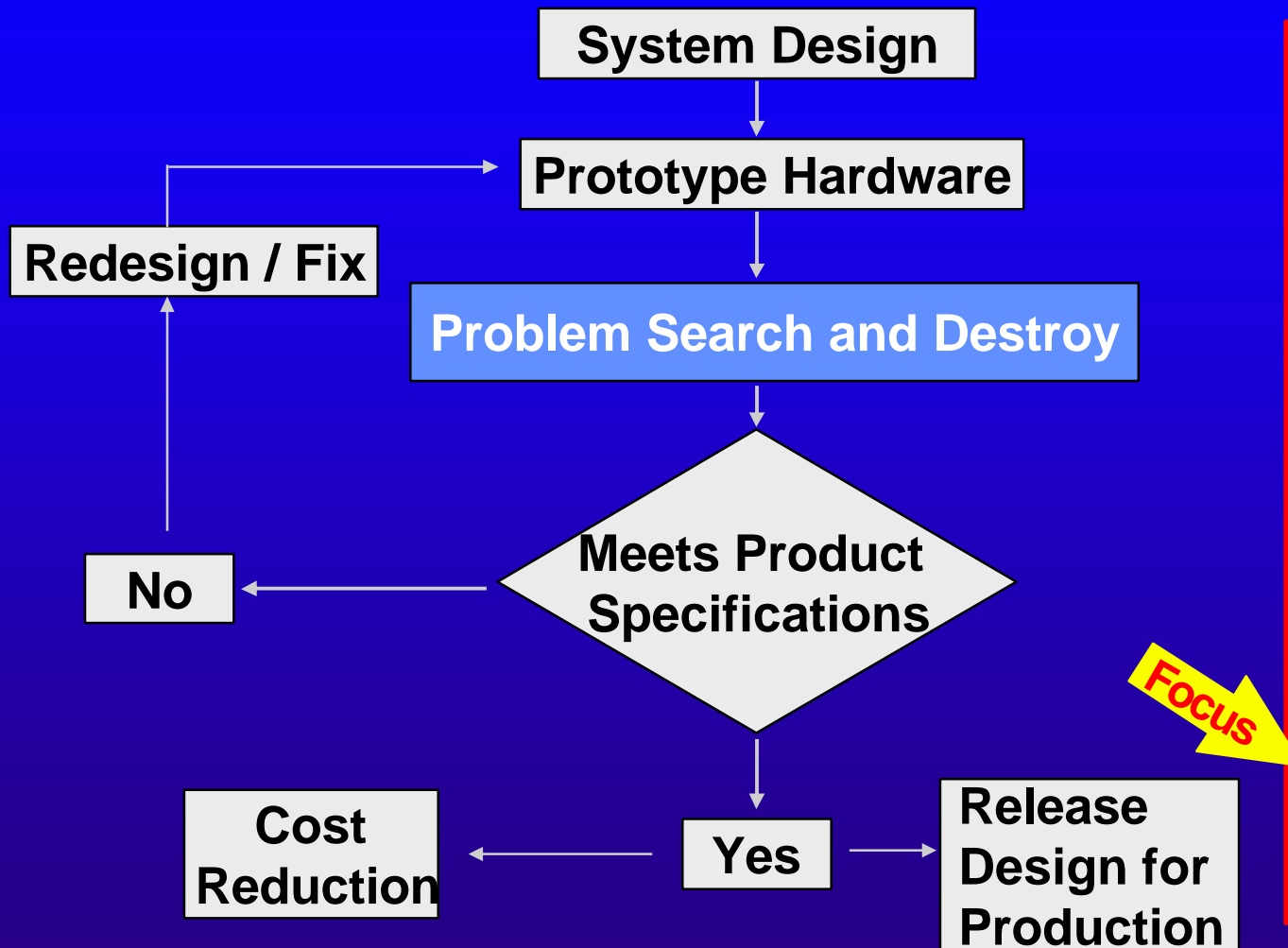
Design Phases

TOLERANCE DESIGN

- Determine the tolerance around nominal parameter values
- Identify those to be tightened and to be relaxed
- Cost-quality trade-off
- Need a monetary decision metric
Quality Loss Function



Design Process... Conventional



- *Build, Test, Iterate*
- *Focused on Problem Solving*
- *Emphasis on Development Phase*
- PPT
- Concept
- Design
- **Development**

Does Actual Performance Match Desired Performance?

- How does the actual parameter performance deviate from the desired performance?
- What statistical characteristics are of importance in determining parameter capability?
- What should the designer do and why?

