The Critical Link Between Test & Evaluation and Modeling & Simulation

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Introductions

- **Name**

- **Organization**

- **Job Title/Duties**

- **Experience in DOE, T&E, M&S**

Agenda

- **Some Basic Definitions**

- **Test and Evaluation (Experimental) Approaches**

- **DOE: the Gateway to Transfer Functions and Optimization**

- **Break**

- **Monte Carlo Simulation, Robust Design, and Tolerance Allocation**

- **Examples of Iterative Use of Modeling and Simulation**

- **Summary of "Modeling the Simulator"**

Some Basic Definitions

- **System:** <u>a collection of entities which act and interact together to achieve some goal</u>

- **Model:** a <u>simplified representation of a system</u> developed for the purpose of studying a system

- **Simulation:** the <u>manipulation of a model</u> in such a way that it allows the investigation of the performance of a system

- **Modeling and Simulation:** a <u>discipline for developing a level of understanding</u> of the interaction of the parts of a system, and of the system as a whole

About Models

All models are simplifications of reality.

There is always a tradeoff as to what level of detail should be included in the model:

If too little detail, there is a risk of missing relevant interactions and the resultant model does not promote understanding.

If too much detail, there is a risk of overly complicating the model and actually preclude the development of understanding.

The "goodness" of a model depends on the extent to which it promotes understanding.

Simplify and Perfect

Types of Models

High-Fidelity Models:
- many variables and many interactions
- highly detailed and complex
- needed for visualization
- difficult to manipulate

Low-Fidelity Models:
- much fewer number of variables
- can be manipulated more easily
- provides higher-level view of system
- presents a more aggregate view of the system

Types of Simulation

Deterministic Simulation:
-     for each combination of inputs parameters, there is one and only one output value
-     $y = f(x)$

Monte Carlo Simulation:
-     provides for variability in the inputs
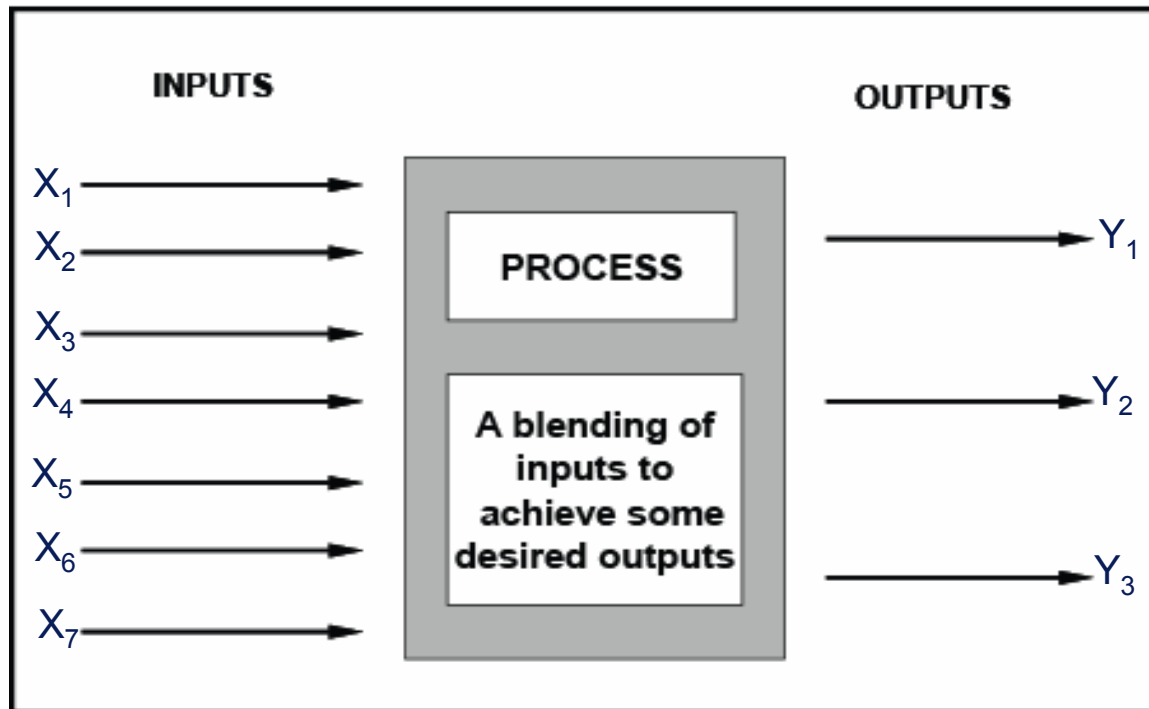- $y = f(x + variation)$, where the variation is modeled as some probability distribution

Discrete Event Simulation:
-     studies a sequence of countable events
-     assumption is that nothing of importance takes place between events

Definition of a Process

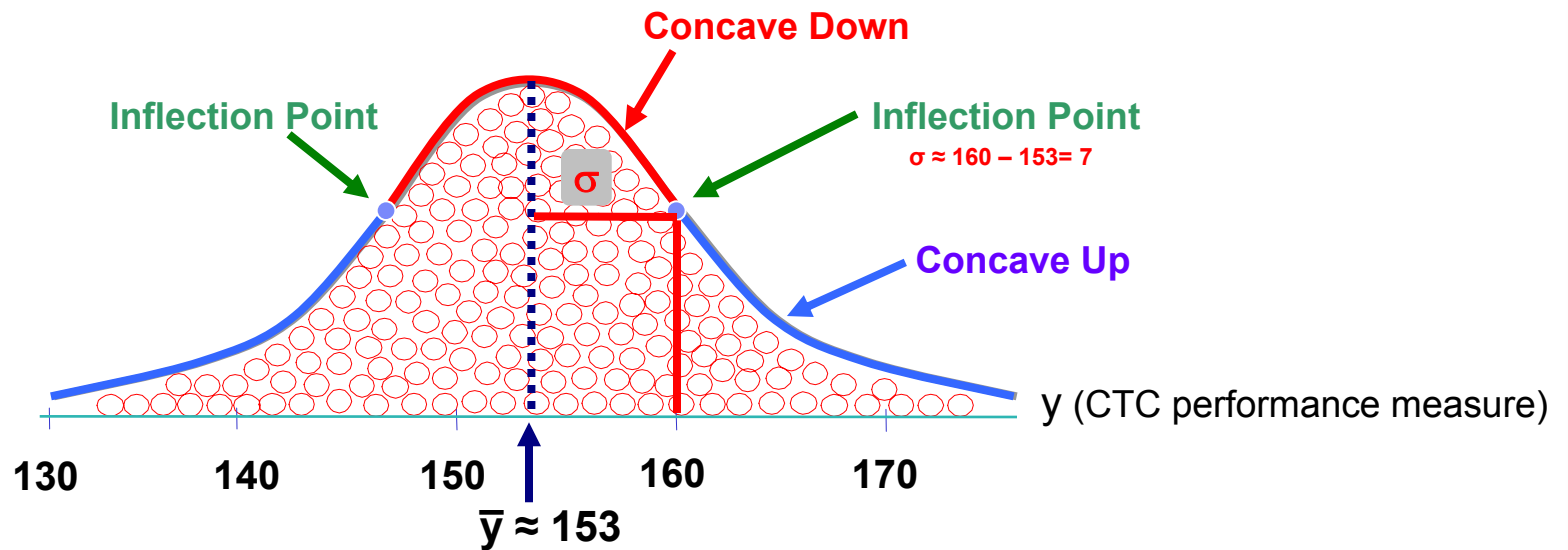# Graphical Meaning of $\bar{y}$ and σ

$\bar{y}$ = Average = Mean = Balance Point

σ = Standard Deviation

Concave Down

Inflection Point

Inflection Point

$\sigma \approx 160 - 153 = 7$

σ

Concave Up

y (CTC performance measure)

130   140   150   160   170

$\bar{y} \approx 153$

$\sigma \approx$ average distance of points from the centerline

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Graphical View of Variation

±3σ: Natural Tolerances

-6σ	-5σ	-4σ	-3σ	-2σ	-1σ	0	+1σ	+2σ	+3σ	+4σ	+5σ	+6σ

68.27%

95.45%

99.73%

99.9937%

99.999943%

99.9999998%
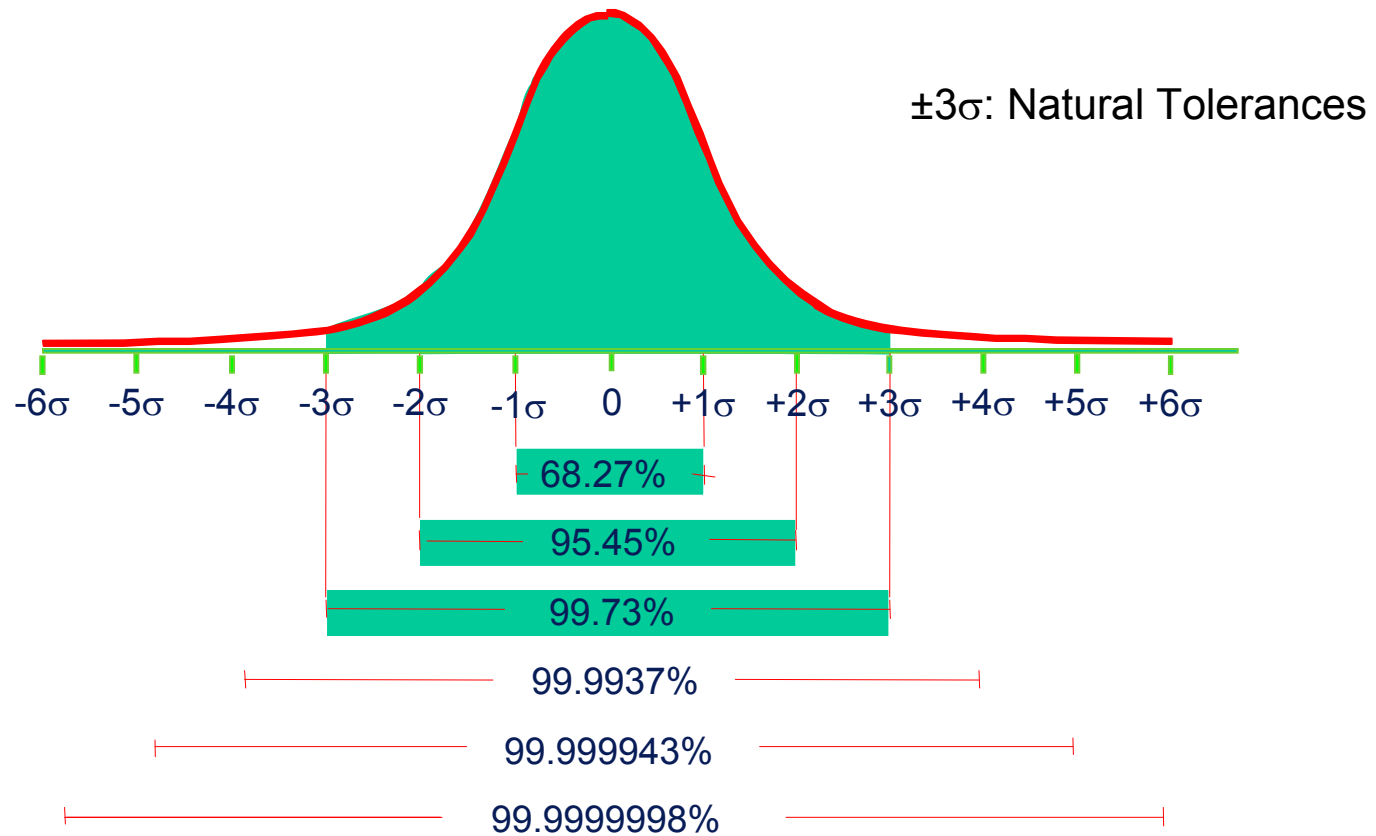
**_Typical Areas under the Normal Curve_**

Experimental Methods

- **Traditional Approaches**

    - One Factor at a Time (OFAT)

    - Oracle (Best Guess)

    - All possible combinations (full factorial)

- **Modern Approach**

    - Statistically designed experiments (DOE) … full factorial plus other selected DOE designs, depending on the situation

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OFAT (One Factor at a Time)
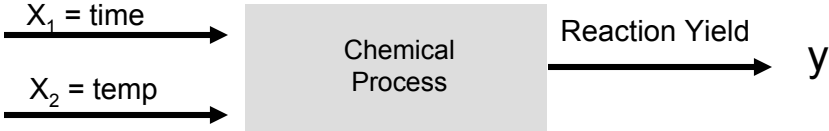
One factor at a time results versus optimal results
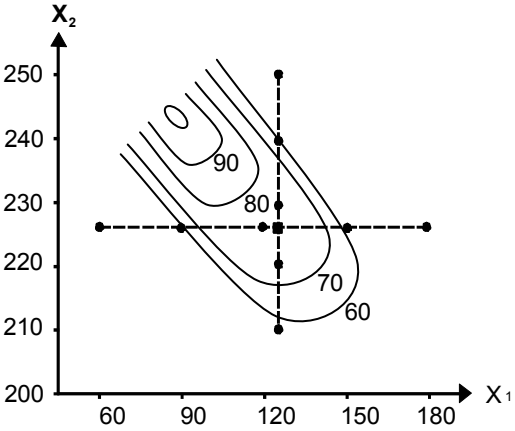
Oracle (Best Guess)

Run	W	P	E	C	A	Y
1	1	2	1	1	1	5
2	1	1	1	1	1	6
3	2	2	1	1	1	5
4	2	1	1	1	2	6
5	1	2	2	2	2	7
6	1	1	2	2	2	8
7	2	2	2	2	2	10
8	2	1	2	2	1	11

Evaluating the Effects of Variables on Y

What we have is:

E = C

A
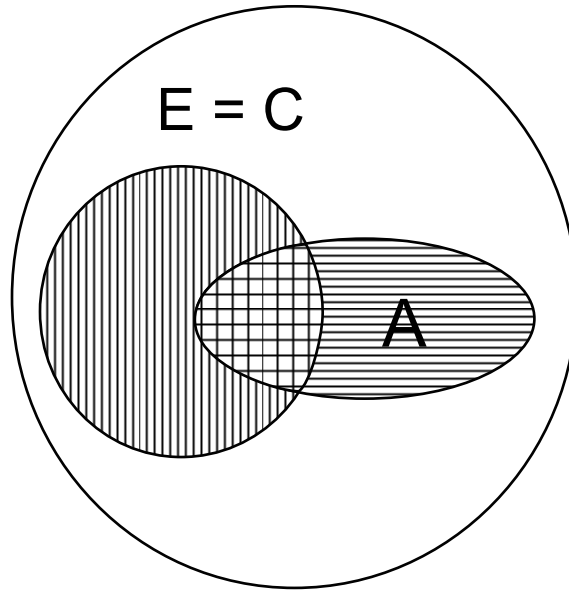
What we need is a design to provide independent estimates of effects:

A

E

C
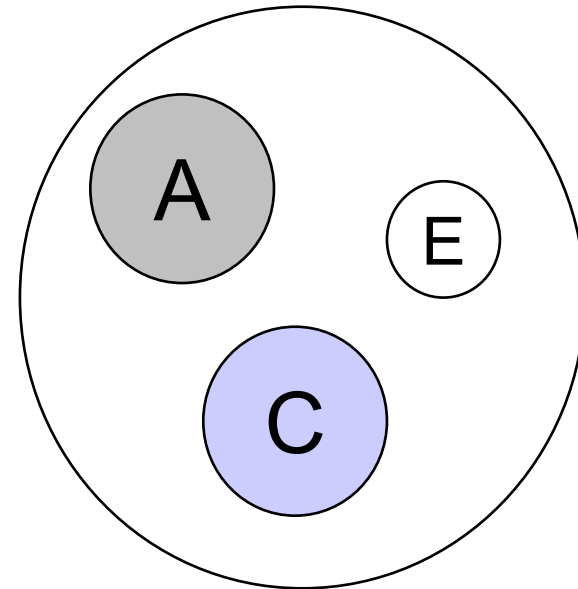
How do we obtain this independence of variables?

All Possible Combinations
(Full Factorial)

MATRIX FORM   **TREE DIAGRAM**

Example 1:

A	B
1	1
1	2
2	1
2	2

A (2 levels)
B (2 levels)

Example 2:
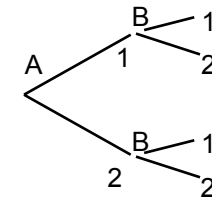
A	B	C
1	1	1
1	2	1
1	3	1
2	1	1
2	2	1
2	3	1
3	1	1
3	2	1
3	3	1
1	1	2
1	2	2
1	3	2
2	1	2
2	2	2
2	3	2
3	1	2
3	2	2
3	3	2

A (3 levels)
B (3 levels)
C (2 levels)

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What Is a Designed Experiment?

Purposeful changes of the inputs (factors) in order to observe corresponding changes in the output (response).

Inputs X_1, X_2, X_3, X_4 → PROCESS → Outputs Y_1, Y_2
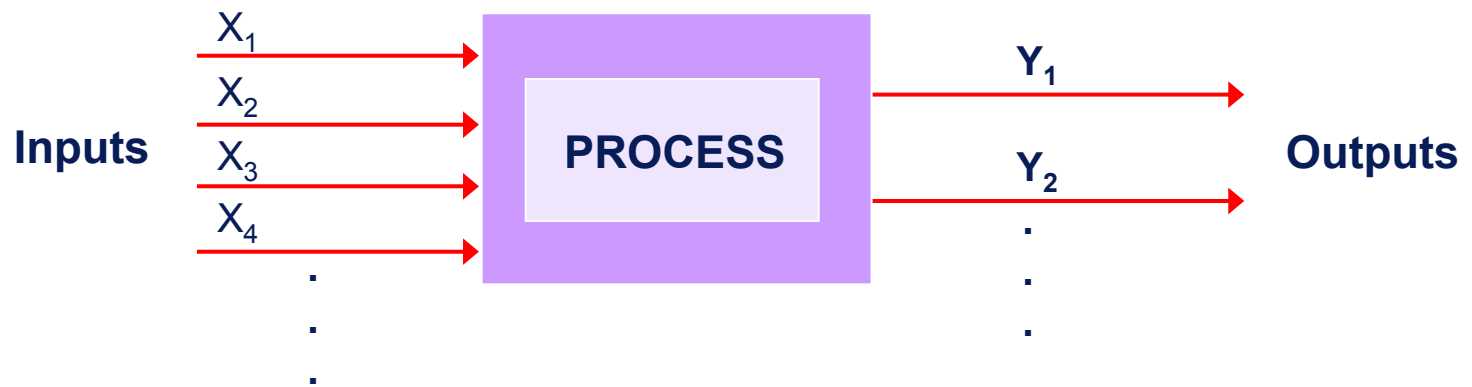
Run	X_1	X_2	X_3	X_4	Y_1 Y_2	$\overline{Y}$	S_Y
1							
2							
3							
.							
.							

DOE Helps Determine How Inputs Affect Outputs

i)   Factor A affects the average of y

A_1 A_2

y
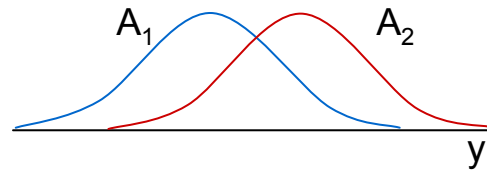
ii)   Factor B affects the standard deviation of y

B_1

B_2

y
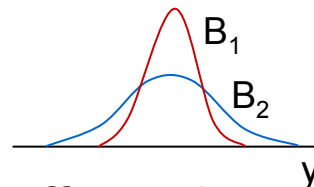
iii)   Factor C affects the average and the standard deviation of y

C_2 C_1

y
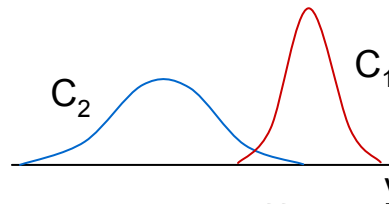
iv)   Factor D has no effect on y

$D_1 = D_2$

y

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Transfer Functions

$$\hat{y} = f_1(x_1, x_2, x_3)$$

$$\hat{S} = f_2(x_1, x_2, x_3)$$
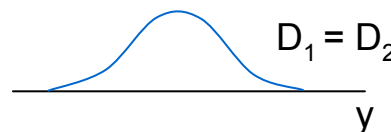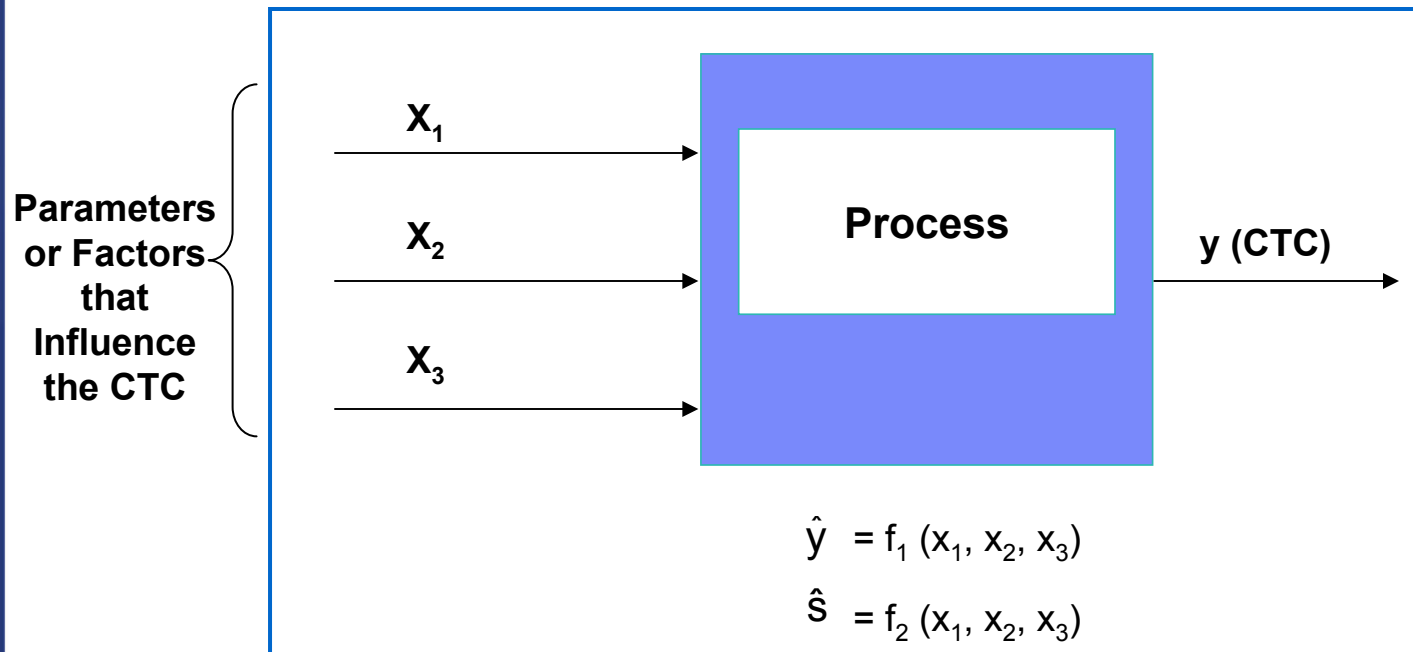
Where does the transfer function come from?

- **Exact transfer Function**

- **Approximations**

  - **DOE**

  - **Historical Data Analysis**

  - **Simulation**

Exact Transfer Function

- Engineering Relationships
  - $V = IR$
  - $F = ma$

R_1

R_2
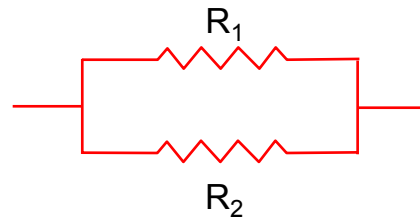
The equation for the impedance (Z) through this circuit is defined by:

$$Z = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

x

ℓ

r
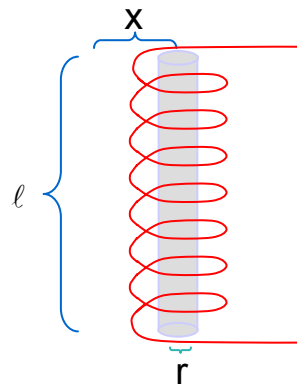
The equation for magnetic force at a distance X from the center of a solenoid is:

$$H = \frac{NI}{2\ell}\left[\frac{.5\ell + x}{\sqrt{r^2 + (.5\ell + x)^2}} + \frac{.5\ell - x}{\sqrt{r^2 + (.5\ell - x)^2}}\right]$$

Where
- N : total number of turns of wire in the solenoid
- I : current in the wire, in amperes
- r : radius of helix (solenoid), in cm
- ℓ : length of the helix (solenoid), in cm
- x : distance from center of helix (solenoid), in cm
- H : magnetizing force, in amperes per centimeter

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Catapulting Power into Design of Experiments

Statapult ® Catapult

The Theoretical Approach

$$I_0 \ddot{\theta} = r_F F(\theta) \sin\theta \cos\varphi - (Mgr_G + mgr_B) \sin\theta$$

$$\tan\phi = \frac{D - r_F \sin\theta}{d + r_F \cos\theta},$$

$$\frac{1}{2} I_0 \dot{\theta}^2 = r_F \int_{\theta_0}^{\theta} F(\theta) \sin\theta \cos\varphi \, d\theta - (Mgr_G + mgr_B)(\sin\theta - \sin\theta_0)$$

$$\frac{1}{2} I_0 \dot{\theta}_1^2 = r_F \int_{\theta_0}^{\theta_1} F(\theta) \sin\theta \cos\varphi \, d\theta - (Mgr_G + mgr_B)(\sin\theta_1 - \sin\theta_0).$$

$$x = v_B \cos\left(\frac{\pi}{2} - \theta_1\right) t - \frac{1}{2} r_B \cos\theta_1$$

$$y = r_B \sin\theta_1 + v_B \sin\left(\frac{\pi}{2} - \theta_1\right) t - \frac{1}{2} gt^2.$$

$$r_B \sin\theta_1 + (R + r_B \cos\theta_1) \tan\left(\frac{\pi}{2} - \theta_1\right) - \frac{g}{2V_B^2} \frac{(R + r_B \cos\theta_1)^2}{\cos^2\left(\frac{\pi}{2} - \theta_1\right)} = 0.$$

$$\frac{gI_0}{4r_B} \frac{(R + r_B \cos\theta_1)^2}{\cos^2\left(\frac{\pi}{2} - \theta_1\right)\left[r_B \sin\theta_1 + (R + r_B \cos\theta_1)\tan\left(\frac{\pi}{2} - \theta_1\right)\right]}$$

$$= r_F \int_{\theta_0}^{\theta_1} F(\theta) \sin\theta \cos\phi \, d\theta - (Mgr_G + mgr_B)(\sin\theta_1 - \sin\theta_0).$$

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Statapult® DOE Demo
(The Empirical Approach)

Run	Actual Factors A	B	Coded Factors A	B	AB	Response Values Y_1 Y_2	$\overline{Y}$	S
1	144	2	-1	-1	+1			
2	144	3	-1	+1	-1			
3	160	2	+1	-1	-1			
4	160	3	+1	+1	+1			

Avg –

Avg +

Δ

The Beauty of Orthogonality

A Full Factorial Design for 3 Factors A, B, and C, Each at 2 levels:

Run	A	B	C	AB	AC	BC	ABC
1	-	-	-	+	+	+	-
2	-	-	+	+	-	-	+
3	-	+	-	-	+	-	+
4	-	+	+	-	-	+	-
5	+	-	-	-	-	+	+
6	+	-	+	-	+	-	-
7	+	+	-	+	-	-	-
8	+	+	+	+	+	+	+

Value Delivery: Reducing Time to Market for New Technologies

INPUT

OUTPUT

Pitch <) (0, 15, 30)

Roll <) (0, 15, 30)

W1F <) (-15, 0, 15)

W2F <) (-15, 0, 15)

W3F <) (-15, 0, 15)

Modeling Flight
Characteristics
of New 3-Wing
Aircraft

Six Aero-
Characteristics

- **Total # of Combinations = 3^5 = 243**
- **Central Composite Design: n = 30**

Patent Holder: Dr. Bert Silich

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Aircraft Equations

C_L = .233 + .008(P)^2 + .255(P) + .012(R) - .043(WD1) - .117(WD2) + .185(WD3) + .010(P)(WD3) - .042(R)(WD1) + .035(R)(WD2) + .016(R)(WD3) + .010(P)(R) - .003(WD1)(WD2) - .006(WD1)(WD3)

C_D = .058 + .016(P)^2 + .028(P) - .004(WD1) - .013(WD2) + .013(WD3) + .002(P)(R) - .004(P)(WD1) - .009(P)(WD2) + .016(P)(WD3) - .004(R)(WD1) + .003(R)(WD2) + .020(WD1)^2 + .017(WD2)^2 + .021(WD3)^2

C_Y = -.006(P) - .006(R) + .169(WD1) - .121(WD2) - .063(WD3) - .004(P)(R) + .008(P)(WD1) - .006(P)(WD2) - .008(P)(WD3) - .012(R)(WD1) - .029(R)(WD2) + .048(R)(WD3) - .008(WD1)^2

C_M = .023 - .008(P)^2 + .004(P) - .007(R) + .024(WD1) + .066(WD2) - .099(WD3) - .006(P)(R) + .002(P)(WD2) - .005(P)(WD3) + .023(R)(WD1) - .019(R)(WD2) - .007(R)(WD3) + .007(WD1)^2 - .008(WD2)^2 + .002(WD1)(WD2) + .002(WD1)(WD3)

C_{YM} = .001(P) + .001(R) - .050(WD1) + .029(WD2) + .012(WD3) + .001(P)(R) - .005(P)(WD1) - .004(P)(WD2) - .004(P)(WD3) + .003(R)(WD1) + .008(R)(WD2) - .013(R)(WD3) + .004(WD1)^2 + .003(WD2)^2 - .005(WD3)^2

C_e = .003(P) + .035(WD1) + .048(WD2) + .051(WD3) - .003(R)(WD3) + .003(P)(R) - .005(P)(WD1) + .005(P)(WD2) + .006(P)(WD3) + .002(R)(WD1)

Hierarchical Transfer Functions

$$Y = \text{Gross Margin} = \frac{\text{Gross Profit}}{\text{Gross Revenue}}$$

$$Y = f(y_1, y_2, y_3, y_4, y_5, y_6)$$

$$= \frac{(Rev_{equip} - COG) + (Rev_{post\ sales} - Cost_{post\ sales}) + (Rev_{fin} - Cost_{fin})}{y_1 + y_3 + y_5}$$

where the terms above are labeled y_1, y_2, y_3, y_4, y_5, y_6 respectively.

$$\underset{y_4}{Cost_{post\ sales}} = f(\underset{x_1}{\text{field cost}}, \underset{x_2}{\text{remote services}}, \underset{x_3}{\text{suppliers}})$$

$$x_1 = f(\text{direct labor, freight, parts, depreciation})$$

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Modeling The Drivers of Turnover

① External Market Factors
(Local Labor Market Conditions)

　　Local Unemployment Rate

　　Local Employment Alternatives

　　Company's Market Share

② Organizational Characteristics
and Practices

　　Supervisor Stability

　　Lateral / Upward Mobility

　　Layoff Climate

③ Employee Attributes

　　Time Since Last Promotion

　　Education Level

　　Job Stability History

Process of Deciding to Stay / Leave

Turnover Rate

DOE "Market Research" Example

Suppose that, in the auto industry, we would like to investigate the following automobile attributes (i.e., factors), along with accompanying levels of those attributes:

A: Brand of Auto: -1 = foreign   +1 = domestic

B: Auto Color: -1 = light   0 = bright   +1 = dark

C: Body Style: -1 = 2-door   0 = 4-door   +1 = sliding door/hatchback

D: Drive Mechanism: -1 = rear wheel   0 = front wheel   +1 = 4-wheel

E: Engine Size: -1 = 4-cylinder   0 = 6-cylinder   +1 = 8-cylinder

F: Interior Size: $-1 \leq 2$ people   0 = 3-5 people $+1 \geq 6$ people

G: Gas Mileage: $-1 \leq 20$ mpg   0 = 20-30 mpg $+1 \geq 30$ mpg

H: Price: $-1 \leq \$20K$ 0 = \$20-\$40K $+1 \geq \$40K$

In addition, suppose the respondents chosen to provide their preferences to product profiles are taken based on the following demographic:

J: Age: $-1 \leq 25$ years old $+1 \geq 35$ years old

K: Income: $-1 \leq \$30K$ $+1 \geq \$40K$

L: Education: -1 < BS $+1 \geq BS$

Question: Choose the best design for evaluating this scenario

Answer: L_{18} design with attributes A - H in the inner array and factors J, K, and L in the outer array, resembling an L_{18} robust design, as shown below:
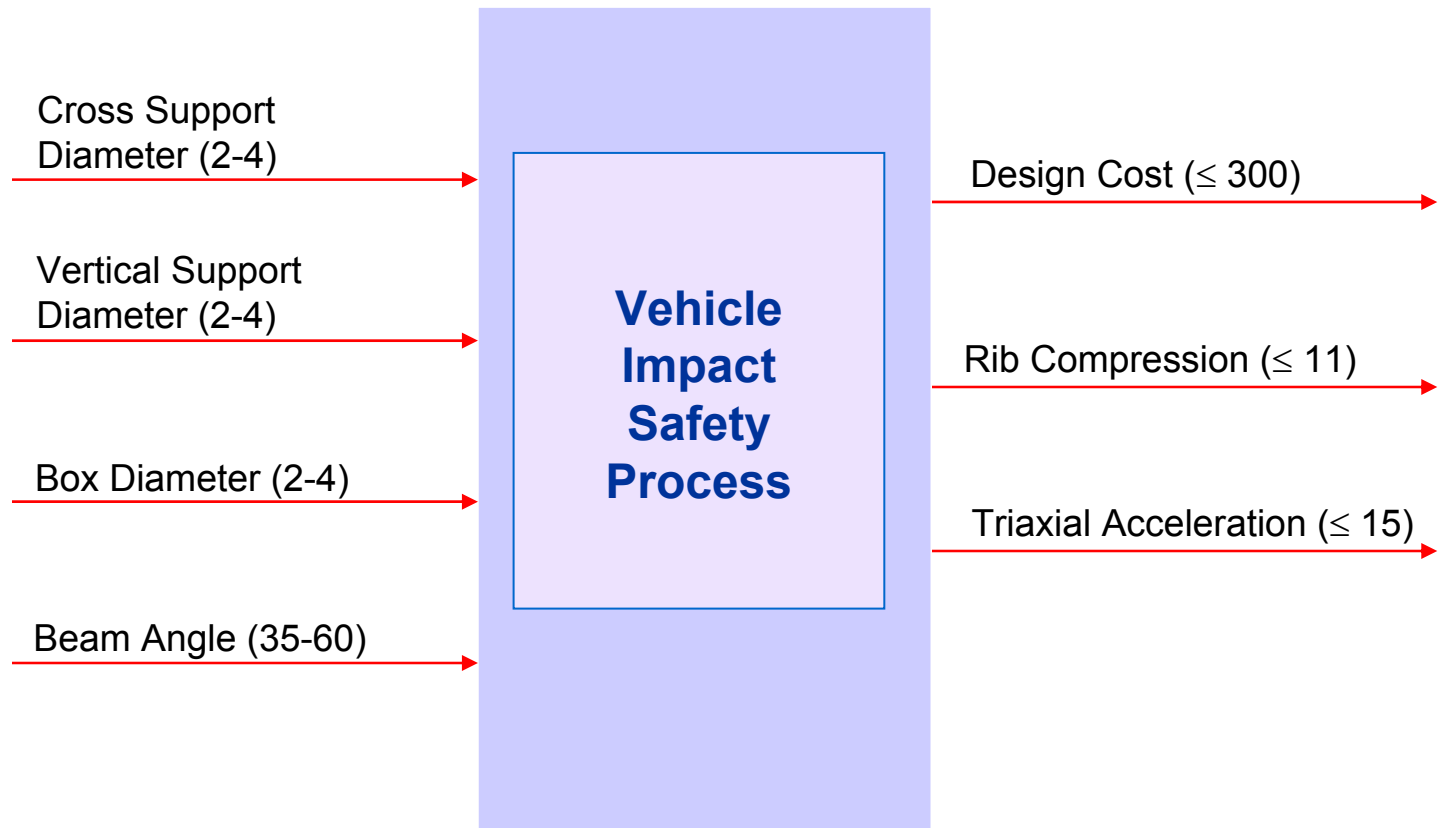
											y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	$\bar{y}$	s
L									-	+	-	+	-	+	-	+				
K									-	-	+	+	-	-	+	+				
J									-	-	-	-	+	+	+	+				
Run*	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**											
1	-	-	-	-	-	-	-	-											
2	-	-	0	0	0	0	0	0											
3	-	-	+	+	+	+	+	+											
4	-	0	-	-	0	0	+	+			Segmentation of the population or								
5	-	0	0	0	+	+	-	-											
6	-	0	+	+	-	-	0	0			Respondent Profiles								
7	-	+	-	0	-	+	0	+											
8	-	+	0	+	0	-	+	-											
9	-	+	+	-	+	0	-	0											
10	+	-	-	+	+	0	0	-											
11	+	-	0	-	-	+	+	0											
12	+	-	+	0	0	-	-	+											
13	+	0	-	0	+	-	+	0											
14	+	0	0	+	-	0	-	+											
15	+	0	+	-	0	+	0	-											
16	+	+	-	+	0	+	-	0											
17	+	+	0	-	+	-	0	+											
18	+	+	+	0	-	0	+	-											

* 18 different product profiles

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Multiple Response Optimization Simulation Example

Cross Support
Diameter (2-4) →

Vertical Support
Diameter (2-4) →

Box Diameter (2-4) →

Beam Angle (35-60) →

**Vehicle
Impact
Safety
Process**

→ Design Cost ($\leq$ 300)

→ Rib Compression ($\leq$ 11)

→ Triaxial Acceleration ($\leq$ 15)

Optimization Using Monte Carlo Simulation

- **Expected Value Analysis**

- **Robust Design**

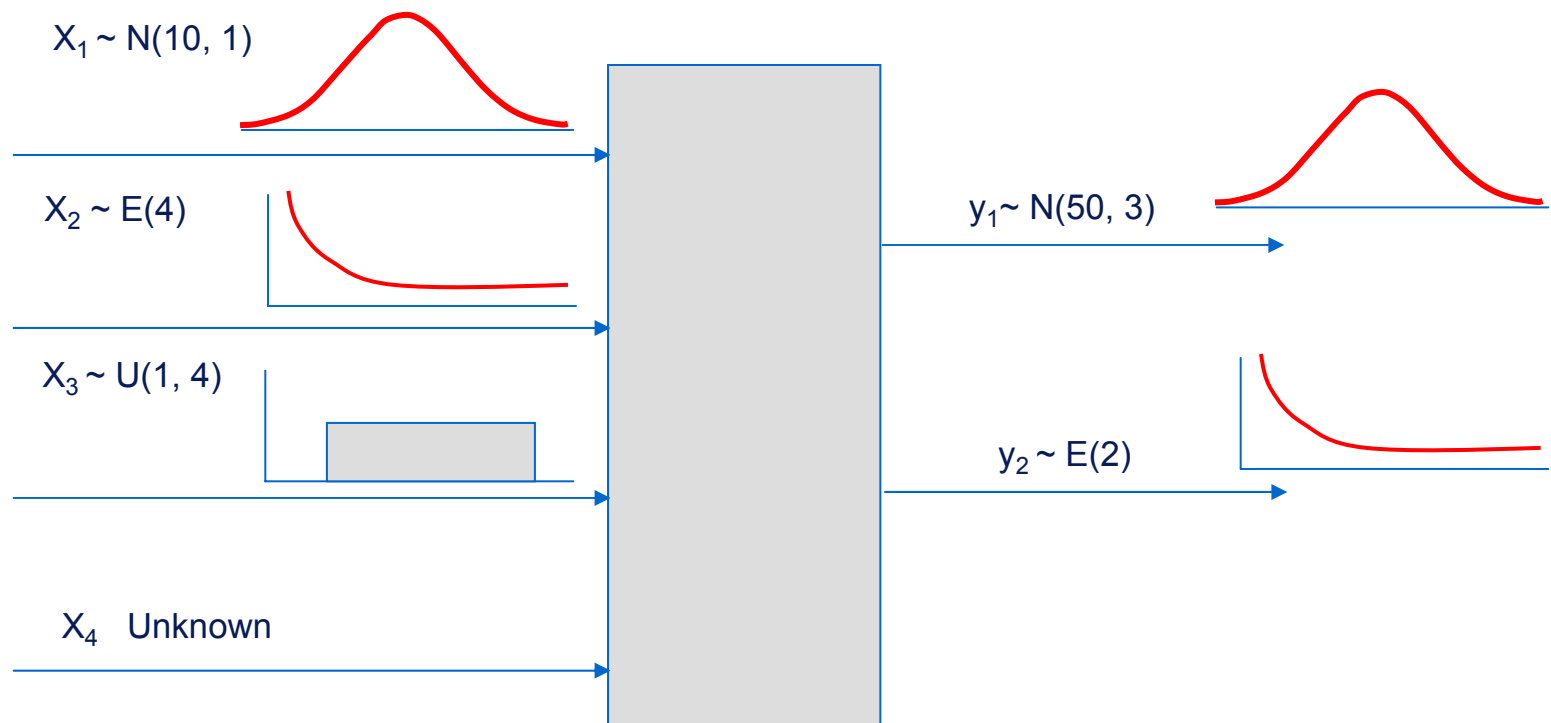- **Tolerance Allocation**

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Expected Value Analysis (EVA)

Previously, we discussed variability in the outputs in great detail. However, the inputs also have variability.

$X_1 \sim N(10, 1)$

$X_2 \sim E(4)$

$y_1 \sim N(50, 3)$

$X_3 \sim U(1, 4)$
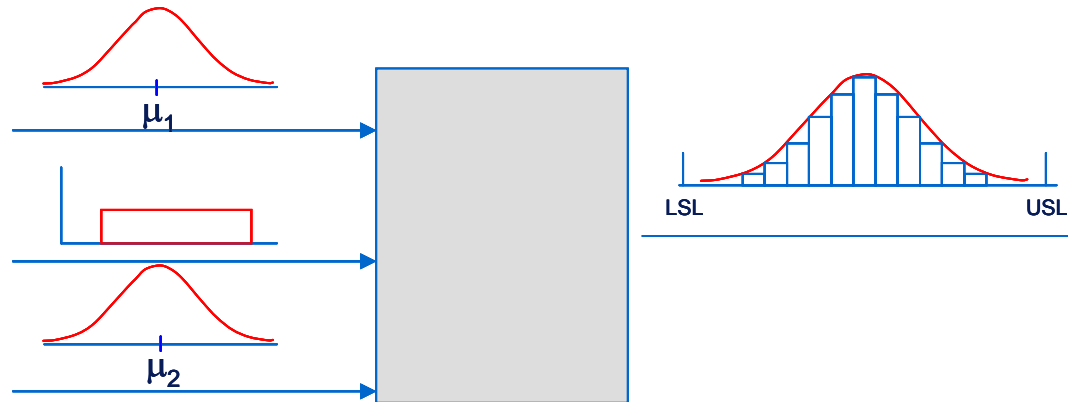
$y_2 \sim E(2)$

X_4 Unknown

If a product has never been produced, how do we know what the distribution of the output is? What is the expected value and variance of y?

Expected Value Analysis Example
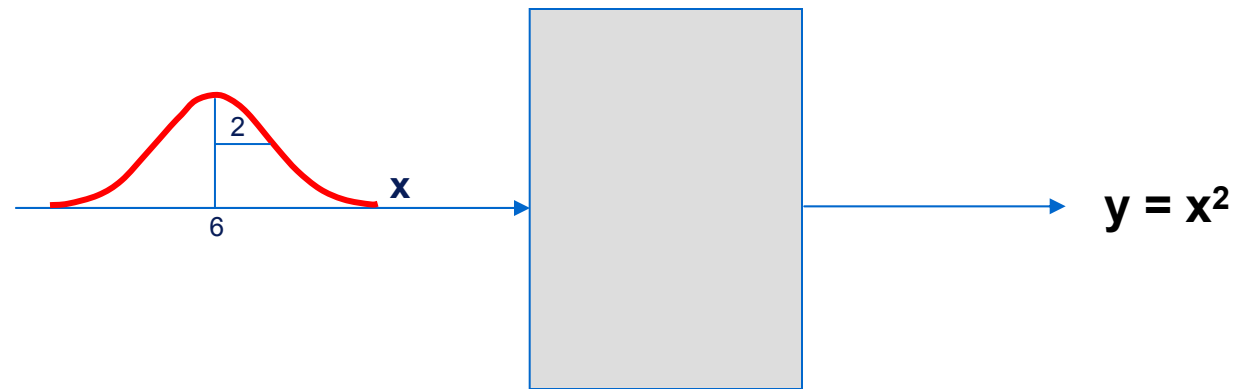
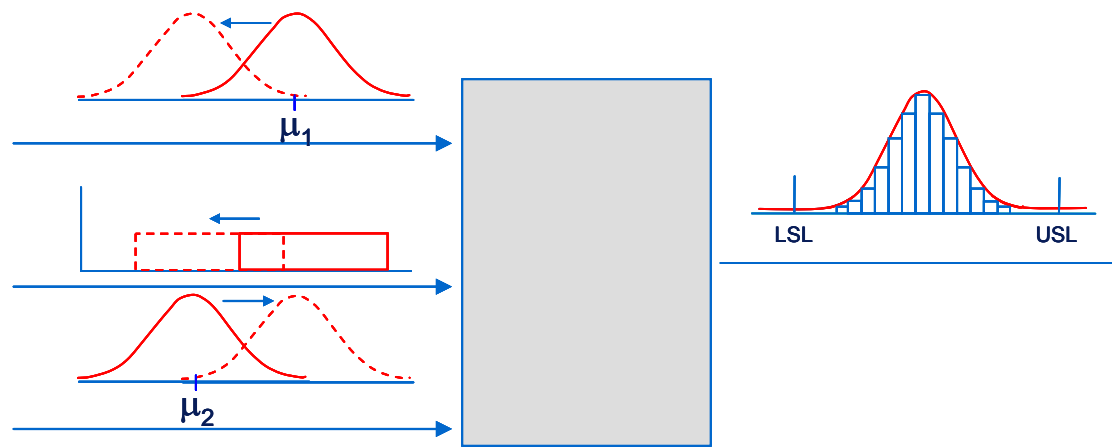- **What is the shape of the output (y) distribution?**

- **What is the mean or expected value of the y distribution?**

- **What is the standard deviation of the y distribution?**

Robust Design

Process of finding the optimal location parameters (i.e., means) of the input variables to minimize dpm.

Why Robust Design?
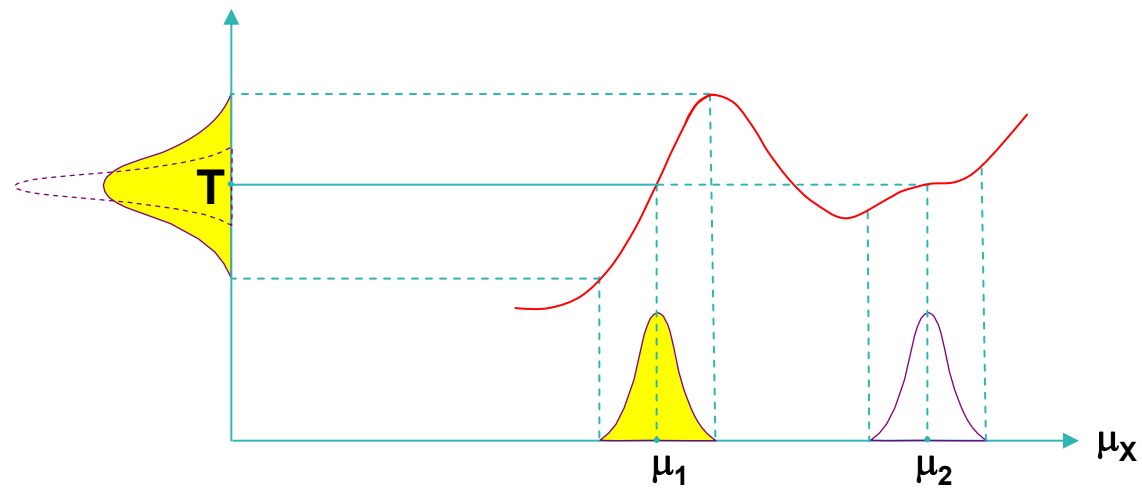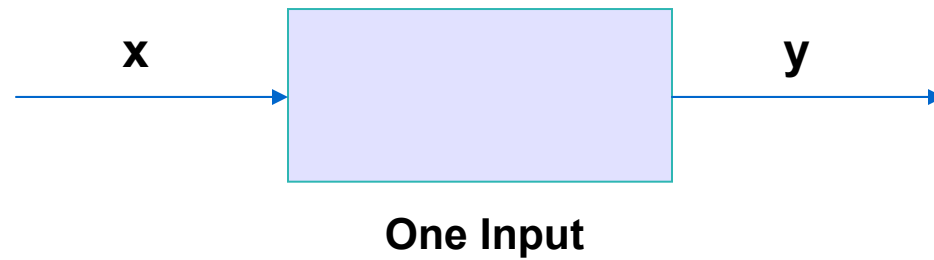
One Input

If μ_X varies, should we select μ_1 or μ_2 to hit y = T?

Robust (Parameter) Design
Simulation Example

Plug Pressure (20-50) →

Bellow Pressure (10-20) →

Nuclear Reservoir Level Control Process

Ball Valve Pressure (100-200) →

Water Temp (70-100) →

→ Reservoir Level (700-900)
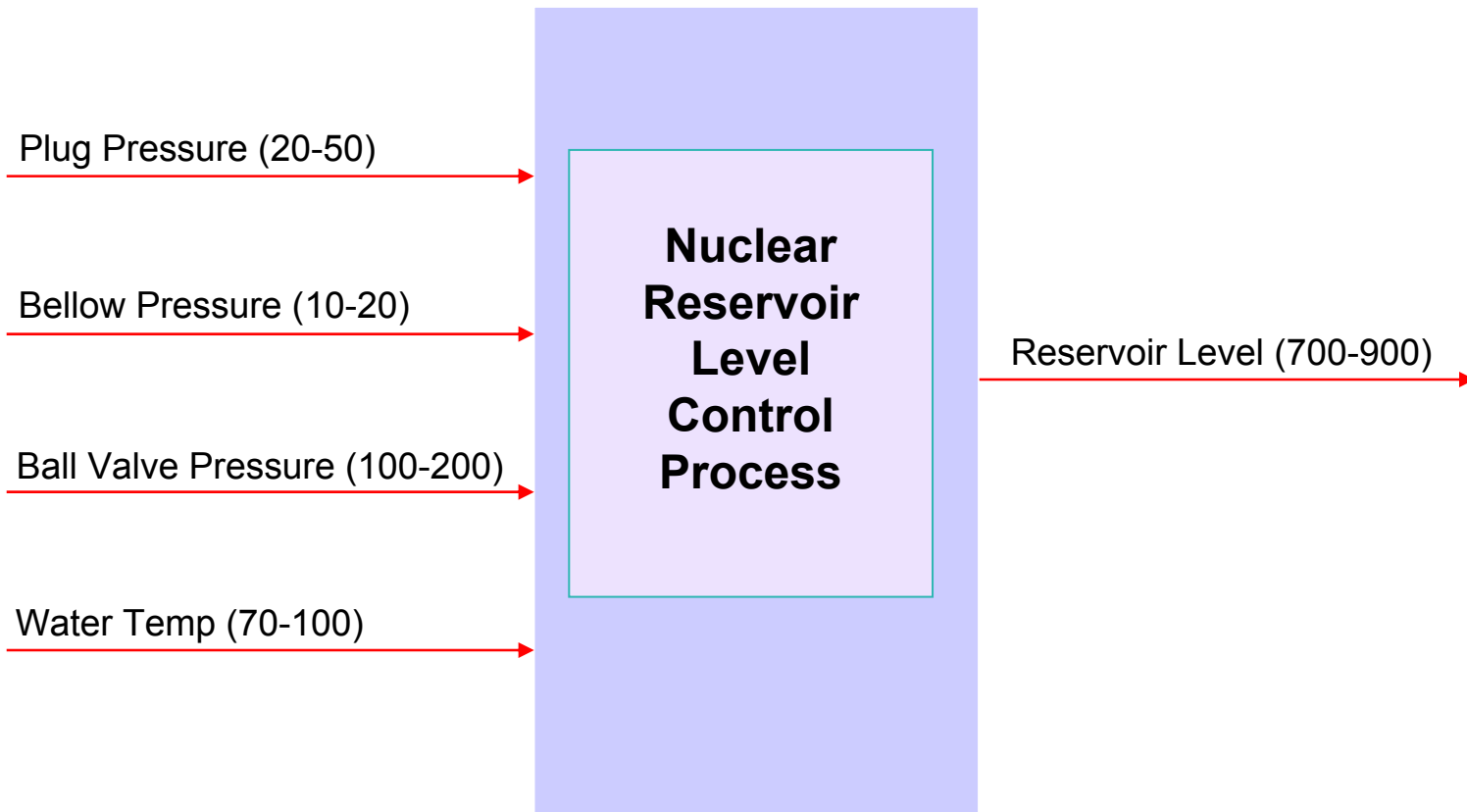
Tolerance Allocation (TA)
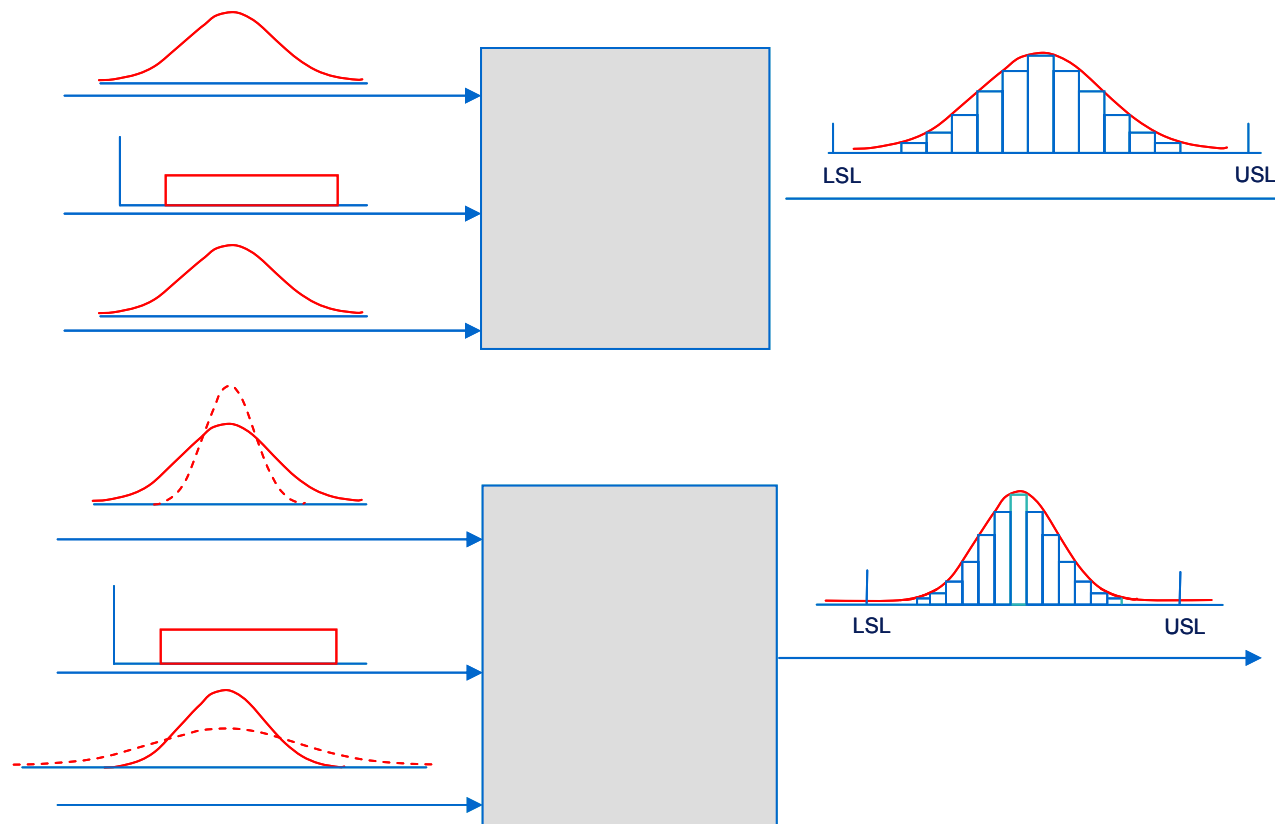
The process of quantifying the sensitivity of the output (y) dpm to changes in the input variables' (X's) standard deviations. It provides the designer the ability to perform cost/benefit tradeoffs via assignment of standard deviations to the input variables.

Tolerance Allocation Example

$$R_1 \sim N(50, 2^2)$$

$$R_2 \sim N(100, 2^2)$$

Impedance

Example

$$Z = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

LSL = 31

USL = 35
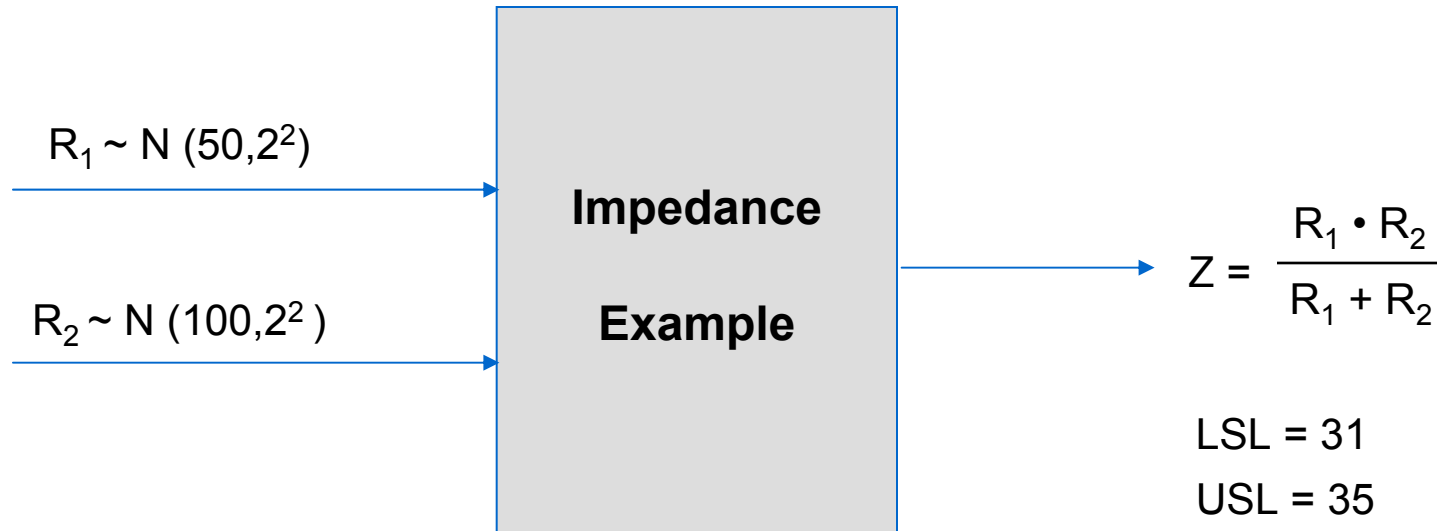
If we were able to change a resistor's standard deviation, which resistor, R_1 or R_2, would have the greater impact on the dpm of Z (impedance)?

Tolerance Allocation Example (cont.)

A reduction of R_1 by 50% reduces dpm by an order of magnitude X, while R_2 has little impact.

Tolerance Allocation Table		
N = 10,000 (in defects per million)		
Impedance Table		
	R1	R2
-50% Sigma	372.40	34,683
-25% Sigma	8,058	36,849
-10% Sigma	23,906	35,663
Nominal	39,220	39,657
+10% Sigma	59,508	37,556
+25% Sigma	92,398	47,317
+50% Sigma	148,113	46,801

A reduction of R_1's standard deviation by 50% combined with an increase in R_2's standard deviation by 50%

$R_1 \sim N(50, 1^2)$

$R_2 \sim N(100, 3^2)$

results in a dpm = 1,254.

Examples of Simulation and High Performance Computing (HPC)

Power

Simulation of stress and vibrations of turbine assembly for use in nuclear power generation
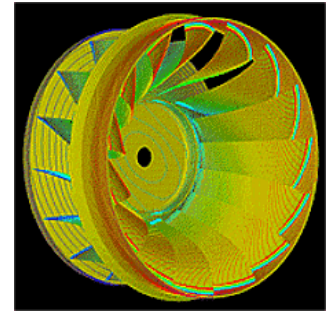
Automotive

Simulation of underhood thermal cooling for decrease in engine space and increase in cabin space and comfort

Aerospace

Evaluation of dual bird-strike on aircraft engine nacelle for turbine blade containment studies
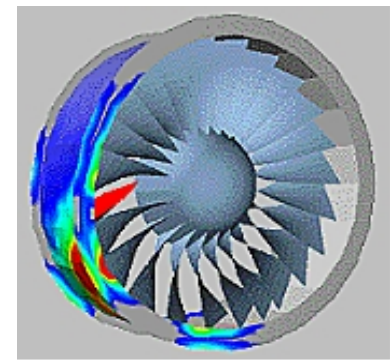
Electronics
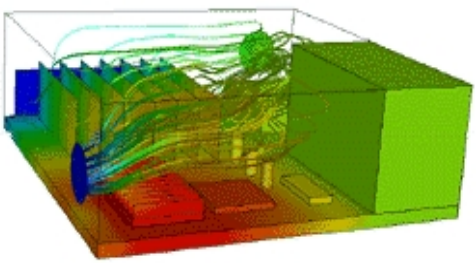
Evaluation of cooling air flow behavior inside a computer system chassis

Examples of Computer Aided Engineering (CAE) and Simulation Software

Mechanical motion: Multibody kinetics and dynamics
>   **ADAMS®**
>   **DADS**
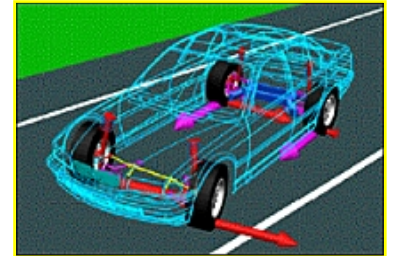
Implicit Finite Element Analysis: Linear and nonlinear statics, dynamic response
>   **MSC.Nastran™, MSC.Marc™**
>   **ANSYS®**
>   **Pro MECHANICA**
>   **ABAQUS® Standard and Explicit**
>   **ADINA**
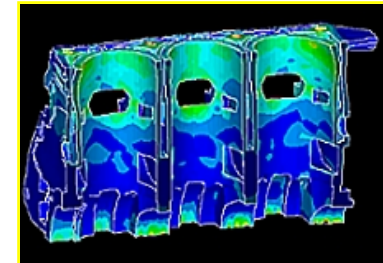
Explicit Finite Element Analysis : Impact simulation, metal forming
>   **LS-DYNA**
>   **RADIOSS**
>   **PAM-CRASH®, PAM-STAMP**
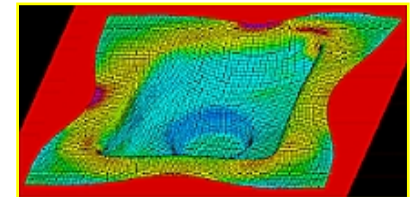
General Computational Fluid Dynamics: Internal and external flow simulation
>   **STAR-CD**
>   **CFX-4, CFX-5**
>   **FLUENT®, FIDAP™**
>   **PowerFLOW®**

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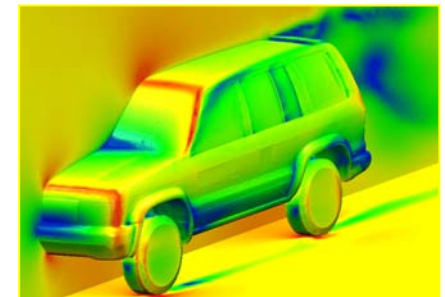
Examples of Computer Aided Engineering (CAE) and Simulation Software (cont.)

Preprocessing: Finite Element Analysis and Computational Fluid Dynamics mesh generation

    ICEM-CFD
    Gridgen
    Altair® HyperMesh®
    I-deas®
    MSC.Patran
    TrueGrid®
    GridPro
    FEMB
    ANSA
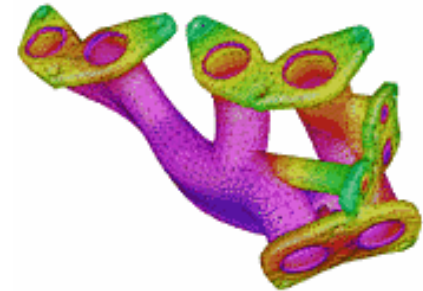
Postprocessing: Finite Element Analysis and Computational Fluid Dynamics results visualization

    Altair® HyperMesh®
    I-deas
    MSC.Patran
    FEMB
    EnSight
    FIELDVIEW
    ICEM CFD Visual3 2.0 (PVS)
    COVISE

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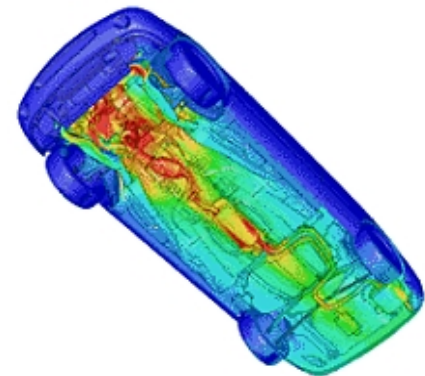
Multidisciplinary Design Optimization (MDO): A Design Process Application
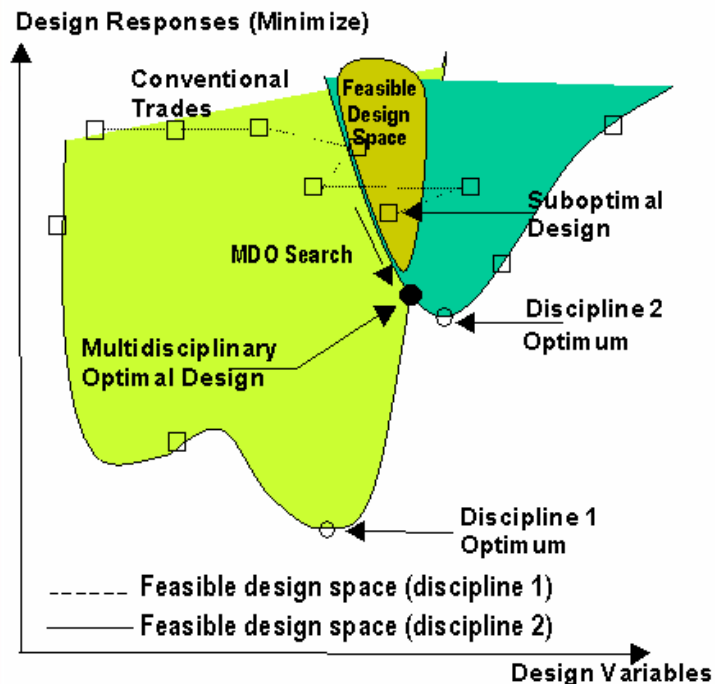
CFD
- CFD
- Structures
- Performance
- Controls
- Cost
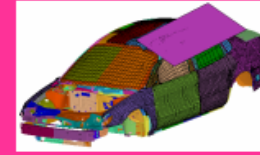
NVH
- NVH
- Safety
- Durability
- Controls Stability
- Cost

Key Elements of MDO

- Massive Computational Problem;
- Solution by decomposition effective for complex systems;
- Multiprocessor computing simplifies MDO solutions conceptually & enables solutions previously intractable;
- Aids in the management of the design process.

Mastery of interactions between the disciplines (or, subsystems) is as important as the methods & tools used within a single discipline

Simplify and Perfect

Latin Hypercube Sampling

- Method to populate the design space when using deterministic simulation models.

- Design space has k variables (or dimensions).

  Ex: Assume k = 2

- Suppose a sample of size n is to be taken; Stratify the design space into n^k cells.

  Ex: Assume n = 5; $n^k = 5^2 = 25$

  Note: there are n strata for each of the k dimensions.

- Each of the n points is sampled such that each marginal strata is represented only once in the sample.

  Note: each sample point has its own unique row and column.

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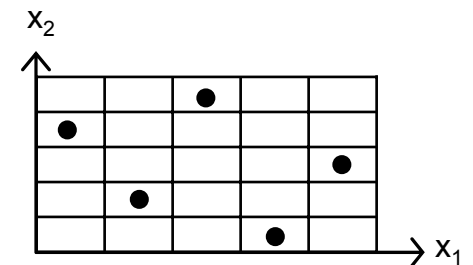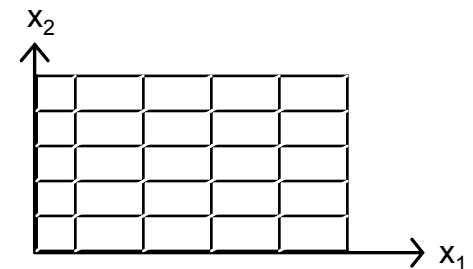
Applying Modeling and Simulation to Automotive Vehicle Design

```
┌─────────────────┐   Many, Many x's   ┌─────────────────────┐   The critical
│    IDENTIFY      │ ─────────────────> │  SCREENING DESIGN   │ ─────────────>
│   CTCs, CDPs     │                    │     (DOE PRO)       │   few CDP's
└─────────────────┘                    └─────────────────────┘
```

Examples of CTCs:

y_1 = weight of vehicle

y_2 = cost of vehicle

Safety CTCs with constraints specified by FMVSS (Federal Motor Vehicle Safety Standards)

y_3 = frontal head impact

y_4 = frontal chest impact

y_5 = toe board intrusion

y_6 = hip deflection

y_7 = rollover impact

y_8 = side impact

RADIOSS
DYNA
MADYMO

no federal requirements on these CTCs

y_9 = internal aerodynamics (airflow)

y_{10} = external aerodynamics (airflow)

CFD

y_{11} = noise

y_{12} = vibration (e.g., steering wheel)

y_{13} = harshness (e.g., over bumps, shocks)

y_{14} = durability (at 100K miles)

NASTRAN

SCREENING DESIGN (DOE PRO)

NASTRAN   RADIOSS   MADYMO

Integrated processes with high fidelity CAE analyses on HPC servers

Examples of Critical Design Parameters (CDPs or Xs):

x_1 = roof panel material

x_2 = roof panel thickness

x_3 = door pillar dimensions $\Rightarrow$ i beam

x_4 = shape/geometry

x_5 = windshield glass

x_6 = hood material, sizing and thickness

x_7 = under hood panel material, sizing and thickness

t_1

t_2

MODELING DESIGN (DOE PRO)	→CDPs→	MONTE CARLO SIMULATION (DFSS MASTER)	→Robust Designs→	VALIDATION

CDPs, CTCs

NASTRAN RADIOSS MADYMO	Response Surface Models	NASTRAN RADIOSS MADYMO
High Fidelity Models	**Low Fidelity Models**	**High Fidelity Models**

Introduction to High Throughput Testing (HTT)

- A recently developed technique based on combinatorics

- Used to test myriad combinations of many factors (typically qualitative) where the factors could have many levels

- Uses a minimum number of runs or combinations to do this

- Software (e.g., ProTest) is needed to select the minimal subset of all possible combinations to be tested so that all n-way combinations are tested.

- HTT is not a DOE technique, although the terminology is similar

- A run or row in an HTT matrix is, like DOE, a combination of different factor levels which, after being tested, will result in a successful or failed run

- HTT has its origins in the pharmaceutical business where in drug discovery many chemical compounds are combined together (combinatorial chemistry) at many different strengths to try to produce a reaction.

- Other industries are now using HTT, e.g., software testing, materials discovery, interoperability testing, IT (see IT example on next page)

HTT Example

- An IT function in a company wanted to test all 2-way combinations of a variety of computer configuration-related options or levels to see if they would function properly together.

- Here are the factors with each of their options:

  Motherboards (5) : Gateway, ASUS, Micronics, Dell, Compaq

  RAM (3)   : 128 MB, 256 MB, 512 MB

  BIOS (3)   : Dell, Award, Generic

  CD (3)   : Generic, Teac, Sony

  Monitor (5)   : Viewsonic, Sony, KDS, NEC, Generic

  Printer (3)   : HP, Lexmark, Cannon

  Voltage (2)   : 220, 110

  Resolution (2)   : 800x600, 1024x768

- How many total combinations are there?

- What is the minimum number of these combinations we will have to test (and which ones are they) in order to determine if every 2-way combination (e.g., Dell Bios with Teac CD) will indeed work properly together?

- To answer this question, we used Pro-Test software. The answer is 25 runs and those 25 combinations are shown on the next page.
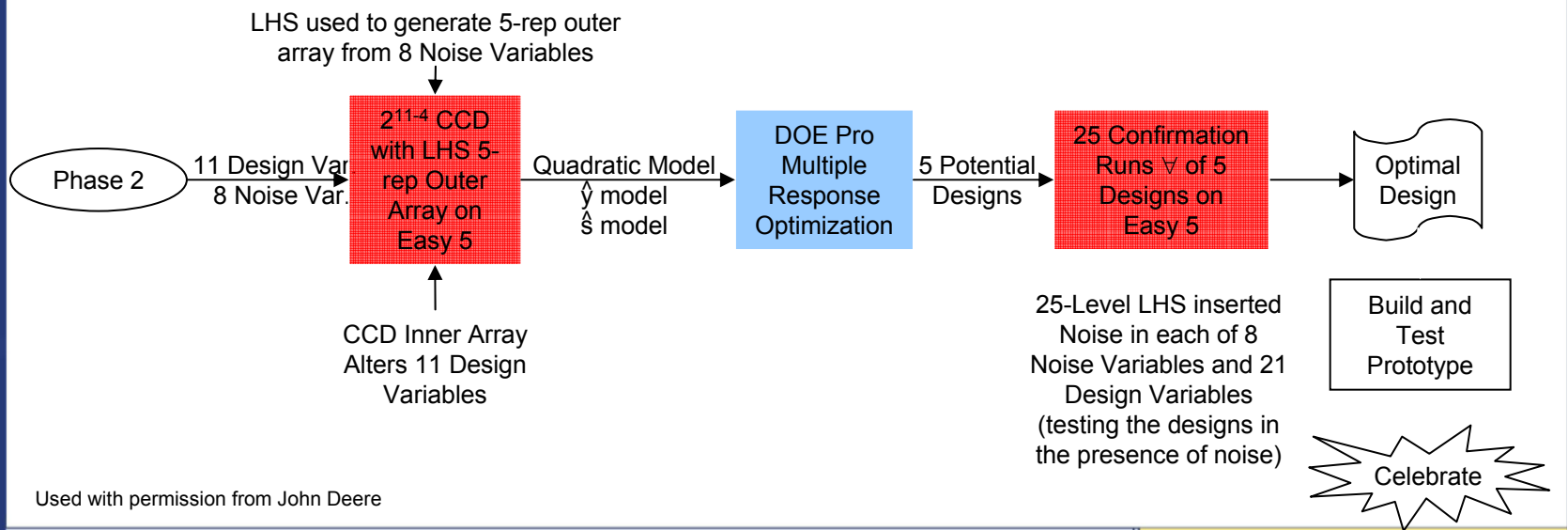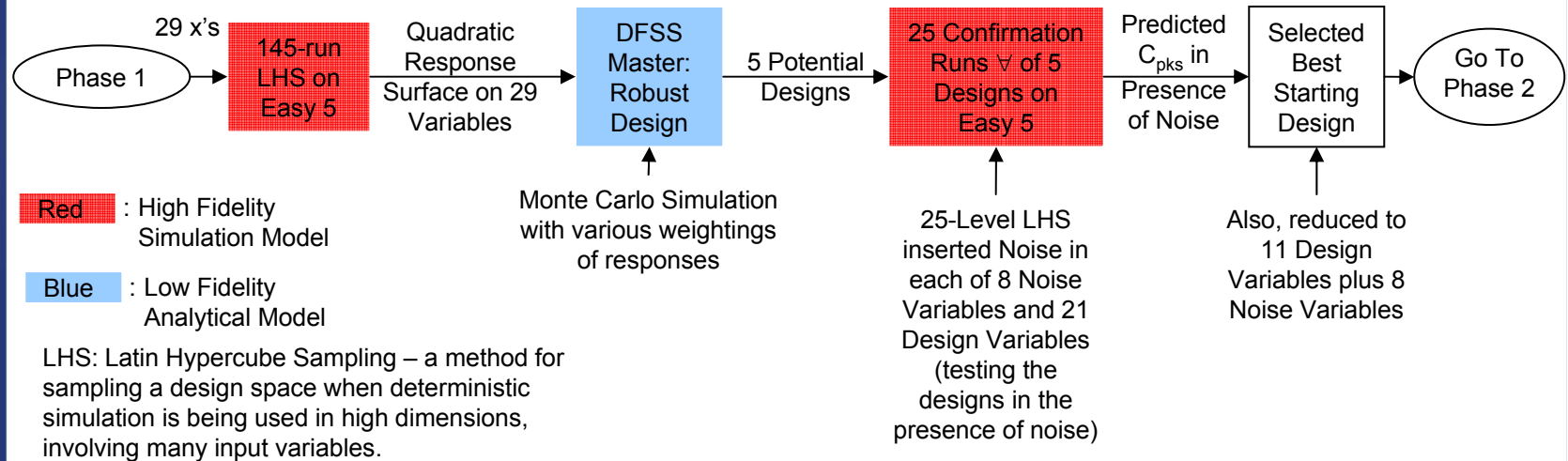
High Throughput Testing (HTT)
(for all two-way combinations)

	5 Levels	3 Levels	3 Levels	3 Levels	5 Levels	3 Levels	2 Levels	2 Levels
	Motherboard	**RAM**	**BIOS**	**CD**	**Monitor**	**Printer**	**Voltage**	**Resolution**
Case 1	ASUS	256 MB	Dell	Generic	Viewsonic	Lexmark	110 V	800 x 600
Case 2	Compaq	512 MB	Dell	Teac	Sony	HP	220 V	1024 x 768
Case 3	Gateway	128 MB	Generic	Sony	KDS	Cannon	220 V	800 x 600
Case 4	Dell	128 MB	Award	Teac	NEC	Cannon	110 V	1024 x 768
Case 5	Micronics	256 MB	Generic	Teac	Generic	Lexmark	220 V	1024 x 768
Case 6	Gateway	256 MB	Award	Sony	Sony	HP	110 V	1024 x 768
Case 7	Micronics	512 MB	Award	Generic	Viewsonic	Cannon	220 V	1024 x 768
Case 8	ASUS	512 MB	Generic	Teac	KDS	HP	220 V	1024 x 768
Case 9	Compaq	128 MB	Award	Generic	Generic	HP	110 V	800 x 600
Case 10	Micronics	512 MB	Generic	Teac	Sony	Lexmark	110 V	800 x 600
Case 11	Dell	256 MB	Award	Generic	KDS	Lexmark	110 V	1024 x 768
Case 12	Gateway	512 MB	Dell	Sony	Generic	Lexmark	110 V	1024 x 768
Case 13	Compaq	256 MB	Generic	Sony	Viewsonic	Cannon	220 V	1024 x 768
Case 14	ASUS	128 MB	Dell	Sony	NEC	Cannon	220 V	800 x 600
Case 15	Micronics	128 MB	Dell	Sony	KDS	Lexmark	220 V	800 x 600
Case 16	Gateway	128 MB	Generic	Teac	Viewsonic	HP	110 V	800 x 600
Case 17	Dell	128 MB	Dell	Sony	Sony	Cannon	110 V	1024 x 768
Case 18	ASUS	256 MB	Award	Sony	Generic	Cannon	220 V	1024 x 768
Case 19	Compaq	512 MB	Dell	Sony	NEC	Lexmark	110 V	800 x 600
Case 20	Gateway	256 MB	Generic	Generic	NEC	Cannon	220 V	800 x 600
Case 21	Micronics	512 MB	Generic	Teac	NEC	HP	220 V	800 x 600
Case 22	ASUS	256 MB	Generic	Generic	Sony	HP	110 V	800 x 600
Case 23	Dell	512 MB	Generic	Sony	Viewsonic	HP	220 V	1024 x 768
Case 24	Compaq	256 MB	Dell	Generic	KDS	Cannon	220 V	1024 x 768
Case 25	Dell	128 MB	Generic	Sony	Generic	HP	110 V	800 x 600

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Example of Iterative Approach to Modeling and Simulation to Optimize Transmission Performance

29 x's

Phase 1 → [145-run LHS on Easy 5] → Quadratic Response Surface on 29 Variables → [DFSS Master: Robust Design] → 5 Potential Designs → [25 Confirmation Runs ∀ of 5 Designs on Easy 5] → Predicted C_{pks} in Presence of Noise → [Selected Best Starting Design] → Go To Phase 2

[Red] : High Fidelity Simulation Model

[Blue] : Low Fidelity Analytical Model

LHS: Latin Hypercube Sampling – a method for sampling a design space when deterministic simulation is being used in high dimensions, involving many input variables.

Monte Carlo Simulation with various weightings of responses

25-Level LHS inserted Noise in each of 8 Noise Variables and 21 Design Variables (testing the designs in the presence of noise)

Also, reduced to 11 Design Variables plus 8 Noise Variables

LHS used to generate 5-rep outer array from 8 Noise Variables

Phase 2 → 11 Design Var. 8 Noise Var. → [2^{11-4} CCD with LHS 5-rep Outer Array on Easy 5] → Quadratic Model $\hat{y}$ model $\hat{s}$ model → [DOE Pro Multiple Response Optimization] → 5 Potential Designs → [25 Confirmation Runs ∀ of 5 Designs on Easy 5] → Optimal Design

CCD Inner Array Alters 11 Design Variables

25-Level LHS inserted Noise in each of 8 Noise Variables and 21 Design Variables (testing the designs in the presence of noise)

Build and Test Prototype

Celebrate

Technologies Used on Transmission Project

- ## High Throughput Testing (HTT)

  To generate a minimal number of test cases; in this scenario, 11 combinations of 29 variables that would allow testing all two-way combinations on Easy 5. This made running the Easy 5 simulator much easier, without interruption.

- ## DFSS Master: for Robust Design and Expected Value Analysis (Monte Carlo Techniques)

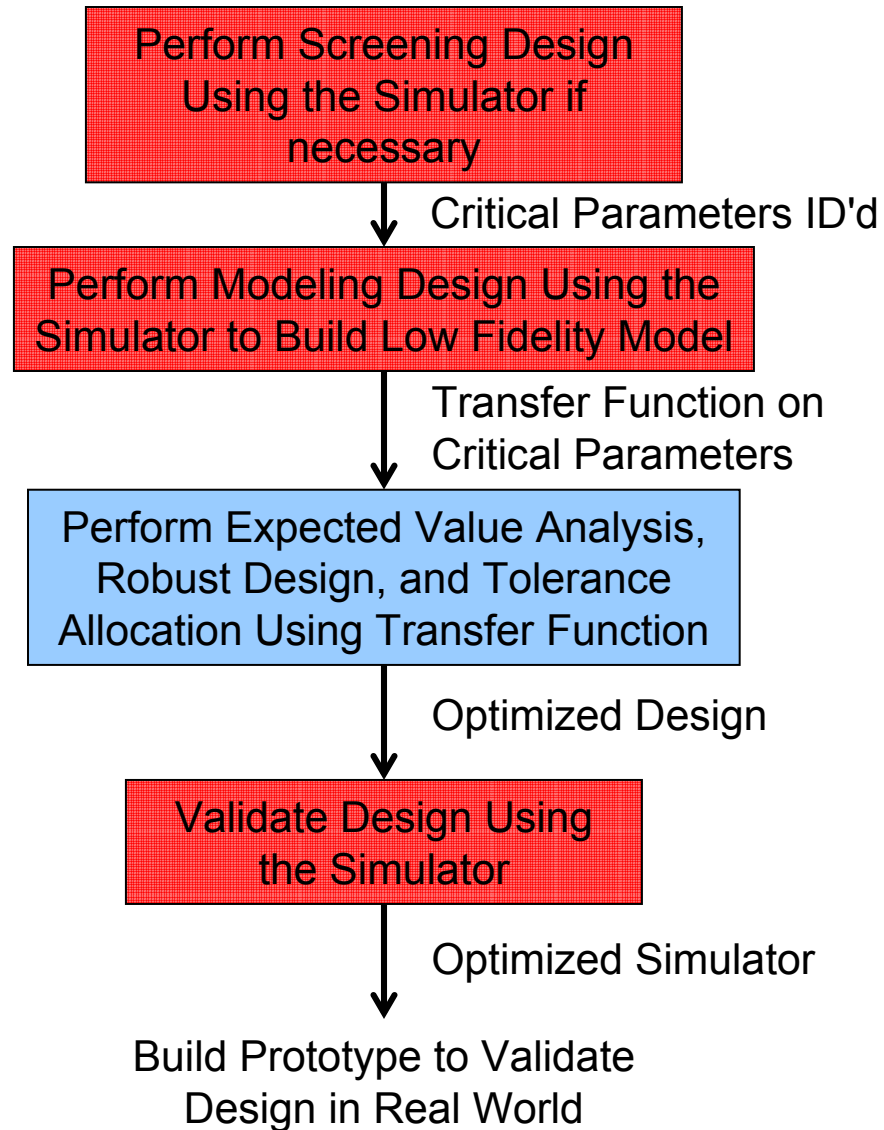- ## Highly Orthogonal Latin Hypercube Sampling

  To populate the design space with test cases which are highly orthogonal. Typically used with deterministic simulation to screen out the CDPs and also to use modeling DOEs on the simulator to generate transfer functions which characterize the simulator

- ## DOE PRO: for Multiple Response Optimization

Summary of "Modeling the Simulator"

Perform Screening Design Using the Simulator if necessary

↓ Critical Parameters ID'd

Perform Modeling Design Using the Simulator to Build Low Fidelity Model

↓ Transfer Function on Critical Parameters

Perform Expected Value Analysis, Robust Design, and Tolerance Allocation Using Transfer Function

↓ Optimized Design

Validate Design Using the Simulator

↓ Optimized Simulator

Build Prototype to Validate Design in Real World

Environments Where Simulation and Modeling Is Beneficial

- **A high number of design variables**

- **A substantial number of design subsystems and engineering disciplines**

- **Interdependency and interaction between the subsystems and variables**

- **Multiple response variables**

- **Need to characterize the system at a higher level of abstraction**

- **Time and/or space must be compressed**

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