Recent Innovations in Design for Six Sigma (DFSS) Testing: Approaches to Speed Technology to the Marketplace

Dr. Mark J. Kiemele
Air Academy Associates

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Agenda

- Brief Overview of Design for Six Sigma (DFSS)
- Factorial Testing and Sequencing of the Tests
- High Throughput Testing
- Multidiscipline Design Optimization with Latin Hypercube Sampling

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Six Sigma Defined

Originally: Metric Based on the Statistical Measure Called Standard Deviation

Expanded To:

WORLD CLASS QUALITY

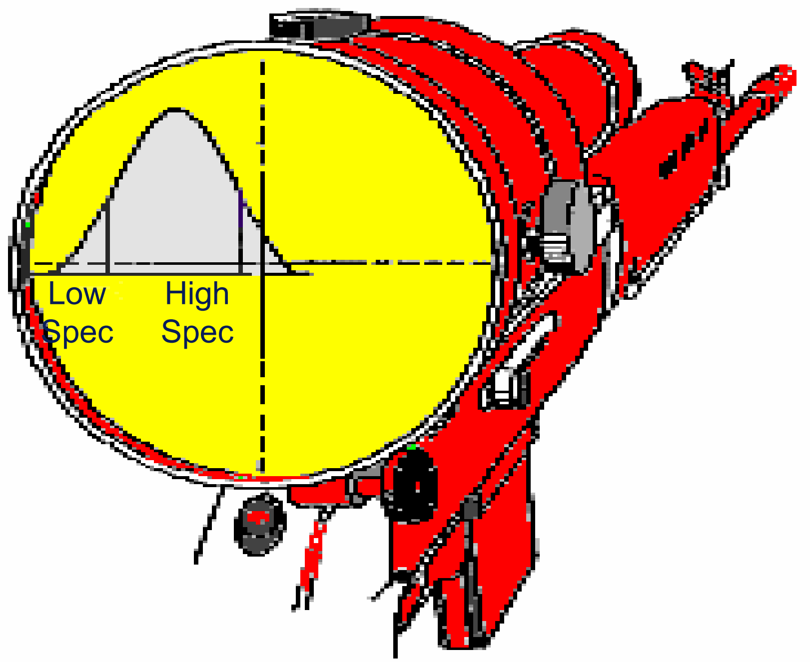
Providing a

BETTER product or service,

FASTER, and

at a **LOWER COST**

than our competition.



VARIATION is the enemy!

"*Always know the language of the enemy.*"

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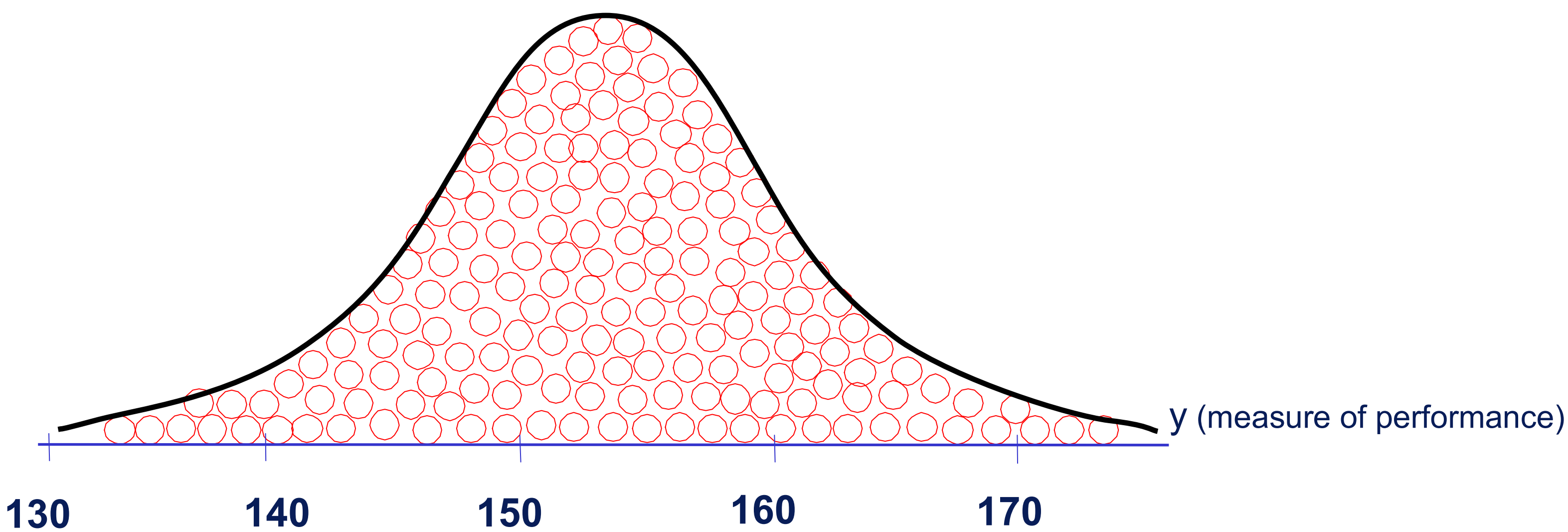
Graphical Meaning of a Distribution



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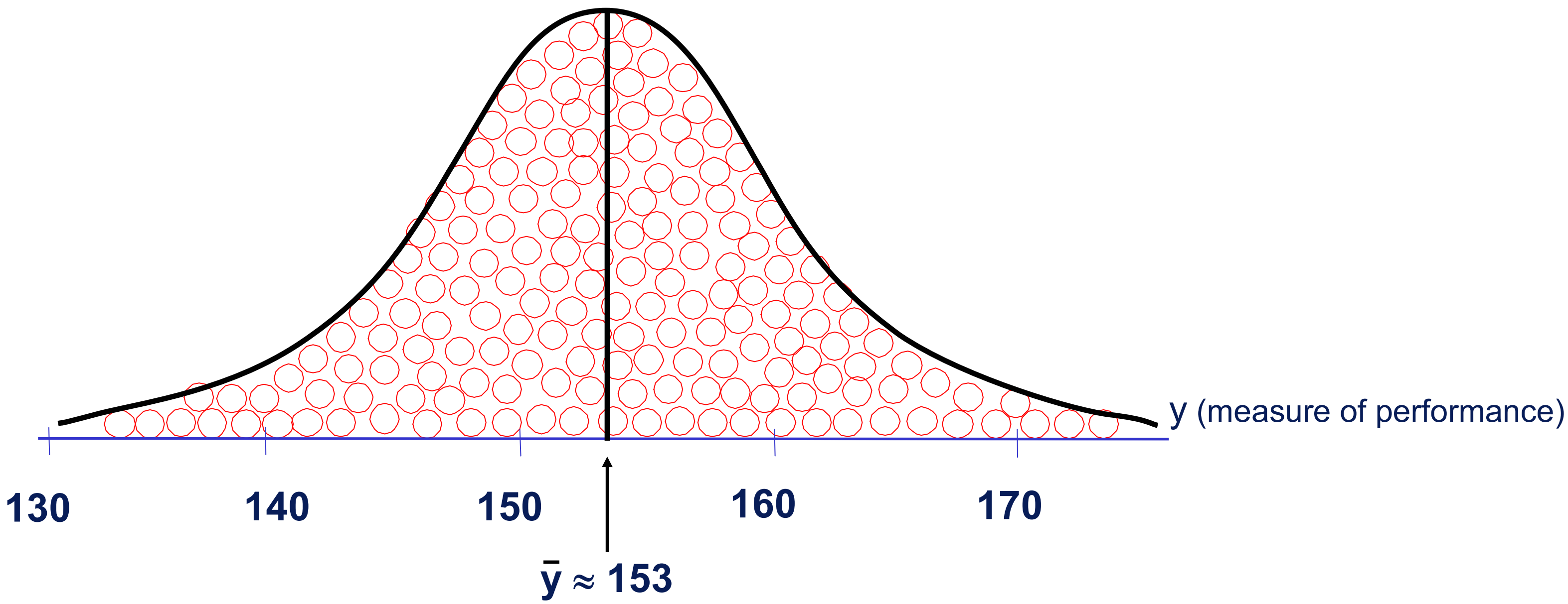
Graphical Meaning of $\bar{y}$



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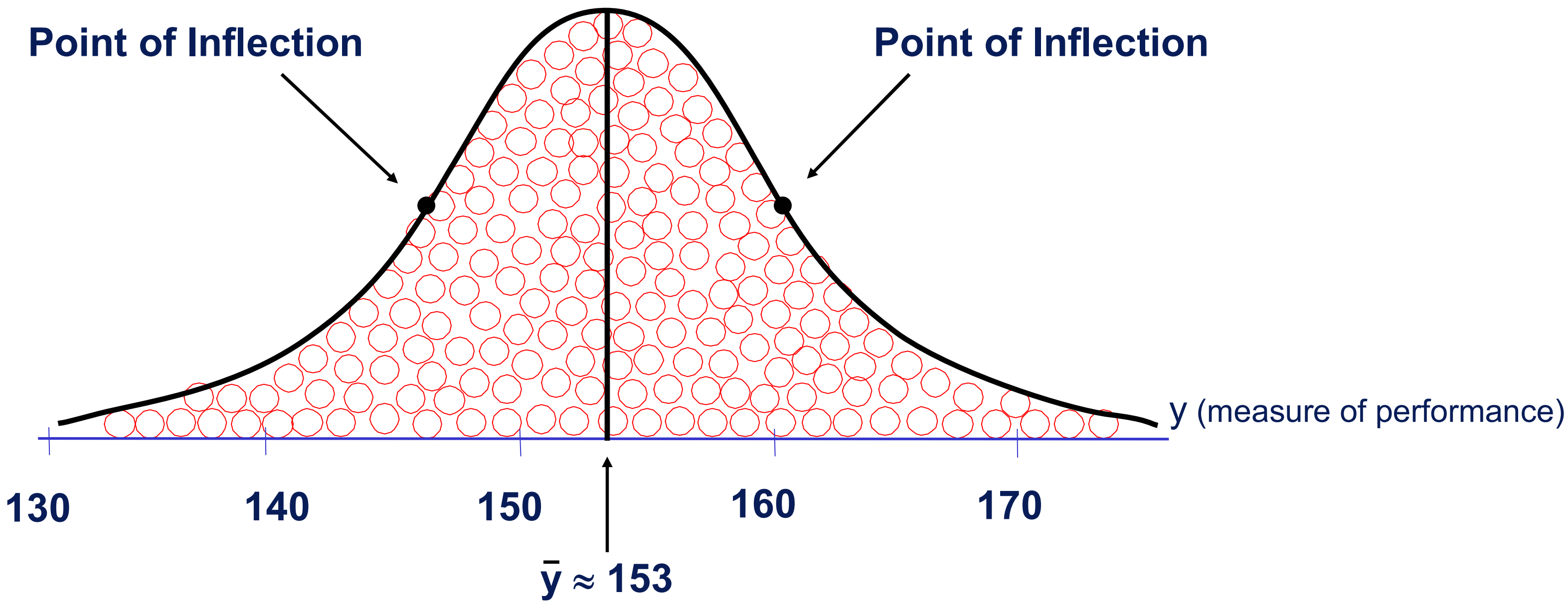
Graphical Meaning of Points of Inflection



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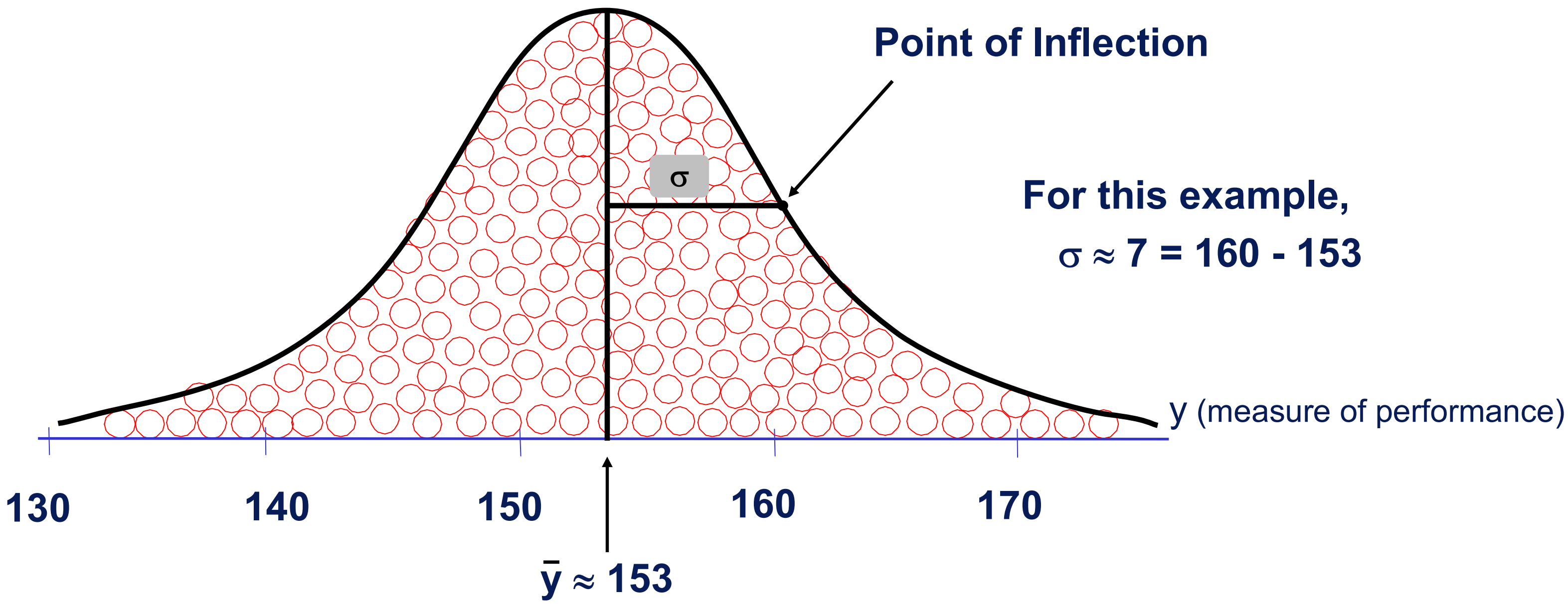
Graphical Meaning of σ

σ = distance from the center of the distribution to a point of inflection



For this example,

$\sigma \approx 7 = 160 - 153$

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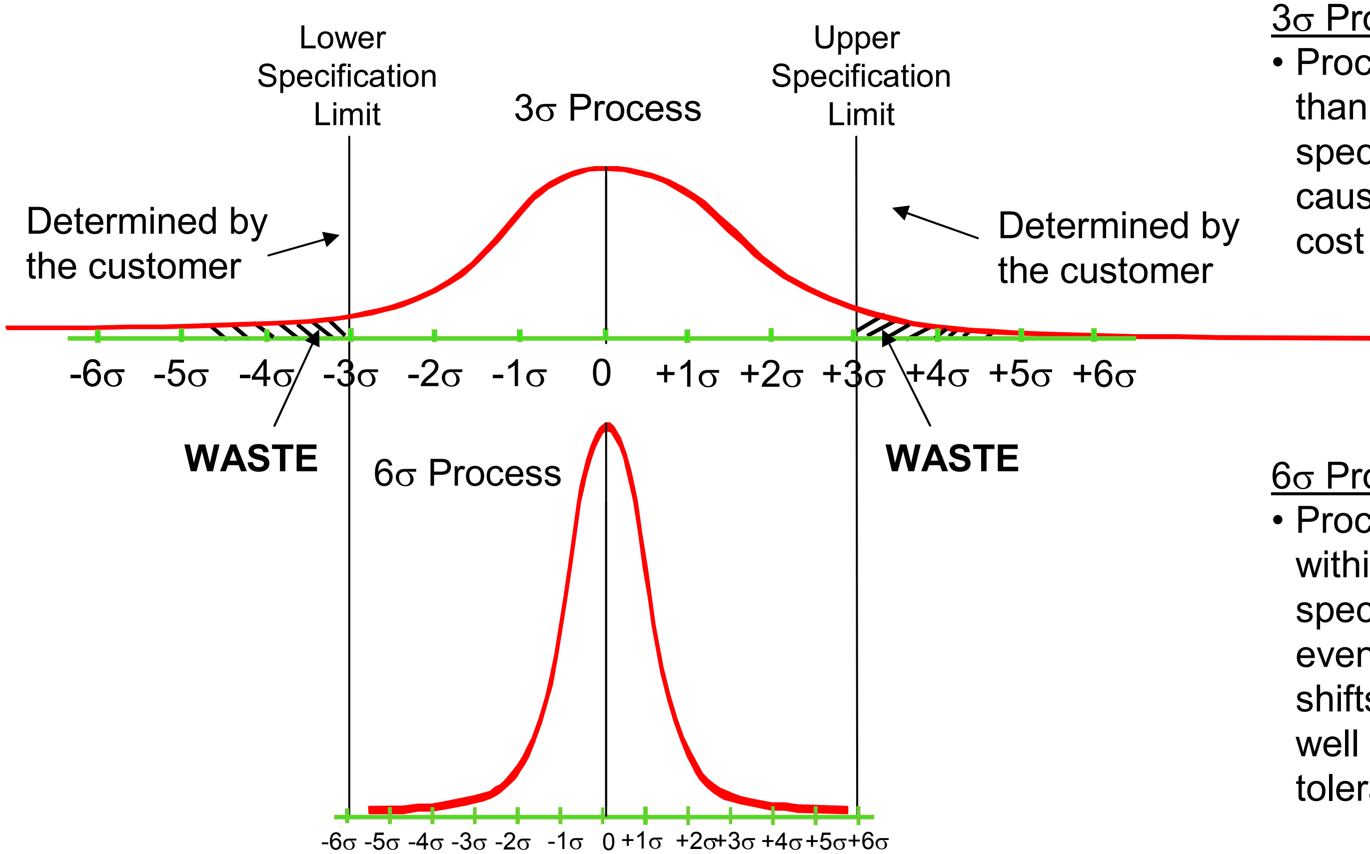
Graphical View of Variation and Six Sigma Performance

The Sigma Capability of a process performance measure compares the Voice of the Process with the Voice of the Customer, and it is defined as follows:

The number of Sigmas between the center of a process performance measure distribution and the nearest specification limit



<u>3σ Process Centered</u>

- Process is WIDER than the specifications, causing waste and cost of poor quality

<u>6σ Process Centered</u>

- Process FITS well within the specifications, so even if the process shifts, the values fall well within tolerances

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Food for Thought...

The systems and products that deliver value to our customers are perfectly designed to achieve the results we are getting today.

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DFSS – What is it?

Design For Six Sigma is:

- **A methodology for designing new products and/or processes.**
- **A methodology for re-designing existing products and/or processes.**
- **A way to implement the Six Sigma methodology as early in the product or service life cycle as possible.**
- **A way to exceed customer expectations.**
- **A way to gain market share.**
- **A strategy toward extraordinary ROI.**

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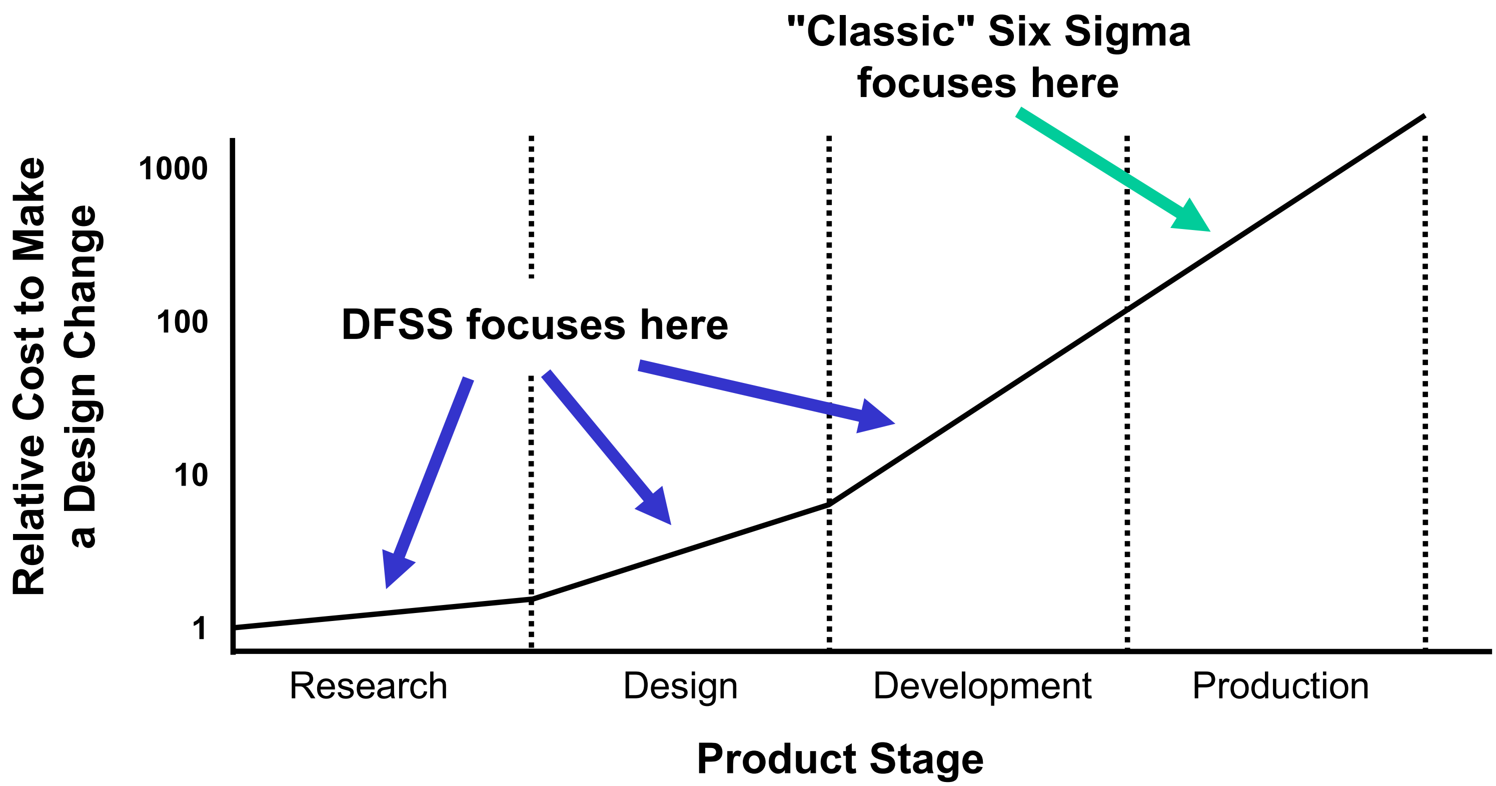
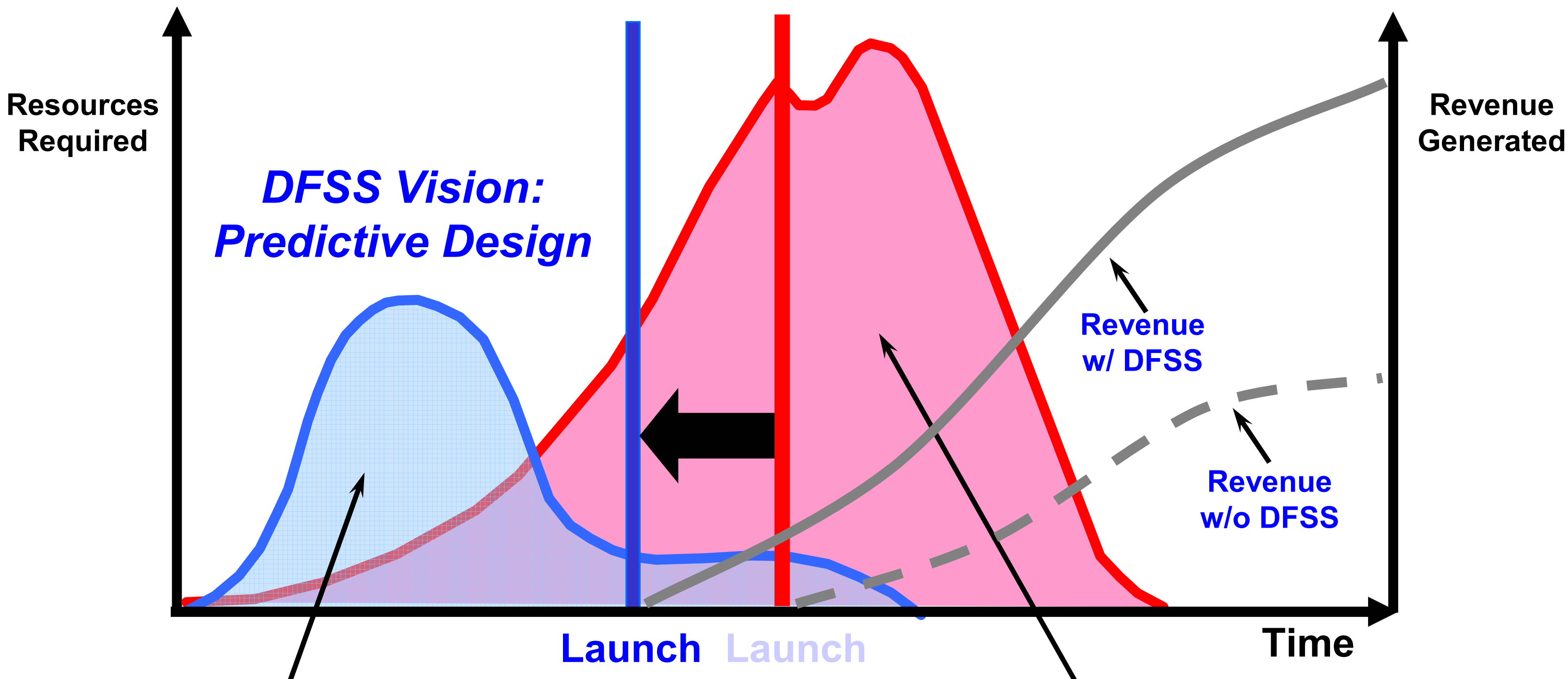
Why DFSS



- "Design in" quality when costs are lowest
- Show customers “Six Sigma” products right from the start

The Opportunity of DFSS



- Early problem identification; solution when costs low
- Faster market entry: earlier revenue stream, longer patent coverage
- Lower total development cost
- Robust product at market entry: delighted customers
- Resources available for <u>next</u> game-changer

Pre-DFSS: Reactive Design

- Unhappy customers
- Unplanned resource drain
- Skyrocketing costs
- Next product compromised

- **Upfront investment is most effective and efficient**
- **Show customers "6σ" products right from the start**

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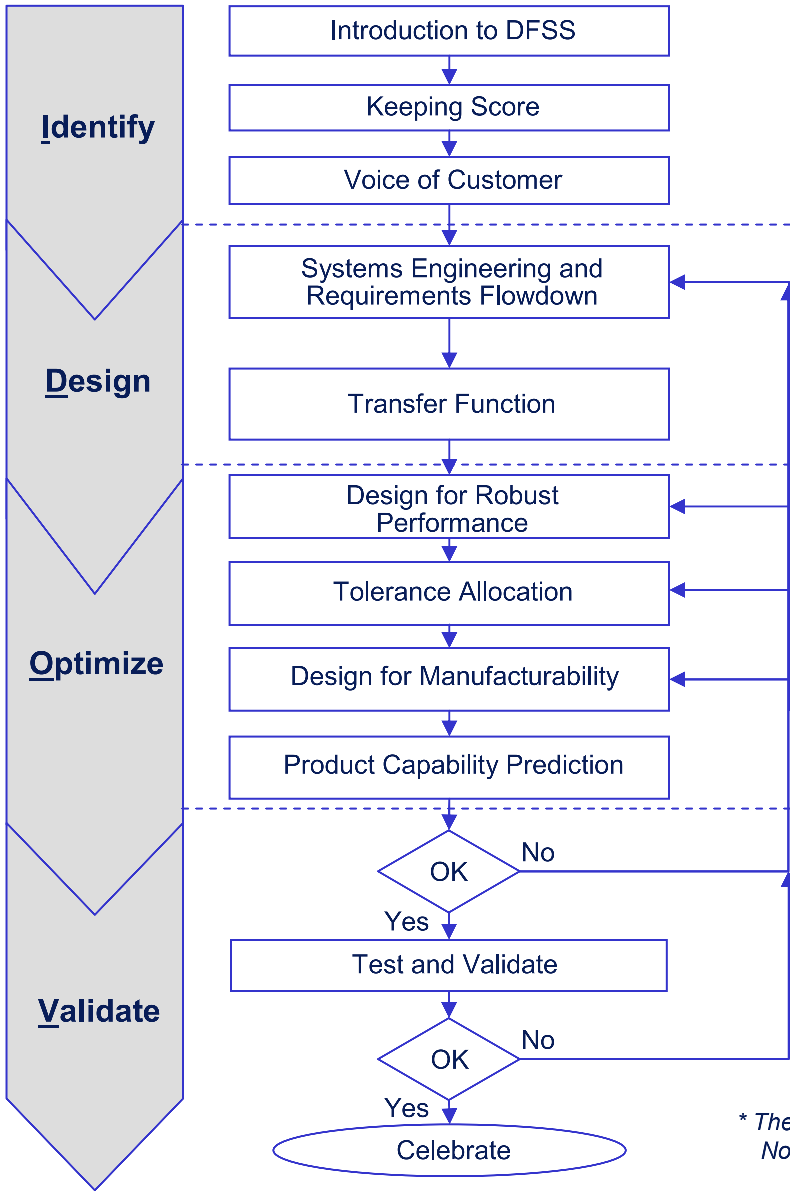
The DFSS Process: IDOV



- Market Assessment / ID New Markets
- Competitive Assessment / Benchmarking Results
- Prioritization of Ideas
- Strategic Alignment
- Prioritized Customer Requirements
- Prioritized CTC's
- House of Quality #1
- Initial Performance Scorecard
- Validate Customer Needs

- Concept Development
- Preliminary Design Risk Assessment
- Prioritized Product Design Characteristics
- House of Quality #2
- Performance/Process Scorecard
- Transfer Function(s)

- Process Development
- Assess Manufacturability
- Process Capability Studies
- Reliability Studies
- Capability Flowup
- Optimal Design
- Tolerances on X's
- Complete Scorecard
- Virtual Prototype

- Prototypes
- Process Validation
- Product Validation
- Capable Product and Process
- Sensitivity Analysis and Control Plans
- Commercialization Support

** The **IDOV** four-phase DFSS process originated with Dr. Norm Kuchar at GE CRD and is used with permission.*

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DFSS Tools

Identify

- Project Charter
- Strategic Plan
- Cross-Functional Team
- Voice of the Customer
- Benchmarking
- KANO's Model
- Questionnaires
- Focus Groups
- Interviews
- Internet Search
- Historical Data Analysis
- Design of Experiments
- Quality Function Deployment
- Pairwise Comparison
- Analytical Hierarchy Process
- Performance Scorecard
- Flow Charts
- FMEA
- Visualization

Design

- Assign Specifications to CTC's
- Customer Interviews
- Formulate Design Concepts
- Pugh Concept Generation
- TRIZ or ASIT
- FMEA
- Fault Tree Analysis
- Brainstorming
- QFD
- Scorecard
- Transfer Function
- Design of Experiments
- Deterministic Simulators
- Discrete Event Simulation
- Confidence Intervals
- Hypothesis Testing
- MSA
- Computer Aided Design
- Computer Aided Engineering

Optimize

- Histogram
- Distributional Analysis
- Empirical Data Distribution
- Expected Value Analysis (EVA)
- Adding Noise to EVA
- Non-Normal Output Distributions
- Design of Experiments
- Multiple Response Optimization
- Robust Design Development
  - Using S-hat Model
  - Using Interaction Plots
  - Using Contour Plots
- Parameter Design
- Tolerance Allocation
- Design For Manufacturability and Assembly
- Mistake Proofing
- Product Capability Prediction
- Part, Process, and SW Scorecard
- Risk Assessment
- Reliability
- Multidisciplinary Design Optimization (MDO)

Validate

- Sensitivity Analysis
- Gap Analysis
- FMEA
- Fault Tree Analysis
- Control Plan
- PF/CE/CNX/SOP
- Run/Control Charts
- Mistake Proofing
- MSA
- Reaction Plan
- High Throughput Testing

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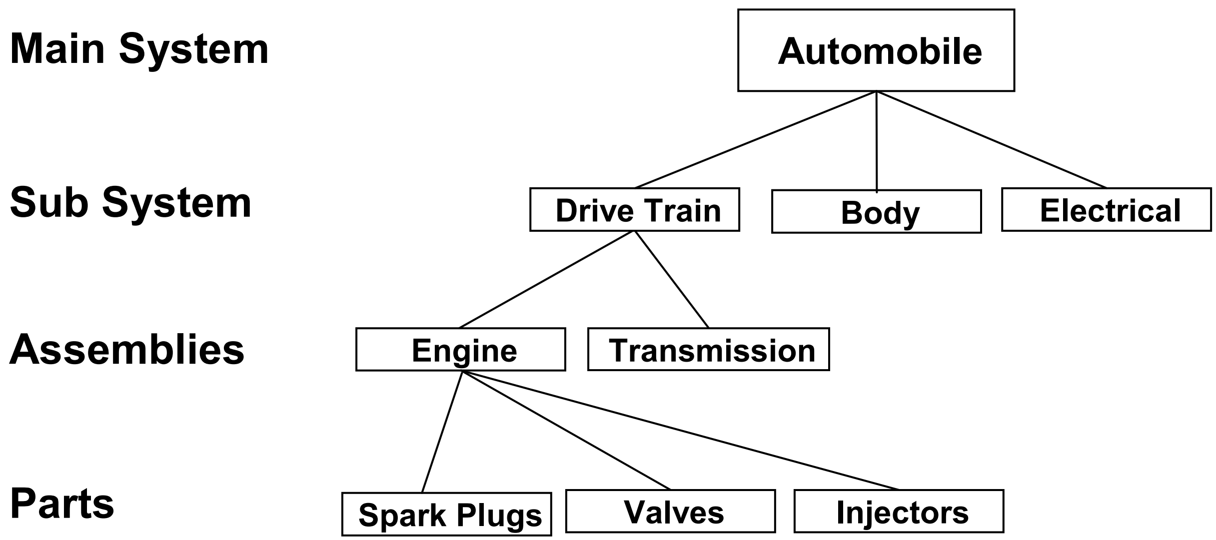
Systems Engineering



- Complex products may require the "Divide and Conquer" approach.
- Flow the system requirements down and roll the capability up.
- System Engineers are the masters of the scorecard and make tradeoff decisions.

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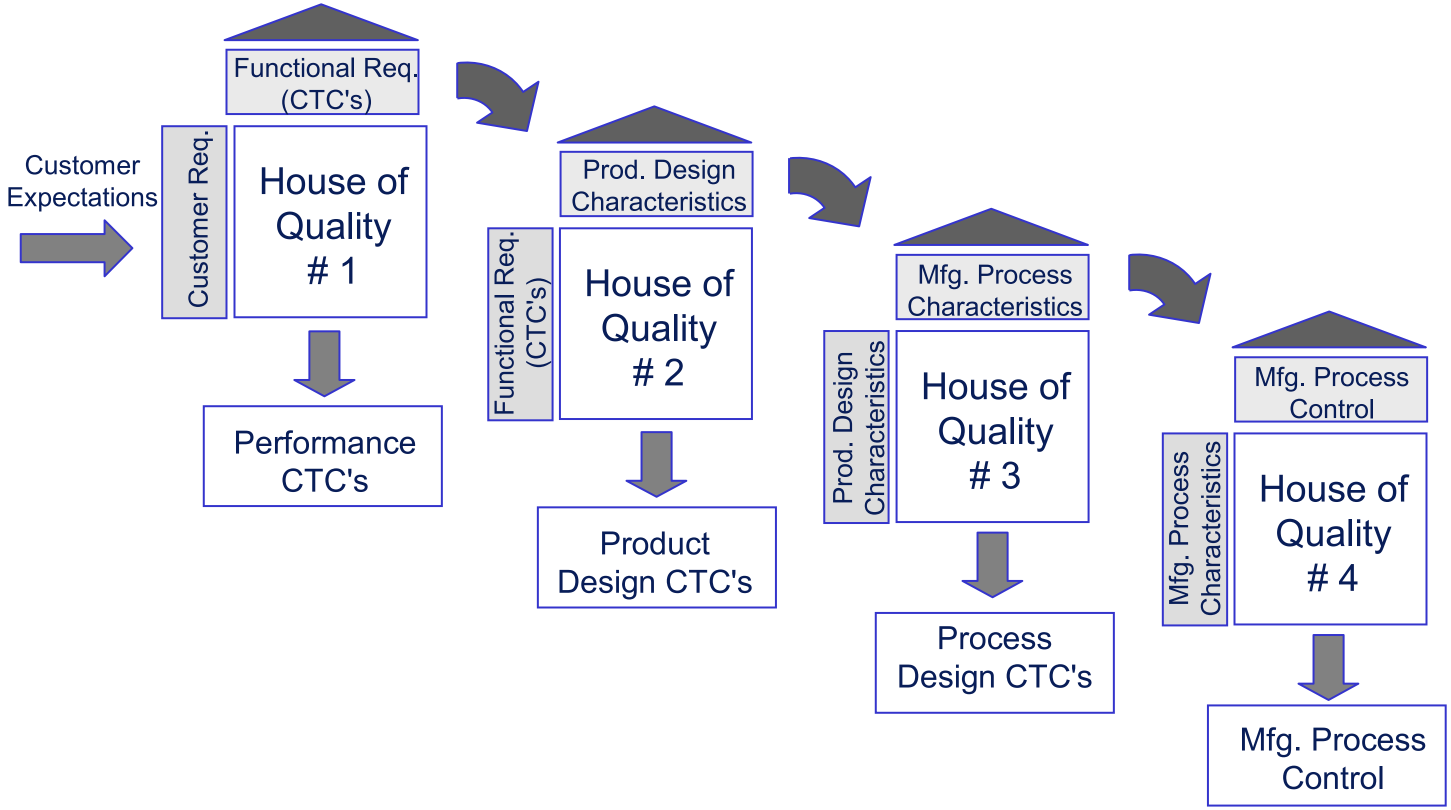
Flowing the Requirements Down



Marketing
- Features
- Quality
- Performance
- Cost

Design Engineering
- Performance
- Reliability
- Cost

Mfg. Engineering
- Manufacturability
- Cost

Manufacturing
- SPC
- Process Capability

DFSS

Six Sigma

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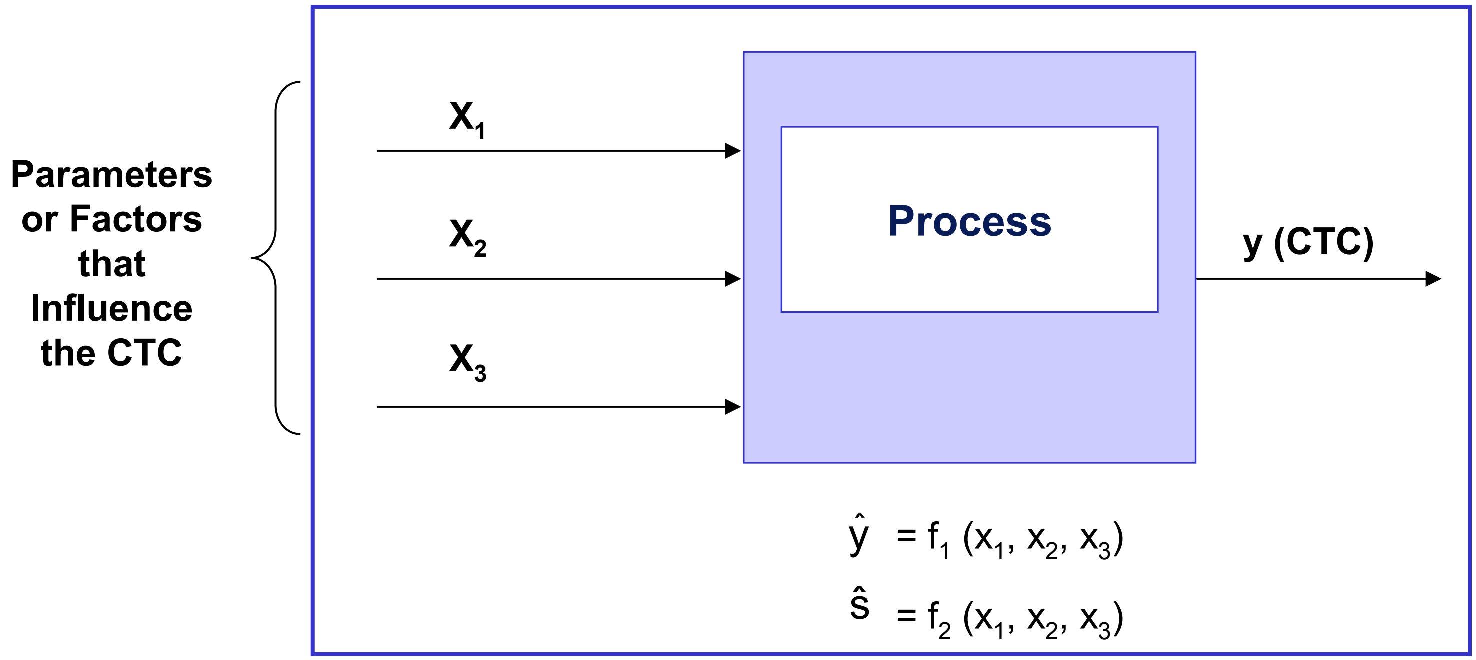
Transfer Functions



Where does the transfer function come from?

- Exact transfer Function
- Approximations
  - DOE
  - Historical Data Analysis
  - Simulation

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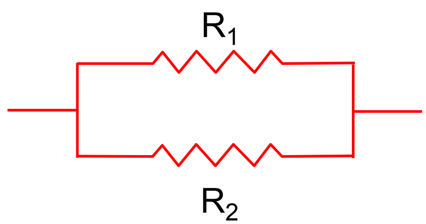
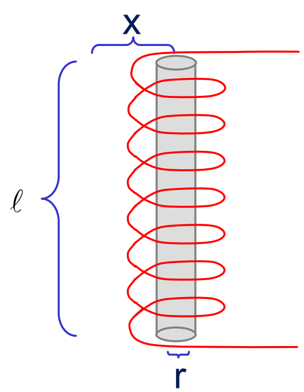
Exact Transfer Function

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



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

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



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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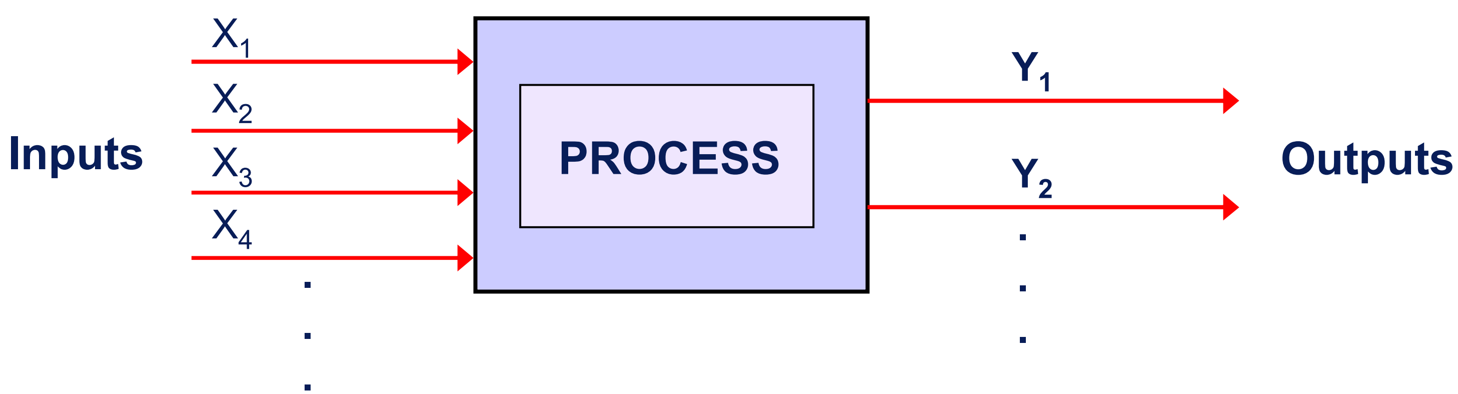
What Is a Designed Experiment?

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



Run	X_1	X_2	X_3	X_4	Y_1	Y_2	. . . . . .	$\bar{Y}$	S_Y
1									
2									
3									
.									
.									

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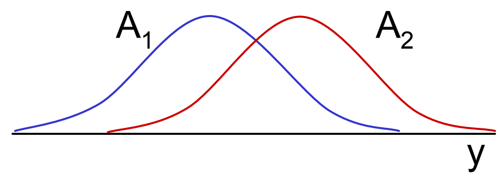
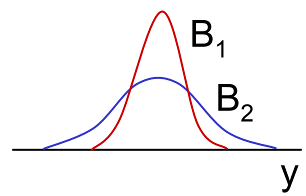
DOE Helps Determine How Inputs Affect Outputs

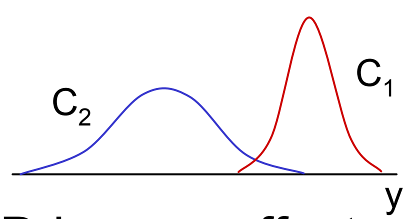
i) Factor A affects the average



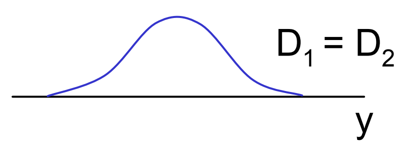
ii) Factor B affects the standard deviation



iii) Factor C affects the average and the standard deviation



iv) Factor D has no effect



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Minimizing the # of Factor Changes

(GRAY CODE SEQUENCE)

<u>Problem</u>: If changing factor settings is time consuming and/or expensive, using a Gray Code sequence to determine the sequence of runs may be useful. A Gray Code sequence orders the runs so that only 1 factor setting changes between runs and the most difficult to change factors are changed less frequently.

16-Run Design

Run	A	B	C	D
1	-	-	-	-
2	-	-	-	+
3	-	-	+	-
4	-	-	+	+
5	-	+	-	-
6	-	+	-	+
7	-	+	+	-
8	-	+	+	+
9	+	-	-	-
10	+	-	-	+
11	+	-	+	-
12	+	-	+	+
13	+	+	-	-
14	+	+	-	+
15	+	+	+	-
16	+	+	+	+

Gray Code by Run #
1
2
4
3
7
8
6
5
13
14
16
15
11
12
10
9

Cycling through the runs from top to bottom (or vice versa) will produce 15 changes:

- D will be changed 8 times.
- C will be changed 4 times.
- B will be changed 2 times.
- A will be changed 1 time.

Thus, the most difficult (or expensive) to change factors should be assigned to A, B, C, D, respectively.

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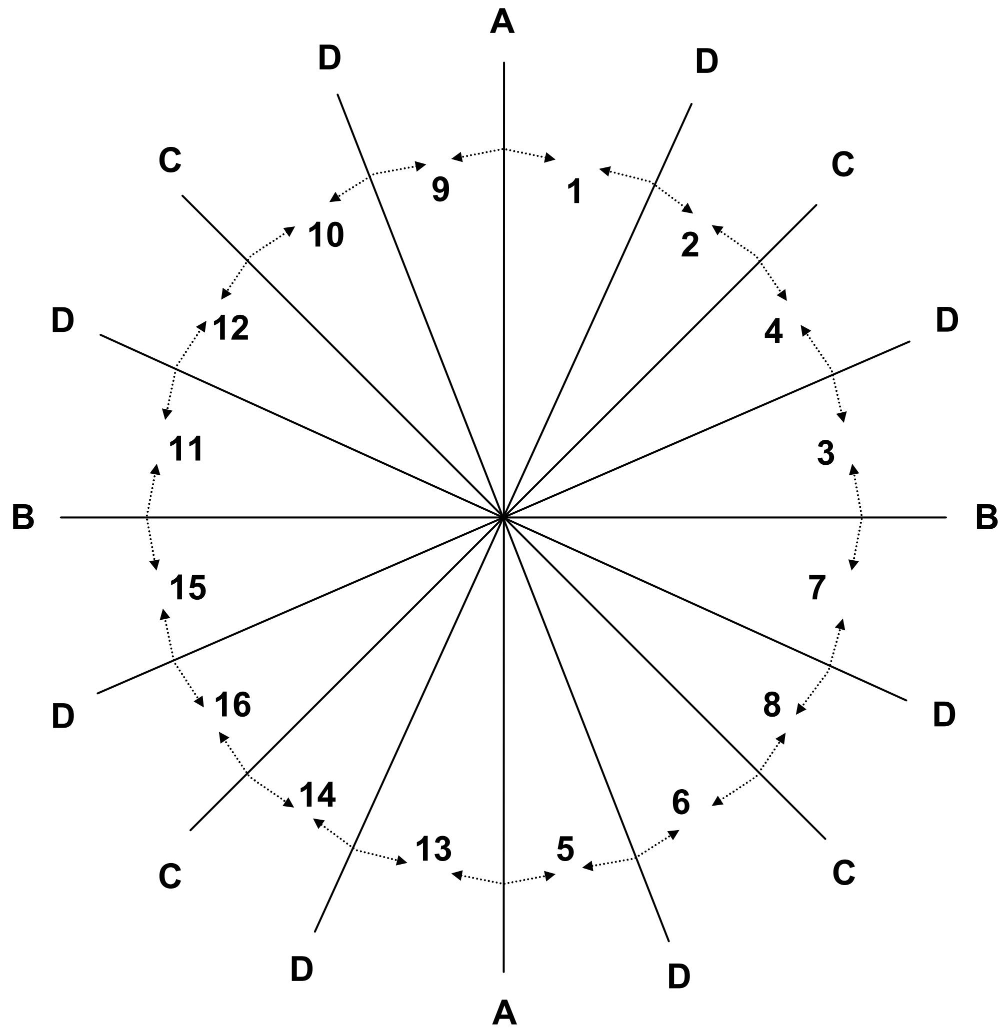
Test Sequence Generator



Gray Code Sequence Generator (Wheel)
by Run Number for 16 Runs and 4 Factors

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Simple DOE Augmentation to Possibly Reduce the Number of Tests

	FACTORS OF SECONDARY INTEREST		FACTORS OF PRIMARY INTEREST	
	A	B	C	D
TRIAL 1	-	-	-	-
TRIAL 2	-	-	-	+
TRIAL 3	-	-	+	-
TRIAL 4	-	-	+	+
TRIAL 5	-	+	-	-
TRIAL 6	-	+	-	+
TRIAL 7	-	+	+	-
TRIAL 8	-	+	+	+
TRIAL 9	+	-	-	-
TRIAL 10	+	-	-	+
TRIAL 11	+	-	+	-
TRIAL 12	+	-	+	+
TRIAL 13	+	+	-	-
TRIAL 14	+	+	-	+
TRIAL 15	+	+	+	-
TRIAL 16	+	+	+	+

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Building a Screening Design

L_{12} Design											
Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	+	+	+	+	+	+
3	-	-	+	+	+	-	-	-	+	+	+
4	-	+	-	+	+	-	+	+	-	-	+
5	-	+	+	-	+	+	-	+	-	+	-
6	-	+	+	+	-	+	+	-	+	-	-
7	+	-	+	+	-	-	+	+	-	+	-
8	+	-	+	-	+	+	+	-	-	-	+
9	+	-	-	+	+	+	-	+	+	-	-
10	+	+	+	-	-	-	-	+	+	-	+
11	+	+	-	+	-	+	-	-	-	+	+
12	+	+	-	-	+	-	+	-	+	+	-

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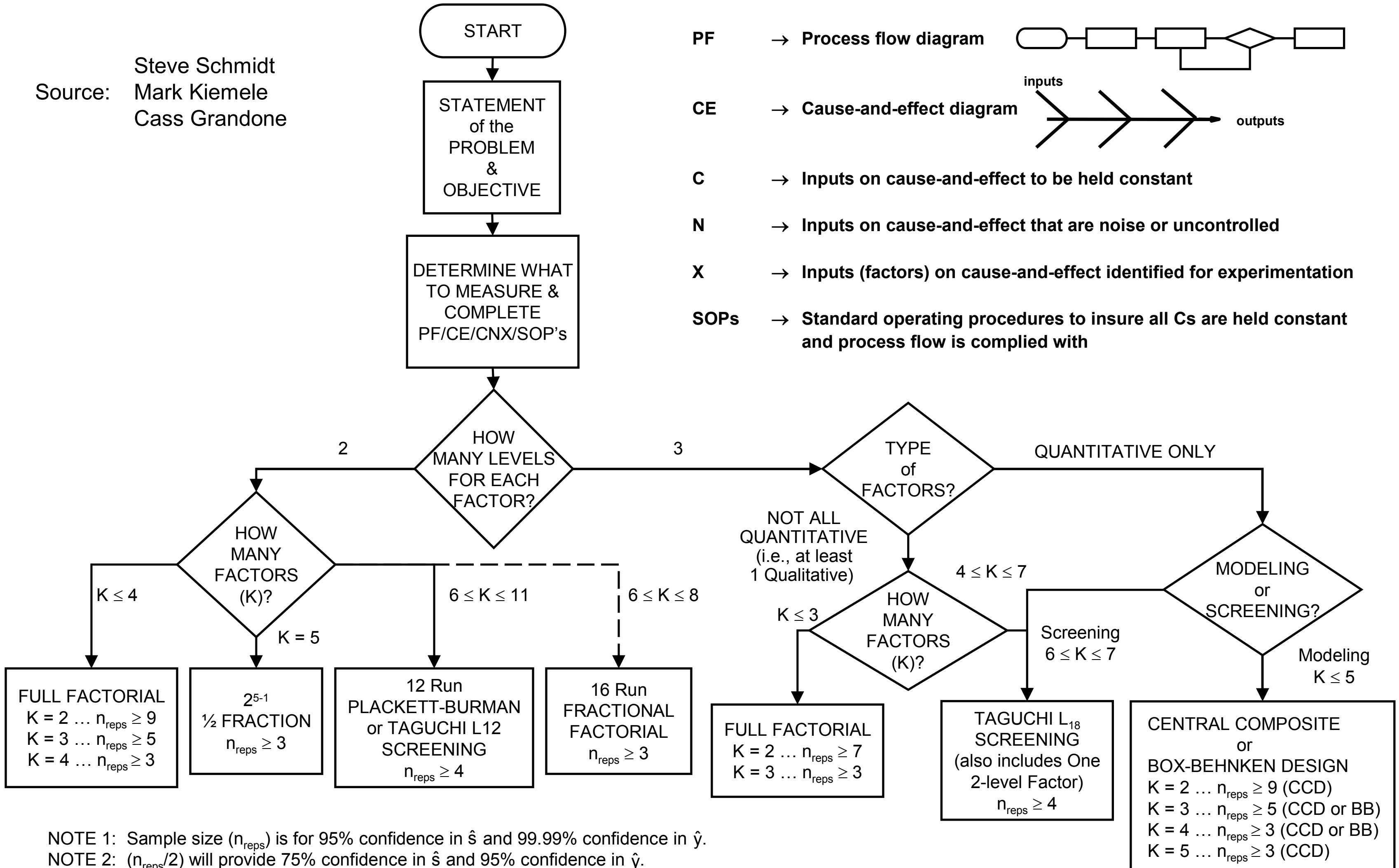
KISS Guidelines for Choosing an Experimental Design

KISS - Keep It Simple Statistically

Source: Steve Schmidt
Mark Kiemele
Cass Grandone



NOTE 1: Sample size (n_{reps}) is for 95% confidence in $\hat{s}$ and 99.99% confidence in $\hat{y}$.
NOTE 2: (n_{reps}/2) will provide 75% confidence in $\hat{s}$ and 95% confidence in $\hat{y}$.
NOTE 3: The 12 Run Plackett-Burman or L12 is very sensitive to large numbers of interactions. If this is the case, you would be better off using the 16 Run Fractional Factorial or a smaller number of variables in 2 or more full factorial experiments.
NOTE 4: For more complete 2-level design options, see next page.

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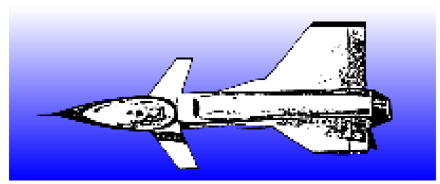
Value Delivery: Reducing Time to Market for New Technologies



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**

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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)

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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, IT (see IT example on next page)

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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.

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High Throughput Testing (HTT)

(for all two-way combinations)

Full Factorial = 8100 runs   HTT = 25 runs

	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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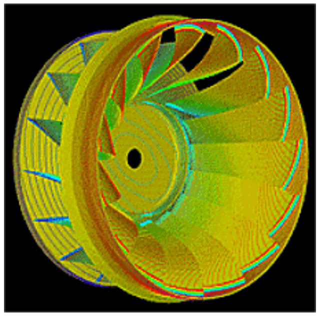
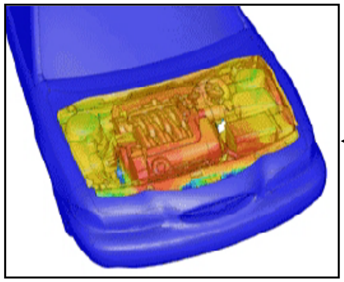
Examples of Simulation and High Performance Computing (HPC)

Power

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



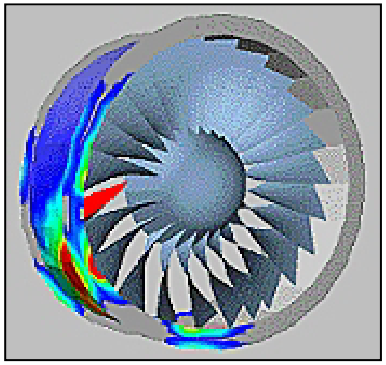
Automotive



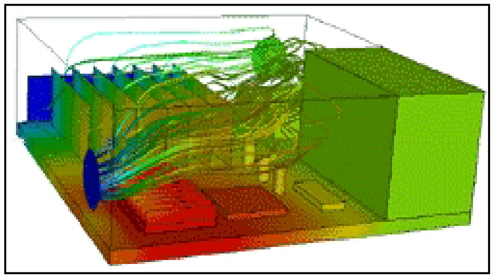
Simulation of underhood thermal cooling for decrease in engine space and increase in cabin space and comfort

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

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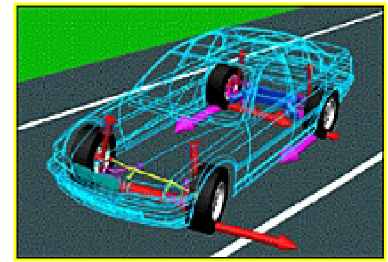
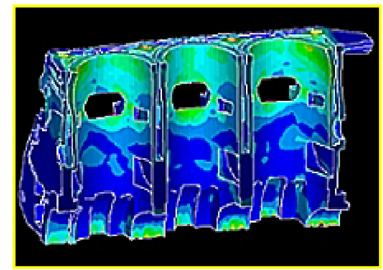
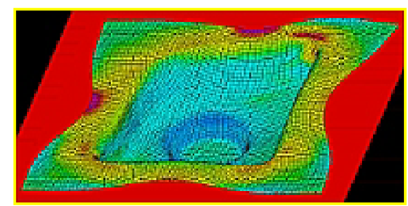
Examples of Computer Aided Engineering (CAE) and Simulation Software



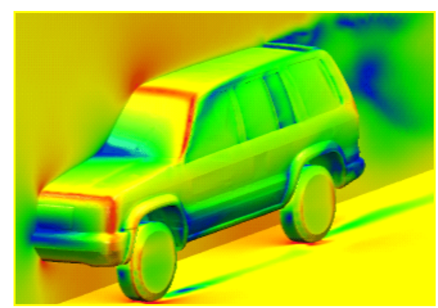
Mechanical motion: Multibody kinetics and dynamics
- ADAMS®
- DADS



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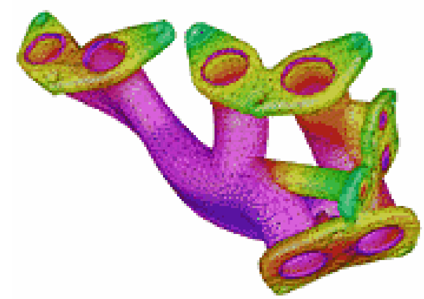
Examples of Computer Aided Engineering (CAE) and Simulation Software (cont.)

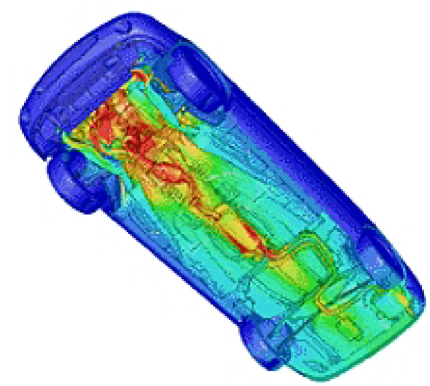
Preprocessing: Finite Element Analysis and Computational Fluid Dynamics mesh generation

- 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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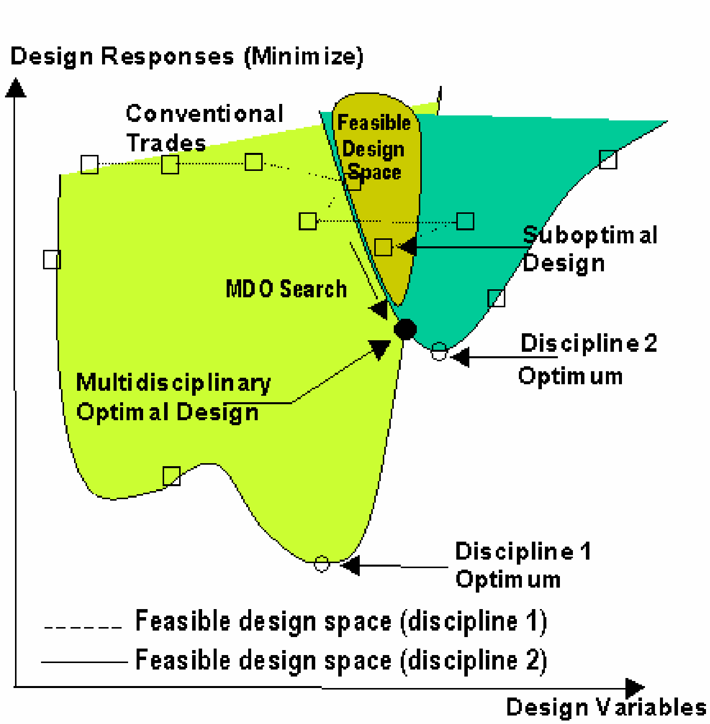
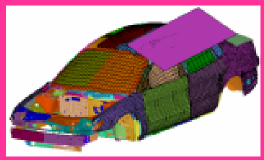
Multidisciplinary Design Optimization (MDO): A Design Process Application



- CFD
- Structures
- Performance
- Controls
- Cost



- 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

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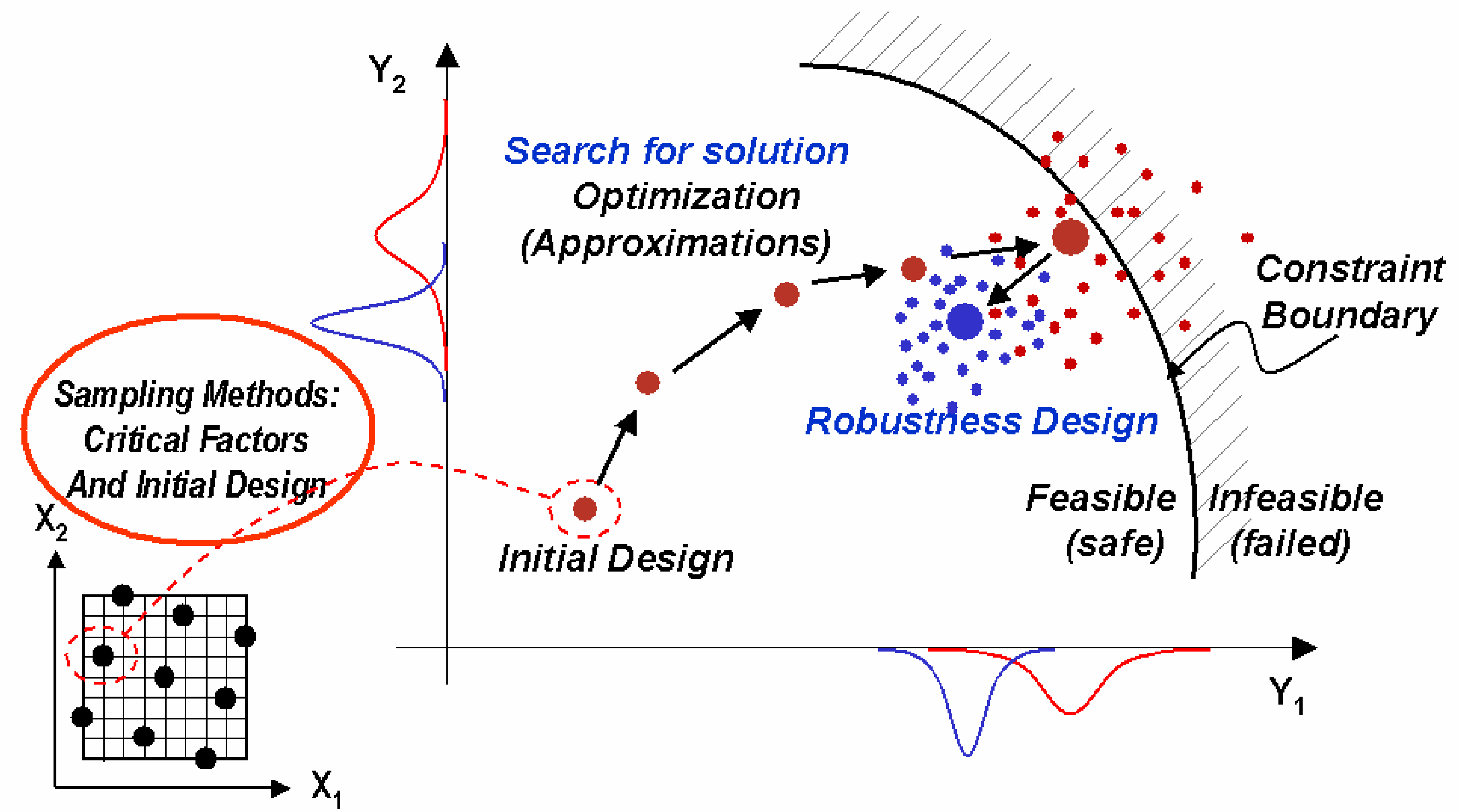
MDO: A Design Improvement Process



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DFSS/MDO Process for Automotive Vehicle Design

IDENTIFY CTCs, CDPs → 300 x's → **SCREENING DESIGN (DOE PRO)** → 50 x's; CTCs, CDPs

NASTRAN RADIOSS MADYMO

Integrated processes with high fidelity CAE analyses on HPC servers

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) — RADIOSS, DYNA, MADYMO:

- 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

no federal requirements on these CTCs:

- y_9 = internal aerodynamics (airflow) — CFD
- y_{10} = external aerodynamics (airflow) — CFD
- y_{11} = noise — NASTRAN
- y_{12} = vibration (e.g., steering wheel) — NASTRAN
- y_{13} = harshness (e.g., over bumps, shocks) — NASTRAN
- y_{14} = durability (at 100K miles) — NASTRAN

Examples of Critical Design Parameters (CDPs or Xs):

x_1 = roof panel material

x_2 = roof panel thickness

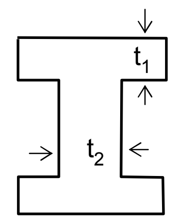
x_3 = door pillar dimensions ⇒ i beam

x_4 = shape/geometry

x_5 = windshield glass

x_6 = hood material, sizing and thickness

x_7 = under hood panel material, sizing and thickness



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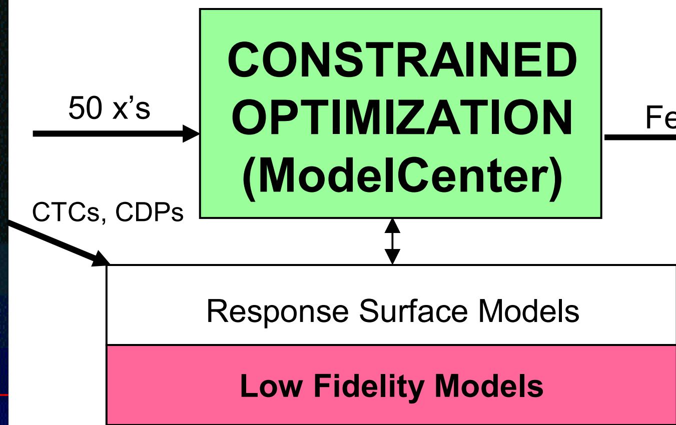
DFSS/MDO Process for Automotive Vehicle Design (cont.)



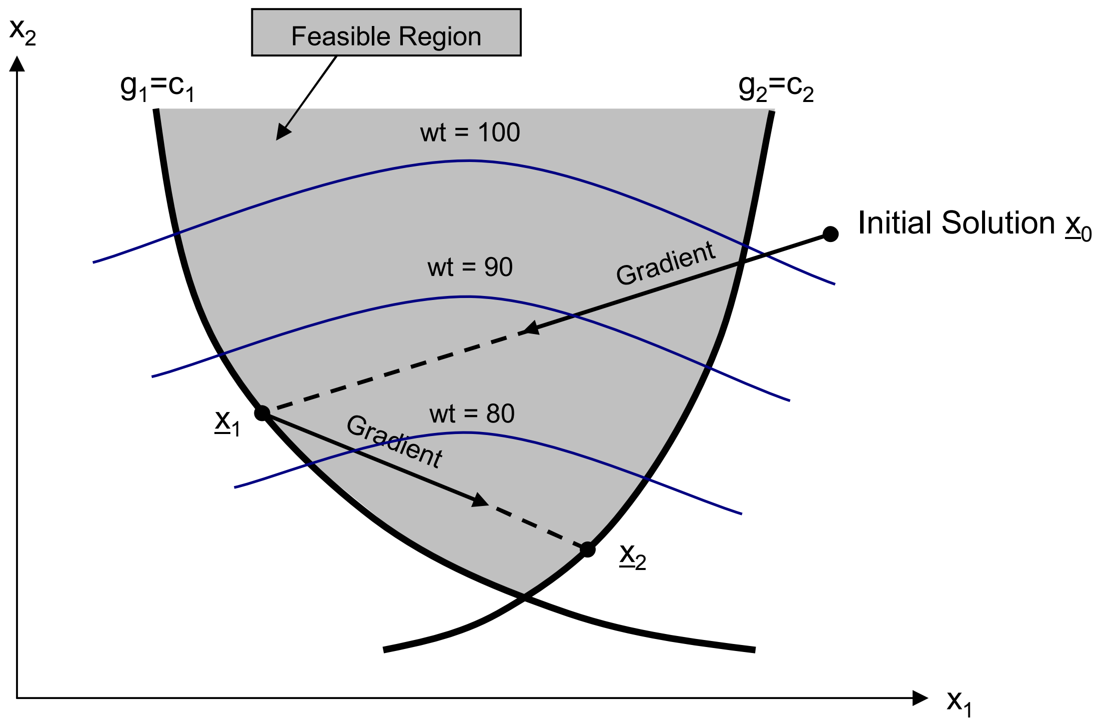
Example

y_1 = Weight (wt)

g_1 = Safety (Constraint: $g_1 \leq c_1$)

g_2 = NVH (Constraint: $g_2 \leq c_2$)

Assume y_1, g_1, and g_2 are all functions of x_1, x_2



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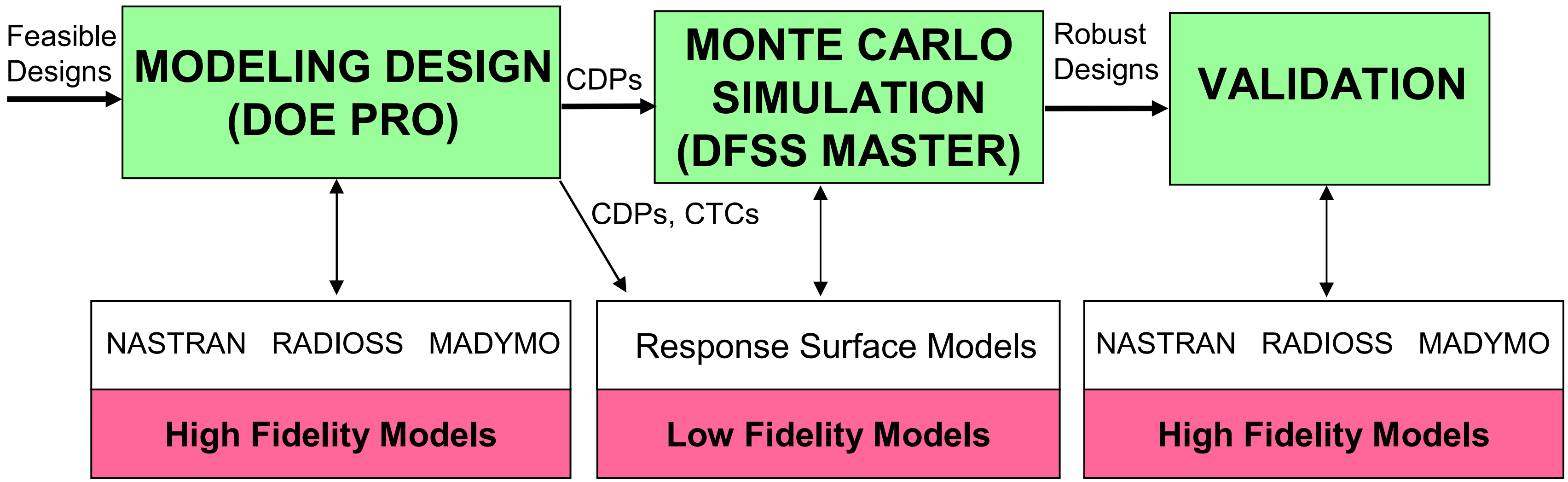
DFSS/MDO Process for Automotive Vehicle Design (cont.)



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Environments Where MDO/HPC Is Beneficial

Design of complex vehicles & systems results in a simulation environment with:

- **A high number of design variables**
- **A substantial number of design subsystems and engineering disciplines**
- **Interdependency and interaction between the subsystems**
- **High resolution, complex models across several engineering disciplines**

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Risk Assessment

- Assess risks of key areas: technology, cost, schedule, market, etc.
- Use formal tools: FMEA, etc.
- Quantify risks: probability of failure and impact of failure
- Formulate responsive projects to reduce high risks
- Track progress with quantitative risk "waterfall"

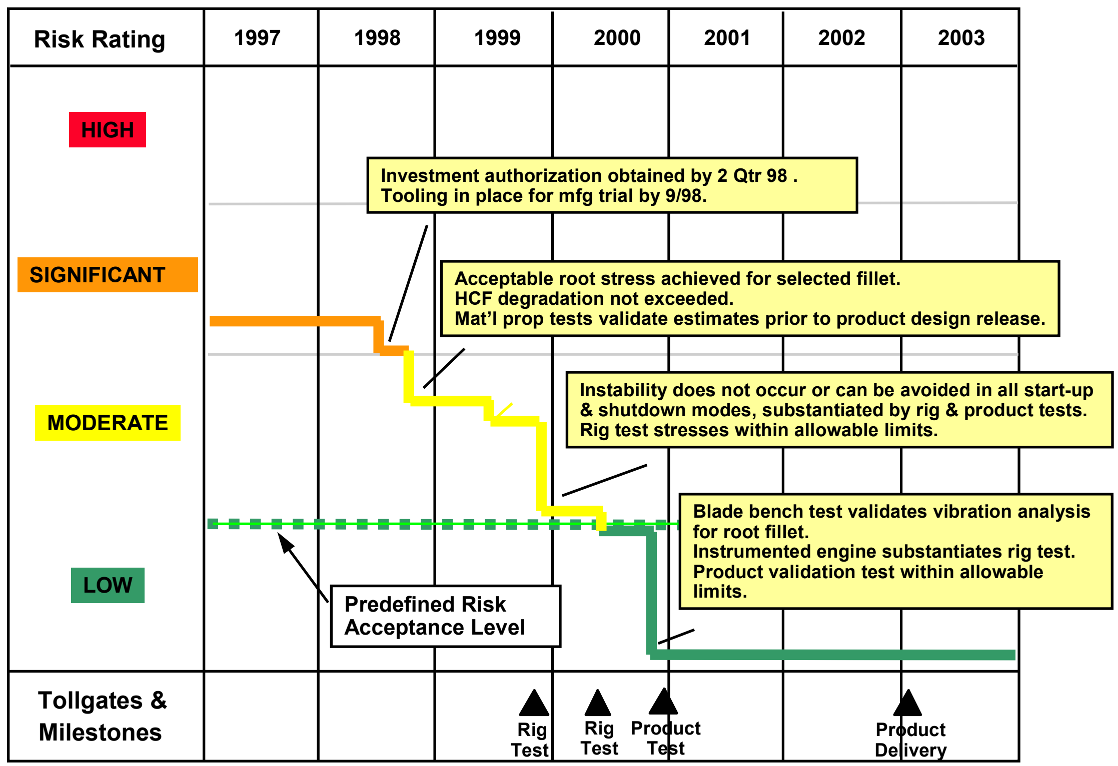
Quantifying Risk

Probability of Failure	1 (Low)	3	5 (High)
High 5	5	15	25
3	3	9	15
Low 1	1	3	5

Impact of Failure

- R Show stopper
- O Significant risk
- Y Fix before production
- G Proceed with caution

Tracking Risk



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Characteristics of a Successful DFSS Implementation

- **Commitment and leadership from the top**
- **Measurable, "stretch" goals for each project**
- **Accountability for project success**
- **Involvement and support of *everyone***
- **Training and implementing an extremely powerful, yet easy-to-use toolset for predicting quality and making tradeoffs before the product or process is even built**

> - **It's very easy to focus on the last item...**
> - **But, the first four – involving *leadership* and *cultural change* – are even more critical for success**

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For Further Information, Please Contact:

Air Academy Associates, LLC

1650 Telstar Drive, Ste 110
Colorado Springs, CO 80920

Toll Free: (800) 748-1277 or (719) 531-0777
Facsimile: (719) 531-0778
Email: aapa@airacad.com
Website: www.airacad.com

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