DESIGN OPTIMIZATION

EGR 7040

Mechanical & Materials Engineering Department

Wright State University

Lesson 01

- Welcome & Introduction
- Course Objectives
- Pedagogy & Course Administration
- Overview of "Design Optimization"

Welcome & Introduction

- **Your instructor**
  - J. A. Camberos, Ph. D., P. E.
  - Research aerospace engineer, currently University Relations Manager for AFRL
  - Technical background includes mechanical and materials engineering (fluid thermophysics), aerospace engineering (hypersonics, MDAO)
  - Interests include history & philosophy of science
- **Your classmates**
  - Class composition ~ 34 graduates, mostly 1st year
  - Aerospace, electrical, mechanical, materials, structural,…

Course Objectives

- Introduce concept of design optimization
- Develop understanding of basic, systematic problem formulation
- Develop problem solving skills
- Develop technical writing and speaking talent

Pedagogy

- PILOT – online courseware tool
- Homework
- Exams (Quizzes)
- Project
  - Written technical report
  - Oral technical presentation
- Final Exam
- Use of Excel and MATLAB

Homework	20 %
Project + Presentation	40 %
Quizzes (2)	20 %
Final Exam	20 %

Design Optimization

Design

- ***Designare***
  - Latin root word, 16th century English/French
- Designate
- Design
- …

en.wikipedia.org/wiki/Design

Optimization

- ***Optimus***
  - Latin root word, 19th Century
- Optimum
- Optimize
- Optimism
- Optimist
- …

Design Optimization

Realization of a concept or idea into a configuration, drawing, model, mold, pattern, plan or specification (on which the actual or commercial production of an item is based) and which helps achieve the item's designated objective(s).

http://www.businessdictionary.com/definition/design.html

Ubiquitous

- **Laplace:**
  - "…les questions les plus importantes de la vie ne sont en effet, pour la plupart, que des problèmes de probabilité."
- **Translation:**
  - "…the most important questions of life which are indeed, for the most part, only problems of probability."

OPTIMIZATION

- "Saving even a few pounds of a vehicle's weight... could mean that they would also go faster and consume less fuel. Reducing weight involves reducing materials, which, in turn, means reducing cost as well."

  – Henry Ford, 1923

- *Today, we have the tools to make this happen.*

THE VALUE OF OPTIMIZATION?

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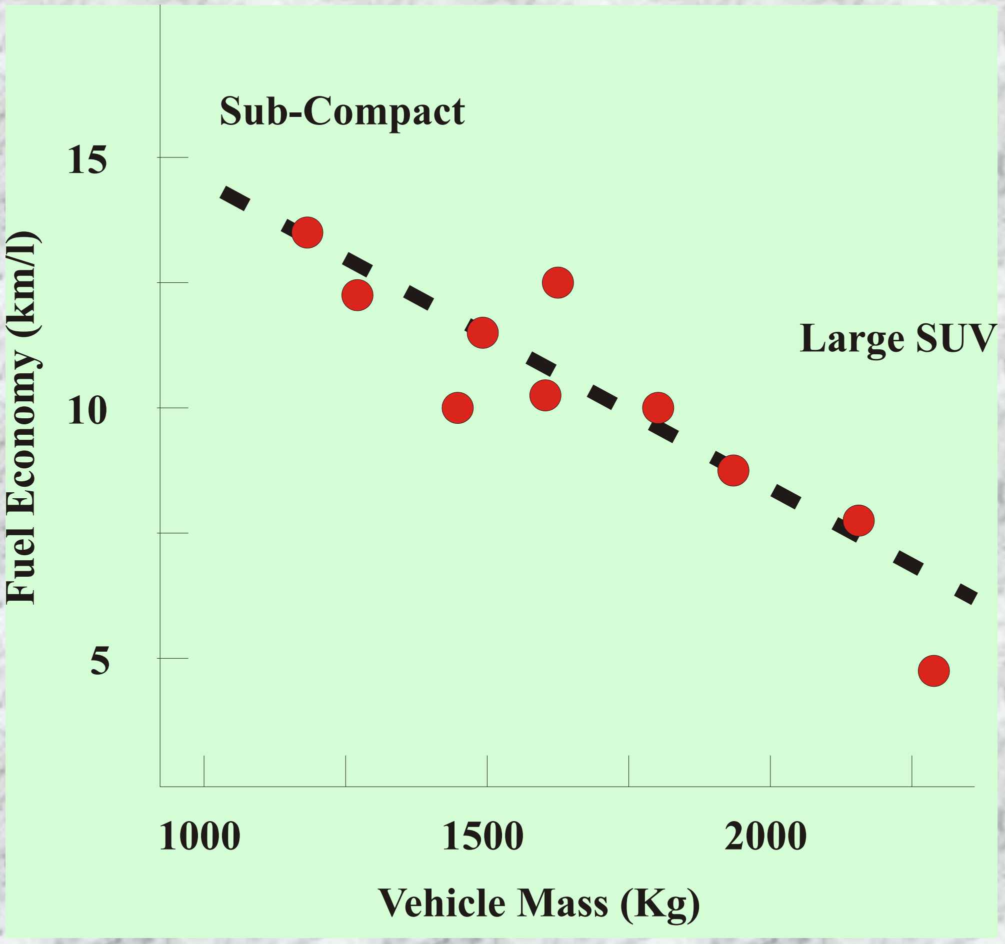
- Quotes from Terrance Weisshaar, DARPA Program Manager, at the AIAA SDM Conference, Austin TX 2005

"MDO is Not Ready for Prime Time"

"Single Discipline Optimization is Just Pocket Change"

AUTOMOBILE MASS vs. FUEL CONSUMPTION

- 50% mass reduction ~100% improvement in mileage
  - Performance is Much Different
- DOE indicates 10% mass reduction ~ 7% increase in mileage



THE VALUE OF OPTIMIZATION

- One Percent mass reduction on all motor vehicles in the U.S. would save $4,000,000,000/yr in fuel
- 100 Kg mass reduction on a 200 passenger aircraft
  - Adds a passenger for the life of the aircraft
  - Reduces per passenger mile air pollution by ½%
- 20 Kg mass reduction on a spacecraft adds a lifesaving medical wxperiment
- Is this "Pocket Change" ?!?

OPTIMIZATION

What is it?

A GENERAL AUTOMATED DESIGN TECHNIQUE

OPTIMIZATION

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What does it do?

Automatically Changes Important Parameters to Find the "Best Design" Satisfying Certain Criteria

OPTIMIZATION

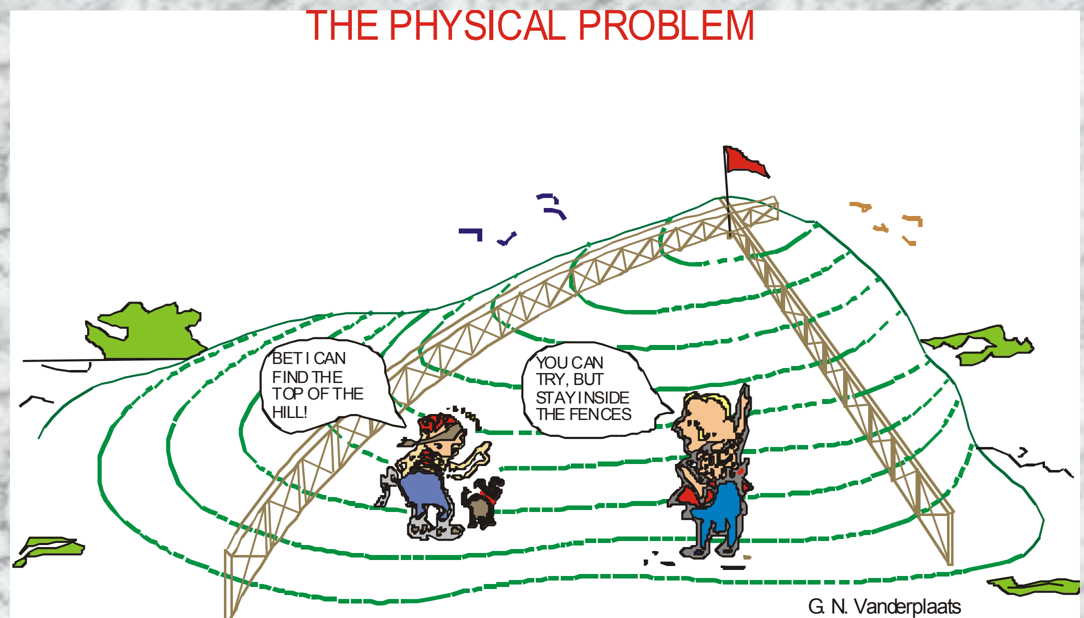
Why should we use it?

- Reduce Design Time
- Improve Design Quality
- Free up Engineer for Creative Work
- ...

Describing the Problem

- **OBJECTIVE:** FIND THE HIGHEST POINT
- **DESIGN VARIABLES**: LONGITUDE & LATITUDE
- **CONSTRAINTS:** STAY INSIDE THE FENCES
  - YOU MAY START OUTSIDE THE FENCES

Locate the top of the hill while blindfolded!

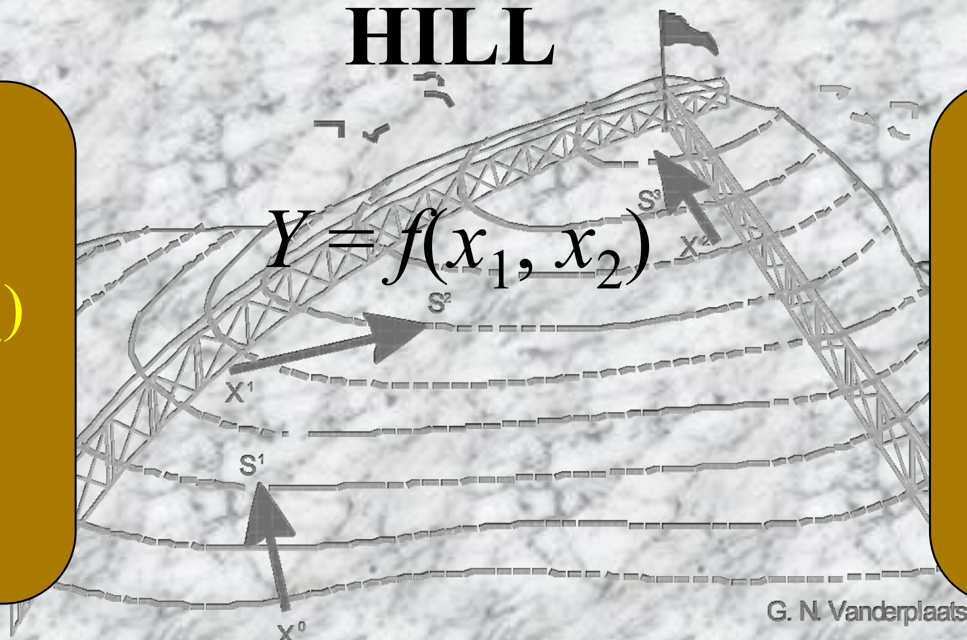


https://www.vrand.com/education.html

The Engineering Problem

- The physical problem can be defined mathematically
  – By convention, < means "inside the fences"

HILL



$$Y = f(x_1, x_2)$$

Fence No. 1

$F_1 = f_1(x_1, x_2)$

< 0 Inside
> 0 Outside

Fence No. 2

$F_2 = f_2(x_1, x_2)$

< 0 Inside
> 0 Outside

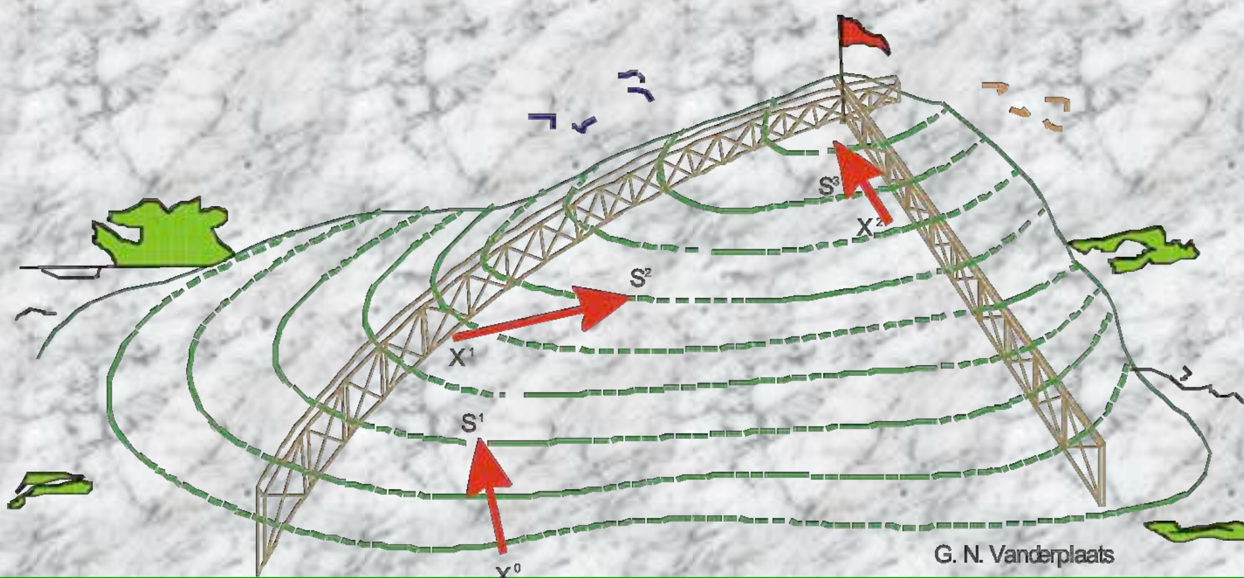
The Optimization Problem

- Objective Function: $$Y = f\left(X_1, X_2\right)$$
- Subject to Constraints: $$F_1 = f_1\left(X_1, X_2\right) \leq 0$$ $$F_2 = f_2\left(X_1, X_2\right) \leq 0$$
- Given Design Variables: $$\left(X_1, X_2\right)$$

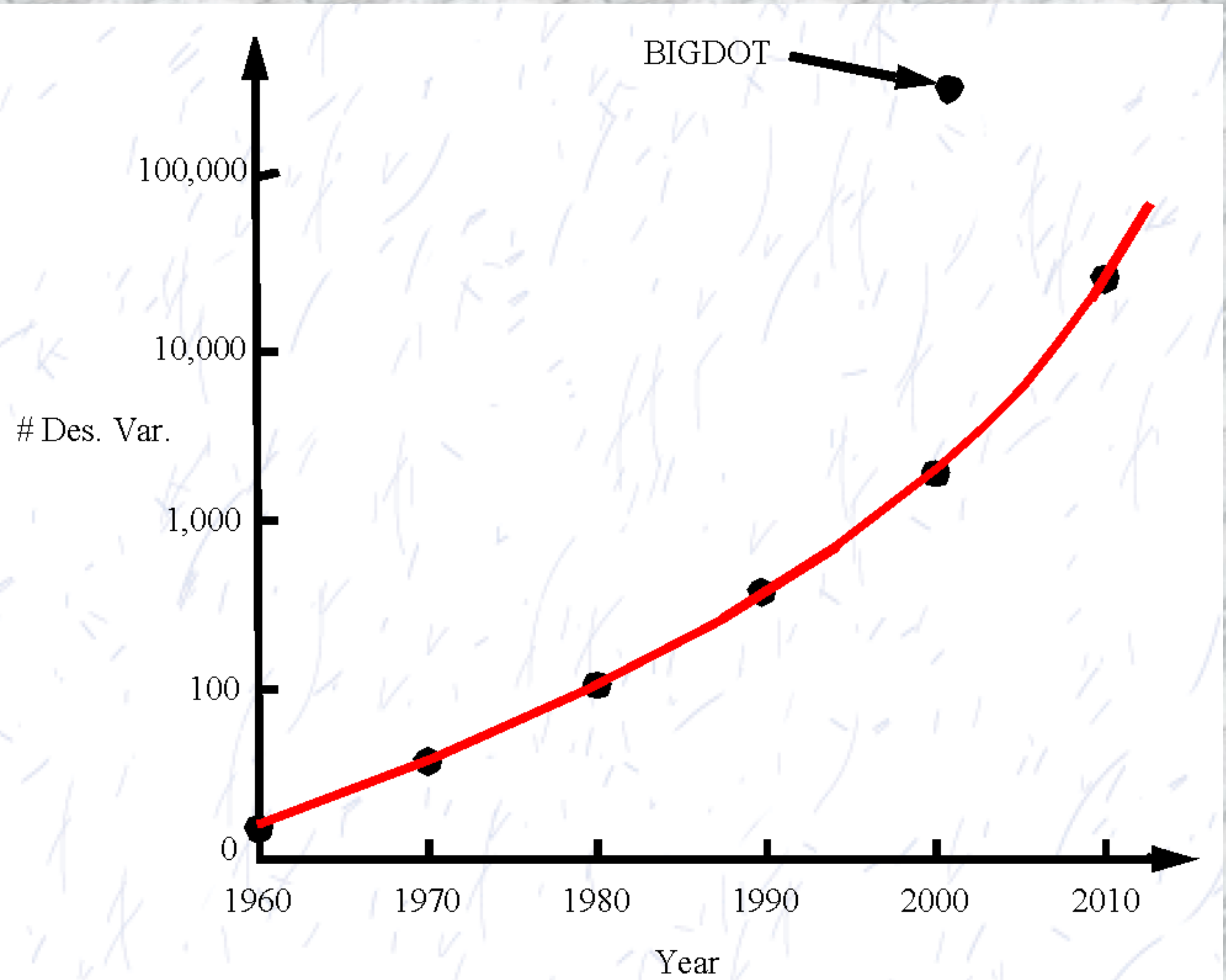
OPTIMIZATION IS A VERY SIMPLE EXTENSION OF THE ENGINEERING PROBLEM

Basic Optimization Process

1. Find a search direction that improves the objective while staying inside the fences
2. Search in this direction until the objective function improves no more
3. Repeat until "convergence"



Optimization Problem Size



Analysis & Synthesis

- **Analysis**
  – detailed examination of the elements or structure of something, typically as a basis for discussion or interpretation.

- **Synthesis**
  – the combining of the constituent elements of separate material or abstract entities into a single or unified entity

Analysis & Design

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- **ANALYSIS**: Given a Component or System, Together With Loads, Materials, etc.
  - Calculate the Responses to See if They Satisfy the Requirements
- **DESIGN**: Given A Set of Requirements
  - Find the Component or System that Satisfies the Requirements with Minimum Mass or Cost, Maximum Reliability, Maximum Performance, etc.

Analysis is a Complement to Design

Formal Design Process

- **Non-linear, constrained optimization task**
  - Find the *Set of Design Variables*, *X*, that will:
    - Minimize (or maximize) $F(X)$
    - Subject to (Such That);

$$g_j\left(X\right) \le 0, \qquad j = 1,\ldots,M$$

$$X_i^L \le X_i \le X_i^U, \qquad i = 1,\ldots,n$$

Design – Example

- Minimize Structural Mass

  ➔ Objective Function

- Subject to Stress Limits:

$$g_j(X) = \frac{\sigma_{ijk} - \overline{\sigma}}{\overline{\sigma}} \leq 0$$ ➔ Inequality Constraints

i = Load Condition

j = Stress Calculation Point

k = Stress Component

General Optimization Problem Statement

- Minimize $F(X)$ Objective Function
- Subject to (Such That):

Inequality Constraints

$$g_j(X) \le 0 \qquad j = 1, M$$

Equality Constraints

$$h_k(X) = 0 \qquad k = 1, L$$

Side Constraints

$$X_i^L \le X_i \le X_i^U \qquad i = 1, N$$

$F(X)$, $g_j(X)$ and $h_k(X)$ may be Linear, Nonlinear, Explicit, Implicit, but *should be continuous with continuous first derivatives*

General Strategy/Approach

- Given $\boldsymbol{X}^0$

- At iteration q, update $\boldsymbol{X}$ by

$$\boldsymbol{X}^q = \boldsymbol{X}^{q-1} + \alpha^* \boldsymbol{S}^q$$

$\boldsymbol{S}^q$ = Vector search direction

α = Step size

- Calculation of $\boldsymbol{S}^q$ requires *gradients* (derivatives)
- Calculation of α^* (for a one-dimensional search) requires several *function evaluations*
  – Some methods don't use a one-dimensional search

Optimization Process

- Given X^q
- Update the Design by

$$\mathbf{X}^q = \mathbf{X}^{q-1} + \alpha^* \mathbf{S}^q \equiv \mathbf{X}^{q-1} + \delta \mathbf{X}$$

- *Note that this is very close to the traditional design process of beginning with a design and modifying it by incremental improvements*

Useful Definitions

- **Design Variables**: Those parameters to be changed to improve the design
- **Objective Function**: The function of the design variables to be minimized or maximized
- **Inequality Constraints**: One sided conditions that must be satisfied for the design to be acceptable
- **Equality Constraints**: Precise conditions that must be satisfied for the design to be acceptable
- **Side Constraints**: Bounds on the design variables that limit the region of search for the optimum

Useful Definitions

- **Feasible Design**: One that satisfies all constraints
- **Infeasible Design**: One that violates one or more constraints
- **Optimum Design**: The set of design variables and the corresponding minimum (maximum) objective satisfying all constraints
- **Kuhn-Tucker Conditions**: Necessary mathematical conditions that must be satisfied for a design to be optimum
- **Two-Variable Function Space**: Geometric representation of a two-variable design problem

Global Optimization, Kriging Accuracy and Related Myths

- **GLOBAL OPTIMIZATION**
  - A *Globally Convergent Algorithm* is one which will find the optimum of a **CONVEX** problem from any starting point: There is only one optimum!
- Genetic and related algorithms claim to find the global optimum in the presence of relative minima
  - **NOT TRUE**: They only have an *Improved Probability* of finding the global optimum

Global Optimization

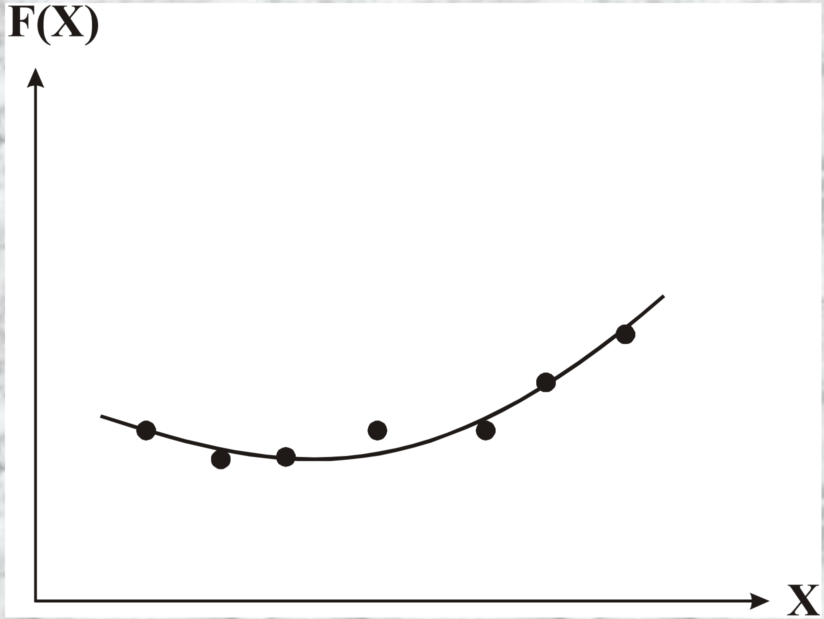
- Only the "Try Them All" method is *guaranteed* to find the global optimum
  - Try ALL combinations/permutations of ALL design variables and pick the best design
  - This is often given as a textbook exercise to demonstrate the folly of such an approach
- Genetic Algorithm (GA) and related methods are certainly useful but only when used properly
- Even when they work, they are very expensive
  - Massive parallelization may help if you have a hundred thousand licenses or so for ABAQUS, FLUENT, Etc.

Kriging Accuracy

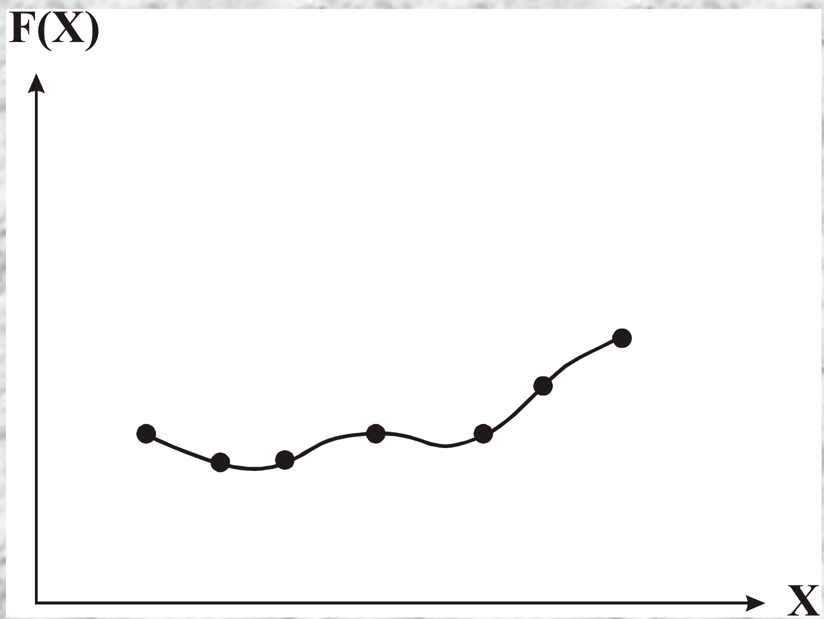
- Response surface optimization may be based on
  - Polynomials
  - Splines
  - Kriging Fits
  - etc.
- Kriging is promoted as "Best" because it models relative minima
  - Don't forget global optimization needs a global fit!

Kriging Accuracy

Quadratic Fit



Kriging Fit



- Kriging *appears* to give a much better fit
  - It captures both minima

Kriging Accuracy

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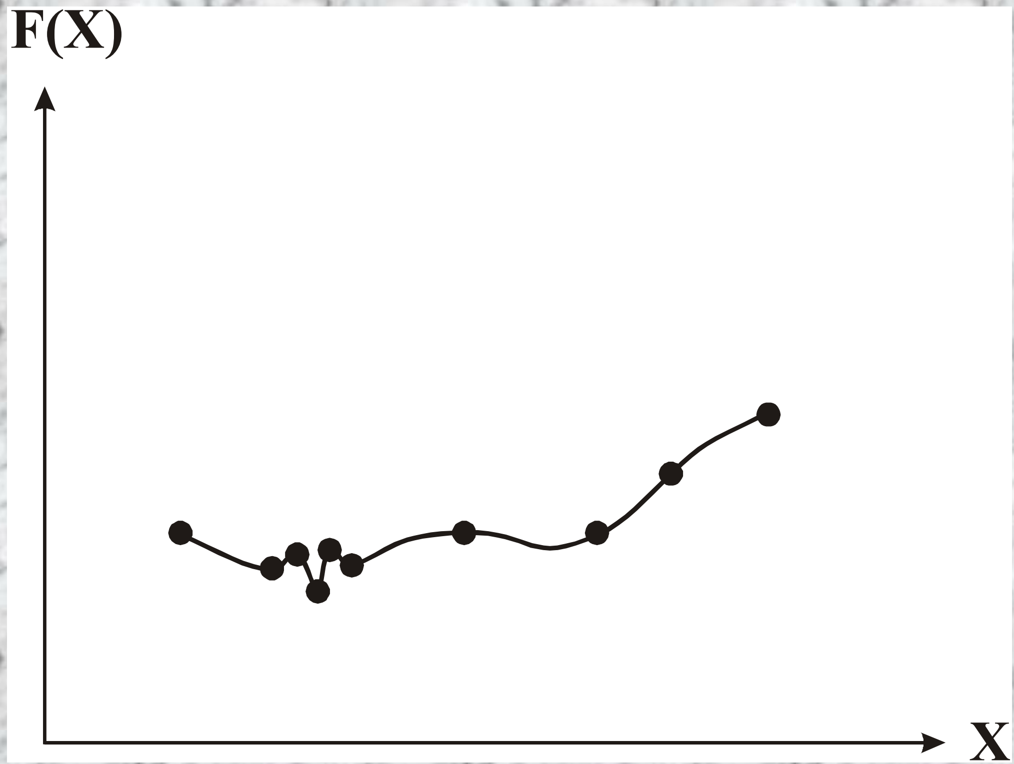
- As the optimization process progresses, we make smaller and smaller steps, leading to a refined Kriging fit

Did we model the function or just noise?



Related Myths

- "All designs have relative minima"
  - Most do not
  - Even for those that do, engineers virtually never worry about that until an optimization expert tells them to
- "Because designs are highly sensitive to parameters, robust optimization is essential"
  - Figures shown to justify this are almost always contrived
  - Does the pad on a tank track really need 6-sigma reliability?

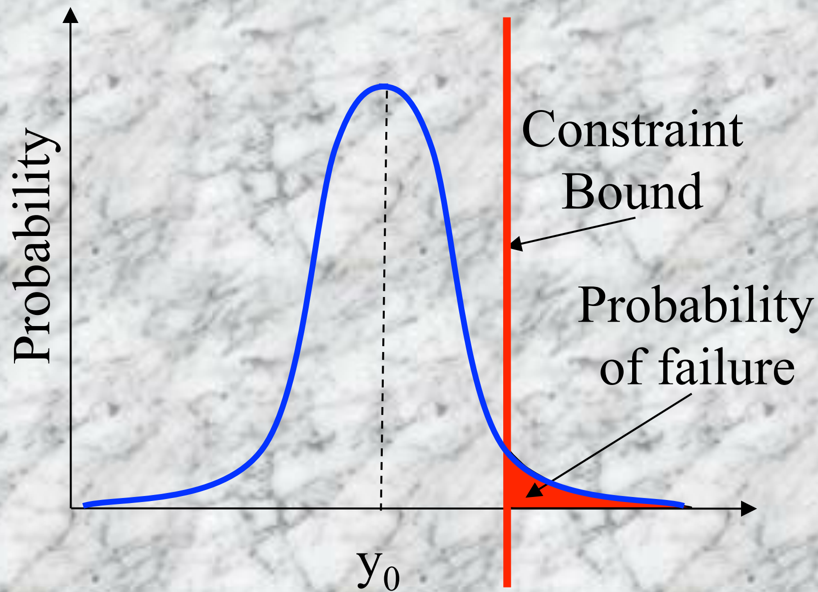
Probabilistic Analysis and Optimization...

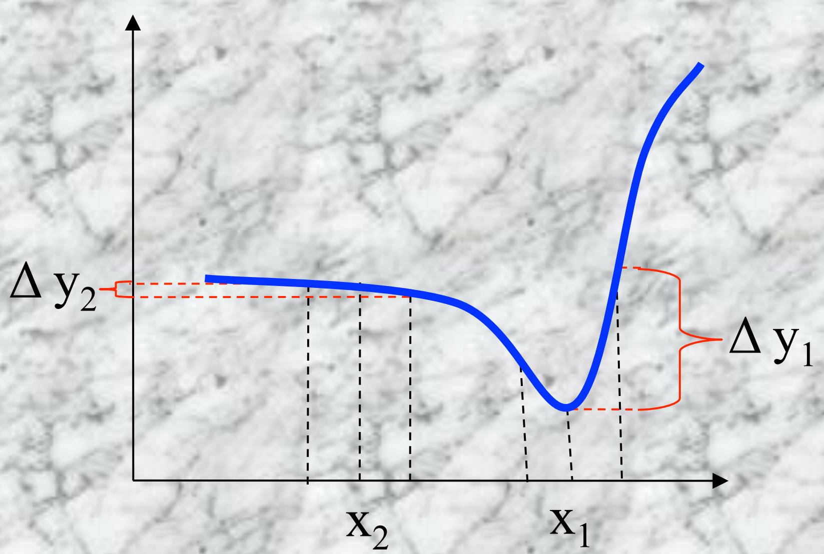
Reliability Optimization

Control probability of failure

Robust Optimization

Control variability of a response





On Using Optimization

- Optimization is a surprisingly "emotional issue"
  - Some people spend a great deal of time identifying problems optimization can't solve and offering excuses why it should not be used…

"It won't wash my cloths so it's not useful for designing rockets"

- A very large percentage of engineering design can benefit from optimization
  - Our goal is to identify opportunities to reduce design time, improve quality and save money

Future Prospects

- Just as spreadsheets are routinely used by accountants
- Just as word processors are routinely used by secretaries, writers, etc.
- *So should optimization be used by engineers*

- Optimization will be widely used when management understands the enormous benefit

If You're not the Lead Dog, the view never changes!

G. N. Vanderplaats

"The organization that makes optimization standard practice and widely used will have an overwhelming competitive advantage."