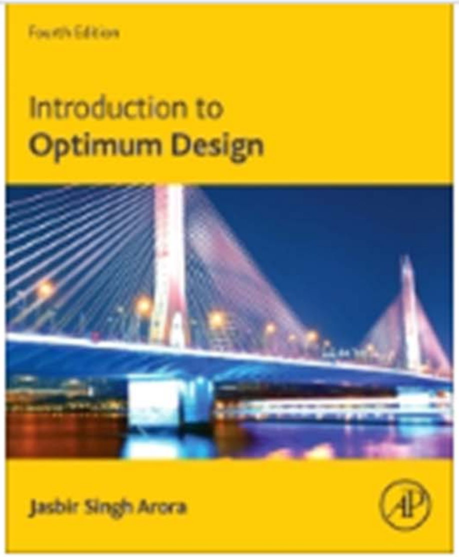
Textbook



Introduction to Optimum Design

4th Edition

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U/G1: Undergraduate/First-Year Graduate Level Course
G1: First Graduate Level Course
G2 Second Graduate Level Course

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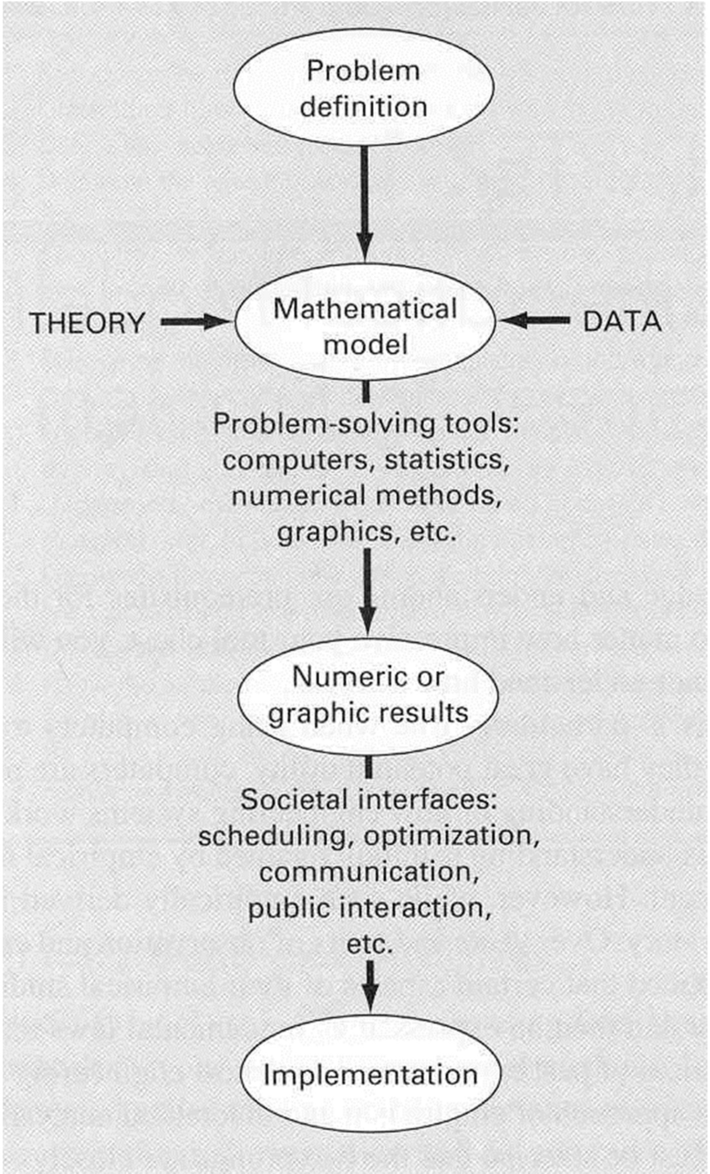
Introduction

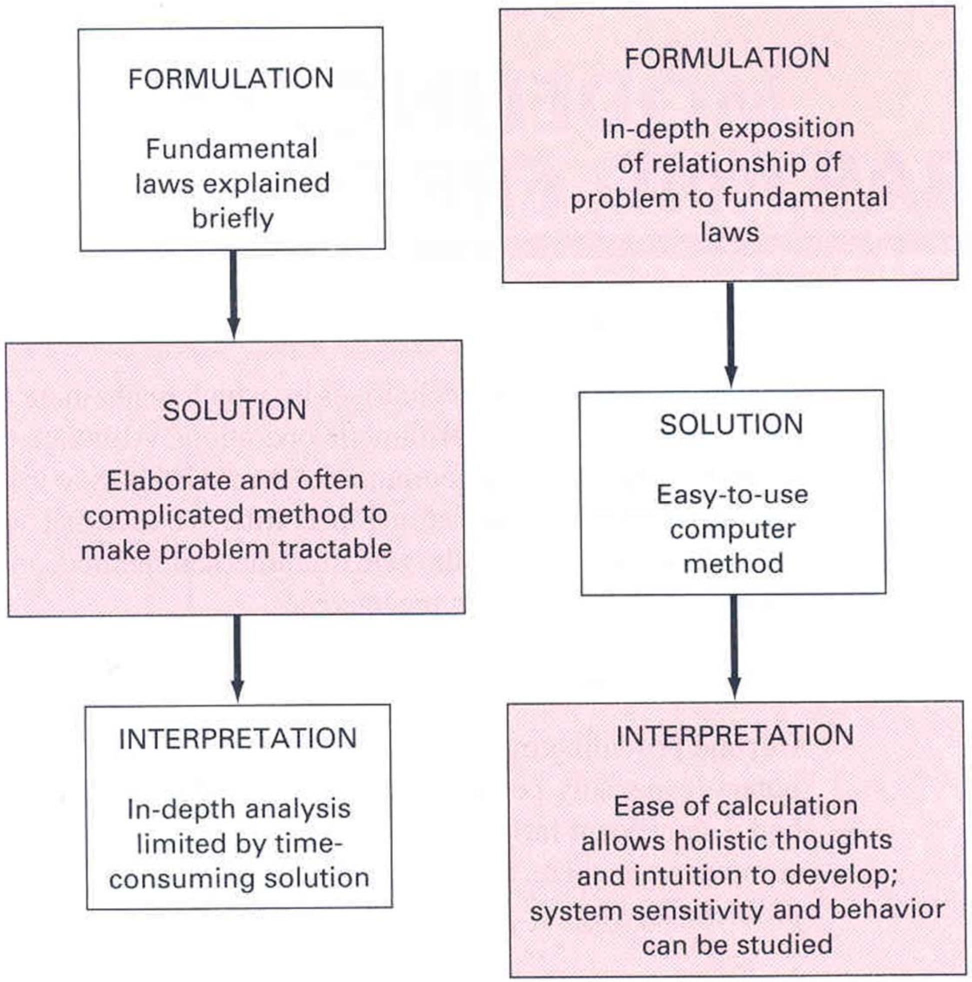
- Engineer
  - Design devices and products that perform tasks in an efficient fashion
  - Constrained by the limitations of the physical world and must keep costs down
  - Confronting optimization problems that balance performance and limitations
- Mechanical Design
  - Selection of materials and geometry
  - which satisfies specified and implied functional requirements
  - while remaining within the confines of inherently unavoidable limitations

Engineering Problem-Solving Process



Three Phases of Engineering Problem Solving

- Precomputer era
- Computer era



Engineering Model (1)

- Model
  - Abstract description of the real world giving an approximate representation of more complex functions of physical systems
  - Increase our understanding of how a system works
  - Physical: scale model, prototype
  - Symbolic: drawings, verbalization, logic, mathematics
- Mathematical model
  - A model that represents a system by mathematical expressions of relevant natural laws, experience, and geometry
  - May contain many alternative designs, so criteria must be introduced in the model
  - Best, or optimum, design can be identified with the aid of mathematical methods

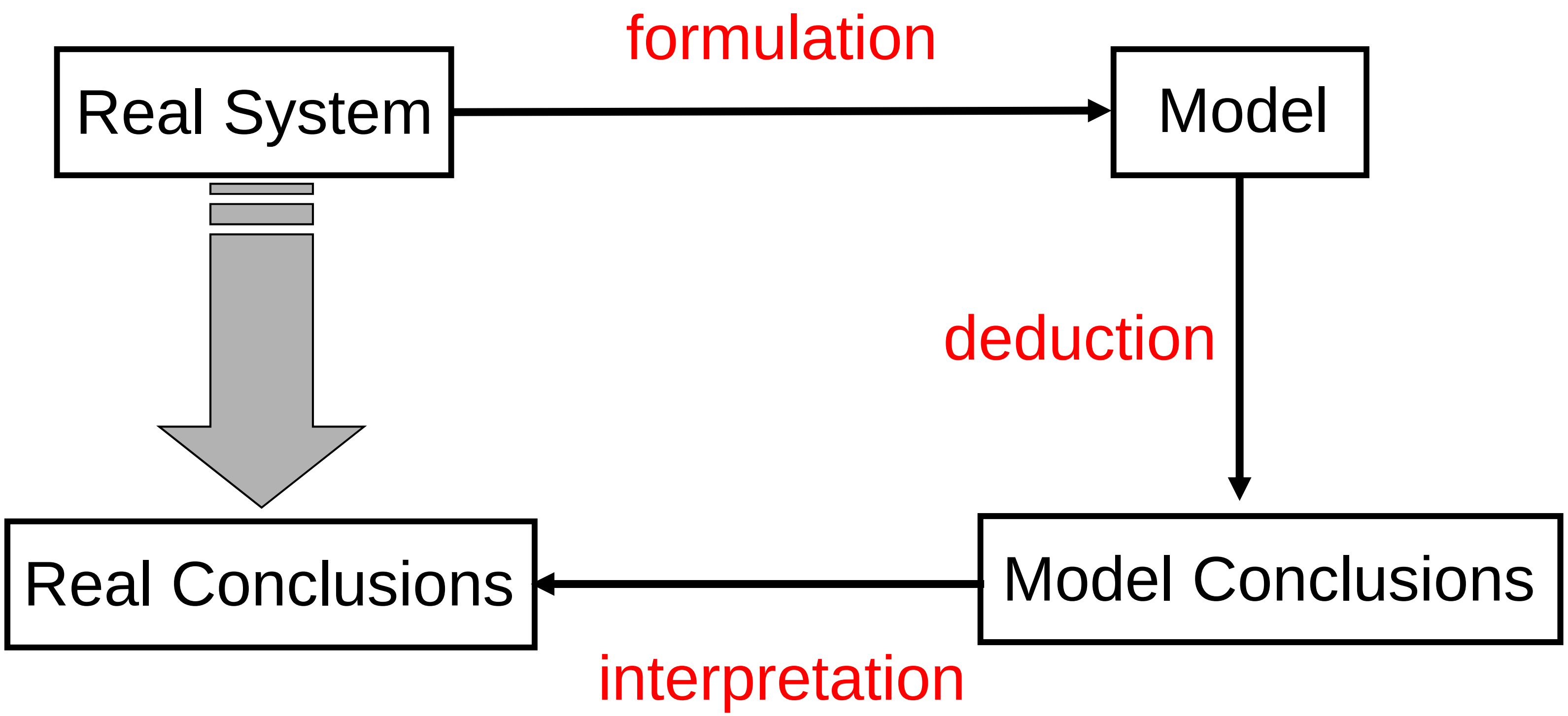
Engineering Model (2)

- Real-life engineering design problem
  - very unstructured
- Most difficult and challenging part
- Depends on experience as well as skill
- Thorough understanding of the first principles and fundamentals of engineering
- Describes the physical behavior of the system ▶ mathematical model

Engineering Model (3)

- Elements of models
  - Variables / Parameters / Constants / Mathematical relations
- Hierarchical levels
  - Every system is analyzed at a particular level of complexity
  - System $\rightarrow$ Subsystems $\rightarrow$ Components
  - "cut across" the links with environment, input/output characterization: free-body diagram, control volume

Modeling Process (1)



Modeling Process (2)

- Formulation
  - Often considered to be an art
  - What aspects of the real system should be included, which can be ignored?
  - What assumptions can and should be made?
- Deduction
  - Involves techniques that depend on the nature of the model
  - May involve solving equations, running a computer program, expressing a sequence of logical statements – whatever it takes to solve the problem of interest relative to the model
  - It should not be subject to differences of opinion, provided that the assumptions are clearly stated and identified
- Interpretation
  - Again involves a large amount of human judgment
  - The model conclusions must be translated to the real world conclusions, in full cognizance of possible discrepancies between the model and its real world

Analysis vs. Design

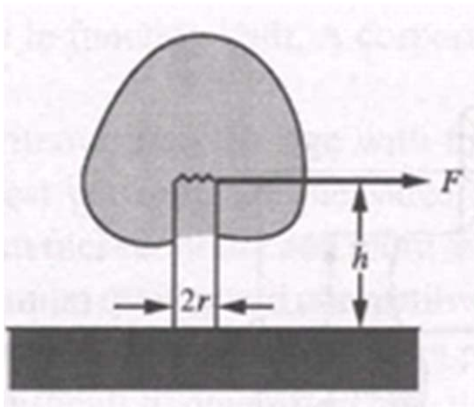
- Engineering analysis
  - To determine the behavior of an existing system
  - Sizes and configurations are given
- Engineering design
  - To calculate sizes and shapes of various parts to meet performance requirements
- ▶ estimate a design and analyze it to see if it performs according to the specifications

Analysis and Design Model

- Analysis model
  - Based on the principles of engineering science
    - Maximum wind force the tree can withstand before it breaks (*F*) if we take the tree as given (σ_{max}, *h*, *r* : parameters)
- Design model
  - Constructed from the analysis models for specific prediction tasks
    - Protect the tree from high winds by appropriately trimming the foliage to decrease *F* and *h* (variables)

Trunk of a tree subject to a wind force *F* at a height *h*

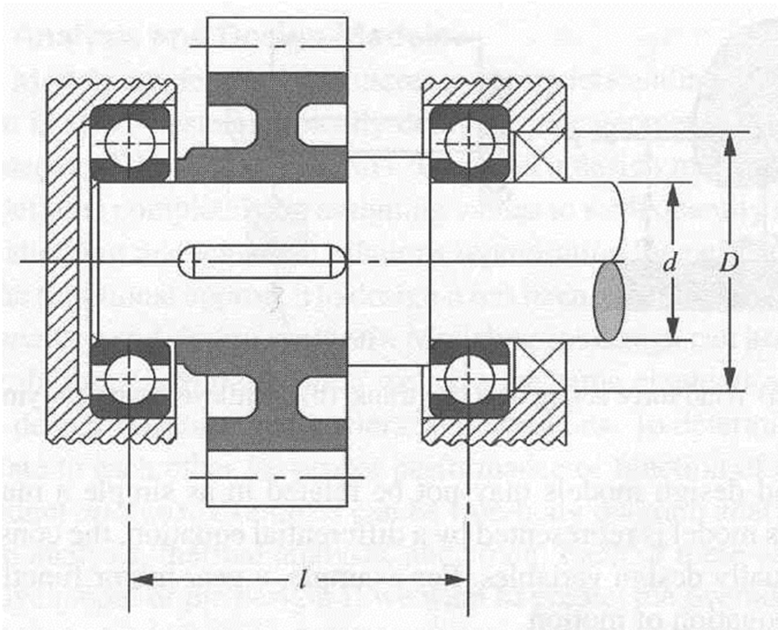
$$\boxed{\sigma = \frac{My}{I} \xrightarrow{I = \frac{\pi r^4}{4}} \sigma_{\max} = \frac{4Fh}{\pi r^3}}$$



Example: Shaft Design

- Influence of a given viewpoint on the design model

	d	*l*	*materials*
Shaft designer	variable	parameter	parameter
Housing designer	variable	variable	parameter
Project manager	variable	variable	variable



Decision Making

- Criterion: evaluating alternatives and choosing the “best” one
  - Not unique, influenced by many factors
    - Design application, timing, point of view, judgment of the designer
  - May change with time
    - Automobile design: maximum power and comfort $\rightarrow$ fuel economy
- Decision-making (Optimization) model
  - A design model that includes an evaluation criterion (*objective*)
- Shaft design example

Criterion	
Weight	
Rigidity	Best meshing of the attached gear
Material and manufacturing costs	Shop manager, ease of manufacturing
Cost	Project or plant manager

Design Optimization

- Goal of engineering
  - To improve the design so as to achieve the best way of satisfying the original need within the available means
- Elements in the design process
  - Recognition of need / act of creation / selection of alternatives
- Design optimization: selection of the “best” alternative
  - How do we describe different designs ? (design model)
  - What is our criterion for “best” design ? (objective)
  - What are the “available means” ? (set of requirements)

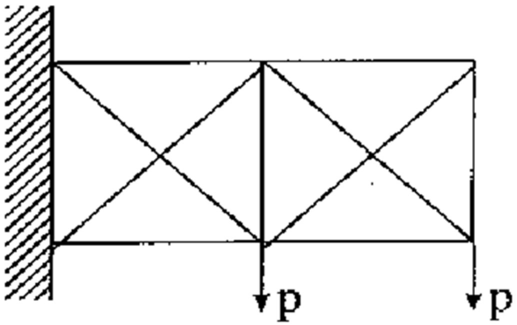
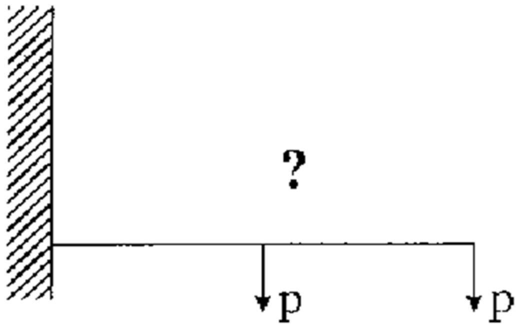
Optimum Design

- Undesirable effects
  - Stress, deflection, vibration, space occupancy, weight, cost
  - Dependent of the application (degree of significance)
  - Tolerable limit
- Desirable effects
  - Power transmission/ energy absorption/ momentary overload/ speed capacity, usable length of life, factor of safety
- Optimum design
  - Best possible one from the standpoint of the most significant effect
  - Minimize/Maximize the most significant undesirable/desirable effect

Problem Formulation Steps

- Identification of *design variables*
  - Parameter chosen to describe the design
  - Independent of each other, minimum number
- Identification of an *objective (cost) functions*
  - Criterion to compare various designs
  - as a function of the design variables
  - Single/Multi-objective
- Identification of all *design constraints*
  - All restrictions placed on a design
  - Explicit/Implicit, Linear/Nonlinear, Equality/Inequality
  - Feasible/Infeasible

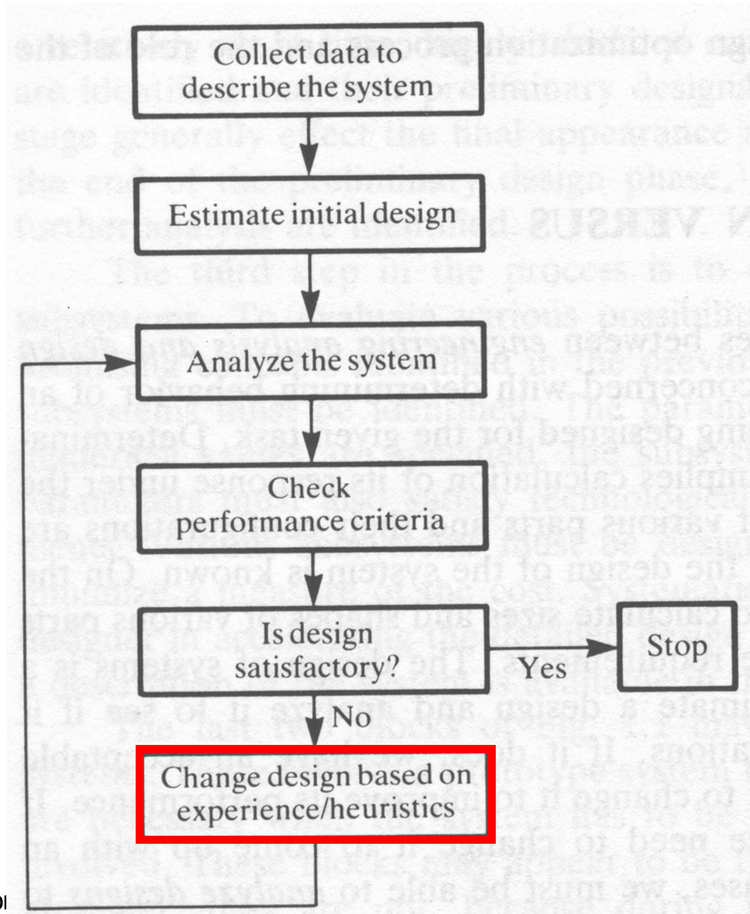
10 Bar Truss Design

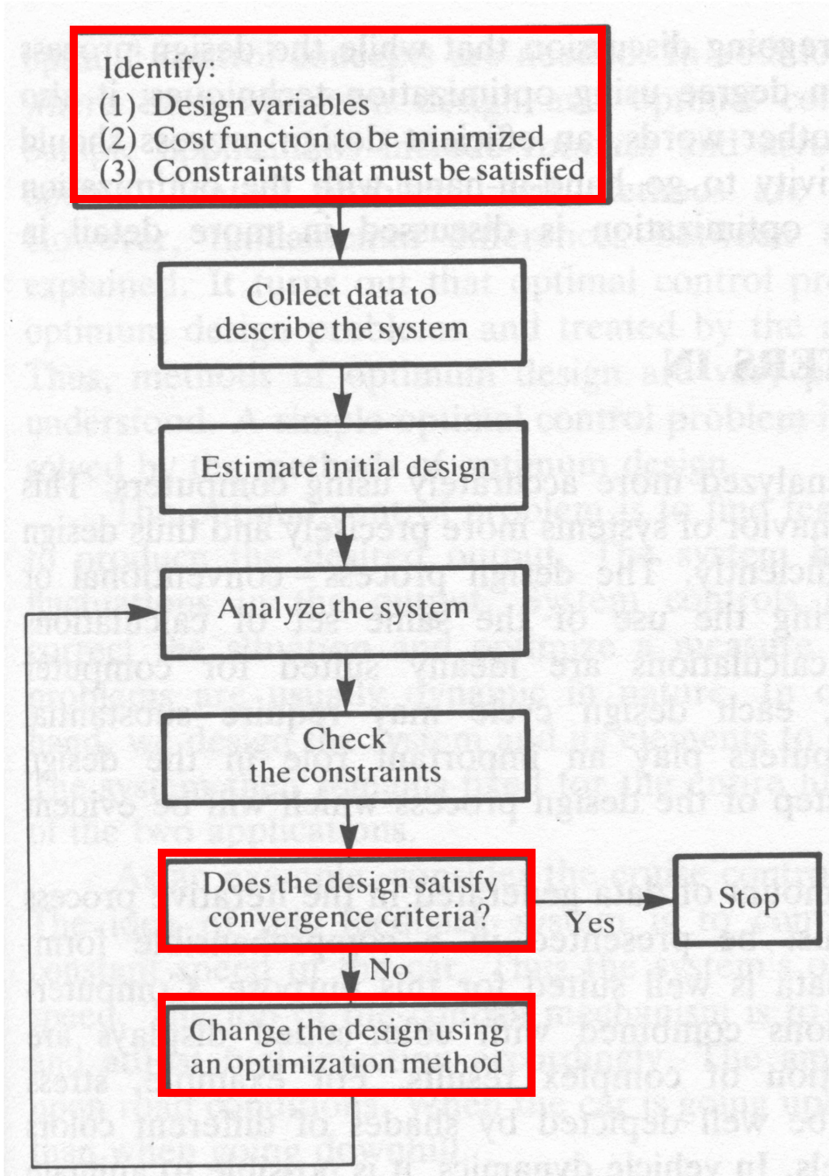
해석 **(Analysis)**	설계 (Design)
	
$\delta = ?$ $\sigma = ?$	$\delta \le \delta_{allow}$ $\sigma \le \sigma_{allow}$
• to obtain the response of a given system • # of unknown = # of equations	• to determine specifications of the system satisfying requirements • # of unknown > # of equations

Conventional vs. Optimum (1)

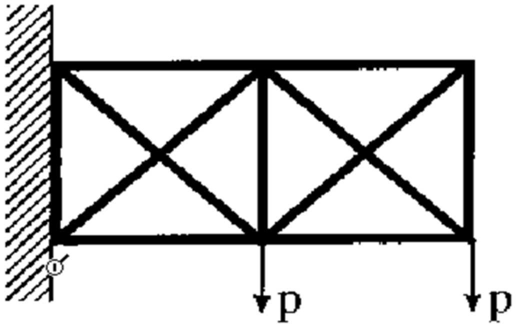
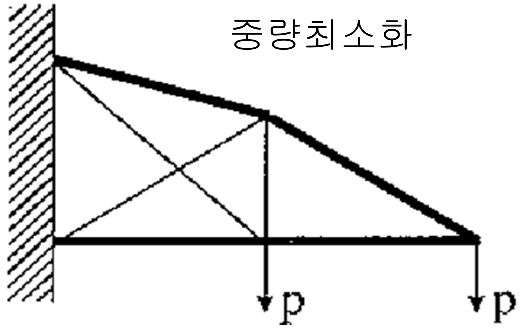
- Conventional design
  - Depends on designer’s intuition, experience, and skill
  - Merits in making conceptual changes/additional specs
  - Difficulties in detailed design (complex constraints)
  - Less formal, no objective function/trend information
- Optimum design
  - Identify explicitly a set of design variables, cost function to be minimized, and constraint functions
  - More organized using trend information

Conventional vs. Optimum (2)





Conventional vs. Optimum (3)

Conventional Design	Optimum Design
	
$\delta \le \delta_{allow}$ $\sigma \le \sigma_{allow}$	$\delta \le \delta_{allow}$ $\sigma \le \sigma_{allow}$

Optimization Problems in Engineering (1)

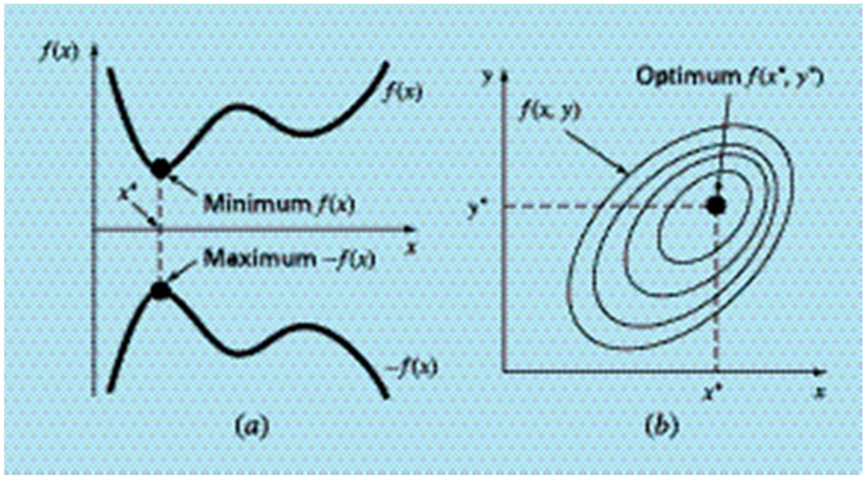
- Design aircraft for minimum weight and maximum strength
- Optimal trajectories of space vehicles
- Design civil engineering structures for minimum cost
- Design water-resource projects like dams to mitigate flood damage while yielding maximum hydropower
- Predict structural behavior by minimizing potential energy
- Material-cutting strategy for minimum cost
- Design pump and heat transfer equipment for maximum efficiency
- Maximize power output of electrical networks and machinery while minimizing heat generation
- Shortest route of salesperson visiting various cities during one sales trip
- Optimal planning and scheduling

Optimization Problems in Engineering (2)

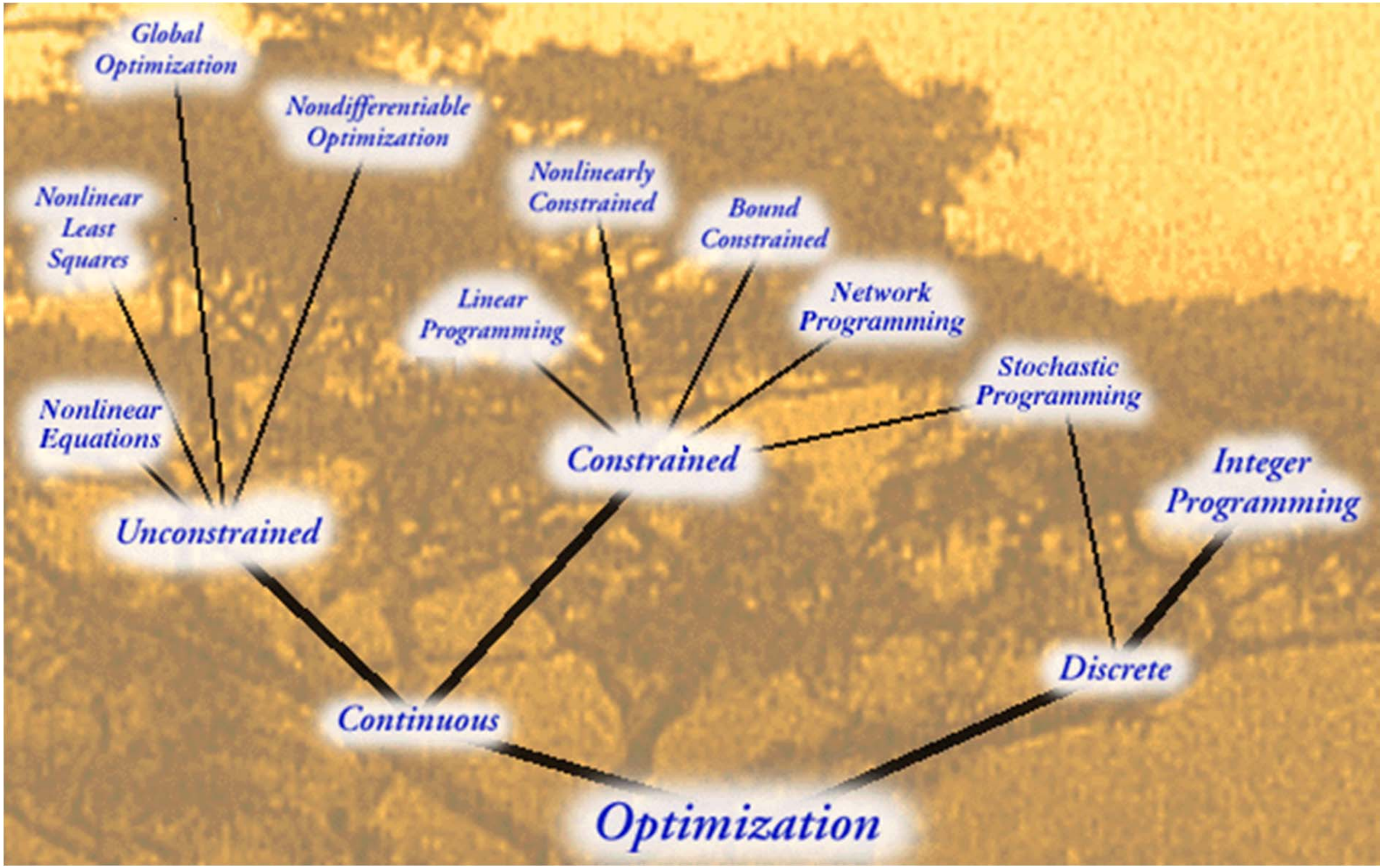
- Statistical analysis and models with minimum error
- Optimal pipeline networks
- Inventory control
- Maintenance planning to minimize cost
- Minimize waiting and idling times
- Design waste treatment systems to meet water-quality standards at least cost

Classification

- Form of design variables
  - Continuous Optimization
  - Discrete Optimization
- Form of functions
  - Linear Programming
  - Quadratic Programming
  - Nonlinear Programming
- Existence of constraints
  - Constrained Optimization
  - Unconstrained Optimization
- Dimensionality
  - One-dimensional Problems
  - Multidimensional Problems



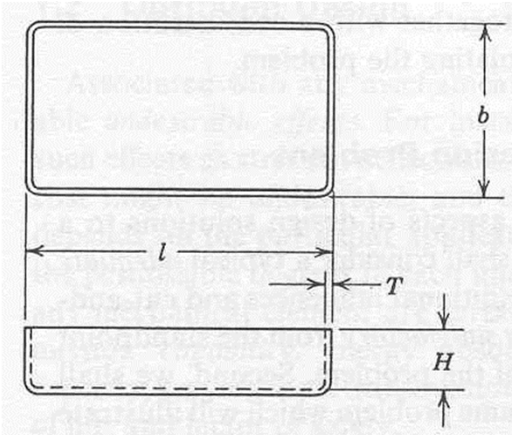
Optimization Tree



 https://neos-guide.org/

Plastic Tray Design (1)

- Basic design problem
  - Design a plastic tray capable of holding a specified volume of liquid, V, such that the liquid has a specified depth H, and the wall thickness of the tray is to be a specified thickness, T. The tray is to be manufactured in large quantities.
- Adequate design solution
  - Geometry
    - Intuition: rectangular ?



    - Infinite number of possible solutions
  - Material: experience?
    - Possible manufacturing techniques: vacuum forming
    - Possible chemical reactions w/ liquid: acrylic thermoplastic sheet

Plastic Tray Design (2)

- Optimum design solution
  - "manufactured in large quantities": cost (most significant undesirable effect)
  - Primary design equation: $C = \underbrace{C_o}_{\text{overhead}} + \underbrace{C_t}_{\text{tooling}} + \underbrace{C_l}_{\text{labor}} + \underbrace{C_m}_{\text{material}}$
  - C_o, C_t, C_l : independent of
    - Reasonable geometrical shapes / Feasible plastic materials
  - Objective: minimize cost C_m
    - selecting the best feasible material and the best values for *b* and *l*

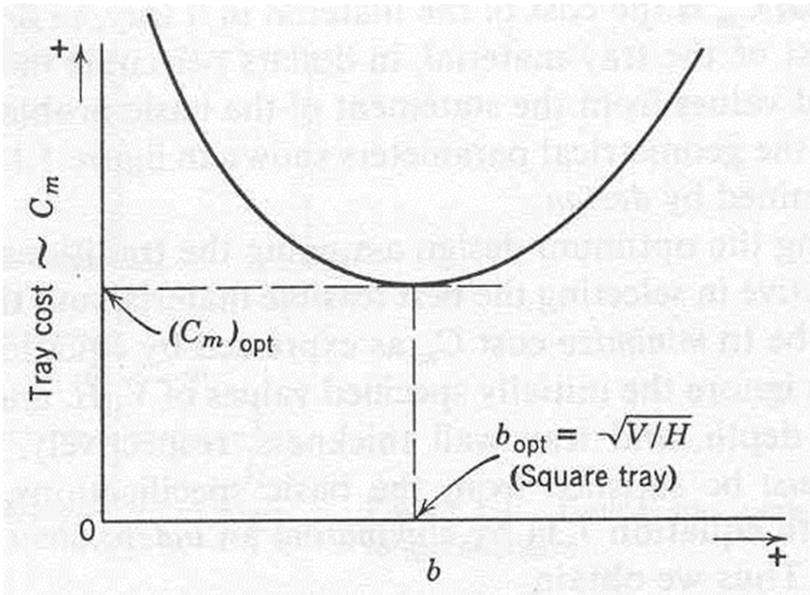
c : unit volume cost of the tray material

	c	
	$/in^3	$/m^3
Acrylic	0.030	1831
Polystyrene	0.012	732

  - Optimum feasible material
    - *c*: polystyrene

Plastic Tray Design (3)

– Optimum geometry for the rectangular tray

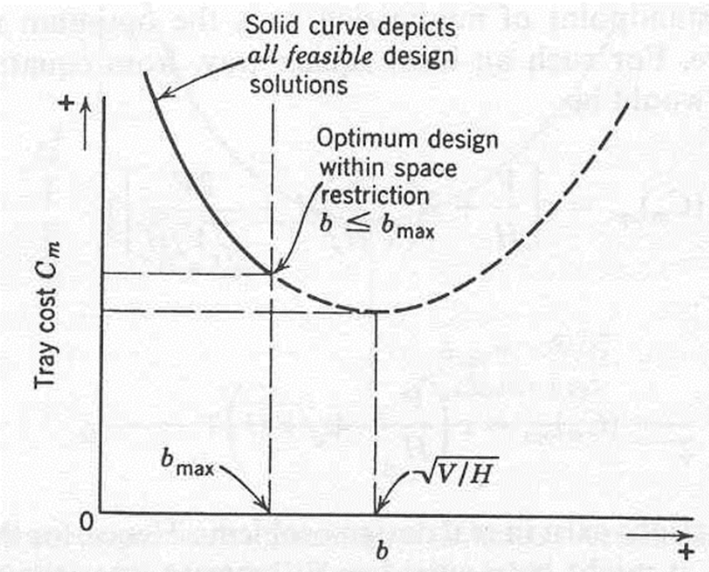


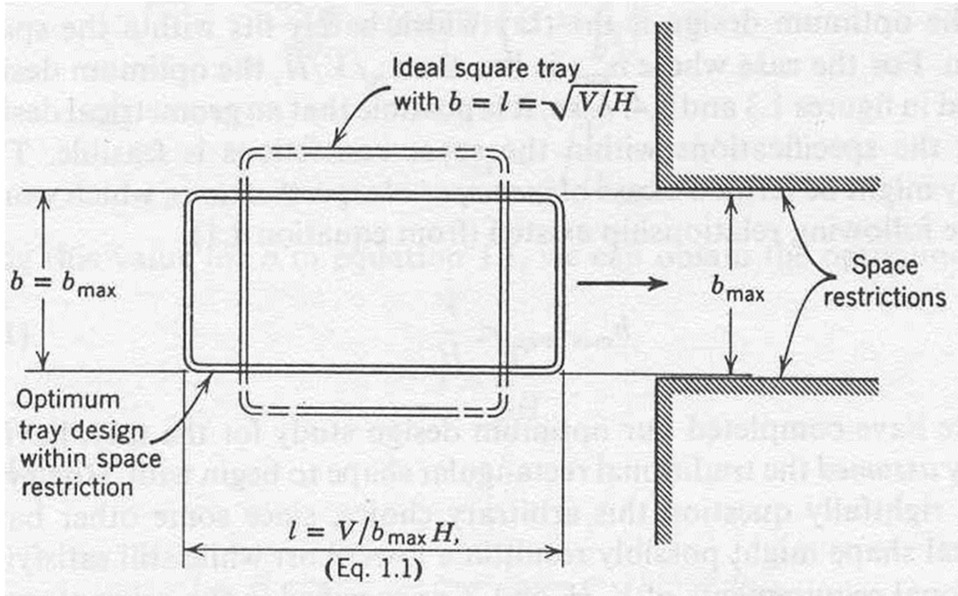
Plastic Tray Design (4)

- Space restrictions: $b \le b_{\max},\ \ l \le l_{\max}$

$$\begin{cases} b_{\max} \ge \sqrt{V/H} \ \text{ and } \ l_{\max} \ge \sqrt{V/H} : \text{ideal square tray is still the optimum design} \\ b_{\max} < \sqrt{V/H} \ \text{ or } \ l_{\max} < \sqrt{V/H} : \text{the tray which barely fits within the space restriction} \end{cases}$$

$$\text{incompatible specifications} : b_{\max} l_{\max} < \frac{V}{H}$$





Plastic Tray Design (5)

- Other basic geometrical shape ?
  - Circle: lowest C_m from the calculus of variations