Multidisciplinary System Design Optimization (MSDO)

Introduction

Lecture 1

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Introductions

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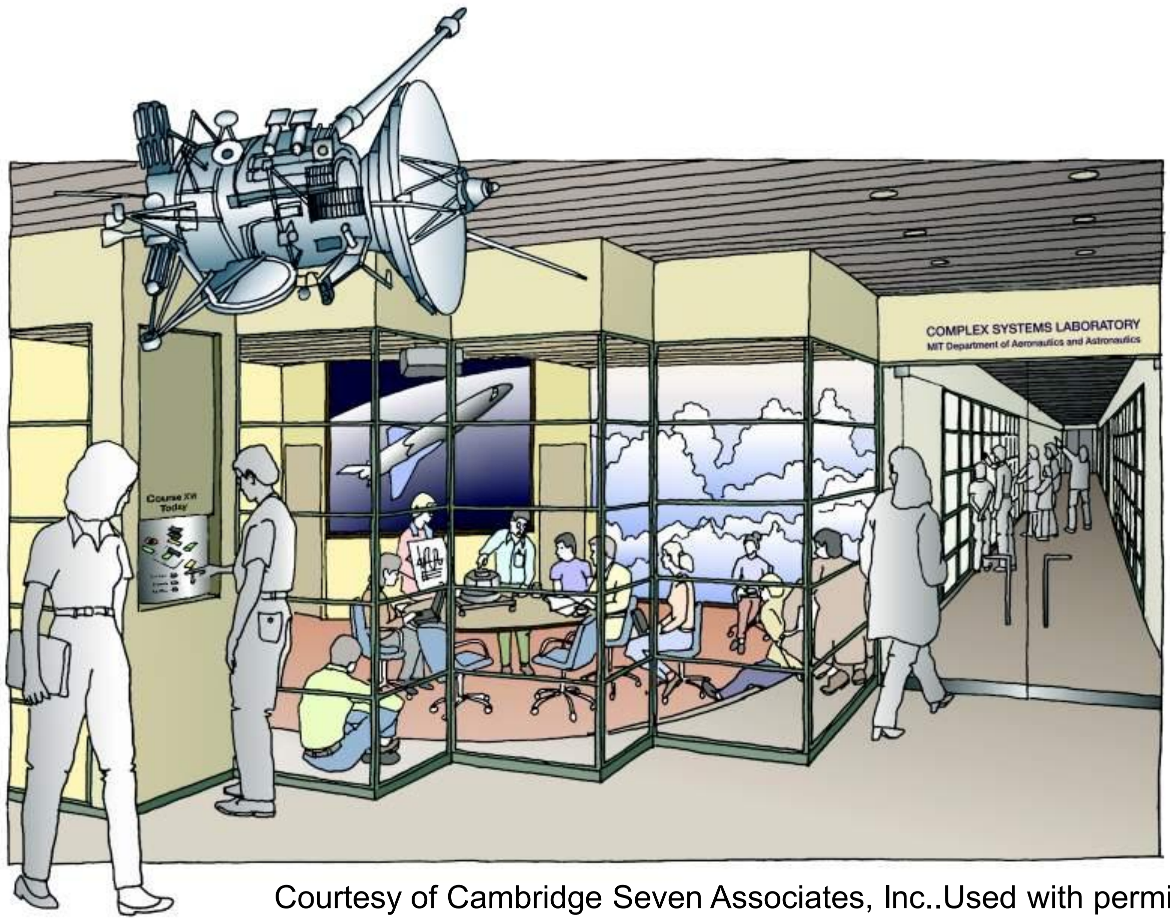
Today's Topics

- Course Rationale
- Role of MSDO in Systems Engineering
- Learning Objectives
- Pedagogy and Course Administration
- A historical perspective on MDO
- MSDO Framework introduction

Course Rationale

Computational Design and Concurrent Engineering (CE) are becoming an increasingly important part of the Product Development Process (PDP) in Industry



A collection of subsystems?

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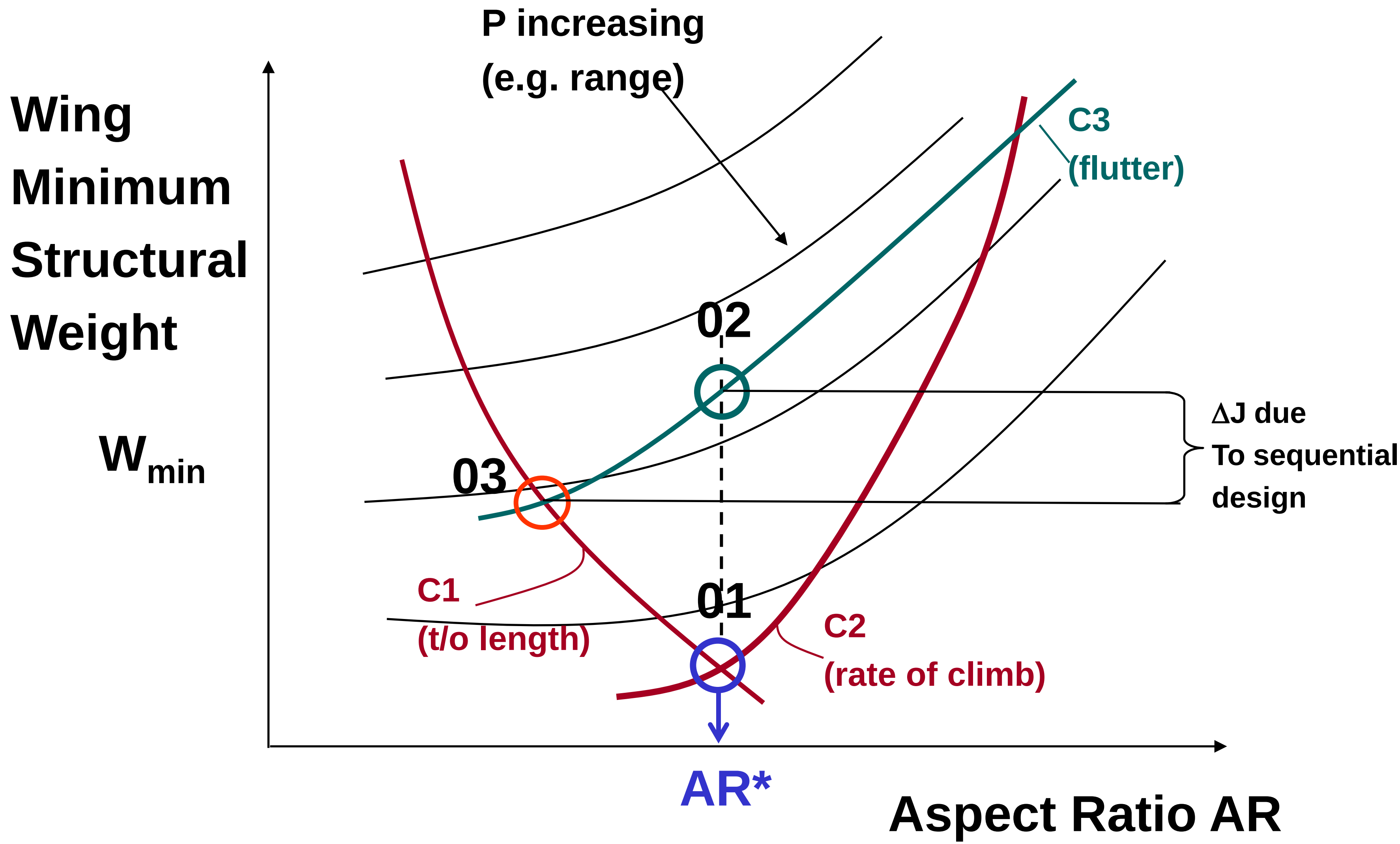
? =

- Fuselage Group
- Electrical Group
- Equipment Group
- Controls Group
- Power Plant Group
- Aerodynamics Group
- Hydraulics Group
- Loft Group
- Stress Group
- Production Engineering Group

Sequential –vs- Concurrent Design



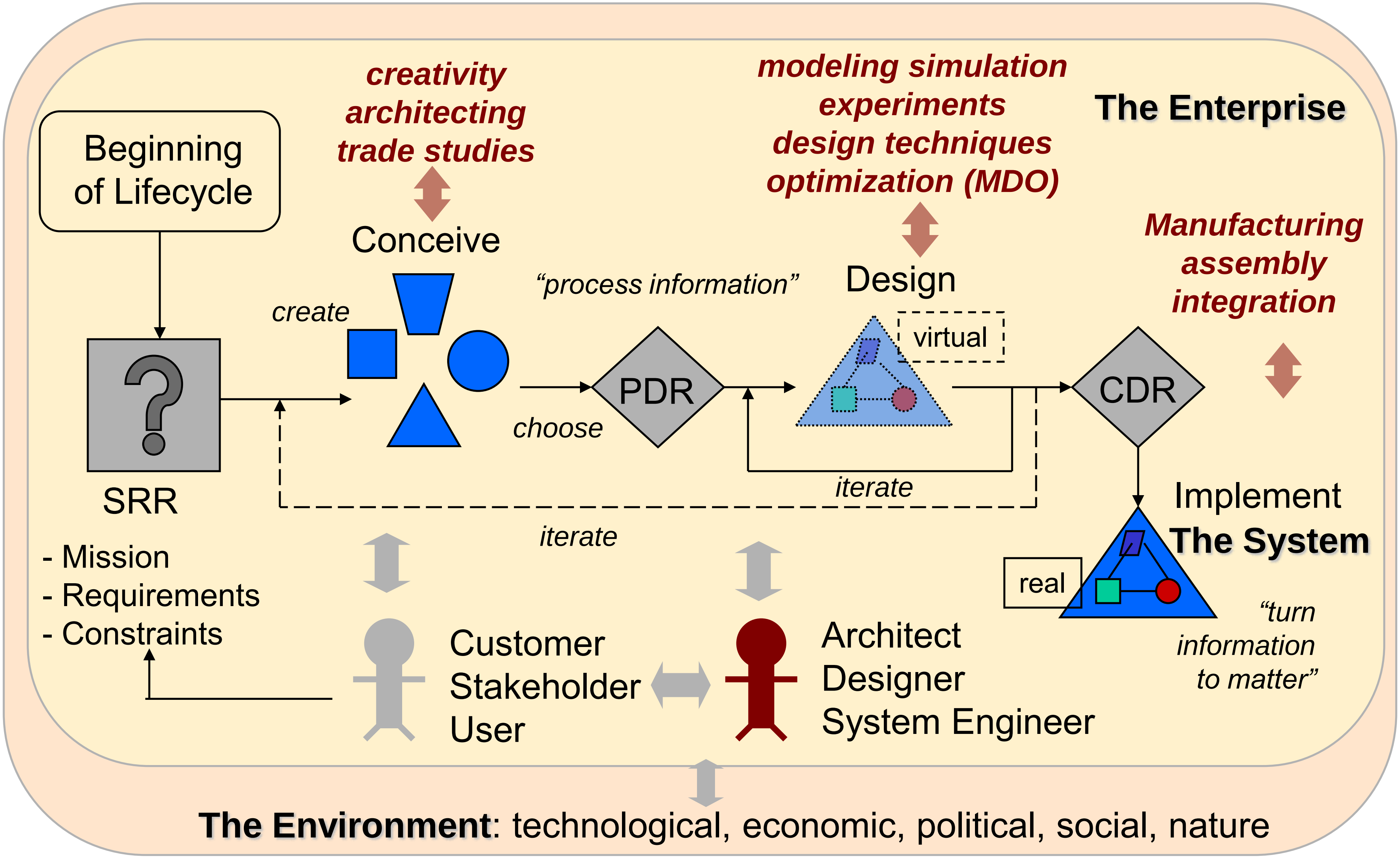
Role of MSDO in Engineering Systems

Goal: Create advanced and complex engineering systems that must be competitive not only in terms of performance, but also in terms of life-cycle value.

Need: A rigorous, quantitative multidisciplinary design methodology that can work hand-in-hand with the intuitive non-quantitative and creative side of the design process.

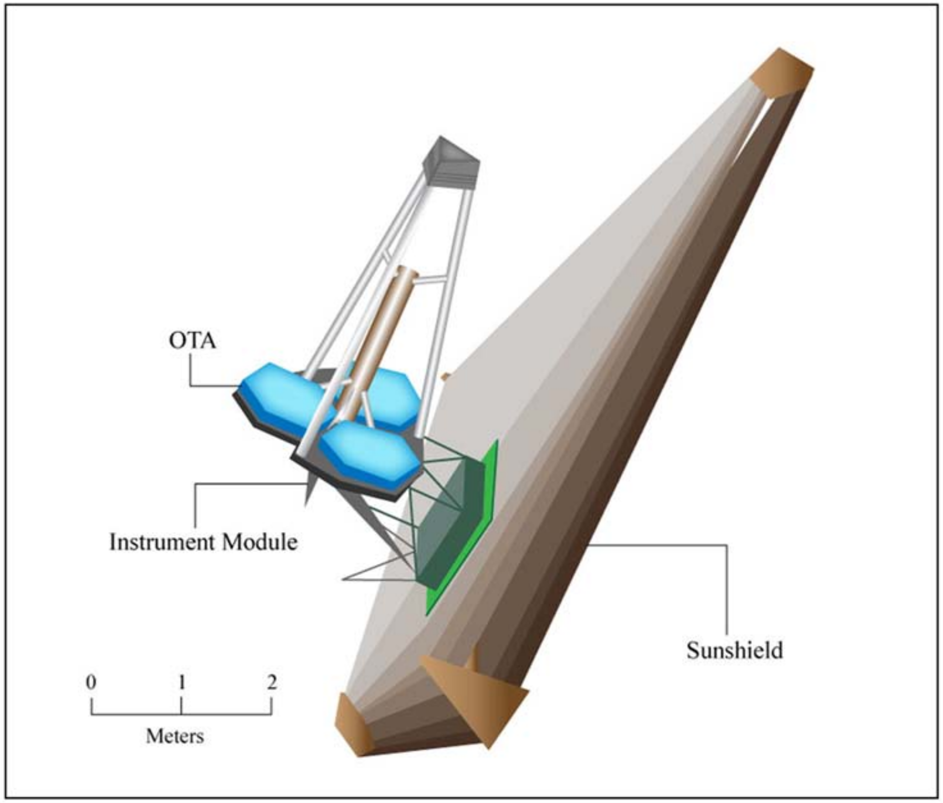
⇨ This class presents the current state-of-the-art in concurrent, multidisciplinary design optimization (MDO)

Product Development Process



Example 1: Nexus Spacecraft

NASA Nexus Spacecraft Concept



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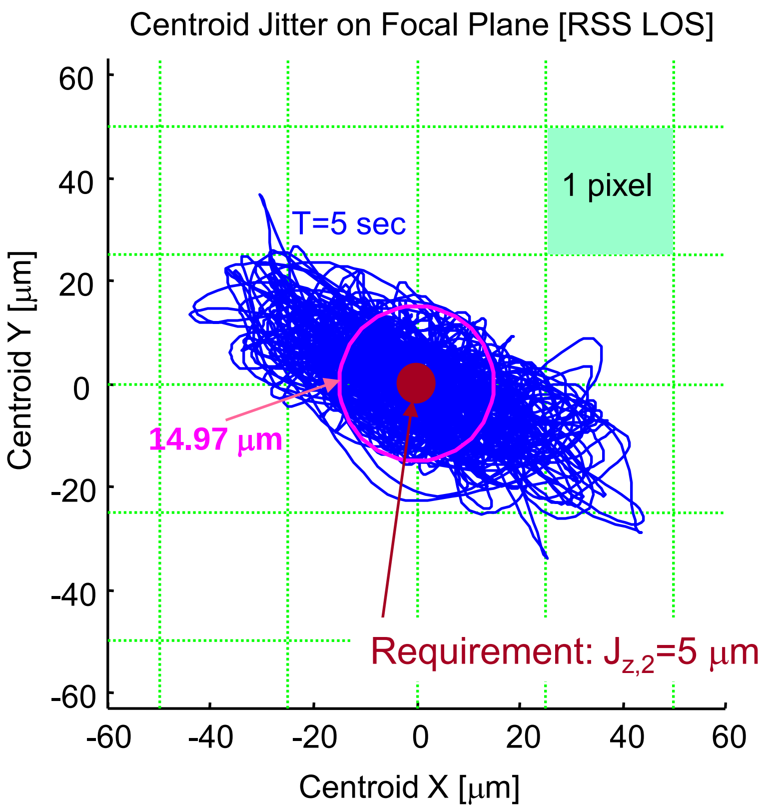


Goal: **Find a "balanced" system design, where the flexible structure, the optics and the control systems work together to achieve a desired pointing performance (RSS LOS), given various constraints**

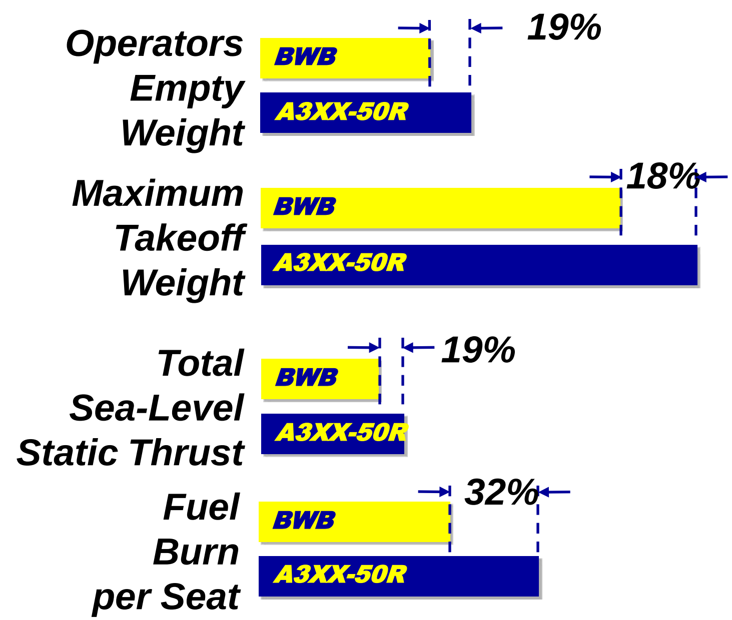
Example 2: BWB Aircraft

Boeing Blended Wing Body Concept

Image of Boeing Blended Wing Body Concept
removed due to copyright restrictions.

Aircraft Comparison of BWB & A3XX-50R

Approx. 480 passengers each
Approx. 8,700 nm range each



<u>Goal</u>: Find a design for a family of blended wing aircraft that will combine aerodynamics, structures, propulsion and controls such that a competitive system emerges - as measured by a set of metrics that matter to the operator.

Course Objectives

The course will …

- Enhance MIT's offerings in the area of simulation and optimization of multidisciplinary systems during the conceive and design phases
- develop and codify a normative (prescriptive) approach to multidisciplinary modeling and quantitative assessment of new or existing system/product designs
- engage both faculty and graduate students in the emerging research field of MDO, while anchoring the CDIO principles in the graduate curriculum

Learning Objectives (I)

The students will

(1) learn how MSDO can support the product development process of complex, multidisciplinary engineered systems

(2) learn how to rationalize and quantify a system architecture or product design problem by selecting appropriate objective functions, design variables, parameters and constraints

(3) subdivide a complex system into smaller disciplinary models, manage their interfaces and reintegrate them into an overall system model

Learning Objectives (II)

(4) be able to use various optimization techniques such as sequential quadratic programming, simulated annealing or genetic algorithms and select the ones most suitable to the problem at hand

(5) perform a critical evaluation and interpretation of simulation and optimization results, including sensitivity analysis and exploration of performance, cost and risk tradeoffs

(6) be familiar with the basic concepts of multi-objective optimization, including the conditions for optimality and the computation of the Pareto front

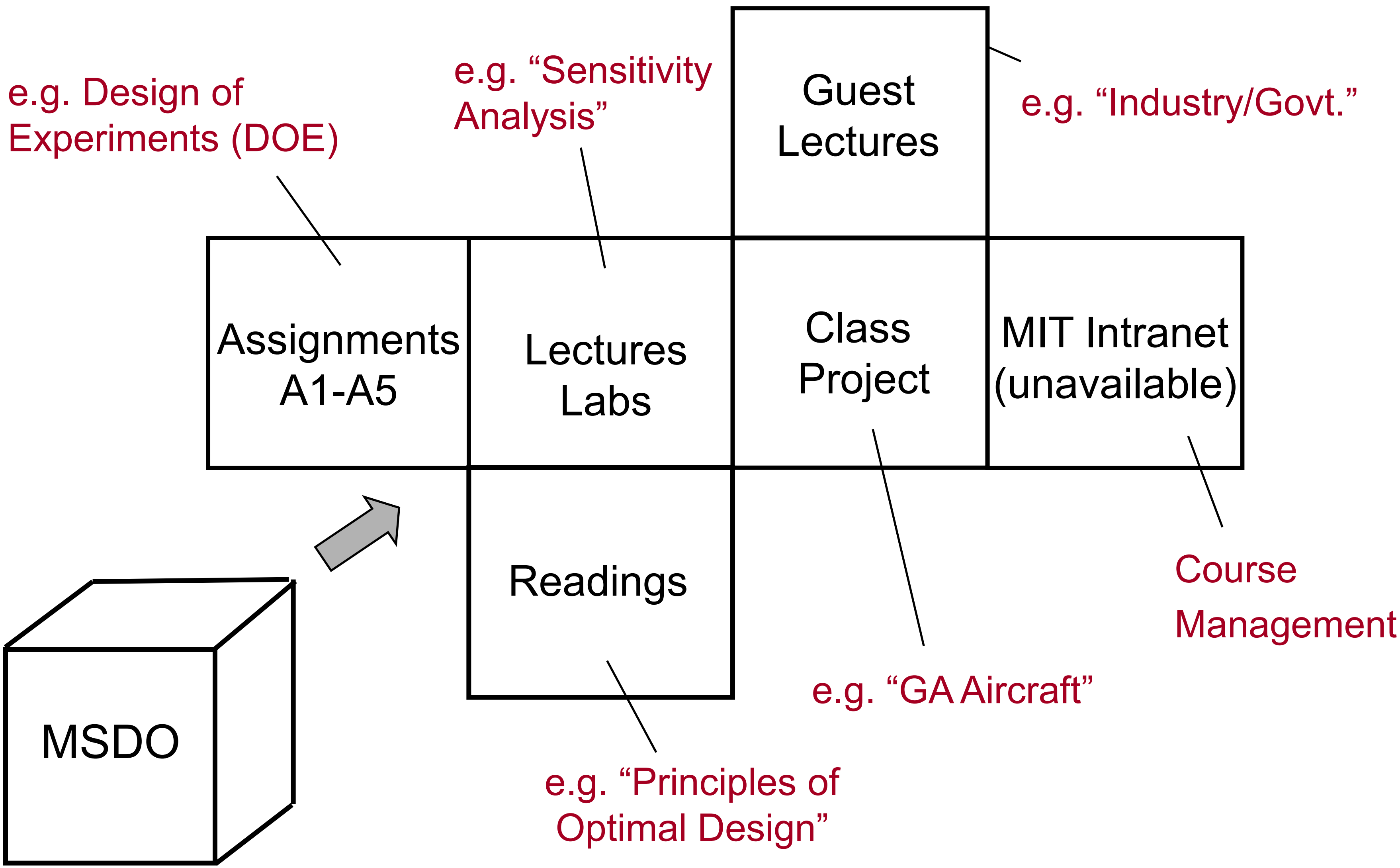
Learning Objectives (III)

(7) understand the concept of design for value and be familiar with ways to quantitatively assess the expected lifecycle cost of a new system or product

(8) sharpen their presentation skills, acquire critical reasoning with respect to the validity and fidelity of their MSDO models and experience the advantages and challenges of teamwork

⇨ How to achieve these learning objectives ?

MSDO Pedagogy



Assignments

Part (a)

Small, simple problems to be solved individually, many just by hand or with a computer. Goal is to ensure learning of the key ideas regardless of chosen project

Part (b)

Application of theory to a project of your choice from either existing class projects or a project related to your research. Solution individually or in teams of two or three.

- Assignments A1-A5 scheduled bi-weekly.
- Usually 2 weeks given to complete.

Lectures

Lecture schedule in separate document.

Module 1: Problem Formulation and Setup
Module 2: Optimization and Search Methods

--- Spring Break ---

Module 3: Multiobjective Challenges
Module 4: Implementation Issues and Applications

Class Project

Form teams of 2-3 students.

Formulate your own project.

-This is an opportunity to push your research forward

-Must be a design problem, must be multidisciplinary

-Write 1 page project proposal in A1 (part b)

Tools and Infrastructure

- **Physical Infrastructure: Design Studio 33-218**
  - some organized labs to support assignments
  - but can utilize facility off-hours
- **Computational Infrastructure:**

  - use Athena, individual PC/laptop or lab computers
- **Software Infrastructure:**

  - MATLAB® (Optimization Toolbox)
  - Excel (Solver)
  - iSIGHT - by SIMULIA – Dassault Systems
  - PHX Model Center – by Phoenix Integration
  - Write your own optimizer (C/C++)

Athena is MIT's UNIX-based computing environment. OCW does not provide access to it.

Textbook

Panos Y. Papalambros and Douglass J. Wilde, "**Principles of Optimal Design** – Modeling and Computation", 2nd edition, ISBN 0 521 62727 3, (paperback), Cambridge University Press, 2000 – Recommended

http://www.optimaldesign.org

Others (Recommended):

Garret N. Vanderplaats, "Numerical Optimization Techniques for Engineering Design", ISBN 0-944956-01-7, Third Edition, Vanderplaats Research & Development Inc., 2001

R. E. Steuer." Multiple Criteria Optimization: Theory, Computation and Application". Wiley, New York, 1986

David E. Goldberg, "Genetic Algorithms – in Search, Optimization & Machine Learning", Addison –Wesley, ISBN 0 201 15767-5, 1989 -

Guest Lectures

- **Lecture 6, Prof. Timothy Simpson, Penn State University: Visualization**

- **Lecture 18, Prof. Dan Frey, MIT: Robust Design**

- **Lecture 22, Dr. Jaroslaw Sobieski , NASA Langley Research Center: Roots of MDO**

Grading

Assignments A1-A5*	50%
Project Presentation	20%
Final Report (Paper)	20%
Active Participation	10%
	100 %

No mid-term or final exams

**** Each Assignment counts 10%***

Historical Perspective on MDO

The need for MDO can be better understood by considering the historical context of progress in aerospace vehicle design.

- **1903** Wright Flyer makes the first manned and powered flight.
- **1927** Charles Lindbergh crosses the Atlantic solo and nonstop
- **1935 DC-3** enters service (12,000 to be produced)
- **1958 B707** enters service
- **1970 B747** enters service
- **1974 A300** enters service
- **1976** Concorde enters service

1970-1990 Cold War and Maturity

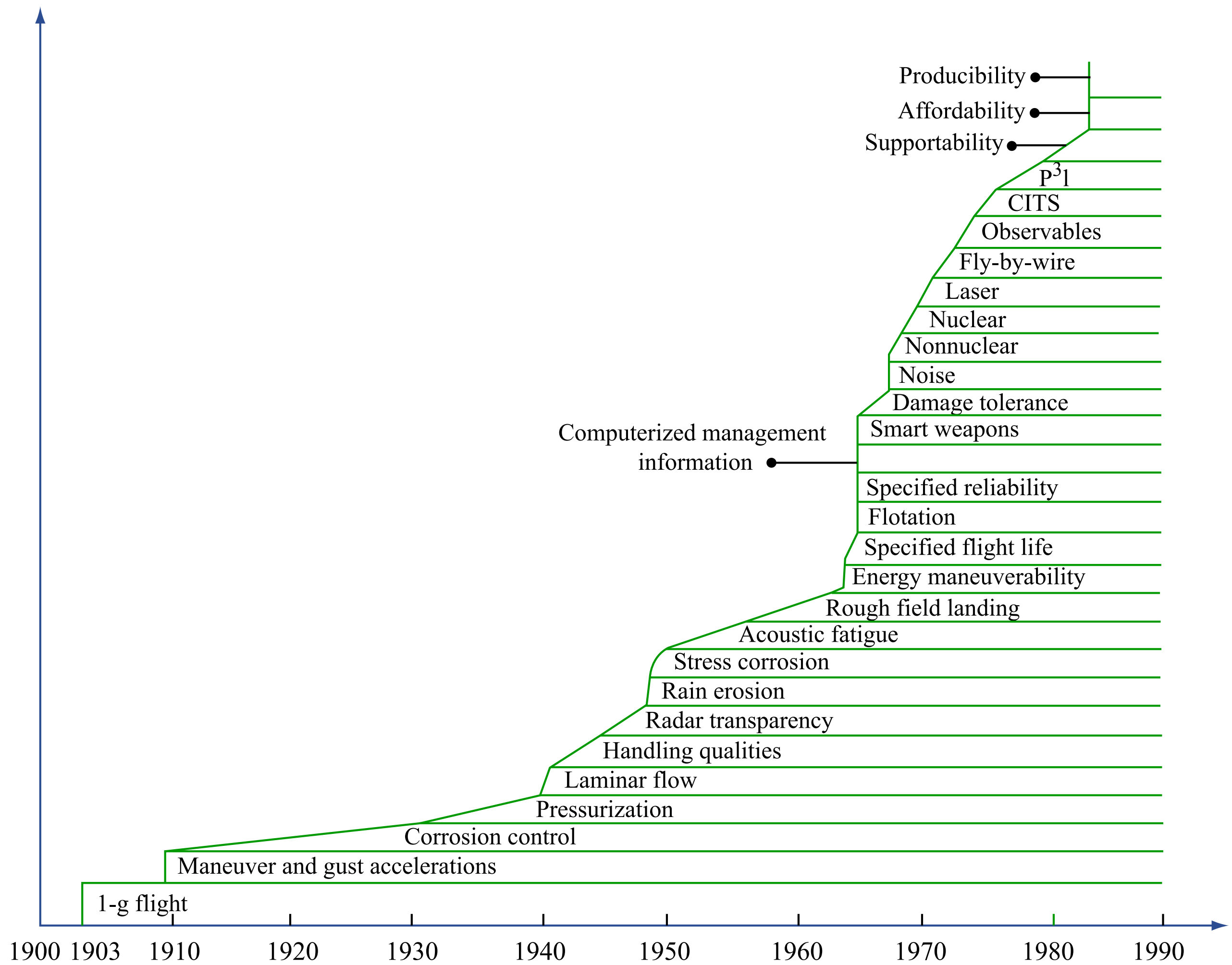
- Big slump in world economy ("oil crisis" 1973), airline industry and end of Apollo program leads to a reduction of engineering workforce around 25%

- Two major new developments: Computer aided design (CAD), Procurement policy changes for airlines and the military

- Earlier quest for maximum performance has been superseded by need for a "balance" among performance, life-cycle cost, reliability, maintainability and other "-ilities"

- Reflected by growth in design requirements, see next slide. Competition in airline industry drives operational efficiency.

Growth in design requirements



Design requirements growth for aerospace vehicles.

Image by MIT OpenCourseWare.

1990-present

- Multidisciplinary design extended to other industries: spacecraft, automobiles, electronics and computers, transportation, energy and architecture

- Thrusts in government and industry to improve productivity and quality in products and processes

- Design process: Globalization results in distributed, decentralized design teams, high performance PC has replaced centralized super-computers, disciplinary design software (Nastran, CAD/CAM) very mature, Internet and LAN's allow easy information transfer

- Advances in optimization algorithms: e.g. Genetic Algorithms, Simulated Annealing, MDO software, e.g. iSIGHT, Model Center …

MDO Timeline

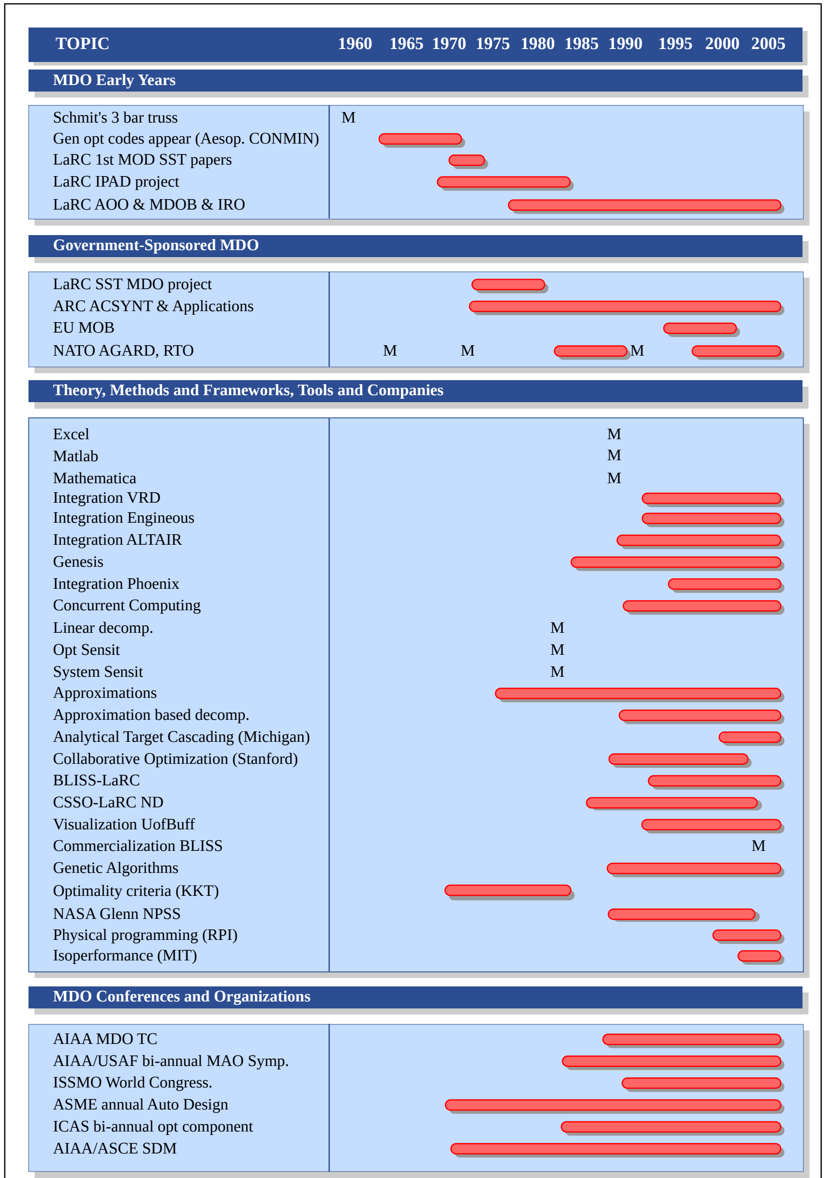
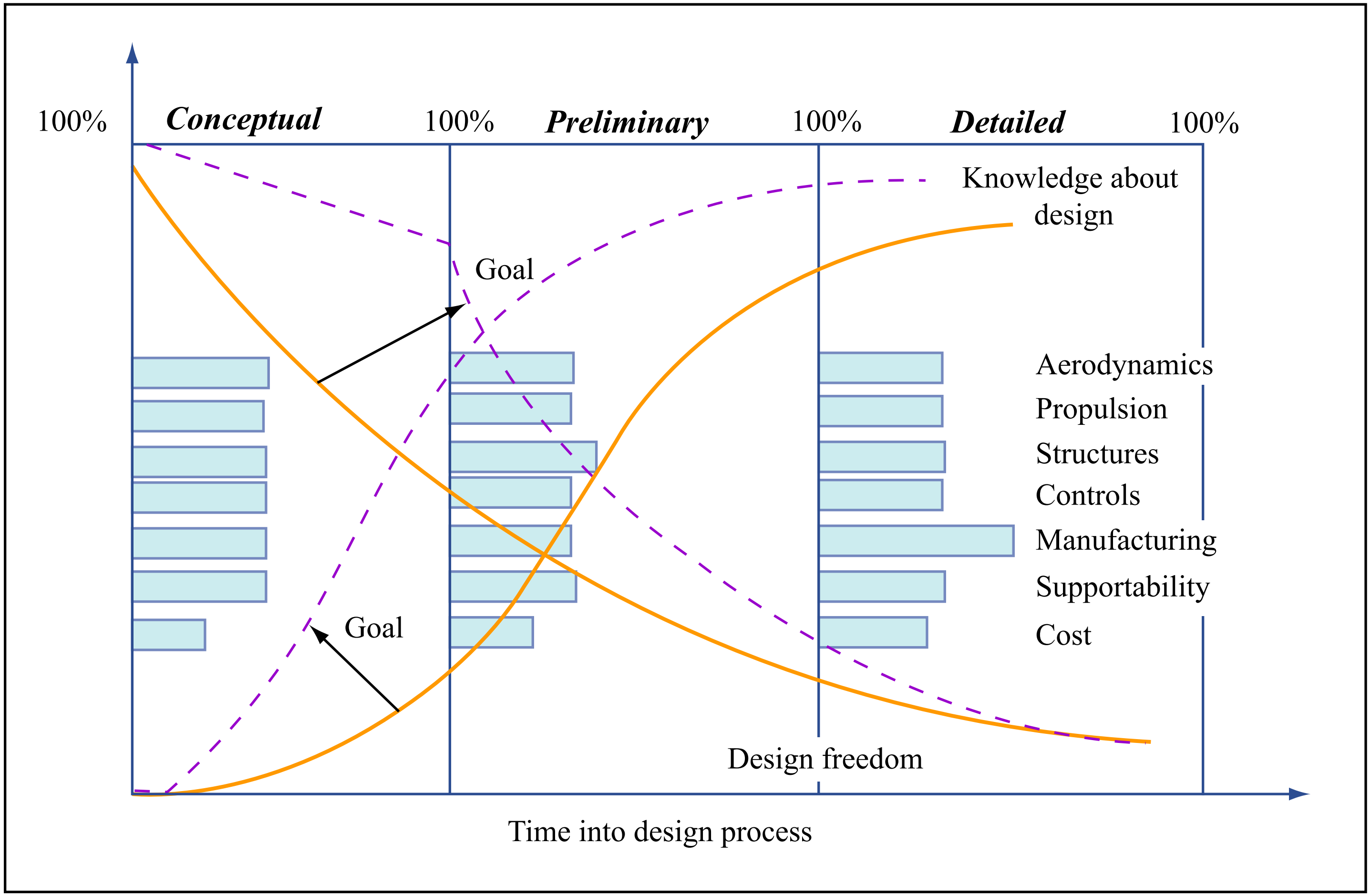


Image by MIT OpenCourseWare.

Agte J., de Weck O., Sobieszczanski-Sobieski J., Arendsen P., Morris A., Spieck M., "MDO: assessment and direction for advancement - an opinion of one international group", *Structural and Multidisciplinary Optimization*, 40 (1) 17-33, January 2010

Design Freedom versus Knowledge



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Goal of MDO: Gain design knowledge earlier and retain design freedom longer into the development process.

Definitions

Multidisciplinary - comprised of more than one traditional disciplinary area described by governing equations from various physical, economic, social fields

System - A system is a physical or virtual object that exhibits some behavior or performs some function as a consequence of interactions between the constituent elements

Design - The process of conceiving and planning an object or process with a specific goal in mind. In the context of this class this refers to the conceiving of a system that will subsequently be implemented and operated for some beneficial purpose.

Optimization - To find a system design that will minimize some objective function. The objective function can be a vector comprising measures of system behavior ("performance"), resource utilization ("time, money, fuel ...") or risk ("stability margins…").

Problem Formulation and Setup

(NLP)

$$\min \mathbf{J}(\mathbf{x},\mathbf{p})$$ → **objective**

$$\text{s.t.} \quad \mathbf{g}(\mathbf{x},\mathbf{p}) \leq 0$$

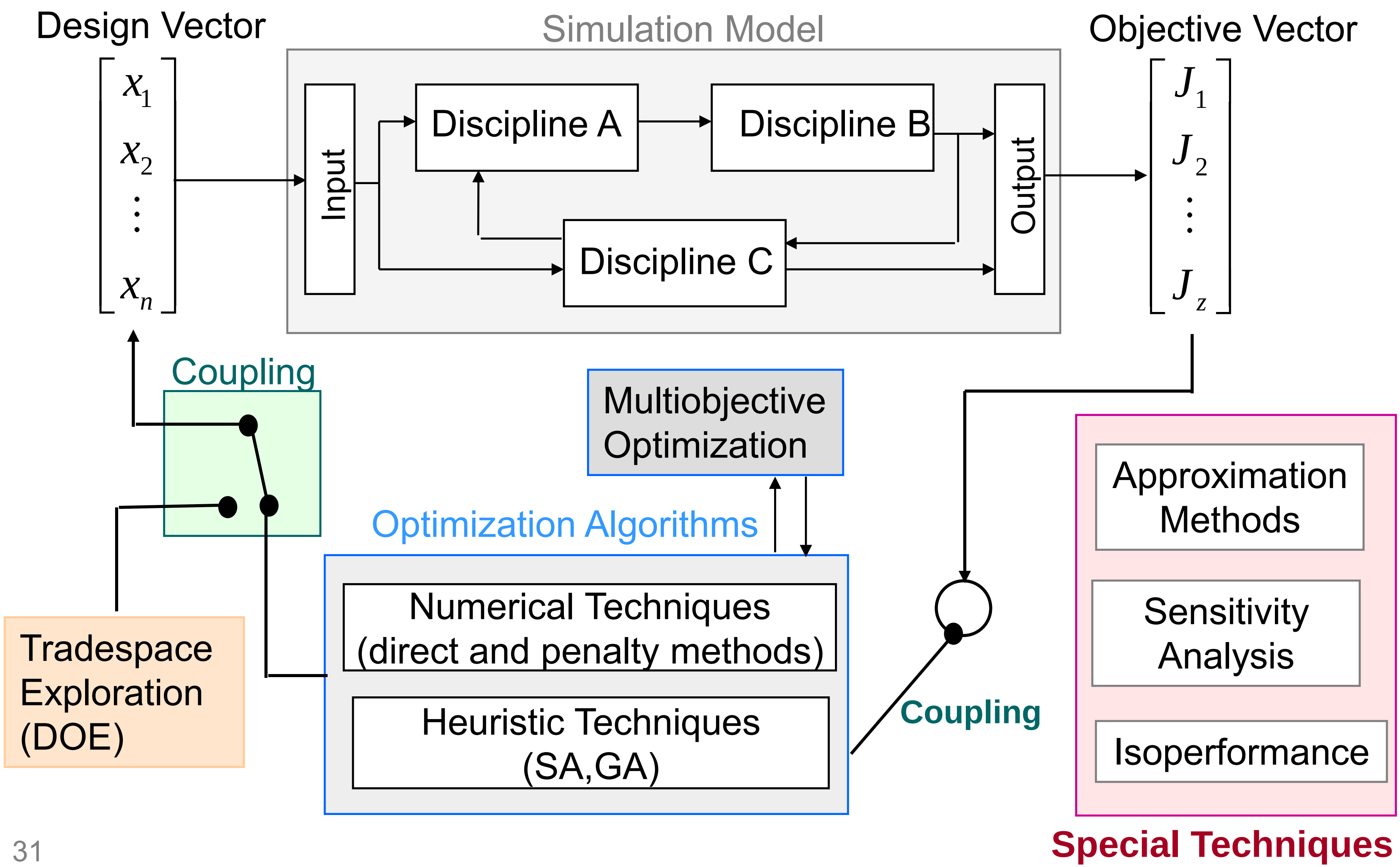
$$\mathbf{h}(\mathbf{x},\mathbf{p}) = 0$$ → **constraints**

$$x_{i,LB} \leq x_i \leq x_{i,UB}$$ → **bounds**

$$\text{where} \quad \mathbf{J} = \begin{bmatrix} J_1(\mathbf{x}) & \cdots & J_z(\mathbf{x}) \end{bmatrix}^T$$

$$\mathbf{x} = \begin{bmatrix} x_1 & \cdots & x_i & \cdots & x_n \end{bmatrix}^T$$ → **design vector**

MSDO Framework



Challenges of MSDO

- Deal with design models of realistic size and fidelity that will not lead to erroneous conclusions
- Reduce the tedium of coupling variables and results from disciplinary models, such that engineers don't spend 50-80% of their time doing data transfer
- Allow for creativity while leveraging rigorous, quantitative tools in the design process. Hand-shaking: qualitative vs. quantitative
- Data visualization in multiple dimensions
- Incorporation of higher-level upstream and downstream system architecture aspects in early design: staged deployment, safety and security, environmental sustainability, platform design etc...

Summary of what you will accomplish

- **Learning Objectives**:
  - decompose and integrate multidisciplinary design models
  - formulate meaningful problems mathematically
  - explore design space and understand optimization
  - critically analyze results, incl. sensitivity analysis
- **Understand current state of the Art in MSDO**
  - see depth and breadth of applications in industry & science
  - get a feel for interaction of quantitative-qualitative design
  - understand limitations of techniques
  - good overview of literature in the field
- **Benefit your research directly … and have fun !**

Assignments

- **Read Chapter 1**
  - **Papalambros, "Principles of Optimal Design"**
  - **Before: Lecture 4**
- **A1 handed out Lecture 2**