16.810 (16.682)
Engineering Design and Rapid Prototyping

Lecture 1

Course Introduction

Instructor(s)

Prof. Olivier de Weck
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Dr. Il Yong Kim
kiy@mit.edu

January 5, 2004
Happy New Year 2004

Mars Rovers MER-A “Spirit” landed Sat 1/3 11:35pm ET

Body Structure (Warm Electronics Box WEB). Ref: http://marsrovers.jpl.nasa.gov

We won’t be designing a Mars Rover this IAP, but …

You will learn about the design process and fundamental building blocks of any complex (aerospace) system
Outline

- Organization of 16.810
  - Motivation, Learning Objectives, Activities
- (Re-) Introduction to Design
  - Examples, Requirements, Design Processes (Waterfall vs. Spiral), Basic Steps
- “Design Challenge” - Team Assignment
  - Int’l Bicycle Corp., Requirement Sheets, Product Team Assignments
- Facilities Tour
Organization of 16.810 (16.682)
**16.810 Expectations**

- 6 unit course (3-3-0) – 11 sessions
  - MWF1-4 in 33-218, **must** attend all sessions or get permission of instructors to be absent
  - This is for-credit, no formal “problem sets”, but expect a set of deliverables
  - Have fun, but also take it seriously
  - The course is a “prototype” itself and we are hoping for your feedback & contributions
  - Officially register under 16.682 (Jan 2004) on WEBSIS
<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
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<tbody>
<tr>
<td>December 2002</td>
<td>Undergraduate Survey in Aero/Astro Department. Students expressed wish for CAD/CAE/CAM experience.</td>
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<tr>
<td>March 2003</td>
<td>Preliminary discussion among faculty and staff – O. de Weck, I.Y. Kim, D. Wallace, P. Young</td>
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<tr>
<td>April 4, 2003</td>
<td>Submission of proposal to Teaching and Education Enhancement Program (&quot;MIT Class Funds&quot;)</td>
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<td>April 22, 2003</td>
<td>Submission of the proposal to CMI (pending)</td>
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<td>May 6, 2003</td>
<td>Award Letter received from Dean for Undergraduate Education ($17.5k)</td>
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<td>June 5, 2003</td>
<td>Kickoff Meeting</td>
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<tr>
<td>Sept 18, 2003</td>
<td>Approved by the AA undergraduate committee (6 units)</td>
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<td>Fall 2003</td>
<td>Preparation</td>
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<tr>
<td>Jan 5, 2004</td>
<td>First Class</td>
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A 2001 survey of undergraduate students (Aero/Astro) – in conjunction with new Dept. head search

- There is a perceived lack of understanding and training in modern design methods using state-of-the-art CAD/CAE/CAM technology and design optimization.

- Individual students have suggested the addition of a short and intense course of rapid prototyping, combined with design optimization.
Needs – from industry

Industry wants/needs (dWo interpretation)

Engineers who

- are trained in integrated design methods and tools
- have personally carried out the design process from conception to implementation at least once.

Engineers who have an initial understanding of:

- importance of requirements
- complementary roles of humans and computers in design
- difficulties at the CAD/CAE/CAM domain interfaces
- value of optimization
- importance of trading off competing objectives
- difference between predicted vs actual behavior of the artifacts they design
CONFOUNDING FACTS

- Engineering requires thorough mathematical & scientific knowledge
- Engineers study science and math extensively
- Engineers may conduct scientific experiments while doing Engineering
- Scientists use engineering methods
- Some great engineers trained as scientists & mathematicians
- Some great scientists trained as engineers
- All require intensity, passion, creativity & intellectual effort

BUT, THEY ARE DISTINCT

“The scientist seeks to understand what is; the engineer seeks to create what never was” - Von Karman
An engineer should be able to ...

- Determine quickly how things work
- Determine what customers want
- Create a concept
- Use abstractions/math models to improve a concept
- Build or create a prototype version
- Quantitatively and robustly test a prototype to improve concept and to predict
- Determine whether customer value and enterprise value are aligned (business sense)
- Communicate all of the above to various audiences

- Much of this requires “domain-specific knowledge” and experience
- Several require systems thinking and statistical thinking
- All require teamwork, leadership, and societal awareness

Slide from Prof. Chris Magee
Boeing List of "Desired Attributes of an Engineer"

- A good understanding of engineering science fundamentals
  - Mathematics (including statistics)
  - Physical and life sciences
  - Information technology (far more than "computer literacy")
- A good understanding of design and manufacturing processes (i.e. understands engineering)
- A multi-disciplinary, systems perspective
- A basic understanding of the context in which engineering is practiced
  - Economics (including business practice)
  - History
  - The environment
  - Customer and societal needs
- Good communication skills
  - Written
  - Oral
  - Graphic
  - Listening
- High ethical standards
- An ability to think both critically and creatively - independently and cooperatively
- Flexibility. The ability and self-confidence to adapt to rapid or major change
- Curiosity and a desire to learn for life
- A profound understanding of the importance of teamwork.

- This is a list, begun in 1994, of basic durable attributes into which can be mapped specific skills reflecting the diversity of the overall engineering environment in which we in professional practice operate.
- This current version of the list can be viewed on the Boeing web site as a basic message to those seeking advice from the company on the topic. Its contents are also included for the most part in ABET EC 2000.
Develop a holistic view and initial competency in engineering design by applying a combination of human creativity and modern computational tools to the synthesis of a single structural component.
“Holistic View” - of the whole. Think about:
- requirements, design, manufacturing, testing, cost …

“Engineering Design” - what you will likely do after MIT

“Human Creativity and Computational Tools”: design is a constant interplay of synthesis and analysis

“Competency” - can not only talk about it or do calculations, but actually carry out the process end-to-end

“Rapid Prototyping” - a hot concept in industry today.

“Structural Components”: part of all aerospace systems, “easy” to implement in a short time
Course Concept

Phase 1
- Problem statement
- Sketch by hand
- CAD
- CAE
- Rapid Prototyping / Validation
  - Manufacturing / Test

Phase 2
- Design Optimization
- Optimum solution
- Rapid Prototyping / Validation
  - Manufacturing / Test
# IAP 2004 Schedule

<table>
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<tr>
<th>Week</th>
<th>Monday</th>
<th>Wednesday</th>
<th>Friday</th>
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<tbody>
<tr>
<td>1</td>
<td>Lecture</td>
<td>L1 – Introduction (de Weck)</td>
<td>L2 – Hand Sketching (Wallace)</td>
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<td>Hands-on activities</td>
<td>Tour - Design studio - Machine shop - Testing area</td>
<td>Sketch Initial design</td>
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<td>2</td>
<td>Lecture</td>
<td>L4 – Introduction to CAE (Kim)</td>
<td>L5 – Introduction to CAM (Kim)</td>
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<td>Hands-on activities</td>
<td>FEM Analysis (Cosmos)</td>
<td>Water Jet Intro machine shop Omax (Weiner, Nadir)</td>
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<td>3</td>
<td>Lecture</td>
<td>Martin Luther King Jr. Holiday – no class</td>
<td>L7 – Structural Testing (Kim, de Weck)</td>
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<td>Hands-on activities</td>
<td>Test part ver. 1 (Kane)</td>
<td>Introduction to Structural Optimization Programs</td>
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<td>4</td>
<td>Lecture</td>
<td>Carry out design optimization</td>
<td>Manufacture part ver. 2 Test part ver. 2</td>
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MWF1-4pm in 33-218 (always meet at 1pm)
Last Lecture of IAP: January 30, 2004
Learning Objectives

At the end of this class you should be able to …

(1) Carry out a systematic design process from conception through
design/implementation/verification of a single structural component.

(2) Quantify the predictive accuracy of CAE versus actual test results.

(3) Explain the relative improvement that computer optimization can
yield relative to an initial, manual solution.

(4) Discuss the complementary capabilities and limitations of the
human mind and the digital computer (synthesis versus analysis).
Grading

- Letter Grading A-F

- Composition
  - Design Deliverables 50%
    - Sketch v1, Drawing v1, FEM Analysis v1/v2, Test Protocol v1/v2, Final Review Slides (3)
  - Parts (v1/v2) 30%
    - (Negotiated) Requirements Compliance
  - Active Class Participation 20%
    - Attendance, Ask Questions, Contribute Suggestions, Fill in Surveys
People

Instructors:
Prof. Olivier de Weck (deweck@mit.edu)
  Assistant: Jackie Dilley (jdliley@mit.edu)
Dr. Il Yong Kim (kiy@mi.edu)
  Postdoctoral Associate
Prof. David Wallace (drwallac@mit.edu) - ME

Staff:
- Teaching Assistant – Bill Nadir (bnadir@mit.edu)
- Software/Design Studio – Fred Donovan (fd@mit.edu)
- Manufacturing – Don Weiner (donw@mit.edu)
- Structural Testing – John Kane (kane@mit.edu)
(Re-)Introduction to Design
Product Development - Design

Improved time-to-climb Performance of F/A-18 in Air-to-Air configuration by ~ 20%

Development of Swiss F/A-18 Low Drag Pylon (LDP) 1994-1996

“design” –

to create, fashion, execute, or construct according to plan

Merriam-Webster
Design and Objective Space

Design Space

Design Variables
- Wing Area: 31.5 [in²]
- Aspect Ratio: 6.2
- Dihedral Angle: 0 [deg]

Objective Space

Performance
- Time-of-Flight: 5.35 sec
- Distance: Ca. 90ft

Cost
- Assembly Time: 87 min
- Material Cost: $4.50

Fixed Parameters
- Air density
- Properties of balsa wood
Basic Design Steps

1. Define Requirements
2. Create/Choose Concept
3. Perform Design
4. Analyze System
5. Build Prototype
6. Test Prototype
7. Accept Final Design
Typical Design Phases

- **Requirements Definition**
  - General arrangement and performance
  - Representative configurations
  - General internal layout

- **Conceptual Design**
  - Conceptual baselines

- **Preliminary Design**
  - Selected baseline
  - Sophisticated Analysis
  - Problem Decomposition
  - Multidisciplinary optimization

- **Detailed Design**
  - Production baseline

- **Production and support**
Product Development Process

“A PDP is the unique sequence of steps or activities, which an enterprise employs to conceive, design, and commercialize a product”

Ulrich and Eppinger

Always involves at least:

- Marketing
- Design
- Manufacturing

\{ \text{core functions} \}
Semiconductor Development Example

1. Set customer target
2. Estimate sales volumes
3. Establish pricing direction
4. Schedule project timeline
5. Development methods
6. Macro targets/constraints
7. Financial analysis
8. Develop program map
9. Create initial QFD matrix
10. Set technical requirements
11. Write customer specification
12. High-level modeling
13. Write target specification
14. Develop test plan
15. Develop validation plan
16. Build base prototype
17. Functional modeling
18. Develop product modules
19. Lay out integration
20. Integration modeling
21. Random testing
22. Develop test parameters
23. Finalize schematics
24. Validation simulation
25. Design rule check
26. Debug product
27. Confirm quality goals
28. Life testing
29. Infant mortality testing
30. Mfg. process stabilization
31. Develop field support plan
32. Thermal testing
33. Confirm process standards
34. Confirm package standards
35. Final certification
36. Volume production
37. Prepare distribution network
38. Deliver product to customers

- Information Flows
- Planned Iterations
- Unplanned Iterations
- Generational Learning
Phased vs. Spiral PD Processes

Phased, Staged, or Waterfall PD Process
(dominant for over 30 years)

- Product Planning
- Product Definition
- System-Level Design
- Detail Design
- Integrate and Test
- Product Launch

Spiral PD Process
(primarily used in software development)

- Product Planning
- Define, Design, Build, Test, Integrate
- Define, Design, Build, Test, Integrate
- Define, Design, Build, Test, Integrate
- Product Launch

Process Design Questions:
- How many spirals should be planned?
- Which phases should be in each spiral?
- When to conduct gate reviews?
Stage Gate PD Process

Planning → Concept Design → System-Level Design → Detailed Design → Integration & Test → Release

Within-Phase Iterations (planned)

Cross-Phase Iterations (unplanned)

Spiral PD Process

- **Planning**
- **Detailed Design**
- **System-Level Design**
- **Concept Design**
- **Integration & Test**

Rapid Prototyping is typically associated with this process.
Basic Trade-offs in Product Development

- Performance - ability to do primary mission
- Cost - development, operation life cycle cost
- Schedule - time to first unit, production rate
- Risk - of technical and or financial failure

Ref: Maier, Rechtin, “The Art of Systems Architecting”
Key Differences in PDP’s

- Number of phases (often a superficial difference)
- Phase exit criteria (and degree of formality)
- Requirement “enforcement”
- Reviews
- Prototyping
- Testing and Validation
- Timing for committing capital
- Degree of “customer” selling and interference
- Degree of explicit/implicit iteration (waterfall or not)
- Timing of supplier involvement
Value of a structured PDP

A structured PDP …

- increases value added, efficiency and competitiveness (e.g. time to market) of the process
- provides something that can be learned and improved
- should be customized to product/market/culture
- should be based on underlying principles
Synthesis versus Analysis

Synthesis
- Creativity
- Intuition – Sanity Checks
- Controls the Process

Analysis
- Number Crunching
- Interfacing
- Configuration Control

Problem definition
Quantitative answers
Graphical Representations

Human Designer
Computer
Database
Form versus Function

Concept: Network Digital Xerography

Functions
- Scanning, printing, and faxing from desktop
- Scan to file
- Network document distribution
- Remote document and device control

Xerox Lakes Document Processing System
F/A-18 Manufacturing Breakdown
Hierarchy I: Parts Level

- **deck components**
  - Ribbed-bulkheads
  - Approximate dimensions
    - 250mm x 350mm x 30mm
    - Wall thickness = 2.54mm

- **frame components**
  - Ribbed-bulkheads
  - Approximate dimensions
    - 430mm x 150mm x 25.4mm
    - Wall thickness = 2mm

- **keel**
  - Ribbed-bulkhead
  - Approximate dimensions
    - 430mm x 660mm x 25.4mm
    - Wall thickness = 2.54mm
Hierarchy II: Assembly Level

- Boeing (sample) parts
  - A/C structural assembly
    - 2 decks
    - 3 frames
    - Keel
  - Loft included to show interface/stayout zone to A/C
  - All Boeing parts in Catia file format
    - Files imported into SolidWorks by converting to IGES format
Hierarchy III: System Level

- L0: Top Kit Collector
- L1: Avionics Sub Kit
  - L2: Transition
  - L2: Turret
  - L2: Cockpit
  - L2: Nose Floor
  - L2: Airframe Sub Kit
- L1: Elec Harness Sub Kit
- L1: Avionics
- L2: Cockpit, LBL Beam
- L2: Cockpit, RBL Beam
- L3: Adds/Removes Hardware & Details

© Sikorsky
# Product Complexity

Assume 7-tree

$$\text{#levels} = \left\lfloor \frac{\log(# \text{ parts})}{\log(7)} \right\rfloor$$

**How many levels in drawing tree?**

<table>
<thead>
<tr>
<th>Product</th>
<th>~ #parts</th>
<th>#levels</th>
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</thead>
<tbody>
<tr>
<td>Screwdriver (B&amp;D)</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Roller Blades (Bauer)</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>Inkjet Printer (HP)</td>
<td>300</td>
<td>3</td>
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<tr>
<td>Copy Machine (Xerox)</td>
<td>2,000</td>
<td>4</td>
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<tr>
<td>Automobile (GM)</td>
<td>10,000</td>
<td>5</td>
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<tr>
<td>Airliner (Boeing)</td>
<td>100,000</td>
<td>6</td>
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- **Simple**
- **Complex**
“Design Challenge” and Team Assignments
Design domain
Forbidden zone
Given holes
Loading
Displacement measure ($\delta$)

Problem statement:
minimize mass
Subject to $\delta \leq \delta_c$
We, the class, are collectively the staff of the “International Bicycle Corporation”.

In the past we produced a “one-size fits all” product (Mass Production)

Recently there has been increased Market competition.

We need to start offering tailored products for different market segments (Mass Customization)

Organization Chart

CEO – de Weck

Consumer Division
1 - Family Economy  2 - Family Deluxe  3 - Crossover  4 - City Bike

Specialty Division
5 - Racing  6 - Mountain  7 - BMX Sports  8 - Acrobatics

Motor Division
9 - Motor Bike

Chief Engineer – Il Yong Kim

Design - Bill Nadir  IT - Fred Donovan  Mfg - Don Weiner  Test - John Kane
Requirements (1): Geometry

Material: Al 6061-T6
Thickness ¼”
Scale ca. 1:5
1. Market Description
This bicycle is to be designed for the mass consumer market. The expected sales volume
is 100,000 per year. Affordability, excellent performance/cost ratio and light weight are
most important to be successful in this market.

2. Requirements
Manufacturing Cost (C):
C ≤ $3.50/part

Performance (δ₁, δ₂, f₁, m):
Displacement δ₁ ≤ 0.060 mm
Displacement δ₂ ≤ 0.009 mm
First natural frequency f₁ ≥ 200 Hz

Mass:
≤ 0.110 lbs

Surface Quality:
2

Load Case:
F₁ = 50 lbs / F₂ = 50 lbs / F₃ = 100 lbs

3. Priorities
"Ishii-Matrix"

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Constrain</th>
<th>Optimize</th>
<th>Accept</th>
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<tr>
<td>Cost</td>
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<td>Performance</td>
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<td>Mass</td>
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Modifications to these requirements have to be negotiated with Management.
# Spiral Development (DSM)

<table>
<thead>
<tr>
<th>1 - Requirements Analysis</th>
<th>2 - Concept/Sketching</th>
<th>3 - CAD Modeling (.prt)</th>
<th>4 - FEM Analysis</th>
<th>5 - Design Optimization</th>
<th>6 - Make Drawing (.dxf)</th>
<th>7 - CAM Layout (.ord)</th>
<th>8 - Manufacture (Omax)</th>
<th>9 - Structural Testing</th>
<th>10 - Accept Part</th>
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Facilities Tour
Facilities Tour

* Design Studio (33-218)
- 14 networked CAD/CAE workstations that are used for complex systems design and optimization.

* Machine Shop
- Water Jet cutter

* Testing Lab
- Static and Dynamic Testing
  Will carry out testing with a customized setup.

* Software to be used:
  - MATLAB
  - Solidworks
  - Cosmos
  - Omax
  - web-based topology optimizer:
Next Steps

- Study 2 Page Requirements Sheets
  - Think about your team’s concept
  - Product Name?
- Look at CAD/CAE/CAM manual
- Register on WEBSIS if not already done
- Complete Attendance Sheet
- Next Lecture
  - Wed 1/7/2004 at 1pm – “Hand Sketching”