# Trends in Multidisciplinary Engineering Education: 2006 and Beyond

Awards Luncheon

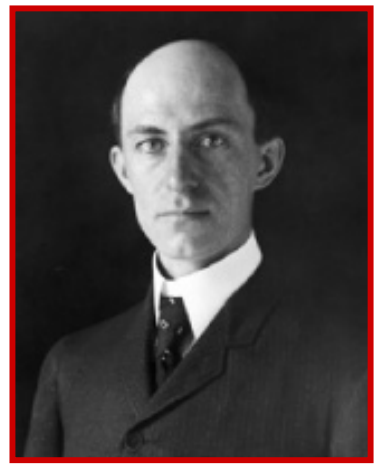
Olivier de Weck and Karen Willcox

September 7, 2006

11th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference

Portsmouth, Virginia

# “What is chiefly needed is skill rather than machinery” Wilbur Wright, 1902



# Outline

- Needs
- Two Key Issues
  - Balancing multidisciplinary engineering education with the fundamentals
  - A lifecycle view of engineering education
- A Vision for the Future
  - Challenges, Opportunities

# Needs

# 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**

***MAO community has mainly focused on this aspect***

- **Much of this requires "domain-specific knowledge" and experience**
- **Several require systems thinking and multidisciplinary skills**
- **All require teamwork, leadership, and societal awareness**

Source: 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.

# NAE attributes of “The Engineer of 2020”

- Strong analytical skills
- Practical ingenuity, creativity
- Good communication skills
- Business, management skills; leadership skills
- High ethical standards, professionalism
- Dynamic/agile/resilient/flexible
- Lifelong learner
- Able to put problems in their socio-technical and operational context

# Balancing Multidisciplinary Engineering Education with the Fundamentals

# What is the right balance?

- Desired attributes of an engineer highlight the importance of leadership, communication, ethics, context, multidisciplinary systems thinking
- Undergraduate engineering curriculum has evolved to strengthen these aspects
  - Communications requirement
  - Leadership, ethics, context, multidisciplinary thinking taught explicitly in engineering classes
  - Conceive-Design-Implement-Operate (CDIO) framework
- Have the engineering fundamentals been compromised?

# MIT Aero/Astro undergraduate curriculum

**1976**:

- 6 Humanities/Social Sciences
- 3 Math
- 3 Physics
- 1 Chemistry/Biology
- 2 Lab
- 5 Engineering (required)
- 3 Engineering (elective)
- 6 Unrestricted
- **Total: 29**

*30 years*

**2006**:

- 8 Humanities/Social Sciences
- 4 Math
- 2 Physics
- 2 Chemistry/Biology
- 2.5 Lab
- 7 Engineering (required)
- 4 Engineering (elective)
- 4 Unrestricted
- **Total: 33.5**

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- Physical properties of gases *or* Aerodynamics
- Rocket propulsion *or* Aircraft engines and gas turbines
- Structural mechanics
- Principles of automatic control *or* Principles of flight guidance

# MIT Aero/Astro undergraduate curriculum

**1976**:

- Aerodynamics
- Propulsion
- Structural mechanics
- Structural analysis
- Estimation and control
- Aerospace dynamics
- Autonomy
- Human factors engineering
- Software engineering
- Digital systems
- Communications
- Computational Methods

- 6 Unrestricted
- **Total: 29**

**2006**:

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# Have the fundamentals been compromised?

- Mathematical skills of engineering undergraduates present a problem, particularly in core engineering classes
  - Many diagnostics document the problem, feedback from students, faculty, tutors
  - At MIT and many other schools
- Challenge: How can we leverage the modern engineering curriculum to strengthen rather than weaken the fundamentals
  - Must overcome the disconnect between upstream math/physics subjects and downstream engineering courses

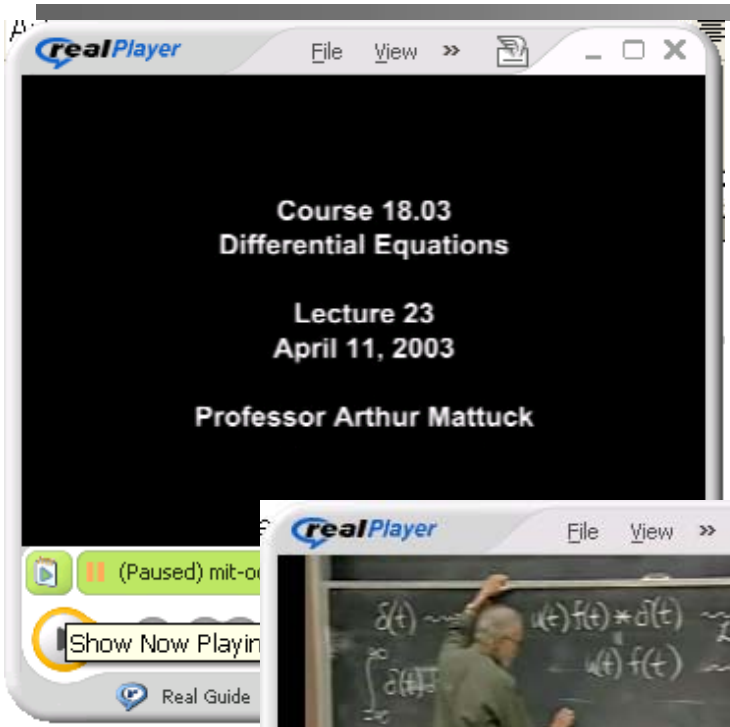
# Integrating the Implicit Mathematics Curriculum

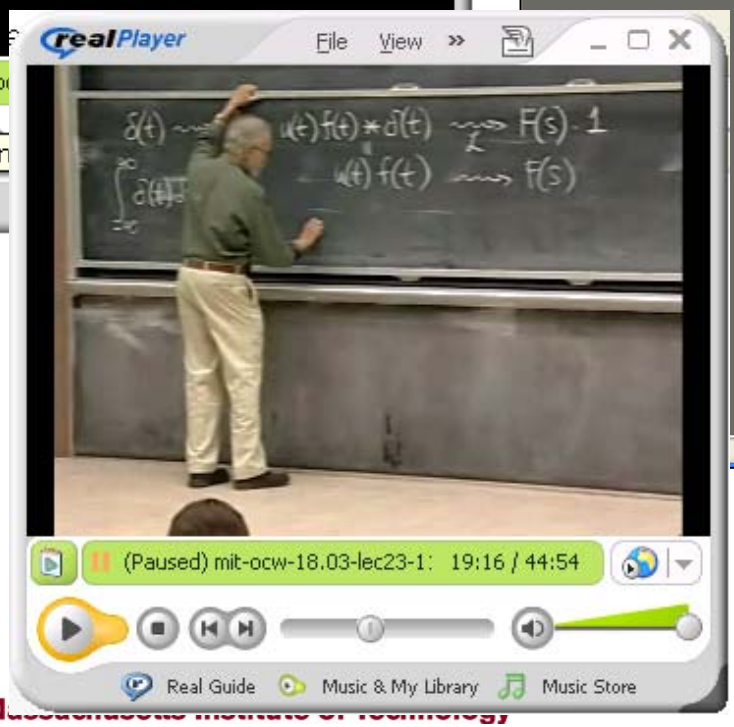
- The Implicit Mathematics Curriculum:
  - What are the mathematical knowledge and skills that we expect of our undergraduate students?
  - How do we expect them to apply these skills (*in the context of core undergraduate engineering classes*)?
  - Where are they learning these skills?
  - How are they learning these skills (*language, examples, context*)?
- Findings:
  - Engineering instructors are not familiar with the material taught in upstream math classes ('what' or 'how')
  - Math instructors are not familiar with specifically how downstream engineering classes use the math skills that they teach
  - Opportunities for bringing engineering examples into math classes and for reinforcing mathematics style of presentation in engineering classes

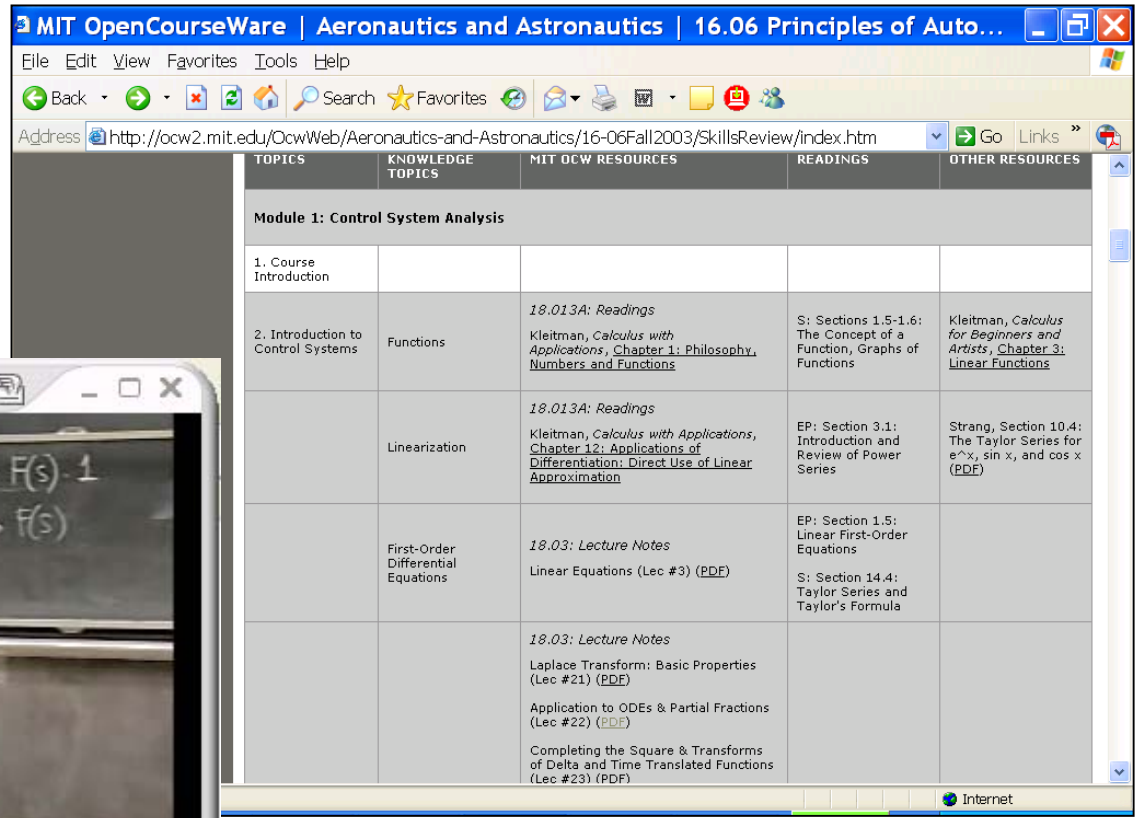
# Flashbacks and Flashforwards

- Create explicit links between engineering courses and upstream math courses
- Curriculum development in 16.06 (Principles of Automatic Control) and 16.901 (Computational Methods in Aerospace Engineering)
- Create lecture-by-lecture mapping between engineering course content and upstream mathematics learning
- Choose appropriate material and a delivery mechanism for an explicit “flashback”
  - During lectures and in lecture notes
  - In homework problems
  - In reading assignments
  - In OpenCourseWare resources

# Flashback Examples



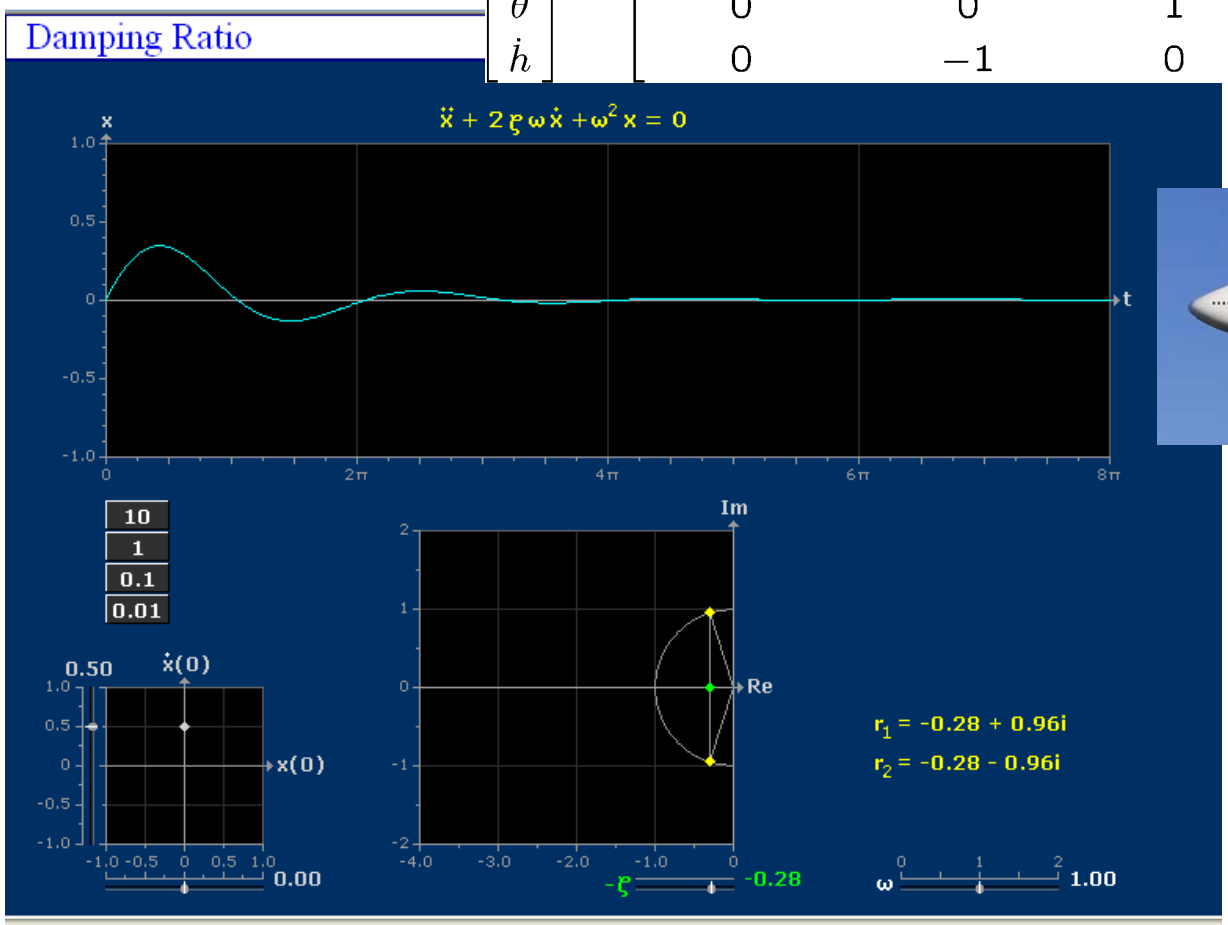




| TOPICS | KNOWLEDGE TOPICS | MIT OCW RESOURCES | READINGS | OTHER RESOURCES |
|---|---|---|---|---|
| **Module 1: Control System Analysis** | | | | |
| 1. Course Introduction | | | | |
| 2. Introduction to Control Systems | Functions | *18.013A: Readings*<br>Kleitman, *Calculus with Applications*, Chapter 1: Philosophy, Numbers and Functions | S: Sections 1.5-1.6: The Concept of a Function, Graphs of Functions | Kleitman, *Calculus for Beginners and Artists*, Chapter 3: Linear Functions |
| | Linearization | *18.013A: Readings*<br>Kleitman, *Calculus with Applications*, Chapter 12: Applications of Differentiation: Direct Use of Linear Approximation | EP: Section 3.1: Introduction and Review of Power Series | Strang, Section 10.4: The Taylor Series for e^x, sin x, and cos x (PDF) |
| | First-Order Differential Equations | *18.03: Lecture Notes*<br>Linear Equations (Lec #3) (PDF) | EP: Section 1.5: Linear First-Order Equations<br>S: Section 14.4: Taylor Series and Taylor's Formula | |
| | | *18.03: Lecture Notes*<br>Laplace Transform: Basic Properties (Lec #21) (PDF)<br>Application to ODEs & Partial Fractions (Lec #22) (PDF)<br>Completing the Square & Transforms of Delta and Time Translated Functions (Lec #23) (PDF) | | |

http://ocw.mit.edu

# Flashback/Flashforward Examples

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{h} \end{bmatrix} = \begin{bmatrix} -6.43e^{-3} & -0.0263 & 0 & -32.2 & 0 \\ -0.0941 & -0.624 & 820 & 0 & 0 \\ -2.22e^{-4} & -1.53e^{-3} & -0.668 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 830 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \\ h \end{bmatrix} + \begin{bmatrix} 0 \\ -32.7 \\ -2.08 \\ 0 \\ 0 \end{bmatrix}$$





Boeing 747:
$U$ = 830 ft/s,
$h$=20,000ft
$W$=637,000lb
Phugoid: $\zeta$=0.29



http://www-math.mit.edu/daimp/

# A Lifecycle View of Engineering Education

# CDIO

- Conceive-Design-Implement-Operate
- Started in mid 1990's with MIT and 3 Swedish Universities, funded by Wallenberg Foundation. Now a network of 20 universities worldwide (http://www.cdio.org)
- Change engineering education from a disciplinary paradigm (structures, controls, aerodynamics , …) to a lifecycle and systems perspective, adopted by MIT Aero/Astro
- Salient points:
  - Every student has carried out the entire lifecycle of a product/system at least once, this has profound pedagogical consequences
  - Outcomes based learning objectives
  - Includes "soft skills": communications, systems thinking,..
  - Deep curricular reform was necessary

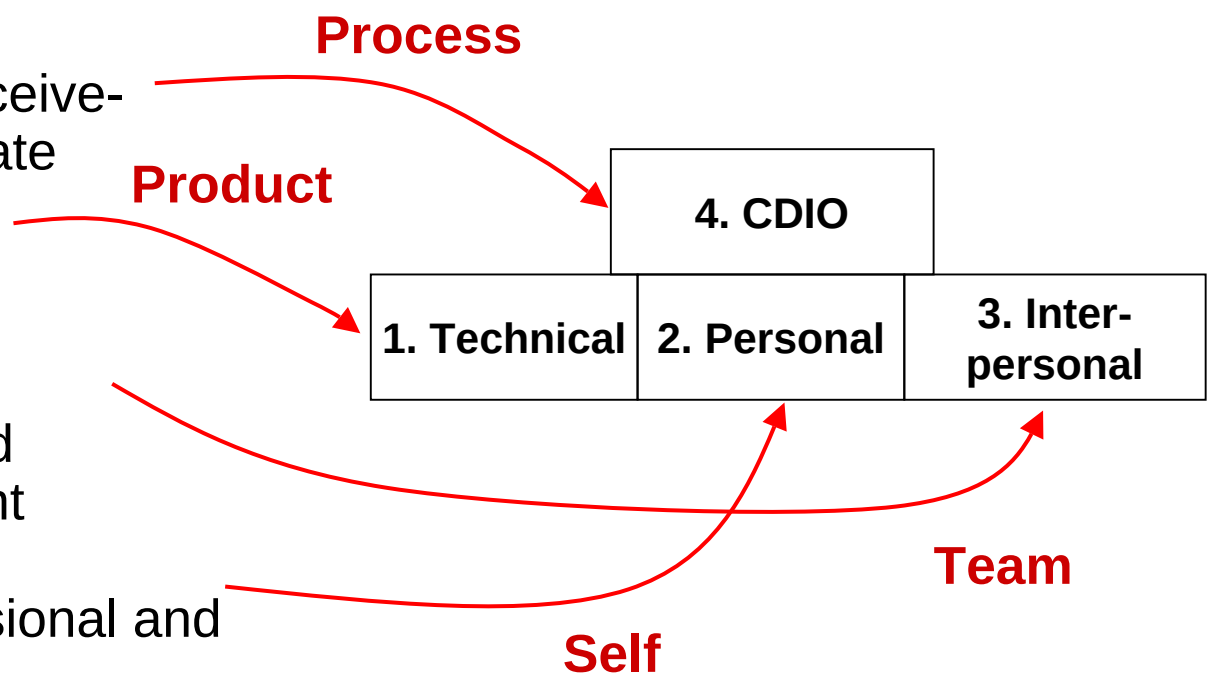
# Mission Statement

- ***The Essential Functions of an Engineer***
  *Graduating engineers should be able to conceive – design – implement – operate complex value-added engineering systems in a modern team-based environment*

# Needs to Goals

Educate students who:

- Understand how to conceive-design-implement-operate
- Complex value-added engineering systems
- In a modern team-based engineering environment
- And are mature, professional and thoughtful individuals




***The CDIO Syllabus - a comprehensive statement of detailed <u>Goals for an Engineering Education</u>***

# CDIO Syllabus Topics

1. Technical Knowledge & Reasoning:
    1. Knowledge of underlying sciences
    2. Core engineering fundamental knowledge
    3. Advanced engineering fundamental knowledge

2. Personal and Professional Skills & Attributes
    1. Engineering reasoning and problem solving
    2. Experimentation and knowledge discovery
    3. System thinking
    4. Personal skills and attributes
    5. Professional skills and attributes

3. Interpersonal Skills: Teamwork & Communication
    1. Multi-disciplinary teamwork
    2. Communications
    3. Communication in a foreign language

4. Conceiving, Designing, Implementing & Operating Systems in the Enterprise & Societal Context
    1. External and societal context
    2. Enterprise and business context
    3. Conceiving and engineering systems
    4. Designing
    5. Implementing
    6. Operating

**Syllabus contains 2 more layers of detail**

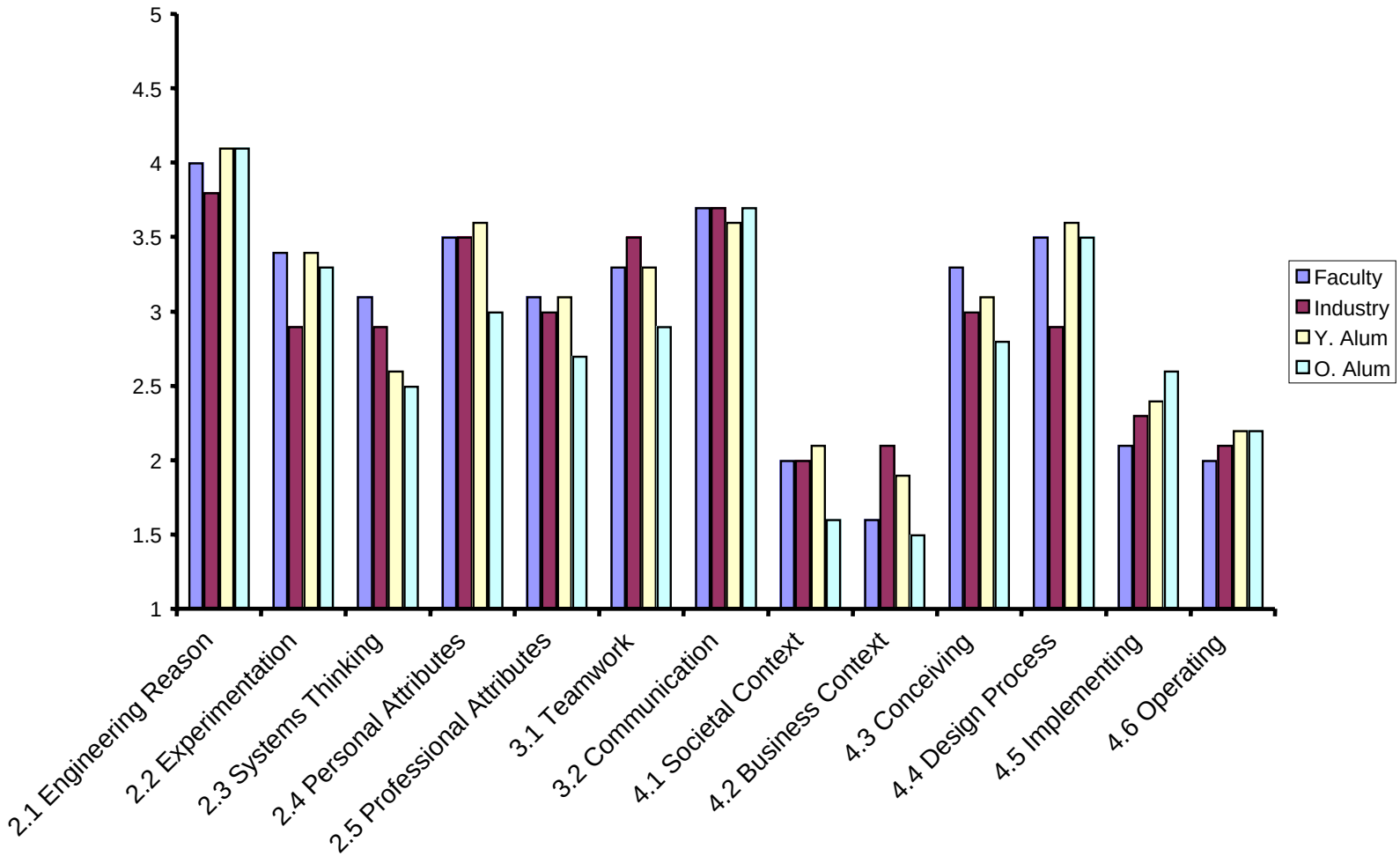
# CDIO SYLLABUS LEVEL OF PROFICIENCY

- 6 groups surveyed: 1st and 4th year students, alumni 25 years old, alumni 35 years old, faculty, leaders of industry

- Question: For each attribute, please indicate which of the five levels of proficiency you desire in a graduating engineering student:

- 1 To have experienced or been exposed to
- 2 To be able to participate in and contribute to
- 3 To be able to understand and explain
- 4 To be skilled in the practice or implementation of
- 5 To be able to lead or innovate in

# CDIO Levels of Proficiency




**REMARKABLE AGREEMENT!**

# Example: 16.810 Course Description

## "Engineering Design and Rapid Prototyping"

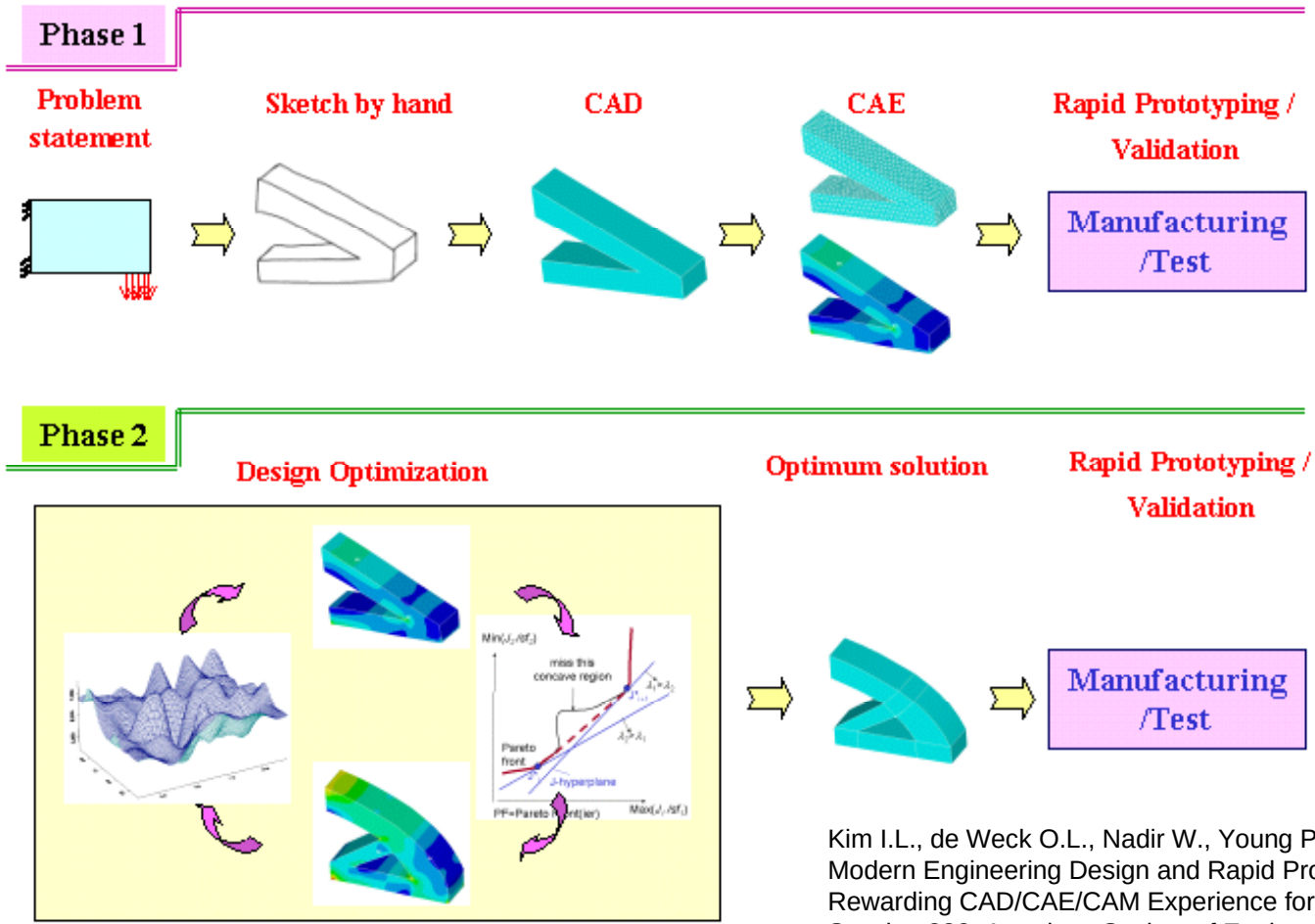
- Learning Objectives:

  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 component or simple system

- Format:
  - IAP (Independent Activities Period):
    - 4-week intense course (16 hours per week)
  - Lectures (6 hrs/week) & Hands-on activities (10 hrs/week)
  - Undergraduate Elective

# Course Description (cont.)

## Outline of course flow

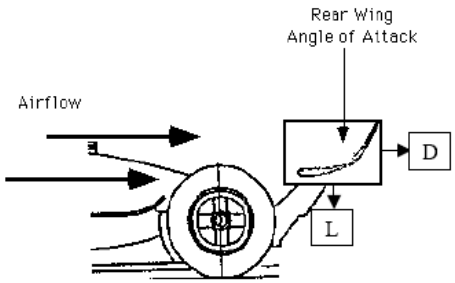


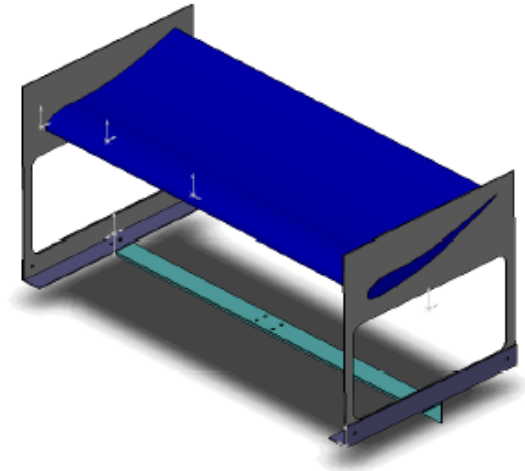

Kim I.L., de Weck O.L., Nadir W., Young P., Wallace D., "Innovative Modern Engineering Design and Rapid Prototyping Course: A Rewarding CAD/CAE/CAM Experience for Undergraduates", Session 332, American Society of Engineering Education (ASEE) 2004 Annual Conference & Exposition, Salt Lake City, Utah, June 20-23, 2004

# Course Description (cont.)

- Target Students:
  - Juniors and Seniors
  - Aero/Astro or Mechanical Engineering.
  - 18 Students per session (maximum capacity of facilities)
  - ~9 teams of 2 students each;  teams of 3 possible
- Learning Objectives:
  - Be able to carry out the conceive-design-implement-operate process for a simple sub-system or  single complex component using the latest CAD/CAE/CAM technology.
  - Explain the subtleties of complementary human design abilities and computer strengths in optimization.
  - Quantify the predictive accuracy of CAE modeling versus actual laboratory test results.

# Project Description – IAP 2005



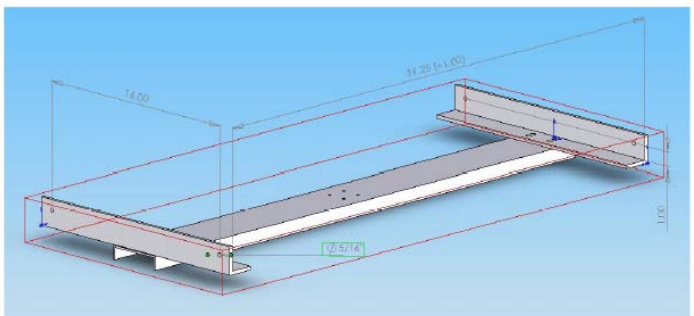



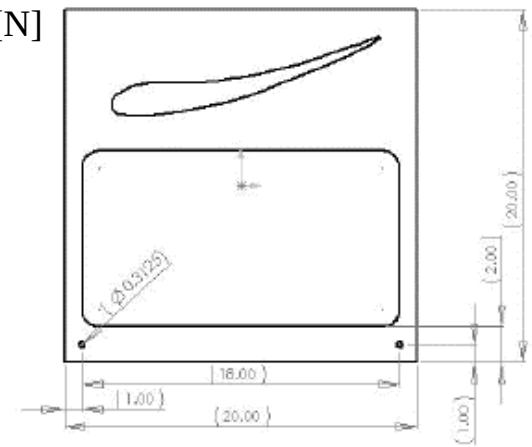
***maximize* [ *F* = *L* – 3**D* – 5**W* ]**

*Where:*

L = measured downforce (negative lift) at specified speed [N]
D = measured drag at specified speed [N]
W = total weight of the assembly (not including test fixture) [N]

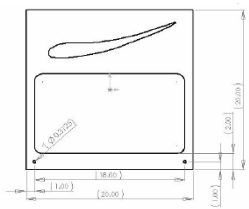
The nominal speed is 60 mph

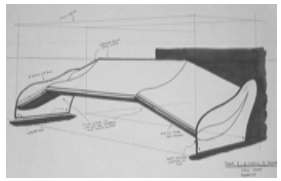


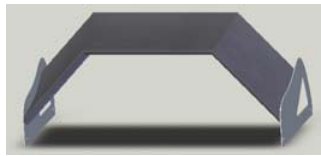


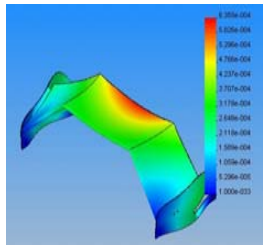
# Project Deliverables – IAP 2005

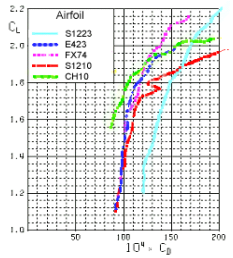
## Phase 1





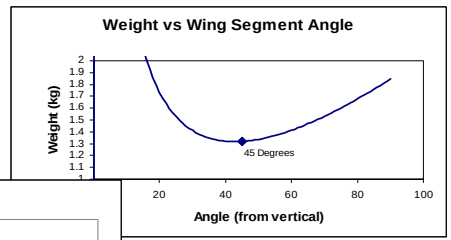


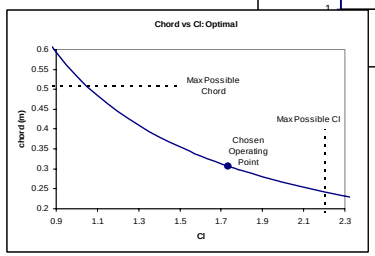




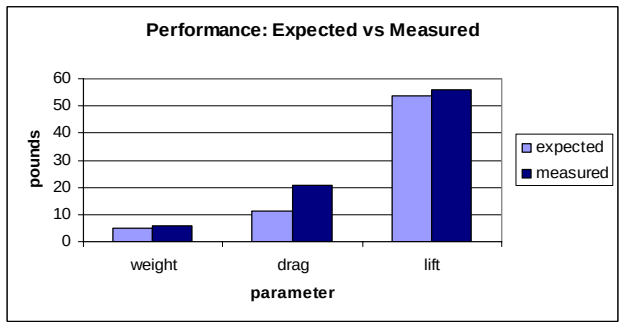

Problem Statement → Hand Sketch → Initial CAD → CAE (FEA) → CAE (CFD)

## Phase 2



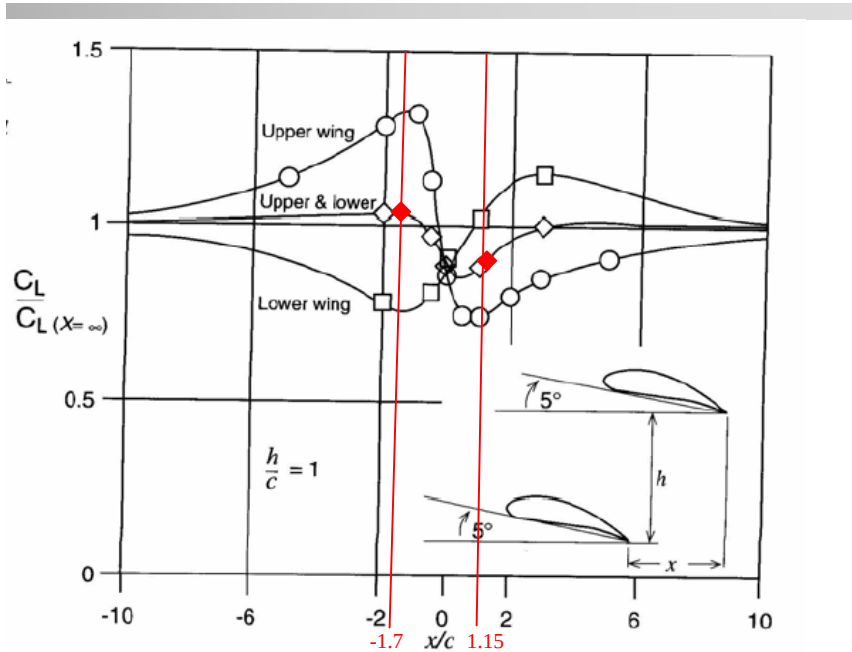

Design Optimization

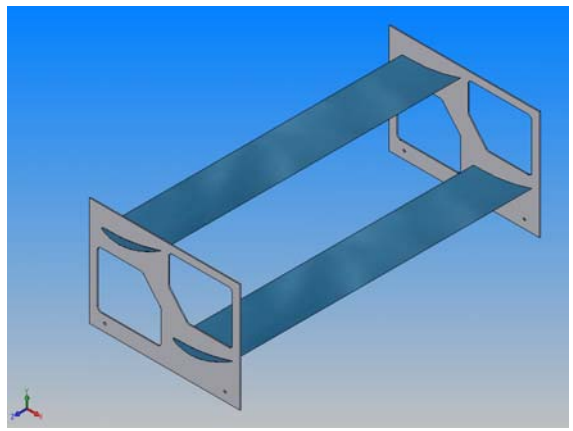

Prototype Testing and Validation

# Learning from Mistakes

- Carrying out a full lifecycle creates memorable learning experiences
- Don't prevent students from making mistakes
- Example: bi-wing configuration
- Excerpt from Student Reflective Memo:

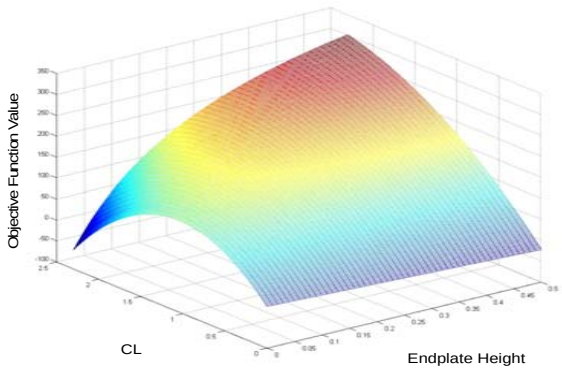


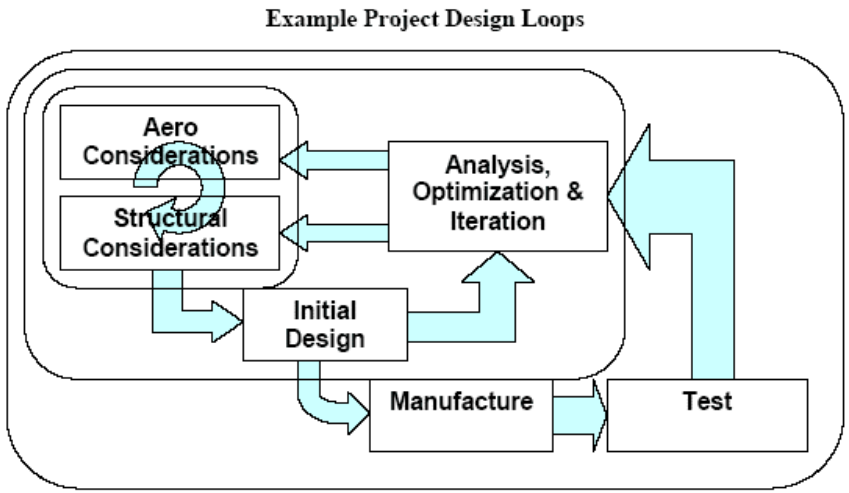

**"I learned the value of constantly checking simulations against reality ….. My rear-wing design used a biplane setup, …due to a huge oversight, the wings were actually arranged in an incorrect orientation which incurred a large drop in down force. ….This experience taught me a great lesson – always triple check your assumptions against your design. I spent hours and hours optimizing a design that was never constructed, simply because I was told to assume that the down force bonus would be experienced. I never bothered to verify this myself, and this disconnection had dire consequences."**



# Use of Optimization

- Manual Iteration
  - Design loops (Spiral method)
- Software
  - Formal software
  - Matlab/Excel (Tradeoff Plots)



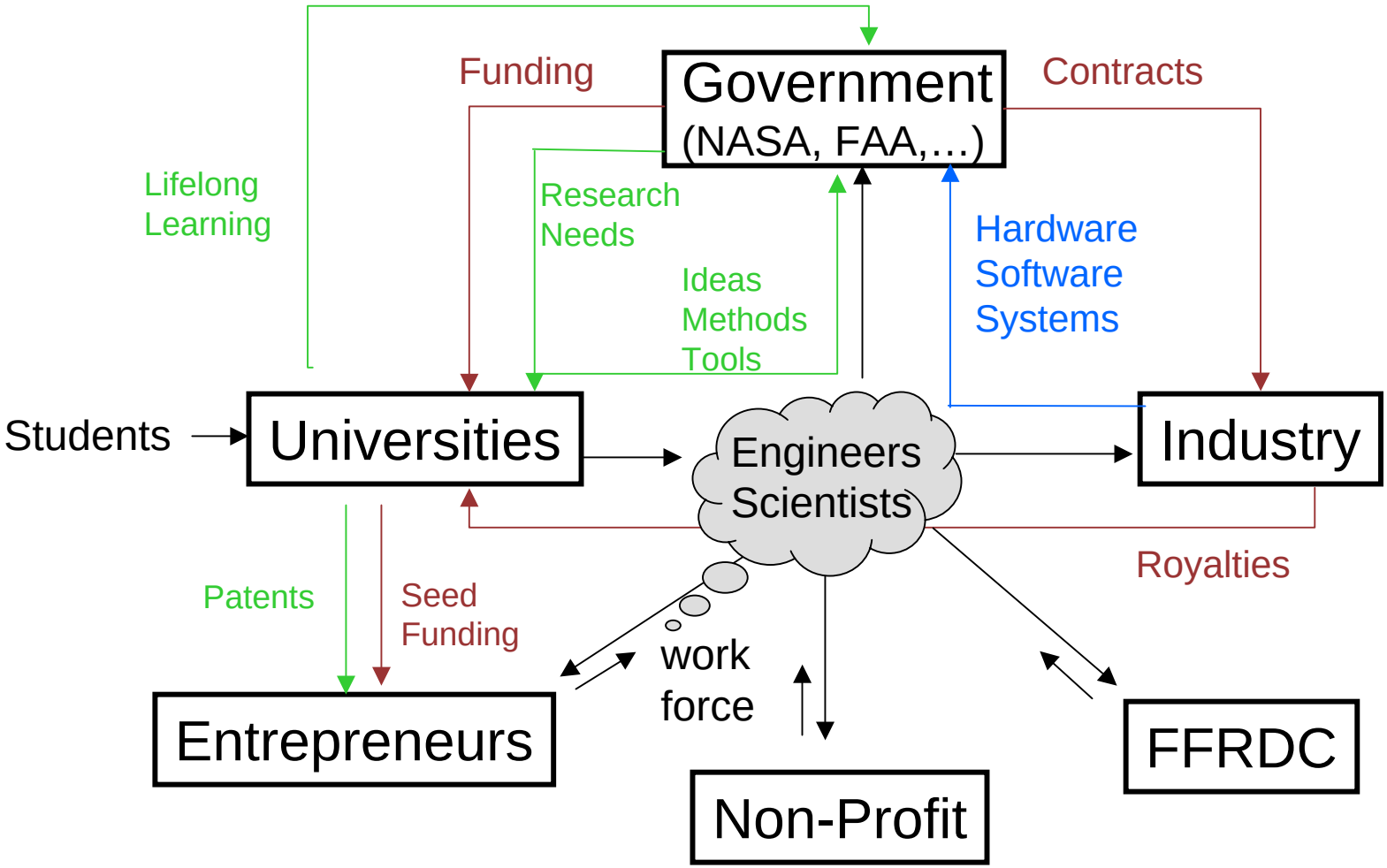



# A Vision for the Future

# Challenges

- Balancing applications with fundamentals
- Working across traditional engineering departments and across schools (engineering, management, biology, …)
- Research funding and multi-year stability for multidisciplinary research in methods & tools development
- Perceptions of “aerospace as a career”
  - industry (MDO providers, MDO users), government, academia

# Stakeholder Value Mapping



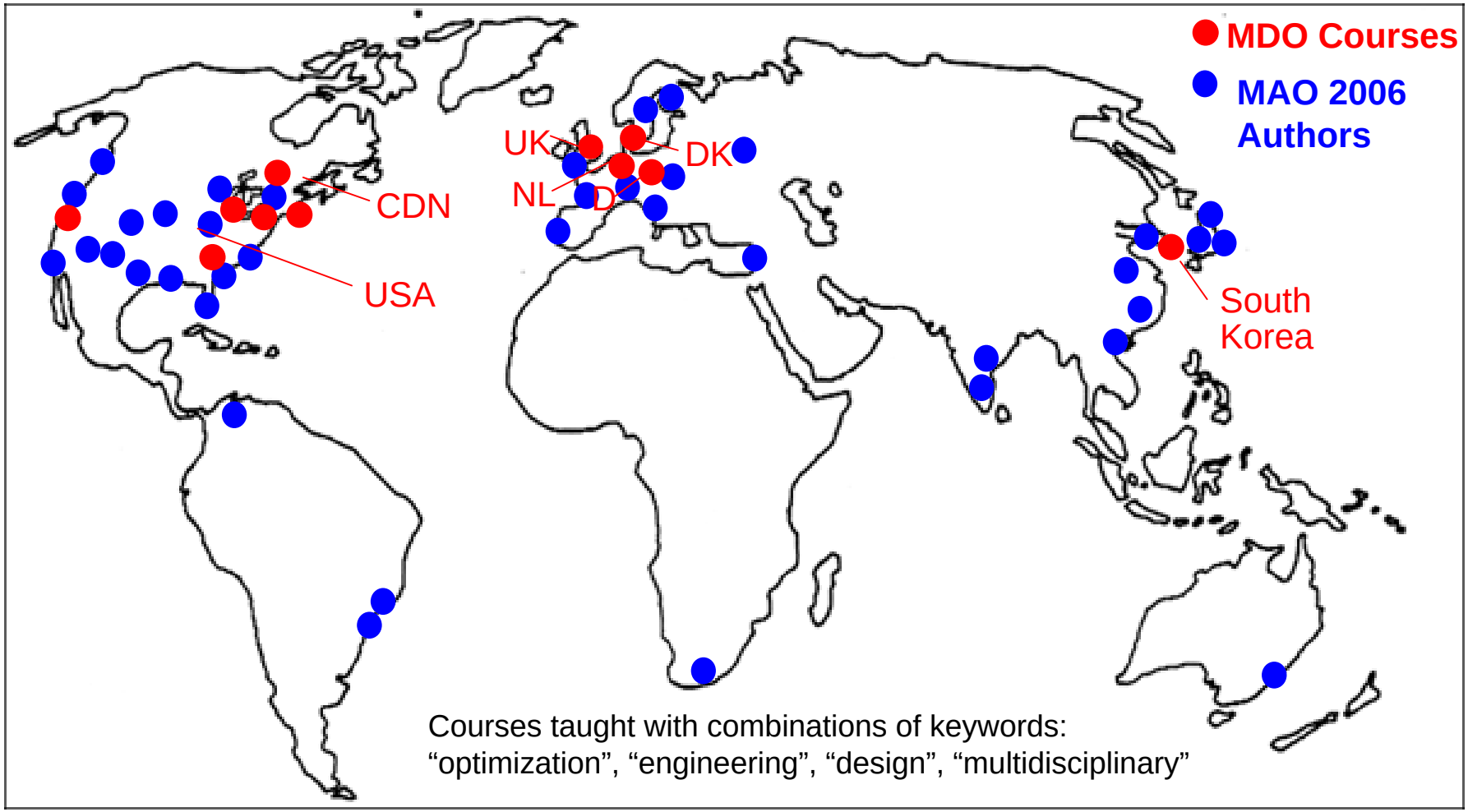

**how do we "architect" this system together?**

# Opportunities

- Active Learning Pedagogy
- Integration of CAD/CAE/CAM Technologies in the classroom environment
- Distance Learning
- Continued Education (19 → 29 → 39 year olds & beyond)
- Globalization
  - Examples at MIT: Cambridge-MIT Institute (CMI), Singapore-MIT Alliance (SMA)
  - Survey of MDO Programs (next chart)

# MDO/MAO Courses Worldwide

Sample Survey – September 2006



# Additional Information

- Open Courseware (OWC)
  - http://ocw.mit.edu
- CDIO
  - http://www.cdio.org

# Thank you !