FOCAPO/CPC Education Panel

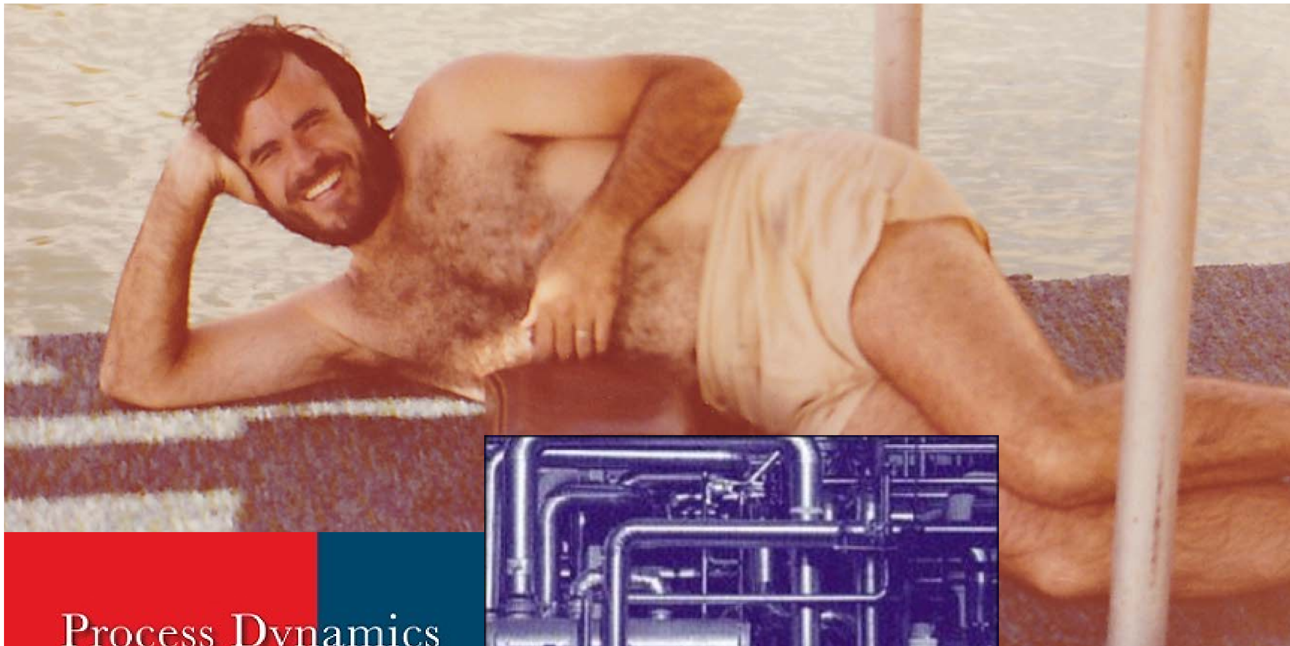
B. Wayne Bequette (Panel Chair)

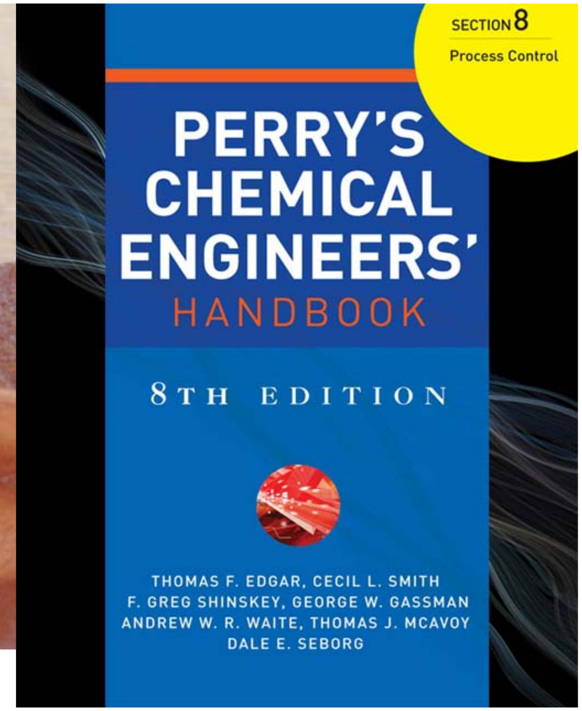
on the behalf of seven distinguished panelists

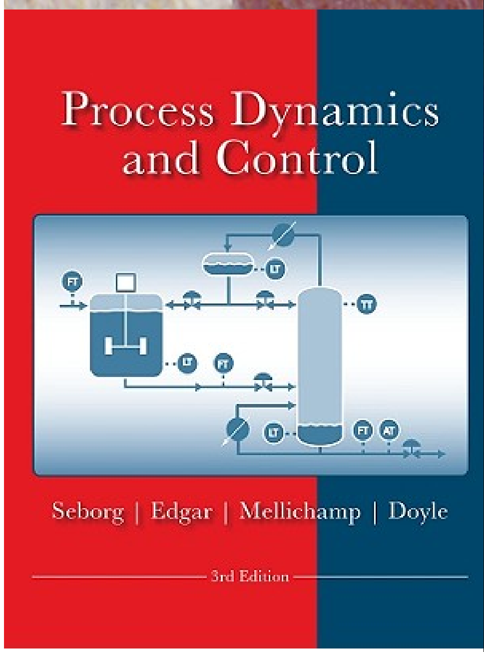
Objective

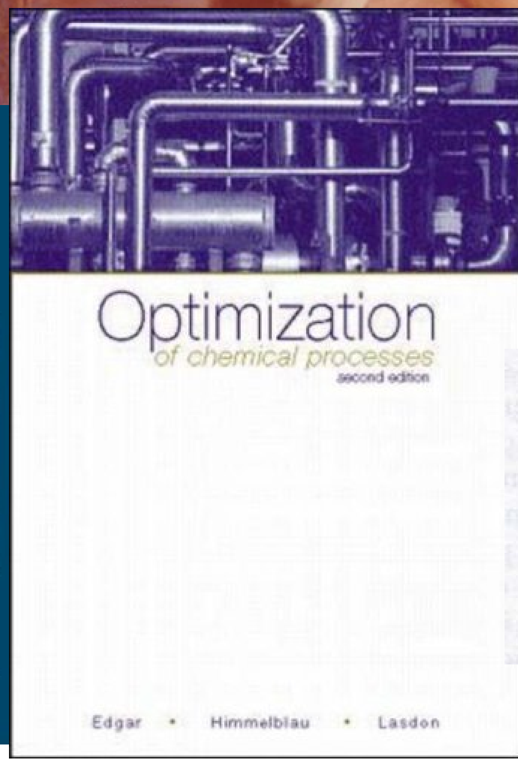
- Discuss the role of systems education within the evolving chemical engineering discipline and the effectiveness of current courses in meeting industrial needs.

Each panelist was asked to provide three slides to summarize their thoughts on the topic







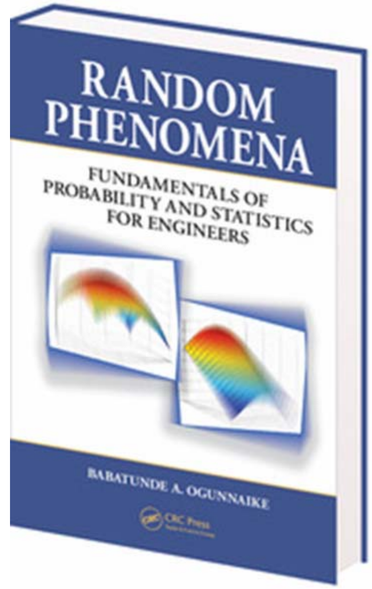


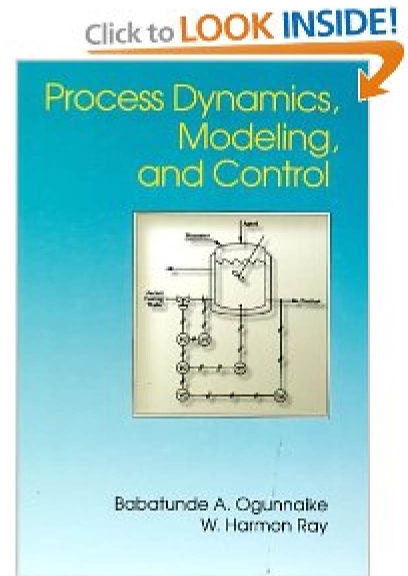
STATUS OF DESIGN METHODS FOR MULTIVARIABLE CONTROL

Thomas F. Edgar
University of Texas
Austin, Texas

(CPC-I, 1976)

I'll use as many slides as I please



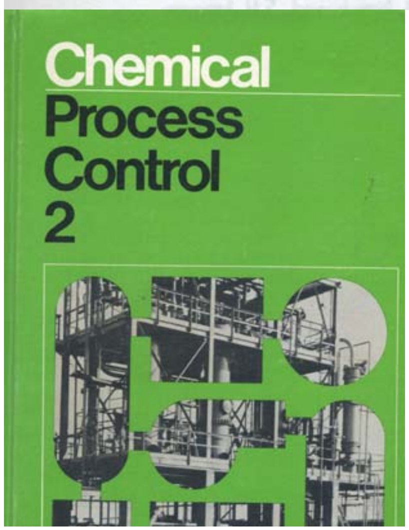


Variability, Uncertainty and Data Analysis in Process Design, Control and Operations

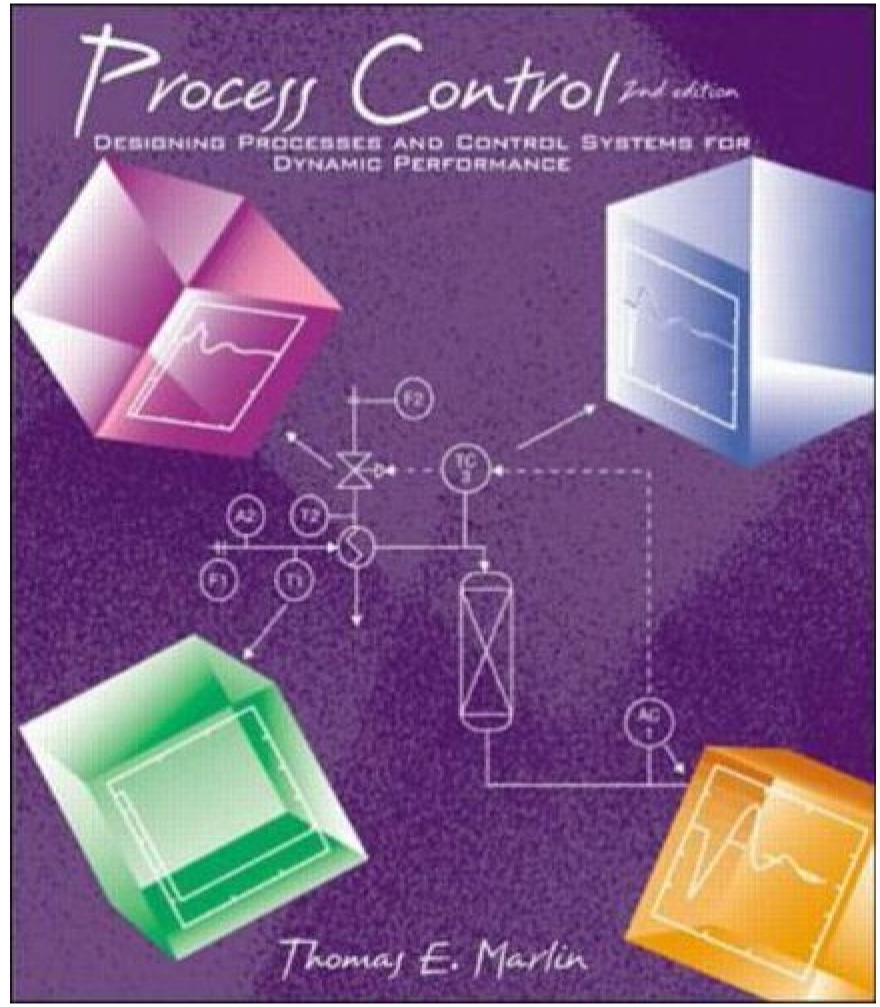
(it is hard to sell textbooks for an elective course)

THE EFFECT ON CONTROL SYSTEMS OF
VIEWING THE PLANT AS A SYSTEM
OF INTEGRATED UNITS

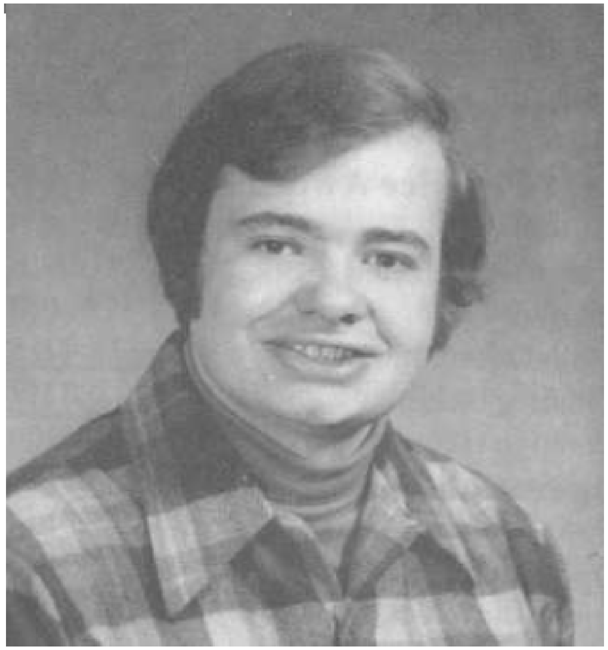
T. E. Marlin
Exxon Research and Engineering
Florham Park, N. J.

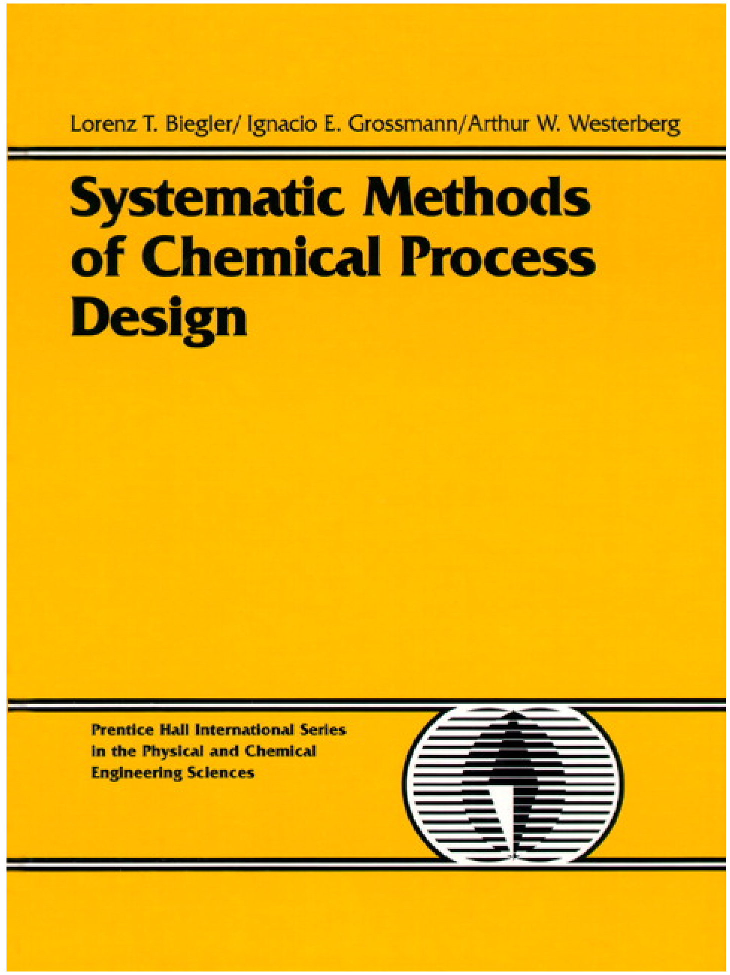


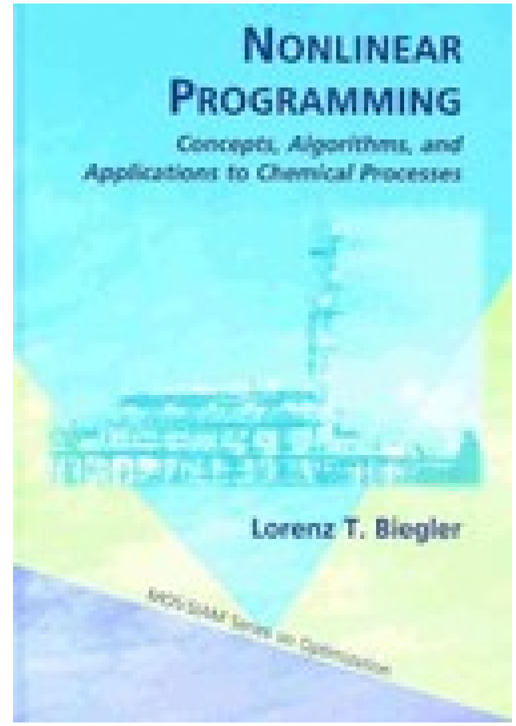
(1981)



Operability in the Process Design course (all ChEs at McMaster major in PSE)



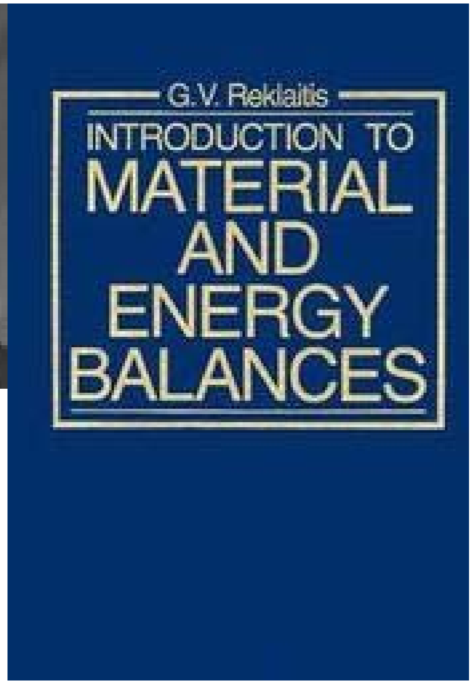


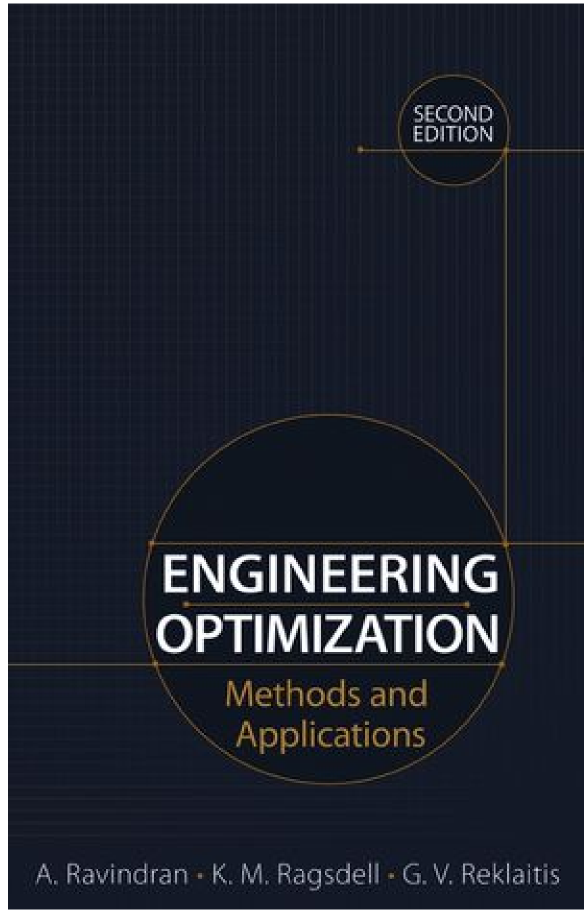


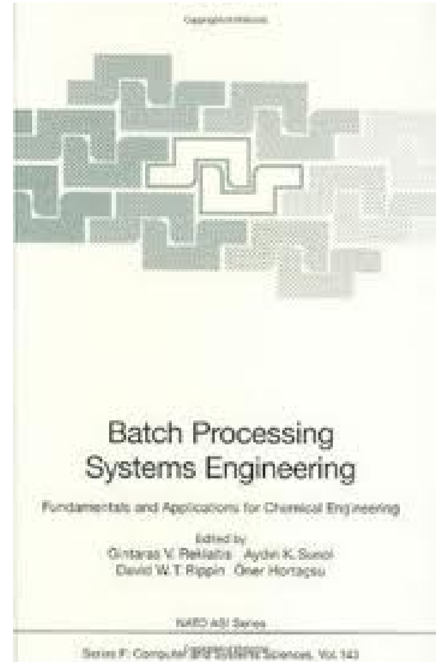
Optimization in Design, Operations and Control
(I'll need 15 minutes for my slides)

Vince Grassi,
Air Products

Meeting Business and Industry needs in a Capstone Design course sequence (we can’t all be writing textbooks)







Elective courses in Operations & Risk Management
(I will use as many slides as Tom Edgar)

Revamping the Goals and Content of a Process Dynamics and Control course

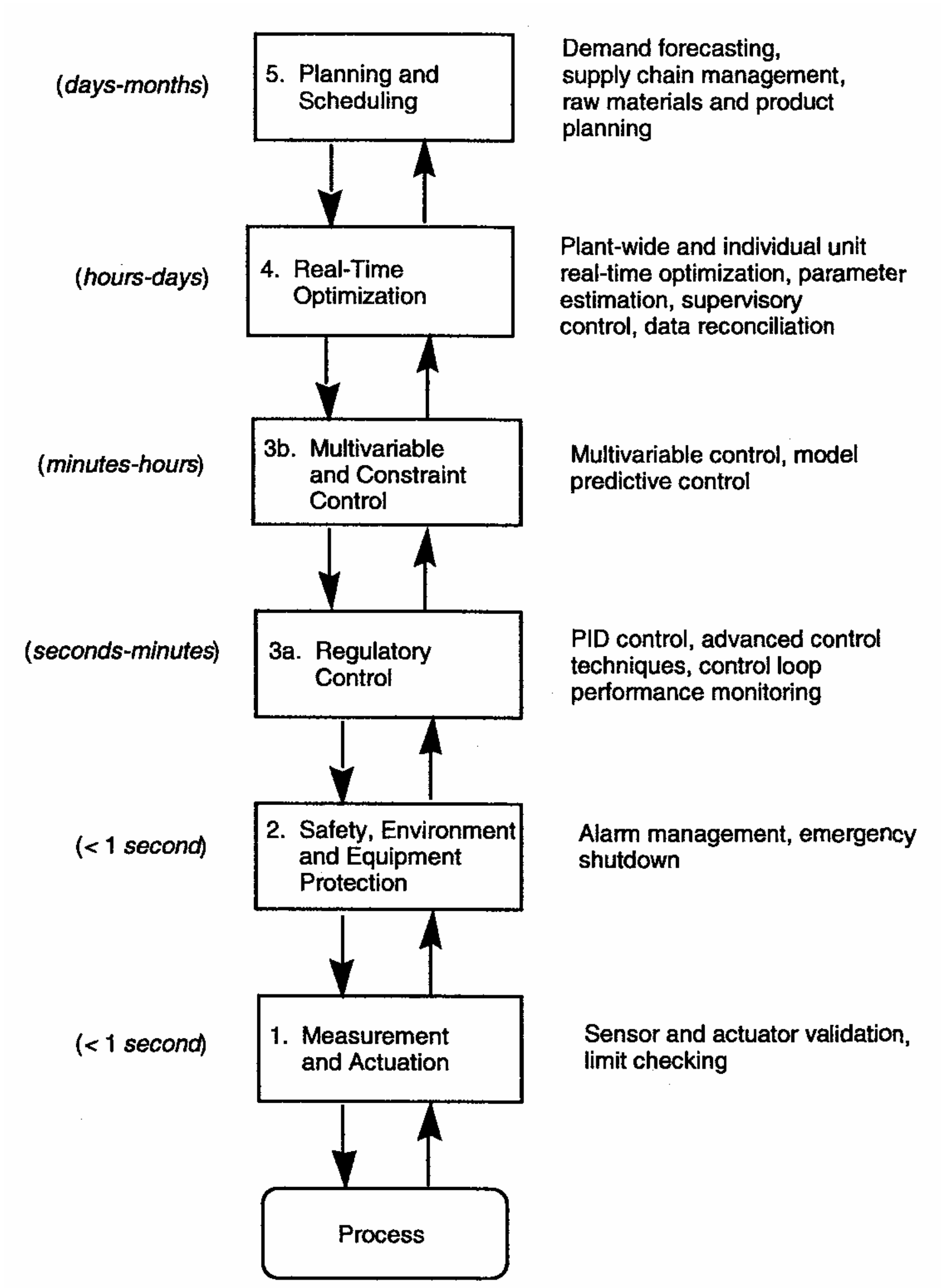
(how to teach all of PSE in a one semester course)

The State of Control Education?

(Tom Edgar)

Industrial Survey: Ranking of Key Control Concepts (10 = highest priority)

1. (8.6) Optimization of a process or operation
2. (7.2) Statistical analysis of data and design of experiments
3. (7.0) Physical dynamic process models
4. (6.9) Statistical/Empirical dynamic process models
5. (6.6) Multivariable interactions and system analysis
6. (5.3) Statistical process control and process monitoring
7. (5.1) Design and tuning of PID loops
8. (3.9) Nonlinear systems dynamics and analysis
9. (2.4) Frequency domain analysis
10. (1.9) Expert systems and artificial intelligence


(days-months)
5. Planning and Scheduling
Demand forecasting, supply chain management, raw materials and product planning
(hours-days)
4. Real-Time Optimization
Plant-wide and individual unit real-time optimization, parameter estimation, supervisory control, data reconciliation
(minutes-hours)
3b. Multivariable and Constraint Control
Multivariable control, model predictive control
(seconds-minutes)
3a. Regulatory Control
PID control, advanced control techniques, control loop performance monitoring
(< 1 second)
2. Safety, Environment and Equipment Protection
Alarm management, emergency shutdown
(< 1 second)
1. Measurement and Actuation
Sensor and actuator validation, limit checking
Process

Optimization of Chemical Processes (Course at UT-Austin)

- Book: T.F. Edgar, D.M. Himmelblau, and L.S. Lasdon, McGraw-Hill, 2001 (2^{nd} ed.), now available for free via the web
- Emphasizes problem formulation, optimization theory and methods, and applications of optimization in chemical engineering
- Typical enrollment of 25 (ChE elective)

The Laboratory Experience and Process Control

- Very few dedicated control labs in existence today
- Introducing students to unsteady state operation is very important
- Simple inexpensive experiments can be pedagogically effective
- How much is necessary (vs. simulation)?

Variability, Uncertainty and Data Analysis
in
Process Control & Operations

Babatunde A. Ogunnaike
University of Delaware

October 14, 2011

Industrial Survey: Ranking of Key Control Concepts (10 = highest priority)

1. (8.6) Optimization of a process or operation
2. (7.2) Statistical analysis of data and design of experiments
3. (7.0) Physical dynamic process models
4. (6.9) Statistical/Empirical dynamic process models
5. (6.6) Multivariable interactions and system analysis
6. (5.3) Statistical process control and process monitoring
7. (5.1) Design and tuning of PID loops
8. (3.9) Nonlinear systems dynamics and analysis
9. (2.4) Frequency domain analysis
10. (1.9) Expert systems and artificial intelligence

3 of 10 involve Statistics & Data Analysis!

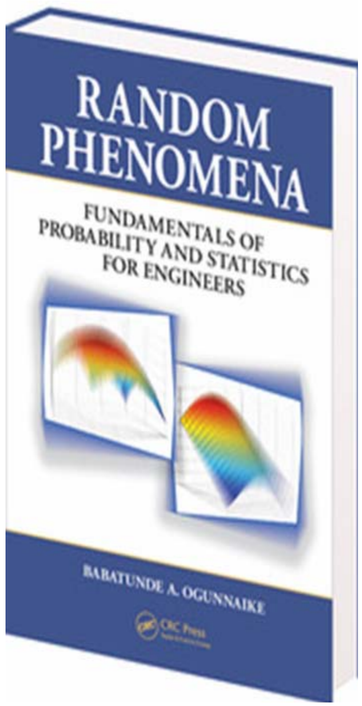
*Courtesy: Tom Edgar

Rationale

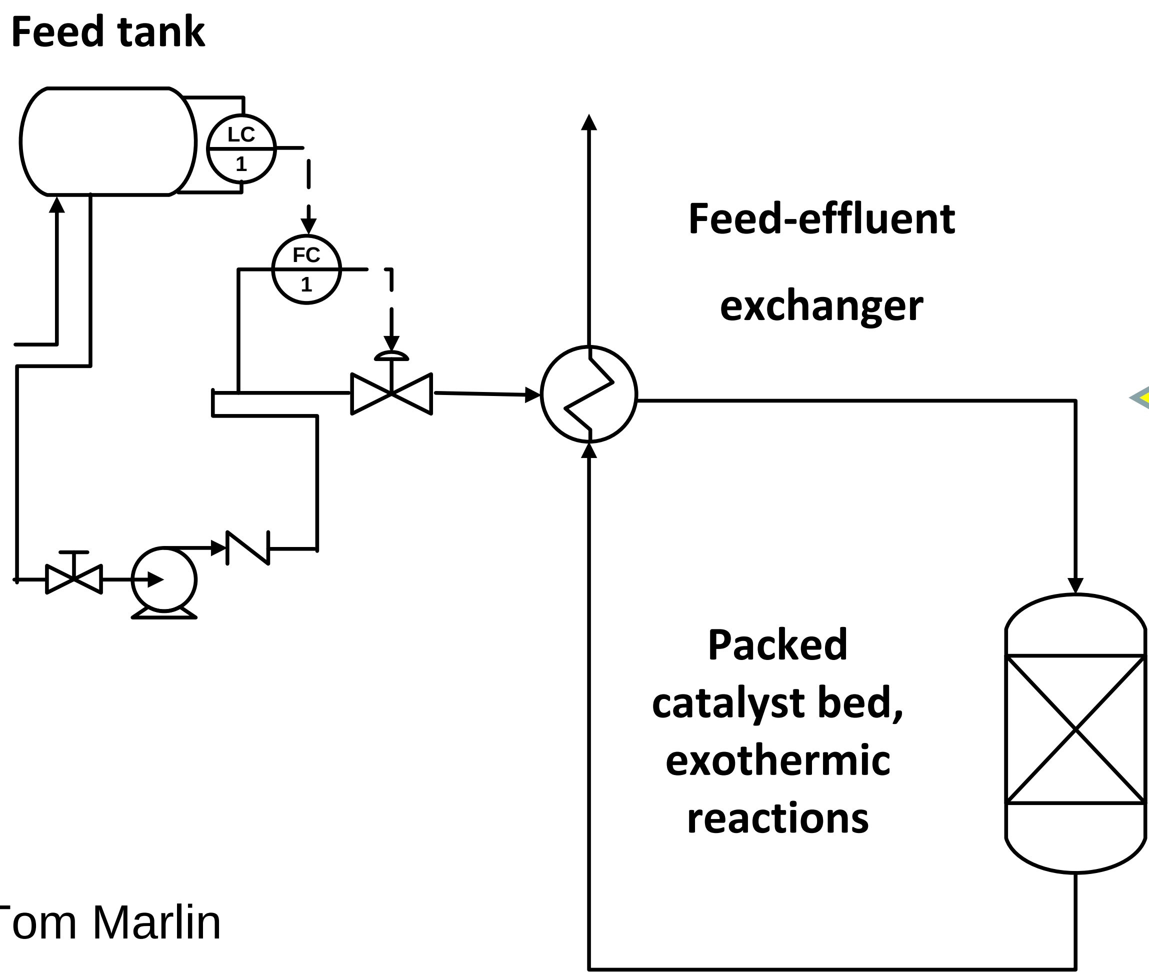
- **Uncertainty and Variability Intrinsic to Process Operations**
- **Implications: Well-trained (process) engineers must know how to:**
  - Design and conduct informative experiments;
  - Analyze and interpret experimental data;
  - Make decisions under uncertainty (including control action decisions; and process optimization)
  - *Characterize and quantify variability and uncertainty*

University of Delaware Course

- **Technical Elective (Not Required)**
- **Introduction to Probability, Statistics and Design of Experiments**
  - Emphasizes fundamentals; (ideal models of uncertainty)
  - Provides systematic treatment of basics
  - Supplements with Applications & Case Studies
- **Applications**
  - Safety and Reliability
  - Quality Assurance and Control
  - PLS/PCA (if time permits)
  - Data-Based Process Optimization



Operability integrates PSE decisions in Process Design



Is this process operable?

If not, the design is flawed

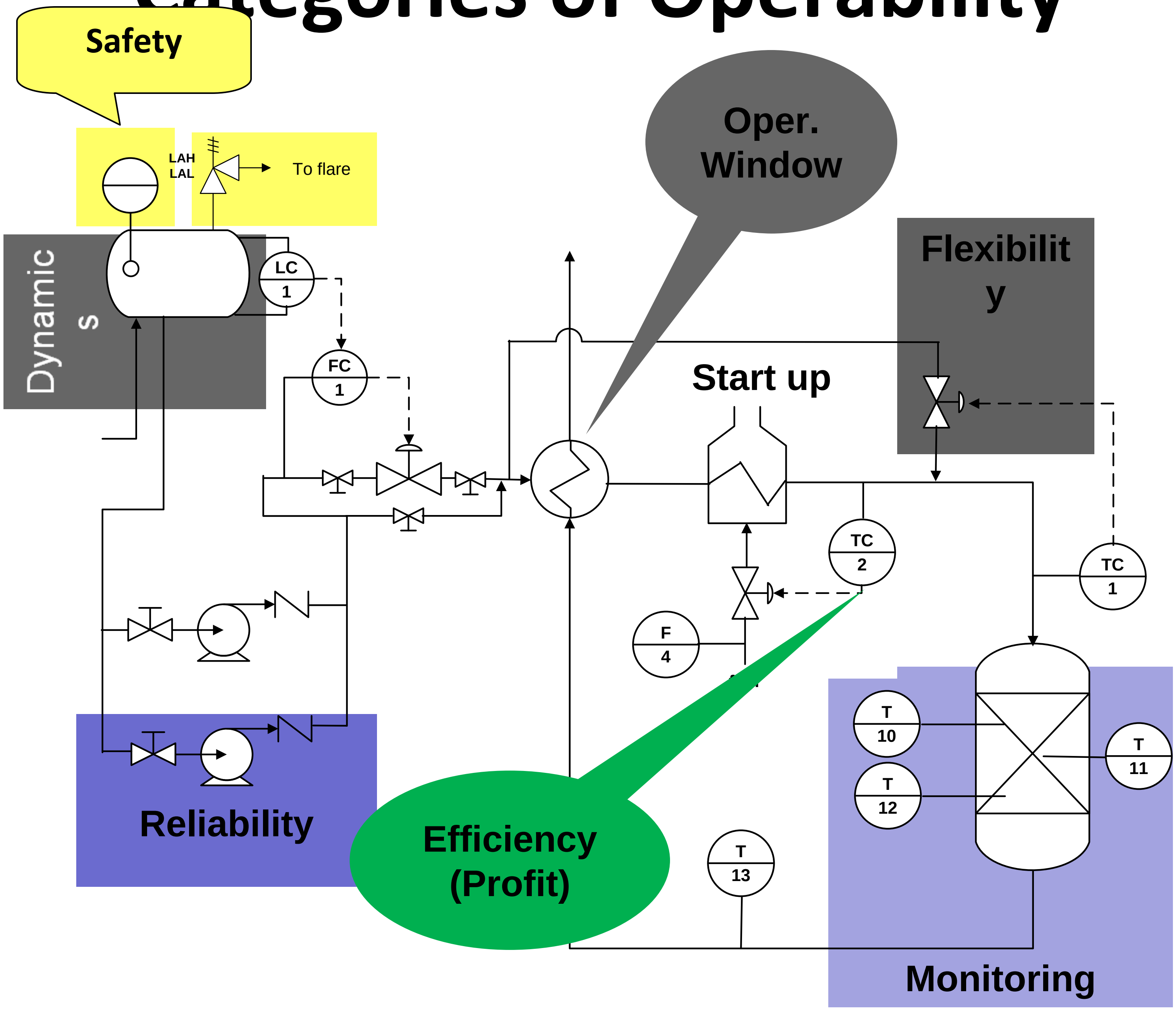
What is "operable"?

Tom Marlin

Categories of Operability

<u>Key Operability issues</u>

1. Operating window
2. Flexibility/ controllability
3. Reliability
4. Safety & equipment protection
5. Operation during transitions
6. Dynamic Performance
7. Efficiency
8. Monitoring & diagnosis



Operability within Process Design

- Set goals and design specifications
- Select process technology
- Define process structure
- Simulate the flowsheet (base case)
- Design equipment (base case)

Iterate as needed

- Operability analysis

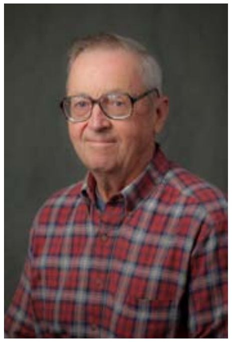
- Economic Evalu
- Construct and start
- Operate over a ran
  startup and shutdow
  and transitions between th

Variability is the key, deliberately introduced (e.g., production rate) and disturbances

Meeting Business and Industry Needs ABET 2010-2011 Criteria (Vince Grassi)

- Engineering programs must demonstrate that their students attain the following outcomes:
  - an ability to apply knowledge of mathematics, science, and engineering
  - an ability to design and conduct experiments, as well as to analyze and interpret data
  - an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
  - an ability to function on multidisciplinary teams
  - an ability to identify, formulate, and solve engineering problems
  - an understanding of professional and ethical responsibility
  - an ability to communicate effectively
  - the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
  - a recognition of the need for, and an ability to engage in life-long learning
  - a knowledge of contemporary issues
  - an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Lehigh ChE Senior Design Capstone Course



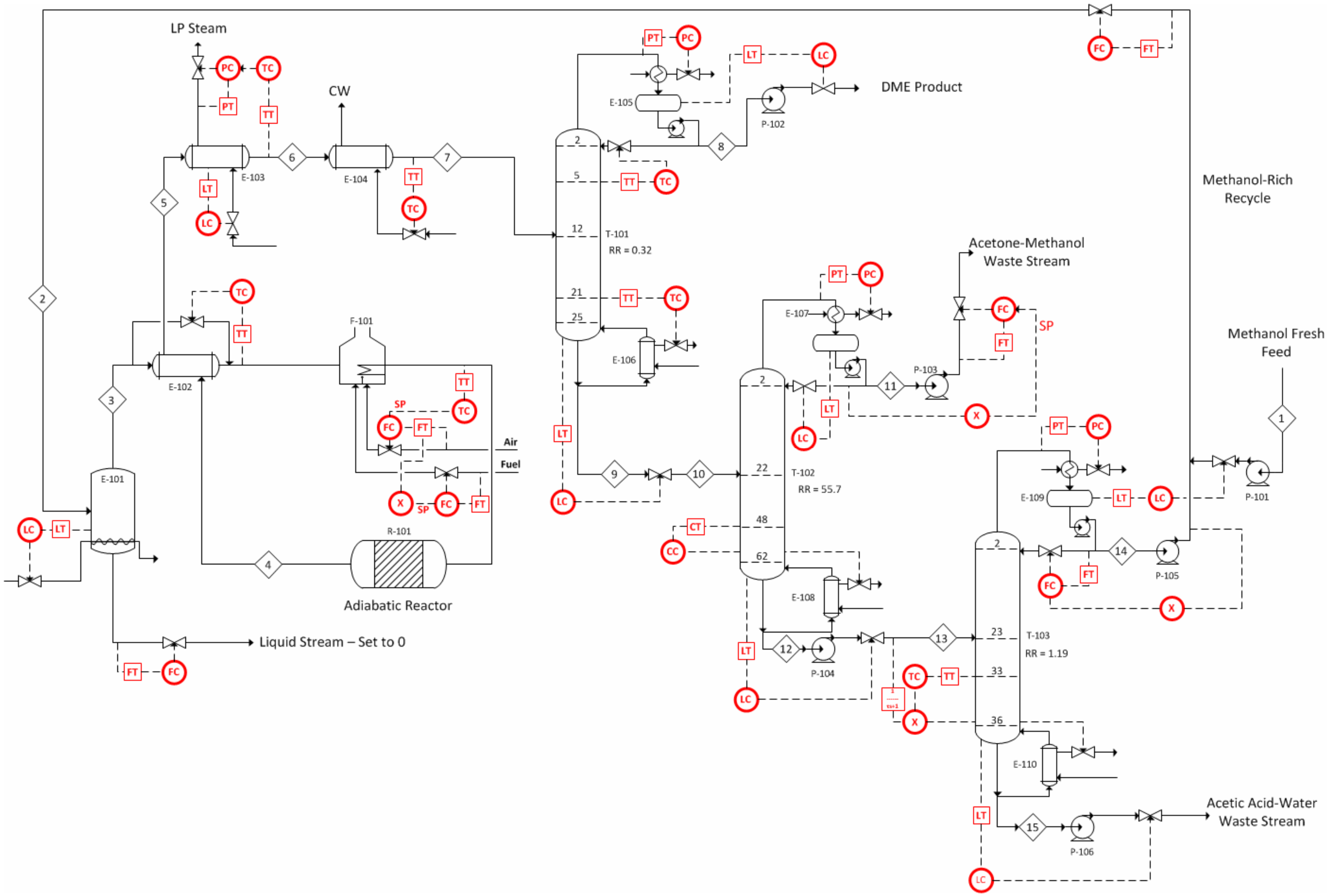
- Fall Semester – Conceptual Process Design
- Spring Semester – Plantwide Control
- Aspen Plus and Aspen Dynamics
- 21 Projects
  - Reaction
  - Distillation
  - Recycle

- 2 or 3 Student Teams
- Industrial Consultants
  - 23 Project Consultants
  - 2 Process Safety Consultants
  - 1 Cost Engineering Consultant

Syllabus

Fall – Conceptual Design	Spring – Plantwide Control
Design Fundamentals	Lessons Learned
Project Overviews by Consultants	Aspen Dynamics
Distillation Design	Distillation Control
Reactor Design	Reactor Control
Azeotropic Distillation	Plantwide Control
Progress Reports	Progress Reports
Reactive Distillation	Human Factors Design
Process Safety	Process Safety
Economics	Special Topics
Special Topics	Group Meetings
Group Meetings	Final Report and Formal Presentation
Conceptual Design Final Report	

Plantwide Control Example



Optimization in Design, Operations and Control (Larry Biegler)

	MILP	MINLP	Global	LP,QP	NLP	DFO…
HENS	x	x	x	x	x	x
MENS	x	x	x	x	x	x
Separations	x	x	x		x	x
Reactors		x	x	x	x	x
Equipment Design		x	x		x	x
Flowsheeting		x			x	
Scheduling	x	x		x		x
Supply Chain	x	x		x		
Real-time optimization				x	x	
Linear MPC				x		
Nonlinear MPC					x	
Hybrid	x	x			x	

Optimization Texts

Engineering

1. Edgar, T.F., D.M. Himmelblau, and L. S. Lasdon, Optimization of Chemical Processes, McGraw-Hill, 2001.
2. Papalambros, P. and D. Wilde, Principles of Optimal Design. Cambridge Press, 1988.
3. Reklaitis, G., A. Ravindran, and K. Ragsdell, Engineering Optimization, Wiley, 1983.
4. Floudas, C. A., Nonlinear and Mixed Integer Optimization, Oxford, 1995
5. Biegler, L. T., I. E. Grossmann and A. Westerberg, Systematic Methods of Chemical Process Design, Prentice Hall, 1997.
6. Biegler, L. T., Nonlinear Programming: Concepts, Algorithms and Applications to Chemical Engineering, SIAM, 2010.

Numerical Analysis

1. Dennis, J.E. and R. Schnabel, Numerical Methods of Unconstrained Optimization, Prentice-Hall, (1983), SIAM (1995)
2. Fletcher, R. Practical Methods of Optimization, Wiley, 1987.
3. Gill, P.E, W. Murray and M. Wright, Practical Optimization, Academic Press, 1981.
4. Nocedal, J. and S. Wright, Numerical Optimization, Springer, 2007

Optimization Courses @ CMU

Undergraduate Course (1/2 semester)

- Basic Concepts in optimization theory
- Basic/small application problems (LP, NLP, MILP, MINLP)
- Optimization Modeling Platforms

Graduate Course

- Algorithmic descriptions and analysis
- Advanced applications
- Optimization Modeling Platforms

Industrial Short Course

Optimization Modeling Platforms

Optimization Modeling

-Less emphasis on algorithm mechanics and construction

-More emphasis on optimization problems in process design and operations

-Develop good modeling practices and interactive models

Modeling Packages

Aspen, HySYS, Pro/II, Prosim and MATLAB, EXCEL

-Process optimization based on SQP, seen as an extension to flowsheet simulation

-Assess trade-offs in flowsheet designs: energy, raw material, capital

Optimization Platforms

GAMS, AMPL, AIMMS…

- Quickly construct, refine optimization models, extend to large-scale systems

-Select and compare wide variety of solvers, assess failures and strengths

-Develop optimization strategies and solutions to real-world engineering systems

PURDUE CHEMICAL ENGINEERING

Centennial Celebration
A Century of People and Progress
1911-2011

Education Panel

Key Points:

- No coverage of operations in dynamics & control course
- No coverage of operability in design
- Elective courses: Operations & Risk Management

G.V. Rex Reklaitis.

January 11, 2012

ChE 555 Computer Aided Process Operations

Goal: *understand the tasks of the operational hierarchy & learn to use models, AI and optimization methods to execute these tasks*

Course format: Lectures plus projects, term paper
Project 1: Data Reconcilliation
Project 2 Matlab MPC
Project 3: Process simulation
Project 4: Fault diagnosis: roller compactor
Project 5: PCA fault detection
Project 6: Planning/scheduling

Text book: None - selection of papers
Software: Matlab and Matlab MPC toolbox, MODEX, PCA, Neural Nets, Batches, Cplex

ChE 555 Computer Aided Process Operations

Dual Level Elective Course

Topics

- Introduction to Computer Aided Process Operations Management
- Manufacturing in chemical & pharma industries
- Data reconciliation and gross error detection
- Regulatory control
- Model predictive control
- Control Practice in Pharma Industry
- Fault detection & diagnosis
- Supervisory control
- Batch Process Simulation
- Planning and Scheduling
- Failure Modes and Effects Analysis (FMEA)
- Process Hazards Analysis

ChE 597/IE 597 Risk Management in the Development of New Products & Processes

Goal: *learn to apply quantitative tools to make best use of available information in order to improve decision making under uncertainty*

Course format: Lectures plus projects, exams, cases

Extended Project: Investment Portfolio Management

Intro to charting; Stock investing competition

Case Study 1: Pharma Project Development

Case Study 2: Inventory Management

Final Project: Student teams

Text: Quantitative Methods for Business

(11th edition) by Anderson et al

Software: EXCEL and VBA (macros), EXCEL Add-Ins (Crystal Ball, OptQuest) and Arena (discrete event simulation)

Computer based self-learning modules made available

ChE 597/IE 597 Risk Management in the Development of New Products & Processes

Topics

- Introduction to Probability
- Decision Analysis
- Utility Theory
- Time Series Forecasting
- Financial Fundaments of Corporations
- Linear Programming
- Solving LP Problems with Spread Sheets
- Sensitivity Analysis
- Linear Optimization with Integer Variables;
- Introduction to Network Modeling
- Discrete Event Simulation
- Multicriterion Decision Making

Revamping Goals & Content of a "Process Dynamics and Control" Course

George Stephanopoulos, MIT

- Current courses and books in undergraduate Process Control have been the result of an evolutionary development over 50 years.
- They still reflect the goals and content of an older and limited vision and mission.
  - Do not prepare the students for handling a broader scope of operational problems, e.g. monitoring, diagnosis, synthesis of control strategies, operability analysis, process safety, process optimization.
  - Do not prepare the students for handling problems outside the scope of (mostly) a continuous process around a steady-state, e.g. understanding monitoring and controlling chemical/biochemical networks or/and biological networks, operating strategies for micro- or nano-scale devices, designing devices as operational systems.
  - Do not engage "systems engineering" in any serious way, thus handicapping the students from addressing complicated or complex problems, e.g. plant-wide monitoring, diagnosis, and control; systems biology
  - Have not simplified and clarified the presentation of fundamental principles, with broad applicability (well outside the scope of process control) despite the richness of new knowledge gained, e.g. the Internal Model Principle is still an afterthought not the central foundation in teaching feedback control, and model-predictive control is seen as an "algorithm" rather than the essence of an optimal regulator.
- As a result the impact of such courses has been limited.
  - Many departments do not see them or treat them as elements of the core curriculum.
  - No department that I know sees them as core of graduate curriculum.
  - Undergraduate students see them as "useful" if you are going to work as a process engineer. But, process engineers see themselves as "unprepared" for the tasks.
  - Very few graduate students, if any, see the relevance of such courses to what they research.
- A Tremendous Educational Opportunity is being "Lost"

Revamping Goals & Content of a "Process Dynamics and Control" Course

George Stephanopoulos, MIT

- A Different Vision:

  A core course on the systems engineering aspects of operating dynamic systems

  - Core, i.e. Essential, not simply Required
  - Building on and Expanding the Chemical Engineering Science of the Curriculum

- A Different Mission:

  Introduce the students to a broad array of operating problems in batch and continuous processing systems:

Revamping Goals & Content of a "Process Dynamics and Control" Course

George Stephanopoulos, MIT

Introduce the students to a broad array of engineering tasks (problems) in operating batch and continuous processing systems:

•Monitoring, Analysis, Diagnosis of operations.

•Monitoring and Control strategies.

•Design of FB, FF, other,Controllers.

•Static and Dynamic Operability.

•Optimization of Process Operations; batch and continuous

•Process Safety

•Continuous Improvement: The elimination of "defects"

Expose students to the operating problems of a broad range of dynamic systems:

•Molecular scale (networks of reactions; biological networks),

•Micro- and nano-scale devices,

•Large-scale batch and continuous plants.

Focus on sharply & clearly defined fundamental principles governing the engineering tasks of operating processing systems.

•Stability, Controllability, Observability of operating systems.

•Internal Model Principle as the foundation for the design of any feedback regulator: Model Uncertainty and External Disturbances.

•The Trade-off between Stability and Performance in Feedback Controllers.

•"Stabilize" before "Optimize": Elimination of defects.

•The Fundamental Necessity for Continuous Improvements.

•Free the educational content from extraneous, incidental (ad hoc), or peripheral material on "techniques".

Engage "systems engineering" thinking throughout the course:

•Early exposure to "integrated" systems. Do not wait until the end.

•Early exposure to a variety of integrated systems

•Treatment of integrated systems: observability, controllability, control and monitoring strategies, etc.

Studio Concept

Direct Link: Theory & App

Lectures and Simulations
- Single classroom
- Interactive learning

Laptop Studio
- Instructor Station
- Student: Power/Ethernet
- MATLAB license (campus)

Class Time

4 credit – 6 contact hours/week

3 days/week, 2 hours each

Total: 1 hour + 50 minutes

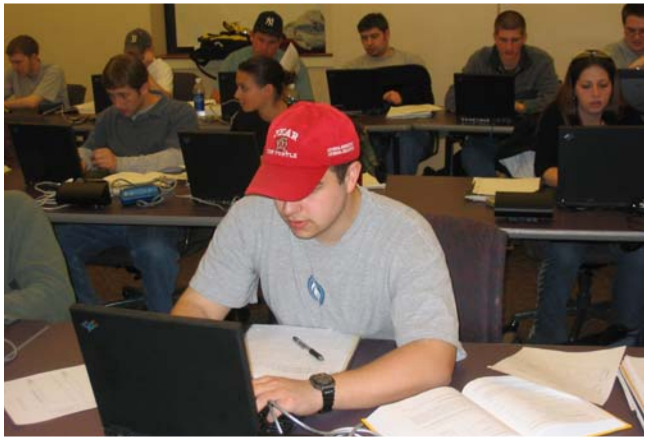
First 45-50 minutes

- Lecture with discussion
- Usually "by hand" using document camera

Second 50 minutes or so

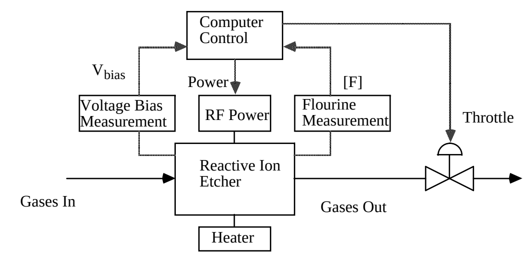
- Groups of two: HW & Modules
- Instructor & TAs rove around
- "Mini-lectures"

Final comments/take home…

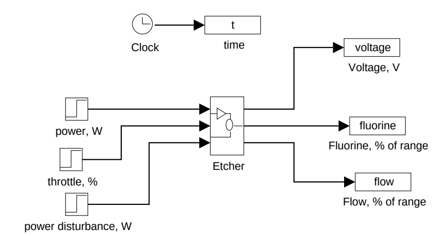


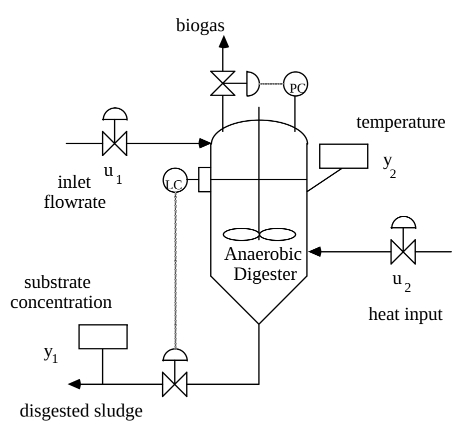
Case Study Projects

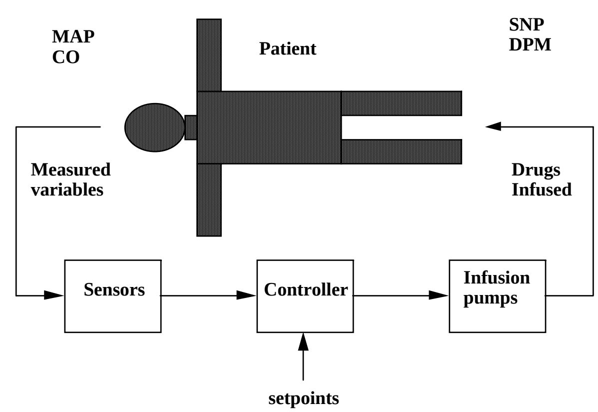
MIMO Control

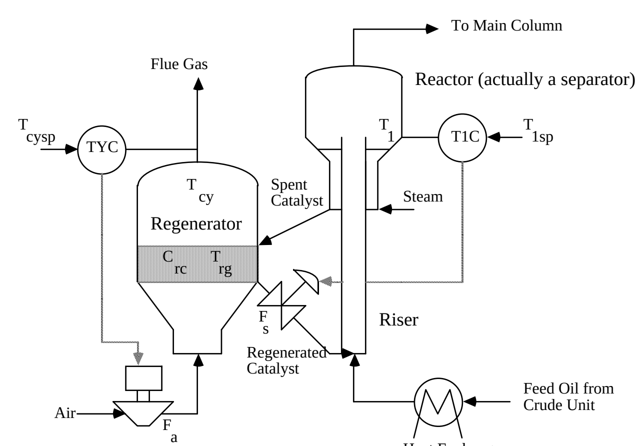


- Final 1/3 of Course
- Choice of Projects
  - Reactive Ion Etcher
  - Lime Kiln
  - Fluidized Catalytic Cracking (FCCU)
  - Anaerobic Sludge Digester
  - Drug Infusion Control (Critical Care)
- Different Advisor (Instructor/TA/RA) for Each Project
- Lit. Review, Model Develop, SISO, MIMO, Written Reports & Final Pres.









- Process systems engineering courses taught by non-PSE faculty?