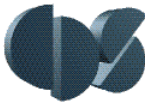


## CDS 101: Lecture 1.1

### Introduction to Feedback and Control



**Richard M. Murray**  
**29 September 2003**

**Goals:**

- Give an overview of CDS 101/110; describe course structure, administration
- Define feedback/control systems and learn how to recognize main features
- Describe what control systems do and the primary principles of control

**Reading (available on course web page):**

- Astrom and Murray, *Analysis and Design of Feedback Systems*, Ch 1
- “For the Spy in the Sky, New Eyes”, NY Times, June 2002.

## Course Administration

CALIFORNIA INSTITUTE OF TECHNOLOGY  
Control and Dynamical Systems

**CDS 101 - Principles of Feedback and Control**  
**CDS 110 - Introductory Control Theory**  
**CME 105 - Process Control**

Fall 2002

<b>Instructor</b> R. Murray, 102 Steele rmurray@cds.caltech.edu	<b>Teaching Assistant</b> Dean Hunderb (grad TA), jshimom@cds Tim Chang, Leon Chiriac, Zhipu Zou, Shrawan Misra Office hours: Friday, 2-3 pm, 102 Steele
<b>Co-instructors</b> M. Dickinson E. Klavins R. Marder D. MacMurtrei	<b>Lecturers</b> M2.3, W1.3, 102 Steele F3.3, 102 Steele (optional)

**CDS 101 vs CDS110a/CME 105:** CDS 101 is a 8 unit (20-4) class intended for advanced students in science and engineering who are interested in the principles and tools of feedback control, but not the analytical techniques for design and synthesis of control systems.  
**CDS 110a/CME 105** is a 9 unit class (20-6) that provides a traditional first course in control for engineers and applied scientists. It assumes a stronger mathematical background, including working knowledge of linear algebra, ODEs. Familiarity with complex variables (Laplace transforms, residue theory) is helpful but not required.

**Lectures:** The main course lectures are on Mondays from 2-3 pm and Wednesdays from 1-2 pm in 102 Steele. CDS 101 students are not required to attend the Wednesday lectures, although they are welcome to do so. In addition, optional lectures will be held on Fridays from 2-3 pm in 102 Steele on supplemental topics. The schedule for these optional lectures is given below.

**Grading:** The final grade will be based on homework sets, a midterms exam and a final exam.

- **Homework:** 50%  
 Homework sets will be handed out weekly and due on Mondays by 5 pm to the box outside of 102 Steele. Late homework will not be accepted without prior permission from the instructor.
- **Midterms exam:** 20%  
 A midterms exam will be handed out at the beginning of midterms week (30 Oct) and due at the end of the midterms examination period (3 Nov). The midterms exam will be open book and computers will be allowed (though not required).
- **Final exam:** 30%  
 The final exam will be handed out on the last day of class due at the end of finals week. It will be an open book exam and computers will be allowed (though not required).  
 For all students who attend the office hours at least once in the first three weeks of class, if your grade on the final is higher than your homework and midterms average, the final will be used to determine your course grade.

**Homework policy:** Collaboration on homework assignments is encouraged. You may consult outside reference materials, other students, the TA, or the instructor. All solutions that are handed in should reflect your understanding of the subject matter at the time of writing.

**Course syllabus**

- CDS 101 vs CDS 110ab
- Lectures
- Grading
- Homework policy
- Course text and references
- Office hours
- Class homepage
- Software
- Course outline

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- Video tapes: 102 Steele, Box G
- Course load: keep track of hours

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### CDS 101/110 Instructional Staff

**Lecturer: Richard Murray (CDS)**

- Overall course management

**Co-Instructors**

- Michael Dickinson (BE/Bio)
- Steven Low (CS/EE)
- Hideo Mabuchi (Ph/CDS)
- Doug MacMartin (CDS)

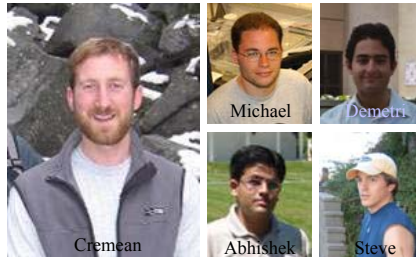


**Head TA: Lars Cremean (ME)**

- Coordinate course infrastructure, TAs

**TAs**

- Michael Reiser (BE)
- Demetri Spanos (CDS)
- Abhishek Tiwari (EE)
- Stephen Waydo (CDS)



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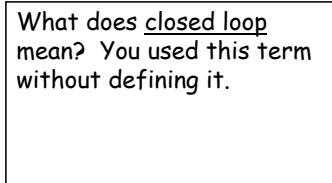
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### Mud Cards

**Mud cards**

- 3 x 5 cards distributed at each lecture
- Describe “muddiest” part of the lecture
- Turn in cards at end of class
- Responses posted on FAQ list by **8 pm** on the day of the lecture (make sure to look!)



**Class FAQ list**

- Searchable database of responses to mud cards and other frequently asked questions in the class



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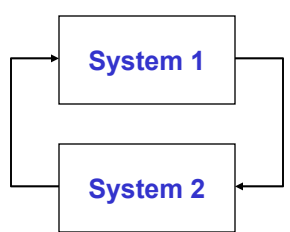
### CDS 101/110/111 Course Sequence

<p><b>CDS 101 – Introduction to the <i>principles</i> and <i>tools</i> of control and feedback</b></p> <ul style="list-style-type: none"> <li>• Summarize key concepts, w/ examples of fundamental principles at work</li> <li>• Introduce MATLAB-based tools for modeling, simulation, and analysis</li> </ul>	}	Fall
<p><b>CDS 110a – Analytical understanding of key concepts in control</b></p> <ul style="list-style-type: none"> <li>• Detailed description of classical control and state space concepts</li> <li>• Provide knowledge to work with control engineers in a team setting</li> </ul>	}	Fall
<p><b>CDS 110b – Detailed design tools for control systems</b></p> <ul style="list-style-type: none"> <li>• Estimation and robust control tools for <i>synthesis</i> of control laws</li> </ul>	}	Winter
<p><b>CDS 111 – Implementation of control systems for engineering applications</b></p> <ul style="list-style-type: none"> <li>• Lab-based <i>implementation</i> of computer control on physical systems</li> </ul>	}	Spring
<p><b>CDS Minor: CDS 110, CDS 140, Senior thesis or Ae/CDS 125</b></p>		

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### What is Feedback?

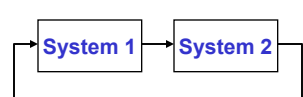
**Miriam Webster:**  
 the return to the input of a part of the output of a machine, system, or process (as for producing changes in an electronic circuit that improve performance or in an automatic control device that provide self-corrective action) [1920]

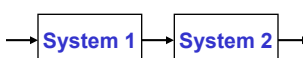


**Feedback = mutual interconnection of two (or more) systems**

- System 1 affects system 2
- System 2 affects system 1
- Cause and effect is tricky; systems are mutually dependent

**Terminology**


Closed Loop


Open Loop

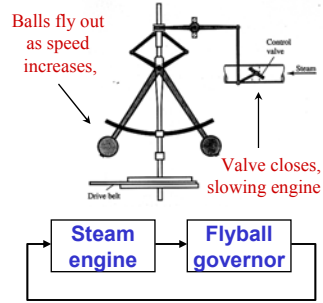
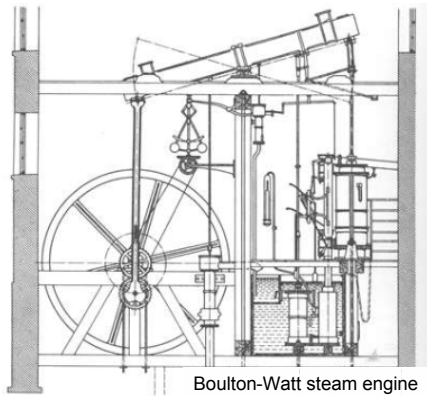
**Feedback is ubiquitous in natural and engineered systems**

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### Example #1: Flyball Governor

**“Flyball” Governor (1788)**

- Regulate speed of steam engine
- Reduce effects of variations in load (disturbance rejection)
- Major advance of industrial revolution



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### Other Examples of Feedback

**Biological Systems**

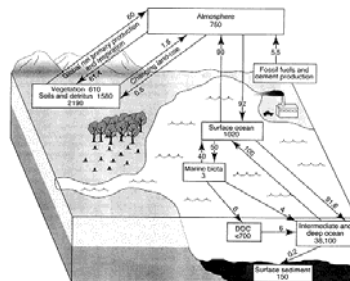
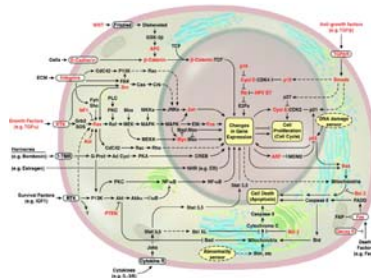
- Physiological regulation (homeostasis)
- Bio-molecular regulatory networks

**Environmental Systems**

- Microbial ecosystems
- Global carbon cycle

**Financial Systems**

- Markets and exchanges
- Supply and service chains



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**Control = Sensing + Computation + Actuation**

In Feedback "Loop"

**Goals**

- Stability: system maintains desired operating point (hold steady speed)
- Performance: system responds rapidly to changes (accelerate to 65 mph)
- Robustness: system tolerates perturbations in dynamics (mass, drag, etc)

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**Two Main Principles of Control**

**Robustness to Uncertainty through Feedback**


- Feedback allows high performance in the presence of uncertainty
- Example: repeatable performance of amplifiers with 5X component variation
- Key idea: accurate *sensing* to compare actual to desired, correction through *computation* and *actuation*

**Design of Dynamics through Feedback**

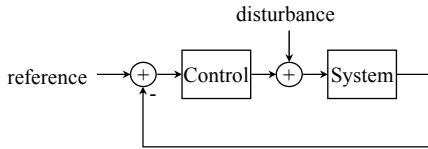
- Feedback allows the dynamics of a system to be modified
- Example: stability augmentation for highly agile, unstable aircraft
- Key idea: interconnection gives *closed loop* that modifies natural behavior

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### Example #2: Cruise Control

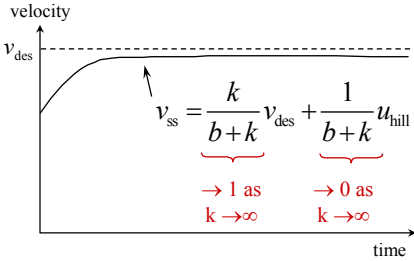


“Bob”



$$m\dot{v} = -bv + u_{\text{engine}} + u_{\text{hill}}$$

$$u_{\text{engine}} = k(v_{\text{des}} - v)$$



$$v_{ss} = \underbrace{\frac{k}{b+k}}_{\rightarrow 1 \text{ as } k \rightarrow \infty} v_{\text{des}} + \underbrace{\frac{1}{b+k}}_{\rightarrow 0 \text{ as } k \rightarrow \infty} u_{\text{hill}}$$

**Stability/performance**

- Steady state velocity approaches desired velocity as  $k \rightarrow \infty$
- Smooth response; no overshoot or oscillations

**Disturbance rejection**

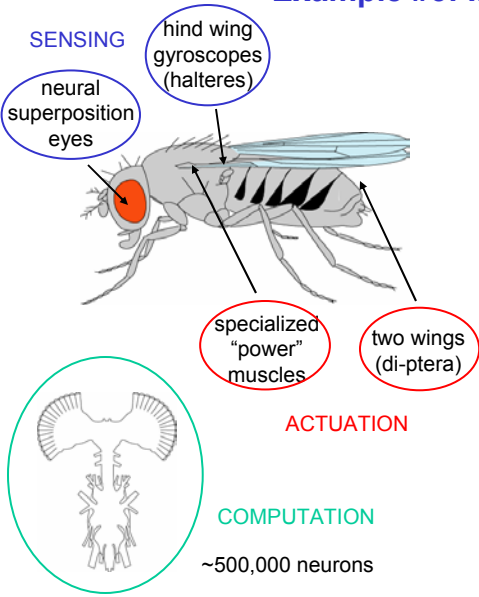
- Effect of disturbances (hills) approaches zero as  $k \rightarrow \infty$

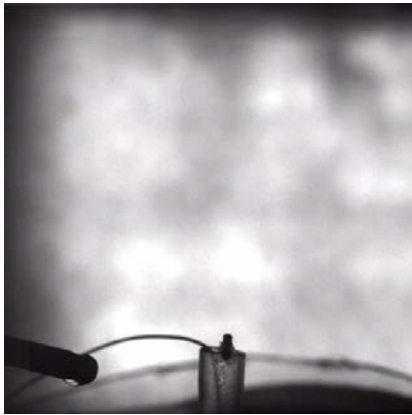
**Robustness**

- Results don't depend on the specific values of  $b$ ,  $m$ , or  $k$  for  $k$  sufficiently large

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### Example #3: Insect Flight





**More information:**

- M. D. Dickinson, Solving the mystery of insect flight, *Scientific American*, June 2001
- CDS 101 seminar : Friday, 10 Oct 03

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## Modern Engineering Applications of Control

### Flight Control Systems

- Modern commercial and military aircraft are “fly by wire”
- Autoland systems, unmanned aerial vehicles (UAVs) are already in place

### Robotics

- High accuracy positioning for flexible manufacturing
- Remote environments: space, sea, non-invasive surgery, etc.



### Chemical Process Control

- Regulation of flow rates, temperature, concentrations, etc.
- Long time scales, but only crude models of process

### Communications and Networks

- Amplifiers and repeaters
- Congestion control of the Internet
- Power management for wireless communications

### Automotive

- Engine control, transmission control, cruise control, climate control, etc
- Luxury sedans: 12 control devices in 1976, 42 in 1988, 67 in 1991

**AND MANY MORE...**

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## Control Tools

### Modeling

- Input/output representations for subsystems + interconnection rules
- System identification theory and algorithms
- Theory and algorithms for reduced order modeling + model reduction

### Analysis

- Stability of feedback systems, including robustness “margins”
- Performance of input/output systems (disturbance rejection, robustness)

### Synthesis

- Constructive tools for design of feedback systems
- Constructive tools for signal processing and estimation (Kalman filters)

### MATLAB Toolboxes

- SIMULINK
- Control System
- Neural Network
- Data Acquisition
- Optimization
- Fuzzy Logic
- Robust Control
- Instrument Control
- Signal Processing
- LMI Control
- Statistics
- Model Predictive Control
- System Identification
- $\mu$ -Analysis and Synthesis

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### Overview of the Course

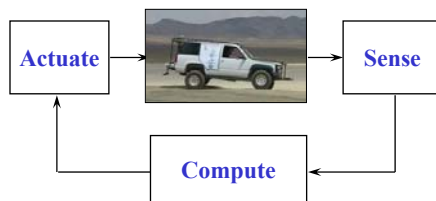
Wk	Mon/Wed	Fri
1	Introduction to Feedback and Control <i>Review of ODEs and linear algebra</i>	MATLAB tutorial, Lars Cremean
2	System Modeling	Insect flight control, Michael Dickinson
3	Stability and Performance	Internet congestion control, Steven Low
4	Linear Systems	Control of CELT, Doug MacMartin
5	Controllability and Observability <i>Midterm exam</i>	Review for midterm, Lars Cremean
6	Transfer Functions	Animal sensory systems, Michael Dickinson
7	Loop Analysis of Feedback Systems	Closed-loop atomic magnetometry, Hideo Mabuchi
8	Frequency Domain Design	Aerospace control systems, TBD
9	Limits on Performance	Thanksgiving holiday
10	Uncertainty Analysis and Robustness <i>Final exam</i>	Review for final, Steve Waydo

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### Summary: Introduction to Feedback and Control



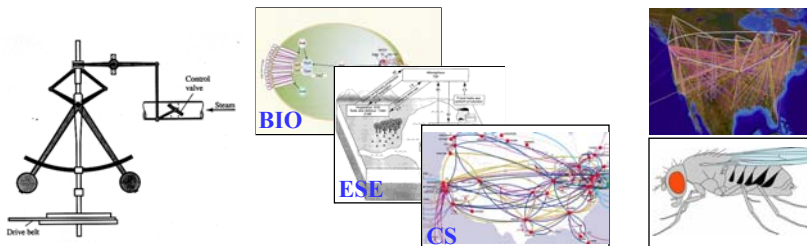
**Control =**

Sensing + Computation + Actuation

**Feedback Principles**

- Robustness to Uncertainty
- Design of Dynamics

**Many examples of feedback and control in natural & engineered systems:**



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