6.777J/2.372J: The MEMSclass

Introduction to MEMS and MEMS Design

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(with ideas from SDS)

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Outline

- > Class odds and ends
- > Intro to MEMS
- > The challenge of MEMS Design
- > Course outline
- > Design projects

and then, Microfab Part I

Handouts

> **General Information Handout**

- **Lecturers: Carol Livermore, Joel Voldman**
- **Text: Senturia's *Microsystem Design***
  - **Beware: Errata on website**

> **Schedule**

> **Student Information Sheet**

- **VERY IMPORTANT**
- **Fill out and hand back at end of class**

Handouts

> **Lecture notes**

- **Handed out at beginning of class**
- **Extra copies available at Carol's office**

> **Library Orientation NEXT FRIDAY FEBRUARY 16**

- **Learn how to use online databases, journals, etc.**
- **This will be VERY useful for Problem Set 2**

… and for life!

Course overview

- Course is broken into two halves
- First half
  - MEMS design and modeling
  - Seven problem sets
    - Differing lengths and complexity
    - Due on due date IN CLASS
- Second half
  - Case studies
  - Design projects
- Grading
  - 15% Problem sets
    - Regrades on psets must be requested promptly
  - 35% Take-home design problem
  - 50% Final project

Course conduct and ethics

- See policy on cooperation in General Info handout
- We encourage teamwork during the psets
  - Literature solutions are OK
  - Students must follow ethical guidelines
    - All students must write up their own pset
    - List those you work with on problem set
    - Cite any literature solutions used
  - Some behavior is patently unacceptable
    - Use of prior years' homework solutions
- Cooperation is essential in final design project
- No cooperation is allowed on take-home design problem
- Any breaches will be dealt severely, with no warnings
- Please consult us *before* doing anything questionable
- web.mit.edu/academicintegrity/handbook/handbook.pdf

Course overview

- What makes this course challenging?
- Relevant physics in lots of fields must be grasped *quickly*
  - We teach a great deal of material in ~2/3 semester
- Every student will learn new concepts
- Design projects
  - Complex open-ended design problems
  - Team dynamics
- All of you can learn MEMS design, and we will try to make it easier and fun!

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What are MEMS?

- > Micro-Electro-Mechanical Systems
- > Microsystems
- > Microfabrication
- > Microtechnology
- > Nanotechnology
- > Etc.

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Lucas Novasensor

What are MEMS?

> **Microfabrication is a manufacturing technology**

- **A way to make stuff**
- **Adapted from semiconductor industry**
  - **With changes**
- **Therefore, MANY standard design principles hold**

> **But has unique elements**

- **New materials: SU-8, PDMS**
- **New ways to shape them: DRIE**
- **New material properties**
  - **Bulk vs. thin film**
- **Different physics regimes**
  - **Si at small scales** →

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Sandia

What are MEMS?

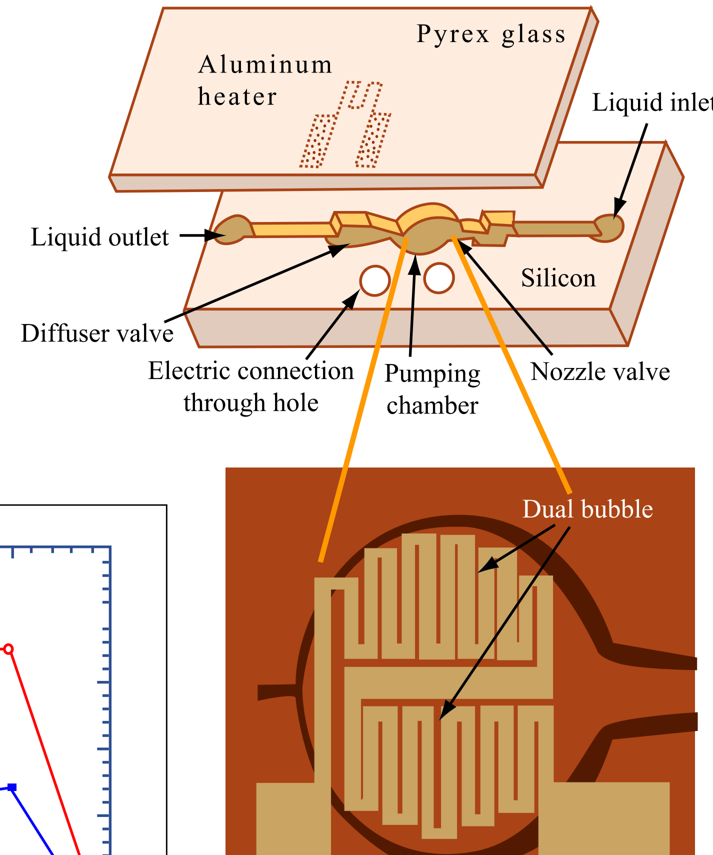
> **Definitions vary**

- **Usually made via semiconductor batch fabrication**
- **Usually small**
  - » **Some important dimension is <1 mm**
- **Ideally, useful**
- **Used to be actual electro-mechanical systems**
  - » **Sensors: Something moves and is sensed electrically**

    OR
  - » **Actuators: An electrical signal moves something**

What are MEMS?

- Now, many “MEMS” have no “E” or “M”
  - Static microfluidic structures
  - But often are multi-domain
  - Electro→other domain is very popular
    - e.g., Electro→Thermal→Fluidic actuation
    - Microbubble pumps



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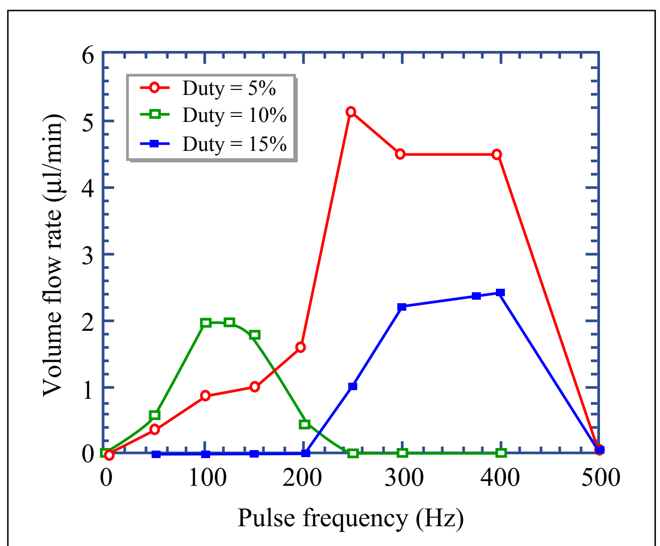
Images by MIT OpenCourseWare.



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Liwei Lin (UCB)

MEMS: Starting points

> **Some starting points:**

- 1961 first silicon pressure sensor (Kulite)
  - » Diffused Si piezoresistors mounted onto package to form diaphragm
  - » Dr. Kurtz (founder) is MIT graduate, of course
- Mid 60's: Westinghouse Resonant Gate Transistor
  - » H.C. Nathanson, *et al.*,

    The Resonant Gate Transistor,

    IEEE Trans. Electron Devices,

    March 1967, 14(3), 117-133.

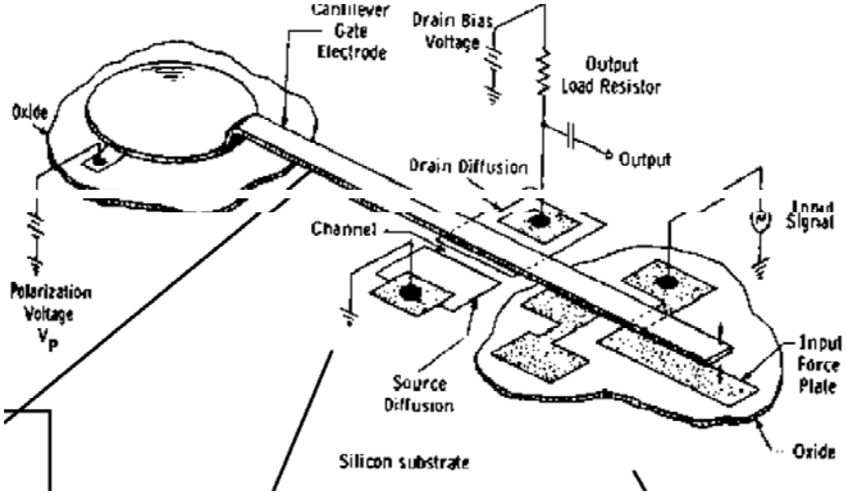


Figure 1 on page 119 in: Nathanson, H. C., W. E. Newell, R. A. Wickstrom, and J. R. Davis, Jr. "The Resonant Gate Transistor." IEEE Transacationson Electron Devices 14, no. 3 (1967): 117-133. © 1967 IEEE.

MEMS: Important early work

- **Stanford Gas Chromatograph (1975)**
  - **SC Terry, JH Jerman and JB Angell, *IEEE Trans Electron Devices* ED-26 (1979) 1880**
  - **WAY ahead of it's time**

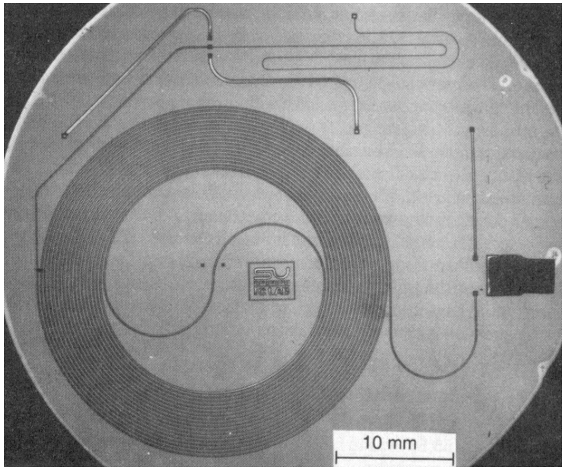
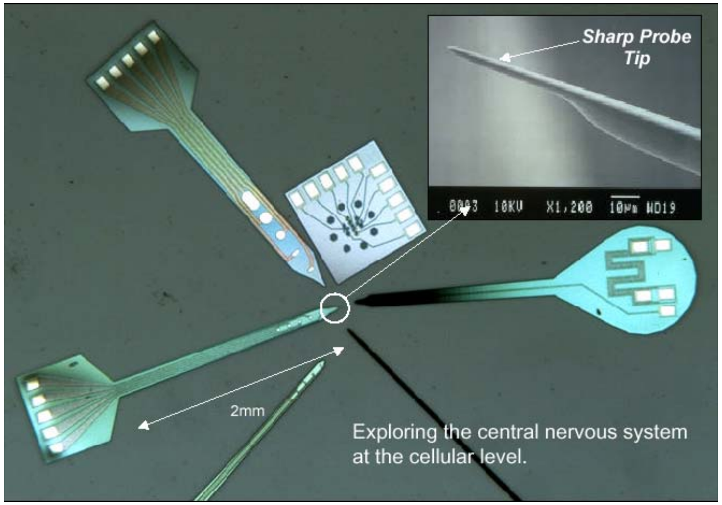


Figure 3 on page 1882 in: Terry, S. C., J. H. Jerman, and J. B. Angell. "A Gas Chromatographic Air Analyzer Fabricated on a Silicon Wafer." IEEE Transactions on Electron Devices 26, no. 12 (1979): 1880-1886. © 1979 IEEE.

- **70's to today: Ken Wise (Michigan) neural probes**
- **70's Inkjet printheads**
- **70's Start of TI DMD project**



Courtesy of Kensall D. Wise. Used with permission.

MEMS: Important early work

- MEMS blossomed in the 80's
- 1982 Kurt Petersen "Silicon as a mechanical material"
  - Proc. IEEE, 70(5), 420-457, 1982.

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- Mid-80's BSAC folks (Howe, Muller, etc.) polysilicon surface micromachining

T. Lober, MIT

R. T. Howe and R. S. Muller, "Polycrystalline silicon micromechanical beams," *J. of the Electrochemical Society*, 130, 1420-1423, (1983).

MEMS: Important early work

- **Electrostatic Micromotors**
  - **Introduced in 1988-1990**
  - **MIT and Berkeley**

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- **Microchip capillary electrophoresis and lab-on-a-chip**
  - **Introduced ~1990-1994**
  - **A. Manz, D.J. Harrison, others**

Fan *et al*., IEDM ’88, p 666.

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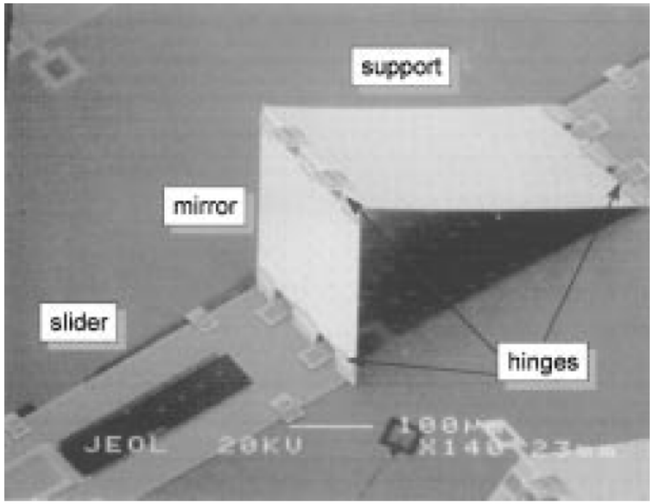
Harrison et al., Science 261:895, 1993

MEMS: Some current hot topics

> Optical MEMS

- Switching of optical signals
- Big boom in the late 90's
- Big bust in the early 00's



Muller et al., Proc. IEEE, 8:1705, 1998.

Fig. 1 on page 1706 in: Muller, R. S., and K. Y. Lau. "Surface-Micromachined Microoptical Elements and Systems." *Proceedings of the IEEE 86*, no. 8 (August 1998): 1705-1720. © 1998 IEEE.

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Lucent micromirror

MEMS: Some current hot topics

> RF MEMS

- **Smaller, cheaper, better way to manipulate RF signals**
- **Reliability is issue, but getting there**

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Figure 9 on p. 17 in: Nguyen, C. T.-C. "Vibrating RF MEMS Overview: Applications to Wireless Communications." *Proceedings of SPIE Int Soc Opt Eng* 5715 (Jan. 2005): 11-25.

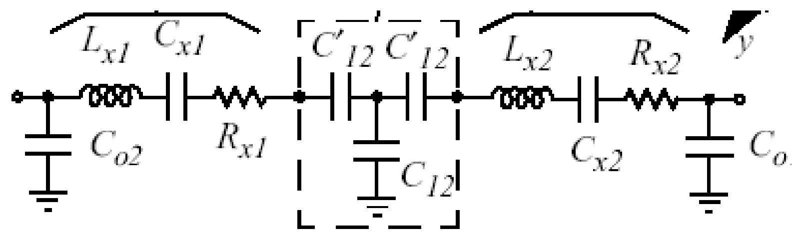

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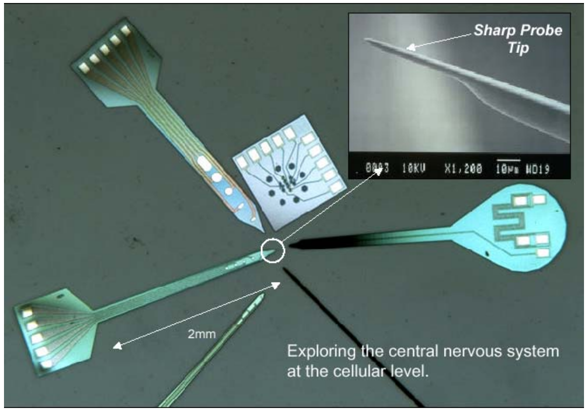
Figure 15 on p. 64 in: Nguyen, C. T.-C."Micromechanical Filters for Miniaturized Low-power Communications." *Proceedings of SPIE Int Soc Opt Eng* 3673 (July 1999): 55-66.

MEMS: Some current hot topics

> BioMEMS

- Shows promise for diagnostics
- Next era of quantitative biology
- No commercial winners yet



Wise (UMich)

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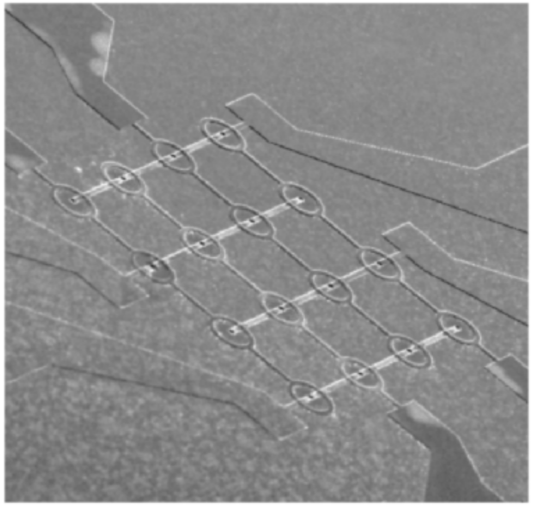

Voldman (MIT)

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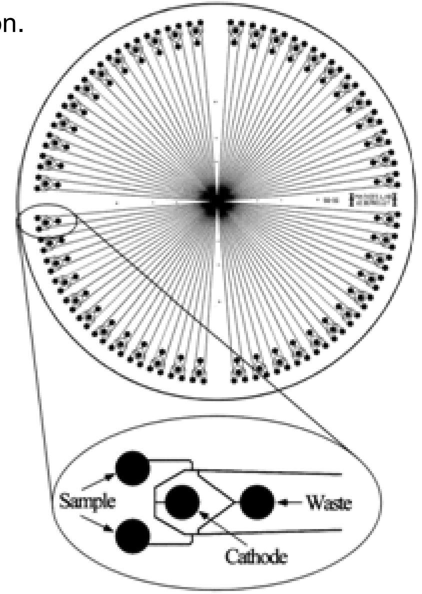
Chen (UPenn)



Mathies (UCB)

Courtesy of Richard A. Mathies. Used with permission.

MEMS: Commercial success

- This isn't just academic curiosity

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- There are products you can actually <u>buy</u>
  - Pressure sensors in your car & in your body
  - Accelerometers EVERYWHERE
  - Gyroscopes
  - Ink-jet print heads
  - Texas Instruments' micro-mirror array

HP

Image removed due to copyright restrictions.

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Motorola Razr

Nintendo Wii

MEMS: Commercial success

> **The major successes have been pressure and inertial sensors**

- **Why?**
  - » **Most mature: 40+ years**
  - » **Huge initial market: automotive**
  - » **Recent access to huger commercial market**
  - » **Easy access to physical signal**
  - » **Smaller than alternatives**
  - » **Cheaper than alternatives**
    - – **In medical market, that means disposable**
  - » **Can be integrated with electronics**
  - » **Moderately precise & accurate**

Image removed due to copyright restrictions.

Honeywell microswitch

Image removed due to copyright restrictions.
Analog Devices pressure sensor.

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- > Design projects

MEMS Design

- For our purposes, design means
  - Create a device or system
  - With quantitative performance parameters (e.g., sensitivity)
  - Subject to constraints
    - Size, price, materials, physics
    - Some clearly defined … some not
- This is hard no matter what the device is

MEMS Design

- **MEMS design is hard because**
  - **The manufacturing technology is actually quite imprecise**
    - **10% tolerance on in-plane dimensions is typical**
    - **Out-of-plane tolerances may be much better**

      … or much worse
  - **Fabrication success is NOT a given AND is tied to the design**
  - **The material properties are unknown or poorly known**
  - **The physics are often "different"**
    - **Not the traditional size scales**
  - **The system must be partitioned**
    - **Which parts to integrate on-chip?**
  - **Packaging is non-trivial**
    - **NOT like ICs**

<u>All these questions should be answered *early on*</u>

Some solutions to this challenge

- Approach #1
  - Make something easy or not useful, etc.
- Approach #2
  - Do incorrect back-of-the-envelope design and then proceed
- Approach #3 (grad student favorite)
  - Create a large range of structures → One of them will work, *hopefully*
- Approach #4 (the MEMS class way)
  - Predictive design of all you know to enable chance of 1st round success
  - Determine necessary modeling strategies for a given problem
    - From analytical to numerical
    - In THIS class we concentrate on analytical and tell you where it fails
  - Be aware of what you don't know, can't control, and what your assumptions are

MEMS Design

- Different levels of design
  - Analytical design
    - Abstracted physics
    - ODEs, Scaling, Lumped-element models
  - Numerical design
    - Intermediate approach between physical and analytical design
  - Physical level:
    - 3-D simulation of fundamental physics
    - PDEs, finite-element modeling, etc.
- Tradeoff between accuracy and effort/time
- Always limited by fundamental knowledge of properties or specifications

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Course goal

- **Course goal: Learn how to design any microfabricated device/system**
- **Learn how to**
  - **Understand the design process**
  - **Partition the system**
  - **Determine and model relevant physics**
  - **Evaluate different designs & fabrication technologies**
  - **Understand the linkage between fabrication and design**

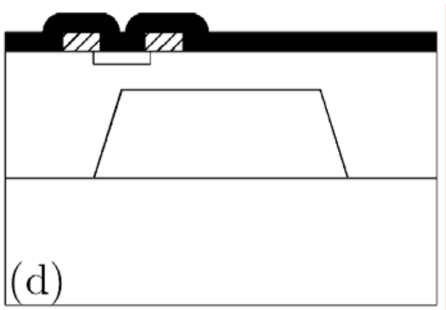
Course outline

> **First up: fabrication and material properties (4.5 lectures)**

> **<u>MEMS fabrication is intimately coupled with design</u>**

- **Not true of many other worlds**
- **Example: diaphragm pressure sensor**
  - » **Would like to use Si because of piezoresistors**
  - » **Material choice sets fabrication technology: KOH**
  - » **Fabrication technology determines shapes and physical limits: diaphragm thickness**
  - » **This in turn affects performance**

deflection ~ (thickness)$^{-3}$



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Photograph of Motorola MPX200 x-ducer.

> **Material properties also matter greatly**

- **MEMS material properties are often poorly characterized**

Course outline

> **Fabrication lectures will focus on MEMS process development**
  - **Unit processes**
  - **Order-of-operations**
  - **Front-end and back-end processing**

> **These themes will be broadcast throughout the term**

Course outline

- Next we introduce the electrical and mechanical domains (2 lectures)
- This gives us something concrete to design

- Split class into two groups for Lectures 6 & 7
- Group 1: Basic Elasticity and Structures
- Group 2: Basic Electronics (Circuits, Devices, Opamps)
- Goal is to teach fundamentals at a slower pace without boring "experts"
- Rejoin at Lecture 8

Course outline

> Split sessions

> Which session should I attend?

> Go for material you are less familiar with

- MEs go to Electronics
- EEs go to Elasticity/Structures

> Notes for both lectures will be available to all

> What if you don't know either subject?

- We will hold makeup lectures of Elasticity/Structures
- Please let us know ASAP if you need a makeup

Course outline

> **Next we present an approach to design (3 lectures)**

- **Lumped-element modeling**
- **Different energy domains all use common language**
  - » **Electrical, Magnetic, Structural, Fluidic, Thermal**
- **Therefore, when you encounter a new domain, you can quickly attach it to existing knowledge**
- **Enables quick design**
- **But has limits…**

Course outline

- Then we explore additional energy domains (6 lectures)
  - Structures, Thermal, Fluids & Transport
  - What physics are relevant?
    - Not all of fluids, just low-Reynolds-number flows
  - How do we extract lumped-element or analytical models?
    - What is the “resistance” of a microfluidic channel?

Course outline

> **Systems issues (4 lectures)**

- **Noise, feedback, packaging, design tradeoffs**

> **Partitioning**

- **A major theme of the course**
- **Can't design device with process**
- **Also can't design device without package**
- **Should you put any electronics on-chip?**
- **Can you design MEMS to make read-out easier?**
- **What are the trade-offs between different choices**

Course outline

> **Finally, case studies**

- **Integrate everything we have up to now to learn about design process of actual devices**
- **Analog Devices accelerometer**
- **TI micro-mirror**
- **BioMEMS such as integrated PCR devices**

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- Take-home and team design projects

Design projects

> **Design is the *heart* of this course**

> **We will have short design problems on the psets**

> **In March, we will have a take-home graded design problem**
> - **Multifaceted: fabrication, electromechanical analytical design**
> - **Students will prove their design to staff**

> **In April, team design projects start**

Design projects

> **Projects, projects, projects**
- **Teams of 4-6 people**
- **Chosen by US, with input from you**
- **Only students taking class for CREDIT can participate**
- **All teams have a mentor**

> **Paper design of a MEMS-based device**
- **Quantitative system-level specifications**
- **Analytical design, finite-element modeling, fabrication, packaging, electronics, calibration, etc.**
- **Final project grade 50% due to team, 50% due to individual**

> **Lectures will focus on case studies**

> ***Almost* no more homeworks**

Design projects

> Project timeline

- Short description March 9
- Your preferences March 23
- Teams assigned April 4
- Preliminary report
  - » Is team functioning and has it started?
- Intermediate report
  - » Is team functioning and is it going to finish?
- Final presentations and report
  - » ~30-min presentation in front of judges
  - » 20-pg manuscript-quality report
  - » *Significant* prize to winning team

Design projects

> **Use to illustrate course approach**

> **A piezoresistive sensor for biomolecular recognition (2003)**

- **The goal of this project is to create cantilever-based device that detects stress induced by molecular binding.**
- **Two cantilevers (operated differentially) will be created out of Si with integrated poly-Si piezoresistors.**
- **The packaged device will be used in a hand-held point-of-care diagnostic monitor and so must be robust, small, and connected to a circuit that gives an output proportional to the logarithm of the concentration ratio.**

> **Show slides from presentation to illustrate design process**

Images removed due copyright restrictions.

Student final presentation: Gerhardt, Antimony L., Saif A. Kahn, Adam D. Rosenthal, Nicaulas A. Sabourin, and Keng-Hoong Wee. "A Piezoresistive Molecular Binding Detector."