CS235: Applied Robot Design for Non-Robot-Designers
How to Fix, Modify, Design, and Build Robots

Reuben Brewer and J. Kenneth Salisbury, Ph.D.

Computer Science Faculty Lunch

Tuesday, November 27, 2012

STANFORD UNIVERSITY

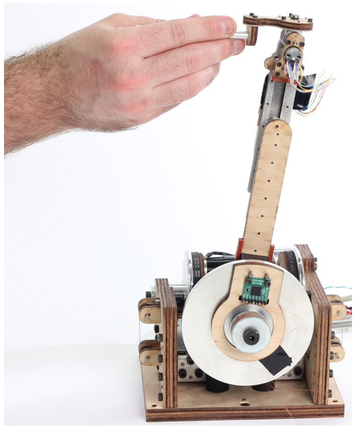
About Reuben Brewer

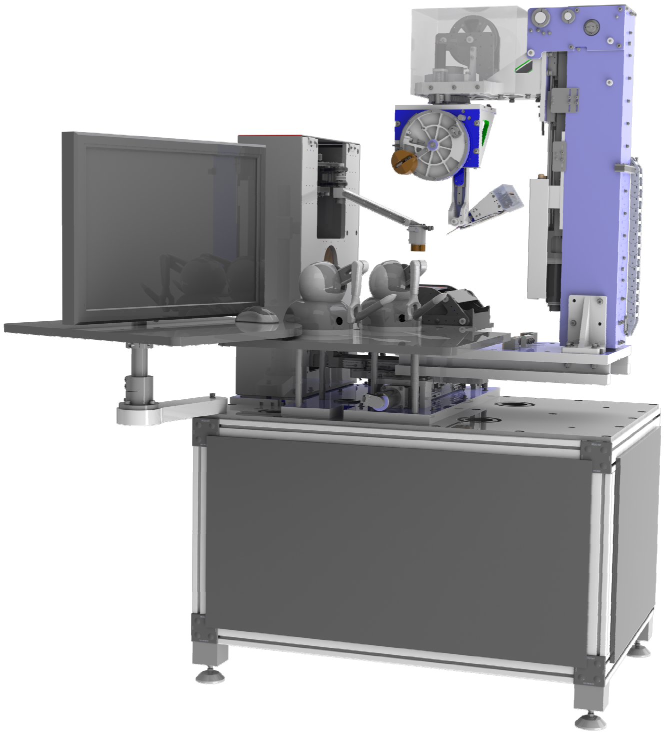
- B.S. in Mechanical Engineering, Johns Hopkins University, 2006
- M.S. in Mechanical Engineering, Stanford University, 2007
- Ph.D. candidate in Mechanical Engineering, Stanford University

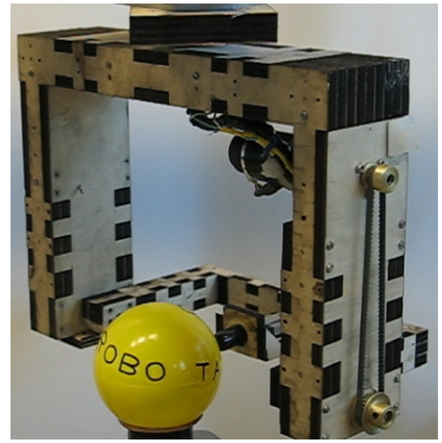
  Advisor: J. Kenneth Salisbury

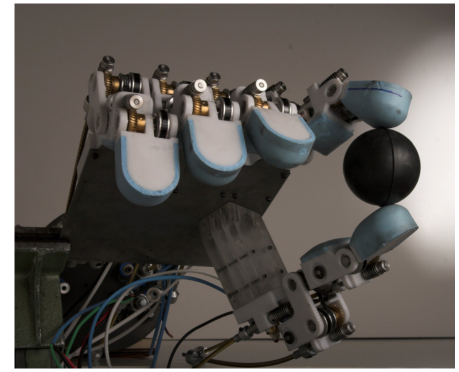
  - Dissertation topic: "Robotic Assistance in IV Insertion"
    - Medical Robotics
    - Electromechanical Design

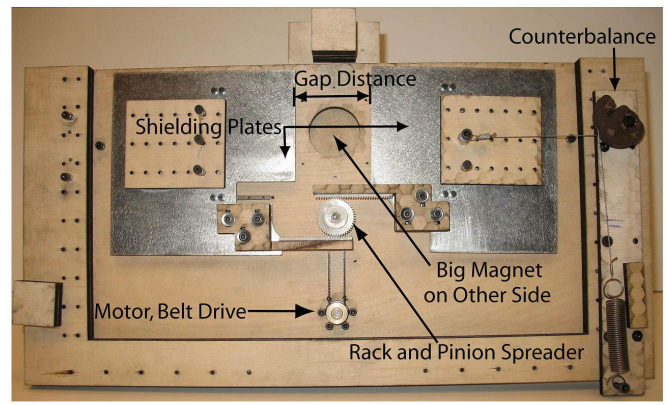
I like to build robots.

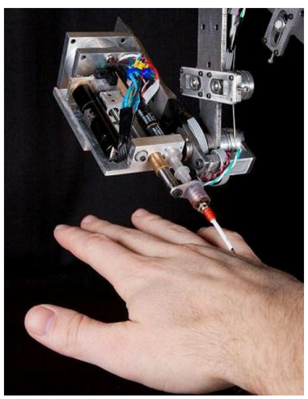


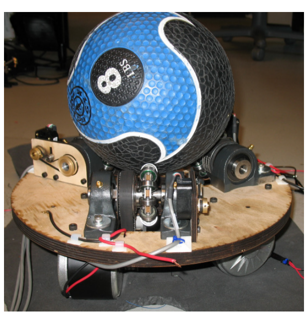


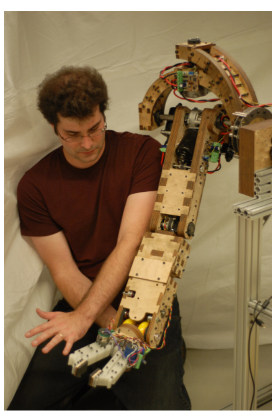


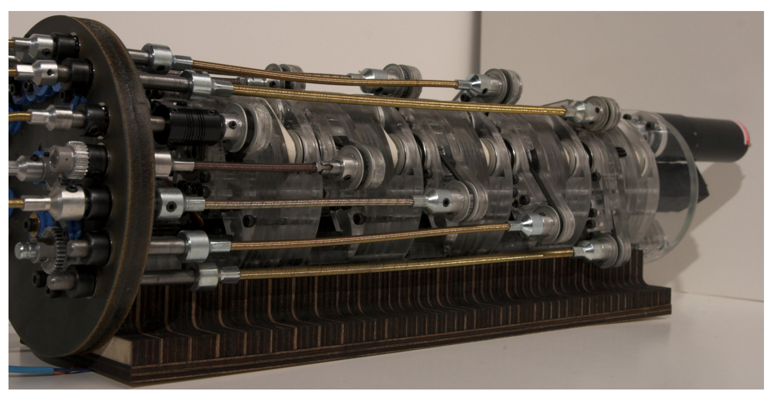












Motivation for the Course

- No other course at Stanford teaches practical mechanical design.
- Most undergraduate programs don't teach this material either.
  - Machine Design: How to calculate the material stress in a bolt. Seriously?
- CS235 was born out of my desire for a practical, consolidated, and comprehensive course on building the mechanics of robots so that students don't have to teach themselves and re-invent the wheel.
- Robotics = electronics, programming, mathematics, controls, and mechanical design.
  - Must have a working knowledge of all these areas to work well in robotics, even if only to speak a common language.

CS Student in Robotics: Can't Escape the Mechanical Side

- Does this scenario sound familiar?
  - As one example, perhaps a student is testing a new computer vision algorithm that allows for a WAM arm to grasp objects more reliably. A week before the paper deadline, a software bug causes the arm to break itself. Although someone familiar with how to install and properly tension a cable transmission could fix this problem in a few hours, no one in the lab knows how. The WAM is returned for repairs that take 1 month, and the paper deadline is missed. As another example, perhaps the student is going to attach a custom 1-DOF gripper with a 1-DOF motorized laser-scanner to the WAM. Without much mechanical experience, the student will likely take a long time to design and fabricate the mechanism, only to discover that the backlash in the gears used in the laserpan mechanism causes the data to be unusable. While the time spent fixing robots and iterating on failed designs is not a total waste as, hopefully, it was a learning experience, this effort is not towards the core of most students' research. If we teach students how to design and build mechanical systems effectively and efficiently, they will be able to spend more time on research and less time maintaining, modifying, and developing the infrastructure to do that research.

But wait! Can CS students really be trusted with a screwdriver and hammer? (intentionally offensive)

A Priest, a Rabbi, and a Minister Walk Into a Bar…

- Stereotypes are bad. We set out to disprove a few:

Mechanical Engineer = car mechanic

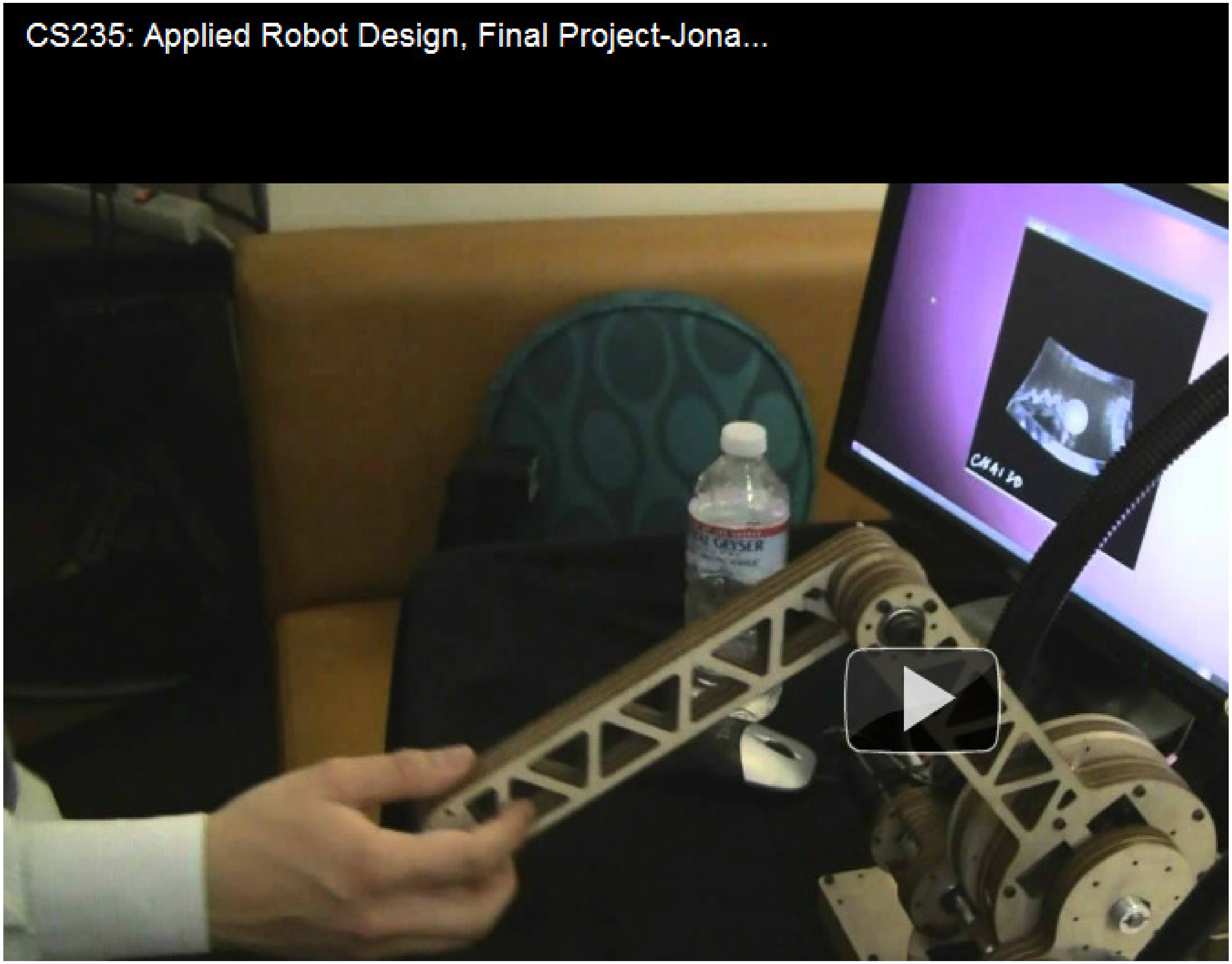
Electrical Engineer = electrician

Computer Scientist = IT support person

Premise of CS235:
With proper training, people of every technical major can build amazing robots.

The HCI Convert

- A visiting CS Ph.D. student with zero mechanical experience built this:



Funding

- $50K Seed Grant from CS Department call-for-proposals ("Truly novel initiatives in education and teaching") in March 2011.
  - Extra ~$10K to cover budget overage and laser-cutter failure.
  - Funded
    - 25%-CAship for Reuben for 3-quarters to develop and teach CS235.
    - Capital overhead for course (tools/electronics that can be reused quarter-after-quarter).
    - Consumables (wood, nitrogen, screws, etc.) that last only 1 quarter.

  - Extra funds for one 50% CAship once we converted CS235 to a full course.

Who Was Interested?

- At the first class, 83 students were enrolled on AXESS.
- ~75 students attended the first class, and 64 students submitted applications.
- 27 students told yes, 20 told no, 9 were waitlisted, and 8 asked to audit on their application.
- We were looking for students with blank-slates in mechanical design.
  - A technical background (e.g. engineering, math, physics).
  - Minimal knowledge of mechanical design and hands-on experience.
  - MUCH easier to teach blank-slates than students with just enough knowledge/experience to be dangerous/convinced they're right.

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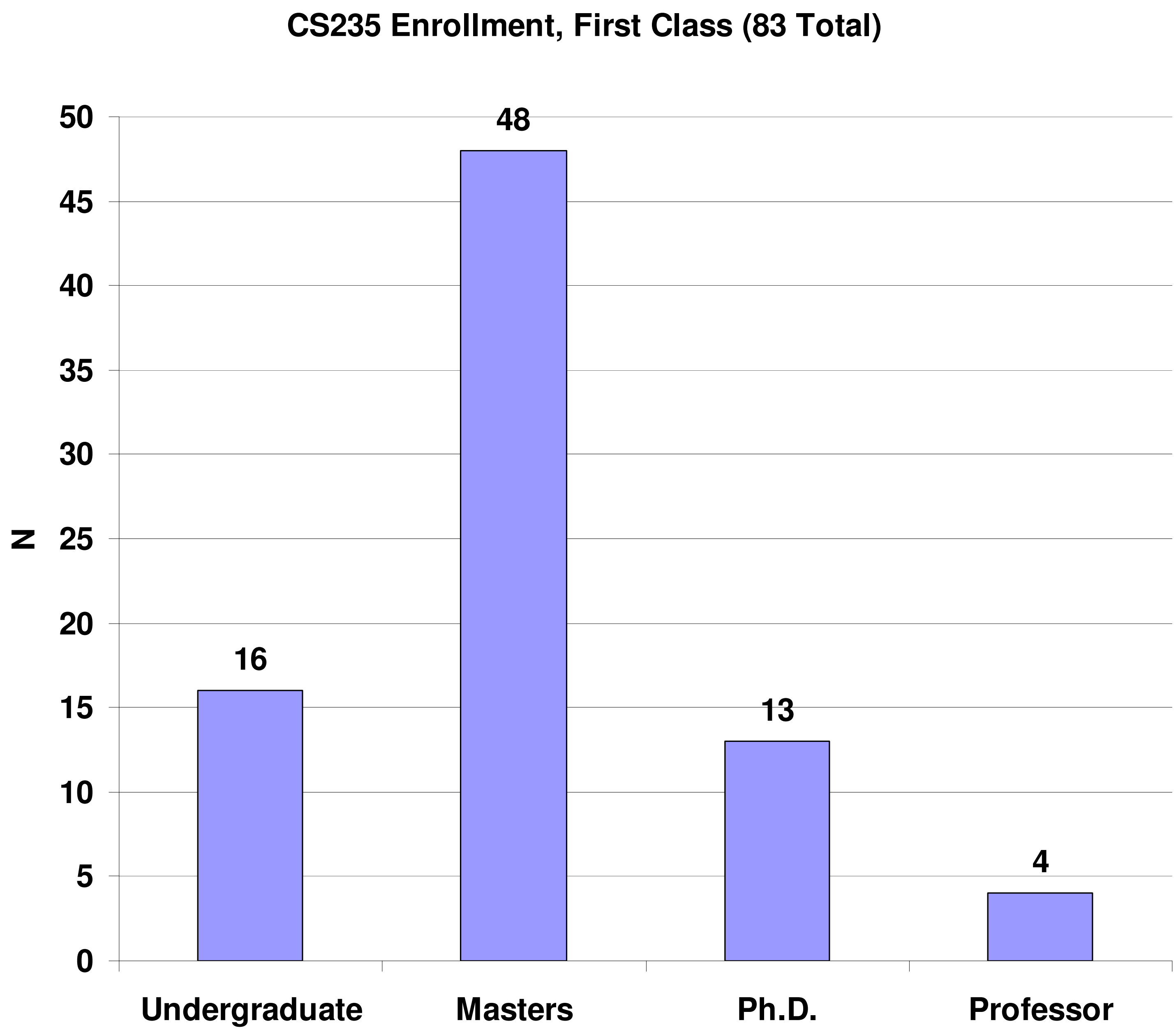
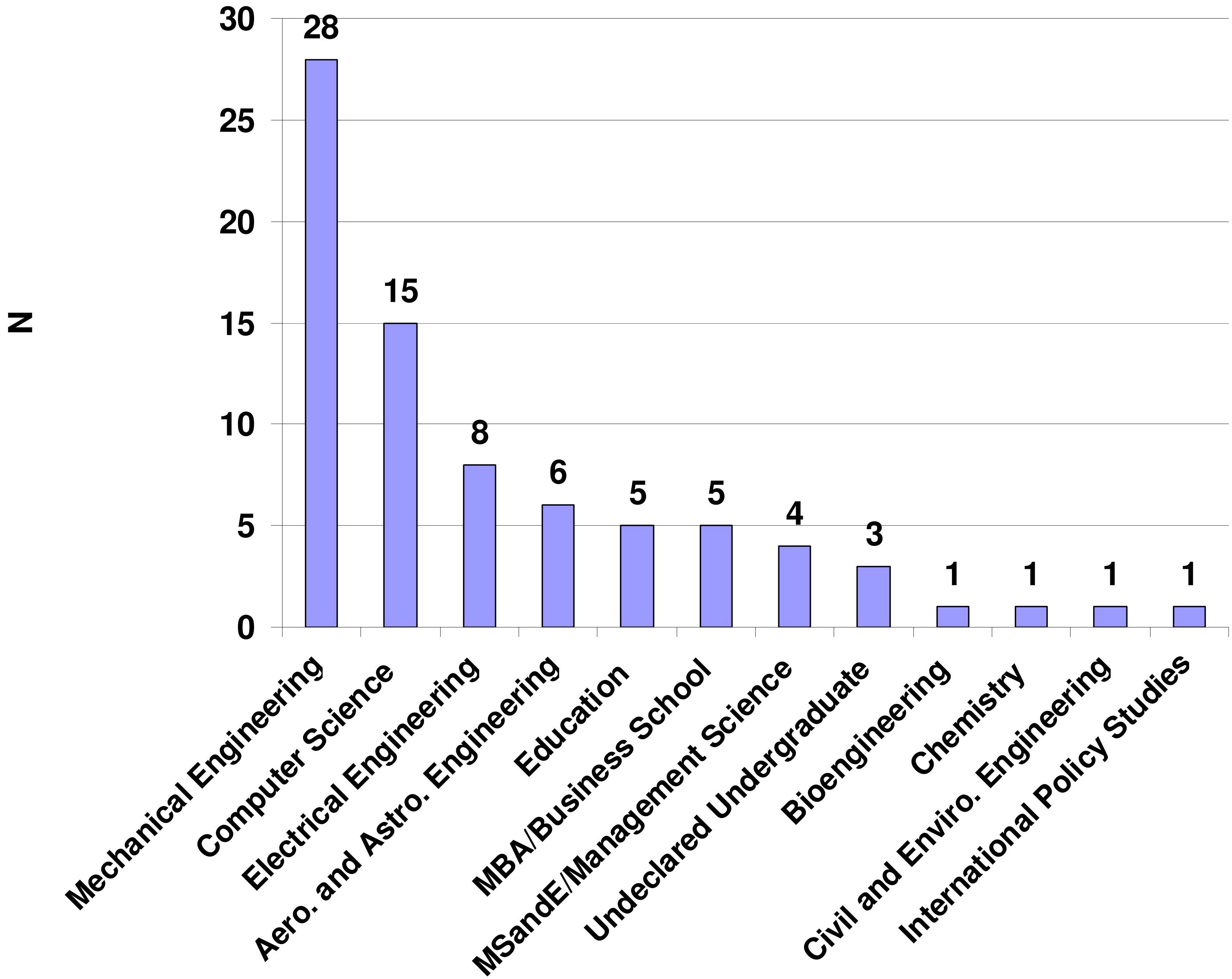
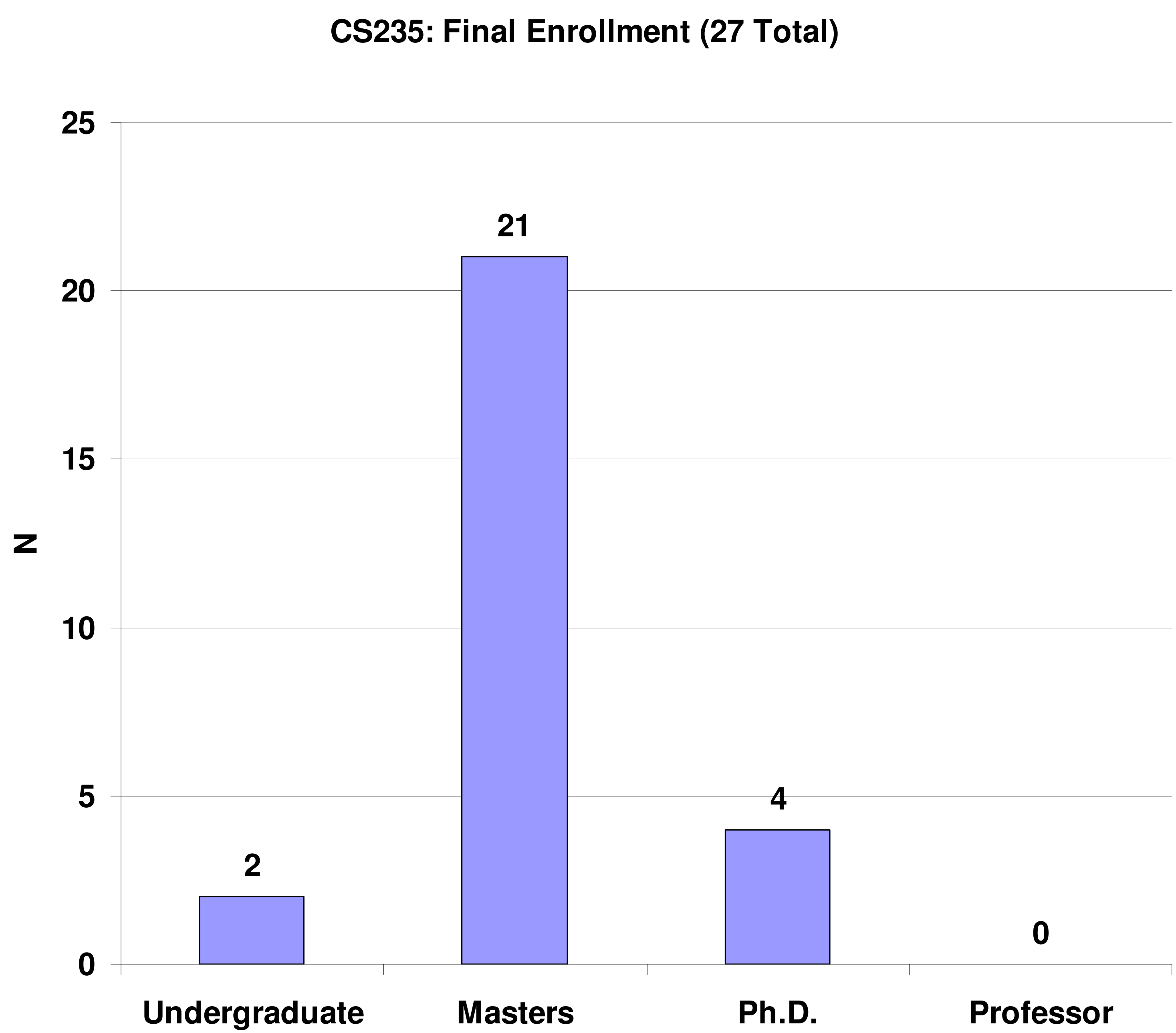
CS235 Enrollment, First Day of Class

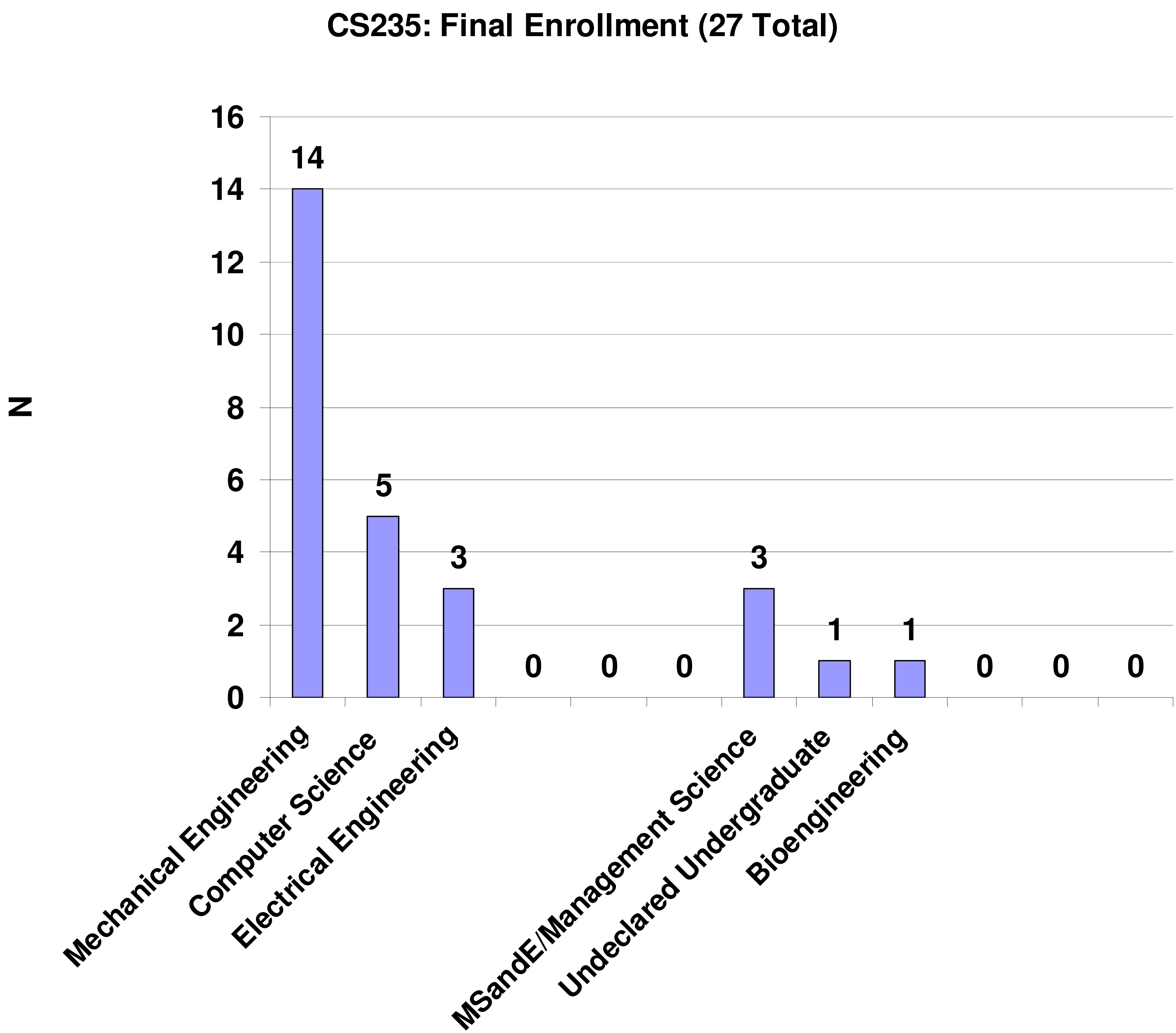


CS235: Departmental Enrollment, First Day of Class (83 Total)



CS235 Final Enrollment




CS235: Final Enrollment (27 Total)
N
0
2
4
6
8
10
12
14
16
14
5
3
0
0
0
3
1
1
0
0
0
Mechanical Engineering
Computer Science
Electrical Engineering
MSandE/Management Science
Undeclared Undergraduate
Bioengineering

Course Format

- Lectures met Monday and Wednesday 4:15-6:05, Clark S361.
  - Reuben prepared and gave
    - Nineteen 2-hr lectures
      - Lectures were based 99% on live demos, examples, and videos. There was typically a large crowd for 10 minutes after lecture as students played with the demo devices.
    - Three 2-hour evening Solidwork-tutorial sessions
- Office hours/prototyping time during lab and final project weeks was anywhere from 5-7 days a week for 8-12 hours a day.
  - 1/3 of these were held by the TA.
  - 2/3 of these were held by Reuben.
- Assignments:
  - 3 labs
  - Final Project (3 weeks)
  - No tests.

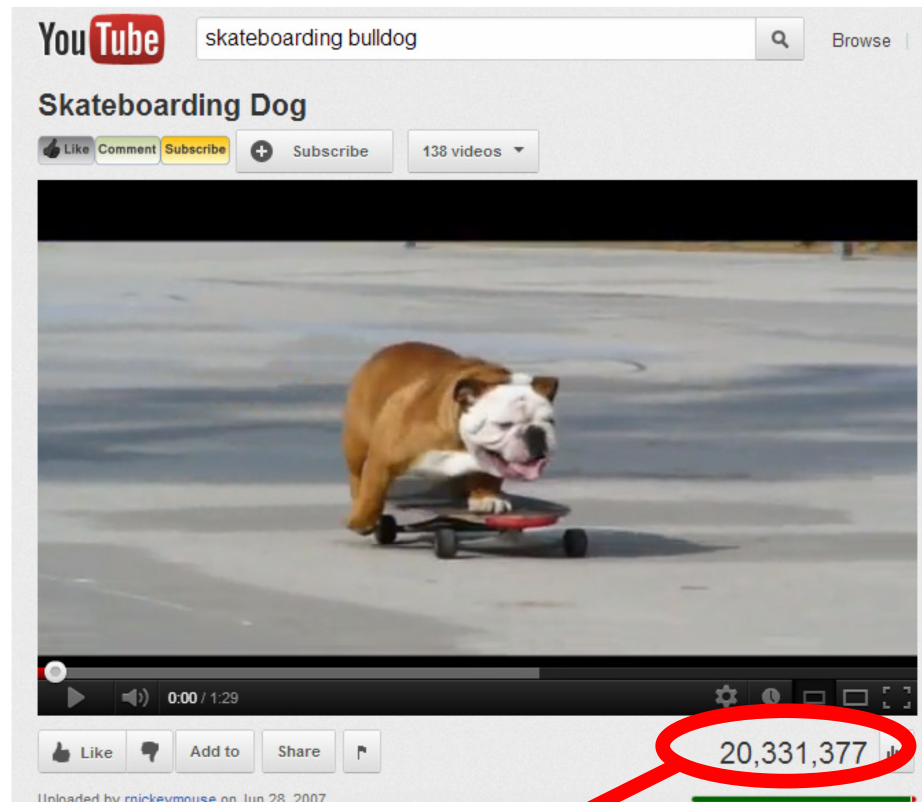
Lecture Topics: Basic to Advanced

- Lecture 1: Course overview, explanation of syllabus, entrance questionnaires, introduction to robotic joints, manufacturing, and design. Introduction to gears.
- Lecture 2: Complete discussion of bearings, start introduction to gears.
- Lecture 3: Discussion of holes, screws, and how to make precise stacks of planar parts.
- Lecture 4: Complete discussion of gears and gearheads.
- Lecture 5: Belts.
- Lecture 6: Friction drives, differentials, friction-differentials, and flexures living-hinges).
- Lecture 7: Introduction to cable transmissions.
- Lecture 8: Completing our discussion of cable transmissions and introducing push-pull cable/sheath transmissions, universal joints, and flexible shafts.
- Lecture 9: Slip-rings and encoders.
- Lecture 10: Completing our discussion of encoders and introducing DC motors and how to connect robots to computers through IO boards.
- Lecture 11: Completing our discussion of DC motors.
- Lecture 12: How to use precise measuring tools.
  Lecture 13: Rigid linkages, spherical bearings, remote-center-of-motion (RCM) mechanisms, and counterbalances.
- Lecture 14: Servo motors, 80-20 aluminum framing, and how to design your robot base/table.
- Lecture 15: Discussing springs and introducing the final project.
- Lecture 16: Discussing the final project.
- Lecture 17: Linear motion / prismatic joints.
- Lecture 18: Cams, wheels, omni-wheels, caster, ball transfers, ultrasonic motors, pancake motors, hub motors, and vibrating motors.
- Lecture 19: Review of ball bearings, different kinds of ball bearings, exit questionnaire.

YouTube Presence

- All lectures, Solidworks tutorials, lab previews, and final project videos are on Youtube at http://www.youtube.com/user/StanfordCS235/videos (or cs235.stanford.edu). Each student's private grading videos are also on YouTube for their reference (unlisted for privacy).
  - The lecture and Solidworks videos averaged 182 views.

CS235: 320 views

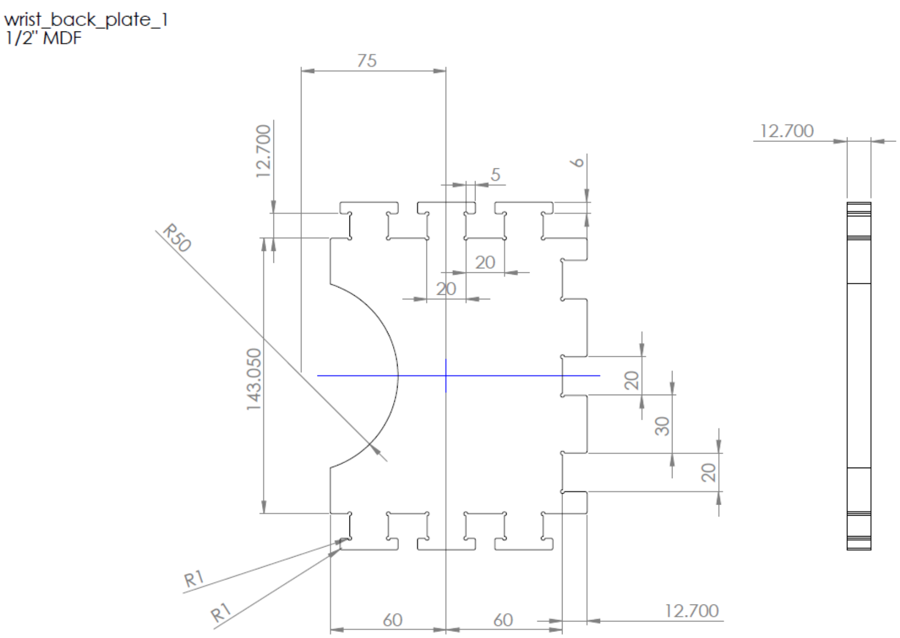


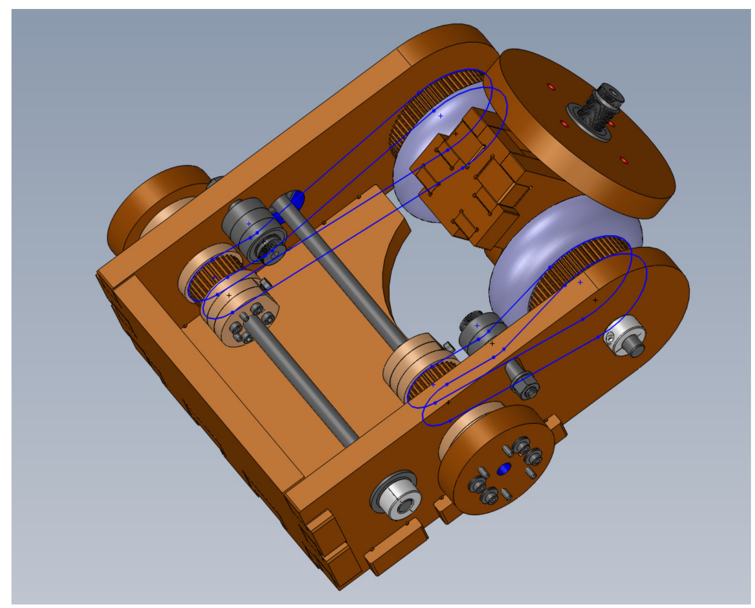
Skateboarding Dog: 20,331,377 views

Solidworks Instruction

- Solidworks = Computer Aided Design
  - Design the robot completely in the computer before you try to build it.
  - Free for Stanford affiliates.

- Held 3 two-hour, interactive tutorials where we practiced making sample parts from Lab 1.





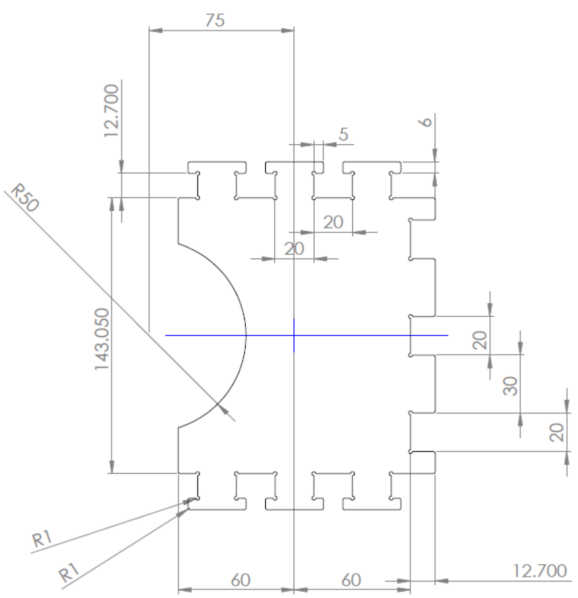
Labs

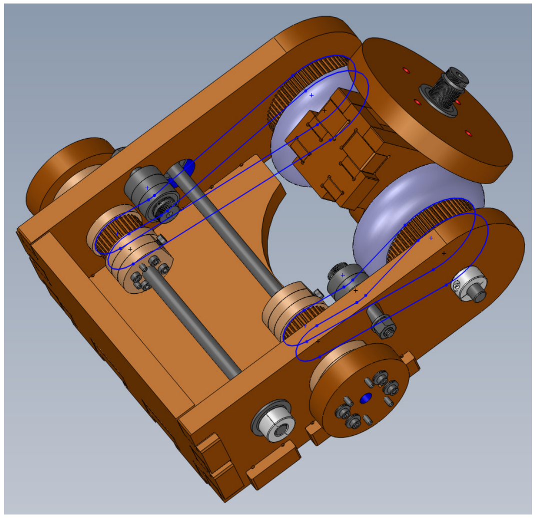
- Spirit of the labs: Hold their hand as long as possible until they get the basics. The labs are for teaching basics, not creativity. Musicians learn scales before they improvise.

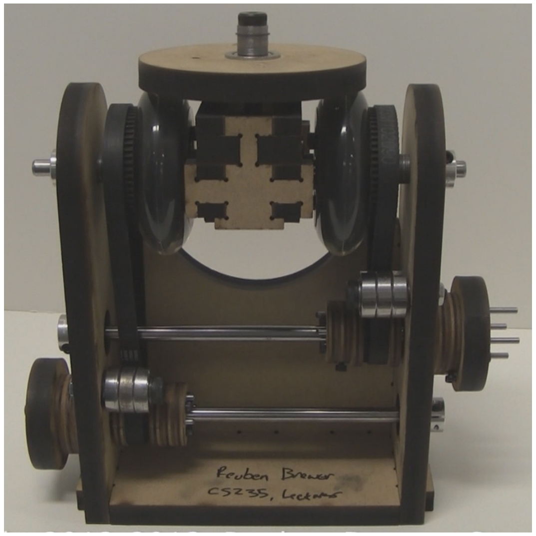
THIS IS A KEY DIFFERENCE FROM OTHER “DESIGN” COURSES.

- Each student made the Solidworks models of the lab based on dimensioned drawings from Reuben. They then assembled the pre-fabricated laser-cut/3D-printed parts and made any other necessary parts themselves.

Drawing → **Solidworks Model** → **Fabrication/Assembly of Prototype**

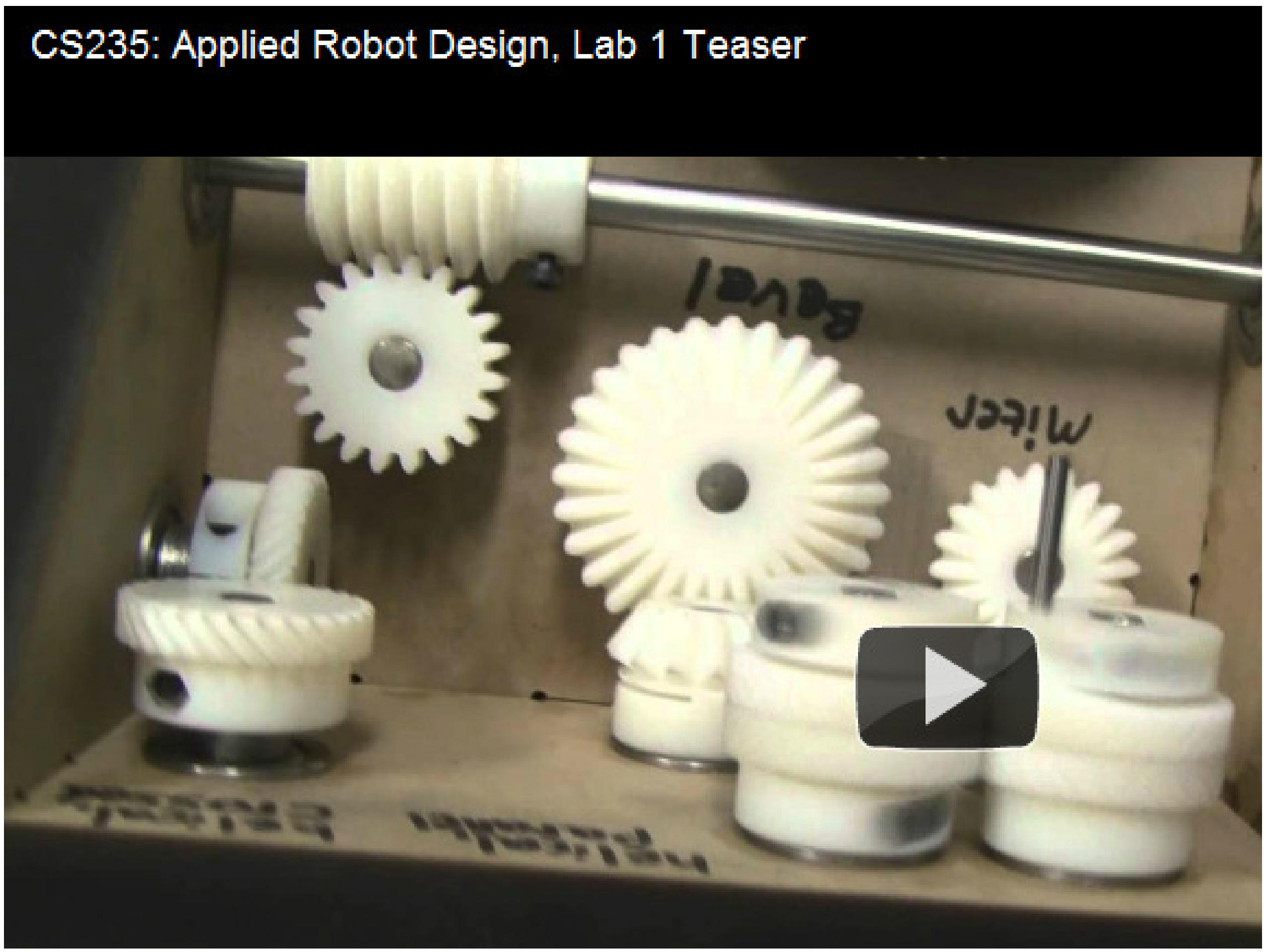




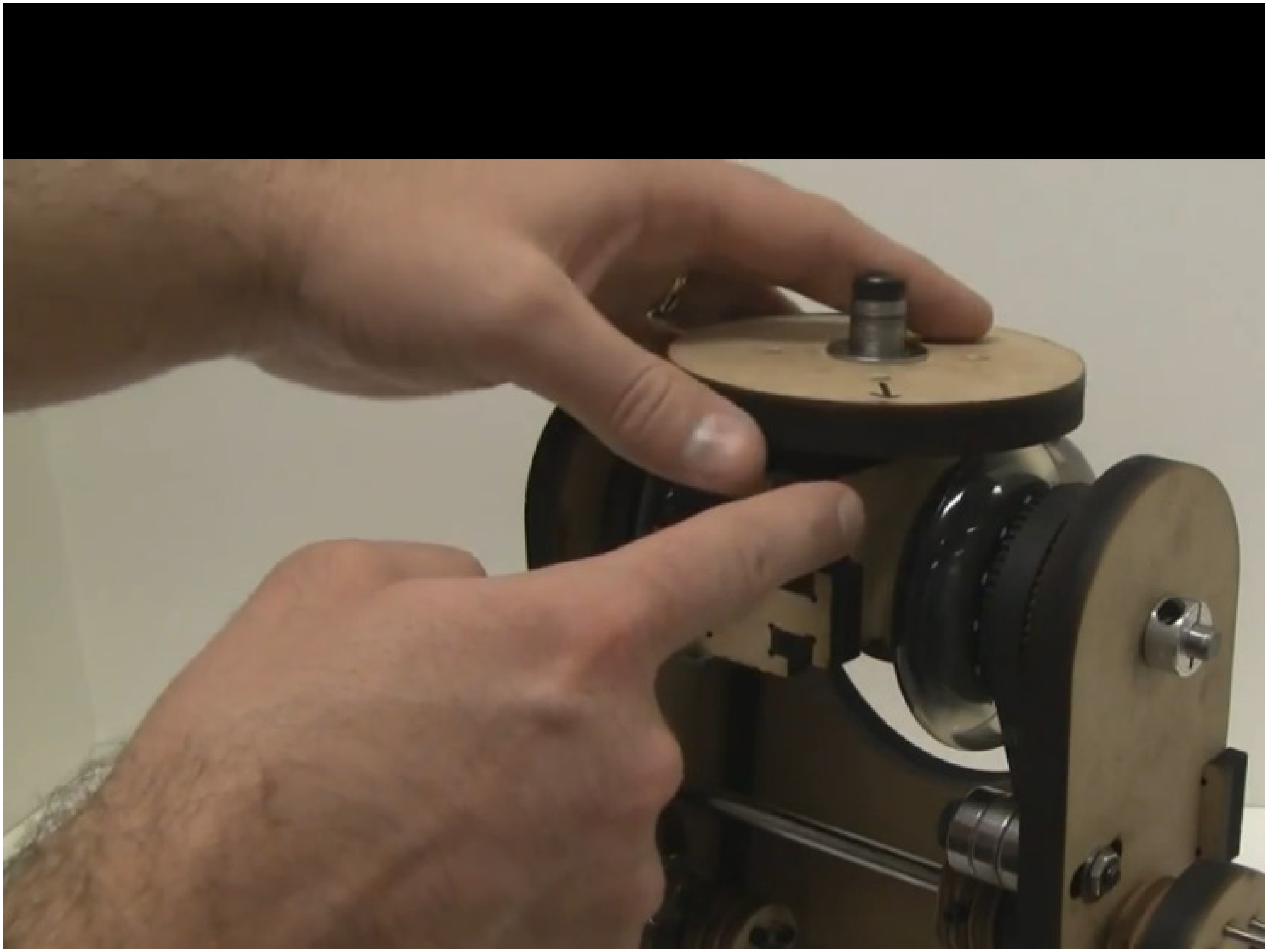


Lab 1: Gears

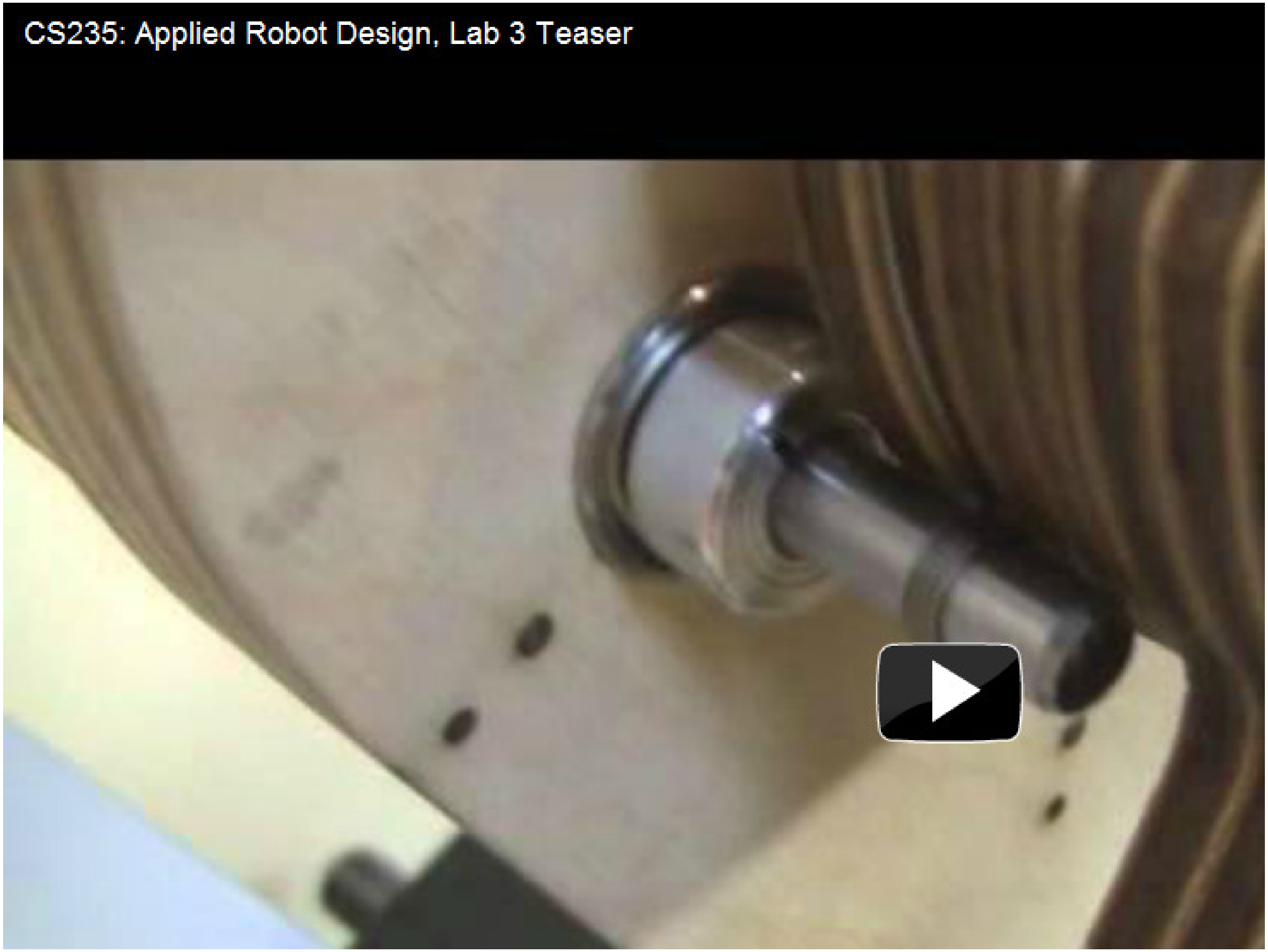
- Beyond teaching about gears, Lab 1 was meant to engrain the basics of Solidworks, bearings, shafts, and basic tool-usage through near-ridiculous repetition. This made Lab 2, Lab 3, and the Final Project MUCH easier.
  - We were concerned with the amount of clicking, so we asked students to raise their hand if they got carpal tunnel. Nobody was able to raise their hand, so we were safe.



Lab 2: Robot Wrist Using Belts and a Differential



Lab 3: Cable-Driven, Rigid-Linkage Remote-Center-of-Motion Mechanism with Passive Gravity Compensation



Final Project

- Spirit of the final project: Show your mastery of the basics and ability to extend them to advanced topics. Demonstrate creativity with electromechanical design.

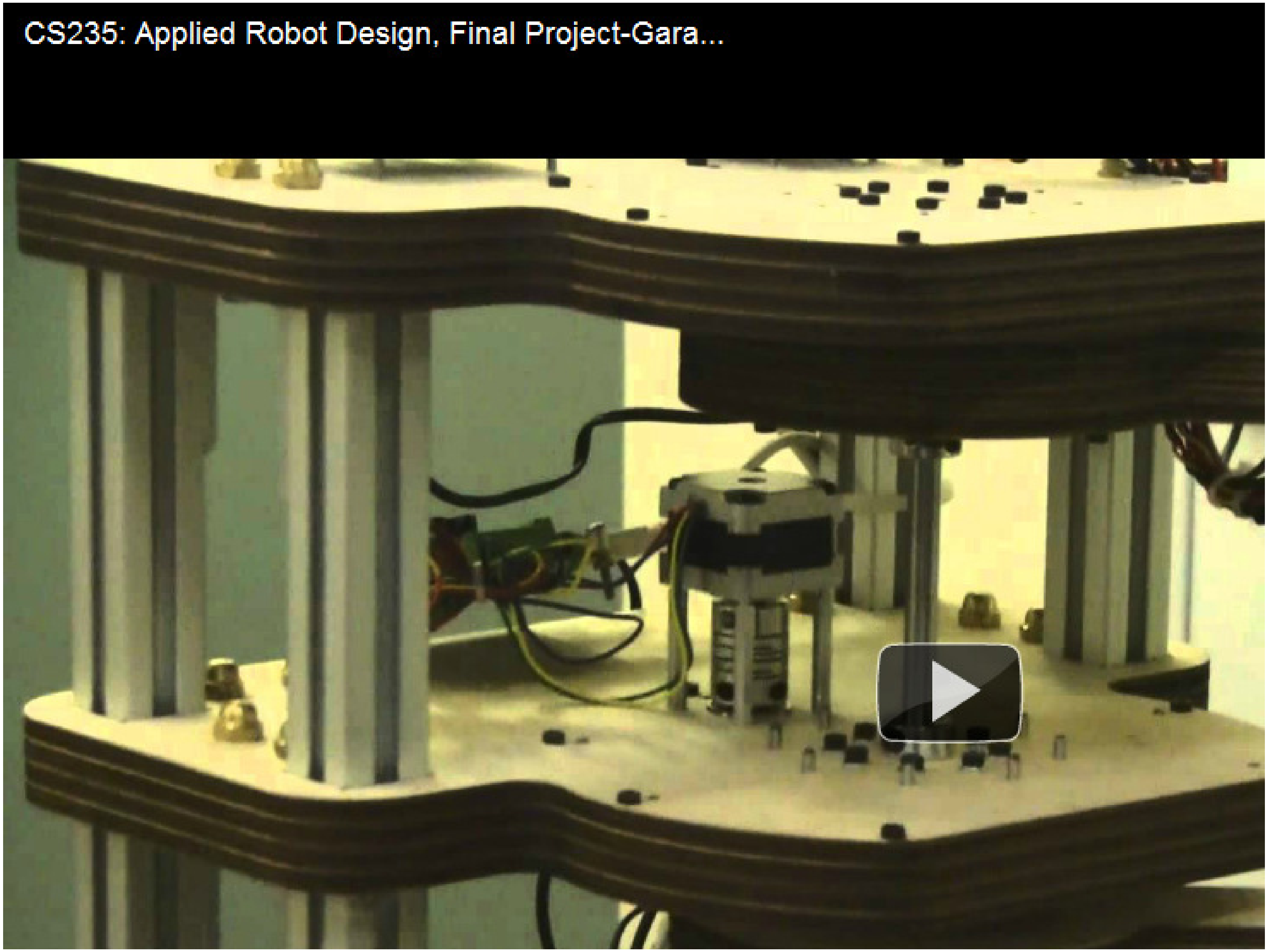
- Nine teams averaging three students each.

- 5 teams built chess-playing robots.
  - Must use at least 1 DC motor with encoder, 1 stepper, and 1 servo.
  - Must use 1 cable-drive and an 80-20 frame.

- 4 teams built research projects (all haptic devices).
  - Khatib had two groups, Okamura had one group, and Salisbury had one group.

- Three weeks to design, build, wire, and code from scratch!
  - Gave plug-and-play Phidgets electronics (motor control, analog in/out, and digital in/out USB boards).
  - Gave GUI and motor-control starter code, but the teams had to extend this significantly.

Final Project: Garai, Hofius, and Jeng

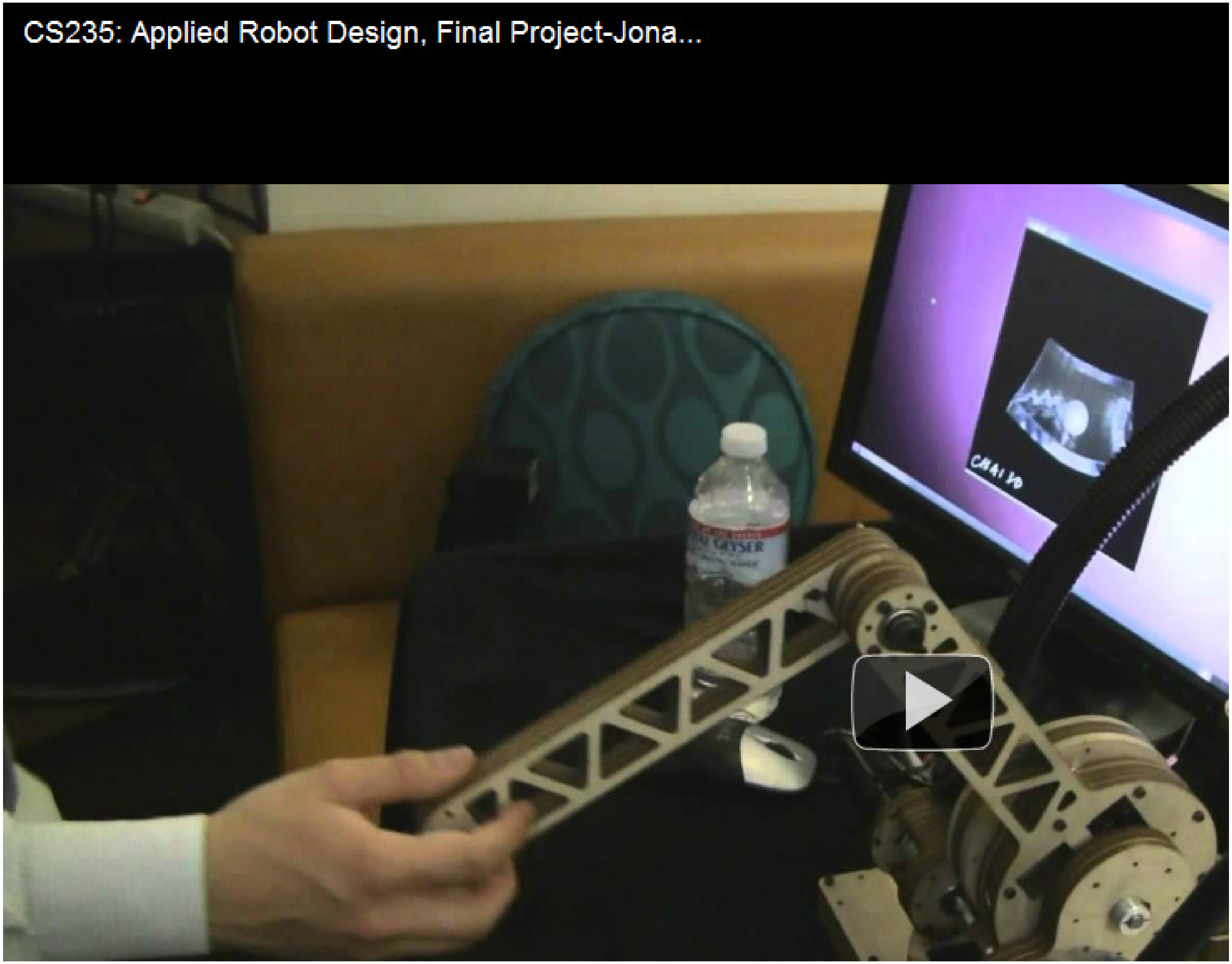


Final Project: Quek and Yeh

Final Project: Kamath, Roy, Siilats, and van Galen Last

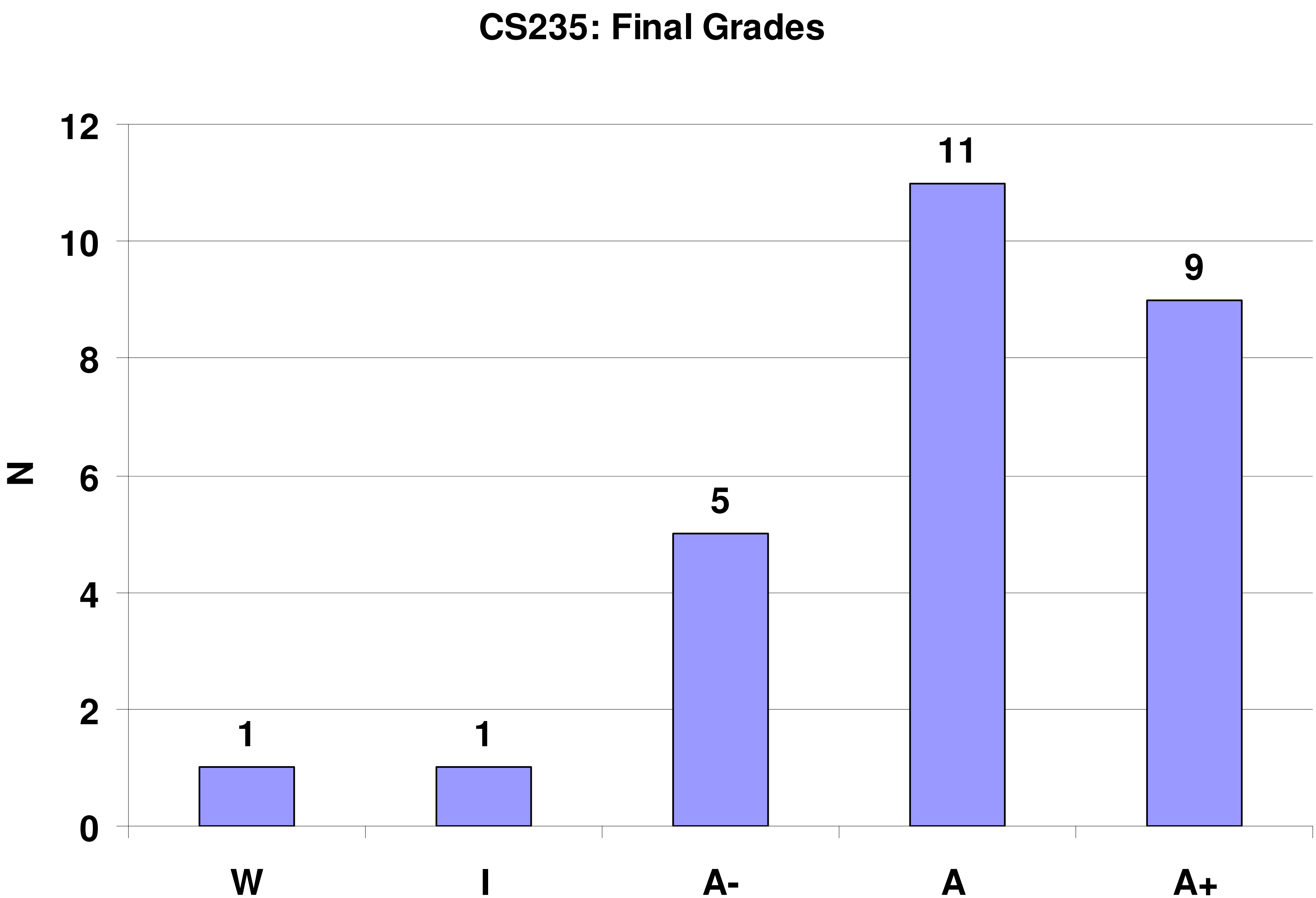
Final Project: Muirhead, Romano, and Stuart

Final Project: Forrslund and Yip



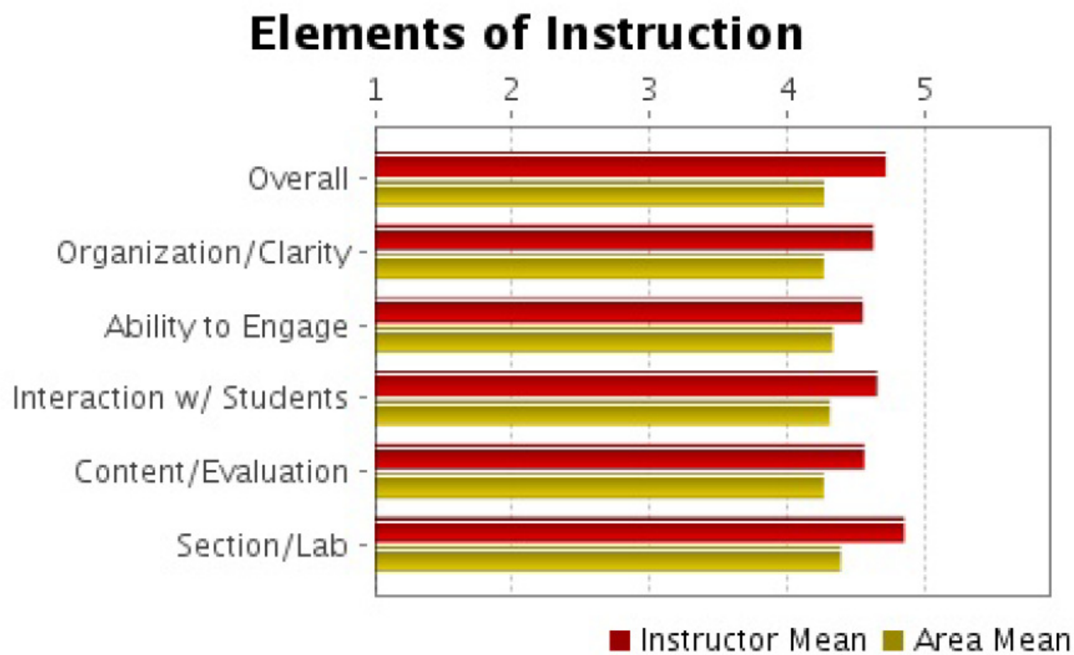
Grades: How'd They Do?

- Most labs were terrific, and every single final project worked. Hence the high grades.



How'd the Students Like CS235? Student Reviews

- This course was an experiment with 3 main questions:
  - Would this course's approach be effective in teaching students how to build robots?
    - Answer: Yes.
  - Can we teach mechanical design to students from many different technical backgrounds?
    - Answer: Yes.
  - Would the students enjoy this course?
    - Answer: Yes.



Corporate Sponsorship

- Thought of vendors that I used and cold-called them.
- “We’re doing something new and cool, and here’s the write-up. Involvement will give you great PR and introduce you to new customers. Students who learn to use your products will likely buy them after grad school when they work for a company or start their own.”

$$$

Corporate Sponsorship: What We Used

- Coherent Inc.,
  - Donated a full maintenance support plan for current laser-cutter.

- Objet Inc.,
  - Donated sample 3D-printed parts.
  - Donated $2500 of resin to print students' custom parts.
  - Attended Final Project Presentations and recorded student interviews.

- Misumi,
  - 30% discount for ALL of Stanford.
  - Gave special evening presentation with live demos of parts.

Corporate Sponsorship: What We Used

- Phidgets, USB motor drivers/DAQ cards: 30% discount.
  - We used Phidgets for all of the motors, sensors, and electronics for the final projects.
- 80/20, industrial erector set: 50% discount.
  - Provided framing for bases of final projects.
- VXB, ball-bearings: 30% discount.
- Sava Cable, cable transmissions: 50% discount.
- Bruce Bauer Lumber: 10% discount.
  - Local vendor.
- Black Diamond Sports, ball-bearings: 7% discount.
  - Local vendor.

Questions?