Overview
Students learn deterministic design, selection, and assembly of machine elements to create and manufacture a robust precision machine or system. Topics include error apportionment & error budgeting, mechanical connections & interfaces, linkages, machine elements, power transmission, structures, selection of manufacturing methods and materials, and metrology. Considers each topic with respect to its principles of operation, mechanics and performance. Students design, build, and test a series of modules including kinematic and elastic averaging couplings and linear and rotary motion axes. Graduate students make two linear motion axes and combine with the rotary axis to create a T-base lathe. Students must before the scheduled topic is covered in class complete the corresponding 2.75x online module and assessment quiz, as lectures focus on use of the materials in actual design scenarios.

Schedule:
Lecture: MW12:30-2 in 3-442, lab is M 2-5, where Prof. Slocum will arrange to be in Hobby Shop or Maker Works (or split time) to assist students with whatever specific questions they may have. Students do not need to be in lab at this time, it is understood some students will have other classes in this time period; however, the course is designed so students can work whenever they want wherever they can, but this is the only time currently scheduled for Prof. Slocum to be in a shop somewhere to answer questions.

Pre-requisites:
1. Undergraduates MUST have take 2.008 (which means also have taken 2.007). NO EXCEPTIONS. IF you really want to take 2.70, then first take 2.008!
2. Graduate students are expected to have had a design and a manufacturing course like 2.007 and 2.008 in their undergraduate career.
3. Students must secure their own access to a machine shop (e.g., MakerWorkshop, Hobby Shop, Edgerton Student Shop) and MUST be competent enough to complete the hardware assignments.
4. Students must have 3D CAD software skills (e.g. SolidWorks) (know how to create dimensioned drawing and a bill of materials, as well as use equation and part configurations)
5. It is strongly suggested that students complete the 2.75x course and on-line exams in IAP before the class begins!
   a. Sign in and create account:
      i. https://lms.mitx.mit.edu/courses/course-v1:MITx+2.75r+2018_Spring/info
   b. Students must before the topic is covered in class complete the corresponding 2.75x online module and assessment quiz, as lectures focus on use of the materials in actual design scenarios.

Textbook and Readings
1. Prof. Slocum wrote the book *FUNdaMENTALS of Design* and it can be freely downloaded from [http://web.mit.edu/2.75/fundamentals/FUNdaMENTALS.html](http://web.mit.edu/2.75/fundamentals/FUNdaMENTALS.html)
2. PMD: Precision Machine Design written by Prof. Slocum
3. Various additional readings (required for graduate students) (Hale & Hopkins)

**Learning Objectives**

1. Develop and demonstrate a deep understanding of deterministic design
   a. Everything happens for a reason (Prayer may be good in one’s personal life, but not for precision machine design.)
2. Understand the functional operation and governing physical laws of machine elements (And become a lifelong learner!)
   a. Understand common mechanisms and machines and be able to explain why they work. i.e. Linkages, Bearings, Flexures, Couplings, Gears, Rails etc.
   b. Learn what exists, how it works, why it works, how to properly use it, to enable a designer to select/buy if possible so you do not reinvent the wheel
   c. Understand underlying physics of how machines work. i.e.
      i. Stress + strain, parasitic forces, beam bending, proper kinematic constraint, kinematics and homogeneous transformation matrices, error budgeting, effective use of free body diagrams, hydrostatics etc.
3. Learn to apply and use deterministic design to create machine modules and close the loop by comparing with analytical models (e.g. error apportionment and error budget) to deterministically guide the design to meet functional requirements
   a. *Complete* a detailed design of a machine module with predicted accuracy, stiffness, and life; and then build and test.
   b. Hone your skills at machining parts and assembling them into machines – overly complex and intricate parts mean more time spent by you in a machine shop!
   c. Cultivate frameworks for identifying problems and designing around them.
      i. Reciprocity, Error Budgeting, St. Venant, Abbe error, structural loops, centers of action etc.

**Expectations**

1. Be good, honest, constructive peer reviewers; be open to constructive criticism, and know how to graciously handle difficult lifeforms.
2. Create/maintain documentation: *All assignments from 2.70 must be posted to a dropbox that will be set up for each student. In addition each student must create and maintain a personal website that summarizes each major projects’ development (concept, engineering, build, test, what learned)*. Since assignments will be done professionally and peer reviewed, they can be a very positive addition to your online portfolio!
3. Document!:
   a. Integral to maintaining your dropbox and website – pictures needed for assignments etc., Lab notebooks or journals are required for sketching and peer review
      i. Part of the satisfaction of design is seeing how far you have come since you started: a fun and rewarding experience!
4. No whining!
   a. Think! Anticipate! Ask yourself “what would I want to see as the customer (professor, manager...)?”
   b. This is to be a fun course for students and staff to learn together to become even better machine designers!
   c. If you want or need something, first try to find it yourself! 😊
5. Assignments are created to help guide students with the design and building of their modules:
   a. An important part of this class is learning to be resourceful both in the shop and with your mind.

**Grading**

1. This is not a course for people who want handholding and who try and count points each week to ensure they have a grade they need for their GPA...
2. Students who carefully listen and focus and want to learn will do great!
   a. Your most excellent reflection on abilities learned will be your website you can show to potential employers/grad schools. A letter grade means nothing compared to what you show you can do!
3. Qualitatively grades in this class mean:
   a. A Grade: The design you create has all the details correct, all elements selected supported by analysis (so the design can be scaled and also meets ISO 9000 requirements) and is ready for production....
   b. B Grade: you work for and are trusted by an “A grade” person, but you are not yet able to handle as much detail or as complex tasks as the “A grade” person.
   c. C grade: you are not really focused and committed to this class as you have lots of other things happening in your complex life...
4. Quantitatively grades in this class come from:
   a. For each of 12 weeks, each student will update their dropbox (set up for each student) and website with assignment elements (see below), and course staff/industry reviewers will comment on the quality of the work posted
   b. Starting in week 2, each student MUST complete the corresponding 2.75x topic on-line and individually do the associated on-line exam. This serves as weekly grade for the material covered.
   c. Starting in week 2, each student MUST review the work of two other (RANDOMLY ASSIGNED) students. You will be graded on how well your assessment matches the assessment of the teaching team.
   d. Final exam on FUNdamentals of Design. Think of this as an interview for a job at Apple, SpaceX, Tesla... YES Prof Slocum has many former students who work at such companies and they have learned that grades are in general useless, so they conduct detailed technical interviews!
      i. At the beginning of the class last year’s final will be given for fun (does not count toward grade), and students peer review, and we go over in class as preview for the course.
<table>
<thead>
<tr>
<th>Possible Points</th>
<th>Grading</th>
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<tbody>
<tr>
<td>13 Weekly Assignments (weekly progress on hands on design &amp; build assignments, and Seek &amp; Geek write-ups)</td>
<td>39 pts, (up to 52 pts max)</td>
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<td>4pts (A+=wow!) 3pts (A=good), 2pts (B=good), 1pt (C=ok)</td>
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<tr>
<td>2.75x on-line quizzes</td>
<td>40 pts</td>
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<tr>
<td>Final Exam</td>
<td>40 pts</td>
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<td>Peer review effectiveness</td>
<td>15 pts</td>
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<tr>
<td>Total Possible Points</td>
<td>134 pts nominal, 147 pts max.</td>
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<td>A+ = 121 – 147</td>
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<td>A = 101 – 120</td>
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<td>B = 85 – 100</td>
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<td>C = 70 – 84</td>
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<td>F = &lt;70</td>
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<td>*No D grades for this restricted elective course</td>
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e. After the course is complete, students who want to contest their grade, may do so by bringing their projects and lab notebook to a meeting with Prof. Slocum for an “interview” to assess do they really know the material in accordance with what they think their grade should be. You may invite your academic advisor but not your parents. Note, the grade change may then be up, or down.

Learning Mechanisms

1. Hardware & Brainware: Weekly
   a. The hardware components will be a series of increasingly challenging modules to design (engineer with appropriate analysis), build, & test. They can be based on a basic overall concept provided by Prof Slocum and made simply and quickly in wood; or students can use the designs provided as a starting benchmark and create more elaborate designs.
      i. The modules will be 1) a kinematic coupling, 2) an elastically averaged coupling, 3) a linear motion axis, and 4) a rotary motion axis (e.g., a spindle).
      ii. Graduate (and advanced undergraduate) students on their own may wish to motorize their linear motion slides.
      iii. All modules must be designed where Stiffness, accuracy, repeatability, and resolution are measured and compared to values predicted and then students reflect to “close the loop on the design process” to see how well lessons have been learned.
      iv. Students get to keep their modules and show them off at interviews and to family, and friends!
   b. The brainware components will help you learn deterministic design:
i. By the end of the week for which it is listed, students MUST complete the 2.75 FUNdaMENTALS topics online and the online assessment. The EDx platform records and reports these grades to course staff, and they are an important part of your grade.

ii. They help with the deterministic design analysis required to create the details for the modules.

iii. Seek and Geek (see below) helps students learn what has been done by others...

2. Peer Review Groups: Weekly
   a. Students self-form 3 person peer review groups that are responsible for honest assessment of each other's work
      i. Each team MUST in first week of class create a fixed weekly meeting time and location, so a course staff person could for example show up and see how things are going 😊.
   b. Part of a student’s grade is being able to provide (and receive) constructive and useful peer review to other students.
      i. Physics does not give a damn about your feelings or personal issues, but you must learn to be able to nicely make others aware of physics when they overlook fundamentals....

3. Seek & Geek Exploration: Weekly (this is a critical learning function and should continue long after the course ends)
   a. Each week, students need to take pictures of mechanisms or machines in the real world that uses/illustrates principles from the reading that week, and create a mini “report” of a page or two to show the image and discuss: What is its function? What are the relevant physics that engineers needed to consider? What questions or thoughts does it inspire in you
      1. This should take no more than an hour each week.
      2. Post the S&G reports (PDF) to the course Dropbox!

4. Machine Analysis: for Graduates (and advanced undergraduates)
   a. Students will be required to deterministically design, including formulate the error budget, for a T-base lathe they will assemble and test from the modules they design and build during the semester. Students will then measure the performance of their lathe to verify their error budget analysis.

5. Dropbox (set up for each student) and Personal Websites: Weekly
   a. There will be a Dropbox for the class with a personal folder for each student. All student assignments should be saved into their folder.
      i. Dropbox is used because of no space limit and most importantly when he is offline on a plane or bus.... All people associated with the course (students, staff, industry helpers) can see all the files and thus do peer review grading!
   b. Each student SHOULD ALSO maintain a website of their peer-reviewed work on the design of the projects through the semester, which should be updated frequently.

Weekly Outline of Assignments
1. Below is a brief description of weekly assignments, which are to be completed, peer reviewed, edited/evolved as needed, and posted on student' dropbox folders.
   a. The work assigned in a week is due by Sunday 9 AM of that week.
   b. Post pdf format of all files
   c. Spreadsheets (xcel) ok, BUT make sure to document cells (as per examples in class). Mystery hunts are not professional.
   d. Peer review can thus begin Sunday morning:
      i. Please keep font size readable (12 pt) for someone riding an exercise bike 😊
      ii. Ideally, student posted deliverables will improve through peer feedback and observing others’ work
      iii. Peer review schedules (random assignments of whose stuff you are to review) will be posted a week in advance.
      iv. Each student will peer review and grade two other students (randomly assigned) each week. Known good graders also will review, and so students can compare how they grade wrt KGGs.

**Week 1:**

*Reading: FUNdaMENTALS Topics 1, 2, 3, (grad students also PMD Chapter 1)*

*Brainware:*

1. Form Peer review teams and schedule set weekly mtg time
2. Form Error Budget Teams (grad students and advanced UGs)
3. Create your website (if you have not already)
   a. It could have sections where you post your weekly Brainware and Hardware assignments, including Seek & Geek reports.
      i. You CANNOT use any website that requires a reviewer to open an account (e.g., Linked In).
4. Create a FRDPARRC table for your first hardware module, which will be a kinematic coupling.
   a. You cannot just “print it”: you will have to manufacture it.
5. Seek & Geek #1.

*Hardware:*

1. Make sure you have shop access.
2. Make a very simple (sketch model, mock-up…) functional kinematic coupling (this is the one time you are allowed to just “hack” it—make from a sketch or just by eye) so you can start to get a feel for them. This is NOT the final KC you will make.

**Week 2:**

*Reading: FUNdaMENTALS Topics 9, 4, (grad students also PMD Chapter 2)*

*Brainware:*

1. Deterministic design of a Kinematic Coupling module that can be preloaded together:
   a. Generate several concepts for a KC module.
   b. Write your own design spreadsheet to design (use appropriate analysis) the KC module concepts, and predict their performance (accuracy, stiffness, and load capacity).
      i. Select what you think is the best concept.
c. Create a solid model and a properly dimensioned and toleranced drawing for the manufacture of the KC parts and assembly.
   i. 3D printing it is not sufficient
2. Seek & Geek #2.

Hardware:
1. Make and test your Kinematic Coupling from materials you can obtain yourself and get together with your peer group to play with each other's systems and discuss.
   a. Compare results with predicted performance... what did you do right? What could be better...
   b. What are the 2nd order effects overlooked that proved to be important

Week 3
Reading: FUNdaMENTALS Topics 6, 8, (grad students also PMD Chapter 5, 6)
Brainware:
3. Deterministic design of a Elastically Averaged Coupling module that can be preloaded together:
   a. Generate several concepts for an EAC module.
   b. Write your own design spreadsheet to design (use appropriate analysis) the EAC module concepts, and predict their performance (accuracy, stiffness, and load capacity)
      i. Select what you think is the best concept
   c. Create a solid model and a properly dimensioned and tolerance drawing for the manufacture of the EAC parts and assembly.
   d. 3D printing it is not sufficient
1. Seek & Geek #3.

Hardware:
1. Make (OK to print) and test your EAC
   a. Load the coupling and use a mounted laser pointer to test and record change in position on piece of paper placed far away...

Week 4
Reading: FUNdaMENTALS Topics 10, 11, (grad students also PMD Chapter 7, 8)
Brainware:
1. Reflect on previous two weeks assignments, and "close the loop" to comment on what you predicted and what you observed and why the difference? Evolve your initial spreadsheets to predict performance.
2. We recommend you update your website accordingly.
3. Seek & Geek #4.

Hardware:
1. Modify and re-test KC and EAC modules as you see fit.

Week 5
Reading: FUNdaMENTALS Topics 5, 7, (grad students also PMD Chapter 10)
Brainware:
1. Deterministic design of a Linear Motion (LM) module:
   a. Create a FRDPAARC for your design.
   b. Generate several concepts for your LM module.
c. Write your own design spreadsheet to design (use appropriate analysis) the LM module concepts, and predict their performance (accuracy, repeatability, stiffness).
   i. Select what you think is the best concept.
   d. Start the solid model for your LM module, to help your visualize the elements as your begin to build the error budget for the system.

2. Seek & Geek #5.

   Hardware:
   1. To help you select the best concept, make sketch models (foam core and/or wood) of your top concepts to get a feel for the performance, errors, etc.

Week 6

Reading: FUNdaMENTALS Topic E, (grad students also PMD Chapter 9)

Brainware:
   1. Based on last week’s hardware tests, evolve the chosen design.
      a. Complete the error budget for your design, including geometric and stiffness elements.
      b. Evolve the solid model accordingly and create detailed part drawings for the components.
      c. At this stage all chamfers, bolts, threads (use the Hole Wizard in SW for example) MUST be in the model.
         i. Create the Bill Of Materials (BOM)

2. Seek & Geek #6.

   Hardware:
   1. Begin manufacture of the parts for your LM module.
      a. Assemble and test along the way if you can...

Week 7

Reading: PMD Chapter 9, 10

Brainware:
   1. Evolve your design as needed as you manufacture and fit parts. Be careful to keep track of “Rev numbers” on drawings.
      a. Update design spreadsheets you have created or used.
      b. Make sure to record in your notebook observations about the design and its manufacture.

3. Seek & Geek #7.
4. Error model for axes implemented

Hardware:
   1. Assemble and test your LM Module.
      a. If there are problems, you can fix over spring break!
   2. Graduate (and advanced UGs) students make a second LM module so with the Rotary Motion Module you can have a T-base lathe! (whats a T-base lathe? Welllll in this class you will find out! Its why we have modern semiconductors, optics ....)

Week 8  SPRING BREAK  (or catch up time!)

   Brainware:
   1. RELAX – go for a run, exercise is good for the psyche 😊
   2. THINK and REFLECT on the first 7 weeks of class
a. Make changes to your modules and website you think are needed

**Hardware:**
1. Take care of yourself!

**Week 9**

**Brainware:**
5. Deterministic design of a *Rotary Motion (RM) module*:
   6. Create a FRDPAAARC for your design.
   7. Generate several concepts for your RM module.
   8. Write your own design spreadsheet to design (use appropriate analysis) the RM module concepts, and predict their performance (accuracy, repeatability, stiffness).
      i. Select what you think is the best concept.
   9. Start the solid model for your RM module, to help your visualize the elements as you begin to build the error budget for the system.

2. Seek & Geek #8.
3. Full Error Model Implemented

**Hardware:**
1. To help you select the best concept, make sketch models (foam core and/or wood) of your top concepts to get a feel for the performance, errors, etc.

**Week 10**

**Brainware:**
1. Based on last week’s hardware tests, evolve the chosen design.
   a. Complete the error budget for your design, including geometric and stiffness elements.
   b. Evolve the solid model accordingly and create detailed part drawings for the components.
   c. At this stage all chamfers, bolts, threads (use the Hole Wizard in SW for example) MUST be in the model.
      i. Create the Bill Of Materials (BOM)

2. Seek & Geek #9.

**Hardware:**
1. Begin manufacture of the parts for your RM module.
   a. Assemble and test along the way if you can...

**Week 11**

**Brainware:**
1. Evolve your design as needed as you manufacture and fit parts. Be careful to keep track of “Rev numbers” on drawings.
   a. Update design spreadsheets you have created or used.
   b. Make sure to record in your notebook observations about the design and its manufacture.

3. Seek & Geek #10.

**Hardware:**
1. Assemble and test your RM Module.

**Week 12**

**Brainware:**
1. Updates to models as needed based on build and test activities
2. Continue to document the design of modules.
3. Seek & Geek #11.

Hardware:
1. Complete any unfinished modules and tests.
2. Graduate (and advanced UGs) students complete second LM module and integrate with other modules to create a small bench top T-base lathe.

Week 13
Brainware:
1. Complete documentation and website for final review
2. Review all materials and prepare for final exam.
3. Final Report on T-Base Lathe (grad students) post to drop box and personal website.

Hardware:
3. Complete and tests and modifications as needed.
4. Those who have chosen to design, build, and test a lathe, assemble and test!

Week 14
Brainware:
1. Website should be done and ready for final review!
2. Review all materials and prepare for final exam.

Hardware:
5. Take care if yourself ☺️ and be healthy and happy for final exams!

Week 15
Brainware:
1. Final Exam!

Hardware:
1. Celebrate!