Boston University, College of Engineering

Course title: **Engineering Device Applications: From Physics to Design**
Course # : **me506**
Related info: This course is listed in mechanical engineering, although it may well appeal to students from other engineering and science backgrounds, since a wide range of devices will be covered. Some of these devices will certainly be "mechanical", but many others will also be based on optics, electromagnetism, circuitry, chemistry, and even quantum mechanics, plus some biological based "devices." The present class in the Spring of 2022 is scheduled to meet on Tu & Th, 3:30pm-5:15pm, in EPC Bldg, Room 209, 750 Commonwealth Ave.

If you are a distance learning (DL) student, please access the class live via Zoom with coordinates (link will be posted on blackboard also):

Meeting ID 957 3260 6671 Passcode: 015332
or https://bostonu.zoom.us/j/95732606671?pwd=ZkNUOUxGS2U1Tzg0eFNUQmlMdnhmUT09

All classes will be recorded and with permission from me, can be accessed if the student in class or DL student is out sick, etc., or if the DL student is granted permission to take the course this way.

Professor: Dan Cole
Contact: **email:** dccole@bu.edu (best way to contact). **Phone:** (617) 353-0432 (my cell if you really need to call me)
Office: Mechanical Engineering Department, 15 Saint Mary's Street, Rm. 133
Directions to office: Go in at 15 Saint Mary's, bear right, go down the long narrow corridor, with the glass walls on the left, through the double doors, and my office is on the left, Rm. 133. My office is very close to the ECL computer lab.

Office hours: 1:00-2:15pm on Monday and Friday. This will be done by Zoom. If you cannot make those hours, please feel free to contact me by email to arrange another time. (The link below will be posted on blackboard also.)
Meeting ID 820 5p30 4635
https://bostonu.zoom.us/j/8205304635

Catalogue description: Senior or graduate standing in the engineering, physics, or the chemistry disciplines, or consent of instructor. Topics include many sensors and actuators, including accelerometers and piezoelectric devices, as well as many other electromechanical devices, plus lasers, quantum dots, atomic force microscope, ellipsometry, plasma etching, advanced semiconductor based devices, scanning electron microscopes, and open to other student suggested directions. Such devices are used considerably in engineering, science, and technology, as well as in commercial high "tech" products, and for instrumentation and measuring purposes. Many devices will be taken apart and analyzed in terms of the operation, physics, design, device optimization, plus considerations of possible deviations from the original design. The intent here is that a confident mastery of these devices will improve the use and application of these devices for engineers, as well as provide a guide where jobs might be obtained in the use and possible enhancements of these devices. About 20 physical demonstrations will be given during the course.

Discussion of the course content: The course will examine a number of engineering/physics based devices that most of us know the names of, but likely only have an inkling as to how they really work. The intent is to fix that last aspect, so everyone ends up a very clear understanding of these devices, and perhaps could even design such a device, or even improve on present designs and features. Here are some devices likely to be covered: accelerometer, piezoelectric based devices, lasers, laser tweezers, ellipsometers, atomic force microscope, scanning electron microscope, a certain "motor" in the human body, and of course various types of sensors, etc. By knowing how these devices work, it should certainly make everyone more competent at making use of them in designs and experiments. In addition, this knowledge may prove to be extremely helpful for jobs in industry, whether you are working to improve a device in a unique way, or, to make the best use of the device in an application.

My intent is to cover about one device per class, although sometimes having this run over into a second class, depending on the topic. Some classes will be spent entirely on the general theory that might pertain to a set of devices, such as for key aspects of quantum mechanics. About 20 physical demonstrations of devices are planned for the course, so folks can clearly see how the devices works. Basic facts will be gone over, as well as the theory of operation.

Each student in the class will become a member of a group or three to four students, depending on the size of the overall class. This group will make (1) an in-class presentation of 10 to 12 minutes in length during the semester to the class, plus (2) submit a final project presentation. Both presentations can go into more detail on devices already discussed in class, or they can be of a totally new device topic. There are plenty of choices to select from! Examples of topics will be given. Groups may want to confer with myself, but really, there are no great restrictions, provided that you do not end up covering material that I will be covering, and that the material you cover includes (1) some theory, (2) some application, and (3) some discussion on the economics associated with the device such as amount sold, revenue, jobs involved in the world, etc. If there is too much to cover in 10-12 mins, then make your topic narrower in scope, such as, don't talk about, for example, all forms of four wheel drive, or all forms of braking mechanisms for automobiles, but limit yourself to only one type, etc. Make your talk interesting! Demos are always welcome. Don't make it a talk of just "fluff", where you just talk generally and really don't touch on how these things work. Remember, we are engineers and scientists, and although economics is important, the makings and design of these devices is what really fuels the growth and changes of our technological industries.

A class project, carried out by the same groups that presented the above during the semester, will be presented at the end of the semester. The criteria will be to present a demonstration of a device of interest to the group, describe the underlying theory, **have the demo be one that you design**, and tell a bit on the economics of the device. What is the difference between the two presentations, namely, the first during the semester and the one at the end? I expect the first one to be simply a review of information you find out, while the final project is much more of your own originality and creativity. Consequently, the final project is worth much more in terms of the course grade, namely, 30%, whereas the in-class presentation is worth 10%.

I suggest you view the in-class presentation as a "warm-up" to what you will eventually do. A really nice scenario, but no pressure on absolutely making this happen, would be to have the in-class presentation be a broad overview of a technology, like capacitance touch screens and how they generally work, while the final project be on one specific capacitance touch screen technology that you find particularly exciting and where you have made specific measurements on size and speed of electrical signals, cross-talk between two and three finger controls, and whatever other ideas you can come up with. For example, in the Spring of 2021, one group came up with a novel electrostatic means of generating large signals that they measured – very impressive! Indeed, I thought some of their ideas were patentable in their own right! Yes, they got a high "A" on that final project!

I should mention that the in-class presentation need not even be on the same general topic as the final project. You can switch areas, which does happen a fair bit, as students find that their initial choice for the in-class presentation does not always lend itself to a good final project idea. That is fine and understandable, as you need to commit to present early on, and it is difficult at the start of the course to know what the final project will be, until you have more of all of this material covered.

I will provide examples.

Several written home-works (HWs) will be assigned during the course, usually either asking questions to be answered on the device demonstrations already given, and/or to provide math details on derivations to make sure students have sufficient math analysis practice. Note that I emphasis details in the derivations as much as I emphasize the demonstrations! However, provided you enter class with the prerequisite of a normal undergraduate through senior's knowledge of calculus and differential equations, you should be fine, as I feel that I cover the additional needed math step by step.

The **grading** will be:

(1) Midterm (25%)
(2) Final (25%) **(material from midterm on)**
(3) Final project (30%) (in groups of three or four)
(4) In-class presentation during semester (10%)
(5) Homework (10%)

For each of these you will receive a numerical grade. The final grade will be computed using the weights above. This grade will then be converted into a "letter" course grade in the following way: 80=>83.33 would be a B-, 83.34=>86.66 would be a B, and 86.67=>89.99 would be a B+, and likewise for the other ranges of 70=>79.99, 90=>99.99, etc.

Please note that there is no book to purchase for this course. All material will be from lecture notes and reading / viewing assignments that can be found on the web.

The midterm will be on class #14 (total of 27 classes), which falls on Thursday, 3/17/2022.

You will find that there will be a great deal of fun, interesting, and useful information that we will go over in this class. Again, I believe the information can be useful for obtaining jobs, for use in technical jobs, and for use in development and in research. Much of this is what I wish I had been presented in one course as a graduate student, but such a course did not exist at the time. You will learn a unique combination of theory and practical application of knowledge. I look forward to working with you!

Class #	Rough order of topics	More detailed information
1	**Intro to course, followed by our first device: accelerometers**	An overview will be given of the material to be covered in the course. We'll go over the syllabus, including grading in the course, HW, presentations, and projects. We'll then start in on our first device, namely, accelerometers, covering first simple notions, and eventually leading up to MEMs accelerometers. Demonstrations will be given, the physics will be discussed, and finally many applications will be discussed, including what is in smart phones. Only part of this will be covered today; the next class will complete this material.
2	**Complete accelerometers. If time permits, begin piezoelectric devices.**	The topics mentioned in class #1 will be completed here for accelerometers. If time permits, then the next device topic will begin: piezoelectric devices.
3	**Piezoelectric devices**	First a rough understanding of these subtle devices will be provided, followed by several physical demonstrations that should be of fair interest. A rough overview of the history of this phenomena will be provided, going back to the Curie brothers. This will be followed by going into the physics of these materials. Finally, we will go over a number of fascinating applications, including in microlithography and the atomic force microscope.
4	**Sensors and actuators**	Other types of "sensors" and "actuators" beyond accelerometers and piezoelectric based. Many that will be discussed involve MEMs devices, such as gyroscopes, microphones, light detectors, pressure detectors, odor/molecule detector, etc. A key demo will be all the sensors in modern smart phones.
5	**Lasers I**	This topic has a fascinating history. A key idea (stimulated emission) was from Einstein in 1918, although most people do not believe he had further ideas on "lasing". Much, much later, in the 1950s the maser was invented by Charles Townes using the stimulated emission notion; this resulted in a Nobel Prize in 1964, although many more Nobel Prizes involving lasers have followed since. What needs to be optimized here to make better devices, and how does one create a lasing action for very different materials, such as gas, liquids, and solids? The basic theory will be covered involving the A&B coefficient ideas from Einstein. Later, when we get into quantum mechanics (QM) to some extent, we will return with more notions about this.
6	**Lasers II**	Many demonstrations will be given. A huge number of applications exist, from simple laser pointers and simple grocery scanning systems, to sophisticated medical applications, excimer lasers in microlithography, atomic force microscope and other very sophisticated instrumentation devices.
7	**Electromagnetic based devices I**	Many devices have electromagnetics (E&M) at their basis, such as the wide variety of electric motors, generators, transformers, electromechanical solenoids, relays, loudspeakers, hard disks, and scientific instruments. However, the full suite of such applications go well beyond this "common" notion of E&M devices, as MRI and other imaging devices such as x-rays, all of optics, radio devices (included on all smart phones), radar, many forms of sensors, and even semiconductor devices, in combination with quantum mechanics, all have E&M at their basis. The macroscopic Maxwell's equations will be covered, and some of the more important consequences.
8	**Electromagnetic based devices II**	The material discussed above in class 6 will be continued here. The material will include a number of demonstrations plus theory; the combination of the two should help to support each other well.

9	**Electromagnetic based devices III**	The demonstrations and theory for the basis of a wide variety of electromagnetic based devices will be continued here. Some devices will be of an electromagnetic mechanical form, others will involve more of a radiation form, and some will be material oriented.
10	**Ellipsometry**	Although this topic could certainly continue to fall under E&M (and does), we will treat it separately here. Ellipsometry is an optical technique for measuring dielectric properties and film thickness by examining the change of polarization of light upon reflection or transmission. Many properties such as surface roughness, crystalline nature, doping, and electrical conductivity can be investigated. Most film analytical labs have one of these devices. Many new uses have been found in recent years, including in medicine, biology, and liquid surface characterization. The basic theory will be covered, and a demo will be given from one of the BU labs.
11	**Scanning electron microscope (SEM)**	An SEM produces images of very small samples by scanning the sample with a focused beam of electrons and, most commonly, examining/collecting secondary emitted electrons. Information can be obtained about the surface structure and the sample composition. Resolutions less than 1 nm can generally be obtained. This device is also actually E&M based, with some subtle quantum mechanical (QM) effects. The SEM is a "workhorse" instrument/device in the nano/micro electronics semiconductor area, but is also used widely in biology and other areas. The basic theory of operation, and its subtleties, will be given. Also, a demo involving a BU SEM lab facility will be arranged.
12	**Review of previous topics for the midterm**	
13	**MIDTERM**	
14	**Pass back midterm, go over answers.**	In addition to going over the midterm answers, physical points of interest not covered to date, but related to the problems given, will be gone over. In each of the devices discussed, what are the key features to be considered when "optimizing" the device?
15	**CT and MRI scans**	CT scans use X-rays to produce images inside the body. MRI (magnetic resonance imaging) uses radio frequency pulses and very strong magnetic fields.
16	**Quantum Mechanics I**	Three lectures will be given on QM, covering the history a bit, the phenomena, the math and physics involved in Schrödinger's wave equation, applications from this analysis, always aiming to describe many of our modern devices, such as the quantum dot, semiconductor devices like transistors, lasers, the atomic clock, efforts on quantum sensing devices, and recent ideas on quantum computing.
17	**Quantum Mechanics II**	The previous lecture material will continue here.
18	**Quantum Mechanics III**	The previous lecture material will continue here. Some demonstrations will be given.
19	**Quantum dots and applications**	Quantum dots (QDs) are made from semiconductor materials and typically are a few nanometers in size. QM effects that will be gone over here, change their properties from bulk size matter of the same material, changing the optical and electronic properties considerably. How this happens, based on previous lectures, and how these QDs will be used in a wide variety of applications, will be discussed here. A demonstration will be given.

20	**Atomic force microscope and tour of lab/device**	Atomic force microscopy (AFM) was discovered in the 1980s. It has the ability to both image atoms and molecules, as well as to place the atom or molecule in very specific locations. The resolution of this device is incredible, on the order of fractions of a nm. We will emphasize the AFM, but this instrument is actually a subset of the more general scanning probe microscopy (SPM) devices. Different SPM versions will be discussed here. A tour and demo will be taken of a BU AFM lab.
21	**An overview of novel semiconductor devices including QM effects**	An overview of various semiconductor devices will be given, from "older" ones to FinFets, plus a discussion on carbon nanotubes and the likely direction of graphene.
22	**The solar cell w/QM, and recent improvements**	The solar cell has been around for a long time. Improvements in lowering crystal defects, in solar cell layout, layers of material, will be discussed. A demo will be given.
23	**Optical tweezer plus molecular motors**	The topic of optical tweezers produced a Nobel Prize in physics 2018. Lasers were effectively used to manipulate objects both in time and space. I.e., small particles (including atoms and molecules) and cells can be maneuvered with light. The physical means by which this can be done will be covered. In this way, "molecular motors" and even properties of DNA molecules, can be studied and analyzed. A molecular motor demonstration will be given.
24	**Topic of student choice, voted on by class earlier in semester**	The class will pick a topic of interest, after the midterm, which will be covered here today. The device topic should of course not be one that is already listed.
25	**Automobile - multi-wheel drive technology**	Finally, much bigger stuff!! However, the devices are still subtle and fascinating.
26	**Class project presentations and demonstrations**	In groups of roughly 3, but also depending on the class size, groups will present their own device topic. A short relevant demonstration is required, as well as the basic theory (although not to the extent normally covered in class), plus a discussion of applications.
27	**Class project presentations and demonstrations**	The remaining groups will present here.