Incorporating Active Learning in an Engineering Materials Science Course

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Abstract

This paper shares the experiences the author has had over the last several years incorporating active learning in the classroom and laboratory. Examined are ways to engage and motivate the students to take an active role in their learning which includes direct instruction, cooperative learning, hands-on "exploratory" classroom and laboratory experiences, reading logs, etc. The author submits that in most classes, some degree of direct instruction is necessary to "actively" engage the student's minds, particularly in introducing new material, but also insists that student-based class activities are essential to reinforce and "connect" this knowledge. Materials science naturally lends itself to a variety of interesting and exciting activities that allow the student to interactively learn about the world of engineering materials. Some of these activities are discussed in their application to atomic structure, diffusion, strengthening mechanisms, failure mechanisms, and ferrous and nonferrous materials.

I. Introduction

In a typical college-level engineering materials science class, which is part of an accredited mechanical engineering program, there is a lot of material covered. Much of this material may be very different from what students have experienced in their other engineering courses. In many institutions, only one materials science course is required[1]. Yet, the principles introduced in this course are critical to understanding the properties (and modification of), and behavior of all of the classes of materials used today in the design, testing and fabrication of engineering components, structures, and vehicles. Since a solid understanding of materials is vital in the design of a successful and safe product, the challenge is to insure that each engineering student has truly learned the concepts presented and can apply them to the processing and selection of the right engineering material.

Certainly every instructor wants a high level of learning from all of his or her students. Through trial and error, I have found that this course lends itself nicely to the incorporation of many active learning exercises that appear to enhance longer-term learning. The goal of these activities is to get the students to actively do the thinking and learning. This paper addresses several activities that are organized under each of the five main subject area blocks of the course, as described below.

II. Course Content

At the United States Military Academy, we currently use William D. Callister's textbook entitled "Materials Science and Engineering, an Introduction", 5th edition. The sections of the book used correlate to the major subject area blocks and topics shown in Figure 1:

General Blocks

I. Atomic Structure, Mechanical and Physical Properties, Defects, Diffusion
II. Strengthening Mechanisms/Nonferrous Phase Diagrams
III. Iron-Carbon Systems/Ferrous Metal Phase Diagrams, Ferrous & Nonferrous Alloys
IV. Failure Mechanisms
V. Non-metals, Electrical Properties

Specific Topics

1. Atomic Structure, Imperfections, Deformation Mechanics
2. X-ray Diffraction
3. Mechanical & Physical Properties
4. Reliability Based Design
5. Slip & Slip Systems
6. Diffusion
7. Cold Work & Annealing
8. Grain Size Strengthening
9. Solid Solution Strengthening, Isomorphous Phase Diagrams
10. Dispersion Strengthening, Eutectic and Eutectoid Phase Diagrams
11. Precipitation Hardening
12. Hardenability
13. Iron-Carbon System
14. Ferrous Heat Treatments
15. Nonferrous Alloys
16. Failure Mechanisms-Ductile/Brittle, Fracture Mechanics, Fatigue, Creep
17. Corrosion
18. Ceramics, Polymers, Composites
19. Ballistic Protection, Armor Design
20. Electrical Properties, Semiconductors, Superconductors

Figure 1. Course Subject Areas

The specific topics shown generally follow sequentially in the five "General Blocks" above. The class is a 3.5 hour semester course with labs. There are 40 class meetings of which 6 are double-period lab exercises that support the five major blocks. Each non-lab class is 55 minutes and classes with labs are 110 minutes. Three 55-minute classes are used for major exams. The course has a comprehensive final and a semester-long materials design project.

III. Class Structure and Interactive Teaching Philosophy

As seen above, there are numerous topics that are covered in 40 meetings. Due to the nature of the course, there is not much time to go into excessive depth in any one area. A major objective is to apply sufficient engineering principles and equations to each area so that students have enough background to explore, and build upon a particular area in the future. Careful planning goes into each lesson to optimize instructional activities.

The key to a successful semester is to *get the class as integrally involved as possible in every lesson*. Even during those times when direct instruction is more appropriate (new/difficult material, time constraints, etc.), a “modified” approach can be used where the students are called upon so they are “directing” the class discussion and taking more ownership in understanding new material. I try to use their thoughts and words when explaining a new concept. Questions can be asked in such a way as to build on previous knowledge to get to the right answer. Of course, this approach does not work as well if the students are not prepared. This approach also takes additional time, but it is worth it since it causes the students to actively think. This translates into constant calling on students, and drawing discussion from them as the class proceeds. The instructor should guide the class in learning key objectives and to point out those areas that the students must learn on their own if constrained by time. The burden is primarily on the student to come prepared to class and to be responsible for his learning in and outside of the classroom. Class size permitting, *all* students should be active in class, being expected to be called upon at least once, if not several times, during the course of a lesson.

In order that the above “interactive class” be effective, the students must understand this learning approach. It is essential to tell them on the first day of class what is expected from them for every class:

1. Come prepared—do the reading and at least attempt the assigned problems.
2. Expect to be quizzed and called upon—be familiar with daily lesson objectives.
3. Be responsible for key material not covered in class.

This approach is not novel, but it has been my experience that this approach works as long as the instructor maintains this set of expectations from the students. It is important to convey ownership of the material by the students—this is the challenge. If allowed, the tendency by many students is to let the instructor do all the work while they dutifully take the notes off the board. The students should be expected to do the learning from the assigned reading the night before, with discussion and clarification occurring the following day in class.

Another important piece of this interactive teaching approach is instructor enthusiasm. Without it, it is difficult to maintain daily student interest and interaction. An attempt should be made in each lesson to connect to students’ personal and professional experiences and interests. The instructor needs to do his part in making the subject matter as exciting and applicable to their daily lives as possible. A student who looks forward to class will most likely be better prepared.

The classroom is configured so that students sit in groups of three or four throughout the semester. This arrangement accommodates the daily group work that the students engage in. We have the luxury of having chalkboards on all walls of the classroom. Figure 2 outlines the structure of each class that is generally followed for each non-lab class. Actual time allotted does vary; quizzes may not occur each lesson though the students are expected to plan for one. The interactive learning and problem solving activities are broken out individually; though, in many classes are intertwined. Overwhelming student response indicates the importance of problem solving during the in-class lesson.

1. Quiz covering past and current lesson, or short review (5 min)
2. Student-led material application "gee-whiz" presentation (5 min)
3. Interactive learning of new material/group activities (25 min)
4. Interactive problem solving: class, subgroups or individual (15 min)
5. Closure, brief overview of assigned homework/reading logs (5 min)

Figure 2. Daily 55-minute class structure

Laboratory Exercises. During laboratory sessions, the class is less structured. The class briefly meets to overview the lab and associated concepts, and then proceeds to the laboratory. The labs are a critical part of the course as they provide active critical hands-on experience that reinforces each block of material. The labs are performed in groups of three or four—or smaller if lab equipment and materials allow. Student response has been overwhelmingly positive on the importance of the labs. I will discuss them later in their relation to the course sequence. The titles of the labs follow in Figure 3.

Lab #1: Mechanical and Physical Properties (Block I)

Lab #2: Eutectic Metallurgy (Block II)

Lab #3: Strengthening Mechanisms (Block II/III)

Lab #4: Welding (Block III)

Lab #5: Charpy Fracture Toughness (Block IV)

Lab #6: Composite Strength and Design (Block V)

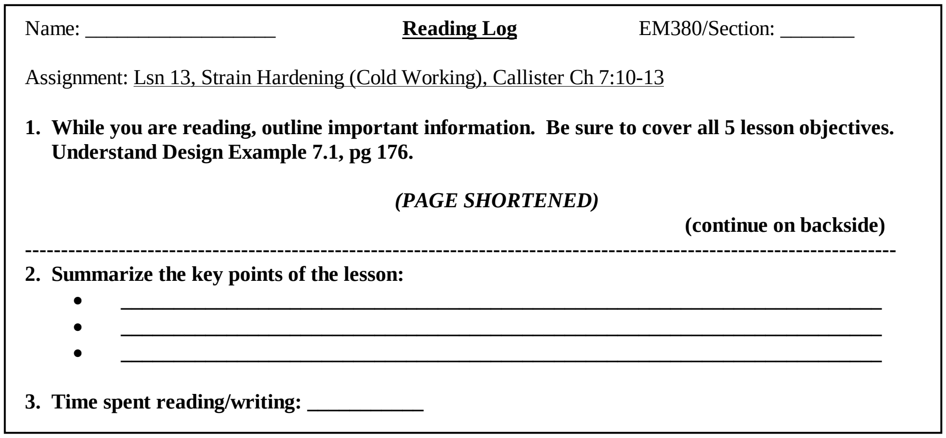
Figure 3. Laboratory Exercises

Materials Design Project (MDP). The materials design project is also an important part of the course where students are involved in a semester-long cooperative learning experience (2 or 3-person groups). The project report is due on the last day of class when each student group gives a 12-minute presentation to the class. The MDP is emphasized throughout the course with periodic progress reviews. Past projects have included golf club shafts, model aircraft wings/fuselages/landing gear, racing bike frames, carabineers for mountain climbing, electromagnetic rail guns, shotgun shells, snowboards, and materials for prosthetics and joint replacements.

Quizzes. Reiterating the philosophy described above to the students, they are told on the first day what is expected from them. Their course guides contain all the objectives for each day's lesson (3-5) that they are expected to be familiar with prior to walking into the classroom. These quizzes generally cover the objectives and are worth approximately 5% of their total grade. The format is multiple-choice, fill-in-the-blank or a definition. The quiz might also be on an assigned homework problem that is also in their course guide. There will always be those students who are unprepared but most try to make an effort. Though the students do not "like" the quizzes, many end-of-course critiques indicate an appreciation for them.

"Gee Whiz" Presentations (5 min). In most classes, following the quiz or review, one student gives an informal oral presentation covering some materials engineering application they have found in a magazine, newspaper, Internet, etc. Some of them bring in hands-on examples, which can be related to the particular block of material we are covering in class, though not required. They are limited to 3 minutes and asked to discuss their example from an engineering materials perspective. Over the years this has been found to be very effective in heightening the awareness of material applications around them and increasing the interest of not only the presenter, but also of the classmates. A couple of minutes are always allowed for class questions and comments. The student's gee whiz is connected to the course material as appropriate. Examples taken from classes this year include C-60 carbon nanotubes, "smart" materials, hip and knee joints, Nextel alumina/aluminum fibers, cryogenic tempering technology, space suit material, capital dome material, zinc-air batteries, solidification in space, conductive epoxy, plastic electronics, polymer dampening materials for railroad crossings, Higgs boson subatomic particles, and copper ribbon deicing technology.

Assigned Homework and Reading Logs. For each lesson there is assigned homework in their course guide which supports the lesson. Generally 3-5 problems are assigned of which one or more may be collected. Reading logs are especially suited for this type of course, particularly in those lessons where concepts versus problem solving are emphasized. These logs are kept simple and collected several times during the semester. An example of a reading log used this past semester follows in Figure 4.



Name: __________________ **Reading Log** EM380/Section: _______

Assignment: Lsn 13, Strain Hardening (Cold Working), Callister Ch 7:10-13

1. **While you are reading, outline important information. Be sure to cover all 5 lesson objectives. Understand Design Example 7.1, pg 176.**

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2. **Summarize the key points of the lesson:**
   - ____
   - ____
   - ____

3. **Time spent reading/writing: ___________**

Figure 4. Lesson 13 Reading Log

IV. Applying Active Learning in the Classroom

Below are illustrations of specific active learning activities that are employed under the five major subject area blocks (and their associated topics) that are listed in Figure 1. As laid out in Figure 2, each class begins with a short quiz or review, a student-led material “gee whiz” presentation, an interactive interchange covering new material, and concludes with students doing problems—at the chalkboards or at their desks. The following descriptions emphasize the “interactive interchange” part of the class. The laboratory exercises for each block are also discussed.

Block I: Atomic Structure, Mechanical and Physical Properties, Defects, Diffusion.

The course begins by learning the importance of atomic makeup of materials and its direct impact on properties. Examples from the five classes of materials (metals, ceramics, polymers, composites, and semiconductors) are kept in the class to elicit discussion throughout the block. A large periodic table is also a permanent fixture. The properties of steel are introduced and used as the material baseline for the entire course-giving the students something “common and tangible” they can compare all materials against. Steel, (plain, medium carbon), finds a special location on the board (all semester) with its major engineering properties noted—unit cell(s), density, melting point, strength range, modulus of elasticity, fracture toughness, and electrical conductivity. The students are required to commit these properties to memory early on.

By lesson two, common engineering failures are re-introduced. Most of the students are aware of the Space Shuttle Challenger accident, the Tacoma Narrows bridge failure, and other major failures, but these are now examined from a materials atomic structure/properties viewpoint. Students are called upon to present to the class results of a small individual engineering failure research effort (2-3 pages) on a famous disaster. This presentation counts as the student’s “gee whiz” for the day, with the class providing other details. Instructor-presented gee whiz examples are also related to that day’s lesson. The examples in their reports are used to elicit class discussion concerning atomic structure throughout the block, again, making atomic structure a more “relevant” and interesting topic.

After working a suitable problem in front of the class using student input, student groups are often sent to the boards to work problems (in some classes they remain at their desks). Time permitting, different groups are called upon to explain the problem to the rest of the class (alternating student speakers). Atomic structure problems in this block include theoretical density and packing factors, Miller indices, x-ray diffraction and diffusion.

On lesson 4, atomic structure is interrupted with the performance of Lab 1; “Mechanical and Physical Properties”[2]. During the preceding lesson, in preparation for the lab, “unknown” samples of three different metals, one ceramic, and two polymers are available for the students to see and feel (a composite sample is in the works). The students, working in groups of 3 or 4, are tasked to be “detectives” in discovering the particular material types (carbon steel, brass, aluminum, silica, polycarbonate, PMMA). By this point, having been exposed to basic material properties from a theoretical standpoint, they are now required to investigate actual physical and mechanical properties. They pinpoint exact material types based on comparing empirical values found in their lab data/calculations to published values from the appendices of their textbook. The students enjoy the challenge--lab results are discussed following the lab turn-in. The instructor is available to the students prior to the turn-in to review data and to give additional "clues" as needed.

During this first block of material, as well as in blocks III and IV, each student group is met with to discuss the progress of their materials design project. The students also submit a short progress report.

Block II: Strengthening Mechanisms/Non Ferrous Phase Diagrams

This block can present a challenge to the students since, for many, this is their first exposure to binary phase diagram analysis. The lever rule graphical approach seems to facilitate learning, though, a knowledge of the basic microstructural phases is required. Student motivation is enhanced if the instructor can make phase diagrams - as one of my students put it - "meaningful to her life".

Prior to discussing dispersion strengthening and associated phase diagrams, the students are introduced to the other strengthening mechanisms. Several easy, in-class and hands-on demonstrations can be accomplished by the students to aid in their understanding of the effects of grain size, cold-working, alloying (solid solution strengthening) and age-hardening on strength and ductility. All that is required are aluminum nails, pennies, coat hangers and access to a furnace[3]. Selective heat-treating of the various items results in significant changes in their properties. The students are usually very surprised as they physically bend, or try to bend, these objects. These demonstrations can be spread over several lessons as the particular strengthening mechanism is being introduced.

Anything that can be brought into the classroom that supports the lesson, and that the students can get their hands on, is always helpful and gets the students talking. Other items that support cold-working and leads to thinking about the textbook design problems are aluminum soda cans (cold-drawn), aluminum sheet/plates, and foil. An over-rolled, splintered piece of brass is always a hit.

When discussing the phase diagrams, I often ask students to volunteer to teach the rest of the class on how to accomplish a particular lever rule problem. The students are forewarned of the general problems they will present either at the start of the daily board work part of the class or during the class prior. Anything one can do to get the students to understand phase diagrams early will pay off later as they learn ferrous phase diagrams and microstructures.

In Lab #2; "Eutectic Metallurgy"[4], the students are again asked to be detectives to determine what alloy of lead and tin (solder) or copper and silver (braze) they are given by using a visual phase counting method. The samples given are either a eutectic, hypoeutectic, or hypereutectic polished sample and students view them under a metallurgical microscope. This exercise gives the students another “real-life” feel for the purpose behind the use of phase diagrams (and more practice using the lever rule).

Block III: Iron-Carbon Systems/Ferrous Metal Phase Diagrams, Ferrous and Nonferrous Alloys

By now the students should have a basic understanding of strengthening mechanisms, the mechanics behind binary isomorphous and eutectic phase diagrams, and now are introduced to ferrous metals and phase transformations. A piano wire hooked up to a transformer is a great in-class demo that can be used to visually tie in the Fe-C phase diagram to pearlitic and non-equilibrium cooled steel microstructures. This demo, with underlying metallurgical principles, is explained at length in a 1984 edition of Scientific American Magazine[5]. Many class discussion questions can be initiated with this demo that basically resembles a long “toaster wire” which can be made to glow bright orange. After an appropriate safety brief, the students run the demo, heating the wire and subsequently quenching a portion of it. The quenched wire turns into martensite and the students are surprised that they can now scratch a piece of glass with it (glass plates provided). This exercise gives more meaning to the various steel microstructures that can be created through simple heat-treatments.

Lab #3; “Strengthening Mechanisms”[2] does a good job of allowing hands-on experience to encompass and summarize all four of the strengthening mechanisms learned. Utilizing a Rockwell hardness testing machine, furnace, and tensile test machine, students test variously heat-treated specimens of brass, copper, steel and aluminum alloys to include the heating (austenitizing) and quenching of medium carbon steel. Through hardness testing and tensile tests, students receive immediate feedback on how they can physically strengthen or weaken a metal.

Lab #4; “Welding”[2] is accomplished directly following the conclusion of ferrous alloys and general metal processing. The students have already learned how ferrous and non-ferrous metals can be adversely affected by welding and now have a chance to physically test good and poorly welded medium-carbon steel strips. We allow them to help us make the welds we are going to test. Every student is given a chance at arc welding. After the welding is completed, the students test their welds on the tensile test machine. Also tested are pre-prepared quenched and over-welded samples. Prior to breaking the welded strips, the heat-affected zones are visually inspected with a brief discussion with the students of how they think the welds will perform.

The last class of this block is spent on non-ferrous engineering metal alloys—Al, Mg, Cu, Ti, Ni-Co, Be, refractories, and noble metals. After a quick review of steel properties, these metals are divided among the class groups. Each group is to become the “expert for the day” on their particular metals. The class is given 10 minutes to prepare and write on the chalkboard a general description of their metal(s) with 5 advantages and disadvantages. The remainder of the class is spent with student group leaders briefing the rest of the class. The instructor interjects as necessary to clarify or emphasis important points. This technique is effective when used occasionally and in those areas of the course where the material is fairly straightforward.

Block IV: Failure Mechanisms

This part of the course is particularly interesting to the students. Keeping with the general "real-life" approach to this course, this block is connected with current or recent material failures in the news such as the Firestone tire problem and the alleged metal jackscrew failures on the tail sections of the Aloha Airlines MD-80 aircraft. The cracking of a Boeing 737 rudder hydraulic valve is also discussed. Students are asked to bring in news articles documenting material failures—bridges seem to be popular this semester. We try to connect these examples to the class failure mechanism being discussed that day. We cover ductile and brittle failures, basic fracture mechanics, fatigue, creep, and corrosion.

Broken samples are kept from the first lab, as well as from the other labs, and students describe the particular failure and fracture surface. Also accumulated over the years are a series of broken items such as piston head fatigue failures, shaft failures, metal structural plate failures, etc. It is important that the students get their hands on the various fracture surfaces to, again, substantiate what they are seeing in their books (fatigue beachmarks, fast fracture markings, etc.).

Lab #5, "Charpy Fracture Toughness"[2,4], is a student favorite that is performed in this block showing first-hand how the environment can affect the toughness of a metal. Charpy samples are broken at 300 deg F, room temperature, 32 deg F (ice water) and at –321 deg F (LN_2). Once again, the students put on their detective hats and decide which metal alloy, of four given, is closest to that used in the hull of the Titanic ocean liner when it sank in 31 degree (F) water. Studies show the Titanic's pearlitic steel had approximately 0.21% carbon in its hull plates along with contaminants that embrittled it, causing it to most likely exceed its ductile to brittle transition temperature[6]. The student lab groups are each given several plain carbon and alloy steel samples, as well as an aluminum alloy sample. In the process of trying to discover the "culprit" metal, the students learn about ductile to brittle transition temperature, differences in toughness between materials, and susceptibility of ferrous and non-ferrous metals to brittle failure under changing environments.

During the corrosion lesson(s), the student groups are again tasked with being "experts of the day" with a spokesperson from each group teaching the rest of the class about one or more of the main forms of corrosion. Certain points are clarified with additional hands-on examples provided. During the lesson prior to these classes, beakers containing aluminum and steel nails are also brought in that have just been submerged in saltwater and low molar HCl acid to initiate chemical attack. These specimens will begin to corrode and provide another visual example to correlate with corrosion types such as "uniform" and "pitting". The resistance to attack by the aluminum provides a basis to discuss passivation.

As in the other blocks, students work problems on the boards (or at their tables) with added emphasis on fracture and fatigue applications.

Block V: Non-metals, Electrical Properties

By this point in the course, the class should have a solid foundation on how materials are atomically structured and what influences their basic properties. Metals have been the main class of materials used to illustrate and explain the effects of structure, defects, strengthening and failure mechanisms. Many of these same mechanisms can be applied to ceramics and to a certain degree to polymers and composites. In this final block of instruction, students are introduced to ceramics, polymers and composites, in that order, starting with a review of atomic bonding that was learned during the first block. Each new class of material's general properties is also compared against the medium plain carbon steel. Students hold a chunk of steel and a comparable sized non-metal and explain to the class *why* there are differences in density, appearance, conductivity, fracture toughness, etc.

There is a myriad of material samples and applications that the instructor can provide to stimulate class discussion, from polymeric-ceramic macro-composite knee and hip joints, to elastomers used in the Space Shuttle solid rocket booster joints. Silly putty always works well in demonstrating creep and viscoelastic effects (the students slam it with a hammer). The more interesting the example, the more likely class discussion will be enhanced. The students are strongly encouraged to connect their gee whiz presentations in this block to the specific class of material discussed that day.

The final lab of the course, Lab #6; "Composites Design", is an exercise where students pull 6-inch strips of single ply and fabric composites and one medium carbon steel strip, and compare their specific strengths. E-glass, Kevlar and carbon fiber are used in the composite construction at various orientations. Theoretical strengths using the rule of mixtures are compared to actual strengths found in the lab. The results truly impress on the students the phenomenal properties of composites—even beating out the all-purpose steel "class favorite".

Due to the military nature of West Point, a special topics class on ballistics is taught following the lessons on ceramics, polymers, and composites (and lab). This provides an opportunity for the students to summarize material structure and properties. Actual armor materials are brought in which include advanced ceramics, cermets, and body armor composite systems that include Kevlar and Spectra fabrics. After a brief introduction on weapon kinetic energies and strain wave velocity calculations (not found in their text), there is a class competition where student groups "design" an ideal lightweight armor on the chalkboard consisting of metals, ceramics, polymers and composites. Each group presents their armor to the class and a vote for the "best design" is taken at the end of the period.

During the electrical properties lesson, an in-class demo on superconductivity is conducted, which requires an inexpensive pre-packaged superconductor kit and liquid nitrogen (borrowed from the chemistry lab). The students explain what the superconductor material is, why it acts the way it does (Meissner effect, etc.), its limitations, and what applications are possible. This provides a nice interactive conclusion to the electrical properties subject area.

Board work problems in this block include polymerization, ceramic flexural strength, fracture mechanics (ceramics), composite single ply analysis, and thermal/electrical problems. It is also at the conclusion of this block, and the last two lessons of the course, when student groups turn in their material design projects and provide a formal presentation to the class. The presentation grade is based on content, quality of the presentation, and participation by all group members.

V. Summary

There are a variety of activities one can do to make the materials science classroom and lab an "active learning" environment. A few examples have been illustrated from each major instructional block, which have been found to be effective. I find myself continually trying new approaches to get students more involved and to better cover the material. It cannot be stressed enough that instructor *enthusiasm* for the subject goes a long way in motivating the students. "Success" is gauged by the amount of student interest and engagement during class, performance on course exams, and by student feedback. The feedback has been very positive with regards to the class activities and labs. A secondary measure of success has been the strong marks on the Materials Science portion of the Fundamentals of Engineering Exam (mandatory for all civil and mechanical majors at West Point), which seem to indicate a moderate retention level.

Again, to be truly interactive with the students and insure active learning, the necessary climate needs to be set on the first day of class, with expectations made very clear to the students that they will be taking an active role in the classroom. And, the instructor must continually maintain this interactive atmosphere on a daily basis. It is hard work for the instructor but the pay off is increased interest and learning by the students, not to mention a more gratifying experience for the instructor.

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