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Teaching physics on line

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Since 1986 we have offered courses on special relativity and general relativity in a variety of formats over computer networks nationwide to a mix of high school students, high school teachers, college students, and college professors. Using ideas from many sources, we have evolved a highly structured format that keep students working every day and talking extensively with one another over the conference system. Obligatory student "Reading Memos" bring a flood of comments and complaints essential to evaluation of student progress and revision of the text. We consider possible reasons why these courses from the United States have not worked with participants in Europe, and speculate about possible consequences of future technological developments. © *1995 American Association of Physics Teachers.*

I. INTRODUCTION

For the past 9 years, we have taught courses with different formats in special and general relativity. In a text-based remote computer conference setting, students receive assignments, exchange messages with other students and the instructor, participate in discussions, and submit answers to exercises.[1,2] We believe that insights derived from our text-based experience will be useful as Internet technology moves forward to the graphics-rich resources of the World Wide Web.

In order to be of the greatest practical benefit, this paper reverses the usual scholarly sequence and begins with an Executive Summary, followed by the background and setting needed to understand our 13 conclusions.

II. EXECUTIVE SUMMARY

The following 13 conclusions are drawn from our experience with computer conference courses:

1. The computer conference setting can be personal, friendly and inclusive. The medium is largely race-neutral, location-neutral, status-neutral, age-neutral, income-neutral, disability-neutral, and would be gender-neutral except for the clue of the first names. Student participation in the discussion (in part forced by our course format) is greater than in any of our face-to-face classes. Some kinds of personal warmth appear to be more freely exchanged in the absence of bodies.

2. Computer conference classes bring instruction to a range of students for whom enrollment in conventional courses is difficult or impossible. Participation can occur conveniently at any time in a busy daily schedule. Some students blossom when in front of a computer screen and accomplish tasks that they otherwise would avoid. The computer conference format can also bring together a critical mass of participants interested in a subject, such as general relativity, for which it would be difficult to assemble enough participants in a local setting.

3. For many participants, the computer conference course acts as a catalyst to open the door to computer usage and the on-line world. Use of electronic communication quickly becomes a routine daily experience.

4. The computer conference format requires more independence and responsibility on the part of the student than most face-to-face courses. The student receives no effort-free bath of information often provided in a lecture. We feel this is a central advantage of computer conference courses.

5. Having to write out what one wishes to say can be an important part of learning in a computer conference course. In this sense the "low-technology" use of text in discussion and answering questions can be educationally effective.

6. Computer modeling and simulation software fits naturally and effectively into a computer conference course, since computers are already used for communication. In addition, there are possibilities for automating management functions of the course, such as posting assignments, monitoring participation, and collating answers to homework.

7. Instructor skills needed in a computer conference course include (beyond mastery of the subject) unvarying politeness, enthusiasm, and optimism and an ability to encourage discussion without immediately giving "right" answers.

8. In the computer conference format, students play an important role in explaining concepts to other students. As all teachers know, this is one of the best ways to learn.

9. Disadvantages of the computer conference setting include absence of visual cues that often aid understanding. When a student asks a question, a rapid corrective interchange is less likely here than in a face-to-face class. This is particularly true of student difficulties with software. In addition, students who fall behind are more often lost to the course than in a regular class setting.

10. The maximum number of students that can be supervised adequately by one instructor is between 25 and 30. This poses difficulties for the scale-up of computer conference courses to the large numbers of customers that can be reached by, say, video lectures.

11. The computer format allows complete recording of all public interchanges and all private interchanges with the instructor, providing a unique opportunity to study and improve the course.

12. The computer conference mode lends an immediacy to the instruction. The material is constantly revised and updated, errors and typos discovered and posted, text passages that students find difficult quickly discussed and later redrafted, course schedule and content continually revised "on the fly" in response to student anguish or fascination. Recent scientific developments reported in the news are immediate subjects of discussion. There is the joy (and valuable practice) of "thinking on your feet"—as it were, standing on tiptoe to witness what is truly current.

13. The structure of the course is crucially important. We find that students need a specific goal to meet almost every day, a goal whose accomplishment is verified by the instructor. In this sense our computer conference courses are much more controlling than class-based courses. We are uncomfortable with this conclusion, but find its usefulness solidly verified in our experience and happily accepted by students.

III. HISTORY AND TECHNOLOGICAL BASE

In 1986 one of us (Smith) offered a relativity class to students at his institution using computer-conference software to encourage students to formulate their thoughts and questions and to increase class participation in dialogue. This was successful,[3] and it occurred to him that these students could just as well be in different geographic locations. The authors of the present paper met at the 1988 *Conference on Computers in Physics Education* at North Carolina State University[4] and agreed to collaborate in teaching a nationwide computer conference course in special relativity. This course was offered first on the college and university level. We required that clusters of students in different locations each have a local "resource professor" to supplement the network interchange and to validate the course results for local credit. We hoped that ultimately these institutions would be willing to pay for outside enrichment to their curriculum, a hope that went unfulfilled (with a single one-time exception: James Madison University). In the meantime the local instructors took on their tasks as an unpaid extra load, which could not go on indefinitely. Finally, this structure made it difficult to enroll single students. As a result we dropped the use of resource professors and now teach few undergraduates.

Each of us currently teaches a separate course. For Smith's special relativity course, the clientele is primarily qualified students in nearby high schools, who earn course credit both at their schools and at the University of West Florida, and who log on to the conference system during their regular school day. They are physically close enough to meet with Smith if desired, although in practice such meetings are rare. Taylor now teaches two courses, special relativity and general relativity, nationwide over the NSF-sponsored Teacher Enhancement Network at Montana State University to a mixed clientele consisting mainly of high school teachers but including also some undergraduates, college teachers, and an occasional high school student. Members of the class do not meet as part of the course, and most participants have no local fellow participant with whom to discuss the material.

Students in both our classes use the Internet to participate. Hookup requires a computer, a modem, communication software, and *interactive* access (not simply email access) to the Internet. Montana State University also provides an 800 number (for an additional fee) to participants who do not have interactive Internet access.

The conference system in our original course was based on a simple electronic mailing list, in which every public message sent by each participant was relayed to all participants in the order received. (Private messages could also be exchanged between individuals.) The public interchange arrived at each terminal as a single linear string of messages jumbled as to topic. The resulting conversation had the logical structure of the following sequence (which is NOT a real dialogue from our course):

A: Hello, how are you?
B: Can someone help me with Figure 2?
C: What is your religion?
D: I'm fine. What day of the week is it?
E: It is the same as Figure 3.
F: Tuesday
G: Presbyterian

Surprisingly, this kind of interchange worked well, particularly when participants began each message with an orienting phrase, such as, "I can't agree with John's statement that time must have a unique meaning for all observers, because..." The format embodied the comfortable chaos of a student bull session. The public discussion in our current courses is much more orderly, with each topic pursued in a parallel but separate conversation.

The text-based nature of the course has educational advantages, as witnessed by the following quotation from a college student who took an early version of the special relativity course.

> This is probably my favorite class this semester. One oddity about it that I've noticed is that by WRITING questions and answers and sending them away, one tends to have a clearer conception of what's going on.

> Typically, I start to write my questions down, and by the time I've got it worded clearly enough I've solved it myself. I've also had the experience of setting out to answer a question, starting to write, and realizing that my solution was completely wrong.

This is an example of "eliciting student constructs of the subject," an important teaching strategy recognized by education research workers.[5] According to this view, learning is improved when students reformulate ideas in their own words using concepts they have previously mastered. Just such interchanges are an organic part of the remote course format.

IV. MULTIPLE SUBMISSION OF HOMEWORK

Multiple submission of homework adapts an idea by Tom Moore of Pomona College. In his lecture course he collects, logs, and returns submitted homework ungraded, handing back with it the complete solutions. His students then correct their own homework in a different color pen and resubmit it, receiving a reduced maximum score for solutions that are not correct the first time.

In our conference courses, students electronically submit only the answers to the exercises, not solutions, after which we post complete solutions and an alternative version of each exercise. Students determine which of their answers is incorrect and submit (for reduced maximum credit) their answers to the alternative versions of these exercises. In order to obtain partial credit for the alternative version, the student must have attempted to answer the original exercise.

We find the greatest work load in each course to be grading homework. Multiple submission of homework answers only (not complete solutions) cuts our grading time to a fraction of that for full grading of exercises. Multiple submission also ensures that students read and understand posted solutions. Students seem happy with multiple submission of homework. One student responded to a question about the method (in an earlier version in which students corrected their original papers after the solutions were posted):

> I like it very much for three reasons:
> 1. It definitely improves my score.
> 2. It gives me more courage and incentive to attempt what looks to be too difficult. I know I will get some credit for the attempt.
> 3. Your detailed solutions, and the requirement that we make the corrections, certainly help the learning process.

V. READING MEMOS

Each week every student in our classes is required to send to another member of the class a so-called Reading Memo, a paragraph or two describing difficulties and perplexities with, and questions about the reading for that week. (This is not to be a summary of the reading.) A copy of the Reading Memo goes to the instructor. The student who receives the memo is asked to answer it. The instructor acknowledges receipt of the Reading Memo, but may or may not respond to its queries. Points toward a final grade are awarded for submission of the Reading Memo but not for its content, since we want to encourage candid reactions.

We have found the Reading Memo to have several benefits for our courses:

1. It encourages students to do the reading in a timely fashion, so that it can be discussed on line. Students also report that they read the text with a new intensity.

2. Weekly rotation of the students paired to send and receive Reading Memos helps each student to get acquainted with others in the class.

3. It provides feedback to the instructor about how students are progressing and feedback to the textbook writer about what parts of the text need improvement. Reading Memos have been central to the revision of two texts by one of the authors of this paper.[6,7] However, Reading Memos also work well when the instructor is not the author of the text.[8]

VI. TIGHT STRUCTURE OF THE COURSE

In its early years, our courses suffered from everyone's natural tendency to put off work until the last minute. Like the rest of us, students often begin working on an assignment only a day or two before it is due. A chapter assigned on Monday would be read the following Saturday and the exercises attempted on Sunday. As a result, few participants had anything to say about that chapter on the conference during the week, and everyone was too busy on Saturday and Sunday to log on. To counter this tendency, we began to segment assignments so that students have a specific goal almost every day of the week. This is the current, highly structured format for a typical week:

SATURDAY: Instructor posts the assignment for the following week on the conference system.

MONDAY: Students submit to the instructor e-mail answers to exercises for the previous week.

TUESDAY: Two students designated by the instructor post "first responder" items to start discussion on the current week's reading. (Each student is assigned First Responder responsibility at least once during the semester. The purpose of this assignment is to be sure that someone "kicks off" discussion early in each week's cycle.) Instructor posts complete solutions to the exercises for the previous week, together with an alternative form for each exercise. Students examine posted solutions and solve the alternative form for any exercise for which they feel their answer to the original was incorrect.

WEDNESDAY: Each student sends a Reading Memo (described above) about the current week's reading to another student in the class, with a copy to the instructor.

THURSDAY: Students submit answers to the alternative forms of exercises they got wrong the first time; maximum credit is less than for the first submission.

FRIDAY through SUNDAY: Students complete this week's assigned homework.

The fixed points in the schedule are surrounded by much public discussion and many private messages. The weekly schedule is reinforced by a system of points earned each week that builds toward the final course grade. Points are awarded for correct homework answers, submitting a Reading Memo, and contributing to the public discussion.

Toward the end of the semester, students carry out projects on special topics, working through a series of guiding questions. For special relativity these include a complicated paradox and an analysis of the operation of and experiments carried out in a linear accelerator. General relativity projects include Inside the Black Hole and The Spinning Black Hole. The projects are assigned and graded as extended homework exercises. There are no examinations in our classes.

In the special relativity class, students use computer software programs called *RelLab* and *Spacetime*[9] that allow them to set up and run scenarios in high-speed kinematics. We pose a weekly paradox for which students set up a computer scenario, carry on a discussion on the conference, and solve as part of their homework. Another software program called *Relativistic Collision*[9] helps students analyze creations, collisions, transformations, decays, and annihilations of particles that move in two space dimensions.

We have fundamental reservations about this highly structured way of teaching, fearful that as motivation it uses deadlines rather than interest in the subject, and that it may reduce the chance for unscheduled reflection. A college professor who took our general relativity course felt the same ambivalence. Early in the course he seemed to approve of the structure:

> It does not get in my way. I'm just trying to understand the material. I think structure is necessary and useful. Of course, there might be better structures, but right now I'm concentrating on learning. Having the problems due regularly certainly fosters my effort.

By the end of the semester, however, he had come to a different opinion:

> I thought that the organization of the course drove us too quickly past interesting questions. In a way I was grateful for the metered flow of the course; it was what I needed to keep me at it. But we also paid for the steady pace by not being able to go deeper or to explore more thoroughly interesting issues and questions. The emphasis on the daily schedule was almost to the exclusion of the kind of follow-up investigation or discussion of interesting questions that might help students to pull their ideas together into coherent arrangements.

A high school teacher whose students were taking the course also criticized the format of daily assignments:

> The many deadlines and requirements for reading memos, responses, bulletin board items, etc. end up getting in the way of the learning process, even though they may also help it. Time, after all, is limited, for the students at least as much as for the teachers, and if you spend too much time on mechanics, it takes away time from digesting and comprehending.

These are the only negative reactions we have received. All other student responses have been positive. Here is a sampling:

> The scheduling for different submissions, assignments, postings, etc. has made it possible to fit everything into an already busy teaching schedule. The workload is just about right.
>
> The structure is a new one as far as taking a course goes, but in place of a traditional classroom setting, I think this is a wild success.
>
> I like the structure very much. ...The deadlines do not seem an obstacle at all to me. I consider that there is one every day, except Friday and Saturday. So it is just part of my daily routine. ...I am delighted with the whole experience, very, very delighted. And I tell lots of people about it.

One high school teacher took special relativity in the fall of 1992, then skipped a year, taking general relativity in the spring of 1994. His is the only student comparison we have between the unstructured and structured formats:

> I think the required structure has served to improve the discussion over when I took special relativity in the Fall of 1992.

We continue to use the structured format for our courses, but hope to experiment with group projects and other innovations that might provide time and occasion for more reflection about what is being learned.

VII. DEMANDS ON THE INSTRUCTOR

Recasting a conventional course into electronic form is time-consuming, particularly because the style is so different from that of a lecture course that each component must be rethought from the beginning. An obvious additional burden falls on the instructor who is also writing the accompanying text. However, the second and later times through the course we find we are able to work no harder than the students, who are warned that they will spend up to 15 h a week on the course. Monitoring the electronic interchange consumes between 30 and 70 min per day. Revising assignments takes about an hour per week and grading homework about 3 h, with record keeping and reporting another 2 h per week.

VIII. A DIFFERENT KIND OF CHUMMY

We all get business letters. Most of us receive personal letters. The lucky among us exchange love letters. Surrounding the physics discussion in an electronic conference course is a halo of chit–chat about the weather and personal concerns and, on good days, a celebration of the subject that astonishes us as we study it together. It is easy to take a dark view of conversation not directed at course material. A college professor who took the course had this to say about discussions on the Montana conference system, called Confer:

> Getting to know your fellow students through Confer was interesting. I was struck by how immediately one could detect characteristic differences in the styles of the different members of the class. I was also struck by how little of the interaction and communication moved the course forward. To get a real discussion going the topic had to be the Hubble telescope, the weather, or—several times—questions of pedagogy. Much of what appeared on Confer was self-expression or posing of questions rather than interactive communication. As a result, I found the dialog surprisingly unuseful although superficially interesting.

We discussed this comment with members of a later class, who felt that this professor did not take sufficient account of the importance of social setting in the learning process. Our reaction, too, is almost exactly the opposite of his. In fantasy we think of a group of students in a regular course gathering late at night to work together on a physics problem set due (of course) the following morning. What will they banter about before getting down to business? What percentage of their interchange about the exercises will be "to the point?" On the other hand, how much does the "efficiency" of their work together depend on mutual respect, friendship, and unspoken acknowledgment of each individual's strengths and weaknesses? Comparing our course with this fantasy, we feel that the percentage of discussion on "real physics" is about the same in both.

Indeed, students in our conference courses seem hungry for "miscellaneous" kinds of discussion, the kinds that allow them to pull back slightly from the highly focused content of the assignments. We believe that a successful remote conference course must nourish development of the "social glue" that encourages a sense of community among these strangers-become-friends.[10] In our early courses we even provided an explicit "COMMONS" conference to encourage students to discuss whatever they wanted, regardless of course assignment.

Of course the thrust of any enterprise can be frittered away in idle conversation. To prevent this, the leadership of the instructor is central. And the instructor's attention is the major tool. We never cut off a discussion, no matter how trivial. We just ignore it and spend our time responding enthusiastically to parts of the discussions we want to encourage. We are quick to praise student insights, which often surprise us in spite of our long acquaintance with relativity. We give answers sparingly, often turn questions back to the class for discussion, and use student questions to direct attention to the central points. Students answering each other's questions augments the sense of community and facilitates learning.

In any committee meeting, every savvy participant is aware of where the power lies. The same unspoken acknowledgment inevitably permeates the conference course, in spite of our jolly demeanor. No participant can or should forget that he or she is accountable for performance in the course. To this end, each student receives electronically a weekly summary of points earned that week, along with the projected semester grade based on points earned to date. These reports are delivered matter-of-factly, with occasional comments such as, "Gene, I did not receive answers to the replacement exercises this week."

When our overall strategy is successful, a kind of warmth similar to that of a personal letter permeates the course. The same psychological distance that allows the uncontrolled and often damaging expression of emotion called "flaming" on the Internet can also permit the expression of positive emotion that might not be considered appropriate in person. This contributes to the friendly atmosphere and the expression of mutual appreciation among students and between student and instructor. Typical is the comment one of us received from a class member who is a teacher:

> I also appreciate your kind and supportive attitude, which comes through loud and clear, even with this impersonal method of communicating. I am trying to be more that way with my students.

Each of the authors has taught physics for more than 20 years. Doubtless we have been princes for all of that time, but no student has given us a similar compliment in person.

IX. EDUCATIONAL RESULTS

We have carried out no formal comparison between student performance in computer conference courses and student performance in our lecture courses. However, we both have taught relativity MANY times in both settings and observe no significant difference in mastery of the subject in the two groups. There is support for this conclusion in the literature.[11] We do find that the college and high school teachers and high school students who take our conference courses are typically more highly motivated than students in our regular college classes. We speculate that this is because our on-line students must take special initiative to enroll in our courses and are self-selected from a much larger reservoir than the students of a single institution.[12]

X. UNSOLVED PROBLEMS

We feel that our courses succeed in important ways, such as providing instruction to those to whom it would otherwise be unavailable, keeping students steadily at work, increasing dialogue among students, and creating a setting that combines accountability with friendliness. However, unsolved problems are more interesting to us, because they set the agenda for work ahead.

1. We are still searching for an administrative setting in which colleges and universities are willing to pay to have their students take our courses.

2. We have not found a course structure that allows us to teach more than approximately 30 students at a time.[13] A larger course takes too much instructor time. Moreover, students in larger computer conference classes tend to vanish into anonymity and can sometimes even disappear without being noticed and privately encouraged by the instructor. A larger remote class also produces a larger volume of daily discussion than can easily be digested by most participants.

3. Our course format does not have specific provisions to promote leisurely reflection in depth about fundamental questions and topics of personal interest raised during the course.

4. Our course format does not accommodate students who wish to join the course at different times or to work at their own pace.

Items 3 and 4 are unsolved problems in most face-to-face courses as well.

XI. FAILURE IN EUROPE

The Internet knows no boundaries. Students from Hawaii and Alaska participate in our courses as easily as students from the 48 contiguous states. A Canadian student participated successfully. On the other hand, we have attempted four times to include students from European universities in our conference courses, and four times we have been disappointed. Twice the students dropped out almost immediately, once a pair of students participated sporadically, and once a single student took half the course and then became an active auditor.

We believe that there are at least four reasons for this lack of success:

1. *Schedule*. European universities have month-long vacations that occur in the middle of our semesters. Participation in the class fails if all students are not working on the same material at the same time.

2. *Language*. Learning something new in a foreign tongue is inevitably daunting. None of our European trials took place in an English-speaking country.

3. *Learning style*. By and large, European students are not accustomed to weekly, much less daily, assignments.

4. *Academic credit*. European students do not receive credit from their universities for participation in our course. Credit from a US university is of little value to them. We have the carrot of course content for these students, but not the stick of grades.

We would like to make further trials with class participants worldwide and welcome inquiries to this end.

XII. COMPARISON WITH THE CONVENTIONAL LECTURE COURSE

Typically society backs into the future, with its eye on what has gone before. We too look backward at earlier courses we have taught in the classroom with new appreciation for the hidden characteristics of that learning situation, good and bad. We identify some of the most obvious differences between our computer conference course and a conventional lecture course:

1. Our computer conference students accept responsibility for conducting the class discussion, and prepare for this discussion by careful reading. Students in conventional courses often do not read the text before the material is covered in class, expecting to receive a "free treatment" in lecture.
2. Our students routinely answer each other's questions and explain course concepts to one another. In conventional courses such mutual aid is not built into the structure (though it often happens informally).
3. Our students exchange personal mail with every other student in the class and know them by name, whereas students in conventional courses usually do not know most of the other students in the class.
4. Our students are required to participate in discussion every week, and there is a full and complete record of every public contribution. Electronic conference dialogue is less confrontational than classroom discussion for most people, with a lower psychological threshold for participation. Many students in conventional courses leave it to others to participate in class discussions.
5. We encourage public discussion of homework exercises, and this discussion usually goes on throughout the week. Students in conventional classes often delay work on their homework until the night before it is due.
6. In classes that include high school teachers, participants comment steadily on the course format and the process of learning which they are experiencing. This can improve learning and help with the ongoing revision of the course. We have rarely experienced this in a lecture class.

On the other hand:

7. Lectures can be given in person to hundreds of students simultaneously and via television to an unlimited number. Student questions in a conventional course can often be quickly answered, whereas in our course it can take days, owing to the slow pace of written exchange. And students who fall behind are more often lost in a conference course than in a lecture course.

In our opinion computer conference courses will never replace in-person teaching, but offer an alternative suitable for a significant number of participants, many of whom cannot take advantage of regular classrooms.

XIII. FUTURE TECHNOLOGICAL INNOVATIONS

We speculate here about technological innovations that might be useful in light of our experience and the unsolved problems listed above. We find our technical needs in the present text-based setting to be remarkably modest.

1. Foremost would be an easy way to exchange equations that include superscripts, subscripts, and Greek letters. As mentioned above, there can be a large educational payoff from having to formulate and write down one's questions and conclusions in natural language, and formalism can be the last refuge of a dilettante. Nevertheless, equations are central to science, and it is hard to run the eye lovingly over such a hideous (and ambiguous) structure as the Schwarzschild metric written linearly in text:

$$d\text{tau\^{}}2=(1-2M/r)dt\text{\^{}}2-dr\text{\^{}}2/(1-2M/r)$$
$$-r\text{\^{}}2d\text{phi\^{}}2.$$

2. The ability to exchange drawings and images would be convenient but not crucial for our particular courses. At present we rarely miss it.
3. Automation of administrative procedures would reduce our load and allow us to spend more time teaching physics and less time with administrative number shuffling. Already Smith is using Unix scripting and scheduling functions to automate the posting of assignments and announcements on specified dates, and to provide weekly reports of student participation levels. Among the remaining possibilities are to automatically acknowledge to students the receipt of their homework and Reading Memos, collate homework, and perhaps pregrade numerical answers. We would like to provide automatic and routine tabulation of these matters to the instructor, alerting him or her to the record of a student who is falling behind or obviously having difficulty.

None of this is crucial to the courses that we presently teach, and none provides fundamental solutions to the unsolved problems enumerated above.

In contrast, our expectation is that easy interfaces to the rich graphics and resources of the World Wide Web will lead to wholly new kinds of conference courses.[14] For example, access to historical and technical material, along with powerful computer programs for search and simulation, should provide students with much greater resources to pursue independent projects. Software that supports and encourages collaboration should increase the opportunity for group work. And a significant part of any course could be introduction to world-wide on-line resources that students can explore and use in their lives from then on. As we move into this new era, we will try to harness new technology to solve our current problems while identifying difficulties organic to the future medium.

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[10]Rae Wahl Rohfield and Roger Hiemstra, "Moderating Discussion in the Electronic Classroom," Chap. 5, Vol. 3 of Ref. 1, pp. 91–104.

[11]R. Hiltz, "Evaluating the Virtual Classroom," in Ref. 2, pp. 133–183.

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[13]A computer-enhanced writing course at the Massachusetts Institute of Technology accommodated only 16 students. See Edward Barrett, "NEOS and the Development of the Electronic Classroom at MIT," Chap. 6 of Vol. 3 of Ref. 1, pp. 111–121.

[14]A home page pointing to various courses on the World Wide Web can be found at the address http://lenti.med.umn.edu/~mwd/courses.html.

Electronic paramagnetism in biomolecular structure and function

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Intrinsic paramagnetic states are ubiquitous in biological systems, and extrinsic paramagnetic probes are often introduced in studies of biomolecular structure. The measurements of electron paramagnetic resonance and magnetic susceptibility are commonly employed in investigations of biomolecular paramagnetism. How the data obtained from these measurements are used to arrive at electronic structure, and how the electronic structure and its changes relate to biologically functional processes, are the subjects of this review. Emphasis is placed upon the role of magnetic measurements in quantifying the special properties which proteins confer upon iron and copper ions.

TABLE OF CONTENTS

I. FUNDAMENTAL INFORMATION AND PRINCIPLES

The biochemical processes of life require complex reaction pathways with carefully regulated reaction rates. Biological macromolecules, such as proteins, which are essential for these processes to occur, can contain thousands of atoms. Often only a small part of such a biomolecule, called the active site, is directly involved. Both the kinds of atoms composing the active site, and the manner in which they are arranged, produce the molecular environments that enable biomolecules to play their vital roles. A major field of research in biological physics is the investigation of relation-

