

TEACHING PHYSICS TO A NON-PHYSICS AUDIENCE - THREE PERSONAL PERSPECTIVES

by S.P. Goldman, F.R. Hallett, and W. Harris

In the first essay, Bill Harris presents a detailed summary of the reasons for physics departments to nurture physics courses for non-scientists, as well as thoughts on the steps to building such a course. The second essay is a vivid personal account by Ross Hallett on the design and implementation of a course and textbook for a physics course for students in the biological sciences. The last essay relates Pedro Goldman's first steps in teaching a physics course to music students, the steps that brought it to its present form and his personal feelings towards teaching in general and towards a non-physics audience in particular.

BILL HARRIS - TEACHING PHYSICS TO A NON-PHYSICS AUDIENCE

Recently, our department launched a new one-semester course called "The Big Questions", open for credit to any undergraduate in our university at 2nd year level or higher. This course is team-taught by four faculty within the Department of Physics and Astronomy, and it addresses four major themes drawn from physics, astrophysics, and biophysics: (1) The nature of space and time (relativity, quantum mechanics, string theory), (2) cosmology and the history of the universe, (3) the formation of the elements, and (4) the origin and evolution of life on Earth.

Courses built on similar broad-appeal strategies are appearing on campuses in growing numbers. Suppose you've agreed to take on one of these. What do you do next?

Step One: Empower yourself, and your department

First, tell yourself - and believe it - that it's quite OK to teach your subject at a level that may seem very superficial to you. In fact, it's more than OK; we have a responsibility to do it. The public ultimately pays our way; they are entitled to hear our exciting findings about the nature of the physical world in a way that means something to them; and furthermore, they should hear the message directly from us. Conveying science to the public has gone through a renaissance over the past two decades thanks to the work of innovative scientist-communicators such as Carl Sagan, Martin Rees, Kip Thorne, Stephen Jay Gould, Brian Greene, and many others. It is a sad commentary that the pioneers of this kind of outreach sometimes had to labor against opposition or apathy from their own professional colleagues - exactly the people who should have been supporting them the most.

We present in this paper three very personal experiences on the design, preparation and communication of physics courses to students not enrolled in programs in the physical sciences.

A crucial step is for your entire department to realize that physics-centered courses for non-physics and non-science students are not just frills to be offered only if your resources allow it. They should be made part of your central teaching mandate. After all, the vast majority of the undergrads we already teach are headed "elsewhere": engineering, biology, chemistry, math, medicine. Why not broaden our umbrella to include students in the humanities, social sciences, and other faculties too? Reaching a student in philosophy or commerce should count for just as much as reaching one in chemistry or geology. Everyone will benefit, and in the long run, we will gain much from a more science-literate society.

Step Two: Understand your audience

Working with students from entirely different parts of your campus can be terrifically refreshing and fun: you will meet many bright, energetic, friendly young people you would never have encountered otherwise. But first, realize that they are not simply clones of your regular Faculty of Science students who have not yet had the benefit of our knowledge. You will quickly find that many of them think differently, and they may not believe that physics is the Answer to Everything even when they've heard what you have to say. Respect them. You will have some very good things to tell them - no doubt about that - but you may not end up changing their lives or converting them to "our" particular path of right and truth. In fact, you may learn more from the experience than they will.

We view physics and its associated thinking skills as very powerful and flexible. Among other things, we routinely claim that we can teach universal problem-solving skills as well as comprehensive insight into the physical world. An extreme version of this outlook was expressed many years ago in a remark by one of my department colleagues (now long retired) who was heard to say, "When will people understand that if you can do physics, you can do anything?"

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Wrong. There are several fundamentally different types of human intelligence - mathematical, linguistic, musical, interpersonal, and so forth (e.g. Gardner 1983) - which do not necessarily overlap with one another. Physicists are not automatically the deepest thinkers on the planet. For every Newton or Einstein in our history, there is a Shakespeare, a Gandhi, a Michelangelo, or a Mozart. Powerful though it is, physics addresses only a small part of human thought and experience.

A strikingly useful metaphor was coined 15 years ago by the American sociologist Sheila Tobias (1990). Relative to the physical sciences, Tobias defines two tiers of undergrads divided by cognitive style and outlook. In our normal diet of physics teaching, most of our classes are made up of her "first-tier" students: they are the ones who have already decided to go into the physical sciences or pre-med programs as career routes. In class, these people tend to accept whatever agenda we give them without comment, they work hard at learning our standard methodology and language, and they tend to be "teaching-blind": even if their instructor is poor, they keep on going in their chosen program.

Second-tier students are different. We don't usually see them in standard physics, math, and chemistry courses, but they are the ones you will face in your wider audiences. The best of them are just as bright as the best first-tier students, and are often more articulate, but they do not come in to your class already assuming that physics - a subject universally thought of as difficult and scary - is worth their time and attention. Good teaching and good communication matter much more to them than to the first-tier people. In fact, just registering for a physics class, with the vague hope that they might find something interesting and exciting, may already be a considerable act of courage for some of them. Once they start taking part, they will often question the reasons for what we do or think at a surprisingly fundamental level.

In other words, check your physics arrogance at the door. Enjoy the differences you will encounter; be persistently friendly, open, and adaptive, and your students will be remarkably responsive in return.

One bit of practical advice: are there astronomers in your department? If so, they almost certainly have a wealth of experience with courses for general audiences. They will be happy to give you useful tips about course design and about the non-science undergrads at your particular campus.

Step Three: Inspiration beats Content

But why would a nonscience student want to take your course in the first place? Some (quite a few, really) will take it for sheer interest; some because they need some kind of generic distribution requirement; and some because they are simply looking for a relatively easy course they can get through with minimal effort. Welcome them all, but talk to them as if they are all part of that first group.

Indeed, you won't be able to explore your material to the depth that you would in a regular physics class. But if you don't have to spend your class time on the detailed methodology of the subject, you gain a lot of freedom to convey the basic excitement and scope of the subject you love. It will be easy for you to do this with energy, enthusiasm, and obvious enjoyment. At bottom, what the students are really there for (whether or not they even realize it!) is inspiration, not content. Don't push to "get through" a certain curriculum packed with material: instead use thoughtful discussion of a few carefully selected issues to draw out the inherent excitement of your subject. Perhaps best of all, lots of opportunities will come up to discuss the way science works, along with the history and process of discovery - something we rarely get to do in our traditional classes. Years later, they will remember that (and you) long after the details have faded.

We routinely lament the creeping corporate takeover of our universities and its associated job-training mentality; and our students are just as unhappy with these pressures as we are. Your physics-for-outsiders course will give them a rare chance to use the university the way it was intended - as a place to trade ideas and enjoy learning for its own sake. You will find that they know instinctively that science is really about curiosity, exploration, and discovery, and those are the things they've come to hear. Pitch your course that way, and use the opportunity unashamedly. Inspiration beats content.

Finally, here are a few random tips that we have learned from our experience with the "Big Questions" course:

When planning your course, go beyond your department and enlist support from your Dean and even your Academic VP. They may be quite willing to help out in tangible ways such as paying for your teaching assistants, special demonstration equipment, or other relatively inexpensive items. Take the lead and get the widest possible support from around campus. Seek out interested colleagues in other departments and design totally new combinations of curriculum.

Just as in any junior physics course, classroom demonstrations are great; the more the better. Think of something new to show them every week, and keep it simple and vivid.

Don't worry too much about designing the optimum curriculum and presentation order for your material. There may be no such optimum, and the most effective order may not be the most logical one. Learning isn't linear.

Give the students lots of opportunity to talk, either with you or amongst themselves. Launch open-ended discussion questions in the middle of your lecture, have them break up into small groups, and then ask a few groups to summarize their thoughts for general discussion. If a heated debate develops, great. Very often, resolving the question actually matters less to them than just the chance to express themselves. Inspiration beats content. If you have a weekly tutorial period, design it for organized small-group discussion.

Put out a "Question of the Week" ahead of time and see what each group does with it. The tutorial groups can also be used as springboards for group projects, student presentations, or end-of-term events like poster fairs.

ROSS HALLETT - TEACHING PHYSICS FOR THE BIOLOGICAL SCIENCES.

The matter had been a subject of meetings and negotiations between the Physics Department and several biological science programs for years, but with no resolution. In 1969, the Department received an ultimatum. Either develop a physics course for biological science students or all biological science programs would drop physics as a core requirement. Physics at the University of Guelph had been a separate department for only 4 years and was struggling to grow and establish a reputation. Since departmental budgets and faculty numbers were closely tied to course enrollments, the loss of these students, which constituted 80% of the class size, was an extremely serious matter.

Unknowingly, I sent an application to the Physics Department at Guelph in the midst of this wrangling. Since I was a recent Ph.D. in biophysics, I was offered a position immediately... no interview, no visit, no questions... just come, we have a job for you! The task, of course, was to assist in the development of new first year physics courses for biological science programs. I quickly learned that this was going to be a three-way process. The course would have to be attractive and valuable to students in programs ranging from botany to microbiology as well as to students in agriculture. But, to gain acceptance it also would need approval from faculty in the biological sciences and from my colleagues in physics. Communication lines between these groups of academics were somewhat frayed.

The first year physics courses that were offered by the Department were standard fair, mechanics in the fall semester, followed by electricity and magnetism (and some atomic physics) in the winter semester. Although it was clear that this was not acceptable, the question immediately arose as to what the biologists actually wanted taught in these courses. The question in my mind was "what topics in physics would help students better understand biological systems and processes". I arranged to meet with several concerned faculty and students in the various biological science programs to better understand their needs. As these discussions developed, I did learn a great deal about physics topics that would be more appropriate. These will be summarized in the following paragraphs. However, the course content was not the only concern of many biologists and I should first describe the philosophical issues that arose (and for which I was totally unprepared).

Some very vocal classical biologists that I met were far more concerned about the impact of physicists on biological science students than on the specific content of the physics courses. Physical scientists always want to reduce a problem to its essence. This can take several forms such as "now class, first assume that the horse is a sphere" in which the instructor tries to eliminate complexity so that simple relationships apply. It can involve breaking a complex system

into several parts, each of which is analyzed separately. Or, finally, it can arise from holding many variables constant while varying the one of interest. These biologists called this "reductionism" and physicists were the leading reductionism villains. In their view, biological systems had to be studied in their full complexity or not at all since any attempt to control, simplify or separate meant that the system was no longer functioning on its own. Other more modern biologists, who were active in molecular biological techniques, opposed this view. But they too were unhappy with the physics courses and expressed serious concern that the courses did not prepare students properly for modern biology. While the classical and the modern groups had been united at condemning the original physics courses, the modern group was very supportive of curriculum change. Several of these faculty members, along with colleagues in physics, have provided extremely valuable suggestions and course materials as the courses Physics for the Biological Sciences I and II and a text book (jointly written by departmental physicists and biophysicists) developed and matured. The reductionism debate raged on for a while, but then died away as the incredible power of new molecular tools revolutionized biology.

The content of the courses currently includes many topics that are rarely covered in first year physics courses and these are reflected in the text "Physics for the Biological Sciences" (4th Edition, Thomson Nelson, Toronto). The first course begins with a thorough discussion of simple harmonic motion and wave phenomena, followed by acoustics (sound, hearing and echolocation) and electromagnetic waves (light, geometrical optics and the optics of vision). This is followed by a section on the absorption and emission of light by molecules. The de Broglie equation and the concepts of wave-particle duality are introduced and then a simple "particle in a box" approach is adopted to determine energy levels of visual pigments. At first, this section was very controversial to some colleagues in physics, who were dismayed to see electronic energy levels introduced in molecules without the prior teaching of the Bohr atom and the hydrogen atom. Over the years, however, this criticism has softened and they now accept the fact that the "particle in a box" approach can be a very simple and direct way of introducing quantum ideas to non-physics majors. The final topic of the fall course is a fairly thorough overview of radioactivity and its applications. Almost none of the material taught in this course is commonly found in standard first year physics courses. The only time any traditional mechanics appears in the first course is in the development of simple harmonic motion.

The second course begins with a strong emphasis on biomechanics that includes both statics and dynamics. This is followed by a small section on scaling, which biological science students find especially interesting (and difficult). Concepts from fluid statics and mechanics that are extremely important in the biological sciences constitute the second part of the course. This section ends with the application of Reynolds number to the swimming behavior of large (e.g. whales) and small (e.g. bacteria) systems. The third section deals with thermal motion of molecules (diffusion, sedimentation and the concept of osmotic pressure) and the course

finishes with an overview of heat and heat flow in biological systems. Almost half of the material presented in this second course is rarely offered in standard first year physics courses. In second year, biological science students can take the elective "Physics of Sensory Systems", which applies the basic principles of electricity to neurophysiology, and/or a basic course in electronics.

The first year courses are "semi" calculus based. This means that calculus is used to derive relationships both in class and in the text. However, the problems that students are required to solve do not require calculus. The teaching methods for the course are also non-traditional. The material has been modularized in a study guide. Each module in the guide has a list of study objectives, each with a step-by-step reading list followed by sample problems and self-tests. When these are mastered, the student can come to the "quiz room" to write a module quiz for credit (and then move on to the next module). If a module quiz is not passed, the student obtains a diagnosis of their weakness from an instructor, and the quiz (a different version each time) can be repeated (up to three times with no penalty). This ability to retry a quiz with no penalty is very important at reducing many biology students' fear of physics.

Colleagues in physics have been extremely supportive of these courses and many have actively participated as lecturers although, at first, some were uncomfortable teaching a physics course in which the primary goal is to give students a better understanding of a different discipline. In a recent review, a committee of biological science faculty and students strongly emphasized the value of the courses, but urged that we try and integrate the modules more effectively. They suggested that there was a tendency to look at the instructional modules alone and miss out on the big picture. Maybe the reductionism debate hasn't completely vanished after all!

PEDRO GOLDMAN - TEACHING "THE PHYSICS OF MUSIC AND SOUND" TO MUSIC STUDENTS

The course

It was my very first lecture. I had in front of me a silent group of stern faces (most of them had to take this 'horrible' course). There was no excitement, no buzz and a feeling of distance and apprehension. I told them that this was the first time I was teaching this course and went on to go through the syllabus. At that point I realised that three students sat crying. They didn't stop crying for quite a while. What should I do? Here I was muttering the course contents and requirements and, as I was doing it, I could feel the class getting into a deep depression (a few students were trying to console and comfort the ones in utter despair). I felt as if I was standing there like some kind of evil torturer!!!

A number of years ago, I was told by my chair that I had to take over Physics 132, the course on 'The Physics of Music and Sound', a course that was then open only to students in the Faculty of Music and was required for students in several departments in that faculty. I accepted reluctantly, as I did not know how I would teach music students. I never

expected my first class to start like this! I had in front of me a group of music students. Many of them had not seen any math or physics for a long time; at least half of the class had, as much as possible, avoided these subjects; and a significant percentage actually hated math and physics. On the other hand there were in class a number of students that were very good at math and physics, and even a couple that were taking a joint degree in music and math! Suddenly I found myself confronted with two big problems: (i) how can I teach to a group of people with such a huge disparity of backgrounds? and (ii) how can I teach to a group of people that dislike what I am going to teach?

I had prepared for my first lecture an introduction in which I talked more about music than physics, for example making a parallel between the revolution introduced by Josquin des Prez, using the until then ostracised thirds in musical harmony, with the revolution introduced in physics by his near contemporary Galileo and with the rest of the Renaissance. I could see big eyes looking at me, more or less trying to find where the catch was. As I went on, expressions seemed to ease and tears to dry, and finally some life seemed to hover over my class! Towards the end of the lecture I could detect a few smiles, though not many.

As I finished my first lecture, I called the three crying students to the front and asked them the reason for their tears. I was told that they had failed Physics 132 the year before, that otherwise they had high marks in the Faculty of Music and that they were terrified of the course. I realised that most of the students were intimidated and frightened by the subject. We don't realise how easy it is for us as physicists to intimidate students!

Many students in class felt that it was unfair to be forced to take this course - they did not choose or like physics, they were music students. These were intimidated students, scared and paralyzed in their ability to try to understand the topics of the course. I encouraged the class to actively participate in the lectures not only by responding to my questions but also by asking questions to better understand the topics. But it was to no avail. The math-weak students wouldn't ask questions that they thought would look silly. The math-strong students wouldn't ask questions so as not to put further down their math-weak colleagues. For both groups of students it was a matter of honour.

I proceeded immediately to fundamentally change my approach to the course and since then the course structure has continued to evolve. I decided to make this not a course on "physics for musicians" but a "music course on physics". The material would be similar, but the emphasis and the language would be that of music and the arts.

The course has now been opened to students in the arts and social sciences and is not required for most of the music students, but they continue to attend. I now start the course with an introduction emphasizing the strong connection over the centuries between music and physics, from the Greek philosophers until the present. Regarding the musical contents of the course, I let the students know that when it comes to music or musical instruments they know infinitely

more than I do and that in that sense they have an advantage (and I a weakness). From the perspective of the physics content, I let them know that it is clear to me that they had chosen music for their life endeavours and that most are intimidated by physics. I tell them that I understand their feelings and respect them, emphasizing that in my personal life, music and the arts are of extreme importance. I tell them that we are going to explore the physics insights into the production, transmission and reception of musical sound and the nature of musical instruments and scales. I emphasize that the understanding that they will obtain will be profound, beautiful, many times surprising and well worth the effort. I make sure that I introduce all the material they need, that the musical aspect of the course is always of paramount importance and that it is clear that my office is open for help. Through the short period in which I introduce elementary concepts, I ask the math-advanced students to be patient, and reassure them that, after this introduction, the course material will be of interest to all.

The material

It is remarkable how hard it is for us, as physicists, to change our ways of thinking. It took me two years to realize that in a course like this we do not need Newton's laws! The fundamental concept for this course is energy. It is interesting how intuitive the concept of energy is and how straightforward it is to introduce the ideas of kinetic energy and 'stored energy'. (Why use the word 'potential'?) The idea that energy can be transformed into other types of energy or transferred between different objects is very easily understood. The extension of these concepts to the fact that the addition of all types of energies of all bodies in a system remains constant if it is isolated, and otherwise it will be lost to the surroundings, follows without any difficulty. It is quite normal to receive questions like 'Is the Universe an isolated system?' The major reward is when they are suddenly aware of a new understanding in what they can feel on a daily basis. For example, the production of musical sound being a succession of energy transfers: from the standing wave in the string to the resonator to the waves travelling in air to the ear-drum and then to the cochlea. It is so wonderful to see every year students amazed by the way in which waves transfer energy!

A concept that the students find fascinating is that of standing waves. After I explain the process of creation of standing waves in terms of constructive and destructive interference of waves travelling back and forth on a string or a column of air, the sudden realisation that that is the moment in which a musical sound is produced is for them an almost mystical experience! Imagine when I make the parallel with an electron in a rigid box, described in quantum mechanics by standing waves! Students are also surprised at the fact that natural modes of vibration can be easily obtained on geometrical grounds by a 'fitting' condition on the wavelengths. And then, they are amazed at the realization that their frequencies f , $2f$, $3f$, $4f$, $5f$... correspond to the musical harmonic series they know so well, and can easily visualize musically as shown in Figure 1 for a fundamental corresponding to the note F_2 .

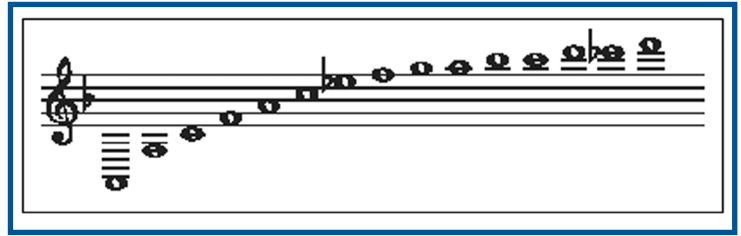


Fig. 1 An example of the harmonic series

Suddenly there is an explanation for the harmonic series!!! The concept of excitation of individual harmonics can be made palpable in terms of excerpts of music written for natural (keyless) wind instruments, particularly if there is a student in class that does play a natural horn or trumpet. And then, as we study scales, the Pythagorean idea of the harmony of the spheres seems to gather all together in a kind of poetic beauty!

To top it off, we explain that the concept of 'colour' of sound is nothing else than a superposition of waves with harmonic series frequencies!!! In this context, their intuitive understanding of a Fourier expansion is superb! The concept of superposition of harmonics to produce colour is then reinforced by a sequence of slides showing how we gradually obtain a saw-tooth periodic function as we progressively add a series of harmonics, each with its proper amplitude; followed by an audible example using a small 'Fourier box' attached to an amplifier and speakers in which each harmonic is superposed with its corresponding amplitude. The concept of colour of sound and its perception becomes truly fascinating!

The students

What a very special group of students are the music students! They are motivated, committed and very hard working. During the middle of the term I was surprised to see students sitting in class in tuxedos or long black dresses! They were performing in recital after the lecture! I was stunned by the fact that they would still come to the lecture that day and leave 15 minutes earlier to walk to the Music building where their performance would take place!

I will never forget my last day of classes of that first year teaching Physics 132. As I entered the classroom, a student that stood outside entered after me and gave the class a cue upon which the students started to sing in a polyphonic choir. I stood in front with tears in my eyes. The humidity in the room must have risen substantially as wet eyes were more common in that room than dry ones.

The lessons I have learned

This course helped me enormously to develop my approach to teaching and to a classroom. I would like to share some of my personal guidelines.

- The most important role of our lectures is to motivate, to inspire and to communicate our enthusiasm to our students.

- Every student deserves the full attention of the teacher, regardless of the student's strengths or weaknesses.
- There is always enough time to answer questions. It is worthier to teach a smaller number of topics for the benefit of the understanding of one of them or for the satisfaction of the curiosity of the class.
- If a question interrupts the flow of the lecture, its answer may be postponed but it will always be addressed.
- Some classes mix students with drastically different backgrounds and strengths. It is essential that they all respect each other's strengths and weaknesses.
- No student should feel that she/he would rather not ask a question to avoid feeling embarrassed. It must be clear that even the simplest of questions is an important question.
- I believe that humour is an inextricable part of lectures. Humour brings spontaneity to the lectures, making the students feel at ease and much more willing to ask questions. It may also serve as an attractive teaching tool.
- Flexibility - I like to stimulate the thoughts and curiosity of the students in the directions they open themselves. This raises the students' level of involvement and excitement and invariably students and myself learn a lot from this.

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