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The practical teaching of quantum mechanics

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Abstract. The author teaches introductory quantum mechanics to third-year students at the University of Pretoria. Quantum mechanics is without a doubt one of the most challenging topics in the physics curriculum. It has been described as ″*All is waves, with nothing waving, over no distance at all!* [1]″ The mathematics of quantum mechanics is demanding, and the interpretation and conceptual understanding of the subject continue to occupy the minds of even some of our greatest thinkers today, more than a hundred years after its foundations were laid. Consequently, at the University of Pretoria, student performance has been notoriously low, students became discouraged, and absenteeism, plagiarism and copying plagued its delivery. The author intervened this year (2018) with a radically different approach to address these challenges. The outcomes have been significant, and the reviews (received from about 50% of the students) indicate that this new approach has worked beyond expectations. In this paper, the many different challenges faced and interventions made will be outlined.

1. Introduction

The author has taught introductory quantum mechanics, solid state physics and statistical physics at the 3rd year level at two different South African universities [2] over a >20-year period. He has experienced very similar challenges in the teaching of these courses over the years, and these challenges have, to a large extent, only grown with time.

In 2018, for the first time, the author introduced a radically different teaching methodology and style that can be described as 'active engagement'. This term is used quite freely in the realm of physics education and speaks to a two-way interaction in the class-room between the instructor and the students as well as group interactions, and also actual doing and exploration during class time [3] as opposed to passive learning.

In this paper, the challenges facing this teacher are summarised in section 2. Whilst these issues have been experienced in the South African university setting, it is very likely that similar problems are being faced elsewhere [4].

In addressing these challenges, the new approach to the teaching and learning pursued by this teacher is discussed in some detail in section 3. This has been done in the context of introductory quantum mechanics at the 3rd year level, but the interventions that have been introduced will be broadly applicable to other subjects in physics, and also to other disciplines of science. So, this paper could well be sub- titled *Innovative teaching methods for 2nd and 3rd year students of* *science*. The interventions are practical for small to medium-sized classes (≤50 students). For larger classes, for example for typical 1st year classes, these schemes could well be impractical, but some elements of the ideas introduced in this paper could be applicable to smaller tutorial classes.

The question should be asked early on [5]: How do we gauge the success of any class? University administrators, especially at many South African universities, simply and blandly look at the pass rates because these are easily quantifiable and translate directly to government financial subsidies that impact in real ways on the university coffers. While this cannot be entirely ignored, there are other attributes, both quantitative and qualitative that must also be considered before one can pass judgement on the success or otherwise of the teaching of a physics class, or any other class for that matter.

Class attendance can be quantified, and is an indication of student appreciation and satisfaction of the course. Class attendance at South African universities is not mandatory, and it is not atypical for attendance rates to dip below 50% half-way through a course. So, an average class attendance rate in excess of 90%, as described below following the interventions discussed in this paper, would be considered exceptional for any third year course at a typical South African university.

The quality of the answers given by the student in various assignments, especially the explanation of steps to their answers and comprehension shown in short notes and essays is also an important indication of the success or failure of a course especially if it can be determined that the student has written in her or his own words, drawn their own diagrams, etc. Original, credible thinking in the classroom is a laudable goal. This is a qualitative assessment of student performance.

Finally, the views and perception of the students of the course are important and must be considered in the assessment of the course. At the 3rd year level, one can expect that the students are sufficiently mature and serious about their work that they can make a fair assessment of the course without making excuses for any lack of effort on their part.

We give a discussion of the student performance and reviews in sections 4 and 5 respectively, and close with some concluding remarks in section 6.

2. Challenges

The below lists some of the challenges experienced by the author in the teaching of 3rd year physics over the years, many of which will resonate with other readers:

Large classes: Class numbers for a typical 3rd year physics class have more than doubled over the past decade to about 50 students, but university administrators have not always provided more support for the lecturers and for the students. Practicals are especially hard to manage, and often these sessions are relegated to cook-book procedures rather than curiosity-driven experimental work, especially in instances where equipment has to be shared by different groups of students resulting in time constraints. Modernising experimental equipment becomes expensive in this climate of increasing student numbers. Similarly, tutorial sessions become difficult to manage effectively as there is little time for one-on-one engagements.

Weak motivation: The majority of students in these large classes are often not strongly motivated about their futures. Many of these students have chosen physics in the hope that this will get them somewhere in life, but often when they are questioned a little deeper, they appear to be unclear about their future. This is an increasing trend observed by the author and deserves more careful scrutiny. This situation is different from before when only a few well-motivated students chose physics, and the vast majority of these had a realistic chance of aiming for an academic career in physics. These academic career opportunities are few and far between these days. This is a problem, and those of us who care about the future of our discipline should be worried about this situation. If the majority of our students are not

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going to become career research physicists or academics, then we need to make a greater effort to impart to them skills that are useful and practical, that will enable them to succeed in life in areas that are far removed from physics.

Weak mathematical background: Increasingly now, students have less rigourous training in mathematics. Perhaps the passing requirements for mathematics have diminished over the years at both high school and at university levels? Certainly, judging by the performance of students in mathematics at high school, it can be assumed that the majority of students entering into university studies of physics are not sufficiently prepared. And so it cannot always be assumed that 3rd year students have all the mathematical abilities to be able to tackle typical 3rd year physics problems. Very often remedial teaching of essential mathematics has to be done in the physics classroom before proceeding with the physics, for example, students need to understand partial differential equations in the context of quantum mechanics. This slows down progress in the physics classroom.

Absenteeism: Class attendance at South African universities is not mandatory and so it is difficult to enforce this. Given the expensive nature of university studies – including tuition fees and living expenses – it is a useful exercise for one to calculate the financial costs involved in missing a single lecture, let alone the academic cost in being absent. But even this is hardly a deterrent for missing class as it is not atypical for attendance rates to dip below 50% half-way through the course at a typical South African physics department.

Information overload: Thanks to modern technology, our students today are growing up in an age of information overload. They are subjected to fleeting images and continuous entertainment, and hardly ever have to toil to get to the bottom of assertions and facts. They know a lot of information or can quickly gain access to pretty much any information, but this is different from understanding that information, its source especially the veracity of that source, its implications, its context, its connection to the world in which we live, and so on. This has the psychological effect of boosting superficial confidence, which quickly comes undone when students are challenged by questions only marginally different from ones already considered. We must ask whether our students can learn in a profound and deep sense in this environment, and whether physics can be taught effectively in this modern information age. Physics requires quiet contemplation and a careful consideration of the facts, attributes that appear to be at variance with the lifestyles of many of our students.

Plagiarism: The upshot of the above is that when posed with a physics question or a problem, the first port-of-call for a typical physics student is the internet. One can even search for the answer to an entire question – intact with numerical values for the various quantities – and find a completely worked solution. Explanations, short notes and essays can be easily cut and pasted into answer books, and this is often done without referencing the source. This is unethical behaviour and adds little or no value to learning. Parroting the work of others without self-discovery is problematic in this day and age, and is leading to the dumbing down of our science cohort.

Copying: Assigning tutorials and other homework exercises becomes a futile exercise as students are very quick to look for answers elsewhere but from within themselves. Student-to-student copying has become a serious scourge and often this is being done blatantly and in open view in the physics class room and shamelessly rushed immediately before appointed deadlines.

Lack of uptake in consultation: There is a requirement that tutors must keep official office hours, but aside from the times immediately preceding a test or an examination, students generally speaking don't make use of this opportunity throughout the semester. The author has for years now had an open-door policy throughout the semester but, aside from the top- performing students, there has been negligible uptake.

Cramming: The end-result of much of the above is cramming before tests, and major cramming before examinations. This is not a sound way to learn to say the least. It is often during these times that students seek out the help from their tutors and their lecturers. Some students have the unrealistic expectation that the entire course can be re-lectured to them in a condensed fashion just before the examination. This is often the case for those students who have missed much of their classes during the semester. This puts an unreasonable pressure on the tutors (many of them being senior students will have their own deadlines and examinations at semester end) and on the lecturer concerned.

It is fair to say that the average physics student at a South African university today is largely undisciplined and expects an easy ride to a top grade that will enable them to leave the university with the best chance of securing the best and highest-paid job possible. The expectations, for the little effort put in, are often unrealistic.

Consequently, many of the students are not understanding deeply, and not able to think independently about physics. The result is poor performance in physics in whichever way one wishes to measure that performance.

It should be agreed that it will be silly to try to do the same things over and over again in the classroom and expect a different result.

3. New approach

The author introduced several interventions [6] in the teaching of the introductory quantum mechanics (PHY356) course during the 1st semester of 2018 that were aimed to address many of the challenges outlined in the previous section. These changes are briefly discussed below.

3.1. Course structure

There are 4x50min contact periods for lectures and 3x50min contiguous contact periods for tutorials per week, for a total of 7 weeks assigned for the course. Since the 3x50min tutorial contact periods per week have largely been unproductive for some of the reasons given above, in the new scheme, the course was viewed as having 7x50min hybrid contact periods per week. By hybrid, it is meant that each contact period may be considered to be a combination of lecture time and quiz time.

In the new scheme, there is no homework, only class work. The class work is done under the supervision of the lecturer. Also, there are no class tests. The two tests that were assigned were take-home tests. It should be noted, then, that the homework and class tests were inverted insofar as when and where these were being executed.

The class mark for this course counted 50% of the final grade, and the examination mark the remaining 50%. The class mark comprised quizzes and two take home tests. The main intervention was the quizzes.

3.1.1. Class register

A class register was taken. For a class of about 50 students, this quickly became a time-consuming task to complete. The positive outcome to this was there was significant pressure on the lecturer to learn to put names to faces, and by mid-semester, this task could be accomplished without any roll-call and with minimal time. The class attendance for this course was well in excess of 90%, up from below 50% half a year before.

There was an added incentive created to be present at class. It is common place for borderline students to petition the head of department to be pushed over a threshold that they might have only just missed, for example, a student could have failed the course by missing the threshold for a supplementary examination by only a percentage point or two, or the student might have gotten a supplementary examination by missing the threshold for passing by a similar margin, or the student might have missed getting a distinction by a similar margin. It was stated upfront by this lecturer that if the student did not attend class regularly, then there will be very little chance to consider their case on an individual basis should they be a borderline student at semester end. So, the register was important and consequential, and the students quickly became acutely aware of that.

3.1.2. Quizzes.
Students were subjected to quizzes on a regular basis [7]. The quizzes were spot quizzes and not always did the students know whether to expect a quiz when they showed up for class. In fact, for the very first lecture, a quiz was handed out at the very beginning of class time without any prior warning. This came as a surprise to many students, especially those who strolled in late.

It quickly became apparent that students needed to show up on time for their quiz or else they ran the risk of not having sufficient time to complete their work. After a while, this lecturer began handing out the quizzes up to 5min before the beginning of class, and this gave an added incentive for students to arrive early for class. Late comers were permitted to continue with their quiz after class (especially if they had a legitimate reason for being late), and this very quickly became a deterrence for sauntering in late.

To a very large extent, this scheme addressed the issue of low class attendance. They quickly realized that they cannot fall behind.

Generally speaking, the students were quizzed for 20-30min upfront, and lectured to for the remaining for 30-20min. Sometimes the students needed more time for the quiz than was anticipated. Rarely were they permitted to hand in their work the next morning. Sometimes the entire period was devoted to the quiz, and sometimes the entire period was devoted to the formal lecture.

What was usually taught on a particular day was generally "quizzable" the next day. The lecturer generally speaking taught in 'short chunks' and quizzed in 'short chuncks' throughout the delivery of the course. Sometimes, the lecturer communicated with the students via Clickup about what was "quizzable" for the next quiz. Sometimes the quizzes were open book quizzes and at other times these were closed book quizzes. The students were generally speaking not permitted to surf the web during quiz time.

If a student ran into difficulties during quiz-time, they were required to publicly make their query and the lecturer then publicly responded so that all students could benefit from the response. The students were not allowed to collaborate with each other. This lecturer was not reluctant to give hints and suggestions. Under this scheme, the students don't get stuck (or shouldn't get stuck). Compare this with the general lack of take up of open office … under the old scheme, a student who battled on a problem at home was expected to stop by during the tutor's official office hours or ask the lecturer. With the passage of time even of only a few hours, and with other competing imperatives, this quest very quickly gets 'lost in the wind'. The lack of immediacy in addressing a student's problem (help on demand) in the past is hugely debilitating and this needs to be better recognised by instructors.

The marking scheme adopted was as follows:

- Wrong answers, incorrect explanations, flawed arguments: 0-50%
- Tedious algebra: minus 5-10%. The students were expected to be efficient in their

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algebraic manipulations. Too many unnecessary algebraic steps resulted in a penalty.

- Correct answer only: 50-60%
- Correct answer with some useful explanations: 60-70%
- Correct answer with detailed and clear explanations in students' own words, diagrams, use of colour, arrows (all as appropriate), neat work, etc.: 70-100%
- Messy work was penalized, e.g. a sketch does not mean that the diagram should be sloppy.

The students realized very quickly that simply getting the correct answer in this class was not sufficient.

There were 49 hybrid periods for this course, which demanded a huge effort on the part of this lecturer. A lot of advance preparation was needed. Setting quizzes almost daily and marking overnight is extremely challenging. There was lots of marking which was shared between the lecturer and the two tutors. The lecturer had to be especially well organized to demand a high level of organization from the students. Quick (24 hour) marking turn-around means that students get quick feedback on their progress. The lecturer's time spent on this course went up perhaps 30-40%.

The question has often been asked: "Was less material covered?" The answer is an emphatic "No!". About the same amount of material was cover, only with greater depth and understanding. It was possible to address some more advanced concepts compared with previous years.

4. Student performance

The below graphs display the mark distribution for the students. The average class mark was in the region of 80%, up by about 15% from similar classes in the past. The average examination mark was in the region of 80%, up by about 20% from similar examinations in the past. The pass rate exceeded 90%, up by about 25% from similar classes in the past.

It is the considered view of this author that the top students would have done just as well perormance- wise in the new approach compared with the old approach. However, it has become clear that the middle- of-the-way students undoubtedly improved their performance significantly compared with similar classes in the past. Overall, the conceptual understandingof the students improved based on the quality of their submissions compared with previous years.

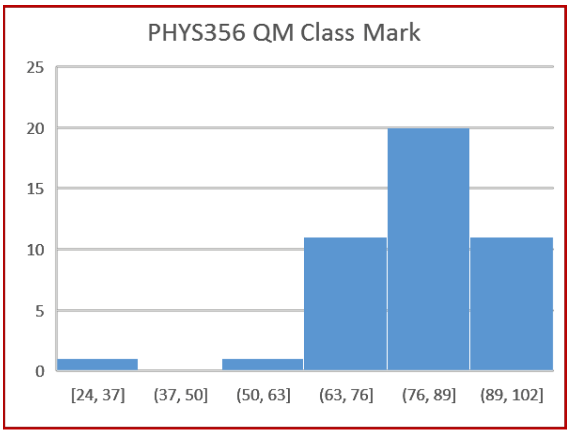

Figure 1: Class mark distribution for PHY356 for 2018

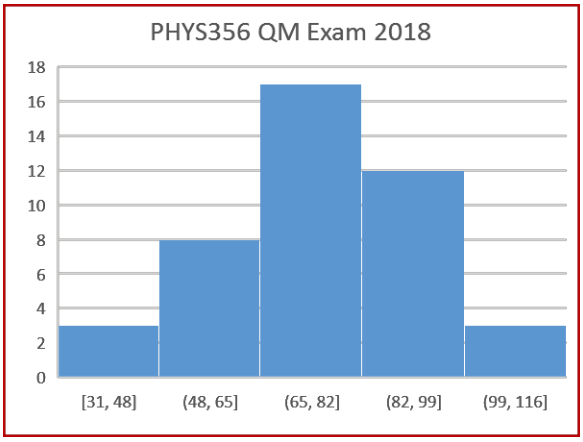

Figure 2: Examination mark distribution for PHY356 for 2018

5. Student reviews

The below are excerpts from some of the student reviews for the course. The return rate for the class reviews exceeded 50%. Almost without exception, the experiences of the students have been very positive. Nobody, other than the tutors *cum* markers, complained about the significant increase in the workload.

> The quantum mechanics course was possibly one of the most enjoyable courses I have taken thus far. I found it interesting and I thoroughly enjoyed the teaching style. The fact that the focus of the course was more on the understanding than the answer was something I agree with as it is in my opinion far more important to understand how to get to the answer.

*

> I found the continuous class tests to be quite helpful and forced me to keep up to date with the syllabus which was an enormous help. I found it a very interesting and informative course which has made me enjoy quantum mechanics more than I previously did. So thank you for the enjoyable course.

*

> I do not feel a simple email will be appropriate to fully explain what this course has meant to me. Thus, I would like to come and see you face to face.

*

> I have through this course gained not only a renewed interest in the subject but also a realisation that I would be remiss in not furthering my studies thereof. I found the subject matter interesting and engaging and I truly learned to appreciate how quantum mechanics combines complex mathematics with physical phenomena.

*

> I think a big part of the reason that I grew to love this subject this much was how engaged I was in class due to mandatory class attendance, the way quizzes forced me to work out concepts semi-independently and by taking notes as the concepts were explained on the board. I felt that the quizzes were more effective in helping me really understand the work than homework would be, since the focus was on getting the work right rather than just getting it done, and doing the work either while or shortly after concepts were explained really helped to ingrain what was being taught in my mind.

*

I also prefer the work being done on the board since I find it much easier to make notes and focus on the flow of information if it is being written out as opposed to given all at once as it would be in a power point presentation.

*

I enjoyed the take home tests since I felt that they really gave me the opportunity to challenge myself to answer the questions as well as I possibly could. Overall, I really enjoyed this course and look forward to possibly continuing to study the subject matter in the future. I am very grateful for the trouble that you went through to make this course enjoyable, understandable and interesting. Thank you for a wonderful course.

*

I would firstly like to thank you. Thank you for all the effort that you put into not only lecturing but also inspiring a true understanding of and interest in quantum mechanics. Your passion for the subject made this class one that I truly looked forward to attending.

*

I was initially a bit sceptical of the teaching method as I am typically quite an independent learner but I found that I actually truly enjoyed this method of learning. It provided the solid basis and understanding that one needs in class while also allowing for opportunities for individual learning at home. In fact, I wish all my classes were conducted in this manner. The way in which this course was conducted meant that we were given a true understanding of the subject matter, rather than simply having learnt about it.

*

I believe that you should continue with this approach in the future. The quizzes were helpful in that you were very supportive and truly encouraged us to think and explore the topics. I think that they were especially effective because often when students attempt problems by themselves, they get discouraged and confused but during the quizzes you would guide us if need be, ensuring that we worked until we understood the problem.

*

I think this is a very good approach to teaching physics, especially at present where many students attempt to pass the classes while not having done many problems or having had much practice. It helped me to stay focused during class, especially knowing that if I did focus properly in class, then the majority of the hard work was already done. I also believe that the chalk-board lectures helped with this focus. Often when the lecturers send out slides, then one can simply read through them at home and so one doesn't focus as much as one should during class. The chalk-board lectures made the class more interactive and also meant that the students could follow along as things were written on the board.

6. Conclusions

Quantum mechanics is without a doubt one of the most challenging topics in the physics curriculum. The mathematics of quantum mechanics is demanding, and the interpretation and conceptual understanding of the subject continue to occupy the minds of even some of our greatest thinkers today, more than a hundred years after its foundations were laid. Consequently, student performance has been notoriously low, students became discouraged, and absenteeism, plagiarism and copying plagued its delivery.

The author intervened this year (2018) with a radically different approach to address these challenges as described in this paper. The outcomes have been significant, and the reviews (received from about 50% of the students) indicate that this new approach has worked beyond expectations. While recognising that pass rates are not the only indicator of success, a 93% pass rate was recorded for the course. The attendance rate for the lectures exceeded 90%. The average class mark improved by about 15% over previous years, and the average examination mark improved by about 20% over previous years.

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