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Teaching Undergraduates Nanotechnology*

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The first nanotechnology undergraduate degree in Australia was established at Flinders University two years ago. In this paper we present our experience of developing and delivering this degree in a climate where 'traditional' physical sciences are under considerable strain. We will discuss the motivation for this initiative, structure of the established course, and educational issues relating to its development.

INTRODUCTION

FLINDERS UNIVERSITY has a strong track record for offering cutting-edge degrees in areas such as biotechnology and information technology. Bachelor degrees were established in both these areas at a critical time when they were emerging technologies with clear economic and cultural potential for Australia. Biotechnology was first offered at Flinders in 1990 and was the first degree of its type in Australia. With the success of these early ventures, Flinders subsequently developed other so-called 'niche' degrees, for example, the Bachelor of Technology (Forensic and Analytical Chemistry) and the Bachelor of Science (Marine Biology). The common theme amongst these degrees is that they are consistently oversubscribed.

In the middle of 1998, a proposal was put forward by the then Departments of Chemistry and Physics to the Faculty of Science and Engineering to establish a new undergraduate course in Nanotechnology. The first intake of students to the course occurred in 2000. The new degree not only sought to teach students a new field of science but also tackled the following educational issues that have long been problems in university education:

- What is the relevance of basic science knowledge to the long-term goals of the students?
- How can students acquire the 'non-scientific' skills in areas such as economics or business or 'generic' skills such as teamwork, oral presentation, report writing and rational argument required to be successful?
- Can all the knowledge acquired during a university degree be drawn into a cohesive package for the students at the end of the course?

Given the current large student numbers at universities, it is vital that these issues are addressed in a course [1, 2].

This paper will discuss the ability of nanotechnology to interest students in science. Many of the educational issues that have determined the course structure and content, its delivery and the outcomes of some of these decisions based on the experiences with the first two years of students, are also detailed.

MOTIVATION

It is now a common problem around the globe that interest in science is waning [3]. Interest of the wider community towards science is at a low-point, especially in the case of physical sciences such as Physics and Chemistry. One, notable, exception to this trend is Forensic Science where young people are still keen to undertake tertiary studies. The root of this sustained interest in Forensic science can perhaps be traced to a 'life-style' issue; the popularity of television such as the X-Files and Crime Scene Investigations and a myriad of murder mystery shows have undoubtedly had considerable impact upon the image of forensic scientists in the mind of the general public. As scientists we may decry the accuracy to which our disciplines are depicted in these shows, but the simple facts are that young people watch and enjoy these shows thus developing an interest and curiosity towards science. The problem remains, however, how to gain and sustain the interest of future university students in studying science.

Sparking student interest in science

There are many reasons for the declining interest in the physical sciences. There is no glamorous image in the media which portrays the life-style of a physical scientist in the same way as there is for the Forensic scientist. While this is the most obvious difference, it is not the prime reason for the lack of interest. First, the physical sciences are perceived as difficult especially given that a firm grounding in mathematics is essential. Many

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current high school students struggle with mathematics and hence scientific pursuits are made even more difficult. Secondly, students see very limited, poor paying career options in the sciences. This is especially true in comparison to other endeavors such as law, medicine or business, which seem to attract a considerable portion of high achievers in the physical sciences from high school.

While these are contributing factors, we believe the main reason for the lack of interest stems from the general perception that there is nothing left of interest, or benefit, in the realm of 'hard' physical sciences. There are a number of examples to illustrate this point. In the post-war years, especially when the space race was in full swing, or the semiconductor industry was beginning to develop, interest in physics and chemistry was perhaps at its highest point. There were obvious, interesting and worthwhile challenges for science that captured the imagination of the general public. This is particularly true of the space-race—what more provocative image for science than a live TV broadcast from the Moon! In recent times, this focus has shifted, and the 'soft' biologically-oriented sciences are now perceived as the key to the future. Clearly, these issues are to some extent driven by the demands and agendas of industrial and political concerns. The general perception today of the physical sciences is that all the interesting problems have been solved, and that physical science will not contribute to society in such a significant way in the future.

The perceived lack of interesting problems and applications leads to a lack of interest. This has put many science departments and in particular physics departments under tremendous pressure, a problem that is especially acute in Australia where student numbers directly determine the vast majority of income for a university, faculty or department.

This is where nanotechnology enters the picture. Nanotechnology has appeared in a variety of media over the last few years, so clearly interest is growing. Most scientists know that physical science is a thriving and constantly developing area. While many of these advancements are critical for future endeavors, they do not necessarily capture the imagination of the general public, or specifically, young students. Nanotechnology is, in some sense, the stuff of fantasy that can stimulate public interest. It is a technology that is still in its infancy, yet will clearly shape our futures with wide-ranging applications from human implants to quantum computing. Nanotechnology does have the potential to solve difficult and currently unsolvable problems with the most mind-boggling and in many cases beautifully simple solutions. Nanotechnology is a captivating example of the importance, excitement, need and challenge for the physical sciences that can again be brought into public view. Given this, interest in these sciences can be rekindled.

The importance of educating young, talented scientists in nanotechnology cannot be underestimated. As outlined, there is little doubt that the technology will be vital in the near future and given this, the importance of bright, well-prepared people to provide the foundations of progress in future nanotechnological applications is obvious.

In the first two years, the course at Flinders has been over subscribed by a factor of 3 for first preferences (people naming the course as their first choice) and a factor of 6 for people naming the course as one of their preferred options. It is worth noting that a requirement for entry into the course is high school level chemistry, physics and mathematics. The students entering have a strong physical sciences background. Clearly, the first hurdle has been cleared—people are interested in nanotechnology and physical sciences.

COURSE DESIGN

Structure

In developing our course structure for nanotechnology we were acutely aware that the science content should not be decreased with respect to a 'traditional' science degree in physics or chemistry. Indeed, to give students anything less than a very firm underpinning in all the basic areas of chemistry, physics and biology would do them a great disservice, as this knowledge will be the basic understanding needed in the careers for which they are preparing.

This raises the first issue faced in designing a Nanotechnology Degree. The field is currently in its infancy and is incredibly broad, spanning chemistry, physics, biology, mathematics and engineering. This is in fact probably an incomplete list but it makes the point: How do you possibly teach all these areas to students in a four-year honours degree? The simple answer is, you don't, and after two years of experience, we still believe this to be the case. Given the expertise at Flinders and the emerging strengths of nanotechnology research in Australia, we have divided our course into two streams—Biodevices and Nanostructures. The structure of the entire course is given in Table 1.

The Biodevices stream is centered across chemistry and biology. It starts from the point of the classic glucose biosensors [4] and then moves to more novel, self-assembled biosensors such as the AMBRI ion channel biosensor [5] and then will move to the use of biological elements as building blocks, etc. The Nanostructures stream is centered across chemistry and physics. It concentrates largely on the roles of surface science and light in forming and probing nanostructures such as quantum dots, [6] nanoparticles [7] or atomic arrays [8]. Just as importantly, some of the topics will concentrate on the applications of these structures. The light aspects of this stream are introduced for two reasons. First, photonics is an active research area and is rapidly developing a strong industrial base

Table 1. Current course structure

First year	
CHEM 1101/1102 Chemistry 1A/B	
PHYS 1101/1102 Physics 1A/B	
MATH 1121 Mathematics 1A	
NANO 1101 Nanotechnology I/NANO 1102 Professional Skills for Nanotechnolgy	
Biodevices Stream	*Nanostructures Stream*
BIOL 1102 Biology 1B	MATH 1122 Mathematics 1B
Second year	
ECON 1002 Economics for Nanotechnology	
COMM 1007 Management for Nanotechnology	
CPES 2002 Instrumentation for Scientists	
CPES 2004 Quantum Phenomena I	
Biosensors Stream	*Nanostructures Stream*
CPES 2009 Analytical Chemistry	CPES 2003 Thermodynamics
CPES 2006 Electrochemistry and Kinetics	MATH 2023 Maths for Physical Sciences
CPES 2006 Organic Chem. 2A	MATH 2111 Vector Calculus
BIOL 2101 Laboratory Skills for Biologists	CPES 2011 Chemical Bonding & Structure
CPES 2011 Chemical Bonding & Structure	CPES 2012 Electromagnetism
BIOL 2220 Molecular Biology	CPES 2007 Optics and Lasers
NANO 2200 Biodevices 1 (includes lab)	NANO 2100 Nanostructures 1 (includes lab)
Third year	
ECON 2014 Science-based Enterprises for Nanotechnology	
Biosensors Stream	*Nanostructures Stream*
CPES 2006 Organic Chem. 2B	CPES 3001 Stat Mech
CPES 3007 Applied Spect. & Anal. Tech.	CPES 3002 Exptl. Data Anal. 2
CPES 3xxx Solution Inorganic Chem	CPES 3004 Solid State and Surface Science
BIOL 3112 Molecular Cell Biol.	MATH 2121 Linear Alg. & Diff. Eq.
BIOL 3171 Molecular Cell Biol. Lab	CPES 3005 Quantum Modeling
CPES 3009 Biol. & Inorg. Chem.	CPES 3003 Quantum Phenomena 2
CPES 2009 Anal. Chem.	CPES 3020 Optoelectronics
NANO 3200 Biodevices 2 (includes lab)	MATH 3013 Complex Analysis
	NANO 3100 Nanostructures 2 (includes lab)
Fourth year	
Honours course work and research project	

in Australia and, hence it can provide employment opportunities for our graduates. Second, developments in photonics in the near future are moving into the realm of nanotechnology.

Significant parts of the two streams are common. Indeed, this reflects the fact that some basic mathematics, physics or engineering, chemistry or biology are fundamental to understanding how to build structures even those on a nanometre scale. The physics and engineering aspects address the forces that make stable structures while chemistry and biology specifically look at the possible building blocks for those structures. In the future, there is a real possibility that the two streams may merge into one as the directions of nanotechnology and its applications become more focused.

In both streams, at least two-thirds of the students' time is still dedicated to basic science whether it is cell biology, thermodynamics or electromagnetism. The other two main components of the course are enterprise management related topics and topics specifically called nanotechnology as indicated by the NANO prefix in their number.

The enterprise management topics are non-science topics in areas such as economics and commerce. As well, in the honours year, the student will be asked to write a business plan based on an commercial idea they initiate. The main reason for the inclusion of these topics is that we believe many of the students will have career paths that lead them into industrial settings where business skills are highly rated alongside traditional science skills. Further, given the infancy of nanotechnology, we believe that graduating students will play a key role in the development and commercialisation of the technology in Australia. The topics in the course are meant to give the students a basic (but by no means complete) introduction to business and management issues. Two of the topics will be touched on in more detail later.

The nanotechnology topics strive to take the basic science presented in each year and apply that knowledge to specific examples of nanotechnology. We hope that this has the effect of tying all the basic science together for the students and shows them that the sum of the parts does make the amazing experiments that underpin nanotechnology applications possible and understandable [9]. Of course, with any luck, an underlying effect here is that students' interest in the basic science is also stimulated. It has some relevance to them.

Process

Students arrive in the course with quite strong science backgrounds. Prerequisites for the course are final year chemistry, physics and mathematics. We build on existing skills in three main ways. Firstly, student interest in their basic science program is maintained by showing them the relevance of the topics from the outset of the course. Secondly, the first year of the program is designed to help students learn how to acquire and assess information independently. Finally, the important issues, both scientific and non-scientific, that students will face as part of the course and beyond are addressed repeatedly both in a formal sense through lectures etc. and an informal sense through group work, presentations and debates [1, 10].

Content

There are a variety of educational issues that were faced in developing the topics for the course. In addressing these we hoped to address some issues that currently face perhaps most university degrees. Starting afresh was an advantage in this respect as new topics could be designed to meet particular goals and address different difficulties that students might face.

NANO 1101: Nanotechnology I. From the structure in Table 1, it is obvious that the students have to make one choice in first year depending on the stream they think they will follow in second year and beyond. Basically the decision is to do mathematics and follow the Nanostructures stream or do biology and follow the Biodevices stream. This decision must be made half way through first year. This is not an ideal situation, as we would prefer to delay this decision until beginning of second year. Unfortunately, we have not, so far, found a way of implementing a structure to achieve this.

Given that the students have this choice to make, Nanotechnology I is offered in the first semester of first year to help define for the students the broad areas of the two streams. This is done through two projects—one based on the ion channel sensor [5] and the other on quantum computing [11]. Students work in groups of six and at the end of the project present both a written and oral report. As part of this process students maintain work log books to enforce the importance of recording of their activities whether in be in a lab recording data or a literature search [12]. Students do all the research on the project topic and critically evaluate the information that they find with the help of a group leader. This starts to develop team skills, critical evaluation, report writing skills and oral presentation skills that are highly valued in the current employment market [10].

More importantly however, it starts the students thinking about the scientific issues that are important in nanotechnology:

- How can structures of nanometer-sized dimensions be built and examined?
- What are the possible applications and uses of these structures?

Can a student understand the intricacies of a quantum computer at the first-year level? Of course not. However, given that they have now discussed the issues in quantum computing, they will understand the importance of basic quantum mechanics. The approach of presenting the big picture conceptualizes the micro learning students undertake in individual topics meaning that when core topics are undertaken in the second and third year, students appreciate their relevance and importance. This is vital given that relevance is a major motivational factor in student learning.

We have in essence tried to answer the question 'Why do I have to learn this?' Often in current university education, this question is answered in a student's final year and many university lecturers seem to be upset that a student would query why they need to know something before then. This does not seem like an unreasonable request and we have used this topic in an attempt to show the students the importance of the basic science in larger issues.

NANO 1102: Professional Skills for Nanotechnogists. This is the first 'non-science' topic that the students undertake and its prime goal is to introduce them to some non-science issues that will in all likelihood be important in their careers. These issues are tackled in three ways. Firstly, a variety of scientists are invited to talk to the students regarding their own careers and the important skills—both scientific and non-scientific—a scientist must possess in the current work environment.

Secondly, the students undertake a series of problem-based learning (PBL) tutorials examining various scientific commercialisation issues such as corporate culture, intellectual property, etc. [1, 13]. PBL tutorials involve the presentation of scenarios to students in a series of steps called triggers. As a group guided by a tutorial leader, students debate, discuss and argue points related to the case presented. In doing so, they first identify the important issues and then, with some research between the tutorials, answer some of their own questions. This is a very effective way of presenting material to students and they tend to engage more deeply in the learning from this approach than they would in the classic lecture only approach. The tutorial learning is strengthened by a series of lectures from people who are experts in the various fields. Further, a subset of the students is then given an 'argument' to contest. This might be a debate, presentation to an enquiry or court case where the students have to argue a particular position. The intention is that this starts to develop the students' ability to present rational arguments based on the facts they find.

Thirdly and finally, the students again work in groups on a project that is based on a scientific idea that has become a commercial success. Some projects include the laser and global positioning system. Students are asked first to understand the scientific basis of the product and then try to learn something about the step from scientific discovery to commercialisation. Again, oral and written reports are required from each group.

Other NANO topics (NANO 2100, NANO 2200, NANO 3100,NANO 3200). There is a dedicated nanotechnology topic in both second and third year for each stream. As nanotechnology is a new science, these topics are quite difficult to put together and much of the material is drawn from the current literature. The most important aspect of the lecture component of these topics is that they draw on students' exposure to basic science to help explain new, exciting applications in nanotechnology. For example, when teaching electronic transport in confined nanostructures, understanding of concepts such as quantum mechanical tunneling and band theory of solids is vital. This again reinforces the relevance and importance of these basic sciences and helps to sustain their engagement with the broader ideas and concepts in science.

Each of these topics also has a lab associated with it. The fact that we started with a new topic, and hence no existing practicals, was a real bonus despite the fact that this meant a large amount of extra work was required. We were able to design new labs many based on very recent literature. Some labs include kinetics using STM, imaging of self-assembled monolayers using STM, various syntheses and measurements of nanoparticle properties, porous Si experiments, construction and characterisation of a solar cell, etc. The complete list is given in Table 2. The theme in these practicals is to again use basic science (often from a couple of different areas) to understand new, exciting applications. Some of the labs are dedicated to just one stream or the other while about two-thirds of the practicals are designed to stretch across both streams.

Table 2. Labs for second-year nanotechnology topics

Experiment 1	STM of Monolayers
Experiment 2	Surface Oxidation of Graphite
Experiment 3	Kinetics and Thermodynamics of Au Colliod Monolayer Self-assembly
Experiment 4	Nanostructured Titania Solar Cells
Experiment 5	Liquid Crystal Displays
Experiment 6	Contact Angle Experiments on Self-Assembled Monolayers
Experiment 7	Luminescence in Porous Silicon
Experiment 8	Vacuum Evaporator
Experiment 9	Rutherford Scattering of Alpha Particles
Experiment 10	Glucose Oxidase Enzyme Biosensors, Part A
Experiment 11	Glucose Oxidase Enzyme Biosensors, Part B
Experiment 12	Plant Tissue-based Voltammetric Biosensor

Each component (theory and practical) is innovative in the use of current literature as the basis for the topics explored. In the theory section, not only are basic scientific concepts extended to the new applications at the core of nanotechnology but possible future directions are explored and discussed. The discussion of the current applications always includes possible scientific and engineering problems. The innovative forward looking approach is both exciting for the students and provides the opportunity to discuss future directions of nanotechnology. Practicals center on the use of applications (often current) to understand basic science and engineering problems. The engineering education often comes through hands on construction of devices while the scientific concepts are probed through measurements using those devices. Finally, the specific nanotechnology topics are presented as a complete package of theory and practical knowledge. It is largely accepted that this is the best approach to scientific education. As both sections of the topics were written at the same time by the same people, this integration has been possible in these topics.

The final innovation in these topics is that in third year students undertake a two-week placement in a research environment. These experiences will be in universities, research institutes and industry. Students will report on their placement when they return to help educate other students regarding the breath of nearby research activity and possible future employment opportunities.

ECON 3011: Science-based Enterprises. This is the final topic that students take in the stream of non-science topics. It attempts to tie all the previous ideas into one topic where the students are given a case study of a new nanotechnology company and must make critical comment as they would in any other business case. The intention is that the students undertaking this topic appreciate that the skills developed could well be ones they will use in their careers as scientists especially in a small company.

Honours

The final year of the degree is divided into two parts. The first is based in course work—as before both scientific and non-scientific. The scientific courses are fourth-year basic science courses while the non-scientific courses involve the production of a business plan based on an idea produced by a small group of students. The second part of the honours year is a research project. The student will spend about 5 months working as a research student in one of the labs at Flinders or perhaps elsewhere on a project of current interest. At the end of the research project, the student again must present an oral seminar and a written thesis. This combined effort of research (science) and business activities will draw together and call on the student's experiences and knowledge gained over the previous three years [2]. Further, it presents them with the exact situation they may encounter after they finish their degree and prepares them to handle those situations.

PROGRAM ASSESSMENT

The course at Flinders is about to start its third year. Given the entire program is not currently in place, it has not been assessed as a whole. Each year is being put in place as the first group of students move through the program. This approach is allowing changes to be made to each year of the program so that the final course is the best it can be. Of course, there have been no graduates from the program so it is impossible to assess student employability. It should be stated though that a variety of employers are constantly being consulted to ensure students are getting the appropriate background.

Individual components within the course have been assessed both formally and informally. Student surveys for all nanotechnology topics are carried out at the end of each semester. In addition, there is a course advisory group that meets twice a year where students are free to discuss any aspect of the course. Finally, the course coordinators talk to the students informally on a weekly basis to help identify any problems. All these assessments have shown that for the most part the students are quite happy with the course. A few modifications to topics have been made after discussions with students and these changes have generally had very positive effects on the topics. The interaction with the students means they have a much more direct input into the decision-making process involved in the course. This is one of the innovative things about the course and has been very positive for all concerned.

FUTURE DIRECTIONS AND CONCLUSION

The third year of the course is now in place. The honours year is in the process of being set up and the involvement of people from outside Flinders especially in research projects is being developed. We have helped several other universities within Australia establish nanotechnology programs which begin in March 2002. We would welcome discussions with other institutions both to help establish new programs elsewhere and improve our own program at Flinders.

The Bachelor of Science in Nanotechnology degree is currently in its second year at Flinders University and has proven very successful. Interest in the physical sciences by very capable students has been affirmed by the numbers who have decided to undertake the degree. Thus far the new topics that are part of the degree have been successful and provided students the opportunity to discuss issues, both scientific and non-scientific, which will be important both to their careers and to the future of nanotechnology in Australia.

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Michael J. Ford, between short intervals as an electronic engineer, undertook his studies at Southampton University, UK, and graduated with a Ph.D. in Physics in 1989. From there he has pursued post-doctoral research and teaching positions in Australia and the US until joining the faculty at Flinders in late 1996. His interests have centered on fundamental studies of atomic-collisions as a probe of the co-operative motion of electrons within atoms. Using techniques developed from this work his interests now lie with condensed matter systems and understanding the electronic motion at a fundamental level and its relation to materials properties.

Leone Maddox obtained a B.Sc. and M.Sc. from the University of Auckland and a Ph.D. from the University of Western Ontario in the area of electrochemical and surface analysis of single crystal mineral samples. Her research has involved examination of gold extraction from clay ores and electrochemical concentration of oxygen from air for respiratory applications. She has been teaching at Flinders since 1997 in a variety of topics and is currently developing and presenting the lecture component of the Biosensors stream of the nanotechnology degree.

Eric R. Waclawik obtained a B.Sc. (Hons.) degree in physical chemistry (1991) and a Ph.D. in laser spectroscopy, investigating energy transfer in polyatomic and diatomic molecule collisions (1996) at Flinders University. In 1997, his postdoctoral research began at the University of Toronto investigating the dynamics of gas scattering at liquid crystal interfaces using molecular beam and laser spectroscopic techniques. In 1998, he moved to the University of Exeter to investigate properties of isolated molecular complexes by Pulsed Nozzle Fourier Transform Microwave Spectroscopy. Currently, he is developing and presenting lectures and laboratory components of the Nanostructures I course for Flinders' Nanotechnology degree.