A critical look at undergraduate teaching of Materials Science

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1. What do we want our students to learn?

We can probably all agree that any degree course should strive to achieve certain general educational aims. It should teach students to analyse ideas and evidence critically, it should develop the ability of students to think logically and creatively to solve problems, and it should enable students to understand general principles within a subject and apply them to unfamiliar situations.

There are also professional qualities we wish to develop in our students - the ability to work in teams, to communicate orally and in writing, to manage projects and their own time. We want our students to have some appreciation of the role of the scientist/engineer in society, how to manage professionally, and some understanding of safety and risk analysis. Many of these professional qualities were initially forced upon us by accreditation, but both staff and students recognise that they render our students more attractive to employers.

We want our students to have a factual knowledge base on which to understand concepts about the structure, properties and processing of materials, and the relationships between them. We would also like our students to be able to go beyond the familiar so that hitherto unmet problems can be tackled in ways that would not be unlike those we might try. The general educational aims and the professional aims are to be attained through teaching the materials content of our degree, not by teaching stand-alone courses on working in teams etc.

2. Our current approach to teaching

Let me attempt to hold up a mirror to how we currently approach our undergraduate teaching. I think most of us see the task of teaching undergraduates as the transmission of authoritative information about materials. The knowledge to be handed on to students at this level is relatively clear-cut and straightforward. The content of our lecture courses is mostly well-established stuff, and our task is to instill it in students. Tutorials are a vital supplement to lectures, but by and large the content of the degree is presented to students in lectures. This view of higher education is consistent with the Robbins Report, endorsed by the 1987 White Paper, in which key functions of higher education were specified as transmission of culture and instruction in skills.

Many of us, staff and students, believe that the fundamental problem we face lies in the amount of information to be transmitted during lectures and assimilated in lectures and tutorials. Some of us wonder whether this problem can be solved by technical fixes to transmit more information faster, such as increased use of computer presentations, use of the internet and so on.

The lecturer's role is seen as communicating knowledge. It is both necessary and sufficient that s/he should be proficient in the subject matter. This way of teaching is about what the lecturer does to students. Student learning will take place as long as a quantity of information gets across to students. As long as the lectures are clear and information is transmitted then any failure of students to learn is the fault of students. When students sometimes say to us that they are ignorant of a particular topic, even though we know they have attended lectures on it, we are inclined to say 'But you did go to the lectures last term didn't you?'.

Most of us probably believe that there are good learners and poor learners, determined by student ability and willingness to work hard. The implication is that problems in teaching and learning reside outside the lecturer, the degree course, or even the University. Increasing the standard of admitted students is one typically mentioned remedy to the problem of poor learning, in addition to technological solutions to transmit knowledge.

3. What do our students learn?

I believe that most of our students learn an *imitation* materials science, a fake mixture of terminology, derivations, facts, 'right' answers to standard questions, manipulations and memorised descriptions. Many of our best students are over-dependent on us as sources of insight and information, and they are unaware of what they do not know. When asked simple, yet searching questions they quickly reveal a poor grasp of the fundamentals. But they have appropriated large amounts of detailed factual knowledge, which they could reproduce for a short time centred on Finals.

This is not a new problem, nor is it unique to our course. In 1929 A N Whitehead wrote in his famous essay *The Aims of Education* the following:

I have been much struck by the paralysis of thought induced in pupils by the aimless accumulation of precise knowledge, inert and unutilised .... The details of knowledge which are important will be picked up ad hoc *in each avocation of life, but the habit of the active utilisation of well-understood principles is the final possession of wisdom.*

Robert Pirsig, writing in *Zen and the Art of Motorcycle Maintenance*, added a twist:

Schools teach you to imitate. If you don't imitate what the teacher wants you get a bad grade. Here, in college, it was more sophisticated, of course; you were supposed to imitate the teacher in such a way as to convince the teacher you were not imitating.

If you are willing to go along with my assertion that our students study an imitation materials science let us consider why this happens. Students very quickly adapt to the requirements they perceive teachers expect of them. They usually try to please their tutors. They do what they think will bring them rewards in the system they are in. They respond to the demands they perceive we make, and they are not necessarily the same demands we would like to think we make of them. This divergence between intended and actual outcomes is apparently ubiquitous in higher education.

There is a lot of evidence in the educational literature that students are painfully aware that the superficial approaches to learning they are using will lead to inferior understanding, even though their examination results may be good. There is also a great deal of evidence that students find superficial approaches to learning deeply frustrating and alienating.

Our Finals papers are perceived as tests of ability at reproducing vast amounts of factual information and derivations. We cannot tell students not to imitate when they look around them and see that imitation, suitably disguised, appears to them to be what we want. We collude in this process. We rarely ask questions in Finals that test understanding. Our style is almost always to ask students to regurgitate factual information, derivations, simple estimates that they have already done in lectures and tutorials. Whenever we have framed a question that involves the application of concepts to unfamiliar territory very few students get it right, and most avoid the question altogether. Consequently we tend not to ask such searching questions. At examiners meetings we ask of each proposed Finals question 'is this question likely to be attempted?'. We all know the answer is 'no' if the question looks unusual or unfamiliar, even though it may be a direct application of taught material but in a new context. So we ask 'safe' questions that do not test understanding 'to be fair to students'. Is it any wonder then that students study in a very superficial way when we examine them in a very superficial way? If students study an imitation materials science it is at least partly because we subject them to an imitation assessment in Finals.

But our assessment methods are not the only reason for students choosing to study an imitation materials science. Perhaps the most significant factor is the work-load. The work-load is such that most students do not feel they have the time to think carefully about much at all. We don't help by not telling them at the beginning of each course what the key ideas and concepts are, and what they are expected to learn and be able to do at the end of each lecture course. They see a vast mass of information, disconnected facts, and formulae with symbols whose meaning they have not fathomed. They do not see a conceptual framework to guide them through the subject and make links of understanding with other courses. Students feel they have no control over their learning because it is all a great rush to try and cram everything in. They lose interest and drop core material to try and make space for subjects they feel they can understand properly if only they can make more time for them.

4. Suggested remedies

There are two things we should do immediately:

(a) The first is to define aims and objectives for the whole degree course, and then for each and every lecture course. These should appear in the course handbook so that every student is aware of what s/he is expected to know and be able to do after each lecture course. Aims may be defined as general statements of educational intent, seen from the students' point of view, while objectives are more specific and concrete statements of what students are expected to learn. I have attempted to provide an example of defining aims and objectives for one of our courses in section 6. All the research that has been carried out in higher education, in all subjects, shows that students regard clear aims and objectives as essential for an effective educational experience. Lack of clarity about the aims and objectives is always associated with poor evaluations, learning difficulties and poor understanding. The purpose of expressing aims and objectives is to improve the quality of education in two senses. (I am using the word 'quality' here in the true sense of the word). First, we cannot teach if we do not know what we want our students to learn. The act of expressing aims and objectives should enable us to think more critically about the educational progress we expect students to achieve, and to design appropriate methods of teaching and assessment to achieve that progress. Secondly the results of the exercise should make clear to students exactly what they have to learn to succeed, and what they can leave aside.

(b) Secondly, using these aims and objectives as templates we should ruthlessly prune. The degree should focus entirely on ideas, concepts and the ways that materials scientists think. Facts are important but *not* as an end in themselves - they motivate the scientific process, they define the diversity and complexity of materials that we seek to explain through theories and models, and they enable us to gauge our understanding by testing our models. Facts have no life outside those who interpret them, and in themselves they imply neither knowledge nor wisdom. Students have to be able to make sense of the data we give them, otherwise it will not stay with them. The pruning will be painful. But 'covering the ground' does not imply that students will cover it, especially if they cannot see why it is included or find the time to internalise it. And by having a set of aims and objectives for each course we will have criteria for what should be cut. Objectives must be continually presented to students in order to provide a clear framework in which they can work. They must be embodied in all that the lecturer says. They force us to make our intentions for student learning explicit. In this way we will avoid turning our students into 'little living libraries of disconnected facts', and instead turn them into critical thinkers armed with a useful knowledge and a deep understanding of materials. That is what we want, our students want, and their employers want. A N Whitehead again hit the nail on the head:

We enunciate two educational commandments, 'Do not teach too many subjects', and again, 'What you do teach, teach thoroughly.' The result of teaching small parts of a large number of subjects is the passive reception of disconnected ideas, not illumined with any spark of vitality. Let the main ideas which are introduced into a child's education be few and important, and let them be thrown into every combination possible. The child should make them his own, and should understand their application here and now in the circumstances of his actual life.

I have been very struck by another aspect of teaching, which I hope we will strive to implement.

Teaching should be a process of working with students to help them change their understanding. It should be about making student learning possible. Teaching should involve finding out about students' misunderstandings, intervening to change them, and creating a context of learning which encourages students to engage with the subject matter. A lecturer who adopts this approach will recognise and focus on the issues that are critical barriers to student learning. To a large extent this aspect of teaching is what our tutorials are meant to provide. But in my experience, which I know is not unique, students frequently fail to see the wood for the trees even in tutorials because they are overwhelmed by the sheer volume of information.

This aspect of teaching views learning a first year course and engaging in research as qualitatively similar processes. Both involve elements of discovery and deep thinking, but of course undergraduate students are provided with help in overcoming learning barriers, which is not available to researchers. But the way in which deep knowledge is obtained does not differ in research and this form of undergraduate teaching. Learning is something the student does, rather than something that we do to the student. 'Transmission of knowledge' is a misleading notion because all knowledge is new and requires to be decoded and internalised if you have not met it before. The thinking underlying this approach to teaching is neatly summarised in the following quotation from Bruner's book *Toward a Theory of Instruction* (1966):

A body of knowledge, enshrined in a university faculty and embodied in a series of authoritative volumes, is the result of much prior intellectual activity. To instruct someone in these disciplines is not a matter of getting him to commit results to mind. Rather it is to teach him to participate in the process that makes possible the establishment of knowledge. We teach a subject not to produce little living libraries on that subject, but rather to get a student to think mathematically for himself, to consider matters as an historian does, to take part in the process of knowledge getting. Knowing is a process not a product.

5. Aims vs. content

If we were asked we could all describe the progress we expect our students to make during a lecture course. But rather than expressing our answer in terms of objectives for the course many of us might frame the answer in terms of the syllabus of the course. This amounts to a statement of what we will be teaching rather than what the students will be learning. Specification of the content to be taught does not indicate how the content contributes to students becoming materials scientists. We must ask what we expect our students to learn and why we want them to learn it. What changes in understanding do we expect students to undergo as a result of experiencing each lecture course, and what will students be able to do as a result of these changes, after they complete the course? Specifying the syllabus of the degree is not enough.

6. An example of specifying aims and objectives

Consider a core undergraduate course on Quantum and Statistical Mechanics.

Its aims might be 'To demonstrate the relevance and application of quantum and statistical mechanics to understanding bonding, electrical, kinetic and thermodynamic properties of materials'. Students will have some understanding of these aims even before they have taken the course.

The objectives might be:

- To understand why quantum mechanics is essential to explain chemical bonding, electrical conduction, the operation of the electron microscope and the tunnelling microscope, the electronic specific heat of metals, and the vibrational specific heat of all solids.
- To derive the energies and eigenfunctions for a particle in a box and the energies of the harmonic oscillator, using the Schrodinger equation. Using these solutions to verify the uncertainty principle and provide an interpretation of the wave function. Understanding how and why electrons in a metal may be modelled by particles in a box in terms of the work function and the concept of jellium. To understand the concept of k-space, and to use it to count quantum states and obtain densities of states for electrons in a 1D, 2D and 3D metal.
- To understand the concepts of indistinguishability of particles and exchange, and how these concepts lead to the classification of particles as fermions or bosons. To understand how these concepts lead to the Pauli exclusion principle for electrons, and to understand the implications of this principle for the thermal and conduction properties of electrons in metals.
- To understand in outline the radial and angular solutions of the Schrodinger equation for the hydrogen atom, and how they lead, in conjunction with the Pauli exclusion principle, to the structure of the Periodic Table.
- To explain the origin of bonding and anti-bonding states in diatomic molecules, and to explain qualitatively the variation of the cohesive energy across the 4d and 5d transition metal series.
- To understand the concept of microscopic states of a system and the derivation of the entropy in terms of them.
- To derive the Boltzmann distribution, and to understand why exponential 'Boltzmann' factors arise in thermally activated processes.
- To understand the concept of the partition function as the link between the microscopic quantum states of a material and its macroscopic thermodynamic properties. To understand the equivalence of the concept of equilibrium in both the microscopic sense of

competing dynamical atomic processes and the macroscopic sense of equality of free energies.

- To understand qualitatively the Fermi-Dirac and Bose-Einstein quantum distributions and to use them to explain the electronic specific heat of metals and the Einstein model of the vibrational specific heat of all solids respectively. To use the density of states and the Fermi-Dirac distribution to derive the relation between the Fermi energy and the electron density in a metal, and the total kinetic energy of electrons in a free-electron model of a metal.

Students won't understand these objectives until they have taken the course, but they act as sign-posts telling them what they are expected to learn. They make clear the concepts that underlie the content, and they also point to topics that appear in other courses. In this way the student is able to develop a concept map for the whole degree, in which different lecture courses are related by common concepts. It is only through such a mental concept map that our students will see the unity of materials science as a discipline.

7. Pitfalls in specifying objectives

It is easy to specify the objectives of a course in a superficial way. For example for a course entitled 'Binary phase diagrams' we might specify the objective as 'To acquire knowledge about binary phase diagrams'. This provides students with no extra information about what they have to do. What does it mean to acquire knowledge about binary phase diagrams? It must imply an understanding of their construction from free energy-composition curves, and thermodynamic constructions such as the phase rule and the common tangent rule. So we might try, as two objectives related to this course 'To explain the construction of binary phase diagrams from free energy-composition curves' and 'To show how the laws of thermodynamics are embodied in the construction of binary phase diagrams, through the phase rule, and the common tangent construction'.

A second possible pitfall is to express the objectives of the course vaguely and virtually free of content: 'To become more critical of established theory', 'To introduce the principal concepts in mechanical properties'. Again, such statements do not help students to understand what they have to do.

8. Conclusion

Specifying aims and objectives is not a cure for all the concerns I have raised here. But it is definitely a step in the right direction, especially if it is followed by thorough pruning of the course content, and by changing the style of our Finals questions so that they test understanding rather than memory. In this way we will put in place a robust framework for defining the content of a first degree in materials science. The framework will be an invaluable aid. Our students will be able to use the framework to guide them through the degree, to see the inter-relations between seemingly disparate lecture courses, and to concentrate their efforts on understanding and thinking rather than memorising. None of this will be easy or painless, but I hope colleagues will agree that it is the best way forward.

Further Reading

Paul Ramsden has written a very readable and thought-provoking discussion of learning and teaching in higher education, summarising a great deal of research in an illuminating and useful way. Many of the ideas in this paper have been taken from his book – all I have done is apply some of them to materials science. The title of his book is 'Learning to teach in higher education', published by Routledge, ISBN: 0-415-06414-7.