Innovative pedagogical practices

Undergraduates as Interdisciplinary Researchers

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Introduction

The ancients attributed propitious events to the conjunctions of the stars. We no longer look to astrology for guidance, but we still need a confluence of affordances to achieve major changes in any collective endeavour, and especially in the ways we teach in higher education. Ideas have single parents but need many midwives to bring them to fruition. So it is that this is the story of a chance conversation in a car park, a threatened dearth of physics students, an open-minded professional body, a trusting pro-vice chancellor and a funding council with funds to disperse and not entirely averse to risk. It is the story of an undergraduate programme of interdisciplinary science, now in its twelfth year, which has brought together a new science curriculum and a variety of novel pedagogies in response to a diverse set of drivers. I will discuss the drivers behind this programme, the way it was developed and the lessons we might take away more generally towards a personalisation of the curriculum for the 21st century undergraduate.

Drivers

Since these drivers did not appear at fixed moments in time, and their importance has varied over the course of development, I consider them here in no particular order.

Interdisciplinarity

The idea that students should be knowledgeable across disciplines has been a key driver in the pedagogic developments that I am going to discuss.

At the research and postgraduate level in science we have seen an increasing emphasis on interdisciplinarity, including research into interdisciplinarity itself (Frodeman, 2012). Many of the problems we face as a society, many of the intellectual challenges, are inherently interdisciplinary. Obvious examples are climate change and astrobiology (the search for extra-terrestrial life). But, for the most part, this has had little impact on the undergraduate curriculum, which is still either discipline-based or multi-disciplinary. Some programmes, such as oceanography or climatology focus on specific areas of interdisciplinarity, but are in essence sub-disciplines with their own methods and norms. By interdisciplinarity I imply the general use of techniques and viewpoints across discipline boundaries. To give one example, students might use a model of the flow of blood as a viscous ideal fluid in a pipe, thereby applying ideas from physics in a biological context. This requires knowledge from the two disciplines both to set up the model and to understand its limitations. It is quite different from multi-disciplinary knowledge, which, in this example, would involve separately the physics of the flow of a viscous fluid and the biology of blood flow. Interdisciplinarity also differs from transdisciplinarity, which is concerned with the study of concepts that transcend discipline boundaries, for example notions of equilibrium, energy, and entropy. Or, to take an example from another context, Gender Studies is obviously transdisciplinary.

Employability

In addition to content and process knowledge, as part of the employability agenda we also aim for students to be able to communicate effectively orally and in writing and to achieve fluency across disciplines. Thus, employability was an important driver from the outset. I wanted to address this through a pedagogy for which the requisite skills would be embedded in the core programme. The fact that skills are embedded, and the subject content is integrated, act as counterweights to the potential superficiality of the programme. The approach ensures that students reach higher level learning and content across the disciplines: it is not science-lite.

Supporting Science

Another driver came from the Institute of Physics (IOP) with the need to respond to the declining numbers of physics graduates at the start of the millennium (IOP, 2001). Physics did not experience the increase in student numbers commensurate with the increasing participation rate in higher education over the last twenty years. By 2000 the numbers were actually in absolute decline and between 1994 and 2001 the number of universities offering physics degrees dropped from 79 to 53 (IOP, 2001). The Institute market tested a number of potential initiatives on the supply side, one of which was an interdisciplinary (or "integrated") science degree which would set physics in a broader context. In this way, instead of preaching about the central importance of physics, one might try to demonstrate it. Thus we had external justification to support an interdisciplinary degree, although not at this stage any financial support (apart from a small marketing budget).

Widening participation

Initially an integrated approach to science was also strongly linked to the widening participation agenda. The idea was that an integrated degree would be a way into university physics for students from schools (of which there were many – IOP, 2010) that lacked the benefit of a specialised physics teacher, and hence without perhaps the support to achieve the grades or preparation required for a pure physics programme. This has been somewhat in tension with our University's demand to drive up entry grades, but in any case it is not a viable financial model because there are too few such students who have the ability to operate across the sciences effectively. Nevertheless, the entry conditions require only two sciences, one of which may be mathematics, so is still weakly linked to widening participation in STEM. We shall come back to "added value" below.

The rise of student-centred learning

There has been growing recognition in STEM subjects of the importance of a student-centred approach to teaching and learning, with some attempt to move away from entirely passive learning in lectures to more active participation and to some group work (Raine and Symons, 2005). The acceptance that this is a good thing provided a receptive, if sceptical audience for our proposed curriculum design: we would deliver the whole core programme through problem-based learning (about which more below). This has somewhat accidentally morphed to include the *personalised curriculum*, a driver that will become our main focus here.

The personalised curriculum is an aspect of current thinking around curriculum co-creation and student-staff partnership. Like much of what I will write about below it is part of the process of treating students as professional scientists and not as professional students. As practicing scientific researchers we choose the topics we work on. It is probably unrealistic to think that students might spend three years freely choosing what they will study (and some extensive guidance is required before you can tackle superstring theory, or the ever-popular black holes), although the existence of MOOCs might begin to challenge that assumption to some extent. But some freedom to explore might be something worth having if it encourages students to take ownership of their learning. Co-creation of curriculum usually focusses on creating materials for the cohort (Healey et al., 2014). In contrast, the personalised curriculum envisages the student creating a course individually for them self.

With these drivers as backdrop we created the Centre for Interdisciplinary Science to develop and deliver the programme. As a consequence of my departmental affiliation, the Centre was (and is) administratively part of the Department of Physics and Astronomy, but its only role is to deliver the Natural Sciences programme and as far as students are concerned it is an independent entity. For the first ten years of its existence it was also to a large extent financially independent of the University, being funded by grant income. The alignment of the stars was crucially important in providing an unrelated series of grants to the programme and continuing support from academic colleagues who believe in what we are doing.

Innovating in Personalised Learning

Innovation is not necessarily the same as invention. In fact, few of our ideas are entirely new; more often innovation involves putting existing ideas together in a novel way. So in writing here about pedagogic design I shall be drawing on elements that are in themselves not altogether new. Here is a list what I think of as the key ideas: research-based (or problem-based) learning; embedded skills; team teaching continuous assessment and, centrally, the personalised curriculum.

The core programme in Natural Sciences is delivered by what is perhaps best described as research-based learning. This involves many elements of problem-based learning (PBL) with some differences. Each five week core module begins with a problem or a research question. (Many of these are available on the Project LeAP website and in Open Jorum. See the references for links.) For example, for the first module:

> The ancient Greek historian Herodotus wrote that “Egypt was the gift of the Nile”. You are commissioned by a publisher to write an article discussing this in a scientific context.

This is a “problem” only in the sense that students need to first elucidate its meaning; it is really a research prompt. Students investigate how much of what the Ancient Egyptians knew of astronomy, biology, chemistry, geology and physics can be related to modern science. (They are provided with an academic essay in the style of a research paper that they have to unpack.) This introduces students to all the disciplines over five weeks, at an introductory level for those new to a particular subject and in a novel context for those who already have some background. (It also provides an example of how to write an essay.)

Students are supported by a detailed list of required reading, with questions to think about to help them read intelligently as preparation for the class sessions. Thus the class preparation is somewhat more scaffolded than is usually understood in PBL, where students are asked to identify for themselves the learning required to address the problem. (See the discussion of scaffolding in Schmidt et al., 2011.) It comes closer to a written form of the guidance one would expect a graduate student to receive from a supervisor. Students have one or two lectures each week from subject experts and three hours of facilitation working in groups with a PBL-style floating facilitator (e.g. Duch et al, 2004). There is also a weekly set of exercises to be completed individually and submitted for marking. The more straightforward exercises are peer-marked at the weekly class tutorial, while the longer ones are tutor-marked.

The fifth week of each module is used for the groups to complete their responses to the problem (or research question!). The pattern is repeated fourteen times during the three years of the BSc degree. While some modules are more integrated than others, each involves more than one discipline. Many of them come closer to PBL than the example in the first module. For example, there is the sad case of Maria, a musician suffering from a neurological disorder, which is introduced by a newspaper report of a disastrous live performance. Students get the results of tests as they go through the module, which prompts them to explore human neuroanatomy in order to come to a diagnosis. The forensics module involves evaluating the forensic evidence for an arson attack, for which each piece of evidence is cleverly insufficient in itself to convict. (The module was constructed for us by the Northamptonshire forensic service.) For part of the assessment in this module students have to act as expert witnesses in a mock court room. Finally, one of my personal favourites is: what limits the ultimate speed at which a human could run? – for which you can begin with the speed of light and work down to more realistic assessments on the basis of physics (heat transfer, fluid flow), chemistry (metabolism) and biology (blood, muscles).

Research-based learning, as implemented throughout the degree, takes us away from the notion that the research-teaching nexus is purely *content-based* in the early years of study (Healy, 2007) to the idea that research-led teaching can (should?) involve also the *research process* right through the programme. This then builds up to the study of the primary research literature in the later stages of the programme and prepares students for the research-apprenticeship of the capstone project. In fact, the PBL approach enables a much closer integration of research and teaching content throughout the degree than is conventionally the case. Our quantum mechanics problem focusses on the electron energy levels in a nanoparticle (rather than the usual and more difficult hydrogen atom) and our study of electromagnetic theory and optics involves negative refractive index materials, in both cases using examples from current research at an introductory level.

Science curricula at many other institutions are integrated in the first year. An interesting variation, in Science One at UBC, involves co-teaching on multi-disciplinary content which allows interaction across the sciences. We know of only one programme, "iSci" at McMaster University, which has a large interdisciplinary component in all years and which is delivered by a form of research-based learning close to what we have described here.

The research-based pedagogy is supported by the emphasis on continuous assessment, both individual and group. Transferable skills are embedded in the programme largely through the authenticity of assessments in core modules. Ashford-Rowe and Brown (2014) give a list of requirements for authenticity, the main one of which is that there should be a product or a performance for a specified audience in a particular context. Thus "do an elevator pitch" is not in itself authentic. (To whom and why?) To support this we have a skills module in each year with "just in time" skills workshops. The timeliness is crucial here: training in skills divorced from the need to practice them is (anecdotally) not very effective.

The skills module provides a solution to another key issue: how to distinguish the record of performance marks from content marks. In our structure, marks for "style" for a piece of work go into the skills module assessment separately from the content marks in the core modules. Thus, students obtain a "personalised" marks profile, which discriminates between presentation and content.

In the initial development of the programme we made use of post-graduate and post-doctoral facilitators in classical PBL mould. This did not work well, despite training and support, largely because these external contributors have no ownership of the programme. (Although it never got to the point that Schmidt (2007) describes of facilitators taking their knitting to the sessions.) For most of the life of the programme we have instead employed a dedicated teaching fellow (in effect, and now in practice, a lecturer with a teaching mandate only) in each of Biology, Chemistry, Physics and Geology (Gretton et al., 2014). For lectures, which we refer to "expert sessions" to emphasise the intended interactivity, we draw on research expertise from about fifty academic staff across the University.

I want to highlight the ways in which the structure I have described allows us to approach a personalised curriculum. It is almost universal now that programmes offer optional modules, which provide multiple pathways through a programme. If the component elements are small, for example through sub-modular choices, the variety can be quite great, but with lecture-based teaching only for very large cohorts is it then efficient. If the timetabling permits cross-disciplinary module choices then the effective cohort size is increased, but this usually presents logistical problems, particularly of interdependency, and many Natural Sciences programmes offer much less choice in practice than a glance at their module listings would suggest. With a small cohort, resources for options are unsupportable to any significant extent.

How then can we offer a personalised curriculum? In a nutshell, our answer is to allow students freedom to generate some of the curriculum content. We shall look at five examples starting with the smallest and simplest.

Applications of Mathematics
Our mathematics support module is taught by a variation of the Keller plan (Keller, 1968) a form of mastery learning. Students are allowed multiple attempts at the weekly exercises for each topic and are awarded a mark only if they demonstrate

competency in that topic. (The original Keller plan prevents students from moving on until they have demonstrated competency: we do not go quite that far partly for logistical reasons, but also because sometimes moving on and coming back to an obstacle can be a way to overcome it.) In addition, students are provided with the opportunity to go beyond competency and look at various applications questions for further credit. These questions involve applications to biology, chemistry, and physics; students are expected to choose a subset that interests them (if any).

Extension tasks
Each core module has a set of open-ended prompts which students can use to do additional research into the topics covered in the module. Students can also propose their own subject. This provides 14 opportunities over three years for students to investigate topics of their own choice. Thus, this is rather more than the opportunity to write an extended essay (figure 1). The choices have to have serious academic rigour and go beyond the module content. Some examples of topics chosen are: Density Functional Theory, The Role of Malonate in Metabolism and Mitochondrial Function, The Implementation of Genetic Algorithms in DNA Computing, The Geomagnetic Field and the Magnetosphere, and the ever popular Black Holes (often done with appropriate mathematical detail).

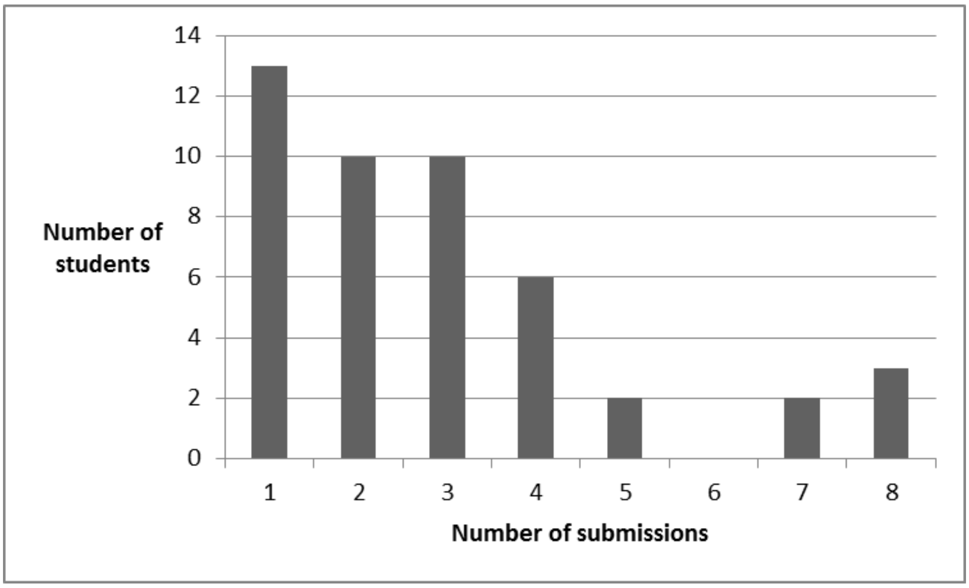

Figure 1: The number of extension tasks submitted by students in the period 2010-2015. This includes students in early years who will have had less opportunity to submit extension tasks. The maximum possible is 14. Around half the students submit none.

The expected workload is 15-20 hours with typically a 2000 word deliverable in the form of an essay, review paper, course booklet, presentation (voice over PowerPoint or PowerPoint with a script). Marks for the extension task feed in to the module in a non-linear way such that (a) There is a threshold for performance on both the core module and the extension task below which neither count. (This is to stop gaming the system to get a few extra module marks from trivial submissions.) (b) The top end is tapered so the addition of the extension task mark cannot take the total module mark to exceed 100%. This non-linearity means that they are only worth doing if done well, and if the student's understanding of the module content puts them in a position to do well.

Year 3 JIST

We have seen how the research process is embedded in the curriculum from research-based teaching to research-led. But the experience of a research scientist as the creator and publisher of content is so far missing, as it is from most undergraduate programmes. To some extent the research apprenticeship of a final year project fills some of the gap, but still absent is the experience of finding a problem and taking it through the peer review process. Finding a tractable problem is probably the most difficult aspect of academic research and seeing it through to appearing in print is the most exhilarating. We want our students – all of them, not just those going on to PhDs and research careers – to experience this. There is, as we shall see, also an important hidden agenda.

The Journal of Interdisciplinary Special Topics derives from a similar activity for year 4 Physics students at Leicester. The basic idea is that students write short (one page) papers on topics of their choice. They submit to the journal which has a rotating editorial board; their papers are sent to other members of the class for refereeing (peer review) and the editorial board decide to publish or not, or require revisions, on the basis of the referee reports. Students may work in groups or alone.

Students are assessed through the number of papers published. (It really is authentic!) Three marks are awarded for each published paper and one mark for each referee report divided between the contributors (with the final average mark scaled to the overall class average). There is some oversight by staff of published papers to ensure that trivialities or obvious howlers are not being awarded marks (although in the real world erroneous papers do get published).

Students meet weekly with a facilitator for help with developing ideas. There are also seed papers written by staff. In the early days students used to base their ideas on these seed papers quite closely. In recent years, a trend has emerged in which students attempt to find novel contexts for analysis, and there is now a stock of past issues of the journal to consult for inspiration.

The journal is now international in the sense that students at McMaster University, one of our student exchange partners, can receive credit for papers submitted to the Leicester journal as part of their writing assignments. (They are subject to the same refereeing process.)

The responses to the pre- and post- evaluation questionnaires for the module yielded little change in attitudes. Our students seem to be well aware of the scientific literature and fairly aware of how science works prior to undertaking the module. Nevertheless, students liked the open content of the module and the experience of the process:

> "Revisions and reviewing are eye-opening."

The negative comments were largely about scheduling and allowing more time, to which we have been responded.

The electronic journal software is the free OJS publishing system so the finished product looks entirely professional. We also produce a paper copy for students as a souvenir using a self-publishing website. Although never intended to be in the public domain, the contents of the journal do appear in search engines. This has led to some publicity for some of the more intriguing papers. One example was “How much of the Amazon rain forest would it take to print the internet?” which appeared in the national press.

Some of this attention has been critical and initially sent shock waves through the University. (“Why are students wasting time on this nonsense?”) In fact as a learning exercise it fulfils several unique functions. It provides a forum for creativity not only in solving problems, but in coming up with problems to solve. Students think up problems that are not necessarily solvable, but which they must try to model as best they can. This opens the door to genuine discussion. (With luck, final year research projects can sometimes provide the same opportunity for problem solving, but usually without the publishing process.) Thus students also learn first-hand about peer review (and its limitations). They learn to respond to criticism (including when it is not justified) which provides an opportunity to develop resilience. And they learn to think critically about work they are not familiar with. They also learn how hard science is if you don’t know which module (if any) you are being tested on! – and, concomitantly, how well you need to know something to be able to draw on it out of context. Finally, and this is the hidden agenda, students get to revise basic science from years one and two in a context which is not patronising (even if for some it is a little intimidating).

More generally, one of the interesting, unanticipated outcomes of the programme pedagogy is that is gives students “permission” to organise academic activities for themselves. Thus, our students have organised a series of seminars by PhD students in STEM disciplines from across the University, thereby providing an opportunity for undergraduates to attend research seminars at an appropriate level, and an audience for PhD students to practice presentations of their work.

We have not yet made any attempt to discriminate between the impact of the programme as a whole and of the personalised aspects of the curriculum. We have used an extensive questionnaire across all four years to obtain a snapshot of student views of the programme, focussing on the graduate attributes that students thought important and their confidence that the programme delivered these. We have also spoken in depth to seven graduates from the programme. Generally speaking students valued what we describe as professional skills and were only slightly less confident on average that the programme delivered these. (The difference is not statistically significant.) They were somewhat less confident about the way in which the programme delivered these skills, expressing on average a mild preference for a somewhat more passive approach to learning. It is certainly true that the pace of the programme is somewhat relentless. Unlike other programmes at Leicester we teach throughout the whole academic year, with a complete module after the Easter break while most other students are revising for examinations. Thus Natural Sciences students have only very short revision periods, although this is not uncommon in PBL programmes.

Interestingly our graduates were much more positive about the pedagogy.

> "With hindsight, PBL has been 'spot-on'"
>
> "With hindsight, I have realised just how many skills that the [Natural Sciences] course [has] instilled in me."
>
> "Without [this degree] I do not believe I would have progressed as far as I have in the short space of time"
>
> "The key to where [I am] today is the research nature of the degree"

Beyond this I think it is encouraging to look at the anecdotal evidence for the added value of the programme. I believe we have changed a few lives for the better.

A number of students have come to us having failed the first year of a degree elsewhere. For some students this is because conventionally taught courses have failed to gain their interest. For others, conventional examinations have proved a barrier for them to show their abilities; at least one of these has gone on to a PhD and most have graduate careers. Another group is students who have the wrong A-level subjects for a science degree or other non-standard qualifications. A number of our graduates in this group are pursuing PhD programmes at top ranking Universities in the UK and abroad. We have had two students who were a long way from qualifying for a medical degree on leaving school, who have gone into graduate-entry medicine. A number of students have chosen careers in teaching who I think will be well-equipped by the range of the degree to inspire the next generation of scientists. Of course, this is largely anecdotal: we have no control experiment to disaggregate the impact of this degree from the effect of three or four years of maturity. And it would be naïve to pretend that we are successful in convincing all our student of the benefits of hard work.

Perhaps, though we should also focus on the impact on the staff. At its core the programme has a team of educators whose every working moment is dedicated to developing their students; in its inner ring, a number of academic researchers who appreciate the skills of our students and supervise final year projects; at its periphery, a cohort of around 50 research academics who willingly contribute a few hours a year to teaching student researchers the subject they love. To quote from two of our academic researchers:

> "Teaching on the Natural Sciences course is refreshing change from single discipline lecturing. The course demands a broader perspective – encompassing not only "what we do" but "why we do it" and "why we do it this way" – and this is reinforced by the interactions with a more broadly inquiring student audience."
>
> "The Natural Sciences degree offers the freedom and flexibility to explore different aspects of the earth system, allied to a direct and hands-on approach to problem-solving (and problem-solving is what most science in practice is about). I like it."

How this practice evolved

I have never believed in the efficacy of lectures after being told, on my first day, to pitch my lectures at the average 2(i) student. Talking over the heads of the weaker students and boring the best ones is not my idea of good teaching. It turns out I am in good company (Freeman et al, 2014, amongst any number of others). So what if we could deliver a whole programme by projects? (A suggestion made to me by the late Professor Will Light at a chance meeting in a car park.) It turned out that we can: it is called problem-based learning (PBL) and some institutions actually do it. Pleasingly the University funded us to visit one of them, the one week staff development programme at the University of Delaware, to see how it was done.

From resource based teaching to problem based learning
At the time, I was director of teaching for Physics and Astronomy and had recently changed the core teaching to what was then known as resource-based teaching (Exley and Gibbs, 1994). This is quite similar to what is now called flipped learning, whereby students are set work in preparation for the lecture, which can then be devoted to higher level learning (Bergmann and Sams, 2012). But the laboratory teaching of practical physics was still done in the traditional way, and evidence from a survey of staff showed that it was not much liked by staff or students. Developing PBL problems for the laboratories was something of a challenge, but we were funded through the HEfCE FDTL4 projects and subsequently through the CETL programme. (This is why a funding council with funding is part of the story.)

A glorious failure and some learning
We learnt a lot from the first failure. (I suspect that anyone for whom PBL works first time is making it too easy for the students.) We learnt that the open-endedness of PBL problems can be a handicap. Problems with many solutions also have trivial solutions. (I am reminded of Rita's solution to the problem of staging *Peer Gynt*: "Do it on the radio".) One way or another, students need to be steered to question more deeply (Hmelo-Silver et al., 2007). In "classical" PBL this is a task for the facilitator, but good facilitators are difficult to clone. We finally settled on clearer written scaffolding, without reverting to the traditional closed laboratory script! Accidentally, we found that the open-endedness of laboratory experiments is not so much in the freedom to design them (which is severely limited by the available equipment), but in the necessity to interpret the results when the equipment is such that the signal to noise is problematic. The PBL problem is not true research in that the experiment is fully understood, but if the question asked is at the limits of the equipment, not set up to produce clear cut results, then the problem drives students to experience the full research *process*. (The conclusions genuinely depend on the data and can differ from group to group.) These ideas on scaffolding and implementing the research process, rather than the research level content, were later taken over to Natural Sciences.

The CETL programme allowed us to develop "Physics in Context" which later became the Interdisciplinary Science degree in the HEfCE/IOP Stimulating Physics and Integrated Sciences programmes (the contribution from the visionary professional body). More recently an external review of the degree led to a recommendation to change the name of the degree to Natural Sciences. So, just to be clear, the Centre for Interdisciplinary Science delivers an interdisciplinary science programme now called the Natural Sciences degree.

Developing the degree

For the development of the degree we started with an away-day for heads of teaching from Departments that had signed up to the programme, and from blank sheets of paper. My instructions were to "write down the topics that you felt these students had to come away with after three years." We could then work back to see what prior material would be essential to support these topics in the earlier years. This was liberating: every topic had to justify its place not because it was necessary for some abstract conception of what a degree should be like, or some fantasy option, but because it would really connect with the third level material. Of course, even with these constraints, we had too much material and we had to limit the scope of the third year, but the approach ensures that students reach graduate level in topics that are considered current and important in each discipline.

It takes a lot of work to develop a PBL module; the payoff is that it takes less recurrent resource (or a better outcome for the same resource – useful interactions replacing all those annually repeated lectures). Much of the work was done by our "summer workers", a small (paid) army of new graduates and current students working over the summer on curriculum content before the idea of co-creation of the curriculum became more widespread. Some of the material generated required academic oversight (i.e. correcting!) but co-creation is not in any case the same as outsourcing. It may be that the students who gained the most from our programme were our summer workers, but their roles unfortunately are not scalable.

The evolution of the personalised curriculum

So how did the personalised curriculum evolve? It came again from experience in the Physics programme. Even departments that take mainly A* students find they must deal with a range of abilities; that range in a department that admits students with A-level grades from A* to Cs and Ds (as Leicester did at one time, although the minimum has since crept up a lot) has an enormous range of aptitudes to cater for. Some institutions allow "over-crediting" in which the number of credits taken is allowed to expand beyond the nominal 120 per year (equivalent to 60 ECTs). Leicester is not one of these institutions. We therefore developed for Physics a system of flexible pacing in which certain material had flexible credit weighting, allowing higher level courses to be taken in earlier years. Apart from the administrative overhead, and the amount of time spent trying to explain the system to students (who eventually got it) and external examiners (who rarely did), the flexible structure worked very well. However, it relies on the existence of additional options at the higher levels once one runs out of core material, something which is unsustainable in the much smaller Natural Sciences programme. The flexibility in Natural Sciences is therefore achieved not between modules, but within the workload for each module. Furthermore, it retains some of the benefits of that co-creation of material we experienced with our summer students.

For many years the summers were a time of major developments often including reworking schedules (numbers, lengths, timings of sessions) as well as content and housekeeping (rubrics, examination structures etc.). Summers are still busy times to develop new material and enhance existing procedures, but now within a fairly fixed framework and without the buzz of summer students.

How this practice is situated theoretically

The literature offers no shortage of advice on how to teach, but much of it is focussed on individual delivery within a defined structure. Our thesis is that individuals can achieve only so much; better to fix the structure than to try to fix the teachers (or as some academics would prefer it, the students). Thus, the pedagogy and curriculum were designed from a blank slate in the light of our understanding of how students learn.

Any one sentence summary of the vast body of educational literature on cognition is likely to sound naïve; but here goes: students learn by doing structured sequences of tasks, adopting a variety of learning styles with multiple opportunities to adapt to feedback and to find relationships between concepts.

Notice that it is the sequences that are structured, not the tasks, which should include those that are open-ended and complex, but appropriate to the stage of development. The multiple opportunities should include interactions with other students as well as teachers, and should involve multiple learning styles and modalities. (In other words, students should act and reflect, read, write, talk, listen, negotiate, build and so on.) The reader may recognise “doing” from experiential learning (Dewey, 1938), “structured” from “constructionist” and “relationships” from “accommodation and assimilation” (Piaget, 1950), “staged” from “proximal development” (Vygotsky, 1978) and “learning styles” from Kolb (1984) and other later authors, but used here in the sense of Waring and Evans (2015) as spelled out in parenthesis above.

My one sentence focus on cognition makes education seem very dry, unexciting and functional, so I would add on the affective side of learning theory that the “doing” has to be motivated, hence the tasks must be meaningful and engaging (hence complex and open-ended), and the feedback immediate; which brings us to PBL.

There are many definitions of what constitutes PBL (Savery, 2006). ITUE at Delaware have:

The PBL pedagogy is *‘a student-centred method of teaching in which students learn by investigating real-world problems and, working in groups, seek out the tools necessary to solve them’.*

(Raine and Symons, 2012, quoting from the Delaware Institute for the transformation of undergraduate education, ITUE)

There are many meta-analyses of PBL (Strobel van Barneveld, 2009) and the advantages and drawbacks are fairly well rehearsed. The advantages can be summarised by saying that PBL provides for a constructive alignment (Biggs, 1999) of interests between pupil and teacher, which provide the environment for the learning process as described above. The disadvantages stem from the possibilities of misalignment where the implementation is not appropriately scaffolded, particularly superficial approaches and free-riding (Wiznia, 2012).

So much for the theory, what about the implementation? I shall look at two contexts: the principles of good teaching (Chickering and Gamson, 1987) on which the student experience surveys (Buckley, 2013, 2014) are based and Gibbs's analysis for the HEA (Gibbs, 2010, 2012). I have put these together in tabular form (Table 1) showing the links between them and with a final column relating to the Natural Sciences programme. Most of these links to Natural Sciences will be self-explanatory given the exposition of the programme above. The other aspects follow from our commitment to PBL delivered by a core of trained teachers. (All of our core teaching staff hold postgraduate teaching qualifications in higher education as well as doctorates in their discipline.) The two known issues with PBL that continue to be problematic are the depth of learning and the related question of "time on task". This appears to be a threshold effect: taking some of our students even a little too far beyond their comfort zone seems to produce not just a small but a dramatic decrease in engagement: the zone of proximal development seems to have a hard edge for some, although not all students. This is an issue that might repay further research.

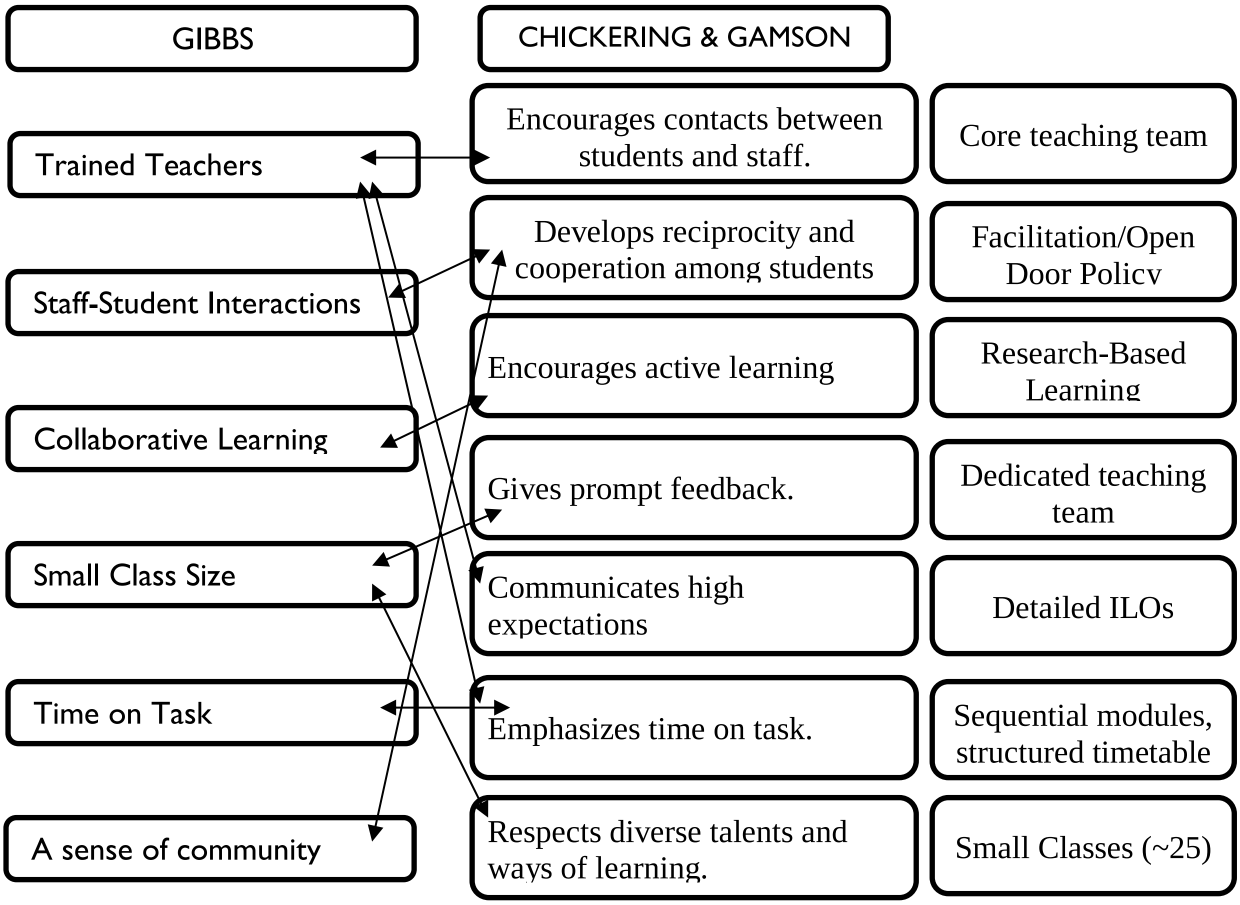

Table 1: Principles of good teaching from Gibbs (2010) and Chickering & Gamson (1987). The final column indicates how these are implemented in the Natural Sciences programme.

However, since much of what I have described here is borrowed, albeit in amended form and in some cases from myself in other contexts, it is *per se* implementable elsewhere. All of the individual components can certainly be introduced independently into other programmes: for example, PBL modules (or flipped modules, in the absence of a problem hook), the undergraduate journal and extension tasks. While one can imagine them as initiatives by individual staff in a module they own, they probably work better as collaborations. Certainly, in all of the programmes in Physics and Natural Sciences for which I have had overall responsibility, the core teaching has been carried out by teaching teams and has been "owned" by the programme as a whole. This has the advantage of pedagogical coherence albeit with the disadvantage of the inertia to subsequently changing anything that everyone has come to agree on.

That the pedagogical developments were, in one way or another, funded projects was crucial to their acceptance. On the other hand, much of the material we have produced is freely available as OERs (on Open Jorum, the IOP website and linked from our own Natural Sciences website at Leicester) and much of the development work does not need to be repeated by potential adopters. In fact, much of the material has been modified for use elsewhere.

An interesting issue, central to the theme of this piece, is the extent to which aspects of the personalised curriculum can be adapted and, in particular, scaled. Our financial masters look at the cost per student-credit and flexibility, in whatever form, undoubtedly increases this. An at least partial solution is to pitch the core programme at weaker students, or those who legitimately devote time to co-curricular pursuits, as for example in the structure of the mathematics modules I described above, using the time saved to provide additional material for stronger or more ambitious students.

What I am arguing then is that, while it is possible to adopt the practices I have outlined piecemeal, it would be far better to design a flexible curriculum from the start. Of course, a personalised curriculum is easier to implement the smaller the cohort and we never envisaged (and have never had) more than around 20 students entering the programme each year. However, I think that the pedagogies we use are highly scalable. Key to the scalability is the combination of bespoke content with a production line structure: all of the 14 core modules over three years in Natural Sciences have the same five week pattern and run sequentially. While the facilitation sessions for PBL may be unsustainable for very large cohorts, a flipped lecture approach to class sessions, within the context of an overall PBL-style problem, is eminently scalable.

Conclusion

I have presented some of the innovative pedagogical ideas that underpin the novel programme content of a degree. The key point is that these came together: it would be impossible to deliver the interdisciplinary content using traditional lecture-based modes to a small cohort in a viable manner. Thus, there was a driver for innovation. Our innovative approaches draw on evidence gathered over a long timescale from educational research and of what works in practice. The traditional lecture-based approach has a long history of surviving challenges to its hegemony (Friesen, 2011), but it looks increasingly inappropriate for the 21st century student (Barber, 2013). Our programme was designed for a specific purpose with a specific content. I would argue that the pedagogies we have come up with are nevertheless not just niche architecture. The structure is both divisible, in the sense that you do not have to buy the whole building, and scalable in part or as a whole to larger accommodations.

There is a tension between the pressure to teach ever larger numbers of students more efficiently and programmes that can deliver a personalised experience for all its students. It is the tension between mass production and individual craftsmanship. In the world of things, that conflict is irreconcilable. In the world of ideas it need not be.

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