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Martin J. PITT
University of Sheffield, Chemical and Process Engineering

WHAT PHYSICS TEACHES, APART FROM PHYSICS, THAT IS VALUABLE IN CHEMISTRY OR RELATED DEGREES AT UNDERGRADUATE LEVEL

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ABSTRACT: Physics education appears to provide experience leading to the development of certain concepts, disciplines and skills which are not physics as such. Certain of these are essential to degree level study of chemistry and chemical related degrees, but tend to be assumed rather than taught by the academic staff. Recognizing such apparently trivial matters as the correct use of units or concepts such as density as a blockage to higher level may assist both students and teachers. [*Chem. Educ. Res. Pract.*: 2003, *4*, 219-225]

KEY WORDS: *chemistry & physics; chemical engineering & physics; supplementary physics course*

INTRODUCTION

UK students commonly enter university at 18 years old, having completed the General Certificate of Secondary (GCSE) education at 16 and having studied three specialist subjects at General Certificate of Education Advanced Level (GCE A-Levels). It is fairly obvious that chemistry and engineering are founded upon physics, yet many students of chemistry and of chemical engineering in the UK enter degree courses without having studied this subject at GCE A-level.

Other degrees which involve the study of chemistry beyond A level include biological and medical related courses, food science or technology, materials science, plus the increasing number of environmental science or engineering degrees. In all of these it is likely that many students will not have taken physics at A level or equivalent.

They will of course have had some physics in GCSE science. However, as pointed out in a recent LTSN briefing paper (Walker, 2001) they will not have studied physics for two years, and therefore will have forgotten much of it. This has been referred to as ‘the Physics Problem’ (Walker, 2001).

In dealing with educational problems, it is preferable to determine what is wrong in very specific manner. Often, this is not the headline subject at all. For example, a student’s failure to deal with chemical equations may be due to a lack of algebra rather than chemistry. It is even worse if a student is labelled lazy or unmotivated or just dull because he or she is lacking a simple concept or skill presumed by the academics to be universal.

The following study was carried out on students of chemical engineering, but is discussed in the more general context of higher or further education involving chemistry.

The origin of a our physics course

The majority of students entering degree courses in Chemical Engineering at this university have GCE A level (or equivalent) in Chemistry, Mathematics and Physics. However, typically 25% have another A level, usually Biology, instead of Physics. Many of the latter wish to specialize in biochemical or environmental engineering, for which the biological knowledge is an advantage. This is not untypical of chemical engineering degrees elsewhere in the UK.

Most engineering degrees assume that the two most desirable A levels are Mathematics and Physics. Indeed, it is often said that engineering is applied physics. However, Chemical Engineering is different. Experience has shown that students can succeed without physics, but find it extraordinarily difficult without chemistry A level or equivalent, and therefore it is an absolute course requirement.

As part of our continual review of the course, we came to the conclusion that at least some of our students were disadvantaged by having to catch up on certain aspects of physics, and devised a first-year course to help them. By running this course we noticed certain educational aspects which may be of wider interest, and which this paper addresses.

Physics A-level

Physics A-levels are made up of modules, some of them optional (Breithaupt & Dunn, 1995). Much of the factual content of a typical physics A-level is largely irrelevant to chemical engineering. In particular, astrophysics and particle physics are unnecessary. We do not build chemical plants in the stars nor move them near the speed of light. Nuclear engineering is a special topic, taken only as an option in most degrees, for which an understanding of radioactivity is required. Students not taking the option can manage without this. Optics and electronics are also not really necessary.

Waves, oscillations and electromagnetic radiation are important in a straight chemistry course, though of less relevance in chemical engineering. Conversely, some mechanics is required for chemical engineering but not pure chemistry.

A FIRST-YEAR PHYSICS COURSE FOR CHEMICAL ENGINEERS

The reduced course contained only those items considered essential. Some are covered in GCSE, but it is unreasonable to expect a student who has not done physics for two years to retain the skill and knowledge without some revision. A standard (and inexpensive) A-level revision guide (Breithaupt & Dunn, 1995) was recommended, but only a relevant selection of topics were covered. The following are the declared course aims.

(1) Quantities related to energy. Students should complete the course with an understanding of the quantities mass, length, velocity, acceleration, force, work/energy, power. They should be comfortable with the relationships between them, and confident in simple calculations using the correct SI units.

(2) Mechanical relationships. Students should understand the difference between scalar and vector quantities, and understand derived quantities such as pressure, moments, momentum and kinetic energy. They should be able to deal confidently with simple calculations involving distance and direction, using both positive and negative signs for quantities.

(3) Electrical properties. This is limited to the most basic requirements to understand electrical power systems, using SI units and examples relevant to this. Students should understand the following quantities and their relationships in a direct current circuit: charge, current, potential difference, resistance / conductivity, power, energy. They should be able to carry out simple Ohm's Law and power calculations.

(4) Energy interchange. The way in which energy is transferred between systems will be dealt with. This includes the understanding and use of heat capacity, specific heat, enthalpy of phase change. The ideal gas laws and pressure-volume work will be reviewed.

(5) Properties of fluids. The basic physical properties of simple gases and liquids will be reviewed. There will be an introduction to fluid statics and dynamics.

A first-year physics course for chemists

Based on the above experience, it is suggested that the following additional topic might be included:

(6) Oscillations and waves. The general behaviour of harmonic oscillators. General theory of waves. Electromagnetic waves.

Course delivery

The course is delivered in tutorial style, only to the students without Physics A-Level, with worked examples. Course material is made available to the others, along with a specimen test paper. All students take a test. Any that do not pass then receive one-to-one teaching to cover the areas in which they were unsuccessful, and have another test.

The test was initially based upon some defects which had been observed in second year laboratory reports and in student difficulties with some parts of the course. It basically consists of some simple calculations of various kinds which are often subsumed within other courses. (For example, given a volumetric flow rate and the density, the lecturer assumes the students can calculate the mass flow rate.) Marks are given for correct units and suitable precision as well as method.

In the first year the aim was to find out what matters needed to be addressed. Over the next two years, course material was developed along with the realization that we were teaching some things that were not specifically physics. Some of these were nominally covered by Chemistry A-Level, but students who had not studied physics were not as secure in their knowledge as would be desirable.

Some of the physics was itself necessary for chemical engineering, but would be of less value in a pure chemistry degree. However, we also have a joint degree in chemistry and chemical engineering, and the author has dual qualifications and has worked in industry both as a chemist and as a chemical engineer.

Further thought suggested the following educational attainments which came out of physics teaching, but which are not strictly physics, and which are equally likely to apply to a chemistry degree course, and many courses involving chemistry.

More science

It is so obvious as to be readily overlooked that students who have done an additional experimental science will have had additional opportunities for experiential learning of the ways of science, including the development of the idea of an experiment and practice in laboratory reports. They will thus be better prepared for a chemistry or chemical engineering first year practical course. While subjects such as computing and management have their own benefits, they do not reinforce the general scientific background of a chemistry A-Level.

Numbers and units

Above all, the study of physics tended to inculcate a certain discipline which was noticeably lacking in many students without this A-Level. For any calculation, students should give the result as a number and a correctly formed unit. It had to be explained that this was not something nice to do, but a vital part of communication. There is a difference between a quantity of heat expressed in calories and the same quantity in joules, or a length in millimetres or centimetres. A megajoule MJ is rather larger than a millijoule mJ. Because positive and negative quantities occur more often in physics, the sign is less likely to be omitted when dealing with chemical thermodynamics.

SI system

The SI system is a coherent system of units. In practice this means that if quantities are expressed in terms of the base units (or units derived from them, such as pascal, Pa, but not multiples) then they can be multiplied and divided without requiring any conversion factors. However, it is also a flawed system in that the base unit of mass is called kilogram, and thus for example a milligram is 10^{-6} times the base unit, not 10^{-3} times. There are also commonly allowed units outside the strict definition, notably minute, hour, bar, litre and tonne. Physics evidently gives more opportunity to practise such calculations, and a better realization of their importance in real world calculations. However, the ability to manipulate quantities and units correctly should be expected of any science or engineering graduate, but not one we can assume has been thoroughly achieved by chemistry A-Level. It was news to some students that a gram per litre is the same as a kilogram per cubic metre.

Note that GCSE physics specifically says the *'candidates will be assessed on their ability to use the following units..'* in many sections (Walker, 2001). A typical A/AS

Level Physics specification (Edexel, 2002a) requires *' understanding of the distinction between base and derived physical quantities and their units in SI.'*
It is interesting to note that a recent textbook on environmental engineering (Mihelcic, 1999) takes a whole chapter, nearly one tenth of the book, just on the subject of units of concentration. This is reasonable, not only to understand the problem correctly, but to carry out related calculations such as those involved in neutralization or kinetics.

Orders of magnitude

Because physics covers many orders of magnitude, A-Level study gives some familiarity with numbers expressed in exponential notation, e.g. 1.4×10^{-7} and the ability to manipulate them. (These are given as important requirements in the Physics specification, Edexel 2002a.) Moreover, such students found it easier to grasp relationships such as 1 mol / dm^3 = 1 kmol / m^3 .

Precision

Initially there was some weakness in both groups of students (but more so in those without physics) in reporting numbers to sensible precision. The default was as many numbers as given by the calculator. For example $80.0 \div 3.0 = 26.7$ not 26.666666666.

While a typical A-Level chemistry specification (Edexel, 2002b) does indeed say that students *'should be able to use an appropriate number of significant figures'* there is a much greater amount of qualitative material ranging from reaction pathways to *'Spiritual, Moral and Cultural Aspects'* (Edexel, 2002b) to be dealt with. The Physics specification (Edexel, 2002a) and, I believe, teaching practice is stronger in this regard.

This is not to suggest that students have full grasp of the concept of errors, since both chemistry and physics undergraduates have been shown to be deficient in this respect (Ryder & Clarke, 2002). However it is a starting point for dealing with numbers which matter. (And in professional life the precision of measurements and specifications is of huge importance.)

Density

The concept of density is not as trivial as it might seem. Weight and volume are things which can be apprehended by the normal senses. Density is a derived intensive property, like concentration, which can also be expressed as mass per volume, and which is hugely important in practical chemical calculations. Over the years I have observed many students (all with good A-level chemistry) fail to do simple concentration calculations. Only recently have I discovered that they were equally incompetent in density, and have been able to trap this error in my teaching.

Ohm's law

For the purist, $V = IR$ is not an exact statement, but it gives a relationship and a conceptual model which can be understood. The point here is that once understood and practised, it can be use for similar relationships which are nothing to do with electricity. Students who can calculate V, I, or R given the other two should also be able to calculate a mass of liquid given its volume and density.

More interestingly, students who understand about electrical flux down a wire with a potential difference as the driving force can use the same model for heat flux driven by a temperature difference or diffusional mass transfer driven by activity difference.

The ideal gas laws

These can be applied to changes which take place without molecular alteration and are thereby of course a piece of physics. (Only if understood at this level can they be further developed to more complex situations and Laws.) The fundamental requirement is to calculate new conditions if one factor changes. For example if the amount of substance and the volume is constant but the temperature is increased from 25 °C to 100 °C, what happens to the pressure? Unless reminded one third of students (with good A level Chemistry) neglected to change the temperature to the Kelvin scale and concluded it went up by a factor of 4. Another third claimed they needed to know the gas constant R in order to do the calculation. (As a result, the gas laws were added to the fluids part of the initial physics course, and nearly all students now do the calculation correctly.)

Energy

An understanding of energy is vital in chemical engineering, and somewhat helpful in thermodynamics generally. One of the motives for this course was the observation from laboratory reports that some students were not able to distinguish between power and energy and were vague about the units of both. Practice is needed in manipulations involving energy per mole (e.g. vaporization).

Formulas and the real world

Students who have done two experimental sciences rather than one will have more experience of relating theory to the observable. In this respect, both biology and physics should aid chemistry. However, physics has rather more quantitative and accessible things that can be measured. It is thus perhaps easier to grasp the physical meaning of a formula.

If we increase the force by hanging weights, we can see the spring extend, so Hooke's Law is comprehensible. By contrast a simple titration requires several manipulations to convert the reading to tell us how much acid there was in the flask. Students may learn to apply rules rather than understand what is going on.

CONCLUSIONS

The study of physics at school along with chemistry has obvious advantages for the significant parts of chemistry and chemical engineering which have a clear physics basis. However, it provides other less recognized concepts and skills which are relevant for the study of chemistry in many university first degree courses. Rather than assuming these to be present university teachers may be advised to ensure they are inculcated or reinforced during the early part of the degree. The course and assessment procedure enabled us to precisely identify and put right certain weaknesses by adjustments to the teaching and in a few cases by individual tutorials.

As roughly equal numbers of males and females take A level chemistry and apply to chemistry degrees, but more than three times as many males take physics A level (UCAS, 2002), dealing with the physics background may be an important step to gender equality.

CORRESPONDENCE: *Martin J. PITT, Chemical and Process Engineering, University of Sheffield, Sheffield S1 3JD, U.K.; fax: 0114 222 7501; e-mail: M.J.Pitt@sheffield.ac.uk*

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