The advent of computers has opened the way to a taught course discussing systems removed from equilibrium. Even turbulent and chaotic processes that are not amenable to analytical argument might be simulated from numerical treatments. If such elements were present in examples that support the theory, Atkins extends his thesis course. Certainly the numerical approach rather than the transfer, rates of processes: photosynthesis provide the equilibrium. Even turbulent and chaotic processes that are not amenable to analytical argument might be simulated with excitement.

First, however, the illustrations of chemical principles by biochemical applications, that I would suggest today, are at a more modest level. They are frequently cited in biochemistry and chemists could adopt them with ease.

For example, the thermodynamics of ATP:

\[ \text{ATP}^{\text{aq}} + \text{H}_2\text{O}^{(1)} \rightarrow \text{ADP}^{\text{aq}} + \text{P}_2^{(aq)} + \text{H}^+^{(aq)} \]

For hydrolysis:

\[ \Delta G^{\text{\circ}} = -30 \text{ kJ mol}^{-1} \quad \text{i.e. exergonic} \]

\[ \Delta H^{\text{\circ}} = -20 \text{ kJ mol}^{-1} \quad \text{exothermic} \]

\[ \Delta S^{\text{\circ}} = +34 \text{ J K}^{-1} \text{mol}^{-1} \quad \text{NB large} \]

ATP is sometimes, although rarely, shown to act bifunctionally as a phosphate donor (e.g. to glucose) or acceptor (in respiration)

\[ \text{glucose} + 2\text{P}_i + 2\text{ADP} \rightarrow 2\text{lactate}^- + 2\text{ATP} + 2\text{H}_2\text{O} \]

where each mol of ATP extracts 30 kJ from each mol of glucose can be shown to be exergonic, again there is an increase in entropy from the splitting of the glucose molecule. Thus in this series there are good examples from biochemical processes that support classical thermodynamics; few chemistry texts use this illustration.

Continuing with ATP, an example where the molecule drives an endergonic reaction can illustrate such reactions and introduce enzymes. For example, the biosynthesis of sucrose

\[ \text{glucose and fructose} \rightarrow \text{sucrose} \]

\[ \Delta G^{\text{\circ}} = +23 \text{ kJ mol}^{-1} \quad \text{endergonic} \]

which is less than the 30 kJ ATP is capable of releasing from the glucose and hence the reaction will proceed. The presence of the enzyme leads to catalysis and reaction kinetics, where the Michaelis–Menten treatment does get an airing in some chemistry courses.

Enzyme inhibition can be treated with profit to chemists. The hydrolysis of acetylcholine in the presence of acetylcholinesterase (ACE) opens the way to a study

\[
\begin{align*}
\text{O} & \quad \| \\
(CH_3)_2N^+ - CH_2CH_2OCCH_3 + H_2O & \quad \| \\
\text{ACE} & \rightarrow H^+ + CH_2C-O^- + (CH_3)_2N^+ - CH_2CH_2OH
\end{align*}
\]

of medicinal, pharmaceutical and agrochemical interest, through the inhibition of ACE by effective pesticides and nerve gases.

The areas of applied organic chemistry are of course a fertile field for exploring links with biochemistry. Table 2 shows the topics that appeared in the chemistry syllabuses of the courses reported in Table 1 which offer links with biology. Of these, heterocyclics, separations and perhaps surprisingly bio-inorganic chemistry appeared in 90% of the syllabuses, while biocolloids and the elemental cycles were in less than 20%. Of the eleven courses examined, three had biochemistry as a part of the curriculum and five offered optional courses that might be said to be biological chemistry.

Clearly, biochemistry does appear in physical sciences courses in many guises. Unfortunately much of its impact and therefore its identity is lost by a lack of coherence. Ideally, it should be brought together and offered as a supportive ancillary course. In the present climate, when course designers are pressed to maintain main subject content, but reduce total hours, biochemistry is often squeezed from the physical sciences curriculum. To keep its standing as a major link between physics and especially chemistry, biochemistry should promote itself as a truly molecular science. Examples of biochemical processes should be used throughout the physicochemical courses to emphasize the molecular basis of biological reactions.

Finally, a movement towards a course, common to both the life sciences and the physical sciences, based on molecular sciences should be a major development for the next decade.

**Biochemistry in the biological sciences undergraduate curriculum**

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Teaching Biochemistry at the tertiary level in the last part of the 20th Century poses a number of problems and presents many challenges to university teachers. In Great Britain, there is a considerable amount of biochemistry in the high school Advanced level biology (and other equivalent) syllabi, and the corresponding Chemistry syllabi have biochemistry options (Wood, 1987). Consequently, most students in their first year at university reading a life science course already have quite a wide, although perhaps superficial, knowledge of traditional biochemistry (e.g. biomolecules, enzyme action, photosynthesis, intermediary metabolism), as well as some knowledge of molecular biology (e.g. DNA, RNA and protein synthesis together with some ideas about the regulation of gene expression, genetic engineering, etc.). The level of understanding achieved in the pre-university years will depend on how good the teaching was in high school.

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reducing that most schoolteachers will have had little formal training in biochemistry. As a consequence, in the first year at university some students may be bored having to repeat material with which they are already (or believe themselves to be) familiar, while others, in contrast, may be hard-pressed to keep up with new and unfamiliar material being taught to them. University teachers must therefore be sympathetic to the different levels of sophistication of knowledge and make use of small-group teaching, problem-solving classes, 'remedial classes' and computer-aided instruction, so that all students have the opportunity of achieving a reasonable level and may then proceed.

Chemistry
To understand biochemistry or molecular biology, there is a requirement for a core of chemical knowledge. Opinions differ on how much chemistry we should 'demand', both before entry to university or during the first year or two at university, and no doubt the arguments will continue. Much of the organic chemistry taught in high school does not deal with the sorts of compounds relevant to biochemistry. There is nothing about organic phosphates, nothing on heterocyclic compounds and only a little about aromatic compounds. This is not a criticism of the courses: inevitably school chemistry is general and is intended to train students who will go into all sorts of fields in their subsequent careers. In any case, in most schools the 'biochemistry' element of A level biology is taught fairly early on in the course, much of it before the majority of organic chemistry has been taught.

The general situation as regards chemistry is exacerbated by the fact that many sixth-formers now do Biology without doing Chemistry. It is therefore not surprising that many of the students on life sciences courses at university and who are required to take biochemistry courses have somewhat sketchy ideas about chemistry. Biochemistry may form the basis of modern biology, but the basis of biochemistry is a chemical understanding of life processes. In addition, there has been a trend towards admitting students to life science courses with a poorer chemistry background than would be required of students for honours biochemistry. There is no easy solution to this problem: we will all need patience and imagination if we are to deal with it.

Service courses
The majority of the students we teach in universities will not be going on to become professional biochemists. Rather, they will be microbiologists, geneticists, physiologists and pharmacologists, all disciplines closely related to biochemistry, as well as to agriculture, food science, plant and animal science and even nursing and dietetics. Because biochemistry and molecular biology are increasingly becoming major parts of these disciplines, 'parent departments' quite appropriately require their students to take a biochemistry course. Some require half a year, some 1 year and some 2 years, and this raises further difficulties. At a time when we are pressed to become more 'efficient' there is the temptation, or tendency, to offer courses in general biochemistry in which students can 'drop off' after a half, 1 or 2 years. In fact, it is not easy to design such courses and frequently academic coherence is sacrificed.

It is also appropriate that such courses should try to keep the interest of their diverse types of students by making the biochemistry reasonably 'relevant' to the students' main subject areas. This is more of a technical problem than an intellectual one, to be solved within the limits of the resources available in a given institution.

Teaching biochemistry to a diverse band of life science students (whether all together or not) also raises the question of overlap between different courses. Should both the Biochemistry and the Genetics Department teach the genetic code, etc. for example? A survey of 185 first-year students in Leeds a few years ago indicated that 54% of them found a degree of overlap 'helpful', 32% were neutral about it, while 14% found it 'annoying'? There is something to be said for exposing students to two (or more) views of the same topic area, although inevitably some of them will be 'bored' by 'having the same thing twice over'. Obviously departments should speak to each other. In any case, the solution to this problem will be to some extent pressed on us as more and more traditional life-science departments come together, more or less willingly, to form Schools of Molecular and Cell Biology or whatever. If we accept that biochemistry forms the basis of modern biology, then we should welcome this as an opportunity and build positively.

I would like to try to develop this theme further, starting from the point that biology, biochemistry, molecular biology and the life sciences generally — are changing very rapidly. Most scientists in these disciplines in the future will need to have a certain 'biochemical vocabulary', and we should argue at length about what that vocabulary should be. This is similar, but not identical, to the problem of how much chemistry is required for a proper understanding of biochemistry. From the biochemist's view point there did not seem to be a problem. Only a few years ago, at a Workshop on Strategies of Biochemical Education (Mehler, 1983), it was generally agreed that biochemistry was what was in textbooks by Lehninger or Stryer, and the very recent survey by Bryce (1986, 1987) would seem to confirm this. However, we should also take into account the student's point of view, both generally and especially that of students on subsidiary biochemistry courses. To deal with the latter first, such students will want to see the relevance of any biochemistry course they are required to take to their field of study. They may not perceive so easily as we, that all the biological sciences are based on biochemistry — especially early on in their university careers. (Many of us have already dealt with, or are still getting to grips with, this problem with medical students.) Aside from this however, whether honours biochemistry or life sciences subsidiary biochemistry, a student's main aim in life is to pass exams. We are all aware that the amount of material learned or amount of knowledge possessed (and not necessarily understood) increases sharply in the few weeks before an exam, and decreases sharply immediately afterwards. Some of the information will be retained, but unless it is used regularly, the majority of it will fade away. We should be asking ourselves if this is what we want. Will the information be remembered and regurgitated at examination be of any use to the students turned out as a professional biochemist or life scientist? There has been an explosion of biological and especially biochemical knowledge in the last two decades and it shows no sign of ceasing. Is there any point in expecting students to remember this accumulated knowledge? (The evidence is that, in any case, they do not!) Surely we ought instead to be teaching our students to develop their intellectual abilities rather than their memories. This means teaching them to find knowledge and information when they need it — a training for future self-education — and to use knowledge to solve problems in biology, whether in research or in industry.

Small group teaching and computer-assisted learning
This is not a good time to propose a revolution when staff are more and more pressed and resources are limited. Unfortunately, on the face of it lectures appear to be efficient — material is 'covered', information is 'given away' (Farnsworth, 1987) — but there is little evidence that the majority of lectures achieve very much at all, at least in terms of giving...
the students a basis for operating successfully in their future careers.

Teaching in small groups, in a variety of ways, in contrast can give the opportunity for interaction, problem solving, collating information, and so on, and generally of using and rehearsing knowledge (Newble & Cannon, 1983). The advantages of small-group teaching have been discussed at length (Wood, 1981; Mehler, 1983). However, most university teachers have a suspicion that such methods are likely to be much more labour intensive than giving lectures. This may be the case, but on the other hand, if lectures are not achieving very much, perhaps we ought to be re-examining our objectives in giving them and ought to consider other teaching methods more readily.

Microcomputer teaching programs offer one way or providing individualized, self-paced, interactive teaching which is less labour intensive. Setting aside the immense amount of time that is initially necessary to expand and develop a sound computer teaching program, there are many advantages (see Saffran, 1987). There are also many pitfalls, and great care and great imagination, coupled with a high degree of programming skill are necessary, and there are probably more bad examples than good ones at present. Nevertheless, this does seem to be one way forward in the present circumstances.

Assessment

Finally, it is appropriate to mention assessment. It is clearly as necessary for us to assess our students' progress and achievement as it is for them. However, most of the assessment systems we use now are adversarial and competitive. They require much remembering and repetition of information, some examination of the ability to organize and synthesize, and some assessment of the ability to use knowledge to solve problems. I would like to see more testing of problem-solving abilities, which means more oral examinations and more tests in which access to the literature and indeed to other people's knowledge and experience is required. Obviously an element of self-reliance is essential, but surely the main point is that the problem can be solved by whatever are the most appropriate means. Here again, teachers will feel that such methods will fly in the face of well-tried traditions and will be more labour intensive. This may be the case, but once again we should be asking ourselves what it is that we want to achieve and whether the methods we presently use are at all successful in turning out graduates in the life sciences equipped to carry out academic and industrial research in the next 30 years.

Conclusions

I have posed many problems and suggested very few solutions that will be readily acceptable at a time when British universities, and especially biochemistry departments, are practically under siege. I have asked for a fundamental reappraisal of our objectives in the light of what we presently do and of whether this achieves those objectives. If it does not, then we have to admit it honestly and start to make changes whatever the circumstances we find ourselves in.

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Core biochemistry required for the biological sciences undergraduate

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Although there have been many discussions in the pages of Biochemical Education and elsewhere on the biochemical curriculum, including a major review of the subject by Mehler (1983) and a previous Education Group Colloquium (1986), there have been few published examples of specific experiences in teaching biochemistry to biological science undergraduates. Biochemistry is taught at Bangor as a first-year subject to students in the biological sciences and to those taking degrees in chemistry, agriculture and forestry. Historically, the course has included an introduction to soil science although this will devolve to an earth science course when the Biochemistry Department becomes integrated into the School of Biological Sciences in 1988. The course consists of 91 lecture periods with 76 h of practical work extending over three teaching terms. Table 1 shows the number of students taking the course during the past 3 years and the number of those continuing in the second and third year to read Honours in biochemistry. Two important considerations arise from this Table. First, biochemistry is taught to a large number of students who will study the subject for 1 year only and hence there is a need to provide a balanced course structure which is essentially biological in outlook. At the same time, the course content has to be sufficiently rigorous to provide the foundation for advanced teaching to Honours level. The large class size also means that there are few opportunities for other than a didactic approach to teaching.

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Table 1. First-year foundation course in biochemistry

Length of course:

Lectures, 91
Tutorials, none
Practical classes, $20 \times 4 \text{ h}$
Assessment:

4 continuous assessment papers (45 min) + 1 essay paper at the end of year (90 min)

*Previously $4 \times 4 \text{ h}$ practical classes were devoted to soil science.