COMMUNICATING CHEMISTRY *

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The roots of the growing idiossincracy towards Chemistry by part of the general public and of secondary level students are analysed in detail. They are traced, on the one hand, to the traditional way by which the subject is introduced, where so many concepts, laws and principles that are utterly irrelevant to modern Chemistry are given disproportionate importance, and on the other, to the lack of a positive attitude in relation to the tremendous benefits that chemical knowledge has provided. The consequences of such inadequacies in the presentation of the subject are very well known, i.e., the image of Chemistry as something boring, old fashioned and that bears no relation to real world. In addition the widespread image of Chemistry as the root of awesome problems of modern society is even more amplified. Such negative attitudes towards Chemistry can be reversed if it was presented as a source of our understanding of material world, of life, of Nature and consequentely of ourselves. Such an approach to Chemistry will convey to the students and eventually to the public in general the idea that Chemistry can be the source of deep intelectual satisfaction, and this should be the central endeavour of those who teach Chemistry.

I shall consider three problems in this article: one is the communication of chemistry to the general public, the second is the communication of chemistry to students in introductory courses, and the third is the communication of chemistry to advanced students.

The public's perception of chemistry is that it is particularly evil. Many of our students also think that it is a subject that should be boiled in its own juice, and that its teachers should be boiled with it, in theirs. Our task is to overcome these attitudes and to generate enthusiasm for our subject by showing all these people – the public and the student – how chemists can take the stones of the earth and turn them into metals; we should show how chemists take the oil from beneath the ground and spin it into fibres and conjure it into drugs; and how chemists can harvest the air and paint the deserts green. We should aim to capture peoples's minds and to enthral them with our subject and its all-pervasive applications.

We should show the public that chemistry is the foundation of a major part of industry, and hence a foundation of society and the basis of the future. Because chemistry has the muscle to be both a major enhancer and a major destroyer of life, chemists have an obligation to be accountable for the ecological impact of their subject. Yet chemists have an equal obligation not to be defensive, for that helps to distort the public's vision of our subject, and – by extension – to grease the public's already slippery hold on science as a whole. It is essential that chemists take the *positive* message of chemistry to the streets and pour it into any willing listener's ear: let us show the extraordinary enhancements of life that have sprung from our activities, and let us be proud of what we can achieve and what you in the future may also achieve.

To encourage young people to come into chemistry, and once there to enjoy it, we chemists should make the public aware that the whole of tangible matter is within chemistry's kingdom, and we should share with them the thrill of understanding the properties of matter in terms of its composition, its structure, and the reactions it undergoes. Chemistry is the *central* science, the point in science from which a view may be had of all the other branches of science. Chemistry is the point at which all sciences meet, where physics touches biology, where rocks are bridged to organisms, and where the inanimate becomes animate.

I would like, initially, to spend some time trying to identify the barriers to understanding that seem to stand between chemists and the general public. Why do our nonchemical but otherwise literate friends slip slowly into slumber when we chemists begin to speak? Why does the public first inwardly groan, then outwardly snore, when a chemist speaks? What is the spring of that deep-seated antagonism towards this our central science?

One origin of the barrier that separates chemists from their friends and their public is, at least in my experience, the quality of curricula in high schools: young minds are irrevocably dissuaded from enjoying our subject by the emphasis of curricula on the past and their slowness to adjust to the present and its sharp, clean vision of the central concepts of chemistry. Let me say at once that I have nothing but admiration for highschool teachers themselves: my concern is with the demand that (in countries that I know, perhaps not in Brazil) they have to struggle to comply with outdated syllabuses: many teachers know that there is a richer vein of the subject to strive towards than the fool's gold they are forced to mine. In the syllabuses that I know, old-fashioned dust-encrusted ideas are given prominence over thc sharp, clean, sinewy images of modern chemistry. I shall say more about that later.

Beyond this failure of chemists to identify and propagate the fascination of their subject, and the failure of what vision there is to percolate uncorrupted into highschool syllabuses, there is generally in the public a fear of the intricacy of chemistry. Specifically, there is a fear of the abstract. Chemistry is a kind of material version of mathematics: as I shall try to explain, chemistry is the most abstract science for dealing with matter. Physics is often more tangible, more readily quantifiable; biology, you can pick up and cuddle; chemistry,

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though, deals with a different, more abstract, level of the behaviour of matter. Thus, to understand a chemist's explanation of the behaviour of a particular substance, it is essential first to understand the nature of atoms and molecules, and then to become familiar with a chemist's deployment of these concepts.

The general public knows the terms atom and molecule, but they think of these central concepts as the epitome of the abstract, the symbol of the difficulty of the subject, rather than the great currency of discourse and simplification of explanation. Almost all explanations in chemistry make use of atoms and molecules: so, to make contact with a chemist's mind, it is essential to make the great leap into the abstract, and to leave the comfortable, familiar world of bulk properties and arrive in the abstract, unfamiliar underworld of atoms and molecules. If we are to make progress with communicating chemistry to the general public, it is essential that we encourage people to be intellectually at home with the shapes, sizes, and compositions of molecules.

Another major difficulty with coming to terms with chemistry, in my view, is that chemists are better at rationalizing rather than prediciting. That is, since there are many competing effects that conspire to determine a particular property, chemists need to exercise judgement in determining which, if any, of these competitors is likely to be dominant. This is a great stumbling block for the general public, just as it is for the starting student of chemistry, because neither knows how to judge which effect is likely to be dominant – to a student and (less articulately) to the general public, I think it seems that on Monday it is electronegativity that will win, but on Tuesday it will be polarizability, on Wednesday *d*-orbitals, and so on through the week. The identification of dominant influences is very difficult, even for professional chemists, and we all have to accept, I believe, that chemistry is often more able to provide explanations than predictions. The need to identify dominant effects among many competing influences lowers people's confidence, for they can never be sure that someone else will not come along, after they have come to a conclusion, and say that they have forgotten the effect of lattice enthalpy, reduction potential, the *trans*-effect, or whatever.

A related point is that even our rationalizing concepts are difficult to master – they are packets of individual concepts, they are the jargon of the subject, not fundamental elements of explanation. It is asking a great deal when we require the public – and also the starting student – to follow an explanation in chemistry that is expressed in a chemist's typical language, when one globule of jargon follows another to give, to the unopened ear, an amorphous pile of words with as much structure as semolina pudding. What we chemists must do is to recognize that our normal explanations are expressed in jargon; then we have to unravel the jargon to find the underlying line of thought in terms of primitive concepts like atoms, nuclear charge, and electron distribution, and then use those primitive concepts – the handful of concepts that we can expect the public to understand – to reach the minds of our audience. In that way, we may all come to understand better what we are saying too!

The appropriate response to most of the difficulties I have outlined appears to me to make an appreciation of the secret lives of atoms and molecules a central component of the general cultural equipment of everyone. There is no longer any difficulty in convincing anyone that atoms and molecules are real entities, and not just figments of a philosopher's fevered imagination: all we have to do today is to show a scanning tunnelling microscope image of individual atoms and molecules. Now we can *see* that benzene is a hexagon, and we are beginning to be able to feel our way along a DNA molecule, and identify the bases one by one, almost by touch.

Images such as those that come from STM studies of molecules on surfaces should enable us to sweep away much of the dreary material that is so characteristic of the chemistry taught in schools, the killing ground of the interest in our subject, the Dead Poets Society of science. Now the eighteenth-century gropings toward an appreciation of the existence of molecules – the miserable law of multiple proportions, the loathsome law of constant composition, and the revolting law of reciprocal proportions – can be booted out of sight and replaced by a photograph of a molecule lying on a surface. That is the way to communicate chemistry, *by direct modern impact*, not through the blur of layers of ancient dust.

Once everyone is familiar with the existence of molecules, the next task in the communication of chemistry is to convey how molecules carry out their actions, be it in the atmosphere, as components of detergents, or as pharmaceuticals. We should show the public that through chemistry we understand the origin of the colour of a flower. That we know why a rose is red does not diminish our delight but gives us a greater understanding of nature. That through chemistry we can understand why the colour of a petal may vary with the acidity of the sap, is an addition to our delight. That we can understand, as well as enjoy, the changing colours of autumn, that through chemistry we know why particular molecules are present in a leaf and why they dominate as the chlorophyll decays, adds enormously to the poetry of the seasons. Joy may be inarticulate, but reflection is empty without understanding.

We chemists should show the public that we can take the fundamental properties of matter and spin from them the additional delight of understanding. We can use chemistry to show why a wine is coloured and what affects its taste, through chemistry we can account for the changes that occur in a kitchen. Through chemistry we know why a curry seems to sear and why menthol seems to cool. Through chemistry we can explain why a pharmaceutical cures, a poison gas destroys, and a polymer forms a fibre. In short, we should show the public that through chemistry we can understand the workings of the world, and (in my view) we who can see have a responsibility to spread our understanding so that others can share our delight. At the very least, sharing knowledge will be the foundation for judgement; at the most it will enthral and elevate the intellect as only the deep joy of illuminating knowledge can.

When communicating chemistry to the public and to our students we should also seek to impart our understanding not only of structures but also of chemical reactions: in particular, we should show why reactions occur and how they occur. To explain *why* chemical reactions occur means that we should try to impart an understanding of that great liberator of the human spirit, the Second Law of thermodynamics. If there is anything in chemistry – indeed in science – that symbolizes the complex and remote, then for the underinformed it is the Second Law. But in my view, the Second Law is one of the Great Simplifications that science has achieved, and its formulation and interpretation are two of the great milestones in the development of an understanding of the human condition. I shall say more about it when I come to deal with the content of courses.

I consider it our duty to show the public how *material* complexity emerges from simplicity in the underworld of atoms. We chemists are hewers of simplicity from complexity: we chemists seek to understand the complex in very simple terms. Thus, we should convey the sense to the general public that even a minor shift of an atom, or even of an electron, can have profound consequences. Photosynthesis, for example, that coiling of energy into a Niagara that impels us and our societies into the future, is essentially no more than the relocation of an electron by a sunbeam. We should show the public that chemists exercise control over matter in the most delicate way: to move mountains, we move atoms. We should explain that from our giant industrial plants down to our smallest test tubes, all that is taking place is the relocation of atoms. Shift an atom here, and conjure a pharmaceutical from a oil. Shift another atom there, and conjure a fibre from a gas. Chemists have become masters over matter through their delicacy, through their tiny tinkering with arrangements of atoms. They know how to do very little; but from that very little springs their immense strength, their ability to move mountains, to feed and clothe nations, and to satisfy the needs of societies.

We should share these mysteries. We should show the public how an atom may be shifted to another location, perhaps with extraordinary consequences. We need not give the detailed recipes for remoulding matter, for that will bring on the snores, but we do need to open our public's eyes by showing some of the events that occur between atoms, molecules, and ions that a chemist needs to induce to bring about a change. We should show the public how chemists think when, in their imagination, they walk through the wall of a reaction flask and enter the world where atoms are exchanging partners.

But how do we communicate the simple richness of reactions, and excite curiosity? Surely, the thing to do is to show our public that they are surrounded by reactions – indeed, show them that they *are* reactions, for if they are not interested in reactions, then they are not interested in themselves. Some may consider that the domain of reactions is the laboratory, where change is confined to the dynamic museum of the test tube. We must break that mould. We should show that wherever the public looks, they will see the consequences of chemical reactions; indeed, let us show them that seeing is itself dependent on reactions, as is life itself. In the first half of the nineteenth century, Michael Faraday was among the most successful communicators of chemical reactions to the previously unseeing. In his famous series of lectures *On the chemical history of a candle*, he took the mundane, and showed that it was a microcosm of chemistry. That could be a model for us today: to capture the attention of the general public, to allow a sense of confidence to grow, and, above all, to fan into flame a vigorous interest in our subject; to do so, we should parade before them the reactions of the mundane and familiar, and then hope that their interest will spread like a forest fire from a single spark. Above all, we should impart the sensitivity of our feelings as chemists towards the matter of the universe, the matter of which we animals are such a fascinating part.

Let me now switch my attention from communicating chemistry to the general public to its communication to future generations – its communication to our students. First, I shall look at some aspects of introductory courses for those who might never see the inside of a test tube again, and then I shall consider more advanced courses for those on the brink of becoming professionals.

Let me begin negatively by asking what is currently in introductory courses is ready for execution? The introductory courses that I am familiar with, and for which I have written, spend an enormous amount of time dealing with clever calculations of the pH of solutions, and a colossal amount of time dealing with pK_a; but do we really believe that we are instilling a sense of what living and breathing chemists are doing in their laboratories when we talk for hours about pK_a? A chemist makes new matter, a chemists finds out how matter may be modified. Chemists are magicians with matter: that is what we should convey. As a general tactical feature, I consider that the ideal procedure for instruction of any concept is that set out in Table 1.

Table 1. The strategy of instruction

1. **Motivate** an interest in the phenomenon.
2. Explain the **physical basis** of an effect.
3. Show how to **estimate** its magnitude.
4. Give **examples** of the effect and its consequences.
5. If there is time, and if it is appropriate, show how to **calculate** its precise value.

The calculation of pH is an ideal example of this approach, especially since the "precise" calculation can be carried out using a spreadsheet, the use of which is a skill that we should impart to all our students. A chemist needs to know the concept of buffer, but to commit a student who is new to chemistry to an hour or two of community service to work out a pH range (which they always get wrong anyway because they always neglect activities) is a horrendous waste of time. Real chemists understand buffers, know broadly where a particular mixture will stabilize the pH, and then get buffer ranges by looking at labels – they are empirical, never calculated. We should not corrupt and deter by giving false impressions of what it is that chemists never do!

What are the great ideas that we should seek to convey to our students so that, after they leave our care, they have acquired something of our special sensitivity to matter? In England we have on the radio a very long-running programme called *Desert Island Discs*, in which a celebrity is invited to select eight gramophone records that they would wish to have with them if they were marooned on a desert island. Just for fun, I would like to invite you to play *Desert Island Principles*, and to select your eight most important principles that you would wish to take to an intellectual desert island. My eight are shown in Table 2.

These eight principles (some, of course, are great truckloads of principles) are the current spring of our mastery, and hence the topics that we should currently convey. Beyond these principles there are the *attitudes* that we should try to instill. In elementary organic chemistry we should convey the importance of understanding the mechanisms of reactions and of the reactions of functional groups. I find it astonishing that in some countries so little is said about organic chemistry in the freshman year – often on the feeble grounds that "it will be done properly next year". It is grossly improper, I consider, for the young minds who intend to do no more chemistry to be sent out into the world not having been exposed to the extraordinary corpus of knowledge and style of thinking that organic chemistry represents. In elementary inorganic chemistry the spring of chemistry's current success is our understanding of the structures of solids and complexes. In elementary physical chemistry, the spring of our success is spectroscopy – particularly that queen of spectroscopic techniques, NMR – and the development of techniques for invading the private lives of individual molecules, and particularly the enhancement of experimental chemistry with computational chemistry. If computational chemistry is so important, shouldn't it find a place in our introductory courses? Look at the insight that we already obtain from molecular structure calculations using computers! The computer is very important in chemical education because it opens up to young minds who are not mathematically inclined (but who may nevertheless still possess a profound chemical insight), the prospect of becoming familiar with the quantitative aspects of the subject through graphics and other user-friendly aspects of computation.

Table 2. The eight great principles of chemistry

1. **Stoichiometry.**
2. **Energy:**
   - Conservation
   - Quantization
   - Degradation
   - The Boltzmann distribution
3. **Atomic structure:**
   - Orbitals
   - Atomic radius
   - Consequences
   - Periodicity
4. **Dynamic equilibrium**
   - The concept of equilibrium constant
   - The approach to equilibrium: rate laws
5. **The electron pair**
6. **Electron transfer**
   - Redox reactions
   - Electrochemistry
7. **Proton transfer**
   - Acid-base reactions
8. **Molecular shape**
   - Stereochemistry

Our current great ideas of chemistry will survive beyond this millennium and into the next, and we should structure our courses around them in order to show our students how we think, how we rationalize, and how we magic with matter. Among the great ideas, foremost in our thoughts, is surely the concept of the atom and its elaborations, the ion and the molecule. Atoms are the currency of our interpretations, and I have no doubt in my mind that, from an as early an age as possible, we should saturate our students with a sense of their reality. There is no need to go into the history of the emergence of atomic theories – that should be left to people interested in the history of science, not the future of it. (There are some places for historical introductions, I admit, where we need the entire cultural background if we are to appreciate the point, but atoms are not one of them). As chemists we need to know about the responsiveness of atoms, for we are concerned with the properties of their electrons. Therefore we need to know about ionization energies, electron affinities, electronegativity and hardness. Almost everything in chemistry comes down to the sizes of atoms – so let us make sure that everyone understands the periodicity of size and its consequences. We should imbue our students with an appreciation of atomic and ionic radii and their implications.

Another major part of our subject has to do with structure, so we currently shall and in the foreseeable future will need to extend our students' appreciation of the structures and shapes of molecules and of the internal structures and shapes of solids, including metals, semiconductors, ceramics, and polymers. We should instill in them a sense of the relationship between the microscopic and the macroscopic, the atomic property and the bulk property, the imagined and the perceived. That surely is one of our grand strategies for the education of a chemist:

Table 3. The grand strategy for reaching understanding

To establish the link between the imagined and the perceived.

Another part of our subject that we should transmit to students now and in the future is an understanding of the motive power of change, for where we are not concerned with structure, we are concerned with the modification of structure – with reactions and their driving power. There is nothing more central to chemistry than the Second Law of thermodynamics, and we should imbue our students with a sense of its power.

The motive power of change is a leaping off place for a discussion of how that change is realized – the great classes of chemical reaction – acid-base reactions and redox reactions. Let us show our students how a chemist can see in the world's processes a handful of reactions that pervade the whole of chemistry. Here is the place to bring in aspects of acid-base behaviour. For this subject, I think an historical approach is beneficial, for it shows how chemists go about their work of identifying the quintessential: first Arrhenius, then Brønsted, and finally Lewis – let us show how the centre of attention shifts, and the concept becomes generalized, and how increasingly we see how the apparently distinct is all actually one. Moreover, through the discussion of reaction types we show how chemists deploy their understanding, particularly in organic chemistry, to construct material that might never nave existed without conscious meddling with nature.

The discussion of redox reactions leads naturally into electrochemistry, but we must expand our students' vision of what electrochemistry is about. It is not just electrode potentials and electrolysis: it is half modern inorganic chemistry. Our young students should see that there are extraordinary consequences arising from the flow of electrons through matter – semiconduction, superconduction, as well as oxidation and reduction. Electrochemistry will be one of the great achievements in chemistry in the next millennium, and we should prepare young minds for it.

Now let me turn to certain aspects of more advanced courses in chemistry. I shall have most to say about physical chemistry, but I would like to make a few remarks on the relative characters of physical chemistry and inorganic chemistry. An instructive aspect is to notice the different ways in which physical and inorganic chemists provide explanations. Inorganic chemists typically seek *parameters* that can be used to correlate trends, such as electronegativity, hardness, and atomic radius, whereas physical chemists typically seek a fundamental understanding of the observation directly, or seek it indirectly by explaining the parameter. Inorganic chemistry shows up another way in which chemists think, and that we should impart to our students – perhaps more than we are doing at the moment. We sometimes tend unwittingly to impress on our students, I think, the sense that in chemistry we can make reliable predictions: then our students are bewildered and lose heart when they trip up and make false predictions. Chemistry is a subject that you can rationalize once you know what has happened: it is very difficult to make reliable predictions. That is the sense that we should convey to our students: we should express more explicitly the essential idea that chemistry is a multidimensional tug-of-war: students should take pleasure from the realization that, as such, chemistry is a microcosm of the real world. There are influences in conflict, and it is the task of the chemist to develop sufficient judgement to be able to anticipate when one influence is likely to dominate. That is the essence of chemistry – and life – that we should instill.

As to physical chemistry itself, we must not avoid confronting the fact that it is an intrinsically mathematical subject. Here we have a real difficulty, and therefore a splendid challenge. A chemistry student is only just tolerant of mathematics. Our task is to respect that attitude but to be true to our own discipline. But what do we *really* mean when we speak of mathematics in physical chemistry? Not very much.

The few topics that we make use of are listed in Table 4.

Table 4. Essential mathematics for physical chemistry

1. Simple differentiation and integration
2. Partial differentials
3. Differential equations
4. Matrices and vectors
5. Complex numbers
6. Fourier transforms

The level of calculus that we need is actually very low: straightforward differentiation, the integration of x^n and e^x, and the concepts of boundary conditions. We need the merest familiarity with complex numbers – just enough to understand the significance of $\psi^*\psi$.

The crucial feature with mathematics for chemists is to ensure that any mathematics is *motivated*. This motivation can be achieved in two ways. One is to ensure that we interpret physically the equations we present and the reason for each stage: that concentration on interpretation should be all-pervasive in science, anyway. Secondly, I think a case can be made for developing mathematics as it is needed, when the sense of its relevance is immediate. Perhaps instead of there being a separate course on mathematics, we should consider organizing a series of "appendices" interspersed throughout the course for developing the techniques that the student currently needs.

One of the main reasons for studying physical chemistry is to acquire the ability to express qualitative ideas quantitatively. Physical chemistry is the subject that gives chemistry its backbone and enables it to stand up to quantitative investigation. Therefore, it may be appropriate to recognize this role explicitly and to include in our courses a sequence of lectures on "model building". In these lectures, we would show our students how to take a series of physically motivated concepts and use them to derive a quantitative expression. Some of the topics that we might include in a course of this kind are already included in conventional courses, so the change would not be much of a revolution. I think we have something to learn from the physicists here, because they are very skilled at developing approximations where the precise treatment of an accurate model is too difficult or where an exact solution would be too obscuring. Some of the topics that we might include are listed in Table 5.

Table 5. Candidates for a "model building" approach

1. Kinetic theory of gases
2. Debye-Hückel theory
3. Collision theory
4. Activated complex theory
5. Rate equations

The kinetic theory of gases, for example, is an extraordinarily rich and beautiful theory which, however, can be presented in a very gloomy and souldepressing way. How much better it would be to present it as a superb example of how an idea of exceptional simplicity can be developed richly. The Debye-Hückel theory is another admirable example of model building, but of a rather different kind. Its central feature is the intricacy with which simple concepts can be knitted together into a continuous fabric. Every step is straightforward, but it is like a journey where you have to change the bus a dozen times. It is intricate, but it is driven by an intense insight into the nature of an ionic solution, and it is immensely rewarding to struggle with and come to understand it.

I find it very difficult to make any original suggestions about how classical thermodynamics should be taught. After all, people have been trying to teach it for centuries, and maybe all the good ideas have been tried. However, let me say at least that there are two supremely important equations in chemical thermodynamics (Table 6).

Table 6. The central equations of chemical thermodynamics

$$\Delta G^o = -RT \ln K$$

$$\Delta G = -w_e$$

These are the two equations at which we should aim, and students should be made to realize the power we are handing down to them when we instruct them in the origin and application of these two equations.

In teaching thermodynamics, we should convey to our students the underlying motive power of the approach to equilibrium – the increase in universal entropy – and we should base all our derivations, I believe, on the chemical potential. The chemical potential is a powerful unifying concept: once the concept is understood, then the whole of equilibrium thermodynamics can be developed systematically, simply, and in a unified manner. We should impart the scientific attitude that a single mode of thought can conquer a multitude of problems.

One great river of knowledge in chemistry is thermodynamics. Another great river of knowledge–there are three Amazons in the continent of chemistry – is quantum theory. (The third Amazon is the description of change). I think that quantum mechanics is almost the only part of the subject where a historical approach may be appropriate because young minds must be seduced away from their classical preconditioning. (But maybe that is an old fashioned view now, and we should perhaps leap straight into the heart of quantum mechanics and show the world the way it *is*). It is essential for us to convey the sense and origin of quantization. But when that has been achieved, we should aim at understanding the three features set out in Table 7.

Table 7. The essentials of quantum chemistry

1. Atomic structure and periodicity
2. Molecular structure in terms of molecular orbitals.
3. The significance and role of perturbation theory.

The last item, perturbation theory, may seem to be on a different scale from the first two, but so many properties in chemistry depend on the response of systems to external influences that I think people should understand at least the qualitative basis of perturbation theory.

Statistical thermodynamics is a potential Sahara for students to be left dead and dying in. But, once again, I think it is possible to identify the central features of the subject. There are only two, and they are set out in Table 8.

Table 8. The central ideas of statistical thermodynamics

1. **The Boltzmann distribution**
   The form of the distribution
   The equipartition theorem
2. **The molecular partition function**
   Definition and interpretation
   Calculation in specific cases
   Calculation of thermodynamic functions, especially *K*

I believe that there is a place for reviewing the scope of the application of the Boltzmann distribution before getting into the complicated business of its derivation. Indeed, a lot of the time we do not even need the distribution itself, but to do our model building we can make use of one consequence of it, namely the equipartition theorem. We should always aim for the heart of a subject – the concepts we actually use.

It goes without saying that in physical chemistry we should teach the third Amazon: the features of change that are so characteristic of chemistry. By change, I have in mind the processes summarized in Table 9.

Table 9. Transport and change

1. **Transport properties of gases**
2. **Diffusion**
   Derivation and interpretation
   Computer solution
3. **Reaction rates**
   Rate laws and their integration
   Computer simulation
   Reaction mechanism

A discussion of the diffusion equation gives us a great deal of conceptual understanding over chemically significant events, and it is an ideal place for the microcomputer to play a role in our teaching. Rate laws will always be a central component of our teaching, but we should adapt our methods of instruction to the new tools – particularly the microcomputer – that are now available. If we want to teach modern kinetics – oscillation and chaos, for instance – then the use of computers is almost mandatory.

I simply do not have time to deal with all the other aspects of our courses: here I have merely touched on some highlights. But let me conclude by looking into the future. The major instructional device will undoubtedly be the microcomputer. Soon the expectation that a course will be computer-orientated will be as commonplace as the current expectation that a course will make use of calculus. Chemistry without computers will be like textbooks without illustrations.

The major advances in physical chemistry will come from the availability of lasers and synchrotron radiation and from the increase in computing power. The new sources of radiation will enhance our ability to determine structure and, perhaps more importantly, will enhance our ability to study the time-evolution of processes and reactions. On the conceptual side of the subject we must expect major advances to stem from the deployment of fractals and chaos. On the experimental side, we should expect physical chemistry to merge ever more completely with inorganic chemistry and with biochemistry. If there were a single field in which we should expect truly great advances, I would put my money on electrochemistry (in its broadest sense). But most pervasive of all, most pivotal in our thinking, must be the role of the computer. We must prepare our students for the paradigm shift that is to come.

In conclusion, let me return to the starting student, the general public, and the advanced student, and emphasize their *common* need. We are asking all of them to appreciate how, and to what extent, we chemists have acquired a mastery over matter. Our communication of chemistry to them should identify what chemistry has already achieved, and should present the modern, central ideas of the subject, not just what we have become accustomed to teach and find it easy to examine. We should never forget that we are training young magicians and – more broadly – are introducing people to the joy of understanding.