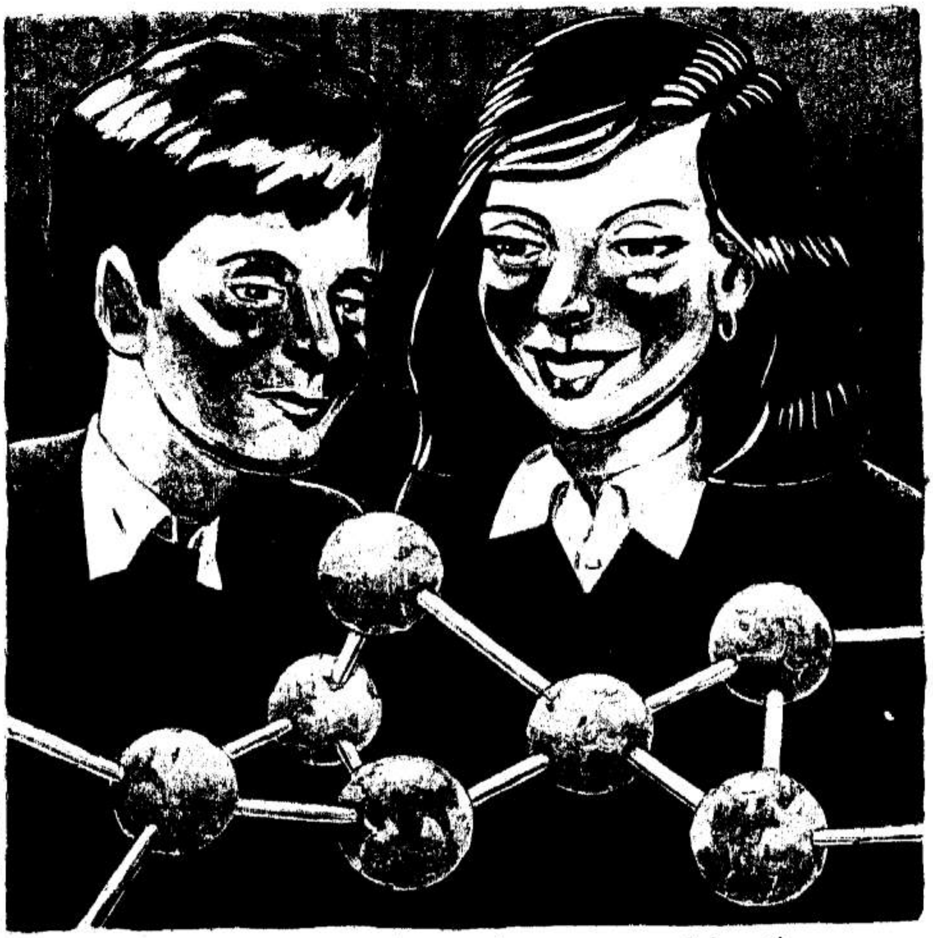


Roald Hoffmann introduces a four-page special section on chemistry with a personal view of the subject's future

Myth busters

As it was, so it is today – chemistry is the art and science of substances and their transformations. The world abounds with natural change that we now know to be molecular. A mash of grapes or potatoes begins fermenting, forming alcohol, and, if we do not interfere, turns into vinegar. Oxygen combines with a haemoglobin molecule, and carbon monoxide does so more eagerly. We age. An aster flowers. A colourless fluid in the gland of a Mediterranean mollusc, exposed to air and sunlight, turns pus-yellow, green, blue, and then a purple that was used to dye rich Romans' togas and colour a strand in the fringes of the ritual garments of the Israelites. A plant in the pea family and woad, produce a nearly identical dye.

There are thousands of naturally occurring molecules on the surface of the earth, and in living things. Any species, while relying on the same underlying carbon-based biochemistry, is likely to harbour thousands of molecules that differ from those of any other species – this is part of the concern about species extinction, an expunging of an unpublished library of chemical experimentation.

With time, we added our own ingenious transformations. These began, of course, with earthly ingredients, but led to new kinds of matter. So the ash of certain plants, "potash", boiled with almost any animal or vegetable fat or oil made soap; a natural phosphate rock treated with sulphuric acid became the fertiliser superphosphate; bauxite, an aluminum oxide ore, could be electrolysed to useful aluminum metal in one and the same ingenious process devised simultaneously continents apart by two 22-year-olds. We have made genes. We have made that purple dye in sufficient quantity to colour x million blue jeans every year.

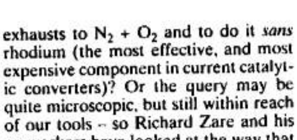
Transformation, A——>B, is at the heart of chemistry. Transformation is simply fascinating. Malcolm Chisholm, Cindy M. Cook and Kirsten Folting at Indiana University, in a recent paper write "Red, pentane solutions of W_2(O-t-Bu)$_6$ initially turn green upon reaction with N_2O and then fade to the straw colour...", and anyone who has played with a chemistry set (in the days before safety restrictions emasculated those sets) feels the adopted Hoosiers' excitement. Colours, bright crystals, even the noxious gases, the occasional explosions, continue to attract the young. If one seeks a metaphor for change, chemistry readily provides one, in every reaction. This is why alchemies arose in various cultures.

The value added in the transformations has made the chemical process and related industries a substantial part of the gross domestic product (GDP) of industrialised countries. And the side-products and profligate wastes of some of our transformations create hazards. Change is something to be feared, even as it must happen. Perhaps this is why people (and societies) are fascinated and threatened by real chemical transformations.

First, chemistry is a science. It is a way of knowing reliably the world at an intermediate level. Not the infinitely small nor the infinitely large, but at that human scale of what you and I can hold in our hands. Chemistry is there in the industrial plant that makes a ton of synthetic indigo, and in the knowledge we have of the length of the unseen bonds in the tiny indigo molecule. It's nice to be in the middle; that's where human beings are.

The science comes in the chemist's gathering of reliable knowledge on the identity and structure of molecules (what is that white powder C that comes out of heating A with B?) And it comes from asking basic questions about the nature of the change, the arrow in A + B ——> C. The curiosity driven question may be macroscopic – how can I devise a catalyst for taking undesired NO in car exhausts to $N_2 + O_2$ and to do it *sans* rhodium (the most effective, and most expensive component in current catalytic converters)? Or the query may be quite microscopic, but still within reach of our tools – so Richard Zare and his co-workers have looked at the way that NO molecules bound (chemisorbed) to a platinum surface come off. The Stanford team determines, remarkably, that the NOs depart while rotating "parallel" to the surface, helicopter-like, rather than "perpendicular", cartwheel-like(see diagram).

Now that is detailed knowledge! And, as soon as I've stopped marvelling at the



experiment, I ask "why?"

Note that the scientific questions that chemistry poses and occasionally answers may be in a discovery mode (how does the NO come off the surface?), or they may be in a creation mode (that better catalyst, most unnatural, yet to be made). One distinguishing feature of chemistry, especially prominent in the synthesis of molecules, is the hefty dose of creation, the making of the new. This endows our science with a second type of art – not only craft, of which there is an abundance, but also the high art of the creation of artifacts of palpable beauty.

Given that it is a science, is chemistry just applied physics? That the question could even be posed betrays the acceptance (by the scientific community, including many chemists) of a reductionist catechism, and an excessive valuation of simplicity as an aesthetic criterion. Most scientists have bought the reductionist mode of thinking as their guiding ideology. Yet this philosophy bears so little relationship to reality.

Every field of human knowledge or art develops its own complexity of questions. The problems facing chemistry are in some ways more complex than those in physics. I think there are vertical and horizontal ways of understanding. The vertical way is classical reductionism. The horizontal way looks at a phenomenon in the context of the complexity or hierarchy of concepts developed within that field.

Let me illustrate the futility of reductionism with a *reductio ad absurdum*. Suppose you receive an anonymous letter. In that letter is a sheet of paper with two lines from a poem. The lines, from John Donne's "The Ecstasy", read:

"Love's mysteries in souls do grow,
But yet the body is his book."

Knowing the sequence of firing of neurons when the poet wrote that line, or in your mind when you read it, or in the mind of the person who sent the letter, knowing the fantastic, beautiful complexity of biochemical actions behind the firing of neurons and the physics and biochemistry behind that, that knowledge is incredible and desirable, that knowledge is going to get you a lot of Nobel Prizes, but . . . it has nothing to do with understanding the poem, in the sense that you and I understand a poem, or drive a car, or otherwise live in this terrible and wonderful world. The understanding of Donne's poem is to be sought at the level of the language in which it is written, and the psychology involved in the writing and reading of it.

Now, if you are willing to accept a leap between the humanities and science, I tell you that even in two "hard" natural science fields as close to each other as chemistry and physics, even there there are concepts in chemistry which are not reducible to physics. Or, if they are so reduced, they lose much of what is interesting about them. The reader who is a chemist I would ask to think of ideas such as aromaticity, the concept of a functional group, strain in a molecule, or a substituent effect. Those are constructs which have a tendency to wilt at the edges as one tries to define them too closely. They can be quantified, to a limit, but they cannot be defined unambiguously. Yet they are of fantastic utility to our science.

In science simplicity and complexity always coexist. The world of real phenomena is intricate, the underlying principles simpler, if not as simple as our naive minds imagine them to be. But perhaps chemistry, the central science, is different, for in it complexity is central. I call it simply richness, the realm of the possible.

Chemistry is the science not so much of the hundred elements, but of the infinite variety of molecules that may be built from them. You want it simple – a molecule shaped like a tetrahedron or the cubic lattice of rock salt? We've got it for you. You want it complex – intricate enough to run efficiently a body with its 10,000 concurrent chemical reactions? We've got that too. Do you want it done differently – a male hormone here, a female hormone there; the blue of cornflowers or the red of a poppy? No problem, a mere change of a CH_3 group or a proton, respectively, will tune it. A few million generations of evolutionary tinkering, a few months in a glass-glittery laboratory, and it's done! Chemists (and nature) make molecules in all their splendiferous functional complexity.

So – a science (and fun at that), and a science very different from physics. And also a vast industry. Neglected within academia, but inevitably providing the economic base which allows academic chemistry to flourish, the chemical industry is vast, and generally healthy. I would include in it all transformations of natural matter, including the winning of metals (a very chemical process) and the production of energy (could you call the combustion of oil, coal, or natural gas anything but chemistry?). By my reckoning, chemistry would then play a significant role in near a quarter of the GDP of an industrialised country.

Most economists limit the definition to the chemical process industries, still broad enough to include synthetic fibres and plastics, bulk chemicals, fertilisers, fuels and lubricants, catalysts, adsorbents, ceramics, propellants, explosives, paints and coatings, elastomers, agricultural chemicals and pharmaceuticals. And more. The US chemical process industry sold \$4.32 x 10^{11} worth of goods in 1990, adding more in value to the raw materials than the cost of those materials.

In my country chemical industry is one of the few large components of the economy which contributes positively to a net negative balance of trade. Given that economic base, chemistry is also a profession. The size of the work force is set by the underlying economy; in the US more than 70 per cent of the PhDs will enter industrial employment; 2,194 PhDs were trained in the US in 1991 (23 per cent female, a significant rise), a little more than 60 per cent of them US citizens. The median age at doctorate was 29.4, and the median time from baccalaureate to doctoral degree has crept up to 6.8 years.

Is the number of chemists too small? Please do not ask the professors, for their addiction to research is pathological; there is no way they will limit the hands and brains they so insatiably need to aid them in their research. Ask the graduate student nearing the PhD; he or she will tell you how many job offers they have. My impression is that the situation is reasonably healthy; our good students are finding jobs, or poorer ones are having trouble.

The system is, in my personal and unpopular opinion, unhealthy. In the US the chemical industry has conspired, with government aid, and working on the addiction to research of faculty at the research universities, to get the most highly skilled component of its workforce (the PhD) trained essentially free of charge to industry (aside from the taxes it pays). At Cornell, the direct industrial contribution to the chemistry department's research budget is around 10 per cent, yet 70 per cent of PhDs go to work for industry. The only way that

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industry will contribute more is if we limit PhD. production; we seem to be psychologically incapable of doing so.

Self-serving scientists have predicted a shortfall of scientists in the near future. This is a mirage, and the punishment I would wish to visit upon those who made those "predictions" is that their children enter the job market in those years. If there be a shortage of people, which I doubt, then (a) it would be good for the economic position of the chemical professional, and (b) it would be resolved, as it always has in the US and UK, by adjusting immigration laws.

What is the challenge of the future to our profession? Not our ingenuity; artists in the molecular trade will soon synthesise taxol (an anti-tumour agent from the bark of a yew tree). Others will learn how to exercise control in two dimensions, making a host of incredible net-like synthetics. Low-temperature solid-state syntheses of inorganics will become standard, and we will bridge the vacuum - high pressure gap in surface science. Maybe I'll leave this to Daedalus, so much more imaginative than I at prognostication. But let me mention here a problem of the profession which will yield less readily to the finely-honed, curious minds of the young people in our graduate schools.

This is education in chemistry, in the broadest sense of the word. I view education as a crucial part of the democratic process; a privilege and a duty of the citizen.I am not concerned about scientific illiteracy (and this is my opinion only, I remind you) so much from the point of view of it limiting our manpower base or affecting our economic competitiveness. What worries me about prevalent chemical illiteracy, a failure of the education process, are two other matters.

First, if we do not know the basic working of the world around us, especially that component that human beings themselves have added to the world, then we become alienated. Around us proliferate chemistries whose workings we do not understand. I doubt that there are many among my colleagues who could do what Mark Twain's Connecticut Yankee in King Arthur's Court could do, that is to reconstruct our technology from all those partial differential equations we know.

Alienation, due to lack of knowledge, is impoverishing. It makes us feel impotent, unable to act. Not understanding the world, we may invent mysteries, new gods. As we are doing now.

My second point of concern about chemical illiteracy returns me to democracy. Ignorance of chemistry poses a barrier to the democratic process. I believe deeply that "ordinary people" must be empowered to make decisions - on genetic engineering, waste disposal sites, on dangerous and safe plants. They can call on experts to explain the advantages and disadvantages, the options, benefits and risks. But experts do not have the mandate; the people and their representatives do.

Here then is the importance of constructing primary and secondary school chemistry courses that reach out to a wide audience. And of training and rewarding teachers that can teach these. Chemistry courses must be faithful to the intellectual core of the subject. But they also need to be attractive, stimulating, intriguing. They must aim primarily at the non-science student, at the informed citizen, not the professional.New chemists, brilliant transformers of matter, will come from among these youngsters. Of this I am sure. But they will not be able to do what they are capable of unless we teach their friends and neighbours, the 99.99 per cent who are not chemists, what it is that we do.

The author is professor of chemistry at Cornell University. He was a joint winner of the Nobel Peace Prize for Chemistry in 1981.