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Hands-on practical chemistry for all*

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Abstract: Practical chemistry is under siege world-wide for various reasons which include cost, safety, waste disposal and teacher training. Yet most chemistry educators regard practical chemistry as very important for various reasons which include motivation, concept learning and skills development.

Using small-scale plastic equipment allows cost, safety and waste disposal problems all to be addressed. We have developed a microchemistry system based on such equipment which is easy for individual students to use and convenient for teachers to implement.

For all these reasons the RADMASTE Microchemistry system is attracting world-wide interest. Alongside other curricular changes this development may help to revitalise chemistry education in many countries.

PRACTICAL WORK

Chemistry has always had its practical side. It had to be so, because it is an experimental science. Whatever was learnt about substances and their behaviour during the past centuries came from observation, practical experience and deliberate scientific investigation. Also, all along, we know that our forebearers applied their knowledge practically in order to make things or do things to improve the quality of life or to overcome enemies. In the process, theories were developed and displaced, giving us greater and greater effectiveness in using our knowledge in practice.

It's a wonderful success story, if we take the long view, and education has and will continue to help maintain it. As knowledge expanded, chemistry educators had to be increasingly selective in their choice of the most important knowledge, skills and attitudes to impart. Aside from this, there have been changing perceptions as to what is most important resulting from changes in educational access. Education for all is now a globally accepted aim, although the extent to which this is achieved varies greatly from region to region. The closer the aim is approached the stronger has been the advocacy for the 'science for all' type of educational philosophy, rather than a 'science for scientists' one.

The 'science for scientists' philosophy has been ascendant for more than a century, and the provision of practical work (laboratory experiences) in science curricula was scarcely questioned during that time [1]. Furthermore, it has been natural to use the equipment basic to current scientific practice. With increasing sophistication of practise, the kind of equipment regarded as basic has changed from test-tubes to microwell plates and from indicators to pH meters, etc. Globally speaking, chemistry educators at both school and university level have been slow to respond to these changes of practice, partly because of ignorance and conservatism, and partly because of increasing costs. The cost increases originate firstly from the increasing sophistication (a pH meter is far more sophisticated and far more costly than indicators) and secondly from the steady progress towards education for all.

What, then, is the position of practical chemistry currently? In my view it is under siege. Serious

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Correspondence: E-mail: BRADLEY@AURUM.CHEM.WITS.AC.ZA questions have been posed about its cost-effectiveness and its purpose. Chemistry is a more expensive and more hazardous subject than history or other humanistic subjects, because of the need for practical work. Furthermore, evidence about what is achieved when students engage in practical work, leads to rather ambiguous conclusions [2,3]. There are both positive and negative indicators as regards knowledge, skills and attitudes, and there are claims that other methodologies can do better at less cost. Demonstrations, 'dry labs', computer-based experiences and films have all made claims as alternatives [4]. I believe that all of them have merit but no one should be regarded as the solution. Nevertheless, the questions remain to be clearly answered: what are the purposes of practical work in chemistry education and how can they be realised?

CHEMISTRY AS A HUMAN ENDEAVOUR

It seems to me that the vital message for chemical education at any level is that chemistry is a human endeavour. This message, equally valid in all societies, is appropriate within both a 'science for all' philosophy and a 'science for scientists' philosophy. It clearly is in tune with other broad aims variously expressed as 'public understanding of science', 'scientific literacy', and 'science, technology and society.' I believe that hands-on practical chemistry experiences are an essential component of the realisation of such aims [5]. Real students working with real substances is the necessary but insufficient requirement.

PRACTICAL CHEMISTRY EXPERIENCES FOR ALL

In the context of education for all, we must therefore accept the challenge of hands-on practical chemistry experiences for all. Here we encounter the cost barrier already referred to. Traditional basic resources are relatively expensive—the chemistry laboratory with water, electricity and gas, storage space and ventilation, the equipment (dominated by heat-resistant glassware) and the consumables (dominated by chemicals, but with a nontrivial glassware breakage component). Increasingly too, costs associated with safety and waste disposal, must be added to the bill. Instrumentation is also essential at more advanced levels if practical experiences are to be meaningful in contemporary terms.

Looking at this list of requirements, one understands why policy-makers question whether it is a justified expense. To answer their well-justified concerns we have to cut costs and we have to improve effectiveness [6]. In developing countries, the situation is acute and several attempts have been made to make substantial cost reductions [7,8]. A major type of approach at school level has been to constitute teacher classroom science kits, the contents of which are carefully selected for cost-effectiveness. These kits vary enormously in their scope and ambition; often they are made up and distributed by government-sponsored local equipment production centres. The concept is appealing in principle, but sustainability is elusive.

At more advanced levels, Sane has pioneered the design, production and implementation of low-cost instrumentation for chemistry [9]. A novel feature of his programme in India has been the bid to provide employment for the socially disadvantaged in the construction of this equipment. Another valuable aspect, has been the policy of conducting workshops for teachers at which they construct their own instrumentation: this not only generates the pride of accomplishment but the knowledge and skills to maintain the equipment thereafter. The concept is again very appealing in principle, but the appeal appears to have been more to inspired academics than to educational decision-makers.

Considering the long-standing, global nature of the problem, it is disappointing that no globally successful solution has emerged. What I have to describe now may have that potential insofar as chemistry is concerned [10].

MICROSCALE CHEMISTRY KITS

We have designed individual student microscale chemistry kits to address these problems and opportunities (Fig. 1). By going to small scale (volumes of 1 mL or less) you solve many problems all at once: the equipment costs less, the chemicals cost less, safety is improved and there is less waste. Another change is that most items in the kit are plastic. This means further cost savings, both initial and recurrent

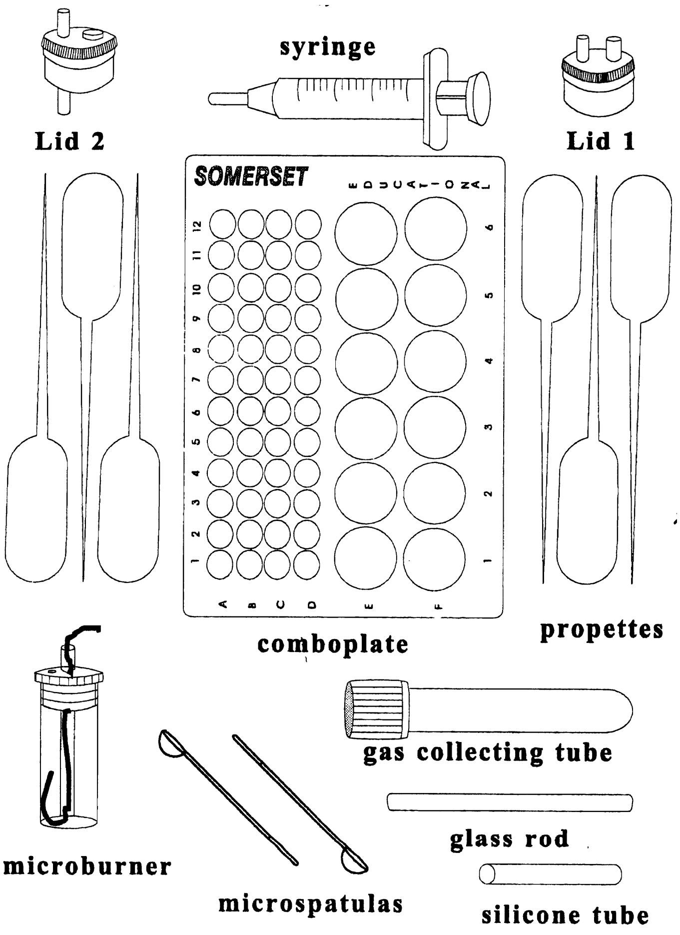

Fig. 1

(breakages), but of course does impose limitations on the kinds of operations that can be supported. The most obvious limitation is temperature; this can be circumvented by careful design of experiments and by using the two or three glass items included in the kit. Heating is provided for by means of a small-scale spirits burner [11], which is very effective for the small quantities of substances used. Another limitation is the range of chemicals that can be tolerated. One or two aggressive inorganic substances (e.g. concentrated nitric acid) and some common organic solvents (e.g. acetone) cannot. Some of these substances are not used at school level anyway, whilst ones that are can be accommodated by careful choice of the plastic. We use an inexpensive plastic which is resistant to organic solvents, for most organic experiments.

For some teachers, much of this may seem to be old news: as Beasley & Chant stated in 1996, with reference to beginning university courses 'The trend from macro is now established.' [12].

They have heard about, and maybe use, microscale equipment. However, once we look more closely at the kit components, we find specific innovations that greatly improve the versatility and convenience of the kits. The heart of the kits is the comboplate® which has two sizes of microwell. The small ones are very suitable for simple reactions and tests, such as one would have previously used a test-tube for. They also serve to hold a specially designed microstand where this is required, for example, in microtitrations. The bigger wells are more like the beakers and flasks of traditional scale. Two plastic well-lids have been designed to fit these and to facilitate the carrying out of gas preparations and reactions using these gases (Fig. 2). They also serve as microtitration flasks, and as a location for an LED for qualitative testing of conductivity. For transfer of solids we have microspatulas and for transfer of fluids we have propettes (Beral pipettes) and a 2-mL syringe. As noted before, there is a microburner and a couple of glass items

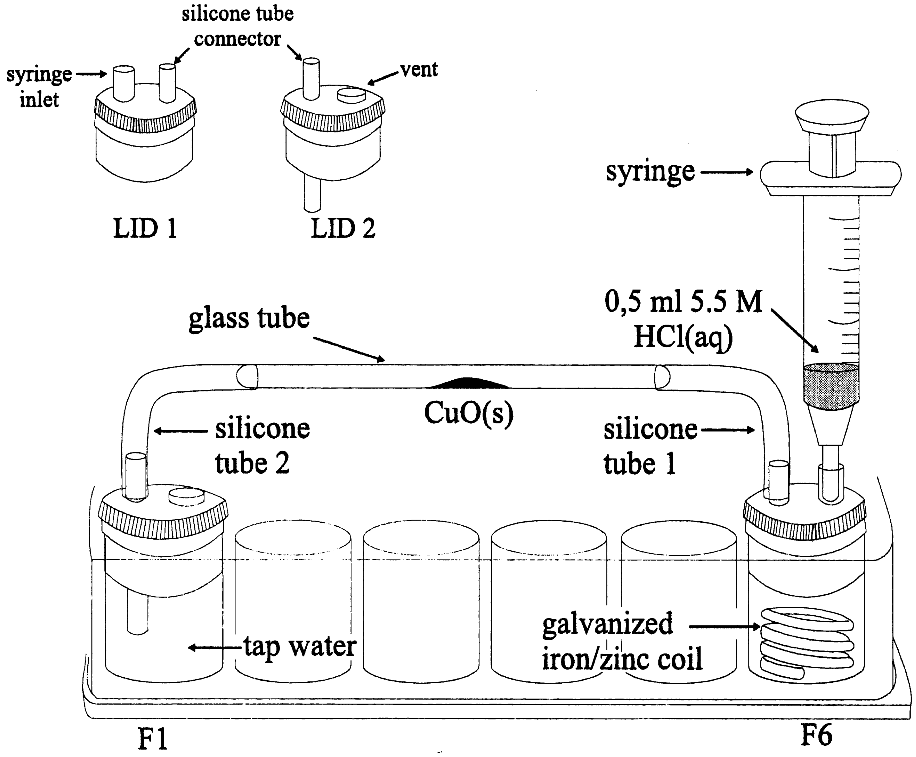

Fig. 2

that allow for direct heating, where reaction conditions demand this. The glass rod can be used for immersion heating (and cooling) and for flame tests with the microburner.

All these items constitute a kit supplied in a small plastic zip-lock bag. The virtue of this is that it is self-contained, compact and easily stored, and portable. It also lends itself to ownership by the student, if that is an appropriate institutional policy. It is then very possible either to take it home (like a calculator or maths set can) or to have it stored (with a student's name on) at the institution. Of course, with ownership goes all the good basic life behaviours of housekeeping. The student can become responsible for the kit, its cleanliness, maintenance, etc. This is beneficial for the student and convenient for the teacher. Of course, the teacher must supervise, but distribution, collection and storage of equipment is reduced from a major exercise to a minor one.

Depending on the exact kit configuration chosen, what I have been describing costs something in the range of $5 to $10, and should last for several years. But, of course, we need more than equipment; we need chemicals. Here, too, convenience for the teacher is important and we currently supply preprepared solutions, as well as a few solids, in quantities suited to one class of students for one year. The cost per student may be $1 to $2 per year. Now, all this is not zero cost, but it is certainly low cost when compared with traditional provisioning. And, if we accept that we do not need a traditional-style laboratory either, then we can see that we can begin even with very little money.

The kits I have described have received widespread approval. Whilst we originally focussed on meeting the needs of poorer educational systems, we have found that more wealthy ones are also interested. Nevertheless, we retain a special interest in the less wealthy and a joint UNESCO-IUPAC/CTC project has been set up to bring the ideas to global attention. Workshops have been conducted in Sao Paulo, Nairobi, Windhoek, Maseru, Moscow, Krasnojarsk, Porto Novo, Abidjan, and Sofia, quite apart from local initiatives in the USA, UK, Australia, South Africa, etc.

Indicative of the impact we have observed, teachers of other sciences have begged for attention to be given to their needs. This has prompted us to provide for environmental science (especially water quality testing), electricity, and some simple food and enzyme experiments. Similarly, in response to appeals from primary science teachers, a 'kiddies kit' has been designed using some of the components from other kits and some additional items. Some pictorial worksheets have been created and we are currently investigating the classroom implementation.

Chemistry teachers at more advanced levels seek quantitative experimentation as well as qualitative. We have partially answered their needs by designing microscale titration. This works on 1/20th scale of traditional titrations, using a 2-mL graduated plastic pipette fitted with a plastic syringe in place of a 50-mL glass burette (Fig. 3). As noted earlier, the larger wells of the comboplate serve as titration flasks. Even though a lesser accuracy is achieved with this small-scale plastic equipment, it seems to us more than good enough to meet the educational objectives of introductory analytical chemistry. It might appear that a good quality balance is essential to support this. We have adopted capsules containing preweighed quantities of solid chemicals as the key to solving this problem [13]. Teachers need only a graduated container to make a solution of specified concentration by introducing a capsule and adding water. This in fact can also be applied to the provision of qualitative reagent solutions, with a lower precision of mass being specified. There are valuable savings in storage and shipping requirements and costs by this means.

Of course there is more to quantitative chemistry than volumetric analysis. Even if an expensive, good quality balance can be avoided, there remains the challenge of instrumental methods that form the backbone of modern chemistry. The low-cost instrumentation for chemistry developed by Sane's group

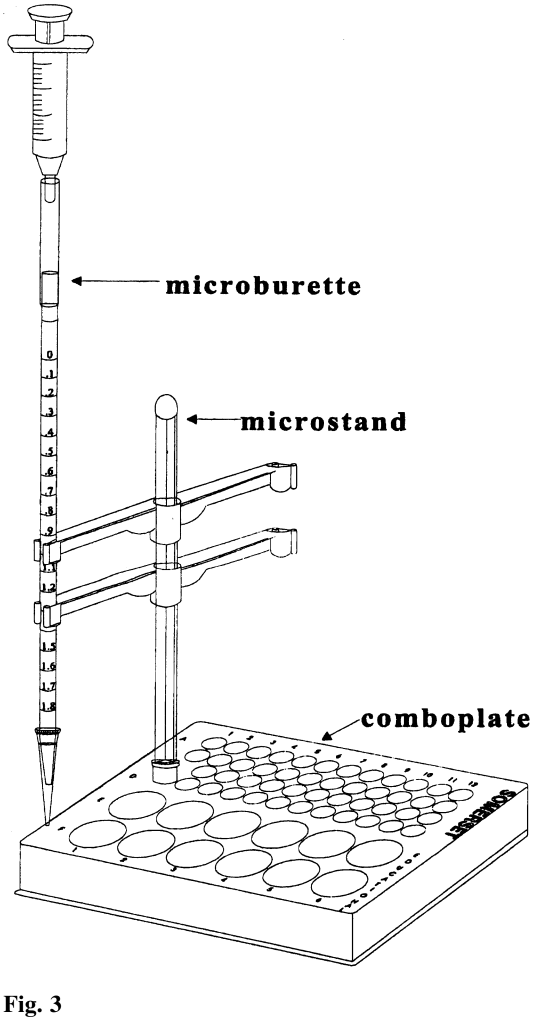

Fig. 3

thus far serves traditional scale practise and we remain keen to develop equivalent instrumentation for small scale work.

The widespread success of these developments is attributable to a fortunate combination of pragmatic chemical educators, manufacturers and distributors. This has allowed good ideas to be translated into affordable and convenient products which are effectively and responsibly marketed.

BEYOND THE EQUIPMENT

At this point, we might loosely say the solution to cost problems is in sight. Teachers who used to say ‘I cannot do practical work, because I do not have the resources’, may not be able to say this any more. The moment of truth has arrived! Competent teachers embrace the opportunities; the less competent do not. Those who do not may lack the necessary practical and management skills, and/or regard practical work as irrelevant to their principal task—helping students to pass the next exam. How do we overcome these problems? It can only be through teacher education, both pre-service and in-service. This education must give attention to practical chemistry, not only covering the theory behind its supposed worth, but also providing adequate personal experiences for the teacher or student teacher. Only in this way can teachers be enabled to say ‘I can do it! I am skilled again!.’ When teachers can say that, and they have convenient resources available, then they will be ready and keen to help students. They will demand of policy-makers that curricular time be made available.

We have conducted research on the implementation of our kits in a variety of South African schools. Some of this has been reported previously [14] whilst more remains to be published [15–17]. Both teachers and students are very positive about the microchemistry kits and their ancillary materials. Concept learning has been demonstrated where teachers are adequately competent. There are no miracles here: student concept learning is strongly dependent on the teacher’s capability to exploit the opportunities created by the positive involvement of the students. Making practical work in chemistry accessible to all highlights the urgency of developing better and more focussed strategies of achieving selected aims for such activity [18].

CONCLUSION

The very positive reception given to the concept of a microchemistry kit system is probably attributable above all to cost and convenience. It is also a virtue that apart from the worksheets the system is philosophically neutral. You can be a conservative or a revolutionary chemical educator, and still be attracted by the low cost and great convenience. And reassured by the positive response of your students, you can go on being conservative or revolutionary. You can also continue comfortably to work within your given national or regional curriculum. We take the long view, and welcome the turning of the tide in favour of practical work. We believe that it may slowly become ‘the centrepiece of the students’ learning experience’ [18].

We have seen some dramatic instances of this classroom potential being realised, where before it was untapped. The excitement created amongst students who have been learning chemistry for some years, when they undertake their first chemistry experiment and they find it is easy and it works, is electrifying. Students who were learning chemistry like they would learn Latin discover they are not the same at all. It is like a deaf person who has been studying music getting a super hearing aid. It is like a blind person who has been studying art, gaining their sight.

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