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# Chemical education in the coming decades – Challenges and opportunities

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**Abstract.** Since non-availability of low-cost, simple and reliable equipment which is easy to fabricate and easy to maintain is one of the major obstacles in improving chemistry teaching in developing countries, the Committee on Teaching of Chemistry (CTC) of IUPAC initiated, in association with UNESCO, a project in 1979 at the Department of Chemistry, University of Delhi. The fourteen-year old project has shown that a variety of solutions are possible based on locally available materials and electronic components. The Delhi University project has also gone beyond the problem of equipment by initiating work in microprocessor-controlled instrumentation, educational software, low-cost computer interfacing, desk top publishing, low-cost audio-visual aids, and small-scale chemical techniques. A vigorous hands-on teacher-training programme is helping to disseminate the Project know-how at the national and the international level.

**Keywords.** Chemical education; low cost equipment.

## 1. Introduction

Chemistry is often labelled as an *experimental* science to emphasize the fact that the experimental approach holds the key to the subject. It follows therefore that laboratory courses should occupy a pivotal place in the teaching of chemistry. Unfortunately, this is not so because the "chalk and talk" method has become the dominant one with the result that the laboratory component is shrinking in content, decreasing in effectiveness but increasing in financial outlay. It is no exaggeration to state that teaching experimental chemistry has become an expensive ritual in a large number of institutions. If the coming generations of chemists are to play their proper role in research, industry, and education, it is vital to take a fresh look at laboratory instruction at all levels.

## 2. Challenges and opportunities

There are many factors which have caused a deterioration in the teaching of experimental chemistry. Amongst the science subjects, chemistry is unique in the sense that it is required to be studied by students from all streams i.e. physical, biological, medical, engineering etc. The large enrolment has complicated the task of laboratory management by making heavy demands on space and on basic facilities like power, gas, distilled water etc. Another serious problem is the escalating costs of chemicals (see table 1) and glassware. The allocations to teaching laboratories have

**Table 1.** Comparative prices in India of some chemicals over the last 30 years. (All prices in rupees for 500 g/500 ml packing).

| Chemical | 1965 | 1976 | 1984 | 1994 |
|---|---|---|---|---|
| Ammonium thiocyanate | 10 | 38 | 50 | 90 |
| Ferrous ammonium sulphate | 5 | 9 | 26 | 66 |
| Calcium chloride | 2 | 4 | 23 | 48 |
| Cadmium nitrate | 22 | 58 | 100 | 540 |
| Copper sulphate | 4 | 22 | 49 | 95 |
| Potassium iodide | 27 | 77 | 255 | 510 |
| Potassium nitrate | 3 | 11 | 30 | 60 |
| Potassium permanganate | 6 | 16 | 45 | 110 |
| Potassium dichromate | 6 | 20 | 57 | 160 |
| Sodium acetate | 5 | 15 | 36 | 68 |
| Glacial acetic acid | 4 | 14 | 24 | 58 |
| Aniline | 8 | 26 | 46 | 150 |
| Benzaldehyde | 13 | 55 | 65 | 175 |
| Fehling solution B | 4 | 14 | 35 | 130 |
| Glycerol | 7 | 35 | 47 | 125 |
| Nitrobenzene | 4 | 20 | 32 | 108 |
| Silver nitrate | 99 | 625 | 3350 | 6200 |
| Cobalt sulphate | 17 | 60 | 328 | 1150 |
| Potassium ferrocyanide | 5 | 15 | 113 | 230 |
| Potassium ferricyanide | 11 | 35 | 113 | 400 |
| Nickel sulphate | 3 | 24 | 52 | 300 |
| Fehling solution A | 1 | 5 | 20 | 85 |

not kept pace with the galloping prices of even routine reagents, solvents, and other chemicals required to run an average course. Of even greater concern is the fact that the teaching style has retained the traditional outlook. Qualitative and quantitative analysis, exercises in organic and inorganic synthesis, and experiments in physical chemistry continue – by and large – to emphasize the classical techniques. Chemical industry and research today is dominated by the instrumentation culture, the roots of which lie in electronics and computers but this technological revolution is yet to touch the chemical education scene in India. The high cost of commercial models is again the reason why student laboratories are starved of even simple equipment. In this case, there is also an additional problem. The lack of familiarity of an average teacher/student with the basics of instrumentation and electronics, generates a 'black-box' mentality and results in poor maintenance. Innumerable chemistry stores have thus become graveyards of idle equipment, much of which probably needs only minimal attention.

The challenges confronting a chemistry teacher in India today are indeed formidable. But it is a fortunate occurrence that there are also unparalleled opportunities to introduce new initiatives. We are now witnessing in this country the growth of electronics and materials technology which heralded the space age in the developed countries in the sixties. Microcomputers, semiconductor devices, and video equipment are either being made, or are easily available. If these technologies are supplemented with simple innovations and better management, answers to many of the problems can be readily obtained.

## 3. The Delhi University Project

To test the feasibility of some of the ideas outlined above, IUPAC CTC, under the inspiring leadership of the then Chairman, Prof. C N R Rao, initiated a pilot project in 1979 in cooperation with UNESCO. The project team, now known as the Edutronics Group, is centred at the Department of Chemistry, University of Delhi. The members of this informal and voluntary team have varied over the years but it has always consisted of school/college/university teachers, students and technicians, all working in their spare time. The Delhi University Project has received substantial support from the University Grants Commission (UGC) and the Department of Science and Technology (DST). Valuable assistance has also been received from the Committee on Teaching of Science (CTS) of the International Council of Scientific Unions (ICSU); the Commonwealth Foundation, London; Committee on Science and Technology for Developing Countries (COSTED), Madras; International Development Research Council (IDRC), Canada; and a number of other national, regional and international agencies.

Since non-availability of good-quality but cheap equipment is one of the major factors preventing modernizing of laboratory teaching, the Delhi University Project began with the following five objectives.

(i) To develop reliable, low-cost locally produced equipment that is easy to fabricate and easy to maintain;
(ii) to find experiments compatible with the equipment that illustrate the principles and practice of modern chemistry;
(iii) to transfer this know-how to teachers through hands-on workshops, manuals and videotapes;
(iv) to set up a production unit which can supply kits and assembled equipment without a significant escalation of cost;
(v) to encourage curriculum changes that ensure that the whole package enables a student to be better trained for a career in chemistry.

It will be useful to review the project under different heads.

### 3.1 *Design and development*

One reason for the high cost of commercial instruments is that they are designed to cater to the multi-purpose needs of industry and research. From a pedagogical viewpoint, the sophistication and versatility of commercial instruments is often a disadvantage. This leads to the concept of a *teaching instrument* which may be defined as having the following features:

- highlights the principles of measurement,
- is user (i.e. teacher/student) oriented,
- is unsophisticated in design and layout to permit quick fabrication and easy maintenance,
- is rugged and reliable,
- has a variable precision which can be upgraded/downgraded as per the requirements of experiments at school/college level.

It is also important that such instruments come as packages consisting of (i)

**Table 2.** Summary of the work done by the Edutronics Group.

The following instruments have been developed by the Edutronics Group:
*p*H meter; conductance meter; colorimeter; polarimeter; electronic 'Beckmann" thermometer; polarograph; nephelometer; and oxygen meter.

Production models of the first three instruments have been designed in three versions namely digital, analog, and meterless type. (The three versions are suitable for M.Sc., B.Sc. and + 2 school level respectively.)
*R* and *D* work on the design of an electrochemical package centred around the 8085 microprocessor-based data logger (DL) is in progress. The DL functions as a stand-alone item when coupled to appropriate sensors; the DL can also off-load data to a PC using a low-cost interface to permit more sophisticated data processing. Apart from its utility as a versatile instrumentation package, a DL can be a very effective tool for teaching the essentials of a microprocessor, of interface design and of machine language programming.
A useful development has been use of carbon rods from discarded batteries to construct zero-cost electrodes and conductance cells. A glass electrode from a soft glass test tube and a variety of simple ion-selective electrodes and other sensors have helped to extend the utility of the *p*H meter. Several other accessories like magnetic stirrer, timer, thermostat and centrifuge, have been designed to complement the equipment.
To facilitate maintenance in student laboratories, a Test Package (continuity tester; transistor tester; I.C. tester; OVA meter; OVA source) has been made utilising the same circuits as the main equipment. This assures compatibility of cost and performance. It also means that a beginner does not have to learn too many different circuits. An attempt to convert a black and white TV into a "student" oscilloscope is in progress.
Nearly 100 experiments, standardised with the equipment, are a blend of pure and applied chemistry. The latter highlight agricultural, biochemical, clinical, environmental, and industrial applications.
All documentation related to the Project, including the two monographs listed in the references, have been printed via the in-house desk top publishing (DTP) system. Video clips to complement the print material are being produced using a camcorder.
Another computer-based activity is the development of simulation packages. Three units dealing with potentiometry, conductometry and colorimetry are ready.

accessories (electrodes, cells, thermostat etc.) (ii) test equipment for calibration and trouble-shooting and (iii) support literature consisting of books, lab manuals, charts, and audio-visual aids. It is desirable to have designs which can be used manually and which can be also interfaced to a microcomputer/microprocessor so that students can learn emerging techniques of data acquistion and data processing. Finally, the entire exercise is meaningful if, and only if, the packages can be marketed at a price affordable by educational institutions in the third world countries.

A summary of the work done under the Delhi University Project is given in table 2.

### 3.2 *Teacher training*

An educational innovation remains an abstract – if not a sterile – exercise unless it is accepted and practised by teachers and students. It follows that all the work described in table 2 is of little significance unless it is field-tested and accepted by specialists, teachers and students. The Edutronics Group has, therefore, laid great stress on hands-on workshops for evaluation and dissemination of the Project know-how. Out of the nearly 70 workshops held so far, three (namely, Madras 1981, Bombay 1985, Delhi 1993) have been international in character where selected specialists and teachers from all over the world have reviewed and tested the prototype models.

**Table 3.** Workshops held by the Edutronics Group outside India.

The know-how generated under the project has been transferred to teachers through workshops. The following training workshops have been held by the Edutronics Group outside India under the auspices of UNESCO and IUPAC in association with national agencies and host institutions.

| City | Country | City | Country |
|---|---|---|---|
| Sao Paulo | Brazil (July '83) | Islamabad | Pakistan (December '86) |
| Georgetown | Guyana (August '83) | Kathmandu | Nepal (February '87) |
| Copenhagen | Denmark (August '83) | Serdang | Malaysia (April '87) |
| Montpellier | France (August '83) | Kabul | Afganistan (October '87) |
| Dhaka | Bangladesh (June '84) | Iloilo | Philippines (May '88) |
| Bathurst | Australia (September '84) | Hong Kong | Hong Kong (May '88) |
| Talwakalle | Sri Lanka (December '84) | Uberlingen | Germany (July '88) |
| Singapore | Singapore (April '85) | Reduit | Mauritius (December '89) |
| Ljubljana | Yugoslavia (June '85) | Moscow | USSR (September '90) |
| Puerto Rico | USA (October '85) | York | U.K. (August '91) |
| Amman | Jordan (October '85) | Uberlingen | Germany (August '92) |
| Rajshahi | Bangladesh (April '85) | Johannesburg | S. Africa (August '92) |
| Bangkok | Thailand (October '86) | Kathmandu | Nepal (June '93) |

About 25 UNESCO-sponsored workshops (see table 3) have been held outside India to generate core groups in various countries/regions who are adapting the Delhi designs to suit local needs. UNESCO has now set up an International Network, with headquarters at Delhi University, to coordinate the activities of the core groups operating in Brazil, France, Germany, Jordan, Puerto Rico and Philippines. The network has established an Equipment Bank for the South Asian countries (excluding India) which will organize (a) training courses in fabrication, use and maintenance of low-cost equipment and (b) provide kits, equipment and spare parts to institutions desirous of using such equipment.

The main thrust of the Delhi University Project is naturally in India where nearly 40 teacher training workshops have been held in every part of the country. The primary support for the Indian programme has come from UGC but NCERT, DST and State Governments have also lent a helping hand. The Centre for Professional Development in Higher Education (CPDHE) – a UGC Academic Staff College at the University of Delhi – has masterminded the teacher-training strategy by bifurcating its three-week refresher course format into two parts (i) a one-week workshop part where teachers learn fabrication and testing of two low-cost instruments (usually a *p*H meter and a colorimeter) and (ii) a two-week follow-up part to be carried out in the home institution. For the latter part, a teacher has to perform eight to ten assigned experiments with the low-cost equipment and submit a feedback report. The UGC-recognised Refresher Course Certificate is issued by the CPDHE only on receipt of a satisfactory feedback report. Every participating college in the programme receives from CPDHE a package of 13 instruments (3 pieces each of *p*H meter, conductometer and colorimeter + 2 OVA sources for calibration and trouble shooting + 2 magnetic stirrers + all accessories like electrodes, conductance cells and cuvettes + tool kit consisting of a multimeter, a soldering iron, pliers, screw driver set etc.) for use in student laboratories. In the first round of the CPDHE programme, refresher courses were held in Delhi to train core groups from different states. In the second round – now underway – refresher courses are being held in states with the help of core group members. The first state to come forward in this decentralization experiment was Madhya Pradesh where the Directorate of Higher Education, the M.P. Council for Science and Technology (MAPCOST), and the State level UGC offered substantial support which enabled regional workshops to be held in 1992–93 in Bhopal, Indore, Gwalior, Rewa, Bilaspur and Jabalpur. Karnataka has closely followed M.P., and Jammu and Kashmir, Rajasthan and Maharashtra are likely to follow soon. To date nearly 600 teachers from 300 colleges from all over the country have been trained by the Edutronics Group under the UGC funded programme conducted by the CPDHE.

### 3.3 *Manufacture and supply*

The typical cost of assembling any instrument/accessory mentioned in table 2 is in the region of Rs. 600 to Rs. 800 if an ordinary cabinet (about Rs. 100) and an ordinary moving coil meter (about Rs. 180) is used. If instead of building a power supply (about Rs. 100) in every instrument, a central power supply to run 8 to 10 instruments is designed for a student laboratory, the effective cost for class work can be brought down further.

The items in the test package (see table 2) are typically in the price range Rs. 200 to Rs. 400 while most of the sensors are virtually zero-cost. The interface for coupling any of the instruments to a PC costs about Rs. 200. The only relatively expensive item is the data logger (about Rs. 4500) but it can be used as an instrumentation package as well as a computer with modest capabilities.

It may seem that the combination of (i) reliable instruments at affordable cost and (ii) a country-wide teacher training programme, should initiate the process of making progressive changes in the laboratory curricula which have remained near-stagnant for three decades. Unfortunately, the matter is not that straightforward for the simple reason that changes in laboratory curricula cannot be sustained unless the teaching-oriented instruments/accessories/test package etc. are manufactured and marketed without a significant escalation in the cost of the items. This is a "chicken and egg" dilemma because curricula changes require that items are available at affordable costs but a commercial unit will not find it attractive to manufacture such items unless laboratory curricula are based on their usage. Further, it is viable to lower the price only if the 'economy of scale' is available which means that changes cannot be confined to a few progressive institutions only.

The possibility of an exciting solution to this dilemma was provided by the decision of the Indira Gandhi National Open University (IGNOU) to use in their Distance Education courses in chemistry the low-cost equipment designed at Delhi University. The budgetary constraint (Rs. 5·3 lakhs were sanctioned for a supply of 1000 pieces of *p*H meter, colorimeter, conductometer etc.), the time constraint (the pieces had to be delivered in 18 months) as well as the fact that the grant was routed though Delhi University (which meant that all University regulations for purchasing, hiring work force, and payment of honoraria had to be observed) forced seeking an unconventional solution in the form of hiring untrained but needy individuals on a daily-wage basis. The heart-warming experience that a group consisting of handicapped and school dropouts could be trained to deliver the IGNOU package on time led to the next step where DST and Delhi University signed a Technology Transfer Agreement with a charitable society for manufacture and supply of the low-cost equipment. By taking over the workforce trained in the IGNOU project, the Society has been able to keep the selling price at only about 10% above the cost price. The Rs. 20 lakh turnover of the Society in two years shows that a coupling of social objectives (i.e. providing training and livelihood to individuals from weaker sections) and educational objectives (i.e. to manufacture good quality items for education at affordable prices) adds a beautiful new dimension to the work described herein.

## 4. Future

Assuming that the work done so far is adopted and adapted by teaching laboratories, a second round of *R* and *D* activities should begin. Amongst the embarrassingly large number of problems requiring attention, the following appear ripe for a swift attack.

(a) Development of additional equipment (e.g. spectrophotometer, cyclic voltammetric set-up etc.) and of additional chemical and bio-sensors;
(b) development of instrumentation, cells, and experiments for electro-organic and electro-inorganic synthesis;
(c) computer simulation of techniques like NMR, IR, Mass Spectrometry etc. where the "do-it-yourself" approach to instrumentation is, of course, not applicable;
(d) introduction of micro/semimicro approach together with a recycling step in every experiment. This will reduce the expenditure on chemicals, improve skills and reduce hazards;
(e) integration of the *R* and *D* work in the form of educational packages (consisting of kits, equipment, print material, audio-visual aids, software) on different chemical themes.

The ten-year old UGC-sponsored Journal *Chemistry Education* (published by Wiley-Eastern, New Delhi) has assigned the highest priority to articles reporting a practical and useful innovation. Similarly the CPDHE, and other academic staff colleges, provide a ready outlet for transferring the know-how to teachers through refresher courses. On the teacher-training front, the services of the core groups in Madhya Pradesh and Karnataka will be utilised for training and establishing similar groups in neighbouring states. It is hoped that the funding responsibility of the training will progressively shift from UGC to the state level and the administrative responsibility will shift from CPDHE to the regional academic staff colleges. Simultaneously, some institutions – particularly the autonomous colleges – will be encouraged to initiate changes in their syllabi so that the equipment and the teacher-training get utilised. Since the student response is the 'acid' test of any teaching/learning strategy, the importance and the urgency of introducing some of the developments in student laboratories cannot be overemphasized.

As the R and D activity picks up, the production set-up organized for the low cost equipment can be expanded for manufacturing and marketing additional items. It is felt that the domestic educational market is large enough to support a small-scale industry provided the product can be manufactured and marketed at prices which are within the capacity of educational budgets. (If adequate guidance from specialists and professionals becomes available, it should be possible to upgrade the designs and the quality control to international standards, thereby opening the possibility of supplying some of the items to educational institutions outside India.) Though this is not possible through a normal commercial approach, a non-conventional mode does appear feasible. In this context, the idea of involving handicapped personnel, school dropouts, destitute women (and other weaker sections of Society) through charitable and philanthropic societies/foundations seems particularly appealing as it confers a social dimension to the Project and also generates some job opportunities. If the equipment finds widespread acceptance, such a work force can also be easily trained in maintenance of not only of low cost instruments but also of other simple but commercially manufactured instruments. The concept of a "barefoot" neighbourhood technician who can repair and service routine and simple apparatus for a nominal charge, may be able to resurrect or reincarnate huge quantities of equipment lying buried in institutional graveyards (known as chemistry stores!).

## 5. Conclusion

The basic objective of the Edutronics Group is to attempt to initiate a self-sustaining process which will emphasize the creative aspects of science education in general and of chemical education in particular. Laboratory instruction has been chosen for special attention because not only is it the backbone of scientific method but also because it is the weakest link in the current educational scene.

It must be stressed that the Delhi University Project does not wish to claim any originality in the technical work carried out so far. A large number of individuals and groups have been developing equipment and experiments all over the world for many, many years. However, the IUPAC/UNESCO/UGC/DST project is perhaps the first example of an initiative where a coordinated and time-bound effort has been made to interlink all facets (like *R* and *D*, teacher training, production set-up etc) of the problem so that the fruits of the Project reach student laboratories in a self-sustainable way. The most significant point about this exercise appears to be its attempt at various types of interfacing (e.g. international/national; low-cost/good quality; chemistry/physics; teachers/students; training/production) *simultaneously*. Each of these interfaces is felt to be sufficiently crucial that neglect of any of them will distort the underlying philosophy and manner of operation. The most significant long-range gain of the Project is that it has catalysed the formation of seed groups in different regions who have a common philosophy but distinct identity which has helped to spread the message in a manner best suited to local needs and local talent. This informal network comprising individuals from developing as well as developed countries, needs to be strengthened and enlarged so that additional time-bound programmes for a continuous improvement of chemistry teaching can be initiated.

The current scenario in education is characterised by at least two vicious circles. The first one is: *How can an educational structure which is not dynamic encourage teachers to be innovative* **and** *if teachers are not innovative how can a structure become dynamic*? The second one is: *How can the one dimensional "chalk and talk" method of teaching/learning be replaced by a multi-dimensional* (e.g. activities, demonstrations, audio-visual aids, problem solving) *approach unless the required resource material is available at a cost which schools/colleges can afford* **and** *how can such resource material be produced and marketed unless the syllabi and the examination pattern become more* *open-minded and more open-ended*? (A discerning reader will easily spot that the two vicious circles are really part of a *super* circle where each question is interlinked to the other three!) In the terminology of the Hartree–Fock model–which may be regarded as a physico-chemical recipe for attacking vicious circles – what is reported here is at best a zero-order approximation. If successive iterations, spearheaded by teachers but supported by every relevant sector of Society (e.g. Government, industrial houses, premier research laboratories, national academies etc.), are carried out over two to three generations, the chemical education scene in the country may alter significantly enough so that individuals capable of pushing the frontiers of chemistry are produced **by** the system and not **in spite** of the system.

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The author recalls with pride and pleasure his association with Professor C N R Rao – a friend, philosopher and guide for over three decades. It was CNR's personal example and personal commitment to the cause of education which encouraged the formation of the Edutronics Group at Delhi University. The finest tribute to Prof. Rao will be if all individuals and institutions who share his concern can join hands to transform the isolated attempts to rejuvenate the teaching/learning process into a mass societal movement so that this country can hope to have the educational system which it surely deserves.

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