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Cost-effective science education in the 21st century—the role of educational technology*

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Abstract: The nonavailability of low-cost, simple and reliable equipment which is easy to fabricate and easy to maintain is one of the major obstacles for improving science teaching in developing countries. In this context, UNESCO in association with the Committee on Teaching of Chemistry (CTC) of IUPAC and the erstwhile Committee on Teaching of Science (CTS) of ICSU initiated a Project *Locally Produced Low Cost Equipment (LPLCE) for Teaching of Chemistry* in India in 1979. In the two decades since its inception, the LPLCE Project has shown that a variety of cost-effective solutions are possible based on locally available materials and electronic components. The Indian 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, audiovisual aids, interactive multimedia modules and small-scale chemical techniques.

INTRODUCTION

It is widely recognized that the role of laboratory instruction in the teaching of chemistry requires a fresh look at all levels. The matter has assumed considerable urgency—particularly in the developing countries—because laboratory courses are shrinking in content, decreasing in effectiveness but increasing in financial outlay; teaching experimental chemistry is threatening to become an expensive ritual. The situation clearly calls for a concentrated attempt in which the academics and the funding agencies at the national and the international level coordinate their efforts to chart new directions.

NATURE OF THE PROBLEM

One of the most important causes for the deterioration in the quality of laboratory curriculum has been the nonavailability of good quality equipment which is cheap and easy to maintain. The problem is particularly severe in the developing countries where commercial models are expensive; their maintenance is also beyond the ability of an average chemistry teacher/student. One consequences is that whereas student laboratories are starved of even basic equipment like a pH meter or a colorimeter, innumerable chemistry stores have become graveyards of idle equipment of much of which requires only minimal attention. Another consequence is that in the absence of adequate instrumentation facilities, the laboratory teaching continues to emphasize obsolete chemical techniques which have little relevance to the needs of modern industry and research. It is obvious that the problem is serious enough to require urgent attention.

A POSSIBLE SOLUTION

It has been known for over 30 years that the semiconductor Integrated Circuits (ICs) provide a versatile and cheap building block for designing a number of instruments useful to a chemist. Research as well as education journals are replete with ideas ranging from simple to sophisticated. In the past 25 years, the semiconductor technology has proliferated world-wide with the result that IC and other electronic devices

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are easily available virtually everywhere. However, mere availability of these devices and of the literature describing their use is not enough; what is needed is an adaptation of this knowledge to suit local educational conditions. This implies that the problem should not be seen in purely technological terms. If the aim is to influence the teaching of chemistry, through a widespread use of instrumentation, then it is essential that teachers and students are involved in the developmental process in every country so that the designs are based on locally available materials and the know-how has indigenous roots. In addition, fabrication of equipment should become an integral part of student activity. Such an approach will automatically solve the problem of maintenance for obvious reasons. There even exists a ghost of a chance that, as confidence and expertise in instrumentation grows, the apparatus buried in the local graveyards referred to earlier may be resurrected or reincarnated!

One reason for the high cost of commercial instruments is that they are designed to cater to the multipurpose needs of industry and research. From a pedagogical viewpoint, sophistication and versatility of a commercial instrument is often a disadvantage. This leads to the concept of *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 precision required for experiments at school/college level,
- can be marketed at a price affordable by educational institutions in the third world countries.

A PILOT PROJECT IN INDIA

To test the feasibility of some of the ideas outlined above, a pilot project was initiated in India in late 1979. The Project has been sponsored by UNESCO in association with the Committee on Teaching of Chemistry (CTC) of the International Union of Pure and Applied Chemistry (IUPAC), the erstwhile Committee on Teaching of Science (CTS) of the International Council of Scientific Unions (ICSU), the Department of Science and Technology (DST), New Delhi and the University Grants Commission (UGC), New Delhi. Valuable assistance has also been received from the Committee on Science and Technology for Developing Countries (COSTED); the Commonwealth Foundation; International Development Research Council (IDRC), Canada; and a number of other regional and international agencies.

The Pilot Project has five objectives:

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

This paper review the progress made in pursuing these objectives.

Development of reliable locally produced low cost (LPLC) equipment

The LPLC Equipment project has progressed in several well-defined stages. The first phase was an exploratory one where a number of circuits for measuring pH and conductance were tried and analysed. This work was carried out via student projects supervised by teachers. An important achievement was to establish the utility of a carbon rod-extracted from a discharged dry cell as a zero-cost electrode material for pH and conductance measurement. An international workshop was held at Madras, India in April 1981 to evaluate the work done during this phase.

The second phase began with the design of a colorimeter which is perhaps the single most useful instrument for teaching of chemistry. This phase also saw the development of several accessories (e.g. an OVA source, and a Magnetic Stirrer) to complement the equipment. The OVA Source—which is a combination of a Resistance Box and a Variable voltage/current Source—is of great utility for calibrating and trouble shooting the LPLC equipment. Another international Workshop, to evaluate the work done during this phase, was held in Bombay in December 1985.

All the equipment developed during the first two phases was of the analogue variety because during early 1980s, a moving coil meter was significantly cheaper in India than a digital panel meter (DPM). When this situation started changing in the late 1980s, development of digital instruments was initiated.

Since a large number of chemistry teachers felt that they would like to acquire more familiarity with the principles of basic electronics, a multipurpose kit has been designed. The kit uses plug-in type solderless connectors which enable quick assembling/dismantling of circuits. Several experiments illustrating key characteristics of electronic components like resistors, capacitors, diodes, transistors and opamps have been developed along with experiments involving basic opamp circuits of practical utility in chemical and biological applications.

Computerised instruments have become ubiquitous in research and industrial laboratories. To initiate students in modern methods of data acquisition, a microprocessor-based Data Logger (DL) has been developed. DL version based on the 8085 microprocessor has been successfully tested with sensors like a glass electrode as well as for off-loading and on-loading data to and from a PC. Since a low-cost interface based on the work done at the Inter American University of Puerto Rico permits a direct coupling of any instrument to a PC, a user has three options namely to couple (a) a sensor with the DL, (b) the DL with a PC and (c) a sensor with a PC. The options provide an enormous flexibility in devising teaching/learning strategies and for carrying out specialised experiments (e.g. kinetics of moderately fast reactions, field-based pollution monitoring, etc.)

Another computer-based activity has been the development of simulation software which permits a user to carry out 'dry' runs of such experiments as are either expensive, or dangerous or time-consuming. Packages for colorimetry, potentiometry and conductometry are ready in BASIC, in PASCAL, and in C languages.

The rapid escalation in the cost of chemicals—like the rising prices of commercial equipment—is having an adverse effect on laboratory curriculum. Whereas in the case of equipment, the difficulties are compounded by a lack of maintenance, the chemicals problem gets exacerbated because the costs are recurring. A three-pronged attack, namely: (a) introduction of microscale approach, (b) inclusion of recycling step as a part of student experiments and (c) substitution of expensive chemicals, provides an alternative which is not only cost-effective but also has—like the locally produced equipment—pedagogical advantages. The Indian Project has initiated attempts to adapt the work done by some leading groups all over the world in the area of small-scale chemistry. As a result, several exciting possibilities have become apparent for dramatically reducing the recurring expenditure on chemicals and for reducing the hazards in using dangerous chemicals.

A summary of the R&D work described above is given in Table 1.

Finding experiments compatible with the equipment that illustrate the principles and practice of modern chemistry

The design of cost-effective tools described above can become a means of improving the teaching of chemistry, if and only if, suitable experiments are developed illustrating the principles and practice of modern chemistry. Thanks to the enthusiasm of a large number of teachers and students, over 100 experiments—which are a blend of pure and applied chemistry—have been standardised to date. This collection representing examples from agricultural, biochemical, clinical, environmental and industrial applications of chemistry and also from thermodynamics, kinetics and titrimetric analysis.

Transferring the know-how to teachers through hands-on workshops, manuals and videotapes

Simultaneous with the developmental work a systematic attempt is made to propagate the project philosophy around the world. The first Senior Visiting Practitioner Award by the Commonwealth

Table 1 Summary of the R&D work done under the Indian Project

The following instruments have been developed:

pH meter: Conductance meter; Colorimeter; Polarimeter; Electronic Thermometer; Polarograph; Nephelometer; and Oxygen meter.

Production models of first three instruments have been designed in three versions namely digital, analogue and meterless type. (The three versions are suitable for MSc, BSc and +2 school level, respectively.) These models can also be coupled to a Personal Computer (PC) through an Interface.

R&D work on the design of an electrochemical package centered around the 8085 microprocessor-based Data Logger (DL) is in progress. The DL functions as a stand-alone item when coupled to appropriate sensors; 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 essentials of a microprocessor, of interface design and of machine language programming.

A useful development has been the use of carbon rods from discarded batteries to construct zero-cost electrodes and conductance cells. A glass electrode from soft glass test tube and a variety of simple ion-selective electrodes and other sensors have helped to extend the utility of the pH meter. Several other accessories like Magnetic Stirrer; Timer; Thermometer; 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.

Nearly 100 experiments, standardised with the equipment, are a blend of pure and applied chemistry. The latter highlight agricultural, biochemical, clinical, environmental and industrial application.

Foundation in 1983 enabled dissemination of the project methodology through a 47-day lecture-cum-demonstration tour of five Commonwealth countries. Since an educational innovation remains an abstraction unless it is accepted and practised by teachers and students, the Indian Project has laid great stress on hands-on workshops for evaluation and dissemination of the Project know-how. The *modus operandi* consists of inviting selected teachers from a particular region for a one-week workshop in which participants fabricate and test the equipment designed under the LPLC Project. Out of the nearly 90 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. About 35 UNESCO-sponsored workshops (see Table 2) have been held outside India to generate Core Groups operating in Brazil, France, Germany, Jordan. Puerto Rico and Phillippines.

A massive country-wide teacher training programme (see Table 3) was launched in India in 1991 by UGC, New Delhi, under the title Regenerating Teaching of Chemistry. This programme was conducted by the Centre for Professional Development in Higher Education (CPDHE).

If a picture is worth thousand words, a movie is literally equivalent to thousand pictures. The availability of extremely compact and user-friendly camcorders have opened the possibility of amateur video shooting which is being experimented for preparation of 'video clips' to supplement the monograph on topics like soldering and calibration of instruments, i.e. where a printed word requires reinforcement though a visual image.

The emergence of the multimedia technology is undoubtedly a development which offers an exciting opportunity to revamp the teaching/learning strategies. Exploratory attempts have been initiated to integrate the print material with graphics, animation, video and audio inputs. It is proposed to develop CD-ROM multimedia diskettes based on the monographs on low-cost equipment and on low-cost experiments.

Table 2 Workshops held outside India. The know-how generated under the Project has been transferred to teachers through Workshops. The following training Workshops have been held outside India under the auspices of UNESCO and IUPAC in association with national agencies and host institutions

Maryland *(USA)*	Aug 1981	Kabul *(Afghanistan)*	Oct 1987
Sao Paulo *(Brazil)*	Jul 1983	Iloilo (*Phillippines*)	May 1988
Georgetown *(Guyana)*	Aug 1983	Hong Kong	May 1988
Copenhagen *(Denmark)*	Aug 1983	Überlingen (*Germany*)	Jul 1988
Montpellier *(France)*	Aug 1983	Reduit *(Mauritius)*	Dec 1989
Dhaka *(Bangladesh)*	Jun 1984	Moscow *(USSR)*	Sep 1990
Bathurst *(Australia)*	Sep 1984	York *(UK)*	Aug 1991
Talwakalle *(Sri Lanka)*	Dec 1984	Überlingen *(Germany)*	Aug 1992
Singapore	Apr 1985	Johannesburg *(S. Africa)*	Aug 1992
Ljubljana *(Yugoslavia)*	Jun 1985	Kathmandu *(Nepal)*	Jun 1993
San Juan *(Puerto Rico)*	Oct 1985	Harare *(Zimbabwe)*	Mar 1996
Amman *(Jordan)*	Oct 1985	Madison, WI *(USA)*	Jul 1996
Rajshahi *(Bangladesh)*	Apr 1985	Lusaka *(Zambia)*	Nov 1996
Rome *(Italy)*	Sep 1986	Mutare *(Zimbabwe)*	Jun 1997
Bangkok *(Thailand)*	Oct 1986	Cape Town *(S. Africa)*	Jul 1997
Islamabad *(Pakistan)*	Dec 1986	Nsuka *(Nigeria)*	Oct 1997
Kathmandu *(Nepal)*	Feb 1987	Male (*Maldives*)	Mar 1998
Serdang (*Malaysia*)	Apr 1987	Washington DC *(USA)*	Jun 1998

Setting up a production unit which can supply kits and assembled equipment without a significant escalation of cost

The typical cost of assembling any instrument/accessory in Table 1 is in the region of US$20 to US$30 if an ordinary cabinet (about US$3) and an ordinary moving coil meter (about US$6) is used. If instead of building a power supply (about US$3) in every instrument, a central power supply to run 8–10 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 1) are typically in the price range US$6 to US$12 while most of the sensors are virtually zero-cost. The interface for coupling any of the instruments to a PC costs about US$8. The only relatively expensive item is the data logger (about US$150) 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 hands-on teacher training programme, should initiate the process of making progressive changes in the laboratory curricula which have remained near stagnant for three decades in many developing countries. Unfortunately, the matter is not that straightforward for the simple reason that changes in laboratory curricula in the third world 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’ problem because curricular 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.

An exciting solution to this dilemma was provided by the decision of the Indira Gandhi National Open University, New Delhi (IGNOU) to use in their Distance Education courses in Chemistry the low-cost equipment designed under the LPLC Project. The budgetary constraint and the time constraint forced seeking an unconventional solution in the form of hiring untrained but needy individuals. The heart-warming experience that a group consisting of handicapped and school dropouts could be trained to deliver the IGNOU package on time shows that a coupling of social objectives (i.e. providing training and livelihood to individuals from disadvantaged sectors) 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.

Table 3 Workshops held in India. Most of the following workshops have been held under the UGC sponsored programme Regenerating Teaching of Chemistry. Each participating teacher fabricates one pH meter and one colorimeter during the one-week Workshop; each participating college gets a package of low-cost instruments for use in their student laboratories. A teacher has to submit a feedback report, based on the use of low-cost equipment, to qualify for a UGC-recognised Refresher Course Certificate

Mysore	Oct 1981	Delhi	Dec 1993
Delhi	Nov 1982	Alwar	Jan 1994
Hyderabad	Nov 1982	Shilling	Mar 1994
Chandigarh	Jan 1983	Udaipur	Apr 1994
Hyderabad	Dec 1987	Delhi	May 1994
Trivandrum	Jan 1988	Beawer	Sep 1994
Jaipur	Apr 1988	Gwalior	Sep 1994
Delhi	Dec 1988	Delhi	Oct 1994
Delhi	Apr 1989	Bhopal	Oct 1994
Bharuch	Apr 1989	Jaipur	Oct 1994
Delhi	Feb 1990	Rewa	Dec 1994
Delhi	Mar 1990	Kota	Jan 1995
Delhi	May 1990	Indore	Feb 1995
Bangalore	Jun 1990	Bhilwara	Feb 1995
Delhi	Feb 1991	Delhi	Feb 1995
Delhi	Dec 1991	Delhi	Mar 1995
Delhi	Feb 1992	Bilaspur	Mar 1995
Delhi	Mar 1992	Raipur	Mar 1995
Bhopal	May 1992	Amritsar	May 1995
Indore	Jul 1992	Bangalore	Jun 1995
Gwalior	Sep 1992	Jaipur	Jan 1996
Bangalore	Nov 1992	Kottayam	Apr 1996
Rewa	Dec 1992	Delhi	May 1996
Bilaspur	Feb 1993	Bangalore	Oct 1996
Goa	Mar 1993	Bangalore	Jul 1997
Jabalpur	Mar 1993	Bangalore	Dec 1997
Jabalpur	Jul 1993	Bombay	Jan 1998
Jammu	Nov 1993	Bangalore	Feb 1998

The experience of the Publication Unit of the Indian Project seems even more promising. Organized to overcome the absurd situation namely that the documentation describing low-cost developments cannot be published through the normal channels involving high-cost, the Unit began by training low-income and needy women for self-employment through desk top publishing (DTP). The hands-on training was provided by the preparation of educational material. Thanks to the generous donation of the hardware and software by international and national agencies, overhead costs became manageable, thereby allowing the publication of useful educational material at spectacularly low price. Table 4 summarises the work done by this Unit.

Encouraging curriculum changes that ensure that the whole package enables a student to be better trained for a career in chemistry

It has been pointed out earlier that the hands-on component of the curriculum in many developing countries needs radical changes because the current syllabi are either inadequate or obsolete or both. The two key requirements for any upgradation namely availability of resource material at affordable prices and availability of trained teachers, have been the focus of the work described above. The progress made in these directions should now catalyse changes in student laboratories. The Indian programme has identified the category of colleges called Autonomous Colleges as the starting point for this experiment since such colleges—by definition—have the mandate to act as pace-setters. It is hoped that some specific progress in this direction will be achieved in the near future.

Table 4 Low-cost educational publications. As an extension of the 16-year-old UNESCO/CTC Project on Locally Produced Low-Cost Equipment, a trial attempt has been made to publish a series of Low-Cost Resource Books in Chemistry for the benefit of teachers and students. It has been found that significant reduction in cost is possible by coupling the use of Desk Top Publishing (DTP) approach with a social objective like training needy individuals—particularly destitute women—for self-employment. The list of publications produced to date under this programme is given below:

A Project titled SITA (Study in Information Technology Applications: Training in Computer Skills for low-income Women), formulated on the basis of the low-cost publications programme, has been approved for support by the World Bank. It is hoped that WB assistance will help to institutionalize the pilot programme

SI. no.	Editor/Author	**Title**
1	K. V. Sane & D. C. West	*Locally Produced Low-Cost Equipment for Teaching of Chemistry*
2	V. M. Khanna, K. V. Sane & C. K. Seth	*Experiments for Introductory Chemistry*
3	H. A. Neidig & W. J. Stratton	*Modern Experiments for Introductory Chemistry*
4	R. B. Bucat & P. J. Fensham	*Selected Readings in Chemical Education Research*
5	G. B. Kauffman	*Classics in Coordination Chemistry*
6	P. J. Towse	*Chemistry: the Key to the Future*
7	R. Blume & H. J. Bader	*Environmental Chemistry in Classroom Experiments*
8	P. J. Towse	*A Proceedings on Cost Effective Chemistry*
9	K. V. Sane & R. Usha	*Profiles in Excellence*
10	K. V. Sane & R. Usha	*Selected Readings in Chemistry* *Volume 1: Low-Cost Experiments* *Volume 2: Low-Cost Equipment* *Volume 3: Computers in Chemistry*

Note 1: Items 9 and 10 are collection of reprints from the UGC Journal *Chemistry Education* edited by K. V. Sane & R. Usha.
Note 2: As per our agreement with the Division of Chemical Education of the American Chemical Society, Title 3 cannot be ordered by individuals residing in the North American Free Trade Area, European Union (Common Market) Japan, Australia and New Zealand. However, sales of single copies are permitted to individuals with addresses in Mexico, but not to corporations or booksellers. This is a specific exception to the North American Free Trade Area.
Please contact S.M.V. Traders & Printers (2616 G.F. Hudson Line, Kingsway Camp, Delhi-110009. India. Tel.: 91 11 713 8609, Fax: 91 11 7132908, E-mail: smv@nde.vsnl.net.in) for information about ordering copies of these publication.

CONCLUSION

There is no doubt that the beginning made by the Indian Project is a step in the right direction. However, this modest step has to be reinforced from many directions if it is to become a self-sustaining and self-evolving mechanism to modernise the teaching/learning process in the third world. Some of the problem areas which need urgent attention are

The need for quality control and quality assurance in the manufacturing set-up organized by the disabled group;

The extension of the LPLC approach to S&T subjects other than chemistry and to all educational levels (i.e. school, undergraduate, post graduate);

Closer coordination between R&D work, teacher-training programmes, manufacturing/marketing setup and curriculum changes;

Closer cooperation between academics, industrial sector and government agencies in the area of S&T education.

It is proposed that a model three year programme be initiated in South Asia, Southern Africa and the Caribbean to consolidate the gains of the LPLCE Project and to remove its shortcomings. The Committee on Science and Technology in Developing Countries (COSTED) of the International Council of Scientific

Unions (ICSU) appears to be an appropriate organization who can (and should) take a lead in this matter with support from suitable national, regional and international agencies.

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