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LABORATORY TEACHING IN UNIVERSITIES IN THE U.S.A.

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Abstract - Undergraduate instruction in chemistry is offered in a wide spectrum of institutions from universities with major commitments to research to community colleges offering technician training to under-prepared students from disadvantaged social backgrounds. Thus, experience may be found in use of modern equipment and instructional aids to making do with meager facilities and equipment, and use of materials of local concern from the immediate environment for study. Example curricula for both service courses and chemistry majors are described in the context of guidelines set forth by the Committee on Professional Training (CPT) of the American Chemical Society. About 85 percent of American bachelors degrees in chemical science are obtained from departments approved under the CPT guidelines. The recent development of computer simulations as aids to laboratory discussion is discussed.

INTRODUCTION

Education is the process by which man's knowledge and past experience is summarized and passed on to the next generation. Texts and classroom lectures are efficient summaries. Laboratory work is not so. Therefore questions arise as to the purpose and necessity of laboratory work for students with various backgrounds and career goals as they study chemistry.

This paper will attempt to outline the general goals and diversity of programs of laboratory instruction in the United States, and to indicate the scope of problems that have been encountered and are being dealt with. Some effort will be made to focus on experience that is relevant to and can be helpful to new programs in developing countries, some of whose experience can also be of help to Americans working in new institutions in the U.S.A.

INSTITUTIONS OF HIGHER EDUCATION

University teaching in the United States is performed in a large variety of institutions. There are about 200 public and private universities, and thousands of four-year colleges and two-year community colleges roughly equal in number. Most of these institutions enjoy virtual autonomy in the design of their curricula. There are large differences in resources or endowments for support of science education and especially laboratory training which is very expensive (Table 1). Thus, instruction in chemistry may be found in universities with

TABLE 1

Public Colleges and Universities

State Universities
Undergraduate and graduate programs
Usually: one emphasizing arts and science
one emphasizing agriculture and technology

State Colleges or Regional Universities
Formerly Teacher's Colleges

Community Colleges - Two-Year Colleges
Vocational training or
Preparation for upper level University

TABLE 1 (CONT.)

Private Colleges and Universities

Non-sectarian
(Open, but very selective on primarily intellectual criteria)
Universities - Large - Strong on graduate programs
Four Year Colleges

Parochial Colleges
Universities - few in number
Many colleges (may be named Universities)

Colleges for Men Only

Colleges for Women Only

Negro Colleges

endowments of over $\$10^9$ and a history of preparing the best young intellects for leadership in their fields to small colleges supported by the resources of communities living on the edge of poverty, and teaching students whose language is not English and whose experience in both intellectual and mechanical endeavours is virtually nil.

Most institutions seek to obtain accreditation from various agencies for their academic programs. The Committee on Professional Training (CPT) of the American Chemical Society has, over the years, established guidelines (Ref. 1) for chemistry departments at universities and four-year colleges seeking to be included on its approved list. Examination of such guidelines will provide us with a general introduction to laboratory instruction as it is done in the United States.

OBJECTIVES AND GUIDELINES FOR UNDERGRADUATE PROGRAMS IN CHEMISTRY LABORATORY

A. Experience
An undergraduate candidate for a B.A. or B.S. degree in chemistry should have experience in synthesis, separation and analysis, structure identification, kinetics, and determination of thermodynamic properties.

B. Skills
He should develop skill and confidence in quantitative manipulations, assessment of reliability of measurements, data analysis, instrumental techniques (IR, UV, NMR), designing experiments, safe laboratory practice, keeping records, and writing reports.

The guidelines recognize the impossibility of a four year curriculum covering the whole of chemistry, especially since most science curricula include substantial components of liberal education in the humanities and arts. Quality of what is done within the guidelines is given great importance as opposed to attempts to "cover everything". About 500 hours of laboratory instruction is recommended for A.C.S. approval of a four year program. CPT appoints committees to visit and assess departments seeking approval.

Of the 10,500 students per annum receiving baccalaureate degrees in chemistry, about 9,000 are trained in 540 approved departments, with the remainder scattered among over 1,000 departments not on the approved list. About 85% of American baccalaureates are obtained in programs approved under the A.C.S. guidelines.

The actual laboratory training received at any given institution is a very complex function of institutional location and resources, special faculty interests and ability to keep up to date, primary institutional goals, numbers of students interested in chemistry, etc.

EQUIPPING AND MAINTAINING LABORATORIES

The National Science Foundation maintains an extensive program of grant awards for the purchase of equipment for the teaching of undergraduates which has enabled most colleges receiving CPT approval to maintain an adequate supply of up-to-date equipment such as spectrometers, computers, etc. Individual colleges have developed ingenious and enterprising schemes for obtaining and maintaining equipment for laboratory instruction involving service to the public and business communities. For example, Carroll College in Wisconsin formally conducts a business of making chemicals and doing analyses using students being trained in practical chemistry. Kearney State College in Nebraska operates a regional water control project for the Environmental Protection Agency.

Universities with strong graduate research programs are often better able to maintain and service undergraduate laboratories and equipment than colleges devoted solely to undergraduate teaching, where most equipment must be set up, maintained and serviced by teaching staff.

TEACHING PROGRAMS

Laboratory teaching programs may be conveniently categorized in terms of

(1) Service programs for:

(a) students in allied sciences (biology and physics) and applied sciences (engineering, agriculture, etc.) whose major interest is not chemistry. Such programs usually include an introductory laboratory course, organic, and occasionally quantitative analysis.

(b) vocational training courses for students planning to be technicians in medical laboratories, nurses, etc.

(2) Programs for chemistry majors.

Both categories will contain programs in various states of evolution from traditional programs in existence after World War II to very modern programs which introduce and employ the latest tools and procedures accessible to the modern experimental scientist. Naturally, the evolution has been more rapid and extensive for the programs for chemists.

Experiments in Service Courses - Introductory Courses

Experiments remain very traditional at most schools - characteristic of laboratory manuals dating back to the post World War II surge in higher education. Modifications reflect improved technology - single pan balances, plastic wash bottles, simple spectrometers, etc. Enormous increases in student populations have caused the demise of experiments using expensive chemicals, and increasing concern for safety and clean air have modified or eliminated the use of some hazardous chemicals like H_2S and benzene. (Some educators are concerned lest it become too expensive to provide "safe" instruction for lab instruction to take place at all).

Many major departments are postponing laboratory work in service courses until the second semester and some have eliminated traditional introductory laboratories for reasons of expense, using the argument that such traditional experiments are out of date and do not show chemistry as it is done today. Others argue that such direct hands-on experience with chemicals as provided by such experiments as ignition of hydrates, titration with indicators, the separations and identifications characteristic of traditional qualitative analysis schemes are the best possible means for connecting the symbolic and theoretical textbook chemistry with actual material structure and behaviour. The role of such laboratory work is usually under fire from students who most often fail to generate much interest in exercises being performed in lockstep with hundreds or thousands of others. Many individual efforts are developing to design experimental work which will promote investigation on the part of the student, arouse curiosity and create motivation for both the student and teacher to seek results from which conclusions may be drawn.

Simulated laboratory experiments, (Fig. 1) using computer-based lessons, may be a means to better acquaint students with laboratory goals in advance of actually performing experiments in the laboratory. Some departments are experimenting with simulated laboratory exercises using computer terminals actually to replace laboratory work in introductory courses.

Service Courses - Quantitative Analysis

In addition to traditional wet chemistry - gravimetric, volumetric, colorimetric analysis of "unknowns" - separation techniques, ion exchange and gas chromatography are taught, and potentiometric measurements in analysis are introduced.

Service Courses - Organic

Traditional organic syntheses are taught including some modern instrumentation for characterizing products. Equipment varies from old fashioned cork stoppered flasks, burners, and melting point tubes to modern ground glassware, heating mantles, rotary evaporators, infrared and NMR spectrometers, etc.

Laboratory Training for Technicians

Many universities give special introductory courses for medical technicians and nurses. Most community colleges with large enrolments of part-time students seeking specific vocational training offer specific courses for training laboratory technicians. The American Chemical Society has published a course (Ref. 2) in modern chemical technology. The approach and motivation is the opposite of the general introductory service course. The emphasis here is on what one can physically do in the laboratory. Theory is employed as background to help the technician understand the reasons for his manipulations and observations. A crude summary of the contents is given in Table II. This program is used by over half the students in Chemical Technology in America.

TABLE II

Modern Chemical Technology* - 10 Volumes
American Chemical Society, Washington (1970)

1. Separation, Purification, Gas Handling.

2. Formulae, Spectra, Photolysis, Conductimetry, Spectrophotometry (Formulae, Atomic, Molecular and Ionic Structure).

3. Tests for metal and non-metal ions (Inorganic and Organic Nomenclature).

4. Sampling, Gravimetry, Titrimetry, Acid-Base.

5. Redox, Co-ordination, Organic Compounds, Redox Titration, Functional Group Analysis, TLC, Distillation - Organic product work up.

6. Alcohols, Halides, Ethers, Acids, N- and S-organics, Optical Activity. Reagents - Na, Br_2, Grignard, Tollen's, Buffers. Tools - IR, pH meter, Polarimeter.

7. Equilibrium, Kinetics, Emission and Absorption Spectroscopy, Rate Experiments, Industrial and Clinical Applications of Spectroscopy.

8. Large Molecules and Natural Products. Polymers, Proteins and Carbohydrates. Prepare industrial products, quality control.

9. Ionization, Electrochemistry, Thermal Analysis, Radioactivity, Corrosion, Batteries.

10. Guidelines to Hazards and Good Safety Practice.

LABORATORY TRAINING FOR CHEMISTS IN UNIVERSITIES

Introductory Courses

Some universities fractionate their students by giving special in-depth courses to the upper ten percent of their entering students, others by giving special remedial attention to the lower ten - thirty percent, with many variations. At the University of Illinois, we have a special "majors" course which requires calculus, treats subject matter in depth, and requires laboratory work designed to train students immediately to professional standards. The introductory laboratory at Illinois involves thirty four-hour laboratory sessions and thirty one-hour lab lectures in an academic year. Exercises and experiments include:

1. Introduction to scientific method in the laboratory (blue bottle)
2. Wet quantitative analysis:
   - Ca as $CaC_2O_4 \cdot \frac{1}{2}H_2O$
   - CO_3^{2-} in soda ash
   - Cu in ore (iodimetry)
   - Fe in ore (MnO_4^- titration)
   - Mn in steel (visible MnO_4^- spectrum)
3. Structure: solid crystal models, symmetry
4. Energetics: calorimetry; ΔH, ΔS, ΔG for $H^+ + OH^- \rightarrow H_2O$
5. Kinetics: aquation of ferroin

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* The present edition has seven volumes, four of which will be revised next year. About 600 students receive two year Associate of Arts (A.A.) degrees each year and are in great demand in the chemical industry. A major oil company plans to add 600 technicians over the next few years. Fifteen graduates in one year at one two year college would be a very large program. The largest program teaches as many as 60 students at one time. Teaching evidently is to small groups, designed for people who are not strong in verbal and mathematical skills yet eager and interested in learning manipulative skills in the laboratory.

Introductory Courses (Contd.)

6. Acid-base equilibria using potentiometry

7. Qualitative analysis - student investigation and identification of 10 ions and 10-12 reagents

8. Preparation and analysis of a complex compound

9. Special project:

    Synthesis of new compounds

    Mechanisms of reactions ($HCrO_4^-$ + NH_3OH^+ for example)

    Miller Experiment - amino acids from CH_4, NH_3 and H_2O

Techniques that are taught include standard wet chemistry, separation and detection, spectrophotometry, potentiometry and data analysis using a computer.

All students who decide to major in chemistry without having the introductory laboratory for majors must either take the laboratory course or a course in quantitative analysis.

Chemistry Majors Laboratory - Core Laboratory

Universities manage laboratory work for chemistry majors in a large variety of ways. Traditionally, each course in organic, physical, inorganic, biochemistry, etc. will have a laboratory component so that students study theory and relevant laboratory practice in parallel. In the late 1960's, the Westheimer Report (Ref. 3), suggested a realignment of chemical subject matter away from the traditional inorganic, organic, analytical and physical into categories of structure, dynamics, and synthesis. This led many universities, including my own (Illinois), to restructure curricula, especially in the laboratory. Laboratory courses have become separate entities, no longer tied to specific lecture courses. Illinois has a core laboratory program for three semesters in the second and third year.

These courses are designed to prepare students to function effectively in research laboratories. The experimental techniques employed are to be the best (latest) available so that a synthesis will be performed by a student just as though he were preparing a new substance or a chemical to be used for research. Reactions are monitored and products characterized with modern instruments, data are analyzed using programmed calculators and computers.

After three semesters in the core laboratory, students will take a specialized laboratory in a traditional field of interest prefatory to spending their fourth year on a research project in collaboration with a professor or a post-doctoral fellow.

Core Laboratory - Second and Third Years

A. Synthesis - organic and inorganic. Objectives: To learn the art and techniques of synthesizing and purifying compounds.

    Acetanilide - dissolution, drying, MP, IR

    Separation - extraction, distillation

    T-butyl chloride - application of previous techniques

    n-butyl acetate - reflux, azeotrope

    4-methyl-2-pentanol dehydration - GLPC

    $Ni(en)_3^{2+}$ and Ni(II) complex with a macrocyclic ligand

    Reaction monitored by TLC

    Identification of unknown - simulated and laboratory

    Two selected experiments

Core Laboratory - Second and Third Years (Contd)

B. Dynamics, Structure, and Physical Methods. Objectives: Training students in electronics as needed for modern chemistry laboratories and in the techniques for studying chemical reactions.

1. Electronics for chemists (Malmstadt-Heathkit) - 20%

2. Kinetics

   Mutarotation of glucose

   Cis$\rightleftarrows$trans azobenzene (thermal and hν)

   Mo(VI) catalysis of $H_2O_2 + I^-$

   Keto-enol tautomerism by NMR

   Formula and K_f for Cu(II) - iminodiacetic acid

   Linkage isomerism in a complex

   Fluorescence - sensitizing, quenching

C. Chemical Fundamentals (some correspondence to traditional physical chemistry laboratories).

Text: Experiments in Physical Chemistry, Shoemaker, Garland, and Steinfeld, McGraw-Hill (1974).

Objectives: To develop knowledge of and skill in using modern instrumentation.

1. Oral reports

2. Experiments

   a. Nuclear magnetic resonance - continuous wave and pulsed NMR
   b. Electron spin resonance
   c. Microwave - rotational spectroscopy
   d. Infra-red spectroscopy
   e. Lattice energy of argon
   f. Dipole moment of a polar molecule
   g. Magnetic susceptibility
   h. Thermochemistry - DTA
   i. Mössbauer spectroscopy
   j. Raman spectroscopy
   k. Molecular beams

Also covered will be use of electronics, oscilloscopes, and computers for data analysis.

It should be clearly noted both in the CPT guidelines and the course outlines above that there is a great deal of choice, allowing for flexibility and evolution of lab programs which can therefore be tailored to interests of teachers and students, change with the times and adapt to changing and variable resources.

Simulated Laboratory

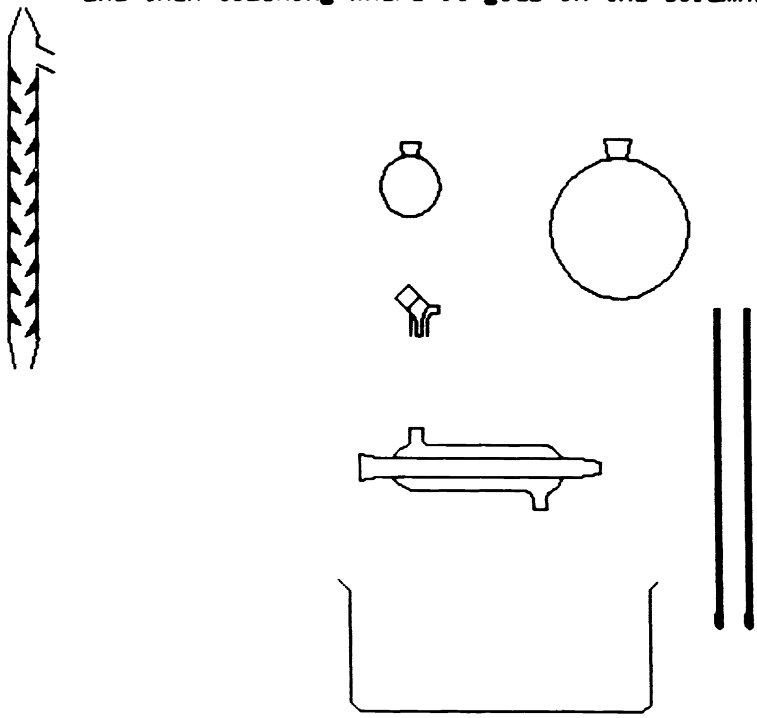
The growing accessibility of computer-based instruction has led to the creation of programs at several institutions for the conduct of simulated laboratory "experiments" in which students may acquaint themselves with laboratory procedure and how to deal with results by communication with a computer terminal. Figures 1a and 1b show computer readout at two stages in a lesson on distillation. The student, by touching a part to be moved and then touching its point of attachment, can "assemble" the apparatus. He then "instructs" the computer to charge the flask with a mixture, programs heating of the flask, and gives instruction on when to cut fractions of distillate. The computer "determines" the composition of each fraction and whether the student has performed a satisfactory distillation.

Simulated experiments available on PLATO include titration, variation of n.m.r. parameters, distillation, formula of a compound from percent composition, measurement of specific heat, organic qualitative analysis, inorganic qualitative analysis, measurement of density, using an analytical balance, electrochemistry, relative activity of halogens.

SIMULATED LABORATORY

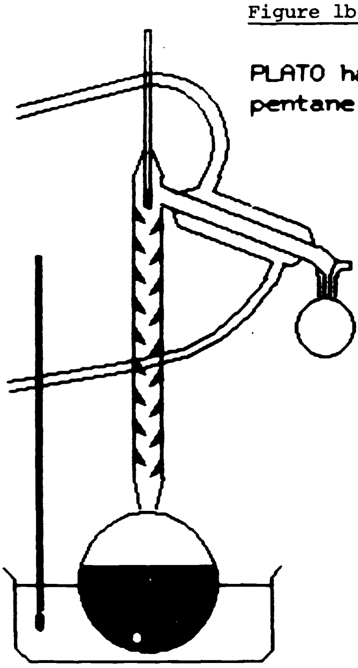
Figure 1a. Parts of apparatus disassembled as seen by student on a PLATO monitor.

Here are the parts to a distillation apparatus. Put the apparatus together by touching a piece and then touching where it goes on the column.



SIMULATED LABORATORY

Figure 1b. Apparatus as "assembled" by student giving "instructions" to the computer.



PLATO has put 100 ml of a 50:50 mixture of pentane and hexane in the distillation pot.

What do you want to do now?

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Of special interest is the recent development of inexpensive desk top computers which can be used to display PLATO programs which could make such programs accessible to students in libraries, laboratories, or home. It is possible that students in the future can be introduced to laboratory procedure and how to handle results (mistakes) in an interesting and efficient manner without the expenditure of resources and time normally required for laboratory instruction. Our use of simulation is primarily for prelaboratory instruction - setting the stage for actual laboratory work. It certainly can be adapted for use where no laboratory or particular equipment is available. (More detailed exhibits from our simulated experiments were presented at the poster session.)

Lecture Table Experiments (Ref. 4)
One of the best ways to introduce large numbers of students to chemical phenomena is to exhibit such phenomena during lectures.

Collections of tested lecture demonstrations are available (Ref. 4), and films and TV tapes of phenomena are becoming available. Skill is required to successfully integrate exhibits with speaking and teachers must work at it for a couple of years, usually, before they are comfortable with it. Most students can be motivated by wonder, and dramatic chemical events like small explosions, copper reacting with nitric acid, complete solidification of a super-saturated solution, the colorful co-ordination and redox chemistry of transition metal ions, all can be easily shown in ways to motivate students to learn and understand.

ORGANIZING CHEMICAL EDUCATION FOR STUDENTS IN DEVELOPING SOCIETIES

A Technical Program for Disadvantaged Americans
A program worthy of attention is that at Xavier University in New Orleans under direction of J.W. Carmichael. The institution teaches mostly black urban students from backgrounds described as disadvantaged. Average scores on college placement tests are far below those of the average entering student. Attrition in beginning science and math courses is typically 40%. With the help of the National Science Foundation, a program designed to prepare the students to do the studies they have not been able to do in the past is under way. A real effort will be made to examine students particularly in terms of cognitive skills in order to determine effectiveness of programs developed. "Evaluation" of educational programs and "accountability" of teachers and administrators for the effectiveness of programs are being eagerly sought in American institutions. Results of such activity if at all worthwhile should be of real benefit to organizers of new programs anywhere.

Personal Observations and Reflections
In 1948-9 the author taught a number of courses at the University of Hawaii which draws students from a wide variety of racial and cultural backgrounds. More recently one of my past assistants, Professor Joseph Stickler, has developed an introductory and organic chemistry program at Ganado College in Arizona which is introducing higher education to American Indians. We have discussed the goals of this conference in light of our own experiences in these positions and also in dealing with occasional students from all parts of the world while teaching at a variety of American institutions, and arrived at the following generalizations:

1. The laboratory, however primitive, is often the best direct introduction one can give students from non-technical backgrounds to technical material. Intellectually, such students often have grave initial difficulty with chemical abstractions presented immediately in the classroom. The concrete experience in laboratory is easier to deal with and so is more effective at arousing interest. Experiments employing local materials familiar to students are especially effective. Simple, easily understood operations should not be avoided because they are too "primitive" or "low level".

2. Students from non-technical backgrounds have difficulty handling equipment compared to students raised with mechanical toys, machine tools, instruments, and engines as part of their every day activity. American laboratories generally have a strong self-corrective component since students tend to communicate, assist, and criticize each other. Students from more authoritarian (and less mechanical homes), tend to look the other way - too embarrassed by their own strangeness - to correct errors by a neighbor.

Personal Observations and Reflections (Contd)

3. It is very important that technical work for students with little technical background employs material to read that is in easily accessible language. This is especially important for students being instructed in a language not their own. It is clear to most of us who are veterans in the educational process that reading chemistry with understanding is the primary block to successful mastery of the material even for students raised in the language of the text and the classroom. The language of chemistry is difficult for most students and studying in a tongue not their own compounds the difficulty.

4. Students can profit enormously from a laboratory program which encourages the solution of laboratory problems with materials on hand, as part of their general training in the methods of scientific inquiry. I have had the experience at a small institution of having student curiosity about chemicals they had synthesized create a need for specialized equipment or apparatus which students themselves built or assembled.

5. For a program to develop, flourish, and keep abreast in a remote location from science centers, teaching staff must be given time to grow in their scientific capability with regular leave to major science centers for study and/or research. Regular contact with research universities helps immeasurably in advising and placing students as well as contributing to personal growth. (The teaching program at Illinois annually has two to four visitors from the college ranks and has included Professor Kasenally from Mauritius who taught a laboratory course as part of his program of study and research while on sabbatical leave.)

6. Most important of all is that a laboratory program be created, that it be conducted with enthusiasm and continued assessment with an eye to improvement.* To quote Henry Bent and James Powers (Ref. 5) "... with a constructive attitude, you can improve, and in trying to improve You Can't Lose ..." and neither can your students.

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* A word of caution. Too much concern with aims or goals and assessment beyond that of simply giving students interesting direct experience with chemicals using resources on hand can be distracting. A story whose source I don't recall tells of students at two schools - one where students were busily conducting experiments while at the other teachers argued endlessly over the proper choice of experiments and the goals that should be fulfilled while students stood by waiting for assignments to begin work.

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