THE FUTURE FOR PERSONAL COMPUTERS IN LABORATORY INSTRUCTION IN ELECTRICAL ENGINEERING

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ABSTRACT

As various educators attest (Er 83, Va 84), the conventional approach to undergraduate laboratory instruction in Electrical Engineering is in considerable disarray: Shortfalls abound; there is too little time available in the curriculum to expose ideas, let alone practice with them; there are too few qualified teaching assistants to provide the desired level of guidance; and, in practical laboratories, there is too little funding to maintain either quality or quantity of instrumentation in rapdily evolving aspects of technology. As well, there appear to be many idealogical issues to resolve (Va 84).

The present paper proposes a direction of the solution for many of these problems. It is written in the hope that it may indicate a direction from which larger concerns of a societal nature can be resolved.

1.0 INTRODUCTION

While there has been a long history (AnM 72) of deliberations involving the role of computers in laboratory education, actual progress has been limited by a succession of factors. These have included, historically, the cost of dedicated machines, inadequacies (including response time and cost) of timesharing through dumb terminals, and, in a more general sense, the failure of simulations operating under economic constraints to convey the totality of laboratory experience. As a result one sees at present, in the age of proliferating processors, an anomaly - the anomaly of perceivable underuse of computers in laboratory instruction outside the domain of computer instruction itself.

But what does the immediate future hold? It is in response to this question that the present paper is written. In it an attempt will be made to bring together fairly obvious techniques, some old and some new, but all within the range of feasibility for resource-limited institutions in the business of serving the educational marketplace.

We are at present at the threshold of a newly-unifiable approach to the provision of laboratory instruction and experience (Ly 84). Techniques and technologies are now in place to allow us actually to implement the dreams of educators in earlier decades for realizing the potential of modern computers in laboratory instruction.

The handle on this new door to the future is quite obvious. It is embodied in the now ubiquitous (Os 84) personal computer (PC) whose current manifestations presently provide local processing to the necessary degree.

It is only recently that sufficient processing power has become available to provide a paedogogically appropriate interaction, at reasonable cost, both of facilities and of facilities management and supervision, as well as of time spent by our student clients. Less obvious is the combination of the lock on the door to future laboratories. All that is likely to be obvious is that the combination is quite complex, with many components, each of which must be put in place.

In a sense, and certainly at a casual level, some of the necessary technology is quite apparent:

2.0 THE AVAILABLE TECHNOLOGY

2.1 Processing Components

I believe it to be obvious that we need a PC with considerable capability as a standalone processor. For example it should have at least a 16 bit word: With insufficient word length, response time will suffer; address space limitations will lead to excess use of secondary storage; modestly complex computations will use too great a fraction of available processor cycles. Equally obviously, appropriate processors are available *now* at low cost, and vastly more capable ones are now at a premium factor of less than 2 to 5, and, within 2 years, at today's prices.+

For many reasons, many obvious and some less so, the laboratory PC should be connected to a local area network. Through this network (or set of interconnected networks), access should be possible to large data bases and high performance processing, as well as to assignable secondary storage, printing and plotting, the latter on a relatively local basis. The details of such arrangements are intimately tied to issues of the local and global economies surrounding the particular laboratory environment (Ly 84).

+ Incidentally, it is in general my belief that for the purposes related to the present paper, the price of the appropriate processors will not greatly reduce, being dominated largely by the costs of promotion, packaging and power supply, but, rather, that performance will increase greatly.

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In general if initial capitalization is not a problem, a greater emphasis should be placed on networking as the means to reduce total cost. However serious problems arise if this idea is carried too far. For example, while it is possible for a memory-endowed, network-connected PC to function as the kernel of a laboratory station with no disks of any kind, such a system, implemented with corresponding economies elsewhere, will perform unsatisfactorily when loaded by many students, and be totally unusable in the event of network failure.

Thus while each station can be connected, for example in a low cost system, to a file server in which the majority of secondary disk storage with backup exists, it is useful to provide each PC with direct access to its own disk(s). A single hard disk with a single removable disk is an ideal (while not low cost) system with the advantage of (almost) complete standalone operation for a majority of uses. If cost is critical, flexibility is maintained but responsiveness suffers if the hard disk is eliminated. A system with a hard disk and an attachable floppy (or equivalent removable) disk may be a best choice, a choice which in the event of various global system failures allows student stations to be set up (slowly) for evolving tasks.

2.2 Human Interface

The appropriate components for the interface to the student experimenter are probably less obvious than those of the processor itself. For example, however perverse, it is probably not necessary, nor desirable, to use a keyboard for much of what is really important to the process of laboratory experimentation. However the keyboard is a very traditional component with some relevance, however limited, and should be included. More commentary on the role of keyboards can be found elsewhere (Pe 84) and following.

What is certainly essential is a display - bit-mapped, high resolution and colour if possible. Unfortunately technology does not yet (nor perhaps will it ever) achieve highest resolution with colour. While there is probably no accessible limit to the uses for higher resolution, colour is less crucial, however important. If resolution beyond 1024 by 1024 pixels is obtainable in colour, then a single display will suffice. However, for economy with additional flexibility, two displays, one monochrome with high resolution, and one colour having RGB control with adequate resolution, may constitute an optimal choice.+

The majority of traditional keyboard functions are best replaced with appropriate menus in conjunction with multiple simultaneous views using windowing techniques. For pointing on the screen a mouse is probably the best, and certainly the most economical choice. Since mouse reliability is improved if operation is on a clean surface, space at the workstation corresponding to a touch tablet may be usefully reserved for a portable surface. A touch tablet with sufficient resolution to act as a digitizer for input of graphic materials, such as circuit schematics, would be a more costly alternative (or addition). A touch-sensitive screen, while apparently attractive, is actually inappropriate as the main input mechanism for ergonomic reasons: Its impacts on posture and screen visibility lead to excessive fatigue; furthermore it is far less appropriate for two-person interaction in the event that economy or paedogogy suggests the use of two-or-more-person laboratory parties.

2.3 Instrumentation

2.3.1 The Evolution of Modern Instrumentation...

In parallel with the evolving process of microcomputer development leading to the personal computer has been an equally important one - the process of computerization of modern instrumentation. That these two developments are not independent is increasingly apparent. The interdependence is most evident at the operator level, in the evolution of control structures presented to the user:

As the sophistication of instruments has increased through application of LSI in general and microprocessors in particular, one sees a particular modern example of the cyclic behaviour of instrumentation developments detailed in Appendix A. Within this cycle, functional capability, supported by new technological development, outstrips the capacity of traditional modes of control. In response, there appear a rash of tentative alternative solutions, only some of which will survive to establish the basis of succeeding cycles. Thus we see at present several related developments.

More and more instruments adopt general-purpose keyboards in an attempt to provide generality. However a keyboard solution is far too general (Pe 84).It depends on a knowledge of context which, while possibly available in the mind of a computer user, is a far less likely an attribute of the more casual user of an instrument. Thus one sees now instruments with display screens whose aim it is to prompt the user, requiring of him less and less specific knowledge. Indeed this is more likely to be the correct approach, being quite consistent with the modern direction of computing in general. In fact in both domains, instrumentation and computing, one sees the result to be keyboard atrophy, the relegation of the keyboard to a secondary or degenerate (press key X)(Pe 84) role. Accordngly one sees a convergence of the computer and instrument modalities. The ultimate examples of this trend are to be found are the instrumentation modules (generators, oscilloscopes, analyzers etc.) available now as PC plugins.+

While the trend is plain, the ultimate consequences are not yet clearly visible. But what might they be? My feeling is that there certainly is one, and with some encouragement, a second, of considerable significance to laboratory education:

+ (Optimal if handled carefully; otherwise two screens can lead to the phenomenon dubbed "schizovisia" by W. Buxton, Computer Science, Toronto).

+ For example from Northwest Instrument Systems Inc., Beaverton, Oregon.

2.3.2 The Future for Personal-Computer-Based Instrumentation...

The inevitable development in the growth of PC-based instrumentation will be the adoption of more and more techniques of modern user interface design. Such techniques, pioneered at Xerox PARC and the University of Toronto, revealed commercially in the Xerox Alto, the Sun and the Apple Lisa, and now popularized in the Apple Macintosh, underlie the success of some recent developments in computer-aided instruction (CAI).

In the domain of PC-based instrumentation such techniques will permit the implementation of a process that can be called User Sophistication Adaptation (USA). In this bilateral process, means are provided for adaptation of the appearance of instrument modalities to the user's needs while, as well, encouraging the user to extend his awareness of less obvious instrument capabilities.

Specifically, in USA, during the initial stage of the use of an instrument, the particularities of the user's needs will be identified. Thereafter the instrument will appear, through the vehicle of the PC display and cursor control (mouse), to be customized to these needs. Thus for those who are very organized and formal, even inherently digital in mind set, a set of labelled tables could be established which characterize the instrument. Alternatively, for those of us more casual folk, a picture of a suitable traditional control panel with knobs and so on could be provided. For yet other purposes, some combination of these views may be preferred. In all cases, control, that is change of value of an instrument parameter, would be by pointing and gesture with mouse-button direction. Of course for those who insist, or for whom S and M holds charm, full keyboard entry of parameter names and values is still possible.

As well however, USA will gracefully allow, at any time, modification to the user's "design". Such adaptation may include for example changes in precision with which some parameter can be set, the number of steps in a control range, or the significance of a small motion of the cursor in the vicinity of a control table value or graphic representation.

As well, there will be a second major trend in instrumentation of direct concern and application to the educational community: This trend will be toward the increasing availability, at low cost, of digitally-controlled instrumentation function modules. Presently we see single-chip DACs and ADCs as simple examples of these modules, with others such as samplers, oscillators etc., appearing in increasing numbers. We can be confident that the pace of growth of variety of such modules is ensured by the need for survival of increasing numbers of PC-based and other instrumentation companies. Thus we in the business of education in a laboratory context, while using conventional instruments, computer-interfaceable instruments, or PC-based instruments, can be assured that the key to the next step in the use of PCs in laboratories is about to be put into place.

2.4 Interconnection

2.4.1 The Tyranny of Numbers...

As technology advances, the conceptual span from devices to systems, that is from basics to applications, widens continuously. Thus while, for example, in Electronics Circuits alone, there is still a need for (and a utility in) experimentation with a single BJT, the ultimate concern may be for systems or subsystems incorporating at least dozens, if not hundreds or thousands, of such devices. Of course one might argue that ICs provide the answer. However this is certainly not the case for example if the internal design of an op amp is the subject of study. Likewise even if the op amp represents the level at which laboratory experience is desired, then certainly the span of interest is at least from one op amp at an introductory stage, to at least 10, or even more, at a more advanced level, say where active filtering is the special subject of study. Thus the span of numbers of devices inherently increases while our ability to flexibility interconnect them, for the purpose of stepwise acquisition of knowledge, does not. It is a fact that plugboard wiring of more than tens of items is simply not a sufficiently reliable process on which to base a learning experience of value. (Unless of course the goal is to exemplify the exigencies of the resource-limited real world.) A solution to this problem can be flexible interconnection, or at least modularization with probing and test, all under digital control.

3.0 VIEWS OF THE MODERN LABORATORY - STAGE 0

3.1 Setup

Just as the trend to instrumentation has been to digital control, so also to digital control can be the thrust in the design of experiments themselves. Reasons for perceiving and following this direction abound:

1) The scope of modern education increasingly expands to include both devices (basics) and systems (applications), that is a range from very few to a great many components.

2) Flexible schemes for ad hoc wiring by novices via plugboards etc. which become unreliable in an uncontrolled environment, lead to excessive time in getting the experiment to work and the need for expert help.

3) Single-use fixed-structure experiments imply a large inventory infrequently used, together with a reluctance to update.

4) Limited laboratory resources imply a limited interval in which to complete experiments and a need for more rapid setup and scheduling.

5) Limited laboratory dexterity in some students implies either a reduction in the scope of individual experiments by all or an incomplete cerebral experience by those having limited manual dexterity.

6) Experiments in some subject areas (such as machines or power electronics for example) are potentially dangerous, if not implicitly forbidden by conventional safety codes, when apparatus is interconnected by hand.

It is likely that for most of the previous points the reader can see the relevance immediately of fixed structures, then, upon reflection, for switched connections as a mean to increase flexibility, and, finally, that switched connections while once requiring manual activation, can now be operated under digital control. It is to acknowledge the fact of the potential (and actual) existence of some of the precursors of digital control that this section is subtitled "Stage 0". Thus many of the approaches I suggest as the way to the future have been manifest in laboratory paedogogy at earlier times. However, it is only now, with the potential advantages of digital control in view, that some of the early valid concerns about the fixed-structure, switch-flexible techniques may be waived.

In summary, then, I recommend that we go (or return) to a situation in which we view preconnected but flexibly-switched experimental modules to be the norm; but I do so with a new fact in mind. That fact is that *now* switching in general can be done economically, can be installed at the location where it is needed rather than where control is to be located, can be remotely digitally controlled, and does not imply the need for a control panel which is limited in size or scope by the need for operator comprehension or access.

For those for whom the obscurity of the previous global generality has reached an intolerable level, consider some examples:

a) Imagine for instance a general-purpose printed circuit board on which op amp experiments are to be done. These experiments are conceived to run from the very basic, employing a single op amp, to the quite complex, requiring many op amps, for example in a signal processing application. While CMOS switches are used to ensure flexibility, not every element is switch-connected. Rather there should be enough switches progressively to build each increasingly-complex whole submodule if desired, and to decompose the most complex modules to that level for which construction from basic components is possible. All swtiches required are located relatively near where they are needed in the analog signal path with distributed remote digital control.

b) In fairly direct correspondence to the op amp example above, consider a board intended for a broad spectrum of experiments in CMOS digital logic. Such a board would include NANDs, NORs, and FLIPFLOPs as well as transmission gates, interconnected by additional transmission gates (i.e. CMOS switches) for digital control. Again the level of decomposition would be appropriate to the span of concern of the laboratory. In the limit it could for example include enough MOS devices (say in a 4007 array connected by switches) to illustrate the construction and behaviour of a basic NOR or NAND. It could certainly show how to augment a two-input NAND to create a 3-input NAND, and, as well as demonstrating the results logically, could allow a student (who wished or was required) to evaluate the resulting change of thresholds. Of course it would have registers and counters suited to systems applications, but suitably decomposible, to convey a sense of complete understanding through testing by parts.

c) Imagine now a laboratory in power machines. Here the power switches are large, imposing (and expensive) relays located in logical positions around the machine and easily identified by quick inspection. Each would probably be equipped with a local status indicator lamp for clarity of interpretation. All relays are connected in turn to a low-power-level controller board from which the configuration is under digital control. In such a system safety and clarity are maximized with cost. Thus lower cost approaches, which sacrifice clarity and safety, are possible. Consider for example a general purpose relay module with traditional screw-on terminals as the logical limit of a search for economy with some disregard for safety.

Now, ideally, that we see there may be merit in applying flexible structures and digital control, what can be said for the measurement aspect of the laboratory educational process? Clearly, while it is possible to continue to use conventional instruments, such an approach certainly offers no new economy. However, approaches do exist for which economy and flexibility both apply.

3.2 Measurement

There are two important aspects of the measurement part of the experimental education workplace. The first concerns the nature of the instrumentation itself. The second concerns the way in which it is connected. As stated before, it is clearly possible to use conventional instruments connected by hand. While this may continue to be a viable mode for unusual measurements a small part of the time, other attractive alternatives, more flexible and economical, exist.

Now, for connection, it is apparent that the techniques applied for flexible control can be extended to the measurement domain. That is, it certainly seems possible to connect instrumentation, whatever its nature, in a flexible manner using switches under digital control. Practical problems, such as capacitive loading, may arise, but are surmountable. This approach, depending on the extent of application and concomitant cost, may provide any degree of flexibility desired. Practically speaking, the inability of a designer either to predict needs or to fund them, is compensated by providing, under digital control, (i.e. PC guidance) the ultimate freedom - to connect an instrument by hand.

Now for the nature of the instruments themselves. Inevitably, conventional instuments will play a role. However computer-controlled instruments offer a degree of flexibility whose implications are extolled elsewhere. There are basically 3 choices. The oldest choice, long available, for example, in industrial laboratories, is that of a conventional instrument augmented by a digital interface. Regrettably the cost of the instrument itself, and its interconnection, limits its use in underfunded environments. In practice, Hewlett-Packard system come closest to filling general needs.

More recently, a variety of PC-based instruments have become available whose purchase price is quite low, and whose cost of connection (at least for a very small number of instruments) is zero (Mi 83).

But the most significant property of these PC-based instruments is the availability, at no additional cost, of measured data to the decision and control needs of the PC in a laboratory environment. Much will be said of this later.

Finally, that is *now* and in the future, increasing numbers of standardized instrumentation- related modules are becoming available. These modules of which DACs and ADCs are very basic examples, allow a new degree of flexibility at modest cost. That novelty, simply put, is to incorporate, within the experimental vehicle itself (for example on the PC board of the op amp experiment), appropriate parts of the measurement system, economically adapted to the environment the experiment itself provides.

But which parts are appropriate? This depends of course on the context including timescale, whether now, or in the future. For example, in an environment in which a PC-based oscilloscope (PCO) is available, buffer amplifiers could be added to the experimental vehicle, which used alone or flexibly-connected to an analog multiplexing network, serve to reduce loading on the experiment itself. However it is now possible, certainly for the low part of the frequency spectrum, to include sample and holds, variable gain amplifiers and A to D converters which, under PC control, effectively replicate the major parts of a PCO.

But why should one do this when a centralized PC-based oscilloscope (PCO) seems more economic? And it may well be, particularly for some applications! But there are applications for which the need is really quite simple, and for which the PCO is overkill. In these times of financial exigency, should we equip for all contingencies, or only for ones for which we have direct need?

3.3 Software

It is apparent that, without any of the changes suggested in Sections 3.1 and 3.2 (Setup and Measurement) above, a PC can be a useful adjunct to a laboratory experience. This is particularly true if the PC has access to a large backing store, either locally via hard and floppy discs, or remotely via networking.

In a very general sense, the facilities potentially available can be distinguished as Computer- Aided-Instruction (CAI), leading to Computer-Aided Learning (CAL) (GoS 82), and Simulation. While the latter is clearly one of the many components of the first, it is sufficiently important to consider separately.

As expanded upon elsewhere (AnM 72), the history of CAI has been long, enduring, and in a sense, disappointing. Its interest in laboratories has been, interestingly, an ambivalent one. Its main thrust (and perhaps the thrust of CAI in general) being for the most part inhibited by the textual basis of traditional computer input- output mechanisms, the emphasis was directed largely away from the experimental. Various features and fixtures of Plato provide a counter-example, but then again Plato was not, and is not, conventional, being a very early example of the appreciation of the importance of graphics (at whatever cost), as was its early contemporary, a pseudo-random-accessed film-based system called Socrates, also at the University of Illinois.

While the main thrust of CAI was counter-experimental in the real physical sense, experimentation was accommodated through the implicit incorporation of simulation. Accordingly there have been waves of enthusiasm for simulation as an alternative to real experimentation. While there are some success stories, the process has failed to match the dreams of its advocates for several reasons, many of which are resolved in the present proposal.

Obviouly for much of the history of CAI, the expense of computing power limited the insights available through simulation. Now, while a PC, itself more powerful than most computers in the 60's and most sensibly-priced ones well into the 70's, can contribute greatly, far greater capability is potentially available (at a price) through networking. Thus the resource issue may well be in hand.

Regrettably however, like other aspects of the application of computers, demand, once tantalized, proceeds to outrun supply. Direct examples of this phenomenon appear for instance in electronics. Where once we would have been happy to simulate a single transistor, but could not afford it, we now want to simulate dozens of hundreds of more complex devices, but cannot afford it. Unfortunately such catalyzed demand seems limitless. But, fortunately, at least in some of its dimensions, there is, if not a limit, at least an important fixed milepost within sight.

One might imagine reality itself to constitute the limit to which simulation strives. But even this is illusory. For reality itself is hierarchical; it is simply that a person's ability to perceive improves on the basis of his previous perceptions.

Thus while the internal reality of a packaged IC is difficult to explore from its external pins, it can be internally represented reasonably well (in some attributes at least) by appropriate smaller parts. Such parts, a physically simulated model of the IC's vitals, are real, but not the reality of the actual IC. They are merely another marker on the road to IC learning.

Thus, in summary, the process suggested here of connecting real devices (and/or their component parts) in the feedback loop established by setup and completed by measurement, comes a long way toward the limit of experimental truth. Potentially, in this way, young experimenters can, as part of their educational process, experience the realities of the relevant technology in an enriched intellectual environment in which reality serves also as its own simulator (WiH 84).

3.4 User's View

The simple ad hoc system which is likely to result at Stage 0, may be most simply described as augmented CAI. Augmentation would primarily be in the areas of setup, reconfiguration, measurement and reporting.

Briefly stated, an experiment would proceed in the following manner: The initial setup would be configured on the basis of an initial interaction with the student; reconfiguration would occur both as the experiment progresses and as a result of the need for help or review; measurement would be dominated by the PC-directed use of specified connections, adjustments and probes; reporting would be on the basis of automatic fillin of tables, creation of graphs etc. Overall, as we shall see, the system provides a reasonably attainable subset of what is generally possible now, but implemented more completely at later stages.

At a somewhat more detailed level, the user view would include:

1) A menu-driven tree-structured global organization with back- tracking at at least two levels to the previous screen or to an appropriate ancestor screen.

2) The ability to revert to early levels, directories etc. and return, without destroying information recorded internally in setups or in internal states of the subject experimental system.

3) A choice of topics and levels of presentation, made both explicitly and implicitly in terms of a user profile, including the possibility of a selectively-accelerated guided tour through the experiment.

4) A simple user-familiarization procedure through which the complexity of the experiment setup is introduced in a non-threatening way, using graphics to relate board layout to circuit schematic.

5) A somewhat conventional instruction manual with conventional query-response interaction but at levels related to the (up-or down-gradable) user profile.

6) Semi-automatic setup of experiment topology with the possibility of a small amount of machine-directed, user-implemented jumper connection, swtich operation, potentiometer adjustment, and component substitution either for instructional purposes or to obviate deficiencies in control hardware.

7) Direction of the experiment through explicit requests made by the PC for a probe connection etc., the completion of which is signalled by button press.

8) A limited degree of available help, often resulting in a directive to "see the laboratory supervisor".

9) A limited ability to reconffigure to a simpler mode in response to the need for help, or remeasurement or other back-tracking.

10) Assisted preparation of the numerical and (limited) graphical aspects of a work report on the screen, with printed copy (eventually) available.

11) Limited concurrent access to word processing services for general observations, notes etc. which may, for most purposes except writing practice, be communicated by access to stereotypical comment menus perhaps created (or at least personalized) on the basis of the initial user-profile interaction.

Thus for special cases *now* , and somewhat more generally in the near future, there are techniques for making the computer-augmented laboratory a true learning experience. However a great deal of practical work is necessary before this can be demonstrated in any general way. But even more importantly, there remains a great deal of work to provide the tools and organization which make the creation of such laboratory materials a lot easier.

4.0 VIEWS OF THE MODERN LANGUAGE - STAGE 1

4.1 Hardware

In the process of evolution of laboratory instruction we have reached a place at Stage 0, from which a new more dramatic step can be taken, a step in which selected more-or-less-obvious components of earlier developments are combined.

At Stage 1 of the continuing process of laboratory instructional development I perceive the following scenario:

1) Each student (or student pair) with PC workstation, preferrbly networked or, less desirably, telecom-connected or at least disc-endowed.

2) Each workstation with a controller interface for digital switch setup.

3) Each workstation with a combination of PC-based instruments and a controller interface for remote instrument modules, which combination depends largely on the local economy.

4) Each workstation equipped with an experiment adaptor to which an experiment board can be connected and within which exist sharable resources for setup and measurement that are best located near to the experiment board.

5) Collections of experiment boards, each intended to serve a coherent technical aspect of curriculum, likely extending over course and semester boundaries, each incorporating digital switch flexibility and some elements of appropriate instrumentation.

6) Interface adaptors and experiment boards conforming to some standardized conventions and protocols.

7) Experiment board designs available as part of an evolving literature in Computer-Augmented Laboratory Learning (CALL).

8) Software systems support for the above with courseware development tools and specific courseware.

4.2 User View

At Stage 1 of laboratory development, the user view advanced in Section 3.4 for Stage 0 would be extended in most aspects listed and, as well, the following features would be added:

1) The facility to reconfigure and probe automatically would be augmented to allow user-independant measurements to be made.

2) To a modest degree, results obtained through more direct user intervention, connecting, probing etc. would be compared with reference values obtained by direct machine measurement and, as well, with stored results taken under the direction of the instructor with a view to corrective diagnosis - apparatus malfunction, user error, user lack of understanding, etc.

3) The Help concept would be extended to include simulation, using the actual experimental apparatus initiated in response to a machine- user exchange in which the question "what happens if" is prompted by the machine and elicited from the user.

4) A degree of adaptation of the instructional program, both of its pace and of its screens, will be introduced on the basis of check measurements made either during experiment commissioning or dynamically as in 1) above.

Thus, in summary, at Stage 1 in the process of modern laboratory development, we enter a new regime where Computer-Augmented Laboratory Learning (CALL) can flourish usng the best available techniques of CAI, provided potentially more economically (particularly at run time) than in conventional environments, since the techniques of self-simulation are inherently available.

5.0 VIEWS OF THE MODERN LABORATORY - STAGE 2

Stage 2 of modern laboratory development will generally concern itself with economies of expansion and replication.

On the software side, adequate ad hoc systems should be in place. However as in any other developing area, hindsight will dictate change. In Stage 2 a retrospective rewrite, in a highly-structured modular machine-independent form, of operating software would be appropriate.

On the courseware side, the impact of access to physical experimentation on the process of efficient courseware construction should be known, allowing advanced courseware-writing tools to be created. For effective use by discipline specialists who are not also computer specialists, these tools must have a low entry cost for naive users, expand gracefully as user proficiency increases, and naturally lead to effective low cost teaching materials.

On the hardware side, developments may not be so obvious, yet are in fact even more important. One would expect that the current trends in instrumentation, coupled with the voracious demand for VLSIable systems that foundaries and others encourage, would lead to more and more candidate instrumentation modules. Likewise ICs implementing appropriate communications protocols will naturally appear for network interconnection in the building, in the room, in the controller and on the board.

However, one important component is far less likely to appear without the concerted encouragement of academics interested in the role of laboratories in technological education, particularly in areas relating to, or utilizing, electronics. It is the flexible device on which the experiment is to be run - an "experiment IC".

These VLSI components, or which there would be very many copies potentially, would, with advancing technology, be the logical descendants of early experiment boards replete with discrete, SSI, MSI and LSI devices. Each VLSIC in its own area would constitute the complete experimental environment, or at least the means to its access. Thus for example for experimentation with op amps, one could conceive of an IC containing a flexibly- interconnected set of CMOS op amps and op amp component elements coupled by CMOS switches. Such a VLSI circuit, as well as including reconfiguration cntrol, would embody at least the front end of a probing and test facility. Since such an IC would operate in the relatively hostile environment of an academic laboratory, it would also include additional facilities by which the instructor could establish its well-being, periodically and upon request by a distraught student.

While existing and contemplated semi-custom array chips offer some promise as candidates for some such components, there is certainly a less than perfect match between need and availability. Could it be that the market provided by electronics-associated academic laboratories is enough to encourage the development of a suitably flexible customized array with adequate self-test facilities? Obviously a lot of basic work remains to be done on all sides. As for the question, only time will tell!

6.0 CONCLUSIONS

The time is right to extend the role of personal computers in education forcefully into the area of practical laboratory instruction. While alone each of us can contribute as individuals, we will be more effective if united by common goals. The intent of this paper has been to suggest one such goal, namely the creation of designs for PC-controllable experimental environments including basic instrumentation, flexibly-connected.

Many challenges remain. Amongst these are to identify and popularize appropriate standard interfaces, communications protocols, instrumentation modules and courseware constructs. With a little planning and coordination ***now*** we might soon do a lot to solve the problems that technological education must face.

7.0 APPENDIX A

7.1 The Instrumentation Evolution and Its Impact on Laboratory Education

The trend to miniaturization evident throughout the history of electronics, and most dramatically apparent in the past decade, has had an interesting effect on the nature of available laboratory instruments. As individual components reduced in size, and as multiple functions were combined in single multipin packages with advances in fabrication technology, traditional instrumentation functions came to occupy less and less space. As this trend proceeded, one saw, in successive eras, a cycle in which the reduction in size of packaged instruments performing traditional functions, was followed by a period of package growth as instrument functionality was increased and the requirements of additional control panel space were relieved.

Underlying this cyclic activity is a basic behavioural property of the market place, itself cyclic with a time scale characteristic of competing business: As components reduce in size, a manufacturer can initially feature reduced package size in his marketing strategy. But a limit is soon reached where the package size is reduced below the perceived minimum for a package of a given type and price. It is simply true that a purchaser will ultimately balk when the cost per cc becomes too great.

Thus, while there is a psychological limit to the size reduction of a given class of instrument package, price must be maintained within the range necessary to support the marketing and maintenance organization on which a corporation's success has been based. One solution to this difficulty, practised for a time in the 60's by at least one very large computer manufacturer, has been to limit the reduction in external package while proceeding with the inevitable reduction in content. While this works for a while, consumers become increasingly aware of the increased emptiness of their purchase.

The solution ultimately reached is usually to increase the functionality and performance of the packaged system, possibly to fill or even to overfill the box, after increasing its size to accommodate additional required controls, and after initially increasing the price because of demonstrable additional performance, secure in the knowledge that subsequent price reduction can be used to maintain a competitive edge.

But what is the effect of all this on instrumentation for Electrical Engineering Laboratory Instruction? Simply put, it is that while instrument size has reduced to some controls-limited minimum, functionality, flexibility, versatility and price have all risen. Regrettably the result is paedogogically very counter-productive. It is that, increasingly, we buy decreasing numbers of more costly multipurpose instruments with our dwindling financial resources. Regrettably however, while each is more versatile, it is simultaneously more confusing, particularly to students in introductory courses, where only a small number of its many functions is desired or necessary.

So what may a solution be? Consider the possibility, as addressed in the body of this paper, of defining a new market for flexible instrument modules, stripped of controls, where the controlling interface is by means of a general-purpose PC, software-adapted to the real need.

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