AC 2010-1128: A SYSTEMS VIEW OF TECHNOLOGY CURRICULA

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A Systems View of Technology Curricula

The Systems Challenge. The combination of new technology and the pressures of economic performance are changing the substance of many engineering and technician jobs as well as the interactions between these traditional roles. Electronics is now a global business where the multi-layer circuit board with surface-mount components is the basic building block. That means that everything at circuit board level and below is not repairable and its production is highly capital intensive. There are major implications for the knowledge and skills at every applications level. The traditional technician job is changing and often being renamed. When this is acknowledged, it points to a systems approach for education programs. The technical job market now has two very distinct components:

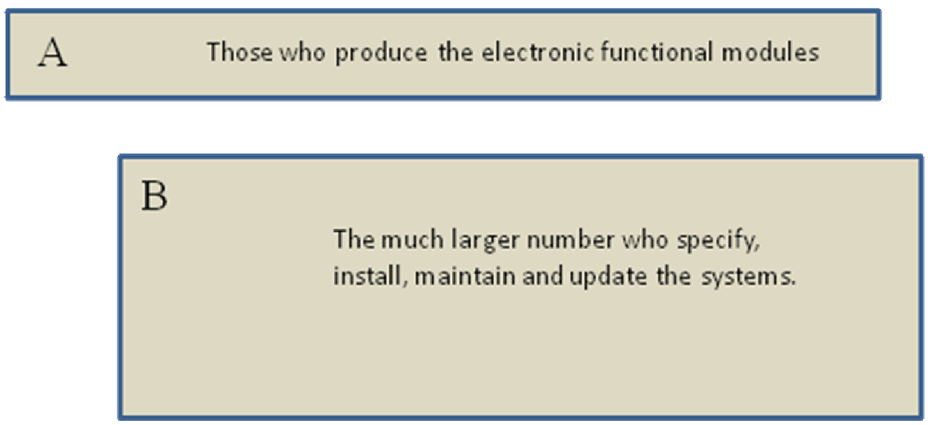

Figure 1. Categories for electronics employment

A school located in an area which has significant electronics manufacturing capabilities (group A in figure 1) will likely have programs to address the specific needs associated with product design, assembly and test. Component integration continues to follow Moore's Law and a new technology family is introduced every two years. The levels of automation and productivity are also increasing so the same number of people can produce much more product. Within that workforce, the level of specialist expertise is rising and the electronics producers are rapidly heading to a point where a BS degree is the entry qualification. This poses many educational challenges both for new recruits and also to continuously update the skills of those employed. However, the main focus of this paper is with those who use the electronic products (category B in figure 1).

It is easy to lose sight of the needs of the much larger workforce that designs, builds and sustains the electronic systems. One of the reasons is that the work is no longer limited to one industry segment. Positions that use electronics skills are now to be found in a wide range of industries including biotechnology, health-care, manufacturing, entertainment, automotive and consumer products. Electronics technology is a key enabler of all of these contemporary industries and is their critical path to meet the efficiency, performance and cost goals needed for success in competitive global markets.

However, the job is no longer about designing with components; it is about connection of functional modules and operating the resulting system efficiently to meet the business goals. The jobs are there, but they are not necessarily labeled for electronics technicians or engineers or even make any distinction between these traditional categories. Employers in many industries are hurting for qualified applicants; yet electronics technology education program enrollments nationwide are down.

This paper is directed towards the educational requirements of the next generation of students who will never have to operate at the traditional component or small circuit level. It therefore addresses the development and implementation of the type systems-oriented curriculum needed to prepare the workforce needed for category B in figure 1.

Towards a Systems-based Curriculum. The generic definition of a "system" is a combination of multiple related elements organized into a more complex whole to perform some useful service. For electronics, a system is an assembly of electronic functional blocks, mechanical components and software that operate together as a unit to perform some function. A generic representation is shown in figure 2.

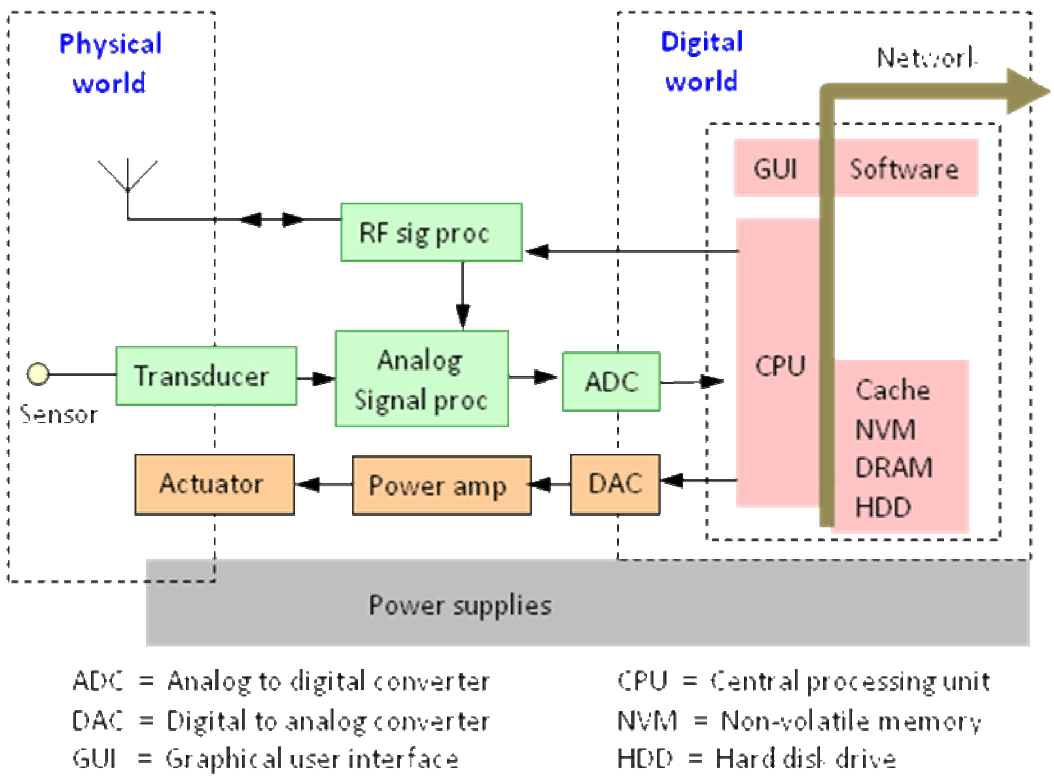

Figure 2. Generic representation of an electronic system

What makes this system complex, powerful and flexible is the combination of computation with massive data collection capabilities. With different sections enabled, the representation applies as readily to a Blackberry, a smart utility grid or an automated factory. Technicians who build, operate or maintain such systems do not have to drill down to manage functionality at the discrete component level but they must understand how the whole system functions and, importantly, know how that system communicates both inside itself and with the outside world. Their needs are poorly served by too many of the existing academic programs. The educational challenge is therefore to build a curriculum that provides enough detail to allow specific cases to be analyzed but also demonstrate the principles that can be applied to any new system. This can be achieved using a top-down approach. It has three immediate advantages:

1. It breaks away from the limitations of the typical treatment that builds up from basic components and invariably runs out of time before it can demonstrate any useful purpose.
2. Since a system is more than the sum of its parts, the systems view shows how interactions lead to both opportunities and latent failure modes that are never considered within a traditional component-based design activity.
3. The general principles of electronics that relate to power management and signal processing are unchanged but now they are delivered through system examples, interactions and contextual applications rather than discrete component circuits.

Curriculum change is rarely quick. New material gradually displaces the obsolete treatments as faculty and tools change. The work described in this paper comes from an NSF funded project that has generated both the methodology and content examples for a systems-centric curriculum. A number of applications cases have been developed as part of a national curriculum development program and used both in 2-year schools and in lower-division university courses. They have been evaluated by faculty, industry users and student groups and are available for general use [1].

Changing Attributes of the Job. As electronics has permeated all business activities, job specifications and reporting relationships have changed. Two or three decades ago, a technician would report to a specialist engineer who knew how the job should be done. Now, the report line is much more likely to be to a physician, a scientist or an engineer who has very little detailed knowledge of electronics. The role has therefore changed from that of an assistant who handled the practical work to an autonomous specialist.

The changes in relationships are very similar to those which have already evolved for IT specialists. In the electronics case, however, there are additional complications from the need to interact with the physical world for data collection, real-time operation, control and possible safety-critical situations. The scale and cost of all hardware has changed jobs dramatically. In the days of manual testing, data acquisition rates were measured in bytes/s. Subsequent processing was equally manual so the cost was determined by wages and error rates were high. Now, data collection at MByte/s rates is routine and automated while a system with the functionality shown in figure 2 can be realized for less than $10. The whole system can be procured as a turnkey product so it becomes an extended tool for the non-electronics professional running the application. Specialist intervention is needed less often but the counterbalance is that systems are rapidly increasing in complexity so there are more varieties of interaction and novel problems. From an educational viewpoint, this means more emphasis on critical thinking, troubleshooting, skeptical self-confidence and good communication with no jargon.

To run a typical electronics system, there are three main technical job activities to consider. They are shown in figure 3.

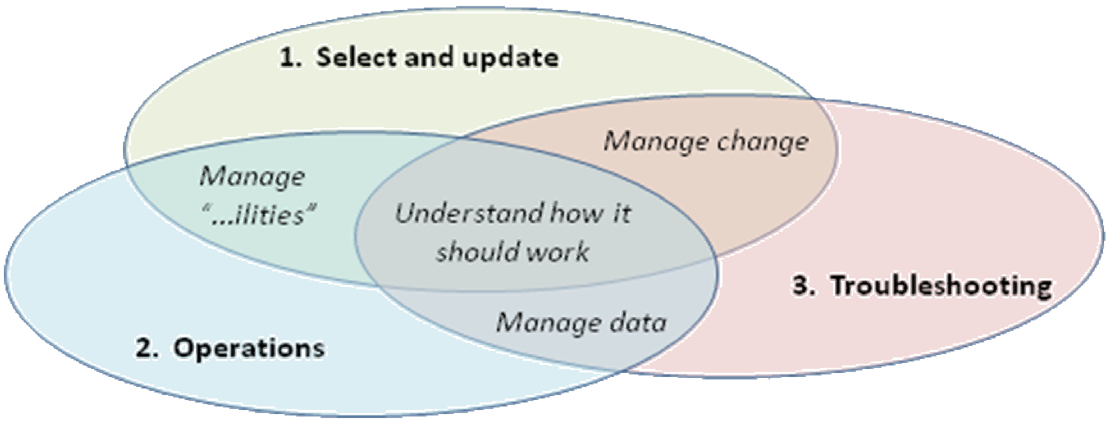

Figure 3. Job activities and interactions

The most critical skill is in the center of the set. A good grasp of how the system *should* work is essential for all the other functions. Given the diverse reporting relationships outlined earlier, it also demands communications skills of a high order. It is one thing to be able to explain a problem to someone who knows more about it than you; it is a much harder job to explain it to someone who knows a lot less but still expects you to deliver.

The implications and interactions may be summarized:

1. *Select and update system components and functions*. The requirements are prepared by the applications-sector professionals but the range of realization options is huge – from interconnecting custom boards to a turnkey system. However, in all cases, the technicians involved in making it happen have to be able to interpret specifications, identify any inconsistencies and manage the signal and power interfaces to other systems.

   Most systems do not remain static; they evolve. The interface between job functions 1 and 2 is covered by many terms, most of which end in "… ility". Examples are: testability, reliability, maintainability, affordability, flexibility and sustainability. They are simple concepts but remarkably difficult to implement together. A systems-oriented course structure allows examples of "…ilities" to be provided in the current and evolved contexts.

2. *System operations* should theoretically be a stable, routine job. However, it rarely achieves that status because the multiple inputs and outputs are always changing. Thus it is necessary to know the sensitivity factors that inter-connect all the variables; what can be considered as noise and which effects demand

prompt action. The top-down approach makes it easy to deal with balance and priorities in ways that are never considered in the more traditional approaches.

> The critical interface between functions 2 and 3 depends on making use of the data available. The capability to convert data to information by selection and precise reporting is an undervalued but essential skill. It also has to be organized and formatted to convey an unambiguous message.

3. *Troubleshooting* has changed significantly. Advanced technology allows many diagnostic routines to be built-in so an error signal or interrogation tool points to the remedy. The best example is in car maintenance. Trouble-shooting has therefore been de-skilled – except for the problems that were not considered by the original designer. These are the problems that are not supposed to happen but since they do, troubleshooting not handled by the embedded tools needs very sophisticated diagnostic skills.

> Troubleshooting points back to function 1. Does the fix imply a permanent change? It is an important decision that requires balanced inputs from many specialists which then have to be coordinated and a viable solution proposed and accepted by all the stakeholders.

At the root of these job functions lies a sound understanding of how the system works. It does not need the depth of the specialist who created the functional blocks. Nor is it the superficial capability that is enough to pass an exam but is then forgotten. What is required is a fluency that can be applied to any of the functions in figure 3 or used to communicate with any of the system stakeholders. It demands a capability to see the technical job in its larger applications context and then drill down to the details – or call in an expert. This is a major outcome measure for any educational process that prepares the technical specialists.

Communications as an Objective. The job relationships shown in figure 3 above indicate that communications is not a stand-alone skill. Technical writing and communication are embedded into every job. Given the diversity of skills involved in every electronic system application, it cannot be assumed that any communication will be checked for technical accuracy after it leaves the originator. Therefore every employee must meet the stand-alone capabilities for effective communication. Among the requirements identified by industry advisors are:

- Document results or log information.
  Work activities must include clearly written descriptions of how the system is supposed to work, the way it worked, and a clear summary of findings. Note taking and summaries are key components of this task.
- Give reports and make presentations.
  This is done in teams using report writing and presentation software.

- Pass down.
  This is an industry term indicating a verbal and or written transfer of information about a process, problem, or piece of equipment to the next shift or work team. Clear, concise communication is critical.
- Teach/instruct.
  In industry it is often the technician's responsibility to conduct on the job training for others or to qualify new technicians for new tasks. Verbal communication skills with individuals and small groups are critical in this task.
- Communicate and listen.
  By email, memos, and letters with appropriate style and vocabulary.
  By media such as video conferencing, web meetings, and podcasts.
  By responding thoughtfully to questions.
  By "marketing" an idea, project, or concept for consideration by management.
- Research and specify.
  Technicians generally do not conduct research per se, but they do research and make recommendations. For example they will be asked to specify a certain piece of equipment and justify the expenditure. This typically involves Internet research, communication with vendors, and consideration of alternatives and trade-offs. Ultimately this results in an approval or authorization in the work place

None of these requirements should be a surprise. They are made by every advisory board every year, so clearly the solution is not getting enough attention. The most successful responses appear to be those where features of typical real world systems are embedded in courses and communication is taught and assessed as an integral part of doing the job. To demonstrate how embedded systems may be tackled in a program, the following two sections show examples of system decomposition into basic concepts and a complementary view of how one basic concept is applied in many systems.

One Concept, Many Systems Applications. The conventional treatment of circuits starts with Ohm's Law then applies it to multiple combinations of series and parallel resistors. This keeps everyone busy with math but it is an application that will be rarely seen. The more important concept is to understand the importance of the time (or frequency) domain. Today's electronics is powerful because analog values can be converted to a time sequence of digital signals. The component link to time is through the RC product (inductance has been demoted to niche applications).

The first decision to be made in any system analysis is, "what is the time range for anything to happen?" A simple RC response is shown for three time domains in figure 4.

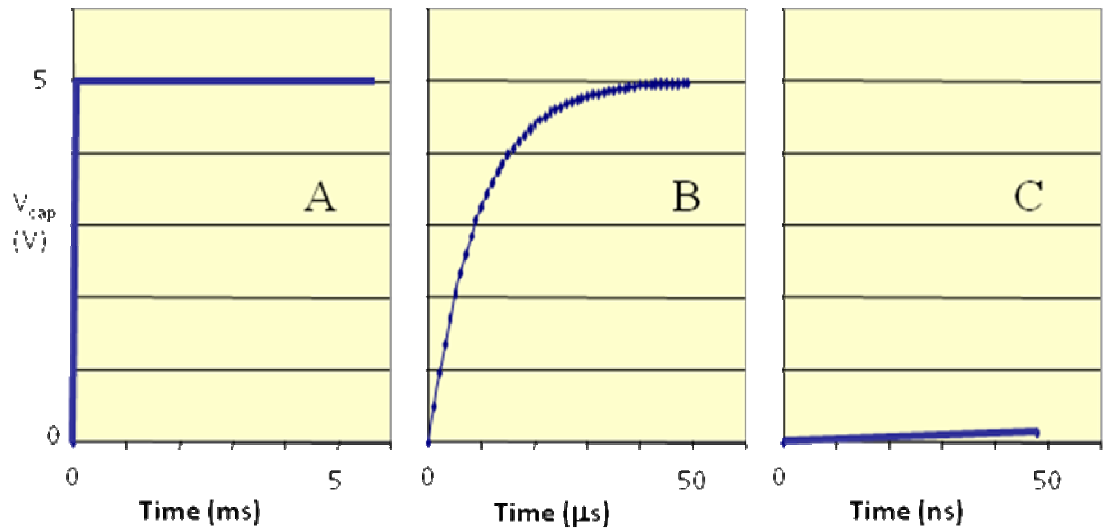

Figure 4. Voltage across capacitor for step input.

The application is for a typical case where one system box drives another. The configuration shows the voltage across the input of second function. The RC time constant for this driver-follower combination is 10 µs. If the application uses signals in the ms range, the coupling is quasi-ideal; the rise time is fast relative to the time interval being used for interrogation. However, on a ns timescale, nothing has yet happened. Only in the range 10 – 500% of the RC value is there any need to analyze the transient effects.

The first step for any systems worker is to know whether they are operating in range A, B or C. It's a simple concept but on one hand it demands a good appreciation of the system time domains and on the other, an understanding of the critical RC components that constrain signal responses. Figure 4 refers to digital signals. Analog signals are more complex and the concept of impedance has to be introduced. Appropriately, figure 4 has an analog counterpart that views condition A as resistive and C as reactive. All the complexity of impedance analysis only has to be called on for frequencies that correspond to the time domain represented by case B. In none of these cases will there be a manual closed-form math solution. It will be done using a network analysis program either by the technician or by a network analysis expert.

Time constants feature directly in many applications. DRAM and the ubiquitous flash memory both use charge storage effects. They need fast charge and discharge times but long storage time. In these cases, the capacitance values are those of single transistors in the fF range. The resistance term is determined by the on and off states of a transistor. This is a good way to introduce the concept that current is limited by an active device (MOS transistor) rather than a passive device (resistor) in ICs.

At the other end of the capacitance value scale, super-capacitors provide values in the farad range and they are now finding many applications for energy storage where the charge transfer rates are too high and too frequent for batteries to be used. A good example is the Kinetic Energy Recovery System (KERS) used in Formula 1 racing cars. It is an exciting and exotic application but the principles are also simple enough to demonstrate in an introductory class that has just learned about RC combinations.

The point of this treatment is to link simple circuit effects to time responses. Whenever an assembly of functions is considered, a few simple questions about response times and their determinants will go a long way to show the principles of operation – or failure. The RC time constant is simple enough to be remembered forever and used in a dialog about system behavior. It is the starting point for further analysis by experts but it also enlightens the non-expert's appreciation of what is happening.

One System Application, Many Concepts. The circuitry inside a chip may be made up from simple transistor pairs or transistor-capacitor combinations but when they are combined in billions, they are much too complex for all but a few specialists. However, one of the great assets of electronics from a teaching viewpoint is that complex functions can be represented as combinations of black boxes and manipulated to give reasonable results. The connection of the output of one IC driving another can be represented by a simple driver-load combination for each signal line as shown in figure 5.

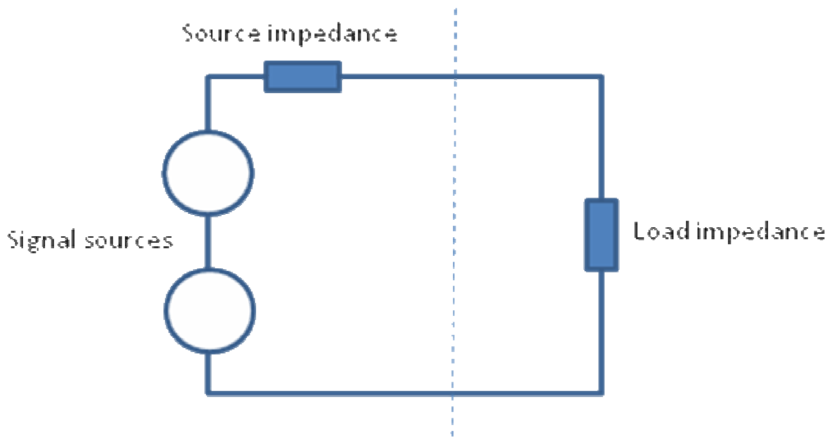

Figure 5. Simple representation of outputs and inputs.

Analysis is now limited to a single loop and all the confusion, tedium and outright aversion induced by mesh analysis can be by-passed in the classroom – as it is in the workplace. If the problem needs more analysis than that represented by figure 5, it is time to call in the experts. As well as teaching students how to configure problems so they can be solved, it is also good to teach them how to recognize problems that they cannot solve. However, they will then have to justify calling in extra resources to the boss and, if approved, subsequently interface with the experts. These are good examples of the application of communications skills at work in the technical domain.

To derive the representation shown in figure 5, it is necessary to examine the system blocks. Figure 6 shows the interconnect side of a home entertainment system.

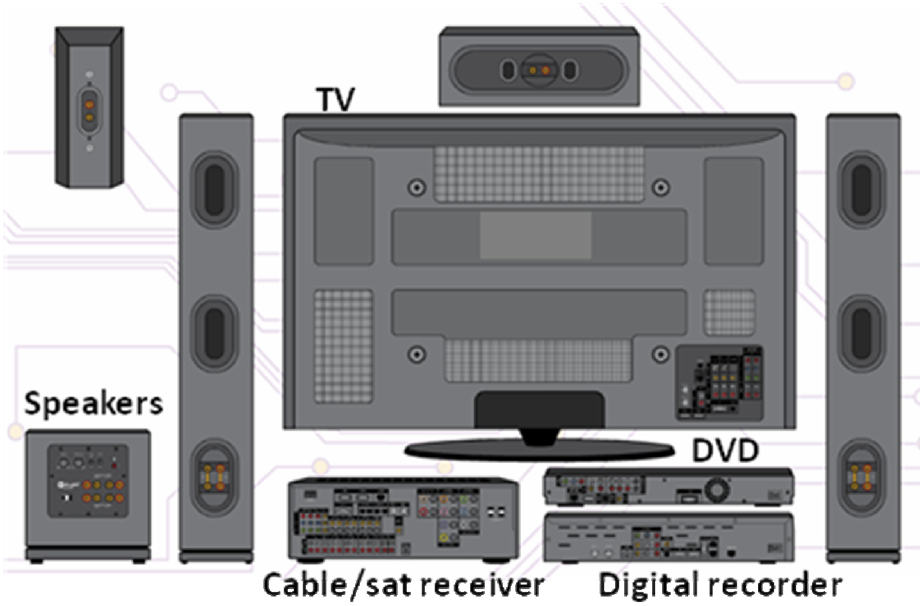

Figure 6. Home entertainment system

The user interaction is limited to prescribed connections of signal and power lines and the system controllers. That still allows many combinations – as anyone who has juggled with four remotes knows all too well. The educational emphasis shifts from the internal operation of the system components to the characteristics of the interfaces and interconnections such as the cables to use, signal levels, bandwidth and (the perennial favorite) good practice for grounding.

Curriculum Change Recommendations. With the above examples in mind, how can the systems view that appears to be the inevitable end point be adopted in technology education? Aside from developing a whole new curriculum which is practically impossible in most institutions, the most likely approach is to implement changes that can be incorporated in one course at a time. Understand the jobs that technicians do. It does not involve extensive circuit analysis or the design of complex electronic functional blocks. Technicians test, measure, install, operate, service, maintain, troubleshoot, repair and calibrate the equipment they use. The curriculum should be built around those final job competencies. Every department or college mission statement almost certainly has words that align with that goal so this suggestion is not revolutionary. However, if existing means do not deliver the required outcomes, other approaches have to be implemented.

Given the objectives, the following guidelines and suggestions can be used to gradually move the curriculum forward one class at a time.

- Critically analyze each course attempting to identify those topics most relevant to the objective stated above. Focus on what can be eliminated, minimized or changed as well as what newer topics should be added. No topic has an automatic right to inclusion; it has to be earned.

- Keep circuit theory and analysis and the related math to a minimum. Teach the fundamentals laws and theories but eliminate the more advanced analysis and design methods that only engineers use. For example in a system approach, mesh and nodal analysis, Laplace transforms and BJT biasing are virtually worthless to a modern technician. However, Ohm's and Kirchhoff's laws, Thevenin's theorem and Fourier theory are crucial. With low-cost PLDs and microcontrollers, there is little need for Boolean minimization, Karnaugh maps and discrete logic.
- Teach more integrated circuits and less discrete component circuits. Focus on specifications and the various I/O ports. Emphasize MOSFETs over BJTs since CMOS is now the undisputed dominant silicon technology.
- Increase the coverage of modern test equipment and test/measurement procedures. Data acquisition is automated and data has to be managed in Gbytes.
- Add more systems examples employing the block diagram/signal flow approach to show how one module or block is interfaced to the next. Teach input/output impedances and interface standards.
- Teach more troubleshooting incorporating key fundamentals and theories as a way to reinforce and apply them.
- Screen and edit textbooks and provide student guidelines as to what is important and what is either unnecessary or marginally relevant. Encourage publishers to adopt a stronger systems approach to content and the desired end result.
- Seek more input from employers as to what is and is not important. Dig deeper to find out what employees really need to know to do the job and what may only be nice to know. Question advisory committee members about real vs. perceived needs.

Most current curricula are simply minimally updated vestiges of programs developed decades ago. Electronics has changed drastically in that period and it is time to make the curricula fit the reality of the jobs and employer needs. After all, it is in the mission statement.

Conclusions. The examples used in this paper show the need for students to be able to:

- Understand how basic electronic concepts are used.
- Map the flow of signals and power across many functions.
- Explain all of the above to non-specialists who will act on the message.

A number of systems have been decomposed to show how very simple concepts such as RC delay times or simple interface models are at the root of the solution. By linking the concepts to realistic applications, students see the importance of what they are learning and also how to make approximations that still give reasonable solutions even in complex systems. The process integrates seamlessly with the operational skills needed for system implementation such as troubleshooting, prioritizing and effective communication.

There are also some less comfortable findings:

- Circuit concepts are widely applied – but not in the format taught in most academic programs.
- Math is widely used to manage data and tools but it is not the math that is taught in most academic programs.
- None of these skills covered in this paper feature strongly in the majority of AAS or BS electronics programs or in the standard textbooks.
- Job titles (engineer, technician, manager, etc.) and hierarchical positions matter for hiring but thereafter career progress is determined by who can do the job best.
- International competitiveness means there is no place for people or organizations that are not continuously updating. Credentials therefore have to be transferrable.
- Communication is not stereotyped; it has to be matched to the receiver and the purpose. It must, however, be clear, accurate and actionable.

Fortunately, some of these features of our systems world are now being addressed in order to rebalance academic technical programs. But it is all too slow.

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Bibliography

1. The full results from the ESYST project can be viewed at: www.esyst.org.