Assessment of Comprehension Retention in a Modern Electrical and Computer Engineering Curriculum

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Background

The breadth of topics emerging under the umbrella of Electrical and Computer Engineering appears to be persistently growing. For example, at the University of Virginia, we now consider advanced materials fabrication techniques and applications, heterogeneous systems, neurological processing, and artificial intelligence all to be related to the field. Complicating this state of affairs further is the requirement for our undergraduates to still attain a level of proficiency in core electrical engineering concepts such as circuit analysis, signal processing, E&M fields, and embedded computing. Furthermore, it is important that the students understand the relationships between these topics and to view them as an entire spectrum, and not as individual courses to be dispensed with at the end of a semester.

To address these concerns, we have undergone a major curriculum update in Electrical and Computer Engineering at the University of Virginia. We have moved all of our undergraduate core material to a studio format of instruction and directed our efforts to breadth-first instruction. Traditional courses in "Circuits," "Electronics," and "Signals and Systems" have evolved into a sequence of three "Fundamentals" courses in which material from each of the three prior segments is taught each semester at increasing levels of depth. "Embedded Computing" is also in a studio format and is taught from the perspective of how it is a component of an overall system. "E&M Fields" is in a studio format and is largely based on experimental techniques learned in "Fundamentals" and "Embedded Computing." Traditional lecture and laboratory courses are still taught in upper-level elective courses, i.e. "Communications" and "Linear Controls."

Such sweeping changes also necessitate a reevaluation of how we assess student learning and concept retention. There are well-known concept inventory tests available, and they have been used in the past with varying degrees of success. However, these tests are "single-topic" in nature and do little to assess how well students visualize concepts from across the breadth of the curriculum.

In the balance of this paper, we present a brief introduction of our breadth-first curriculum and give examples of concept-spanning topics covered at various levels. We will also show several examples of in-class laboratories that span concepts and encourage students to think with a holistic view of the curriculum.

We will discuss the current state of concept inventory testing and our vision of how these inventories need to be updated for a breadth-first curriculum. We then present examples of assessment criteria for concept inventories suitable for testing how well students assimilate concepts in a breadth-first fashion. We envision such inventories as assessing not only mastery of a particular topic, but also how well students understand the interrelated nature of the entire curriculum. We propose techniques such that student scores provide meaningful feedback on both breadth and depth; i.e. a score for each. We also present mechanisms such that instructors
may evaluate the experiential side of the curriculum and how well students can bridge theoretical concepts with measured laboratory results.

**Our curriculum reorganization**

Research indicates that student depth of conceptual understanding is increased when students are exposed to material multiple times with increased depth of presentation at each iteration. In essence, this approach balances cognitive loads on task learning by incrementally teaching concepts. Furthermore, we view this approach as a mechanism for creating successful students that may come from a diverse range of backgrounds and interests; students may excel at one particular subarea of the curriculum and yet develop a basic level of understanding in areas at which they are less comfortable.

Our curriculum reorganization began in 2014 and was phased in for each successive cohort of students over the succeeding two years; the logistics, scheduling, and approach of this reorganization have been described previously. We were able to build upon experiences gained in our earlier course development of "Introduction to Embedded Computing," which provided a valuable model for both pedagogical approaches as well as laboratory and instructor resources that would be required. All of these courses are taught in a studio style in which the laboratory and lecture material are combined into a single cohesive period and in the same physical space, as shown in Figure 1. Each class meeting typically consists of a short lecture in which concepts that are relevant to the experiment are introduced followed by the experimental section of the meeting; all classes have both experimental, and lecture components and each course in the sequence is taught each semester.

Educational research has demonstrated the effectiveness of hands-on project-based learning, and we have incorporated that as an essential element of all of our Fundamentals courses. Our courses also incorporate active learning techniques that have been shown to increase the depth of student conceptual understanding. Furthermore, all three courses include a printed circuit design project that naturally teaches the students the importance of external standards, constraints, developing test plans, and the importance of learning new tools, a goal of ABET accreditation. In the first semester, students design a simple signal generator circuit, in the second a LED-based music visualizer is designed, and in the final semester, an ECG system is the project. Note that the projects in each semester are progressively more complex, both in the physical layout required but also in the underlying design concepts.

"Fundamentals 1", the first course in the sequence necessarily has content that is focused on the core laws of A.C. and D.C. circuit analysis and techniques such as Thevenin equivalents.
However, some depth of coverage is deferred for later courses in the sequence to cover basics of transistors as switches, Fourier series, and simple operational amplifiers.

"Fundamentals 2" begins with more in-depth coverage of operational amplifier applications and how they relate to signals concepts such as filtering and mathematical computations. As concepts such as Laplace, Fourier, and second order response are introduced, they are linked directly to both hardware experiments in class, and simulations that confirm concepts using multiple approaches. We make extensive use of the VirtualBench and Multisim for these activities.¹¹,¹²

"Fundamentals 3" is the final course in the sequence, and has similar topic coverage of our previous course, "Fundamentals 2", but goes into far greater detail, including topics cascaded filters, pole-zero placement, frequency response and stability, canonical system representations, and an introduction to sampling and digital signal processing techniques.

In each of these courses, we are exploiting the breadth-first approach, and asking students to assimilate concepts that tend to focus on a system level approach to solving problems, analyzing circuits and systems, and considering a broad range of implications when synthesizing a new design. This requires the students to learn to link concepts from across the breadth of the curriculum. While the new courses assimilated concepts found in the old courses as building blocks, new material was added to emphasize links between these existing concepts; we seek to mask the boundaries of the subject areas intentionally. We are also proposing a new approach to concept inventory testing to assess the efficacy of concept connectivity.

Concept inventory testing background

Concept inventory testing is a well-known technique for assessing student understanding of a subject area. Typically these tests seek to assess comprehension without requiring students to memorize long strings of calculations. Tests usually consist of a sequence of questions that are posed in the form of multiple-choice assessments and seek to test perception of relationships between variables and processes. Such tests have been developed going as far back as 2000 and cover a wide variety of topic areas. For example, among others Evans et al. discuss separate tests in Electromagnetics, Signals and Systems, Strengths of Materials, Circuits, Thermodynamics, Chemistry, Dynamics, and Statistics.¹³ It should be noted that all of these tests are individual subject matter tests within a discipline. For example, the Signals and Systems Concept Inventory requires no awareness of circuit theory, and the Electronics concept inventory presumes no knowledge of Signals and Systems, even though both topics are taught within the boundaries of Electrical and Computer Engineering.¹⁴,¹⁵

Are concept inventories a meaningful assessment of student comprehension? It is a valid question and one that needs to be addressed. We assert that the most important skill set that we must impart to our students is the ability to take conceptual understanding within a domain,
i.e. electrical engineering, and teach students how to apply logic and reason to solve problems that they have not seen before; i.e. general problem-solving skills. They must be able to construct tests to prove the correctness of their solutions and understand what part of the theory applies to the problem at hand. It has been demonstrated that good problem-solving skills are an indicator of good conceptual understanding within a domain, but that the converse is not may not be as true.\textsuperscript{16} We believe that concept inventory tests must seek to test understanding of how concepts are linked as an improved measure of problem-solving ability.

**Examples of linked-concept laboratories and test questions**

One of the highlights of our program is our *Introduction to Embedded Systems Design* course, a required companion course in our *Fundamentals* series.\textsuperscript{7} We do not treat this as simply a microcontroller programming course, but one in which principles of programming and hardware are combined to solve fundamental electrical engineering problems in signal processing, control, and feedback. We employ the *MSP430 Launchpad* \textsuperscript{TM} from Texas Instruments as the primary platform for this course.\textsuperscript{17} It is a relatively simple device to learn yet one that will likely be encountered in the professional experience of an embedded system designer. Additionally, the capabilities of the part are such that while it is sufficient for the experiments and design exercises of the class, students must consider the constraints imposed on them by the hardware and consider resource management as part of many exercises.

A typical experiment in many microcontroller courses is the generation of pulse width modulated signals (PWM) using timer hardware, and typically this is used to dim LED's or perhaps control the speed of a small motor without much further explanation. However, we can create much deeper links to other parts of our curriculum with exercises in waveform generation such as shown in Figure 3.

![Figure 3 PWM and Filtered Signal](image)
This experiment required an understanding of both the time and frequency domains. One of the timer peripherals in the MSP430 is configured to operate as a PWM source, and the duty cycle of the waveform is modulated in software to generate the waveforms shown in the upper trace of Figure 3. From an embedded perspective, this exercise involves learning to work with peripherals and to manage interrupts and timing. However, we ask them to add a simple passive resistor-capacitor to filter the output, recovering the waveform in the lower trace. We use the FFT abilities of the VirtualBench to explore the harmonic content of both signals and students see that all of the frequencies in the output are indeed contained in the PWM signal source feeding the filter and that the filter alters the amplitudes of the higher frequency components.

To test comprehension of the relationships between the underlying concepts a test question might be posed in the following way:

1) The discrete-valued signal illustrated by the top trace is applied to a low-pass RC circuit, and the continuous-valued signal represented by the bottom trace is observed across the capacitor. Note that the top trace is made up from pulses of different widths. If the capacitance is decreased by a factor of two without any other changes to the circuit what will be the observed result on the bottom trace?
   a) The bottom yellow trace will remain unchanged as the Fourier Series components of the input and output waveforms are not related.
   b) The bottom yellow trace will become “smoother” as it attenuates more of the higher frequency components of the Fourier Series representation of the input waveform.
   c) The bottom yellow trace will become more “jagged” as it does not attenuate many of the higher frequency components of the Fourier Series representation of the input waveform.
   d) None of the other choices is correct.

Another question might be posed from a design perspective.

2) Suppose you are to create a simple filter to recover a triangular waveform from a PWM waveform generated by the timer hardware of your MSP430. Which of the following best describes your constraints?
   a) The PWM frequency must be substantially greater than the fundamental frequency of the underlying triangle waveform being recovered and the break frequency of the filter must be substantially less than the PWM frequency.
   b) The PWM frequency may be the same as the underlying triangle wave frequency as long as the break frequency of the filter is substantially less than the PWM frequency.
   c) The break frequency of the filter is unimportant as long as the frequency of the underlying triangle wave is low enough.
   d) None of the other choices is correct.

From the Fundamentals courses, inventory questions may also probe understanding between time domain, frequency domain, and component selection choices as well as modeling and device operation. By way of example, consider the following from Fundamentals 2:
Figure 4 Simple Op Amp Amplifier

The operating conditions for the circuit are described and then a question is posed such that the students are required to integrate an understanding of the circuit with concepts of systems definitions.

3) Which statement best describes the system shown in Figure 4?
   a) The system is definitely nonlinear and could behave with memory.
   b) The system definitely has memory and could behave linearly.
   c) The system is definitely linear and could behave memorylessly.
   d) The system is definitely memoryless and could behave nonlinearly.

As a further example, the following question is taken from a rectifier-capacitor power supply experiment in *Fundamentals 3* in which students observe the inter-related effects of ripple voltage, filter capacitance, and line A.C. line harmonics. The experiment is shown in Figure 5.¹⁸

Our experimental hardware, designed at the University of Virginia, allows us to develop simple yet safe power supply experiments that use line voltages at the source and a transformer for the voltage step-down. A unique feature is the inclusion of instrumentation for measuring the currents in the transformer center-tap, and hence the diode currents as well. Since these currents are highly non-linear and triangular in shape, they provide an excellent means of observing the effects of the circuit design on the spectral content of line currents and leads to a discussion of power distribution issues related to line harmonics.
A typical test question from this experiment might be formulated as:

4) Given the circuit above, assume that the average voltage at V_Out is 20 volts and the ripple peak to peak voltage is 1 volt. The frequency of the voltage source, V1 is 60HZ. Assume that under these conditions C1 is 270 μF. If the value of C1 is increased by a factor of 100, which of the following is true?
   a) The value of the ripple at V_Out will increase, and the magnitude of the higher order line current harmonics in the transformer will be unaffected.
   b) The value of the ripple at V_Out will decrease, and the magnitude of the higher order line current harmonics in the transformer will be unaffected.
   c) The value of the ripple at V_Out will decrease, and the magnitude of the higher order line current harmonics in the transformer will increase.
   d) The value of the ripple at V_Out will increase, and the magnitude of the higher order line current harmonics in the transformer will decrease.

Note that this question probes student comprehension of the inverse relationship between ripple voltage and also the counter-intuitive concept that increasing the capacitor value increases the high-frequency content of the current waveforms.

By way of example, this question was included as part of a sample test for 4th-year students at the University of Virginia. The students involved had been through all 3 Fundamentals courses as well as Introduction to Embedded Computing; no review sessions or study guides were issued for this test. Students were only told that they would be having concept tests from earlier coursework. However, for most students, it had been a full academic year since they had the last course in the sequence. 77% recognized the effects on ripple correctly, and 43% were able to integrate both concepts and see the relationship to line harmonics.

Another sample of a test question administered to the same group of students related to small signal modeling of bipolar junction transistor amplifiers and the spectral content of the output under different operating conditions. The circuit in this example is shown in Figure 6. It is a basic common emitter amplifier with a bypassed emitter resistor. This circuit is directly from a laboratory experiment in Fundamentals 3 in which students not only measure the gain but look at small signal limits, distortion as a function of signal amplitude and frequency response.
The question given to the students is shown below. Note that it is asking about the integration of electronic concepts, i.e. small signal limits and transconductance, with concepts from signals and systems related to distortion spectra.

5) Given the circuit above, assume that VCC = 10V, VCE = 4V, ICQ=10mA, and β=250. The circuit is operating under conditions in which the reactance of all of the capacitors is negligible. The magnitude of sinusoidal source V2 is 4V peak to peak at 1 KHZ. The output is observed at V_RL. Which of the following best describes the output?
   a) The output is a greatly amplified sinusoidal signal at 1KHZ, and the spectrum of the output will contain primarily the 1 KHZ fundamental.
   b) The output is a greatly amplified sinusoidal signal at 1KHZ, and the spectrum of the output will contain essentially the 1 KHZ fundamental with some minor components at 2KHZ and 4 KHZ.
   c) The output will approximate a square wave, and the spectrum of the output will contain components at 1KHZ, 3KHZ, 5KHZ, etc.
   d) The output will be an unamplified replica of the input, and the spectrum will contain only the original 1 KHZ component.

For this question, 93% of the students recognized the circuit as an amplifier. 47% understood that the output would be distorted, with 70% of those choosing option "b" which would be the correct response if the small signal model were exceeded by a small amount. 30% of the group
that recognized distortion realized that the output was driven to saturation and that the harmonic content would resemble that of a square wave.

Summary and conclusions

As the breadth of sub-areas that are considered to be part of electrical and computer engineering expands, it is necessary for us to explore how curriculum design should be addressed. If we are to prepare students for a career in modern industry, it is imperative that we reconsider the skill-set that an undergraduate needs to succeed. Virtually none of our undergraduates go into single-topic specialties with their undergraduate degrees; they are members of multi-disciplinary design teams and are frequently in leadership-track positions in which they must consider technological problems with concerns for the complex relationships across topics - the boundaries are fuzzier than ever.

At the University of Virginia we are addressing this with a new breadth-first curriculum that places a strong emphasis on experiential learning and integration of topics from across the curriculum. Anecdotally, we have found this process to be successful. We have had extremely positive feedback from job recruiters and other external professionals interacting with our students. Upper-level students that went through our earlier program and had the opportunity to interact with current students universally tell us that they wish that they could have gone through the Fundamentals sequence as opposed to our earlier offerings. Our first cohort of students in this program just completed their Capstone designs, and both our faculty as well as external industrial reviewers commented on the marked improvement in the quality of our projects compared to earlier years.

Now we feel that it is important to move to more quantitative assessments that will provide us with feedback on how students can master the material in a manner that allows them to integrate the curriculum as a whole. We believe that testing in the style outlined in this paper is a significant step in this process.

References


