Development of Concept-Linking Inventories for a Breadth-First Approach in Electrical Engineering Fundamentals Pedagogy

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Abstract

Our Electrical and Computer Engineering (ECE) Department started an effort three years ago to revise core courses in electrical circuits, electronics, and signals & systems. The revision effort sought to combine the three subjects into a tightly integrated three-course sequence. An objective was to include aspects of all three subjects in all three courses so that students would develop an understanding of relationships across the subjects. This revised approach introduced challenges to the assessment of learning outcomes. Traditional concept inventories are well established for individual topics such as electronics and signals and systems, but these single-subject inventories are not intended to assess relationships spanning multiple subjects. We endeavor in this paper to present our view of the interrelation among these core subjects and the resulting additions to concept inventories needed to assess understanding developed to bridge the topics.

Keywords

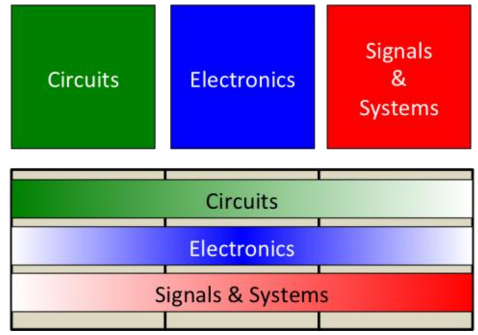
Concept inventory, core electrical engineering, subject integration, circuits, electronics, signals, and systems

Introduction

Concept inventories are well known for assessing student comprehension of fundamental ideas within a particular subject area. The tests may be administered at the beginning and end of a course with the difference between the two scores used to evaluate changes in conceptual understanding. These tests can be used to identify weaknesses in student comprehension and serve as feedback for curricular modification. Concept inventories measure understanding of concepts and also provide a good indication of problem-solving skills. Thus, students who understand concepts tend to be good problem solvers, but good problem-solving skills do not necessarily imply a solid grasp of concepts.[1,2]

Separate concept inventories exist for the individual subjects of electrical circuits, electronics, and signals & systems.[3,4] Each of these concept inventories focuses on one particular subject and therefore will not necessarily test concepts that link these topics. A curriculum that intentionally blurs the separations among these related subjects could be only partially evaluated using instruments that focus on the individual subjects separately.

Our Electrical and Computer Engineering (ECE) Department started an effort three years ago to revise core courses in electrical circuits, electronics, and signals & systems. The revision effort sought to combine the three subjects into a tightly integrated three-course sequence as illustrated in the figure below. An objective was to include aspects of all three subjects in all three courses so that students would develop an understanding of relationships across the subjects. This goal



required that gaps among the three subjects be bridged so that the students would come to view the various topics as parts of a unified whole single subject rather than as disjoint and independent studies.

The unification of circuits and electronics with signals and systems rendered existing concept inventories necessary but insufficient to evaluate our new curriculum. We could continue to draw upon the existing inventories to assess understanding of subject-specific concepts, but the evaluation of subject-spanning concepts would need new inventories. Thus, we have started to define inventories appropriate for subject-spanning concepts. We refer to these new inventories as "concept-linking" inventories.

A Breadth-First EE Core Curriculum

Relatively few of our undergraduates are hired to design discrete circuits such as transistor amplifiers, but these low-level concepts are still valuable to introduce ideas such as operational limits and tradeoffs. Engineering students should learn that large-scale systems are assembled from smaller building blocks, and a good designer must understand concepts spanning from the smaller blocks to the larger systems. Similarly, pedagogical research has shown that students benefit from instruction that progresses across a breadth of material starting from an elementary level of understanding and advancing to deeper levels with repeated exposures.[5,6]

In response, we have developed a new core curriculum for electrical and computer engineers centered on a three-course sequence, the *Fundamentals of Electrical Engineering Series*. These courses replace our prior sequence of core subjects: *Circuits*, *Electronics*, and *Signals and Systems*. Each of the new courses uses a breadth-first approach to the core subjects so that each course covers topics from all of the subject areas with different emphasis and levels of detail.[7]

The first course in the new sequence, *Fundamentals 1*, includes much material from the old circuits course because students must understand basic circuit concepts before they can progress to more advanced topics. However, the breadth-first approach necessitates selective deferment of previously covered circuits material, such as details of transient and phasor analysis, to be covered in future courses. This deferment frees time in the course to include more exposure to diodes, MOS transistors, and ideal operational amplifiers. An introduction to the Fourier series is included to complement the material on sinusoidal steady state analysis.

The second course, *Fundamentals 2*, constitutes the core of the three-course sequence. This course builds upon the circuits and electronics topics presented in Fundamentals 1 to provide greater depth. A more rigorous view of the continuous-time signals and systems material is integrated with detailed electronics and circuits that can be best evaluated in the context of signal theory. One objective of this course is to convince students that the abstract mathematics of signals and systems has concrete applications in the analysis and design of electronic circuits.

The third course, *Fundamentals 3*, further extends and expands concepts first taught in *Fundamentals 1* and *2*. *Fundamentals 3* builds upon basic concepts associated with devices such as MOSFETS, BJTs, and operational amplifiers and employs signals concepts such as the Fourier and Laplace transforms to design more complicated systems. *Fundamentals 3* also expands and emphasizes discrete-time signals and system concepts.

Typical signals and systems courses rarely include practical experimentation because of challenges to integration of the mathematical concepts with physical demonstrations. The integrated nature of the new *Fundamentals* course sequence enables seamless incorporation of continuous-time signals and systems concepts within the analog circuits in *Fundamentals 1, 2,* and *3*. Each semester a design project is included that encompasses all elements of the class. This project includes design, analysis, simulation, and rendering a working printed circuit. Ultimately these designs also require the students to work with external standards and constraints, a goal emphasized by ABET.[8]

Bridging Concept Inventories

A primary objective of the curriculum revision was to relate concepts from the three subject areas: circuits, electronics, and signals and systems. While the new courses were assembled mostly from concepts found in the old courses, new material was added to emphasize relationships among the existing concepts. This new material bridges the boundaries of the subject areas and seeks to develop linkages of understanding. Thus, new concept-linkage inventory elements are needed to assess student understanding of the relationships among concepts from the three subject areas.

This task is more daunting than one might expect from a superficial consideration of the challenge. For example, the questions constructed for inclusion in a concept-linkage inventory must be more carefully considered and reviewed than typical test questions. Inventory questions should evaluate understanding of important concepts and how they are linked across the span of the discipline rather than specific skills or detailed mathematical manipulation. They should be clear, direct, unambiguous, and disconnected from particular presentation styles.

It is with these constraints in mind that we have started the process of developing inventory questions to assess understanding of concepts that bridge elements of the three subject areas covered by our new *Fundamentals* sequence. A few examples are provided here to clarify our intentions and challenges.

The first example bridges the time domain with the frequency domain as it also bridges discrete-valued signals with continuous-valued signals. The oscilloscope image shown in Figure 1 includes Signal 1 as the upper trace shown in red. Signal 1 exhibits pulse width modulation (PWM) with a varying duty cycle. This PWM signal is discrete-valued: it is either high or low.

Signal 2 is the lower trace shown in yellow. This signal is the output voltage measured across the capacitor in an RC circuit with the PWM signal at the circuit input. Signal 2 is continuous-valued: it can take on any value between two extremes.

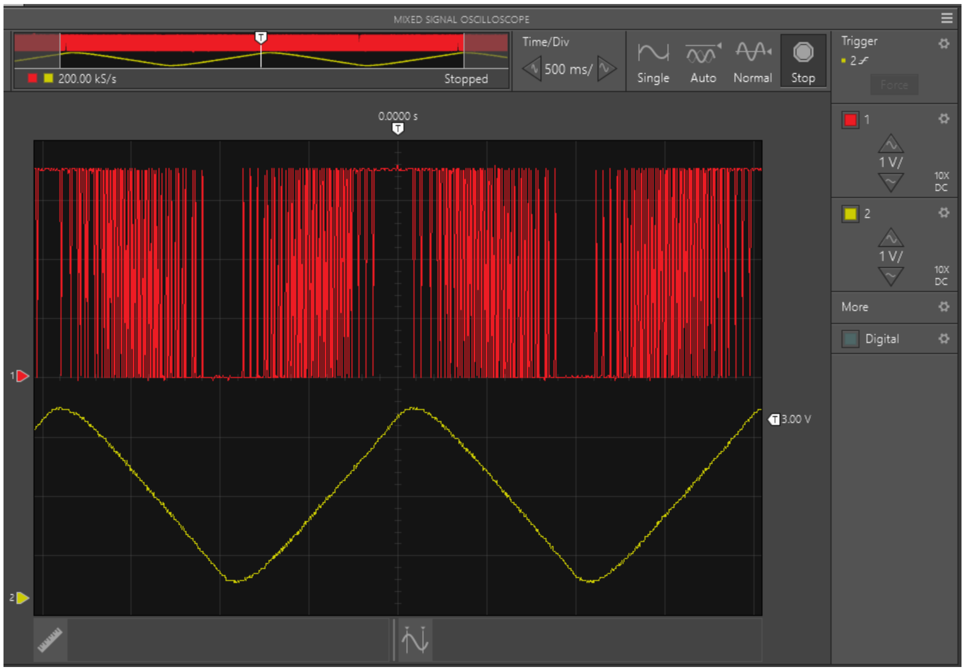


Figure 1

The relationship in this oscilloscope image illustrates that the RC circuit behaves as a time-domain integrator that integrates the discrete-valued pulses of the PWM signal to produce the continuous-valued Signal 2. Alternately, this same relationship illustrates that the same RC circuit behaves as a frequency-domain low-pass filter that rejects the high-frequency components of the discrete-valued PWM pulses while passing the low-frequency components of the discrete-valued PWM pulses. Good inventory questions should probe understanding of the circuit from these two linked points of view. A possible question might probe understanding integration's impact on spectral content:

"The discrete-valued signal illustrated by the top red trace is applied to an RC circuit, and the continuous-valued signal illustrated by the bottom yellow trace is observed across the capacitor. Note that the top red trace is made up from pulses of different widths. If the capacitance is decreased without any other changes to the circuit,

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."

A more specific inventory question relates power supplies to the Fourier series. This question requires the students to understand relationships between the shape of current pulses and harmonic content. The question is structured to determine whether students assimilate the relationship between time domain information, such as the ripple voltage, with frequency domain concepts. Finally, the question assesses the ability of the students to understand fundamental engineering tradeoffs. In this case, we may decrease the output voltage ripple at the expense of increasing line harmonics.

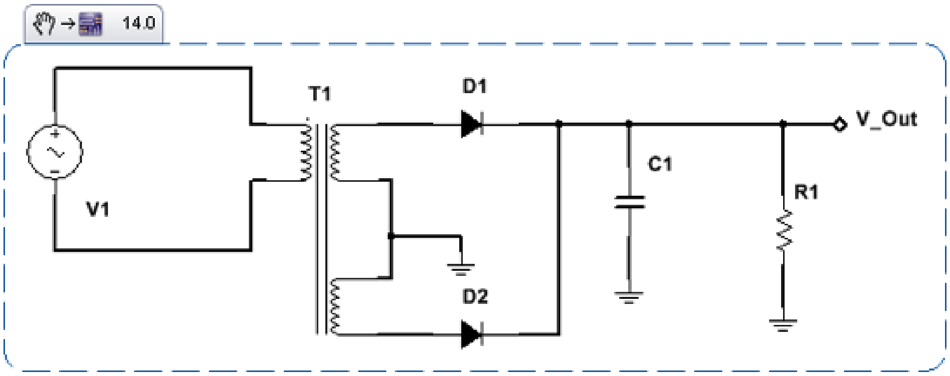


Figure 2

"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 uF. 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."

This example question was included in a concept inventory quiz given to students who had completed the three *Fundamentals* courses in the prior semester. Of those students, 77% recognized that ripple would decrease, but only 43% recognized that ripple decreased and harmonics increased. Questions structured in this way allow instructors to assess comprehension linkage in both time and frequency domains as well provide feedback that will be used to influence our teaching of this material in the *Fundamentals* sequence. This style of question is currently an integral part of our *Fundamentals* courses, especially *Fundamentals 2* and *3*.

This example question shows our preference for inventory questions that do not require significant calculations or extensive evaluation of a problem. Rather, a student who understands the concept being evaluated should be able to determine the best answer through thoughtful consideration of the question parameters and answer options.

Conclusions

As the landscape of skills required in a modern engineering career continues to evolve, the curriculum in an engineering education must also evolve to keep pace. As engineers face increasingly complex and interrelated system level design issues, development of a concept-linking mindset in our students is vital. We expect that concept-linkage inventory development will continue apace with our evolving curriculum. Curriculum development and assessment methods can no longer be considered static in nature; the two are both intertwined and concept-linking in themselves.

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