Feature

On the Use of Concept Inventories for Circuits and Systems Courses

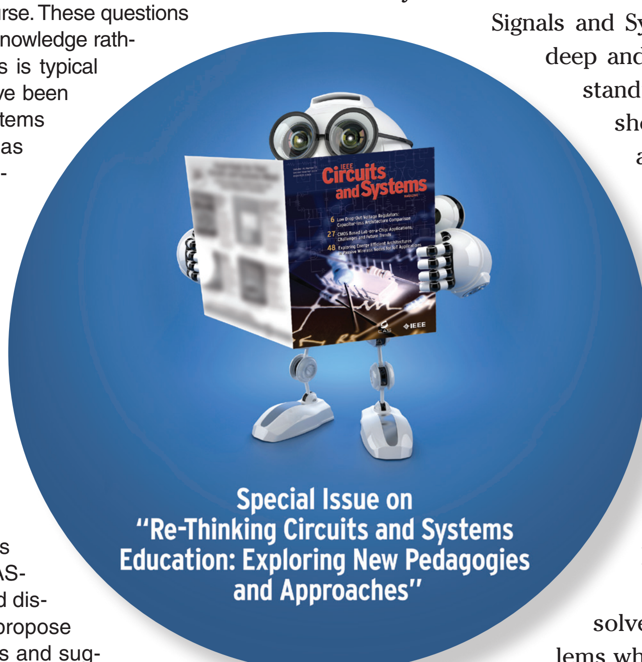
Tokunbo Ogunfunmi, Geoffrey L. Herman, and Mahmudur Rahman

Abstract

Concept inventories (CIs) are standardized assessment tools used to evaluate a student's conceptual understanding of important concepts in a course. These CIs offer the engineering education community a reliable, accepted, and numerical means to assess and compare how well different teaching methods can help increase conceptual understanding.

Typically, the CIs consist of about 25 multiple-choice questions covering core concepts in the course. These questions are designed to test conceptual knowledge rather than problem-solving ability as is typical of examination problems. CIs have been developed for Circuits and Systems (CAS) related courses such as Electric Circuits, Digital Logic Design, Electronic Circuits, Signals and Systems (both Continuous-time and Discrete-time), etc.

In this paper, we provide an overview of these CAS-related concept inventories. These CIs have been developed based on both research and years of experience teaching these basic courses. Many universities have adopted these tests and used them in their course offerings. We report our experiences with the use of some of these CAS-related CIs in our institutions and discuss their effectiveness. We propose possible extensions of these CIs and suggest ideas for other concept inventories in other CAS-related areas. Finally, we suggest ways in which the CAS community can get involved using these concept inventories and hopefully improve their pedagogy in these courses.



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Digital Object Identifier 10.1109/MCAS.2014.2333614
Date of publication: 20 August 2014

I. INTRODUCTION

Electrical engineers have powered rapid innovation and development in diverse fields: from banking to engineering to medicine to internet/information technology and nanotechnologies. As the depth and breadth of topics in electrical engineering continuously expand, students must master the core subjects of circuits and systems such as Electric Circuits, Digital Logic and Signals and Systems. Critically, developing deep and accurate conceptual understanding of core concepts has been shown to accelerate learning and improve performance [1]. While the field and technology continues to advance, teaching and pedagogy has been slower to adapt. To continue fueling innovation and change, our teaching of core electrical engineering topics must adopt new, effective methods so that the next generation of engineers can keep pace.

Students are often able to solve standard examination problems while still possessing deep misconceptions or having only memorized rote procedures [1–3]. This shallow learning renders students unable to solve novel or unfamiliar problems. However, students with deep, accurate conceptual understanding, possess more adaptive knowledge and are able to learn new material faster [1–2].

Concept inventories (CIs) are standardized assessment tools that evaluate a student's conceptual understanding of important concepts in a course [3]. These CIs offer the engineering education community a reliable, accepted, and numerical means to assess and compare how well different teaching methods can help increase conceptual understanding.

We begin by giving an overview of three of these CAS-related CIs. CIs have been developed for Circuits and Systems (CAS) related courses such as Electric Circuits, Digital Logic Design, Electronic Circuits, Signals and Systems (both Continuous-time and Discrete-time), etc. These CIs have been developed based on both research and years of experience teaching these basic courses. Many universities have adopted these tests and used them in their course offerings.

Later in this section, we present definition of a CI and some history of CIs. We then discuss education-related research results on the effectiveness of the Concept Inventory. In Section II, we present detailed discussions of three CAS-related Concept Inventories : Signals and Systems Concept Inventory (SSCI), Electric Circuits Concept Inventory (ECCI) and Digital Logic Concept Inventory (DLCI).

Experience or results of using these Concept Inventories in some universities are presented in Section III. In Section IV, we present some ideas for possible extensions of these Concept Inventories; we propose adding more questions. In Section V, we suggest ideas for new concept inventories in other CAS-related courses like Electronic Devices, Electronic Circuits, VLSI Design and Control Systems. In Section VI, we discuss how the IEEE CAS community worldwide can benefit from using these Concept Inventories to hopefully improve their pedagogy. We also suggest ways in which the CAS community can get involved developing concept inventories and finally, in Section VII, we present Summary and Conclusions.

A. What Is a Concept Inventory?

In the last two decades, the teaching of introductory college physics has undergone a revolution that has been both motivated and guided by the Force Concept Inventory (FCI) [4]. This revolution was catalyzed by the evidence that students who had excelled on conventional examinations failed to correctly answer the simple, conceptual questions on the FCI [3, 5]. This emphasis on conceptual understanding revealed how often students passed courses through "rote memorization of isolated fragments and by carrying out meaningless tasks [3]." This failure exposed fundamental flaws in physics instruction and led to the adoption of "interactive engagement" pedagogies [5]. Due to the impact of the FCI, concept inventory (CI) tests are being developed for a number of science and engineering fields [6–23].

Generally, a CI is a short multiple-choice test, consisting of around 25 questions [11]. Questions are constructed to force students to choose between the correct conception and a set of common misconceptions (distracters) [3]. CIs are intentionally non-comprehensive, testing only the most important or concepts in a course [12]. They are designed with the primary goal of measuring the effectiveness of an instructional method's ability to remedy common misconceptions. They have also been used as diagnostic tests to identify and classify misconceptions and as placement exams for higher level courses.

B. Education-Related Research Results on the Effectiveness of Concept Inventories

Hake's seminal pedagogical comparison study collected FCI data from 62 courses [5]. He demonstrated that interactive engagement teaching methods increase conceptual learning beyond the level attained by traditional lecture teaching methods [5]. Hake measured the effectiveness of the courses by comparing the pre-course averages on the FCI referred to as Si with the post-course averages on the FCI referred to as Sf. These averages were scaled from 0 to a maximum of 100. The average gain for a course is $<\text{Gain}>$ [5].

$$<\text{Gain}> = S_f - S_i. \tag{1}$$

The maximum possible average gain for a course is $<\text{Gain}>\text{max}$.

$$<\text{Gain}>\text{max} = 100 - S_i. \tag{2}$$

The normalized gain g is the ratio of the actual average gain G to the maximum possible average gain $<\text{Gain}>\text{max}$.

$$\langle g \rangle \equiv \frac{\langle \text{Gain} \rangle}{\langle \text{Gain} \rangle_{\text{max}}} \equiv \frac{S_f - S_i}{100 - S_i}.$$

The normalized gain provides an estimate for how much of the course material students learned that they did not understand prior to starting a course. Normalized gain provides a way to compare the teaching effectiveness of different courses independent of the students' prior experience. The relative effectiveness of instructional methods can be categorized into levels of gain as shown in Table 1 [5].

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Table 1.
Ratings for gains in conceptual understanding.

High-g	$\langle g\rangle \geq 0.7$
Medium-g	$0.7 \geq \langle g\rangle \geq 0.3$
Low-g	$\langle g\rangle < 0.3$

Hake found that all 14 traditional courses ($\langle\langle g_{14T}\rangle\rangle$) produced low-g learning gains regardless of instructor qualifications, institution, and the age of the students. In contrast, 85% of the 48 interactive engagement courses ($\langle\langle g_{48IE}\rangle\rangle$) produced medium-g gains. The gains for each course are shown in Figure 1 [5]. Consequently, this study promoted the use of interactive engagement techniques in physics education and helped to establish that CIs can be powerful motivators for the adoption of interactive engagement techniques in the classroom [4].

C. Research on the Effectiveness of Concept Inventories in Engineering

CIs for engineering topics have been developed both by independent researchers/developers and large collaboratives such as the Foundation Coalition [22]. The Foundation Coalition has been developing more than thirteen CIs [12–21], including CIs for circuits, electromagnetics, electronics, signals & systems, and waves. Many of these CIs are hosted by the ciHUB (ciHUB.org) for free and open use by both practitioners and researchers [23]. We present the documented use of three widely adopted CIs to show the range of uses of CIs in engineering education.

Paul Steif's Concept Assessment Tool for Statics (CATS) is perhaps the most widely adopted engineering concept inventory [24]. It has been the subject of core theoretical research about the validity of concept inventories [25], used as a research instrument to test the effectiveness of new pedagogies [26, 27], and used to better classify what concepts students struggle to learn in Statics [28]. The CATS instrument is unique among the CIs. While most CIs offer instructors a single metric concerning students' conceptual understanding, the CATS instrument can provide instructors with seven metrics demonstrating students' understanding of seven core concepts in statics [25]. Therefore, instructors can use subsets of questions from the CATS if they want to specifically target students' understanding of a single concept.

Kathleen Wage and John Buck developed the Signals and Systems Concept Inventory (SSCI) [6]. The SSCI was initially used to compare learning gains in interactive engagement versus traditional lecture offerings of signals and systems courses [29]. These studies replicated the findings of Hake's study, showing that students in interactive engagement course demonstrated medium learning gains whereas students in traditional lecture courses demonstrated low learning gains [29]. Similarly, one of the authors has used the SSCI to demonstrate that a "flipped" version of a signals and systems course was more effective than traditional lecture versions [30]. The SSCI has also been used to gain a deeper understanding of students' misconceptions in signals and systems, demonstrating that terms with technical and colloquial definitions (such as "filter") were harder for students to learn [31].

The development of the Thermal and Transport Concept Inventory (TTCI) created an opportunity for faculty across institutions to negotiate which concepts should be considered "core" for thermal and transport courses [32, 33]. This type of activity is vital to the dissemination and validation of best practices in teaching a topic. Unless faculty agree on what concepts are critical or core, demonstrations of excellent pedagogy are

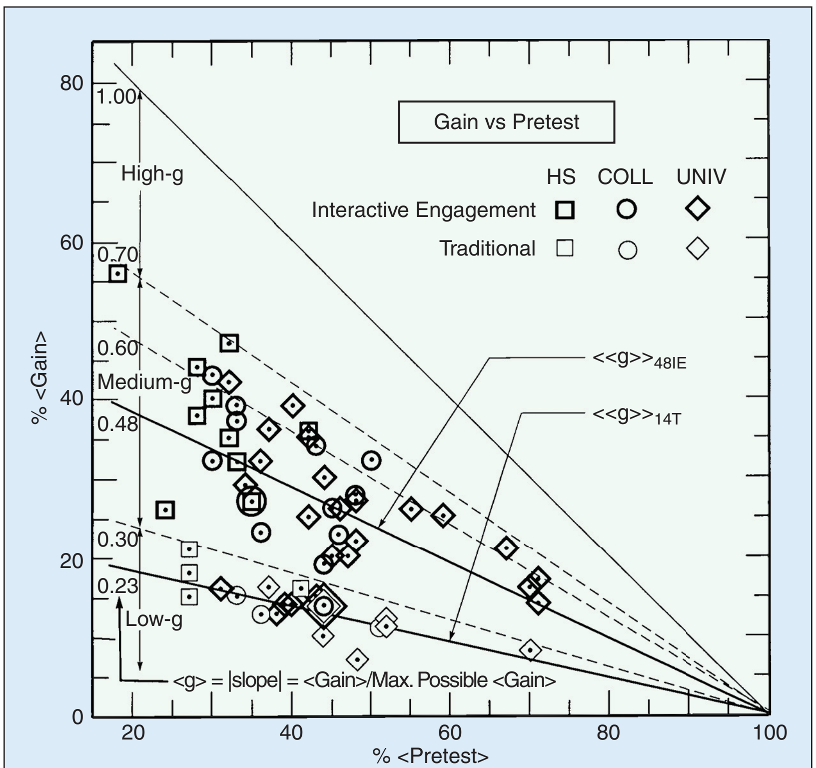


Figure 1. Plot of learning gains by instructional methods reproduced from Hake [5].

less likely to translate across contexts. The TTCI has also been used as a foundational research tool, evaluating and validating theories of conceptual change, particularly Michellene Chi's theory of emergent concepts [33, 34]. Finally, the TTCI has also been used to evaluate the effectiveness of new pedagogies such as an "ontology training" pedagogy [35, 36].

There are other CI's that have been developed and some are still in the process of being developed. A repository of sorts of CI's is the website at www.cihub.org [22–23].

II. Circuits and Systems Related Concept Inventories

Here we provide a brief description of 3 concept inventories: SSCI, ECCI and DLCI which may be useful for the IEEE Circuits and Systems Society community.

A. The Signals and Systems Concept Inventory (SSCI)

The Signals and Systems Concept Inventory (SSCI) [6] is a set of multiple-choice questions that measures students' understanding of fundamental concepts such as signal transformations, linearity, time-invariance, transforms, convolution, etc. There are two versions of the SSCI for Signals and Systems. One deals with Continuous-Time (CT) signals and systems and the other deals with Discrete-Time (DT) signals and systems. CT and DT SSCI each has 25 multiple-choice questions typically closed-book exam taken without calculators. The SSCI has been administered in several universities as a component of student learning assessment that is required by the American Board for Engineering and Technology (ABET) Engineering Accreditation Commission to ensure student learning [69].

The composition of the discrete-time DT SSCI test questions is shown in Figure 2 [6] as an example. The CT SSCI test has a similar composition but for continuous-time systems.

As examples, Question 6 of the CT SSCI test and Question 7 of the DT SSCI test are shown in Figures 3 and 4 respectively. For the DT SSCI, Questions 1–4, 14 are about Math and are not difficult questions. The concepts tested are time/frequency signal plots, time reversal, time shifts and signal transformations. Question 14 tests the recognition of the form of the solution to a linear constant-coefficient difference equation (LCCDE) with sinusoidal forcing functions in a differential equation. Questions 5, 23, and 24 are about Linear Time-invariant (LTI) systems. Recognizing linear and time-invariance properties is important. Also, the analytical tools required such as linear convolution, properties of linear convolution are tested. Determination of the property of a system given its input and output signals tests the students' ability to synthesize these properties by reverse thinking processes. Questions 8, 15, 23 test the concept of linear convolution and its properties when applied to a Linear, time-invariant (LTI) system. Questions 6, 7, 9–11, 13, 15–22, 25 test the transform properties with applications to pole-zero plots, Fourier series, etc. Many of the questions involve relating two or more concepts such as time-domain signals, with filtering, with pole-zero plots. Question 22 tests Bode Plots.

Over the last seven years, we have administered both the CT and DT SSCI tests in undergraduate and graduates courses in Linear Systems (CT test) and Digital Signal Processing (DT test). A detailed discussion of one of the uses of CT SSCI test is presented in [49]. Some preliminary results are also in [50]. Comparing the class rankings in the standard exams and in the SSCI CT Test, we found that there's a correlation between students who do well in the standard exams and those who do well in the conceptual tests. The students whose SSCI score and exam scores are not correlated suggest that they may be good at solving design and mechanistic problems, requiring step-by-step procedure but not good at conceptual understanding. The reverse is also true. This suggests that the instructor should be able to present the material to suit the varying learning styles of the students [51–52].

Also, [6] contains analysis of CT or DT SSCI test results for 900 students from seven institutions from 2001 to 2005.

The SSCI test results enabled us to achieve the following goals:

(1) To determine how much conceptual understanding the students have developed by the end of the class compared to the beginning of the class
(2) To correlate the performance on the end-of-term exam with the performance on the SSCI test which is designed to test the conceptual understanding, but not necessarily the steps of problem solving and system design.
(3) To determine the concepts which the students have had difficulty understanding so that there may be more emphasis on those concepts the next time the course is offered.
(4) To relate the performance of students on their ability to relate pre-requisite course material (e.g. in Electric Circuits) with the new material in the Linear Systems course.
(5) To recommend alternate pedagogical methods for presenting the material in the course based on the results of the SSCI test.

B. The Electric Circuits Concept Inventory (ECCI)

A first course in electric circuits is intended to serve the purpose of educating an engineering student about the fundamental behavior of five basic individual active

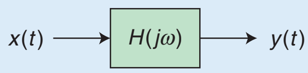
#	Category	Concept(s)
1	Math	Time/frequency: Select the plot of the sinusoid with the highest frquency
2	Math	Time-reversal: Given a plot of $p[n]$, recognize the plot of $p[-n]$
3	Math	Time-shift: Given a plot of $p[n]$, recognize the plot of $p[n-1]$
4	Math	Basic signals: Recognize a plot of $u[n]-u[n-2]$
5	Math	Periodicity of DT sinusoids: Given a plot of $\cos(\omega_0 n)$, recognize plot of $\cos((\omega_0+2\pi)n)$
6	LTI	Time invariance: Given an input/output pair for an LTI system, recognize the output when the input is a shifted version of the original input
7	Sampling	Mechanics: Given a plot of the samples of $x(t)=\sin(2\pi(3)t)$, determine the sampling period T that was used to obtain them
8	Sampling	Nyquist: Given plots of 4 sinusoids, determine which one could be sampled at a rate of 5 Hz without aliasing
9	Trans/Filt	Filtering of a sinusoid: Given an LTI system defined by a plot of its frequency response (magnitude and phase), determine the output when the input is a sinusoid
10	Trans	Time/frequency: Given plots of a windowed sinusoid and its transform, recognize the transform of a higher-frequency windowed sinusoid given its time plot
11	Conv	Convolution: Given plots of the input and the impulse response, recognize the output of an LTI system
12	Trans	Transform properties: Given a plot of $P(e^{j\omega})$, find the plot of $R(e^{j\omega})$ when $r[n]=p[n]*p[n]$
13	Trans	Transform properties: Given a plot of $P(e^{j\omega})$, find the plot of $R(e^{j\omega})$ when $r[n]=2p[n]$
14	Conv	Commutative property of convolution: Recognize that reversing the roles of the input and the impulse response does not change the output of LTI system
15	Trans	Fourier series: Given a plot of a periodic signal, select the equation that best represents it
16	Math	Difference equations: Recognize the form of the solution to an LCCDE with sinusoidal forcing
17	Trans	Transform properties and LTI systems: Given a system with freq. response $H(e^{j\omega})=e^{-j\omega\alpha}$ and a plot of the system output $y[n]$, find the plot of the corresponding input $x[n]$
18	Trans	Poles/zeros: given a set of PZ plots, find those corresponding to stable, causal systems
19	Trans	Poles/zeros: given a set of PZ plots, find those corresponding to real impulse systems
20	Trans	Poles/zeros: given a set of PZ plots, find the one corresponding to decaying exponential impulse response
21	Trans	Poles/zeros: given a set of PZ plots, find the one corresponding to particular frequency response magnitude plot
22	Trans	Fourier transform: Given a plot $x[n]$, determine the DC value of its Fourier transform
23	LTI/Conv	Convolution/LTI properties: Given the impulse responses of two systems, determine the causality of their cascade and parallel connections
24	LTI	Linearity/Time Invariance: Given 3 input/output pairs, infer whether a system could be linear and/or time-invariant
25	Trans/Filt	Filtering of windowed sinusoids: Given plots of a windowed sinusoid, its Fourier transform magnitude, and the frequency response magnitude of a filter, selct the plot corresponding to the output

Figure 2. DT SSCI concept table (from [6]).

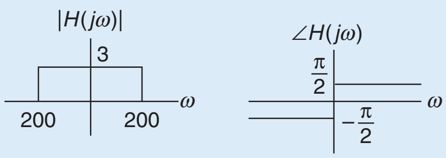
and passive elements as well as the basic concepts and laws that govern their group behavior when connected in a circuit or a system. The learning challenges faced by students of electric circuits are prodigious; each new concept is built on a foundation of many other concepts where the students are encouraged to think through problems based on concepts and not only follow a set of problem solving procedure usually outlined in text books. Every new problem is an interwoven conceptual hurdle.

A literature search revealed that there was some effort to produce Concept Inventory questions for Electric Circuits course in the past. Some of these have also been published [53–54] or made available online [55, 23]. Also, faculty from various universities that have taught Electric Circuit courses over the years at have provided us with sample questions and significant insight that we are planning to tap into in creating more questions for our ECCI database. One of the requirements is for the questions to

Question 6
Consider the LTI system with input $x(t)$ and output $y(t)$ shown in Fig. 3(a). The magnitude response $|H(j\omega)|$ and phase response $\angle H(j\omega)$ (in radians) of the system are shown in Fig. 3(b).



(a) System for Question 6.



(b) Magnitude and Phase Response of the System in Question 6.

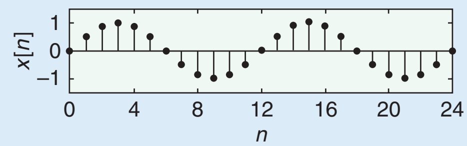
Suppose that the input $x(t) = \cos(50t)$ for all time. What is the output $y(t)$?

(a) $3\cos\left(50t + \frac{\pi}{2}\right)$
(b) $\cos\left(50t + \frac{\pi}{2}\right)$
(c) $3\cos(50t)$
(d) $3\cos(200t)$

Figure 3. Question 6 on the CT SSCI test (from [6]).

Question 7
A continuous-time signal $x(t) = \sin(2\pi(3)t)$ is sampled with sampling period T seconds to produce a discrete-time signal $x[n] = x(nT)$. Which of the following choices of T would give the signal $x[n]$ shown in Fig. 6(a)?

(a) 1/24 (b) 1/6 (c) 1/12 (d) 1/36



(a) Signal $x[n]$ for Question 7.

Figure 4. Question 7 on the DT SSCI test (from [6]).

test certain concepts that are usually overlooked or not very clear in textbooks. Examples included in concept inventories are more carefully prepared to elucidate a certain concept compared to end of the chapter problem sets in text books. We consider that this selection aspect of examples will bring an improvement in the delivery of the concept.

The ECCI has been developed by combining many questions suitable for testing core concepts [63–64], including online, interactive questions [65–68]. The database of questions has not yet been processed through the Delphi method. Currently, we allow instructors who wish to use the questions to pick 25 multiple-choice questions from the database and use them for their classes. Eventually we hope to standardize on the 25 questions that will be included after the Delphi expert process has been completed.

1) Major Topics in DC Electric Circuits Courses
The major topics taught in a first DC circuit course can be summarized into three parts as shown in Table 2. A second course may focus on AC Circuit Analysis and cover other topics such as Sinusoidal Steady-state analysis, AC Power Analysis, Three-Phase Circuits, magnetically Coupled Circuits, Two-port networks, etc.

The Electric Circuits Concept Inventory (ECCI) is a set of multiple-choice questions that we use to measure students' understanding of fundamental concepts such as DC and AC Circuits. First and Second-order circuits, etc., and Advanced Circuit analysis topics are covered. These questions do not test problem solving steps but test major concepts and ability of students to understand the concepts in the context of the problem and apply the required methods to solve the problems.

The ECCI as we envision it is different from the Engineer-in-Training (EIT) or the Professional Engineer's (PE) examinations [69–70] that are needed for professional engineering registration. The ECCI is designed to test conceptual understanding and presents a different pedagogical approach. In addition, the EIT and PE exams include other materials not just on electric circuits.

We plan to collect and collate all similar concepts questions generated by others and ourselves and build

Table 2.
List of topics in DC circuit analysis.

Topic	Sub-Topics
Introduction to DC circuits	Concept of charge, current and voltage, concept of power and energy Introduction to circuit elements, Ohm's law Nodes Branches and loops Kirchhoff's laws, voltage/current division Wye-Delta transformations
DC circuit analysis methods	Nodal and mesh analysis Circuit linearity properties Source transformations Norton's theorem Thevenin's theorem Maximum power transfer
Other DC circuit analysis methods	Operational amplifiers Capacitors and inductors First-order circuits Second-order circuits

Q. Find the voltages V_1 and V_2 as indicated in the figures below

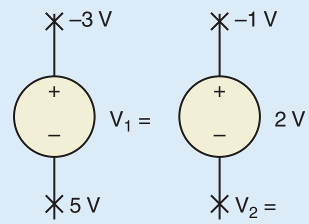


Figure 5. Finding polarity of voltage sources.

Q. Determine whether the circuits are valid or not and why

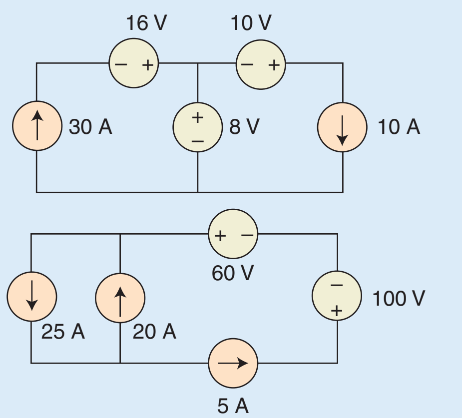


Figure 6. Finding validity of a circuit.

Q. Calculate power delivered and power absorbed by the elements in the circuit

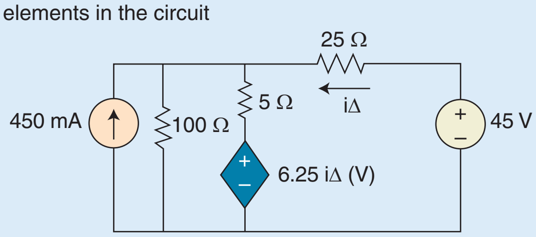


Figure 7. Verifying correct solution of a valid circuit.

up an ECCI test database that can be used in every offering of Circuits course at all universities who wish to participate. We encourage other faculty to adopt the test. This test fulfills the United States Accreditation Board for Engineering and Technology (ABET) requirement for assessment [69–70]. It also helps to track the effectiveness of teaching styles by testing whether the students are learning the basic concepts in the course.

The rationale behind a conceptual inventory has also been discussed in Section I followed in Section II by major topics in a DC circuit course. Now, we use a few examples of the concepts we have found to be sometimes confusing for students to understand and use in solving circuit problems. More details can be found in some of our published papers [63], [64], [71]. These examples test the fundamental conceptual circuit topics. For each example, the concept involved is first identified and explained, followed by a circuit diagram and a question.

2) Fundamental Conceptual Topics

In this subsection examples which deal with fundamental concepts associated with basic circuit elements and their different configurations are presented.

a) Concept: Relationship Between Potential (Volt), Charge (Coulomb), and Energy (Joule).

This example illustrates the relationship Energy (Joule) = Charge (Coulomb) × Potential (Volt) between the three fundamental quantities in a circuit. It clarifies the concepts that the reference potential is 0 V when the charges are at infinity and that the Potential of any point acquires a polarity depending on whether negative or positive Charges are moved from infinity to that point.

Q. Potential difference from point C to F is 1.65 V. It takes 2.56 nJ to move 6×10^9 protons from A to C. How much work needs to be done to move 3×10^8 electrons from F to A?

b) Concept: Polarity of Voltage Sources

In this example the polarity notation scheme in voltage sources is clarified. A terminal denoted by + or − does not necessarily indicate that it is at positive or negative potential, rather the terminal denoted by + is at a higher potential (V_{High}) than that denoted by − which is at a lower potential (V_{Low}). Both terminals can be at positive, negative or a combination of both potential polarities. The voltage of the source shown next to its symbol with either + or − sign indicates the $V_{High} - V_{Low}$ value. The authors observed that this notation scheme is very confusing to a student.

c) Concept: Validity of a Circuit

This example illustrates the concept that a point in a circuit has a unique polarity and a branch can only flow a unique current.

d) Concept: In a Valid Circuit Power Delivered = Power Absorbed

This is a very convenient concept which can be used readily by the students to verify whether their solution of the circuit is indeed correct without the need to look for a correct answer. The use of this verification builds up their confidence in their ability to solve and verify the correctness of solutions of valid circuits all by themselves.

C. The Digital Logic Concept Inventory (DLCI)

Instruction of digital logic and computer organizations varies widely across institutions and instructors [37]. Instructors argue about the effectiveness of top-down versus bottom-up approaches, the current importance of historically important concepts such as Boolean algebra minimization, and the importance of teaching students to use tools such as VHDL versus teaching foundational concepts such as discrete mathematics [37]. Therefore the development of the Digital Logic Concept Inventory (DLCI) like the TTCI began by using an iterative survey method called a Delphi process to catalyze a dialogue among faculty from 22 institutions to identify the most important and difficult concepts in digital logic [37, 38]. This panel of experts identified four primary concepts as critical for students to learn in a first course on digital logic: Number representations, Boolean logic, medium-scale integrated (MSI) circuits, and state and sequential circuits.

After identifying these core concepts, students were interviewed as they solved common digital logic problems to identify common, persistent misconceptions. Based on these interviews, we identified a smaller subset of concepts that proved especially difficult for students [39–42]. In number representations, students commonly incorrectly equate overflow and carry-out bits [39]. In Boolean logic, students struggle with the concept that they need to explicitly complement variables when English specifications indicate that a predicate needs to be false for a specification to be satisfied (See Figure 8 for an example) [40]. In MSI, students commonly conflate multiplexers and decoders to be the same device or incorrectly conceive of them as functional or structural opposites (See Figure 8 for an example CI question) [41]. Additionally, the average student used four, often mutually exclusive, conceptions of state (e.g., defining state as the value of the external inputs and outputs of a circuit and then later defining state as the values stored in the flip-flops) [42].

DLCI items were constructed to test these difficult concepts [43]. After constructing the DLCI, it was refined through beta testing [43]. Students were interviewed while taking the DLCI to ensure that students' choices reflected misconceptions that they possessed. Similarly, the DLCI was presented to the Delphi experts for their feedback and refinement of the instrument to increase the likelihood that the DLCI would be applicable to digital logic courses across institutions. All panelists indicated that the DLCI reflects core conceptual knowledge and 80% indicated that the DLCI alone could estimate how much a student's conceptual framework matches the accepted disciplinary conceptual framework [43]. Finally, the current version of the DLCI was administered at six institutions across the United States with data collected for research purposes. The DLCI was demonstrated to be reliable across institutions with Cronbach $\alpha = 0.75$ with no evidence of bias [44].

Question 7. Alice and Bob have the following requirements for their sandwiches

Alice must have a sandwich with bacon by itself.

Bob must have a sandwich that does not have both lettuce and bacon.

Which set of Boolean expressions correctly specifies all sandwiches that their individual requirements?

Use the following variables that equal 1 when the ingredients are present.

b = bacon; l = lettuce; t = tomato

1) **Alice** = b **Bob** = $l \oplus b$
2) **Alice** = b **Bob** = $\overline{lb}$
3) **Alice** = $b\bar{l}\bar{t}$ **Bob** = $l \oplus b$
4) **Alice** = $b\bar{l}\bar{t}$ **Bob** = $\overline{lb}$

Figure 8. Misconceptions about Boolean logic assessed by the DLCI.

The DLCI has since been used in pedagogical comparison studies as well as foundational research to better understand how students learn digital logic concepts. The first pedagogical comparison study revealed that teaching the exclusive-or (XOR) concept as an odd/even detector circuit rather than in contrast with the inclusive-or (OR) concept led to students developing a more robust conception of XOR that accurately scales to multiple input variables [45]. More recently, the DLCI has been used to demonstrate that both interactive engagement pedagogies and motivation-focused, project-driven pedagogies produce deeper conceptual understanding than traditional lecture and laboratory-based pedagogies [46].

Research with the DLCI has also been used in research to extend our understanding of how students develop their conceptual frameworks in digital logic. Exploratory correlational studies with the DLCI has revealed that the original conceptual grouping of number representations, Boolean logic, MSI, and state may be inadequate or even incorrect [47]. For example, these studies revealed that students who held misconceptions about MSI circuits also misconceived of memory addressing and encoding of state in flip-flops [45]. These correlations revealed that

Question 4. Which statement is true about decoders?

5) Every decoder is the opposite of a multiplexer (i.e., performs the inverse operation of a MUX)
6) Every decoder has one input and many outputs
7) Each output of a decoder implements a different Boolean function
8) All combinational logic in a circuit can be replaced by a single decoder

Figure 9. Misconceptions about medium-scale integrated circuits assessed by the DLCI.

Table 3.
Results of analysis of Question 7 (shown in Figure 8).

Quintile	a	b	c	d	# of Students
1	0%	0%	33%	**67%**	43
2	0%	2%	40%	**58%**	48
3	13%	6%	39%	**42%**	31
4	9%	14%	49%	**28%**	43
5	16%	16%	45%	**24%**	38

students struggle with a more central, hidden concept related to when and how address or encode information. These correlational studies accompanied by a secondary analysis of the Delphi results has revealed that there may be a more appropriate structure for digital logic courses and the DLCI than the original list of four conceptual categories. We have since proposed that digital logic conceptual understanding relies on three core concepts and skills: Information encoding (or addressing), state, and translating across levels of abstraction (e.g., describing the functional behavior of MSI components while also understanding how to construct those components) [47].

To check the validity and nature of misconceptions we correlated students' performance on the whole DLCI with their performance on individual items. Students were grouped into quintiles based on their DLCI total scores. Students in the first quintile had the highest scores, and students in the fifth quintile had the lowest scores. We examined which distractors the different quintiles chose. Table 3 shows that students in the first quintile never chose the "bacon-by-itself" misconception distractors (a and b), but students chose these distractors with increasing frequency as the quintile increased. We see similar behavior (although less pronounced) with the "not both" misconception distractors (a and c) as students chose these distractors with increasing frequency as the quintile increased. Students with a stronger conceptual understanding of digital logic don't struggle with omitting visible negated variables, but still struggle with the translation of "not both" into logic, while weaker students struggle with both concepts. The difference in prevalence of the two misconceptions may indicate which misconceptions are more robust against instruction.

III. Experiences with CAS-Related Concept Inventories

Results from the use of CT and DT SSCI Concept Inventories are available in the literature. Examples are shown in [6, 49, 50]. We have used several variations of the ECCI on many offerings of our Circuits courses. Here we discuss some recent results from a class of 23 students. The ECCI used had 20 questions with multiple parts. Total number of questions is 35. Figure 10 shows the number of Incorrect answers for each of the 35 questions.

Figure 11 shows the overall scores for all the students plotted with number of students.

Figure 10 shows that many students have no problem with Questions 3b, 6a or 16. However, several students find the concepts in Questions 1c, 10a and 10b very hard as depicted by the results in Figure 10. The take-away from this result is that we need to make sure Questions 1c, 10a and 10b are conceptually challenging to students and need to be emphasized or taught differently next time the class is offered. All of the students scored between 16 and 32 out of 35 possible score as shown in Figure 11. The overall class average was 23.35 and the standard deviation was 4.42. This is encouraging and shows students have no problem with many of the concepts.

IV. Possible Extensions of CAS-Related Concept Inventories

We believe there is room for improvement in the Concept Inventories that are being used today. Here, we present some of our ideas to effect that improvement.

A. Possible Extensions to the Signals and Systems Concept Inventory (SSCI)

From our experience, some aspects of signals and systems are not tested by the current CT or DT SSCI tests. However, it has been our experience that these tests are limited in scope and need to be extended to cover other important concepts in Signal and Systems. We plan to introduce new additional questions covering some aspects of the topics we feel are important and extend the current test questions in the Discrete-Time SSCI Test. These new test questions will include topics such as relationship between Laplace and Z transforms, conversion of continuous-time system to discrete-time system by sampling, fast Fourier transforms, properties of discrete-time Fourier transform, relationships between time and frequency as in duality properties, sampling and filtering properties of signals, multi-rate signal processing, finite word-length effects, etc. They will be reported in a future paper.

B. Possible Extensions to the Electric Circuits Concept Inventory (ECCI)

In the following we add examples of a few other important concepts that should help build up confidence in a student's understanding of how circuits operate.

1) Concept: Potential (Current) Cannot Change Instantaneously in a Capacitor (Inductor)

The concept that it takes an infinite amount of current (voltage) to bring about a change in the dc voltage (current) across a capacitor (inductor) instantaneously is

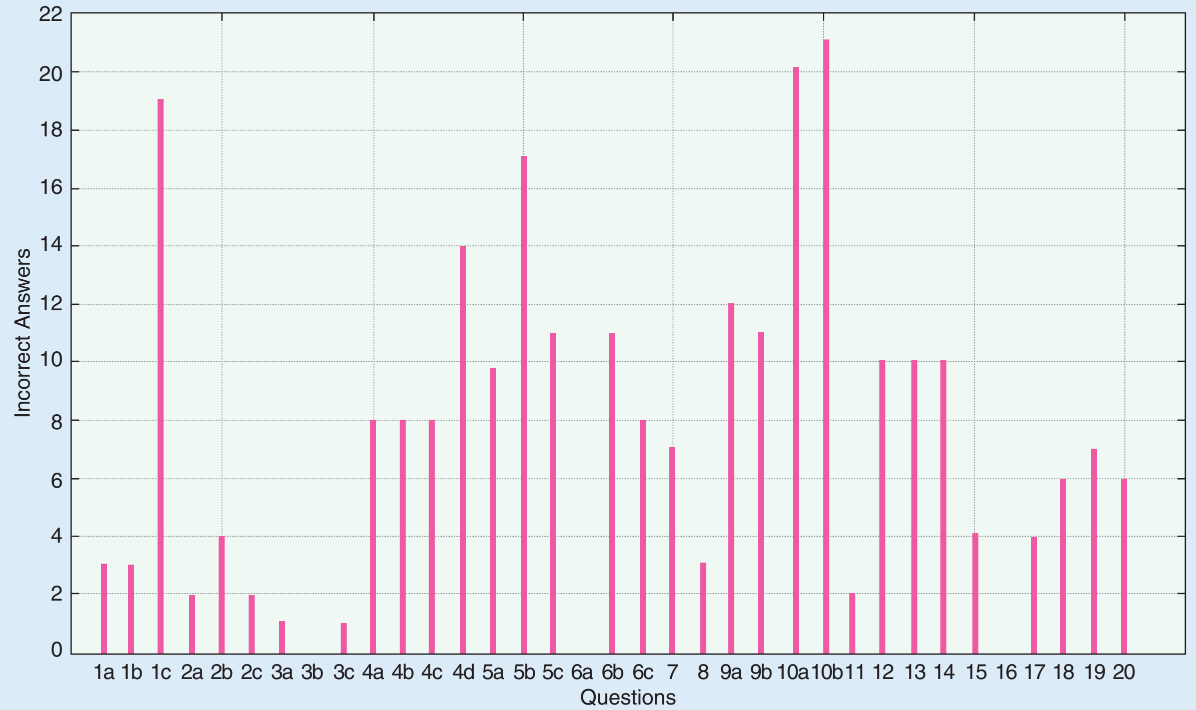


Figure 10. Results (by question) of ECCI test for a recent class.

illustrated in this example shown in Figures 12 and 13. We note that these questions do not assume that the students have mastered the insights that Dirac impulses can be allowed in the signals for currents or voltages.

2) Concept: Current (Voltage) Source in a Mesh (Node) Equation

In mesh (nodal) analysis, voltages across elements in a closed mesh (currents entering and exiting a node) is sought. Students often are confused when they come across current (voltage) sources in a mesh (in a branch) which is clarified in the following examples in Figures 14 and 15. In mesh (node) analysis, the unknown voltage across (current along) a current (voltage) source in the mesh (branch) is indicated by a voltage (current) symbol and the mesh (node) equations are completed as usual in terms of these unknowns. These unknown voltages (currents) do not increase the total number of unknowns and therefore equations required to solve the circuit.

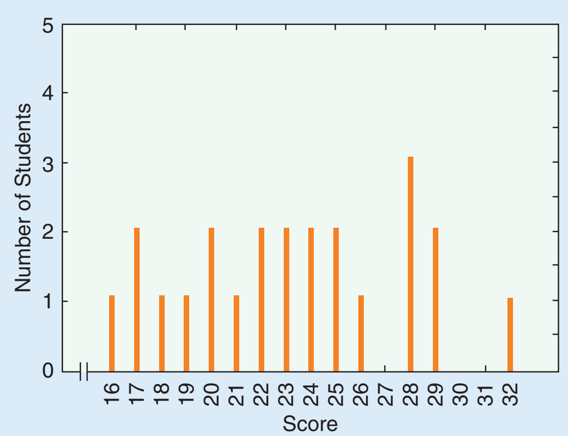


Figure 11. Overall results of ECCI test for a recent class.

C. Possible Extensions to the Digital Logic Concept Inventory (DLCI)

Based on the findings of the DLCI, future work will seek to test the hypothesis of the new, deeper conceptual framework proposed in [47]. First, we will conduct foundational research by exploring the differences between

Q. Sketch and label the current/voltage response for the given current/voltage inputs in the following circuit elements.

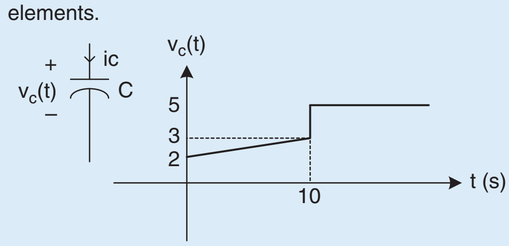


Figure 12. No instantaneous change in voltage across a capacitor.

Q. Sketch and label the current/voltage response for the given current/voltage inputs in the following circuit elements.

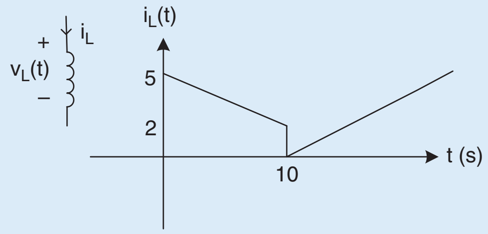


Figure 13. No instantaneous change in current in an Inductor.

Q. Write an appropriate mesh equation to solve for I_o in the circuits below.

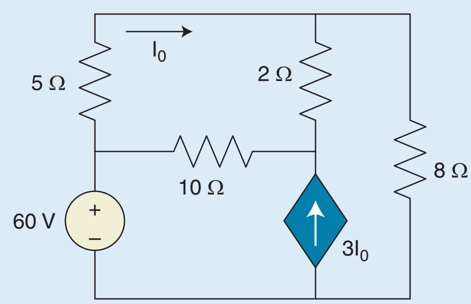


Figure 14. Current source in a mesh equation.

Q. Write an appropriate node equation to solve for current i in the circuit below.

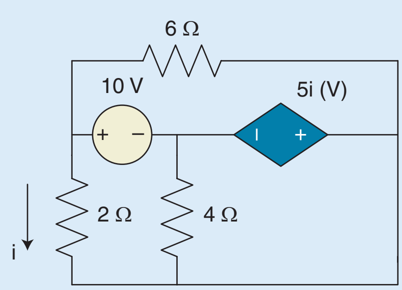


Figure 15. Voltage source in a node equation.

how digital logic experts and novices solve problems and analyzing when and how they use or fail to use the proposed concepts. Second, we plan to restructure the DLCI around the new conceptual framework to test the validity of these new constructs with techniques such as factor analysis.

Third and most importantly, we will explore whether this new framework will increase the adoptability of the DLCI across institutions. Despite the efforts to boost the adoptability of the DLCI through the Delphi process, there are still numerous minor differences across institutions and courses that frustrate the broad dissemination of the DLCI. For example, some misconceptions more readily appear in Mealy-model finite state machines (FSMs), so some items in the DLCI use a Mealy-model FSM. However, many institutions teach only about Moore-model FSMs. Similarly, some institutions teach fractional representations while others do not, so there are currently two versions of the DLCI: one with fractional representations (which more reliably reveal misconceptions about number representations) and one without fractional representations. Narrowing the focus of the DLCI will enable us to still characterize students' core conceptual frameworks while avoiding some of these "implementation" details.

V. Developing New CAS-Related Concept Inventories

Unquestionably, one of the most important developments in this century has been the avalanche advancement of solid state device technology into physical regions never before imagined possible. The attendant consequences for economies around the globe has propelled Science Technology Engineering and Mathematics (STEM) teaching to top levels of concern among politicians and urgent course demand among budding would-be engineers. Unfortunately, even the rudiments of the subject need grounding in what used to be advanced physics: many lose heart at the mysteries of quantum mechanics and the subtleties of new transistor architectures.

Especially, the use of electrical and electronic Integrated Circuits (IC) and systems has become essential in all aspects of a modern society as such all engineering majors require appropriate inclusion of these in their core curriculum. The courses in this area are intended to serve the purpose of educating engineering students about the fundamental behavior of electrical and electronic circuits and systems, and further the basic concepts and laws that govern their group behavior when individual sub-systems are connected in a complex circuit or a system.

From their direct experience in teaching courses in this area to multidisciplinary engineering classes and research over recent years, some coauthors of this article have been able to identify conceptual situations the students find it most difficult to handle. The topics range from basic circuit and systems to novel pedagogical method to enhance conceptual understanding of more complex ICs and systems [71–72].

We have developed and applied a Variational Thermodynamic (VT) methodology to extract closed-form expressions representing various quasi-static characteristics of systems that are currently on the cutting edge. Our approach is based on the notion that IC systems, which are built upon solid state sub-systems, are thermodynamic in nature and not just isolated circuit elements obeying certain circuit laws. Further, our approach strongly supports the proposition that the inversion phenomenon in a Metal-Oxide-Semiconductor (MOS) device is an authentic phase change which conforms to the modern physical theory. Our analysis clearly identifies entropy production occurring within specific regions of the electronic system for specific operating conditions as a consequence of specific design choices. Our results provide visual representation of this entropy production. The accuracy of our approach is not internally constrained: our results must be, and have been, verified by experiment to good accuracy.

We have applied our analysis to the complex real system of a Trench-Insulated-Gate-Bipolar Transistor (TIGBT), shown in Fig. 16, for the purpose of validating our results with those measured, such as terminal capacitances and threshold voltage. Our analysis also reveals characteristics of these systems which are not physically measureable making it possible for a student learner to have a complete grasp, up to design level, of the overall behavior of the system under study. The process can be taught to students who are familiar with elementary calculus and be implemented on MATLAB®.

Based on our VT methodology we have proposed and developed a novel pedagogical analysis method to treat the electrostatic behavior of complex systems incorporating doped silicon regions in tandem where mobile charges are significantly—even dominantly—present [73–74]. Standard instructional methods fall short of making this claim. We plan to identify some key concepts involved in this analysis and formulate questions similar to the circuit questions described in Sections III and IV above.

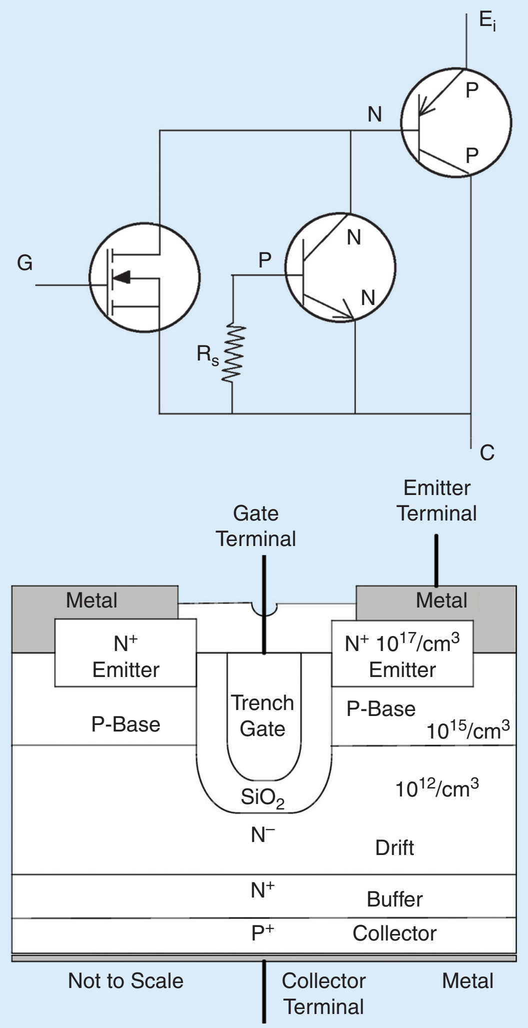


Figure 16. A cross section of the TIGBT structure showing main interacting sub-regions of the system.

VI. How to Get Involved

We invite the CAS community to get involved in the use and/or development of Concept Inventories for CAS-related courses. We describe four potential benefits.

1) A significant barrier to the use of effective teaching practices is that faculty do not systematically collect evidence about the effectiveness of their teaching practices [75]. While many faculty care deeply about helping their students learn, this lack of evidence collection will frustrate their efforts. When they do not collect evidence about the effectiveness of their teaching practices, they cannot know whether they have actually helped. Concept inventories provide a simple and time efficient method for collecting evidence on the effectiveness of teaching practices. The concept inventory examples presented in this paper have been developed over a period of many years. During each year, difficulties, common errors, and misconceptions students experienced for a certain conceptual circuit were investigated and documented. In each subsequent year, a particular concept was presented to the class based on the finding in a previous year by addressing the issues. The authors assessed the improvements in the presentation of the concepts from exam grades obtained by students and found that application of this concept inventory in their pedagogical approach to enhance the quality of the understanding.
2) Faculty often teach independently of all colleagues. They have sole jurisdiction over the courses' content, pedagogy, etc. While this system allows for great academic freedom, it also stifles hard pressing conversations that allow faculty to question their own assumptions and keep them from truly transcending "this is the way I learned it." Engaging in the process of creating a concept inventory is an excellent forum for a community of educators to grapple with what is truly core in their disciplines and how that core

should be taught. While faculty will still maintain their freedom, their teaching will be enriched by the feedback and dialogue with their peers.

3) Additionally, because faculty often teach independently, they are left to discover common student mistakes, misconceptions, and difficulties on their own. Concept inventories provide one way to quickly and easily share about common student pitfalls.
4) The IEEE CAS community can contribute to developing new Concept Inventories for subjects like Control Systems [76], Electronic Circuits, [77–78], VLSI Design [79], Electromagnetics [80], etc.

VII. Summary and Conclusions

Concept inventories represent an enormous, yet underutilized, resource for improving the quality of circuits and systems instruction. With their ability to test students' understanding of core concepts, they provide an essential means for comparing pedagogy across institutions. These comparisons will allow us to optimize instruction scientifically and scholarly. In the midst of new instructional tools (tablets, smart phones, etc.), instructional pedagogical styles (e.g. flipped-classrooms, active learning, problem-based learning, etc.) and platforms (MOOCs), we need to move beyond hunches and anecdotes to justify the cost, time, and energy to adopt these new tools.

Additionally, the future development and enhancement of CIs offers new avenues for collaboration and growing the community of CAS instructors. CIs provide an effective means for disseminating knowledge about common student misconceptions and errors, shortening the learning curve for new instructors. CIs also provide a means for promoting dialogue about what is central or important for students' future success in the evolving needs of the workforce of tomorrow.

There is a need and an opportunity for extension of current CIs and development of new CIs of interest to the IEEE Circuits and Systems community. We encourage others to get involved. You may contact any one of the authors to get involved.

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