Introduction and Motivation

Deep understanding of a topic requires concepts to be well represented and connected. Students who have misconceptions of topics may not have the proper representation of concepts, or connect the concepts properly. If assessments targeted deep understanding, it would help lecturers to understand misconceptions and what should be done to correct them. Students' understanding of concepts can be developed and assessed at varying skill levels in the cognitive domain.

One framework developed to categorize thinking skills in the cognitive domain is Bloom's taxonomy (Bloom, 1956; Anderson & Krathwohl, 2001). Bloom's taxonomy is a hierarchical organisation of educational objectives. The cognitive domain has been used to improve educational pedagogies, and has been applied in the development of educational assessment methods. The original Bloom's Taxonomy (1956) is comprised of six categories: knowledge, comprehension, application, analysis, synthesis, and evaluation. In the revised version (Anderson & Krathwohl, 2001), the categories were renamed to action process verbs to represent active thinking and engagement. The knowledge category was renamed to "remembering" and the "creating" category was added above the evaluation level. The study described in this paper incorporated the taxonomic levels from the cognitive domain of Bloom's Taxonomy (1956) and included the creating category (Anderson & Karthwohl, 2011) as well as the questions from a conceptually-based assessment measure in signals and systems processing.

Concept Inventories (CIs) are designed to assess an individual's conceptual understanding of topics through multiple-choice questions. The possible selections for each question represent one correct selection— for typical CIs, and not multi-tiered response CI questions (Treagust, 1986; 2011). The other selections represent possibilities based on common misconceptions, and are intended to help instructors identify the misconceptions students may have for that particular concept, or question. Concept inventories can also be designed incorporate various types of questions that assess single concepts, multiple concepts, the synthesis of concepts, or require reverse reasoning. The Signals and Systems Concept Inventory (SSCI) (Wage, Buck, Wright, & Welch, 2005) is one example of a CI used to evaluate students' understanding of analogue and digital signal processing concepts. Researchers and practitioners have developed other assessments instruments using the cognitive domain of Bloom's taxonomy in signals and systems (Ursani, Memon, & Chowdhry, 2014), and integrated the taxonomy with other concept inventories (Rhodes & Roedel, 1999).

The purpose of this study was to evaluate the SSCI using Bloom's taxonomy as a framework to classify to concept inventory items in the domain of analogue and digital signal processing. We sought to answer two research questions, 1) Can Bloom's Taxonomy be used to categorize concept inventory questions and interpret students' responses? And 2) What do students' explanations of these concepts reveal about their level of learning based on the cognitive domain of learning in Bloom's taxonomy?

Bloom's Taxonomy applied to Conceptual Understanding

Prior research has shown that properly designed assessments lead to self-regulated learners by providing them, and lecturers, with evidence of learners' knowledge, understanding and skills. Properly designed assessments, that target varying levels of cognitive skills, can be used to identify where students have misconceptions, and where focused learning is needed. Other taxonomies that categorize cognitive skills, such as Structure of Observed Learning Outcomes (SOLO)(Biggs & Collis, 1982), have been used as an alternative to Bloom's. Taxonomies that categorize skills in the cognitive domain are suggested as an integrated strategy in curriculum design and guidance in assessment (Smith, 2011).

The cognitive domain of Bloom's Taxonomy, and the revised taxonomy, is comprised of several levels, discussed in the introduction section. The overall structure of Bloom's Taxonomy is hierarchical, where the lower levels are required to apply the upper levels. For example, in order for a student to use cognitive skills classified as analysis, the student would also need to be able to utilize knowledge, comprehension and application skills. A description of each level and sublevels is included in a later section (Table 2), which was applied to classify the SSCI questions.

Conceptual understanding is important to developing deep understanding (where concepts are well represented and connected) in engineering topics, however students often focus on the acquisition of procedural knowledge (Rittle-Johnson, Siegler, & Alibali, 2001; Streveler et al., 2014). When assessments, or other learning activities, do not specifically require the application of knowledge or skills beyond procedural knowledge development, students may not be able to perform well, or have difficulties performing, at higher cognitive levels.

Methods

We used a case study method (Yin, 2009) because this approach was conducive to answering the explanatory research questions and the context for the collection and analysis of data. We administered the continuous-time (CT) and discrete-time (DT) versions of the SSCI to students in a digital communications unit, where they were required to choose one of the multiple choice selections, and provide a written explanation, providing the reasoning behind their choice, in a text box for each question. We mapped concept inventory questions to the applicable levels of Bloom's taxonomy, and categorized students' written explanations of their answers to the questions based on the type of knowledge used, and the cognitive level applied in their responses. The questions that comprise the SSCI, were grouped according to category and the concept tested by the SSCI developers. Table 1 provides an overview of the types of concepts tested by each SSCI question from the CT and DT versions, to provide context for the assessment instrument and type of question when Bloom's taxonomic levels are applied in the later sections of this paper.

Table 1: Signals and Systems Concept Inventory Conceptual Areas

Category	Question (CT/DT)	Concepts
Math	Q1, Q2, Q3, Q4, Q5 (DT-only)	Time/frequency, time-reversal, time-shift, basic signals, periodicity of sinusoid
Linearity Time Invariance	Q5/Q6	Time invariance
Sampling	Q7 (DT-only), Q8 (DT-only)	Mechanics, Nyquist

Trans/Filtering	Q6/Q9, Q25	Filtering of a sinusoid, Filtering of windowed sinusoids
Transforms	Q7/Q10	Time/frequency
Convolution	Q8/Q11, Q12/14	Convolution, communicative property of convolution
Transforms	Q9/Q12, Q10/Q13	Transform properties

Data Collection and Analysis

We conducted two separate, and one group interview with two signal processing experts, who had additional expertise in teaching signals and systems-related units. The coders used to categorise the concept inventory questions and responses were experts in the subject matter, and one of the coders was also an expert in educational theory and research. The interviews were used for the experts to classify the questions from both CT and DT versions of the SSCI under one of the six levels of the cognitive domain of Bloom's Taxonomy. After several iterations, the experts converged at classification for each question from the continuous-time and discrete-time tests, presented in Table 2.

Table 2. Question Classifications for the Cognitive Domain of Bloom's Taxonomy

Level	**Sublevels**	**Definition** *(Bloom, 1956; Anderson & Krathwol, 2001)*	**SSCI Question Classification**	
			Continuous-time	***Discrete-time***
Knowledge	Specifics, Procedure and methodology, Principles and theories	Student recalls or recognizes information, ideas, and principles in the approximate form in which they were learned.	No questions	No questions
Comprehension	Interpretation, Translation, Estimation	Student translates, comprehends, or interprets information based on prior learning.	Q1, Q2, Q3	Q1
Application	Recall, comprehension, and application	Student selects, transfers, and uses data and principles to complete a problem or task with a minimum of direction.	Q4, Q6, Q13,	Q9, Q7, Q8, Q6
Analysis	Differentiate, compare/contrast, distinguish, relate	Student distinguishes, classifies, and relates the assumptions, hypotheses, evidence, or structure of a statement or question.	Q8, Q5	Q2, Q3, Q4, Q5, Q9
Evaluation	Compare and evaluate	Student appraises, assesses, or critiques on a basis of specific standards and criteria.	Q9, Q10, Q11, Q12, Q25	Q12, Q13, Q14, Q25

Synthesis/ Creating *(revised, 2001)*	Design, Construct, Develop, Formulate	Student originates, integrates, and combines ideas into a product, plan or proposal that is new to him or her.	Q7, Q14,	Q10, Q11, Q25

The student data were collected from the administration of the multiple-choice and text component of the CT and DT SSCI tests to undergraduate electrical engineering students over two different semesters. The text component of the SSCI required students to provide an explanation for their multiple-choice selection. Data obtained from students' written explanations were used to code each response at the cognitive level the students applied to explain their answers. The unit, in which students were tested, had prerequisite units that included material for analogue and digital signal processing, so students were exposed to both the continuous-time and discrete-time concepts tested in the SSCI questions.

Classification Rationale

All of the questions in the SSCI were design to assess conceptual knowledge, however certain questions were designed to evaluate one, or multiple concepts, while at least one question (Q25) was designed to require the synthesis of concepts from multiple questions. No questions were classified at the "Knowledge" level, confirming the fundamental purpose of a concept inventory, which is designed to assess student understanding more than the recall, or recognition, of information cognitive level. Earlier questions in the inventory, designed to be less difficult (Wage et al., 2005), were classified at the lower levels. Questions at the comprehension level required students to have knowledge-level skills as well. For example, Q1 requires students to recall that the period is inversely proportional to the frequency (knowledge) and then compare waveforms with different wavelengths and amplitudes (comprehension). Another question, i.e. Q25, was designed to be a synthesis question, required students to synthesize several concepts as well as evaluate and compare the carefully designed distractors selections provided. For this question, a student must know how filters are represented in the frequency domain. However if students are to think of the questions in terms of convolution, they must synthesize and evaluate the output of the Linear Time-Invariant system. This question requires higher-level cognitive skills in order to comprehend that lower frequencies will pass through a low-pass filter, represented by its frequency response, and apply, and then evaluate that effect in the time domain.

Results

Continuous-time vs. Discrete-time Versions

During the analysis, we utilized technical content experts to separately classify each question set from the continuous-time and discrete-time versions of the concept inventory. For the questions that had a matching counterpart on both versions of the SSCI, we found that the continuous-time version and discrete-time version of the question were not always classified at the same cognitive level. Table 3 compares the differences for each question that had a pair on both versions (questions that appeared in the CT-only, or DT-only are not listed in for this analysis). Classifications that were not the same at the CT and DT levels are identified with an asterisk. Question 8/11 is one example where the discretization of the signal made it more complicated to find the nonlinear signal. Students who have difficulties understanding the concept of frequency, especially for discrete signals, would have more difficulty with the discrete-time version of this question, because they would need to understand the concept of frequency and why an linear time-invariant system should not change the frequency.

Table 3. Taxonomic differences for continuous-time and discrete-time SSCI questions

Question (CT/DT)	Continuous-time Level	Discrete-time Level
Q1	Comprehension	Comprehension
Q2	Comprehension	Analysis*
Q3	Comprehension	Analysis*
Q4	Comprehension	Analysis*
Q5/Q6	Analysis	Application*
Q6/Q9	Application	Application
Q7/Q10	Synthesis/ Creating	Synthesis/ Creating
Q8/Q11	Analysis	Synthesis/ Creating*
Q9/Q12	Evaluation	Evaluation
Q10/Q13	Evaluation	Evaluation
Q12/14	Evaluation	Evaluation
Q25	Evaluation	Evaluation

Type of Knowledge Used

We found that students correctly (and incorrectly) used procedural knowledge in their explanations or reasoning for their selection—or what they believed to be a correct selection—but did not always reinforce the procedural explanation with a conceptual knowledge. The following instances show how three different students responded to one of the questions (Q2), which asked participants to interpret the time-shifting property of the given waveform.

Correct multiple-choice selections:

> Procedural: *"p [0] = 3, so i just evaluated p[2 - 2] which should be 3 which means at n = 2 it should be 3 and so on."*
>
> Conceptual: *"A negative time-shift indicates that the waveform is shifted to the right on the time axis. That is, it is delayed, not advanced."*
>
> Mixed: "*for n = 0, p'[0] = p[0-2] = which is a shift to the right*"

Student Explanations at Differing Levels of the Cognitive Domain

Students' responses varied at the cognitive level for each of the questions. We identified more instances of students responding at a lower cognitive level, than what was expected for a complete understanding of that specific question, as identified by the experts. Table 4 provides examples from students' explanations for several questions, and includes the identified cognitive level for the given SSCI and how the student response was coded.

Table 4. Discrete-time SSCI Question Level and Example Student Responses

Q1: Comprehension
"b has the shortest period, frequency is the inverse there for this answer will have the highest." (Comprehension)
"fourier transforms break the time signal into frequency compontents, i picked the signal with higest amplitude as i am not sure what determines the frequency on the graph" (Knowledge & incorrect)
"The frequency is how fast something takes to complete one wavelength. A) takes 10s. C) takes 10s D) takes 20s B) takes <2.5s" (Analysis)
Q2: Analysis
"Shifted two units to the left without reversal." (Comprehension)
"moving the signal back 2 spaces as it is n – 2" (Comprehension; incorrect selection)
Q3: Analysis
"Reversed, shifted two units to the right." (Comprehension; incorrect selection)
"Signal is transformed this way by the [2-n] property" (Application)
"odd symetric with Q2" (Knowledge)
Q25: Evaluation; Synthesis/ Creating
"The lower frequency signal only is able to get through the pass-band." (Comprehension)
"the magnitude is 1" (Knowledge; incorrect selection)
"LTI system is LPF, therefore the high frequency signal is attenuated leaving the low frequency signal only" (Comprehension)
"It looks like the signal is being passed through a lowpass filter therefore filtering out the higher frequencies at around n = 100-160" (Application; incorrect selection)

Discussion and Recommendations

Understanding and appropriately applying the hierarchy of thinking skills—from lower level to higher level— is important to building a strong and accurate conceptual understanding of a subject, such as signal processing. From students' written explanations, we found that the level of depth for understanding varied across students and questions. We are not able to definitively determine the cognitive level for how students think or completely understand each topic, because their written explanations were limited in how they represented their cognitive thought processes. Lecturers can use the findings from this study as a framework for understanding how their students think about concepts and how students represent conceptual ideas. Lecturers should also reflect on their own practices regarding how they can build and develop students' current thinking, in order to achieve understanding at higher cognitive levels.

Our analysis that applied a Bloom's taxonomy framework was conceived after the SSCI administration to students, and after the creation of the SSCI. We recommend incorporating the various cognitive levels at the question design stage, as well stages where students can be guided in developing their cognitive skills at higher levels. This study aimed to link the cognitive levels of Bloom's taxonomy and an established assessment instrument, such as the continuous and discrete versions of the SSCI. From our approach we were able to begin to identify how students respond to conceptual questions, and what is possible to analyse using a specific assessment instrument and cognitive evaluation framework.

At the current stage of this research, we have not completely refined the process for assessing and guiding students to develop higher level cognitive skills needed to conceptually understand certain engineering topics. Future work in this area will include evaluative approaches to guide students' written responses on a constructed response scale in order to maximize the text, used to be indicative of students' understanding.

Further, lecturers often require students to do analysis, but expect students to synthesize the information. We recommend lecturers incorporate, or require, an explanation to a multiple-choice question that is used to assess varying levels of conceptual understanding. From students' explanations, lecturers can then identify possible misconceptions or impediments to students' understanding of conceptual ideas that build on one another. The process of thinking and learning requires the application of lower-level and higher-level cognitive skills, so it is critical to build on strong foundational knowledge in order to advance to more complex knowledge. Evaluating conceptual understanding at the different cognitive levels will have more implications for improving how concepts are taught and developing more meaningful assessments.

Our conclusions from this study demonstrate that multiple-choice questions alone are not an adequate way of assessing students' conceptual understanding. Even with the inclusion of an explanatory component, it is difficult to effectively determine higher level thought processes based on students' response and the nature of the questions, or assessment. We acknowledge the situated nature of cognition and how this type of task can elicit certain responses, compared to other activities or assessments. Future work on this research topic will include amendments to the task to include questions and more specific, or structured instructions, that elicit responses with varying levels of cognitive processes, so that teachers can gain greater insights into students' cognitive thought processes.

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