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Abstract – **Concept inventories play a growing role in assessing student understanding in engineering curricula. A common application of concept inventories is a pre/post-test assessment in a course. For this reason, it is important to confirm the validity of any new concept inventory, i.e., to verify that the inventory measures what it is designed to assess. The Signals and Systems Concept Inventory (SSCI) is a 25-question multiple-choice exam assessing core concepts in undergraduate signals and systems courses. This paper presents two analyses supporting the validity of the SSCI. The first analysis compares the responses of 40 students to final exam questions with their responses to related SSCI questions. This analysis finds statistically-significant correlations between the SSCI and the final exam for questions on convolution and Fourier transform properties. The second analysis examines the interview responses of 18 students to SSCI questions on frequency-selective filtering and convolution. The interviews suggest students have a strong understanding of high and low frequency, have some understanding of the relationship between time and frequency domains, but struggle to interpret frequency responses. The interviews also suggest that many students retain some conceptual understanding of convolution after their memory of the convolution integral has faded.**

Index Terms – Assessment, concept inventory, interview, signals and systems, validity.

INTRODUCTION

Students who can organize facts and ideas within a conceptual framework learn new information quickly, and are more likely to recognize appropriate applications of these ideas in novel situations [1]. Consequently, many instructors make conceptual understanding one of the desired outcomes in undergraduate courses, even though they are often unsure how to assess this outcome. New accreditation criteria [2] and the increasingly international nature of engineering education is increasing the demand for outcome assessments that are portable across campus and national boundaries.

The Signals and Systems Concept Inventory (SSCI) is a 25-question multiple-choice test designed to evaluate students' understanding of fundamental concepts in signals and systems. Popularized by Hestenes *et al.,* developers of the Force Concept Inventory for physics [3], concept inventories provide an objective instrument for quantifying students' conceptual grasp of particular topics. Development of the SSCI began in late 2000 with support from the National Science Foundation (NSF)-funded Foundation Coalition, and continues with ongoing funding under NSF's Assessment of Student Achievement program. The SSCI has both continuous-time (CT) and discrete-time (DT) versions, representing the two common courses in an undergraduate signals and systems (S&S) sequence. Each SSCI question includes four possible answers: the correct answer plus three distractors that reflect common student misconceptions. Over 1400 students have taken the SSCI, and the resulting data has been used to analyze the effects of active and collaborative learning [4], project-based courses [5,6], graphical vs. textual programming interfaces for signal processing [7] and the impact of prerequisite courses on S&S conceptual understanding [8].

A significant component of this paper is an extension of our analysis presented in [9] of student interviews based on the SSCI. Relatively little other research has been published on S&S conceptual understanding. Nasr *et al.* [10,11] conducted an extensive sequence of interviews probing student misconceptions in S&S. This research was conducted in the context of an aeronautical engineering course, rather than the electrical engineering curriculum, and predominantly focused on electronic circuit implementations of CT linear, time-invariant systems. In spite of the different emphasis between these disciplines, this unrelated research identified similar misconceptions to those found in previous SSCI analyses [8, 12].

The following section describes an analysis correlating students' performance on open-ended S&S exam problems with their performance on related CT-SSCI questions. Subsequent sections describe our protocol for student interviews based on a subset of CT-SSCI questions, and the results of analyzing those interviews. The final section summarizes the evidence from these two related studies

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supporting the content and construct validity of the SSCI.

SSCI VS. TRADITIONAL EXAM QUESTIONS

How does the level of students' conceptual understanding affect their ability to work problems? Do students who perform well on concept inventory questions perform similarly on more traditional measures of student learning, such as open-ended analytical questions? These issues must be addressed in the process of establishing the content validity of the SSCI. As a part of the SSCI validation study, this section compares students' performance on the conceptual questions with their performance on the open-ended analytical problems that made up part of a final exam in an S&S course.

George Mason University (GMU) Study

At GMU, *Signals and Systems I* (ECE 220) is the first S&S course that students take. This course focuses exclusively on CT linear systems, and is often taken concurrently with courses in both circuits and differential equations. ECE 220 follows an introductory course on signal analysis that provides students with basic knowledge about sinusoids, complex exponentials, and simple filtering methods, in addition to teaching them Matlab programming skills. Students take *Signals and Systems I* during the second semester of their sophomore year or first semester of their junior year.

The workload for ECE 220 consists of two class meetings, one recitation session, and one laboratory session per week. In fall 2006 one of the authors (KEW) taught the course using active and collaborative learning methods [4]. Class time was divided between short lecture segments on key concepts and in-class group exercises. Students were expected to do the assigned reading prior to coming to class so that they would be adequately prepared to participate in the interactive problem-solving sessions. Each class meeting began with a quiz on the assigned reading. The textbook for the course was *Linear Systems and Signals* by Lathi [13]. For more information on how ECE 220 was taught, refer to the course webpage (http://ece.gmu.edu/~kwage/ece220/fall06).

Forty-four students took ECE 220 in fall 2006. The CT-SSCI was a required component of the course, but students had a choice of whether to participate in the research study. Of the 44 students enrolled, 40 signed informed consent forms, agreeing to have their exams and other data analyzed. The SSCI was administered as a pretest during the initial laboratory session. Students had up to one hour to complete the pretest. The SSCI was also administered as the first part of the final exam and was worth 25% of this exam. The other 75% of the final exam grade was based on students' answers to five traditional open-ended exam problems. Students were given both parts of the final at the beginning of the exam period. They were required to complete the multiple-choice SSCI questions within the first hour, and then had the remainder of the 2 hour and 45 minute exam period to complete the open-ended problems. While students worked on the SSCI, they were not permitted to use calculators, books, or notes. Once they turned in the SSCI, they could use three 8.5"x11" sheets of notes, but calculators and books were still not permitted.

Results of the GMU Study

In fall 2006 the CT-SSCI posttest average was 67% for the 40 students participating in the study. 33 of these 40 students also took the SSCI pretest, and their pretest average was 39%. The average gain for the course, as defined by Hake [14], is <g>=0.46. By Hake's definition this is a "medium" gain, consistent with the gain achieved in other courses using interactive learning methods.

Figure 1 shows a scatter plot of scores on the SSCI versus scores on the open-ended problems for the 40 students taking ECE 220 in fall 2006. As the figure indicates, the SSCI scores are significantly correlated ($p<0.001$) with scores on the remainder of the final exam. For this population, students who have greater conceptual understanding (as measured by the SSCI) perform better on open-ended analytical questions.

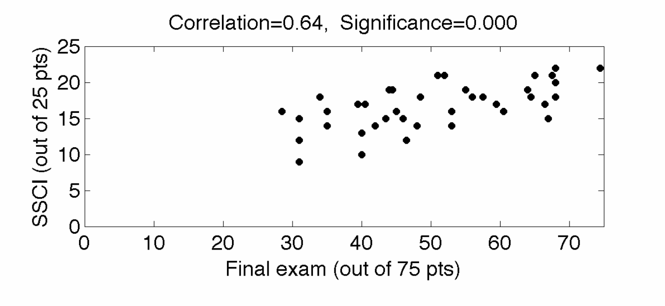

FIGURE 1
COMPARISON OF SCORES ON THE CT-SSCI WITH SCORES ON FINAL EXAM PROBLEMS FOR 40 STUDENTS WHO TOOK ECE 220 IN FALL 2006.

Individual parts of two final exam problems are closely related to two SSCI questions. Problem 1c on convolution and Problem 3b on Bode plots relate to CT-SSCI questions 8 and 22, respectively. Two of the authors (KEW and JKN) reviewed the final exams independently and coded students' responses to 1c and 3b using a 4-level scheme: 3=correct, 2=minor errors, 1=major errors, 0=completely wrong. The independent coding differed for only 6 of 40 students. These six cases were discussed and a consensus on the coding was reached.

Problem 1c (P1c) on the final exam asked students to compute the output of a linear time invariant (LTI) system with an impulse response equal to a square pulse when the input consists of the sum of two non-overlapping rectangular pulses. The correct answer is the convolution of the impulse response and the input, which for this problem results in a triangular pulse followed by a trapezoidal pulse. The related CT-SSCI question (Q8) asks students for the output of an LTI system when the impulse response is a square pulse and the input consists of a single rectangular pulse. The answer to this question is a trapezoidal pulse. Since the starting/ending points of the pulses in P1c and Q8 are not the same, the trapezoidal pulses in the correct answers are not identical. The distractors for Q8 probe whether students multiply instead of convolve, add instead of convolve, or convolve to obtain the right shape, but make a mistake in determining the extent of the output. Table I compares student responses to P1c and SSCI Q8. As the table shows, all students who were able to correctly convolve the signals for the open-ended problem also chose the correct answer to the related SSCI question. The majority of students who made minor errors in the analytical convolution were also able to choose the correct answer for the multiple-choice question. Some students with major errors or completely wrong answers to the analytical convolution were still able to answer Q8 correctly, but others chose the answer with the right shape, but wrong extent. It is notable that the only student who selected the SSCI distractor indicating he would add the input and impulse response to obtain the output of an LTI system was also completely unable to do the analytical convolution problem. Assuming that students who made minor errors had a correct understanding of convolution, whereas those who made major errors did not, it is possible to reduce Table I to the 2x2 contingency table shown in Table II. Applying Fisher's exact test [15] to this table indicates a statistically significant ($p<0.004$) positive correlation between students' performance on P1c and CT-SSCI Q8.

TABLE I
PROBLEM 1C VERSUS CT-SSCI QUESTION 8

		Problem 1c			
		correct	minor errors	major errors	wrong
SSCI Q8	correct	19	5	5	2
	wrong (shape ok)	0	2	5	1
	wrong (add sigs)	0	0	0	1
	wrong (multiply sigs)	0	0	0	0

TABLE II
CONTIGENCY TABLE FOR PROBLEM 1C VERSUS CT-SSCI QUESTION 8

		Problem 1c	
		correct	incorrect
SSCI Q8	correct	24	7
	incorrect	2	7

Problem 3b (P3b) on the ECE 220 final exam gave students a system function and asked them to sketch the frequency response magnitude of the system using a standard Bode plot. The system had two poles and one zero, and a DC offset. Sketching the Bode plot should be straightforward for students, assuming they understand how poles and zeros affect the magnitude response of a system. P3b is closely related to SSCI Q22, which gives students the Bode magnitude plot for a system with frequency response $H(j\omega)$ and asks them to identify the magnitude plot for a new system obtained by cascading $H(j\omega)$ with another system which has a pole located at 100. Q22 assesses whether students understand what adding a pole does to the magnitude response plot. The distractors for this question probe whether students confuse poles and zeros, cannot distinguish between a pole at 10 and a pole at 100, and whether they think a pole causes an additional DC offset. Table III summarizes the comparison between students' responses to the open-ended Bode plot question and the SSCI Bode plot question. The majority of students who prepared the correct plot for their answer to P3b also chose the correct answer for CT-SSCI Q22. Many students with minor and major errors in their answers to P3b were also able to select the correct answer to Q22. Overall, the correlation between the SSCI question and the analytical problem is not as clear as it was for the convolution question. Analysis via Fisher's exact test does not reveal a statistically significant correlation between P3b and Q22.

TABLE III
PROBLEM 3B VERSUS CT-SSCI QUESTION 22

		Problem 3b			
		correct	minor errors	major errors	wrong
SSCI Q22	correct	10	11	6	0
	wrong (pole at 10)	1	2	0	4
	wrong (zero at 100)	2	0	1	0
	wrong (-40dB offset)	1	1	1	0

Another problem on the ECE 220 final exam is closely related to a set of SSCI questions. Final Exam Problem 4 (P4), focuses on the Fourier transform and Fourier transform properties. Rather than relating to a single SSCI question, this problem relates to six SSCI questions that probe students' understanding of various aspects of the Fourier transform. These six questions (9-11, 15, 16, 21) make up a Fourier transform subtest of the CT-SSCI [8]. The first part of P4 tested students' ability to execute the mechanics of a routine inverse Fourier transform with a familiar transform pair (rectangle to sinc function). The second part of P4 required students to synthesize several Fourier transform properties to obtain the correct answer. Figure 2 shows scatter plots of students' scores on the CT-SSCI Fourier subtest with their scores on P4a and P4b. The maximum possible score on P4a was 7 points, while that on P4b was 8 points. As the plots indicate, the Fourier subtest score is statistically significantly correlated with the responses to P4b, but not with P4a. This is consistent with P4a testing the students' ability to execute a procedure amenable to rote memorization, and thus not necessarily related to conceptual understanding. P4b, on the other hand, requires conceptual insight in order to deconstruct a complex problem into its constituent subproblems, and thus it is reasonable that performance on this problem correlates significantly with the conceptual subtest on Fourier transform properties.

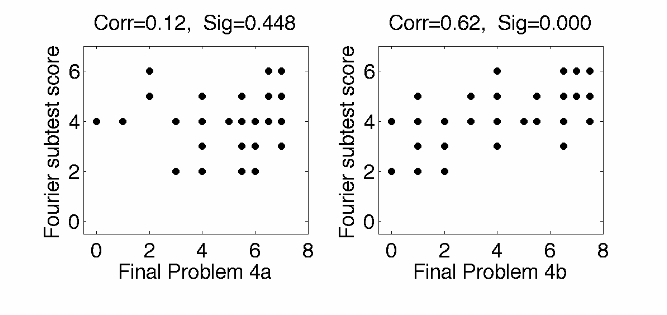

FIGURE 2
COMPARISON OF SCORES ON THE SSCI FOURIER SUBTEST WITH SCORES ON FINAL EXAM PROBLEM 4. THESE SCATTER PLOTS CONTAIN THE RESULTS FOR 40 STUDENTS (SOME POINTS OVERLAP). THE FOURIER SUBTEST CONSISTED OF 6 QUESTIONS (MAX SCORE=6), AND THE TOTAL POINTS POSSIBLE FOR PROBLEMS 4A AND 4B WERE 7 AND 8 POINTS, RESPECTIVELY.

The analysis of the ECE 220 final exam data with the linked CT-SSCI data provides evidence supporting the content validity of the convolution and Fourier transform problems of the CT-SSCI. There is a statistically-significant correlation linking the performance on these concept inventory questions to traditional open-ended exam problems assessing the same topics. At the same time, this data suggests we may need to revisit CT-SSCI Q22 if performance on this problem remains uncorrelated with related exam problems. Our investigation of these correlations is ongoing, and we plan to analyze additional data from the Spring 2007 offering of ECE 220 at GMU.

INTERVIEW DESIGN

Students' choices on multiple-choice concept inventories provide some information about their understanding, and suggest possible confusions when they choose distractors. Interviewing the students provides a more complete picture of their thought processes, and may reveal lurking confusions even when they choose the correct answer. These interviews are an important component of verifying both the content and construct validity of a concept inventory instrument. Students' responses provide insight about whether the questions are clear and whether they assess the intended concepts.

Interview Protocol

The interviews focused on six conceptual questions about S&S, including five questions taken from the CT-SSCI. The remaining question was written specifically for the interviews. The interviews were semi-structured, in that the students were asked multiple-choice questions, but the interviewer could probe students further based on their answers. Students were provided with a paper copy of the questions, and then asked to explain their reasoning aloud as they arrived at their answer to each question. The interview sessions were recorded with a digital voice recorder. After completing the conceptual questions, students were asked some general questions about S&S and the SSCI instrument, including the following:

- Do you feel you have a good grasp of the material covered in your signals and systems class?
- Did this exam cover the material in the course. Were there topics on the exam that were not included in your course? Or vice versa?
- Did you have enough time to complete the exam?
- Were the questions hard to read or easy to read?

At the conclusion of the interview, students had the opportunity to ask questions about the exam or the research study.

Conceptual Questions

Five of the six interview questions focused on concepts related to frequency-selective filtering, which is one of the most important topics covered in S&S courses. To master filtering, students must also understand sinusoidal signals, frequency responses, and the relationship between the time and frequency domains. The sixth interview question focused on convolution, which is another fundamental topic covered in S&S courses. The list below summarizes the conceptual questions used for the interview. Reference [8] provides a complete description of the SSCI questions and discusses the development process for the SSCI.

- **CT-SSCI Question 1 (Q1)**: This question probes whether students understand the meaning of frequency. The students must choose which of four graphs of sinusoids has the highest frequency.
- **CT-SSCI Question 6 (Q6)**: This question involves filtering a single frequency cosine with a lowpass filter. The students must use graphs of the magnitude and phase responses of the filter to determine the output signal.
- **CT-SSCI Question 7 (Q7)**: This question investigates students' understanding of time-frequency relationships. The students are shown a windowed sinusoid and its associated Fourier transform. They are then shown a sinusoid at a higher frequency and asked to chose the correct plot for the Fourier transform of the second signal.
- **CT-SSCI Question 8 (Q8)**: This question was described in the second section of the paper.
- **CT-SSCI Question 25 (Q25)**: This question requires students to synthesize the concepts probed in Questions 1, 6 and 25. They are given an input signal with two sequential windowed sinusoidal pulses at different frequencies, and the Fourier transform of the input signal. The students are also given the frequency response of a lowpass filter, and must choose which time signal represents the output of the filter for the input given.
- **Additional Question (Qadd)**: In addition to the CT-SSCI questions listed above, the interviews included a new question. This question probes students' understanding of the relationship between time and frequency domains in a manner similar to CT-SSCI Question 7, but instead of using windowed sinusoids, it uses two random signals. These signals are obtained by filtering white noise with two lowpass filters with different bandwidths. For most students, this is a novel application of the concept and intuition developed in Question 7. See [9] for the exact text of this question.

Interview Pool

We interviewed 18 S&S students from UMass Dartmouth as a part of this study. The first group of interviews took place in Feb. 2006 and the second group in Feb. 2007. All of the interviews were conducted by an instructor (KEW) from George Mason University. At the time of the interviews, the students had completed the CT S&S course and were enrolled in the DT S&S course taught by one of the authors (JRB). Each student received $20 compensation for participating in the interviews, and signed an informed consent form to authorize the anonymous use of their responses, as well as the collection of academic and demographic data. Three of the interview participants were female, one was an under-represented minority, and one is registered as a disabled student with dyslexia. The interview subjects represented a wide range of grades in CT S&S (D- to A+), overall GPA (1.9 to 3.9), and CT-SSCI posttest scores (44% to 84%).

INTERVIEW ANALYSES AND RESULTS

Three of the authors (JRB, KEW, MAH) coded the transcripts independently and then discussed discrepancies until consensus could be reached on a code for each response in each category. Four categories were used to code the transcripts as follows. The first category was whether the students' final answer was correct or not. Table IV shows the number of students in each group who answered each question correctly. Note that the convolution question (Q8) was only asked in the second group of interviews. Though the sample sizes are small, the distribution and character of the responses across groups 1 and 2 is similar so the remainder of the discussion describes the interview sample as a whole.

TABLE IV
NUMBER OF STUDENTS ANSWERING THE QUESTION CORRECTLY

	Group 1 Correct	Group 2 Correct	Total Correct
Q1	9	9	18
Q6	8	5	13
Q7	8	8	16
Q8	n/a	9	9
Q25	8	6	14
Qadd	6	5	11

The second category of coding, "reasoning", indicated the quality of the students' reasoning in answering each question. Students were classified in one of four categories: right, partial, muddled, and wrong. "Partial" reasoning indicated the students' solution process was moving in the right direction but there may have been minor errors. "Muddled" indicated that students had difficulty explaining their reasoning and justifying their response. Table V summarizes the reasoning scores for the entire sample. Note that the results for Q8 include only answers from the second group of interviews.

The third category of coding, "process", indicated the process students had used to generate their solution. The coding specified whether students used a logical chain of reasoning or process leading to the answer, the process of elimination, or guessing. The category "blend" indicates that students blended these types of processes to arrive at their answer. Table VI summarizes the reasoning for questions 6, 7, 8, 25, and the additional question. Question 1 is not included in these results because it could be solved by inspection (i.e., just looking at the graphs).

The final category was students' confidence in their answer. For the first group of interviews, the coders assigned the confidence level based on how the student stated their answer. For the second group, the students were explicitly asked to identify whether they were "very confident", "somewhat confident", "not confident" or "guessing" about their answer. The analysis shows that students were overall either somewhat confident or very confident about their responses to a majority of questions. For group 1, responses were coded as either very confident or somewhat confident for 36 out of 45 responses. For group 2, students reported they were somewhat or very confident on 42 of the responses.

Part of our goal with the interviews was to establish the validity of the SSCI questions as capturing students' conceptual understanding or the lack thereof. The interviews have helped confirm that students do have conceptual understanding in some areas and lack the ability to articulate their reasoning in other areas. In addition, for the questions they were most likely to answer correctly (e.g., Q1 regarding the frequency), they were also most likely to provide clear explanations. As the conceptual complexity increases (e.g., Q25 which requires synthesis of a few ideas), the students' have greater difficulty obtaining the right answer and provide less clear explanations.

TABLE V
NUMBER OF STUDENTS WITH EACH TYPE OF REASONING

	Right	Partial	Muddled	Wrong
Q1	18	0	0	0
Q6	8	8	2	0
Q7	13	2	2	1
Q8	4	4	1	0
Q25	12	3	2	1
Qadd	10	2	5	1

TABLE VI
NUMBER OF STUDENTS USING EACH TYPE OF SOLUTION PROCESS

	Process	Elimination	Blend	Guess
Q6	11	3	4	0
Q7	8	4	6	0
Q8	0	0	8	1
Q25	15	2	0	1
Qadd	8	3	4	3

Analysis of responses to the convolution question (Q8) for the second group revealed that while all nine students selected the correct answer, only four students could acurately state the convolution integral that would be used to derive that answer. This suggests that some conceptual understanding may persist longer than memorized formulas, however additional data is needed to verify this hypothesis.

The interviews have also raised several new questions that should be investigated further. The first of these concerns the interrelationship between some S&S concepts and other areas. For example, how much of students' ability to analyze information about a signal from graphs showing different representations of that signal (as in Q25) is determined by their understanding of basic mathematical constructs and how much is determined by their understanding of S&S? The interview analysis also raised questions regarding the students' use of technical and non-technical language when explaining their thought processes. Namely, are students using vocabulary expected of experts in S&S or are they using more familiar language (e.g., "wiggles" for oscillation, "bumps" when describing frequency responses)? Finally, since the SSCI has been explicitly designed so that students do not need to use formulas or equations to answer the questions, the interviews have also begun to reveal some of the rote procedures that students develop to solve S&S problems. Another important question is when do students simply apply rote procedures and when are they able to justify their answers conceptually? Further investigation is needed to answer all of these questions. The study is ongoing, with additional interviews taking place at GMU in spring 2007.

CONCLUSION

Establishing validity is an important priority for any concept inventory. This paper presents evidence supporting both the content and construct validity of the SSCI compiled from a two-pronged research effort including SSCI data, student interviews, and traditional final exam problems. Interviews reveal that students' understanding of time-frequency relations are well linked to SSCI performance on related questions, and that their conceptual understanding of convolution persists after most have forgotten the formal convolution integral.

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