

Progress on Concept Inventory Assessment Tools

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PROGRESS ON CONCEPT INVENTORY ASSESSMENT TOOLS

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Abstract $\frac{3}{4}$ *The Foundation Coalition and others have been working on the development of Concept Inventory (CI) assessment instruments patterned after the well-known Force Concept Inventory (FCI) instrument of Halloun and Hestenes. Such assessment inventories can play an important part in relating teaching techniques to student learning. Work first got started two years ago on CIs for the subjects of thermodynamics; solid mechanics; signals and processing; and electromagnetics. Last year work got underway on CIs for circuits; fluid mechanics; engineering materials; transport processes; and statistics. This year work began on chemistry; computer engineering; dynamics; electronics; and heat transfer. This panel session will discuss the progress on these concept inventories. More, importantly, the panelists will discuss the early student data that are emerging from the process of continuous improvement of the instruments. Results will be compared to the data collected by Hake that are segregated by how the content was managed and delivered (e.g., “traditional” lecture mode compared to the “interactive engagement” mode, as defined by Hake). Discussions of effective practices for use in the development of CIs will also be discussed.*

Index Terms $\frac{3}{4}$ *assessment, continuous improvement, concepts, misconceptions, engineering sciences, evaluation*

INTRODUCTION

The body of research knowledge on student learning has become quite rich in the last 15 years, but, because of its newness, this knowledge generally remains unfamiliar to most instructors whether their academic home is in science departments or in engineering departments. As a result, this rich research literature on student **learning** has yet to have widespread influence on either the presentations in textbooks or the emphasis and pedagogy used in the classroom. For

the most part, teaching of engineering subjects continues to be patterned after how instructors were taught when they were students of the subject, rather than being informed by research on learning. We believe that we are on the verge of seeing vast improvements in how much and how well students learn - we hope that this panel session can hasten this advancement.

One of the hindrances to reform in science, technology, engineering and mathematics (STEM) education has been the absence of good assessment instruments that can measure the value added to student learning by new ways of teaching important material. As pointed out by several studies, including the three video case studies, *Lessons from Thin Air*, *Private Universe*, and, particularly, *Can We Believe Our Eyes?* [1], students subjected to traditional instruction and assessment often do not adequately resolve the misconceptions that they either bring to a subject or gain while studying a subject. These misconceptions, sometimes referred to as alternative views or student views of basic concepts because they make sense to the student, block the establishment of connections between basic concepts, connections which are necessary for understanding the macroconceptions developed in further work.

The literature on student misconceptions in several of the disciplines found in engineering is quite rich. For example, for chemistry see [2-3]; for dynamics see [4-20]; for thermal sciences see [21-48]. There is much that can be learned from this literature about how widespread these misconceptions are and how persistent they are even under “good” instruction. Although these studies defined many student misconceptions, none presented good, reliable, valid assessment instruments that could be used by instructors in a “production” mode to judge the adequacy of their instruction.

The mechanics part of physics education is probably farther along the reform path than other disciplines due to

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the existence of an assessment instrument that tests basic concepts. The well-known Force Concept Inventory (FCI) assessment instrument of Hestenes, et al. (see [49], but also see related work in [50-54]) has been in use for over 15 years and is now credited with stimulating reform of physics education. Such assessment inventories can play an important part in relating teaching techniques to student learning. The design of these instruments relies on the designer(s) knowing the misconceptions commonly held by students in a discipline. Concept Inventory (CI) assessment instruments use these misconceptions as distracters to see if a student can pick out a correct concept from among the common misconceptions. Outside of engineering, CIs are under development in biology including evolution, calculus, electricity and magnetism in physics, and geology, to mention only a few.

CIs, if they were available in various engineering disciplines, offer the potential to be one of the best "ABET EC 2000" assessment instruments for showing continuous improvement of student learning within a discipline. For example, the data on the FCI, published by Hake [51] can be used to compare one instructor's results with many, many other instructors. Indeed, the FCI, given as a pretest and as a post-test in physics mechanics has caused instruction to improve [55].

DEVELOPMENT PROGRAM FOR CONCEPT INVENTORIES IN ENGINEERING SUBJECTS

In 2000 the Foundation Coalition began a program to develop CIs in engineering disciplines. During the 2000-'01 academic year, development of CIs in electromagnetics, strength of materials, systems and signals, and thermodynamics was begun. During the 2001-'02 academic year, development of CIs in circuits, fluid mechanics and engineering materials was started. During the current 2002-'03 academic year, the coalition has begun work on chemistry, computer engineering, dynamics, electronics and heat transfer CIs. Due to variations in the sizes of the development teams and the length of time each instrument has been under development, the instruments vary in their maturity and readiness, but most of those begun in the first two years of construction are ready for wide scale testing, if not implementation. One important task that remains for all instruments is establishing the instruments' validity and reliability.

During the Foundation Coalition's work on CIs, two other groups began development of CIs on engineering disciplines. Miller et al. [56] at the Colorado School of Mines began work on a CI during 2001-'02 for thermal and transport processes. Similarly, Reed-Rhoads [57] began work during 2002-'03 on a statistics CI. Representatives of these two CI teams have joined with the CI teams of the Foundation Coalition, to form a CI developers group to share experiences and best practices in the development process.

All but three of the CIs discussed above are represented on the panel for this session. There are a few other engineering-discipline CIs in various stages of development, but we concentrate here on those discussed above and represented by panel members.

THIS PANEL SESSION

The purpose of this session is to review the CIs under construction by teams represented by panel members. In the sections below we give a short description of each CI represented, by beginning with the level of the CI (what course and where it is typically found in the curriculum), what is new since a similar panel was convened at FIE 2002, and what are the directions for the future. Each sub-section below addresses one of the subject CIs with the panel member representing that CI listed in the section title in parentheses. The CIs sub-sections are ordered alphabetically within the year in which they were begun.

It is hoped that this session will heighten the awareness of the engineering education community to this work. The panelists also hope to solicit input and assistance in their development and testing. The CI teams having panel representatives involve more than 50 people, adding to the CIs' applicability and usefulness once developed. Also, to be discussed will be ways in which a CI can be developed, based on experience gathered by the teams represented on the panel.

2000-01 CIs

Electromagnetics (Branislav Notaros)

The Electromagnetics Concept Inventory (EMCI) is an assessment tool designed to measure students' understanding of fundamental concepts in electromagnetics. Although primarily intended for junior-level electromagnetics courses in electrical engineering departments, the EMCI can also be used in a variety of undergraduate and graduate electromagnetics-related courses in engineering and physics departments. The EMCI Version 1.0 is composed of three exams: EMCI-Fields, EMCI-Waves, and EMCI-Fields & Waves, to allow instructors to target specific knowledge areas. The EMCI-Fields consists of 23 multiple-choice questions on electrostatics, magnetostatics, and time-varying electromagnetic fields. It is designed for a typical first-semester electromagnetics course in a two-semester sequence. The EMCI-Waves, consisting of 23 questions on uniform plane waves, transmission lines, waveguides, and antennas, is intended for a typical second-semester course in the two-semester sequence. The EMCI-Fields & Waves is an integral test with 25 questions on all basic topics in undergraduate electromagnetics. Instructors teaching a one-semester electromagnetics course may either use both the EMCI-F and EMCI-W (at the same time or at different points in the semester) or use the EMCI-F & W only.

Since FIE 2002 in Boston, development of a new version of the EMCI has been conducted, based on

discussions at the CI Developer's meeting and at the CI Panel session, as well as on the feedback from instructors using the first version of the tests. In addition to improving several parts of the tests, the primary goal is to include many more prerequisite concepts in the EMCI, so that the portion of the instrument devoted to these concepts will be around 40%, while the rest of the questions will test concepts covered in the course.

Future work will include completion of the new version of the EMCI, further dissemination and field testing of the instrument, and validity/reliability evaluation.

Signals and Systems (Kathleen Wage)

The Signals and Systems Concept Inventory (SSCI) is a 25 question multiple-choice exam designed to assess students' understanding of fundamental concepts in undergraduate linear signals and systems courses as typically taught in the late sophomore or early junior year of electrical and computer engineering curricula. The exam emphasizes conceptual understanding over computational mechanics and contains distracters, or incorrect answers, designed to capture common student misconceptions. There are separate versions of the SSCI exam for continuous time (CT) and discrete time (DT) material. The core concepts addressed by these exams are grouped into six categories: background mathematical concepts, linearity and time-invariance, convolution, transform representations, filtering, and sampling. The SSCI development began in fall 2000, and both the CT and DT exams have undergone one major revision based on the results of testing in 2001-2002 to produce the current versions (2.0).

Assessment instruments require extensive testing and validation before being adopted by the broader community, and we are currently conducting such tests for the SSCI. To date, seven schools have used the SSCI. Results of the initial validation study (using data from 4 schools) are reported in [58]. In 2002-2003 we are gathering additional data for the study. Interviews conducted with 23 George Mason University students who took the DT SSCI shed light on some common student misconceptions and led to small wording revisions on the exams.

We are seeking additional participants for the SSCI study. Interested instructors should contact the panel member or John Buck (jbuck@umassd.edu). Additional information about the SSCI and password-protected versions of the exams are available from the SSCI website: <http://ece.gmu.edu/~kwage/research/ssci>.

Strength of Materials (Paul Steif)

The Strength of Materials Concept Inventory (SoMCI) addresses strength of materials, a subject taken by all mechanical and civil engineering students, typically after statics. The instrument addresses the first level of strength of materials, covering stress and strain, axial loading, shear, bending and torsion.

Since FIE in Boston, the SOMCI working group has been developing a clear set of concepts to be the focus of the inventory. Members of the group solicited input from colleagues from various institutions to develop an initial, comprehensive list of possible concepts. At a SOMCI working group meeting in January 2003, the suggested concepts was discussed and clarified and duplicates eliminated. A revised list has been developed. During this same period, work has also proceeded on the development of concept questions. At the January meeting, the group discussed candidate questions, and attributes of good concept questions were identified. Since that time, individual members have been devising questions with these attributes in mind, questions which are to be discussed at the late March meeting. In addition, a preliminary list of common misconceptions has been developed. By triangulating between Concept Statements, Concept Questions, and common misconceptions, the group hopes to develop a cohesive instrument.

The concept list will be sent to colleagues at various institutions for their input as to the importance of each concept and the frequency with which it is a source of student errors. Based on this input, a final set of concepts will be developed, which will focus the group's on-going efforts to develop concept questions.

Thermodynamics (Clark Midkiff)

The Thermodynamics Concept Inventory (TCI) is a multiple choice instrument designed to assess students' understanding of background and fundamental concepts in a first thermodynamics course.

Work on the TCI began in late 2000, and the instrument is now in its fifth revision. It has proven difficult to achieve balance in question subject matter and even more challenging to obtain the correct balance of prerequisite conceptual questions versus questions surveying material taught during the first course. Six subject areas identified for the TCI are: (1) systems and system diagrams, (2) energy and energy transfer (work and heat), (3) concept of state, (4) thermodynamic balances, (5) cycles and processes, and (6) reversibility and irreversibility. Interestingly, *all* of these topics are presented in prerequisite chemistry and physics courses. Compared to similar concept inventories developed for other subjects by the Foundation Coalition, the first four versions of the TCI served more as a measure of preparedness and less as an achievement test. The new TCI departs significantly from previous versions with heavier emphasis on material taught first in the class and use of the specialized jargon of thermodynamics.

Evaluation of the updated TCI is underway and extensive testing of the revised instrument at multiple sites is slated for Fall 2003.

2001-02 CIs**Circuits (David Rancour)**

The Circuits Concept Inventories (CCI) are used in the first and second Circuit Theory courses at University of Massachusetts, Dartmouth. Circuit Theory I is the first course in the major for electrical and computer engineering students. The typical student entering the first circuits course will already have taken two semesters of calculus, two semesters of physics and two semesters of freshman engineering. Circuit Theory I topics include basic properties of electricity, network theorems, nodal and mesh circuit analysis, natural and forced responses, and AC circuit analysis. For Circuit Theory II, a second course in the electrical and computer engineering majors, coverage includes applications of Laplace transforms, impulse response, convolution, Fourier analysis, and Bode plots.

The original pool of 41 questions has been increased to 93, largely by including topics that were not covered in the prototype exams. Four different authors wrote the questions in the prototype exams, so the format varied. Some questions contained multiple correct answers and the total number of choices per question ranged from 3 to 6. Revised versions of the CCI have exactly four choices per question with only one of the choices being correct. Some new questions use reverse reasoning, e.g., find the correct input given a system and an output. The prototype exams were given once per term whereas the revised exams are administered at the beginning and end of the term, as pre-test and post-test, in order to measure student gains.

The CCIs must be checked for content and construct validity. We plan to use gender and race ANOVA tests to verify construct validity, and peer review to determine content validity.

Fluid Mechanics (Jay Martin)

A cooperative effort between mechanical engineering faculty at the Universities of Wisconsin and Illinois has been directed toward development of a Fluid Mechanics Concept Inventory (FMCI). Fluid mechanics typically follows thermodynamics in the sequence of courses in thermal sciences in many engineering curricula with the exception of many chemical engineering curricula. As such, fluid mechanics covers both the mechanics and dynamics of fluids, and builds on basic physics and Newtonian mechanics.

Our first step was identification of the concepts that needed to be examined by experienced faculty, in contrast to writing questions first. It turns out that this was considerably more difficult than would have been required for the Force Concept Inventory (FCI). Fluid mechanics, like other engineering subjects, does not have the same kind of readily identifiable model as the FCI, and this provides challenges for developers of concept inventories for use in engineering. Once the key concepts were identified, questions were

developed to explore student understanding of each of the concepts. A number of criteria were used in the development of the questions. For example, following the structure of the FCI, numerical calculation was avoided and questions were developed that included graphic and visual representation of the concept being examined.

The FMCI was evaluated by students who have completed fluid mechanics. This ensured that common misconceptions held by students have been included in the answers and that ambiguities and uncertainties were eliminated. Further, a group of instructors who teach fluid mechanics evaluated the inventory. This provided a check on the validity of the instrument.

Materials (Stephen Krause)

The Materials Concept Inventory (MCI) is intended to be used to assess conceptual gains in introductory engineering materials or materials science courses. Such course are usually taken by students in most engineering disciplines after the required chemistry course or courses are completed. It is usually scheduled in the sophomore year, but occasionally, at some schools, during the junior year. It is often a prerequisite for design and/or manufacturing classes and the MCI might prove to be a useful tool as a pretest in these classes.

Since FIE 2002, a number of new aspects of the MCI have been explored. One is a comparison of the pre and post test results for students at Arizona State University and Texas A & M University. There are significant differences between the institutions on a number of questions in pre- and post-test results as well as differences in gains on some questions. It is possible that these are due to curricular differences in the schools or possibly in topical emphasis in the courses. However, in spite of institution-to-institution differences, the MCI can be very useful for ABET continuous improvement use within any one institution. Another area of new results is the sources of misconceptions, both from topics on prerequisite material as well as new material. It is often the case that students selecting the correct answer do so for the wrong reason and, conversely, discuss the correct logic on a questions and then select an incorrect answer. More information can be found in another FIE 2003 paper [59].

Future work will include the following: additional data will continue to be collected to improve statistics and explore class to class variation; results on questions on the same topic will be compared to examine validity of questions; and work will continue to identify sources of student misconceptions.

Thermal and Transport Processes (Ruth Streveler)

The subject matter covered by the Colorado School of Mines-led CI team is thermal and transport phenomena (e.g. thermodynamics, fluid mechanics, heat transfer) and is focused on the introductory course in each of these subjects

with primary focus on transport courses typically found in chemical engineering curricula. Many of the topics in this concept inventory are unified by the conceptual misunderstanding theory of Michelene Chi and colleagues, which describes the misuse of causation (macroscopic cause and effect) to describe molecular-level phenomena where observable patterns emerge from random molecular motion. In the last year, our team has completed a Delphi study (a methodology developed by the Rand Corporation and named for the Oracle at Delphi [60, 61]) designed to reach consensus among approximately 30 experienced engineering faculty about the difficulty and importance of fundamental concepts in the thermal and transport sciences. Our purpose was to identify concepts of high importance and low student understanding to use as the focus for creating our concept inventory. Based on the results of this study, 12 concepts were identified for inclusion in the concept inventory including conservation of linear momentum, the Bernoulli equation, differential vs. integral analysis, entropy and the 2nd Law of Thermo dynamics, heat vs. energy, heat vs. temperature, internal energy vs. enthalpy, reversible vs. irreversible processes, steady-state vs. equilibrium processes, system vs. control volume analysis, thermal radiation, and viscous momentum flux.

Now that we have identified key concepts for inclusion in the thermal and transport concept inventory, we will spend the next year drafting multiple-choice questions that focus on each concept. Volunteer students will answer a draft version of each question in a “think-aloud” format so that we can identify common misconceptions associated with the concepts. Text from the “think-aloud” sessions will then be used to create incorrect but plausible multiple-choice answers, or distracters, for each question. This technique allows common student misconceptions to be identified when the concept inventory is used with students. As time permits, we will also begin field-testing the completed questions to collect data for reliability and validity studies.

2002-03 CIs

Chemistry (Michael Pavelich)

The objective for the Chemistry CI (ChCI) is to develop and validate several small CIs for general chemistry that can be used as diagnostic tools in classroom teaching for subsequent engineering courses, especially those in materials science. CI questions specific to the topics of bonding, intermolecular forces, electrochemistry, equilibria, acid/base, and thermodynamics are the focus.

Questions for the ChCIs have either been developed or are being developed and some reliability data collected. We are working to incorporate the insights reported from previous research on misconceptions in chemistry. A graduate student in chemical education is involved, using the development and testing of questions as part of her thesis work.

During the Fall, 2003 semester the questions developed will be tested for reliability and validity using students from several institutions. We will then package the validated questions into small, 10 minute, ChCIs that can be used by professors as diagnostic tests of student understanding in courses relying on topics from general chemistry

Dynamics (Gary Gray)

The Dynamics Concept Inventory (DCI) team is developing a CI for sophomore-level dynamics. Dynamics is generally taken by mechanics, aerospace, civil, and industrial engineers and the pre-requisite is usually statics and two semesters of calculus. The efforts of this team are focused on the second half of the dynamics course, that is, rigid body dynamics, since the Force Concept Inventory (FCI) of Hestenes[49] sufficiently covers particle dynamics.

At the FIE meeting in Boston, the DCI team agreed to use the Delphi process, patterned after that used for the Colorado School of Mines-led CI team, to determine a list of the important concepts, as well as misconceptions, in dynamics. We began the process by recruiting 25 seasoned faculty from a diversity of institutional types ranging from community colleges to research universities, and included minority and women faculty. We asked them to describe those concepts in rigid body dynamics that their students have difficulty understanding. The team told the Delphi participants to focus on areas in which students often display insufficient conceptual understanding rather than focusing on student difficulties with analysis skills. Once the raw data was collected from the Delphi participants, it was categorized, summarized, and final statements for each of the 24 important concepts (and misconceptions) were developed. In Round 2 of the Delphi process, we asked each of the participants to estimate the proportion of their students who understand the issue or concept at an acceptable level at the end of dynamics, and to tell us how important they believe it is for students to understand the concept. This data has been collected and has determined 11 concepts from rigid body dynamics that should be covered on the DCI. Student focus groups have also been used to address misconceptions that involve the concepts identified by the Delphi process. More information can be found in [62]

The DCI team has created concept questions for each of the 11 concepts and refined those questions for inclusion on the first draft of the DCI, which we plan to have completed by the end of 2003. The DCI will then be tested at several institutions during the spring 2004 semester.

Statistics (Teri Reed-Rhoads)

The Statistics Concepts Inventory (SCI), currently under development, will yield score profiles that specifically describe students' abilities to design and conduct experiments as well as to analyze and interpret data. This research is especially timely as an increasing number of post-secondary programs include outcome requirements

specifically related to students' abilities to demonstrate statistical thinking and problem-solving skills. Our objective is to formulate a standardized tool, useful across courses as well as curricula, that assesses these analysis and synthesis abilities. Our expectation is that the instrument will be most useful for introductory courses, but that, like Hestenes' Force Concept Inventory [49], should provide insight about the level of understanding achieved by students at various points in the engineering pathway.

In the initial phase of the project, we completed a modified Delphi Technique to identify critical topics in statistics. We also used such resources as the Advanced Placement Exam syllabus [63] and the table of contents in widely used textbooks. From this list and existing misconceptions literature in statistics (see [64]), we developed an initial set of multiple choice items. This version of the SCI was administered at the end of the Fall 2002 semester, along with a demographics questionnaire and the Survey of Attitudes Towards Statistics [65] to 139 college students in four introductory statistics courses in engineering, mathematics, and communication at the University of Oklahoma. Detailed results of this pilot study are reported in another FIE 2003 paper [64].

An item-by-item analysis will guide our revision of the instrument. In addition, we will conduct task-based focus group interviews with students who have completed the SCI, to refine the stems and distractors. We will then administer the revised SCI to new groups of students in introductory statistics classes at OU. We will continue to seek a variety of courses and expand our samples to other institutions as well. Meanwhile, we will begin to construct a website with the intention that ultimately the SCI can be web-based.

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