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Developing a Measure of Interdisciplinary Competence*

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Calls for greater investments in interdisciplinary education and a shift to outcomes-based accreditation criteria in engineering have led to a need for a measure to assess interdisciplinary learning. The present study describes the development and testing of a survey-based, self-report measure to assess the interdisciplinary competence of undergraduate engineers. Using a nationally representative sample of 5249 undergraduates from 31 institutions, three discrete scales related to interdisciplinary competence emerged from factor analytic procedures: Interdisciplinary Skills, Recognizing Disciplinary Perspectives, and Reflective Behavior. Construct validity of the metrics is demonstrated through a description of the rigorous research and development process for the survey items. Statistical analyses indicate that scales significantly distinguish groups of students (i.e., by engineering discipline and by class standing), thus demonstrating the metrics' concurrent validity.

Keywords: interdisciplinary skills; learning outcomes; assessment

1. Introduction

In recent years, the scientific and engineering communities have called for greater investment in interdisciplinary education to foster innovation (e.g., [1, 2]). In the field of engineering, the shift to outcomes-based accreditation criteria in the mid-1990s sought to promote the development of multidisciplinary team skills among undergraduates. More recently, the National Academy of Engineering [3] has acknowledged the increasingly interdisciplinary nature of engineering practice and called for greater attention to preparing engineers to work in cross-disciplinary teams and settings; this enlarged problem space requires engineers to access, understand, evaluate, synthesize, and apply information and knowledge from multiple fields as they solve complex engineering problems.

Given the growing emphasis on the preparation of the engineering workforce and particularly on the need to cultivate engineers' interdisciplinary skills, we developed a measure of 'interdisciplinary competence' for use in program and institutional assessment and large-scale research on undergraduate engineering education. Currently, there are few tools available to assess interdisciplinary learning; two that have been described in the literature are both scoring rubrics. The first of these rubrics identifies more than 50 criteria to be used in the assessment of interdisciplinary writing [4]; the second rubric guides the assessment of student projects—for example, undergraduate theses or capstone projects [5]. Both tools are particularly useful for classroom-level assessments and small-scale program evaluations. Engineering educators, however, require a suite of assessment tools to meet their needs for large-scale program evaluation (recognizing that most engineers in the U.S. are educated in comprehensive universities enrolling large numbers of students), for the purposes of programme accreditation (which requires evidence of student learning), and to benchmark progress toward common educational goals nationally. In this paper, we describe the development and testing of a survey-based measure to assess undergraduate engineering students' perceptions of their interdisciplinary competence. The measure that we have developed is based on an extensive review of the literature on interdisciplinarity across many fields of study. Given its grounding in this literature, we believe the measure described here could be adapted readily to contexts other than engineering.

2. Literature review

2.1 *Defining interdisciplinarity*

A vast literature across many fields (including education, sociology of science, philosophy of science, cognitive science, research administration, and interdisciplinary studies) yields many definitions of interdisciplinarity but surprisingly little

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empirical research on the concept (see, for example, [6–10]). Within U.S. engineering programs, an accreditation requirement that undergraduates in engineering programs develop the ability to 'work in multidisciplinary teams' [11] has led to wide use of the term among engineering educators, but considerable ambiguity remains as the existence of similar terms (e.g., cross-disciplinarity, interdisciplinarity, transdisciplinarity) often leads to confusion [12]. In an attempt to bring some clarity to the discussion, scholars who study interdisciplinarity generally distinguish between multidisciplinarity and interdisciplinarity. Multidisciplinarity typically refers to efforts that bring together the perspectives, tools, or insights of two or more disciplines to explain a phenomenon or solve a problem. While multidisciplinary efforts concatenate disciplinary knowledge [13], or present it in 'serial fashion' [14], they do not achieve the synthesis or integration of disparate disciplinary knowledge into a cohesive whole that many argue is the marker of interdisciplinarity (for an extended discussion, [9]).

Interdisciplinarity, in contrast, integrates disciplinary contributions and thus obscures the separate contributions of individual disciplines. The process of achieving integration reportedly requires identifying, evaluating, and rectifying differences between disciplinary insights [13, p. 221] to achieve a new understanding. Such 'cognitive advancement' is not possible without the integration or synthesis of disciplinary methods, knowledge, or insights into something new [5]. Definitions that center on the achievement of disciplinary integration have won a number of adherents in the interdisciplinary studies community, and the following definition is often cited or paraphrased in the literature. In this definition , interdisciplinarity is defined as 'a process of answering a question, solving a problem, or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline or profession . . . and draws upon disciplinary perspectives and integrates their insights through construction of a more comprehensive perspective' [15, pp. 393–394].

2.2 Conceptualization of interdisciplinary competence

Our review of the literature yielded eight different dimensions of interdisciplinarity. The following sections describe these dimensions, which formed the basis for our measure. We focus our citations on the works that are most central to the dimensions we discuss.

2.2.1 Awareness of disciplinarity

Many observers of interdisciplinarity argue outright or imply that disciplines are fundamental to the creation of knowledge and thus to interdisciplinarity [2, 13, 15, 16, 18]. Newell and Green, for example, defined interdisciplinary studies as 'inquiries which critically draw upon two or more disciplines and which lead to an integration of disciplinary insights' [18, p. 24]. Definitions that focus on integration make similar claims about the disciplinary grounding of interdisciplinary work. To develop interdisciplinary competence, these definitions imply that one must first be aware of disciplinary boundaries and approaches to study. Such awareness requires epistemological transparency; one must understand what constitutes a discipline or field. Scholars argue that disciplines should be understood, in part, as cognitive apparatuses that structure scholarly inquiry by making assumptions about the nature of a domain of knowledge, identifying ways to study the elements of that domain, and establishing processes to validate knowledge. This understanding implies the existence of a scholar community that establishes and regulates, to some degree, communal values and norms [e.g., 9, 19–27].

2.2.2 Appreciation of disciplinary perspectives

Awareness is not equivalent to appreciation. Nikitina writes that in the process of developing interdisciplinary competence, it is necessary to develop 'an appreciative attitude towards other "stories" and disciplinary frames of reference' [28, p. 413]. The process of gaining disciplinary knowledge and an appreciation of disciplinary perspectives involves movement from having a general knowledge of a discipline to 'more specific knowledge of how each of its elements informs its insights into the problem' [29, p. 126]. Appreciation of the potential contributions of another discipline may be necessary for learning what can be 'borrowed' from another discipline as one addresses complex issues and questions.

2.2.3 Appreciation of non-disciplinary perspectives

Under the broad umbrella of interdisciplinary approaches to knowledge, the need to appreciate non-disciplinary knowledge, experiences, and perspectives has been most fully engaged by those writing about what is increasingly called 'transdisciplinarity.' Whereas early definitions of transdisciplinarity focused on the assumed unity of knowledge and the search for universal concepts or theories that could be applied in many different disciplines (e.g., see [9]), today transdisciplinarity often refers to scholarship that transgresses the boundaries between academia and communities outside academia. Advocates of transdisciplinarity often invoke conceptualizations of Mode 2 knowledge, arguing that they are motivated less by the desire to advance knowledge in the disciplines than the need to solve problems affecting individuals and their communities [30, 31]. Burger and Kamber contrast these new modes of research activity with conventional views of research as value-neutral and distanced from its context of application. They define transdisciplinarity as comprising '1) cognitive and social cooperation across disciplinary boundaries, 2) an intention towards the direct application of scientific knowledge in both political decision-making and societal problem solving, and 3) the participation of non-scientific stakeholders within research processes' [32, p. 44]. In engineering, cross-sector work of this kind is common. In the interest of parsimony we have captured the goals of transdisciplinarity under the umbrella term "interdisciplinarity" since the two terms share, at least, the fundamental goal of learning and application across disciplinary boundaries. In many cases, advocates of interdisciplinarity also assume that interdisciplinarity will better serve the cause of innovation and provide solutions to practical social problems as well [7, 33].

2.2.4 Recognition of disciplinary limitations

Openness to a variety of disciplinary and non-disciplinary sources of knowledge may result in greater awareness of the limitations of one's own field of study. Nikitina writes that thinking in an interdisciplinary way requires first 'defining and defying of limits imposed by one discipline, and making decisions to reject or accept different disciplinary theories based on their relevance and credibility' [28, p. 17]. In a review of the academic major, the Association of American Colleges (now the Association of American Colleges and Universities) argued that in addition to understanding the organization of their major fields and learning to think like practitioners in those fields, undergraduates should also recognize 'the necessarily partial vision' of their fields and critically reflect on 'the successes and limitations of any particular approach to knowledge.' They should also ask 'searching questions about the values, assumptions, perspectives, consequences, entailments, limits, and choices inherent in any intellectual enterprise' [34, p. 5].

2.2.5 Interdisciplinary evaluation

Despite the increase in the number of interdisciplinary programs in U.S. colleges and universities [35], some have argued that methods and criteria to evaluate the effectiveness of these programs are lacking or weak [5, 36]. To 'perform' interdisciplinarity successfully, students and faculty need to be able to evaluate the effectiveness of interdisciplinary work. In a study of faculty beliefs about assessing interdisciplinary student work, Boix Mansilla and Duraising [5] identified three core dimensions of faculty views about the quality of students' interdisciplinary work. Such work demonstrated: 1) disciplinary grounding, 2) cognitive advancement through integration of disciplinary concepts, theories, methods, and/or perspectives, and 3) critical awareness. The seeds of interdisciplinary evaluation thus appear to require that students develop not only awareness and appreciation of the knowledge, methods, and perspectives of the disciplines, but also an understanding of the limitations of disciplinary knowledge for addressing particular problems or providing insights into particular phenomena.

2.2.6 Ability to find common ground

The literature on interdisciplinarity offers countless discussions of potential barriers to its achievement. Rogers et al. capture a number of these, pointing to the 'incommensurability of concepts, different units of analysis, differences in world views, expectations, criteria and value judgments,' which constitute 'epistemological obstacles' to interdisciplinarity [37, p. 268]. Kockelmans went as far as to argue that 'specialization makes integration virtually impossible' [38, p. 147] but introduced the term 'common ground' to describe the basis for collaborative work among researchers from different disciplines [29, 39].

Some argue that finding common ground is fundamental to interdisciplinarity because it makes possible integration of knowledge rooted in different disciplines [39]. Klein [13] argued that disciplinary insights must not only be evaluated (as suggested earlier), but eventually rectified if integration is to be achieved. Similarly, Newell argued that creating common ground might involve 'modification or reinterpretation of components or relationships from different disciplines to bring out their commonalties so that linkages can be identified between sub-systems' [40, p. 20].

2.2.7 Reflexivity

Repko [29] writes that the interdisciplinary research process is necessarily a reflexive one. Reflection occurs when evaluating information sources or evaluating complex problems or controversial issues, for example. Interdisciplinary competence involves the ability to reflect on one's biases and the choices one makes when defining problems or interests, building understanding, problem solving, and how these biases will influence directions, understandings, and solutions.

2.2.8 Integrative skill

Boix Mansilla and Duraising define interdisciplinary understanding as 'the capacity to integrate knowledge and modes of thinking in two or more disciplines or established areas of expertise to produce a cognitive advancement in ways that would have been impossible or unlikely through single disciplinary means' [5, p. 219]. They also note, however, that the integration of disciplinary perspectives is not an end in itself but instead is a means to understand how to apply new knowledge. Finding common ground is viewed as a prerequisite to integration and synthesis of knowledge, and eventually, a more comprehensive understanding. Newell writes, 'By definition, interdisciplinary study draws insights from relevant disciplines and integrates those insights into a more comprehensive understanding' [40, p. 2]. In the end, the goal of integration is to explain a phenomenon that is 'greater than the sum of its disciplinary parts' [29, p. 131].

3. Data and methods

We developed the interdisciplinary competence measure for a study of undergraduate engineering education funded by the U.S. National Science Foundation, entitled *Prototype to Production: Processes and conditions for preparing the Engineer of 2020* (NSF EEC-0550608). The final instrument was administered to a sample of engineering undergraduates (second-year students through undergraduates in their fifth year of study) from a nationally representative sample of 31 U.S. colleges and universities (Table 1).

3.1 Survey development

A team of education and engineering researchers developed survey-based instruments for undergraduate engineers. Relying on a literature review of engineering, interdisciplinary studies, education, business, research management, cognitive science, philosophy, and sociology of science, the team generated a set of potential items that captured the eight dimensions of interdisciplinary competence previously summarized. Table 2 describes the dimensions of interdisciplinary competence tapped by these survey items.

In addition, the team spent a year conducting interviews and focus groups with engineering administrators, faculty members, students, and alumni at five U.S. colleges and universities to understand how engineering programs sought to develop students' interdisciplinary skills through the curriculum and co-curriculum. Another year was devoted to drafting potential survey items (for this and other competencies of interest), which were then vetted with engineering faculty at the University Park campus of The Pennsylvania State University.

Once reviewed and revised, survey items related to interdisciplinary competence were pilot tested with undergraduate engineering students at Penn State's University Park and Altoona campuses (n = 482). The team used factor analysis techniques to explore pilot results and further revised the survey items based on these findings. Factor analysis is a data reduction technique used to identify like items that exhibit similar tendencies. This statistical procedure seeks to determine the degree of correlation between a set of variables (in this case multiple survey items). If items are highly correlated and vary together, they can be combined to form a single scale. Scales comprise multiple related items that ideally measure the same construct and are useful for reducing the number of variables. We present results of this pilot analysis in Section 4. Following

Table 1. Nationally representative sample of institutions (n = 31) comprising the full data set for analysis

Research institutions:	**Master's/Special institutions:**
Arizona State University (Main & Polytechnic)[1]	California Polytechnic State University[3]
Brigham Young University	California State University, Long Beach
Case Western Reserve University	Manhattan College
Colorado School of Mines	Mercer University
Dartmouth College	Rose-Hulman Institute of Technology
Johns Hopkins University	University of South Alabama
Massachusetts Institute of Technology[1]	
Morgan State University[2]	**Baccalaureate institutions:**
New Jersey Institute of Technology	Harvey Mudd College[1]
North Carolina A&T[2]	Lafayette College
Purdue University	Milwaukee School of Engineering
Stony Brook University	Ohio Northern University
University of Illinois at Urbana-Champaign	Penn State Erie, The Behrend College
University of Michigan[1]	West Virginia University Institute of Technology
University of New Mexico[3]	
University of Texas, El Paso[3]	
University of Toledo	
Virginia Polytechnic Institute and State University[1]	

[1] Institution participating in the companion qualitative study.
[2] Historically black college or university.
[3] Hispanic-serving institution.

Table 2. Survey items included in the pilot survey administered on two campuses. Each item is mapped onto one of the eight dimensions of interdisciplinary competence that emerged from the literature review

Dimension of interdisciplinarity from literature review	Item STEM: To what extent do you agree or disagree with each of the statements below?[1]
Awareness of disciplinarity	If asked, I could identify the kinds of knowledge and ideas that are distinctive to different fields of study.
	I recognize the kinds of evidence that different fields of study rely on.
Appreciation of disciplinary perspectives	I value reading about topics outside of engineering.
	I enjoy thinking about how different fields approach the same problem in different ways.
	My general education courses rarely give me ideas useful for understanding engineering or solving engineering problems.
Appreciation of non-disciplinary perspectives	In solving engineering problems I often seek information from experts in other academic fields.
	Each academic field has its limitations when it comes to solving real-world problems.
Recognition of disciplinary limitations	Not all engineering problems have purely technical solutions.
Interdisciplinary evaluation	Given knowledge and ideas from different fields, I can figure out what is appropriate for solving a problem.
Ability to find common ground	I see connections between ideas in engineering and ideas in the humanities and social sciences.
	I'm good at figuring out what experts in different fields have missed in explaining a problem/solution.
Reflexivity	I often step back and reflect on what I am thinking to determine whether I might be missing something.
	I frequently stop to think about where I might be going wrong or right with a problem solution.
	I usually know when my own biases are getting in the way of my understanding a problem or finding a solution.
Integrative skill	I can take ideas from outside engineering and synthesize them in ways that help me better understand.
	I can take material from different engineering fields and integrate it in ways that help me better understand.
	I can use what I have learned in one field in another setting.

[1] Scale: 1 = Strongly disagree, 2 = Disagree, 3 = Neither agree nor disagree, 4 = Agree, 5 = Strongly agree.

this process, the research team again met with focus groups of Penn State engineering faculty members and administrators to review the amended items one final time to assess the survey's construct validity (i.e., whether items represent their intended purpose).

3.2 Sample and data treatment

We used institution- and program-level information for the 2007–2008 academic year for enrolled students in accredited U.S. engineering schools to draw a disproportionate, mixed random/purposeful, $6 \times 3 \times 2$ stratified sample with the following strata: six engineering disciplines (biomedical/bioengineering, chemical, civil, electrical, industrial, and mechanical); three levels of highest degree offered (bachelor's, master's, and doctorate); two levels of institutional control (public and private). Sample institutions are representative of the population with respect to institutional type, mission, and highest degree offered. Five institutions that were participants in a companion qualitative study were purposefully included in the study. One offers only a general engineering degree, so three institutions offering general engineering degrees were also included in the sample, resulting in a sample consisting of seven disciplines (biomedical/bioengineering, chemical, civil, electrical, general, industrial, and mechanical, which together accounted for 70% of all U.S. baccalaureate engineering degrees awarded in 2008.

A university-based survey research center selected 23 additional institutions at random within the sampling framework and was responsible for data collection through a web-based questionnaire. Of the 32 737 student surveys sent, 5249 were returned for a response rate of 16%. Though a higher rate was desired, survey response rates have been declining, perhaps because of the increased use of surveys in general through web-based forms [31, 41–43]. We accounted for differences between the sample of responses and the undergraduate engineering population for 31 institutions, weighting cases based on response rates by gender, discipline, and race/ethnicity within an institution as well as response rates across institutions.

Missing data were imputed based on procedures recommended by Dempster et al. [44] and Graham [45] using the Expectation-Maximization (EM) algorithm of the Statistical Package for the Social Sciences (SPSS) software (v.18). We employed a principal axis analysis (Oblimin with Kaiser normalization rotation) to reduce multiple survey questions to fewer scales. Each item was assigned to a scale based on the magnitude of the factor loadings, the effect of keeping or discarding the item on the scale's internal consistency reliability, and professional judgment. Scales were formed by taking the sum of respondents' scores on the component items and dividing by the number of items in the scale, as prescribed by Armor [46].

3.3 Analyses of interdisciplinary competence scales

To demonstrate the reliability and usefulness of our interdisciplinary competence measures, we conducted factor analyses to empirically identify the dimensions of interdisciplinary competence and completed analyses to examine how well the interdisciplinary competence scales discriminate between students' levels of class standing and their discipline of enrollment within engineering. An analysis of covariance, controlling for SAT score, gender, and race, was conducted to test for statistically significant differences between groups.

3.4 Limitations of the study

Our study has several limitations that should be considered when interpreting the results. First, the sample includes only U.S. engineering schools. Students from non-U.S. cultural backgrounds may understand the survey items devised to study interdisciplinary competence in engineering undergraduates differently, and this variation in interpretations may result in a different factor structure and thus different scales. Researchers adopting measures used in previous studies are advised to examine validity when these scales are used in new populations [47]. Additionally, the study sample does not represent all engineering disciplines; however, the seven disciplines represented produce about 70% of all U.S. engineering baccalaureate degrees.

One criticism of survey-based measures of learning outcomes is that they are self-reported by students rather than derived from more objective measures of student performance, such as tests or direct observations of student performances (see, for example, [48]). Most studies of self-reported data, however, indicate a moderate to strong correspondence between students' self-reports and more objective measures, especially under conditions similar to those present in this study. These conditions are: 1) the information requested is known to the respondents; 2) the questions are phrased clearly and unambiguously; 3) the questions refer to recent activities; 4) the respondents think the questions merit a serious and thoughtful response; and 5) answering the questions does not threaten, embarrass, or violate the privacy of the respondent or encourage the respondent to answer in socially desirable rather than in truthful ways (as summarized by [49, 50]). Self-reported responses are also considered valid and reliable when comparing the outcomes of groups of students (rather than when assessing individual students) [51]. Nonetheless, such criticisms compel researchers to examine the validity of self-reported measures. In the next sections of this paper, we present evidence of the validity of our measure of interdisciplinary competence and suggest avenues we were not able to pursue.

4. Findings

4.1 Results from the pilot study

A three-factor solution including the interdisciplinary competence items emerged from the pilot analysis labeled as follows: 1) Appreciation and Application (Cronbach's alpha = 0.76); 2) Reflection (Cronbach's alpha = 0.77); 3) Recognizing Interdisciplinarity (Cronbach's alpha = 0.60). We assigned these preliminary labels for the factors in a way that summarized the survey items contained within each factor. These names changed following the analysis of national-level data. The high values of internal consistency (Cronbach's alphas) suggest that items group together statistically as well as conceptually. Although the items *within* each factor group together, the correlation coefficients *between* factors are all below 0.4 (Table 3). This indicates that the factors are measuring different aspects of interdisciplinary competence, a finding that we did not anticipate in developing the items.

We removed three items from the survey following the pilot test. The first two items removed (Table 4) formed a separate factor from the other items but exhibited a Cronbach's alpha value of 0.19. Based on this low internal consistency, we decided to omit both items from the measure. We removed a third item because it loaded as its own factor. This was the only survey item focused on 'multidisciplinarity,' which we defined as working across different *engineering* fields. All other items include the incorporation of knowledge from fields *outside* engineering, perhaps explaining why this item formed its own factor.

4.2 Final scales resulting from factor analyses of the full data set

Once the full survey data were collected and cleaned, we again factor analyzed the interdisciplin-

Table 3. Factor analysis results ($n = 482$) of the pilot survey of items related to interdisciplinary competence. Each factor name attempts to capture the essence of the survey items from which it is comprised. Alpha values denote the internal consistency of each scale (a value of at least 0.7 is generally ruled as acceptable by psychometricians). Values in the right column denote the mean and standard deviations (in parentheses) for each item

Factor	Item STEM: To what extent do you agree or disagree with each of the statements below?[1]	Alpha if item deleted	Item means (Std dev.)
Appreciation and application (Alpha = 0.760)	I value reading about topics outside of engineering.	0.74	4.07 (0.92)
	I enjoy thinking about how different fields approach the same problem in different ways.	0.73	3.72 (0.88)
	Not all engineering problems have purely technical solutions.	0.75	4.18 (0.71)
	In solving engineering problems I often seek information from experts in other academic fields.	0.75	3.35 (0.95)
	Given knowledge and ideas from different fields, I can figure out what is appropriate for solving a problem.	0.72	3.86 (0.85)
	I see connections between ideas in engineering and ideas in the humanities and social sciences.	0.73	3.72 (0.85)
	I can take ideas from outside engineering and synthesize them in ways that help me better understand.	0.72	3.79 (0.70)
	I can use what I have learned in one field in another setting.	0.74	4.05 (0.63)
Reflection (Alpha = 0.771)	I often step back and reflect on what I am thinking to determine whether I might be missing something.	NA	3.90 (0.75)
	I frequently stop to think about where I might be going wrong or right with a problem solution.	NA	3.85 (0.80)
Recognizing interdisciplinary (Alpha = 0.601)	If asked, I could identify the kinds of knowledge and ideas that are distinctive to different fields of study.	0.50	3.93 (0.67)
	I recognize the kinds of evidence that different fields of study rely on.	0.51	3.91 (0.63)
	I'm good at figuring out what experts in different fields have missed in explaining a problem/solution.	0.54	3.36 (0.83)
	I usually know when my own biases are getting in the way of my understanding a problem or finding a solution.	0.58	3.71 (0.75)
Items removed from the survey	Each academic field has its limitations when it comes to solving real-world problems.		4.01 (0.87)
	My general education courses rarely give me ideas useful for understanding engineering or solving engineering problems.		3.02 (1.24)
	I can take material from different engineering fields and integrate it in ways that help me better understand.		3.71 (0.79)

[1] Scale: 1 = Strongly disagree, 2 = Disagree, 3 = Neither agree nor disagree, 4 = Agree, 5 = Strongly agree.

Table 4. Correlation coefficients between each of the factors related to interdisciplinary competence that emerged from the pilot survey ($n = 482$)

	Appreciation and application	Reflection	Recognizing interdisciplinarity
Appreciation and application	1		
Reflection	0.11	1	
Recognize	–0.34	–0.23	1

ary competence survey items. These were among a total of 51 survey items created to assess several different engineering learning outcomes, including fundamental math and science knowledge and skills, engineering design skills, contextual awareness, leadership, communication, and teamwork skills. Nine learning outcome scales emerged from this analysis, three of which are related to interdisciplinary competence and which closely resemble the three factors derived from the pilot data: Interdisciplinary Skills, Reflective Behavior, and Recognizing Disciplinary Perspectives (Table 5). The Interdisciplinary Skills scale assesses students' perceptions of their abilities to think about and use different disciplinary perspectives in solving interdisciplinary problems or to make connections across academic fields. The Reflective Behavior scale operationalizes the 'reflexivity' dimension of

Table 5. Factor analysis results of the full survey related to interdisciplinary competence administered to undergraduate engineers (n = 5249) at 31 institutions. Each factor name attempts to capture the essence of the survey items from which it is comprised. Alpha values denote the internal consistency of each scale (a value of at least 0.7 is generally ruled as acceptable by psychometricians). Values in the right column denote the mean and standard deviations (in parentheses) for each item

Factor	Item STEM: To what extent do you agree or disagree with each of the statements below?[1]	Alpha if item deleted	Item means (Std dev.)
Interdisciplinary skills (Alpha = 0.79)	I value reading about topics outside of engineering.	0.78	4.21 (0.87)
	I enjoy thinking about how different fields approach the same problem in different ways.	0.76	4.04 (0.79)
	Not all engineering problems have purely technical solutions.	0.78	4.26 (0.73)
	In solving engineering problems I often seek information from experts in other academic fields.	0.78	3.50 (0.94)
	Given knowledge and ideas from different fields, I can figure out what is appropriate for solving a problem.	0.76	3.99 (0.67)
	I see connections between ideas in engineering and ideas in the humanities and social sciences.	0.76	3.89 (0.91)
	I can take ideas from outside engineering and synthesize them in ways that help me better understand.	0.75	4.02 (0.76)
	I can use what I have learned in one field in another setting.	0.76	4.23 (0.67)
Reflective behavior (Alpha = 0.73)	I often step back and reflect on what I am thinking to determine whether I might be missing something.	NA	4.03 (0.76)
	I frequently stop to think about where I might be going wrong or right with a problem solution.	NA	3.85 (0.77)
Recognizing disciplinary perspectives (Alpha = 0.68)	If asked, I could identify the kinds of knowledge and ideas that are distinctive to different fields of study.	0.58	3.69 (0.88)
	I recognize the kinds of evidence that different fields of study rely on.	0.51	3.81 (0.75)
	I'm good at figuring out what experts in different fields have missed in explaining a problem/solution.	0.69	3.38 (0.92)

[1] Scale: 1 = Strongly disagree, 2 = Disagree, 3 = Neither agree nor disagree, 4 = Agree, 5 = Strongly agree.

interdisciplinarity identified through the literature review. The Recognizing Disciplinary Perspectives scale taps students' perceived understandings of disciplinary knowledge, methods, expectations, and boundaries and how that knowledge might be applied in different situations.

Each of these factors exhibits high internal consistency, with Cronbach's alpha values ranging from 0.68 to 0.79. Even when we removed individual items, factors maintained alpha values of at least 0.50. Because Recognizing Disciplinary Perspectives contained fewer items, the effect of removing a single item was greater on the remaining alpha value than it was for the Interdisciplinary Skills scale.

Correlation coefficients between each interdisciplinary competence scale and pairwise comparisons for the other outcome scales ranged from 0.17 to 0.44 (Table 6). These low values indicate that the scales are indeed providing different information, as they tended not to co-vary with one another. The emergence of the same three factors from two separate populations of students (the two-institution pilot test and the 31-institution full sample) lends further support for the claim that the scales are measuring distinctive aspects of interdisciplinary competence that are relevant to undergraduate engineering students.

4.3 Validity of the interdisciplinary competence scales

Construct validity 'involves making inferences from the sampling particulars of a study to the higher-order constructs they represent' [52].

The research and development process for survey items comprising the scales, which involved engineering faculty and administrators, contributes to the construct validity of the measure. According to engineers, survey items assess interdisciplinary competence for engineering undergraduates. This review by a group of experts within the field builds confidence that engineering students would interpret the survey in the intended manner. We developed the survey items after a review of the literature on interdisciplinarity, which is largely speculative rather than empirical in nature. Thus, the dimensions of interdisciplinarity that we identified, although consistent with the literature, may not fully describe the construct of interdisciplinary competence or how it is manifested in engineering

Table 6. Correlation coefficients between each of the nine student learning outcome scales that emerged from factor analysis of the full survey (n = 5249)

	Interdisciplinary skills	Recognize disciplinary perspectives	Reflective behavior	Fundamental skills	Design skills	Contextual awareness	Teamwork skills	Communication skills	Leadership skills
Interdisciplinary skills	1								
Recognizing disciplinary perspectives	0.42	1							
Reflective behavior practice	0.37	0.31	1						
Fundamental skills	0.29	0.28	0.30	1					
Design skills	0.42	0.34	0.32	0.62	1				
Contextual awareness	0.44	0.42	0.17	0.36	0.66	1			
Teamwork skills	0.36	0.28	0.23	0.36	0.58	0.54	1		
Communication skills	0.38	0.31	0.24	0.45	0.64	0.54	0.64	1	
Leadership skills	0.34	0.32	0.24	0.44	0.71	0.60	0.74	0.71	1

[1] Interdisciplinary competence scales are shaded in gray.

education contexts. In future studies, we hope to assess directly interdisciplinary competence in engineering students; these assessments could provide the basis for a test of the content validity of the survey-based measure we have developed to date.

The analyses that we are able to conduct with our data, however, provide considerable evidence of concurrent validity, which assesses the ability of an operationalization to distinguish between groups that it should be able to distinguish theoretically [53, 54]. The three interdisciplinary competence scales discriminate, with varying levels of success, between engineering disciplines targeted for the study. To demonstrate this, we conducted an analysis of covariance for all fourth- and fifth-year students for each scale. In these analyses, we controlled for students' race/ethnicity, gender, and SAT composite score and compared each pairwise difference of the adjusted means (Table 7).

For the Interdisciplinary Skills scale, students from three disciplines reported significantly higher skills than the other disciplines: biomedical/bioengineering, general engineering, and industrial engineering. These three disciplines are ones that we would expect to be more interdisciplinary in outlook because they draw on multiple engineering fields (general engineering), link engineering with other fields (biomedical/bioengineering), or emphasize a systems perspective (industrial engineering). It thus stands to reason that students enrolled in these disciplines would report higher interdisciplinary skills levels than students in the other disciplines, thereby supporting the scale's concurrent validity.

We observed fewer differences by discipline for the Recognizing Disciplinary Perspectives scale. Chemical engineers reported significantly lower ratings on this scale than biomedical/bioengineers and electrical engineers. Chemical engineers' self-ratings, which are the lowest of all seniors in the study, are consistent with the finding for the Interdisciplinary Skills scale. Potential explanations for these consistent findings include a lack of emphasis on interdisciplinarity in the chemical engineering curriculum, which might lead to less exposure to other fields and thus less familiarity with other disciplinary perspectives. Previous analyses of curricular emphases in these fields show that chemical engineering students and faculty reported less emphasis on topics associated with interdisciplinarity than counterparts in other fields [55] and thus may be less familiar with the content, concepts, theories and methods associated with other fields of study.

Although the high levels of confidence in Recognizing Disciplinary Perspectives reported by electrical engineers (compared with chemical engineers) may seem counterintuitive, two explanations may be possible. First, as a field of study, electrical engineering is composed of distinctive subdisciplines, and seniors' knowledge of these fields may have influenced their understanding of the term 'discipline' and thus their ratings of their abilities. It is also possible that the strong discipline-focus in electrical engineering programs makes students aware of how their discipline differs from others; engineering fields that are more interdisciplinary in focus may not make such distinctions as obvious to undergraduates, stressing similarities or affinities

Table 7. Adjusted means for 4th- and 5th-year seniors of the three scales related to interdisciplinary competence for each engineering discipline. Mean differences are calculated by subtracting the comparison discipline's mean from the focal discipline's mean (i.e., positive values indicate a greater mean value for the scale for the focal discipline)

	Interdisciplinary skills			Recognizing disciplinary perspectives		Reflective behavior	
Focal discipline	**Mean**	**Comparison discipline**	**Mean difference[1]**	**Mean**	**Mean difference[1]**	**Mean**	**Mean difference[1]**
Biomedical/ bioengineering	40.12	Chem	0.22	30.70	0.18	40.10	0.11
		Civil	0.13		0.10		0.08
		Elec	0.17		0.03		0.05
		Gen	–0.06		0.13		–0.12
		Indus	0.07		0.05		0.07
		Mech	0.13		0.10		0.12
Chemical engineering	30.91	Bio	–0.22	30.52	–0.18	30.99	–0.11
		Civil	–0.07		–0.09		–0.03
		Elec	–0.04		–0.15		–0.06
		Gen	–0.28		–0.05		–0.23
		Indus	–0.15		–0.13		–0.04
		Mech	–0.09		–0.09		0.01
Civil engineering	30.98	Bio	–0.15	30.60	–0.10	40.02	–0.08
		Chem	0.07		0.09		0.03
		Elec	0.03		–0.06		–0.03
		Gen	–0.20		0.03		–0.20
		Indus	–0.07		–0.04		–0.01
		Mech	–0.01		0.00		0.04
Electrical engineering	30.95	Bio	–0.17	30.66	–0.03	40.05	–0.05
		Chem	0.04		0.15		0.06
		Civil	–0.03		0.06		0.03
		Gen	–0.23		0.10		–0.17
		Indus	–0.10		0.02		0.02
		Mech	–0.04		0.06		0.07
General engineering	40.18	Bio	0.06	30.57	–0.13	40.22	0.12
		Chem	0.28		0.05		0.23
		Civil	0.20		–0.03		0
		Elec	0.23		–0.10		0.17
		Indus	0.13		–0.08		0.19
		Mech	0.19		–0.03		0.24
Industrial engineering	40.05	Bio	–0.07	30.65	–0.05	40.03	–0.07
		Chem	0.15		0.13		0.04
		Civil	0.07		0.04		0.01
		Elec	0.10		–0.02		–0.02
		Gen	–0.13		0.08		–0.19
		Mech	0.06		0.04		0.05
Mechanical engineering	30.99	Bio	–0.13	30.60	–0.10	30.98	–0.12
		Chem	0.09		0.09		–0.01
		Civil	0.01		0.00		–0.04
		Elec	0.04		–0.06		–0.07
		Gen	–0.19		0.03		–0.24
		Indus	–0.06		–0.04		–0.05

[1] Disciplinary pairwise comparisons of the means are calculated as the 'focal discipline' subtracted by the 'comparison discipline.' Significant differences ($p < 0.05$) for the pairwise comparisons are shaded in light gray and were determined via an analysis of covariance, controlling for gender, race/ethnicity, and SAT composite score.

across fields rather than differences. This interpretation is supported by previous analyses, which demonstrate that the seven engineering disciplines in the full study are arrayed on a continuum from more to less interdisciplinarity based both on students' learning outcomes and in reports of curricular emphasis by program chairs and faculty [55].

Finally, general engineers reported significantly higher scores for the Reflective Behavior scale than chemical engineers and mechanical engineers. Students enrolled in the purposely designed general engineering programs that populate our sample would be expected to report higher levels of confidence in their reflective behavior than other students because it tends to be stressed in these programs. In addition, though the disciplines can be arranged on a continuum on this scale, having only two items from which to calculate an average for the scale may contribute to the difficulty in observing statistically significant differences between additional disciplines.

Items comprising the Reflective Behavior scale seem to tap students' metacognitive skills, whereas the Interdisciplinary Skills scale tends to tap actual behaviors. Students in biomedical/bioengineering students and in general engineering programs reported the highest ratings for these items, suggesting that fields that are more interdisciplinary in focus either attract students who tend to self-regulate their learning more than those in other fields or that curricula and/or pedagogies used in these fields help students develop metacognitive skills. Reflection and interdisciplinarity, as our discussion of the dimensions of interdisciplinarity suggests, are not mutually exclusive. Moreover, reflection is a key aspect of the problem solving and design process in engineering, in which all engineers engage to a certain extent. The abilities measured by the Recognizing Disciplinary Perspectives scale, therefore, might be achieved in a variety of ways and be associated with a variety of activities. This may explain the more limited ability of the scale to distinguish between students in different engineering disciplines.

We also explored whether scales differed in their abilities to distinguish between students at different levels of class standing (Table 8). Our comparisons of students in their second, third, and fourth/fifth years of undergraduate study did not show statistically significant differences on the Recognizing Disciplinary Perspectives and Reflective Behavior scales. Differences in curricular approaches may be at work here, as different programs within the same field may emphasize differentially the dimensions of interdisciplinary thinking that we have identified. Variations in program curricula would make it more difficult to show development across class standing. Another potential curricular explanation for the mixed results for the Reflective Behavior scale may be that many U.S. engineering students are introduced to problem solving early in the curricular sequence; if this skill is taught early, and perhaps used more often, it would be more difficult to demonstrate substantial gains as students progressed through their majors.

In contrast, fourth-/fifth-year students reported significantly higher Interdisciplinary Skills than less-advanced students. Though the survey was cross-sectional in design (individual students were not followed over time, but we compared populations of students at different stages of their academic careers), one would expect students further along in their programs to report significantly higher Interdisciplinary Skills. The higher skill level reported by fourth-/fifth- year students relative to their less-advanced colleagues is consistent with prior research. Single-institution longitudinal studies of undergraduate engineering students show limited cognitive development during the first two years of college. The first two years of the engineering curriculum are typically comprised of rote learning and the application of formulae in foundational science and math courses that tend not to promote more advanced forms of thinking [56, 57]. In higher level courses during the third and fourth years, however, a different educational environment may play a role in cognitive development. Similar work by Arum and Roksa [58] in non-engineering environments in the U.S. also suggests that, in general, students experience limited development of critical thinking skills and complex reasoning during their first two years of college. Since interdisciplinary skills require higher-order thinking skills, such as synthesis and evaluation, higher levels reported by fourth-/fifth- year engineering students in our study are consistent with expectations and provide further evidence of the validity of the scales.

Table 8. Adjusted means for the Interdisciplinary Skills scale by students' class standing. Mean differences are calculated by subtracting the comparison year's mean from the left-column class standing's mean (i.e., positive values indicate a greater mean value for the scale for the class standing column)

	Interdisciplinary skills		
Class standing	**Mean**	**Comparison year**	**Mean difference[1]**
Sophomore	3.91	Junior	–0.03
		Senior	–0.06
Junior	3.94	Sophomore	0.03
		Senior	–0.03
Senior	3.97	Sophomore	0.06
		Junior	0.03

[1] Pairwise comparisons calculated as the 'class standing' subtracted by the 'comparison year.' Significant differences ($p < 0.05$) are shaded in gray and were determined via an analysis of covariance, controlling for gender, race/ethnicity, engineering discipline, and SAT composite score.

5. Discussion

Evidence supports the construct validity of the three scales that we developed to measure interdisciplinary competence among engineering undergraduates. Evidence is strongest for the scale measuring Interdisciplinary Skills, which distinguishes among students in different engineering fields and in different years of study in ways that would be expected theoretically. Our analysis provided more limited evidence of construct validity for the two related scales: Recognizing Disciplinary Perspectives and Reflective Behavior. Additional research is thus recommended to further test and potentially improve the scales and also consider the contribution of this work to conceptualizations of interdisciplinarity in engineering education. We also consider the conceptual contributions that this research makes to the study of interdisciplinary competence in undergraduate education contexts.

5.1 Future research

Although we were able to provide evidence of the construct validity of the Interdisciplinary Skills scale, we were not able to test the content validity of the interdisciplinary competence scales because direct measures of interdisciplinary knowledge and skills do not exist. An important direction for future research, then, is the comparison of students' performance on authentic interdisciplinary tasks that requires the application of knowledge and skills from multiple disciplines (inside and outside engineering) with scores on our self-report measure. Such research could provide additional evidence of the validity of the Interdisciplinary Skills measure.

Additional work to improve the Reflective Behavior and Recognizing Disciplinary Perspectives scales is also warranted. The Reflective Behavior scale is composed of two survey items, limiting the sensitivity of the measure. We relied on the interdisciplinarity literature to identify this dimension, but further investigation of the metacognition literatures (which the scale may be tapping) as well as measures of engineering problem solving may suggest additional behaviors that are associated with reflective practice.

More qualitative studies of how engineering students interpret the concept of 'discipline' might help researchers better understand how interdisciplinarity is understood by engineering students and faculty. Findings from Lattuca's [9] study of college and university faculty members' interdisciplinary research and teaching led her to speculate that understandings of the term interdisciplinarity are related to individuals' conceptions of the scope and boundaries of their own fields of study. The use of the terms multi- and interdisciplinarity by different engineering faculty may reflect such differences, and these may be passed along to students through academic socialization processes. In addition, further specification of the term 'discipline' in the stem of the survey items for this scale or in the survey items themselves should assist students and researchers with interpreting items and scale scores.

5.2 Conceptual contribution of the study

Although many scholars suggest that multidisciplinarity and interdisciplinarity are different approaches to knowledge creation, our study suggests that the two may not be entirely separate. In the context of undergraduate education, multidisciplinarity may in some cases constitute a step on the path toward interdisciplinarity. Recall that definitions of interdisciplinarity describe it as a *process* of knowledge creation rather than solely as a *product* of research teaching activities. Many scholars argue that disciplinary grounding is a prerequisite to interdisciplinary knowledge creation. In the context of undergraduate education, this implies that students must first understand and be able to apply disciplinary knowledge before they can integrate disciplinary concepts, theories, methods, and insights in a process of interdisciplinary knowledge production. Our review of the literature on interdisciplinarity lends support to this conceptualization: dimensions of interdisciplinarity could be interpreted as a developmental learning trajectory for interdisciplinary competence. We previously suggested this possibility in Lattuca and Knight [12]. The three scales we have developed might be used in longitudinal studies of engineering students' interdisciplinary skills to see if the recognition of disciplinary perspectives and reflective behaviors developmentally occur prior to the development of robust interdisciplinary skills. The cross-sectional nature of our data did not allow us to fully test this conceptualization, but scales might be used in such an investigation that could rely both on the Interdisciplinary Skills scale and other authentic assessments. Furthermore, individual items could be adjusted to apply these measures to contexts beyond undergraduate engineering.

6. Conclusion

In this study we described the development and psychometric properties of a measure of interdisciplinary competence designed for use in large-scale assessments and research studies of undergraduate engineering education. The measure consists of three scales assessing different dimensions of engineering students' ability to think and work in interdisciplinary ways. We provided evidence supporting the construct validity of the three scales that emerged during our research process, but note that the evidence is strongest for the scale measuring Interdisciplinary Skills; our analyses offer more limited evidence of construct validity for the two related scales, Recognizing Disciplinary Perspectives and Reflective Behavior. In future studies, researchers adopting these measures for use in new populations should again examine their validity rather than assuming that the instrument will produce equally valid data for different student populations. Differences in academic field and national and cultural settings may influence how research participants respond to survey questions.

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