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Development of Scoring Rubric for Evaluating Integrated Understanding in an Undergraduate Biologically-Inspired Design Course*

INBAL E. FLASH GVILI[1], MARC J. WEISSBURG and JEANNETTE YEN
School of Biology, Center for Biologically Inspired Design, Georgia Institute of Technology, 310 Ferst Drive, Atlanta, GA 30332.
E-mail: inbalfg@weizmann.ac.il, marc.weissburg@biology.gatech.edu; jeannette.yen@biology.gatech.edu

MICHAEL E. HELMS[2]
School of Interactive Computing, Tech Square Research Building, 85 Fifth Street NW, Atlanta GA 30308, Georgia Institute of Technology

CRAIG A. TOVEY
School of Industrial and Systems Engineering, 755 Fesrt Drive, NW, Atlanta, GA 30332, Georgia Institute of Technology

[1] Currently at Department of Science Teaching, Weizmann Institute of Science, 234 Herzl Street, Rehovot 7610001 Israel.
[2] Currently at College of Computing, 801 Atlantic Drive NW, Atlanta, GA 30332, Georgia Institute of Technology.

The key intended learning outcome of interdisciplinary engineering courses and programs is the development of students' ability to integrate knowledge known as integrated understanding. Still, there are only few examples of assessment tasks designed to deliberately assess this attribute in engineering education, and little is known about how to develop credible scoring rubrics that can assess integrated understanding promoted by specific interdisciplinary courses. In this paper we offer an operational definition of integrated understanding developed based on the literature. We also present a method for designing credible scoring rubrics for course-specific integrated understanding based on this definition. Our process establishes the rubric's validity through aligning course learning objectives with the rubric criteria and reliability through involving course teachers who often come from different disciplinary backgrounds in developing performance-level descriptions. We tested the method by applying it to design a rubric for evaluating integrated understanding in an interdisciplinary undergraduate elective course in Biologically-Inspired Design. The resulted rubric was used to grade students' reports (n = 27) by the course teachers who came from disciplines as varied as Biology and Engineering. Reliability calculated through Intra-Class Correlation (ICC) was good to excellent with regard to all criteria. The rubric can thus be reliably used by the course teachers to draw valid conclusions regarding progression in students' integrative understanding in their course. Additionally, this method can be used to establish credible scoring rubrics for evaluating students' integrated understanding following participation in other interdisciplinary engineering courses.

Keywords: assessment; integrated understanding; biologically-inspired design

1. Introduction

Assessment has been identified as one of the five key research areas in engineering education [1, 2]. This focus is not surprising since credible assessment serves both participant and stakeholder interests. That is, engineering educators and students can benefit from application of assessment strategies to facilitate students' learning, whereas stakeholders can obtain information about the quality of instruction or educational programs [3]. Towards this end, the Accreditation Board for Engineering and Technology programs (ABET) has been increasingly emphasizing the need for clear articulation of learning objectives, which in turn will support credible assessment [4].

Assessment of learning in interdisciplinary engineering courses and programs is the focus of this paper. Interdisciplinary courses and programs are important to engineering education as they can support the development of 21st century practices required for addressing complex research and design problems [5–10]. Examples of such practices are life-long learning, critical thinking, creative thinking, ethically and socially responsible problem solving, and awareness of the nature of science and design. These practices are also recognized as important by ABET [4]. Interdisciplinary courses and programs are assumed to promote these practices through immersing students in purposeful knowledge integration [7]. This differs from multidisciplinary courses and programs that engage students in examining central issues from two or more disciplinary perspective, but do not require synthesis [11–14].

However, assessing learning in interdisciplinary programs and courses remains a challenge due to their special properties. One of these is the uniqueness of each interdisciplinary program and course, which renders program evaluation rather proble-

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matic as there are no nationally recognized learning outcomes and normed tests of students' achievement [15]. This creates a need to operationalize learning, i.e. define learning objectives and design assessment strategies, for each interdisciplinary program and course [15, 16]. A second unique attribute is that interdisciplinary learning objectives are process rather than content oriented [15], which requires the use of performance based instruments such as scoring rubrics [17], which can result in inconsistent grades when different faculty apply them to students' work [18–20]. Lack of consistency in grading is further exacerbated when graders come from different disciplinary backgrounds and thus employ different methodologies and epistemologies [12, 21, 22]. The challenge is then, how to design credible (valid and reliable) scoring rubrics that can assess the specific learning that takes place in a unique interdisciplinary course or program.

2. Biologically-inspired design course

The context for this study was an interdisciplinary research and design course in Biologically-Inspired Design (BID) offered by Georgia Institute of Technology every fall semester for the last nine years (2005-2014). Biologically-Inspired Design, also known as Biomimetics and Bionics, is a rapidly developing domain that focuses on interdisciplinary research and development of design solutions based on understanding of biological processes [23, 24]. In other words, it involves comprehending, abstracting, translating and applying biological processes or design principles to the engineering domain in order to improve human technology [25]. Biomimetics' process draws from disciplines as varied as biology, engineering, and design, and can thus serve to engage undergraduate students from these respective disciplines.

The course offered by Georgia Institute of Technology is a 3 credit, 15 week-long undergraduate course that meets twice a week for 1.5 hours and its pedagogy has been previously described [26,27]. The course is open to up to 40 undergraduate junior, senior and graduate students. Students in the following majors receive degree credit for this course, but it may be taken by others as an elective: biology, mechanical engineering, biomedical engineering, industrial systems engineering and materials science engineering. The course has been co-taught for 7 years by a team of four teachers, an industrial system engineer, two biologists, and a computer scientist. All teachers have experience at conducting Biologically-Inspired Design in their respective disciplines.

The course is designed to provide a foundation in key ideas in Biologically-Inspired Design and to develop students' integrated understanding. This is expected to take place as students work in interdisciplinary teams toward conceptualizing and testing a biologically–inspired design, and thus practice interdisciplinary collaboration. To assist students from different disciplines to integrate knowledge through collaboration, they are supplied with integrative concepts and processes, which were guided by the idea that interdisciplinary communication is "the formulation of uniform, discipline-transcending terminology or a common methodology" [28]).

3. Using structure—mechanism—function schema as an integrative terminology in BID course

Structure—Mechanism—Function (SMF) schema is a key integrative idea used in the course to facilitate interdisciplinary communication between engineering and biological knowledge. This schema is essentially equivalent to Structure-Behavior-Function (SBF) representation [29]. Like SBF, SMF serves as a schema for systems conceptualization that enables student understanding of complex systems behaviors and functions [30], especially when coupled with a function oriented approach [31]. We use *mechanism* instead of *behavior* since the word "behavior" has a discipline-specific meaning to many types of biologists (i.e. ecologists, organismal biologists) regarding actions performed by organisms. The different representations in the SMF framework complement each other to provide a concise system-level description. Thus, *function* is the effect of, or output of the object given a specific input. A function can be also stated as a goal or purpose of observed actions of organisms; that is their behaviors. For example, a function of a mollusk shell can be described as resisting breakage. Finding shelter and carrying a load are additional examples. The *structure* comprises the components of the biological materials or forms, their shape and how they are organized in relation to each other to support the function; the *mechanism* explains how the different structural components dynamically interact amongst themselves and the environment to achieve a given function. In the mollusk shell example, the mechanism explains how the biological material elements dissipate the forces imposed upon them to resist breakage. In addition to being a key integrative cross-cutting idea in the course, the SMF schema is meant to help students abstract biological design principles from organisms' structural features [32]. These biological principles are then applied to identify engineering problems that can be effectively solved by their implementation.

Before we go into the details of our scoring rubric design process and present its resulting product, we will provide a critical overview of assessment tasks and tools previously used to evaluate learning in other interdisciplinary engineering courses and programs. Our overview focuses on the assessment of integrated understanding, a.k.a. interdisciplinary understanding, interdisciplinary integration and integrative learning, as this skill was found to be a unique learning outcome of interdisciplinary courses and programs [33]. We will than present a novel operational definition of integrated understanding we crafted in order to allow us to design assessment tasks and tools that are specific to the context of the BID course.

4. Literature review

4.1 Critical overview of assessment tasks and tools previously used to evaluate integrated understanding

The idea that integrated understanding resulting from interdisciplinary learning can and should be operationally defined, is relatively novel [9, 34–35]. There are few studies that address this topic generally [9, 33–38], and only four that describe assessment tasks and associated rubrics that were empirically tested and shown to be appropriate for use in interdisciplinary engineering courses and programs [33, 36–38]. These studies are presented below together with the approach towards assessment of learning they illustrate.

As Table 1 shows Besterfield-Scare and colleagues [36] and Borrego and colleagues [37] used significantly different task and criteria for evaluating integrated understanding than the studies by Mansilla and colleagues [33] and Chan and colleagues [38]. The differences between the two camps' assessment approaches seem to be related to the theories they hold with regard to the nature of interdisciplinary learning and knowledge. The first camp, represented by the first two papers, appears to hold a *cognitive* approach. That is, knowledge is seen as abstractions that are not anchored in specific practices. Concurrently, interdisciplinary learning is viewed as a process where isolated bits of information (concepts) from different disciplines are acquired. Integrated understanding, the result of this learning, is viewed as the ability to correctly integrate these concepts around a central notion. The second camp, represented by the last two papers, seems to hold a *situated* approach, where knowledge is seen as inseparable from specific practices. In alignment with this worldview, interdisciplinary learning is seen as a process where the terminologies and methodologies of different disciplines are reconstructed to create novel and useful integrative terminology and methodology situated in the needs of specific interdisciplinary community of practice. The result of this learning is seen as the ability to creatively apply integrative terminology and methodology to solve another complex problem or to explain a complex phenomenon.

In this study we adopted the situated approach to learning as it better aligns with the BID course's curriculum. However, since there was no preexisting definition of integrated understanding within BID, we constructed a definition that is anchored in relevant literature.

4.2 Our operational definition of integrated understanding in BID course

As previously mentioned, our view of integrated understanding is aligned with the situated approach, yet it is adapted to the needs of BID course. These adaptations are anchored in the literature as follows. We noticed two common elements amongst interdisciplinary learning contexts. The first is that integrated understanding is learned through overcoming context specific constraints. By example, integrative understanding in General Studies takes place when students are challenged "to mediate the rhetorical, theoretical, and methodological differences inherent in multiple disciplinary discourses" [33]. Integrative understanding in Engineering Education, on the other hand, often occurs when teams of students are

Table 1. Assessment task and criteria analyzed in four studies that evaluated integrated understanding

	Besterfield-Scare et al. (2004)	**Borrego et al. (2009)**	**Mansilla et al. (2009)**	**Chan et al. (2010)**
Learning Context	Industrial Engineering program	Two-semester Green Engineering course	Interdisciplinary Studies program	Biomedical Engineering program
Assessment task	Drawing concept maps whilst considering Industrial Engineering as a central concept.	Drawing concept maps whilst considering Green Engineering as a central concept.	Submitting research papers as final assessment tasks in courses taken.	Submitting a final project report at the end of a semester-long project.
Criteria	Comprehensiveness, Structure, Correctness, Naiveté, Focus, Approach, Organization, Sophistication.	Comprehensiveness, Organization, Correctness.	Purposefulness, Disciplinary Grounding, Integration, Critical Awareness.	Structural, Behavioral, Functional dimensions of integrative learning (understanding).

required to work across team members' different disciplinary perspectives during the design selection, evaluation, or testing [37, 38].

The second common element is the use of integrative ideas to draw together disciplinary knowledge. Integrative ideas can be either cross-cutting concepts (e.g. structure-behavior-function, complex systems [38, 39], water [40], sustainability [41]), or overarching practices such as Life-Cycle Analysis [42]. Moreover, in Mansilla et al. (2009) [33], a key criterion for evaluating successful knowledge integration is the use of students' developed integrative devices in their writings.

Based on these observations we define integrated understanding in BID course as *the ability to apply integrative ideas to connect disciplinary knowledge from different domains when participating in a specific interdisciplinary practice*. Our definition of disciplinary knowledge pertains also to knowledge learned in different contexts, whether within the same discipline or in different disciplines, and other informal learning experiences [43].

5. Methodology

Herein we describe the process for designing a valid and reliable scoring rubric for assessing integrated understanding as previously defined. Overall, the process starts with selecting a key course learning and assessment task, defining intended learning outcomes (learning objectives) aligned with the definition of integrated understanding, continues with the design of a scoring rubric that assesses these learning outcomes, and concludes by using established methods [17] to assess the validity and utility of the rubric, as recommended by modern pedagogical practice [44–46].

5.1 Establishing validity

5.1.1 Phase 1: Selecting a key course learning task

Our rubric design process started by selecting a key course learning task which products can be assessed. We chose a task referred to as *Found Object Exercise*. The overall goals of the task were that students will develop ability to: (1) apply SMF schema to represent a biological system from a functional perspective, and (2) integrate this system level representation with an analysis of adaptive or evolutionary advantage, when conducting and reporting on a simple scientific inquiry.

The learning task design was influenced by 'the scientific method' concept, according to which scientific inquiry is composed of key sub-processes employed in sequential order [47]. The National Research Council (NRC) sequence was modified by replacing the second stage of asking a research question with two sequential steps of hypothesis development and rooting new ideas in the context of existing cultural knowledge. The task thus guided the students through the following processes: (1) observing; (2) developing an hypothesis; (3) rooting new ideas in the context of existing cultural knowledge; (4) revising the hypothesis and conducting an experiment, (5) analyzing data, and (6) stating conclusions. Each of these processes was encouraged in a series of assignments that build upon the prior steps and concluded with a summative assignment of writing a final research report.

This report was chosen as the assessment device since it was the summative assignment for the second course learning unit. It is in the second unit that, for the first time, students were asked to integrate biological and engineering knowledge in the context of carrying out a Biologically-Inspired Design project. Thus, students and teachers can use the feedback gained from this experience to further improve interdisciplinary learning in the following course units.

5.1.2 Phase 2: Defining intended learning outcomes

We defined intended learning outcomes for the Found Object Exercise by considering its overall goal and the instructions given to students in each sequential assignment. We will briefly present each assignment, and the intended learning outcomes related to it.

The first assignment focused on natural object description. The students were directed, in both textual and verbal description of the assignment, to observe a natural object (an organism or part of an organism such as a seed or appendage) within its natural environment and describe "how the object is integrated into its surroundings and...the detailed structure." The students were then asked to identify a striking property of the natural object. A property could be either a structure (e.g. the outer covering of a mushroom) or a behavior performed by an organism (carrying a load). This was loosely defined to facilitate inquiry, but also bridge the basic science-engineering gap produced by different disciplinary perspectives. Biology students for instance, may be more comfortable with observations on organismal level processes whereas engineering students may prefer to examine particular structural features of a biological system. The students were further asked "why the structure is the way it is, what functions are afforded, and what advantages do these functions afford the organism". This last instruction was given to prompt the students to generate hypotheses regarding the function of the property, and how the function is achieved through changes in the system's structural elements, i.e. mechanism. These hypotheses are based on the student's observation and prior general knowledge. Finally, the students were asked to illustrate their understanding of the natural object "using relevant multiple representations (e.g. tables, graphs, drawings)."

The following learning intended learning outcomes were formulated for the first assignment:

(1) describe natural object's property (either structure or behavior), hypothesizing regarding its function and mechanism through which function is achieved.
(2) illustrate SMF properties of the natural object in multiple representations.

The second assignment focused on hypothesis statement. The students were directed to develop an hypothesis (putative explanation) of the function previously described, based on their observations and what they already know. The instructions specified a "clear articulation of the hypothesis about the mechanism of interest using at least 3 fundamental Biology and Engineering concepts". The concepts are assumed to have been learned by the students in previous disciplinary courses. Fundamental concepts provide frameworks for evaluating different mechanisms, such as scaling laws, the role of material anisotropy, homeostasis etc. These often are specific to particular areas of knowledge or subjects (e.g. Biomechanics, Material Science, and Physiology). Verbal instructions specified that a clear hypothesis is one where a causal association is phrased in a manner that allows the audience to understand how it could be verified. This corresponds to a predicted outcome for a comparison or manipulation. Hypotheses construction assumes that students have general prior knowledge appropriate for advanced students in science and engineering, and are capable of basic causal reasoning-making logical connections between putative causes and their effects. The following intended learning outcome was formulated for this assignment:

(1) apply at least 3 engineering and biology fundamental concepts when stating hypothesis about a mechanism that can explain the function previously described.

The third assignment focused on literature search. The ability of engineers and biologists to find information relevant to their Biologically-Inspired Design ideas often is limited by domain specific language or concepts. This assignment is designed to help bridge that gap. Written instructions given to the student specified that they conduct their survey using 2 of the 3 techniques they learned in class: (1) using phylogenetic relatedness (i.e. searches that use evolutionary relatedness to find further information); (2) searching for convergently evolved structures or processes (i.e. searching for the same function or mechanism in distantly related animals), or examining co-option or exadaptation of the structures or processes (i.e. searches focused on identifying how the given function or mechanism may have arisen from structures or processes with another purpose); or (3) searching for human technological translation of the structures/behavior observed. Written instructions indicated that the information in at least two articles be described clearly using SMF language. The following two intended learning outcomes were formulated for this assignment:

(1) apply search strategies to locate two relevant papers.
(2) represent information about biological systems mentioned in two relevant papers using SMF schema.

The fourth assignment focused on informed experimentation. Students were asked to revise or reformulate their hypothesis based on readings of the primary literature, with the same requirements that governed the initial hypothesis. The goal of this assignment was to get students to perform simple, basic experiments that address some aspect of the function and mechanism of their natural object. The students were thus asked to "describe or design the key experimental test" and "describe the results" of their hypothesis test. Instructors stressed that appropriate experiments should be simple, and be performed at home or in an informal setting. The instructors stressed that there was no need for statistical analysis, but that the results be clearly described with precision and accuracy. The following learning objectives were formulated for this assignment:

(1) restate the hypothesis previously described in light of literature.
(2) design an experiment to test the hypothesis.
(3) describe the results in light of the revised hypothesis with a picture, graph or text.

The fifth and final assignment of the 7 week sequence focused on the discussion of the experiment and its results. The students were instructed to make a conclusion about their hypothesis in light of the data they obtained, to discuss what their data means about the advantages or adaptive value of the tested phenomena, and to suggest a next question based on their data that can increase understanding of the tested phenomenon. Students were told the next question could either further investigate the phenomenon in the organism, or investigate how to translate the mechanism into human technology. This concluding task facilitates students' ability to synthesize all the individual tasks into a coherent inquiry process report, write a discussion that integrates knowledge from different empirical studies reported in the literature and evaluate the unique contribution of their study to the field of biology and engineering. The following intended learning outcomes were formulated for this assignment:

(1) interpret the results in light of hypothesis.
(2) relate findings to the adaptive value.
(3) articulate the next questions.

5.1.3 Phase 3: Establishing performance-level descriptions for each intended learning outcome

In the next step the leading course instructor identified two good, two bad and two intermediate Found Object final reports. The leading teacher did not use any formalized criteria when choosing the examples, but rather, her overall impressions of quality. Three other course teachers applied a preliminary version of the rubric shown in Table 2 to score the six students' Found Object exercises. The teachers came from different disciplines: biology, industrial systems engineering and computer sciences. They have been associated with previous versions of this course as co-teachers, guest lecturers, group facilitators and project scorers. The preliminary rubric presented the learning outcomes related to each assignment as a criterion, and an associated scale of 0–4 points corresponding to meeting none, a few, some, most, and all of the criteria. However, this preliminary rubric lacked well-defined descriptions of what met the criteria. The teachers independently evaluated the selected examples of students' performance with the preliminary version of the rubric. Grading discrepancies were discussed and a shared description of performance levels for each criteria was constructed (Table 2).

In this process the teachers made an effort to avoid the use of descriptors such as *good analysis*, which retards reliable judgments regarding student performance. To better understand the consensus the teachers came to after looking at the provided examples, we will illustrate using students' examples of low and high levels of performance for each criterion.

5.1.3.1 Natural object description

Poor to Good (1-2). This student chose avian bones as the subject, but the observations are very limited and confined to structure:

> *"I found two bones in my rough dissection. These bones, I deduced, were the radius and ulna. Both bones were curved, though the ulna had greater curvature. Further, the radius and the ulna were of differing thicknesses (the radius was much thinner than the ulna)".*

The descriptions lack statements about advantage to the organism. Moreover, none of the observations clearly link the structural properties to the function or mechanism. The student provided one sketch that did not accurately describe the object. The sketch lacked labels for the components mentioned in the text, and was not to scale. This student got a mean score of 1.5. In another example, a student speculated about the possible functions of the peel of a banana, but did not comment on potential structures or mechanisms corresponding to this function, noting only that *"it is bitter, it decomposes over time"*. There was a simple unlabeled line drawing.

Very Good to Excellent *(3–4)*. This student was interested in the attachment of oysters, and took detailed observations of natural oyster clusters:

> *"It looks like the oyster shell produces a cement like substance from one side that allows it to stick to other surfaces or for other oysters to stick to it. The purpose of the cement is to allow oysters to aggregate into large communities forming intertidal reefs that filter water, provide protection from storms, and build a habitat for other species. . . there is probably some secretion mechanism that encourages self-assembly of the cement on one outer surface."*

The student clearly articulates the function as sticking as well as sub-functions such as secretion, and identifies the components (cement produced from one of the sides of the shell). There is a clear statement of advantage to the organism as "aggregation" as well as how this affects other species. The representations included schematic drawings and photographs that all were clearly labeled and with scales, along with a flow diagram about the functions involved in sticking. In another example, a student was interested in the ability of ants to carry large loads, observing that the ants coordinate their limbs such that they always have 2 legs on one side and a third leg on the ground at the same time, which allows them to balance the weight. The student suggested that efficient movement while carrying a load allows for more efficient foraging, therefore improving survival.

5.1.3.2 Hypothesis statement

Very Poor *(0)*. The student was hypothesizing about the protective function of the banana peel. The report stated that:

> *"longitudinal fibers* [of the Banana peel] *offer better protection from infection"*

There is no logical justification for this causal mechanism. That is, the potential mechanism is not relevant to the proposed function. Moreover, the student proposed the following test: *"the cut will be clean if fibers are oriented in one direction"*, which, as stated would not verify anything about protection or fiber orientation.

Poor to Good *(1–2)*. The hypothesis is based on

Table 2. A full analytical rubric for assessing integrative understanding as expressed in students' final research reports

	Excellent (4 points)	**Very Good (3 points)**	**Good (2 points)**	**Poor (1 point)**	**Very Poor (0 points)**
Natural Object Description Describe natural object's property (either structure or behavior), hypothesizing regarding its function (F) and mechanism (M) through which function is achieved. Illustrate SMF properties of the natural object with multiple representations.	Detailed & accurate description of SMF relations including statement about benefit to organism- adaptive or evolutionary advantages. AND Clearly labeled and accurate depiction of the object's SMF relations in pictorial and graphical representations	Detailed & accurate descriptions of either S and F or S and M relations including statement about benefit to organism- adaptive or evolutionary advantages. AND Clearly labeled and accurate depiction of the object's S and F or M relations in pictorial or graphical representation.	Short description of S and F, or S and M relations, or S, M & F described but at least one is not correct or precisely articulated and statement about benefit to organism- adaptive or evolutionary advantages is not clearly stated. AND Clearly labeled yet not accurate depiction of the object's S and F, or S and M relations.	Short description of S. Not related to F. No statement about benefit to organism- adaptive or evolutionary advantages. AND Unlabeled pictorial representation.	No Description or any visual representation.
Hypothesis Statement Apply at least 3 engineering and biology fundamental concepts when stating hypothesis about the mechanism that can explain the function previously described.	Hypothesis is framed using 3 fundamental concepts, is related to observed F, and explicitly states casual M phrased in a manner that allows the audience to understand how it could be verified.	Hypothesis is framed using 2 fundamental concepts, is related to the observed F, and explicitly states casual M phrased in a manner that allows the audience to understand how it could be verified	Hypothesis is framed using 1 fundamental concept, is related to the observed F, but does not explicitly states casual M.	Hypothesis is framed using 1 fundamental concept, yet is not related to the observed F, does not include causal M, nor way in which it could be verified.	Hypothesis is framed without using any fundamental concept, is not related to the observed F, does not include causal M, nor way in which it could be verified.
Literature Search Represent information about biological systems mentioned in the two relevant papers with SMF schema. Apply search strategies to allocate two relevant papers.	Two of the papers described address the function and the biological systems are clearly represented using complete SMF relations. AND Use of two different search strategies.	Two of the papers described address the function and the biological systems are clearly represented using complete SMF relations. AND At least one of the search strategies was used.	Two of the papers described address the function yet the biological systems are represented using SMF not completely or accurately. AND At least one of the search strategies was used.	Only one of the papers described addresses the function, even if the biological system was clearly represented using SMF. AND At least one of the search strategies was used.	None of the papers described address the function.
Informed Experimentation Restate the hypothesis previously described in light of literature. Design experiment to test hypothesis. Describe the results in light of the revised hypothesis with a picture, graph chart, or text.	Clearly stated hypothesis regarding causal M related to F restated in light of the literature. AND Proposed experiment tests the causal M using appropriate manipulations or comparisons. AND Results are clearly described using SMF relations with a picture, graph, chart or text.	Clearly stated hypothesis regarding causal M related to F restated in light of the literature. AND Proposed experiment tests the causal M using appropriate manipulations or comparisons. AND Results are not clearly described.	The hypothesis includes no causal M, yet is restated in light of the literature. AND Proposed experiment tests the causal M. AND Results are not clearly described	The hypothesis includes no causal M. AND Proposed experiment does not test the causal M AND Results are not clearly described	No experiment was described.
Discussion Interpret the results in light of hypothesis. Relate findings to the adaptive value. Articulate the next questions.	Results are interpreted correctly and/or alternative explanations considered. AND Findings are related to the adaptive value. AND Next questions that would result in greater understanding of the phenomenon are articulated.	Results are interpreted correctly in light of revised hypothesis. AND Findings are not related to the adaptive value. AND Next questions that would result in greater understanding of the phenomenon are articulated.	Results are interpreted correctly in light of revised hypothesis. AND Findings are not related to the adaptive value. AND There are no next questions suggested that would result in greater understanding of the phenomenon..	Results are not interpreted correctly in light of revised hypothesis. AND Findings are not related to the adaptive value. AND There are no next questions suggested.	No results are discussed.

observations of the growth form of a common plant, the American Beauty Berry. The student describes a number of aspects of the plant including leaf shape, location of leaves and berries along the stem etc. A typical passage is:

> *"There is about 140 pea-sized bright purple berries growing from each cluster, with an inch in each cluster. The two leaves that are sticking out from the clusters are 2-3 times the size. . . . Each berry is attached to a branch those branches are connected to a larger branch that holds the leaves and the leaves' branches are connected to the main stem that connects to the roots".*

The student than asks a question and states a hypothesis:

> *"How much does the leaf have an effect on the berry clusters? From observations it looked as if the leaves were the direct and most important source of food for the berries using sunlight and photosynthesis to create glucose. The predicted outcome was that the leaves would die first and following quickly after that the berries would shrivel up because of the lack of sun from the leaves."*

The "hypothesis" itself is not suggested by the previous descriptions, which deal only with structures. The hypothesis as phrased does not clearly identify a causal connection, although the prediction suggests the mechanism is altered photosynthesis. There is no if-then statement or comparison suggested that would allow the hypothesis to be confirmed; why the leaves might die is intrinsically linked to whether the hypothesis is logical. For instance, a drought that kills the leaves would also have a systemic effect on the plant and would not constitute a valid test. Hence the articulation is unclear. In this example energy was really the only core concept applied when framing the hypothesis.

Students who wrote a clear causal statement but did not suggest a statement that revealed how to validate the hypothesis by using comparison as a natural control, also received 1-2 points. An example follows:

> *"Certain parts of the vines are able to sense the shadows and the darkness to know they need support to get enough sunlight".*

Sensory feedback was a central concept, although one could also argue use of energy also framed the hypothesis, at least implicitly.

Very Good to Excellent *(3–4)*. This student observed dogs, and noticed that:

> *"dogs come in many different shapes and sizes, but no matter how the dog was shaped, the animal was still able to maintain balance and prevent itself from falling".*

The student defines this as postural stability, and further notes that large and small dogs characteristically display different postures, for example:

> *"small dogs typically maintain crouched postures while large dogs tend to be less crouched".*

The hypothesis builds on these observations by articulating a potential causal mechanism:

> *"I propose that in order to maintain postural stability, large dogs have adopted different postures from small dogs to prevent falling".*

The hypothesis includes a causal mechanism (balance is produced by posture), as well as a comparison that allows the hypothesis to be tested: a different posture leads to stability in large vs. small dogs. Biomechanics, scaling, stability and movement kinematics are relevant core principles discussed in class, as is the concept of within species comparisons.

5.1.3.3 Literature search

Poor to Good *(1–2)*. The student was interested in properties that make leaves impermeable to water. Only one of the articles directly addressed the topic, examining surface properties on two different (but related plants). The description does not compare the properties of different leaves, and it is unclear whether the literature search utilized either phylogeny or convergent evolution as a framework. There are hundreds of papers on this topic across a large range of animals and plants, and the absence of any comparative statements or discussion of evolutionary convergence was taken as an indication neither one of these concepts was applied.

The papers were described using SMF perspective:

> *"The hydrophobic properties of the leaf allow it to repel water by using a combination of micro bumps and a thin layer of wax (Burton & Bhushan, 2006). Both bumps and wax help reduce friction and adhesion on the leaf."*

Very Good to Excellent *(3–4)*. This student was examining how mushrooms protect themselves from thermal extremes. The student searched a variety of literature, noting that resistance to freezing is conferred by anti-freeze proteins that "*are a great example of convergent evolution*". The student citied papers describing these proteins in both plant and animal taxa. The student also included literature describing technical applications of anti-freeze proteins, thus meeting the required number of search criteria. The following description of one of the papers is typical:

> [The paper] *"described the ability of certain fungi to inhibit ice growth. Proteins in enoki and shiitake mushrooms bind to ice crystals that form to inhibit the growth or recrystallization of the ice. The proteins exist to prevent cell damage occurring via the recrystallization of extracellular water. The proteins inhibit ice recrystallization by lowering the freezing point of the water but not*

the melting point in a process that is called thermal hysteresis."

The description uses SMF framework, identifying the function as inhibiting ice crystal growth, the mechanism as lowering freezing point with the structures being anti-freeze proteins.

5.1.3.4 Informed experimentation

Poor to Good *(1–2)*. This student was interested in the function of plant roots to direct the plant towards resources, and wrote:

> *"Do the roots migrate first? I've decided to test this by removing the plant from soil, separating the roots roughly into halves, and putting the halves in different situations—one in water fed with plant food, the other in plain water, which would represent the nutritionally-dry area. If the roots in the nutritious water stay stronger or more numerous. . .".*

As written, it is not clear why the roots would migrate differently, although one might infer this would be because root growth is affected somehow by different nutrient conditions. Thus, the causal mechanism is unclear. The expected outcome does not address the issue of speed, but of growth or persistence. Therefore the measurement does not relate to mechanism of more rapid growth. In describing the results, the student wrote:

> "*While I clearly observed one plant growing roots preferentially in nutrient-rich areas, that may only be a function of basic allocation of resources (it could have grown one side or the other)..*"

Here, the data collected does not even test migration (the stated issue), or the expected outcome (strength or number). The description of the results is vague - there is no definition of "preferential" that applies to the data collected. There are no qualitative (e.g. pictures) or quantitative data that clearly illustrate these results. The clause ("that may be a function") is either illogical or poorly phrased and difficult to interpret. This particular report had multiple flaws, and was therefore scored at the low end of the range, whereas only one of the flaws noted above would have placed it at the other end of the range. Students occasionally tested their "hypothesis" on a found object of a different type than the one used for their observations. This also would be considered an experiment that does not test the hypothesis.

Very Good to Excellent *(3–4)*. The student was interested in properties of mushrooms that regulate water balance, and proposed a series of experiments that examine water absorption under various conditions. The student, based on readings, suggests the skin might be like an impermeable (or hydrophobic) barrier that prevents water loss, or that the mushroom absorbs water from its surroundings. The student wrote:

> *"In an attempt to understand which parts of the mushroom are most responsive to moisture, or are moisture absorbers, an experiment exposing varying parts of the mushroom were done. WHOLE_FORM ABSORPTION: If the moisture content is reduced in a mushroom, the overall absorption of the mushroom will become greater* [compared to a mushroom that was not dry] *to reinstate moisture balance. MEMBRANE_FRACTURE ABSORPTION: If the hydrophobic membrane is compromised, the absorption level through that compromised slit will increase compared to an intact mushroom."*

Although the phrasing is a little awkward in certain places, these are clearly cause-effect relationships stated as comparisons that allow testing. By testing different parts of the mushroom, the student presents a third, but implicitly stated hypothesis that the different parts have different absorption properties because of differences in their materials. This intent is clear from the observation that sparks the hypothesis where the student talks about different parts of the mushroom. The experiment is well described by the diagram showing the different conditions and parts of the mushroom. The data is qualitative (in pictures), but clearly labeled. It showed how dyed water is taken up by the various structures over time, so the data conveyed accurately even though it is not quantitative. The text associated with a pictures clearly describes the results.

5.1.3.5 Discussion

Poor to Good *(1–2)*. This example was taken from the student report examined above, where the phenomenon of interest was root growth. The student writes:

> *"It seems that, while plants do grow more heartily in nutrient-rich environments, a property that is well known and very much explored, they may not have the ability to sense or specifically "choose" nutrients or make "choices" related to those that would allow them to seek better areas. While I clearly observed one plant growing roots preferentially in nutrient-rich areas, that may only be a function of basic allocation of resources (it could have grown one side or the other), and not an indication of migration since soil would rarely have patches of differing quality that would be so pronounced."*

The experiment did not involve a choice (see above), so any conclusion about choice does not reflect the data. Moreover, although the student did suggest that the experiment does not validate the initial hypothesis about choice (migration), the student offers that this is because the experiment does not replicate natural conditions (a speculation that is not verified), not because the structure of the experiment does not investigate choice. In another case, a student speculated that

> *"differences in light levels affecting photosynthesis change leaf wettability [by changing stomatal opening]"*

The experiment failed to document changes leaf wettability. The student suggested this was because the manipulation was insufficient, and failed to acknowledge the hypothesis might be wrong. Although the data actually showed growth responses in different conditions, the student does not discuss the significance of this data in light of the advantage to the plant, that is, to take advantage of good conditions by growing more. There is no next question. The combination of all these errors resulted in a score at the lower end of the range.

Very Good to Excellent *(3–4)*. This student was concerned about the properties of leaves that may allow them to channel or direct water, with the hypothesis that the leaves preferentially direct water to the base of the plant. The student had two sub-hypothesis that concern whether the impermeable leaf surface directs water to the leaf central groove, and about how the leaf is resistant to forces (impact of rain water) such that it maintains this grooved shape in the rain. The student deals with each sub-hypothesis individually. For the first aspect, the student writes:

> *"From the first outcome, my funneling hypothesis was correct, where the leaf does in fact funnel water down to the center of the plant. It did it so smoothly with the help of the waxy surface... These results show that indeed, the leaf is built the reduce friction so that water is funneled easier to the roots, without damaging the leaf surface, which in turn would affect the photosynthesis properties of the leaf."*

This is a clear conclusion based on the data, and interprets the evidence in light of the advantage to the plant (maintaining photosynthesis). For the second hypothesis, the student observed that the leaf funnels small volumes of water but collapses when large volumes are poured on it. The student writes:

> *"However I discovered that the center support only holds up a certain amount of water. I believe that this mechanism is used to limit the amount of water that can be poured onto the leaf when it rains . . . the structural support of the leaf not only helps limit the amount of water being funneled, but it is also a fail-safe system that helps reduce structure damage to the leaf, when it is overloaded".*

The original hypothesis here did not include any conditions. The student realized that it was not strictly correct, but proposed a reasonable explanation. For both hypotheses, the student discussed the possible advantage, in this case, directing water to the roots, and resisting damage that compromises photosynthesis. From these results, some questions arise:

> *"Why do certain plants have that shape, and others don't? What are the advantages of being "V" shaped versus other forms of leafs [sic]? How does the microstructure of the leaf allow it to perform such supportive tasks?"*

Answering the first two questions would address the specific advantages of these properties as a function of the environment, although they could have been phrased more usefully, such as by identifying specific comparisons or conditions (e.g. wet vs. dry environments). The third question examines specific structures that might contribute to the phenomenon.

5.2 Reliability assessment

After consensus was established among the three teachers, we analyzed the extent to which applying the scoring rubric on the other 27 students reports resulted in consistent assessment. Thus, each one of the teachers independently assigned scores for the remaining 27 reports. Table 3 shows the statistical tests for the inter-class-correlation (ICC) agreement between the three teachers. Assessments of the three teachers were well correlated for each of the criteria and the total score, although some correlations were less robust than others. Thus, criteria 1, 3 and 5 have an acceptable correlation of 0.712 and up, and criteria 2 and 4 have a correlation of 0.654 and 0.655 which is slightly less acceptable.

6. Discussion

Overall, our method produced a scoring rubric that can be used to draw valid and reliable conclusions regarding the success of the second course unit to facilitate student's integrated understanding. Using the rubric allowed teachers from very different disciplines to come to similar assessments, although

Table 3. Results of inter-rater reliability test for each criterion in the scoring rubric. Table gives the correlation, upper and lower confidence limits, and the results of the statistical test, numerator and denominator degrees of freedom, and the p value

Criteria		95% Confidence Interval		F Test with True Value 0			
	Intra-class Correlation	Lower Bound	Upper Bound	Value	df1	df2	Sig
Natural Objects Description	0.712	0.532	0.846	8.326	25	50	0.000
Hypothesis Statement	0.654	0.454	0.810	7.013	25	50	0.000
Literature Search	0.814	0.680	0.904	14.85	25	50	0.000
Informed Experimentation	0.655	0.457	0.811	6.824	25	50	0.000
Discussion	0.793	0.649	0.892	6.824	25	50	0.000
Final Score	0.849	0.730	0.924	19.7	25	50	0.000

some criteria where more difficult to grade consistently than others. The difference in ICC agreement among the three teachers, when comparing grades given for criteria 1, 3 and 5 and to criteria 2 and 4, may be explained by considering the intended learning outcomes represented by these different groups of criteria. Criteria 1, 3 and 5 require description of specific organisms and summarizing specific literature sources using SMF schema. These exercises have been enacted in the course for some time and thus can be considered shared knowledge amongst course teachers. In contrast, hypothesis generation and experimental design using SMF schema are relatively new exercises in the course and introduced formally just recently (in the last year) upon the realization that engineering students need opportunities to learn these skills to understand basic scientific research.

A second, and non-mutually exclusive reason for the differences in ICC agreement relates to discipline-specific expectations of the teachers. Describing an object, executing a clearly defined search strategy, or discussing experimental results may be less affected by disciplinary perspectives than determining whether a hypothesis is logical or appropriate. All teachers attempted to avoid penalizing students for hypotheses or experiments that would be inappropriate for individuals with extensive prior knowledge. However, judgments about performance in criteria 2 and 4 invariably involved perceptions about whether the hypotheses or experiments reflected basic causal reasoning (i.e. are "logical"). Deciding whether a hypothesis is appropriate is thus affected by prior knowledge and traditions of a specific discipline. In particular, biology has often thought to have more context dependency and less universally applicable rules than other fields [48]. This may strongly affect what is considered logical, especially when biologists and engineers have significantly different knowledge bases.

7. Concluding remarks

In this paper we answered calls to facilitate credible assessment of learning in engineering education generally, and of interdisciplinary learning in particular. In that we successfully overcome two of the major challenges in interdisciplinary education—creating common ground between teachers with different epistemological and methodological perspectives when judging students' products, and establishing valid instrument for assessing integrated understanding in specific courses.

The value of our method is that it encapsulated close collaboration between an educational researcher and the course teachers. Specifically, the course-specific operational definition of integrated understanding and related intended learning outcomes were developed by the educational researcher in collaboration with the leading course teacher, and the establishment of performance level descriptions for each learning outcome was developed in collaboration between course teachers who came from different disciplinary backgrounds. This approach can be used by teachers of any other interdisciplinary courses to develop valid and reliable educational assessment.

Another advantage of using the method described here is in increasing teachers' awareness of what their students need to know to improve their integrated understanding in interdisciplinary education courses generally, and those specifically focused on BID. This may help teachers evaluate what student backgrounds are appropriate, or suggest preliminary tests that help teachers guide their students in acquiring the knowledge necessary to promote integrated understanding.

The benefit of close collaboration is also a limitation of this method. The process we went through when constructing and validating the rubric presented in this paper was time consuming. Still, it had significant effect on the clarity of the learning outcomes, and increased the alignment of these with the course learning and assessment exercises. To conclude, despite the time and efforts required to apply this method properly, the improvement in quality of instruction gained by applying it is considerable. We thus highly recommend it to others who wish to establish credible rubrics to assess integrated understanding in their interdisciplinary engineering courses.

Finally, the complete learning and assessment unit we present here can now be applied in similar Biologically-Inspired Design courses. Of note is that both the rubric and the Found Object assessment task will have to be employed together as the validity of the rubric stems from the alignment of the Found Objects exercise with rubric criteria. Furthermore, instructors of other BID courses that co-teach a course will have to go through similar process of applying the rubric to a set of students' performance exemplars to define what reasonable a priori knowledge is, and be prepared to discuss discrepancies that might stem from different expectations in this regard. The teachers who used the procedure presented here made no attempt to reconcile these discrepancies when grading the other reports beyond the initial exemplars' set, which might have increased the reliability of the scoring rubric. Nonetheless, the rubric resulted in consistent assessment by teachers with this level of effort, and consistency may well improve over time as more experience with the rubric would promote consensus among teachers.

The next step in our research project is using the established rubric to evaluate students' performance at the end of the course and compare it with their performance upon concluding the second unit to assess changes in students' integrated understanding.

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Dr. Inbal Flash Gvili is a Post-Doc Fellow in the Department of Science Teaching at the Weizmann Institute of Science. She holds a MSc in Life Sciences from the Weizmann Institute of Science and PhD in Science Education from The Hebrew University in Jerusalem. During a post-doc at the Center for Biologically Inspired Design at Georgia Tech she conducted educational research in collaboration with the teachers of Biologically Inspired Design course for undergraduate students in Biology and Engineering. In her recent work she is conducting collaborative action research with high school and middle school science and engineering teachers focusing on the development and evaluation of teaching and assessment strategies adapted for the teachers' practical needs.

Marc Weissburg, PhD is Professor of Biology and Co-director of the Center for Biologically Inspired Design at Georgia Tech. Dr. Weissburg has been teaching biologically-inspired design for 10 years to a variety of audiences, ranging from undergraduate students in science, engineering, architecture and design, to industry professionals and practicing scientists. He has been active in developing biologically-inspired design pedagogy for K12 programs and informal science learning organizations. Dr. Weissburg also works with various companies to develop biologically-inspired design solutions and embed biologically-inspired design methods into industry design cycles. An ecologist by training, he is using principles derived from ecological network analysis as ways to develop more sustainable resilient infrastructure, and examining how principles of animal navigation may be adapted for use in human technology.

Jeannette Yen, PhD is the Director of the Georgia Institute of Technology's Center for Biologically Inspired Design (CBID). The goals of CBID are to bring together faculty who seek to facilitate interdisciplinary research and education for innovative products and techniques based on biologically-inspired design solutions. CBID participants believe that science and technology are increasingly hitting the limits of approaches based on traditional disciplines, and Biology may serve as an untapped resource for design methodology, with concept-testing having occurred over millions of years of evolution. She has been a Professor of Biology at Georgia Tech since 2001 with a PhD in the environmental science of biological oceanography.

Michael Helms, PhD is a Research Scientist in the College of Computing at Georgia Institute of Technology. Michael holds a PhD from the Georgia Institute of Technology, an MS from DePaul University, and an undergraduate degree from University of Illinois at Urbana-Champaign. He works closely with Center for Biologically Inspired Design at Georgia Tech to build cognitive models of analogical design and computational tools to support biologically inspired design. Recent work focuses on understanding the process of problem formulation and evolution, including the role it plays in analogical evaluation and its effect on creativity.

Craig Tovey, PhD is the David M. McKenney Family Professor for sustainability, energy, and environment leadership in the School of Industrial and Systems Engineering at Georgia Tech. He received an A.B. Magna Cum Laude degree in applied mathematics from Harvard College, and an MS in computer science and PhD in operations research from Stanford University. In addition to doing work in optimization algorithms, probabilistic modeling, and computational complexity, he has pursued interdisciplinary research and teaching in biology, political economy, energy, and sustainability for more than 25 years. His honors include a NSF Presidential Young Investigator award, a National Research Council Senior Associateship, and a university award for interdisciplinary research and teaching. He is a co-founder and co-director of the Center for Biologically Inspired Design at Georgia Tech.