Assessing Students' Integrative Learning in Biomedical Engineering from the Perspectives of Structure, Behavior, and Function

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Abstract – **Learning in biomedical engineering is highly interdisciplinary: students need to integrate concepts between engineering and life sciences, and be able to design and develop technologies with physiological considerations. In this study, biomedical engineering students' artifacts were analyzed in detail according to the structure-behavior-framework (SBF) framework. The SBF framework has been investigated by educational researchers and learning scientists; in particular, the behavioral and functional dimensions were proved to be related to a sophisticated level of understanding of complex systems. Existing research results also indicate that experts (or expert-like learners) show a deeper understanding of the behavioral and functional aspects of systems. In the current study, a 5-level scale comprising structural, behavioral, and functional dimensions of integrated learning was constructed to assess student learning in a biomedical engineering project course. Our results indicate that high achievers and low achievers were different in the behavioral and functional dimensions. The results also indicate significant relationships between behavioral and functional dimensions of learning and students' final course performance. These findings align with existing results in cognitive science and learning sciences on expert-novice differences, which help connecting engineering educational inquiries to the rich body of literature and findings in human learning.**

Index Terms – Biomedical engineering education, Integrated learning, Learning Sciences, Structure-behavior-function (SBF) framework.

INTRODUCTION

The National Academy of Engineering (NAE) projected in *The Engineer of 2020* that tomorrow's engineering graduates would need to *collaboratively contribute expertise across multiple perspectives in an emerging global economy* [1]. Indeed, engineering education in the 21st century emphasizes on not only "know-how" but also "know-why". There exist vast number of works in which innovative pedagogies and constructivist learning environments were implemented in engineering teaching and learning, one can refer to [2] for a number of cases. Recently the research community also actively looks into how engineering students learn. For example, there are studies in assessing engineering students' conceptual and procedural knowledge about thermodynamics [3], as well as the investigation into conceptual understanding in graduate-level engineering and mechanics courses [4].

This work focuses on the biomedical engineering discipline. Learning in biomedical engineering differs from that in other engineering areas by its interdisciplinary nature: students have to integrate concepts in bio-medicine and engineering to design and implement technologies with biomedical considerations. How do engineering students approach design situation and construct new understanding? What are the different kinds and levels knowledge representations engineering students and do they differ among more or less mature students? In this study, a 3-dimensional 5-level assessment scheme was used to assess students' integrative learning in a design project related to ECG recording device and its biomedical applications. Our scheme is derived from the structure-behavior-function (SBF) framework by Geol *et al.* [5]-[6] and the scale for constructive learning by Chan *et al.* [7]. The SBF framework was extensively applied by educational researchers to examine the differences between experts and novices, for example, in their knowledge about complex systems [8]-[9].

The purpose of the current study is to analyze biomedical engineering students' integrative learning from the structural, behavioral, and functional perspectives. It addresses two main research questions:

- Do high achievers and low achievers in integrative learning differ in terms of the structural, behavioral, and functional dimensions of their learning?
- How do students' understandings in structural, behavioral, and functional dimensions predict their course performance?

In answering these questions, we have developed a coding scale based on the SBF framework, and it is used to assess artifacts prepared by students in a guided-project course. The coding results are then mapped against the student grades to analyze possible implications of course assessment activities.

THEORETICAL FRAMEWORK

I. Biomedical Engineering Education

Biomedical engineering is one of the emerging fields in the 21st century. It is a discipline in engineering with a strong medical focus [10]. According to the National Institute of Health (NIH) [11], biomedical engineering aims at promoting biomedical advances to diagnose and treat disease and to prolong a healthy and productive life. Furthermore, *advances in the field are accomplished through interdisciplinary activities that integrate the physical, chemical, mathematical, and computational sciences with engineering principles in order to study biology, medicine, and behavior*. An integrated knowledge base is often essential to address real-world biomedical engineering problems that are complex in nature [12].

II. Integrative Learning

The aim of integrative learning is for students to make connections across disciplines and apply what they have learned to solve more complex problems [13]. Indeed, in a knowledge economy, it is critical for working professionals to be able to recognize the underlying relations between concepts and structures that may seem very different, and to be able to integrate them into some new forms. For example, biomedical engineers need to reconcile practices between engineering and life sciences, which requires cognitive flexibility and true interdisciplinary thinking [14]. Biomedical engineering educators had suggested integrated learning as an appropriate pedagogy [15]. One common integrative learning activity in engineering education is to assign students to work on design projects [16]-[17]. A case for curriculum design and pedagogical implementation of integrative learning in a biomedical engineering course was described in [18].

III. Structure-Behavior-Function Framework

The current study extends the structure-behavior-function (SBF) framework to analyze students' integrative learning in biomedical engineering. Early work on SBF model can be traced back to the works by Geol *et al.* [5]-[6]. They worked on model-based analogy in the field of computer science and artificial intelligence, which involved creating ontologies of useful abstractions by making claims about what kinds of inferences are needed and what kinds of knowledge are required to draw the needed inferences. An early form of SBF model has been proposed in [5], in which the design problem is abstractly characterized as a constrained function-to-structure mapping. In such ontology, the structure of a device is viewed as constituted of components and substances. According to [5] and [6], such substances have locations relative to the components in the device. They also have behavioral properties, such as voltage of electricity, and corresponding parameters. A function in SBF models is represented as a schema that specifies the possible input and output of the device, and any changes to the internal causal behavior of the device due to the input. Later cognitive scientists [9] and [19] offered a simpler view of structure, behavior, and function:

- **Structure** refers to the elements and physical construction of a system
- **Behavior** refers to the dynamic mechanisms and workings that allow the structures to carry out their function
- **Function** refers to the purpose of the system or subsystem

Similar to many complex systems in other areas, biomedical engineering technologies involve heterogeneous components and multiple levels of organization; in addition, their design needs to be driven by the physiological needs and considerations. Therefore learning in biomedical engineering requires a deep understanding of individual components (structure), their characteristics and properties (behavior), as well as their inter-relationship and the overall purpose of the system (function). Here we see assessing student learning using the SBF model will inform about integrative learning in biomedical engineering.

METHOD

I. Subjects

Participants included 28 second year undergraduate students (8 females and 20 males) from a biomedical engineering programme at a university in Hong Kong. They formed a total of 14 groups (12 two-member groups, 1 three-member group, and 1 single member group) to perform project works in biomedical engineering. To allow for a comparison of high achievers and low achievers in the data analysis, an equal number (N = 14) of students in the two categories were identified according to their overall performance in the biomedical engineering course. Similar approach has been adopted by Taraban *et al.* [3]. To reduce bias in coding, the coder was blind to the participants' performance of during the coding process.

II. Procedure

The participants underwent a semester-long guided project course as described in [18]. The course was about the design of a portable electrocardiogram (ECG) monitor from scratch using basic electronic components (op-amp, resisters, and capacitors) and the use of printed circuit board (PCB) techniques to fabricate such a device. Participants were also required to propose a biomedical application and perform the corresponding pilot experiments using their resulting devices. The course consisted of introductory lectures and hands-on tutorials. They were assessed in terms of class participation, initial design exercises, interim demos, and the final presentation and report.

III. Measures

In the current study, two types of data were used in the measurement:

- Scores in structural, behavioral, and functional dimensions obtained by coding the final project reports
- Overall course performance of individual participants

The two data were independent because the coder and the instructor were different persons. In addition, grading of final project reports was done by the course instructor using evaluation criteria other than perspectives under the SBF framework.

Table I shows the scale used for analyzing integrative learning from the three dimensions in the SBF framework. Earlier work on SBF just coded student data into the three dimensions. This study extended the framework using a more detailed framework with five levels of complexity for each dimension. The scale consists of five levels adopted from [7], ranging between the least and the most sophisticated level of learning and integration. The five levels are:

1. **Off-task.** Do not show correct understanding about the problem situation and fail to provide correct solutions;
2. **Retelling.** Simply repeat the contents of existing course materials as the answers;
3. **Project completion.** Satisfy the basic requirements of project assessment;
4. **Problem solving / application.** Solve the problem with suitable approaches and be able to apply the solution to real world situations; and
5. **Knowledge building / innovation.** Innovative, new ideas that are based on sound subject domain knowledge have been generated from the problem solving process.

We used a commonly adopted approach in educational research for the scale development [20]-[21], in which a scale was first developed from initial understanding of the data and be refined into a more objective scale that preserved as much of the intuitive understanding as possible. Student design work reflecting their knowledge representation were coded on the three dimensions (SBF) ranging from lowest to highest level of complexity. A rating at Level 1 to 5 in each of the aspects was converted to 1 to 5 scores, respectively. At the end of the coding process, each report would receive the scores for *structure*, *behavior*, and *function*, each ranged between 1 and 5.

Each participant receives a final course grade at the end of the semester according to their overall performance in the course. The grade was assigned according to multiple assessment criteria including participation during lecture's class discussion, design of the initial circuit for core components in the ECG monitor, device performance and circuitry organization, ability to plan and conduct scientific experience with the resulting device, as well as the soundness and correctness of the biomedical application proposed for the device.

In the current study, the final course grade was converted to a performance score ranged between 1.00 and 4.00 according to the grade point average (GPA) scale, where 4.0 represents an A grade, and 1.00 represents a D grade, respectively.

TABLE I
LEVELS OF INTEGRATIVE LEARNING IN STRUCTURAL, BEHAVIORAL, FUNCTIONAL PERSPECTIVES

Structure	*Behavior*	*Function*
	Level 1: Pre-factual Mentioning	
Misses out critical components in system; or includes irrelevant components	Ignores the behaviors and properties of the components; or states wrong descriptions for the component behaviors	Does not mention about the function and application of the system
	Level 2: Retelling	
Introduces all key system components (protective circuit, virtual ground, INA, and common mode feedback) by copying the descriptions available from the project specification	Correctly states the characteristics and properties of every key system component with references to project specification and materials recommended by the instructor (textbooks, lecture notes, and recommended reference materials)	Repeats the basic function of the system as given in the project specification (e.g. a device for ECG signal analysis)
	Level 3: Project Completion	
Includes level 2 and further elaborates on each of the system components	Includes level 2 and performs simple experiments to validate the expected behaviors with actual measurements	Includes level 2 and be able to propose a simple biomedical application of the resulted circuit, and validates the design with laboratory experiments
	Level 4: Problem Solving / Application	
Includes level 3, also explains and interprets the system structures in accordance to their function in bio-medicine	Includes level 3 and discusses the system behavior in accordance to biomedical application	Includes level 3 and further elaborates on the biomedical application proposed, and links the descriptions to the structure and behavior of the system
	Level 5: Knowledge Building / Innovation	
Includes level 4 and adjusts existing components or introduces relevant new components in the overall structure and justifies their roles from the system's behavioral and functional perspectives	Includes level 3 and leverages on the system characteristics in the design of the proposed biomedical application, and/or takes in consideration of the system constraints in the design of such application	Includes level 4 and adapts or adjusts the system structure to address special functional needs of the proposed application, and evaluates the design with laboratory experiments

RESULTS

I. Descriptive Statistics

Table II lists the mean scores for structure, behavior, and function obtained by the high achievers and the low achievers.

TABLE II
MEANS AND STANDARD DEVIATIONS OF STRUCTURE, BEHAVIOR, AND FUNCTION FOR HIGH ACHIEVERS AND LOW ACHIVERS

	Structure		*Behavior*		*Function*	
Group	M	SD	M	SD	M	SD
Low (N=14)	3.36	0.50	2.71	0.73	2.29	0.73
High (N=14)	3.57	0.51	4.14	0.86	4.29	0.73
Overall	3.46	0.51	3.42	1.07	3.29	1.25

III. Differences in Structural, Behavioral, and Functional Dimensions and Achievement Levels

Analyses were conducted to investigate whether differences existed regarding structural, behavioral, and functional aspects in student artifacts by the high achieving and the low achieving groups. Analyses of variance (ANOVAs) were conducted on the structure, behavior, and function scores. There was no significant difference in structure between the high achieving group and the low achieving group ($p > .05$). However, significant differences were found in behavior, $F(1, 26) = 22.41$, $p < .001$, $\eta^2 = .46$, favoring high achieving group ($M = 4.14$, $SD = 0.86$) over low achieving group ($M = 2.71$, $SD = 0.73$). Significant differences were also found in function, $F(1, 26) = 53.08$, $p < .001$, $\eta^2 = .67$, favoring high achieving group ($M = 4.29$, $SD = 0.73$) over low achieving group ($M = 2.29$, $SD = 0.73$).

IV. Relationships between Structural, Behavioral, and Functional Dimensions and Overall Performance

Table III shows the zero-order correlations for structure, behavior, function, and performance scores. There was a strong association between performance and behavior ($r = .55$, $p < .01$), as well as performance and function ($r = .66$, $p < .001$). There was however, no significant relationship existed between performance and structure ($p > .05$). There were a strong positive correlation between behavior and function ($r = .85$, $p < .001$). There were also significant correlations between structure and behavior ($r = .44$, $p < .05$), and between structure and function ($r = .43$, $p < .05$).

TABLE III
ZERO-ORDER CORRELATIONS FOR STRUCTURE, BEHAVIOR, FUNCTION AND PERFORMANCE (N = 28)

Variable	*Structure*	*Behavior*	*Function*
Behavior	.44*		
Function	.43*	.85***	
Performance	.32	.54**	.66***
*(Note: *p < .05; **p < .01; *** p < .001)*			

To further explore the relationships between structure, behavior, function, and performance, a hierarchical multiple regression analysis was conducted to examine the contribution of the behavioral and functional dimensions to the overall performance in integrative learning (Table IV). The hierarchical multiple regression analyses were conducted with the structure variable entered first, followed by the behavior variable and lastly by the function variable.

TABLE IV
UNSTANDARDIZED AND STANDARDIZED REGRESSION COEFFICIENTS FOR HIERARCHICAL REGRESSION ANALYSIS PREDICING PERFORMANCE (N = 28)

Variable	*B*	*β*	R^2	R^2 Change
Step 1				
Structure	.81	.32	.10	.10
Step 2				
Behavior	.61	.51	.32	.21**
Step 3				
Function	.69	.67	.44	.12*
*(Note: *p < .05; **p < .01)*				

From the regression, structure alone does not have significant contribution to the prediction of performance ($R^2 = .10$). Nevertheless when behavior scores were entered, R^2 changed to .32, adding 21.1% of variance, and finally when function scores was also entered, R^2 further increased to .44, adding 12.2% variance. The results demonstrated that both behavioral and functional dimensions predict final course performance significantly.

DISCUSSION

This study assessed students' integrative learning in biomedical engineering. A scale was constructed under the SBF framework and consisted of 5 distinct levels of sophistication of learning and integration. In this section, we discuss our findings and their implications to biomedical engineering education and integrative learning. Nevertheless, the principles can be extended to engineering education in general.

I. High Achievers and Low Achievers are Different in the Behavioral and Functional Dimensions of Their Learning

The first research question examined whether high achievers and low achievers differ in terms of the structural, behavioral, and functional dimensions of their learning. Consistent with the existing cognitive science and learning sciences literatures on the SBF framework (e.g. [8] and [19]), high achievers and low achievers in our study differ significantly in the behavioral and functional dimensions. According to Hmelo-Silver *et al.* [8], advanced recognitions in behavior and function offer an understanding of the deep principles for the experts (or the high achievers in our case) that organize their overall knowledge of the system. From our study, we found that the high achievers were relatively stronger in integrating between their knowledge in electrical circuitry and biomedical applications, especially in the behavioral and functional dimension. In addition, our findings also consistent with the existing literature in a sense that high achievers and low achievers do not demonstrate clear difference in terms of the structural dimension. Hmelo-Silver *et al.* [8] suggested that structures are the most recognized aspects of a complex system for novices (or the low achievers in our case). In our study, both high and low achieving students were able to describe the electrical circuitry technically accurate and detailed, however, only the students from the high achieving group demonstrated their ability to apply sound technical knowledge about the electric circuitry to propose non-trivial applications in bio-medicine.

II. Behavior and Function Contribute Significantly to Performance

Our second research question investigated the relationships between the structural, behavioral, and functional dimensions of student learning and the final course performance. The results indicate that both of the behavioral and functional dimensions in integrative learning were correlated significantly and positively with students' final performance in the course, with high achievers obtained significantly higher scores in both behavior and function. The findings also show that behavior and function were significantly correlated to each other. Here the results suggest that an understanding of the structure aspects of a system is the basic condition for achieving the learning outcomes. Indeed both the low achievers and the high achievers attained similar scores in the structural dimension. However, good performance in an integrative learning course also requires a well understanding and learning in both the behavioral and functional aspects. Regression analysis indicated that behavior and function aspects predict performance. As Hmelo-Silver *et al.* pointed out [8], understanding the behaviors and functions of a system indicates a more elaborate network of concepts and underlying principles about the system. For biomedical engineering students, in particular, they have to master the concepts between electronic engineering and the life sciences disciplines [15], the ability to identify interrelationships between system components and physiological applications is thus critical for the high achievement.

III. Implications to Engineering Education and Future Works

Collins *et al.* [22] suggested that organizing learning around deep principles such as structure, behavior, and function might enable students to understand new complex systems they encounter. Indeed, technologies nowadays are ubiquitous and pervade into every aspects in life. The systems, although looking more and more user-friendly and simple apparently, often becoming more complex in their fundamental nature. The SBF framework helps guiding the teachers and learners to look behind the scenes at phenomena that are not readily perceptually available [8]. The 3-dimensional framework with different levels further provides some kinds of rubrics to indicate depth and complexity for each dimension. These could be pointers and descriptors for scaffolding student learning. Such principles can be extended to engineering teaching and learning as well. With the support of our research findings, we see the prospects of connecting integrative learning in engineering education to the well-established cognitive science and learning sciences research framework on SBF. In particular, the following are potential areas that worth investigation:

- How will the scale proposed in the current study be modified for other subject areas of engineering?
- How do engineering students develop more sophisticated representations focusing on behavior and function (not just structure) and how to enhance student learning and development in such direction?
- How to enhance students' understanding and learning in the behavioral and functional dimensions of engineering subject contexts?
- How do the pedagogical design of integrative learning which involves integration between engineering and other disciplines (e.g. biomedicine, geology, and education) be further enriched by the theoretical framework of SBF?
- How to incorporate the SBF framework with different levels into the curriculum design and assessment of integrative learning in engineering education?

IV. Limitations

Our current results are subject to the following limitations:

- The sample size is relatively small (N = 28) for rigorous statistical analysis. Therefore the findings should be treated with caution. Nevertheless, the scheme proposed in the current study can be applied to the evaluation of student learning with a larger sample sizes.
- Since individual participants were nested in groups, on-going work is being undertaken to perform the statistical analysis with multilevel modeling. In addition, multiple coders will be employed to further increase the reliability of the coding. Inter-rater reliability will also be examined.
- The current study only includes quantitative analysis on student learning. Qualitative analyses (such as interviews and instructor's observation) have been planed as follow-up studies.

CONCLUSION

This study is established on the conceptual framework of SBF and integrative learning. A 5-level scale for assessing student learning in the structural, behavioral, and functional dimensions was constructed. The scale was used to assess students' learning in a project course in biomedical engineering. The results aligned with findings from existing literatures in cognitive science and learning sciences. The two research questions in the study were answered, that

1. High achievers and low achievers differed in behavioral and functional dimensions of their integrative learning.

2. Behavioral and functional dimensions of learning contribute significantly to the overall performance in integrative learning.

To conclude, the current work contributes to engineering education in the following sense:

- It contributes an exemplar for assessing engineering learning using the well-established SBF framework with effects on performance; thus highlighting the importance of educating students the complexity of SBF.
- Our results align with existing findings from cognitive and educational research, noting the need to consider student cognition that help connecting engineering educational inquiries to the rich body of literature and findings in human learning.
- Through a concrete example in biomedical engineering, the framework provides the possibilities for integrating learning with assessment – the different levels of SBF can be used for assessment as well as criteria for engineering students to move towards more expert-like learning thus enhancing the outcome of engineering teaching and learning.

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