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Assessing Integrative Learning among Engineering Students Using a Structure-Behavior-Function Framework

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1. Introduction

Society now moves forward rapidly along with technology. Technological advancement also brings about a paradigm shift in education (Bransford, Brown & Cocking, 1999). One needs to be equipped with competency and new knowledge to deal with complex issues in the real world (Drucker, 1999). Certainly engineers have made significant contributions. However, a dilemma now arises for the engineering discipline to think about how to proactively develop the engineers of tomorrow, who carry a mission to sustain the technology trajectory. According to the US National Academy of Engineering, “*engineering graduates of tomorrow need to collaboratively contribute expertise across many perspectives in an emerging global economy that is fueled by rapid innovation and marked by an astonishing pace of technological breakthroughs”* (NAE, 2004). The UK Royal Academy of Engineering also summarized in a study (Spinks, Silburn, & Burchill, 2006) that “*the engineering industry now looks for engineers who take a role as an integrator who can operate and manage across technical and organizational boundaries*”. To this, engineering educators needs to nourish *deep learners* for the new economy. Engineering education research, however, has long been focusing heavily on teaching and curriculum development (Streveler, & Smith, 2006). Haghighi (2005) also called for a broader community of engineering educators to shift from teaching to *learning*. Here we see the prospect of Learning Sciences in informing theories and practices of engineering learning, and the promise of interdisciplinary collaborations between engineering educators and learning scientists to enhance engineering learning.

This proposal explores the potential of the structure-behavior-function (SBF) framework in assessing and fostering engineering students’ learning. The framework, first developed in engineering (Goel, & Chandrasekaran, 1989; Goel *et al*., 1996) has been adopted and tested by learning scientists in complex systems (Hmelo, Holton, & Kolodner, 2000; Hmelo-Silver, & Pfeffer, 2004; Hmelo-Silver, Marathe, & Liu, 2007). While many progress has been made on curriculum design in engineering education, our approach attempts to bridge engineering with Learning Sciences through assessing engineering students’ knowledge structure and knowledge processing to promote students’ integrative learning. In particular, a framework that distinguishes different levels of integrative learning in engineering was defined by extending the SBF model with perspectives of constructive learning (Chan *et al*., 1992) and knowledge building (Chan, Burtis, & Bereiter, 1997). In the following, we describe the background of the framework, provide information on preliminary studies on the validity of the framework, and we also discuss potential applications and research in engineering learning that can be derived.

2. Background

2.1. Integrative Learning in Engineering

Technologies nowadays have become pervasive and are widely implemented in almost every aspect in both real and virtual worlds. Such implementation also brought about new design considerations. For example, on top of conventional requirements such as robustness, soundness, and correctness, there are also new engineering design criteria such as reusability, sustainability, and environmental friendliness. Golshani, Panchanathan, and Friesen (2000) argued that “*students are not exposed to the basics and the complete picture of this important field* (of engineering)”. Engineering curricular had ever been urged to become “*more board based and interdisciplinary*” (Engineering Council, 1988). Integrative learning has been suggested as an appropriate pedagogy for engineering teaching and learning (Froyd and Ohland, 2005; Heywoord, 2005: Ch 8). The aim of integrative learning is for students to make connections across disciplines and apply what they have learned to solve more complex problems (Hubern, & Hutchings, 2004). In a knowledge economy, it is critical for engineers to be able to recognize the underlying relations between concepts and structures, and to be able to integrate them into some new forms. Such structures may seem very different apparently. For example, biomedical engineers need to reconcile practices between engineering and life sciences, which requires cognitive flexibility and true interdisciplinary thinking (LaPlaca, Newstetter, & Yognathan, 2001).

One common integrative learning activity in engineering education is to assign students to work on design projects (Dym *et al.*, 2005; Foulds, Bergen, & Mantilla, 2005). For example, in an integrated course for freshmen at Arizona State University, introductory engineering concepts were integrated with coursework in English composition, rhetoric, calculus, and physics (Roedel *et al*., 1995, 1997). Another case for curriculum design and pedagogical implementation of integrative learning in a biomedical engineering course was described (Yu *et al*., 2009). Studies on integrated programs revealed that integration helps students understand the connection between engineering and different disciplines, and enabled them to synthesize multidisciplinary solutions (Al-Holou *et al*., 1998). Olds and Miller (2004) also reported from a study on first-year integrated engineering curriculum that interactions with faculty and peers were a kind of critical learning experience. While most studies on integrative learning in engineering focus on curriculum and pedagogical design, there are still relatively few works about how to develop the conceptual understanding provided the grammar of the subjects (Heywood, 2005: p. 217). The current study therefore responses to such need by examining assessment innovation as well as exploring how to enhance integrative learning through assessing engineering students' knowledge structures and constructive processing.

2.2. Structural-Behavior-Function (SBF) Framework

The SBF framework was first used in artificial intelligence in computer science to provide vocabulary for describing systems (Goel *et al*., 1989; 1996). Early form of SBF model includes the KRITIK system (Goel & Chandrasekaran, 1989), which was an intelligent tutoring system for learning how device work. Goel *et al.* (1996) further elaborated that the structure of a device was viewed as constituent components and substances, and had locations relative to the components in the device. The behavioral properties of a device were reflected by characteristics such as voltage of electricity and corresponding parameters. A function in SBF models is represented as a schema that specifies the behavioral state the function takes as input, the behavioral state it gives as output, and a pointer to the internal causal behavior of the design that achieves the function.

As SBF describes a system's multiple interrelated levels and its dynamic nature, learning scientists have suggested using SBF to analyze complex systems (Hmelo-Silver and Pfeffer, 2004). They also 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 components to carry out their function; and
- **Function** refers to the purpose of the system or subsystem

Table 1 gives a simplified analysis of a typical computer system in SBF terms as adopted from the perspective of Hmelo, Holton and Kolodner (2000).

Table 1. Simplified Structure-Behavior-Function Model of a Computer System.

Structure	*Behavior*	*Function*
• Web server	• Receive HTTP requests and response with corresponding resources and services	• Host web contents and act as a web interface between the client and the system
• Application server	• Execute procedures (e.g. scripts, routines, programs) according to the requests propagated from the Web server	• To provide and support computational logics of the system
• Relational database	• Store data according to predefined data structure and tables. Supports data searching (e.g. using SQL commands) and relational operations	• Store user and system data. Return data according to the search command issued by the Application server

Hmelo-Silver *et al.* (2000, 2004, & 2007) showed that structures are the most cognitively available level of a complex system for novices, and experts differ from novices by organizing their knowledge of the system with deep principles at the behavioral and functional levels. Perkins and Grotzer (2000) also suggested that students tend to miss the connection within the system and the complex causal relationships. One possible cause is that learners tended to pay attention to the saliently available structure rather than the underlying function (Hmelo-Silver and Pfeffer, 2004). Goel and Chandrasekaran (1989) suggested that the emphases of structures, functions, and behaviors of systems, together with the connections between those parts, allows for effective reasoning. Hmelo-Silver, Marathe, and Liu (2007) further suggested using SBF as a conceptual representation can provide a deep principle useful for thinking and learning about complex systems.

3. Levels of Integrative Learning in SBF Perspectives

Engineering students need to work on projects involving complex systems but often they focus on surface features and procedural knowledge where learning is fragmented. SBF will provide a useful scheme in assessing students' knowledge structures; we further elaborate the SBF scheme with levels of knowledge processing to unveil students' models of understanding. Table 2 shows a scale that distinguishes levels of integrative learning from the three dimensions in the SBF framework (Chan & Chan, in preparation). There are 5 levels of complexity for each of the structural, behavioral, and functional dimensions, ranging between the least and the most sophisticated level of learning and integration. The 5 levels were identified based on Chan *et al.*'s examination on constructive learning (1992) and knowledge building (1997) when students are engaged in processing scientific information. They are:

1. *Off task:* does not show an understanding about the subject knowledge contents in the disciplines
2. *Repeat of information:* correctly repeats the information already available in texts and project specifications; does not show any integration between disciplines
3. *Correctness and soundness:* be able to provide answers to the questions given in the project specification (attainment at this level is often regarded as having achieved the basic requirements, though little or no integration among disciplines is shown)
4. *Problem solving / integration:* tackles the problem from the perspectives of structure, behavior, and function; and be able to integrate knowledge for coherence
5. *Extrapolation / knowledge creation:* understands the underlying deep principles across problems or situations and be able to integrate knowledge in multiple domains to formulate new problems

The above 5-levels of integrative learning are further elaborated in Section 3.1 to 3.5 below.

3.1. Level 1-Off Task

At level 1, learners do not show an understanding about the subject knowledge contents. For the structure aspect, a rating of Level 1 is assigned to contents that had missed out one or more of the critical components required in the system, or included components that are irrelevant to carrying out the system function. For behavior, these correspond to the ignorance of the behaviors and properties of the component, or having stated wrong descriptions for the component behaviors. For function, artifacts that do not mention anything about the function and applications of the system will be considered as Level-1.

3.2. Level 1-Repeat of Information

At Level 2, learners correctly repeat existing information available in texts and project specifications. Typical artifacts at Level 2 include those that simply copy a diagram and restate the descriptions from the project specification without giving the elaborations of their own. Other examples are the inclusion of long paragraph of information about components that are saliently available from the World Wide Web (such as the Wikipedia) but without further elaboration. This principle applies to the structure, behavior, as well as function aspects. It should also be noted that while Level 1 works involve wrong or irrelevant conceptions and information, Level 2 works involve a direct retelling of facts and information that have already been widely available or easily accessible. At Level 2, the extent to which a piece of information is processed is greater than Level 1, but still shallow. In fact, students often show detail retelling in their assignments, examination answers and project reports.

3.3. Level 3-Correctness and Soundness

Artifacts that reflect an attainment of Level 3 provide answers to the questions given in the project specification, which indicated sufficient comprehension of the problem situation and provided the sound solution(s). Attainment at this level is often regarded as having achieved the basic requirements, though little or no integration among structure, behavior, and function dimensions is shown. It is worth noted that in many of the conventional assessments, answers attaining Level 3 will normally receive full scores or equivalent. Nevertheless we expect "something more" for integrative learning.

3.4. Level 4-Problem Solving / Integration

Level 4 artifacts tackle the problem from the perspectives of structure, behavior, and function, and are able to integrate knowledge for coherence. They indicate a connection between the given problem situation and existing subject knowledge, and the application of the subject knowledge as learnt from the lectures to attempt to solve the problem. Attempts are also made to modify existing structure and behavior to achieve new functions, that is, learners are able to extrapolate from structure and behavior in the engineering domain and propose applications in another domain to achieve integration.

3.5. Level 5-Knowledge Creation / Innovation

This is the most desirable level for student integrative learning. Learners attaining this level understand the underlying deep principles across problems or situations and be able to integrate knowledge in between structure, behavior, and function (which involves multiple domains) to formulate new problems. It corresponds to an extension of students' prior knowledge as well as subject knowledge taught in the lectures. At this level, new knowledge is built as a result of the awareness of the insufficiency of current knowledge and given information in achieving an optimal solution for the problem situation. Learners achieving Level 5 not only comprehended the lecture materials and problem situation thoroughly, but also knew how to inquire and explore additional information and resources so as to provide the best answer – although there is no single best answer for the integrative project learning. Achievement at Level 5 also requires the ability to consider and relate the structure, behaviors, and functions aspects when approaching the problem.

Table 2 below provides a matrix that summarizes the 5 levels of integrative learning in structure, behavior, and function dimensions.

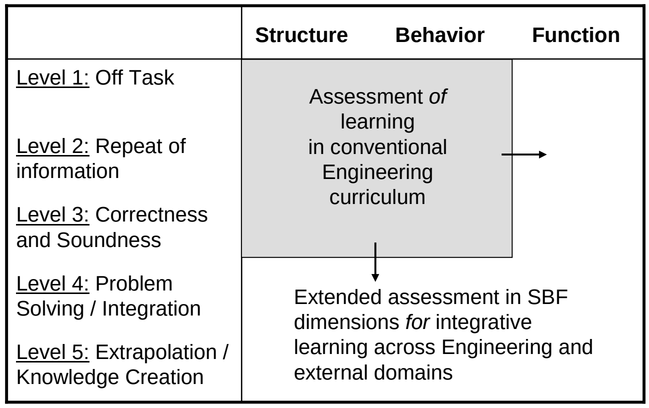
Table 2: Levels of integrative engineering learning in structure, behavior, and function dimensions.

Structure	*Behavior*	*Function*
	Level 1: Off Task	
• 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: Repeat of Information	
• Introduces key system components 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	• Repeats the basic function of the system as given in the project specification (e.g. a device for ECG signal analysis)
	Level 3: Correctness and Soundness	
• Further elaborates on each of the system components	• Performs simple experiments to validate the expected behaviors with actual measurements	• Be able to propose a simple biomedical application of the resulted circuit, and validates the design with laboratory experiments
	Level 4: Problem Solving / Integration	
• Further explains and interprets the system structures in accordance to their function in bio-medicine	• Discusses the system behavior in accordance to biomedical application	• Elaborates on the biomedical application proposed, and links the descriptions to the structure and behavior of the system
	Level 5: Extrapolation / Knowledge Creation	
• Includes level 4 and adjusts existing components or introduces relevant additional components in the overall structure and justifies their roles from the system's behavioral and functional perspectives	• Includes level 4 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

4. Implications to Engineering Learning

In a report from the US National Research Council committee on assessment, Pellegrino, Chudowsky, and Glaser (2001) commented that “*most educational tests measure knowledge of basic facts and procedures to produce overall estimates of proficiency for an area of the curriculum*”. Although their report is in the context of school education, many engineering educators indeed have also taken similar view (Heywood, 2005: p.417). Here we see that lower levels (Level 1 to 3) structure, being most saliently observable, is relatively easy to justify about its correctness. In addition, ability to comprehend behavior as at lower levels (Level 1 to 3), which involves mostly procedural knowledge, is also commonly adopted as questions for assessments in engineering courses. Function, however, usually involves the transfer or application of the engineering subject knowledge into another domain. Therefore the later is often considered as out of syllabus only included as a “bonus question” in assignments and examinations. Yet we see that *function* is indeed an important dimension for assessing students’ integrative learning. Compare to our proposed rubric (Table 2), conventional tests and assessments in engineering teaching and learning mostly involve the structure and behavior dimensions at Level 1 to 3. Specifically, they only covers 6 of the cells reside at the upper left hand corner of the 5-level × 3-dimension matrix in Table 2. There is a need for extending the assessment *of* learning in conventional engineering curriculum both horizontally and vertically into an integrative assessment scheme *for* learning across engineering and external (*application*) domains (Figure 1).

Figure 1. Relationship between conventional assessment of learning in engineering and the proposed assessment



for integrative learning in SBF dimensions.

Collins *et al.* (1993) 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 teachers and learners to look behind the scenes at phenomena that are not readily perceptually available (Hmelo-Silver, & Pfeffer, 2004). The 3-dimensional framework with different levels further provides some kinds of rubrics to indicate depth and complexity for each dimension, as well as defining desirable learning outcomes for domains integration. In particular, how the function demanded in a discipline can be fulfilled by sound and correct construction of materials and components (structure), as well as the utilization of the components’ behavior according to engineering principles. These different levels could also be pointers and descriptors for scaffolding students’ understanding and integration in engineering learning.

Olds, Moskal and Hiller (2005) concluded in the paper about the importance of assessment in engineering education that “*the ultimate purpose of engineering education assessment (or any type of evaluation) should be to improve student learning, which begins with setting objectives and renews itself with each assessment activity*”. Indeed, assessment not only plays a role for measuring learning but also scaffolding learning (Black & Wiliam, 1998; Shepard, 2000). The proposed SBF assessment framework distinguishes different levels of sophistication of learning achievements in the structure, behavior, and function. It also aligns problem solving, knowledge creation and cross-domain integration to higher levels of achievement of integrative project learning. In this way, engineering educators can be informed about how to design project works that provoke students’ integrative learning.

5. Preliminary Findings

The authors and collaborators have ever applied the proposed SBF framework to assess engineering students’ learning (Chan & Chan, 2010; Chan, Yu, & Chan, 2010). Here we present results from our previous studies in two contexts: (1) computer system modeling as complex systems learning and (2) biomedical engineering.

5.1. Study One: Complex Systems Learning

A basic version of the SBF framework was employed for assessing engineering students’ project design (Chan & Chan, 2010). The study investigated how engineering undergraduates learned about computer system modeling in a collaborative inquiry-based learning environment. Specific research questions were:

1. To investigate how students learn about computer modeling using the structure-behavior-function (SBF) framework for understanding complex system; and
2. To examine the relationships between collective and individual learning, specifically to investigate the relations (SBF) identified in students’ collaborative group work with their subsequent individual performance.

The participants were 124 engineering undergraduates (104 males, 20 females) at the second to the third year (70 second year students, 54 third year students). The participants took a course for computer simulations and system modeling. These participants formed into groups of 3 to 5 engaging a collaborative-inquiry project about capacity sizing for an imaginary trading system. There were 32 groups in total. Data sources included students' collaborative group progress reports (collaborative understanding) and individual learning based on students' examination results. A learning environment designing for collaborative inquiry for learning of computer system modeling was developed. Student groups were asked to simulate working as consulting companies and assigned different roles among the group members such as project manager and analyst programmers.

Students' understanding of computer system modeling as complex system in collaborative work was coded using a single level SBF framework. The coding scheme identified a target list of the trading systems structures and a list of corresponding behaviors and functions. Each group project report was coded for evidence of the presence of SBF concepts. Multi-level statistical analyses indicated that there are few effects of gender; there were no effects of *structure*, but students' collaborative understanding of *behavior* and *function* significantly predicted students' individual performance.

5.2. Study Two: Integrative Learning in Biomedical Engineering

In a separate study (Chan, Yu, & Chan, 2010), the framework in Chan and Chan (2010) was extended to a 5-level × 3-dimension matrix for assessing integrative learning in biomedical engineering contexts. The framework presented in the current work is a generalized version of the proposal from Chan, Yu, & Chan (2010). Two main research questions were addressed:

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

Participants in Study 2 included 28 second year undergraduate students (8 females and 20 males) from a biomedical engineering programme. They formed a total of 14 groups to perform project works in biomedical engineering. A semester-long guided project course which consisted of introductory lectures and hands-on tutorials was conducted. The subject contents was about designing 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. They were assessed in terms of class participation, initial design exercises, interim demos, and the final presentation and report. Measurement data included scores in structural, behavioral, and functional dimensions obtained by coding the final project reports, and the overall course performance of individual participants.

Zero-order correlation results showed that structure, behavior, and function were all positively related to course performance. Furthermore, hierarchical-level multiple regression analyses were conducted with the structure, behavior, and function as group-level variables and performance as individual-level variable. Results showed that group-level structure alone does not have significant contribution to the prediction of performance. Nevertheless both behavioral and functional dimensions predict final course performance significantly.

These preliminary results align with existing findings 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. These evidences also support the validity of the proposed framework and suggest various implications and further lines of research for innovation.

6. Concluding Remarks: Next Steps for Research and Practice

Reacting to the calls and needs in engineering learning the SBF theory, being connected to conceptual representation (Hmelo-Silver, Marathe, and Liu, 2007), deep principles (Collins *et al.* 1993), and complex systems understanding (Hmelo, Holton, & Kolodner, 2000; Hmelo-Silver, & Pfeffer, 2004), may provide an important approach to address various areas in engineering learning. In particular, the extended SBF framework proposed may contribute to advances in engineering research and practice, for example:

1. Use the SBF framework to characterize and assess engineering student learning (Chan, & Chan, 2010; Chan, Yu, & Chan, 2010); to identify different models of understanding; and to test such association with related variables
2. As an scale and instrument to compare student learning and understanding under different pedagogies, and to examine student changes after intervention studies
3. Adapt the framework for assessment that scaffolds constructive integration and learnin in different and related domains

4. Select student artifacts at various SBF profiles, and to illustrate how different students' models can help teachers understand more about their student learning (barriers and precursors)
5. Involve engineering university teachers to adapt the framework into rubrics for assessing their students' understanding (ongoing work being undertaken)
6. Engage engineering students to use the framework for self- and peer-assessment

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