World Transactions on Engineering and Technology Education
Vol.5, No.1, 2006

A structured approach to developing learning objectives and assessment tools for an engineering course to enhance the process of learning

Sindhu R. & Nalam J. Rao

Indian Institute of Science
Bangalore, India

ABSTRACT: The instructional design of a course aims at achieving some well stated learning objectives. Learning objectives are statements of what students should be able to carry out in order to demonstrate their mastery of a course and the desired skills. The learning objectives in the cognitive domain are classified into six levels by Bloom. However, the categories of knowledge specific to engineering add a second dimension to these learning objectives. Vincenti identified six categories of engineering knowledge as fundamental design concepts, criteria and specifications, theoretical tools, quantitative data, practical constraints and design instrumentalities. Objectives and assessment instruments guide an instructional designer in selecting the content, developing an instructional strategy, and choosing an assessment process. The learning objectives can best be exemplified through a set of problems, graded as per the number of Vincenti's categories addressed, under an identified Bloom's category. In this article, the authors present a structured approach to developing the learning objectives assessment instruments within the context of a Bloom-Vincenti taxonomy for a first course on digital systems.

INTRODUCTION

The instruction for a course is usually designed to achieve some well stated learning objectives. A learning objective is a statement of what students should be able to perform after completing the course. The most commonly used taxonomy of the cognitive domain for creating learning objectives is due to Bloom [1]. It identifies six stages, not necessarily in strict hierarchical order, of cognitive development (recall, comprehension, application, analysis, synthesis and evaluation). While this taxonomy is used at all levels of learning, it does not specifically address the issues related to those categories of knowledge that are specific to different disciplines. When these categories of knowledge are not explicitly addressed when designing instruction, more specifically at the time of preparing learning objectives, there is every possibility of some of these categories of knowledge being ignored. One categorisation of engineering knowledge is due to Vincenti [2]. Vincenti identified six categories of engineering knowledge as follows:

- Fundamental design concepts;
- Criteria and specifications;
- Theoretical tools;
- Quantitative data;
- Practical constraints;
- Design instrumentalities.

Rao and Sindhu have proposed a framework that combines Bloom's taxonomy and Vincenti's categories of engineering knowledge to prepare learning objectives for engineering courses [3]. Bhat and Rao have suggested a framework for preparing the learning objectives for a course on control systems within the Bloom-Vincenti framework [4].

There are three main components of a learning objective: *verb* (specify action, measurable), *condition* (condition under which task to be performed) and *criterion* (accuracy). Different techniques of writing objectives have been proposed by different educationists; two of them are commonly used. One is proposed by Mager and the other proposed by Gronlund. Mager-type objectives are very much precise and must have all three components, which require an unduly large number of objectives to be prepared so as to ensure that the learning by the student is complete from the point of view of the instructor [5]. To overcome such difficulties, Gronlund suggested a system of writing objectives at two levels [6]. He suggested that the first level should define general objectives followed by sample specific behavioural objectives at the second level. The teaching should be directed towards the achievement of general objectives whereas sample specific objectives indicate the scope of the learning.

Assessment instruments form the basis for students to understand the proficiency they should achieve for the stated learning objectives. They also serve as a vehicle for continuous improvement. Students perceive the relative importance of the contents of the course only on the basis of assessment instruments. The manner in which students engage with a subject can readily be altered by changing the assessment instruments. Students mainly put their efforts into meeting such assessment requirements [7][8].

It has often been found that instructors find it more convenient to express learning objectives more through those problems that students should be able to solve. Therefore, assessment instruments could be used to express the Gronlund's second level learning objectives. These learning objectives can be suitably modified when there is agreement regarding those problems that are proposed to be used for assessment. Consequently, the design of assessment instruments takes the centre stage in the process of instructional design. In this article, the authors present a structured approach for ensuring that assessment instruments are designed as per the learning objectives identified in the context of Bloom and Vincenti.

INSTRUCTIONAL DESIGN

Meaningful learning occurs when a learner has a knowledge base that can be used with fluency to make sense of the world, solve problems and make decisions. Instructional design refers to the process of the analysis of learning needs and goals, and the development of a delivery system to meet those needs. It includes the development of instructional materials and activities, as well as the tryout and evaluation of all instruction and learner activities.

Most instructional design models recognise the *identification of learning objectives* and the *development of assessment instruments* as two important steps in instructional design. However, different models propose different sequencing of these steps. For example, Dick and Carey's model specifies that the *development of assessment instruments* should be carried out immediately after the *identification of learning objectives* [9]. Reiser and Dick's model, which reflects class-room activities, identifies the *development of assessment instruments* as an activity that should be undertaken many steps later to the *identification of learning objectives*. It is proposed here that these two tasks, namely, the *identification of learning objectives* and the *development of assessment instruments*, should be undertaken in a structured approach in the case of courses on engineering subjects because of the nature of engineering knowledge.

THE NATURE OF THE LEARNING OBJECTIVES OF AN ENGINEERING SUBJECT

In order to optimise the effectiveness of instructional design, it is important to make the design conform to important principles of learning and assessment, yet also fit the needs, skills and resources of teachers, learners and their community. The most popular classification of learning objectives in the cognitive domain is as per Bloom's taxonomy. Bloom identified six levels within the cognitive domain, from the simple recall or recognition of facts, as the lowest level, through increasingly more complex and abstract mental levels, to the highest order, which is classified as evaluation. The six levels are recall, comprehension, application, analysis, synthesis and evaluation. However, learning objectives prepared as per Bloom's classification do not necessarily meet the needs of courses in engineering.

Engineering education became predominantly *engineering science* oriented after the 1950s, and *engineering* itself was eventually purged out. Several attempts are being made to restore *engineering* to engineering education. For example, 3a-3k criteria, as defined by ABET 2000, is an attempt in this direction. While these criteria certainly serve the purpose of bringing the attention of the instructor to all the relevant engineering aspects of an engineering subject, they do not provide a structured approach to create learning objectives. Such an approach can be provided by identifying the different categories of engineering knowledge. Vincenti provided such classifications as follows:

- Fundamental Design Concepts (FD): Operational principles of the devices. Operational principles also exist for those components within a device;
- Criteria and Specifications (CS): It is necessary to translate qualitative goals for the device into specific, quantitative goals. Design criteria vary widely in perceptibility. The assignment of values or limits is usually (but not always) particular in design, and is best looked upon as part of the design process;
- Theoretical Tools (TT): Mathematical tools, physical principles and theories that are based on scientific principles but motivated by, and limited to, a technologically important class of phenomena, or even to a specific device. This includes an assortment of theories that involve some central and *ad hoc* assumptions about phenomena crucial to the problem that may be termed as phenomenological theories. Quantitative assumptions are introduced for calculative expedience;
- Quantitative Data (QD): Descriptive (physical constants) and prescriptive (how things should be) data;
- Practical Constraints (PC): These represent an array of less sharply defined considerations derived from experience in practice, considerations that frequently do not lend themselves to theorising, tabulation or programming into a computer;
- Design Instrumentalities (DI): These refer to the procedural knowledge. Instrumentalities of the process include the procedures, ways of thinking and judgemental skills by which it is carried out.

THE CREATION OF LEARNING OBJECTIVES

The following procedure is proposed to prepare the learning objectives of a course.

1. Identify the learning objectives of the course at the first level of Gronlund as per Bloom's taxonomy;
2. Identify the specific categories of knowledge from Vincenti that should be addressed with regard to each learning objective identified in Step 1;
3. Prepare a large number of instruments (question bank) that would assess the mastery of each learning objective and a subset of the Vincenti's categories as chosen by the instructor for that objective;
4. Sample questions, graded as per some chosen subsets of Vincenti's categories, are presented as sample learning objectives from Gronlund's second level;
5. The topics of the course should then be organised into well defined modules that take into account the sequencing and interrelations of the topics. Steps 1 to 5 should be repeated at the level of modules.

It should be noted that there are no unique ways to implement these steps. The proposed process sequence is presented with respect to the first course on digital systems that is offered in many engineering programmes around the world.

THE DEVELOPMENT OF LEARNING OBJECTIVES AND ASSESSMENT TOOLS FOR A COURSE ON DIGITAL SYSTEMS

Consider some learning objectives for a course on digital systems, with several examples listed below.

Sprinkler System

- Bloom's cognitive domain level is application;
- Learning objective for Gronlund first level: Design a digital circuit for a given application;
- Learning objective for Gronlund second level (sample behavioural objective): A sprinkler system is to be controlled by an electronic circuit with specifications as follows:

- Input W = 1 if the smoke detector alarm (SDA) has activated and 0 otherwise;
- Input X = 1 if the sprinkler emergency cut-off switch (SECOS) is activated and 0 otherwise;
- Input Y = 1 if the manual activation control (MAC) is on and 0 otherwise;
- Register Z is an 8-bit register controlled by a temperature probe. Z contains the ambient temperature of the room ranging from 0 to 255 degrees Fahrenheit. Z contains eight accessible bits labelled $Z_7Z_6Z_5Z_4Z_3Z_2Z_1Z_0$, with Z_7 being the most significant bit;
- Output F activates/deactivates the sprinkler system depending upon whether or not F=1/0.

The sprinkler system should activate under the following circumstances:

- (SECOS is off) AND ((MAC is on) OR (Z >= 128) OR ((Z >= 96) AND (SDA has activated)))

The Vincenti category addressed is CS (Criteria and Specification).

Determination of Acidity or Alkalinity of Water

The learning objective (Gronlund first level) is to translate the verbal description of a problem into a circuit diagram. The learning objective (Gronlund second level) (sample behavioural objective) is as follows: the pH scale is often used to determine the acidity or alkalinity of water and is given by a number in the range 0 through 14. A pH of 7 is neutral while a pH less than 7 is acidic and a pH greater than 7 is alkaline. A logic circuit is to be designed to monitor and control the pH level of a swimming pool. The pH level of the water is applied to the input of a circuit as a binary number and the circuit is to maintain the pH level between 6 and 7 by activating a valve to release acid if the pH is greater than 7, or by activating another valve to release the base if the pH is less than 6. The circuit should also have four LED indicators that are activated under the following conditions (using suitable assumptions):

- 7<pH>6: green LED should be illuminated;
- pH>7: blue LED to indicate alkalinity;
- pH<7: yellow LED to indicate acidity;
- pH>9 or pH<5: red LED as a warning.

The Vincenti categories addressed are FD (Fundamental Design Concepts), CS (Criteria and Specification) and TT (Theoretical Tools). The Bloom’s Cognitive Domain level is application.

Design of an Arithmetic Logic Unit

The learning objective (Gronlund first level) is to translate the verbal description of a problem into a circuit diagram. The learning objective (Gronlund second level) (sample behavioural objective) involves the following: an Arithmetic Logic Unit (ALU) is an essential component of computing systems, providing the combinational logic needed to implement commonly used arithmetic functions. In this exercise, the student has to design a 32-bit (ie the design will cater for numbers represented with 32-bits) ALU. The ALU is to provide options (ie *instructions*) for *ADD* and *SUBTRACT*, as well as bitwise operations for *AND* and *OR*. The number formats used are to be 2's complement.

The ALU requires input as follows:

- Two 32-bit numbers A and B.
- Two single bit lines used to indicate which operation is required.

The ALU’s output should be as follows:

- A single 32-bit result Y.
- Flags (ie single bits) for overflow, zero and sign of Y. The overflow flag should indicate whether the last ADD or SUBTRACT produced a 2's complement overflow. The zero flag is true if Y is all zeros, and the sign flag indicates whether Y is positive (denoted by a zero) or negative (denoted by a one) in the 2's complement sense.

The input/output lines of the design *MUST* be named as follows:

- A<0:31> and B<0:31> where bit 31 is the least significant.
- Y<0:31> where bit 31 is again the least significant.
- OV, ZR and SN for the overflow, zero and sign bits.
- S0 and S1 for the operation select lines. These lines are coded as follows:
  - Add A to B : S0 = 0, S1 = 0
  - Subtract A from B : S0 = 0, S1 = 1
  - Bitwise AND A and B : S0 = 1, S1 = 0
  - Bitwise OR A and B : S0 = 1, S1 = 1

The circuit is to be designed using IC 74LS283 for the adder circuit. The functional correctness of the design should be determined by the student by ascertaining the maximum propagation delay of the circuit.

The Vincenti categories addressed are FD (Fundamental Design Concepts), CS (Criteria and Specifications), TT (Theoretical Tools), QD (Quantitative Data) and PC (Practical Constraints). The Bloom’s Cognitive Domain level is application.

The above assessment tools are selected to indicate that they would assess the mastery of each learning objective and a subset of the Vincenti categories chosen by the instructor.

Traffic Light Controller

An example is given to demonstrate that the same question can be modified to address the different categories of Vincenti in the same classification of Bloom. Consider the problem given below.

The learning objective is to identify the Bloom and Vincenti classification. The Bloom’s Cognitive Domain level is synthesis.

The learning objective (Gronlund first level) is to determine the function and performance of a given digital circuit. The learning objective (Gronlund second level) (sample behavioural objective) covers the following: design a traffic light controller implemented as a state machine. The light controls a simple road crossing with no turn arrows. Road sensors indicate whether cars are present in the south-north (ISN) and east-west (IEW) directions. Light controls are encoded by a two-bit signal (red = 00, yellow = 01 and green = 10). However, for this problem, it is assumed that there are two outputs (OSN and OEW) that can take on the values R, Y or G. The light control in the north direction (OSN) is identical to the light control in the south direction. The light control in the east direction (OEW) is identical to the light control in the west direction.

The Vincenti categories addressed are FD (Fundamental Design Concepts) and TT (Theoretical Tools).

The rules of digital system design (Theoretical Tools), design concepts of sequential circuits (Fundamental Design Concepts) have to be understood by students in order to solve this problem. The modified question is given below to address the Vincenti categories of CS, FD and TT.

The students is to design a traffic light controller implemented as a state machine. The light controls a simple road crossing with no turn arrows. Road sensors indicate whether cars are present in the south-north (ISN) and east-west (IEW) directions. The light controls are encoded by a two-bit signal (red = 00, yellow = 01 and green = 10). However, for this problem, it is assumed that there are two outputs (OSN and OEW) that take on the values R, Y or G. The light control in the north direction (OSN) is identical to the light control in the south direction. The light control in the east direction (OEW) is identical to the light control in the west direction. The controller's behaviour should meet the following requirements:

- The controller is clocked every one second;
- When the light for one road goes red, the light for the other road simultaneously goes green;
- A three-second yellow light should precede a red light;
- The green light is minimum 30 seconds long;
- The maximum wait for a green light (if stopped by a yellow light) should be 33 three seconds.

Following these rules, students are to design a circuit describing the behaviour of this controller.

The Vincenti categories addressed are FD (Fundamental Design Concepts), CS (Criteria and Specification) and TT (Theoretical Tools).

Since the design has to satisfy the given criteria in the question, it also automatically satisfies CS (Criteria and Specification). The question is further modified as given below, thereby addressing the Vincenti categories of PC and QD.

The student is to design a traffic light controller implemented as a state machine. The light controls a simple road crossing with no turn arrows. Road sensors indicate whether cars are present in the south-north (ISN) and east-west (IEW) directions. Light controls are encoded by a two-bit signal (red = 00, yellow = 01 and green = 10). However, for this problem, it is assumed that there are two outputs (OSN and OEW) that take on the values R, Y or G. The light control in the north direction (OSN) is identical to the light control in the south direction. The light control in the east direction (OEW) is identical to the light control in the west direction. The controller's behaviour should meet the following requirements:

- The controller is clocked every one second;
- When the light for one road goes red, the light for the other road simultaneously goes green;
- A three-second yellow light should precede a red light;
- The minimum green light is 30 seconds long;
- In the absence of active road sensors, the green light should be given to the road with the last active input;
- The maximum wait for a green light (if stopped by a yellow light) should be 33 seconds;
- If both road sensors are constantly active, the green light should alternate between the roads while observing the minimum green and yellow light constraints.

The student is to design a digital circuit that meets the requirements as given above with minimum number of ICs.

The Vincenti categories addressed are FD (Fundamental Design Concepts), CS (Criteria and Specification), TT (Theoretical Tools) and PC (Practical Constraints). In order to design the given circuit with the minimum number of ICs (Practical Constraint), the data associated with the ICs have to be properly internalised by the student. This problem demonstrates the method of creating graded questions to address the chosen categories of Vincenti, as well as the same classifications of Bloom.

CONCLUSION

Learning objectives go hand in hand with assessment tasks – after all, what should be assessed is what has been learnt and students learn to meet the needs of assessment instruments.

The structured approach presented here helps the instructor to create questions in a graded manner, addressing different subsets of Vincenti's categories of engineering knowledge.

REFERENCES

1. Clark D., Learning Domains or Bloom's Taxonomy (2000), http://www.nwlink.com/~donclark/hrd/bloom.html
2. Vincenti, W., *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*. Baltimore: John Hopkins University Press (1990).
3. Rao, N.J. and Sindhu, R., Identification of learning objectives of an engineering course as a Bloom-Vincenti matrix in the context of ABET Outcomes. *Proc. Inter. Conf. on Learning Organizations in a Learning World*, Bangkok, Thailand (2005).
4. Bhatt, C.B. and. Rao, N.J., A framework to generate learning objectives based on Vincenti's categorization of engineering knowledge. *WSEAS Trans. on Advances in Engng. Educ.*, 2, **3**, 224-229 (2005).
5. Mager, R., *Preparing Instructional Objectives* (2nd edn). Belmont: Fearon-Pitman Publishers (1975).
6. Gronlund, N.E., *Stating Behavioral Objectives for Classroom Instruction* (3rd edn). New York: Macmillan (1985).
7. Thorpe, M., Assessment and *third generation* distance education. *Distance Educ.*, 19, **2**, 265-286 (1998).
8. Northcote, M., Online assessment in higher education: the influence of pedagogy on the construction of students' epistemologies. *Issues in Educational Research,* 13, **1**, 66-84 (2003).
9. Dick, W. and Carey, L., *The Systematic Design of Instruction* (4th edn). New York: HarperCollins College Publishers (1996).