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The Learning Hierarchy Technique: An Instructional Analysis Tool in Engineering Education

M. Alias
Centre for Graduate Studies
Kolej Universiti Teknologi Tun Hussein Onn
86400 Batu Pahat, Malaysia
maizam_alias@hotmail.com

D.E. Gray
School of Management
University of Surrey
Guildford, United Kingdom

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Learning hierarchies as the products of learning task analyses have been widely used in the preparation of instructional materials in general. This technique enables the instructor to identify the enabling objectives for a chosen terminal objective in a systematic way. Being systematic increases the chances of identifying all the enabling objectives that are essential to the achievement of the chosen terminal objective. This article describes how the technique was applied to the teaching and learning in engineering, drawing examples from a structural design course in civil engineering. Specifically, the article describes how the learning hierarchy is derived and validated and how it is subsequently used in the design and development of instructional and assessment materials.

Introduction

As engineering educators, we often have high expectations of our students. For example, upon completion of our semester course we expect them to be able to apply their knowledge to solve or to provide solutions to real life problems. These expectations, commonly known in the education context as the long-term goal or terminal objective are learning outcomes that are naturally complex in nature and can only become a reality if the associated lower-level learning objectives are already achieved. The lower-level objectives that are associated with a particular terminal objective are also known as the enabling objectives. As its name implies, achievement of the associated enabling objectives will enable a learner to achieve the terminal objective. Identification of these enabling objectives is therefore, crucial to the achievement of the terminal learning objective. Another term for learning objective which is commonly used within engineering education is expected learning outcome (ELO). Therefore, the term learning objective and ELO may be used interchangeably in this article.

Learning outcomes that are the product of planned instructions is often based on carefully identified set of learning objectives although not all learning objectives result in the ELO. Having a tool or technique that would enhance the potential of identifying all the enabling objectives is therefore, essential to effective teaching and learning in general. One of the techniques that are particularly relevant in the identifications of enabling objectives is the learning hierarchy technique. This article will discuss the learning hierarchy technique which is based on the work of Robert M. Gagné [1]. Before going into the specifics of the technique, the different types of learning objectives will be discussed first.

Taxonomy of learning objectives

Knowing a category to which a learning objective belongs is important because it influences choice of instructional strategy. Two well-known classification systems for learning objectives which is based on how learning could be demonstrated are that of Gagné's [1] and Bloom's [2]. Although, the learning hierarchy technique is based on Gagné's work, Bloom's taxonomy is mentioned here because his was established earlier than Gagné's and may be more familiar to readers.

Bloom [2] classifies learning objectives into three domains; cognitive, affective and psychomotor skills. In general, the cognitive domain refers to thinking skills, affective domain to feeling and psychomotor skills to physical actions. Gagné [1] classifies learning outcomes into five categories; intellectual skills, verbal information, cognitive strategies, attitudes and motor skills [1]. According to Gagné, [1], intellectual skills are procedural knowledge, which are the learned capabilities of 'knowing how' and the capabilities that make it possible for a person to deal with symbols. An example of an intellectual skill is the ability to do numerical addition or subtraction. Gagné [1] further sub-categorises intellectual skills into concept learning (C), rule learning (RL) and problem solving (PS). Following his classification system, verbal information (VI) is not considered an intellectual skill because the demonstration of its existence is limited to the ability to state ideas. Intellectual skills therefore, are comparable to cognitive skills in the Bloom's taxonomy excluding knowledge. Finally, cognitive strategies according to him, refers to "…techniques of thinking, ways of analysing problems, and approaches to the solving of problems…which control the learner's own internal processes…" (p. 48). This is what is commonly known as meta-capabilities, i.e., learning about learning. Gagné's [1] definition of motor skills which is similar to Bloom's refers to the learned capabilities that enable a person to execute "…movements in a number of organized motor acts..." (p. 62). Two examples of motor skills in structural design are:

i. Manoeuvering a computer mouse to produce the desired effect on the computer screen when using a Computer Aided Design package for drawing

ii. Putting a mark on paper - where desired - in free-hand sketching to communicate design ideas

Lastly, Gagné's [3] attitude skills refer to the learning outcomes that relate to "…acquired mental states that influence the choices of personal actions." (p. 63). Two examples of attitudes that are relevant to design success are:

i. Choosing to learn from own and other peoples' experiences by ensuring similar mistakes are not repeated, and incorporating past successes into current design where appropriate,

ii. Choosing to communicate to and with other specialists - such as an architect, contractor and services engineer -when necessary by:

    - Informing them of the ongoing situation, or any expected changes to be made,
    - Seeking them in matters that require specialist attention.

In summary, any expected learning outcome can be classified into one of the five domains of Gagné's (or three of Blooms) depending on how they can be demonstrated.

Hierarchical Relationships Between Learning Outcomes

Learning outcomes in a specific area of study are often hierarchical in nature, which can be diagrammatically illustrated as instructional curriculum maps or learning hierarchies. According to Gagné, Briggs and Wager [4] an instructional curriculum map (ICM) illustrates "…the functional relationships among instructional objectives…" that are "…not from the same domains." (p. 159). Figure 1 gives an example of an ICM for structural design that shows the relationship between the long-term goal of 'Able to design a structure to solve a design problem' to the other learning objectives in the various domains. An ICM therefore, include all five domains as suggested by Gagné, [1] or three domains by Bloom, [2]. A learning hierarchy on the other hand is an arrangement that illustrates the hierarchical relationships between specific intellectual skills only. The educational significance of the learning hierarchy technique is therefore, upon its useful in the identification and sequencing of learning objectives in the intellectual domain.

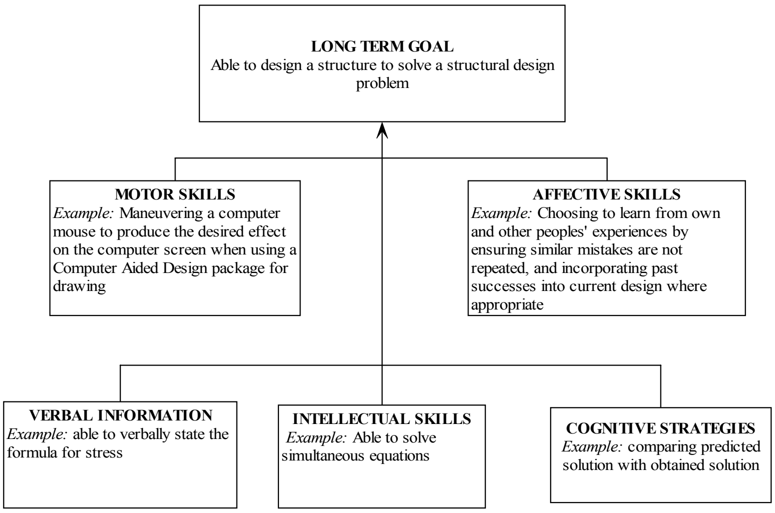

Figure 1. An example of an ICM in structural design [5]

The importance of clear and explicitly stated learning objectives and the appropriate sequencing of these objectives in teaching cannot be over-emphasised especially where weak learners are concerned.

The Learning Hierarchy Technique

The learning hierarchy technique is the result of analyses of a learning task. The technique was first developed in 1962 by Gagné (cited in [6]). Initially, it has been primarily used for programmed instructions such as those used in the military service. Following that, there has been considerable research on it, particularly in the teaching and learning of mathematics and the sciences [6-15]. These studies show that successful identification of enabling objectives through the learning hierarchy technique is the first step towards successful achievement of a long-term goal. Engineering educators need to be aware of the potential of the learning hierarchy technique as a teaching and learning tool that may contribute to greater effectiveness in engineering education. What more, with high attrition rate in some engineering programmes, poor teaching has been one of the most frequently cited reasons given by leaving students [16]. Therefore, effective instruction is definitely one of the factors that need to be looked into regarding the reported problem and the learning hierarchy technique may contribute towards a more effective instruction in general. The next section will discuss how the learning hierarchy technique can be derived and validated in detail.

Deriving And Validating A Learning Hierarchy

An instructor can derive and validate a learning hierarchy using a three-stage iterative process.

Stage 1: Identifying the terminal objective. The highest level objective which is commonly known as the terminal objective is identified and written in measurable term. Having the objective explicitly stated also provides a means for assessing a student's mastery later on.

Stage 2: Gagné's question [11] "what must the learner be able to do in order to learn this new element, given only instructions?" (p. 121) is then posed. The answers to this question will be stated in the form of other behavioural objectives and become the hypothesised sub-ordinates (enabling objectives) to the terminal objective. The same question is asked of each of these subordinate objectives and the process is repeated until such a time that the bottom level skills appear to be simple enough to be performed by the learner population. The hypothesised learning hierarchy is then said to be developed [8].

Stage 3: The hypothesised learning hierarchy is then validated through consultations with subject matter experts and making the necessary adjustments. If necessary, a more rigorous validation procedure would be adopted that includes trying out test items (based on identified learning objectives) on a group of target learners and to be followed by statistical analyses of item responses [6, 11].

Once validated, the learning hierarchy can be used to design and sequence instruction as well as to develop evaluation instruments.

Example Application In Civil Engineering Structural Design

In this section, an application of the learning hierarchy technique for a chosen terminal objective in the teaching and learning of structural design will be presented. This application was for a design task in a foundation engineering programme, i.e., a programme equivalent to the first year of an undergraduate programme. The learning hierarchies to be discussed have been successfully used to design instructional materials in a previous study on the effect of spatial visualisation skills instruction on problem solving in structural design [17].

Identification of the Terminal Objective

As stated previously, the first step in the learning hierarchy technique is to identify the terminal objective. As many problems encountered in engineering studies are less structured in nature as compared to those in the mathematics and sciences, a terminal objective that fits the description, of such a problem need to be identified. It was decided that the expected learning outcome or terminal objective to be chosen for this purpose was “to be able to design of a short braced column”. A short column here is defined as a column that fails as a result of “material failure by initial yielding of the steel at the tension face or initial crushing of the concrete at the compression face.” [18]. This particular terminal objective was chosen due to the following reasons:

- Among the three basic structural elements, beam, column and slab, taught at this level, the reinforced concrete column is one found to be a challenging topic to teach and learn. In many instances, conceptual understanding is critical to finding the appropriate problem solution, i.e. procedural understanding on its own is not sufficient for arriving at a problem solution.
- The tasks that are associated with column design have the general characteristics of design problems, i.e., ill-defined and unstructured but not “too unstructured” to the point where developing the learning hierarchy becomes inconceivable. As mentioned before, many applications of the learning hierarchy techniques have been for well-structured and closed problems, i.e. problems with one correct answer. Therefore, careful choice of ‘less-structured problem’ is important because a terminal objective that is “too unstructured” may pose difficulties that have not been encountered previously.

This particular terminal objective is also chosen because

i. the achievement of this terminal objective could be realised within a relatively short time, i.e., several periods of instructions as opposed to a semester of instructions.

ii. this terminal objective encompasses problems that could assess problem solving skills

In accordance with the procedure described previously the explicit form of the chosen terminal objective was formulated, as stated below.

> *"At the end of the course the students will be able to design a short braced reinforced concrete column supporting an axial load and bending moment whereby the students are given (i) the plan and elevations of the building of which the column is a structural member, (ii) the characteristic dead and imposed loads and (iii) the relevant references and design manuals. Students will demonstrate their achievement of the target skill through their ability (i) to prepare a structural drawing of the column, (ii) to document the calculations that were used in their design process and (iii) to provide in writing the assumptions and justifications for their design decisions."*

Derivation of the Learning Hierarchy

The first level of sub-ordinate objectives was derived by asking Gagné's question "what must the learner be able to do in order to learn this new element, given only instructions?" with regards to the chosen terminal objective. By asking the above question two enabling objectives were identified. The two enabling objectives which are the immediate sub-ordinates to the terminal objective are identified as:-

i. the ability to generate an initial design.
ii. the ability to evaluate and refine the initial design, i.e., can judge the appropriateness of the initial design.

Both objectives are classified as problem solving skills (PS). By asking the same question of the two sub-ordinate skills, more enabling skills were identified. Sub-ordinates to skill (i) are

- the ability to estimate member size
- the associated area for the reinforcement steel.

Sub-ordinates to skill (ii) are

- the ability to evaluate and refine for the ultimate limit-state requirements
- the ability to evaluate and refine serviceability limit-state requirements.

Figure 2 illustrates the partial learning hierarchy initially derived, showing the terminal objective, two immediate sub-ordinates and their respective sub-ordinates.

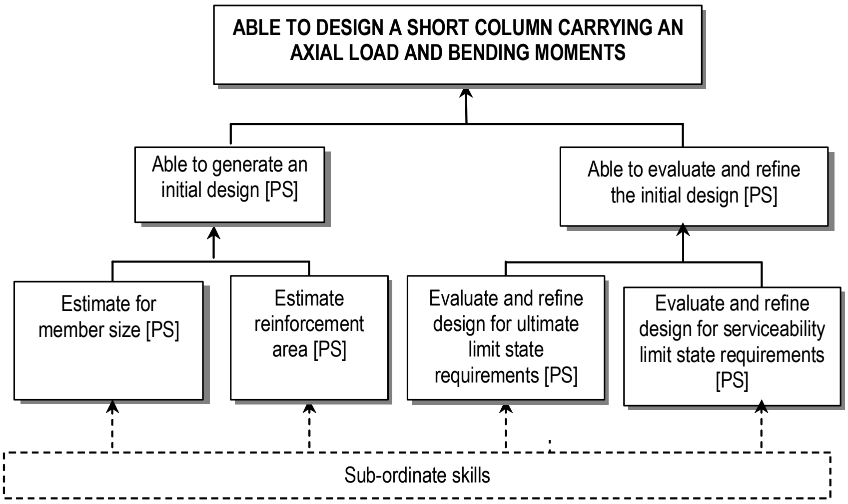

Figure 2. A learning Hierarchy showing the terminal objective, two immediate subordinates and their immediate subordinates [6]

Further partial hierarchies were derived by posing the same Gagné's question. In other words, the full learning hierarchy were derived and developed in parts to cater to the large number of enabling skills involved as the complete learning hierarchy may take several pages. Upon completion of the analysis, the sub-hierarchies were then combined to obtain the overall learning hierarchy for the chosen terminal objective.

By asking Gagné's question of the lowest level skills in Figure 2, further sub-ordinate skills were obtained as illustrated in Figure 3. Figure 3 shows the required enabling skills for generating an initial design, i.e., it requires the ability

- to generate an estimated member size, or to be more specific to suggest the appropriate column dimensions (breadth x depth)
- to generate an estimated reinforcement areas

The learning hierarchy in Figure 3 shows the requirements for multiple skills in the generation of an initial design which refutes the notion that the generation of an initial design is a trivial task as often assumed by many teachers (the researcher included). Interestingly, some of the enabling skills that were identified are found to be very much spatial in nature and therefore, were grouped into another category of skills i.e. the spatial visualisation skills (SV). This particular group of skills could have been easily overlooked had it not been for the benefit provided by the learning hierarchy technique.

For the next step in the iterative process, the objective 'Able to evaluate and refine the initial design' was treated as the terminal objective, and Gagné's question was posed again. The enabling skills for the present terminal objective were identified and the hierarchy is given in Figure 4. The same procedure was repeated for 'Ensure that the column satisfy the requirements for a braced column' which is an immediate sub-ordinate to the 'evaluate and design element for the ultimate limit-state' objective. The follow up iteration process resulted in four more partial hierarchies, which are not illustrated in this article. The iterative process is repeated until such a time where the instructor was satisfied that the skills identified could be assumed to be present in all learners. The partial hierarchies obtained were seven in total which when merged forms the learning hierarchy for the terminal objective '*… able to design a short braced column that supports an axial load and a bending moment…*'.

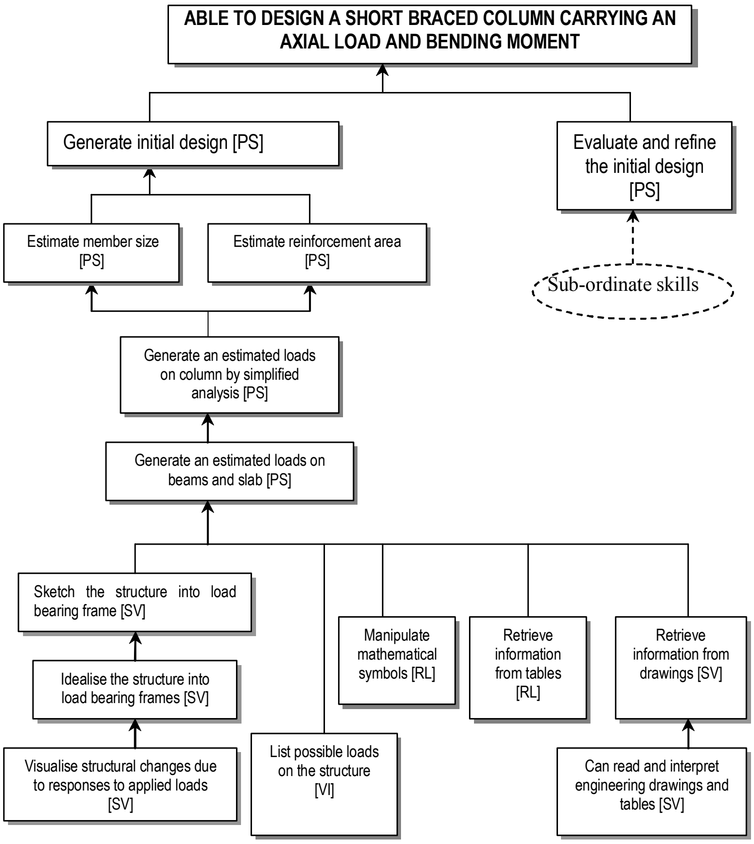

Figure 3 A learning hierarchy for generating an initial design for a short column which includes spatial visualisation skills [6]

Validation of the Learning Hierarchy

For the chosen terminal learning objective, a three-step procedure was used to validate the derived learning hierarchy. The procedure is in fact the first three steps of the validation model that was developed by White [6, 11]. The three-step procedure is as follows with the first two steps embedded in the hierarchy development process.

- defining the terminal objective in behavioural and measurable terms
- asking Gagné's question "What must the learner be able to do in order to learn this new element, given only instructions?" of the terminal objective and each subordinate (enabling) objective sequentially
- consulting experienced subject matter experts which in our case consultation with three subject matter experts, who had had more than

four years' experience in teaching structural design to engineering students and incorporating their feedback where necessary

The three-step validation procedure was deemed sufficient for the purpose at hand, i.e., to identify the enabling skills required for achieving the terminal objective and to have a rough idea of the relationship (hierarchical and otherwise), between the enabling skills (spatial skills or other wise). Eliciting detailed and accurate hierarchical relationships between enabling skills was not necessary because an instructor was available for students' queries. However, if the learning materials to be developed are for distant learners, where there is no opportunity for instant instructor feedback, there may be a need for higher accuracy in the sequence of the presented materials. In such a case the validation process will have to include a try out and response analyses as explained previously.

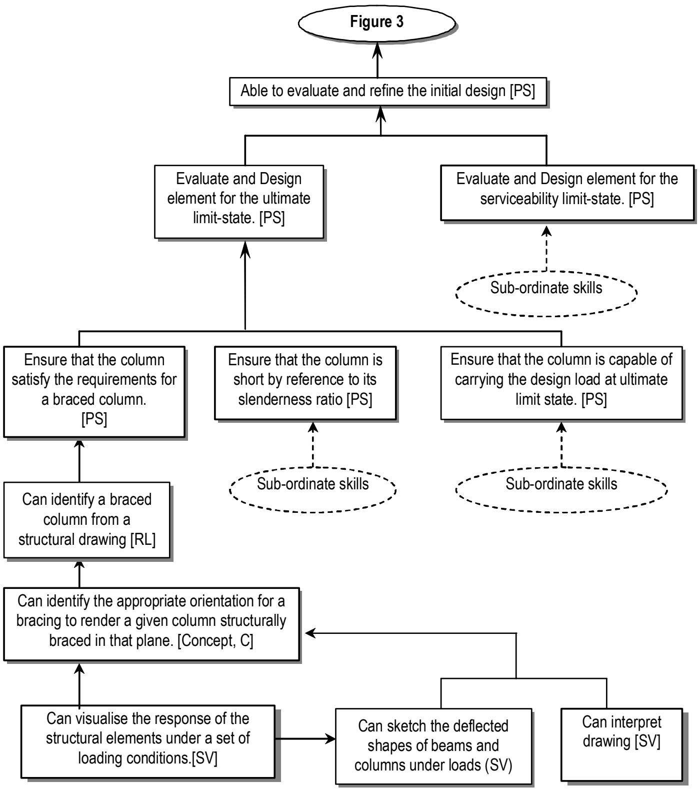

Figure 4. The partial learning hierarchy for "Able to evaluate and refine the initial design" [5]

BENEFITS OBTAINED FROM THE DERIVED LEARNING HIERARCHY.

As described before, the application of the learning hierarchy technique on a chosen terminal objective elicited a set of enabling objectives that are hierarchically arranged. The hierarchically arranged objectives effectively form a "road-map" for achieving the terminal objective. With the "road-map" in hand, an instructor can then design the most appropriate instructional activities that will lead to the achievement of the terminal objective. In our case, the enabling objectives were subsequently used to decide on a spatial skills intervention, design and sequencing of learning materials as well as for the design of formative and summative evaluation instruments.

Spatial skills intervention

Interestingly in our specific case, spatial visualisation skills were found to be one of the enabling objectives, i.e., is a pre-requisite to the ability to design a short column. It was then decided that there was a need to evaluate students' spatial visualisation skills which were subsequently found to be inadequate. A study was then carried out to determine if instruction on spatial visualisation skills would result in better spatial skills performance [19]. The study used the quasi-experimental pre and post-test design method. The mean gain scores between the two groups (experimental and control) were compared. The experimental group gained statistically significantly higher (n =29, $\bar{x}$ =4.55, s= 2.73) compared to the control group (n= 28, $\bar{x}$= 3.0, s=2.68). It was concluded that the spatial visualisation skills intervention benefited students. The decision for the spatial skills intervention was one of the unexpected results from the application of the learning hierarchy technique.

Designing instructional materials

The direct benefit of the learning hierarchy technique is the identification of enabling learning objectives. An example of such an objective that has been formulated using this technique (extracted from Figure 3 and 4) is here given.

> *"At the end of the lesson, students will be able to predict the behaviour of structure under given loading conditions, demonstrating the ability by sketching the deflected shapes of beam and columns under loads"*

The combination of this objective in combination with the knowledge that some students may not have adequate pre-requisite spatial visualisation skills, a simple as teaching aid to teach qualitative understanding of the relationships between deflections, tension, compression and bending moments for various categories of reinforced concrete beams was designed. The teaching aid was in the form of a beam model made from foam with a longitudinal line on it to represent steel reinforcements. To test the usefulness of the teaching aid, a quasi-experimental study with post-test only was carried out on two equivalent groups of civil engineering students [17]. The experimental group that was taught using models as teaching aids obtained statistically significantly higher mean score (n = 61 $\bar{x}$ = 27.34, s = 12.03), compared to the control group (n = 71, $\bar{x}$ = 23.99, s = 6.94) which indicates that the learning materials used helped to improve learning in students. Although the model was simple but it makes learning more meaningful, a necessary condition for learning to occur [20]. The model helped students to relate their concrete experiences to the abstract concept that they are supposed to acquire, the ability which is lacking in many students with poor spatial visualisation skills. In this instance, knowledge of the enabling objectives guides us to design the appropriate instructional materials.

Design of formative and summative evaluation instrument

In formative evaluation, an instructor is not usually interested the grades, rather the objective is to determine what has been learned and not learned by students on a specific unit. To do this, the formative test was constructed by rewriting each enabling objective into a question that becomes a test item. In the summative evaluation, the emphasis is on measuring students learning on the course in total and for the purpose of giving grades. For this purpose, samples of enabling objectives from each individual unit were selected and rewritten into question forms. In simple terms, knowing the enabling objectives guide us in the design of evaluation instrument which were then used to determine if the identified learning objectives have been achieved.

In summary, the learning hierarchy technique helped to identify the enabling skills and their hierarchical relationships which has the potential to be useful in the

- Formulation of learning objectives for the topic on column design
- Design and development of instructional materials as well as planning and sequencing of instructional events for the topic.
- Design and development of assessment tools for diagnostic, formative as well as summative assessments for this particular topic.

Conclusion

The application of the learning hierarchy technique in the teaching and learning of civil engineering was illustrated using a learning task in structural design as an example. The technique was shown to help in the identification of the enabling skills that are necessary to achieving the identified terminal objective, which in this case is the ability to design a reinforced concrete column. Knowledge of these objectives was then used in the design of learning materials and evaluation instruments. Being systematic, this technique enhances the potential of identifying the relevant enabling objectives, thus, reduces the chances of overlooking them. For example, in this case, the demand for spatial visualisation skills in the design of column was not only highlighted but also identified as pre-requisites to the terminal objective, which later led to a serious effort to improve spatial visualisation skills among our engineering students. The drawback of the learning hierarchy technique is that, it is quite time consuming. However, the advantage far exceeds the drawback, as the derived learning hierarchy can serve as the “road-map” leading to a more systematic and effective instructions. In summary, the learning hierarchy technique is a technique that can be useful to teaching and learning in engineering and is of particular relevance in identifying and sequencing of learning objectives and learning materials which are essential towards achieving the engineering learning goals. Application of the learning hierarchy technique by engineering educators could therefore translate into better teaching and learning which may support other efforts that attempt to enhance the effectiveness of engineering education.

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About the authors

Dr. Maizam Alias is an associate professor in Technical Education at the Tun Hussein Onn University College of Technology, Malaysia. She obtained her PhD in education from the University of Surrey, her MSc. in Structures form the National University of Malaysia and her BSc. in Civil and Structural engineering from University College Cardiff in the U.K. She is currently the head of programme at the centre for graduate studies. Dr. Alias has had over 20 years experience of teaching in higher education. A major part of her teaching experience involves teaching civil engineering students in polytechnics. Her research interests include engineering education, post-graduate education and teacher training for technical education.

Dr David E Gray is a Senior Lecturer in Work-Based Learning and the Head of Executive Programmes at the University of Surrey. His research interests include work-related learning, knowledge management and interactive communications technology in learning (particularly in work-based settings). His work at the University of Surrey has included the management of a range of programmes including an MSc. in Interactive Training Systems and BSc. in Work Based Learning. He has provided consultancy services in a range of areas from executive coaching to e-learning development for organisations including Toshiba, BP UK Oil and the Civil Service.