Systems Approach to Engineering Education Design

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Abstract: The design and delivery of engineering education to diverse cohorts of adult learners is challenging. The sheer volume and diversity of published literature relating to the scholarship of teaching and learning presents a challenge to educational designers and teaching practitioners alike. A systems approach to design and development, incorporating key principles from the literature, can assist practitioners (particularly those new to teaching) in the effective design and delivery of technical courses. This paper presents a research-based educational lifecycle model to support the design of engineering education. The paper then describes a requirements-driven development methodology that has been applied successfully to the design and delivery of a number of technical courses involving different cohorts of adult learners. The application of the methodology to the development of an introductory radar systems course is used as a case study throughout the paper.

INTRODUCTION AND AIMS

The design, development and delivery of engineering education must be undertaken carefully to be effective in facilitating learning among diverse cohorts of adult learners. The many nuances associated with teaching diverse groups of adult learners, combined with the challenges of exploring technically complex engineering topics add to the challenges of delivering effective engineering education. A systems approach to design and development, incorporating key teaching and learning principles, can assist practitioners (particularly those new to teaching) in the effective design and delivery of technical courses.

Education can be considered a *system* at any one of a number of levels, including at the individual course level (Biggs, 1991, pp. 221-228). A *learning system* (as defined by Biggs) can be thought of as a complex integration of course structure and content, assessment methods, and teaching methods delivered in such a way as to facilitate the desired learning outcome in a group of students.

A large volume of published literature associated with the scholarship of teaching and learning (SOTL) exists dealing with the design and development of effective educational systems. The literature associated with the SOTL dates back hundreds of years and spans a variety of disciplines. The sheer volume and diversity of the SOTL makes it challenging for practitioners to maintain an awareness of current trends and ideas, particularly practitioners from non-teaching disciplines.

The conceptual framework presented in this paper has been applied successfully to a number of technical courses involving different cohorts of adult learners. The framework was developed and described, in detail, in a doctoral dissertation (Faulconbridge, 2008) and is presented here as part of the dissemination process.

The aims of this paper are to:

- describe selected key principles from the SOTL that should be considered when designing new technical courses;
- present a conceptual framework that has been found effective in applying established systems thinking to the design, development and delivery of technical courses;
- explain how the framework supports the integration of selected key learning principles from the SOTL in order to make the technical course as effective as possible; and
- present a range of measures that indicate the effectiveness of the framework when applied to practical situations.

A case study, involving the development of an introductory radar course, is used to illustrate the application of the framework. The case study is introduced more completely in the relevant section of the paper.

SELECTED PRINCIPLES FROM THE SCHOLARSHIP OF TEACHING AND LEARNING

A relevant selection of key principles from the SOTL has been incorporated into the conceptual framework, including consideration of:

- some of the fundamental differences between educating adults and children, as explored by researchers such as Knowles (1990);
- the likely learning style diversity within groups of adult learners, and that student boredom, failure and withdrawal from courses may result from mismatches between preferred learning styles and the design and delivery of courses (Felder and Silverman 1988);
- the need to encourage *deep learning* (Biggs 1991) by students in complex and integrated engineering and technical courses, where the structure of the knowledge and a deep level of understanding are important; and
- the importance of the human aspect of the teacher-student relationship in promoting effective and deeper learning by the student (Ramsden 2003), including the willingness of the teacher to learn and improve based on student review and feedback.

SELECTED FUNDAMENTALS FROM SYSTEMS ENGINEERING

The conceptual framework also integrates a number of key principles from the systems engineering field, including:

- the establishment of a clear need for the course before embarking on course design;
- the generation of concise functional requirements for the course in the form of learning objectives and outcomes;
- consideration of assessability (or testability to use systems engineering vernacular) whilst writing the functional requirements;
- the design of a course structure and content that is traceable to the functional requirements and need for the course, and mindful of the remaining course lifecycle; and
- incorporation of course verification and validation via course assessment, review and feedback.

THE NEED FOR A CONCEPTUAL FRAMEWORK

When confronted with the size and complexity of the SOTL, engineering educators (especially those that are new to the teaching discipline) may find it beneficial to use a conceptual framework that incorporates key principles from the SOTL for the design, development and delivery of technical education to adult learners. The systems philosophy pioneered by engineering disciplines such as systems engineering provides an ideal basis upon which such a framework can be developed.

This section describes a conceptual framework that may help practitioners in this regard, by guiding them through a five-stage process.

SELECTION OF A SUITABLE LIFECYCLE MODEL

Lifecycle models have long been used by project managers and systems engineers to divide complex problems into logical sequences of smaller, more manageable and measureable stages, allowing periodic review and feedback at appropriate points in the problem-solving process. Project management and systems engineering standards present generic lifecycle models that can be tailored to specific complex problems (See PMI (2004) and ISO/IEC-STD-15288:2008 (2008)). Designing, developing and delivering engineering education can be considered an example of a complex problem that could benefit from being broken into stages using a suitable lifecycle model. Houle (1972) proposed such an educational lifecycle model. This model has been refined and simplified using the concepts in standards such as ISO/IEC-STD-15288:2008, and is illustrated in Figure 1.

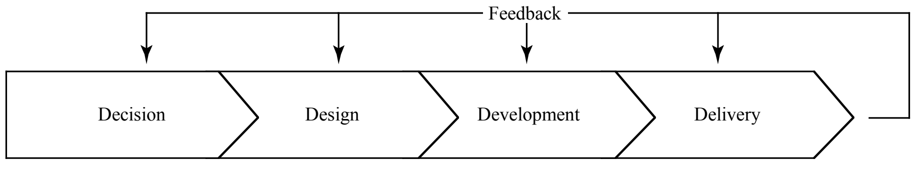

Figure 1. A simplified educational lifecycle model (Faulconbridge, 2008).

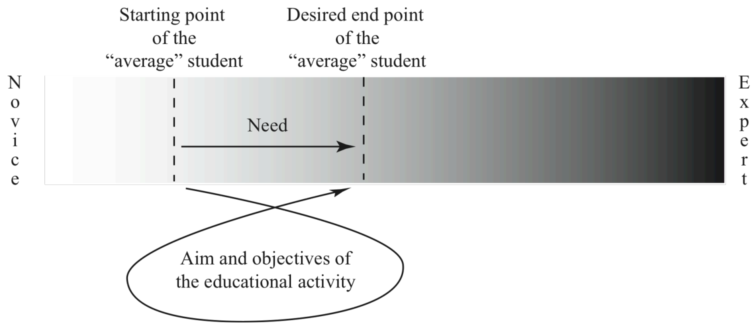

Figure 2. Learning effecting change in the "average" student (Faulconbridge, 2008).

The conceptual framework presented in this paper explains the lifecycle phases as a sequential series of design and development activities, akin to the waterfall approach to engineering design. This is not to suggest that all course designs proceed in this way, but it is presented here to simplify the explanation. The framework presented here may also be used as a basic building block to support alternative educational design approaches, including incremental and evolutionary course development.

STAGE 1: DECISION

While there is variation and debate over the definition of learning, a theme that unites many authors and researchers is that learning is about effecting change in the learners (Gagne (1965), Knowles (1990), Jarvis et al., (2005), and Ramsden (2003)). The first stage in the lifecyle model is, therefore, the identification of a need to effect change in a group of learners, and the subsequent decision to develop an educational activity to address that need.

Establishing a credible need for an educational activity and being able to communicate this effectively to the students is critical in adult education (Knowles, 1990). By carefully considering the need for the learning and expressing that need in practical and relevant terms, the adult learner is more likely to be motivated, and to commit to a deeper approach to the learning experience (Biggs, 1991). This was also observed in a recent University of New South Wales (UNSW) survey reported by Lee and Trembath (2002).

Establishing a need for a system before embarking on a system development is also considered to be a critical first step in any systems engineering processes. This step involves the identification of stakeholders and an elicitation of their expectations of the new system. In the case of a new course, the need may come from stakeholders such as potential students, but is also likely to include current and future employers and industry groups. A well-documented need also supports course delivery validation at the conclusion of the delivery stage to highlight any necessary changes. Changes identified by validation can be incorporated via the feedback mechanism illustrated in the lifecycle model.

Boyle (1982) provides a way of visualising the need for a new course by considering learning to be a continuous and recurrent process within a person's life. Jacks (1931) also describes adult education as having *continuity*. Taylor (1994) explores the concept of adult learning as a journey from *novice* to *expert* in his NOVEX model, and Biggs (1989) does the same using his SOLO taxonomy.

Combining these ideas, a way of viewing the learning need is as a desired change in an "average" learner, expressed in terms of broad learning aims and objectives. This is illustrated in Figure 2.

The Royal Australian Navy (RAN) identified a need to provide a theoretical understanding of radar systems to selected officers with during their training. These officers are seaman officers who are training to become Principal Warfare Officers (PWOs) on RAN warships. PWOs are responsible for the operational aspects of RAN warships through the command and control of the onboard tactical communications systems, weapons and sensors. When they begin their training, all PWO trainees have practical experience with the various systems onboard their warships, but may lack a solid theoretical understanding of how these systems work and interact. To address the RAN's training need, a radar course was designed and developed using the conceptual framework presented in this paper. The radar course is used in this paper as a case study to help illustrate how the conceptual framework can be applied to develop effective technical courses for diverse groups of adult learners.

STAGE 2: DESIGN

The design stage uses the broad aims expressed by the course need to derive learning objectives and detailed learning outcomes, prior to determining detailed content requirements.

Biggs (1991) emphasises that, in order to promote deeper learning approaches in adult learners, the design stage must be based on a structure that includes a clear knowledge framework with logical interconnections between different parts of the framework. In this way, the structure should assist learners to put the objectives and outcomes of the course into a meaningful context. The learners are able to consider the structure of the course as a *knowledge structure* that helps them not only understand what they are going to learn, but why that learning is important to them, which Knowles (1990) describes as particularly important for adult learners.

From a systems engineering perspective, the knowledge structure is analogous to a functional architecture that clearly illustrates what the students are going to learn in such a way as to provide some context and rationale. The knowledge structure therefore includes statements of requirement (in the form of detailed learning objectives and outcomes) organised in such a way as to be meaningful to key stakeholders (such as the students). Systems engineering literature and standards, such as ANSI/EIA-632 (1999), provide guidance on the attributes of effective requirement statements. This guidance helps in the development of well-written learning outcomes and objectives.

The knowledge structure for the PWO radar course utilises a *functional* breakdown of a naval combat system, expanded where relevant to illustrate areas where radar plays an important role. Figure 3 illustrates a partial expansion of the knowledge structure for the PWO radar course, relating particularly to the requirement for *air search* functionality on a warship.

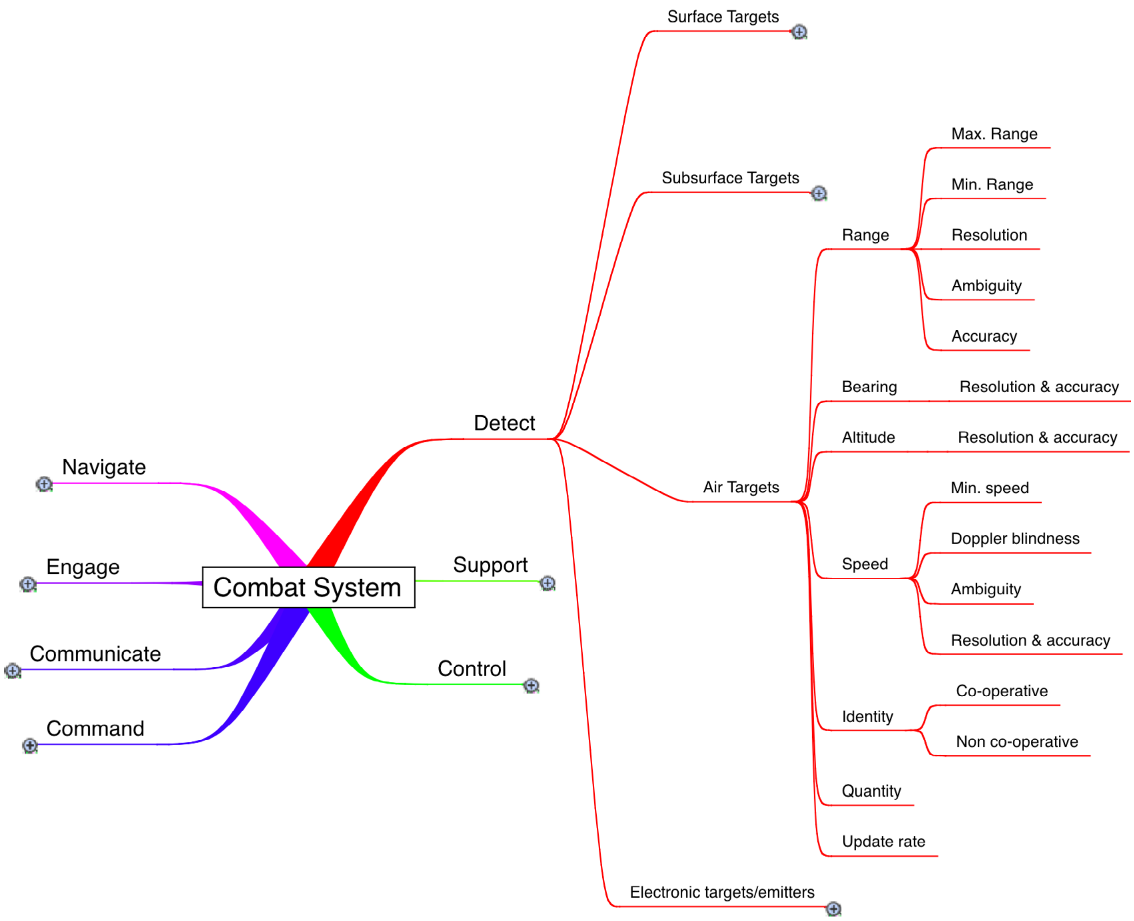

Figure 3. A partial knowledge structure for a radar systems course (Faulconbridge, 2008).

From this knowledge structure, PWO students can see the importance of the *Detect* functionality in a naval combat system. Within the *Detect* function, there is the need to detect *Surface Targets*, *Subsurface Targets*, *Air Targets*, and *Electronic Targets*. Each category of target can be further expanded, as illustrated for *Air Targets* in Figure 3, to show the information required from each detection, including range, bearing, altitude, speed, and so on.

It should be noted that the knowledge structure in Figure 3 does not mention radar systems, but does help explain the critical importance of the data and information that is ultimately provided by radar (and other sensors).

Once a suitable knowledge structure is determined, the structure of the course can be determined that will address the desired outcomes in the knowledge structure. Sternberg (1999) describes a logical course structure that builds on the knowledge structure as being accommodating of different learning styles within the group of learners. The *course structure* may be expressed as a series of inter-related course modules, and is therefore analogous to a system/subsystem-level *physical architecture* developed in a systems engineering process.

For each of the course modules, the preferred mix of learning and teaching resources and approaches to be used to deliver the modules can be determined. Determining and designing this mix represents the detailed course design, and it must be mindful of following course lifecycle stages, particularly the course delivery. An example of this is an appreciation of access to resources such as labs and equipment during delivery. In the case of the PWO radar course, when delivered at UNSW@ADFA, lecturers have access to a fully equipped microwave laboratory (including an anechoic chamber), a self-contained radar system trainer, and various static radar displays. If the same course is delivered at other locations, the lecturers may not have access to these resources. Detailed course design must, therefore, account for the resources available to support delivery.

At each transition (knowledge structure→course structure→resources and approaches) linkages and dependencies should be maintained to communicate the role of each element of the course in delivering specified parts of the knowledge structure. These linkages and dependencies are directly analogous to the systems engineering concept of *requirements traceability*. During the delivery of the course, this approach helps to explain to learners why the specific elements of the learning are important, and how they contribute to achieving the aims of the knowledge structure.

Traceability is a convenient way of ensuring that all of the learning outcomes in the knowledge structure have been captured and addressed by the course structure, and that the course structure does not contain content that does not contribute to the knowledge structure (Faulconbridge, 2008). Systems engineers may refer to unnecessary course content as being an example of *requirements creep*. Avoiding requirements creep in course content is consistent with the recommendations of Entwistle and Ramsden (1983) who state that deeper approaches to learning can be encouraged by managing student workload, and avoiding excessive course content.

Figure 4 illustrates the concept of traceability as it applies in this framework. A matrix (akin to a *requirements allocation matrix*) is a convenient way of establishing and maintaining the relationship between the knowledge structure and the course structure. The allocation matrix for the PWO radar course is illustrated in Figure 5, showing learning objectives from the knowledge structure across the top of the matrix allocated to course modules in the course structure down the left hand side.

The assessment strategy should also be considered and integrated into the design phase in order to encourage deeper learning approaches by the adult learners. Ramsden (2003) suggests that the assessment strategy needs to encourage deeper understanding and critical thinking, and provides 14 "rules" to guide the development of assessment regimes. Palmer (2004) recommends using *authentic* assessment by aligning assessment with relevant professional practice. Authentic assessment is used in the PWO radar course by integrating operational radar system analysis into the assessment strategy.

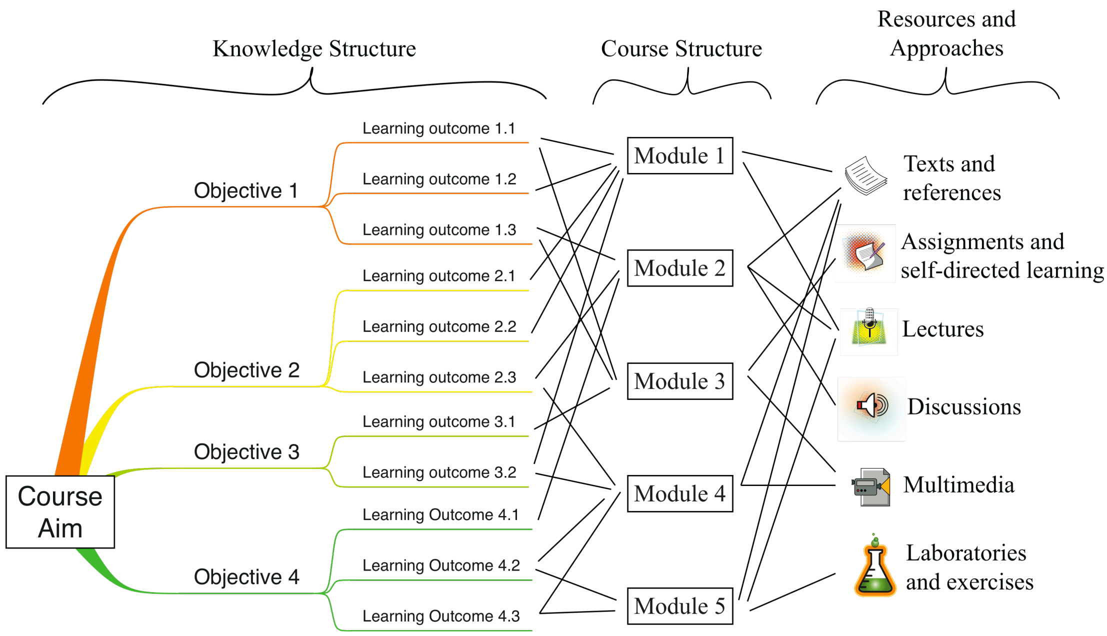

Figure 4. The conceptual design of an educational activity (Faulconbridge, 2008).

Major Modules	Radar's role	Radar's context	Range measurement	Range resolution	Min/max range	Range ambiguity	Angle measurement	Angular resolution	Speed measurement	Speed ambiguity	Target identity	Target quantity	Refresh rate	Performance in weather	Performance in clutter	Performance in EW	Radar horizons	Target characteristics	Emitter detection	Emitter location	Emitter identification	Emitter attack	
	Major Learning Objectives																						
1. Introduction	■	■																					
2. Pulse Radar			■	■	■	■						■											
3. Radar antennas							■	■				■	■	■									
4. Displays & interfaces	■	■																					
5. Radar range equation					■			■					■					■					
6. CW radar							■		■						■								
7. CW-FM radar			■	■	■	■	■	■	■	■													
8. Pulse Doppler radar									■	■	■	■											
9. Tracking radar							■									■							
10. Pulse compression			■	■	■	■																	
11. Synthetic aperture							■	■			■												
12. SSR											■												
13. Natural Environment					■									■			■						
14. Clutter															■								
15. Radar receivers														■	■	■							
16. Electronic support																			■	■	■		
17. Electronic attack																		■				■	
18. Electronic protection														■	■	■							

Figure 5. Allocation matrix for a radar systems course (Faulconbridge, 2008).

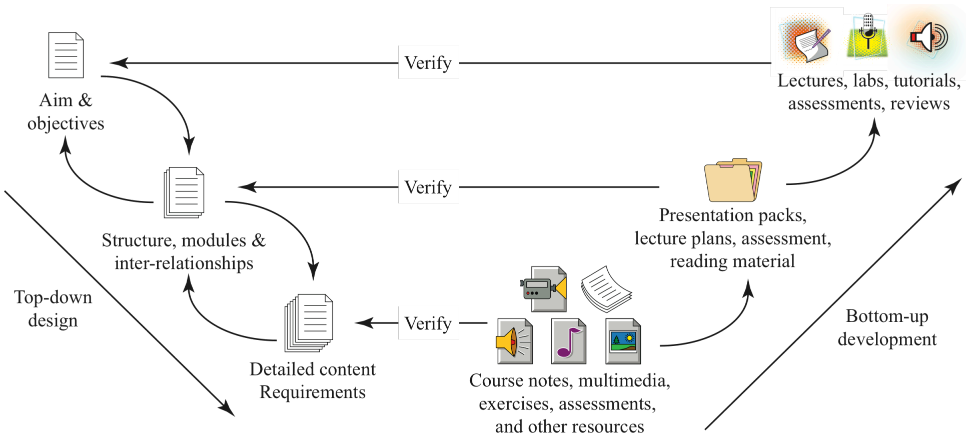

Figure 6. VEE diagram applied to an educational context (Faulconbridge, 2008).

STAGE 3: DEVELOPMENT

During the development stage, the resources and materials identified during the design stage need to be selected and sourced (if they exist) or developed in accordance with the requirements determined during that stage. Examples of materials and resources include course notes, multimedia, exercises, practicals, and assessments. Once sourced, or developed, the designers verify that the material meets the detailed content requirements determined during the design stage. The basic resources can then be grouped and organised into presentation packs and lecture materials, before again being verified as addressing the requirements of the course design and structure.

The iterative development process described here can be illustrated and explained using the VEE construct pioneered by Forsberg and Mooz (1991). The VEE construct, as it applies to this conceptual framework, is illustrated in Figure 6.

The figure is "read" from top left going down the left hand side of the VEE, before crossing to the other side of the VEE and working up towards the top right hand corner. The key benefits of this design and development approach include:

- The ability to trace aims and objectives down to detailed course content requirements, and the ability to trace detailed course content back to the defined aims and objectives;
- The identification and definition of the inter-relationships between the elements of the course structure and content;
- Progressive verification as the development proceeds enabling problems to be detected and addressed as early as possible in the process; and
- Development of learning aims and objectives that are assessable and integrated into the course structure, and detailed content to support the development of meaningful assessment regimes.

Although the VEE construct has been explained in this paper as a series of sequential development stages, the VEE construct can also be used as a basic building block applied to incremental and evolutionary course developments. Incremental and evolutionary development approaches are viable course development approaches but are beyond the scope of this paper or case study.

STAGE 4: DELIVERY

The teaching and learning activities are delivered to the students using the resources developed in the previous stage, and the learning is assessed in accordance with the assessment strategy. Knowles (1990) provides a useful set of guidelines describing the delivery stage of adult educational experiences. These include the following recommendations:

- Ensure that the learners understand the need for the learning experience. This can be achieved by providing insight into the early stages of the lifecycle to explain the need for the education, the development of the knowledge structure, and how the modules and detailed course content trace to the achievement of the need.
- During delivery, provide the learners with ongoing feedback on their progress towards the goal or aim of the educational experience.
- Make use of the experiences within the group of learners by considering those

experiences to be valuable learning resources.

Various sources provide guidance on how to promote deeper learning approaches to students during the delivery stage. For example, Biggs (1991) recommends promoting an active learning environment including periods of "learning by doing" followed by reflection; and promoting interaction with others, including interaction with experts in relevant fields, and interaction among the learners.

Felder and Silverman (1988) and others provide guidance on the likely learning style diversity within groups of adult learners, and the importance of accommodating this diversity during the delivery stage. Sternberg (1999), for example, recommends that a variety of presentation techniques are used and that long, spoken lectures should be avoided.

STAGE 5: FEEDBACK

The lifecycle model accommodates ongoing improvement to account for new information or a more mature understanding of the requirements. This improvement typically occurs at the end of each delivery. Student appraisals are a major example of feedback that may drive elements of the course to be revisited and revised.

Ramsden (2003) describes good teaching practice as including a willingness to learn from students (especially their feedback and assessment results) as a way of improving teaching. Ramsden cites research that concludes that students are very astute judges of effective teaching. This challenges the popular view that students confuse popular lecturers with good lecturers. Ramsden's view is consistent with Marsh (1987) who states that properly collected student feedback is reliable and valid, and relatively free from contamination and sources of bias. To support their evaluation approach, UNSW (2007) relies on relevant scholarly research that indicates students can provide valid observations and judgements on a range of aspects of teaching quality.

A complete conceptual framework, therefore, must accommodate feedback, review and improvement. The lifecycle model (Figure 1) and the VEE construct (Figure 6) shows that this feedback can be used to revisit and revise each of the lifecycle stages in the conceptual framework as required.

THE INTEGRATED CONCEPTUAL FRAMEWORK

The individual concepts shown in Figures 1, 2 and 6 can be combined to illustrate the integrated framework, as shown in Figure 7.

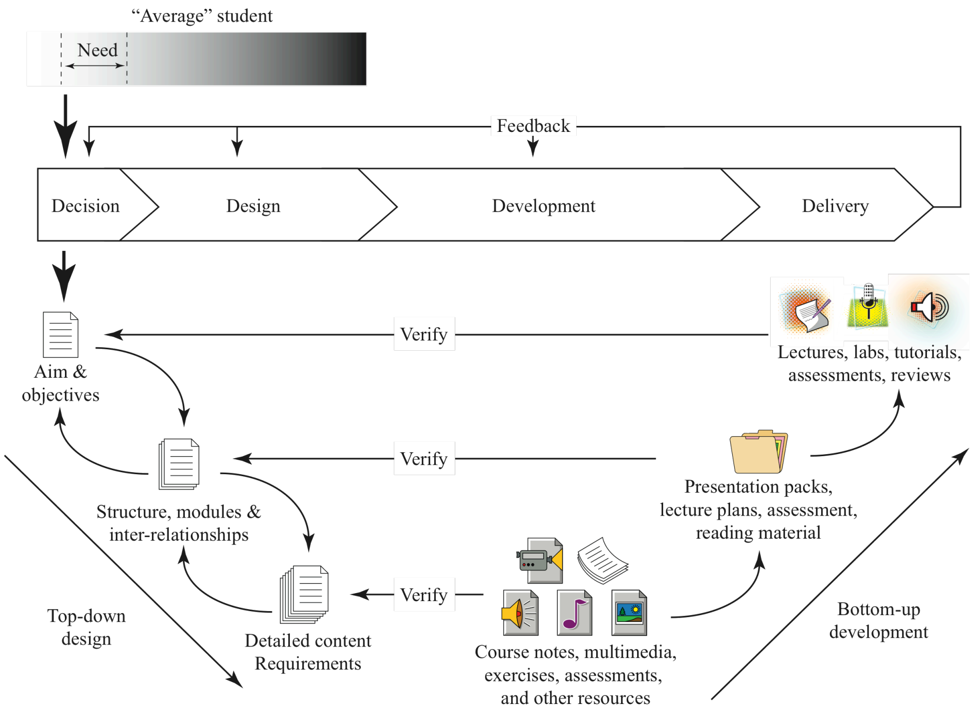

Figure 7. The integrated conceptual framework (Faulconbridge, 2008).

EVALUATION OF THE CONCEPTUAL FRAMEWORK

The conceptual framework presented in this paper has been used to develop successful courses in radar systems, avionics systems and systems engineering. Faulconbridge (2008) provides a detailed explanation of how the framework was used in each case, and the measures used to judge the effectiveness of each application of the framework.

The effectiveness of the framework has been judged by: the continued use of the courses in serving their original purpose; the significantly expanded application of each of the courses to serve additional audiences and educational needs; the technical publications that have resulted from the application of the framework; and the positive responses from students and experts who have reviewed the courses and publications.

This paper discussed the application of the conceptual framework to the development of a radar systems course initially developed for officers under training in the Royal Australian Navy. This course continues to be delivered and refined in accordance with the feedback element of the conceptual framework. The framework has also been successful in adapting the original radar course to support other educational needs at UNSW@ADFA including:

- professional development short courses;
- Masters-level technology courses; and
- undergraduate engineering courses.

Elements of the radar course were also used to support the sensor sections of a course in military electronics delivered to 3rd year avionics engineering students at the Queensland University of Technology (QUT) in 2009.

The conceptual framework presented in this paper also resulted in the publication of a radar systems textbook (Faulconbridge, 2002). Since its publication in 2002, more than 1,000 copies of the text have been sold. The Royal Netherlands Navy, and a provider of professional development courses in the United States have also adopted the text to support their radar training requirements.

CONCLUSION

The conceptual framework presented in this paper combines systems thinking and key aspects of the Scholarship of Teaching and Learning, and is an effective tool for the design, delivery, and review of technical courses to different cohorts of adult learners. A case study was used to illustrate how the framework has been used to develop a radar systems course for RAN officers.

The framework was developed around a simplified, five-stage, educational lifecycle model. The first stage in the lifecycle model is the identification of a learning need, and the decision to develop a learning activity to address that need. The educational need sits on top of a virtual VEE and initiates a top-down design and development effort. The process builds on the educational need by developing an integrated and meaningful knowledge structure. From this knowledge structure, a suitable course structure and the content of the associated modules and resources are determined. Once the design stage has been completed, the development and sourcing of appropriate learning resources begins. The resources are verified against the relevant design requirements before being integrated to form presentation packs. The course is delivered to the target audience during the delivery stage. The target audience provides a major source of review and feedback during and after the delivery, which is used to feed back into subsequent design and development process. The feedback is designed to improve the learning experience and to ensure the experience addresses the defined learning need.

The framework described in this paper provides teachers with a simple but effective tool to design and deliver technical courses for adult learners.

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BIOGRAPHIES

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Ian has a Doctorate, Masters, and Bachelors degree in engineering and an MBA in project management. He is a Fellow of Engineers Australia, a Chartered Professional Engineer, a Senior Member of IEEE, and a Registered Professional Engineer in Queensland.

Since 1990, he has held engineering, project management and academic positions in the fields of avionics, simulation, radar, communications and information systems. He is both an active academic and consultant. He teaches part-time at UNSW@ADFA, USQ, and QUT; and consults through his own management consulting business.

Prof. David Dowling

Professor David Dowling is passionate about helping engineering students learn and achieve their career goals. As Professor of Engineering Education at the University of Southern Queensland his research and development activities are focused on enhancing curricula, and teaching and learning environments. David was Associate Dean (Learning and Teaching) from 1995 to until January 2009. He was a President of the Australasian Association for Engineering Education in 2005-2006, and was awarded an Australian Learning and Teaching Council Citation in 2008. David was the lead author of the recently published first year text: Engineering Your Future: An Australasian Guide.