AC 2008-242: DEVELOPMENT OF AN ELECTROMAGNETICS COURSE CONCEPT INVENTORY

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Development of an Electromagnetics course concept inventory

Abstract
The results of the early stages of the development of an electromagnetics concept inventory and of the development of an on-line tool for automatic delivery, marking and analysis of concept inventory tests are presented. Specifically, key electromagnetics concepts and common student misunderstandings are identified, as a precursor to the establishment of the core concepts to be included in the inventory. The use of an on-line tool (OASIS) for automated delivery and analysis of concept inventories is outlined.

Introduction

Some seemingly academically well-prepared students struggle with their tertiary studies in the area of electromagnetics. Furthermore, these same students often report excessive study times for their courses and appear unduly stressed. We hypothesise that these students have misunderstood key physics concepts, which underpin later courses in engineering electromagnetics.

We propose the development of an electromagnetics course-concept inventory (EMCI), to be used in second- and third-year electromagnetics courses in a four-year electrical engineering degree. This concept inventory (CI) is to be used to provide lecturers with a quantitative measure of the level of class understanding over a range of core concepts. By delivering and analysing pre- and post-tests, such a tool can also facilitate the quantitative assessment of the effectiveness of particular teaching interventions or student engagement strategies. It is also intended that the tool could be used over successive years to reliably quantify entry standards into various courses and to check that standards are being maintained.

One of the individuals responsible for popularizing the use of concept inventories in Physics education is Richard Hake, Professor Emeritus at Indiana University. In Hake's words[1] "I see no reason that student learning gains far larger than those in traditional courses could not eventually be achieved and documented in disciplines other than physics, from arts through philosophy to zoology if their practitioners would:

1. reach a consensus on the **crucial** concepts that all beginning students should be brought to understand
2. undertake the lengthy qualitative and quantitative research required to develop multiple-choice tests of higher-level learning of those concepts, so as to gauge the need for and effects of non-traditional pedagogy, and
3. develop interactive engagement methods suitable to their disciplines."

We are attempting to follow this path for electromagnetics teaching. In this paper we discuss the process used to identify the key concepts around which the questions for an electromagnetics concept inventory are to be written. The routine use of concept inventories as a diagnostic tool would be enhanced if tools were available for automatic delivery and analysis. We further describe the use of a web-based skills practice and summative assessment tool (OASIS) for such a purpose.

History of Concept Inventories

The use of CIs as assessment tools in the STEM (science, technology, engineering and mathematics) communities arose from the work of David Hestenes and his graduate students at Arizona State University two decades ago. As discussed in Alstrum's[2] thorough review of concept inventory development, they sought to determine the extent of their students' mastery of physics concepts, in particular in the area of mechanics. The research began with the Mechanics Diagnostic Test of Halloun and Hestenes. This test was further developed into the well-known Force Concept Inventory (FCI)[3]. The FCI gained prominence when the Harvard physicist, Eric Mazur, used it and revealed the extent of his own students' misconceptions[4]. Richard Hake, from Indiana University, subsequently led the effort to validate this instrument with data from over 6000 students[5]. Hake has subsequently passionately advocated the use of the FCI in physics education, and has presented convincing results derived from FCI assessments in support of a move from lecture-centered instruction to more active, hands-on approaches.

While study of concept mastery is well developed in physics education research, it is only recently that concept mastery studies have received attention in engineering education research. Inventories have now been created and are continuing to be developed for several fields, including electromagnetic waves, signals and systems, strength of materials, thermodynamics, materials science, statistics, heat transfer, fluid mechanics, chemistry, biology, electromagnetics and circuits. The initial coordinating force behind many of these efforts was the Foundation Coalition (details of which may be found at http://www.foundationcoalition.org/index.html). Their efforts have formalized the manner in which CIs are developed, validated and deployed.

In recent times, responsibility for the dissemination of information on the development and the use of CIs has been assumed by a group known as Concept Inventory Central (details of which may be found at: https://engineering.purdue.edu/SCI/workshop). This dissemination occurs principally by way of workshops run at major education conferences[6] and via information stored on their website.

There are two CIs identified on the Foundation Coalition and Concept Inventory Central websites that have relevance to this research: specifically, the Electromagnetics Concept Inventory[7] and the Wave Concept Inventory[8]. Our research has been significantly informed by their efforts. However, there are major differences between the electromagnetics courses in our department and those for which these instruments were developed. In particular, we include considerably more magnetics content, including treatment of magnetic circuits, transformers and rotating machinery. There are consequential adjustments in the manner of our treatment and sequencing of the fields material. In the light of the above differences, it was judged that the existing inventories were not appropriate for our courses. Instead, we chose to carry out research that would enable us to develop our own electromagnetics inventory from scratch. This paper reports the early stages of our research and development.

Structure of a Concept Inventory

A concept inventory is a diagnostic assessment instrument that usually includes a small number of multiple-choice questions (MCQ) designed to cover concepts from a particular subject area; for example, electromagnetics. Typically, an assessment might be based on ten concepts, with three questions per concept, giving a total of 30 questions. The MCQ consist of a statement followed by a number of options as answers. The answer options consist of two types:

- The correct choice
- A number of incorrect options, called distractors.

Ideally, these distractors are carefully chosen so as to correspond to common misconceptions held by students.

Some CI developers use multiple true-false (MTF) items (in which there is more than one correct answer) as an alternative to multiple-choice items. Multiple-choice items are favoured by most CI developers because the goal of a CI is to understand student misconceptions based on their responses and multiple-choice items provide a better basis for zeroing in on specific misconceptions. Those who favour MTF items do so because they wish to probe cognitive development levels as well as simply identifying the extent to which common misconceptions are held. Knowledge of multiple correct answers has been tied to the levels of learning[8] as presented by Bloom's Taxonomy of Educational Objectives[9].

Developing a Concept Inventory

Richardson[10] has identified five activities that must be carried out in the process of constructing a concept inventory:

1. Determine the concepts to be included in the inventory.
2. Study the student learning processes for those concepts.
3. Construct an assessment instrument in which each concept is targeted by several multiple-choice items.
4. Administer beta versions of the instrument to determine reliability and validity.
5. Revise the inventory to improve readability, reliability, validity and fairness.

Because most CIs are designed to be completed in about 30 minutes, CI instruments can cover only a small number of concepts, typically ten. The first step in constructing a CI assessment instrument is the identification of such concepts. This identification usually entails surveying domain experts. Recently, inventory developers have used the Delphi method to identify the important concepts: "The Delphi method is based on a structured process for collecting and distilling knowledge from a group of experts by means of a series of questionnaires interspersed with controlled opinion feedback"[11]. Typically the domain experts will be asked to identify both the key concepts and also the areas where students display the most serious misunderstandings. The process is iterative: the inventory developers repeatedly circulate the latest compiled lists of key concepts and core misunderstandings for voting on by the domain experts, gradually reducing the number of items to around ten.

Following the identification of the key concepts, the student learning processes for these concepts are probed. This second step typically involves the construction of a series of open-ended questions, each of which focuses on a single key concept. Students are then asked to give written responses to these questions, and these responses are analysed. Of primary interest are the incorrect responses, because these help reveal common misconceptions. To illuminate these misconceptions, the inventory developers either interview the students individually or facilitate focus-group discussions to determine why the students gave the responses that they did.

In the third step, the misconceptions identified via the above processes are then used to inform the design of the multiple-choice items in the concept inventory, in particular the distractors. It is generally considered that student input as outlined above is essential in the generation of effective distractors. For example, without dialogue with students there is a high probability that inventory developers may fail to identify the actual reasons for incorrect student responses and may therefore produce distractors that are ineffective and inappropriate. Each key concept is targeted by more than one multiple-choice item. In this way a more reliable determination can be made of a student's grasp of each concept. It may also be that a student has an adequate grasp of a concept in one context but harbours misconceptions in another.

The fourth step is to administer beta versions of the CI to large numbers of students and to analyse the results statistically to establish the reliability and validity of the CI in identifying misconceptions. Reliability is essentially a measure of whether students will answer items similarly if they take the CI more than once. Validity is concerned with whether the items truly are exposing the misconceptions they are designed to reveal. Reliability can be established through statistical analysis of the results, while validity must be addressed throughout the development of the instrument.

The final step is to revise the inventory (in the light of the results from the beta test) in order to improve reliability and validity.

Developing the University of Auckland EMCI

The first step in the development of the EMCI at the University of Auckland was to examine the learning outcomes for the courses in the electromagnetics stream[12]. These had been collected as part of a related education-research project[13]. The learning outcomes for the year-two and year-three courses (ELECTENG 204 and ELECTENG 307, respectively) are provided in Appendix 1.

The second step was to categorize the subject matter and then identify the important concepts in each category to be covered in the two courses. These concepts were identified from the course outlines, which had themselves been developed over several years by a number of different academic staff. These electromagnetics concepts are presented in Appendix 2.

The third step was to circulate this concept list to a range of electromagnetics teaching staff and ask them to rank the ten most important concepts for each course and to identify the misconceptions that students are likely to have about each of the concepts in the complete list (i.e. that in Appendix 2). While this did not exactly follow the format for a Round 0 Delphi study[11], we found that busy academic staff were more receptive to participating in this study when provided with a broad concept list, rather than working from a "blank sheet". However, all of the participants (i.e. the domain experts) were encouraged to add to the broad concept list on the basis of their experience.

The key areas identified and the related concepts are presented in Table 1.

Key Areas Identified	Related Concepts
Electrostatics	forces on charges, E, D, electric field lines
Electric Potential	relation between V & E, equipotential curves
Magnetostatics	magnetic field produced by currents, H, B
Gauss's Law	
Capacitance	
Interaction with materials	conductance, permittivity, permeability, boundary conditions
Magnetic fields produced by currents	Ampere's Law, Biot-Savart Law
Magnetic forces on moving charges and currents, and torques on current loops	
Induced emf	motional emf, transformer emf, Faraday's Law, Lenz's Law
Inductance	

Table 1. Key areas and Concepts identified by Domain Experts

The areas in which students commonly display misconceptions (as identified by the domain experts) are presented in Table 2. It is interesting to note that several of the student misunderstandings identified by the domain experts are generic: they are also prevalent in a range of areas beyond electromagnetics.

What models are and why they are useful in Engineering
The use of complex numbers in the analysis of AC circuits and the related use of phasors
The difference between vectors and phasors
How voltage / electric field and current / magnetic field are related
Why and how we use dB units
Electric Potential (e.g. some students do not know that the voltage drop across a short circuit is zero volts)
Lenz's Law
Use of conservation of energy / power to determine whether answers are sensible

Table 2. Common student misconceptions

Iterative voting (underway at the time of submission of this paper) will be used to rank the ten most important concepts and to rank the associated misunderstandings of these concepts. It is interesting to note that to some extent the concepts and to a greater extent the misunderstandings presented in Tables 1 and 2 relate mainly to material covered in the year-two course rather than the year-three course. The implication of this observation is that the domain experts perceived that the most significant impediments to student learning in the year-three course were misunderstandings of material presented in a pre-requisite course a year earlier. Indirectly, this is confirmation of the premise underlying the adoption of course concept inventories in general.

Subsequent stages of development of the concept inventory will involve:

- student focus groups, in which the students will be asked to write about the key concepts (to identify misconceptions)
- the writing of the multiple-choice questions (including distractors)
- the circulation of an alpha version of the inventory amongst subject experts
- a validation trial of a beta version of the inventory on students
- the psychometric evaluation of the inventory, possibly followed by further revision.

Both the delivery of the CI and the analysis of the student responses can be performed effectively by Internet-based software, and there are clear advantages in doing so[14]. In particular, automated data acquisition and analysis is virtually essential if responses from large numbers of students are to be processed in a timely fashion. Fortunately, within our department we have developed a software package (OASIS) which is well suited to such assessment delivery and analysis[15,16].

OASIS

The Department of Electrical and Computer Engineering at the University of Auckland saw computer-based assessment as the best way to maintain educational standards in the face of increasing workloads. Partly for reasons of cost, and partly because of perceived deficiencies in some commercial packages, the Department produced its own software package, OASIS, (which stands for Online Assessment System with Integrated Study). OASIS is a Web-based tool used for skills practice and summative assessment. OASIS is written in the Python programming language and uses the PostgreSQL database for data storage. It runs on the Linux Operating system. The tool delivers individualized tasks, marks student responses, supplies prompt feedback, and logs student activity. OASIS comprises a large question database and server-side program (Figure 1) that delivers questions to students, marks their responses, provides instant feedback, and records students' activities. Because the Web server carries out all processing, students need only a computer with Internet access and a standard browser, making OASIS well suited to student-centred and large-class learning. The present version of the OASIS software package has been successfully used since 2003, with a prototype version being used prior to that[15]. Currently the capability of OASIS is being extended beyond the areas of skills practice and assessment, into the realm of educational research.

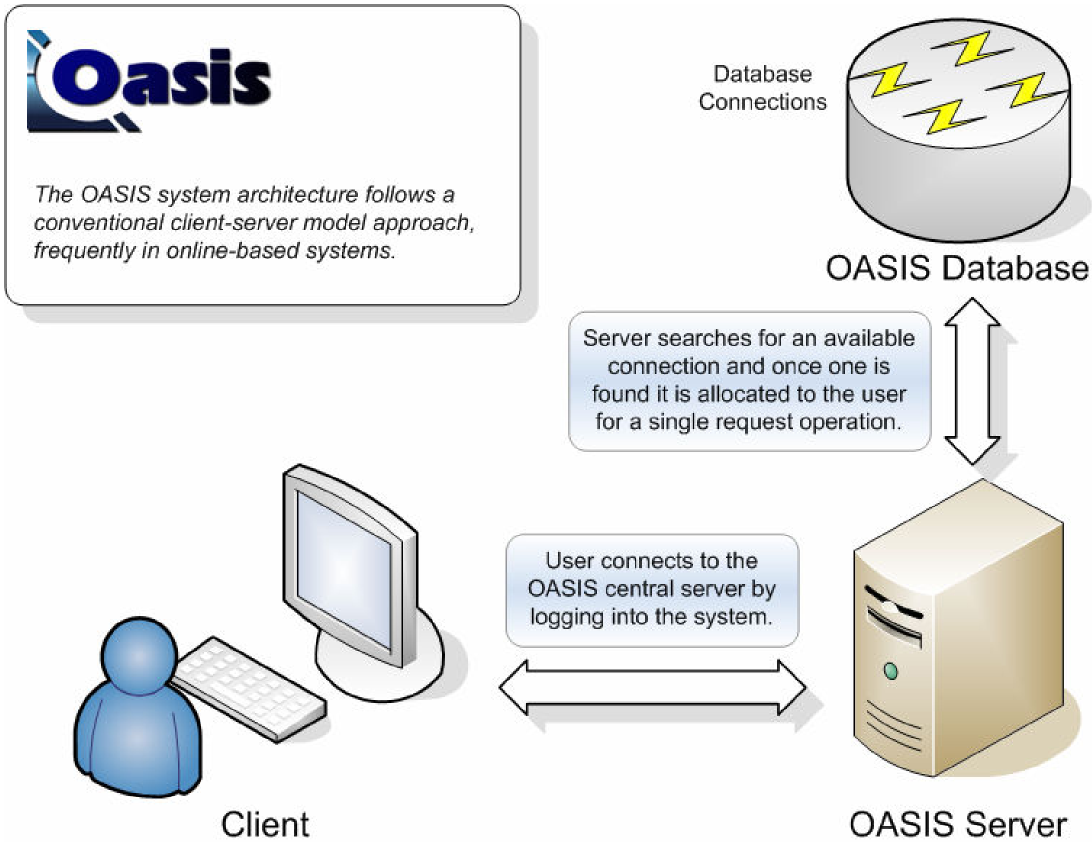

Figure 1. Schematic diagram of OASIS Architecture

Automated delivery and analysis of concept inventories

The implementation of concept-inventory questions on OASIS is straightforward and well within the current capabilities of OASIS. The only difference is that concept inventories use MCQ and (sometimes) MTF questions (with many graphical items) whereas most practice questions on OASIS are numerical. The implementation of these MCQ and MTF questions did however necessitate a small number of changes in the OASIS Question Editor software. If automated concept inventory delivery tools are to be widely adopted, it is important that the entry of questions is easy and requires no special expertise. The Question Editor (Figure 2), supplemented with a standard software package for the production of graphics, spares instructors the need to become familiar with the HTML mark-up language.

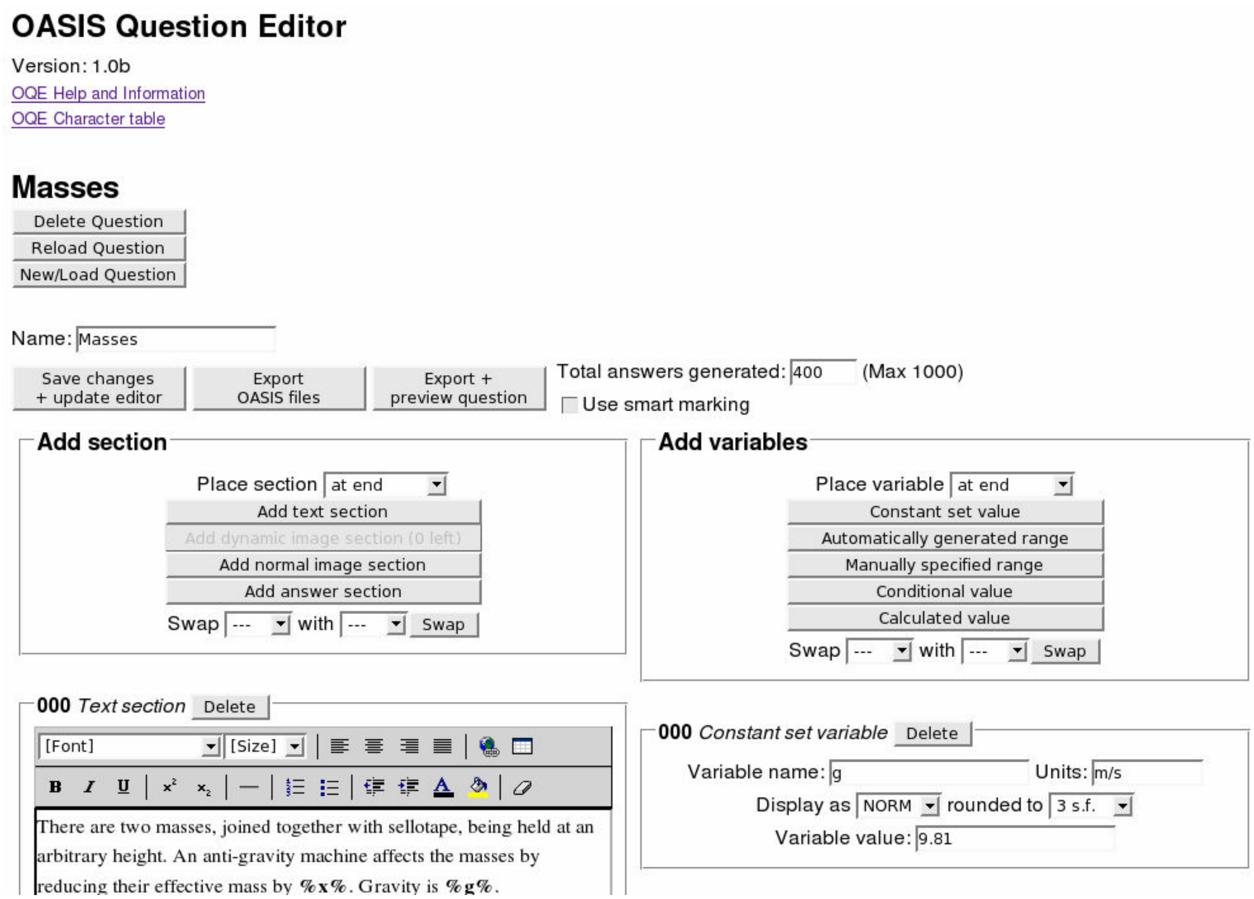

Figure 2. OASIS Question Editor

We are currently working on the development of software to analyze student performance on the course-concept questions. The project software specifications require statistical analysis of correct answers and also, more importantly, of misconceptions held by students. The three quantitative measures required are reliability, discrimination and difficulty.

For a test to be useful it must be both reliable and valid. Validity can only be addressed during development of the instrument. However, reliability can be measured. We are using the Kuder-Richardson Formula 20 (KR-20) to evaluate test reliability. The KR-20 reliability value is based on: number of test items, student performance on every test item and variance for the set of student test scores. The KR-20 index ranges from 0.0 to 1.0, with tests with an index of 0.6 or better generally regarded as being acceptable.

The Point Biserial Correlation is being used to measure the ability of a particular question to differentiate between the students who scored well overall on the test from those who did not. The Point Biserial Correlation Coefficient is based on: student performance on that test item, test score average of the students who answered the question correctly and standard deviation of the set of student test scores. The index ranges from -1.0 to +1.0, and generally a correlation of +0.2 and above is desirable.

Item difficulty is easily quantified from correct vs. incorrect answer statistics.

Conclusions

A multi-phase iterative research project to develop an electromagnetics concept inventory for years two and three of a four-year electrical engineering degree is described. The primary deliverables of our (on-going) research will be an electromagnetics concept inventory and an on-line tool which can automatically deliver concept inventories to students and analyse their responses. The results of the first two phases of the research (to identify the relevant subject-specific concepts and misunderstandings and to develop an on-line tool for automated delivery and analysis of concept inventories) are presented.

A (modified) Round 0 Delphi survey of Domain Experts has identified a range of core electromagnetics concepts and a range of common student misunderstandings. These differ from previous concept inventories in that they also include concepts and misunderstandings related to magnetic circuits, single-phase transformers and induction machines. Iterative voting (underway at the time of submission of this paper) will identify the ten most important concepts and the most significant misunderstandings of these concepts. It is interesting to note that several of the student misunderstandings identified by the Domain Experts are generic: they are also prevalent in a range of areas beyond electromagnetics.

In parallel with the development of the electromagnetics concept inventory, we are expanding the functionality of an on-line student practice tool (OASIS) to facilitate the automated delivery, marking and analysis of concept inventories. Facilities developed to date include automated delivery and marking of multiple-choice questions, a question-editor to facilitate entry of questions, and analysis software to quantify question reliability, discrimination and difficulty.

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Appendix 1 Learning Outcomes

ELECTENG 204 Engineering Electromagnetics

The learning outcomes of this course are:

1. To be able to explain the conduction, dielectric and magnetic properties of materials and be able to calculate current densities, field strengths and energy storage in electrical materials.
2. To be able to apply electrostatic and magnetostatic principles to the analysis of appropriate engineering systems.
3. To be able to calculate the magnetic field arising from simple combinations of conductors carrying steady electric currents.
4. To be able to use Ampere's law and the Biot-Savart law for the calculation of the magnetic fields arising from simple combinations of conductors.
5. To be able to apply the principles of electromagnetic induction to the analysis of appropriate engineering systems.
6. To be able to apply Faraday's law to the analysis of appropriate engineering systems.
7. To be able to explain Maxwell's equations expressed in integral form.
8. To be able to analyze simple transmission lines subject to transients, including:
   (a) the ability to draw and explain a distributed-parameter representation of a transmission line
   (b) the ability to relate the distributed-parameter values to transmission-line characteristics such as characteristic impedance and velocity of propagation.
   (c) the ability to calculate reflection and transmission coefficients of mismatched transmission lines
   (d) the ability to explain the characteristics of lossy transmission lines, specifically loss, dispersion and cross-talk.
9. To be able to perform calculations involving simple magnetic circuits, including calculations of magnetomotive force, flux and reluctance and the design of simple inductors.
10. To understand the operation of, and be able to perform simple calculations on, permanent magnetic circuits.
11. To be able to describe the equivalent circuits used to represent single-phase transformers and to calculate the equivalent circuit parameter values from short-circuit, open-circuit and DC tests performed on such transformers.
12. To be able to describe the equivalent circuit used to represent an induction machine and to perform simple calculations of output power, output torque, efficiency, input power and input current for such machines.

ELECTENG 307 Transmission Lines and Systems

The learning outcomes of this course are:

1. To extend the treatment of transmission line concepts introduced in ELECTENG 204 to include:
   (a) the ability to analyze transmission lines subject to AC excitation
   (b) the ability to use a Smith Chart to analyze mismatched transmission lines.
2. To be able to explain basic antenna performance characteristics, such as radiation pattern, gain, beam-width, input impedance and bandwidth.
3. To be able to explain both the sources of EMI and the shielding techniques employed to reduce such interference.
4. To extend the treatment of the basic concepts of electromagnetism begun in ELECTENG 204 to include
   (a) the ability to explain Maxwell's equations in both integral and differential form
   (b) the ability to demonstrate the development of the wave equation from Maxwell's equations
   (c) the ability to explain the sources of electromagnetic radiation.
5. To be able to calculate key characteristics of wave propagation in free space and in a general dielectric, such as wavelength, wave number, propagation constant and attenuation.
6. To be able to explain the concept of wave polarization and to categorize the types of polarization used for various communications systems.
7. To be able to characterize the behaviour of a plane wave normally incident on conductors and on general dielectrics.
8. To be able to apply a transmission-line model to the investigation of wave propagation in general media.

Appendix 2 Key Electromagnetics Concepts

ELECTENG 204 Concepts

Electrostatics
Coulomb's law
Electric field strength and electric flux density; the relationship $D = \varepsilon E$
Electric potential and potential difference
Relationship between E and V
3D vectors for force / field representation
Conductors in electric fields
Gauss's law
Storage of electric energy
Capacitance
Dielectric materials, including polarization

Magnetic Field and Steady Electric Currents
Magnetostatics
Magnetic field intensity and magnetic flux density; the relationship $B = \mu H$
Ampere's law
Magnetic field of a current element (Biot-Savart law)
Magnetic fields of a current loop and of a solenoid
Magnetomotive force
Force on a current element in a magnetic field
Force between two long parallel current-carrying conductors
Torque on a coil in a magnetic field

Electromagnetic Induction
The motion of charges in magnetic fields
Electromotive force induced in a conductor moving through a magnetic field
Electromotive force induced in a stationary circuit by a changing magnetic field
Faraday's law and its applications
Inductance (self and mutual)
Maxwell's equations in integral form (excluding displacement current)

Magnetism
Magnetic properties of matter
Domain theory
Magnetization curves
Magnetic field energy storage
Magnetomotive force
Magnetic circuits
Permanent magnets
Hysteresis and eddy-current losses
AC excitation of a magnetic core
Equivalent circuit and phasor diagram of a magnetic core

Transformers
Ideal (single-phase) transformer
Equivalent circuit of a (practical) single-phase transformer
Open- and short-circuit tests
Efficiency and voltage regulation
Autotransformers

Introduction to Electrical Machines
Electromechanical energy conversion
Linear and rotary transducers
The DC commutator machine
The 3-phase induction machine

Transmission Lines
Distributed-parameter modeling of transmission lines
Characteristic impedance and velocity of propagation
Surges and pulses on lossless lines
Reflection and transmission coefficients
Time-domain reflectometry
Characteristics of lossy lines - loss, dispersion, crosstalk

ELECTENG 307 Concepts

Transmission Lines
AC operation
Characteristic impedance and propagation constant
Input impedance
Smith chart
Distributed parameters R, L, G and C
Skin effect

Fields and Waves
Displacement current
Maxwell's equations (in both integral and differential form)
The wave equation
Plane waves in free space - wavelength, propagation constant
Waves in a general dielectric - wavelength, propagation constant, attenuation
Wave polarization
Application of transmission-line model to wave propagation in general media
Reflections from perfect conductors and dielectrics at normal incidence
Introduction to antennas - radiation pattern, gain, beam-width, input impedance and bandwidth
EMI sources / shielding techniques